

**LONG TERM SEISMIC PROGRAM
FINAL REPORT**

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The Diablo Canyon Power Plant, San Luis Obispo County, California.

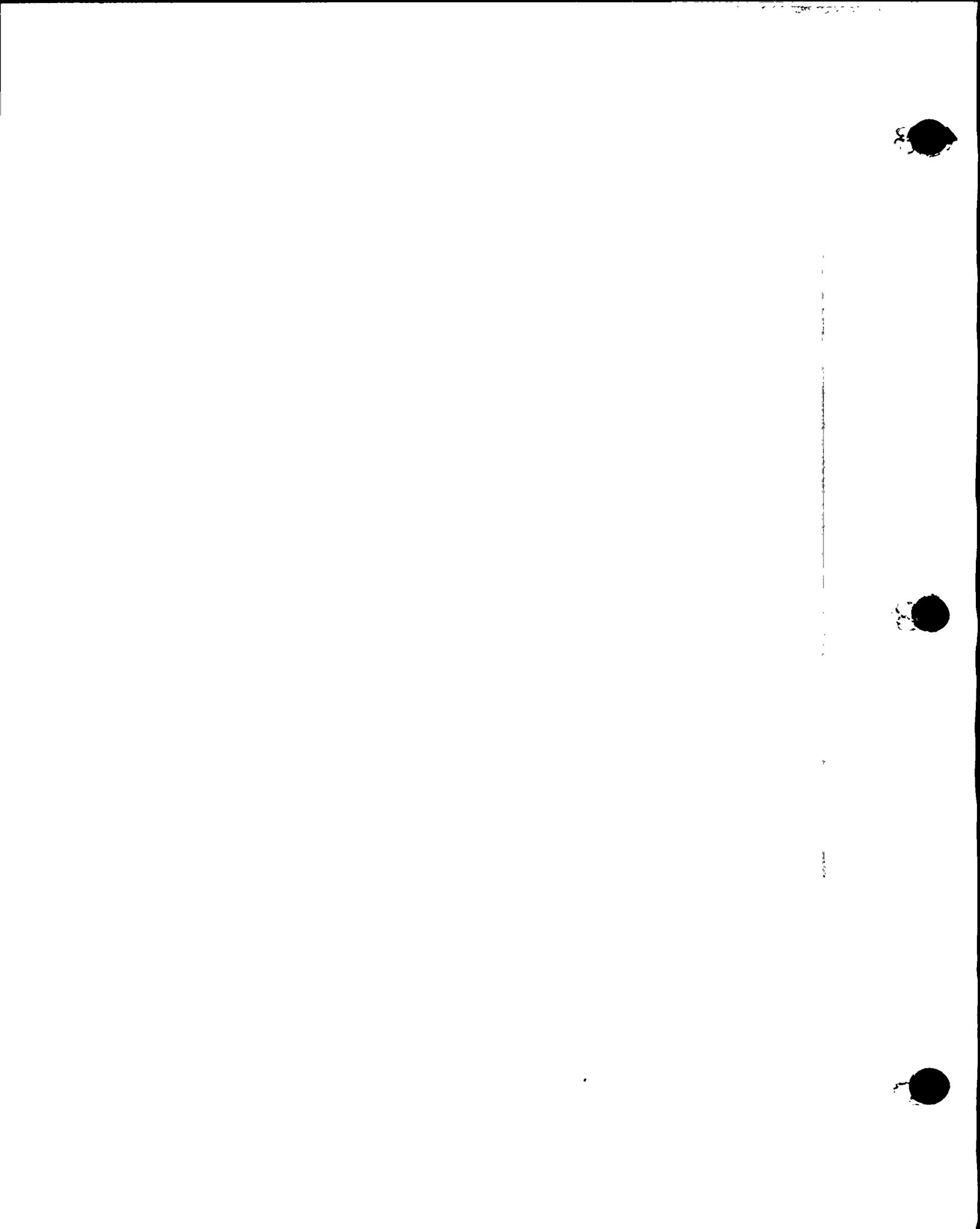


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LONG TERM SEISMIC PROGRAM
FINAL REPORT



EXECUTIVE SUMMARY

Pacific Gas and Electric Company (PG&E) has performed a reevaluation of the seismic design bases for the Diablo Canyon Power Plant, as specified in the Unit 1 Full-Power Operating License, DPR-80, Condition 2.C.(7), issued by the Nuclear Regulatory Commission (NRC) on November 2, 1984. This report documents PG&E's work performed in accordance with that requirement, and demonstrates that PG&E has satisfied the requirements of the license condition.

The Long Term Seismic Program evaluations of existing and new geologic and seismologic data, and the interdisciplinary work related to characterization of seismic sources of significance to the Diablo Canyon site, enabled PG&E to conclude that a maximum earthquake magnitude of 7.2 on the Hosgri fault zone provides a very conservative basis for evaluating the adequacy of structures, systems, and components. A substantially enlarged data base of strong-motion recordings close to large earthquakes together with simulation procedures were used to estimate conservative free-field ground-motion spectra. Current engineering procedures provided a reliable basis for evaluating structural responses to the ground motions generated by the maximum earthquake. A probabilistic risk analysis incorporating the results from a seismic hazards analysis and fragility assessments, as well as deterministic evaluations, supported the conclusion that the seismic design and existing seismic margins of Diablo Canyon Power Plant are adequate.

BACKGROUND

In 1973, PG&E applied to the NRC for operating licenses for Diablo Canyon Power Plant, Units 1 and 2. During the licensing process, the NRC's Advisory Committee on Reactor Safeguards (ACRS) reviewed the seismic and nonseismic aspects of the Plant. On July 14, 1978, the ACRS issued a letter report to the Commission stating

that it had completed its review of the operating license application. The ACRS letter concluded that if due consideration were given to the items in its report, and subject to completion of the necessary Plant modifications and preoperational testing, there was reasonable assurance that Units 1 and 2 could be operated at full power without undue risk to the health and safety of the public.

With regard to seismic issues, the ACRS stated:

The ACRS notes that, for distances less than 10 km from the earthquake source, there are currently no strong motion data for shocks larger than magnitude 6 and few reliable data for shocks of magnitude 5 and 6. Also, the theory and analyses of earthquake and seismic wave generation, of seismic wave transmission and attenuation, and of soil-structure interaction are in a state of active development. The Committee recommends that the seismic design of Diablo Canyon be reevaluated in about ten years taking into account applicable new information.

It was this recommendation that eventually led to issuance of the conditions on Unit 1's low-power and full-power operating licenses requiring a reevaluation of the seismic design bases of the Plant.

In a meeting on August 2, 1984, the NRC voted in favor of issuance of a full-power license for Unit 1. It subsequently issued an Order that became effective with issuance of Unit 1 Facility Operating License DPR-80 on November 2, 1984. In DPR-80, the license condition, Item 2.C.(7), reads as follows:

Seismic Design Bases Reevaluation Program

PG&E shall develop and implement a program to reevaluate the seismic design bases used for the Diablo Canyon Nuclear Power Plant.



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The program shall include the following Elements:

- 1) PG&E shall identify, examine, and evaluate all relevant geologic and seismic data, information, and interpretations that have become available since the 1979 ASLB hearing in order to update the geology, seismology and tectonics in the region of the Diablo Canyon Nuclear Power Plant. If needed to define the earthquake potential of the region as it affects the Diablo Canyon Plant, PG&E will also reevaluate the earlier information and acquire additional new data.*
- 2) PG&E shall reevaluate the magnitude of the earthquake used to determine the seismic basis of the Diablo Canyon Nuclear Plant using the information from Element 1.*
- 3) PG&E shall reevaluate the ground motion at the site based on the results obtained from Element 2 with full consideration of site and other relevant effects.*
- 4) PG&E shall assess the significance of conclusions drawn from the seismic reevaluation studies in Elements 1, 2, and 3, utilizing a probabilistic risk analysis and deterministic studies, as necessary, to assure adequacy of seismic margins.*

PG&E shall submit for NRC staff review and approval a proposed program plan and proposed schedule for implementation by January 30, 1985. The program shall be completed and a final report submitted to the NRC three years following the approval of the program by the NRC staff.

PG&E shall keep the staff informed on the progress of the reevaluation program as necessary, but as a minimum will submit quarterly progress reports and arrange for semi-annual meetings with the staff. PG&E will also keep the ACRS informed on the

progress of the reevaluation program as necessary, but not less frequently than once a year.

PG&E's reevaluation effort was named the "Long Term Seismic Program." The objective of the Long Term Seismic Program was to satisfy the license condition set forth above, using new techniques and data developed since 1979, to reevaluate the seismic design bases. The Program has consisted of three phases, starting with Phase I, during which the Program Plan was developed. In Phase II, the Program Plan was refined and the scope of work was focused and priorities established. In the final phase, Phase III, the program tasks were implemented and documented, and this final report was prepared.

LONG TERM SEISMIC PROGRAM

Phase I—Program Plan Development

Following issuance of the low-power license condition in early 1984, PG&E initiated efforts to formulate a detailed program that would be responsive to the license condition. Expert consultants also participated in this effort. In addition, there were frequent interactions during Phase I between the NRC Staff and PG&E to address and resolve comments by the NRC Staff on the intent and goals of the Program: meetings were held on May 8 to discuss the requirements of its license condition, on May 24 to review the license condition with the ACRS subcommittee, and on June 14 to review the license condition with the full ACRS. Topical meetings were held on geology and tectonics on October 4, 1984; on earthquake magnitude and ground motions on November 15; on soil/structure interaction on November 16; and on probabilistic risk assessment on December 11, 1984. A final meeting to review the Program Plan was held on January 10, 1985.

The Program Plan was submitted to the NRC Staff on January 30, 1985, as required by the license condition. The plan consisted of eight technical areas, each of which was responsive in whole or in part to one of the four elements of the license condition (Table 1).



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Table 1

RELATIONSHIP OF LICENSE CONDITION ELEMENTS TO THE PROGRAM PLAN

LONG TERM SEISMIC PROGRAM PLAN	LICENSE CONDITION			
	<u>Element 1</u> Geologic and Seismic Data Compilation, Collection, and Evaluation	<u>Element 2</u> Earthquake Magnitude Reevaluation	<u>Element 3</u> Earthquake Ground-Motion Reevaluation	<u>Element 4</u> Assessment of Adequacy of Seismic Margins through Probabilistic Risk Analysis and Deterministic Studies
SECTION 3 Geologic Investigations Neotectonics Studies Geophysical Data Collection Seismic Source Characterization (Work Plan Tasks 1 through 9)	X	X		
SECTION 4 Assessment of fault characteristics and collection of seismicity data to reevaluate earthquake magnitude (Work Plan Tasks 3 and 9)	X	X		
SECTION 5 Empirical Ground-Motion Studies			X	
SECTION 6 Numerical Ground-Motion Studies			X	
SECTION 7 Soil/Structure Interaction Analysis				X
SECTION 8 Seismic Hazard Analysis				X
SECTION 9 Seismic Fragility Analysis				X
SECTION 10 Probabilistic Risk Analysis				X

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Throughout the review of the Program Plan, during the first half of 1985, the NRC Staff and PG&E communicated through correspondence and public meetings. The ACRS also held public meetings, in March and July 1985, to review the Program Plan with the NRC Staff and PG&E. The ACRS agreed that the Program Plan was responsive to the license condition in a letter to the Commission following its full committee meeting July 11-13, 1985. The NRC Staff approved the Program Plan on July 31, 1985.

The overall responsibility for the Long Term Seismic Program was with PG&E's Senior Vice President and General Manager, Engineering and Construction, Donald A. Brand, assisted by Vice President of Engineering, William H. Wallace. The Program Manager, Lloyd S. Cluff, assisted by four Assistant Program Managers, had responsibility for Program implementation and direction.

PG&E selected staff and consultants to perform the work associated with the major technical areas of the Program. The participants were chosen on the basis of their leadership in technological development, their experience in their respective areas of expertise, and their familiarity with the licensing of the Plant.

CONSULTING BOARD AND TECHNICAL ADVISORS

A Long Term Seismic Program Consulting Board and Technical Advisors were key components of the Program organization. The primary function of the Consulting Board, which consisted of individuals eminently qualified in the subject areas of the Program, was to provide guidance to PG&E and its consultants to ensure the objectives of the license condition were achieved and that relevant theories, analytical techniques, and other pertinent, newly developed information were considered. This function was accomplished through reviews of technical developments and results as they became available. The Consulting Board actively participated in Program development and evaluation of investigative methods, suggested priorities for work tasks, and reviewed work in progress. The members of the Consulting Board and their affiliations are:

Clarence R. Allen, California Institute of Technology
 Bruce A. Bolt, University of California, Berkeley
 C. Allin Cornell, Stanford University
 Thomas M. Leps, Independent Consultant
 Cole R. McClure, Bechtel Civil, Inc.
 H. Bolton Seed, University of California, Berkeley

The Consulting Board met 19 times during the Program; the board's final report is presented following this Executive Summary.

Technical Advisors were assigned to each of the technical areas of the program. The Technical Advisors worked directly with the Program team to review the scope of work and to advise on the development of technical solutions. Continuing guidance from the Technical Advisors throughout the Program assured timely resolution of issues and contributed significantly to the expertise necessary for successful conduct of the technical investigations.

Phase II—Scoping Study

Following submittal of the Program Plan on January 30, 1985, work began on Phase II, an effort to refine and focus the scope of work. The objective of the Scoping Study was to develop detailed work plans to be carried out in each of the major tasks of the Program, and to schedule interfaces for each of the Program tasks. High-priority technical activities also were conducted.

During the first half of 1985, Phase II work proceeded in parallel with NRC Staff review of the Program Plan. The Scoping Study was performed taking into consideration comments from the NRC Staff and its consultants. Attention was focused on identifying the technical considerations that could most affect the Program in addressing the license condition. The first step in developing the work plans required defining the objectives for each task. When these were established, a series of subtasks and areas of investigation were identified that addressed each objective. Priorities were then set for the tasks according to their usefulness and potential for addressing the technical considerations. A report summarizing the results



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of Phase II was submitted to the NRC Staff on January 30, 1986.

Phase III—Implementation

As the Phase II effort neared completion and the details of specific work plans became more clearly defined, technical activities were initiated to implement Phase III of the Program. These activities included compilation and review of existing data, gathering necessary field data, developing computational models, developing logic trees and technical criteria, and, later, performing sensitivity studies and iterative analyses. The technical investigations were reviewed by the Technical Advisors, who aided in their development and implementation, as appropriate. In addition, the Long Term Seismic Program Consulting Board evaluated the validity and adequacy of the scope and results of these investigations.

Phase III encompassed all the interrelated, technical aspects necessary for a reevaluation of the seismic design bases, including studies of geology, seismology, geophysics, and neotectonics; seismic source characterization; ground-motion modeling and characterizations; soil/structure interaction assessments; seismic hazard analyses; seismic fragility analyses; probabilistic risk analyses; and deterministic evaluations.

COMPLIANCE WITH THE LICENSE CONDITION

Element 1 of the License Condition

PG&E shall identify, examine, and evaluate all relevant geologic and seismic data, information, and interpretations that have become available since the 1979 ASLB hearing in order to update the geology, seismology and tectonics in the region of the Diablo Canyon Nuclear Power Plant. If needed to define the earthquake potential of the region as it affects the Diablo Canyon Plant, PG&E will also reevaluate the earlier information and acquire additional new data.

To satisfy Element 1, PG&E conducted a 3-year program of literature review, discussions with researchers, field investigations, and office analyses to assess the neotectonic setting and earthquake potential of the south-central coast of California. In active tectonic environments such as coastal California, faults that have the potential for releasing significant earthquakes have stratigraphic and geomorphic evidence of repeated fault displacements and associated secondary deformation, such as folding. Reliable evidence for evaluating the potential for significant future earthquake activity is found in geologically young deposits and surfaces. Detailed geologic studies of these surfaces and deposits can reveal the past history of faulting and folding and provide valuable clues for predicting future earthquake activity. By understanding the amount and style of deformation during the past 500,000 years, active faults can be characterized, and related earthquake activity can be assessed with confidence.

Our studies addressed all the technical considerations identified in the Program Plan and Scoping Study. The investigations included a thorough review of existing published and available unpublished literature, data and interpretations; acquisition of additional geological, seismological and geophysical data in the onshore and offshore regions; and an evaluation of the past and contemporary tectonic setting and seismic source potential of south-central coastal California.

In addition to the evaluation of all relevant available geologic and seismologic data, extensive new data bases were developed for use in the Program:

- 990 kilometers of new high-resolution and deep-penetration seismic reflection surveys were commissioned, and the data processed and analyzed
- 9,037 kilometers of post-1978 seismic reflection data were purchased or acquired from government agencies and analyzed
- 5,849 kilometers of pre-1978 seismic reflection data were reviewed



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- Marine terraces were mapped in detail and dated along 90 kilometers of the south-central California coast
- Sixty-six trenches and natural exposures totaling 8,210 linear feet were logged and interpreted
- 240 boreholes varying in depth from about 15 feet to about 120 feet were drilled and logged
- More than 300 water-well and oil-well records were acquired and interpreted.

A significant additional study, not initially planned as part of the Program, was the installation and operation of the PG&E Central Coast Seismic Network, an 18-station high-gain network of telemetered seismographs installed along the coastal region from Ragged Point south to Point Sal. The network was designed to supplement the seismographic coverage of the region around the Diablo Canyon site by the University of California at Berkeley, the California Institute of Technology, and the U.S. Geological Survey. The data acquired by the network, and incorporated into the Program, have greatly improved the accuracy and resolution of locations and focal mechanisms of microearthquake activity in the region.

The existing information and the newly acquired information were evaluated and analyzed to assess the neotectonic setting and earthquake potential of the south-central coast of California, and particularly the Diablo Canyon site. This extensive data acquisition and analysis effort that fulfills Element 1 of the license condition has greatly improved our understanding of the site region and provides a high level of confidence in our conclusions regarding the geology, seismology, and tectonics important to assessing the earthquake potential of this region.

SUMMARY OF SIGNIFICANT FINDINGS AND RESULTS

Contemporary Tectonic Setting. Recent plate motion studies indicate that the south-central

California region is undergoing deformation resulting from northwestward movement of the Pacific plate relative to the North American plate, regionally modified by clockwise rotation of the Transverse Ranges. Most of the strike-slip motion between these plates is occurring on the main plate boundary fault zone, the San Andreas, located 75 kilometers east of the Diablo Canyon site (Figure 1). Comparatively minor amounts of slip are also occurring along other regional faults. Rotation of the Transverse Ranges has resulted in north-northeast-directed crustal shortening east of the Hosgri fault zone. This shortening is accommodated by displacement along west-northwest-trending reverse faults and by uplift, subsidence, or tilting of intervening crustal blocks. The Diablo Canyon site is located on one of these, the San Luis/Pismo structural block, which is bounded on the northwest by the Hosgri fault zone, the most significant seismogenic structure for Diablo Canyon.

The west-northwest-trending faults and crustal blocks east of the Hosgri are structurally separated from the offshore Santa Maria basin by the Hosgri fault zone. The offshore Santa Maria basin is not shortening northwestward as is the region east of the Hosgri fault zone; it is characterized by gradual block subsidence and scattered reverse and thrust faults that trend north-northwest, subparallel to the strike of the Hosgri fault zone. These faults are most prevalent in the southern offshore Santa Maria basin generally south of Point Sal. There is little evidence of contemporary compressional deformation west of the Hosgri between the latitude of Point Sal and the northern end of the Hosgri fault zone.

A well-developed series of late Quaternary wave-cut marine terraces and associated deposits are preserved along much of coastal California. In the site region, the coastline intersects the northwest-trending structural grain of the region. The wave-cut terraces, therefore, provide an excellent geologic strain gauge with which to





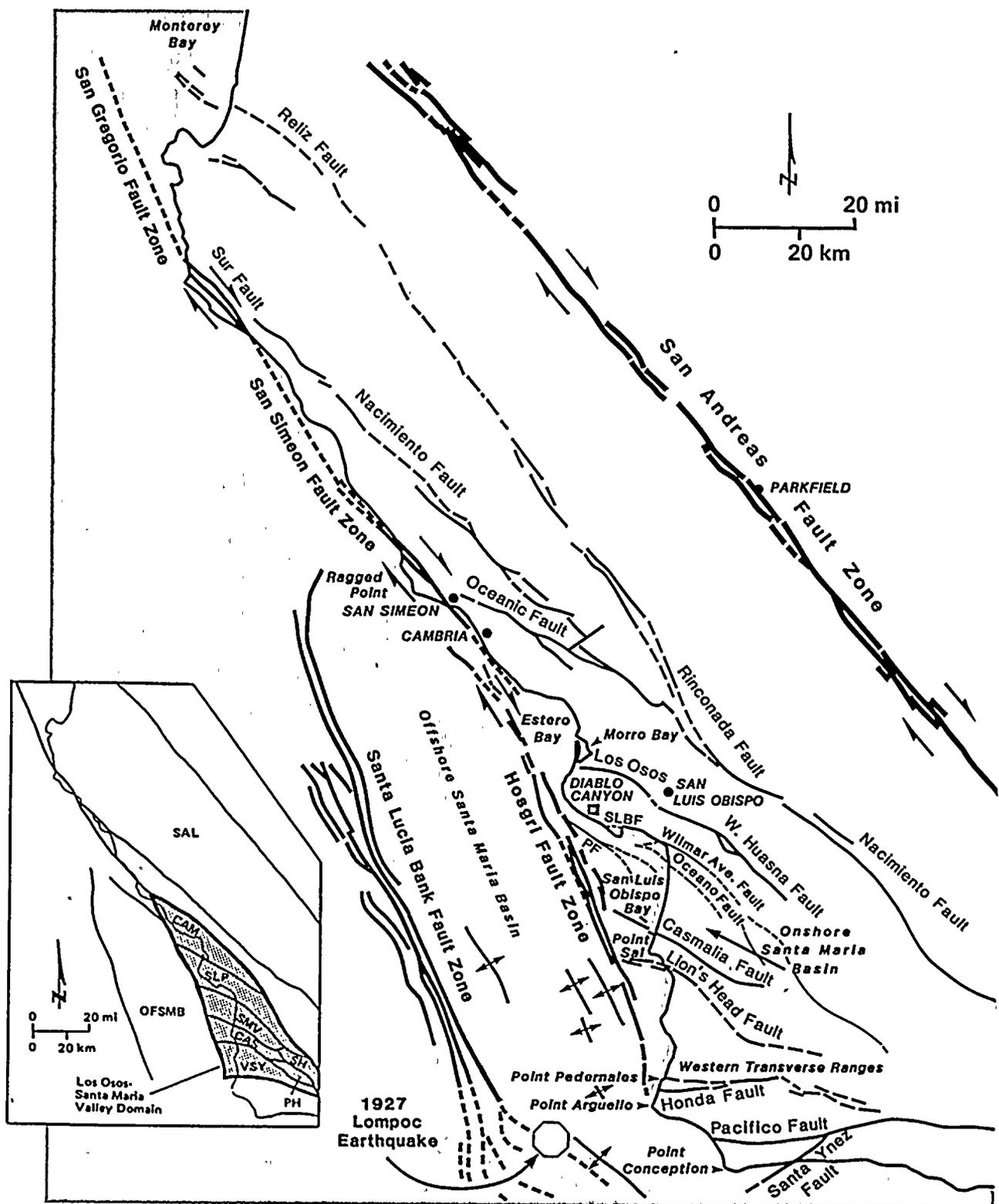


Figure 1

Map of regional faults and tectonic setting of the south-central California coastal region. SLBF is San Luis Bay fault; PF is Pecho fault. Structural blocks in inset map are SAL, Salinian; CAM, Cambria; SLP, San Luis/Pismo; SMV, Santa Maria Valley; CAS, Casmalia; VSY, Vandenberg; SH, Solomon Hills; PH, Purisma Hills.



evaluate the contemporary style of crustal deformation that characterizes expected future earthquake activity.

San Luis/Pismo Structural Block. The Diablo Canyon Power Plant is located on the southwestern part of the San Luis/Pismo structural block. The block is bounded on the northeast by the Los Osos fault zone, on the southwest by a diffuse zone of minor faults, and on the west-northwest by the Hosgri fault zone. Detailed mapping of marine and fluvial terraces documents rigid uplift of the block during at least the past 500,000 years. Folding of the Pismo syncline within the interior of the block probably ceased at least 1 to 2 million years ago. Previously mapped faults within the block, the Edna, San Miguelito, Indian Knob, and Pismo faults, do not disrupt the late Quaternary terraces, indicating absence of fault activity within at least the past 500,000 years. This documented lack of activity demonstrates that these faults are not active and, therefore, need not be considered as potential seismic sources. In addition, detailed mapping of marine and fluvial terraces demonstrates the absence of any previously unrecognized Quaternary faults and folds in the Plant area.

Recent studies have suggested that low-angle detachment faults may play a significant role in the regional tectonic setting of California. In this regard, Tertiary folds within the San Luis/Pismo structural block may have been associated with displacement of low-angle detachment faults at depth during a previous episode of deformation that ceased at least 1 to 2 million years ago. The lack of Quaternary deformation of these folds demonstrates that if these low-angle faults are present, they are not active.

Hosgri Fault Zone. Slip along the Hosgri fault zone for the past 2 to 3 million years is characterized by high-angle, strike-slip displacement. The zone extends from an en echelon step with the southern part of the San Simeon fault zone (offshore of Cambria) to its southern termination northwest of Point Pedernales.

A pre-Pliocene (2 to 5 million years ago) episode of compression produced reverse and thrust faults

within and immediately west of the Hosgri fault zone, many of which are imaged in geophysical data; however, these data show many examples where these faults are truncated by unbroken erosional horizons and undeformed sediments that are about 2 million years of age or older. These data demonstrate that these thrust faults are not active in the current tectonic environment.

The lateral slip rate on the northern end of the Hosgri fault zone, at the location of the Cambria en echelon step, is evaluated to be between 1 and 3 millimeters per year. Due to north-northeastward crustal shortening east of the Hosgri, the lateral slip rate decreases significantly to the south. The upper bound of the vertical component due to uplift and subsidence along the fault zone adjacent to the San Luis/Pismo structural block is about 0.4 millimeter per year; it is less than 0.2 millimeter per year in Estero Bay and San Luis Obispo Bay.

Los Osos Fault Zone. The Los Osos fault zone is a southwesterly dipping reverse fault zone that forms the northeastern structural margin of the San Luis/Pismo structural block. The fault consists of a segmented 2-kilometer-wide zone of discontinuous, subparallel and en echelon fault traces that clearly extend from Morro Bay southeast to the Lopez Regulating Reservoir, a distance of 36 kilometers. The fault is divided into four discrete segments that have distinct physical and behavioral differences and displacement histories. Displacements of marine and fluvial deposits indicate a late Quaternary net slip rate of not more than 0.2 to 0.5 millimeter per year.

Southwestern Boundary of San Luis/Pismo Structural Block. The San Luis/Pismo structural block is bounded along its southwestern margin by a diffuse zone of minor deformation consisting of northwest-trending reverse faults and monoclines. Individual structures within the zone, including the San Luis Bay, Wilmar Avenue, Pecho, and Oceano faults, are limited in extent and lateral continuity; the entire zone is 4 to 6 kilometers wide and about 60 kilometers long. This broad zone of minor deformation is in marked contrast to the northeastern margin of the San Luis/Pismo structural block, which is defined primarily by a



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single, well-defined fault zone, the Los Osos fault zone.

1927 Lompoc Earthquake. The November 4, 1927, Lompoc offshore earthquake was an important consideration in the previous Hosgri evaluation. Because this event is the largest historical earthquake to have occurred in the offshore region of south-central coastal California, we have evaluated it using current seismological methods and data.

The Lompoc earthquake was studied using waveform modeling analyses of regional and teleseismic records of the 1927 earthquake motions, and comparing them with recordings from recent, well-recorded western California earthquakes. Significant new information about the earthquake was developed during this effort. The Lompoc earthquake was found to have a nearly pure reverse fault mechanism striking N20W and dipping at 66 degrees northeast, a focal depth of about 10 kilometers, and a moment magnitude of 6.6 based on a seismic moment of 1×10^{28} dyne-centimeters. A review of the original magnitude data revealed that the surface-wave magnitude value for the event is 7.0 (rather than 7.3 or 7.5, as reported in earlier studies); this assessment was corroborated using a comparison with the 1983 Coalinga earthquake. The epicenter of the 1927 earthquake was constrained based on good-quality seismic recordings to be at approximately 34.5°N, 120.9°W, about 25 kilometers west of Point Arguello (Figure 1), and thus is not associated with the Hosgri fault zone. This location is in the actively compressing zone of folds and faults west of the Hosgri fault zone. This epicentral location is also consistent with intensity and tsunami data from the earthquake. The location and focal-mechanism data do not permit a conclusion that it was located near Point Sal, or to the south along the southern reach of the Hosgri fault zone, as has been previously suggested.

CONCLUSIONS

The requirements of Element 1 of the license condition have been met, and the reevaluation activities outlined in the Program Plan and Scoping Study have been completed. The

Program has incorporated the significant developments in earth science knowledge acquired during the past 10 years together with an extensively expanded data base for the Diablo Canyon region to provide a greatly improved understanding of the tectonic environment and earthquake potential in the region of the Diablo Canyon Power Plant. The detailed studies documented that the Hosgri fault zone is a segmented, steeply dipping, dominantly strike-slip fault, and is the most significant seismogenic structure for the site. Application of current seismological methods led to a clearer understanding of the location and mechanism of the 1927 Lompoc earthquake. It was also established that the magnitude of that event was 6.6 Mw and 7.0 Ms, and not 7.3 or 7.5 Ms as previously believed.

Element 2 of the License Condition

PG&E shall reevaluate the magnitude of the earthquake used to determine the seismic basis of the Diablo Canyon Nuclear Plant using the information from Element 1.

Based on the voluminous geologic, seismologic, and geophysical information developed and analyzed in response to Element 1, PG&E reevaluated the magnitude of the earthquake used to determine the seismic bases for the Diablo Canyon Power Plant.

In addressing this Element, we characterized the potential seismic sources of significance to the site. This characterization included aspects such as geometry, style of faulting, length of fault segments, and slip rate that relate not only to maximum earthquake magnitude, but also to other aspects of importance to the seismic hazard analysis, such as earthquake recurrence. To arrive at estimates of maximum earthquake magnitude on the Hosgri and other faults, we conducted a detailed study of the segmentation of the faults, and have considered the results derived from multiple maximum magnitude approaches. As a result of this analysis, we have arrived at high-confidence estimates of maximum earthquake magnitude on the Hosgri fault zone and other faults.



Based on geometric and geologic characteristics, the Hosgri fault zone can be divided into several segments. In particular, structural interactions with active faults to the east of the Hosgri fault zone affect the slip rate, trend, and continuity of the zone and are discrete segmentation points. In various combinations, these segments define possible rupture lengths on the Hosgri fault zone.

SUMMARY OF SIGNIFICANT FINDINGS AND RESULTS

The Hosgri fault zone was confirmed as the controlling seismic source. The dominant style of faulting on the zone is strike slip, with a minor dip-slip component. Through an evaluation of the magnitude-related characteristics of the Hosgri fault zone, we derived a conservative maximum earthquake magnitude of 7.2 M_w , at a distance of 4.5 kilometers. This maximum magnitude was used in the subsequent ground-motion analyses. It should be noted that the best-estimate of the maximum magnitude distribution from a multi-factor logic tree analysis was 7.0 M_w . However, we have very conservatively chosen a value that is two-tenths of a magnitude unit larger than this best-estimate for the ground-motion analyses.

The lack of deformation of late Quaternary deposits and associated surfaces in the Plant vicinity precludes the existence of significant unknown faults at the surface. In addition, there is evidence documenting no significant folding in the site vicinity during at least the past approximately 500,000 years and possibly the past 1,000,000 years. Therefore, we conclude that a blind Quaternary fault is not present at depth beneath the site area. In addition, any fault that might be inferred to exist in the San Luis/Pismo region on the basis of folding in the Tertiary section can be considered to be incapable of generating significant seismic events due to the lack of Quaternary surface deformation.

CONCLUSIONS

The requirements of Element 2 of the license condition have been met, and the reevaluation activities described in the Program Plan and Scoping Study have been completed. It is

concluded that a maximum earthquake magnitude of 7.2 M_w on the Hosgri fault provides a very conservative basis for seismic margin evaluations.

Element 3 of the License Condition

PG&E shall reevaluate the ground motion at the site based on the results obtained from Element 2 with full consideration of site and other relevant effects.

The evaluation of free-field ground motions at Diablo Canyon site was based on key findings of the studies performed to address license condition Elements 1 and 2. The ground-motion reevaluation activities integrated the results from both empirical and numerical modeling studies to assess the ground motions at the site and to provide specific ground-motion data needed for engineering analyses.

In the past decade, the worldwide data base of strong ground-motion recordings close to large earthquakes has been greatly enlarged, and enhances our ability to apply well-developed empirical approaches to estimate site-specific ground motions. In addition, procedures for the simulation of strong motion using numerical modeling techniques have been significantly improved and refined. These procedures have been further refined, validated, and applied to the Diablo Canyon site using site-specific information. By using these new developments, and the empirical and numerical approaches in a complementary, site-specific manner, we have obtained ground-motion estimates in whose accuracy we have a high level of confidence.

Specifically, the following were developed in response to Element 3 of the license condition: an updated worldwide strong motion data base for rock and soil sites; site-specific horizontal and vertical response spectra at the median and 84th percentile levels; and ground-motion input data for seismic hazards, fragility, and soil/structure interaction analyses. These data consisted of ground acceleration response spectra, earthquake time histories, and characterizations of the spatial incoherence of earthquake ground motions.

The Diablo Canyon site is classified as a rock site, based on local subsurface geologic conditions and



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shear-wave velocity profiles. The potential seismogenic zones in the Diablo Canyon site region are confined to the upper crust to a depth of about 12 kilometers, as evidenced by seismicity data for the region. Accordingly, the criteria for selecting records to be included in the strong motion data base were:

- Records from rock or rock-like sites
- Records from shallow crustal earthquakes.

Application of these selection criteria to strong-motion records obtained worldwide between 1935 and 1987 has yielded a large, up-to-date ground-motion data base applicable to the Diablo Canyon site:

- 217 records for peak ground acceleration
- 88 records for response spectral acceleration
- 51 shallow crustal earthquakes having magnitudes ranging from 4.6 to 7.4 and various styles of faulting.

Site-specific horizontal and vertical response spectra were developed at the median and 84th percentile levels. The development of site-specific response spectra was based on direct estimation of the response spectral acceleration at individual frequencies appropriate for the site-specific criteria for earthquake magnitude, source-to-site distance, style of faulting, and local site conditions.

To develop the spectra, we used the maximum earthquake magnitude on the Hosgri fault zone, which was conservatively assessed to be 7.2 M_w , and a source-to-site distance of 4.5 kilometers.

Three different approaches were used to obtain the site-specific acceleration response spectra at the Diablo Canyon site. These three approaches, which demonstrate the consistency of the results, are based on:

- Statistical analysis of near-source strong motion recordings.

- Peak ground acceleration and response spectral acceleration attenuation relationships from regression analyses.
- Numerical modeling studies.

SUMMARY OF SIGNIFICANT FINDINGS AND RESULTS

The response spectra obtained from the three approaches were compared with one another. It was found that the response spectra obtained using the attenuation relationships from regression analyses envelop the corresponding response spectra obtained from the statistics of near-source records and those from numerical ground-motion modeling studies. The regression analysis results, at the 84th percentile level, were conservatively chosen for use in the seismic margin studies.

CONCLUSIONS

The requirements of Element 3 of the license condition have been met, and the reevaluation activities described in the Program Plan and Scoping Study have been completed. Specifically, a substantially enlarged data base of strong-motion recordings close to large earthquakes and a refined and validated numerical modeling procedure have been jointly used to reevaluate the free-field ground motions at the Diablo Canyon site and to provide specific ground motion inputs into the seismic hazard analysis, the seismic fragility evaluations, and the soil/structure interaction analyses.

Element 4 of the License Condition

PG&E shall assess the significance of conclusions drawn from the seismic reevaluation studies in Elements 1, 2, and 3, utilizing a probabilistic risk analysis and deterministic studies, as necessary, to assure adequacy of seismic margins.

PG&E has performed a comprehensive probabilistic risk analysis as well as deterministic studies. As a prerequisite to these studies, PG&E performed seismic soil/structure interaction analyses. These analyses examined the effects of dynamic interaction between structures and the supporting rock medium on the seismic response



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of the structures, and generated seismic responses for the structures that were required for fragility analyses and seismic margin assessments. The soil/structure interaction analysis activities included characterization of site rock profiles and properties; development of three-dimensional dynamic models for structures; parametric studies to evaluate the sensitivities of seismic soil/structure interaction response; identification of important seismic soil/structure interaction parameters to be considered; and computer analyses to generate responses for structures subjected to various seismic inputs consistent with site-specific earthquake response spectra. The results of the seismic soil/structure interaction analyses were used in the fragility and deterministic evaluations.

Input data to the probabilistic risk analysis included seismic hazards and fragility evaluation results. The objectives of the seismic hazards analysis were to provide a probabilistic representation of the earthquake ground motions at the site in a format suitable for use in the probabilistic risk analyses. The objective of the seismic fragility evaluation was to assess the seismic capacity of the structures and equipment that are included in the probabilistic risk analysis model. The probabilistic risk analysis then integrated the results of these two evaluations to assess the importance of various structures and items of equipment to seismic risk.

The deterministic analyses were based upon comparisons of seismic demands created by deterministically developed ground motions with capacities of structures and equipment derived from seismic fragility data used in the probabilistic risk assessment. Seismic motions, both in the free-field and at selected Plant locations, were also compared with the corresponding quantities obtained from seismic qualification bases established during the licensing process.

SUMMARY OF SIGNIFICANT FINDINGS AND RESULTS

Soil/Structure Interaction. A complete reevaluation of the effects of soil/structure interaction on the seismic response of power block structures was conducted. The results of these analyses indicate substantial soil/structure

interaction effects for the short, stiff containment interior structure and the auxiliary building. The soil/structure interaction effects due to coherent ground motion input was, however, found to be relatively small for the taller and more flexible containment shell and the turbine building.

To account for the effect of horizontal variations of ground motions on the soil/structure interaction response, separate analyses were performed that incorporated site-specific spatial incoherence functions. The results of these analyses show that the spatial incoherence of ground motions generally results in reductions in the soil/structure interaction responses. At the structural base near the center, such reductions increase gradually with increasing frequency. For frequencies above 10 hertz, these reductions amount to about 6 percent for the containment structure, 15 percent for the auxiliary building, and 20 percent for the turbine building.

The effect of base uplift on the seismic response of the containment structure was investigated using a two-dimensional nonlinear analysis procedure. The results of the study show that base-uplift generally results in small reductions in the horizontal acceleration responses and in the base shear and overturning moment; however, it causes small increases in the horizontal and vertical displacements and in the vertical acceleration responses in the high frequency range.

Seismic Hazards Analysis. The seismic hazards analysis included consideration of all seismic sources that could affect the Diablo Canyon Power Plant site. Logic trees were developed for the Hosgri, Los Osos, San Luis Bay, Santa Lucia Bank, West Huasna, offshore Lompoc, Rinconada, Nacimiento and San Andreas faults. As a result of these analyses, it was shown that the Hosgri fault zone dominates the seismic hazard at the site. The Los Osos and San Luis Bay faults taken together contribute only 3 to 5 percent to the total seismic hazard. Contributions from the other faults are insignificant.

Seismic Fragility Analysis. The seismic fragility evaluation established that the Diablo Canyon safety-related structures and equipment,



important to evaluating the probability of core damage have high median seismic capacities. The turbine building has the lowest median seismic capacity of all the structures; nevertheless, it has an adequate margin of safety. The seismic adequacy of safety-related equipment is also acceptable. Loss of function due to relay chatter was found to be important for the 4-kV switchgear. However, the 4-kV switchgear chatter failure mode is recoverable by operator action in the control room, and the probabilities associated with operator action were included within the probabilistic risk assessment system model.

Probabilistic Risk Assessment. The probabilistic seismic risk assessment integrated the results produced by the seismic hazards and seismic fragility evaluations. The objective of the probabilistic seismic risk assessment was to assess the importance of various structures and items of equipment to seismic risk. To put the seismic risk in perspective, the risk from other external and internal initiators was also quantified.

The probabilistic risk assessment showed that the majority of seismic risk is due to a very small group of components. Of these, the turbine building is the largest contributor; however, even this building contributes very little to the total risk. Except for offsite power, the equipment has minor impact on seismic risk. Offsite power is potentially a large contributor, but only when coupled with other component failures. Furthermore, the loss of offsite power is mitigated by the ability to take timely recovery actions.

The mean core damage frequency due to seismic initiators, including nonseismic random equipment failure, operator failures, and maintenance unavailability that occur independently of any seismic initiator, was found to be 3.7×10^{-5} . The seismic component is a small contributor to the total mean core damage frequency of 2.0×10^{-4} .

Overall, the seismic risk assessment shows that the Diablo Canyon design is well-balanced, with no outstanding weak links. The components and structures are strong, and the seismic risk is low.

Deterministic Comparisons. As a part of the Long Term Seismic Program studies, deterministic comparisons were made between the responses of the structures as calculated from the site-specific ground motions due to the maximum earthquake on the Hosgri fault zone and those used as the bases for design.

Comparison of the site-specific horizontal response spectra (for 5 percent damping) corresponding to the maximum earthquake magnitude with the 1977 Hosgri evaluation (Newmark) spectrum is shown in Figure 2. As can be seen, the 1977 Hosgri evaluation spectrum envelops the site-specific 50th percentile spectrum at all frequencies, and the 84th percentile spectrum at all frequencies below about 15 hertz. The magnitude of the exceedance for frequencies above 15 hertz is approximately 10 percent.

The result of the soil/structure interaction analyses, including results of studies performed to account for the spatial incoherency characteristics of ground motion, provided deterministic plant responses to the site-specific ground motions. These plant responses were developed in the form of floor response spectra at various locations in the power block structures, including at the top of basemats. On comparison, these floor response spectra showed some exceedances over the corresponding floor response spectra developed as a part of the original design or Hosgri evaluation bases at various structural frequencies. However, the average values of these exceedances at certain key frequencies are within approximately 10 percent of the design spectrum. Such exceedances are not significant from the perspective of seismic design adequacy, because they are accommodated by the existing design margin.

ADEQUACY OF SEISMIC MARGINS

Probabilistic Risk Analysis. When the total risk at Diablo Canyon is compared with that of other Westinghouse plants for which probabilistic risk assessments have been made, Diablo Canyon compares favorably, as shown in Figure 3. Although a few risk-reduction improvements to systems and procedures are being implemented,



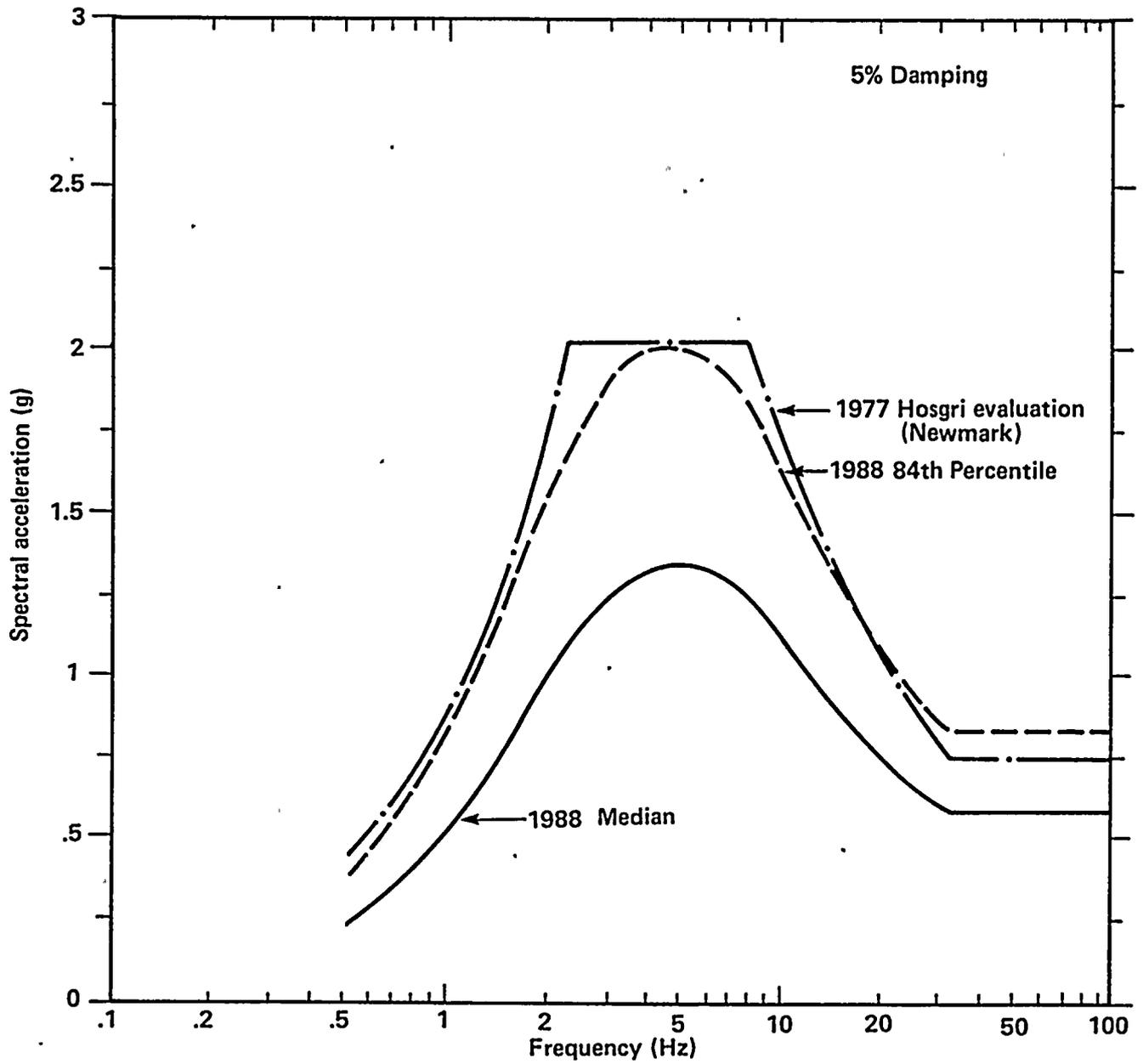


Figure 2

Comparison of the 1988 site-specific median and 84th percentile horizontal response spectra with the 1977 Hosgri evaluation (Newmark) response spectrum.



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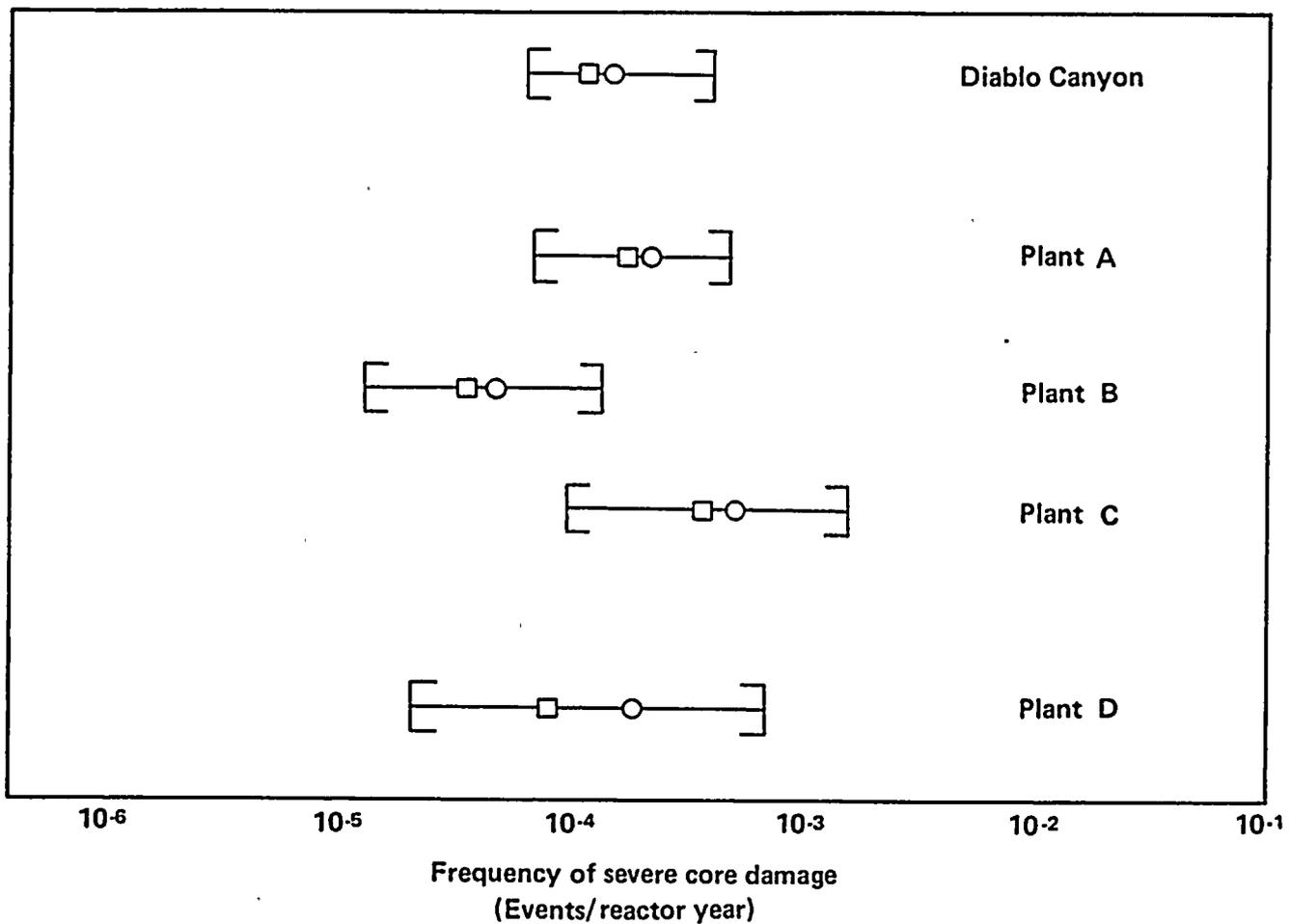
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EXPLANATION

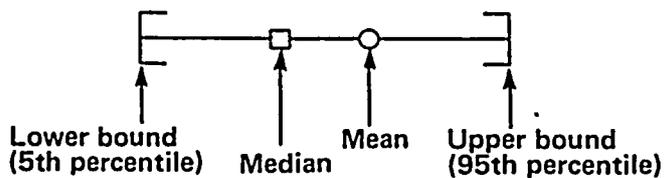


Figure 3

Comparison of total risk for Westinghouse nuclear power plants.

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no modifications were required to assure reliable and safe operation of the facility.

Deterministic Margin Assessment. In the deterministic evaluations, component capacities were defined in terms of their high-confidence-of-low-probability-of-failure capacity levels appropriate for comparison with an 84 percent probability of non-exceedance ground response spectrum, that is, HCLPF₈₄. The HCLPF₈₄ capacities have been defined in terms of the 5 percent damped average spectral acceleration in the 3 to 8.5 hertz frequency range. It should be noted that both the seismic hazard and the fragilities have been defined in terms of average spectral acceleration in the 3 to 8.5 hertz frequency range of the average of the two horizontal components of ground motion. Although peak ground acceleration is customarily used for this purpose, the ratio of the spectral acceleration at any specific frequency of interest in the 3.5 to 35 hertz range to the average spectral acceleration in the 3 to 8.5 hertz range showed smaller and more consistent variabilities.

When interpreting these HCLPF₈₄ capacities, the following statements of the Expert Panel on Quantification of Seismic Margins (NUREG/CR4334) should be noted:

The measure of margin adopted by the Panel is a high-confidence-of-low-probability-of-failure (HCLPF) capacity. This is a conservative representation of capacity and in simple terms corresponds to the earthquake level at which, with considerable confidence, it is extremely unlikely that failure of the component will occur. From the mathematical perspective of a probability distribution on capacity developed in seismic PRA calculations, the HCLPF capacity values are approximately equal to a 95 percent probability of not exceeding about a five percent probability of failure.

There is a margin above the conservative capacity values selected by the Panel. The median capacity, which corresponds to the 50 percent probability of exceedance, is generally at least of factor of 2 greater than the HCLPF capacity. Thus, there is no

proverbial "cliff" or sudden failure which is expected to occur immediately beyond the HCLPF capacity. From another perspective, the conservative capacities are close to the lower-bound cutoff values below which there is no significant likelihood of failure.

These very conservative HCLPF₈₄ capacities have been compared with responses to an 84 percent probability of non-exceedance site-specific ground motion spectrum for a maximum earthquake magnitude in these evaluations. However, it should be noted that the 84 percent probability of non-exceedance site-specific spectrum used in this comparison is also very conservative. The ratio of the 84 percent to the 50 percent spectra is approximately 1.5. Thus, even when the HCLPF₈₄ average spectral acceleration equals the 84 percent site-specific spectrum (that is, 0 percent margin), the median capacity will still be roughly a factor of 2.0×1.5 , or 3.0 above the 50 percent site-specific spectrum. Thus, even a 0 percent deterministic margin reached in this manner corresponds to a very remote possibility of failure.

Among the Plant components, only the 4-kV switchgear relay chatter mode has a HCLPF₈₄ capacity that is lower than the 84 percent probability of non-exceedance site-specific ground-motion spectrum. However, the relay chatter function mode has a median capacity that is more than two times as great as the 84 percent probability of non-exceedance ground-motion spectrum. Thus, at this earthquake ground motion level, relay chatter of the 4-kV switchgear is highly unlikely. Furthermore, the ease of recovery by means of specific Plant procedures essentially eliminates any concern due to relay chatter.

The second lowest HCLPF₈₄ capacity is for the overall turbine building structure. The reported HCLPF₈₄ capacity is a factor of 1.14 greater than the 84 percent probability of non-exceedance site-specific ground-motion spectrum, so a 14 percent margin exists before this HCLPF₈₄ capacity is reached. Even if the demand were to reach this level, failure is highly unlikely, because the median capacity is estimated to be a factor of 2.65 greater than the HCLPF capacity.



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Other than the turbine building, all Plant structures and components whose failure could lead to seismic risk to the Plant have at least a 40 percent margin between the HCLPF capacity and the 84 percent probability of non-exceedance site-specific ground motion.

CONCLUSIONS

The requirements of Element 4 of the license condition have been met, and the reevaluation

activities described in the Program Plan have been completed. The Program has demonstrated that the Diablo Canyon Power Plant has adequate seismic margins.

CONCLUSION OF THE LONG TERM SEISMIC PROGRAM

It is concluded on the basis of the results presented above that PG&E has fully satisfied all the elements of License Condition 2.C.(7).



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Clarence R. Allen
Thomas M. Leps

Bruce A. Bolt
Cole R. McClure

C. Allin Cornell
H. Bolton Seed

BOARD OF CONSULTANTS - DIABLO CANYON LONG TERM SEISMIC PROGRAM

July 30, 1988

Mr. Donald A. Brand, Senior Vice President
Pacific Gas and Electric Company
77 Beale Street, Room 2917
San Francisco, CA 94106

Re: Diablo Canyon Long Term Seismic Program—Board of Consultants' Final Report

Dear Mr. Brand:

Responsive to the request by Program Manager Lloyd S. Cluff, your Board of Consultants for the program is pleased to submit its final report on the findings of this extensive and possibly unprecedentedly detailed and sophisticated evaluation of the seismic characteristics of a major plant site, and the related effects of an extreme seismic event on the plant and its appurtenant facilities.

Board members have participated, on a review and advisory basis, both as individual technical advisors and as a full Board. In the latter role, the full Board has met formally, beginning on October 25, 1984, on nineteen occasions. The first six meetings were documented by minutes prepared by PG&E staff, each of which minutes was reviewed, edited and endorsed by the Board. The following thirteen meetings, covering the period November 1, 1985 through July 20, 1988, were documented by reports prepared and signed by the full Board. The Board considers that its involvement in the program has been continuing and thorough, and that it is thereby qualified to offer its judgment both on the general conduct of the program and on the more important conclusions arrived at by PG&E staff and its consultants, as follows:

General Conduct

1. The Diablo Canyon Long Term Seismic Program has been responsive to the technical advice provided by the Board throughout the program.
2. The technical and analytical methods used throughout the investigative and assessment activities have been representative of the best approaches developed to date.
3. The conclusions reached, and the manner in which they have been developed and supported have been thoroughly documented, and are judged by the Board to be reasonable and appropriate.



Technical Comments

The basic elements of the program reviewed herein address the following main areas:

- The Tectonic Setting
- Seismic Source Characterization
- Ground Motions
- Seismic Hazard Analysis
- Probabilistic Risk Analysis
- Deterministic Evaluation

In brief, the Board offers its comments on each of these program areas in the following paragraphs.

The Board considers that the three-year geologic, geophysical and seismological program conducted for the LTSP is one of the most exhaustive investigations of its kind ever undertaken. It included a thorough review of extensive published and unpublished data and the acquisition of a great amount of new data. The evaluation of this information to assess the earthquake potential was thorough and comprehensive, and the Board concurs with the expressed conclusions.

In our opinion, the report correctly determined that the Hosgri fault is the most significant seismogenic structure of the site area. Thorough, detailed field investigations provided new information on the characteristics of known faults, and identified previously unknown faults. For example, mapping of features such as the San Luis Bay fault, although of significantly less seismogenic importance than the Hosgri fault, is indicative of the degree of detail characteristic of the investigation. Such detailed studies provided the basis for a very reliable tectonic model of the region.

The relocation of the 1927 Lompoc earthquake, a rather controversial matter ten years ago, is an example of the application of modern seismological methods to obtain higher resolution than was previously possible. The comparison of observed with synthetic records led to a significant revision of the magnitude and location of this important event, and an understanding of its mechanism.

The seismic source characterization carried out in this study was a major interdisciplinary effort, and portions of the work must be credited with being at the frontiers of seismology and geology. In particular, the geological concept of fault segmentation, which played a major role in the effort, was significantly clarified in its application to the Program. The Board fully supports the assignment of the maximum earthquake magnitude on the Hosgri fault ($M_w = 7.2$) that resulted from the seismic source characterization, and, in fact, individual members of the Board participated actively with the project team in the comprehensive logic-tree process that led to this magnitude determination.

The studies made to determine the ground motions associated with the maximum earthquake on the Hosgri fault have involved (a) the compilation of an extremely comprehensive data base of ground motion recordings, (b) the analysis of these records to evaluate the range of motions likely to be developed in the event of the occurrence of the maximum earthquake on the Hosgri fault, (c) the use of advanced earthquake ground motion simulation procedures to provide an alternative basis for assessing the probable range of ground motions that could be produced by the maximum magnitude earthquake, and (d) the final selection of a deterministic ground motion spectrum that provides a conservative basis for evaluating the adequacy of plant structures, components, and systems.



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The response of the plant to the maximum earthquake 84th percentile level motions has been evaluated using the most advanced soil/structure interaction analysis procedures currently available. Improved computer programs were developed and used to determine these responses and the results provide a reliable basis for evaluating the seismic response of the plant to the motions generated by the maximum earthquake motions.

The probabilistic seismic hazard analysis used a state-of-the-art, but well-established method, explicitly incorporating the multiplicity of source characterization hypotheses and ground motion prediction models provided by the relevant scientific teams. The probabilistic risk analysis, including the fragility assessments and systems analysis, benefitted from far more time, financial, and technical resources than previously ever committed by industry to the study of the likelihood of seismically induced plant damage. The results of these studies therefore provide important support to the plant safety conclusion.

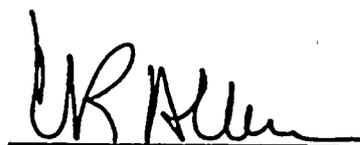
Evaluations of the seismic capacity of structures and components have been made using the HCLPF-based approach, which provides an acceptable basis for evaluations of this type, and on the basis of seismic capacities determined in previous studies of the seismic adequacy of the Diablo Canyon facility. Comparisons of these capacities with the evaluations of seismic response of plant structures, components, and systems have demonstrated adequate margins of safety.

Concluding Remarks

The Board is fully satisfied that the scope and conduct of the program have been exemplary, and that the talent brought together to carry out the program has been of the highest order of professional competence and experience in this special field.

To the best of our ability to judge, therefore, it is our consensus that PG&E has met the requirement of the NRC license condition, and has verified the adequacy of the seismic margins of the Diablo Canyon Power Plant.

Respectfully submitted,



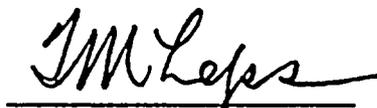
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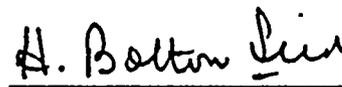
C. Allin Cornell



Thomas M. Leps



Cole R. McClure



H. Bolton Seed

MEMBERS, BOARD OF CONSULTANTS

cc: William H. Wallace, VP—Engineering
Lloyd S. Cluff, Manager—Geosciences





Chapter 1

INTRODUCTION

Pacific Gas and Electric Company (PG&E) has performed a reevaluation of the seismic design bases for the Diablo Canyon Power Plant, as specified in the Unit 1 Full-Power Operating License, DPR-80, Condition 2.C.(7), issued by the Nuclear Regulatory Commission (NRC) on November 2, 1984. This report documents PG&E's work performed in accordance with that requirement, and demonstrates that PG&E has satisfied the requirements of the license condition.

BACKGROUND

In 1973, PG&E applied to the NRC for operating licenses for Diablo Canyon Power Plant, Units 1 and 2. During the licensing process, the NRC's Advisory Committee on Reactor Safeguards (ACRS) reviewed the seismic and nonseismic aspects of the Plant. On July 14, 1978, the ACRS issued a letter report to the Commission stating that it had completed its review of the operating license application. The ACRS letter concluded that if due consideration were given to the items in its report, and subject to completion of the necessary Plant modifications and preoperational testing, there was reasonable assurance that Units 1 and 2 could be operated at full power without undue risk to the health and safety of the public.

With regard to seismic issues, the ACRS stated:

The ACRS notes that, for distances less than 10 km from the earthquake source, there are currently no strong motion data for shocks larger than magnitude 6 and few reliable data for shocks of magnitude 5 and 6. Also, the theory and analyses of earthquake and seismic wave generation, of seismic wave transmission and attenuation, and of soil-structure interaction are in a state of active development. The Committee recommends that the seismic design of Diablo

Canyon be reevaluated in about ten years taking into account applicable new information.

It was this recommendation that eventually led to issuance of the conditions on Unit 1's low-power and full-power operating licenses requiring a reevaluation of the seismic design bases of the Plant.

In early 1984, the NRC Staff prepared a draft of a license condition for the reevaluation of the Diablo Canyon seismic design bases. The draft condition included examination and evaluation of all relevant geologic and seismic data and interpretations that had become available, a reevaluation of the maximum earthquake magnitude and associated ground motions, and a probabilistic risk assessment. The draft license condition was discussed at a public meeting held on March 26 and 27, 1984, at which the Commission reviewed the status of the Plant operating license process, including the need for adding a seismic license condition to the low-power license.

In mid-April 1984, the Commission issued an Order authorizing PG&E to conduct low-power testing at Diablo Canyon Unit 1. In its Order, the Commission discussed recent developments regarding the characterization of the Hosgri fault, and the NRC Staff's proposal that PG&E conduct further geologic and seismic studies. The Commission noted that there was no indication that recent geologic information invalidated the seismic design bases for Diablo Canyon.

On April 18, 1984, the NRC Staff issued Amendment No. 9 to Unit 1 Facility Low-Power Operating License No. DPR-76. Included in the license amendment was License Condition 2.C.(9), quoted below:



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Seismic Design Bases Revalidation Program

PG&E shall develop and implement a State-Of-The-Art Program to revalidate the seismic design bases used for Diablo Canyon. PG&E shall submit for NRC staff review and approval the proposed Program Plan and proposed schedule for implementation by January 30, 1985. The program shall be completed and a final report be submitted to the NRC by July 1, 1988.

In early May 1984, the NRC Staff met in a public meeting with PG&E to discuss details regarding implementation of the license condition. The NRC Staff presented additional information on the license condition to the ACRS in public meetings on May 24 and June 14, 1984. The ACRS reviewed the license condition and, in a letter dated June 20, 1984, reported to the Commission that:

We believe that the elements outlined in the NRC Staff's proposal will provide a suitable basis for the seismic reevaluation. We believe also that the NRC Staff's proposal is responsive to the July 14, 1978 ACRS letter in which the ACRS suggested that the seismic design of Diablo Canyon be reevaluated in about ten years taking into account applicable new information.

The ACRS also requested that it be given the opportunity to review and comment on the PG&E program plan and schedule, and that the NRC Staff meet with the ACRS as appropriate to discuss the evaluation of the PG&E work. The ACRS also noted:

It is to be expected that new geological and seismic information will continue to be developed in the future, here as well as elsewhere. In addition, there will be improved understanding in the seismic response and capability of nuclear power plants. A systematic framework for evaluating this information would be useful. The proposed seismic reevaluation plan should provide such a basis in part.

Recommendations from consultants to the ACRS, who provided technical guidance on how the program should be implemented, were also included in the June 20, 1984 letter.

The NRC Staff reported on the development of the license condition in Diablo Canyon's Safety Evaluation Report, Supplement No. 27, in July 1984. The Staff included elements on geology/seismicity/geophysics, earthquake magnitude, ground motions, and probabilistic risk assessment. It also required that PG&E meet periodically with the Staff and the ACRS. The NRC Staff concluded that there was no reason to modify previous conclusions regarding the seismic design bases for the Diablo Canyon Power Plant while the requirements of the seismic license condition were being carried out by PG&E and the NRC Staff.

In a meeting on August 2, 1984, the Commission voted in favor of issuance of a full-power license for Unit 1. It subsequently issued an Order that became effective with issuance of Unit 1 Facility Operating License DPR-80 on November 2, 1984. In DPR-80, the license condition became Item 2.C.(7), and was revised to read as follows:

Seismic Design Bases Reevaluation Program

PG&E shall develop and implement a program to reevaluate the seismic design bases used for the Diablo Canyon Nuclear Power Plant.

The program shall include the following Elements:

- 1) *PG&E shall identify, examine, and evaluate all relevant geologic and seismic data, information, and interpretations that have become available since the 1979 ASLB hearing in order to update the geology, seismology and tectonics in the region of the Diablo Canyon Nuclear Power Plant. If needed to define the earthquake potential of the region as it affects the Diablo Canyon Plant, PG&E will also reevaluate the earlier information and acquire additional new data.*

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- 2) *PG&E shall reevaluate the magnitude of the earthquake used to determine the seismic basis of the Diablo Canyon Nuclear Plant using the information from Element 1.*
- 3) *PG&E shall reevaluate the ground motion at the site based on the results obtained from Element 2 with full consideration of site and other relevant effects.*
- 4) *PG&E shall assess the significance of conclusions drawn from the seismic reevaluation studies in Elements 1, 2, and 3, utilizing a probabilistic risk analysis and deterministic studies, as necessary, to assure adequacy of seismic margins.*

PG&E shall submit for NRC staff review and approval a proposed program plan and proposed schedule for implementation by January 30, 1985. The program shall be completed and a final report submitted to the NRC three years following the approval of the program by the NRC staff.

PG&E shall keep the staff informed on the progress of the reevaluation program as necessary, but as a minimum will submit quarterly progress reports and arrange for semi-annual meetings with the staff. PG&E will also keep the ACRS informed on the progress of the reevaluation program as necessary, but not less frequently than once a year.

PG&E's reevaluation effort was named the "Long Term Seismic Program." The objective of the Long Term Seismic Program was to satisfy the license condition. The Program has consisted of three phases (Figure 1-1), starting with Phase I, during which the Program Plan was developed. In Phase II, the Program Plan was refined and the scope of work was focused and priorities for the tasks were established. In the final phase, Phase III, the program tasks were implemented and documented.

The Long Term Seismic Program was to be conducted for the Diablo Canyon Power Plant as

a single entity. This fact was recognized by the NRC Staff when it performed the safety evaluation for the Unit 2 operating license. There was no special distinction made for either of the two units; therefore, the findings and conclusions of the Program would apply equally to both units.

PHASE I—PROGRAM PLAN

Program Plan Development

Following issuance of the low-power license condition in early 1984, PG&E initiated efforts to formulate and develop a detailed program that would be responsive to the license condition. Expert consultants also participated in this effort. In addition, there were frequent interactions during Phase I between the NRC Staff and PG&E to address and resolve comments by the NRC staff on the intent and goals of the Program: meetings were held on May 8 to discuss the requirements of its license condition, on May 24 to review the license condition with the ACRS subcommittee, and on June 14 to review the license condition with the full ACRS. Topical meetings were held on geology and tectonics on October 4, 1984; on earthquake magnitude and ground motions on November 15; on soil/structure interaction on November 16; and on probabilistic risk assessment on December 11, 1984. A final meeting to review the Program Plan was held on January 10, 1985.

The Program Plan was submitted to the NRC Staff on January 30, 1985, as required by the license condition. The plan consisted of two sections of introductory material and discussions of eight technical areas, each of which was responsive in whole or in part to one of the four elements of the license condition (Table 1-1).

In response to Element 1, PG&E proposed a geologic investigation to gather appropriate geological and geophysical data for use in the other parts of the Program (Sections 3 and 4 of the plan). The geologic investigation was organized into three tasks: 1) site and regional data collection, processing, and interpretation, 2) evaluation of the tectonic models, and

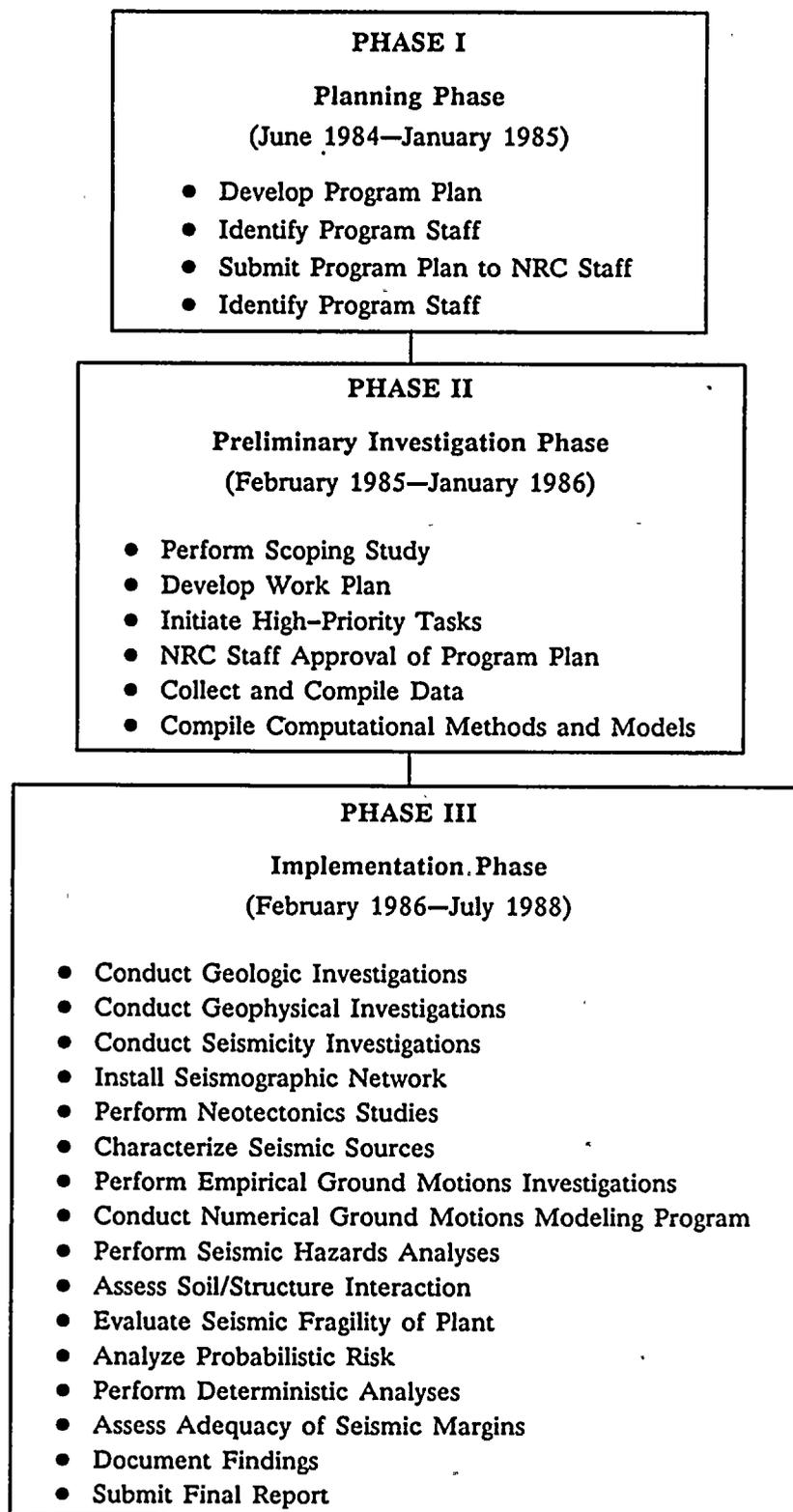


Figure 1-1

Long Term Seismic Program phases.



Table 1-1
RELATIONSHIP OF LICENSE CONDITION ELEMENTS TO THE PROGRAM PLAN

LONG TERM SEISMIC PROGRAM PLAN	LICENSE CONDITION			
	<u>Element 1</u> Geologic and Seismic Data Compilation, Collection, and Evaluation	<u>Element 2</u> Earthquake Magnitude Reevaluation	<u>Element 3</u> Earthquake Ground-Motion Reevaluation	<u>Element 4</u> Assessment of Adequacy of Seismic Margins through Probabilistic Risk Analysis and Deterministic Studies
SECTION 3 Geologic Investigations Neotectonics Studies Geophysical Data Collection Seismic Source Characterization (Work Plan Tasks 1 through 9)	X	X		
SECTION 4 Assessment of fault characteristics and collection of seismicity data to reevaluate earthquake magnitude (Work Plan Tasks 3 and 9)	X	X		
SECTION 5 Empirical Ground-Motion Studies			X	
SECTION 6 Numerical Ground-Motion Studies			X	
SECTION 7 Soil/Structure Interaction Analysis				X
SECTION 8 Seismic Hazard Analysis				X
SECTION 9 Seismic Fragility Analysis				X
SECTION 10 Probabilistic Risk Analysis				X

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3) seismic source characterization. An analysis to estimate the maximum earthquake magnitude in the region of the Plant was proposed in response to Element 2 of the license condition (Sections 3 and 4 of the plan). Ground-motion studies to reevaluate the ground motions that could result from the earthquake scenarios, using both numerical and empirical techniques, were responsive to Element 3 of the license condition (Sections 5 and 6 of the plan). The remaining four tasks proposed were responsive to Element 4 of the license condition. These tasks were the soil/structure interaction analyses (Section 7 of the plan), seismic hazard analysis (Section 8 of the plan), fragility analysis (Section 9 of the plan), and probabilistic risk assessment (Section 10 of the plan). The Program Plan required that the Long Term Seismic Program be conducted in accordance with the applicable requirements of PG&E's Quality Assurance Program. As required by the license condition, the plan also provided for submittal of quarterly progress reports, for semiannual meetings with the NRC Staff, and for annual meetings with the ACRS.

PG&E structured the Program Plan to accommodate possible changes and to be sufficiently flexible to permit newly developed information and techniques to be appropriately considered. The flexible nature of the Program also provided an opportunity to incorporate any significant developments from outside the Program that warranted consideration, such as data from recent earthquakes.

Throughout the review of the Program Plan, during the first half of 1985, the NRC Staff and PG&E communicated through correspondence and public meetings. The ACRS also held public meetings, in March and July 1985, to review the Program Plan with the NRC Staff and PG&E. The ACRS agreed that the Program Plan was responsive to the license condition in a letter to the Commission following its 303rd full committee meeting July 11-13, 1985. The NRC Staff approved the Program Plan on July 31, 1985. In its approval letter, the NRC Staff noted:

We conclude that the program as amended by your responses, is responsive to the four elements of License Condition 2.C.(7) in the

Diablo Canyon Unit 1 License DPR-80 and our comments.

We conclude that the program is sufficiently flexible to accommodate new information or new hypotheses regarding the tectonics of the region as they appear. We also conclude that the overall organization and administration of the program are appropriate.

Program Staffing

The overall responsibility for the Long Term Seismic Program was with PG&E's Senior Vice President and General Manager, Engineering and Construction, Donald A. Brand, assisted by Vice President of Engineering, William H. Wallace (Figure 1-2). Program management was assigned to Lloyd S. Cluff, Manager of PG&E's Geosciences Department, who had responsibility for Program implementation, management, and completion. Due to the complexity and scope of the Long Term Seismic Program, he was assisted by four Assistant Technical Managers, as follows:

Frank W. Brady—Assistant Technical Manager in the area of Geosciences.

Bimal E. Sarkar—Assistant Technical Manager, with W. H. White, of the Structural Engineering studies.

William H. White—Assistant Technical Manager, with B. E. Sarkar, of the Structural Engineering studies.

Bruce D. Smith—Assistant Technical Manager in the area of Probabilistic Risk Assessment.

PG&E assembled a team of highly qualified experts to perform the work associated with the major technical areas of the Program. The participants were chosen on the basis of their leadership in technological development, their experience in their respective areas of expertise, and their familiarity with the licensing of the Plant. They were:

Geology/Seismology/Geophysics, and Seismic Source Characterization

William U. Savage, PG&E, Technical Leader

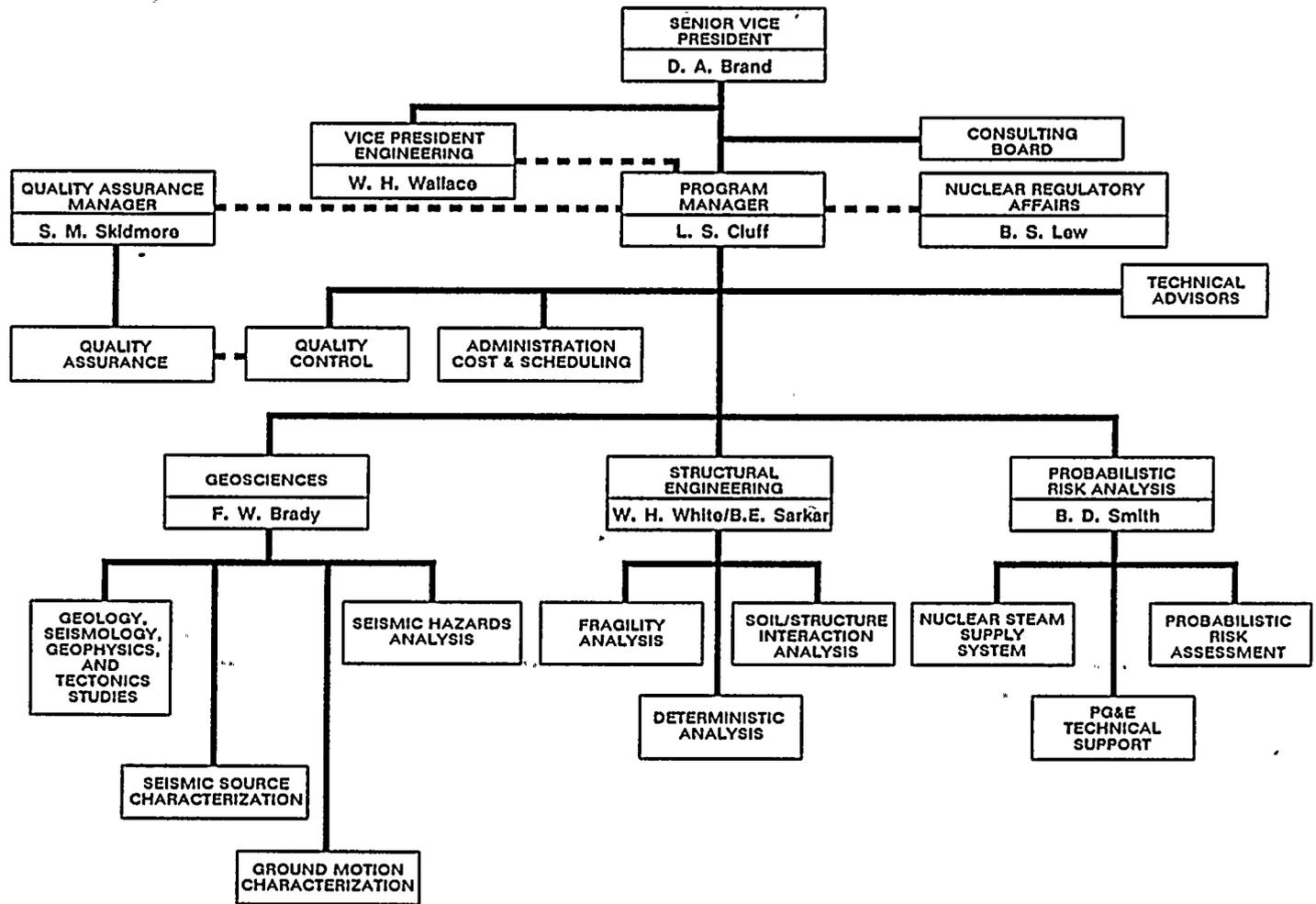


Figure 1-2

Long Term Seismic Program organization.

Kevin J. Coppersmith, Geomatrix Consultants, Inc.
 N. Timothy Hall, Earth Science Associates
 Douglas H. Hamilton, Earth Science Associates
 William R. Lettis, Geomatrix Consultants, Inc.

Ground Motion Characterization and Seismic Hazards Analysis

Yi-Ben Tsai, PG&E, Technical Leader
 Robin K. McGuire, Risk Engineering, Inc.
 Khosrow Sadigh, Geomatrix Consultants, Inc.
 Paul G. Somerville, Woodward-Clyde Consultants

Engineering Evaluations

Bimal E. Sarkar, Bechtel Power Corporation, Technical Leader
 Shankar Bhattacharya, PG&E
 Robert Kennedy, Structural Mechanics Associates
 Thomas Kipp, NTS Engineering
 Wen Tseng, Bechtel Power Corporation
 Donald Wesley, Impel

Probabilistic Risk Analyses

Bruce D. Smith, PG&E, Technical Leader
 Dennis C. Bley, Pickard, Lowe, and Garrick
 B. John Garrick, Pickard, Lowe, and Garrick
 Harold F. Perla, Pickard, Lowe, and Garrick
 Donald J. Wakefield, Pickard, Lowe, and Garrick

Consulting Board and Technical Advisors

A Long Term Seismic Program Consulting Board and Technical Advisors were key components of the Program organization. The primary function of the Consulting Board, which consisted of individuals eminently qualified in the subject areas of the Program, was to provide guidance to PG&E and its consultants to ensure the objectives of the license condition were achieved and that relevant theories, analytical techniques, and other pertinent, newly developed information were

considered. This function was accomplished through reviews of technical developments and results as they became available. The Consulting Board actively participated in Program development and evaluation of investigative methods, reviewed work in progress, and suggested priorities for work tasks. The members of the Consulting Board and their affiliations are:

Clarence R. Allen, California Institute of Technology
 Bruce A. Bolt, University of California, Berkeley
 C. Allin Cornell, Stanford University
 Thomas M. Leps, Independent consultant
 Cole R. McClure, Bechtel Civil, Inc.
 H. Bolton Seed, University of California, Berkeley

Technical Advisors were assigned to each of the technical areas of the Program. The Technical Advisors worked directly with the Program team to review the scope of work and to advise on the development of technical solutions. Continuing guidance from the Technical Advisors throughout the Program assured timely resolution of issues and contributed significantly to the expertise necessary for successful conduct of the technical investigations. The Technical Advisors were:

Geology/Seismology/Geophysics

Clarence R. Allen
 Jan D. Rietman
 Cole R. McClure

Earthquake Ground Motions

Bruce A. Bolt
 H. Bolton Seed
 Donald V. Helmberger

Soil/Structure Interaction

H. Bolton Seed
 William J. Hall

Fragility Analysis

Robert P. Kennedy
 John Reed

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Seismic Hazard Analysis

C. Allin Cornell
Robert P. Kennedy

Probabilistic Risk Assessment

C. Allin Cornell
Robert P. Kennedy
Ralph J. Keeney

The Consulting Board met 19 times during the Program; the board's final report is presented following the Executive Summary.

PHASE II—SCOPING STUDY

Following submittal of the Program Plan on January 30, 1985, work began on Phase II, an effort to refine and focus the scope of work. The objective of the Scoping Study was to develop detailed work plans to be carried out in each of the major tasks of the Program, and to schedule interfaces for each of the Program tasks. In addition, high-priority technical activities also were conducted. For example, PG&E began the design and installation of the Central Coast Seismic Network. To aid in the development of the scope of work, representative ground-motion models were selected and preliminary ground-motion analyses were performed, and preliminary seismic hazard analyses were conducted.

During the first half of 1985, Phase II work proceeded in parallel with NRC Staff review of the Program Plan. The Scoping Study was performed taking into consideration comments from the NRC Staff and its consultants. Attention was focused on identifying the technical considerations that could most affect the Program in addressing the license condition. The first step in developing the work plans required defining the objectives for each task. When these were established, a series of subtasks and areas of investigation were identified that addressed each objective. Priorities were then set for the tasks according to their usefulness and potential for addressing the technical considerations.

Because the tasks had to be conducted in parallel, rather than in series, due to the limited time, the

expected products and results of each task and the integration of the tasks were estimated in the formulation of the work plans. This was necessary because, in several areas, conduct of one task was contingent upon the results of another task. For example, data for ground-motion tasks depended on the results from the geology, seismology, and geophysics tasks. The principle data for the seismic hazard analyses were based on both the geology/seismology/geophysics and the ground-motion activities. The soil/structure interaction assessment provided the link between the geosciences tasks and the fragility assessment. The results of the fragility assessment and the hazards analysis were used for the probabilistic risk analysis. Thus, the Program was structured to update and integrate the results from all tasks before final conclusions could be reached.

The refined set of work tasks and associated schedule for Phase III resulting from the Scoping Study were submitted to the NRC Staff on January 30, 1986. They were discussed in detail at the first semiannual meeting with the NRC Staff on March 11 and 12, 1986.

PHASE III—IMPLEMENTATION

As the Phase II effort neared completion and the details of specific work plans became more clearly defined, technical activities were initiated to implement Phase III of the Program. These activities included compilation and review of existing data, gathering necessary field data, developing computational models, developing logic trees and technical criteria, and, later, performing sensitivity studies and iterative analyses. The technical investigations were reviewed by the Technical Advisors, who aided in their development and implementation, as appropriate. In addition, the Long Term Seismic Program Consulting Board conducted periodic meetings to evaluate the validity and adequacy of the scope and results of these investigations.

Toward the latter half of Phase III, when the data-gathering and model-development work had essentially been completed, follow-on studies and further iterations of analytical portions of the program were performed. A significant part of the final effort of the Program was the probabilistic



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risk analyses and the deterministic evaluations. These two elements could not be finalized until the results of the other tasks were available. Finally, the work was reviewed and documented.

Phase III encompassed all the interrelated, technical aspects necessary for a reevaluation of the seismic design bases, including studies of geology, seismicity, geophysics, and neotectonics; seismic source characterization; ground-motion modeling and characterization; soil/structure interaction assessments; seismic hazard analyses; fragility analyses; probabilistic risk analyses; and deterministic evaluations. The objective of the Long Term Seismic Program was to satisfy the license condition set forth above, using new techniques and data developed since 1979 to assess the adequacy of the seismic margins. This objective was accomplished by the investigations in the relevant technical areas (Table 1-2). Work in each of these areas is described in the following chapters.

COMPLIANCE WITH REPORTING REQUIREMENTS

Throughout the Long Term Seismic Program, PG&E complied with the specific reporting requirements of the license condition. Following approval of the Program Plan, PG&E filed its first progress report in December 1985 for work performed through October 1985. Thereafter, progress reports were filed quarterly.

PG&E initially held public meetings with the NRC Staff semiannually to discuss program progress, significant findings, and deviations from the Program Plan. As data were accumulated and milestones were reached, it became evident that more frequent information exchanges were needed. The Program, as approved by the NRC Staff, called for frequent interactions between PG&E and the NRC at both working and management levels. Public workshops were therefore convened approximately every 3 months to keep the NRC Staff informed of ongoing efforts and preliminary conclusions, and to allow the Staff and their consultants to comment on and focus needed efforts into specific areas of concern. The interactive workshops provided

valuable assistance to PG&E in establishing priorities and allocating resources.

When additional information was requested, PG&E provided this material to the NRC Staff. Documented submittals were also provided to the ACRS. At various points in the Program, the NRC Staff and its consultants visited the Diablo Canyon Power Plant and the vicinity to view the field investigations and to examine the structures and equipment. In addition, the Staff's consultants conducted independent investigations and analyses to confirm the appropriateness of PG&E's investigations and methods of study.

Following is a list of NRC panel members that reviewed the various technical areas of the Long Term Seismic Program.

Staff Advisor for Geology/Seismology/Geophysics:

David B. Slemmons, University of Nevada, Reno

Ground Motion Panel:

Jean B. Savy, Lawrence Livermore National Laboratory
Ralph J. Archuleta, University of California, Santa Barbara
Steven M. Day, San Diego State University
Keiti Aki, University of Southern California

Soil/Structure Interaction Panel:

Morris Reich, Brookhaven National Laboratory
Carl J. Costantino, City College of New York
George Gazetas, Rensselaer Polytechnic Institute
Anestis S. Veletsos, Rice University, Texas

Fragility Panel:

R. Fitzpatrick, Brookhaven National Laboratory
Michael P. Bohn, Sandia National Laboratory
James J. Johnson, EQE, Inc.
M. Ravindra, EQE, Inc.

Probabilistic Risk Assessment Advisory Group:

Robert Fitzpatrick, Brookhaven National Laboratory
G. Bezoki, Brookhaven National Laboratory
K. Aliefendioglu, Brookhaven National Laboratory





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Table 1-2

**RELATIONSHIP OF LICENSE CONDITION ELEMENTS TO DISCUSSIONS IN THE
LONG TERM SEISMIC PROGRAM FINAL REPORT.**

	<u>Element 1</u> Geologic and Seismic Data Compilation, Collection, and Evaluation	<u>Element 2</u> Earthquake Magnitude Reevaluation	<u>Element 3</u> Earthquake Ground-Motion Reevaluation	<u>Element 4</u> Assessment of Adequacy of Seismic Margins through Probabilistic Risk Analysis and Deterministic Studies
CHAPTER 2 Geology/Seismology/Geophysics/ Tectonics Investigations	X			
CHAPTER 3 Seismic Source Characterization		X		
CHAPTER 4 Characterization of Ground Motions			X	
CHAPTER 5 Soil/Structure Interaction Analysis				X
CHAPTER 6 Probabilistic Risk Analysis				X
CHAPTER 7 Deterministic Analysis				X
CHAPTER 8 Assessment of the Adequacy of Seismic Margins				X

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Additionally, as required by the license condition, PG&E held status briefings for the ACRS to keep it informed of the progress of the Program. The NRC Staff also periodically briefed the ACRS regarding the progress of the Program. These briefings allowed the ACRS to comment on the scope or content of the PG&E effort.

Following is a list of consultants to the ACRS who participated in technical reviews of the Long Term Seismic Program.

Geology

John C. Maxwell

Geology and Tectonics

Benjamin M. Page

Geophysics and Seismology

George A. Thompson

Engineering

Mihailo D. Trifunac

The frequent interactions between the NRC Staff and PG&E have proven valuable to the successful completion of the Long Term Seismic Program. This Final Report represents the culmination of PG&E's efforts over the past 4 years to satisfy License Condition 2.C.(7).

SUMMARY

PG&E complied with License Condition 2.C.(7) of the Unit 1 Facility Operating License, DPR-80, by performing a comprehensive reevaluation of the seismic design bases of the Plant.

State-of-the-art investigative methods and analytical techniques, which were reviewed by the NRC Staff and its consultants throughout implementation of the Program, were used in the reevaluation. Specifically, PG&E identified, examined, and evaluated all recent relevant geologic and seismic data, information, and interpretations that have become available since 1979, as well as collecting and compiling extensive new data, to update the data base on the geology, seismology, and tectonics in the region of the Plant. PG&E used this information to characterize and evaluate seismic sources of potential significance to ground motions at the Plant site, and the maximum earthquake magnitude associated with the controlling seismic source. These evaluations and findings are discussed in Chapters 2 and 3 of this report.

Based on the above findings, PG&E reevaluated the ground motions at the site, giving full consideration to site conditions and other relevant effects, and developed appropriate ground-motion data for use in engineering analyses. This reevaluation and the results are presented in Chapters 4 and 5.

Finally, PG&E assessed the significance of conclusions drawn from the above studies by conducting a probabilistic risk analysis and deterministic studies. Chapters 6 and 7 document the results of this work. The conclusions of the study regarding the adequacy of the seismic margins are presented in Chapter 8.





Chapter 2

GEOLOGY/SEISMOLOGY/GEOPHYSICS/TECTONICS INVESTIGATIONS

To Address *Element 1 of the License Condition*

ELEMENT 1 OF THE LICENSE CONDITION

PG&E shall identify, examine, and evaluate all relevant geologic and seismic data, information, and interpretations that have become available since the 1979 ASLB hearing in order to update the geology, seismology and tectonics in the region of the Diablo Canyon Nuclear Power Plant. If needed to define the earthquake potential of the region as it affects the Diablo Canyon Plant, PG&E will also reevaluate the earlier information and acquire additional new data.

OBJECTIVES

To satisfy Element 1, PG&E conducted an extensive program of literature review, discussions with researchers, data collection and compilation, field investigations, and analyses to assess the neotectonic setting and earthquake potential of south-central coastal California. These studies addressed all the technical considerations identified in the Program Plan for the Long Term Seismic Program, and are detailed in the Long Term Seismic Program Work Plan (PG&E, 1986). The investigations included a thorough review of existing published and available unpublished literature, data and interpretations, acquisition of additional geological, seismological and geophysical data in the onshore and offshore regions, and an evaluation of the past and contemporary tectonic setting and seismic source potential of south-central California. In the following sections, we discuss our methods and scope of work for conducting the geological,

seismological and geophysical investigations, and present our key findings regarding the tectonic setting and potential earthquake sources in the region. Results from the studies conducted to satisfy this element provided data necessary for completing subsequent elements of the license condition, including the evaluation of earthquake magnitude, discussed in Chapter 3, and the assessment of ground motions, Chapter 4.

METHOD OF STUDY

Following issuance of the license condition by the NRC, PG&E developed the Long Term Seismic Program Plan. After approval of the Program Plan by the NRC in July 1985, PG&E carried out the Phase II Scoping Study and developed a Work Plan to implement the geosciences investigations necessary to reevaluate the tectonic setting and seismic potential of the region (PG&E, 1986). The Scoping Study included preliminary probabilistic and deterministic source characterization and ground motions analyses and was designed to identify those technical considerations of greatest significance to the Diablo Canyon site region. Work tasks were then designed to address the significant considerations, which were defined as "those technical factors in the disciplines of the earth sciences that are most significant in characterizing the potential earthquake environment at Diablo Canyon." The significant considerations included:

- 1) Hosgri fault zone
 - Sense of slip
 - Dip and down-dip extent
 - Total length and segmentation
 - Slip rate



- Maximum earthquake magnitude
- 2) Edna and San Miguelito faults
 - Capability
 - Sense of slip
 - Maximum earthquake magnitude
 - Slip rate
 - 3) West Huasna, Rinconada, and Nacimiento faults
 - Sense of slip
 - Slip rate
 - 4) Little Pine and Foxen Canyon faults, onshore Santa Maria Basin
 - Capability
 - Geometry
 - Sense of slip
 - Total length
 - 5) 1927 Earthquake
 - Location and tectonic association
 - 6) Potential for Unknown Nearby Faults and Folds
 - Existence and capability
 - 7) Tectonic Model

To accomplish the work and be fully responsive to Element 1 of the license condition, PG&E assembled an experienced and capable professional team and encouraged a high level of interaction within it. The team was composed of PG&E staff scientists and engineers, consultants from geotechnical engineering companies, independent consultants, the Long Term Seismic Program Consulting Board, Technical Advisors, and PG&E management.

To update the data base, we carried out exhaustive reviews of the published and unpublished literature, acquired public and proprietary geophysical and geologic data, installed a seismic network, performed extensive field investigations, and conducted personal

interviews with researchers working in the region of interest. Discussions were held with scientists with the U.S. Geological Survey (USGS), the California Division of Mines and Geology (CDMG), local and national academic institutions, and other state and federal agencies (Table 2-1).

An important aspect of the conduct of the technical work, both in the field and in the office, was that it was performed in a direct and open fashion. NRC reviewers and other interested persons were invited to view any and all field localities and original data.

Interim findings and results were presented as separate papers and as major parts of special symposia at professional meetings (Table 2-2). This presented the work to the professional community and provided ongoing evaluation of the Program and its preliminary results as they evolved.

As a result of this open and receptive scientific approach to the conduct of the work, PG&E, in concert with its consultants and advisors, has developed a comprehensive, well-integrated expertise regarding regional geology, seismicity, and tectonics in order to assess the earthquake potential of south-central coastal California. This high level of understanding has been achieved from the contributions of the Program team members, the generous sharing of data and interpretations by the individuals listed in Table 2-1, and our integration of this with data and interpretations from the available literature.

SCOPE OF WORK

After incorporating the data and information gained from reviewing the literature and meeting with individuals, we conducted an extensive series of studies and analyses to augment the available data. These studies are summarized below, using the organization of the scope of work for the tasks presented in the Phase II Work Plan (PG&E, 1986).



Table 2-1

**INDIVIDUALS CONTACTED TO UPDATE THE
GEOLOGY/SEISMOLOGY/GEOPHYSICS/TECTONICS DATA BASE**

<u>Person Contacted</u>	<u>Institution</u>	<u>Topic</u>
T. C. Bache	Science Applications International Corp.	Seismic Source Modeling
L. A. Beyer	U.S. Geological Survey	Marine Gravity Data
N. E. Biggar	Woodward-Clyde Consultants	Regional Faults
R. D. Brown	U.S. Geological Survey	Tectonics, Regional Geology
T. H. Bruce	California Department of Water Resources	Regional Faults
T. S. Cleath	Consulting Hydrogeologist	San Luis Obispo Area Geology and Hydrology
J. K. Crouch	Crouch, Bachman, and Associates	Tectonics, Marine Geophysics
J. F. Davis	California Division of Mines and Geology	Regional Geology, Seismology, Tectonics
T. L. Davis	Consulting Geologist	Tectonics, Structural Geology
J. P. Eaton	U.S. Geological Survey	Regional Seismicity
W. L. Ellsworth	U.S. Geological Survey	Regional Seismicity
W. Foxall	Consulting Seismologist	Worldwide Faulting Data
G. A. Frazier	Science Applications International Corp.	Seismic Source Modeling
R. A. P. Gaal	California State Lands Commission	Marine Seismic Data
C. A. Hall	University of California, Los Angeles	Tectonics, Geologic Field Mapping
T. C. Hanks	U.S. Geological Survey	1927 Earthquake Data
W. P. Harbert	Stanford University	Tectonics, Paleomagnetic Data
E. Hart	California Division of Mines and Geology	Active Faults
E. G. Hoskins	Consulting Geologist	Discovery of the Hosgri Fault Zone
E. Humphries	University of Oregon, Eugene	Tectonics
G. L. Kennedy	Los Angeles County Museum	Paleontology, Paleoclimate
P. L. K. Knuepfer	State University of New York, Binghamton	Fault Segmentation
F. W. Lester	U.S. Geological Survey	Regional Seismicity Data
S. D. Lewis	U.S. Geological Survey	Seismic Data Processing
A. G. Lindh	U.S. Geological Survey	Regional Seismicity Data
B. P. Luyendyk	University of California, Santa Barbara	Tectonics, Marine Geophysics, Paleomagnetic Data



Table 2-1 (Continued)

**INDIVIDUALS CONTACTED TO UPDATE THE
GEOLOGY/SEISMOLOGY/GEOPHYSICS/TECTONICS DATA BASE**

Person Contacted	Institution	Topic
S. M. Marks	U.S. Geological Survey	Regional Seismicity Data
D. S. McCulloch	U.S. Geological Survey	Tectonics, Marine Seismic Data
D. R. Muhs	U.S. Geological Survey	Uranium Series Dating, Paleoclimate
J. S. Namson	Consulting Geologist	Tectonics, Structural Geology
B. M. Page	Stanford University	Regional Geology and Tectonics
W. D. Page	Woodward-Clyde Consultants	Regional Geology and Tectonics
D. L. Reed	University of California, Santa Cruz	Tectonics, Marine Geophysics
T. K. Rockwell	University of California, San Diego	Soils Chronostratigraphy
D. B. Slemmons	University of Nevada, Reno	Regional Geologic Studies
D. P. Schwartz	U.S. Geological Survey	Regional Tectonics and Fault Segmentation
S. W. Stewart	U. S. Geological Survey	Regional Seismicity Data
R. H. Sydnor	California Division of Mines and Geology	Regional Geology
G. A. Thompson	Stanford University	Offshore Tectonics and Structure
R. A. Uhrhammer	University of California, Berkeley	Regional Seismicity Data
G. E. Weber	Consulting Geologist	San Simeon Fault, Quaternary Activity of San Gregorio/Hosgri System
J. F. Wehmiller	University of Delaware	Amino-acid Racemization, Paleoclimate
J. H. Weise	Consulting Geologist	San Luis Obispo Area Geology
R. J. Weldon	University of Oregon, Eugene	Tectonics
I. G. Wong	Woodward-Clyde Consultants	Seismicity Data





Table 2-2

**PAPERS PRESENTED AT PROFESSIONAL MEETINGS
BY LONG TERM SEISMIC PROGRAM SCIENTISTS**

*SEISMOLOGICAL SOCIETY OF AMERICA
EIGHTY-SECOND ANNUAL MEETING
SANTA BARBARA, CALIFORNIA
MARCH 25, 1987*

SESSION: STRONG GROUND MOTION

D. J. Wald, P. G. Somerville, D. V. Helmberger: COMPATIBILITY OF ACCELEROGRAMS OF THE 1979 IMPERIAL VALLEY EARTHQUAKE WITH SLIP-DISTRIBUTION ASPERITY MODELS

SESSION: SEISMOTECTONICS

P. L. K. Knuepfer, M. J. Bamberger, J. M. Turko, K. J. Coppersmith: CHARACTERISTICS OF THE BOUNDARIES OF HISTORICAL FAULT RUPTURES

SESSION: INSTRUMENTATION AND NETWORKS

W. U. Savage, S. E. Pauly: BALANCING DESIGN OBJECTIVES FOR A LOCAL TELEMETERED SEISMIC NETWORK: A CASE HISTORY IN SOUTH-CENTRAL CALIFORNIA

*GEOLOGICAL SOCIETY OF AMERICA
EIGHTY-THIRD ANNUAL MEETING
CORDILLERAN SECTION
HILO, HAWAII
MAY 20-22, 1987*

SESSION: SEISMOTECTONICS OF THE CENTRAL CALIFORNIA COAST RANGES I: GENERAL SEISMOLOGY AND SEISMIC REFLECTION

W. U. Savage, M. K. McLaren: RECENT SEISMICITY OF SOUTH-CENTRAL COASTAL CALIFORNIA

W. U. Savage, D. V. Helmberger: SOURCE CHARACTERISTICS AND TECTONIC ASSOCIATION OF THE 1927 LOMPOC, CALIFORNIA EARTHQUAKE

SESSION: SEISMOTECTONICS OF THE CENTRAL CALIFORNIA COAST RANGE II: SAN SIMEON, PISMO SYNCLINE—SANTA MARIA BASIN

W. U. Savage, J. M. Howie, C. R. Willingham: INTEGRATED DEEP CRUSTAL STUDIES ONSHORE/OFFSHORE SOUTH-CENTRAL COASTAL CALIFORNIA

K. L. Hanson, W. R. Lettis, E. L. Mezger, G. E. Weber: LATE PLEISTOCENE DEFORMATION ALONG THE SAN SIMEON FAULT ZONE NEAR SAN SIMEON, CALIFORNIA



Table 2-2 (Continued)

**PAPERS PRESENTED AT PROFESSIONAL MEETINGS
BY LONG TERM SEISMIC PROGRAM SCIENTISTS**

E. L. Mezger, K. L. Hanson, N. T. Hall, T. D. Hunt: EVIDENCE FOR QUATERNARY FAULTING IN LOS OSOS VALLEY, SAN LUIS OBISPO COUNTY, CALIFORNIA

J. M. Coyle, N. T. Hall, J. V. Hengesh, W. R. Lettis: QUATERNARY DEFORMATION ALONG THE SOUTHWESTERN MARGIN OF THE SAN LUIS/PISMO SYNFORM, PISMO BEACH, CALIFORNIA

K. I. Kelson, W. R. Lettis, G. E. Weber, G. L. Kennedy, J. F. Wehmiller: AMOUNT AND TIMING OF DEFORMATION ALONG THE WILMAR AVENUE, PISMO, AND SAN MIGUELITO FAULTS, PISMO BEACH, CALIFORNIA

SESSION: SEISMOTECTONICS OF THE CENTRAL CALIFORNIA COAST RANGE III: FOLD-FAULT AND SLIP RATES

N. T. Hall: LATE QUATERNARY HISTORY OF THE EASTERN PLEITO THRUST FAULT, SAN EMIGDIO MOUNTAINS, CALIFORNIA

G. E. Weber, W. R. Lettis, K. L. Hanson: LATE PLEISTOCENE UPLIFT RATES ALONG THE CENTRAL CALIFORNIA COAST, CAPE SAN MARTIN TO SANTA MARIA VALLEY

C. R. Willingham, D. H. Hamilton: THE NATURE OF THE HOSGRI FAULT ZONE—PART I: STRUCTURE AND EXTENT

R. G. Heck, C. R. Willingham, D. H. Hamilton: THE NATURE OF THE HOSGRI FAULT ZONE—PART II: EFFECT ON STRATIGRAPHY AND TIMING OF TECTONIC EVENTS

D. H. Hamilton: CHARACTERIZATION OF THE SAN GREGORIO/HOSGRI FAULT ZONE, COASTAL CENTRAL CALIFORNIA

C. N. Branch, N. T. Hall: EVIDENCE FROM HIGH-RESOLUTION SEISMIC REFLECTION DATA FOR STRIKE-SLIP MOVEMENT ALONG THE HOSGRI FAULT ZONE, OFFSHORE CENTRAL CALIFORNIA

D. H. Hamilton, N. T. Hall: STRUCTURE AND TECTONICS OF THE SAN LUIS-PISMO-SANTA MARIA REGION, COASTAL CENTRAL CALIFORNIA

F. R. Bickner, P. R. Vaughan: EVIDENCE FOR HOLOCENE ACTIVITY OF THE SAN SIMEON FAULT FROM DEFORMED FLUVIAL TERRACES NEAR SAN SIMEON, COASTAL CENTRAL CALIFORNIA

N. T. Hall, T. D. Hunt, P. A. Vaughan, F. R. Bickner, W. R. Lettis: TRENCHING AND MAPPING INVESTIGATIONS OF THE LATE QUATERNARY BEHAVIOR OF THE SAN SIMEON FAULT, SAN LUIS OBISPO COUNTY, CALIFORNIA

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Table 2-2 (Continued)

PAPERS PRESENTED AT PROFESSIONAL MEETINGS
BY LONG TERM SEISMIC PROGRAM SCIENTISTS

T. K. Rockwell, F. R. Bickner, P. R. Vaughan, K. L. Hanson: APPLICATIONS OF SOIL GEOMORPHOLOGY TO DATING AND CORRELATION COASTAL TERRACE DEPOSITS ACROSS THE SAN SIMEON FAULT ZONE, CENTRAL CALIFORNIA

SUMMARY: L. S. Cluff

*INTERNATIONAL ASSOCIATION OF SEISMOLOGY
AND PHYSICS OF THE EARTH'S INTERIOR
19TH GENERAL ASSEMBLY
VANCOUVER, CANADA
AUGUST 11, 1987*

SESSION: INTERPRETATION OF STRONG MOTION WAVE FORMS

P. G. Somerville, D. J. Wald, and D. V. Helmberger: COMPATIBILITY OF ACCELEROGRAMS WITH SLIP-DISTRIBUTION ASPERITY MODELS

*GEOLOGICAL SOCIETY OF AMERICA
1987 ANNUAL MEETING
PHOENIX, ARIZONA
OCTOBER 26-29, 1987*

SESSION: TECTONICS-GEOPHYSICS

T. M. Niemi, N. T. Hall, G. I. Shiller: SEAFLOOR SCARPS ALONG THE CENTRAL REACH OF THE HOSGRI FAULT ZONE, SOUTHERN COAST RANGES, CALIFORNIA

*AMERICAN GEOPHYSICAL UNION
1987 FALL MEETING
SAN FRANCISCO, CALIFORNIA
DECEMBER 6-11, 1987*

SESSION: STRONG GROUND MOTION

D. J. Wald, P. G. Somerville: SEMI-EMPIRICAL MODELING OF RECORDED ACCELERATIONS FROM THE 1979 IMPERIAL VALLEY EARTHQUAKE

P. G. Somerville, J. P. McLaren, C. K. Saikia: FORMULATION AND VALIDATION OF A PROCEDURE FOR THE SITE-SPECIFIC ESTIMATION OF SPATIAL COHERENCE OF GROUND MOTIONS CLOSE TO AN EXTENDED SOURCE

SESSION: FAULT MECHANICS AND EARTHQUAKE RUPTURE PROCESSES

P. L. K. Knuepfer and K. J. Coppersmith: IMPLICATIONS OF THE CHARACTERISTICS OF END-POINTS OF HISTORICAL SURFACE FAULT RUPTURES FOR THE NATURE OF FAULT SEGMENTATION



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Table 2-2 (Continued)

PAPERS PRESENTED AT PROFESSIONAL MEETINGS
BY LONG TERM SEISMIC PROGRAM SCIENTISTS

SESSION: EDGE & RELATED SEISMIC PROJECTS ONSHORE/OFFSHORE CENTRAL CALIFORNIA

M. Talwani, W. Mooney, W. U. Savage, C. R. Willingham, G. A. Thompson, A. Levander, and A. Trehu: EDGE AND RELATED SEISMIC PROJECTS - ONSHORE, OFFSHORE CALIFORNIA

D. H. Clark, D. H. Hamilton, N. T. Hall, and R. G. Heck: TIMING AND STYLE OF NEOGENE DEFORMATION WITHIN THE OFFSHORE SANTA MARIA BASIN, CALIFORNIA

C. R. Willingham, and J. D. Rietman: DEEP SEISMIC AND POTENTIAL FIELD CRUSTAL STUDY ACROSS THE SOUTH CENTRAL CALIFORNIA BORDERLAND AND ADJACENT ONSHORE AREAS

J. M. Howie, and W. U. Savage: INITIAL CRUSTAL VELOCITY MODEL FOR SOUTH-CENTRAL CALIFORNIA COASTAL MARGIN

M. K. McLaren, and W. U. Savage: RELOCATION OF EARTHQUAKES OFFSHORE FROM POINT SAL, CALIFORNIA

SPECIAL SESSION: THE WHITTIER NARROWS EARTHQUAKE

D. J. Wald: SIMULATION OF ACCELEROGRAMS OF THE 1987 WHITTIER NARROWS EARTHQUAKE

*U.S. GEOLOGICAL SURVEY WORKSHOP ON FAULT SEGMENTATION AND CONTROLS OF RUPTURE INITIATION AND TERMINATION
PALM SPRINGS, CALIFORNIA
MARCH 7-9, 1988*

K. J. Coppersmith and R. R. Youngs: ASSESSING THE PROBABILITY OF FUTURE RUPTURE SEGMENTATION FOR SEISMIC HAZARDS ANALYSES

P. L. K. Knuepfer: IMPLICATIONS OF THE CHARACTERISTICS OF END-POINTS OF HISTORICAL SURFACE FAULT RUPTURES FOR THE NATURE OF FAULT SEGMENTATION

*GEOLOGICAL SOCIETY OF AMERICA
EIGHTY-FOURTH ANNUAL MEETING
CORDILLERAN SECTION
LAS VEGAS, NEVADA
MARCH 29-31, 1988*

W. R. Lettis and N. T. Hall: METHODS FOR EVALUATING FAULT SEGMENTATION - AN EXAMPLE FROM CENTRAL COASTAL CALIFORNIA





Table 2-2 (Continued)

**PAPERS PRESENTED AT PROFESSIONAL MEETINGS
BY LONG TERM SEISMIC PROGRAM SCIENTISTS**

D. H. Clark, N. T. Hall, T. D. Hunt, W. R. Lettis: **STYLE AND TIMING OF SLIP
ON THE SAN MIGUELITO FAULT, SAN LUIS OBISPO COUNTY, CALIFORNIA**

K. J. Coppersmith and R. R. Youngs: **ESTIMATING FUTURE COSEISMIC
RUPTURES FROM FAULT SEGMENTATION DATA**



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Task 1: Characterization of the Hosgri Fault Zone

The Hosgri fault zone lies offshore along its entire length, from near Point Estero south to near Point Arguello. Characterization of the fault as a potential seismic source, therefore, is dependent on indirect observations using geophysical techniques, coupled with regional tectonic assessments based on seismicity data and the characterizations of adjacent faults and folds. In this task, existing geophysical data were acquired, reprocessed, and reviewed and additional common-depth-point geophysical investigations were performed to characterize the location, lengths of segments, down-dip geometry, and sense of displacement of the Hosgri fault zone. Shallow, high-resolution geophysical and bathymetric data were collected and analyzed to assess recency of displacement and locations of sea-floor scarps or other indications of young deformation along individual traces of the fault zone.

The geophysical investigations primarily included interpretation of numerous shallow and deep seismic reflection profiles, and integration of seismic and well data. Temporal and spatial relationships between the Hosgri fault zone and contiguous rock bodies and geologic structures, and the deformational history of the fault were interpreted from the combined data set.

The process of geophysical characterization encompassed four elements:

- 1) **Data Acquisition:** Prior to this study, PG&E had acquired and interpreted an extensive, pre-1978 data base of both proprietary and non-proprietary seismic data. During the course of this study, we examined additional geophysical data that had been collected since 1978, and acquired several new data sets (Table 2-3, Figure 2-1 and Plates 1 and 2). We also identified offshore areas for which detailed geophysical data were not available or were available but had not been studied; these areas are mostly in California State
- 2) **Data Processing:** The 1986 Comap and Digicon common-depth-point data sets commissioned by PG&E were processed using procedures and parameters designed to enhance the quality of reflectors in the vicinity of the Hosgri fault zone. We also reprocessed more than 400 kilometers of existing proprietary common-depth-point seismic lines to improve the quality of images across the Hosgri fault zone between Point Estero and Point Pedernales.
- 3) **Geophysical Interpretation:** The seismic data were interpreted in an integrated manner using both high-resolution and common-depth-point data sets to identify faults, map both shallow and deep structures, and assess the timing of deformation along the entire length of the Hosgri fault zone. Faults identified on the seismic records (picks) were correlated laterally and vertically with picks from adjacent lines within and between the various data sets. Appropriate reflecting

waters within 3 miles of the coastline, and in areas outside the parts of the offshore Santa Maria Basin that have been the focus of recent exploration for hydrocarbon potential. To address this need, we acquired State Lands Commission common-depth-point and high-resolution seismic reflection data sets for the near-shore area between the middle of San Luis Obispo Bay and Point Arguello, and we commissioned the acquisition of common-depth-point and high-resolution seismic reflection data (the 1986 Comap Survey) in the area from the middle of San Luis Obispo Bay north past Cape San Martin (Figure 2-1). In addition, as is discussed under Task 7, PG&E commissioned two very-deep-penetration geophysical lines (the 1986 Digicon survey) across the Hosgri fault zone in Estero and San Luis Obispo bays. These deep crustal studies were carried out as a cooperative data-acquisition effort with Rice University, Houston, the Houston Area Research Council, and the U.S. Geological Survey.



Table 2-3
GEOPHYSICAL DATA BASE

PG&E

Pacific Gas and Electric Company

Diablo Canyon Power Plant
Long Term Seismic Program

Acquisition Contractor	Date Shot	Owner/ Client	Primary System Energy Source	Data Categories						Survey Length (km)	General Survey Area	Shiptrack Map	
				CDP (Fold)	Record Length (sec)	Boomer	3.5 kHz	Echo Sounder	Side Scan Sonar			Plate	Sheets
Aquatronics	1974	PG&E	Sparker	6	1.3		X	X	X	479	Point Arguello to San Simeon within 10 km of coast line	2	1-3
Bolt, Barenek and Newman (BBN)	1973-4	PG&E	Sparker	N/A	1	X		X		121	Point Conception to Monterey Bay within 15 km of coast line	2	1,2
Consolidated Geotechnical (CGI)	1976	CGI/PG&E	Sparker (30 kj)	12	2					1340	Santa Maria Basin, Point Conception to Cape San Martin	1	1-3
Standard Oil of California*	1973	Standard Oil of California*	Sparker	N/A	1	X		X	X	145	Estero Bay	-	-
Comap Alaska*	1986	PG&E	Water guns (160 cu in)	24	2	X	X	X	X	500	San Luis Bay to Cape San Martin, within 6 km of coast line	1 2	2,3
Digicon Geophysical*	1986	State Lands Commission	Air guns (3,520 cu in)	60	4					592	Point Arguello to San Luis Bay within 7 km of coast line	1	1
Digicon Geophysical*	1986	PG&E	Air guns (6000 cu in)	45	16					290	Two lines, coast line to base continental slope. Morro Bay and San Luis Bay, one tie line	1	2
Fairfield Industries*	1979	Minerals Management Service	Sleeve exploder	12	1		X	X	X	4720	Santa Maria Basin, Point Conception to Point Estero	2	1-3
Fugro	1978	PG&E, USGS	Sonia (3.5 kHz)	N/A	0.5		X			485	Santa Maria Basin, Point Pedernales to Point Sal	2	1
Geophysical Services, Inc. (GSI)*	1980	Ogle Petroleum/ PG&E	Air guns	48	5					1296	Santa Maria Basin, Point Pedernales to Point Buchon	1	1,2
JEBCO Seismic Inc.*	1988	JEBCO/ PG&E	Air guns (3,380 cu in)	60	4					58	Northeastern Santa Maria Basin, Point San Luis to Point Piedras Blancas	1	2
Nekton "45"*	1983	Nekton/ PG&E	Water guns	36	3					154	East-central Santa Maria Basin	1	1,2



Table 2-3 (Continued)
GEOPHYSICAL DATA BASE

Acquisition Contractor	Date Shot	Owner/ Client	Primary System Energy Source	CDP (Fold)	Record Length (sec)	Data Categories				Survey Length (km)	General Survey Area	Shiptrack Map	
						Boomer	3.5 kHz	Echo Sounder	Side Scan Sonar			Plate	Sheets
Nekton "164"	1986	State Lands Commission	Water guns (60 cu in)	24	3	X	X	X	X	1338	Point Arguello to San Luis Bay within 7 km of coast line	1	1,2
Seiscom Delta*	1977	Ogle Petroleum/ PG&E	Air guns	48	6					42	Southwest of San Luis Bay	1	2
Seisdata Services, Inc.*	1986	Seisdata/ PG&E	Vibroseis [®]	48	12					200	Onshore Santa Maria Basin	9	—
USGS, R/V Bartlett	1972	USGS	Sparker	N/A	3					121	Santa Maria Basin, Point Arguello to Lopez Point	1	2,3
USGS, R/V Kelez	1973	USGS	Sparker	N/A	3	X				1207	Point Sal to Cape San Martin within 10 km of coast line	2	2,3
USGS, R/V Lee	1975	USGS	Air guns (1326 cu in)	N/A	3	X	X			986	Point San Luis to Lopez Point within 10 km of coast line	2	2,3
USGS, R/V Lee*	1979	USGS	Air guns	24	8					250	Santa Maria Basin, east/west regional lines	1	1-3
USGS, R/V Polaris	1972	USGS	Sparker	N/A	1.5	X				745	Santa Maria Basin, Point Conception to Point Sal	2	1,2
USGS, R/V Scammon*	1980	USGS	Boomer	N/A	0.5	X				337	Northeastern Santa Maria Basin, Point Estero to Cape San Martin	2	2,3
Western Geophysical, Inc.	1974	Western Geophysical/ PG&E	Air guns	46	6					220	Eastern Santa Maria Basin, Point Arguello to Estero Bay	1	1,2
Western Geophysical, Inc.*	1975 & 1982	Western Geophysical/ PG&E	Air guns	46 & 60	6					250	Northeastern Santa Maria Basin, Point Buchon to Cape San Martin	1	2,3
										15,876	Approximate kilometers of seismic reflection data utilized in the Program study		

*Data acquired by PG&E after 1979.



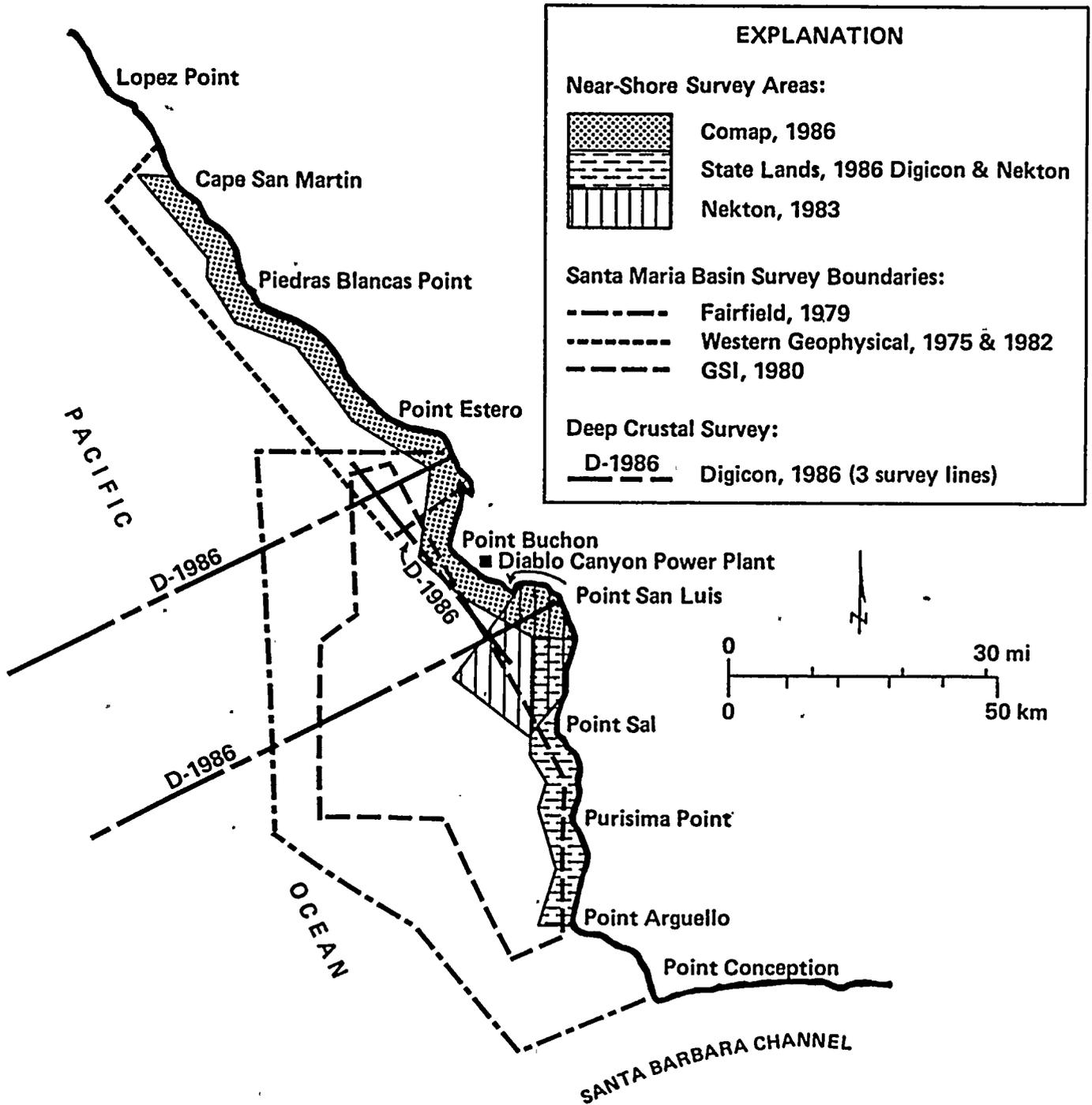


Figure 2-1

Index map showing general areas of major marine geophysical data sets acquired for the Long Term Seismic Program since 1979.

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horizons were selected for mapping based on the principles of seismic stratigraphy and were then mapped using conventional loop-tie techniques. The resulting geophysical interpretations were compiled as cross sections, trend maps, structure contour maps (time-based) and isotime maps (Plates 3 to 9).

- 4) **Geological Interpretation:** Seismic source characterization of the Hosgri fault zone requires that interpretations of structural geology and deformational history be derived from the geophysical interpretive products using the most accurate geologic calibrations available. The two primary calibrations we made were (1) to tie the geophysical lines to geologic data from offshore wells (such data have recently entered the public domain and have greatly improved the accuracy and confidence in the offshore structural interpretations); and (2) to convert the time-based sections and maps to depths using seismically derived velocity models (the depth sections provide a one-to-one horizontal to vertical cross section, allowing geometrically accurate representations of fault dips, stratigraphic thickness and correlations, and fold geometries).

The updated geophysical data base and its geophysical and geological interpretations have been used to help reevaluate the seismic source characteristics of the Hosgri fault zone. This characterization also incorporated results from the other tasks described below.

Task 2: Neotectonic and Quaternary Geology Studies

Quaternary (Table 2-4) studies were conducted to assess the Neogene tectonic deformation within the south-central coastal region of California. The primary objectives of these studies were to collect and interpret data for (1) identifying and characterizing areas of Quaternary deformation; (2) evaluating the late Cenozoic evolution of geologic structures in the region; and (3) assessing the relationship of Quaternary structures to one another and to regional tectonic events. Thus the

investigations centered on the study of Quaternary stratigraphic strain recorders, such as marine and fluvial terraces, as well as site-specific geologic mapping, trenching, drilling, topographic profiling, and soil-stratigraphic analysis.

In interplate tectonic environments such as the North America-Pacific plate boundary, faults that have the potential for generating large earthquakes have typically experienced repeated displacements. Ground deformation associated with moderate to large magnitude earthquakes on such faults is characteristically expressed by surface displacement along the fault trace and by secondary, localized fracturing, warping and/or tilting. In addition to high-angle faults, which tend to be expressed at the surface, low-angle thrust faults that may or may not reach the surface also occur in interplate tectonic environments. Moderate magnitude earthquakes at Coalinga in 1983 and Whittier Narrows in 1987 did not have associated surface faulting and are interpreted to have occurred on such "blind" thrust faults that did not rupture the surface. Displacement along such faults at depth is typically expressed by coseismic uplift of the surface that produces recognizable asymmetric surface anticlines over the long term. If the faulting is occurring within the contemporary tectonic environment, the anticline will deform late Quaternary deposits and surfaces. Recent studies by Suppe (1983), Namson and Davis (1988), Davis and others (1986), and Medwedeff (1988) strongly indicate a genetic relationship between low-angle blind thrust faults and folding. Thus, although blind thrust faults do not by definition rupture the surface, their presence can be discerned from associated folds and their activity assessed from the age and rate of Quaternary fold deformation. Where geophysical data of adequate depth of penetration and quality can be obtained, blind thrusts often can be imaged. Where an adequate stratigraphic section exists over a blind thrust, the timing and extent of displacement along it can be studied quantitatively through construction of retrodeformable cross sections (Suppe, 1983). Evaluation of the presence or absence of active fold deformation, therefore, provides the most direct and reliable method for assessing any potential that low-angle





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thrust faulting is an active process in the contemporary tectonic environment.

The neotectonic and Quaternary investigations performed during this study were designed to identify and evaluate surface deformation associated with both surface faults and possible blind thrust faults. The results of these investigations are presented on Plates 10 through 20. Surface faults were evaluated by investigating the geologic record preserved in the deposits cut by the faults. At places where the ages of the deposits are known, the most recent fault activity was assessed by evaluating the age of the youngest deposits that are displaced or deformed by the fault and/or by evaluating the age of the oldest deposits that overlie the fault and are not displaced or deformed. Blind thrust faults were evaluated by detailed regional mapping of Quaternary surfaces to assess either the presence and locations of fold deformation or to demonstrate the absence of such deformation.

The degree of confidence in evaluating fault activity depends upon the quality, quantity and strength of the evidence, which may vary from fault to fault or from location to location. The most reliable and useful geologic evidence for evaluating the potential for future faulting is found in sediments or rocks that are geologically young, generally of late Quaternary age. In this respect, the south-central coastal region of California presents excellent conditions for assessing Quaternary fault activity and related ground deformation such as folding, warping or tilting. A well-developed flight of marine terraces is preserved along much of the coast and the northerly trending coastline crosses the northwesterly structural grain of the region. The terraces thus provide an excellent strain gauge with which to evaluate late Quaternary deformation throughout the past 500,000 years.

Figure 2-2 illustrates the flight of marine terraces along the coastline south of the Diablo Canyon Power Plant. Detailed mapping and dating investigations were performed to identify and evaluate areas of disruption or other local deformation of the terrace sequence. Dated emergent terraces were used to assess rates of coastal uplift and to delineate areas of tectonic deformation (for example, uplift, subsidence,

tilting). Absence of localized disruption of the terrace sequence would provide strong evidence for the absence of late Quaternary deformation. The plant site itself is situated on the terrace sequence allowing the ability to demonstrate conclusively the absence or presence of late Quaternary deformation in the site vicinity (Figure 2-3).

Ages of Quaternary deposits were estimated using one or more of several dating techniques to assess the recency, rate, and recurrence of deformation. These techniques included:

1) Numerical dating methods

- Uranium-series dating of invertebrate coral and vertebrate bone and teeth samples
- Radiocarbon dating of charcoal, wood, peat, and organic-rich soil by accelerator, conventional and mean-residence-time techniques

2) Calibration dating methods

- Relative degree of soil profile development
- Amino acid racemization of marine mollusk shells
- Thermoluminescence analysis of silt deposits

3) Correlation dating methods

- Correlation of marine terraces to paleo-sea levels
- Paleoclimate analysis of marine invertebrate faunal assemblages and correlation to dated marine oxygen-isotope stages.

The study of each geographic area or potential seismic source generally progressed through an increasingly focused program from regional reconnaissance mapping and air photo interpretation, through detailed geologic mapping, to site-specific mapping, geophysical studies, drilling, and trenching. Regional studies were conducted to identify and assess the nature and distribution of late Cenozoic faults in the south-central coastal region. Detailed studies were conducted at selected localities along identified





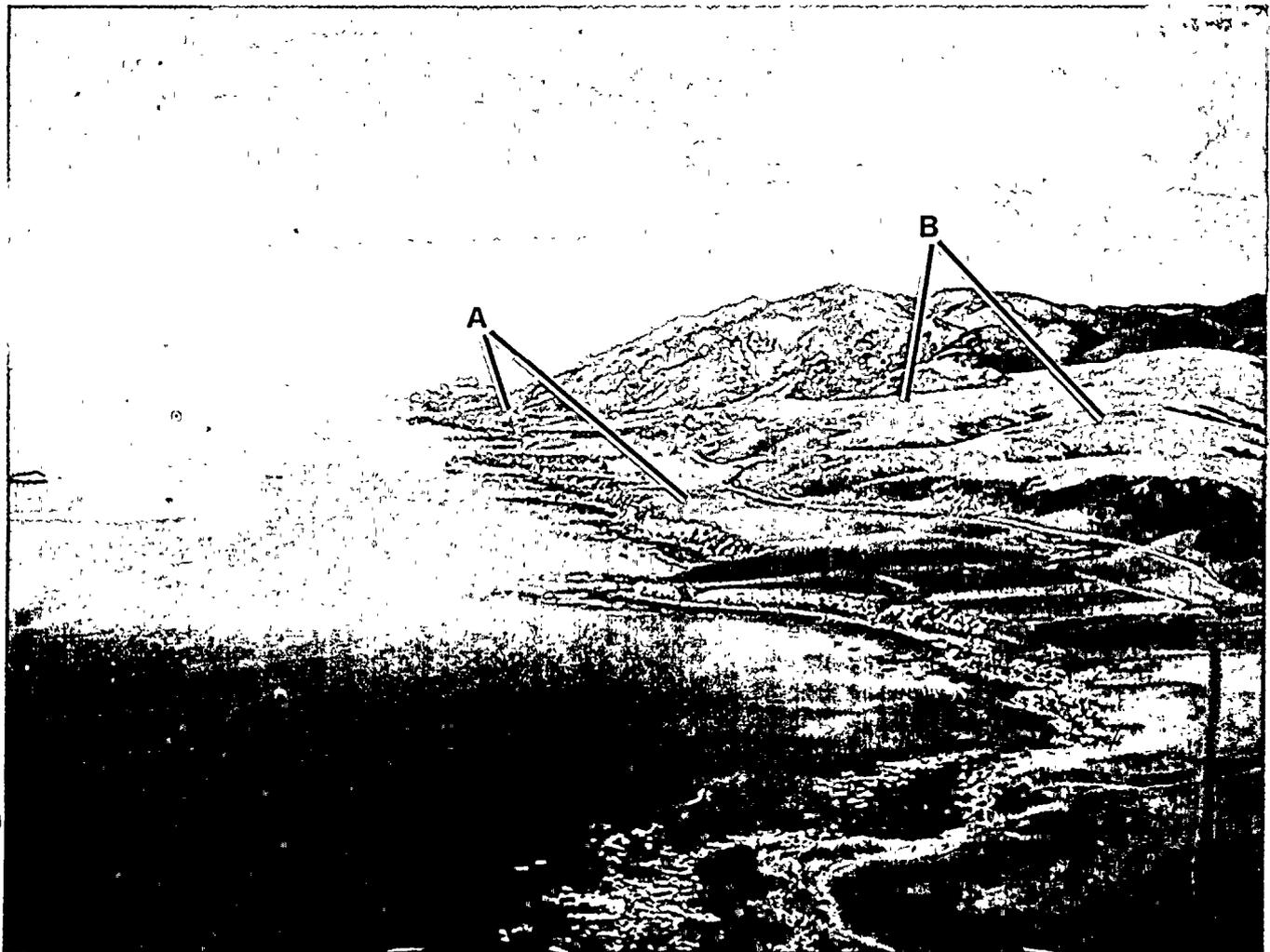


Figure 2-2

Photograph of coastline north of Point San Luis (view is north). A flight of emergent late Quaternary marine terraces is present along the coast and provides an excellent strain gauge for assessing late Quaternary deformation. A indicates composite surface of Stage 5a (83,000 years), Stage 5e (120,000 years) and Stage 7 (214,000 years) marine terraces. B indicates rolling, dissected surfaces of Stage 9 (320,000 years), Stage 11 (430,000 years), Stage 13 (480,000 years) and Stage 15 (560,000 years) marine terraces.





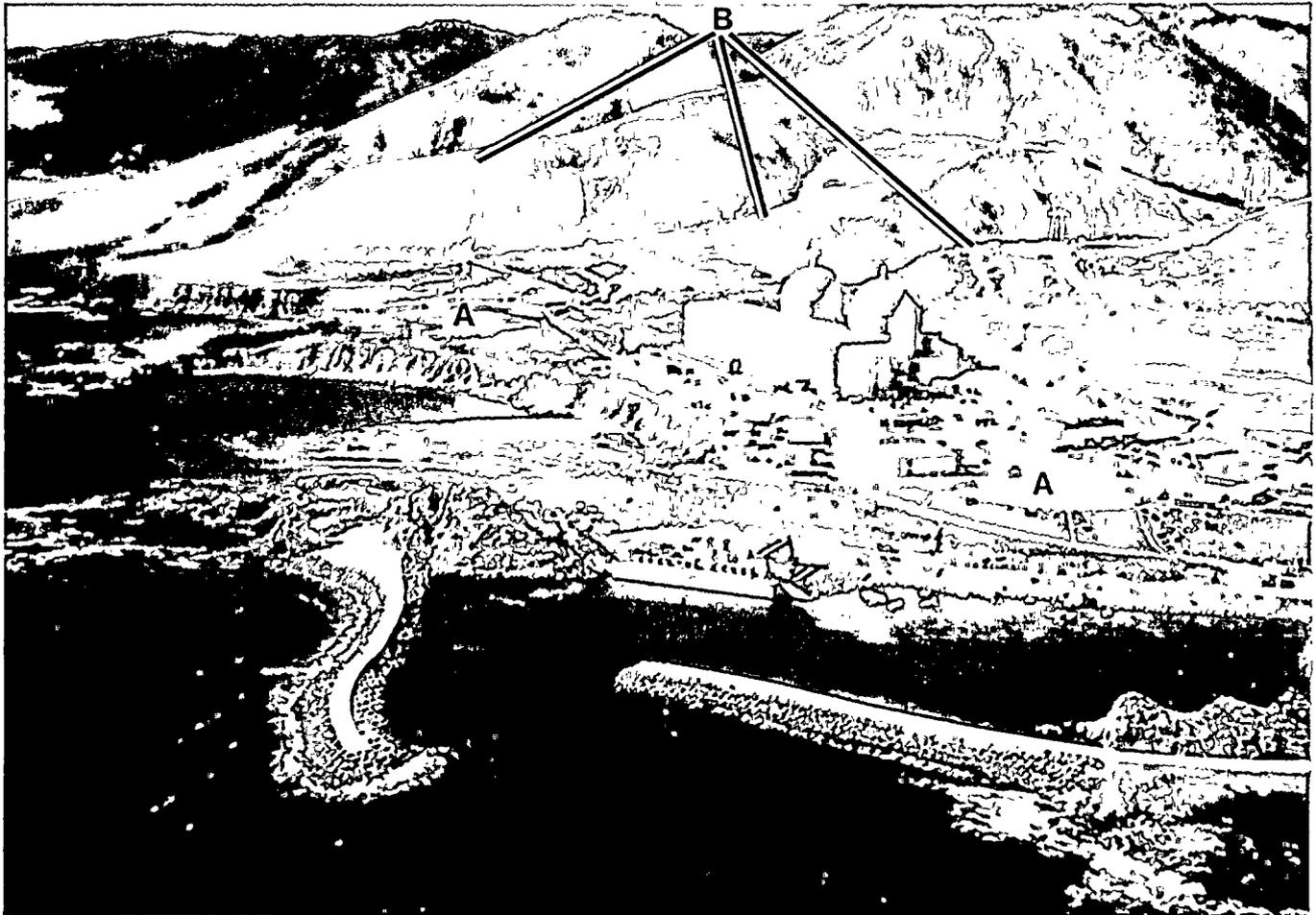


Figure 2-3

The Diablo Canyon Power Plant is situated on a flight of emergent late Quaternary marine terraces that range in age from about 80,000 to 350,000 years old. Higher, older marine terraces are cut into the hills behind the Plant. A indicates composite surface of Stage 5a (83,000 years), Stage 5e (120,000 years) and Stage 7 (214,000 years) marine terraces. B indicates dissected surfaces of Stage 9 (320,000 years) and Stage 11 (430,000 years) marine terraces.



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faults to assess the physical and behavioral aspects of the fault important to the characterization of the fault's seismic source potential. To the extent possible, these localities contained datable late Quaternary deposits, soils and/or geomorphic surfaces to provide information on the age and recurrence of past surface-faulting events. The areas in which these studies were conducted are shown in Figure 2-4. A total of 240 boreholes, having a depth range of 5 to 35 meters, were drilled during the study, using a truck-mounted, continuous-flight auger. Sixty-six trenches and natural exposures were logged and interpreted (Table 2-5). Investigations were conducted in the region adjacent to the Diablo Canyon plant site to evaluate potential seismic sources, including the Edna and San Miguelito faults, the Los Osos fault zone, faults within and along the northeastern margin of the Santa Maria Valley, and any previously undetected faults that might be present in the San Luis/Pismo region.

Investigations were also conducted in the San Simeon area to characterize the San Simeon fault zone and related structures. The San Simeon fault zone, which is partly onshore, makes an en echelon right stepover to the offshore Hosgri fault zone near Cambria. Because of this en echelon relationship, characterization of the neotectonic behavior of the San Simeon fault zone provided important constraints on the style, sense, and rate of slip of the Hosgri fault zone, particularly the northern part of the Hosgri that lies directly south of the San Simeon fault zone in the Estero Bay/Point Buchon area.

Quaternary studies were also conducted in the offshore area along the Hosgri fault zone (Plate 4). The studies included mapping the thickness of the post-late Wisconsinan sediments along its entire length, analysis of geomorphic features observed on high-resolution geophysical records, detailed bathymetric mapping in the area between San Luis Bay and Estero Bay, dredge sampling, and local submarine investigations by diver-geologists in San Simeon Bay, San Luis Obispo Bay and offshore of Point San Luis.

Task 3: Seismology Studies

Seismicity data within the south-central coastal California region were analyzed using improved crustal velocity data (see Task 7) and original earthquake readings from the U.S. Geological Survey, the University of California Seismograph Stations, and the Seismological Laboratory of the California Institute of Technology. We also used recent, well-recorded earthquakes as master events to relocate less well recorded events. Using revised locations and improved velocity models, additional focal mechanisms were evaluated and revised as required. The catalog of historical earthquakes of magnitude 5 or greater was reviewed and updated.

A significant additional study, not initially planned as part of the Program, was the installation and operation of the PG&E Central Coast Seismic Network, a high-gain network of telemetered seismographs installed along and within about 20 kilometers of the coastline from Ragged Point south to Point Sal (Figure 2-5). The network was designed to supplement the seismographic coverage of the region around the Diablo Canyon site by the University of California at Berkeley, the California Institute of Technology, and the U.S. Geological Survey. The objectives of the network are threefold: (1) to collect seismological data useful in refining our understanding of local and regional tectonics in coastal California; (2) to locate accurately and characterize any nearby earthquakes that may produce strong-motion acceleration recordings at or near the Diablo Canyon Power Plant, and (3) to assess ground motion site response. The network uses radio and microwave telemetry to transmit data to PG&E offices in San Francisco, where an online computer system and our seismological staff monitor the functioning of the system and analyze the data obtained. Stations in the network have operated since July 1986, and data gathered from that date through May 1988, have been incorporated into the Program and this final report.

The earthquake catalog for the region was updated for the period 1973 through May 1988. From October 1987 to the present, the



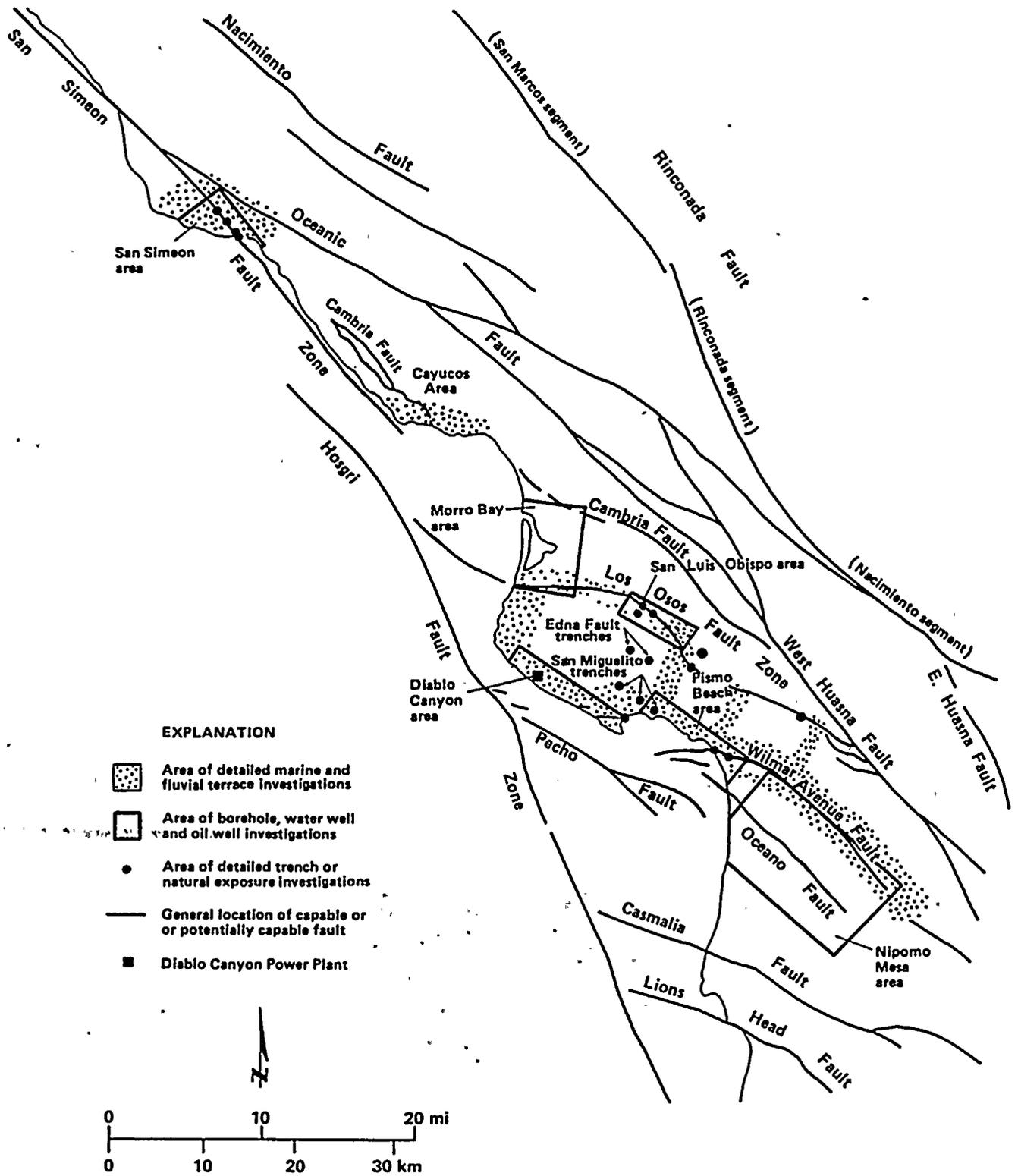


Figure 2-4

Index map showing areas of detailed onshore geologic investigations conducted during the Long Term Seismic Program.

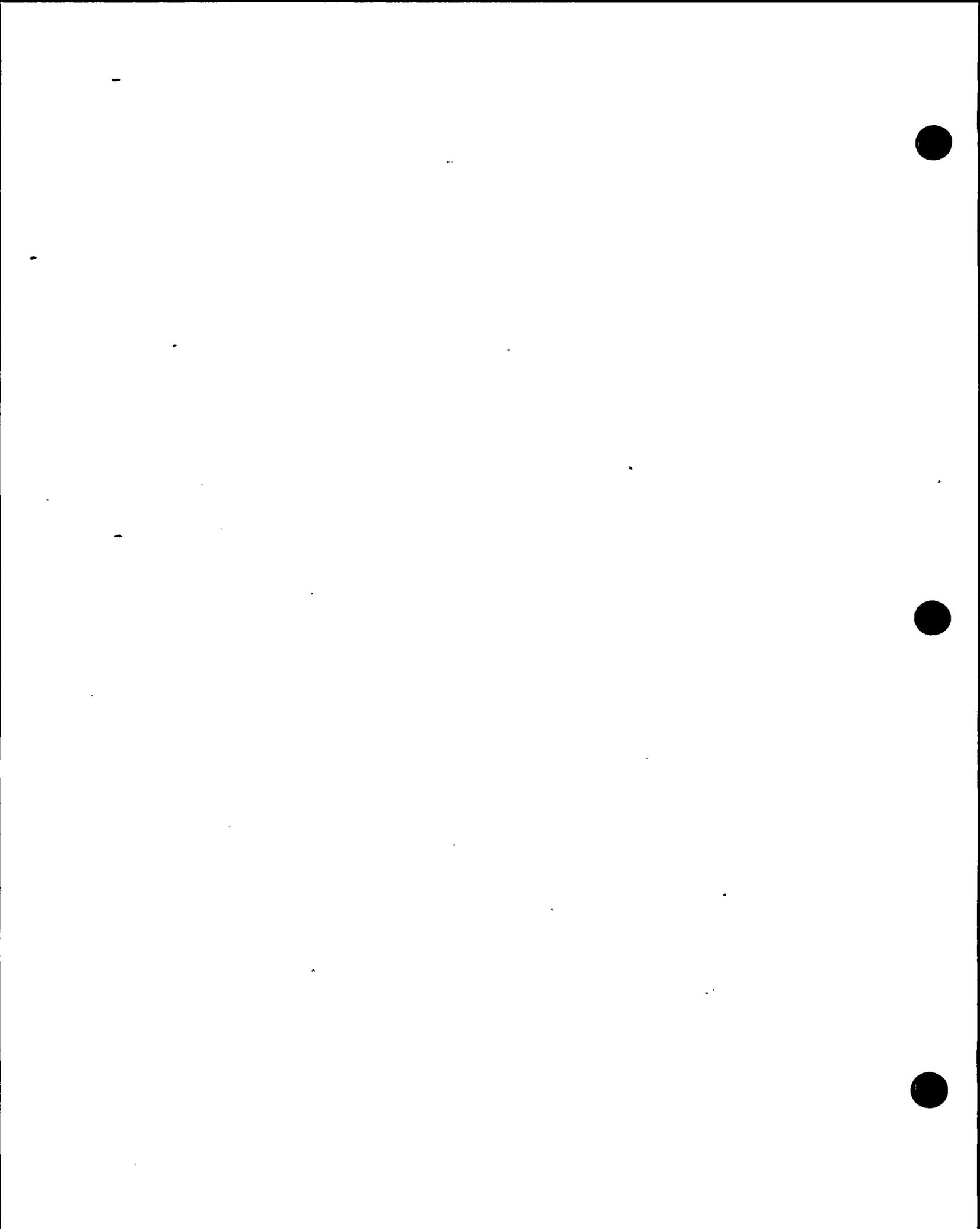


Table 2-5

**SUMMARY OF NUMBER AND LENGTHS OF TRENCHES AND NATURAL
EXPOSURES LOGGED FOR THE GEOLOGIC INVESTIGATIONS**

<u>Fault</u>	<u>Trenches</u>			<u>Natural Exposures Logged</u>		
	<u>Number</u>	<u>Length</u>		<u>Number</u>	<u>Length</u>	
<u>(m)</u>		<u>(ft)</u>	<u>(m)</u>		<u>(ft)</u>	
San Simeon	18	512	1,680	2	15	50
Los Osos	11	393	1,290	1	6	20
San Miguelito	12	256	840	-	-	-
Edna	11	256	840	-	-	-
Wilmar Avenue	3	201	660	3	549	1,800
San Luis Bay	-	-	-	1	232	760
(Other Areas)	-	-	-	4	82	270
TOTALS	55	1,618	5,310	11	884	2,900

100-100000

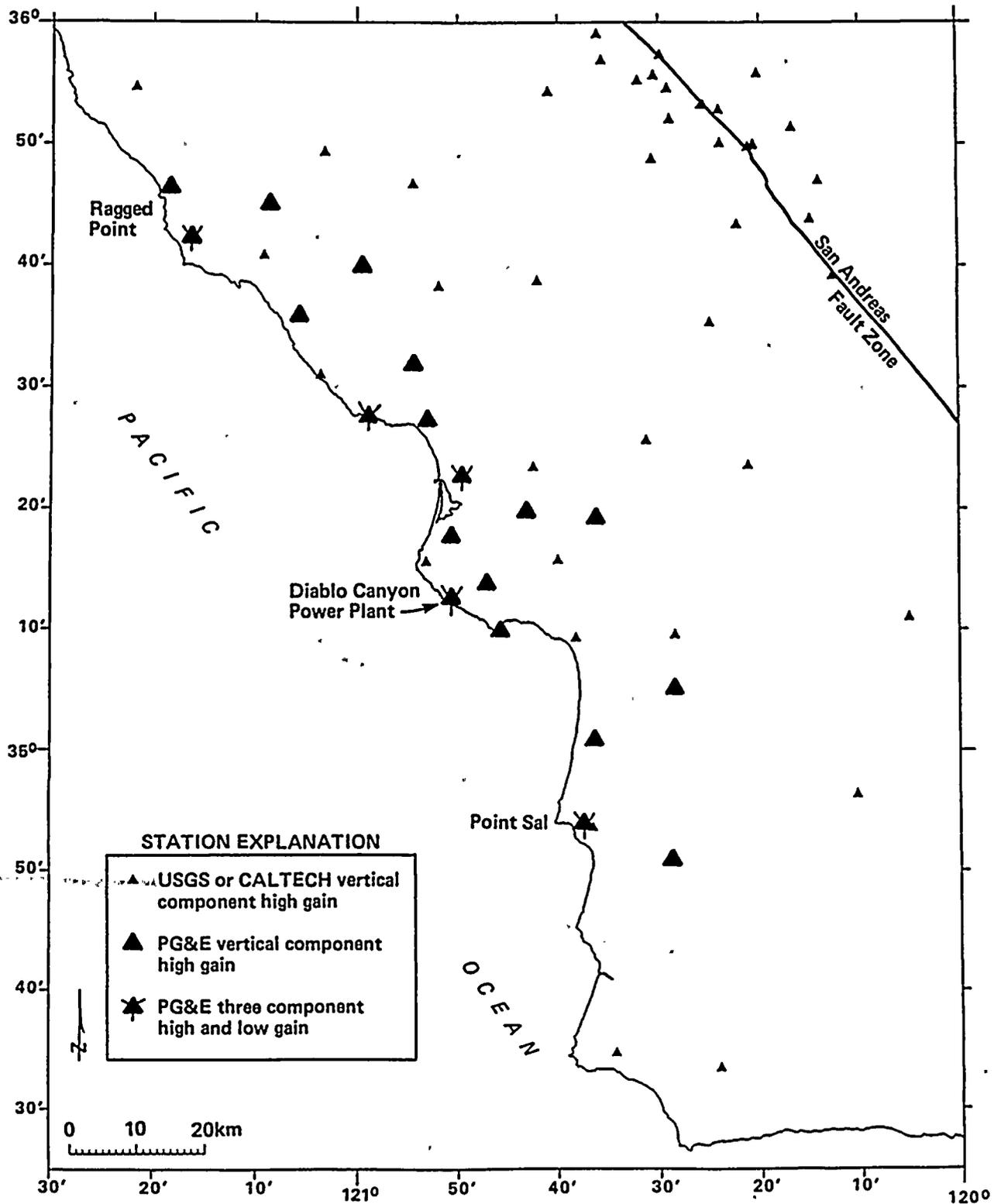


Figure 2-5

Location map of seismograph field stations in the PG&E Central Coast Seismic Network and U.S. Geological Survey seismograph stations.

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earthquake catalog includes events from the PG&E Central Coast Seismic Network data set, supplemented by U.S. Geological Survey readings for the larger events. The increased resolution of hypocentral locations and control on nodal planes of focal mechanisms was important for understanding the complex geologic and tectonic setting along the Hosgri fault zone and other faults in the region.

The November 4, 1927 Lompoc earthquake was analyzed to assess its seismic moment, focal depth, focal mechanism, and epicentral location using teleseismic recordings of the event recorded at the De Bilt, Netherlands, seismographic station. Comparisons were made between the 1927 event, the well-studied 1983 Coalinga earthquake, and other recent earthquakes also recorded at De Bilt. Regional recordings from the Tucson, Berkeley, and Mount Hamilton seismograph stations also were used. The body waveforms were modeled for these two events at each station to evaluate the source parameters. The 1927 location was constrained using relative wave travel-time comparisons on the De Bilt records for the 1927 and 1983 events. Other data previously used to constrain this location were also evaluated.

Task 4: Studies of Edna and San Miguelito Faults and San Luis/Pismo Fold Trend

The Diablo Canyon Power Plant is located along the coast on the southwestern flank of the Pismo syncline. Geologic investigations were conducted to evaluate the amounts and rates of deformation of the syncline through Tertiary and Quaternary time. In particular, marine and fluvial terraces were mapped to quantify rates of late Quaternary uplift/subsidence and to establish the contemporary style of deformation (for example, folding, tilting, block uplift along faults) in the area. The marine terraces are well preserved along the coast from Morro Bay south to Nipomo and provide an excellent strain gauge with which to (1) delimit areas undergoing similar tectonic deformation; (2) assess Quaternary faulting within and bordering the Pismo syncline, in particular the amounts and rates of neotectonic deformation along the Edna, San Miguelito and Pismo faults and the Los Osos fault zone; (3) look for the

potential for previously unrecognized faults; and (4) document the absence of faulting in undeformed areas. Rates of coastal uplift deduced from the marine terraces also provide data for indirectly assessing the relative rate of vertical displacement across the adjacent reach of the offshore Hosgri fault zone. Detailed mapping and trenching were conducted along the Los Osos fault zone and the Edna and San Miguelito faults to provide specific data on fault behavior and geometry.

Data from these onshore geologic studies were integrated with data obtained from offshore geophysical studies to assess onshore/offshore continuity of structures and any lateral changes in fault geometry or behavior. Geologic cross sections were developed across the block to evaluate deep structure and the Cenozoic history of deformation in the area. The cross sections incorporated available surface geologic mapping, subsurface water-well and oil-well data, and onshore and offshore seismic reflection data.

Task 5: Studies of Onshore Santa Maria Basin

Geological and geophysical studies were performed to evaluate deformation within and along the northeastern margin of the onshore Santa Maria Basin. Quaternary marine terraces and eolian sand deposits were mapped from Pismo Beach south to the Santa Maria Valley in order to quantify rates of late Quaternary uplift or subsidence and to identify and evaluate areas of late Quaternary faulting or folding. As described later in this report, these investigations identified a northwest-trending, diffuse zone of faulting and flexure along the northeastern margin of the onshore Santa Maria Basin. Water-well and oil-well data were acquired for the Nipomo Mesa, Arroyo Grande flood plain, and northernmost Santa Maria Valley areas to assess the lateral extent of these structures and their relationship to previously identified faults and folds in the eastern and northern Santa Maria Valley as well as to structures identified beneath San Luis Obispo Bay. Nine Vibroseis[®] seismic reflection lines were acquired to image the geometry and displacement history of the faults at depth (Plate 9). Trenching and logging of natural exposures across the

1941

1942

1943

1944

1945

1946

1947



Wilmar Avenue and San Luis Bay faults were performed to obtain site-specific data on slip rate, recency and sense of displacement, and near-surface fault geometry. We integrated data from the onshore investigations with geophysical data from San Luis Obispo Bay in order to assess the continuity of these structures into the offshore.

Task 6: Studies of Regional Faults

During the course of the Program, regional faults considered to be potentially significant to understanding the regional tectonic setting were assessed in terms of sense of slip and late Quaternary slip rate. Several of these faults were of special interest for evaluating the contemporary tectonic setting of the San Luis/Pismo region. The faults evaluated include the West Huasna, Rinconada, Nacimiento, Casmalia, Lion's Head, Little Pine and Foxen Canyon faults. Based on review of previous work and discussions with scientists working on these faults, focused field reconnaissances were carried out. Selected remote sensing data and onland geophysical profiles and interpretations also were reviewed.

Task 7: Deep Crustal Studies

Developing an understanding of the relationship between the pattern and style of deformation of surface geologic structures and a possible mid- to lower-crustal decollement was an important aspect of the Program. In this task, regional crustal structure data and interpretations were compiled and reviewed, including seismic refraction and reflection studies in western California, and particularly the geophysical profile trending northeast through Morro Bay analyzed by Trehu and Wheeler (1986). Additional onshore data were acquired by PG&E through participation in a proprietary Vibroseis[®] survey in the Santa Maria Valley and adjacent areas to the north and south (Plate 9). To improve the data base for deep crustal interpretation of the areas from the onshore coastal margin southwest across the Hosgri fault zone, the offshore Santa Maria Basin, and structures as far west as the continental slope, PG&E initiated an investigation of the

south-central California coastal margin. This deep crustal geophysical study was a cooperative investigation among PG&E, the U.S. Geological Survey, Rice University, and the Houston Area Research Council. The objective of the study was to obtain seismic reflection and refraction data that could be used, along with geological and seismological data, to develop an integrated model of the entire crustal structure across the south-central California continental margin.

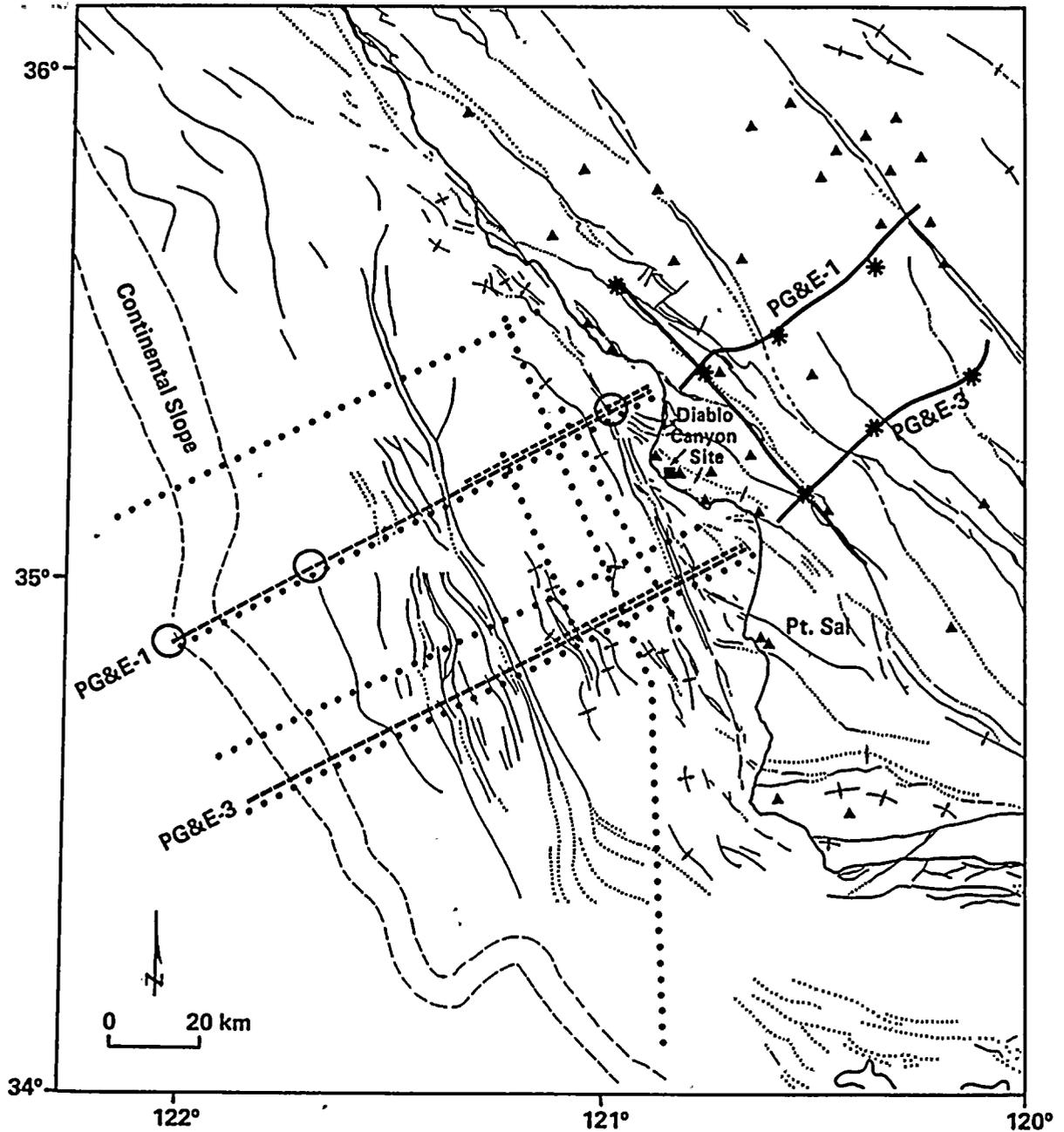
The data collection portion of the study was conducted in late October and early November 1986. The data were acquired by Digicon Geophysical Corporation. There were six major components to the field investigation (Figure 2-6):

- 1) A deep seismic reflection survey by PG&E along three seismic lines, totaling 290 kilometers.
- 2) A deep seismic reflection survey by Rice University and the Houston Area Research Council along five lines, totaling 430 kilometers.
- 3) An onshore/offshore wide-angle seismic refraction survey by PG&E, that recorded offshore airgun sources and onshore large buried explosions. The data collected overlie the offshore reflection lines and extend onshore eastward to the San Andreas fault.
- 4) A high-resolution coastal-zone refraction study by Rice University.
- 5) An onshore reversed refraction line recorded by the U.S. Geological Survey.
- 6) An offshore refraction study by the U.S. Geological Survey using ocean-bottom seismometers.

These data have been analyzed by PG&E, and are being evaluated along with various other data sets in ongoing research at Stanford University, Rice University, the University of California at Santa Cruz and at Santa Barbara, and the U.S. Geological Survey. Regional gravity and aeromagnetic data have also been incorporated into the crustal structure interpretation.







- EXPLANATION**
- | | | | |
|-------|------------------------|---|--------------------------|
| | Marine reflection line | ○ | Ocean-bottom seismograph |
| ----- | Airgun refraction line | * | High explosive shot |
| ----- | Sonobouy recording | ▲ | Seismograph station |
| ———— | Refraction recorders | | |

NOTE: Base map explanation provided on Plate 3.

Figure 2-6
 Location map for the participants and their respective types of data acquisition performed during the 1986 Digicon deep crustal study.

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During the final integrative stages of the Program, the kinematic interaction of selected faults at seismogenic depths was analyzed using a three-dimensional computer-graphics model. Both shallow fault interactions and relationships at depth were examined.

Task 8: Studies of Regional Tectonics

The tectonic setting of south-central coastal California was evaluated from the broad range of diverse data and analyses developed and compiled during the Program. The following principal steps were carried out to assess the current tectonic setting:

- 1) The plate-tectonic history of the California coastal margin from the late Mesozoic to the present was reviewed and an updated synthesis was prepared. Using this information as a framework, the deformational history of the onshore/offshore Santa Maria Basin and adjacent areas was described. Particular attention was paid to clarifying the style and rates of deformation during the past 5 million years, during which time a significant change in relative Pacific-North America plate motion has occurred.
- 2) Data indicating current plate and regional deformation vectors were reviewed, including geodetic data and plate motion models. An effort was made to assess realistic uncertainties in these data and interpretations.
- 3) Present-day stress and strain data, derived from earthquake focal mechanisms and borehole stress measurements, were reviewed.
- 4) Late Quaternary fault slip rate, crustal deformation, and uplift data were compiled.

To achieve a balanced assessment of the significance and relevance of all informed opinions in assessing current tectonics, we conducted interviews with four individuals who have presented and published tectonic

interpretations in the region of interest: James Crouch of Crouch, Bachman and Associates, Santa Barbara; Thom Davis, consultant, Los Angeles; Clarence Hall of the University of California at Los Angeles; and Bruce Luyendyk of the University of California at Santa Barbara. These individuals discussed the data sets used to develop their tectonic interpretations, and elaborated on their published tectonic models in the context of more recently acquired data and published tectonic interpretations of the Hosgri fault zone.

SIGNIFICANT FINDINGS AND RESULTS

The completion of the Long Term Seismic Program has resulted in the accumulation of new data, analyses and interpretations regarding the geology, seismology; geophysics and tectonics of south-central coastal California. In this section we focus on the findings and results of these studies that are significant for the evaluation of the earthquake potential in the region. These results are the basis for establishing the parameters used for assessing the characteristics of the potentially significant seismic sources affecting the Diablo Canyon site, as discussed in Chapter 3. This section first discusses the tectonic setting followed by detailed discussions of seismicity, the Hosgri fault zone, Los Osos fault zone, and faulting along the southwestern boundary of the San Luis/Pismo structural block.

Tectonic Setting

The Diablo Canyon Power Plant is situated on the coast of south-central California (Figure 2-7). This coastal region lies north of the east/west trending western Transverse Ranges, west-southwest of the north-northwest-trending Santa Lucia and San Rafael Ranges and east of the San Simeon/Hosgri zone of near-coastal faults and the bordering offshore Santa Maria Basin to the west. The triangular region thus defined is herein called the Los Osos/Santa Maria Valley domain (Figure 2-8).





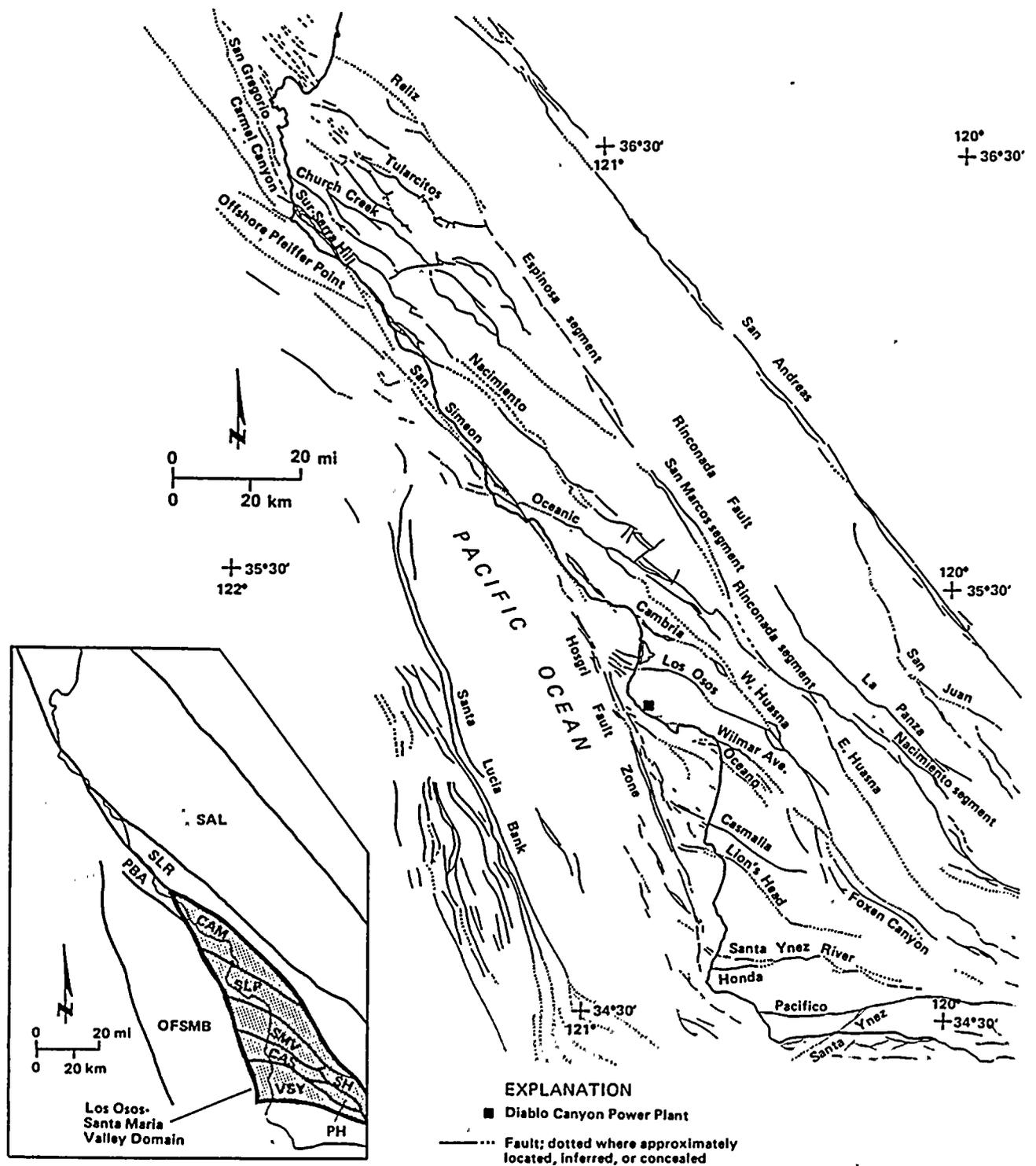
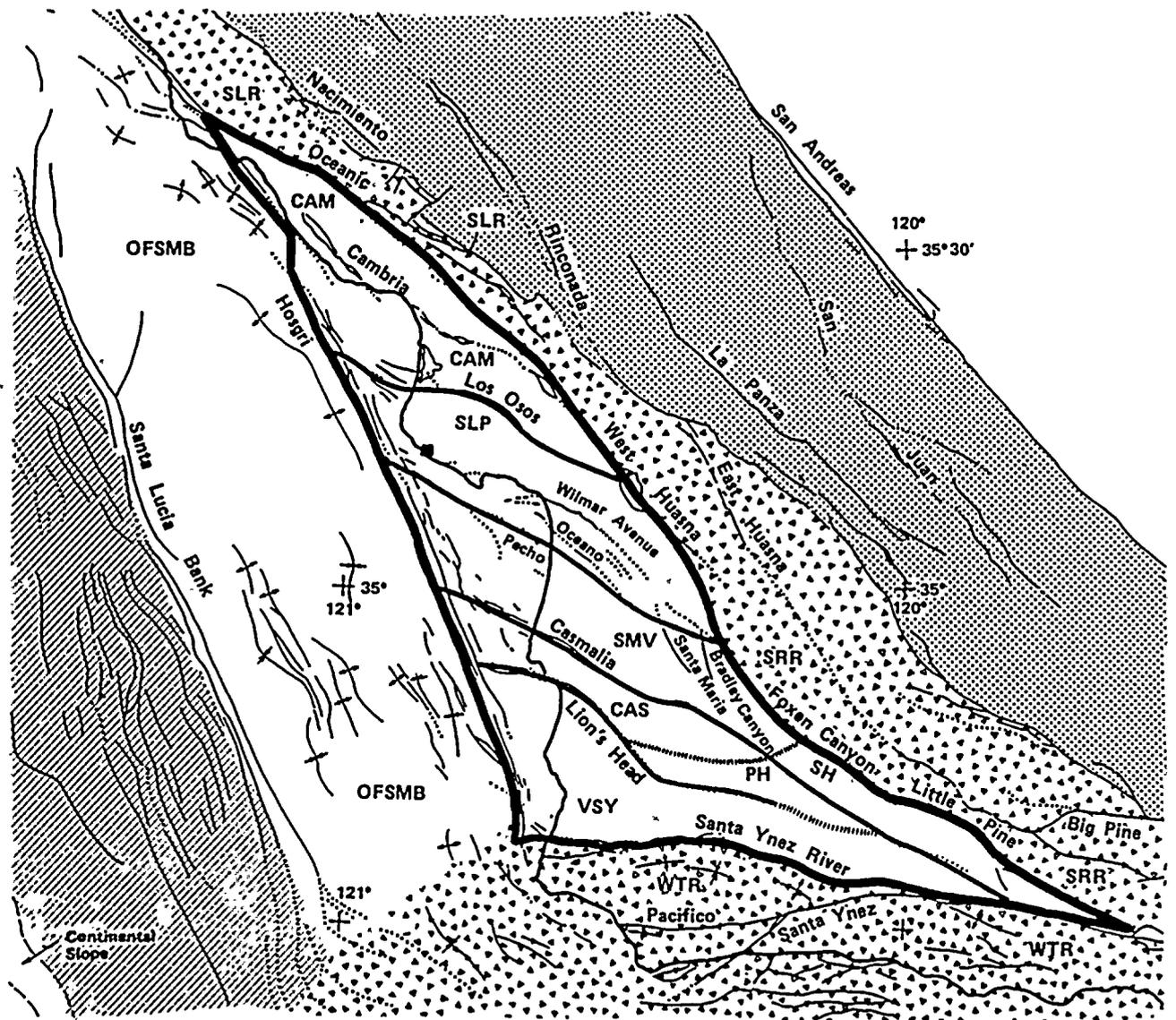


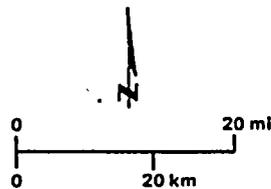
Figure 2-7

Map of structural blocks and faults in the south-central California coastal region illustrating the regional geologic setting of the south-central California Coast. SAL = Salinian block, SLR = Santa Lucia Range block, PBA = Piedras Blancas Anticlinorium, CAM = Cambria block, SLP = San Luis/Pismo block, OFSMB = Offshore Santa Maria Basin block, SMV = Santa Maria Valley block, CAS = Casmalia block, VSY = Vandenberg/Santa Ynez Valley block, PH = Purisima Hills block, SH = Solomon Hills block.

1. 4. 3. 5. 6. 7.



Note: Base map from Plate 3



- EXPLANATION**
- Fold axes
 - Fault, dotted where inferred
 - Los Osos/Santa Maria Valley domain boundary
 - Structural block boundary, hachured where indistinct
 - Salinian Terrane
 - Stanley Mountain Terrane
 - San Simeon Terrane
 - Patton Terrane
 - Diablo Canyon Power Plant
- } Sur-Obispo Composite
(McCulloch, 1987)

Figure 2-8

Map of the Los Osos/Santa Maria Valley Domain illustrating the general distribution of major basement terranes. CAM = Cambria block, SLP = San Luis/Pismo block, SMV = Santa Maria Valley block, CAS = Casmalia block, VSY = Vandenberg/Santa Ynez Valley block, WTR = Western Transverse Ranges, SRR = San Rafael Range, SLR = Santa Lucia Range, OFSMB = Offshore Santa Maria Basin, PH = Purisma Hills block, SH = Solomon Hills block.

1954

1955

1956

1957

1958



REGIONAL TECTONIC ENVIRONMENT

Plate Motions. Deformation within the Los Osos/Santa Maria Valley domain is ultimately driven by shear arising from relative motion between the Pacific and North American plates. The plate boundary is a broad, heterogeneous zone of right-slip faulting centered along the San Andreas fault (Crowell, 1962; Wilson, 1965; Dickinson and Snyder, 1979) and extending in width from the western Great Basin (e.g., Stewart 1967, 1983) to the continental slope (McCulloch, 1987). Within this broad zone of deformation, movement of large crustal blocks, such as rotation of the western and central Transverse Ranges (Hornafius and others, 1986) and extension within the Basin and Range province, has locally influenced the pattern and style of deformation. As described below, rotation of the western Transverse Ranges, in particular, has influenced contemporary deformation within the Los Osos/Santa Maria Valley domain.

Assessment of the relative motion between the North American and Pacific plates is based on the analysis of two types of data: (1) marine magnetic anomalies, hotspot tracks, transform azimuths, and earthquake slip vectors, and (2) geologic observations and geodetic measurements along the San Andreas and other faults within the broad plate boundary zone.

The transcurrent relative motion between the Pacific and North American plates that has characterized the plate boundary during the late Cenozoic was established during the interval of time between 29 million years ago (Atwater and Molnar, 1973) and 17 million years ago (Graham, 1978) when it replaced orthogonal or oblique subduction along the plate boundary. The presence of large Miocene basins along the continental shelf of California indicates that transform plate motion during most of the Miocene was transtensional.

In the early Pliocene, the south-central coast of California was affected by an episode of compressional deformation. This commonly has been attributed to a change in the azimuth of Pacific plate motion to a more northerly direction with respect to the Hawaiian hotspot reference

frame (Page and Engebretson, 1984; Engebretson and others, 1985; Cox and Engebretson, 1985; Zoback and others, 1987) and/or to westward displacement of the Sierra Nevada block due to Basin and Range extension (Wright, 1976). The change from slightly transtensional to slightly transpressional relative plate motion appears to have occurred between 3.9 and 3.4 million years ago (Harbert and Cox, 1988). The shift from transtension to transpression along the plate boundary restrained westward movement of the crust west of the extending Basin and Range (north of the Garlock fault) so that compression within the central part of the plate boundary region was further enhanced. Mid-Pliocene to Recent folding and uplift suggests that this change in plate motion resulted in compression and crustal shortening oriented roughly orthogonal to the Pacific-North American plate boundary (Mount and Suppe, 1987; Harbert and Cox, 1988). The strike of resulting fold axes and reverse thrust faults is subparallel to rather than oblique to the major strike-slip faults within the boundary suggesting that they are not simply the product of right wrenching. The initiation of a pronounced episode of rapid uplift of the southern Coast Ranges, which probably started in mid-Pliocene time, about 3.5 million years ago, and continued into the early Quaternary, about 2 to 1 million years ago, corresponds in timing with this change to a transpressional tectonic environment. Both overall regional uplift and differential uplift of the Santa Lucia Mountains apparently slowed during the early to mid-Quaternary. This may indicate that the initial rapid uplift occurred in response to the change in tectonic environment but that the rate of uplift slowed as a steady state of transpressional deformation was attained.

Work completed for this study generally agrees with this timing except for evidence indicating that compression in the offshore Santa Maria Basin began about 6.0 to 5.2 million years ago. The compression may have increased in intensity about 3.9 to 3.4 million years ago producing offshore folds such as the Queenie, Purisima, and Lompoc structures. Most of this offshore compression had ceased by 3.0 to 2.8 million years ago, although local areas of the southern

offshore Santa Maria Basin exhibit evidence of younger folding. The onset of primary convergent event recorded in offshore structures more nearly corresponds to the opening of the Gulf of California around 5 million years ago and the resultant change in rate and distribution of slip along faults of the San Andreas system.

Recent plate motion studies agree with regional geologic data which indicate that the North America-Pacific plate boundary at the latitude of central California is continuing to experience transpressional or pure translational right shear. The NUVEL-1 plate-motion model estimates relative motion between these plates to be 48 to 50 millimeters per year towards N35°W (DeMets and others, 1987; Gordon and others, 1987), which is approximately 6 to 8 millimeters per year slower but in the same general direction as predicted by the earlier RM2 model of Minster and Jordan (1978). The plate motion model of Saucier and Humphreys (1988) as modified by Humphreys (written communication, 1988) estimates the relative motion to be approximately 53 millimeters per year towards approximately N46°W. The plate motion model of Pollitz (cited in Mount and Suppe, 1987), which does not incorporate Basin and Range extension, estimates relative motion of 44 millimeters per year towards N30°W.

Estimates of relative motions between the North American and Pacific plates based on geologic and geodetic observations are typically significantly less than those calculated by these plate motion models. Geologic and geodetic studies indicate that the San Andreas fault is presently the locus of approximately 35 millimeters per year of the motion between the North American and Pacific plates in a direction N41°W (Sieh and Jahns, 1984; Kroger and others, 1987; Jordan and Minster, 1988). Additional plate motion is represented by extension within the Basin and Range province at a rate of about 10 millimeters per year in roughly a N56°W direction (Gordon and Sauber, 1988). Combined displacement on the San Andreas fault and extension in the Basin and Range, however, does not accommodate the total amount of relative plate motion predicted by the plate

motion models described above. Vector solutions of relative plate motion using the NUVEL-1 model suggest a plate motion deficit, termed the San Andreas discrepancy, of about 9 millimeters per year in a N14°E direction (Jordan and Minster, 1988). This unaccounted plate motion may be the result of one or more of the following factors: the NUVEL-1 estimate of plate motion may be too high; the estimate of the amount and direction of extension in the Basin and Range may be incorrect; additional slip may be occurring on faults across the western United States; crustal shortening may be occurring along folds and faults; or slip may be occurring as steady, aseismic deformation within the crust. It is likely that this plate motion deficit is accommodated, at least in part, on right-slip faults between the continental slope and the southern Great Basin and by compressional deformation within the plate boundary zone. The NUVEL-1 model, for example, which calculates relative motion of 48-50 millimeters per year towards N35°W, predicts about 4 millimeters per year additional northwest right slip and 4 to 10 millimeters per year northeast-southwest compression normal to the San Andreas fault in central California (DeMets and others, 1987). The earlier RM2 model, which calculated relative motion of about 56 millimeters per year towards N35°W, predicts about 14 millimeters per year additional northwest right slip and 8 to 9 millimeters per year NE-SW compression (Minster and Jordan, 1978).

Crustal Block Rotation. In addition to confirming the motion of large lithospheric plates, recent paleomagnetic investigations strongly indicate discordant motion of smaller regional crustal blocks within the North America-Pacific transform boundary zone. Paleomagnetic declination data, for example, indicate that the Transverse Ranges and parts of the Mojave region have rotated clockwise up to 100 degrees in the Neogene (Luyendyk and others, 1980, 1985; Hornafius and others, 1986; Carter and others, 1987; Ross and others, 1988; Valentine and others, 1988). Since about 6 million years ago, the western Transverse Ranges have rotated 35 degrees clockwise and the San Gabriel Mountains 15 degrees counterclockwise, implying oroclinal

bending of the Transverse Ranges in Pliocene and Pleistocene time (Hornafius, 1985; Hornafius and others, 1986). Luyendyk and others (1980, 1985) attribute these movements to rigid block rotations within a right shear couple, resulting in right slip on northwest-trending faults, left slip on (presently) east-trending faults, and clockwise rotation of the originally north-south-trending Transverse Ranges.

Hornafius and others (1986) suggest that the tectonic history of the western Transverse Ranges involved (1) clockwise rotation during the Middle Miocene (17 to 10 million years ago), and (2) oroclinal bending since 6 million years ago with additional clockwise rotation to the west and counterclockwise rotation to the east. They propose that compression along the north margin of the western Transverse Ranges may be a result of the change from a releasing to a restraining geometry as the San Andreas fault migrated eastward to the Gulf of California.

Deep Crustal Structure. The plate tectonic history of the south-central coastal region of California, as summarized above, has involved a long history of pre-Miocene lateral terrane transport (such as the granitic Salinian terrane and the Franciscan Sur/Obispo Composite terrane, as identified by McCulloch, 1987) and subduction of the Farallon and Pacific plates beneath North America. Prior to the onshore/offshore field program conducted in the fall of 1986 as part of Task 7 (Figures 2-6 and 2-9), crustal structure studies of the characteristics and relationships of these major crustal components in the region north of the Transverse Ranges were limited to the part of the region onshore and north of Morro Bay:

- In refraction studies of the Gabilan Range in the Salinian terrane, Walter and Mooney (1982) interpreted Salinia to be a thick-skinned granitic block overlying gneissic/amphibolitic or oceanic lower crustal material.
- Trehu and Wheeler (1987) interpreted reflection/refraction data collected along a line colinear with the onshore portion of PG&E-1 (Figure 2-6) extending from Morro

Bay northeast to the Central Valley. They observed a lateral velocity transition in the upper- and middle-crust from the Sur/Obispo Composite terrane with Franciscan velocities on the west, to the Salinian terrane with granitic velocities on the east; the transition overlies an interpreted low-velocity wedge in the lower crust at depths of 14 to 22 kilometers. They speculate that the wedge is composed of sediments subducted beneath the Sur/Obispo and western Salinian terranes.

- Until recently, understanding of the crustal structure beneath the Sur/Obispo terrane of coastal California has been based primarily on analysis of earthquake data (Mutch and others, 1981; Oppenheimer and Eaton, 1984). These studies indicate a crustal thickness of 20 to 24 kilometers near the coast, with upper crustal velocities consistent with Franciscan velocities as found in other areas of central California.

Interpretation of data obtained during the 1986 deep crustal study has greatly expanded upon and improved these earlier interpretations. The deep crustal structure study shown in Figure 2-6 and described earlier in this report has yielded data that have been analyzed by many of the participants in the study, discussed in recent professional meetings (Savage and others, 1987; Walter and Sharpless, 1987; Talwani and others, 1987; Howie and Savage, 1987; Meltzer and Levander, 1987; McIntosh and others, 1987; Trehu and others, 1987; Willingham and Rietman, 1987), and presented in graduate theses (Howie, 1987; Meltzer, 1988; Putzig, 1988). The primary structural and tectonic features addressed in these studies are shown in Figure 2-9. This figure integrates the onshore and offshore refraction and wide-angle reflection analysis discussed by Howie and Savage (1987) along line PG&E-3, with additional constraints provided by interpretation of the deep-penetration marine reflection profiling along line PG&E-3 (Plate 8) and by interpretations of the onshore Vibroseis[®] survey (Plate 9).

The continental margin crustal structure along PG&E-3 exhibits three major features:



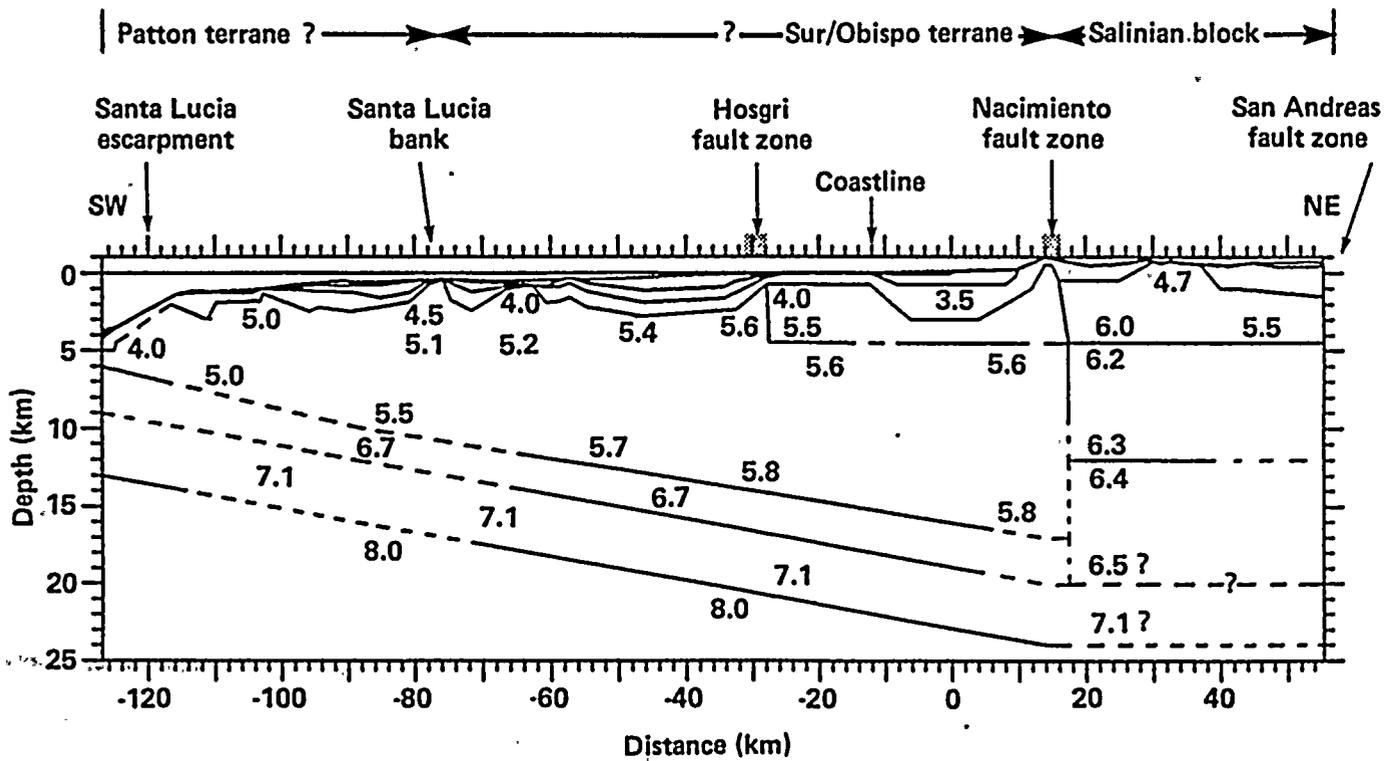


Figure 2-9

Crustal structure velocity model and regional geologic and physiographic features along the offshore and onshore trace of reflection and refraction line PG&E-3 shown in Figure 2-6.

100-100000-100000

100-100000-100000

100-100000-100000

- A complex basin structure that extends from the Santa Lucia escarpment at the continental slope eastward to the onshore basins lying east of the Hosgri fault zone. The structural interpretation of the sedimentary structures in the upper crust has been made from the extensive common-depth-point data offshore and the Vibroseis[®] survey north of the Santa Maria Basin onshore (Plate 9) supplemented by data from 2- to 3-kilometer deep borings made for petroleum exploration.
- Basement velocities from the vicinity of the Nacimiento fault zone west to the Santa Lucia Bank are typical of Franciscan rocks (4.5 to 5.8 km/sec). East of the Nacimiento fault, velocities are characteristic of granitic basement. No velocity contrast occurs across a down-dip projection of the Hosgri fault zone at a depth greater than about 4 kilometers.
- An east-dipping (about 4.5 degrees) lower crustal zone interpreted to be a two-layer section of oceanic crust is interpreted to extend from beneath the Santa Lucia escarpment as far east as the down-dip projection of the Nacimiento fault. This crustal layer is imaged on reflection lines as relatively continuous horizons present in the lower crust beneath and west of the Santa Lucia Bank and as intermittent horizons between the Bank and the Hosgri fault zone. This lower crustal zone does not appear to be disrupted as it passes beneath the Hosgri fault zone (at depths of about 14 to 16 kilometers) or other faults prominent in the near-surface part of the crust.

The crustal structure along line PG&E-1, which passes to the north of the Diablo Canyon site, exhibits these same general features. Putzig (1988) interprets a thickening of the oceanic crust along this line beneath the offshore Santa Maria Basin. He also models a steepening of dip of the oceanic plate as the plate approaches the subsurface vertical projection of the Nacimiento fault zone. This lower crustal warp may explain the geophysical features that Trehu and Wheeler (1987) interpreted as a low velocity wedge. Such a wedge is not imaged in PG&E-3, nor has it been

noted by others studying the October–November 1986 data set. The gently east-dipping oceanic crust underlies the Los Osos/Santa Maria Valley domain; to the northeast the oceanic layer appears to steepen beneath the Salinian block, and to the south it is affected by the upper crustal thickening and deepened lower crustal root associated with the western Transverse Ranges (Keller and Prothero, 1987).

Los Osos/Santa Maria Valley Domain. The Los Osos/Santa Maria Valley domain is characterized by west-northwest-trending reverse faults that border a series of similarly trending structural blocks. From northeast to southwest, these blocks are the Cambria, San Luis/Pismo, Santa Maria Valley, Solomon Hills, Casmalia, Purisima Hills, and Vandenberg/Santa Ynez Valley blocks. The Cambria block may be further divided into two blocks separated by the northwest-trending Cambria fault of uncertain activity. These blocks and the bordering reverse faults that define the internal structure of the domain are shown on Figure 2-8. The domain is underlain by the San Simeon Terrane of the Sur/Obispo Composite basement (Page, 1981; McCulloch, 1987) which consists primarily of the Franciscan assemblage, a Mesozoic accretionary wedge complex. The western Transverse Ranges and the area bordering the northeastern margin of the Los Osos/Santa Maria Valley domain are underlain by the Stanley Mountain Terrane of the Sur-Obispo Composite basement (McCulloch, 1987) which consists of rocks similar to the Great Valley Sequence. To the northeast, outside the Los Osos/Santa Maria Valley domain, the Sur-Obispo Composite basement is tectonically juxtaposed against Salinian granitic basement along the Nacimiento and Rinconada faults within the Santa Lucia and San Rafael Ranges.

The west-northwesterly structural grain and tectonic style of the Los Osos/Santa Maria Valley domain is unique in the south-central coastal California region (Figure 2-8). This structural grain is transitional between the east/west trending structural grain in the Transverse Ranges and the north-northwest trending structural grain of the Santa Lucia and San Rafael Ranges. To the west, the west-northwest-trending reverse faults and structural blocks of the Los Osos/Santa Maria

Valley domain terminate against the north-northwest trending Hosgri and San Simeon fault zones.

The pattern and development of structures in the offshore Santa Maria Basin west of the Hosgri and San Simeon fault zones contrast sharply with those in the near-shore/onshore domain. The offshore basin is characterized by gradual block subsidence and by scattered faults and long, broad wavelength late Cenozoic folds that trend north-northwest, subparallel to the Hosgri and San Simeon fault zones (Plate 3). These faults and associated folds are most prevalent in the southern offshore Santa Maria Basin south of the general latitude of Point Sal. From Point Sal north to about the latitude of Cambria, Neogene deformation within the offshore basin is localized on the Queenie structure, which is isolated in the west-central part of the basin, and at the general latitude of Point Buchon opposite the San Luis/Pismo block along the basin's east margin. In addition, north of Cambria, a wide belt of folding and faulting referred to herein as the Piedras Blancas anticlinorium, locally deforms the eastern margin of the basin.

Two of the major structural units within the Los Osos/Santa Maria Valley domain that are undergoing rigid block uplift (the San Luis/Pismo and Casmalia blocks) are the sites of large, northwest-trending synclines and anticline (Hall, 1976). These folds deform Miocene and Pliocene strata. Detailed mapping of Quaternary marine and fluvial terraces, however, indicates that fold deformation within the blocks ceased prior to 500,000 years ago and probably 1.0 million years ago. Documentation of the absence of Quaternary folding of the Pismo syncline, a major fold structure within the San Luis/Pismo block, is presented later in this section.

CONTEMPORARY REGIONAL TECTONIC SETTING

The Quaternary tectonic environment of the Los Osos/Santa Maria Valley domain results from northwestward movement of the Pacific Plate relative to the North American plate, locally modified by clockwise rotation of the western Transverse Ranges. Rotation of the western

Transverse Ranges, which are underlain by relatively thick crust (about 33 kilometers thick, Keller and Prothero, 1987), compresses the Los Osos/Santa Maria Valley domain underlain largely by Franciscan basement about 12 to 20 kilometers thick, against the relatively stationary Santa Lucia and San Rafael Ranges underlain in part by more rigid Salinian granite. The resulting north-northeast-directed crustal shortening is accommodated by displacement along west-northwest-trending reverse faults and by uplift, subsidence or tilting of intervening crustal blocks (Figure 2-10). At depth, the crustal shortening is accommodated by plastic deformation, which occurs below the brittle/ductile transition at a depth of about 12 kilometers, the base of the observed seismogenic zone.

The results of extensive Quaternary field studies performed during the Program indicates that crustal shortening in the northern and northwestern parts of the Los Osos/Santa Maria Valley domain is now accommodated primarily by reverse faulting and uplift or subsidence of the intervening structural blocks, with no significant folding within the blocks. Detailed studies of Quaternary surfaces and deposits confirm that folding ceased at least 0.5 to 1 million years ago. Faulting is probably also the predominant mode of contemporary deformation in the southeastern and southern parts of the domain, but some local folding may be occurring in conjunction with the faulting in these locations.

The pattern and style of contemporary tectonism within the Los Osos/Santa Maria Valley domain is not compatible with an interpretation that low-angle (including listric) thrust faulting is involved in the deformation of at least the northwestern part of the domain. The domain is instead deforming by rigid block uplift or subsidence along west-northwest-trending reverse faults. Quaternary studies confirm that fold deformation is not occurring as would be predicted by low-angle, fault-propagation or fault-bend fold models. In addition, the association of seismicity with deforming blocks or specific faults (for example, the Point Sal earthquakes of 1980 and 1984) down-dip to the base of the seismogenic zone supports an

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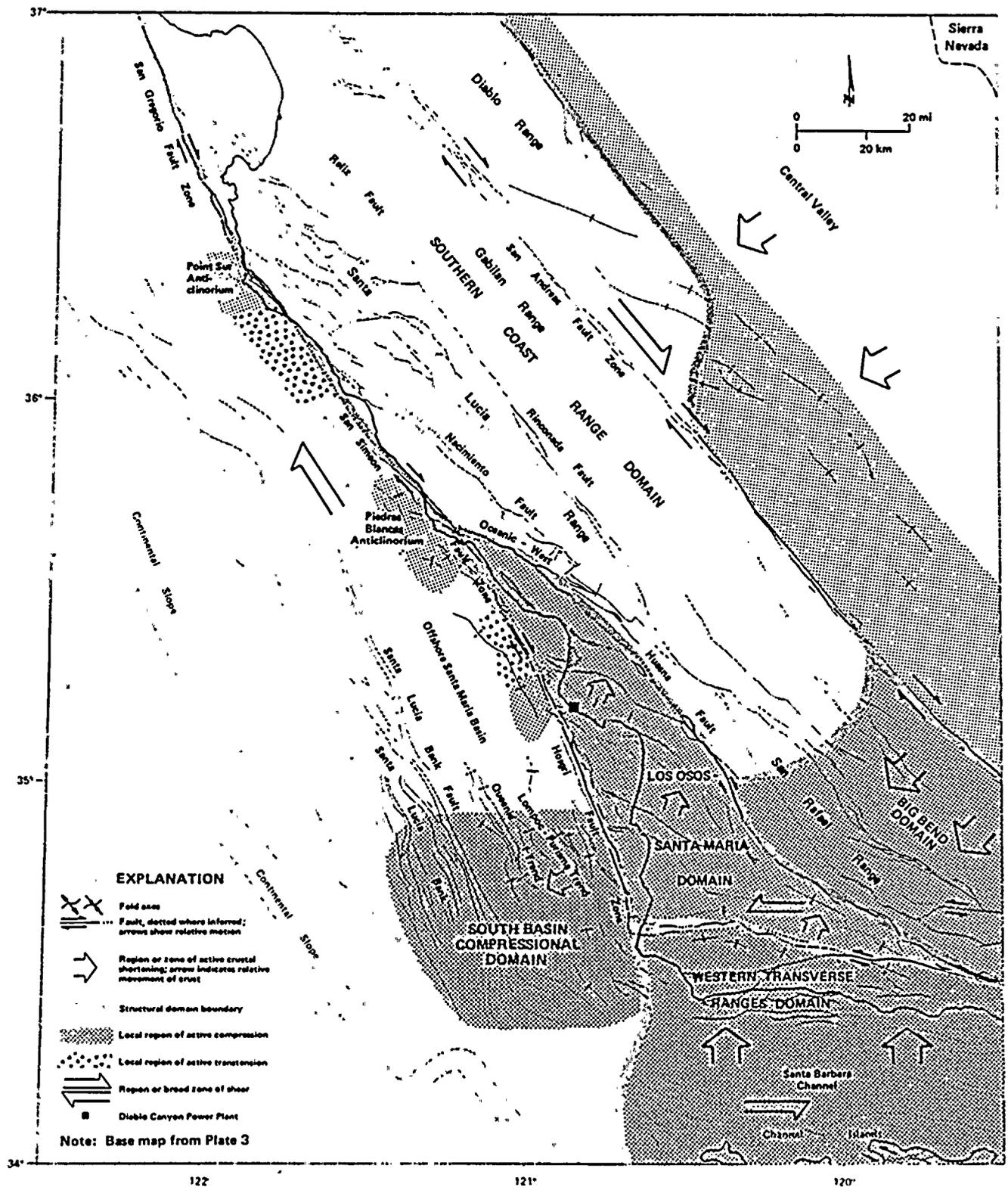


Figure 2-10

Contemporary tectonic setting of south-central California illustrating regions of active compression and relative directions of crustal movement.

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interpretation of high-angle rather than low-angle faulting. Similarly, the evidence that the crust east of the Hosgri fault zone is shortening in a north-northeast direction while the Hosgri strikes north-northwest indicates that the long-term and ongoing deformation of the Los Osos/Santa Maria Valley domain is not compatible with an inference of listric thrust behavior on the Hosgri fault zone. Thus, we conclude that the low-angle faults imaged locally within the Hosgri fault zone are not active within the contemporary tectonic regime.

The onshore Los Osos/Santa Maria Valley domain is structurally separated from the offshore Santa Maria Basin across the Hosgri and San Simeon fault zones. As described below, these fault zones are characterized by high-angle, right lateral strike-slip displacement at a rate of about 1 to 3 millimeters per year. The offshore Santa Maria Basin is not shortening in a north/south direction but is moving northwest at a rate equal to the slip rate on the San Simeon and Hosgri fault zones relative to the Santa Lucia-San Rafael Range block. Because of north-northeast-directed crustal shortening within the Los Osos/Santa Maria Valley domain, the rate of relative right lateral displacement along the San Simeon and Hosgri fault zones should progressively decrease southward. The kinematics of deformation in the south-central coastal California region are summarized on Figures 2-10 and 2-11.

The Los Osos/Santa Maria Valley domain is one of several areas of Quaternary crustal shortening in the south-central California region (Figure 2-10). Crustal shortening is prominent within the southern part of the offshore Santa Maria Basin, herein referred to as the South Basin Compressional Domain. Clark and others (1987) describe an anticline, called the Queenie structure, within this domain that formed by a pulse of compression during the early Pliocene. The compression resulted in about 1 to 2 percent crustal shortening between the Hosgri fault zone and Santa Lucia Bank fault about 6 and 3 million years ago. The Lompoc trend includes a pair of en echelon anticlines that overlie a steeply northeast-dipping reverse fault. Seismicity and sea floor topography suggest that this trend is associated with Quaternary activity. Other fold

trends in the domain include the Purisima and Pedernales trends. In general, most of the folds are southwest-verging which suggests that this offshore domain is characterized by southwest-directed compression.

Other domains in south-central California that exhibit evidence of crustal shortening include the Big Bend compressional domain and the western Transverse Ranges domain (Figure 2-10). The Big Bend domain lies between the San Andreas and West Huasna fault zones northeast of the southern part of the Los Osos/Santa Maria Valley domain. Northwest-trending Quaternary folds and faults characterize the Big Bend domain. Southwest-directed compression in the Big Bend domain apparently is a result of westward displacement of the Sierra Nevada block due to Basin and Range extension. In contrast, the western Transverse Ranges domain, which lies along the southern margin of the Los Osos/Santa Maria Valley domain (Figure 2-10), is characterized by generally east-west-trending folds and faults and left-lateral fault displacement. Compression in this domain appears to be oriented north-south and is probably a result of clockwise rotation of the western Transverse Ranges.

Localized areas of compression also occur along the western margin of the San Simeon and Hosgri fault zones (Figure 2-10). The Point Sur anticlinorium separates the offshore Sur basin from the Monterey Bay region and is interpreted to be related to the transfer of strain between the San Gregorio and Sur fault zones. The Piedras Blancas anticlinorium is a northwest-trending structural high west of the south-central San Simeon fault zone. Folds and faults associated with the anticlinorium locally deform Tertiary strata and Quaternary deposits indicating active late Cenozoic compression in the area. These structures are related to westward-branching strands of the San Simeon fault zone such as the Arroyo del Oso fault (Plate 13). Off Point Buchon, a local upwarp of Pliocene strata occurs along the eastern margin of the offshore Santa Maria Basin. This upwarp is spatially associated with the intersection of the San Luis/Pismo structural block and the Hosgri fault zone.

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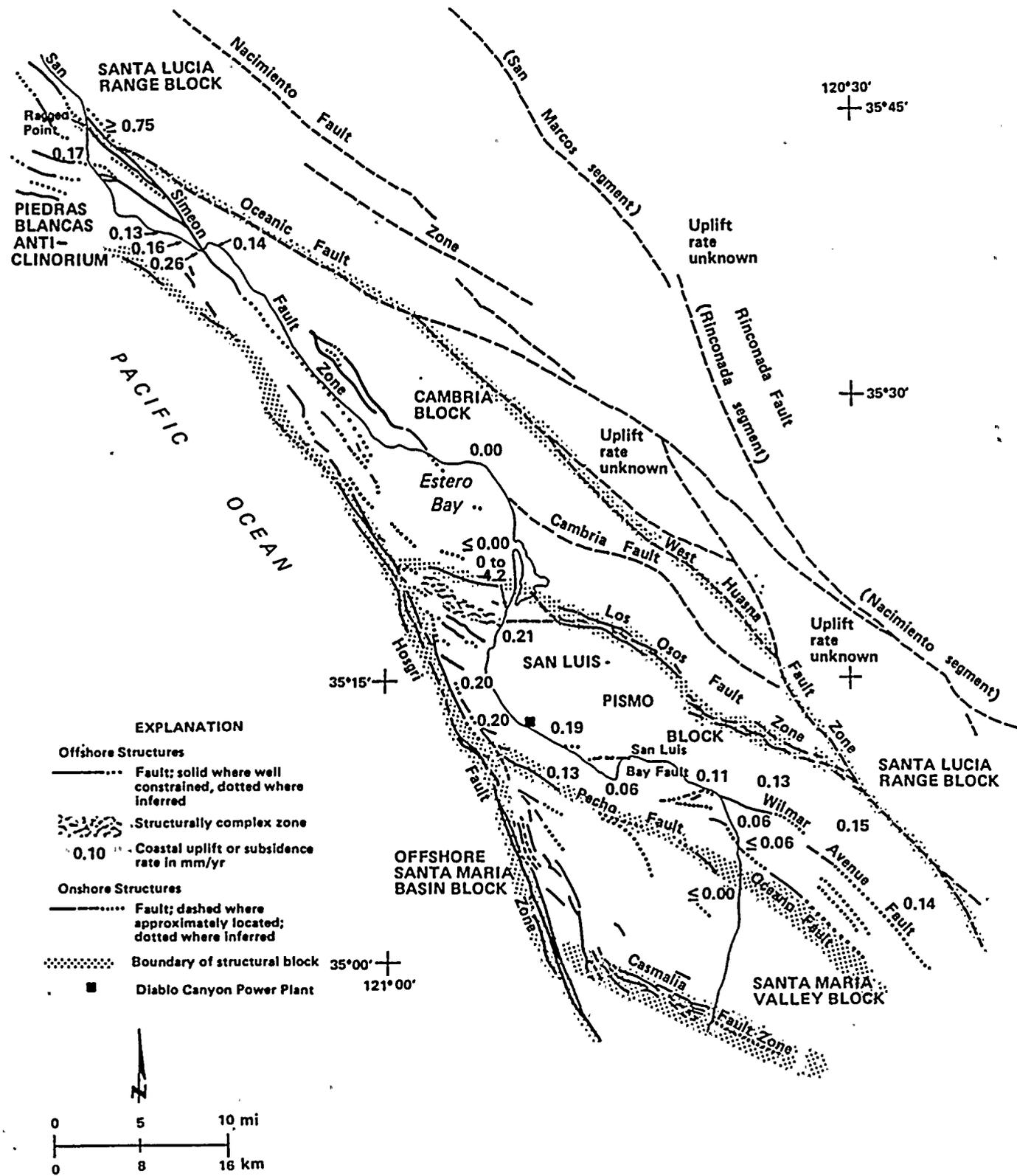


Figure 2-11

Map illustrating distribution of northwest-trending structural blocks and general location of faults in south-central coastal California. Uplift rates are derived from marine terrace shoreline angle elevations and are used, in part, to define the regional structural blocks.

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LOCAL TECTONIC SETTING

The Diablo Canyon Power Plant is located on the west-southwest part of the San Luis/Pismo structural block. As described above, this block is one of a series of elongate, west-northwest-trending structural blocks within the Los Osos/Santa Maria Valley domain (Figure 2-11). These blocks are defined primarily on the basis of relative differences in uplift (or subsidence) rates and surface morphology. They are typically separated from one another by zones of reverse faulting or flexure and they terminate to the northwest against the more northerly trending Hosgri and San Simeon fault zones.

San Luis/Pismo Structural Block. The San Luis/Pismo structural block is bordered on the northeast by the Los Osos fault zone, on the southwest by a diffuse zone of small faults (including the San Luis Bay, Wilmar Avenue and Oceano faults), and on the west by the Hosgri fault zone (Figure 2-11). The southeastern end of the San Luis/Pismo structural block terminates at the West Huasna fault zone. The characteristics of the Los Osos fault zone, the zone of faults along the southwestern boundary of the San Luis/Pismo structural block, and the Hosgri fault zone, based on detailed investigations conducted during the Program and in previous studies, are described in later sections of this report.

Several geologic structures have been mapped within the San Luis/Pismo structural block on the basis of bedrock relationships (Hall and Corbato, 1967; Hall, 1973a, 1973b; Hall and Prior, 1975; Hall and others, 1979). These structures include the Pismo syncline and the San Miguelito, Edna, Pismo, and Indian Knob faults (Plate 3). These structures were investigated during the Program to assess their history of deformation, lateral continuity, geometry, sense of displacement, and recency of activity. Data from these studies indicate that each structure within the block experienced some level of activity during the late Miocene and/or Pliocene, but that activity progressively decreased during and subsequent to deposition of the late Pliocene Squire Member of the Pismo Formation and ceased prior to

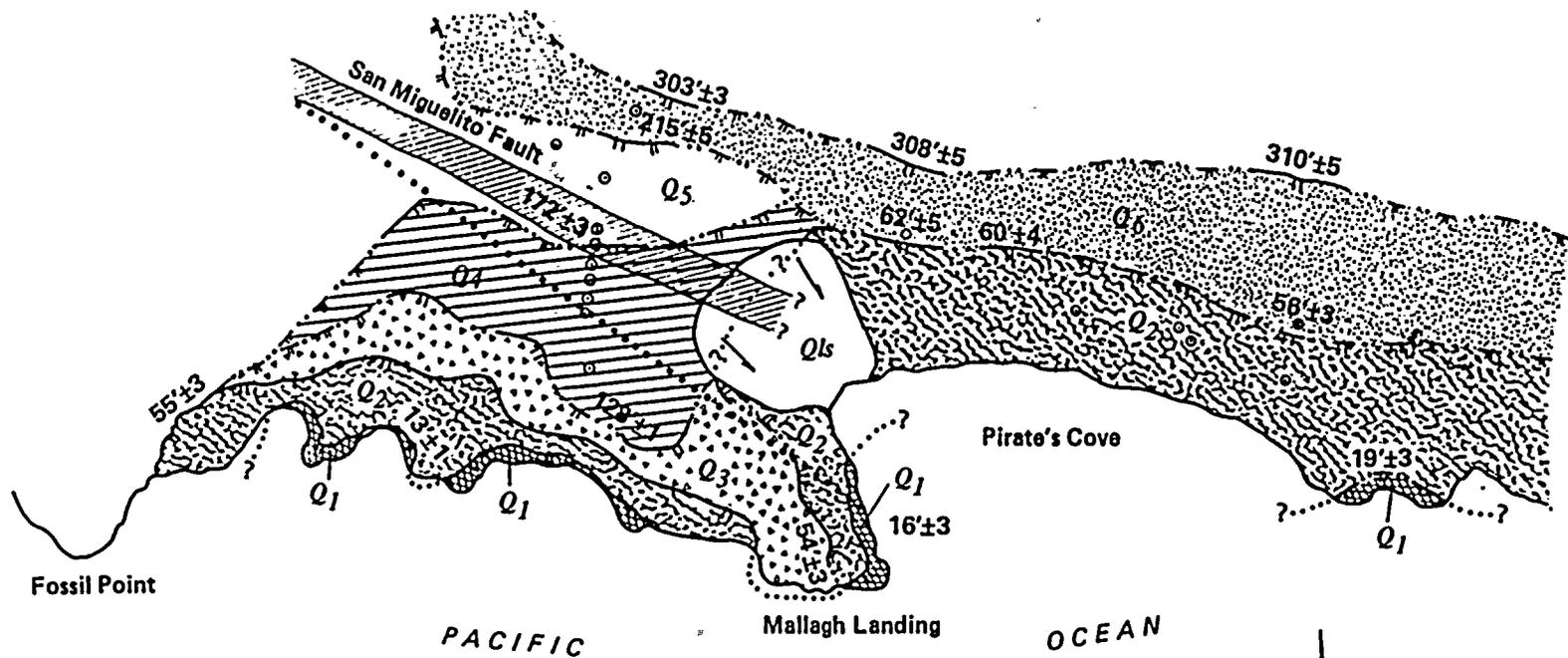
development of a flight of late Quaternary marine terraces.

Results of the marine terrace mapping along the western and southern margins of the part of the San Luis/Pismo structural block exposed onshore are presented on Plates 10 and 11. A longitudinal profile illustrating the elevations of marine terraces along the coast from Morro Bay to the Santa Maria Valley is shown on Plate 12. The spatial and temporal distributions of these terraces were used to: 1) delimit the margins of the San Luis/Pismo structural block; 2) differentiate subblocks within the San Luis/Pismo structural block that have undergone differing rates of long-term uplift; and 3) assess the deformational history within the San Luis/Pismo structural block, in particular the existence, amounts and rates of any Quaternary deformation along the Edna, San Miguelito, and Pismo faults, and the Pismo syncline (Plate 3).

Results of this work document the absence of late Quaternary (past 500,000 years) folding across the axial trace of the Pismo syncline and absence of late Quaternary displacement along the Edna, San Miguelito (Figure 2-12), and Pismo (Figure 2-13) faults (Plates 10 and 12). The San Luis/Pismo structural block is being uplifted at rates of 0.11 to 0.22 millimeter per year with no evident internal deformation except locally on small faults along the southwestern margin of the block (Figure 2-11). The plant site itself is situated on a well developed sequence of marine terraces (Figure 2-3). The spatial and temporal distribution of this terrace sequence is sufficiently well resolved to preclude potentially unknown faulting in the plant site vicinity, as well as any other significant deformation, such as warping, tilting, or distributed shearing. For example, a series of small northwest-trending faults observed north of Point Buchon on high-resolution seismic reflection data, called the Crowbar faults (Plate 5), project toward the coast between Montaña de Oro and Point Buchon but do not displace or deform the marine terrace sequence and thus are not capable (Figure 2-14, Plates 10 and 12).

Uplift of the San Luis/Pismo structural block is accommodated along its northeastern margin by





EXPLANATION

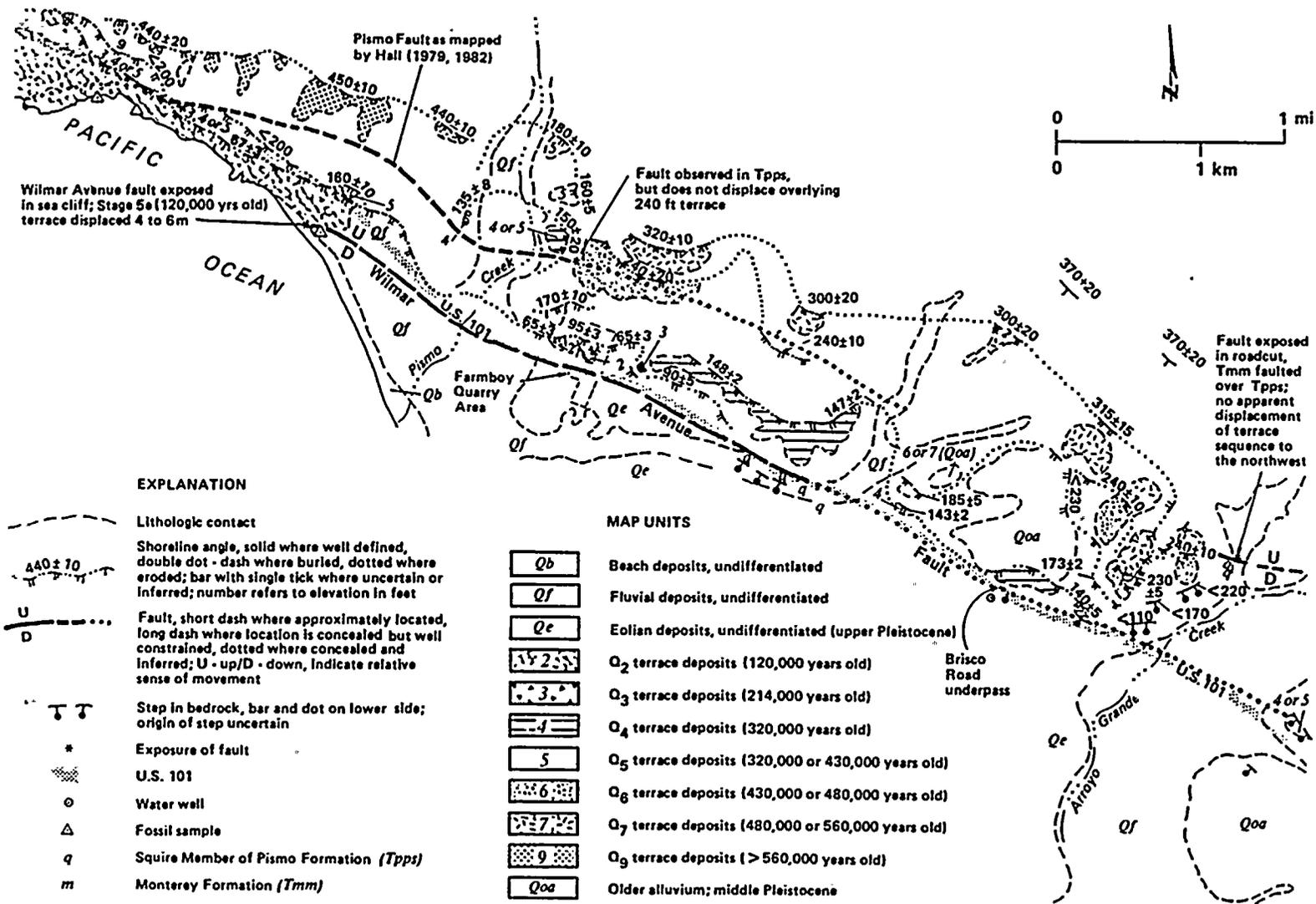
- Borehole
- Shoreline angle of marine platform, solid where well constrained, double dot-dash where concealed; dotted where eroded; elevation in feet
- Landslide
- Zone within which the San Miguelito fault is constrained
- San Miguelito fault after Hall (1973a)
- Q₁ terrace deposits (83,000 or 105,000 years old)
- Q₂ terrace deposits (120,000 years old)
- Q₃ terrace deposits (214,000 years old)
- Q₄ terrace deposits (320,000 years old)
- Q₅ terrace deposits (320,000 or 430,000 years old)
- Q₆ terrace deposits (430,000 or 480,000 years old)

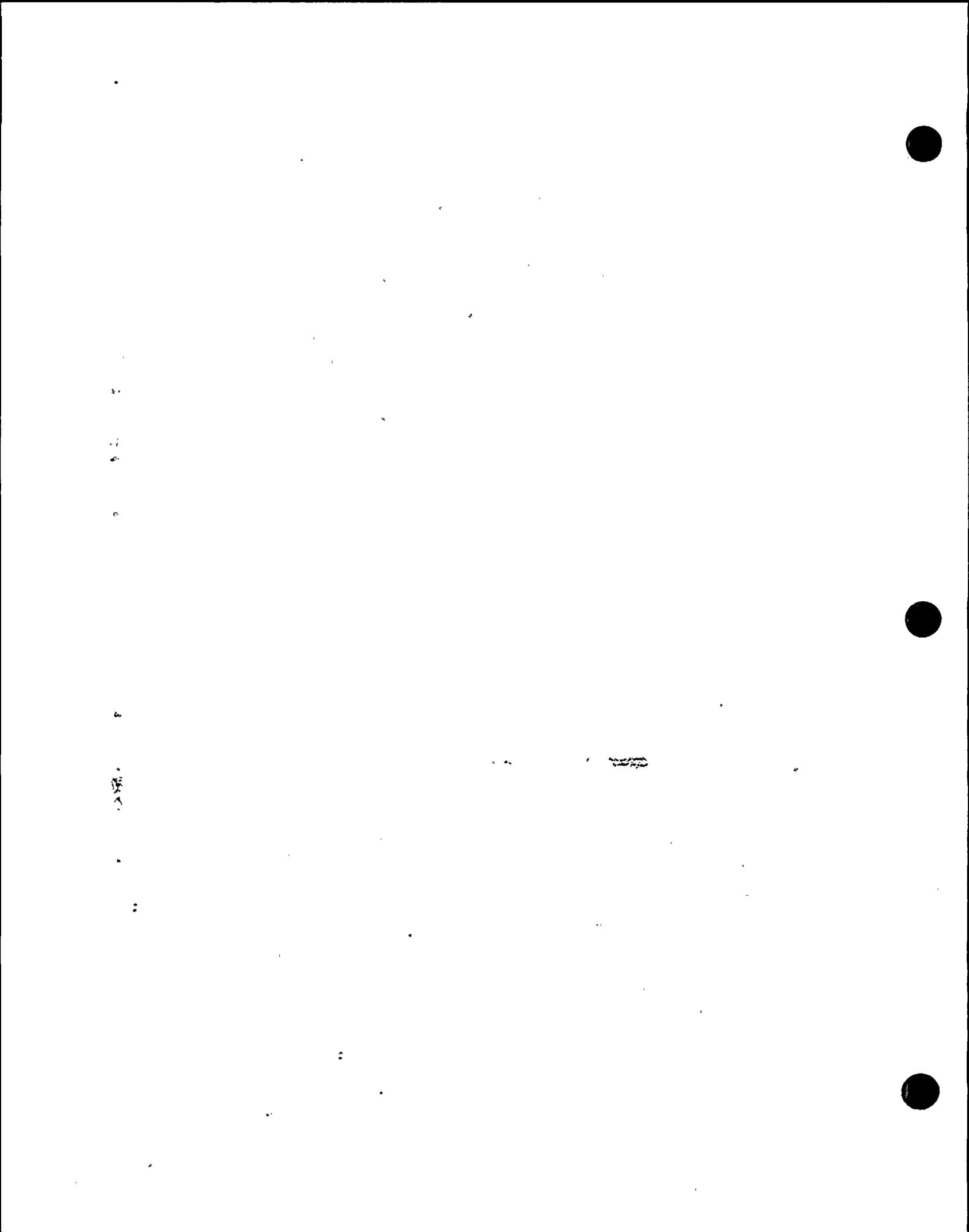
Note: Detailed marine terrace map and longitudinal profile shown on Plates 10 and 12

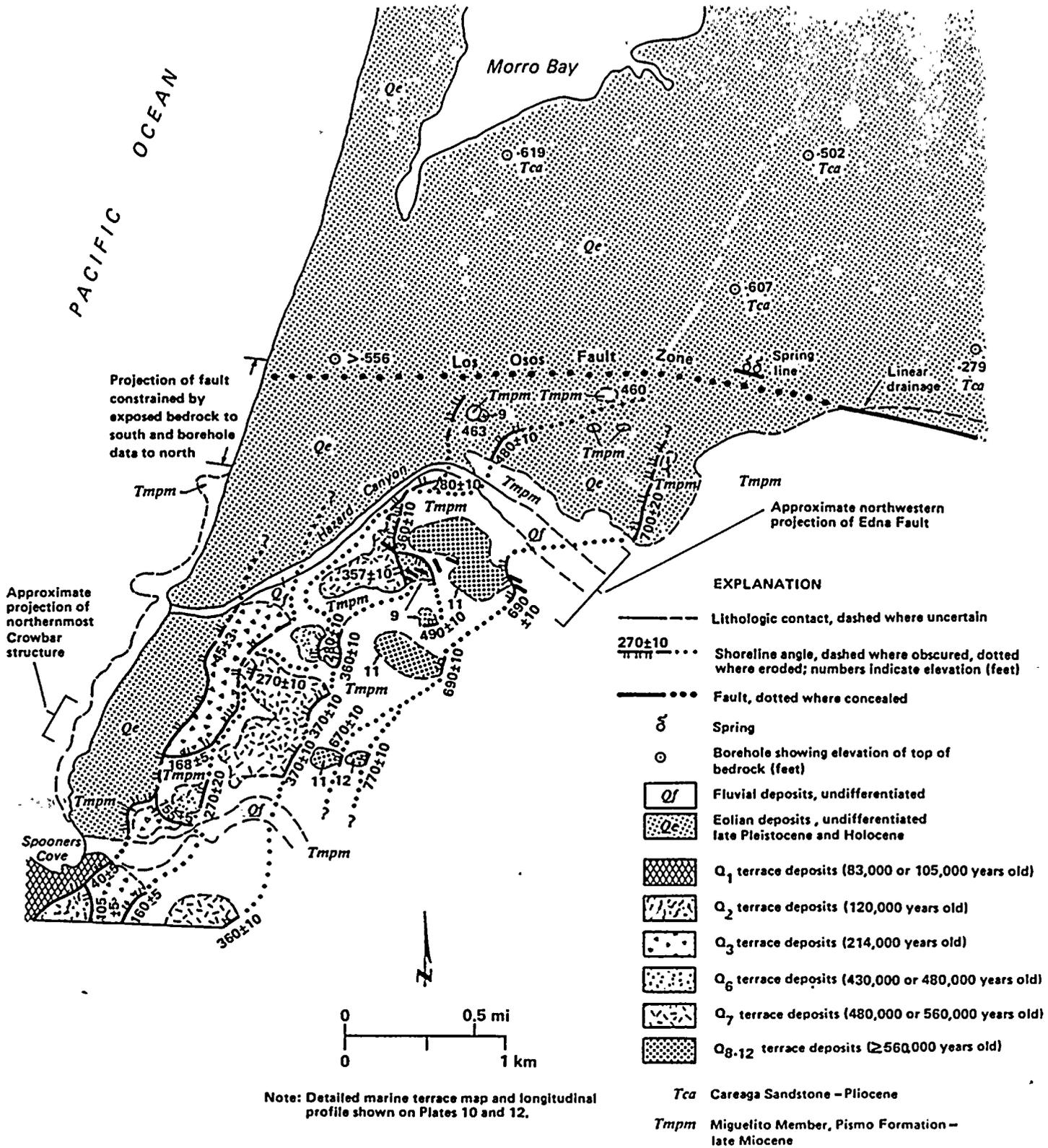
Figure 2-12

Generalized geologic map of Quaternary deposits in the Avila Beach/Mallagh Landing area illustrating distribution of marine terraces and interpreted location of the San Miguelito fault.









.Figure 2-14

Generalized geologic map of Quaternary deposits in the Montaña de Oro and Morro Bay areas illustrating distribution of marine terraces and interpreted location of the Los Osos fault zone.

displacement on the Los Osos fault zone, and along its southwestern margin by both warping and faulting. This interpretation is supported by marine high-resolution geophysical and bathymetry data, which show that uplift is occurring on the offshore Pecho fault along the southwest boundary of the San Luis/Pismo block. The geophysical data also show that uplift of the block relative to the offshore Santa Maria Basin is occurring across the Hosgri fault zone (Figure 2-11).

In addition to the absence of deformation of late Quaternary marine terraces along the Edna and San Miguelito faults, trenching investigations along these structures did not reveal evidence suggesting Holocene activity. Interpretation of exposures from six trenches across the San Miguelito fault show that it has a Pliocene history of high-angle, strike-slip displacement. Eleven trenches across strands of the Edna fault show that it represents minor, discontinuous shearing of the depositional contact between Tertiary strata and underlying Franciscan basement rocks. The absence of Holocene displacement on the Edna and San Miguelito faults is supported by the almost complete absence of geomorphic expression along the fault traces except from differential erosion.

Subblocks Of The San Luis/Pismo Block. The San Luis/Pismo structural block is divided into four subblocks on the basis of topographic expression and differences in uplift rates (Figure 2-11). From northwest to southeast, these subblocks are the Estero Bay, Irish Hills, Edna, and Newsom Ridge subblocks (Figure 2-15). These subblocks probably reflect differing amounts and rates of deformation along the bordering fault zones and thus provide an indication of constraints on the physical and behavioral characterization of these faults.

Figure 2-16 is a generalized topographic map or "envelope map" of the onshore San Luis/Pismo block. The onshore part of the block consists of three distinct topographic subblocks (Figures 2-16 and 2-17). The Irish Hills subblock is characterized by relatively high relief and crest elevations of 425 to 550 meters. The

southeastern boundary of this subblock coincides with San Luis Obispo Creek, an antecedent stream that drains an interior valley and cuts across the San Luis/Pismo structural block. The northwestern boundary of the Irish Hills subblock is interpreted to be approximately coincident with the present coastline. The Edna subblock is characterized by low relief and crest elevations of 180 to 240 meters. Its southeastern boundary coincides with Arroyo Grande Creek, also an antecedent stream that, like San Luis Obispo Creek, cuts across the San Luis/Pismo structural block. The Newsom Ridge subblock is characterized by relief comparable to the Irish Hills subblock, with maximum crest elevations of 425 to 550 meters. The southeastern end of the San Luis/Pismo structural block is not well defined on the basis of topography, because it merges into the Santa Lucia Mountains range front across the structural boundary corresponding to the West Huasna fault zone.

Offshore, at the northwest end of the San Luis/Pismo structural block, the Estero Bay subblock is characterized by a bedrock platform locally mantled by thin post-late-Wisconsinan deposits and featured by several northwest-trending, discontinuous seafloor ridges. The highest ridge is 59 meters below sea level and the ridge system is informally named "59-meter-ridge" (Figure 2-11). The bedrock platform and 59-meter-ridge are interpreted to be an offshore continuation of the San Luis/Pismo structural block. In this interpretation, the present coastline between Morro Bay and Pt. Buchon is an erosional escarpment produced by present and former sea-level highstands. The presence of a flight of marine terraces along the coast, however, requires that the geographic location of the coastline has not retreated during the late Quaternary. The difference in elevation from onshore to offshore, therefore, more likely reflects different rates of uplift rather than erosional retreat of the coastline. The offshore bedrock platform, therefore, is probably a separate offshore subblock of the San Luis/Pismo structural block that has undergone low rates of uplift or subsidence or has been stable during the late Quaternary. 59-meter-ridge is a detached piece of the Estero Bay subblock that has been





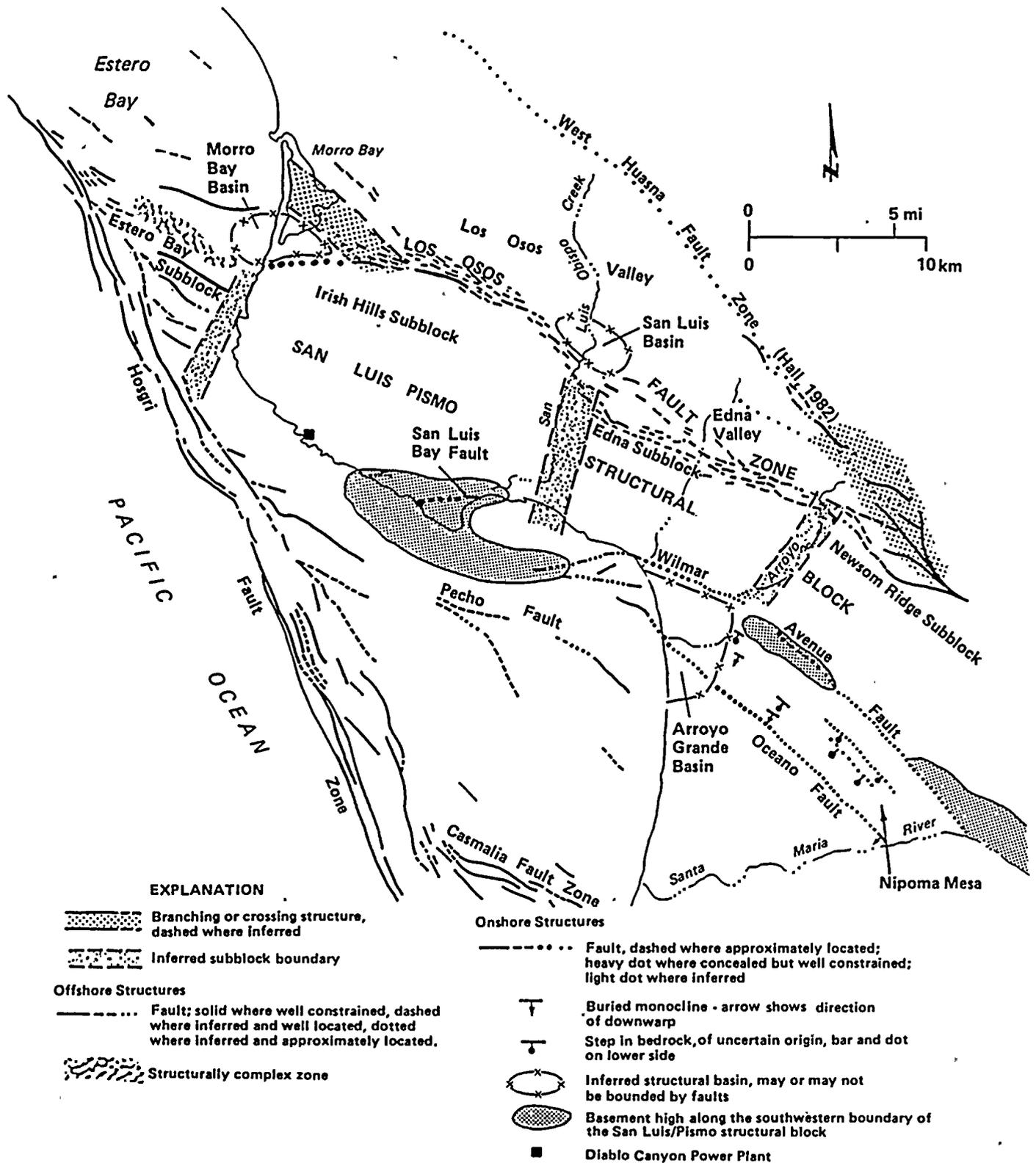


Figure 2-15
Structural elements associated with the San Luis/Pismo structural block.



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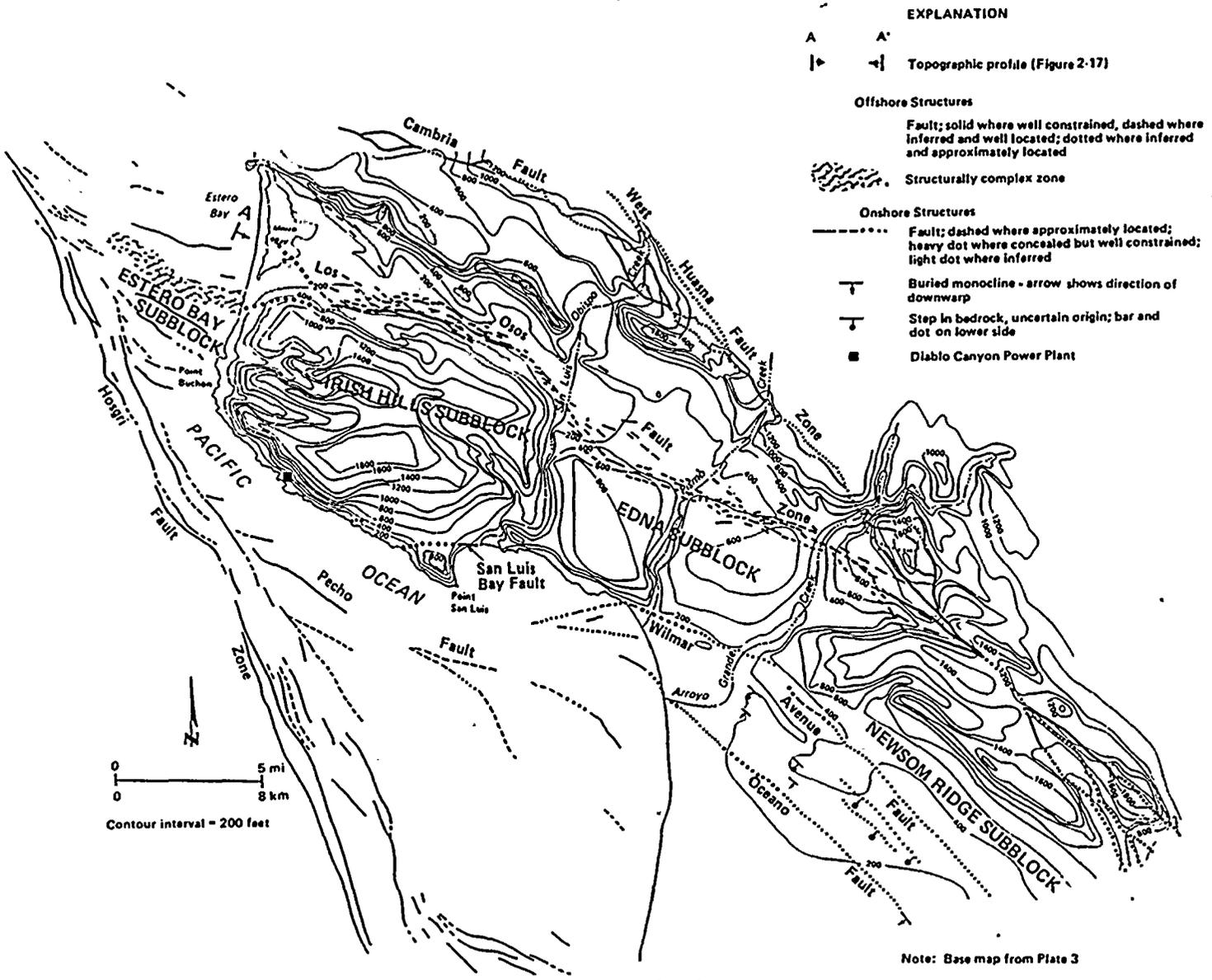


Figure 2-16

Generalized topographic contour map illustrating subblocks of the San Luis/Pismo structural block. Contours generalized from parts of the Morro Bay South, San Luis Obispo, Port San Luis, Pismo Beach, Arroyo Grande NE, Oceano, Tar Springs, Nipomo, Santa Maria, Husana, Guadalupe, and Twitchell Dam U.S. Geological Survey 7.5-minute topographic quadrangles.



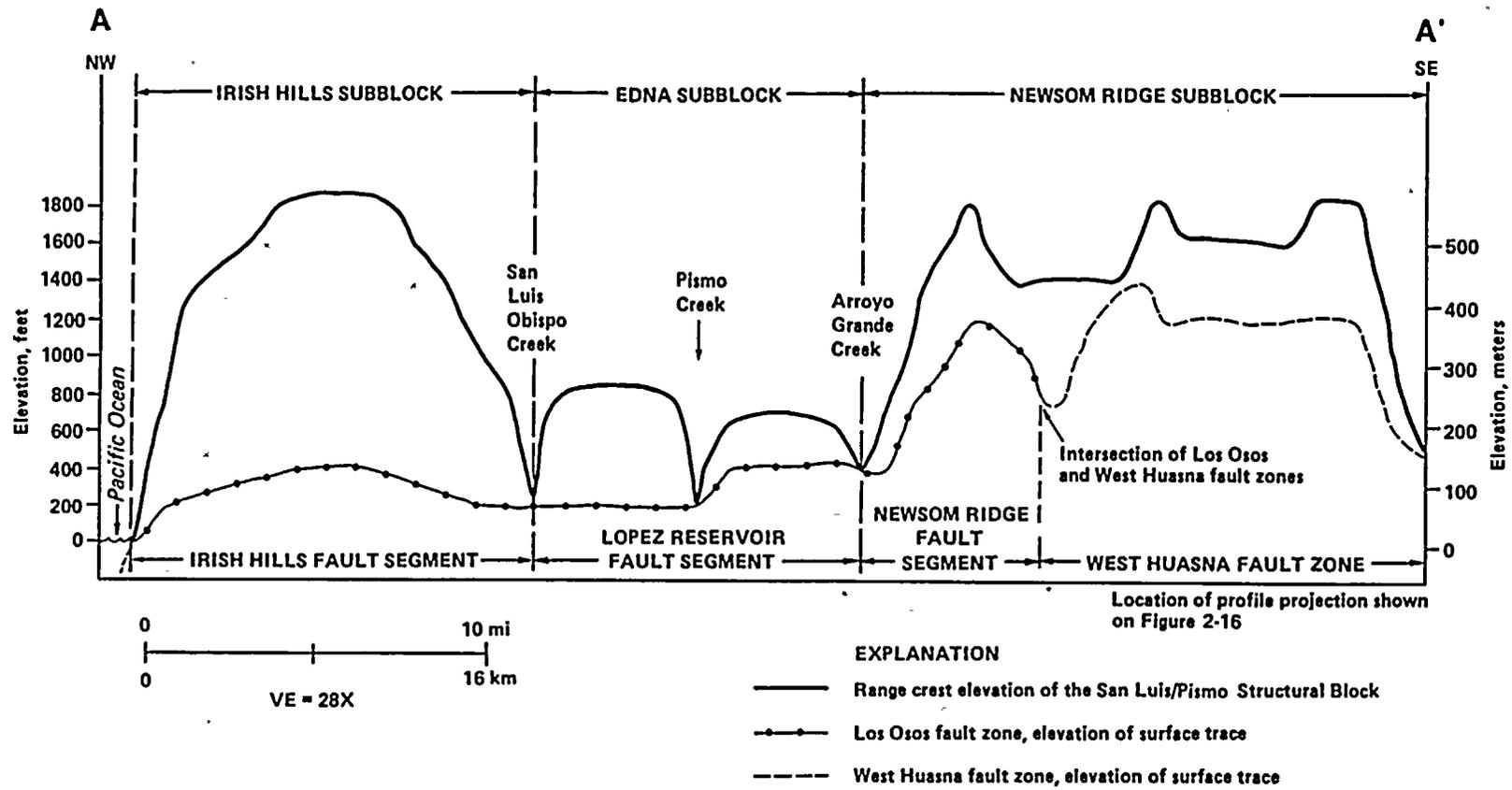


Figure 2-17

Topographic profiles illustrating: (1) range crest elevation and subblocks of the San Luis/Pismo structural block; and (2) surface trace elevation and segmentation of the Los Osos fault zone.

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locally tectonically elevated between the Los Osos and Hosgri fault zones.

Seismological Investigations

A detailed understanding of historically and instrumentally recorded earthquake occurrences is an important element in establishing the current tectonic setting and evaluating potential seismic sources within south-central coastal California. The seismic activity in the Los Osos/Santa Maria Valley domain, within which the Diablo Canyon plant site is located, is the primary topic of study. However, seismological data from within the adjacent onshore and offshore areas provide important regional constraints and are included herein. The data set reviewed in this study comes from the geographic area extending from the western Transverse Ranges (34 degrees latitude) on the south, the San Andreas fault on the east, near the northern end of the southern Coast Ranges at Monterey Bay (37 degrees latitude) on the north, and the continental slope on the west. The historical earthquake record derived from recent compilations and analyses of earthquake felt and damage effects as well as instrumental data is discussed in the next section. Earthquakes of magnitude estimated to be 5 or larger have been evaluated as part of this study. One of the largest historical earthquakes in the region is the November 4, 1927 Lompoc earthquake. In the past, the location and tectonic association of this earthquake have been uncertain. This event is discussed separately in terms of its source mechanism, location, and tectonic association. Following these discussions the regional and local seismicity and focal mechanism data sets for earthquake and microearthquake activity from 1973 to the present are addressed.

HISTORICAL SEISMICITY

The early historical earthquake record in south-central coastal California is contained in records of the Spanish missions built along the coast in the late eighteenth and early nineteenth centuries (Townley and Allen, 1939; Topozada and others, 1979). The distribution of missions and other settlements was too sparse to provide a detailed record of occurrences and accurate

locations of earthquakes during this time period. It is probable, however, that earthquakes within the region of magnitude 7 and larger would have been recognized as such by the mission reports. Smaller earthquakes may have been reported, but without enough information to locate them or estimate their magnitude using their felt areas. Beginning in the 1850's, the rapid expansion of settlement along the coast provided more sources of historical information, particularly newspapers, that decreased the magnitude-detection threshold within the region to about magnitude 6 by about 1880 (Topozada and others, 1981).

In 1887, the first California seismographic instruments were installed at the University of California at Berkeley and at Lick Observatory, but instruments sufficient to detect and locate moderate earthquakes in the south coastal region were not installed until 1927 to 1932 (Bolt and Miller, 1975). The scientific reporting of earthquakes in California increased greatly after the turn of the century, and it is likely that all onshore events of magnitude 5 and larger have been identified since about 1900. However, Topozada (1987) noted that for some earthquakes around the turn of the century in the Parkfield and coastal region, the occurrence of a magnitude 5 event was detected but the magnitude value itself may not have been recognized by early studies of historical events. The threshold of detection and location of earthquakes using instrumental data was near magnitude 4 for the region by 1935 (Savage and McNally, 1974) and has continued to decrease as seismic networks in central and southern California have continued to expand in density and improve in sensitivity.

The historical earthquake data set provides two types of information important to the study:

- The largest magnitude earthquakes in the region are responsible for virtually all of the seismically related tectonic deformation. The sum of seismic moment released by earthquakes of magnitude 4 and smaller in the area do not equal the moment of just a few magnitude 5 events. Thus the occurrence of the large events helps us to interpret the

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nature of current tectonism in terms of the location of deformation, its rate, and its style.

- The recurrence of earthquakes of various magnitudes on individual faults is a significant source characterization parameter (Chapter 3). Typically, however, the historical record is not sufficient to define fault-specific recurrence rates. Further, recent fault-specific recurrence evaluations in a variety of tectonic settings have found that the frequency of occurrence of small earthquakes on a fault in a short time period is usually a poor indicator of the rate of occurrence of large earthquakes (Youngs and Coppersmith, 1985). Regional earthquake recurrence rates that include numerous faults may be estimated from the historical record and provide a useful comparison with earthquake recurrence estimates that are derived from geologically-estimated fault moment rates (Chapter 3).

These aspects of the historical earthquake data set are considered for the earthquakes of approximately magnitude 5 and larger for the region of interest. These events, 20 in number, are shown in Figure 2-18 and tabulated chronologically in Table 2-6. These events are discussed in the following with reference to structural blocks and faults shown in Figure 2-7.

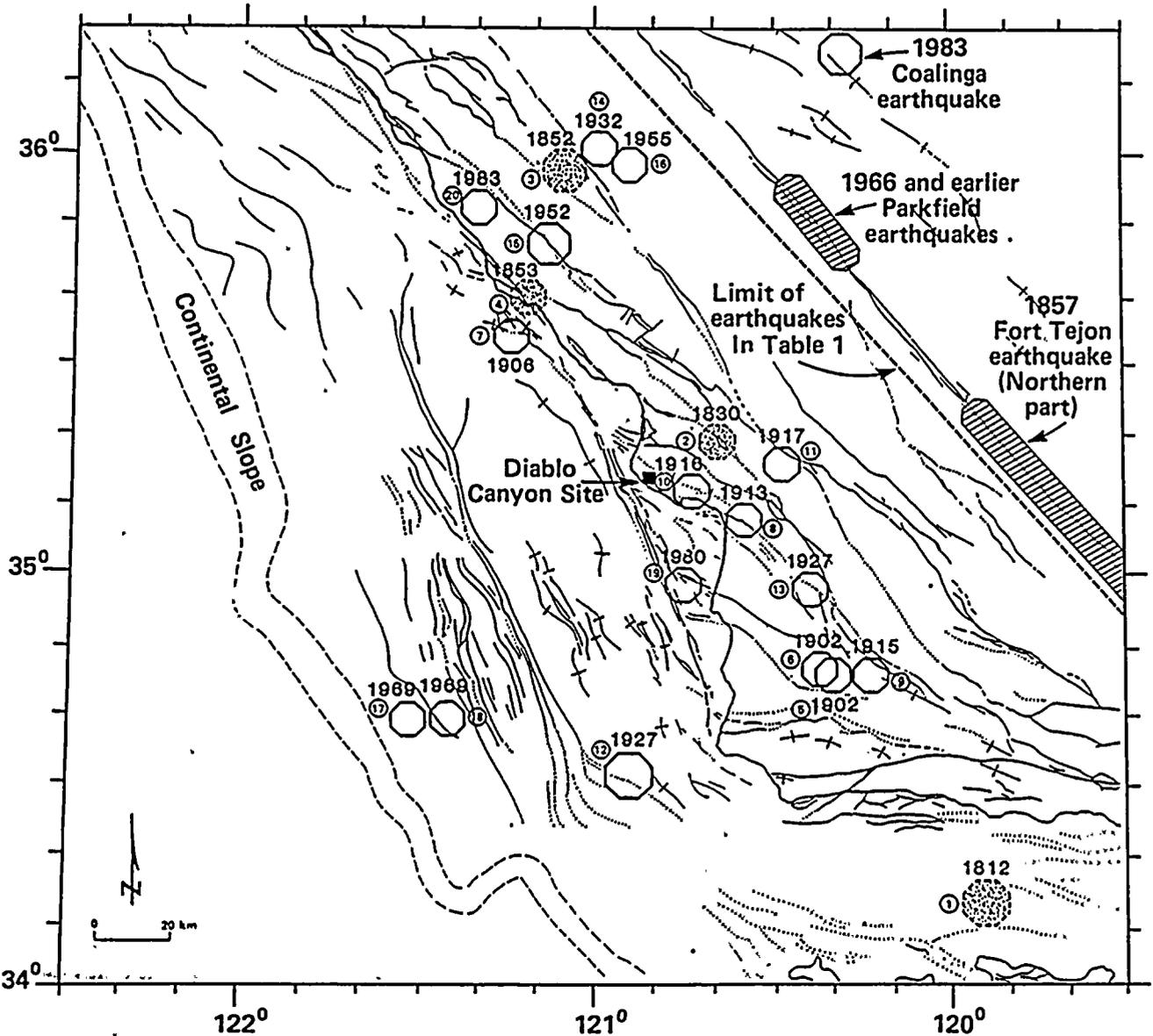
1. December 21, 1812: Topozada and others (1981) compiled and interpreted the intensity data from this earthquake, including reports of seismic sea waves in the Santa Barbara Channel. Topozada and others (1981) concluded that this earthquake occurred offshore to the southwest of Santa Barbara. Using the extent of the area of strong shaking for the earthquake, they concluded that the magnitude of the earthquake was about 7.1. The 1812 earthquake is geographically associated with the Transverse Ranges. Allowing for the uncertainty in the location noted above, the earthquake likely occurred along one of the generally east west-trending seismically active faults along the southern margin of the Transverse Ranges within the Santa Barbara

Channel. The occurrence of seismic sea waves suggests the possibility of dip-slip fault movement at the sea floor.

2. 1830: The occurrence of an earthquake affecting San Luis Obispo during 1830 is noted in the annual report from the mission located there. Topozada and others (1981), in summarizing the report, quote that, "the buildings are in bad condition." The only specific reference to earthquake effects is to cracked or broken walls of the "house of Santa Margarita." The exact location of this building is not identified by Topozada and others (1981). It is reasonable to accept that an earthquake causing damage to the San Luis Obispo mission actually did occur in the area in 1830, although a clear tectonic association for this event is precluded. As was noted by Topozada and others (1981), the limited reports of felt and damage effects (none were reported from missions to the north or south) suggest that the event was localized and not of large magnitude. It is herein considered to possibly be of magnitude 5 and to have occurred in the vicinity of San Luis Obispo.
3. November 27-30, 1852: Reports of widely felt earthquakes were noted on October 26 and November 26 of 1852. On November 27-30, earthquakes that caused "fissures 30 miles long in Lockwood Valley" were reported (Topozada and others, 1981). They note that, while there are Lockwood Valleys in both Monterey and Ventura Counties, there are no reports of earthquake damage during this time from Santa Barbara or Los Angeles. An earthquake large enough to produce surface faulting or even shaking-induced settlement in Lockwood Valley in Ventura County should have been felt in the communities to the south. Thus Topozada and others (1981) consider that an earthquake centered in Lockwood Valley, Monterey County, could have produced many of the historical reports. The dates and locations of the reports are not all consistent, however. An epicentral location in Lockwood Valley is



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Earthquake epicenter:

1812—Year of event

⊙ Event number
(Table 2-6 and text)

● Event location that is poorly constrained

○ Event location that is within 20 kilometers and generally within 10 kilometers

▨ Historic earthquakes with fault rupture along San Andreas fault zone

Magnitude

○ 5.0 — 5.9
 ○ 6.0 — 6.9
 ○ 7.0 — 7.9

NOTE: Base map explanation provided on Plate 3.

Figure 2-18

Historical earthquakes of magnitude 5 and larger, 1812-1988, in south-central coastal California.

100-100000

Table 2-6

HISTORICAL EARTHQUAKES IN THE SOUTH-CENTRAL COASTAL CALIFORNIA AREA
WITH MAGNITUDE 5 AND LARGER, 1912-1988

Event No.	Date	Magnitude	Location	Location Accuracy	Associated Fault or Structure
1	21 Dec., 1812	~7.1	Offshore, southwest of Santa Barbara (34.2°N, 119.9°W; Topozada and others, 1981)	<50 km	South side of Transverse Ranges in Santa Barbara Channel. Probably dip-slip on an east-trending fault.
2	1830	~5	In vicinity of San Luis Obispo (35.3°N, 120.65°W; modified from Topozada and others, 1981)	poor	Unknown; effects observed between The Los Osos and Rinconada faults.
3	27 to 30 Nov., 1852	~6?	Uncertain report of event near Lockwood in Lockwood Valley, Monterey County (35.95°N, 121.1°W; modified from Topozada and others, 1981)	very poor	Unknown; closest fault is the Rinconada. Earthquake may not have been in area covered by this table.
4	17 Dec., 1852 1 Feb., 1853	~5	San Simeon? (35.65°N, 121.20°W (1 February); Topozada and others, 1981)	poor	Unknown; closest major fault may be San Simeon fault zone.
5	27 to 31 Jul., 1902	~5 1/2	6 kilometers west of Los Alamos (34.75°N, 120.33°W; Guptil and others, 1980)	<10 km	Los Alamos/Baseline fault.
6	12 Dec., 1902	~5	Los Alamos (34.76°N, 120.37°W; modified from Real and others, 1978)	<10 km	Los Alamos/Baseline fault.
7	6 Dec., 1906	~5	Offshore, south of Point Piedras Blancas (35.55°N, 121.25°W; estimated from Topozada, 1987)	<20 km	South flank of Piedras Blancas anticlinorium.
8	20 Oct., 1913	~5+	Arroyo Grande (35.12°N, 120.58°W; estimated from Topozada, 1987)	<10 km	Faults along southwestern margin of San Luis/Pismo block.
9	11 Jan., 1915	5.2	3 to 5 kilometers east of Los Alamos (34.75°N, 120.23°W; Guptil and others, 1980)	<10 km	Los Alamos/Baseline fault.
10	1 Dec., 1916	~5	Avila (35.18°N, 120.73°W; modified from Topozada and others, 1978)	<10 km	Los Osos fault or faults along southwestern margin of San Luis/Pismo block.



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Table 2-6 (Continued)

HISTORICAL EARTHQUAKES IN THE SOUTH-CENTRAL COASTAL CALIFORNIA AREA
WITH MAGNITUDE 5 AND LARGER, 1812-1988

Event No.	Date	Magnitude	Location	Location Accuracy	Associated Fault or Structure
11	9 Jul., 1917	~5 (Series)	Lopez Canyon (32.25°N, 120.475°W; modified from Topozada and others, 1978)	<20 km	Between the Riconada and West Huasna faults.
12	4 Nov., 1927	7.0 (M _S)	Offshore, west of Point Arguello (34.5°N, 120.9°W; this report)	<20 km	Compressional structure west of Point Arguello, near south end of Santa Lucia Bank fault.
13	18 Nov., 1927	~5	Near Santa Maria (34.95°N, 120.40°W; modified from Topozada and others, 1978)	<~10 km	Faults along southwestern margin of San Luis/Pismo block.
14	26 Feb., 1932	5.0(M _L)	San Ardo (36.0°N, 121.0°W; Bolt and Miller, 1975)	<20 km	Near the Rinconada fault.
15	22 Nov., 1952	6.2 (M _L)	Bryson (35° 46.1'N, 121° 08.7'W; Dehlinger and Bolt, 1987)	<5 km	Near the Nacimiento fault zone.
16	2 Nov., 1955	5.1 (M _L)	San Ardo (35° 57.6'N, 120° 54.9'W; Savage and McNally, 1974)	<5 km	East of Rinconada fault.
17	22 Oct., 1969	5.4 (M _L)	Offshore west of the Santa Lucia Bank (34° 37.41'N, 121° 32.06'W; Gawthrop, 1975)	<10 km	Zone of northwest-striking faults and folds near the Santa Lucia escarpment.
18	5 Nov., 1969	5.6 (M _L)	Offshore west of the Santa Lucia Bank (34° 37.91'N, 121° 26.04'W; Gawthrop, 1975)	<10 km	Zone of northwest-striking faults and folds near the Santa Lucia escarpment.
19	29 May, 1980	4.9 (M _L) 5.1 (m _b)	Offshore, west of Point Sal (34° 57.5'N, 120° 45.5'W; this report)	<5 km	Associated with the offshore portion of the Casmalia fault zone (close to Hosgri fault zone).
20	29 Aug., 1983	5.2 (M _L)	Near San Simeon (35° 50.17'N, 121° 20.70'W; Eaton, 1984)	<5 km	Near the San Simeon fault zone.

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shown in Figure 2-18, with an assumed magnitude of 6 or greater, but this event may be either greatly mislocated or entirely fictitious. This uncertainty precludes a tectonic association for the event.

4. 1852-1853: Earthquake reports identify the Don Jesus Pico residence at San Simeon in San Luis Obispo County as having been damaged by earthquakes on December 17, 1852, and February 1, 1853 (Topozada and others, 1981). Considering the uncertainty associated with available earthquake reports of that time, it is possible that these two reports are associated with the same event. The damage may have been associated with the possible Lockwood Valley event on November 27-30 or may have been an independent event not reported from any other locality. This possible independent event is shown on Figure 2-18 at San Simeon with a magnitude of 5. This event could be associated with activity beneath the onshore-offshore Piedras Blancas anticlinorium, with the presently seismically quiescent San Simeon fault zone, or with the zone of seismicity along the Santa Lucia Range front.
5. July 27-31, 1902: A series of earthquakes occurred during the end of July that contained two prominent events, on July 28 and July 31, both of about magnitude 5 1/2 (Real and others, 1978; Topozada and Parke, 1982). The sequence was located in the vicinity of Los Alamos by Real and others (1978) and Topozada and Parke (1982) using reports of felt effects, damage to structures in Los Alamos and surrounding areas, and the occurrence of ground cracks. Guptill and others (1980) considered these earthquakes to be associated with the Los Alamos/Baseline fault zone and located them 6 kilometers west of Los Alamos.
6. December 12, 1902: This earthquake has been located by Real and others (1978) at the same location as the July 28, 1902 event, near Los Alamos. The magnitude value has not been determined, but it appears from the epicentral intensity to be slightly smaller than the largest July events. The earthquake is herein considered to have a magnitude value of about 5.
7. December 6, 1906: This earthquake damaged the lighthouse at Piedras Blancas, and was felt in San Luis Obispo and Santa Maria (Townley and Allen, 1939). Topozada (1987) used intensity data to locate the event offshore just south of Point Piedras Blancas along the southern flank of the Piedras Blancas anticlinorium. He estimated the magnitude at 5.
8. October 20, 1913: As updated by Topozada (1987), this earthquake was most strongly felt at Pismo Beach and Arroyo Grande, and was reported felt as far away as Santa Barbara and Carpinteria. The intensity data suggest a location close to the coast at the northwest end of the Santa Maria Valley, in the vicinity of the faulted southwest margin of the San Luis/Pismo structural block. Topozada (1987) estimated a magnitude value of 5 or somewhat greater.
9. January 11, 1915: This event was another in the series of damaging earthquakes near Los Alamos. Topozada and Parke (1982) located the earthquake slightly to the southeast of the 1902 activity (consistent with the conclusions of Guptil and others, 1980) and assigned a magnitude value of 5.2. Guptil and others (1980) placed the event 3 to 5 kilometers east of Los Alamos and associated it with the Los Alamos/Baseline faults.
10. December 1, 1916: Bolt and Miller (1975) list the location of this event as just offshore of Avila Beach in San Luis Obispo Bay. This location is consistent with reports published by Coffman and others (1982) indicating that some of the Union Oil refinery smokestacks tumbled over at Port San Luis and that a landslide blocked the railroad tracks in the canyon behind the town of Avila. Additional felt information given in the San Luis Obispo Morning Tribune of December 2, 1916, indicate that the earthquake was strongly felt in the city of San Luis Obispo and "...caused

many of the people, especially in the business district, to leave the buildings...." At Avila and at the San Luis Hot Springs objects were thrown off shelves, and a large landslide moved in Dairy Canyon two miles north of town. The newspaper article also reported "...an upheaval of the waters in the Bay of San Luis Obispo, as the trembling continued out to sea." Using these observations, the earthquake appears to have been very local to the coastal region near Avila, where the epicenter has been placed in this study. This event appears to be associated with the Irish Hills subblock of the San Luis/Pismo block, beneath which the Los Osos, Pecho, and San Luis Bay faults extend. The maximum intensity appears to be about VI (modified Mercalli scale), but the geographic distribution of available intensity observations are not sufficient to estimate the magnitude of the earthquake using felt areas. The local effects suggest, however, that the magnitude was probably near 5.

11. July 9, 1917: A series of felt earthquakes occurring over three days culminated in four distinct and damaging events on July 9. The events were reported by a ranger stationed in Lopez Canyon, northeast of Arroyo Grande, and caused chimney damage, rocks rolling down the hillsides, and loud sounds (Palmer, 1918). No reports are known from neighboring communities. The sequence is treated herein as a single earthquake of magnitude 5 located in Lopez Canyon, though the actual magnitude of the largest event may not be quite that large. This location is between the West Huasna and Rinconada faults along the eastern margin of the Franciscan Sur/Obispo terrane.
12. November 4, 1927: This earthquake, termed the Lompoc earthquake after the community strongly shaken in the event, is the largest historical earthquake in the offshore domain west of the Hosgri fault zone. The location of the event is constrained by teleseismic, aftershock, and intensity data as discussed later in this chapter to be about 25 kilometers west of Point Arguello at approximately 34.5°N, 120.9°W. The surface-wave magnitude value is 7.0, as discussed later along with additional source characteristics of this event. The 1927 earthquake is associated with the south basin compressional domain of folding and faulting (Figure 2-10).
13. November 18, 1927: Although this event occurred only two weeks after the magnitude 7.0 Lompoc earthquake, it is clearly not an aftershock. The event was most damaging and strongly felt at Santa Maria, with apparently lower-intensity motion on the south side of the Santa Maria Valley (Townley and Allen, 1939). The felt area extended from San Miguel and Parkfield on the north to the Santa Barbara Channel on the south, suggesting a magnitude of about 5. The event appears to have occurred along the zone of faulting bounding the south side of the San Luis/Pismo block, probably very near the town of Santa Maria.
14. February 26, 1932: This event was widely felt along coastal California and was located by UC Berkeley (Bolt and Miller, 1975). The magnitude value of 5.0 was also determined by UC Berkeley. This event was noted by Poley (1988) as occurring near the town of San Ardo and to be part of an ongoing sequence of earthquakes in this locality.
15. November 22, 1952: The Bryson earthquake of M_L 6.2 as revised by Savage and McNally (1974) from the value of 6.0 determined by UC Berkeley (Bolt and Miller, 1975) produced damage (modified Mercalli VII) locally at the small settlement of Bryson and was felt as far away as San Francisco and Los Angeles (Dehlinger and Bolt, 1987). Relocations of the event have been performed using regional phase data calibrated to known, more recent earthquake locations and are shown in Table 2-7.



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Table 2-7

Location	Reference
35° 47.9' N, 121° 11.4' W	Savage and McNally (1974)
35° 48.2' N, 121° 13.3' W	Gawthrop (1975)
35° 46.1' N, 121° 08.7' W	Bolt and Dehlinger (1987)

The locations in Table 2-7 are very similar, and all indicate a location a few kilometers to the west of the Nacimiento fault zone. The Dehlinger and Bolt (1987) location is shown in Figure 2-18. The Nacimiento fault zone occurs along the east side of a wide band of smaller earthquakes (discussed below) and also is the faulted boundary zone between the relatively stable Salinian block on the east and the more mobile Sur/Obispo Composite terrane to the west. The lack of evidence for significant late-Quaternary geologic activity along this zone suggests that the 1952 earthquake is an infrequent event.

16. November 2, 1955: This earthquake occurred near the town of San Ardo with magnitude 5.2 (Bolt and Miller, 1975; Savage and McNally, 1974, determined a revised ML value of 5.1). Table 2-8 shows locations determined for this event.

Table 2-8

Location	Reference
36° 00' N, 120° 55' W	Bolt and Miller (1975)
35° 57.6' N, 120° 54.9' W	Savage and McNally (1974)
35° 59.0' N, 120° 57.3' W	Gawthrop (1975)

The Savage and McNally (1974) location is shown in Figure 2-18. This location is several kilometers southwest of a November 1985 series of smaller earthquakes in the area (largest event of magnitude 4.5) discussed by Poley (1988). This area contains a zone of thrust faults dipping toward the Rinconada fault (Jennings, 1975) and is a producing oil field. This local zone is unusual in its

relatively high level of seismic activity compared to other areas within the Salinian block. It appears to be an area of limited faulting adjacent to the Rinconada fault near San Ardo and not to be representative of other portions of the Rinconada fault.

17. October 22, 1969: This is the first large event in a swarm occurring beneath the offshore Santa Lucia Bank and has a magnitude of 5.4 ML. The earthquake location for this event was revised by Gawthrop (1975) to that shown in Figure 2-18.
18. November 5, 1969: This earthquake is the largest of the 1969 Santa Lucia Bank swarm, with a magnitude of 5.6 ML. Gawthrop (1975) recomputed the location of this event to that shown in Figure 2-18, the west side of the Santa Lucia Bank. Dewey (1979) used this event as a master and relocated the other events in the swarm relative to it. He found that the swarm events clustered within about 15 kilometers of the November 5 event. This event is further discussed later in this chapter.
19. May 29, 1980: This earthquake occurred offshore of Point Sal with magnitude values of 4.9 ML and 5.1 mb (Stover and von Hake, 1982). The earthquake was widely felt but no damage was reported. The event location was revised by Eaton (1984) using integrated central and southern California station readings. McLaren and Savage (1987) updated the location (Figure 2-18) using a master event analysis, which is discussed later in this chapter. Although located very near the Hosgri fault zone, this event is associated with the offshore portion of the Casmalia fault zone.
20. August 29, 1983: This magnitude 5.2 ML earthquake was located by Eaton (1984) using integrated northern and southern California station readings at the location shown in Figure 2-18. The earthquake cracked chimneys and did other minor building damage at San Simeon. The location lies to the east of the surface expression of the offshore San Simeon fault zone.

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In summary, the historical earthquake record in the south-central coastal California region is generally consistent with the regional tectonic setting derived from an evaluation of late-Quaternary deformation. The Los Osos/Santa Maria Valley domain and adjacent elements of the Sur/Obispo terrane (characterized by Franciscan basement) contain the preponderance of the historical events of magnitude 5 and larger. For most events in this century, the associations between specific fault zones and individual earthquakes is reasonably good. The historical earthquake record is also generally consistent with the seismicity data for the past 15 years, as discussed in a later section.

THE 1927 LOMPOC EARTHQUAKE

The 1927 Lompoc earthquake occurred offshore and before the deployment of regional seismic arrays in California, with the result that the location and mechanism of the earthquake have been subject to considerable uncertainty. This has resulted in corresponding uncertainty in the tectonic association of the event. However, the development of synthetic seismogram techniques in recent years has provided an opportunity to obtain more accurate estimates of the location, focal depth, focal mechanism, and seismic moment of the earthquake using the available seismograms that were recorded. Synthetic seismogram methods have been widely used to analyze the source parameters of many recent California earthquakes using global network stations. As a result of this experience, teleseismic travel paths between earthquakes in California and stations in Europe are quite well understood, allowing comparison of detailed features of earthquake sources. This allows us to make more accurate estimates of the source parameters of a sparsely recorded earthquake such as the 1927 Lompoc earthquake by comparing its seismograms with those of more recent earthquakes, such as the 1983 Coalinga earthquake, whose source parameters are well known.

Teleseismic seismograms of the Lompoc Earthquake. After inspecting several dozen teleseismic recordings of the 1927 Lompoc earthquake, the station at De Bilt, the

Netherlands, was selected for use in a comparative study. This station has been in operation using high-quality, well-calibrated, long-period Galitzin instruments since 1922. The pass-band of the instrument is adequate for good teleseismic recording of long-period body waves. The Galitzin instruments have also remained in operation since they were installed, providing recordings of recent earthquakes on the same instrumentation that recorded the 1927 event.

The events selected for comparison are the November 5, 1969, magnitude M_L 5.6 Santa Lucia Bank earthquake and the May 2, 1983, magnitude M_S 6.5 Coalinga earthquake. The De Bilt seismograms for the 1927 Lompoc earthquake and these two more recent events are shown in Figure 2-19a. The similar P-to-S amplitude relationships of these seismograms suggest that the three events all have similar focal mechanisms. The large P amplitude relative to S is consistent with the reverse-slip mechanisms previously obtained for the 1969 and 1983 events (Bent and Helmberger, 1987). The similarity of the well-recorded S, SS, and SSS phases for the 1927 and 1983 events further indicates similarity in focal mechanism for the two events (Figure 2-19b).

The ratio of SV to SH has proven useful in evaluating focal mechanisms, and was used by Choy (1985) in determining the focal mechanism of the Coalinga earthquake displayed in the upper panel of Figure 2-20. Since the De Bilt station is located near an SH node of the Coalinga event, we find a very small S arrival on the transverse component (Figure 2-19b) as predicted. The Lompoc seismogram shows a stronger SH arrival, and the lower panel of Figure 2-20 illustrated the amount of rotation in strike necessary to achieve this adjustment.

Forward computations were performed using the existing source models for the Coalinga and Santa Lucia Bank events and a well-constrained Coalinga aftershock (Bent and Helmberger, 1987) to generate synthetic seismograms for comparison with the De Bilt recordings. The agreement between the recorded and synthetic seismograms is very good, as shown in Figures 2-21 and 2-22

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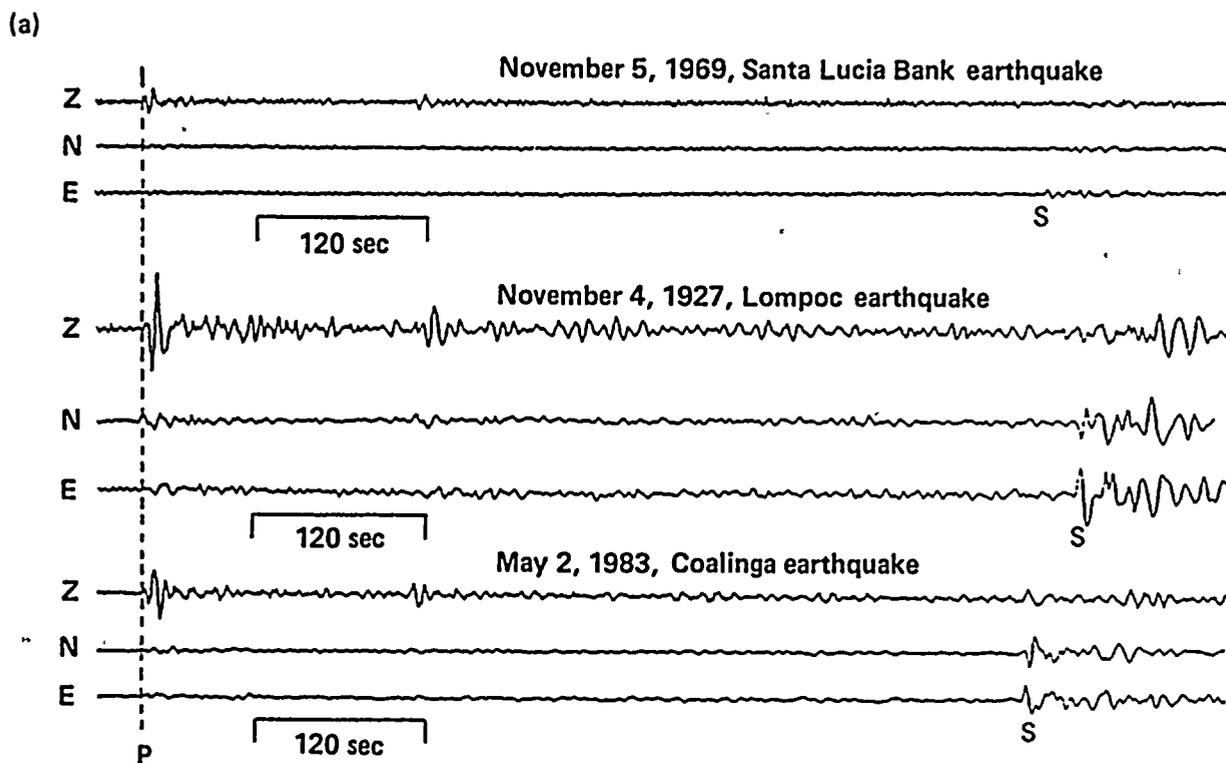
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(b)
Rotated horizontal records

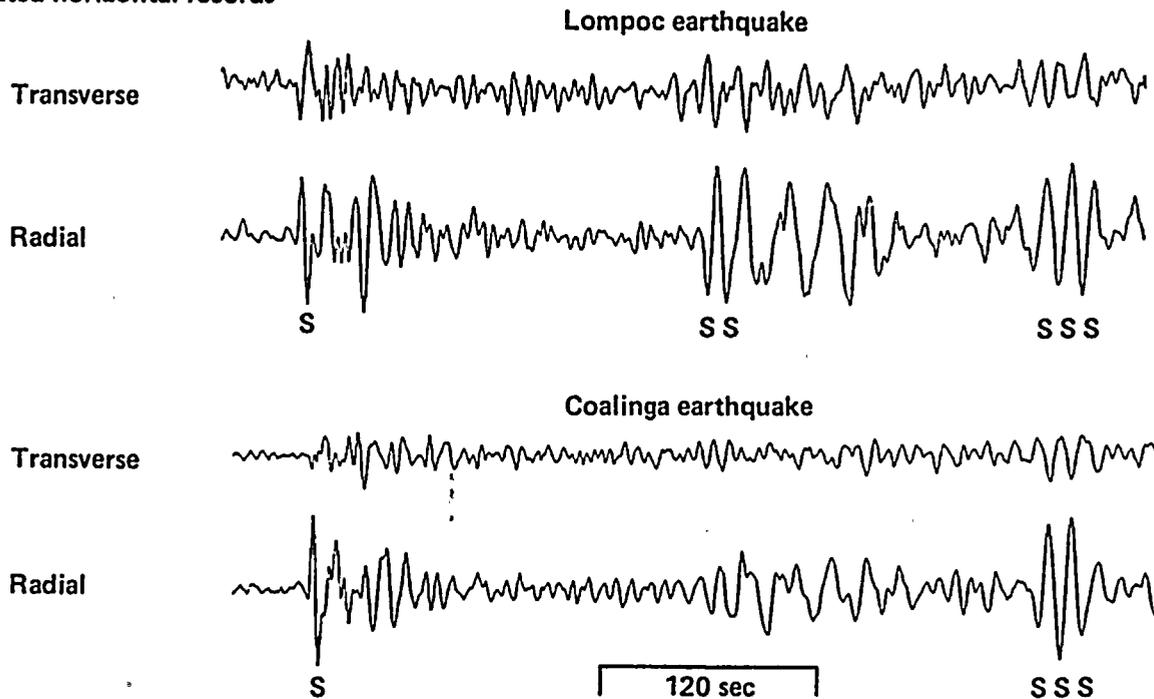


Figure 2-19

Comparison of seismograms observed at De Bilt, the Netherlands, for the 1927 Lompoc earthquake and two modern events (a); comparison of horizontal De Bilt seismograms of S waves rotated to transverse and radial components for the 1927 Lompoc and 1983 Coalinga earthquakes(b).



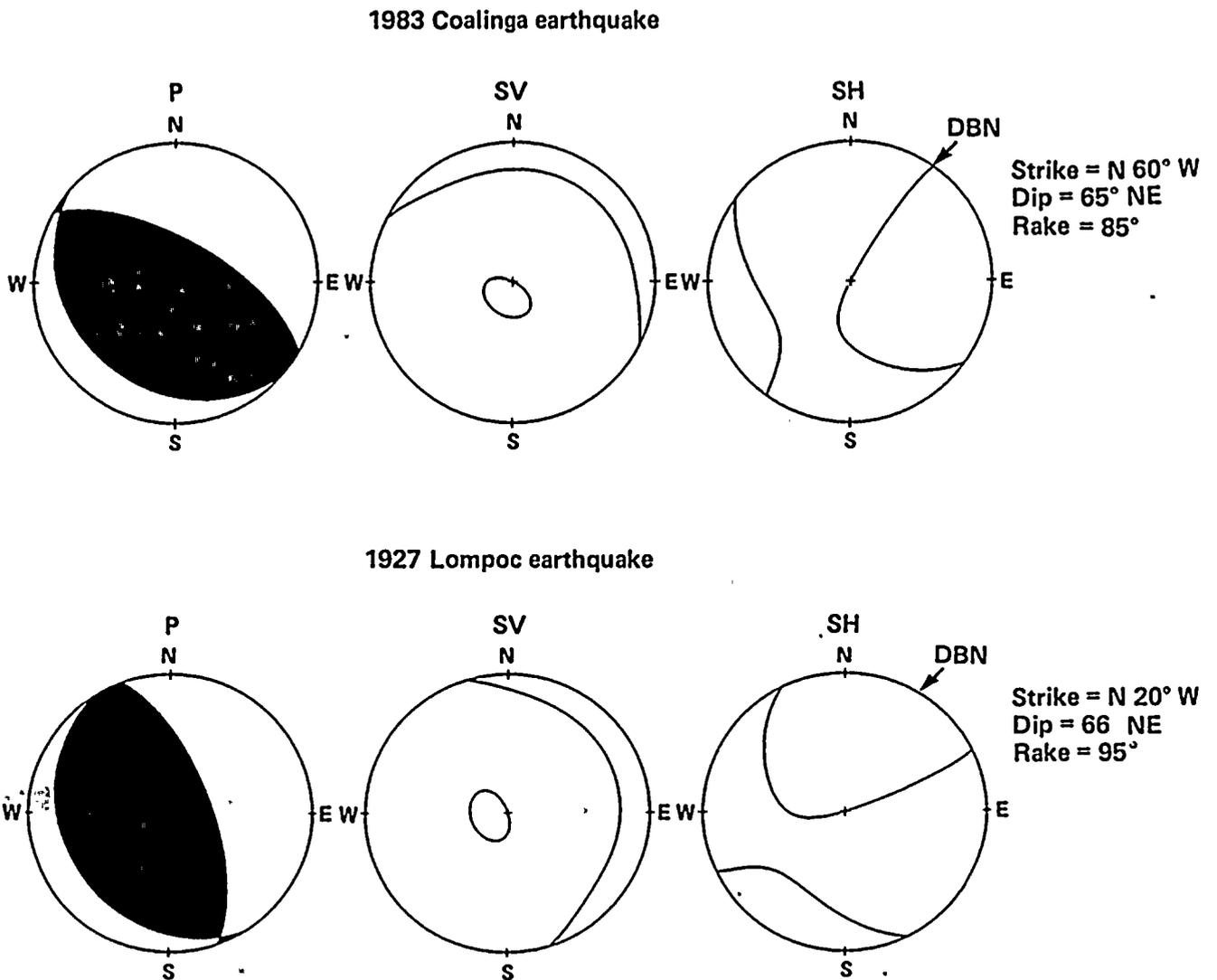
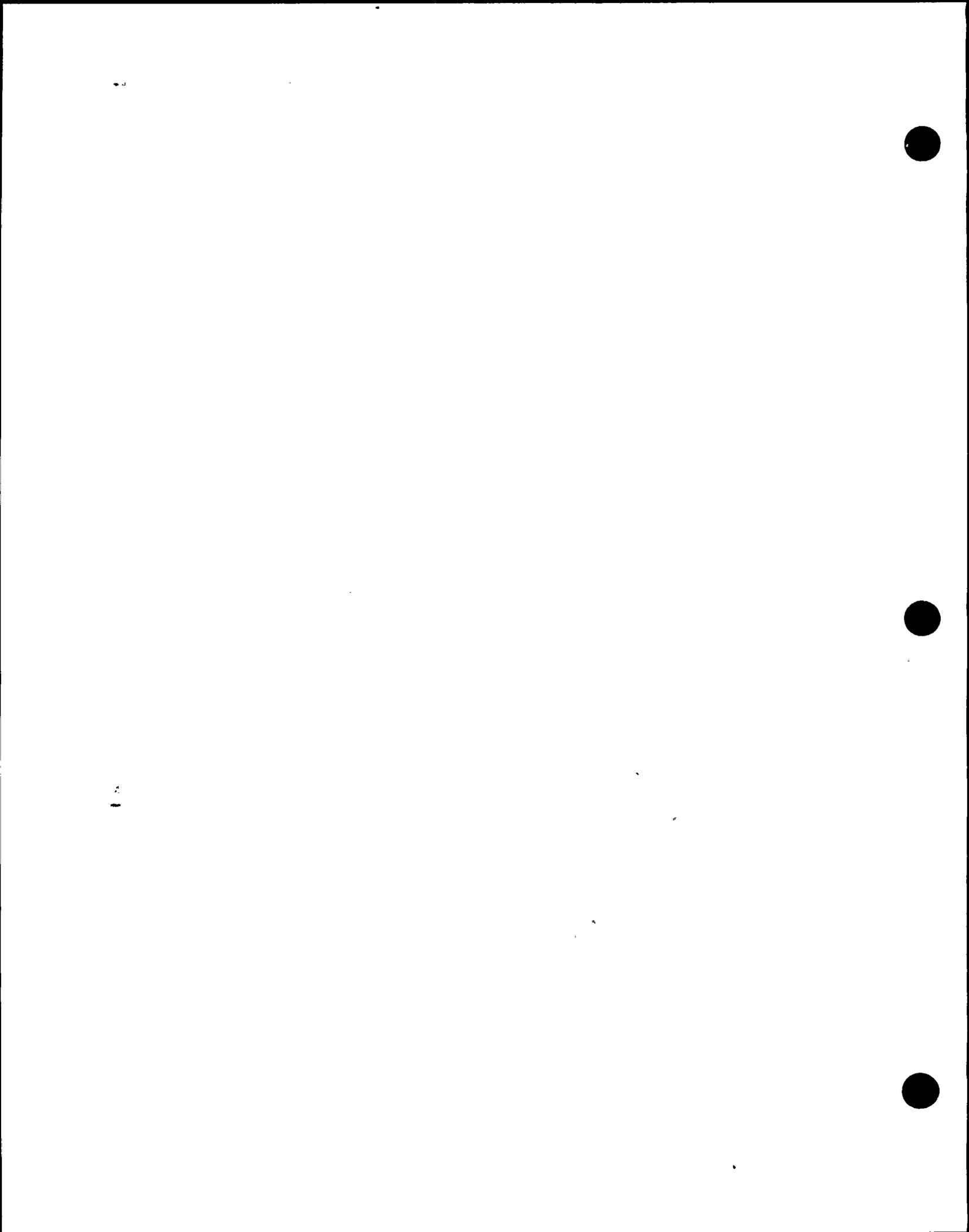


Figure 2-20

Focal mechanism plots indicating nodal planes for P, SV, and SH for the 1927 Lompoc and 1983 Coalinga earthquakes. The azimuth to De Bilt (DBN) from the epicentral area is indicated for the SH plot.



07/22/83

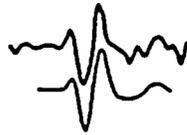
Coalinga aftershock



$M_0 = 0.5 \times 10^{25}$ dyne-cm
 $h = 8$ km
 $\delta t_s: 1, .5, 1$ sec

11/05/66

Santa Lucia Banks



$M_0 = 0.15 \times 10^{26}$ dyne-cm
 $h = 8$ km
 $\delta t_s: 1, 1, 1$ sec

05/02/83

Coalinga mainshock



$M_0 = 0.45 \times 10^{26}$ dyne-cm
 $h = 10$ km
 $\delta t_s: 1, 3, 1$ sec

11/04/27

Lompoc



30 sec

$M_0 = 1.0 \times 10^{26}$ dyne-cm
 $h = 10$ km
 $\delta t_s: 2, 2, 2$ sec

EXPLANATION

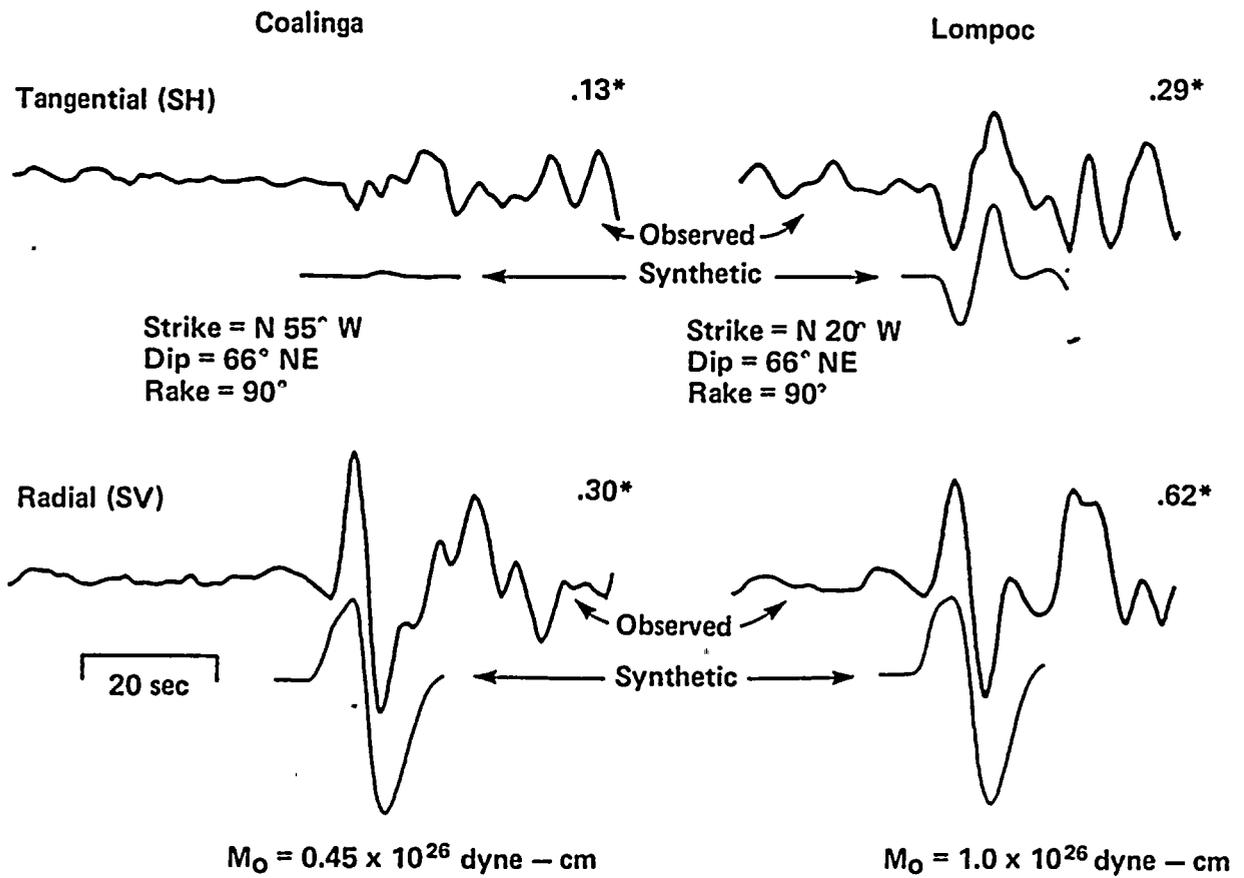
M_0 = Seismic moment
 h = Depth
 δt_s = Source time function

= Observed
 = Synthetic

Figure 2-21

Comparison of observed P waves with synthetic waveforms computed from existing models (upper three events) and the Lompoc earthquake mechanism in Figure 2-15.





* Relative SH to SV Amplitudes

Figure 2-22

Comparison of observed (rotated) S waves with synthetic waveforms for the 1927 Lompoc and the 1983 Coalinga earthquakes.

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for P waves and radial and transverse S waves respectively. This serves to calibrate the absolute amplitude level of this station to that of the worldwide network. To generate the synthetic seismograms for the Lompoc earthquake, advantage was taken of the detailed correspondence between the recorded seismograms of the Lompoc and Coalinga earthquakes, and the mechanism of the Coalinga earthquake was used as a starting model in the search for the mechanism solution of the Lompoc earthquake. The principal modifications were to rotate the strike clockwise by 40 degrees to 340 degrees, to double the seismic moment to match the observed P wave amplitude, and to extend the source time function to a 2-2-2 second trapezoid to account for the larger seismic moment.

As illustrated in Figure 2-21, the agreement between the recorded and synthetic P-wave seismograms of the Lompoc earthquake is excellent. The relative timing of the P, pP, and sP phases strongly constrain the depth of the Lompoc earthquake to be very similar to that of the Coalinga earthquake, about 10 kilometers. Figure 2-22 shows the comparison between recorded SV and SH seismograms and synthetic seismograms calculated using the model developed from the P-wave data. The closeness of fit confirms the selected source model. The uncertainty in strike and dip is about 5 degrees, with somewhat larger uncertainty in rake. The preferred mechanism shown at the bottom of Figure 2-20 explains the regional seismograms (discussed next) quite well.

Regional Seismograms of the Lompoc Earthquake. Modeling regional seismograms is considerably more difficult than modeling teleseismic waveforms because of the complications of the crustal waveguide. However, by removing the shorter wavelengths, it becomes possible to interpret the long-period Pnl phase at the beginning of the seismograms. The details on the construction of these synthetic waveforms are discussed by Helmberger and Engen (1980) and Wallace and Helmberger (1982).

The gains of the regional instruments that operated in California and Arizona in 1927 were low enough that the Lompoc earthquake P waves

were recorded on scale. The data were digitized from Byerly (1930) because the original seismograms from the Berkeley, Lick Observatory, and Tucson stations could not be located. Appropriate instrumental responses and characteristics were used to process the digitized data to produce the radial-component seismograms shown in Figure 2-23. The wave polarities at Berkeley and Lick are opposite even though the stations differ by only 10 degrees in azimuth from the epicentral area, strongly constraining the mechanism solution. Synthetic seismograms covering this range of azimuths are shown in Figure 2-23 using the mechanism shown at the bottom of Figure 2-20 with the moment value of 1×10^{28} dyne-centimeters. The sharpness of the nodal crossing in the synthetics is more subdued, as seen for the Berkeley and Lick computations, than it is in the actual recordings at the three stations. The comparison between the data and the synthetics for a strike direction of 340 degrees is shown at the bottom of Figure 2-23 and is an excellent fit, further confirming the nearly pure reverse mechanism of the 1927 Lompoc earthquake.

Location of the Lompoc Earthquake. The location of the Lompoc earthquake using data from seismograms has been the subject of a considerable amount of uncertainty, as summarized by Hanks (1979). Gawthrop (1978b) used published teleseismic travel times to locate the event just off Point Sal at 34.9°N , 120.7°W (Figure 2-24). This location technique is subject to errors in clock times and variability in procedures used to pick arrival times and leads to a large uncertainty in Gawthrop's location. Hanks (1979) used S-P times of aftershocks recorded at southern California stations in determining his location off Point Arguello at 34.6°N , 120.9°W (Figure 2-24). This method assumes that the immediate aftershocks occurred at the same location as the rupture zone of the mainshock. The S-P times from the nearby Santa Barbara station range from 12 to 14 seconds with a mean value of 12.8 seconds, and appear to be unambiguous. The arc corresponding to the 12.8 second S-P distance from Santa Barbara is shown in Figure 2-24, along with arcs representing a 10-kilometer uncertainty. Byerly's (1930) S-P

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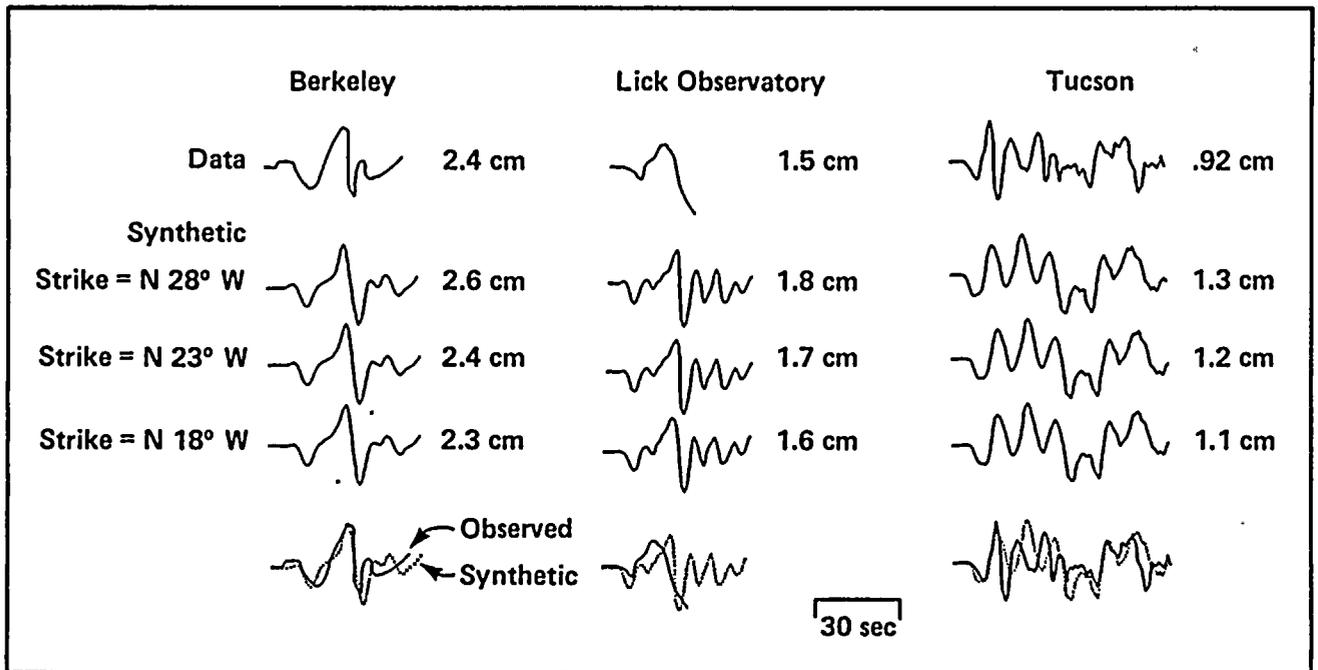
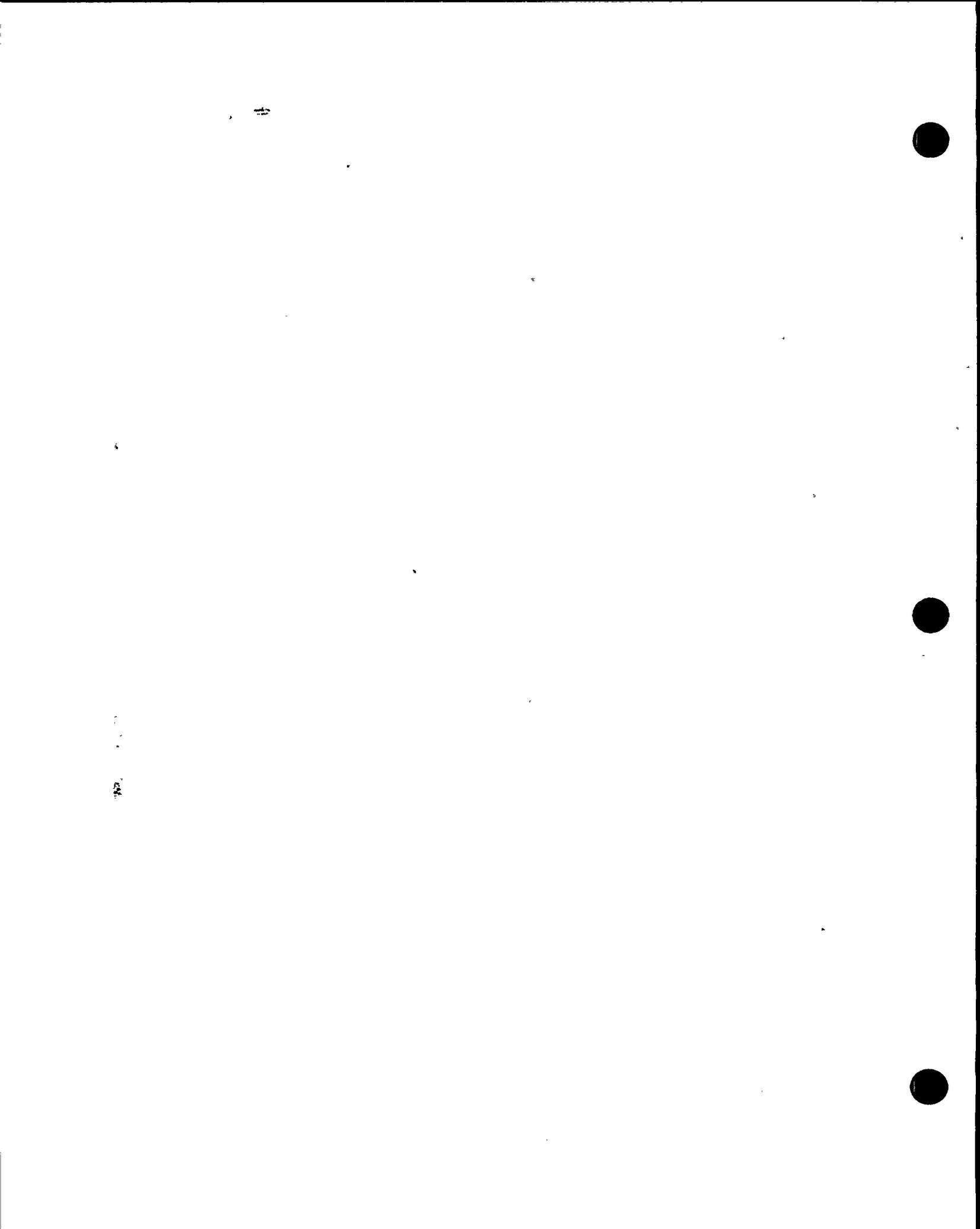
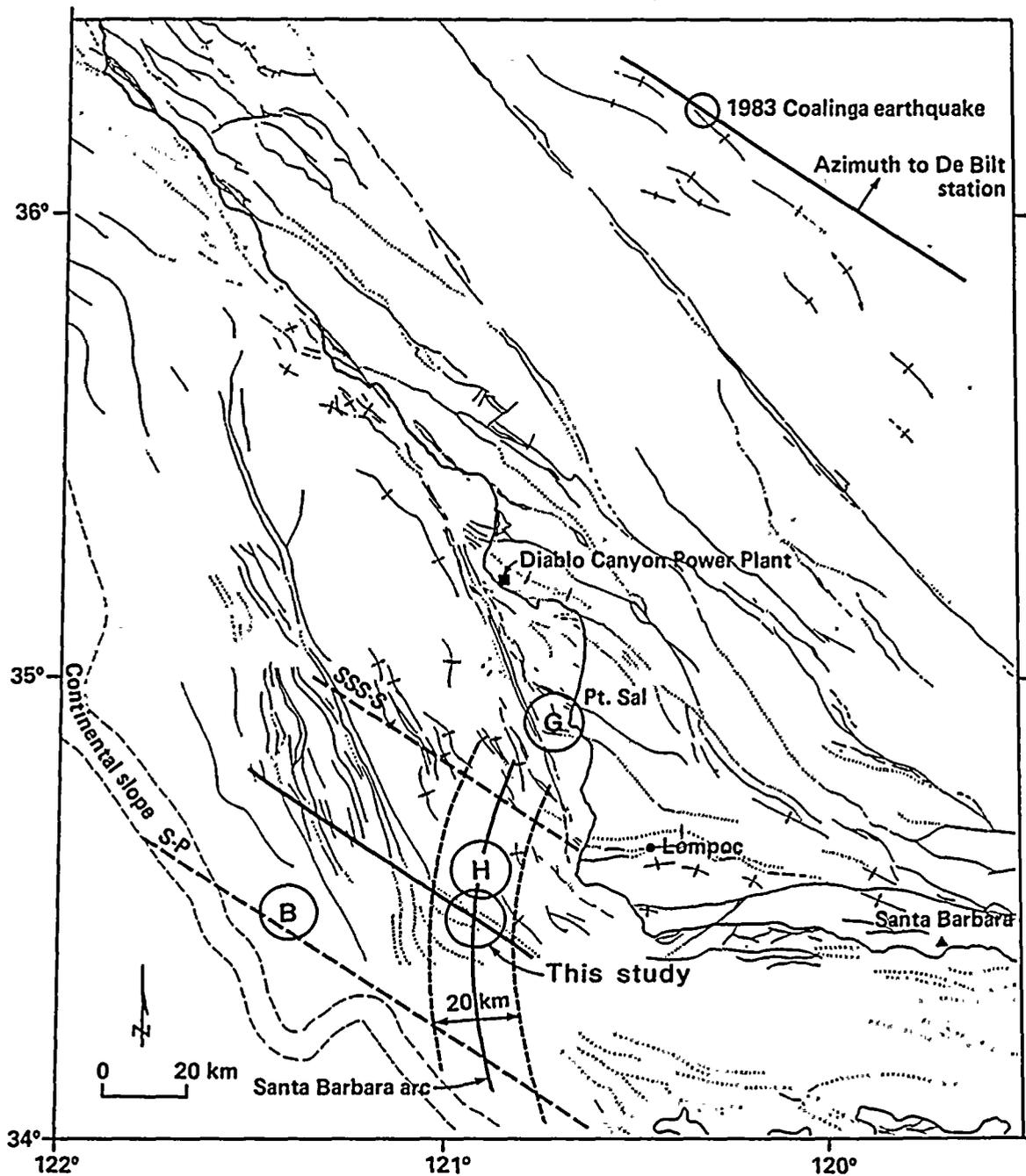


Figure 2-23

Observed radial Pnl waves at the regional stations Berkeley, Lick Observatory, and Tucson compared with synthetic waveforms for three strike directions.





EXPLANATION

1927 Lompoc Earthquake Epicenters

- (B) Byerly (1930)
- (H) Hanks (1979)
- (G) Gawthrop (1978)
- This study
- } Arcs drawn from De Bilt and Santa Barbara seismograph stations

NOTE: Base map explanation provided on Plate 3.

Figure 2-24

Constraints on 1927 Lompoc earthquake location from De Bilt P, S, and multiple S phases compared with 1983 Coalinga earthquake location and from S-P times for aftershocks recorded at Santa Barbara.

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times for the mainshock at Berkeley are more uncertain than those for aftershocks at Santa Barbara because of the emergent behavior of P and S. Consideration of the regional S-P data results in greater uncertainty in the latitude than in the longitude of the location. Byerly's location of the event is also shown in Figure 2-24.

The high quality of the De Bilt teleseismic records allows us to obtain additional constraint on the latitude of the location. The similarity in waveforms between the Coalinga and Lompoc seismograms at De Bilt, which is due to their similarity in mechanism, depth, and seismic moment, allows accurate estimation of S-P and SSS-S times by overlaying and aligning the waveforms. The difference between S-P times at De Bilt for Coalinga and Lompoc is 10 ± 1 seconds, which corresponds to a difference in distance of approximately 220 kilometers. The difference between SSS-S times is 9 ± 2 seconds which corresponds to a difference in distance of approximately 165 kilometers. The difference between these two estimates may be attributable to their different dependence on focal depth and source finiteness. The two distance estimates and their average are shown as two dashed arcs and one solid arc in Figure 2-24. The solid arc intersects the Santa Barbara S-P arc at 34.5° N, 120.9° W, approximately 40 kilometers west of Point Conception and quite close to the Hanks (1979) location. Although the De Bilt record analysis still has uncertainty in constraining the latitude of the earthquake location, a location as far north as Point Sal substantially violates the De Bilt S-P observation.

Further constraints on the location of the Lompoc earthquake come from observations of the effects of the earthquake. Topozada and Parke (1982) reviewed the intensity observations for the 1927 event. They concluded that the small size of the area experiencing intensity VI or greater is not consistent with a location near the coast. They chose a location arbitrarily equidistant between the locations of Gawthrop (1978b) and Hanks (1979). Topozada and Parke (1982) also noted that the intensity data indicate that the instrumental magnitude value should be less than 7.5.

The tsunami accompanying the 1927 event was not only observed along the California coast (Byerly, 1930) but was recorded at Honolulu and Hilo (McCulloch, 1985). McCulloch (1985) argues that submarine landsliding can probably be eliminated as a cause of the tsunami due to a lack of areas offshore of Point Arguello that have had appreciable downslope movement and due to doubts that such slides could generate transoceanic tsunamis. The tectonic generation of a tsunami is favored by the dip-slip focal mechanism found for the 1927 event. The location of the earthquake determined in this study (Figure 2-24) is in an area where the water depth ranges from 300 to 800 meters. Such substantial water depths are needed to generate a transoceanic tsunami, thus favoring the epicentral location west of Point Arguello and further precluding one near Point Sal.

The location constraints discussed above place the event in the compressive tectonic domain (Figure 2-10) of northwest-striking faults and folds significantly west of the Hosgri fault zone. The epicentral region lies west of the southern extension of the Lompoc structure as it trends past Point Arguello and to the east of the southern end of the Santa Lucia Bank fault. The epicentral area, about 25 kilometers offshore, has been mapped with limited geophysical data since the area lies west of areas of recent petroleum interest. Regional structural trends in this area vary from northwest to north-northwest and are characterized by folding and faulting, in reasonable consistency with the compressional Lompoc earthquake focal mechanism. Along the strike of these structures to the northwest there is evidence for low-level, late-Quaternary deformation. The cumulative evidence for the location of the Lompoc earthquake as discussed herein clearly does not permit the recently referenced location near Point Sal (Gawthrop, 1975, 1978b; Topozada and others, 1978; Real and others, 1978; California Division of Mines and Geology, 1981; Goter, 1988) and stated or potential association with either the Hosgri fault zone or faults associated with the Casmalia block.

Magnitude of the Lompoc Earthquake. The magnitudes of large earthquakes that occurred in the first half of this century have been the subject

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of intensive reevaluation during the past decade. In particular, Geller and Kanamori (1977) reviewed the procedures used by Gutenberg and Richter to estimate magnitudes and concluded that their original estimates of surface wave magnitudes are equivalent to the 20-second surface wave magnitude M_s based on present-day standard long-period instruments. These original estimates are found in the worksheets of Gutenberg and Richter, which have recently been archived by the Millikan Library at the California Institute of Technology.

The worksheet for the Lompoc earthquake showed ten estimates of long-period body-wave (M_B) magnitude obtained from five different stations; the average value is 7.3. Seven estimates of surface wave magnitude were given, which yielded an average value of 7.0.

Gutenberg and Richter (1956) subsequently introduced "unified magnitude," which was calculated from a weighted average of long-period body wave and surface wave magnitudes, with the ratio of weighting between these being three to one. The revised magnitude of the Lompoc earthquake became 7.3, reflecting the large weight given to the larger body wave magnitude. However, as pointed out by Geller and Kanamori (1977), this revised magnitude does not correspond to the 20-sec surface wave magnitude that is usually used to describe the magnitudes of large earthquakes; whereas the original surface wave magnitude measurement by Gutenberg and Richter does correspond to M_s . This indicates that the surface wave magnitude of the Lompoc earthquake is 7.0.

The surface wave magnitude of the Lompoc earthquake relative to that of the Coalinga earthquake can be estimated by taking the ratio of peak surface wave amplitudes averaged over the two horizontal components of the De Bilt seismograms. The ratio of approximately 4 yields an M_s difference of 0.6 unit, giving an M_s estimate of 7.1 for the Lompoc earthquake based on the M_s of 6.4 for the Coalinga earthquake. This estimate is nearly the same as the value of 7.0 measured by Gutenberg and Richter from eight teleseismic stations.

The seismic moment of the Lompoc earthquake estimated from the De Bilt seismograms can be used to calculate the moment magnitude. Using the relation of Hanks and Kanamori (1979), the moment magnitude is found to be 6.6, somewhat less than the M_s of 7.0.

Conclusions. The focal mechanism, focal depth, and location of the 1927 Lompoc earthquake have been established based on a comparison with the 1983 Coalinga earthquake, using seismograms from the continuously recording station at De Bilt, Netherlands. The mechanism is nearly pure dip slip on a plane striking N20° W and dipping 66° NE, and the focal depth is 10 kilometers. The seismic moment is estimated to be 1×10^{26} dyne-centimeters, corresponding to a moment magnitude of 6.6. The surface wave magnitude of the earthquake, as measured by Gutenberg and Richter, is confirmed to be 7.0 rather than 7.3 as estimated by earlier studies.

The 1927 earthquake is located in the compressional tectonic domain offshore of Point Arguello, near 34.5° N, 120.9° W. The 1927 earthquake is clearly not located near Point Sal, nor is it located along the Hosgri fault zone.

UPDATE OF INSTRUMENTAL SEISMICITY

Since the beginning of seismographic operation in California in 1887 at UC Berkeley and the Lick Observatory on Mount Hamilton, improvements in instrumentation and increases in numbers of stations have improved the accuracy of location of earthquakes in the state and have reduced the magnitude threshold of earthquake detection and location. Bolt and Miller (1975) and Hileman and others (1973) have summarized the seismographic station history in northern and southern California, respectively, through the early 1970's. Major changes in the seismographic operation occurred in 1927-30 with the installation of Wood-Anderson seismographs at many stations and in the 1950's and 1960's with the installation of higher-magnification instruments and the construction of many new stations. The data base derived primarily from recordings made by these stations constituted the regional seismicity data for south-central coastal California presented in the Diablo Canyon FSAR (Pacific Gas and Electric

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Company, 1974) through 1972. However, the seismographic coverage of this region was provided by stations located at distances of a hundred kilometers or more from the region. In 1966, for example, the closest seismograph to the Hosgri fault zone was 75 kilometers to the northeast of San Simeon.

In the mid to late 1960's, the U.S. Geological Survey installed a rapidly increasing number of telemetered, high-gain, vertical-component seismographic stations. This network growth was focused during the first years on the greater San Francisco Bay Area, but by the early 1970's geographic coverage had substantially expanded to the northwest and southeast along the San Andreas fault and in the Coast Ranges. Figure 2-25 shows the present-day distribution of U.S. Geological Survey, PG&E, Caltech, and UC Berkeley seismographic stations operating in California between Monterey Bay and the Santa Barbara Channel along with a histogram showing the number of stations operating each year since 1966 within the south-central coastal area that is more than 20 kilometers from the San Andreas fault (shown as the outlined region in Figure 2-25.) The major features of this recent seismographic history are as follows:

- The first stations installed within the coastal region began operation during 1969, but did not substantially improve coverage of the coastal region near the San Luis/Pismo block. The primary focus at that time and for much of the following decade was the San Andreas fault rather than adjacent areas.
- Earthquake detection and location within the coastal region was significantly improved with the stations installed in 1978 and 1979. By the start of 1980, the detection threshold and location accuracy in the coastal region, particularly in the northern half of the region, were comparable to those of other regional networks in northern and southern California.
- Between December 1980 and mid-May 1981, the U.S. Geological Survey operated twelve portable seismographs within the coastal region outlined in Figure 2-25. These instruments collected dual-gain,

three-component data to supplement the permanent network stations. Six sites were occupied during 1980, with a total of 12 sites occupied in 1981. The duration of recording was typically several months or longer at each site (Mutch, 1983).

- Using the experience gained during the 1980-81 temporary study, the U.S. Geological Survey installed additional station sites during the period 1982-1984. In 1985, a small, closely-spaced dense array of stations was operated near the Arroyo Grande oilfield south of San Luis Obispo.
- In 1986 the PG&E Central Coast Seismic Network started operation. This network greatly supplemented the U.S. Geological Survey data collection for the coastal region by reducing the magnitude detection to near magnitude 1.0 and by increasing the accuracy of hypocenter and focal mechanism calculations. PG&E stations were installed in 1986 and 1987, with two additional sites occupied in 1988. Five of the PG&E stations installed at the coast were dual-gain three-component stations, which improved earthquake location and focal depth resolution in the near offshore region.

The two most significant changes in seismic network coverage of the coastal region shown in Figure 2-25 occurred in 1980 when the coastal zone station density increased substantially and 1987 when the PG&E Central Coast Seismic Network reached full operation. These dates were chosen as break points for displaying the seismicity data from 1973 on.

1973-1979. Computerized earthquake catalog files were obtained from the U.S. Geological Survey and the California Institute of Technology for this time interval. Since each institution operated independent stations and computed earthquake locations and other parameters independently, the two data files contained duplicate listings for many earthquakes in the central part of the region. The duplicates were removed by examining the cataloged events that were located between north latitudes 35°N and

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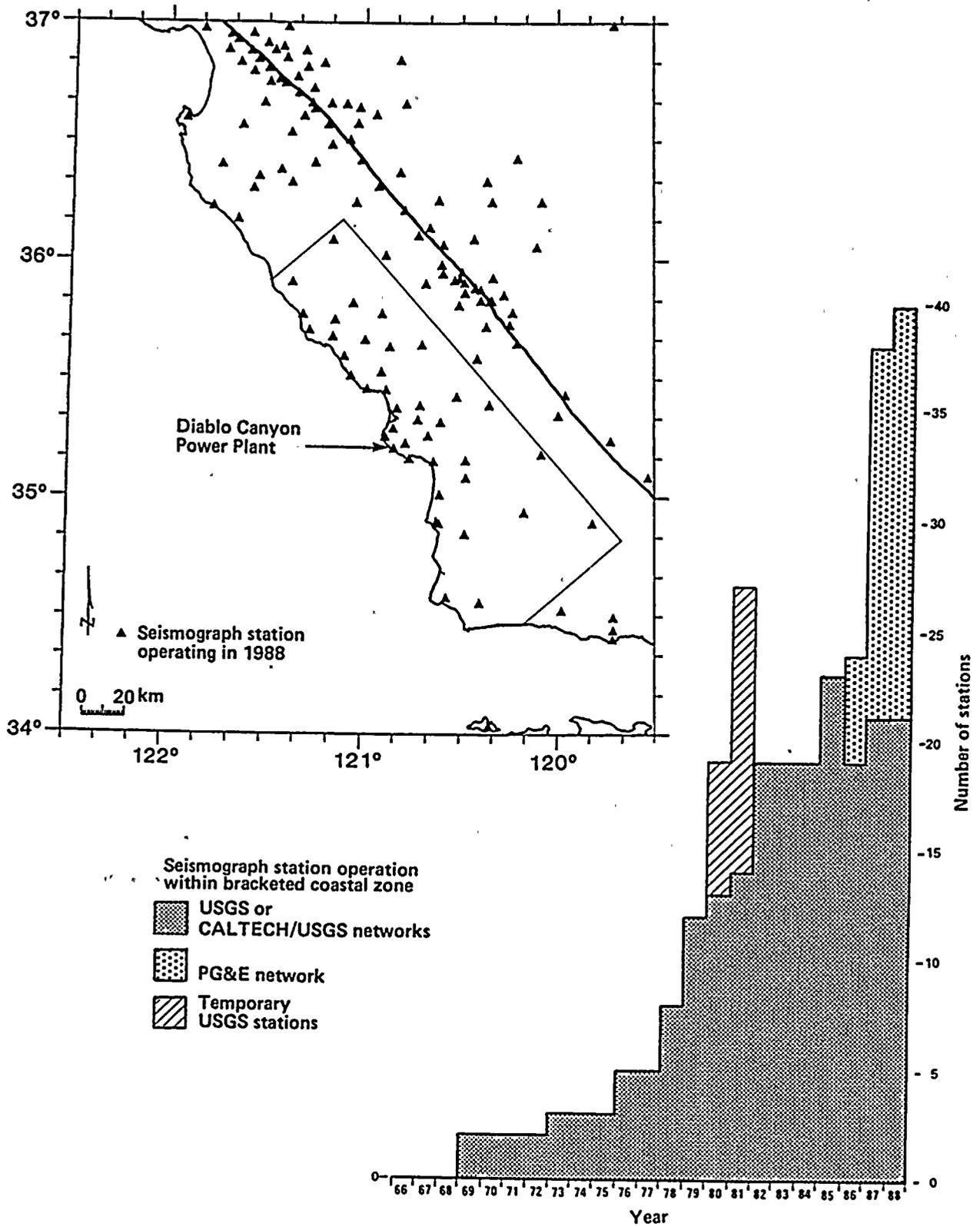


Figure 2-25

Map of U.S. Geological Survey, PG&E, California Institute of Technology, and U.C. Berkeley seismograph stations for 1988, and histogram of number of stations operating per year from 1966 in the outlined coastal zone shown in the map.

35°50'N. For events for which duplicate catalog entries existed, determined by comparing origin times, the better-quality location was chosen. In general, we found that the routine U.S. Geological Survey cataloging practices did not include events that were very far outside of their network, so when duplicates were found within the above latitude boundaries the better location tended to be the U.S. Geological Survey location. For events located north of the latitude band searched for duplicates, we used only the U.S. Geological Survey data set. For events south of the latitude band, we used only the California Institute of Technology data set.

The resulting combined data set is plotted in Figure 2-26. Although duplicate events have been removed, there are two sources of non-uniformity in Figure 2-26 that must be recognized.

- During the 1970's, arrival time, amplitude, and duration data were not routinely exchanged between the central and southern California networks. Thus for earthquakes that occurred in the south-central coastal area, which lies outside of both the networks, the cataloged hypocentral data are generally less accurate than the locations that could be derived by combining the data sets. Savage and McNally (1974), Smith (1974), and Gawthrop (1975), used combined phase data to relocate earthquakes in this region prior to the early to mid 1970's (several of their relocations of larger events are noted in Table 2-6).
- Earthquake magnitude values are not uniformly assessed within the region due to differing procedures used for the two networks and due to the lack of routine data exchange. Habermann and Craig (1988) have also pointed out the temporal nonuniformity of U.S. Geological Survey-determined magnitude values in central California. The southern California network catalog in particular contains a modest number of earthquakes for which no magnitude value has yet been determined. These events are seen in Figure 2-26 as the relative increase in

numbers of events shown with magnitude 0.0 to 1.0 south of 35°50'N latitude. Most of these events should be considered to have magnitudes between about 1.5 and 2.5, sufficiently large for them to be located using the southern California network.

1980-May 1988. Computerized earthquake catalog files for the period January 1, 1980, through May 31, 1988, were obtained from the U.S. Geological Survey in Menlo Park and the U.S. Geological Survey/California Institute of Technology in Pasadena for this time period. A similar procedure as used for the 1973-1979 interval was applied to a slightly different area to remove duplicates from the two catalogs. The resulting combined data set is shown in Figure 2-27. Station data from the area between the two networks began to be routinely shared in January 1981. This provided an overall improvement in location accuracy for the coastal zone and offshore to the west. The increased numbers of magnitude 0.0-to-1.0 events seen south of latitude 35°50'N reflects the presently incomplete magnitude analysis of some earthquake data in the southern California network, as noted above.

October 1987-May 1988. The earthquake catalog for this time period was refined using the data recorded by the Central Coast Seismic Network. Readings obtained from the PG&E network were augmented by selected phase data from U.S. Geological Survey and California Institute of Technology stations to produce a single integrated catalog of hypocentral data. This data set is shown in map view in Figure 2-28. For about a year prior to October, 1987, the level of seismic activity in the coastal region near the Diablo Canyon site from San Luis Obispo Bay north to Estero Bay was very low. The first five PG&E stations were installed in this area, but data from only a few events were obtained due to the reduced level of activity. These data are included in the detailed study of the seismicity of the San Luis/Pismo structural block discussed below.

Routine data analysis for the Central Coast Seismic Network proceeds as follows:

- Continuous telemetry of data from the field stations is monitored in the PG&E General



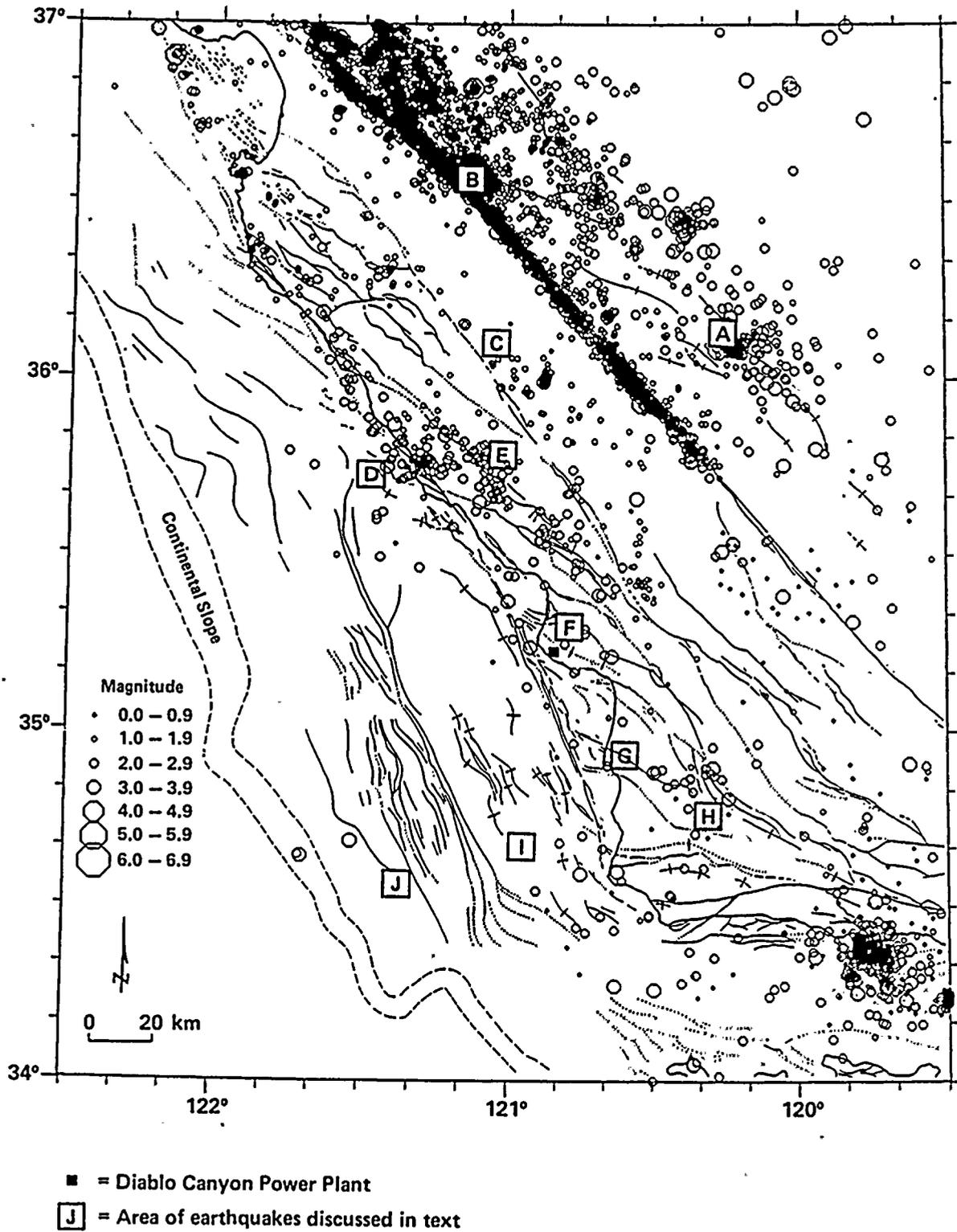
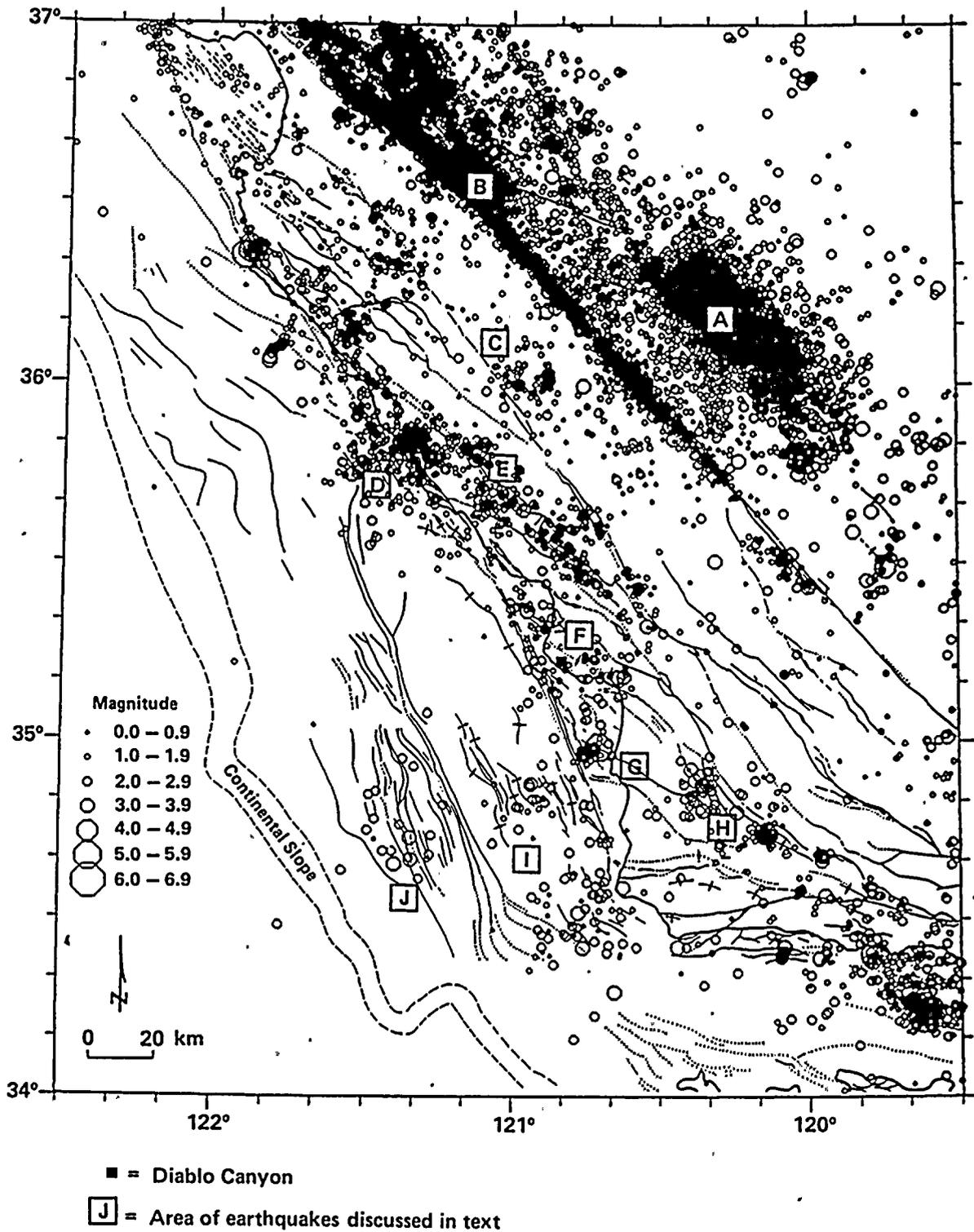


Figure 2-26

Seismicity data from U.S. Geological Survey and California Institute of Technology, January 1, 1973, through December 31, 1979.

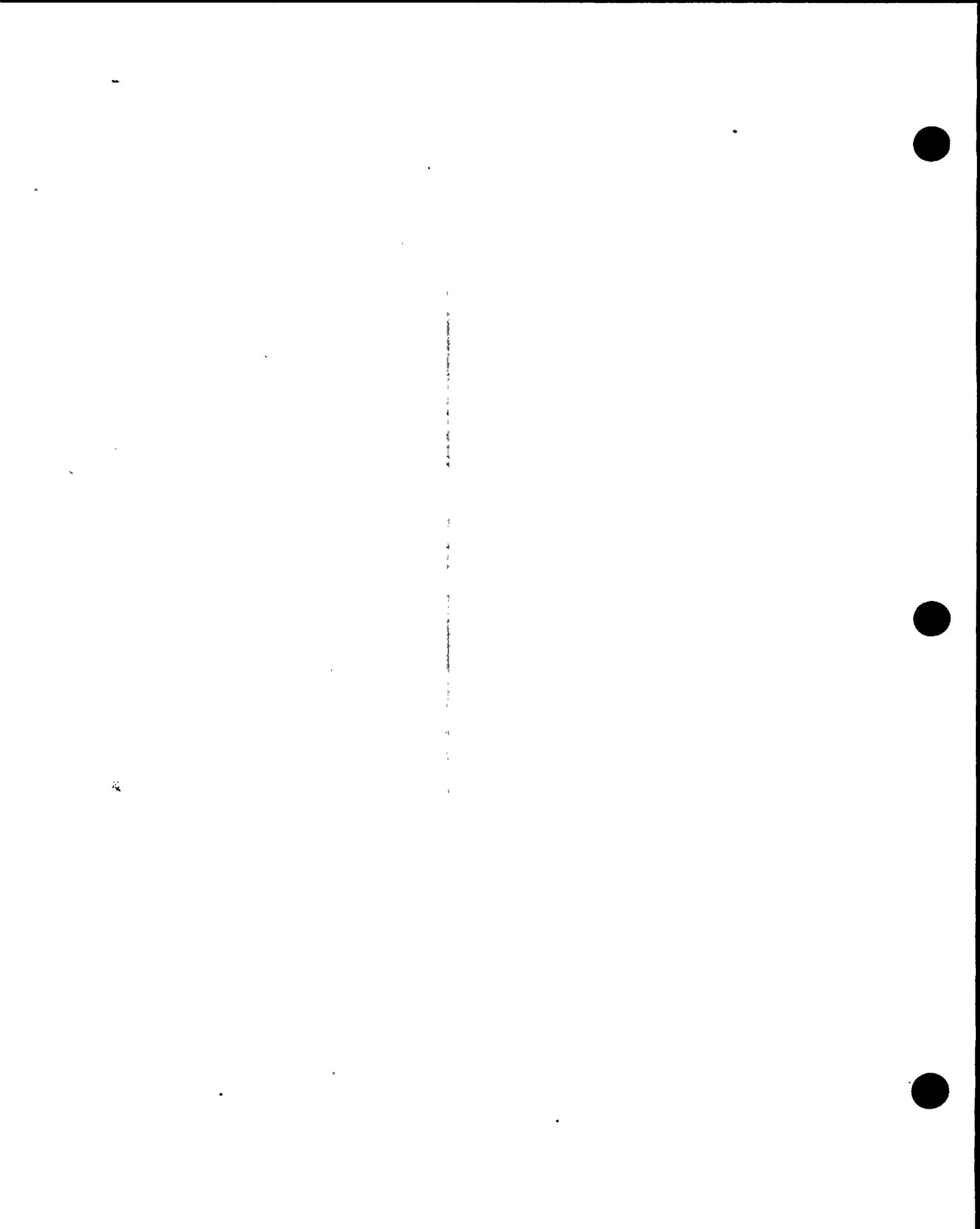


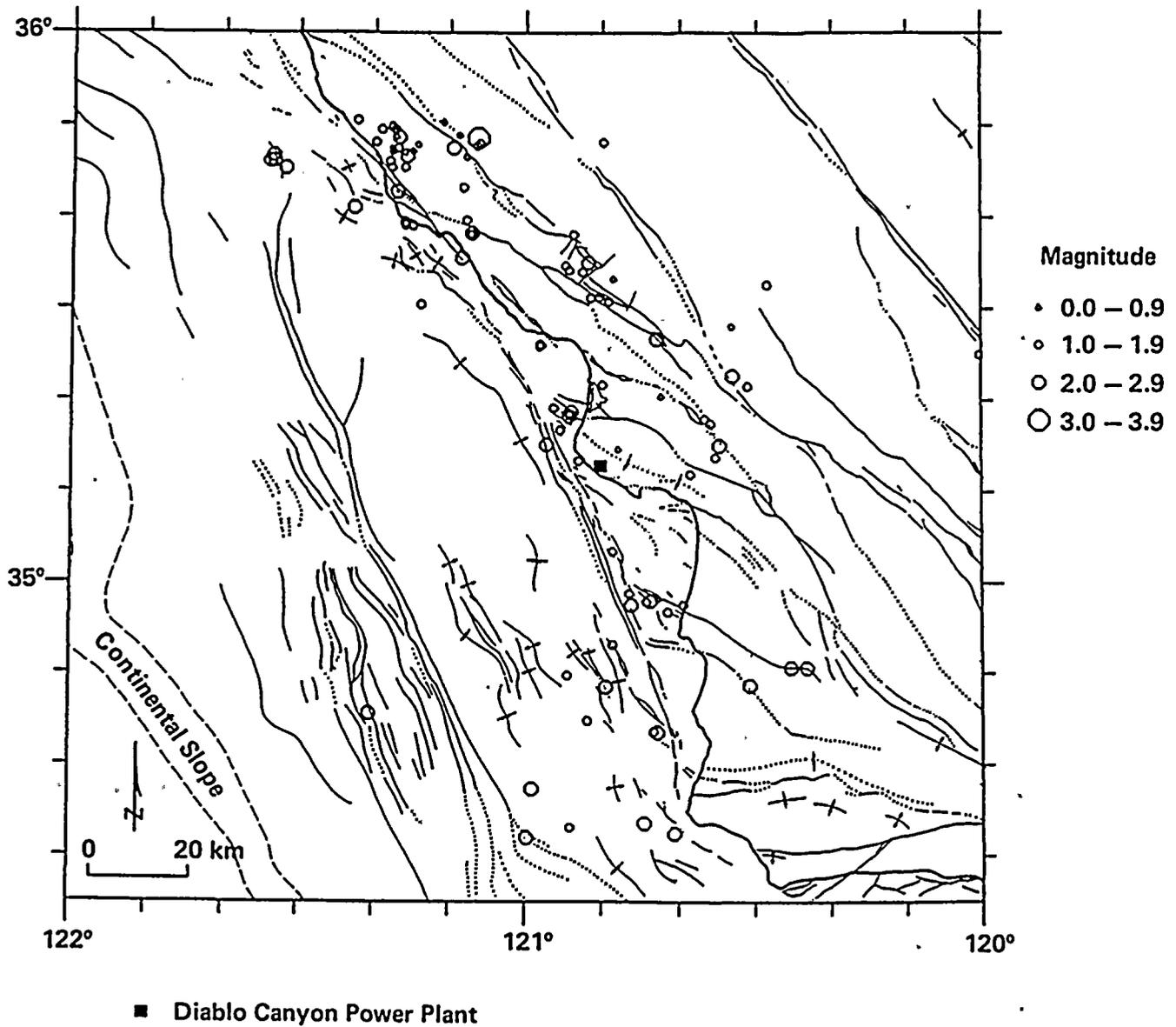


NOTE: Base map explanation provided on Plate 3.

Figure 2-27

Map of seismicity data from the U.S. Geological Survey and California Institute of Technology, January 1, 1980, through May 31, 1988.





NOTE: Base map explanation provided on Plate 3.

Figure 2-28

Map of seismicity data from the PG&E Central Coast Seismic Network, October 1, 1987, through May 31, 1988.

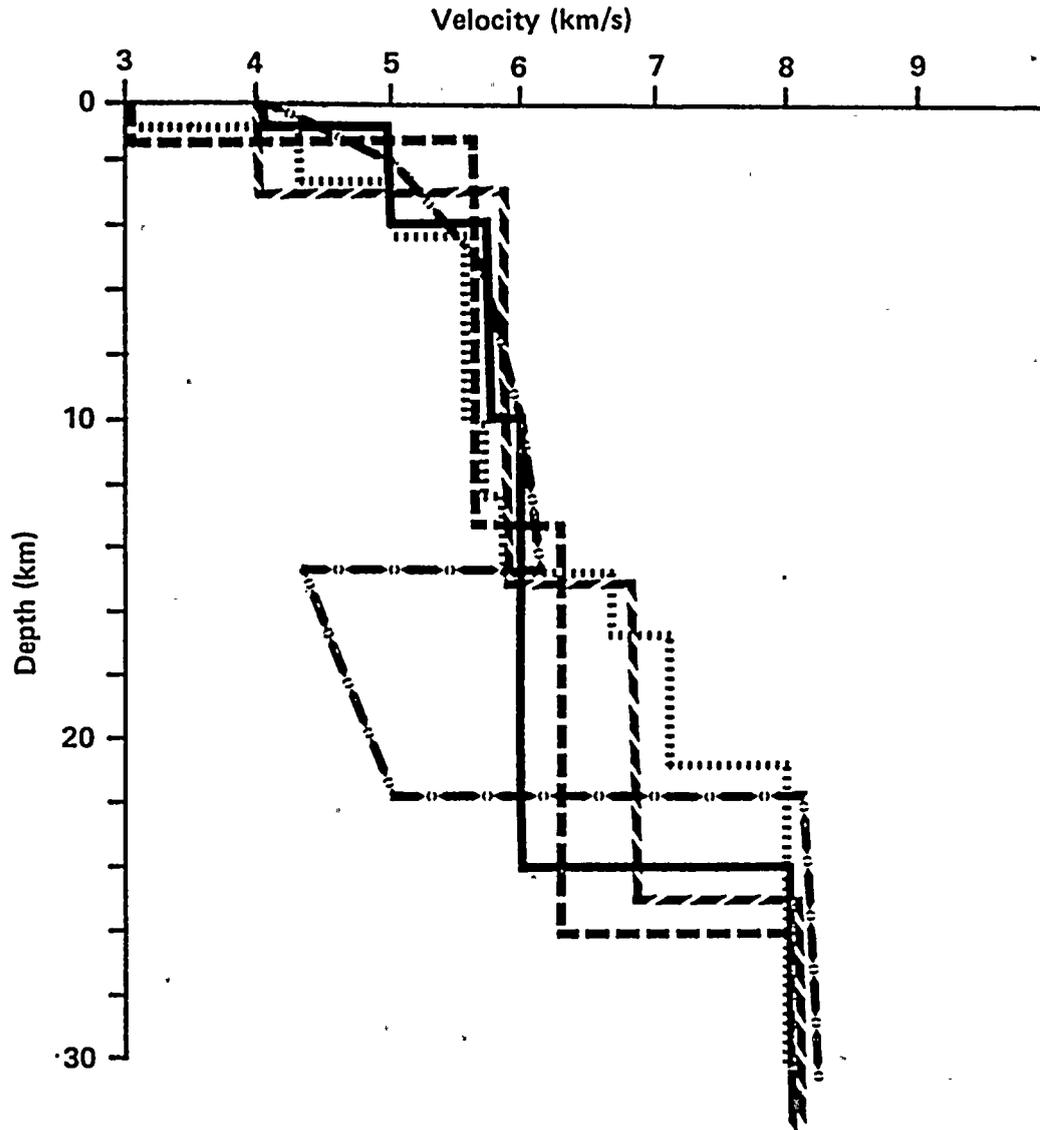
Office by an online computer system (the FROG system designed by NEWT, Inc.). An earthquake detection algorithm monitors the digitized telemetry channels in subnet and full net combinations to detect and store any data potentially representing earthquakes. All detected events are also transmitted by ETHERNET to a seismic workstation for post-event processing (Tull, 1984). A computerized telephone alert is issued for system malfunctions and for larger triggering events.

- The status of the system is monitored and a preliminary analysis on all detected events is performed. Earthquakes within or adjacent to the network are located, magnitude values are calculated, and the data are archived. In an average month, about 175 triggers are stored, consisting of 110 noise events, 50 regional or teleseismic events, and 15 earthquakes occurring near or within the network.
- For all local earthquakes, readings are sought from the U.S. Geological Survey in Menlo Park and at the California Institute of Technology to augment the PG&E readings. These data are incorporated in the routine location procedure using the program HYPOELLIPSE (Lahr, 1984). Stations more distant than 100 kilometers from the hypocenter are typically not used in the locations. First-motion data are examined for all events, and focal mechanisms are computed when adequate data exist using the program FPFIT (Reasenber and Oppenheimer, 1985).
- Earthquake locations and focal mechanisms are computed using two velocity models for the region. The first is a Franciscan-basement model provisionally developed from the 1980-81 U.S. Geological Survey temporary network operation by A. Lindh (Mutch, 1981). We also use a more detailed model derived from the deep crustal studies (Figure 2-9). These two models are shown in Figure 2-29 along with several other regional velocity models for central California. In most cases there are no appreciable

differences in earthquake locations or focal mechanisms produced by differences in the velocity model used since the close-in station density is usually high and since there are no significant lateral velocity variations identified in the seismogenic crust between the Nacimiento fault zone and as far offshore as the Santa Lucia Bank. However, for earthquakes whose hypocenters are near a vertical velocity contrast in a particular model, the associated focal mechanism may not be well constrained. The relatively well constrained focal mechanism data set that results from this evaluation is shown in Figure 2-30 for the October 1987-May 1988 period. Magnitude values for these events range from 0.9 to 2.3.

On the basis of monitoring the PG&E network operation, the detection threshold within the central part of the network and extending about 10 kilometers offshore is judged to be about magnitude 1.0, while for far-offshore areas and near the north and south ends of the network it is about magnitude 1.8. These detection levels are non-uniform, which is reflected in the graph of cumulative number versus magnitude for the catalog (Figure 2-31). The PG&E magnitude values have been calibrated to U.S. Geological Survey coda magnitude values, but are subject to a variety of small biases and variations (Habermann and Craig, 1988). Figure 2-31 also shows the U.S. Geological Survey data set for the period January 1984 through May 1988 for comparison. The curve for the PG&E network shows an inflection near magnitude 1.8, indicating the lack of detection of events as noted above. There is another inflection point near magnitude 1.0 representing the lower detection limit of the network that is governed by noise conditions along the coast. For the U.S. Geological Survey network the magnitude detection threshold is about 1.7. The slope of the curve (b-value) for events larger than 1.7 is about 1.1, similar to that for the PG&E data set (1.2). The short-term microearthquake study done by the U.S. Geological Survey in the area (Mutch, 1981) obtained a b-value for several hundred events of 0.85. Such variations in small catalogs is common. Regional studies of the



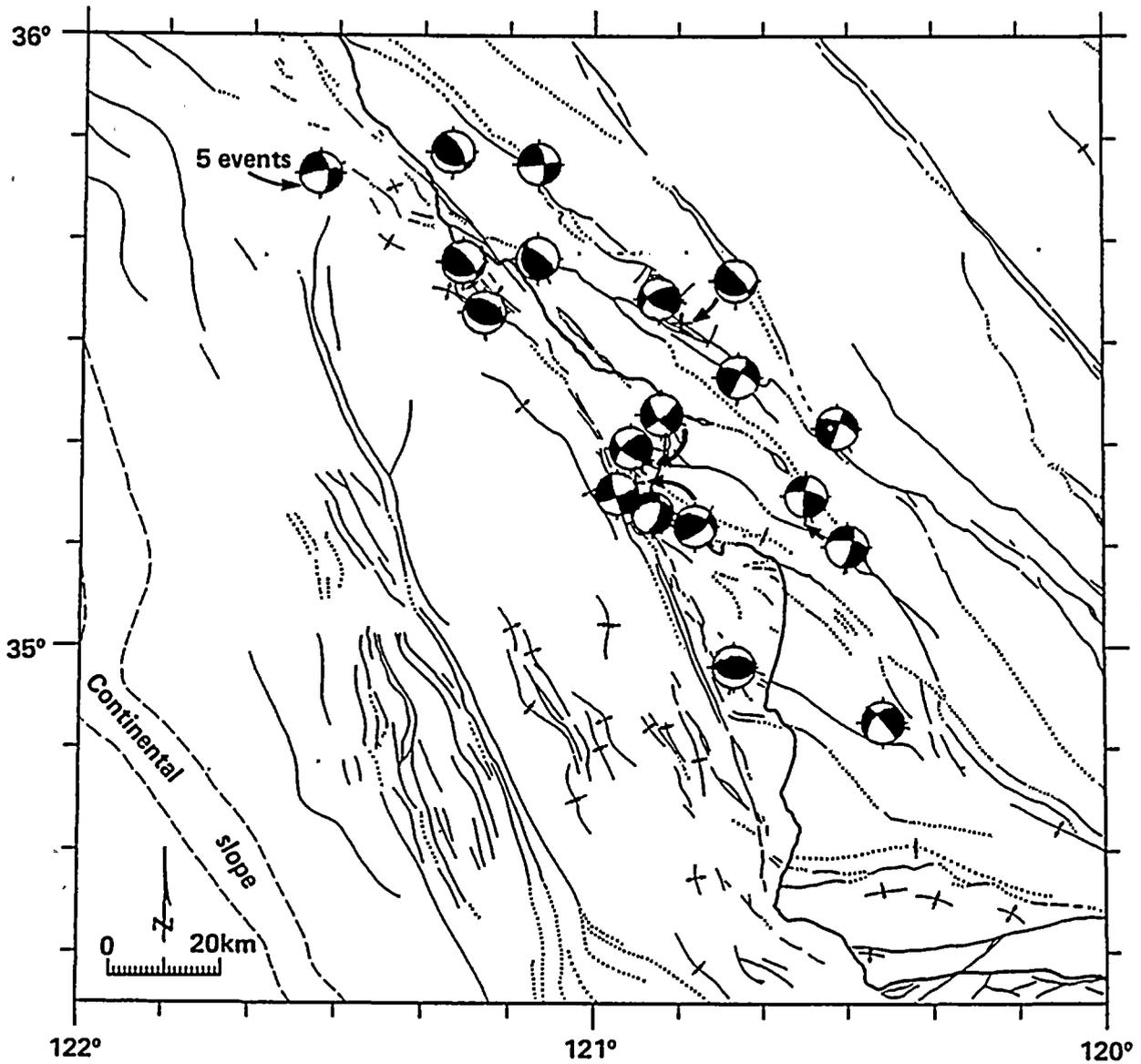


EXPLANATION	
	Mutch (1981)
	Eaton (1984)
	Trehu and Wheeler (1987)
	USGS (1987)
	PG&E (this report)

Figure 2-29
Crustal velocity models for the south-central Coastal California region.



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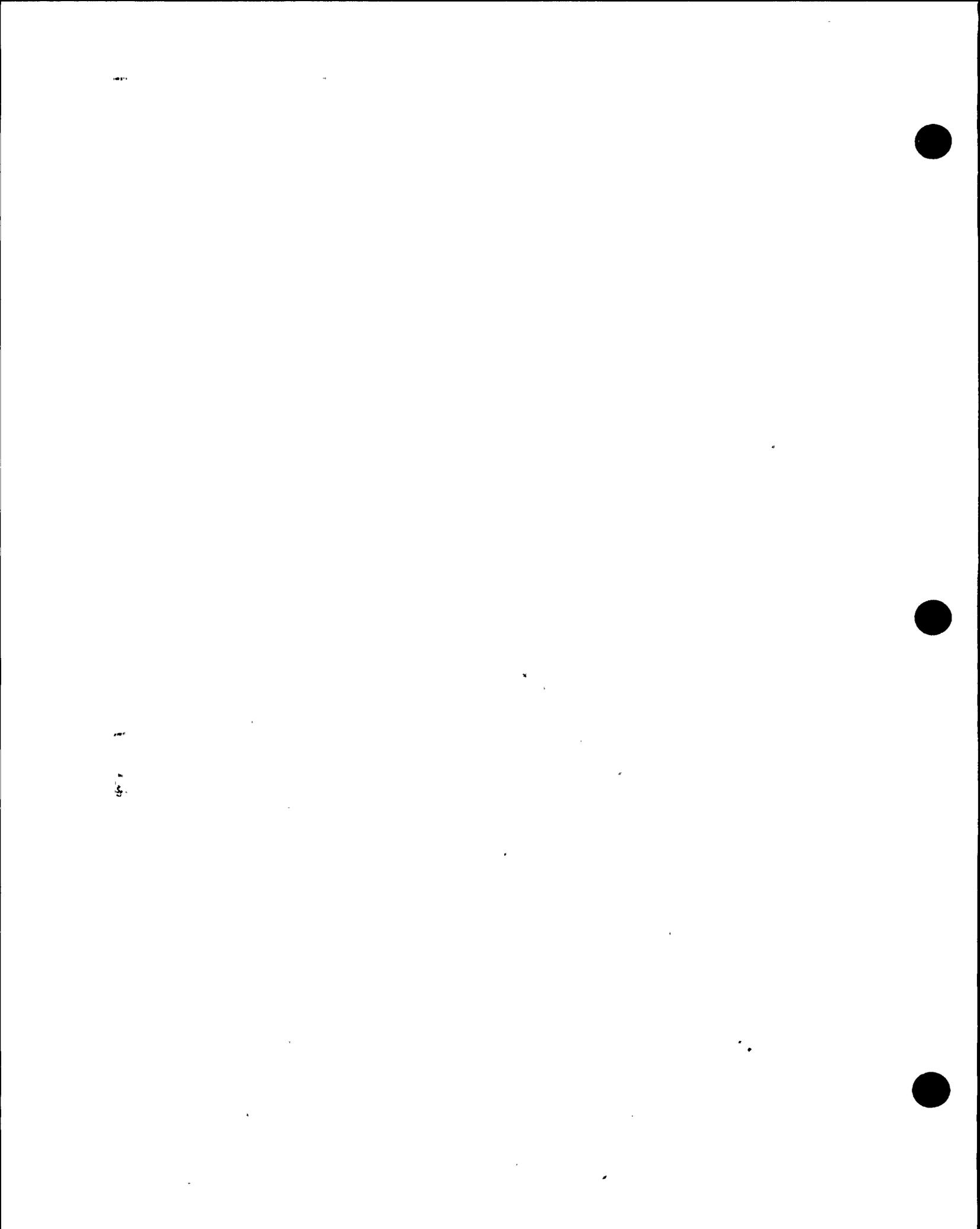
EXPLANATION

-  Lower hemisphere first motion plots
- White — Dilation
- Black — Compression

NOTE: Base map explanation provided on Plate 3.

Figure 2-30

Focal mechanisms calculated using Central Coast Seismic Network data for the period October 1, 1987, through May 31, 1988. The events shown range in magnitude from 0.9 to 2.3.



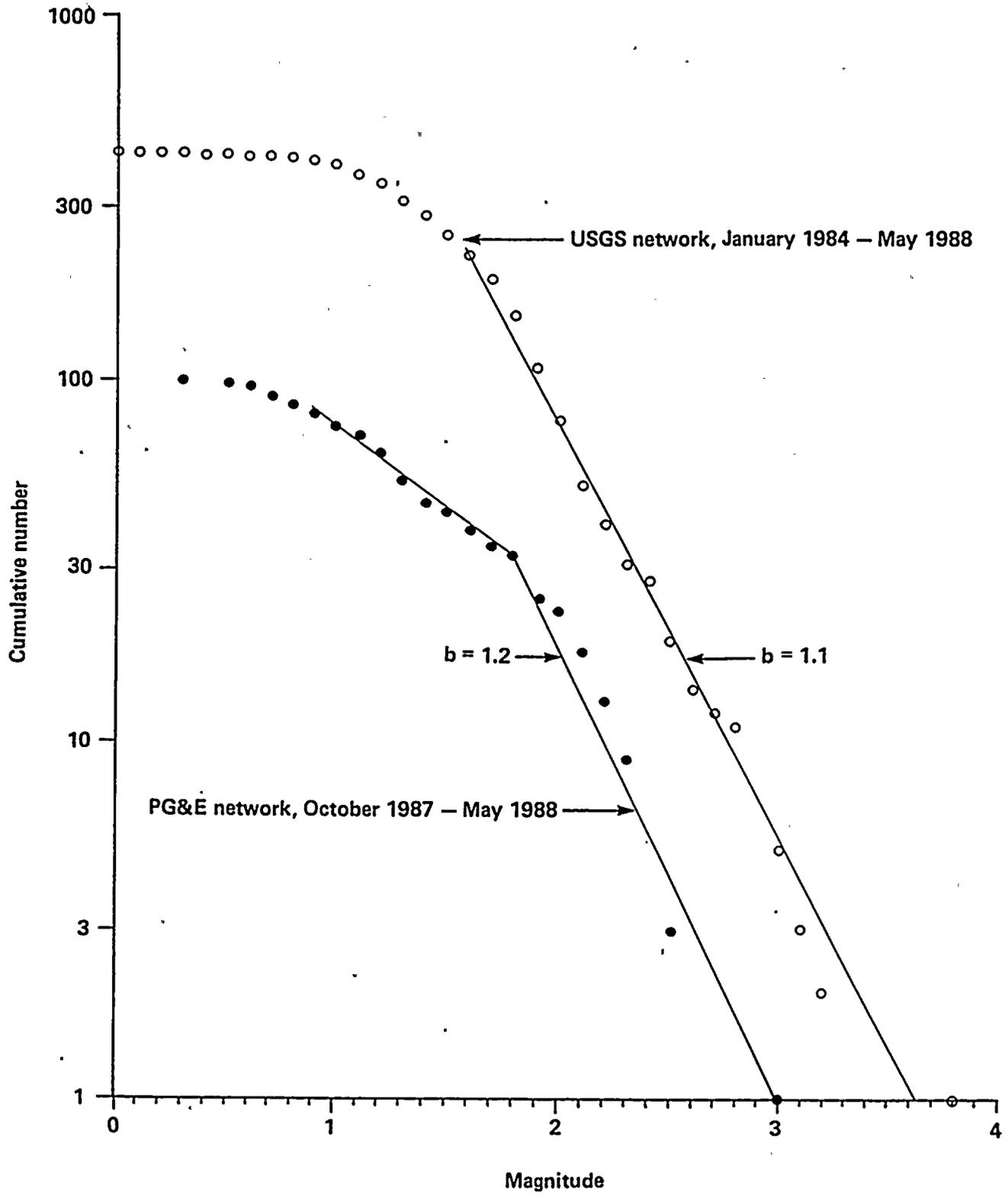


Figure 2-31
Cumulative number of earthquakes of magnitude M and greater for south-central coastal California.

entire catalog of historical and instrumental events within the central Coast Ranges find b -values to be about 0.8 to 0.9 (for example, Uhrhammer, 1985). The increased sensitivity of the PG&E network has resulted in 100 events being recorded during the same time interval in which the U.S. Geological Survey network recorded 40 earthquakes. These additional data for a relatively short time interval have provided significant additional data to the following analysis.

Analysis of Seismicity Data. The suite of data presented in Figures 2-26 through 2-28 and 2-30 constitutes a very detailed and comprehensive picture of seismic activity during the past 15 years. To add to this data base we have compiled focal mechanisms within the south-central coastal California region for earthquakes of magnitude 3.0 or greater whose mechanisms have been reasonably well constrained using first-motion data or waveform modeling. These earthquakes are listed in Table 2-9 and their focal mechanisms are shown in Figure 2-32. In order to discuss key aspects of this data base, we have used a geographical sequence identified by letter codes on Figures 2-26 and 2-27 to specify the locality under consideration. Place names and fault names have generally been omitted to allow a clear view of the data. These names are shown on other figures in this chapter.

A. One of the most prominent features of the recent seismic history in central California is the mainshock-aftershock sequence of the May 2, 1983, Coalinga earthquake. This sequence is a dominant feature in Figure 2-27, but in the earlier period the same locality exhibits only scattered seismicity (Figure 2-26). Eaton (1985) has discussed details of the patterns of moderate-magnitude earthquakes preceding the 1983 event. The focal mechanism of the mainshock was nearly pure reverse/thrust faulting, as shown in Figure 2-20.

B. Another prominent regional seismicity feature is the dense alignment of small earthquakes along the San Andreas and Calaveras fault zones exhibited during the entire period from 1973 to the present. This long-recognized linear pattern has led many individuals to expect

active faults other than the San Andreas fault zone to be clearly marked by linear (or planar) patterns of small earthquakes. The fact that such patterns are the exception, not the rule, has frustrated attempts to directly use microearthquake data to map major active faults in detail. The southeastern extension of the trace of the San Andreas fault zone in Figures 2-26 and 2-27, along which virtually no microearthquake activity can be seen, serves as a prominent example of the difficulties in identifying active faults with earthquake alignments.

C. The San Ardo area along and east of the Rinconada fault has been the site of small and moderate (up to magnitude 5) earthquakes during much of this century (Dehlinger and Bolt, 1987; Poley, 1988). This seismic activity appears to be related to local geologic structure, possibly influenced by the nearby oil-field operations, rather than regional behavior of the Rinconada fault.

D. The seismic activity in the Piedras Blancas region is bounded on the east by the Nacimiento fault zone, extends to the west across the San Simeon fault zone, and diminishes off the flanks of the faulting and folding associated with the Piedras Blancas anticlinorium. This region has been the locus of ongoing moderate-level seismic activity in both the historical record of larger earthquakes (four events shown in Figure 2-18) and the recent instrumental record since 1973 (Figures 2-26 and 2-27). This region is shown in greater detail in Figure 2-33, in which the following features are noted:

- To the west of the San Simeon fault zone, earthquake activity is generally scattered and appears to be associated with the deformation within the broad basement uplift of the Piedras Blancas anticlinorium. To the south of latitude $36^{\circ}45'N$, the San Simeon fault zone serves as the eastern boundary to the seismic activity, just as it serves as the eastern limit of the Piedras Blancas anticlinorium. In the cross sections of Figure 2-33, the seismic activity dies out at a depth of about 10 to 12 kilometers.

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Table 2-9

SELECTED EARTHQUAKES FOR FOCAL MECHANISMS ($M \geq 3$)
IN SOUTH-CENTRAL COASTAL CALIFORNIA SHOWN ON FIGURE 2-32

<u>Date</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Magnitude</u>	<u>Computed Depth</u>	<u>Reference</u>
4 Nov. 1927	34.5 N	120.9 W	7.0	10.0	This report
22 Nov. 1927	35° 46.1'N	121° 08.7'W	6.2	—	Dehlinger and Bolt, 1987
25 Nov. 1952	35° 49.6'N	121° 08.2'W	4.4	—	Gawthrop, 1975
2 Mar. 1955	36° 00.6'N	120° 57.4'W	4.8	—	Gawthrop, 1977
2 Nov. 1955	35° 57.6'N	120° 54.9'W	5.1	—	Gawthrop, 1975
1 Feb. 1962	35° 01.5'N	120° 54.8'W	4.5	—	Gawthrop, 1977
6 Sept. 1969	35° 20.8'N	121° 04.7'W	3.7	—	Gawthrop, 1977
22 Oct. 1969	34° 37.4'N	121° 32.1'W	5.4	—	Gawthrop, 1977
5 Nov. 1969	34° 37.9'N	121° 26.0'W	5.6	8.0	Gawthrop, 1977; Bent and Helmberger, 1987
27 May 1970	36° 00.6'N	120° 53.1'W	3.6	—	Gawthrop, 1977
3 Oct. 1971	36° 08.0'N	121° 11.4'W	3.0	—	Gawthrop, 1977
1 Mar. 1972	35° 48.8'N	121° 24.0'W	3.6	—	Gawthrop, 1977
24 Sept. 1974	35° 09.0'N	120° 57.4'W	3.0	—	Gawthrop, 1977
21 Dec. 1976	35° 45.8'N	121° 16.5'W	3.4	4.9	Dehlinger and Bolt, 1987
13 Aug. 1976	35° 23.2'N	119° 42.6'W	5.9	11.3	Eaton, 1984

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Table 2-9 (Continued)

SELECTED EARTHQUAKES FOR FOCAL MECHANISMS ($M \geq 3$)
IN SOUTH-CENTRAL COASTAL CALIFORNIA SHOWN ON FIGURE 2-32

<u>Date</u>	<u>Latitude</u>	<u>Longitude</u>	<u>Magnitude</u>	<u>Computed Depth</u>	<u>Reference</u>
29 May 1980	34° 57.5'N	120° 45.5'W	5.1	9.2	Eaton, 1984
8 Sept. 1980	35° 44.0'N	121° 20.0'W	3.5	5.0	Dehlinger and Bolt, 1987
25 Apr. 1981	35° 47.2'N	121° 07.6'W	3.0	3.2	Dehlinger and Bolt, 1987
13 Jul. 1981	35° 47.7'N	121° 27.2'W	3.0	4.9	Dehlinger and Bolt, 1987
23 Sept. 1982	34° 52.2'N	120° 21.8'W	4.0	4.8	Eaton, 1984
28 Aug. 1983	35° 49.7'N	121° 18.4'W	3.5	6.2	Dehlinger and Bolt, 1987
29 Aug. 1983	35° 50.2'N	121° 20.7'W	5.4	6.6	Eaton, 1984
29 Aug. 1983	35° 52.4'N	121° 17.6'W	3.2	2.5	Dehlinger and Bolt, 1987
12 Apr. 1984	35° 42.2'N	121° 06.0'W	3.1	9.0	Dehlinger and Bolt, 1987
25 Oct. 1984	34° 44.3'N	120° 08.6'W	4.2	8.3	Jones, 1988
9 Sept. 1985	35° 35.5'N	120° 47.0'W	3.0	2.3	Dehlinger and Bolt, 1987
24 Nov. 1985	36° 02.3'N	120° 52.1'W	4.5	11.3	Poley, 1988
6 Nov. 1986	34° 43.9'N	120° 9.2'W	4.0	6.5	Jones, 1988
7 Dec. 1986	35° 22.0'N	120° 56.7'W	3.2	6.5	This report

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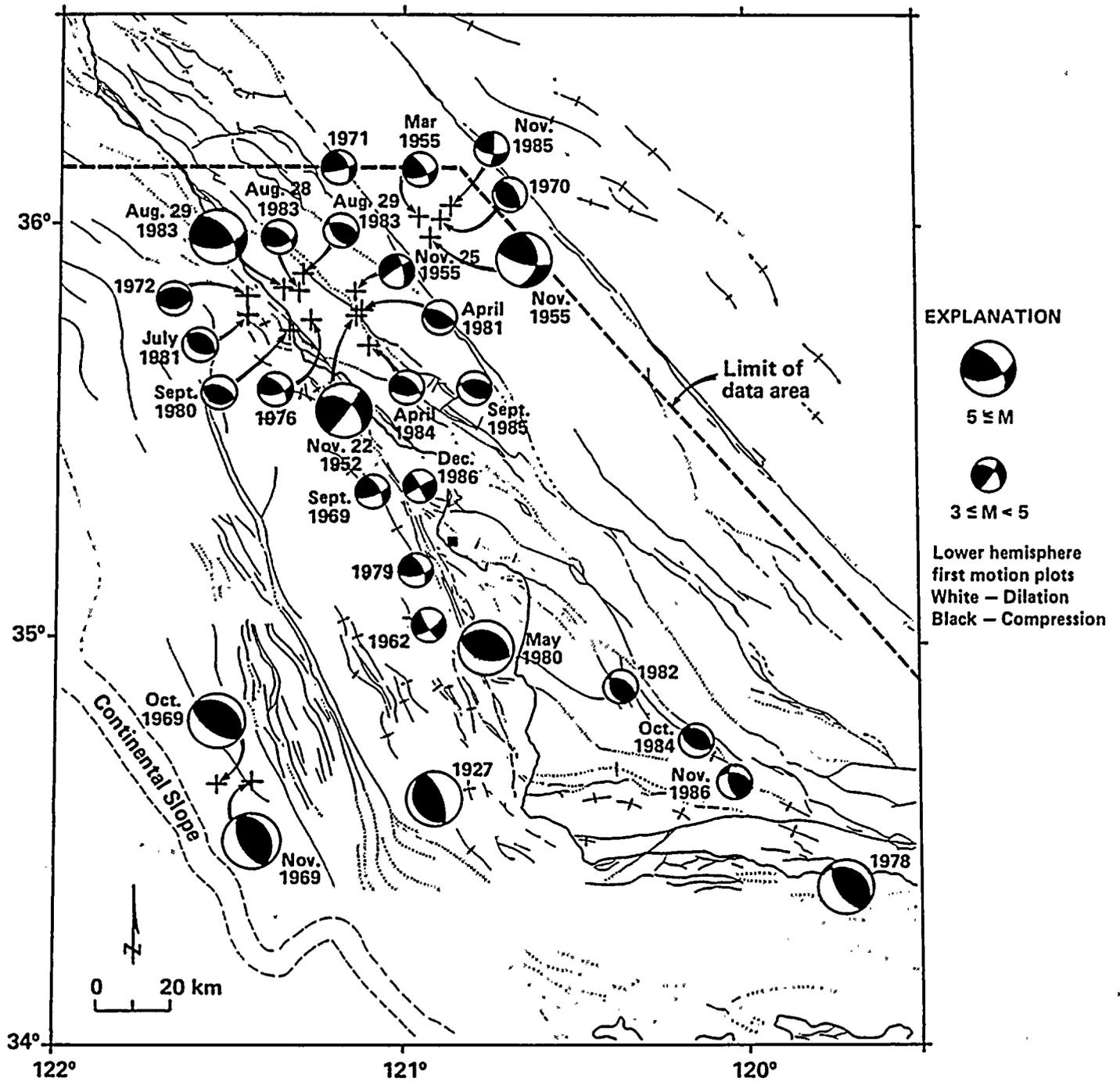
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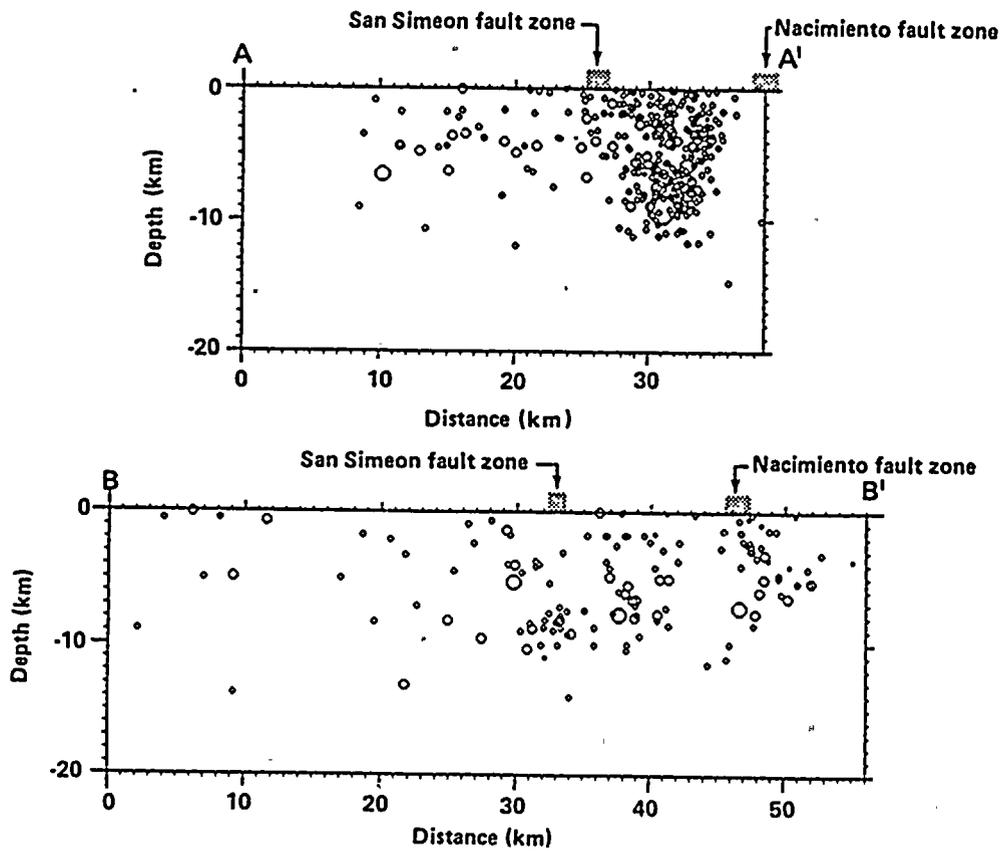
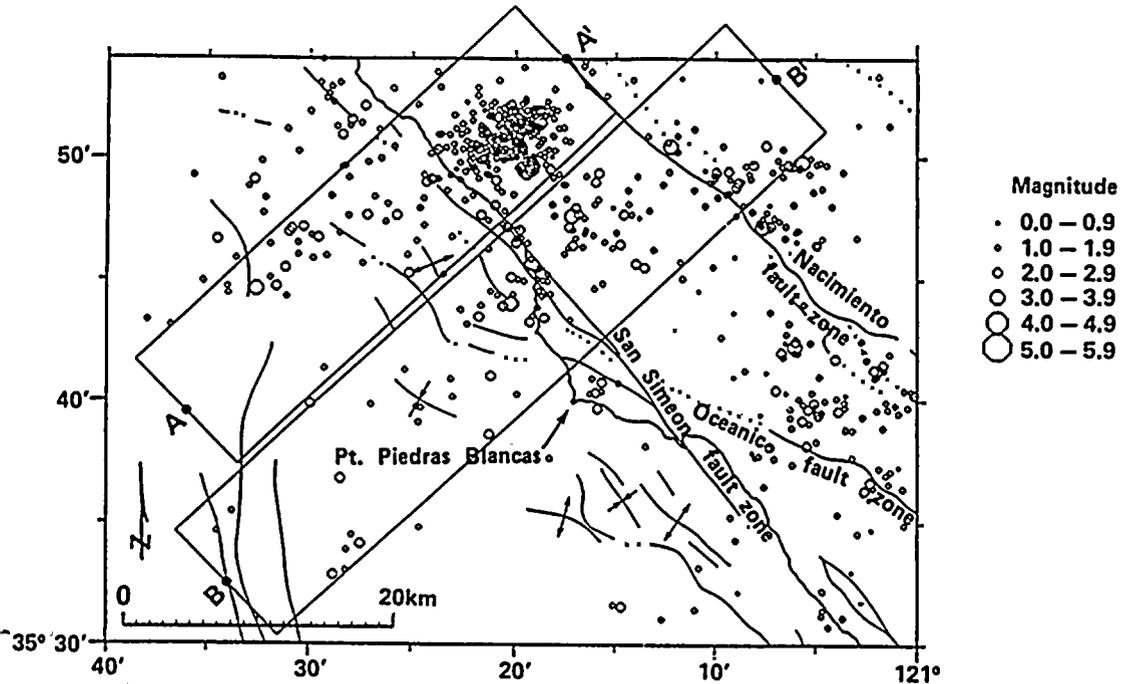
■ Diablo Canyon Power Plant

NOTE: Base map explanation provided on Plate 3.

Figure 2-32

Compilation of focal mechanisms for earthquakes of magnitude 3 and greater in the south-central coastal California region.





NOTE: Base map explanation provided on Plate 3.

Figure 2-33

Seismicity map and cross sections in the Piedras Blancas area, 1980-1988.

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- Focal mechanisms west of the San Simeon fault zone (Figures 2-30 and 2-32) indicate both strike-slip and reverse faulting with generally northeast-striking P axes. This pattern is consistent with the strike and type of faults mapped onshore and of faults and fold axes imaged offshore.
- To the east of the San Simeon fault zone, the seismic activity is dominated by the two strong events of 1952 and 1983 (Figure 2-18) and several concentrations of recent micro-earthquake activity (Figures 2-26 and 2-27). The major faults in the region, the San Simeon fault zone and the broader Nacimiento fault zone, appear to delimit this relatively active area on the west and east respectively. In the cross sections of Figure 2-33, seismic activity east of the San Simeon fault zone is seen to die out at about 12 kilometers depth, with only a few small (and thus probably not well located) events occurring a few kilometers deeper. This transition depth appears to be slightly deeper in the area east of the San Simeon fault zone than to the west. No well-defined lineations are noted.
- The right-oblique focal mechanism of the 1983 magnitude 5.0 event (Figure 2-32) has a fault plane that strikes parallel to the San Simeon fault zone. This event occurs within the dense cluster of activity seen in Figure 2-33. This nodal plane would project to the surface very near the trace of the San Simeon fault zone, suggesting a possible association. However, the event could as well be associated with less major faulting in the basement to the east of the surface trace of the San Simeon fault zone.

Additional focal mechanisms in the area between the San Simeon and Nacimiento fault zones also exhibit right-reverse movement, on northwest-striking planes, including the 1952 Bryson earthquake (Figures 2-30 and 2-32). There are also several mechanisms with predominantly dip slip. The focal mechanisms and hypocentral data indicate a deformational pattern

of distributed right shear with a northeast-directed component of compression.

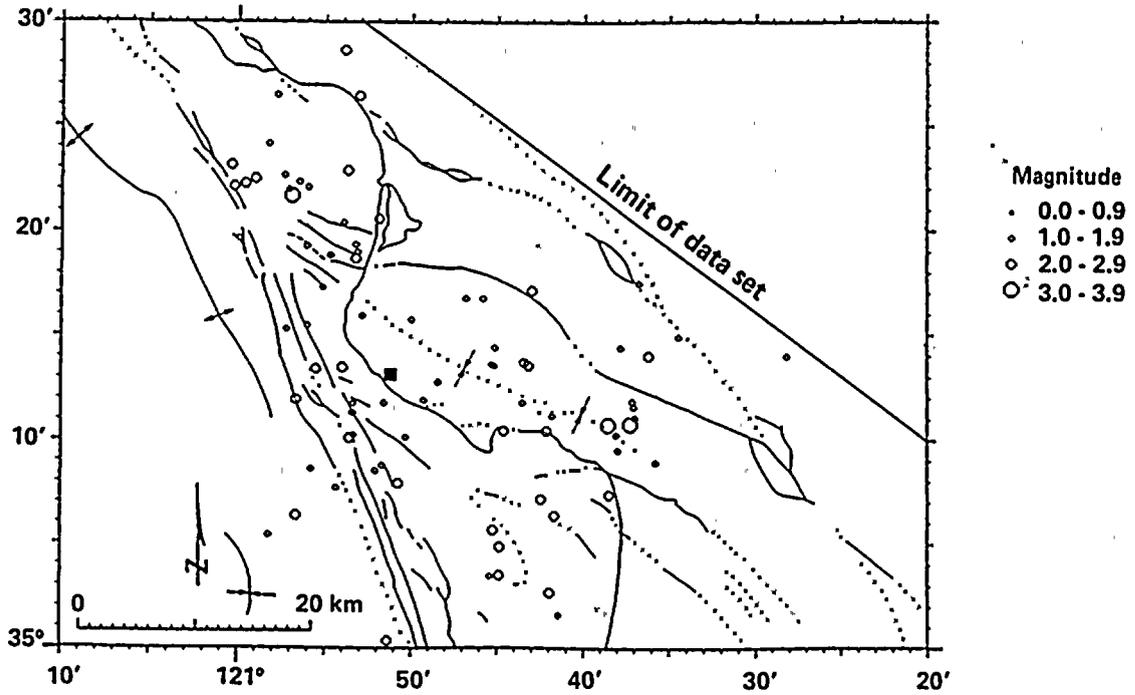
E. Southeast of the Piedras Blancas region, between the Oceano and West Huasna faults on the west and the Nacimiento fault zone on the east, an elongate zone of microearthquake activity extends to the southeast to near the intersection of the West Huasna and Rinconada faults (Figures 2-26 and 2-27). This area is underlain by Franciscan basement directly adjacent to the western edge of the Salinian terrane. Several focal mechanisms along this trend exhibit primarily right or right-oblique slip along steeply dipping planes generally striking northwest. The seismicity pattern suggests that distributed and low-level right-slip deformation is presently occurring along this terrane boundary.

F. The San Luis/Pismo structural block is characterized by scattered microearthquakes within the interior of the block and adjacent to its boundaries with an abrupt termination in seismic activity at the plane of intersection of the block with the Hosgri fault zone. This seismic activity is associated with the Irish Hills subblock and with the triangular block offshore to the northwest of the Irish Hills subblock, the Estero Bay subblock. To focus on the details of the seismic activity in this area, earthquake relocations were performed for the 1980-1988 data set, combining the U.S. Geological Survey data shown in Figure 2-27 and the PG&E data shown in Figure 2-28. Relocations were computed using the PG&E velocity model (Figure 2-29). Only events of magnitude 1.5 and larger were included, distance weighting in the relocations was imposed beginning at 75 kilometers with no readings used beyond 100 kilometers, and events with standard locations errors greater than 20 kilometers were excluded. The resulting data are shown in Figures 2-34 and 2-35. Focal mechanisms for events in this local area are shown in Figure 2-36. This mechanism data set includes events from the PG&E network (Figure 2-30) augmented by events from the 1980-86 period for which single-event mechanisms could be reliably constrained. No composite mechanisms were prepared, since the variability in mechanisms was

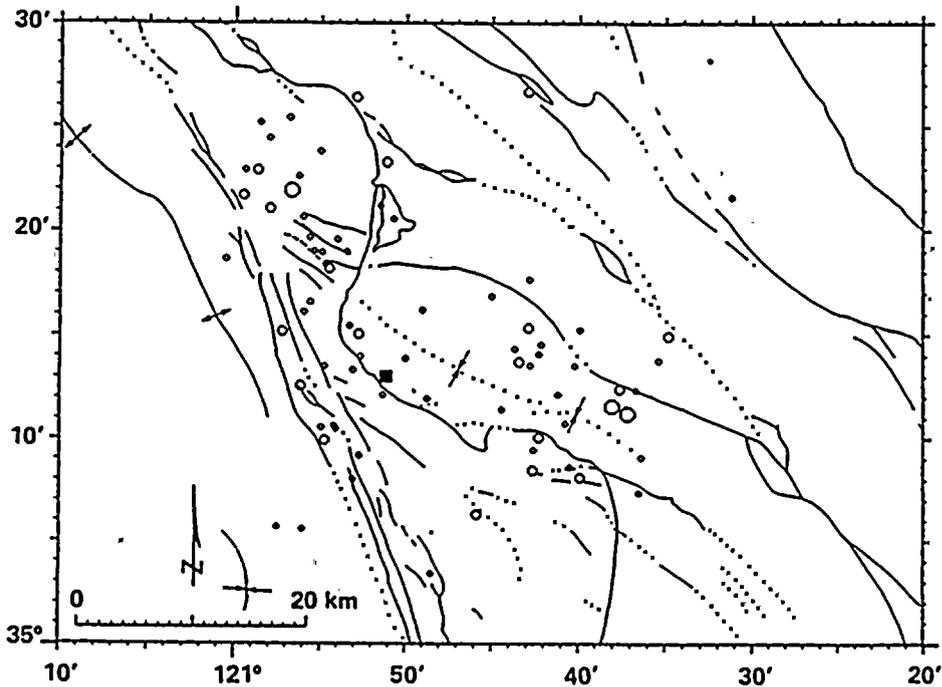




1980 - May/1988 USGS locations



Relocations

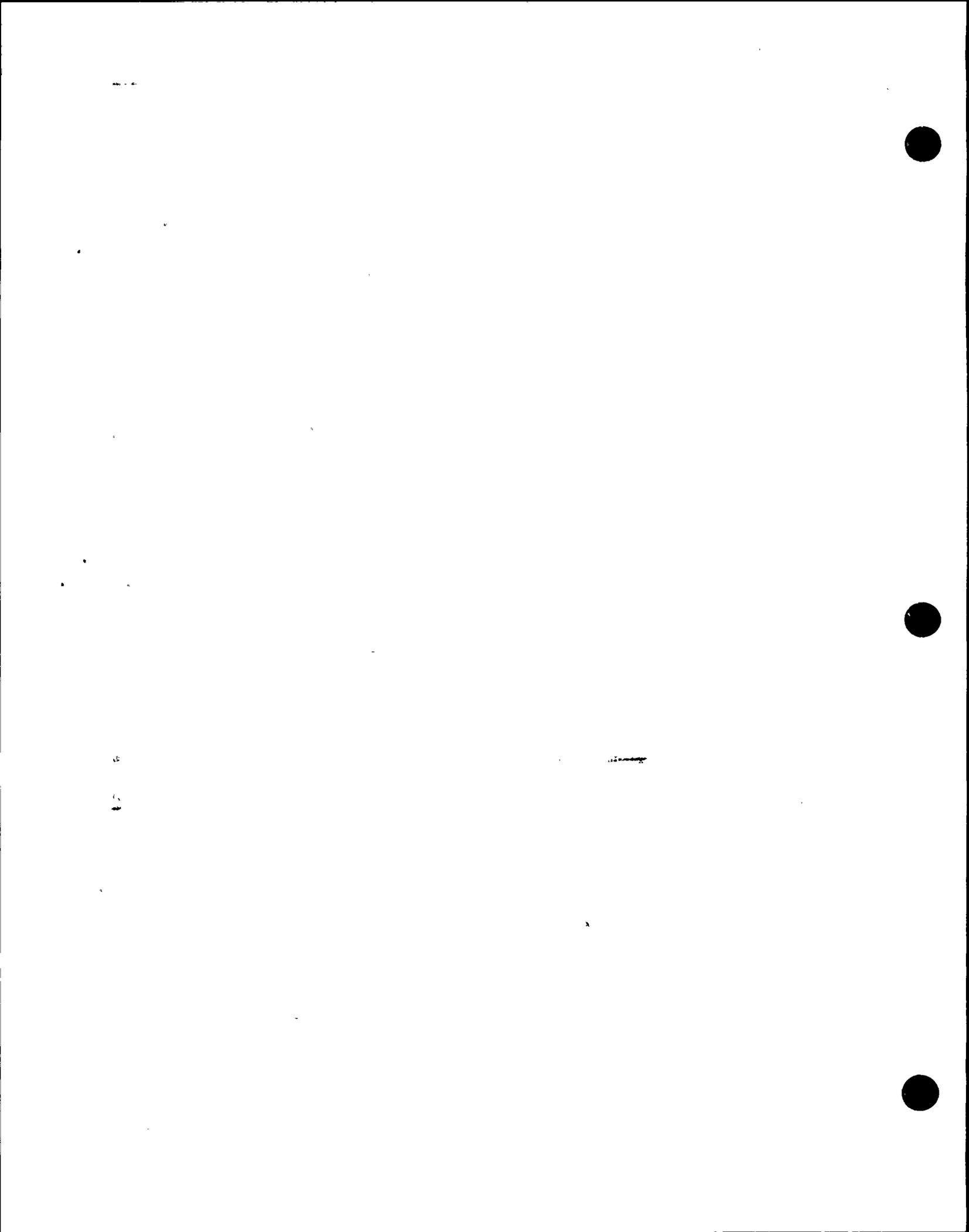


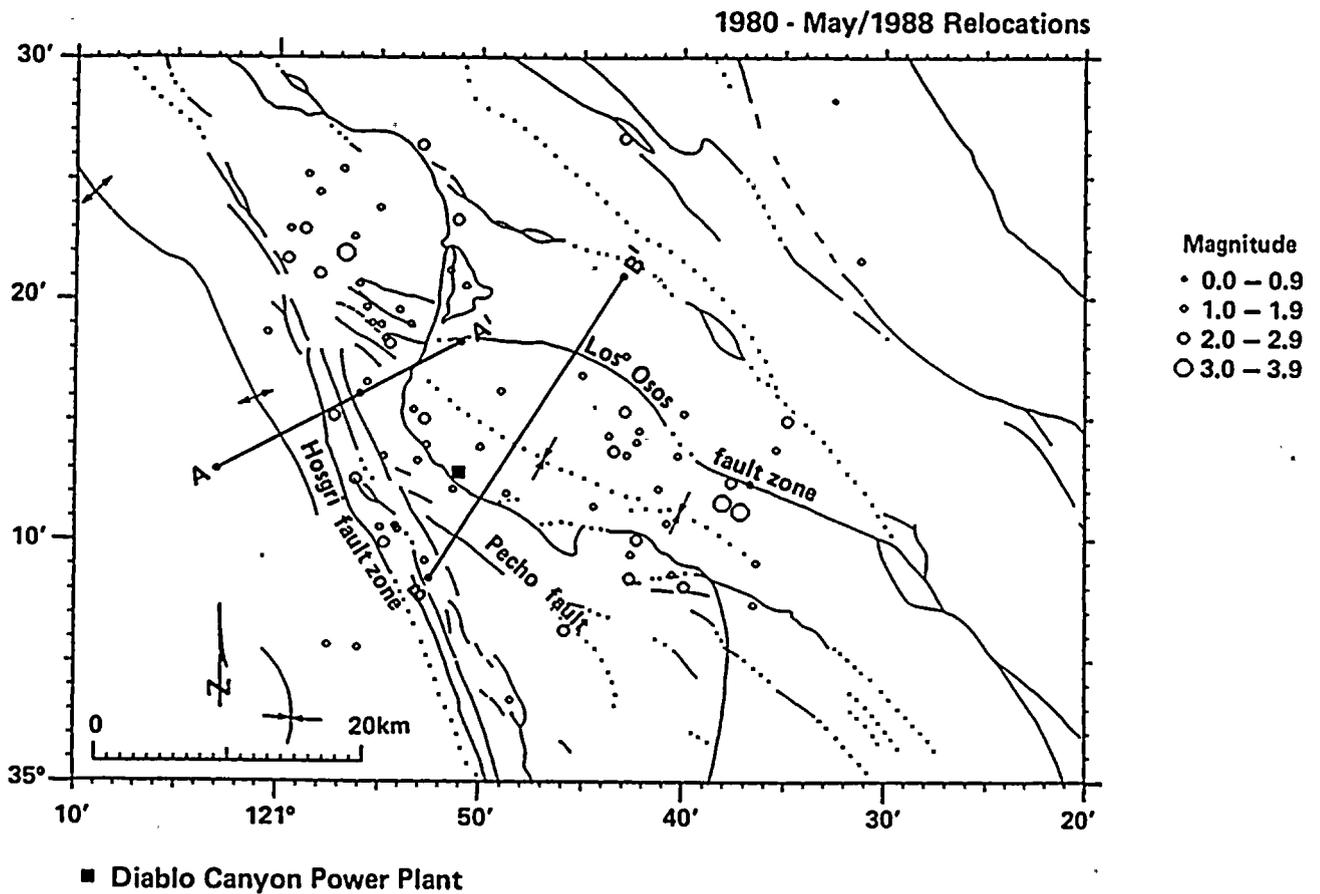
■ Diablo Canyon Power Plant

NOTE: Base map explanation provided on Plate 3.

Figure 2-34

Seismicity maps of original U.S. Geological Survey and relocated earthquakes for the period 1980-1988 at the western end of the San Luis/Pismo structural block.





NOTE: Base map explanation provided on Plate 3.

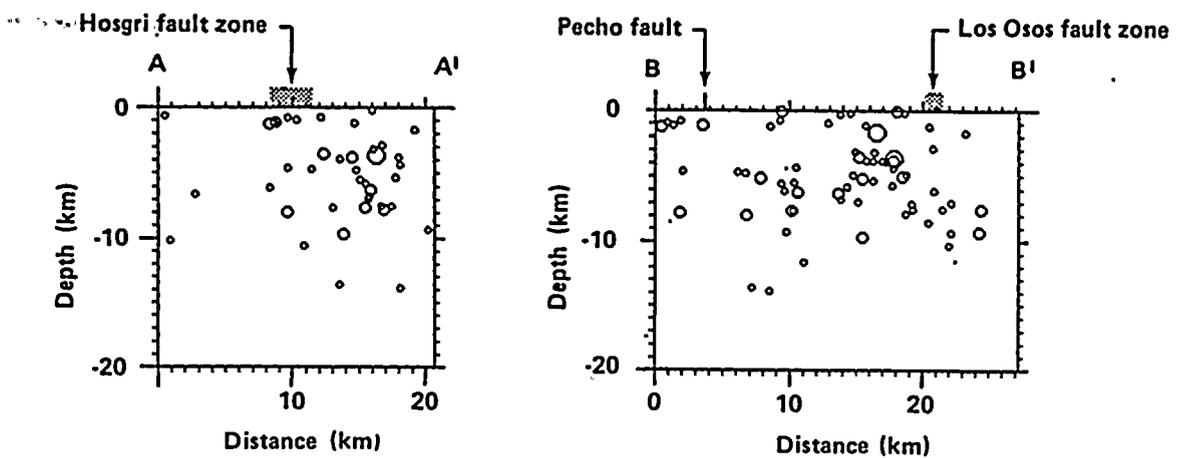
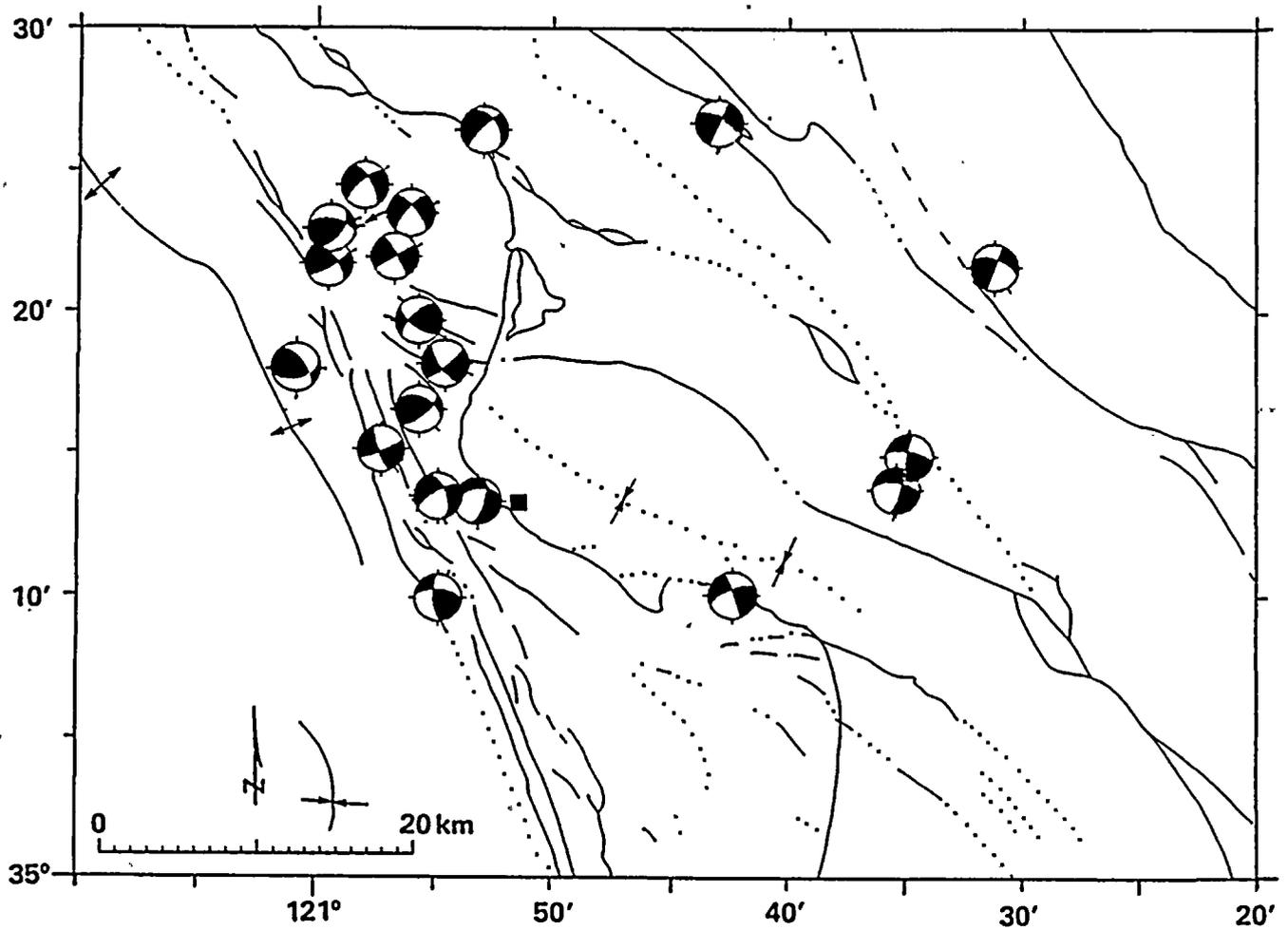


Figure 2-35

Cross sections of relocated earthquakes for the period 1980-1988 near the western end of the San Luis/Pismo structural block. The cross sections include all earthquakes projected perpendicular to the section.





EXPLANATION

 Lower hemisphere first motion plots
White – Dilation
Black – Compression

 Diablo Canyon Power Plant

NOTE: Base map explanation provided on Plate 3.

Figure 2-36

Focal mechanisms for the period 1980-1988 near the northwestern end of the San Luis/Pismo structural block. The magnitudes of the events shown range from 0.9 to 3.2.

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found to be large within this area, and interpretative errors could be introduced with composited data. The following observations are made for this locality:

- Microearthquake activity shown in Figures 2-34 and 2-35 indicates that the deformation associated with the western end of the San Luis/Pismo structural block does not extend west of the Hosgri fault zone. At depth, this termination appears to be nearly vertical at least to a depth of about 9 kilometers. Three small (magnitude less than 2) microearthquakes are shown west of the Hosgri fault zone in Figure 2-34. Two of these events lie about 6 to 8 kilometers west of the Hosgri fault zone west of San Luis Obispo Bay and, although small, are reasonably well located. The instrumental data indicate that the level of seismicity in past decades in this area of the offshore Santa Maria Basin is extremely low. The third small event occurred in 1985 and is relocated 2 kilometers west of the Hosgri fault zone opposite the Estero Bay subblock. The focal mechanism for this event (Figure 2-36) is reasonably well constrained to be right reverse. It is possible that this event is mislocated several kilometers to the west and it is associated with the activity located directly along the Hosgri fault zone.
- The seismic activity along and east of the Hosgri fault zone adjacent to the San Luis/Pismo structural block may be associated with the block-Hosgri interface or may be associated with minor faulting within the block, or both. The focal mechanism data at the west end of the San Luis/Pismo structural block suggest that the events located very near the Hosgri fault zone traces are produced by right-reverse slip along the Hosgri fault zone. Several earlier and less well-located events also suggest dominantly right slip along the Hosgri fault zone in this area (Figure 2-32). Just to the east of the Hosgri fault zone, particularly in central Estero Bay, there is a variety of mechanisms. This suggests that the Estero Bay subblock is being complexly

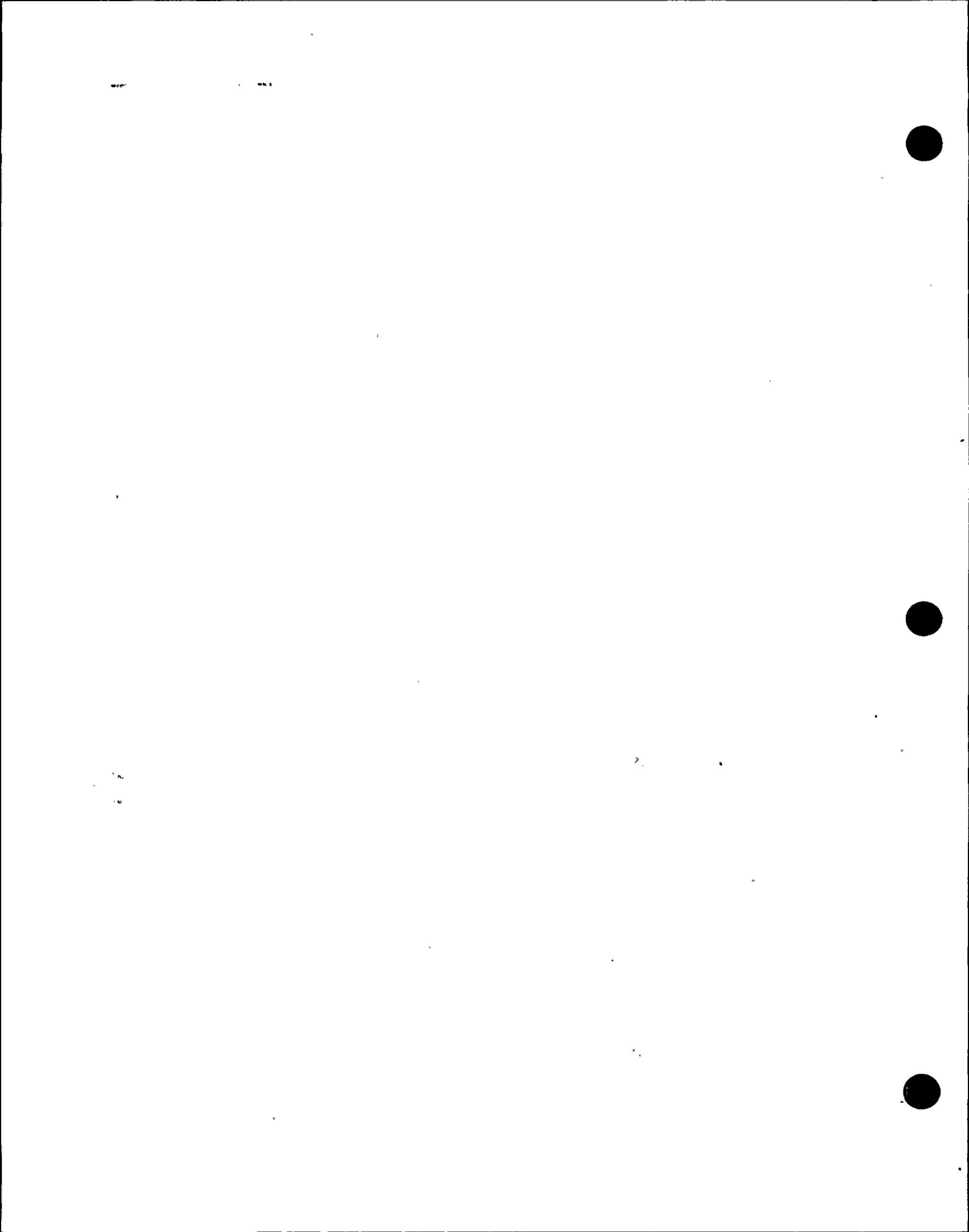
deformed between the northward converging traces of the Hosgri and Los Osos fault zones.

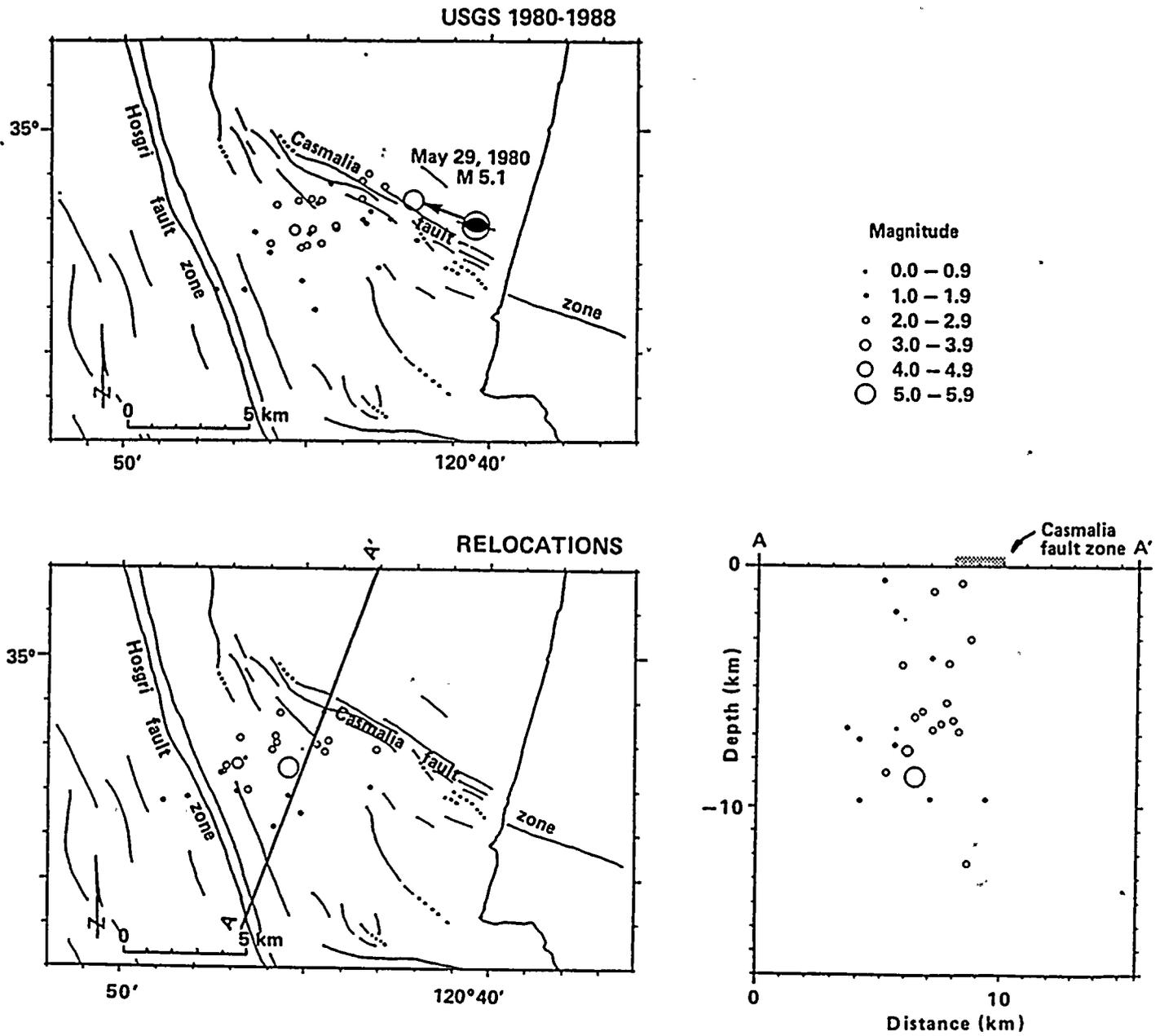
- The cross sections in Figure 2-36 indicate that the transition from brittle to ductile deformation at depth within the crust occurs about 10 to 12 kilometers beneath the Hosgri fault zone and beneath the Irish Hills and Estero Bay subblocks of the San Luis/Pismo structural block. Only a few small-magnitude events have been located in the depth range of 12 to 15 kilometers.
- The seismic activity located along the Hosgri fault zone from the north end of the fault to northwest of Point Sal appears to occur only along the portion of the Hosgri fault zone abutting the San Luis/Pismo structural block. The portions of the Hosgri fault zone in northern Estero Bay and central San Luis Obispo Bay are essentially devoid of microearthquake activity.

G. The localized zone of seismicity offshore of Point Sal contains the magnitude 5.1 event of May 29, 1980 and a magnitude 3.8 earthquake in 1984. These events have been relocated using a master event approach. The revised locations, the mainshock focal mechanism, and a cross-section perpendicular to the Casmalia fault zone are shown in Figure 2-37. The activity is generally bounded by the Hosgri fault zone on the west, and lies between the Hosgri and the Casmalia fault zones. The deepest event is at a depth of 12 kilometers, but most of the activity occurs between 4 and 9 kilometers. There is a suggestion of a slight southwest dip to the zone. The focal mechanisms of the 1980 and 1984 events are well-constrained to strike parallel to the trend of the Casmalia fault zone, not the trend of the Hosgri fault zone, and to indicate essentially pure reverse/thrust motion.

H. Earthquake activity in the southeastern portion of the Santa Maria Valley and along the southeastern part of the Casmalia block exhibits several small clusters of events set in a diffuse background (Figures 2-26 and 2-27). Focal mechanisms in the area (Figures 2-30 and 2-32) suggest both reverse and oblique-slip faulting on







NOTE: Base map explanation provided on Plate 3.

Figure 2-37

Seismicity map, cross section, and focal mechanisms for the seismicity near the western end of the Casmalia structural block offshore of Point Sal. The cross section includes all earthquakes projected perpendicular to the section.

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planes approximately parallel to the strike of the Casmalia block axis.

I. Earthquakes that have occurred west of the southern part of the Hosgri fault zone are less well-located than onshore or near-shore events, although the epicentral locations are probably not biased since no large lateral changes in velocity have been observed offshore. Even with S-wave data from the Point Sal seismograph station, focal depths are uncertain. The azimuthal coverage by seismic stations is also limited, which hinders the development of reliable focal mechanisms for microearthquake activity in this area. This region contains two subgroups of earthquakes. The group north of the letter I in Figures 2-26 and 2-27 is in the vicinity of the northern ends of the offshore Lompoc and Purisima structures, near the northerly margin of the South Basin Compressional domain, (Figure 2-10). These structures, containing both folds and reverse/thrust faults, exhibit evidence of some late-Quaternary compressional deformation. These features extend to the south-southeast as a broad fault/fold zone to south of Point Arguello, near the group of offshore microearthquakes south of the letter I. This area, up to about 25 kilometers offshore of Point Arguello, is near and to the east of the epicentral area of the 1927 Lompoc earthquake. The only well-constrained focal mechanism for this offshore region is for the 1927 event.

J. A scattered zone of earthquake activity lies far offshore, between the southern Santa Lucia Bank and the continental slope. This region east of the continental slope lies below a complex zone seen in the reflection image of PG&E-3 (Plate 6). The November 5, 1969, magnitude 5.6 earthquake occurred in this area. These events indicate that this part of the continental margin is seismically active on reverse faults trending northwest (Figure 2-32). However, the zone of activity does not appear to be very extensive to the north or the south. Events in this region may have been incompletely detected prior to 1980, as can be seen in the lack of events in the 1973-1979 interval (Figure 2-26). The offshore earthquake detection threshold since about 1980 has been sufficient to provide reasonably uniform

coverage to less than magnitude 2.0 of the entire offshore area to the continental margin.

Discussion of Regional Seismicity. The refined understanding of the tectonic setting in south-central coastal California discussed previously in this chapter is an important complement to the interpretation of historical and instrumental seismicity in the region. Of particular importance is the recognition of significant differences in deformational style from domain to domain, with changes occurring in short distances across domain boundaries. Previous researchers who have recently discussed seismicity in the region have noted some of the variations; for example, Eaton (1984) noted a regional north-to-south change in focal mechanisms of larger recent earthquakes from strike-slip to reverse-oblique. Eaton (1985) has also noted general differences in seismicity patterns between areas of strike-slip faulting and areas of reverse and thrust faulting. Dehlinger and Bolt (1987) note variations in tectonic properties of seismic zones along the trend of the Coast Ranges, but specifically address only a transect corridor extending from the Piedras Blancas area northeast to the San Andreas fault zone. In other regional studies, seismicity has been generally associated with the Hosgri fault zone without discriminating among associations with adjacent structures and domains (Gawthrop, 1975, 1978a; Lindh and others, 1981; Crouch and others, 1984).

This report incorporates the earthquake data discussed in these previous publications, and refines the previous broad regional interpretations to achieve a detailed synthesis. The present study has identified specific tectonic domains within south-central coastal California as shown in Figure 2-10. Recent and historical seismicity data as discussed above have been incorporated in the identification and characterization of these domains along with geological and geophysical data and interpretations. In spite of the relatively short historical record of earthquake activity, the neotectonic deformational patterns identified in the geologic record are consistent with the detailed seismicity patterns.

The nature of the Hosgri fault zone has received particular attention in our analysis of seismological

data within south-central coastal California. The Hosgri fault zone is a fundamental, nearly vertical structural boundary between the fault-bounded blocks of the Los Osos/Santa Maria Valley domain on the east and the offshore Santa Maria Basin on the west (Figure 2-10). The available seismicity data indicate that observed (short-term) activity occurring along or in close proximity to the Hosgri fault zone reflects local tectonic interactions along the parts of the zone that form interfaces with actively deforming structures in these adjacent structural blocks and domains. Areas where seismicity has been located along or close to the Hosgri fault zone are characterized by geologic evidence of ongoing tectonism; conversely, seismically quiet reaches of the Hosgri fault zone bound areas for which geological and geophysical data indicate little or no late Quaternary deformation. The areas of notable seismic activity and evidence of active tectonism correspond to the San Luis/Pismo and Casmalia structural blocks along the east side of the Hosgri fault zone, and the south basin compressional domain along its west side. The correspondence between areas of recognized active tectonism in domains adjacent to the Hosgri fault zone and the occurrence of seismicity defined by small events along or in close proximity to this fault, suggests that infrequent larger earthquakes along the fault zone also are likely to originate through the local rupture zone as relief of strain associated with movement of adjacent blocks or structures.

Hosgri Fault Zone

The Hosgri fault zone is the southernmost component of the San Gregorio/Hosgri fault system, a complex system of faulting that is subparallel to the central California coast (Figure 2-38). From north to south other major fault zones in this system are the San Gregorio, Sur and San Simeon fault zones. This system splays off the San Andreas fault near Bolinas on the north (Jennings, 1975) and appears to die out approximately 410 kilometers to the southeast near Point Pedernales (Cummings and others, 1987; this study). The Hosgri fault zone is about 110 kilometers long, generally consists of two segmented linear north-northwest trending

strands, and lies offshore throughout its length. It forms a major structural boundary between the 2- to 3-kilometers-thick, mildly deformed Neogene section of the offshore Santa Maria Basin to the west and the west-northwest trending, highly folded and faulted rocks of the Los Osos/Santa Maria Valley domain of the southern Coast Ranges to the east.

Although there is evidence that the San Gregorio/Hosgri fault system changes character along its length, we can make use of the data available along its length to assist in characterizing the behavior of the zone in the reach closest to the site. In particular, we have examined the behavior of the fault system in the onshore reach of closest approach to the site, which is the San Simeon fault zone near San Simeon Point. We recognize that the applicability of observations made at various locations along the system to the behavior of the Hosgri fault zone near the site probably decreases with distance. Nevertheless, there is a reasonable geologic basis for concluding that many of the characteristics of the San Simeon fault zone are representative of those to be expected near the site. Therefore, in this section, we present the results of our San Simeon fault zone investigations in the context of their importance in characterizing the Hosgri fault zone to the south.

PREVIOUS STUDIES

The Hosgri fault zone was first reported as a "structurally disturbed zone" in a limited study of three seismic reflection profiles (Wolf and Wagner, 1970). Hoskins and Griffiths (1971) published a map (Figure 2-39) that did not name or discuss the fault but illustrated it as a significant offshore structure forming the east margin of the offshore Santa Maria Basin.

The potential relevance of the yet unnamed fault to the Diablo Canyon site was recognized and extensive geophysical surveys were begun in 1973-74 to map and characterize the fault. These early studies by consultants to PG&E (Table 2-3) and the U.S. Geological Survey (Wagner, 1974) utilized sparker and other analog high-resolution geophysical systems. Based upon these studies, PG&E's consultants concluded that the Hosgri





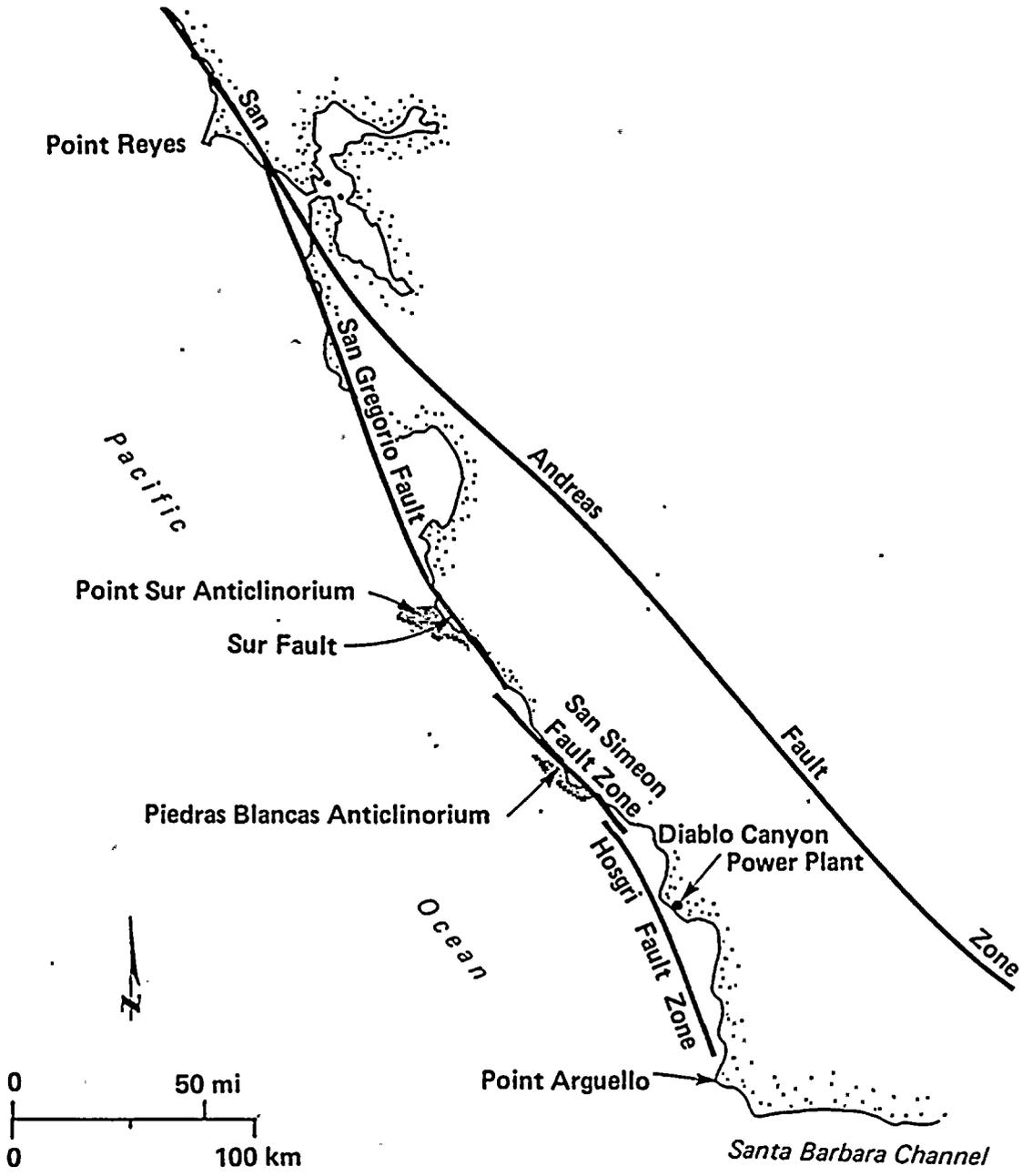


Figure 2-38
Major components of the San Gregorio/Hosgri fault system in coastal central California.

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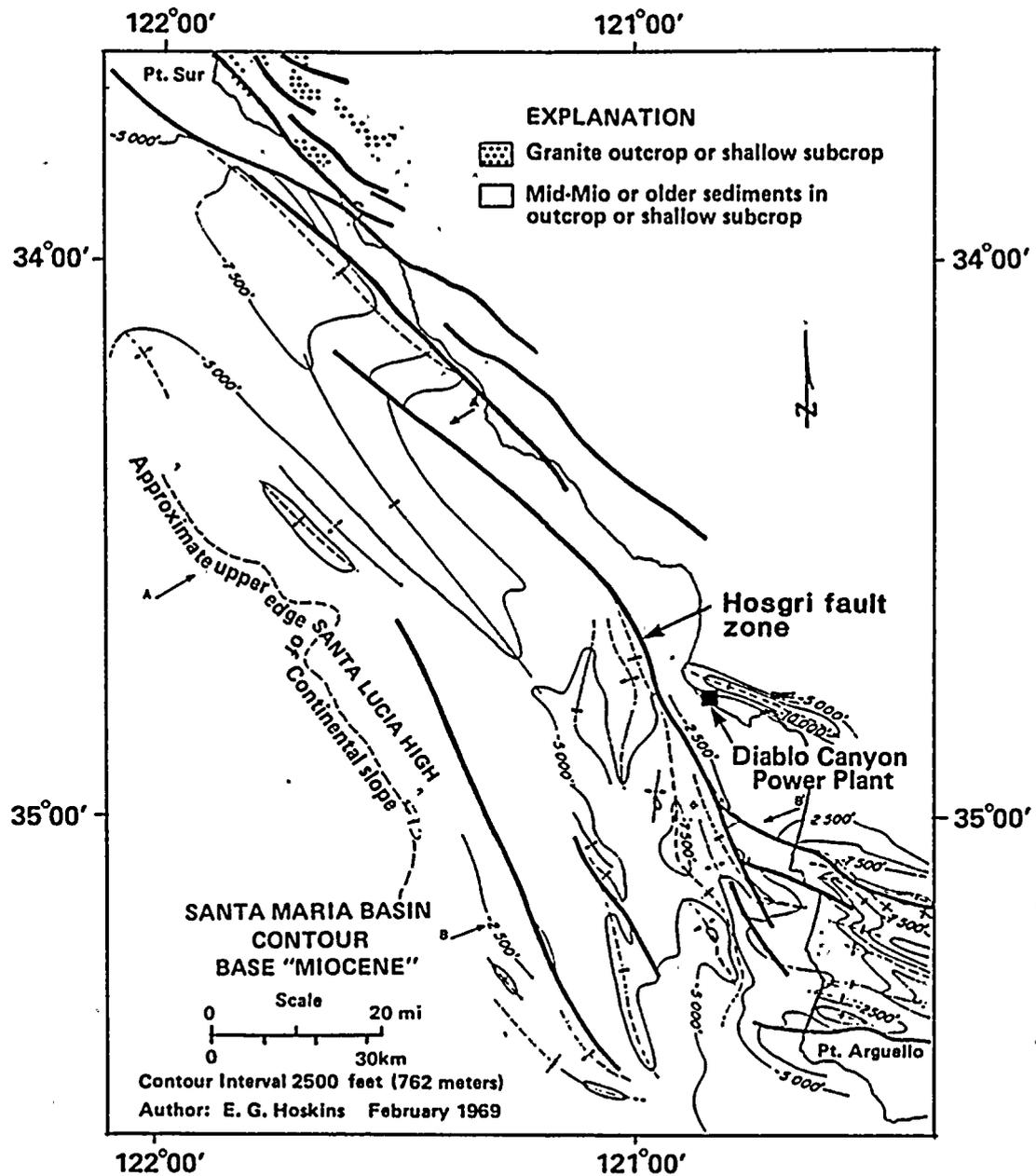


Figure 2-39

Map of the offshore Santa Maria Basin showing initial documentation of feature that would later be named the Hosgri fault zone (modified from Hoskins and Griffiths, 1971).

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fault zone was a complex extensional basin-margin tectonic boundary along which some strike-slip displacement had occurred, and which, on the basis of limited, local evidence of late Quaternary displacement, was a capable fault as defined by the Atomic Energy Commission in 10 CFR Part 100 Appendix A (PG&E, 1974). The U.S. Geological Survey investigation also concluded that the fault is capable and Wagner (1974) named it the "Hosgri" fault after Hoskins and Griffiths.

Onshore parts of the San Simeon fault zone were first mapped by Taliaferro (1944), who referred to it as the Arroyo Laguna thrust zone. PG&E (1974, 1975) later mapped the fault zone and assigned the name San Simeon fault. The most detailed geologic mapping of pre-Quaternary stratigraphy and structure is provided by Hall (1976) and Hall and others (1979). Additional data for the offshore region between San Simeon Bay and Point Estero and north of Ragged Point were obtained and interpreted by Leslie (1980, 1981), and were used to update the PG&E interpretation in 1980.

Between 1974 and 1984, the major focus of research on the San Gregorio/Hosgri fault system was the estimation of the amount and timing of large-scale, right-lateral strike slip along it. The concept of large-scale right slip along parts of the coastal fault trend during Cenozoic time was introduced by Silver (1974), who proposed 90 kilometers of post-Cretaceous slip along the San Gregorio fault zone. Hall (1975) later proposed 80 or more kilometers of right slip on the San Gregorio/Hosgri fault system based on stratigraphic relationships among units as young as late Pliocene. Graham (1976) identified several pairs of apparently offset features that he interpreted to indicate more than 100 kilometers of pre-Pliocene right slip along the San Gregorio/Hosgri fault system. This view was further developed by Graham and Dickinson (1977 and 1978). Greene (1977) suggested about 110 kilometers of right slip along offshore faults extending across Monterey Bay, with 40 kilometers of this slip assigned to the San Gregorio fault zone. Several of these interpretations were first presented at an informal meeting convened by W. R. Dickinson at Stanford University in

1976, and later at a "San Gregorio/Hosgri fault" symposium held as part of the 1977 Geological Society of America Cordilleran Section meeting. Some of the interpretations presented at the symposium were later published in Special Report 137 of the California Division of Mines and Geology (Silver and Normark, 1978). Dickinson and Snyder (1979) and Blake and others (1978), in regional overviews of plate motion and basin development inferred 115 kilometers of right slip on a San Gregorio/Hosgri fault system based on the work of Hall (1975) and Graham and Dickinson (1977). Similarities in basement and Tertiary sedimentary rocks in the Point Reyes area, Santa Cruz Mountains, and Monterey area led Clark and others (1984) to postulate about 150 kilometers of right slip on the San Gregorio fault zone since late Miocene time.

In contrast to the above estimates, several authors have argued for lesser amounts of Neogene displacement on the San Gregorio/Hosgri fault system. Hamilton and Willingham (1977, 1978, 1979) proposed that cumulative post-middle Miocene right-lateral slip on the Hosgri fault zone is on the order of 10 to 15 kilometers or less, on the basis of comparison of stratigraphic sections on both sides of the fault in San Luis Obispo Bay. Hamilton (1984) concluded that displacement along the San Gregorio/Hosgri fault system in the past 5 million years has amounted to about 5 kilometers of right-lateral displacement. The major parts of the system, according to Hamilton (1984), have an earlier history of movement as part of a late Paleocene "proto-San Andreas" fault system, which underwent around 250 kilometers of right slip along a combined San Andreas-San Gregorio trace at the north, with the amount distributed southward on several strands including about 100 kilometers along a San Simeon/Hosgri strand. Based on interpretations of field relations between Monterey Bay and Point Sal and on correlations of stratigraphic sections on opposite sides of the San Simeon/Hosgri fault zone, Seiders (1979) suggested that there has been less than 30 kilometers of post-late Miocene and less than 50 kilometers of post-Oligocene displacement.

Evidence for Quaternary activity along the San Simeon fault zone has been reported by several

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workers in the area (PG&E, 1974; Hall, 1975; Envicom, 1977; Weber and others, 1981; Weber, 1983; and Manson, 1985). Traces of the fault zone mapped by these workers are summarized on Plate 10. Based on mapping of marine terraces between Cayucos and Cape San Martin, and correlation of marine terraces across the San Simeon fault zone, Weber (1983) suggests a Pleistocene slip rate of between 5 and 19 millimeters per year of right slip, with a preferred estimate of 8 to 10 millimeters per year for the past 350,000 to 400,000 years. Weber and others (1981), Weber (1983), and Manson (1985) conclude that offset of unconsolidated eolian sand at San Simeon Bay by small secondary faults within the zone suggests late Pleistocene and probable Holocene activity on the fault.

Crouch and others (1984) proposed that post-Miocene deformation within central California west of the San Andreas fault is characterized by a system of listric faults splaying upward from a gently east-dipping "aseismic detachment zone" that underlies the region at a depth of 10 to 12 kilometers (Figure 2-40). They observed that "estimates of strike slip may have been overstated." They cited: (1) the existence of asymmetric folds with faults closely parallel to their axes; and (2) the absence of folds arranged in an en echelon pattern indicative of wrench faulting, to conclude that, although some strike slip is probable, "the folds and faults, as well as present morphology of the offshore Santa Maria Basin, chiefly reflect post-Miocene northeast-southwest-directed compression." In this interpretation the Hosgri fault zone is one of a region-wide system of shallow-dipping listric thrust faults. However, Snyder (1987) provides an alternative interpretation for the listric faults that does not require a regional detachment zone.

A recently developed thrust model for California coastal tectonics is presented by Davis and McIntosh (1987) and Namson and Davis (1988), who envision the Hosgri fault zone as an east-dipping thrust fault responding to compressional stress directed normal to the North American/Pacific plate margin. Namson and Davis (1988) suggest that all interplate strike-slip motion is accommodated along a weak, or

low-stress San Andreas fault, a view supported by Zoback and others (1987) and by Mount and Suppe (1987). The remnant stress field is thus dominated by convergence of roughly 8 to 10 millimeters per year perpendicular to the San Andreas fault as called for by the global plate motion models described earlier (Minster and Jordan, 1978; DeMets and others, 1987; Jordan and Minster, 1988). The Hosgri, Nacimiento and Rinconada faults, as well as thrust faults that lie buried within the cores of folds along the western margin of the San Joaquin Valley, are shown in the Namson and Davis (1988) model to root in a basal thrust operating along the brittle-ductile transition zone at depths of 12 to 20 kilometers (Figure 2-41). Above this zone, crustal shortening is accommodated by fault-bend and/or fault-propagation folding driven by slip on thrust faults which often do not reach the surface (blind thrusts). Using the retrodeformational techniques developed by Suppe (1980, 1985) to analyze shortening in allochthonous folded structures, they depict the Hosgri fault zone near San Simeon Point as a thrust that dips 20 degrees northeast below the sea floor to a depth of 7.5 kilometers. Between 7.5 kilometers and 10 kilometers depth the Hosgri fault zone increases its dip to 30 degrees, then flattens and extends eastward to the San Andreas fault as a horizontal detachment surface (Figure 2-41).

As a part of our review of existing data, interpretations and literature for the Hosgri fault zone and tectonic setting of south-central coastal California, we interviewed four prominent researchers conducting geological and geophysical studies in the region. These researchers included James Crouch, Thom Davis, Clarence Hall, and Bruce Luyendyk. During the interviews, each of these individuals reviewed their data sets, interpretations, and/or models regarding the Hosgri fault zone and Cenozoic tectonic setting of the region. In general, the data and opinions expressed by these individuals are contained in the published literature summarized above or in the Tectonic Setting section of this report. However, in each interview, the individuals provided an update of more recent data acquired by them or by others, and the implications of these data regarding their interpretations or





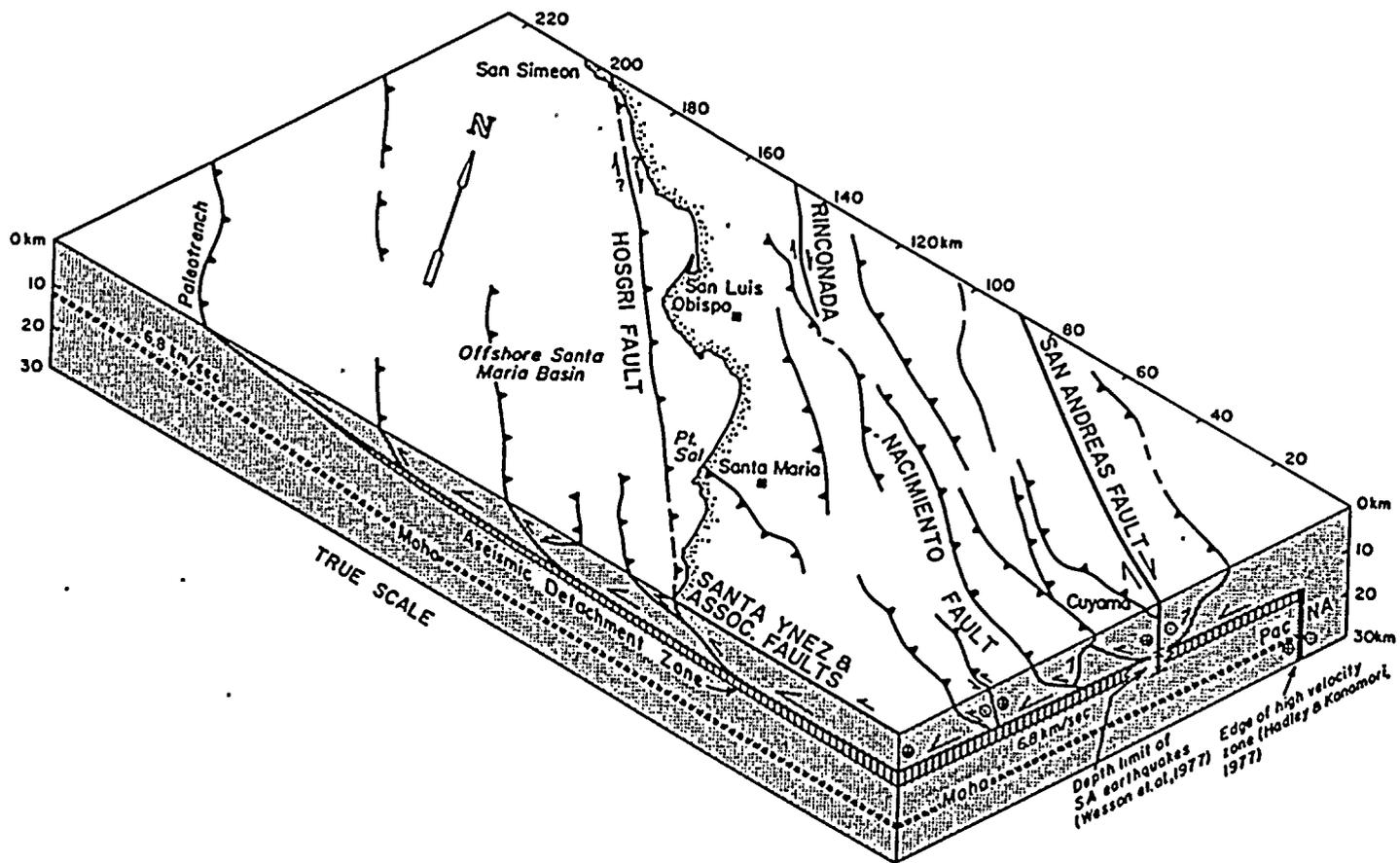


Figure 2-40

Block diagram illustrating inferred upper crust detachment of the central California margin due to northeast-southwest compression (from Crouch and others, 1984).

1982-3

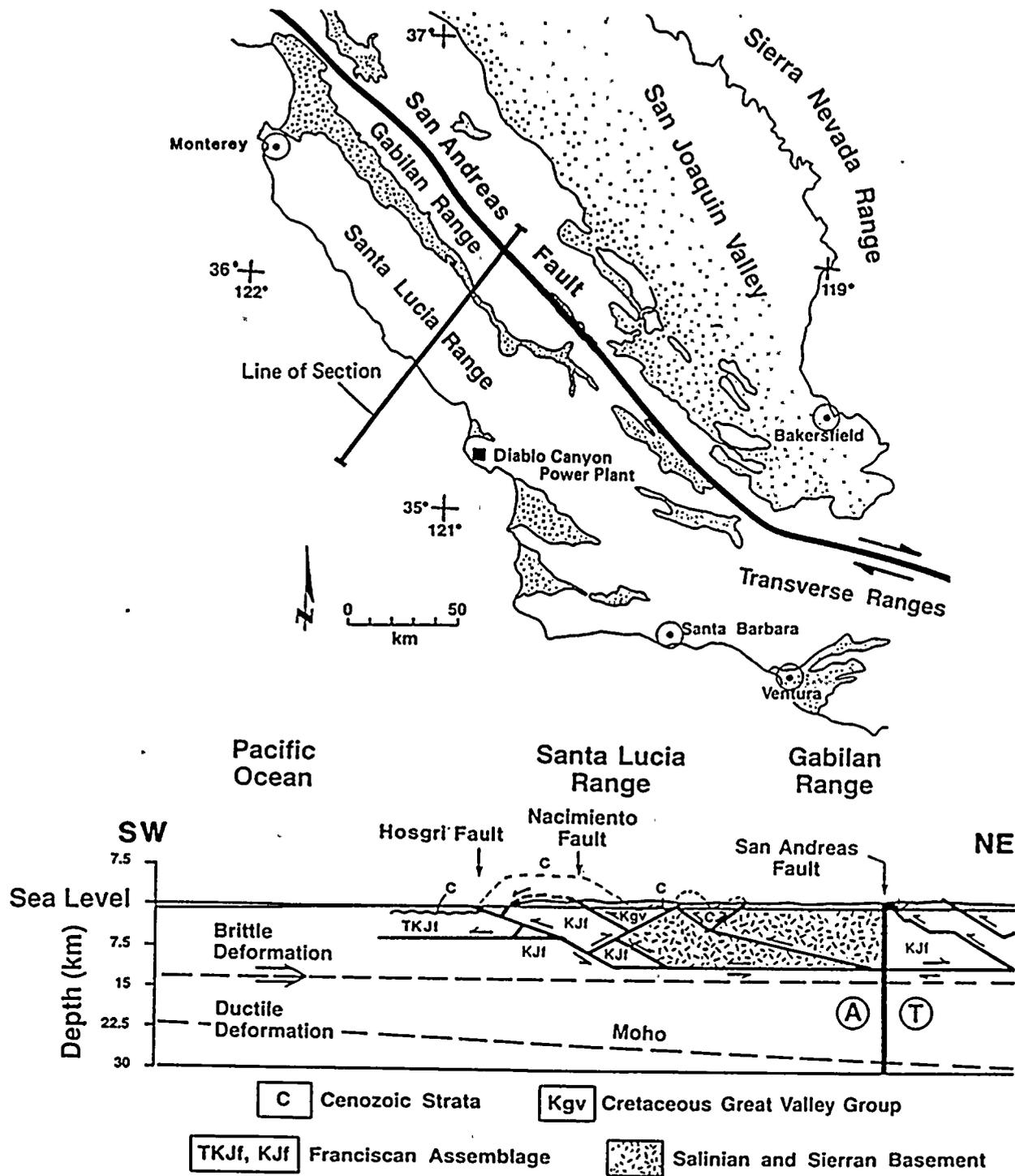


Figure 2-41

Geologic cross section illustrating a tectonic model for deformation across the North America/Pacific plate boundary. Transpressive motion along the plate boundary is resolved into two strain components. One component is tangential to the plate boundary and is strike slip on the San Andreas fault. The other component is normal to the plate boundary and is compression on thrust faults and folds across the California Coast Ranges. Thrust faults root in the brittle-ductile transition zone, defined by the maximum depth of earthquakes, and shortening above this zone is accommodated by folding and faulting. Below the brittle-ductile transition zone, shortening occurs by ductile deformation processes or incipient subduction (modified from Namson and Davis, 1988).

models. These data, interpretations, and models are summarized below.

James Crouch favors a thrust fault interpretation for the Hosgri fault zone and a tectonic model that the Hosgri fault zone and related thrust faults in the Santa Maria Basin are listric into a detachment or decollement surface at depth. This interpretation is published (Crouch and others, 1984) and is based primarily on offshore seismic reflection data across the Hosgri fault zone between the general latitudes of Point San Luis on the north and Point Sal on the south. Crouch believes that the geophysical data in this reach of the Hosgri fault zone more truly image the character of the fault zone than in other areas. Crouch reviewed with us deep penetration seismic data acquired since his 1984 publication and concluded that these data support his interpretation of the Hosgri as a listric thrust fault. The only significant variation in his interpretation since 1984 that he discussed is that he currently believes that the Hosgri fault zone has experienced little or no lateral displacement whereas earlier he concluded that minor lateral displacement may have occurred on the fault.

Thom Davis has conducted extensive studies on the general tectonic environment of south-central California and has addressed the Hosgri fault zone indirectly as it relates to the tectonic setting. Davis applies the techniques of retrodeformable structural cross sections for assessing the genetic association of surface deformation with deformation occurring at mid- and deep-crustal levels. In general, Davis believes that significant late Cenozoic crustal shortening has occurred in south-central California along subsurface low-angle faults or detachment surfaces. These faults have produced "fault-bend" or "fault-propagation" folds in the upper crust. In a preliminary cross section at the general latitude of Point San Luis, Davis concluded that the Hosgri fault zone cannot be an active listric thrust fault (Davis and McIntosh, 1987). In his interpretation, the Hosgri is a former basin-margin normal fault dipping steeply to the west that has subsequently been rotated to dip steeply to the east.

Clarence Hall favors a right-lateral strike-slip fault interpretation for the Hosgri fault zone. Hall bases his interpretation primarily on detailed stratigraphic studies and regional correlations of distinct stratigraphic sections or "packages" on either side of the fault. Hall believes that at least 80 kilometers and probably more than 100 kilometers of right-lateral displacement has occurred in the middle and late Cenozoic on the Hosgri/San Simeon fault zone. This interpretation was published in 1975. In 1981, Hall published a paper ascribing the regional tectonostratigraphic relationships in the Los Osos/Santa Maria Basin to pull-apart basin development along a major right-lateral strike-slip fault that he called the San Luis Obispo Transform fault, of which the Hosgri fault zone was an important element. Hall reviewed with us data and opinions published by others since 1981 and concluded that the Hosgri/San Simeon fault zone has probably been the locus for possibly more than 100 kilometers of cumulative Cenozoic right-lateral displacement.

Bruce Luyendyk has investigated the concept of allochthonous block rotation as an important style of tectonic deformation in south-central California. He and his students have acquired an extensive data base of regional paleomagnetic data that indicate significant clockwise rotation of the Transverse Ranges in two pulses, one during the middle Miocene and one in the Pliocene and Quaternary (Luyendyk and others, 1980, 1985; Hornafius and others, 1986). Luyendyk interprets the rotation to probably result from a right shear couple within the North America/Pacific plate boundary. In Luyendyk's model, the Hosgri fault zone is a major right-lateral strike-slip fault along the western margin of the rotating western Transverse Ranges. Luyendyk and his students have more recently acquired seismic reflection data to directly assess the nature of the Hosgri fault zone. They interpret these data to indicate that the Hosgri fault zone is a high-angle strike slip fault that extends south of Point Arguello as a complex en echelon system of faults before merging with or terminating against east-west trending structures in the Santa Barbara Channel (Steritz, 1987; Steritz and Luyendyk, 1987).





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Each of the individuals interviewed cautioned against using their published data and interpretations to directly assess the late Quaternary behavior of the Hosgri fault zone. Each individual commented that their data apply more generally to the late Cenozoic history of the fault zone rather than specifically to the late Quaternary history and/or that the focus of their research was not the seismogenic behavior of the fault zone. They emphasized, however, that their data and interpretations should be considered and that an interpretation of the contemporary tectonic setting of the Hosgri fault zone must be consistent with the primary structural elements of their model.

Thus, since its discovery, the Hosgri fault zone has been interpreted by these individuals to manifest a broad range of deformational styles and rates of slip and to have functioned as an active fault in a variety of tectonic environments throughout either Neogene or much of Cenozoic time. It is important to recognize that these individuals generally utilized unique data sets that cover a specific geographic area and/or geologic time interval. Although the varying interpretations presented by these individuals are often contradictory, each may be consistent with the data, geographic area, and geologic time interval on which the interpretation is based. In many instances, the specific data set is useful for characterizing some aspects of the Hosgri fault zone but not for characterizing other aspects. For example, the stratigraphic analyses by Hall are useful for characterizing cumulative slip on the fault zone but not for directly assessing fault geometry. Similarly, the analysis of seismic reflection data by Crouch is useful for characterizing down-dip geometry of elements within the Hosgri fault zone but not for quantifying cumulative displacement or slip rate. This emphasizes the need to integrate a variety of data sets to fully characterize the contemporary behavior of the Hosgri fault zone from which an assessment of the future seismogenic behavior can be made.

CHARACTERIZATION OF HOSGRI FAULT ZONE

Objectives. A primary objective of the Long Term Seismic Program is to characterize the Hosgri fault zone as a potential earthquake source. To accomplish this objective, we integrated a variety of geophysical, seismological and geological data sets along the entire length of the fault zone that specifically address the Quaternary behavior of the fault zone. Such a characterization involves assessing the fault zone's history of deformation, rate of recent deformation, geometrical factors such as length and down-dip width, and the evaluation of its role in the current tectonic regime.

In the following sections we describe the basic interpretive products that were developed to characterize the Hosgri fault zone and the results of our analysis. Key factors affecting the evaluation of the fault zone as a potential seismogenic source include segmentation, down-dip geometry, and sense and rate of current slip.

Geophysical Characterization. The Hosgri fault zone lies offshore along its entire length, from its northern termination west of the southern San Simeon fault in the Cambria/Point Estero area to its southern termination offshore of Point Pedernales (Figure 2-38, Plate 3). Characterizations of the fault zone are therefore dependent on indirect observations using geophysical techniques, coupled with regional assessments based on seismicity data and tectonic analyses. In our analysis of the Hosgri fault zone and the adjacent offshore Santa Maria Basin we make reference to a large number of geophysical data sets that, for the convenience of discussion, are grouped into three categories:

- Potential field data refer to the regional aeromagnetic and gravity maps published by McCulloch and Chapman (1977) and Beyer and McCulloch (1988). These regional data do not have the resolution for detailed characterization of the fault zone. Their



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primary utility is in identifying changes in basement rock characteristics and morphology and in confirming seismic data interpretations which involve basement rocks. Because these maps are in the public domain, they are not included in this report.

- Seismic reflection data sets are classified as either common-depth-point or high-resolution. Some surveys contain both classes of data. Common-depth-point refers to data that were recorded using a multichannel cable and common-depth-point or similar field techniques that allow for post-survey digital processing to improve signal-to-noise ratios and correct geometric distortions. These data represent the primary source of images of the fault zone at depth but do not provide a good image of the upper few tens of meters of section beneath the seafloor. Because this type of data is a primary exploration tool for the petroleum industry, the offshore Santa Maria Basin was extensively surveyed using this technique beginning in the mid-1970s. Since 1979, PG&E has acquired over 7,000 kilometers of common-depth-point reflection data for use in the Program either through purchase of propriety data sets or by contracting directly for the survey (Table 2-3 and Plate 1).
- High-resolution data refers to records from a series of low-energy, mid- to high-frequency sonic sources where the data are recorded in analog or digital form using a single-channel recorder. Depending on the source and the local geology, these data usually image only the seafloor or the upper few meters to few hundred meters of section beneath the sea floor. Their primary use in this study was to map seafloor geomorphic features and identify deformation of the most recent sediment layers that cannot be imaged by the common-depth-point techniques. An extensive set of high-resolution data was acquired by PG&E in the coastal zone area along the entire reach of the Hosgri fault zone. The survey coverage is shown on Plate 2, and the surveys are listed in Table 3.

Seismic imaging of the fault zone is difficult because of a combination of factors including shallow water depths, shallow basement rocks (Franciscan assemblage), tightly folded sedimentary rocks adjacent to the fault zone, and the complex nature of the upper portion of the fault zone. In addition, the seismic time sections are distorted by the rapid lateral velocity changes resulting from juxtaposition of rocks with different acoustic properties. To remove such distortion, our analyses are based on detailed maps and depth-corrected sections such as those presented on Plates 1, 2, and 4 to 8. The plates were specifically designed to illustrate the data coverage, interpretation methods, and the key geologic features that were used to develop our results. The objectives of the individual plates, the data on which they are based, and the technical approach to producing them are briefly described below.

Plates 1 and 2, Seismic Survey Shiptrack Maps: These plates show the common-depth-point and high-resolution surveys utilized in the program. These maps were originally produced on ten sheets at a working scale of 1:24,000 from navigational tapes and maps supplied by the survey contractors. They have been reduced to three sheets at 1:100,000 for the report. This reduction has necessarily resulted in some loss of legibility and detailed information but still provides the basic information on data density and location needed as part of the evaluation of the interpretive products.

Plate 4, Near-Surface Faults, Thickness of Post-Late Wisconsinan Sediments and Seafloor Geomorphic Features: This map depicts the data that are used to assess the late-Quaternary deformation along the Hosgri fault zone and adjacent faults to the east. The isopach shows the thickness of post-late Wisconsinan sediments that have been deposited since the last sea level lowstand approximately 18,000 years ago. The formation and deformation of the small basins containing these sediments reflects late-Pleistocene and Holocene deformation. Also depicted on this map are faults that occur within the upper one-half second on the geophysical records and geomorphic features such as scarps that may reflect faulting. This map was



constructed using the data sets shown on Plate 2, including both high-resolution and common-depth-point records.

Plate 5, Structural Trend Map: This map depicts all of the geologic structures that were mapped from both the common-depth-point and high-resolution data sets. It is intended to show the trends, continuity, and plan-view spatial relationships of the geologic structures in the sedimentary rocks of the offshore Santa Maria Basin. The structural trend map includes structures of varying depths and ages that are derived from the numerous data sets. Information regarding the age of deformation and relative depths of individual structures is provided in the text of the report when they are discussed.

Plate 6, Depth-Corrected Velocity Models Across the Hosgri Fault Zone: This plate was constructed to illustrate variations in the true down-dip geometry along the northern two-thirds of the Hosgri fault zone. The fault zone is very complex geometrically: several closely spaced traces occur in a 1- to 3-kilometer wide zone; variations in dip of the fault planes occur both down-dip and between the strands; and a complex history of deformation has resulted in varying patterns and styles of folding. The vertical and horizontal juxtaposition of rock bodies with significant velocity differences results in the time-based seismic sections presenting a distorted geometrical view of the fault zone. A velocity model, based on geologic relationships and measured velocities, was applied to the reflection records and used to produce true-scale models of the fault showing dip and the spatial relationships between the traces.

Plates 7 and 8, Interpreted Seismic Sections Across the Central Santa Maria Basin: These sections depict the geologic horizons (formations and unconformities) that were mapped in the central area of the offshore Santa Maria Basin and whose relative thicknesses and deformation overprints were used in the basin analysis to identify the principal deformational pulses in this portion of the basin. These sections were produced by tying the seismic records into well data and using the techniques of seismic

stratigraphy (Vail and others, 1977) to identify the horizons.

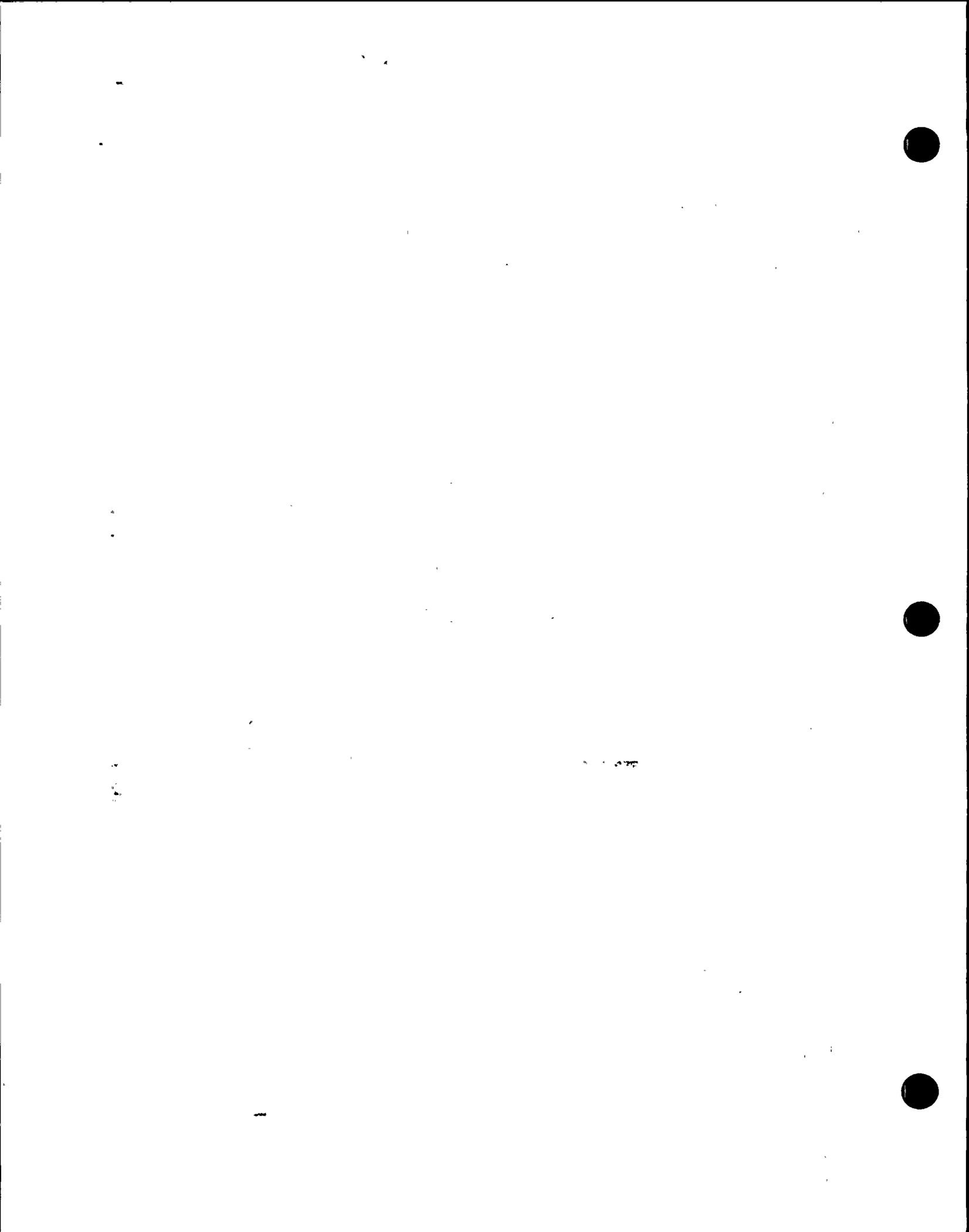
SEGMENTATION

The Hosgri fault zone displays abundant geologic evidence of segmentation along its length. At particular points along its length, geometric and geologic relationships show rather abrupt changes in behavior. In this section we describe these "segmentation points" in terms of the various data that allow us to recognize them. In the following section, we will describe the character of the fault zone in the various reaches between the segmentation points.

The segmentation points (Figure 2-42) that will be discussed are the following: The Cambria stepover between the San Simeon and Hosgri fault zones, the intersection between the Hosgri and Los Osos fault zones, the intersection between the Hosgri fault zone and the Pecho fault, the intersection between the Hosgri fault zone and the Casmalia fault zone, the intersection of the Hosgri fault zone and Lion's Head fault, and the southern break-up of the Hosgri fault zone near Point Pedernales.

Cambria Stepover. The Cambria stepover is the segmentation point between the Hosgri and the San Simeon fault zones. The right-step is about 5 kilometers wide and is an extensional or "releasing stepover" (defined, for example, by Barka and Kadinsky-Cade, 1988) as indicated by the existence of small normal-fault bounded grabens in the stepover region. In addition, a local extensional basin filled with sediments that are post-late Wisconsinan in age is present within the en echelon stepover (Plate 4). In the stepover region, the nature of folding to the west of the fault zone changes. To the south, a series of relatively broad folds are present that trend subparallel to the Hosgri trend. However, to the north of the stepover, a series of tighter folds exist that have a more westerly trend. These folds appear to be related to the southern side of the Piedras Blancas anticlinorium, a transpressional structure associated with the San Simeon fault zone north of San Simeon (Plates 3 and 5).

Los Osos Fault Intersection. Where the Los Osos fault zone intersects the Hosgri fault zone,



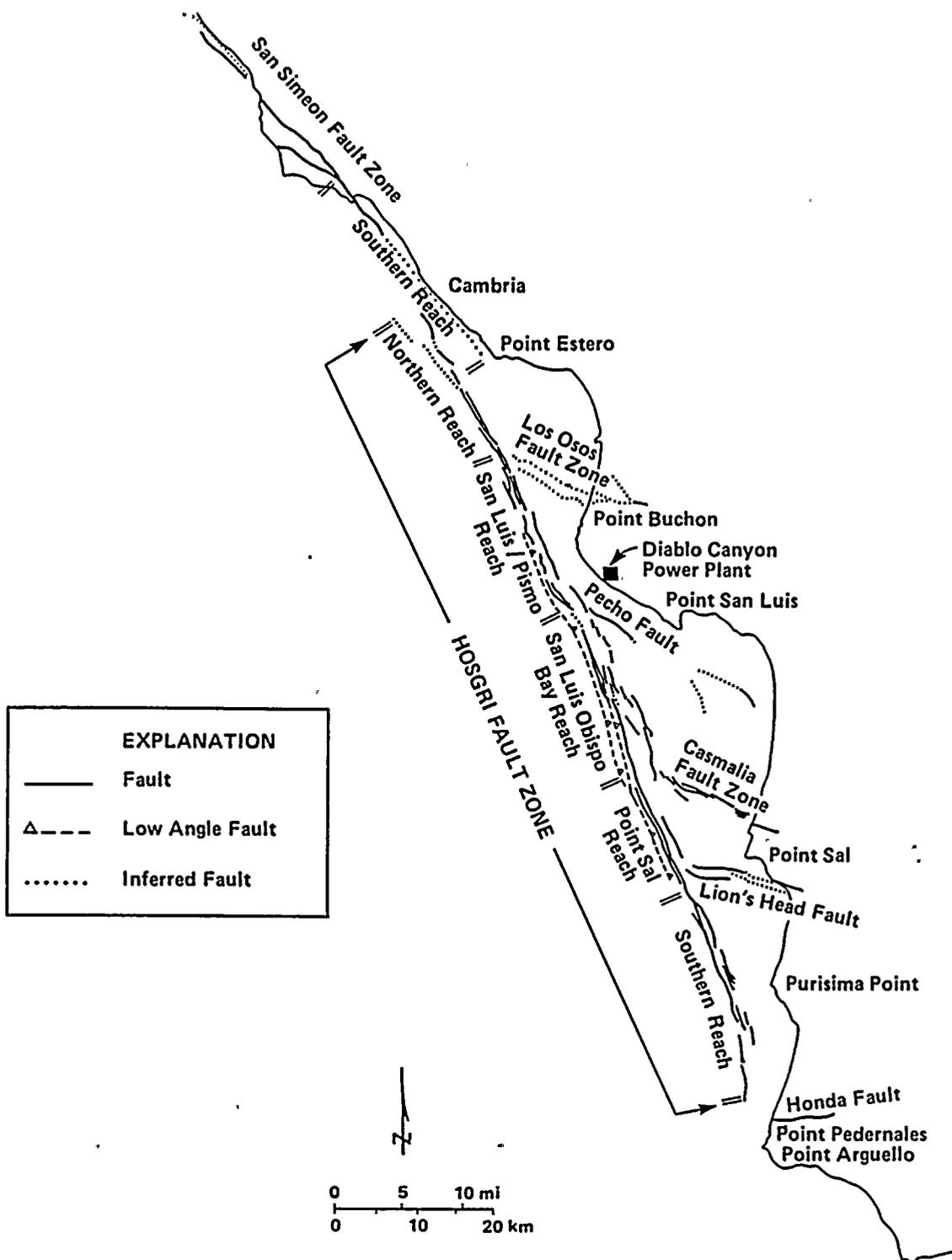


Figure 2-42
 ..Segmentation points and intervening reaches along the Hosgri fault zone.

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several geometric and structural changes are evident. The Hosgri fault zone makes an approximately 11-degree westerly bend at this point and the width of the fault zone and the number of fault traces abruptly increases from north to south. The Los Osos fault zone is the northeasterly boundary of the San Luis/Pismo structural block and this point marks the northwesterly corner of the uplifted block. Because of this structural relationship, the relative vertical component of slip on the Hosgri fault zone probably increases south of this point due to uplift of the San Luis/Pismo block. Offshore seismic reflection data show that the Tertiary faults and folds of the block that are present east of the Hosgri fault zone are not present west of the fault zone. Local topographic features such as the locally uplifted "59-meter" ridge at the Los Osos/Hosgri intersection probably reflect local compression at the intersection between these two fault zones.

Pecho Fault Intersection. The Pecho fault marks the location of the southwestern boundary of the San Luis/Pismo structural block. Therefore, the intersection of the Pecho fault with the Hosgri fault zone, like the Los Osos fault intersection, probably marks a change in the relative vertical component of slip across the Hosgri fault zone. The fault zone also makes a slight bend at this location. Structural trends from the seismic reflection interpretations (Plate 5) show a pronounced decrease in mapped folds and faults south of the Pecho fault on the east side of the Hosgri fault zone, most likely due to the change in uplift across the southern boundary of the San Luis/Pismo block to the generally unfolded, subsiding Santa Maria Valley block.

Casmalia Fault Zone Intersection. At the latitude of the intersection of the Casmalia fault zone with the Hosgri fault zone, abrupt changes in the style of deformation occur not only along the Hosgri fault zone but within the adjacent region east and west of the fault zone. At the intersection, the eastern-most trace of the Hosgri fault zone abruptly ends to the south. The Casmalia block is currently being uplifted in a manner similar to the San Luis/Pismo block and, therefore, the relative vertical slip rate across the

Hosgri fault zone probably increases locally to accommodate the block uplift. An abrupt change in the character of deformation to the west of the Hosgri fault zone also occurs at this location (Plate 5). To the north of the Casmalia intersection, a few long, gentle folds are mapped in the eastern part of the offshore Santa Maria Basin. To the south, a series of folds and faults, including the Purisima and Lompoc trends, are present west of the Hosgri. Nowhere else along the entire Hosgri fault zone is this level of deformation observed to the west of the Hosgri fault zone.

Lion's Head Fault Intersection. The Lion's Head fault represents the southern boundary of the Casmalia structural block and, as a result, marks a change in the relative vertical slip rate on the Hosgri fault zone. Beginning immediately south of the Lion's Head fault intersection, the Hosgri fault zone shows most dramatically its role as a boundary between differing strain provinces to the east and west. To the west, a series of long north-northwest-trending folds and faults are mapped that trend subparallel to the Hosgri fault zone; to the east, folds and faults are much shorter, of lesser wave length, and trend west-northwest to east-west and terminate to the west at the Hosgri.

Southern Termination. Toward its southern termination near Point Pedernales, the Hosgri fault zone begins to lose continuity and the number of main traces decreases until no through-going fault is evident. In addition, unlike most of the length of the fault zone, the Hosgri fault zone no longer makes a clear boundary between different styles and trends of strain (Plate 5).

DESCRIPTION AND DOWN-DIP GEOMETRY

Detailed descriptions of the offshore San Simeon (southern reach) and Hosgri fault zones are given in the following paragraphs. The San Simeon fault zone is observed onshore along part of its length and the characterization of the offshore section is based, in part, on the onshore observations of the fault zone. The Hosgri fault zone lies offshore along its entire length and its descriptions are



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derived from the previously described geophysical characterization methodology.

For convenience in describing this complex fault zone we have divided it into "reaches" that are bounded by the segmentation points discussed in the preceding section. Although in some cases there is a direct correspondence, the reaches described in this section are not necessarily identical to rupture segments as discussed in Chapter 3, Seismic Source Characterization. More than one of these reaches may rupture during a single surface-faulting event. The reaches are described in the following order from north to south (Figure 2-42).

Southern Reach of the San Simeon Fault Zone
 Northern Reach of the Hosgri Fault Zone
 San Luis/Pismo Reach
 San Luis Obispo Bay Reach
 Point Sal Reach
 Southern Reach of the Hosgri Fault Zone

Southern Reach of the San Simeon Fault Zone.
 The San Simeon fault zone is shown on Figure 2-38 and in greater detail on Plates 3 and 5.

The San Simeon fault zone is a northwest-trending, predominantly strike-slip fault that subparallels the central California coast from near Lopez Point to Point Estero. It is locally exposed onshore from San Simeon Point to north of Ragged Point, a distance of 20 kilometers (Figure 2-43). As part of the Long Term Seismic Program, an extensive field investigation was conducted to characterize the onshore reach of the San Simeon fault zone, and a program of geophysical exploration, seafloor sampling and bathymetric analysis was conducted to assess the offshore continuity of the fault to the northwest and southeast.

Based on offshore geophysical investigations, the northern termination of the San Simeon fault zone lies offshore north of Lopez Point and is manifest as either a right step or a right bend into the Sur fault (Figures 2-38 and Plate 3). To the southeast, the San Simeon fault zone dies out west of Point Estero where right slip is transferred to the west across a 5-kilometer-wide right stepover,

called the Cambria stepover, to the Hosgri fault zone. The total length of the San Simeon fault zone, including its offshore and onshore reaches, is 87 kilometers.

As shown by the onshore studies, the fault zone is constrained at San Simeon Cove within major boundary faults that define a zone about 122 meters wide (Figure 2-43). The zone splays to the northwest and has several traces that trend more westerly than the N35°W strike of the main eastern trace of the fault zone. The dominant sense of movement along major strands within the zone is right-lateral strike slip, but faults within the zone that trend more westerly exhibit a significant component of dip-slip displacement.

The southern reach of the San Simeon fault zone is interpreted to trend N38°W for 28 kilometers from San Simeon Bay to its termination off Point Estero (Plate 5). Along this reach, the fault is inferred to have one main trace.

The fault trace is crossed by several geophysical lines in San Simeon Bay, but due to limited data quality in the shallow water area, it is directly observed in the subsurface on only a single line. For 5 kilometers southeast of San Simeon Bay, the trace is interpreted from a series of low east-facing seafloor steps. Additional evidence for fault location and recency of activity comes from warping of the late Wisconsinan unconformity and overlying sediment in this area (Plate 4).

From the point 5 kilometers south of San Simeon Bay, the fault zone is inferred based on geomorphic evidence to lie east of the geophysical data coverage and to continue for a distance of 15 kilometers along the straight rocky coast. Because no fault is seen in the geophysical lines and the sea cliff is not cut by a fault, the fault zone, if present, must lie in a narrow linear corridor between the shoreline and the shoreward limit of the geophysical survey lines.

Beyond the southeast end of straight section of coastline, the fault zone has been projected southward for an additional 7 kilometers to Point Estero based on a series of northeast-facing seafloor steps and notches (Plate 4). Again, it is not imaged in the subsurface or nearshore geophysical data. However, good quality





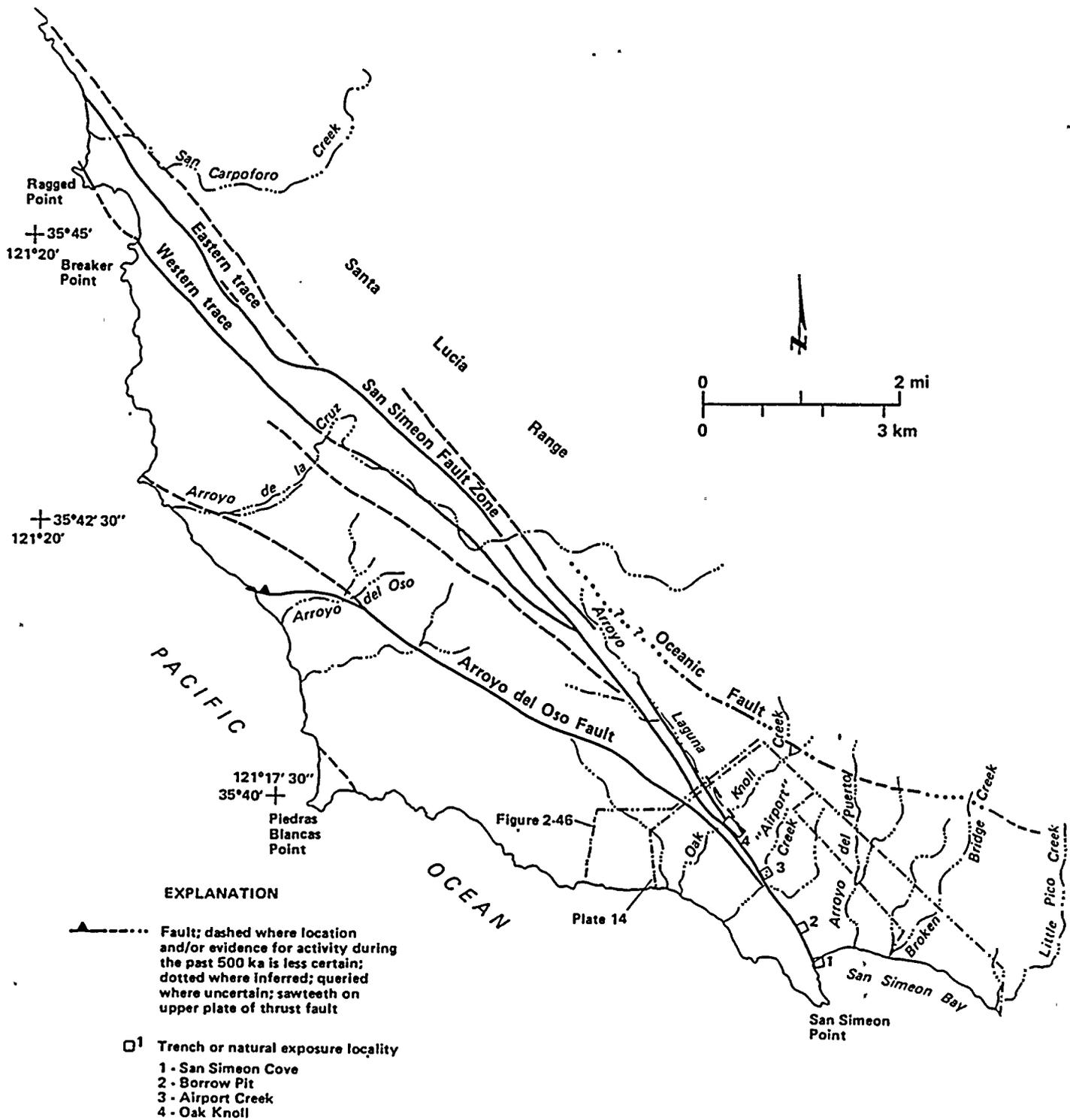


Figure 2-43
Index map showing locations of study areas, San Simeon fault zone.



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geophysical data across the projected fault trace in Estero Bay preclude extending the fault zone beyond Point Estero. At Point Estero, the San Simeon fault zone is interpreted to die out and its strike-slip displacement is transferred to the Hosgri fault zone at the Cambria en echelon stepover.

Northern Reach of the Hosgri Fault Zone. The northern reach of the Hosgri fault zone trends N40°W for 20 to 22 kilometers between the Cambria stepover area and the intersection with the Los Osos fault zone in Estero Bay at the north end of the San Luis/Pismo structural block (Figure 2-42, Plate 5, Sheet 2). The salient features of this reach include the northern termination of the fault zone, the stepover to the southern reach of the San Simeon fault zone described previously, and the intersection with the Los Osos fault zone and the San Luis/Pismo block.

Within this reach, two closely spaced traces have been mapped; a western trace which exists only south of the latitude of Morro Rock and an eastern trace which runs the entire length of the reach. The western trace closely parallels the axis of an anticline and is associated with gas-saturated sediments. This strand is apparently acting as a conduit for hydrocarbon escape to the ocean.

The eastern trace is a prominent, near-vertical discontinuity on the seismic records (line W-76A, Plate 6). Near its northern termination the fault dips 80 to 90 degrees to the northeast. Short, west-verging splays merge with this near-vertical east strand at a depth of 1 to 2 kilometers (Plate 6, W-76A). The splays clearly branch from the main trace, do not cut it, and are interpreted as one-sided flower structures. North of Point Estero the eastern strand loses definition as a prominent fault break and dies out.

Further north, seismic lines across the southwestern flank of the Piedras Blancas anticlinorium (Plate 5, Sheet 3) show a series of west-northwest trending folds that are clearly not cut by any vertical faulting, confirming that the Hosgri fault zone does not continue northwest through or around the anticlinorium.

In the 11-kilometer-long, 5-kilometer-wide Cambria stepover region between the San Simeon and Hosgri fault zones, a series of normal faults and small grabens are present (Plates 4 and 5, Sheet 2). These features are interpreted as pull-apart structures suggesting that right slip along the southern reach of the San Simeon fault zone is transferred to the northern reach of the Hosgri fault zone.

San Luis/Pismo Reach. Along this reach, the Hosgri fault zone forms the western boundary of the San Luis/Pismo structural block. The fault zone extends S20°E for approximately 20 to 22 kilometers from the intersection with the Los Osos fault zone on the north to the intersection with the Pecho fault on the south. This reach is the part of the Hosgri fault zone closest to the plant site.

Three closely spaced structural components are present within this reach (Figure 2-44). Two discontinuous vertical faults, denoted as the eastern and western strands, are generally parallel to and within 2 kilometers of each other. A third, buried, low-angle fault lies outboard of the western strand and appears to merge with it at depth. The geometrical relationships of the three fault strands with each other are shown on Plate 5 (Sheet 2) and on Plate 6 (lines GSI-85 and 86).

The western strand is usually near vertical in the upper 1 kilometer of the section and gradually decreases in dip to about 65 to 70° NE at a depth of 3 to 4 kilometers. The eastern strand generally appears to dip about 70 to 80° NE through its observable down-dip image. Both strands are expressed geomorphically by discontinuous sea floor scarps and both offset the late Wisconsinan unconformity (Plate 4, Sheet 2).

The eastern strand forms the apparent structural boundary between the complexly folded and uplifted San Luis/Pismo block and the offshore Santa Maria Basin to the west. There is a marked change in the trend, length, and wavelength of structures across the eastern strand. West of the eastern strand, folds and faults typically parallel the Hosgri fault zone. To the east, the structures trend more to the northwest, in line with the trend of the uplifted San Luis/Pismo block, and terminate westward against the Hosgri fault zone.



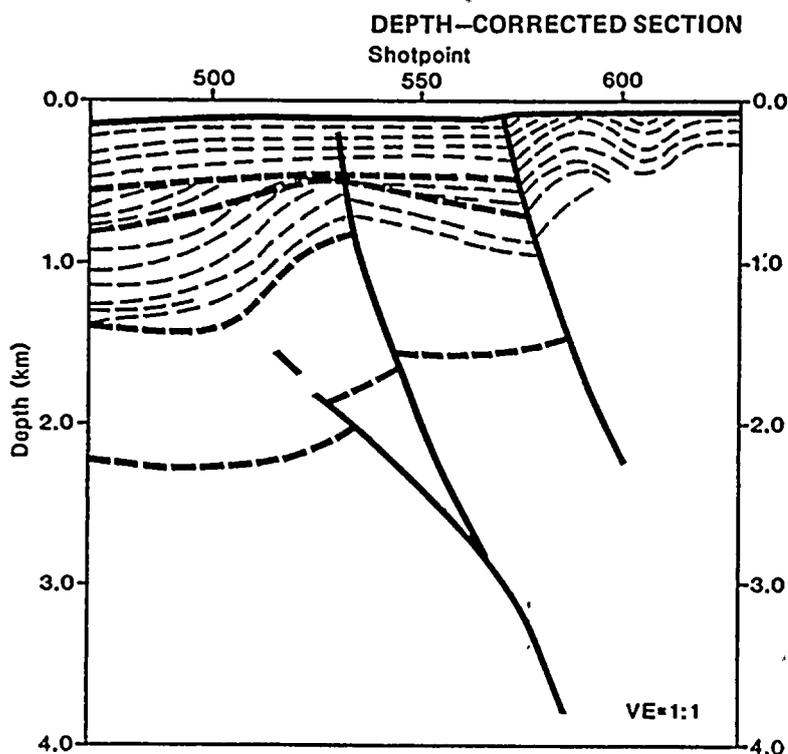
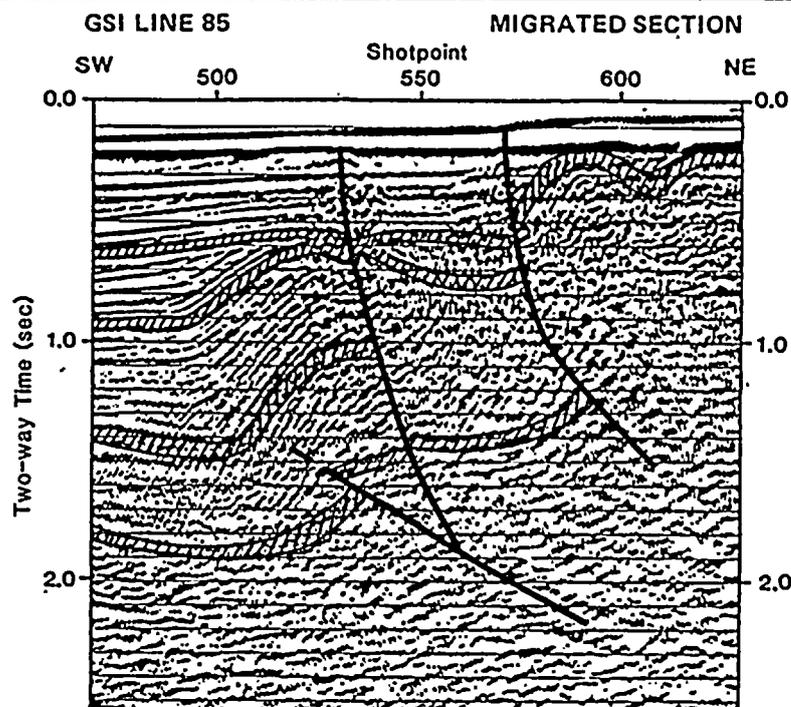


Figure 2-44

Common-depth-point seismic reflection record across the Hosgri fault zone offshore of Point Buchon. East and west high-angle strands, low-angle fault component, and associated folding are shown. Depth-corrected section illustrates true dip of fault plane. Velocity-depth-conversion procedure is described on Plate 6. Note truncated anticline at shotpoint 525 and tight folding east of fault zone. Stratigraphic and structural relationships in the upper 0.5 seconds are best observed on high-resolution records.



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There is a noticeable westward deflection in the trend of the Hosgri along this reach, which is most pronounced directly west of Point Buchon. A monoclinical fold which deforms the mid-Pliocene unconformity is also present in this area. Both the deflection of the fault trace and monoclinical fold are believed to be the result of compression associated with ongoing uplift of the structural block east of the Hosgri fault zone acting on the area to the west.

The low-angle fault component is present beneath and somewhat to the west of the western strand at depths of 1 to 2 seconds (Plate 12). It dips 35° to 45° NE in the upper section, and increases in dip to about 60° NE at depths of 2 to 3 kilometers where it apparently merges with the western strand. In this reach, the low-angle fault is not observed to cut the western strand. The low-angle fault also does not cut a prominent Pliocene/Miocene unconformity which is best shown on Plate 6 (lines GSI-85, 86, and JEBCO-126) at a depth of about 1 kilometer (1 second). This unconformity is not displaced anywhere along the entire length of the low-angle fault indicating that the major episode of compressional faulting had ended prior to the deposition of the Pliocene sediments on the unconformity.

San Luis Obispo Bay Reach. South of the intersection with the Pecho fault the Hosgri fault zone crosses San Luis Obispo Bay on a strike of $S15^{\circ}E$ for 23 kilometers to an intersection with the Casmalia fault zone (Figure 2-42). Along this reach, the zone consists of a continuous west trace and several discontinuous eastern traces within a zone 2- to 3-kilometers wide. The relatively continuous western strand is vertical at the surface but becomes shallower dipping (60 to 75° NE) (Plate 6, line GSI-101) to depths of 4 kilometers. Tertiary strata lying between the two traces dip to the southwest and appear to be downdropped in a half-graben. Several minor folds are mapped subparallel to and between the two fault traces. The western trace and several of the eastern traces locally offset the late Wisconsinan unconformity indicating late Pleistocene activity along this reach.

A low-angle fault plane is also present throughout this reach west of the westernmost near-vertical fault strand. It dips 40° NE at the north end of San Luis Obispo Bay and shallows in dip to the south. The geometrical association of the faults and their down-dip geometry are indicated on Plates 5 (Sheets 1 and 2) and 6 (lines JEBCO 126 GSI-101, and 106), respectively.

In the San Luis Obispo Bay reach the low-angle fault is more prominent than elsewhere along the length of the Hosgri fault zone and has been reported in the literature (Crouch and others, 1984). Our mapping has shown that there are two such low-angle faults in this area that overlap on the southern portion of Sheet 2, Plate 5. This is also seen on Plate 6, JEBCO line 126, where there are two low-angle faults. The lower fault is correlative with the low-angle fault that continues north to Point Buchon, while the upper fault is correlative with the low-angle faults imaged on GSI lines 101 and 106. Plate 6 also shows the changes in dip that occur along the low-angle strand as it crosses the bay. South of line GSI-106 it rapidly steepens and appears to be vertical by line 107. The shallowest dips, 20 to 30 degrees, occur in the area just north of the intersection with the Casmalia fault zone. These dips increase to about 60 to 70 degrees at depths of 2 to 4 kilometers. Neither low-angle fault appears to disrupt the Miocene/Pliocene unconformity in this reach.

Point Sal Reach. The Point Sal reach is a 14- to 18-kilometer long section of the fault zone that lies between the intersection with the Casmalia fault zone and the southern limit of the Lion's Head fault zone (Figure 2-42). The Hosgri fault zone forms the western boundary of the Point Sal high, a basement high within the Casmalia block that is uplifted between the Casmalia and Lion's Head fault zones. This basement high is also well defined by potential field data.

The Point Sal reach is imaged as a zone of complex faults and folds. Even though the data density is quite high in this area, the structural complexity is difficult to resolve. Two parallel high-angle faults in a zone 1-kilometer wide, as well as a series of low-angle faults to the west, are mapped in this area. As in the San Luis Bay

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reach, the western high-angle fault is continuous and appears to be near vertical (70 to 90 degrees) to depths in excess of 2 kilometers.

The eastern fault is shorter in length (6 kilometers) and is truncated to the south by the Lion's Head fault zone and to the north by a syncline on the south side of the Casmalia fault zone (Plates 3 and 5, Sheet 2). This strand also dips steeply to the northeast.

At the southern end of the reach a series of shallow-dipping west verging faults splay from the main trace and have the appearance of a flower structure (Plate 6, Line GSI-107). Such structures are typically associated with strike-slip deformation. These low-angle faults lie in proximity to the near-vertical western trace throughout this reach and gradually steepen in dip to merge with the western trace south of the Lion's Head fault, at the latitude of seismic line GSI-107.

Southern Reach of the Hosgri Fault Zone. The southern reach is a 24- to 26-kilometer section of the Hosgri fault zone that lies between the flower structure southwest of the Lion's Head fault and a point about 4 kilometers northwest of Point Pedernales where the fault zone breaks up into short, en echelon traces and apparently dies out (Figure 2-42, Plate 5, Sheet 1). The northern part of this reach is about 5.5 kilometers west of Purisima Point and strikes N20°W. The southern reach is not continuous with the Point Sal reach at the surface but is separated by an en echelon left step of 0.5 to 2.0 kilometers. At the midpoint between Purisima Point and Point Pedernales, the southern reach bends to a more north/south strike of N5°W.

The southern reach of the Hosgri fault zone is imaged on regional gravity data as the western flank of a series of gravity lows that roughly parallel the coast between the mouth of the Santa Maria River and the mouth of the Santa Ynez River. This contrasts with the entire zone to the north where gravity lows attributable to thick sediments in the offshore Santa Maria Basin are generally situated west of the Hosgri fault zone. A prominent gravity high west of the northern part of the reach suggests that basement has been

raised along the western side of the Hosgri fault zone. The southern reach is seen as an indistinct northwest-trending trough on regional aeromagnetic data used by Chapman and McCulloch (1974). There is a magnetic high west of the reach in the same location of the gravity high which further supports the interpretation from seismic data that the basement has been locally elevated along the western side of the Hosgri fault zone (Plate 7, Sheet 3).

The duality of east and west fault traces is no longer a dominant characteristic of the Hosgri fault zone in this reach. Although there are two mappable traces along the reach south of Point Sal, the nature of these traces differs from the usual east/west duality to the north in that neither trace clearly marks the eastern limit of the offshore Santa Maria Basin. Rather, they lie within a section of raised and folded strata of probable middle Tertiary age. Down-dip images are usually limited to the upper 2 kilometers (Plate 7, Sheet 3, line 114) where both fault strands appear to be within ± 5 degrees of vertical. Locally, dips in the range of 75 degrees to the west and east are observed.

West of Purisima Point, there is a component of vertical displacement on the Hosgri fault zone with the apparent sense of movement generally up on the west. This is in accord with the observed gravity and magnetic highs west of the Hosgri fault zone that suggest that the basement is raised along the fault.

Between Point Sal and Purisima Point, the Hosgri fault zone truncates east/west trending folds situated east of it and separates them from the northwest-southeast trending folds and faults of the Purisima trend that parallel it to the west.

In a local area northwest of Purisima Point, the axial traces of east/west trending folds that are truncated by the Hosgri fault zone are bent to the south as they approach the eastern side of the Hosgri zone. This southward bending suggests a history of left-lateral slip along this portion of the Hosgri fault zone. The age of this deformation is not well constrained but post-dates or is concurrent with growth of the folds, which are Miocene and Pliocene in age.



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South of Purisima Point, the Hosgri fault zone resembles the San Luis Obispo Bay reach in that there may be an eastern trace that forms the eastern limit of the offshore Santa Maria Basin and other traces of the fault zone to the west that cut through the flank of the Tertiary section deposited within the basin. This eastern trace has a more southeasterly trend than the western trace so that it diverges progressively to the south from the west trace. The intervening area is cut by several smaller faults. Both the eastern trace and the intervening smaller faults die out as they approach what is interpreted to be the northwestern boundary of the Transverse Ranges block. South of their termination, the western fault trace bends to the south so that its strike is due north. As it passes into the Transverse Ranges block, the sense of vertical movement changes from up on the west to up on the east. The western trace continues for 4 kilometers, curves to the east and disappears 4 kilometers northwest of Point Pedernales. No feature mapped further to the southeast is continuous with or has the character of the Hosgri fault zone where it is last seen. Faults and folds that trend east/west to northwest-southeast south of Point Arguello cross any reasonable southern projection of the Hosgri fault zone. These observations indicate that the Hosgri fault zone probably terminates northwest of Point Pedernales.

DEFORMATIONAL HISTORY

The Hosgri fault zone has had a long history of recurrent Cenozoic displacement and associated fold deformation. This history of deformation encompasses a variety of tectonic settings and consequently has produced a complex pattern of faulting and folding along the length of the fault and bordering areas. In interpreting the recent tectonic behavior of the Hosgri fault zone, therefore, it is important to recognize those structures produced during earlier tectonic events and to distinguish them from structures related to Quaternary deformation along the fault zone and in bordering areas. For example, we have recognized a significant pulse of compression in the region from about 6.0 million or 5.2 million to 3.0 million or 2.8 million years ago that produced most of the late Cenozoic folds in the offshore Santa Maria Basin and the low-angle fault

components along the Hosgri fault zone. In this section, we describe the style and timing of pre-late Quaternary deformation along the Hosgri fault zone and the adjacent offshore Santa Maria Basin in order to fully evaluate the recent history of the fault zone.

Paleogene. The Hosgri fault zone may have developed as a major structure during the Paleogene. As described earlier, significant lateral displacement along parts of the San Gregorio/Hosgri fault system has been proposed by Hall (1975), Graham and Dickenson (1977), Dickenson and Snyder (1979), Blake and others (1979) and Clark and others (1984). Studies by Seiders (1979) and Hamilton (1984) indicate that most of this displacement probably occurred in the Oligocene or earlier. Interpretation of seismic reflection data in the southern offshore Santa Maria Basin indicates that Paleogene sedimentary rocks are locally present west of the fault as far north as the latitude of Lion's Head but are not present to the east of the fault north of the Santa Ynez River. These stratigraphic relationships suggest but do not require Paleogene lateral displacement prior to desposition of Miocene sedimentary rocks. If the Hosgri fault zone developed in the Paleogene as an element of a transcurrent fault system, it likely originated as a subvertical strike-slip fault.

Neogene. From the late Oligocene through the middle Miocene, the Hosgri fault zone may have formed the eastern margin of a series of rapidly subsiding basins within a transtensional system (McCulloch, 1987). Thick sections of Miocene Volcanics and Monterey Formation are present in these basins west of the Hosgri fault zone (Plate 8). These deposits thicken eastward toward the Hosgri and thin abruptly east of the Hosgri, suggesting that the fault zone formed the eastern structural boundary of the subsiding basin. Consequently, the Hosgri fault zone may have acted in the Miocene as a high-angle, presumably right-lateral, fault with a significant component of down-to-the-west displacement.

The Miocene episode of transtensional displacement along the Hosgri fault zone changed to transpression in the late Miocene about 6 to 5.2 million years ago. Structures within the Hosgri



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fault zone and bordering areas record a major late Miocene to middle Pliocene episode of tectonic transpression or convergence in the region. These structures are illustrated on seismic lines presented on Plates 6, 7, and 8. The onset of this convergence is roughly contemporaneous with the eastward jump of the Pacific spreading center into the Gulf of California, an increased rate of right-lateral slip on the San Andreas fault, and a late Miocene pause in the clockwise rotation of the Transverse Ranges. The transpression or convergence, therefore, may reflect a reorganization of regional plate motions along, and locally within, the North America-Pacific plate boundary.

This period of regional tectonic transpression or convergence is reflected by high- and low-angle reverse faulting and related folding that deforms sediments as young as 2.8 to 3.0 million years along the Hosgri fault zone and throughout the southern Santa Maria Basin (Plates 6, 7 and 8). This low-angle faulting associated with the convergence deforms but does not displace the Miocene/Pliocene unconformity. Seismic lines GSI-85, 86, 101, 106 as well as JEBCO-126 (Plate 6) show both northeast- and southwest-verging, high- and low-angle reverse faults that do not break this unconformity or overlying strata. In fact, although this unconformity is deformed locally, it is not broken by this style of faulting anywhere within the immediate vicinity of the Hosgri fault zone on any seismic data set examined to date.

Folding associated with the transpression or convergence, however, continued regionally into the middle Pliocene and persisted locally into the Quaternary in the southern part of the offshore Santa Maria Basin. Evidence of this deformation is shown, for example, on seismic lines GSI-97 (Plate 7, Sheet 1) where broad, low-amplitude folds occur below shot points 500, 650 and 1,300 at a depth of 1.0 second. Analysis of these folds suggest that many developed during the early Pliocene prior to about 2.8 to 3.0 million years ago.

Retrodeformable analysis of one of the more prominent of these folds, the "Queenie" fold (Plates 7 and 8), suggests that folding began in

the late Miocene or early Pliocene about 6.0 to 5.2 million years ago and ceased prior to development of a regional mid-Pliocene unconformity about 3 to 2.8 million years ago. Similar analysis across the offshore Santa Maria Basin from the Hosgri fault zone to the Santa Lucia Bank fault indicates that the total amount of post-Miocene crustal shortening is on the order of 0.5 to 0.75 kilometers or 1 to 2 percent (Clark and others, 1987). This analysis indicates that there is no "hidden" crustal shortening (that is, unaccounted for blind thrusting) west of the Hosgri fault zone such as the 17 percent proposed by Crouch and others (1984).

Folds imaged in seismic reflection data in the offshore Santa Maria Basin display both southwest and northeast verging asymmetric geometries (Plates 6, 7 and 8). However, southwest-verging folds, such as the Queenie fold, form the dominant sense of asymmetry, while northeast-verging folds appear to have formed over secondary backthrusts. The dominance of southwest-verging folds and their underlying causative faults suggests that shortening was rooted to the northeast, possibly within the Hosgri fault zone.

North of Point Sal, deposition was continuous over the trace of the Hosgri fault zone after the Miocene/Pliocene hiatus until Pliocene time when another period of erosion formed the early/late Pliocene unconformity. After this hiatus, deposition resumed over the Hosgri fault zone. The early/late Pliocene unconformity is not as well defined as the Miocene/Pliocene unconformity. However, it can be traced over most of the basin (Plate 7) except between Point Sal and Purisima Point where continued uplift has elevated Miocene Sisquoc and Monterey sediments to near seafloor level where only 5 to 20 meters of post-late Wisconsinan sediments (Plate 3, Sheet 2) cover the older rocks. The early/late Pliocene unconformity also terminates on the flanks of the Queenie and Lompoc anticlinal structures.

Implications of Deformation to Hosgri Fault Zone. Offset of post-Miocene sediments, as imaged in high-resolution seismic data, documents Quaternary movement along the Hosgri fault zone

(Plate 4). While minor disruption of post-Miocene strata occurs near several structures related to compression in the offshore Santa Maria Basin, the sediments are pervasively broken only where affected by high-angle faulting within the Hosgri fault zone (Plates 6 and 7).

The Hosgri fault zone generally displays an apparent northeast-side-up sense of vertical displacement. Much of this apparent sense of slip is likely a result of the early development of the fault zone as the eastern margin of the offshore Santa Maria Basin. As described above, regional transtension from about 17 to 6 million years ago and subsequent compression or transpression across the basin from about 6 to 3 million years ago resulted in general subsidence of the southwestern block of the Hosgri fault zone relative to the northeastern block.

While the apparent sense of vertical offset across the Hosgri fault zone is generally northeast-side-up over much of its length, detailed analysis of seismic reflection data indicates that lateral slip has been the dominant sense of movement along the fault. Locally, the sense of displacement of the top of basement fluctuates between northeast-side-up to southwest-side-up (for example, Plate 7, Sheet 3 seismic lines GSI-106, 107A and 114). Similarly the sense of displacement of the mid-Pliocene unconformity changes from northeast-side-up on seismic line GSI-107 to southwest-side-up on line GSI-101, and back to northeast-side-up on line GSI-86. Such reversals in apparent sense of vertical slip strongly suggest that strain along the Hosgri fault zone, either throughout its history or in the Quaternary, has been due to lateral slip.

Along the eastern margin of the offshore Santa Maria Basin from the latitude of Point Sal south, three prominent anticlinal structures are developed in the Neogene section, the Queenie, Lompoc and Purisima structures (Plate 5). These fault-cored anticlines all strike roughly N35°W and form the more prominent members of a trend of folds that converge to the south with the more northerly trending Hosgri fault zone.

The primary structural relief of the Queenie, Lompoc and Purisima folds formed during the

period of crustal shortening that occurred between about 6 and 2.8 million years ago. Initial deformation involved the formation of northeast-vergent folds that developed over reverse faults originating in the crust to the southwest. These original structures were subsequently overprinted by southwest-vergent folding and faulting which emanated from deeper crustal levels to the east or northeast. Plate 7 shows both the northeast and southwest vergent structures occurring within the Queenie structure.

A similar reversal of direction of shortening may have affected the southern reach of the Hosgri fault zone. However, southwest-verging structures in this area appear to have largely obliterated any evidence of preexisting northeast-verging structures.

The southwest-verging structures in the immediate vicinity of the Hosgri fault zone that developed in the time interval of 6.0 to 2.8 million years ago are imaged on seismic data primarily as low-angle faults. These faults appear to merge at depth with the high-angle faults of the Hosgri fault zone. These high-angle faults may have been inherited from the early Miocene history of transtensional high-angle strike-slip faulting, in which case the southwest-verging low-angle faults are "rooted" into them, or they may have formed contemporaneously with or subsequent to the Miocene and Pliocene low-angle faults. In each case, the high-angle faults clearly exhibit Quaternary activity while the low-angle faults do not, indicating that the locus of activity in the current tectonic setting has shifted to the high-angle faults of the Hosgri fault zone. As described below, the primary sense of slip on these high-angle faults has been right lateral, strike-slip displacement, with local areas of right-oblique displacement.

STYLE AND RATE OF LATE QUATERNARY DEFORMATION

Sense of Slip. To evaluate the contemporary tectonic behavior of the Hosgri fault zone, it is important to characterize the most recent style of faulting and rate of slip. Our understanding of the sense of slip has developed through a multi-disciplinary examination of the Hosgri fault

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zone and the associated San Simeon fault zone. For example, inferences regarding sense of slip come from surface observations along the San Simeon fault zone, constraints on the geometry of the Hosgri fault zone, considerations of regional stress and history, and implications of relative plate motion models. We summarize the relevant scientific arguments for strike-slip faulting on the Hosgri fault zone in Table 2-10. Arguments for dip-slip faulting are presented on Table 2-11.

Some data suggest that strike-slip faulting on the Hosgri fault zone may also be compatible with some amount of dip-slip or oblique displacement. This is apparent from earthquake focal mechanisms, for example, or the suggestions of steep easterly dips in the seismic reflection data. As described in the Tectonic Setting section of this chapter, it is also possible that the sense of slip on the Hosgri fault zone may change along its length, ranging from more purely strike-slip in the northern reach to perhaps equal components of strike-slip and dip-slip towards its southern end, south of Purisima Point.

Slip Rate. The most definitive data regarding the late Quaternary slip rate on the Hosgri fault zone have come from geologic investigations in the San Simeon area. Pleistocene and Holocene slip rates have been calculated for the primary active onshore traces of the San Simeon fault zone based on: a) offset marine terraces, b) deflected drainage channels, and c) stratigraphic and structural relationships observed in trenches. A summary of the range of slip rates calculated using these data is provided in Table 2-12. These values generally range from about 0.5 to about 9 millimeters per year, with most data suggesting a range in slip rate from 1 to 3 millimeters per year.

Offset Pleistocene Marine Terraces. A sequence of marine terraces has been mapped to the northeast and southwest of the San Simeon fault zone along its southernmost onshore reach. The fault zone forms a linear, northeast-facing topographic scarp across the terrace sequence (Figure 2-45). From youngest to oldest, these terraces are designated the San Simeon Point, San Simeon, Tripod, Oso, and La Cruz terraces (Weber, 1983) (Plate 14). The distribution of Quaternary marine terraces in this area and a

longitudinal profile illustrating the elevations of shoreline angles on both sides of the fault zone are shown on Figures 2-46 and 2-47, respectively. These five terraces are interpreted to correlate with marine oxygen isotope stages 3 or 5a, 5a or 5c, 5e, 7 and 9 based on: 1) a comparison of relative terrace spacing to a global paleosea-level curve; 2) relative degree of preservation and soil-profile development; and 3) lateral correlation of the third-highest terrace to the dated substage 5e marine terrace near Cayucos. Additional higher (older) terraces were noted during reconnaissance mapping, but were not mapped in detail due to their lack of lateral continuity and difficulty in estimating ages.

The marine terrace sequence is clearly disrupted by the San Simeon fault zone. Detailed mapping of the extent and elevation of marine terrace strandlines (Figure 46, Plate 14) shows that late Pleistocene deformation is concentrated along two or possibly three primary fault traces. The marine terrace sequence southwest of the fault zone is elevated relative to the terrace sequence northeast of the fault zone, indicating that vertical dip-slip separation has also occurred on the fault (Figure 2-45, Figure 2-47). The ratio of strike-slip to dip-slip displacement, however, is about 10:1, indicating that the San Simeon fault zone is predominantly a strike-slip fault.

The Oso terrace provides the best constrained slip rate based on mapping of marine terrace strandlines. As shown on Plate 14 and summarized on Figure 2-48, the location and elevation of the Oso strandline on both sides of the fault zone is constrained by field mapping and by subsurface data from boreholes, soil pits and exploration pits. Estimates of lateral offset of this shoreline angle range from 150 to 550 meters (Figure 2-48). The maximum value is based on the assumption that a small, less than 250-meter-long headland may have been present on the southwest side of the fault during the formation of the Oso strandline. The maximum size of the headland was estimated by comparison of the configuration of the Oso strandline to modern headland-bay beach shorelines (Vasso, 1965; Silvester and Ho, 1972; Silvester, 1976). This value added to the present 300 meters



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Table 2-10

FACTORS FAVORING STRIKE-SLIP FAULTING ON THE HOSGRI FAULT ZONE

- The Hosgri fault zone aligns with a system of other known regional strike-slip faults including the San Simeon and San Gregorio fault zones.
- The San Simeon fault zone is a high-angle strike-slip fault with a late Quaternary slip rate of 1 to 3 millimeters per year. The Cambria stepover is a releasing step which transfers strike-slip displacement at the south end of the San Simeon fault zone to the Hosgri fault zone. No other structures have been identified which can accommodate the lateral deformation associated with the San Simeon fault zone.
- Focal mechanism solutions in the vicinity of the Hosgri fault zone near Estero Bay and the San Luis/Pismo structural block show right-reverse slip.
- Regional focal mechanism solutions indicate both convergent and strike-slip displacement. P-axes of focal mechanisms indicate NNE-SSW maximum compression, which is consistent with strike-slip, not dip-slip, displacement on the Hosgri fault zone.
- Borehole breakout stress orientations show regional northeast compression, which is compatible with strike-slip, not dip-slip, displacement on the Hosgri fault zone.
- Macrofabric analysis of late Cenozoic rocks in the Los Osos/Santa Maria Valley domain indicate a NNE-SSW maximum compression (Vittori, 1987), which is consistent with strike-slip, not dip-slip, displacement on the Hosgri fault zone (Nitchman and others, 1988).
- The orientation of the Hosgri fault zone with respect to the orientation of the vector of unresolved movement along the North America-Pacific plate margin favors primarily strike-slip and locally transtensional displacement along the Hosgri fault zone.
- The Hosgri fault zone is a fundamental structural boundary separating regional domains of contrasting regional structural trends and seismicity. The change in structural trends occurs along the near-vertical western trace of the fault zone.
- The 1980 and 1984 Point Sal earthquakes indicate that seismicity is occurring adjacent to the east side of the Hosgri fault zone at depths of up to 10 kilometers. Focal mechanism solutions indicate that these earthquakes occurred on a fault trending more westerly than the Hosgri fault zone. The existence of faults at depths approaching the base of the seismogenic crust directly east of the Hosgri fault zone supports an interpretation of high-angle rather than low-angle faulting on the Hosgri fault zone.
- Kinematics of block rotation in the Transverse Ranges require right-lateral strike-slip displacement along the Hosgri fault zone, unless this slip occurs on other unidentified faults.
- Some stratigraphic correlations require early Tertiary strike-slip displacement along the Hosgri-San Gregorio system. Indirect evidence for right-lateral slip includes the presence of Paleogene sedimentary rocks on the west side of the Hosgri fault zone as far north as Lion's Head, while comparable Paleogene sedimentary rocks on the east side of the fault zone are not recognized north of the Santa Ynez River.

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Table 2-10 (Continued)

FACTORS FAVORING STRIKE-SLIP FAULTING ON THE HOSGRI FAULT ZONE

- Faults and folds north of Lion's Head bend to the north as they approach the Hosgri fault zone from the east, which is consistent with right-lateral slip along the Hosgri fault zone.
- Numerous flower structures imaged on seismic reflection data suggest a significant component of strike slip along the Hosgri fault zone. Both positive and negative flower structures imaged in GSI and JEBCO seismic lines (plate 12) display geometries similar to those occurring along other known lateral slip faults (Harding, 1985; Harding and others, 1983).
- The reversal in the direction of drag of sedimentary beds in a vertical profile of the Hosgri fault zone in Estero Bay is consistent with that expected from strike-slip displacement.
- Fold geometry east of the Hosgri fault zone is not compatible with active thrust faulting on the Hosgri fault zone.
- Abrupt changes in fold geometry occur across the entire length of the fault zone. These changes are not compatible with active thrust faulting on the Hosgri.
- The Los Osos, Pecho, San Luis Bay, Casmalia and Lion's Head faults are reverse faults that intersect the Hosgri fault zone at oblique angles. The NE-SW crustal shortening represented by these faults requires lateral slip along the more northerly trending Hosgri fault zone.
- Bends in the Hosgri fault zone exhibit compressional and tensional features consistent with right-lateral strike-slip displacement.
- The near-surface expression of the Hosgri fault zone is more complex than the structure at depth, which is consistent with the general character of strike-slip faults known elsewhere.
- The linear trace of the Hosgri fault zone from Estero Bay to Point Pedernales indicates the fault plane is subvertical to vertical, which is compatible with strike-slip faulting. This degree of linearity is not consistent with dominantly dip-slip faulting.
- High-resolution seismic reflection data across the Hosgri fault zone indicates that the upper 1 kilometer of the fault plane is vertical. The relative vertical offset across the fault varies along trend, and in conjunction with flower structures interpreted at Estero Bay and opposite Point Sal in seismic reflection profiles, indicates that the primary slip direction is horizontal.
- Common-depth-point seismic reflection data along the Hosgri fault zone show dips ranging from near vertical to as shallow as 60 degrees on depth-corrected dip sections; the consistency of the dip direction indicates an oblique slip component. The Hosgri fault zone is imaged as a high-angle fault in all areas. Low-angle components steepen with depth and are interpreted to merge with the high angle component. Low-angle components are not present along all reaches; therefore, lateral continuity of the Hosgri fault zone on a regional scale favors high-angle, strike-slip displacements.

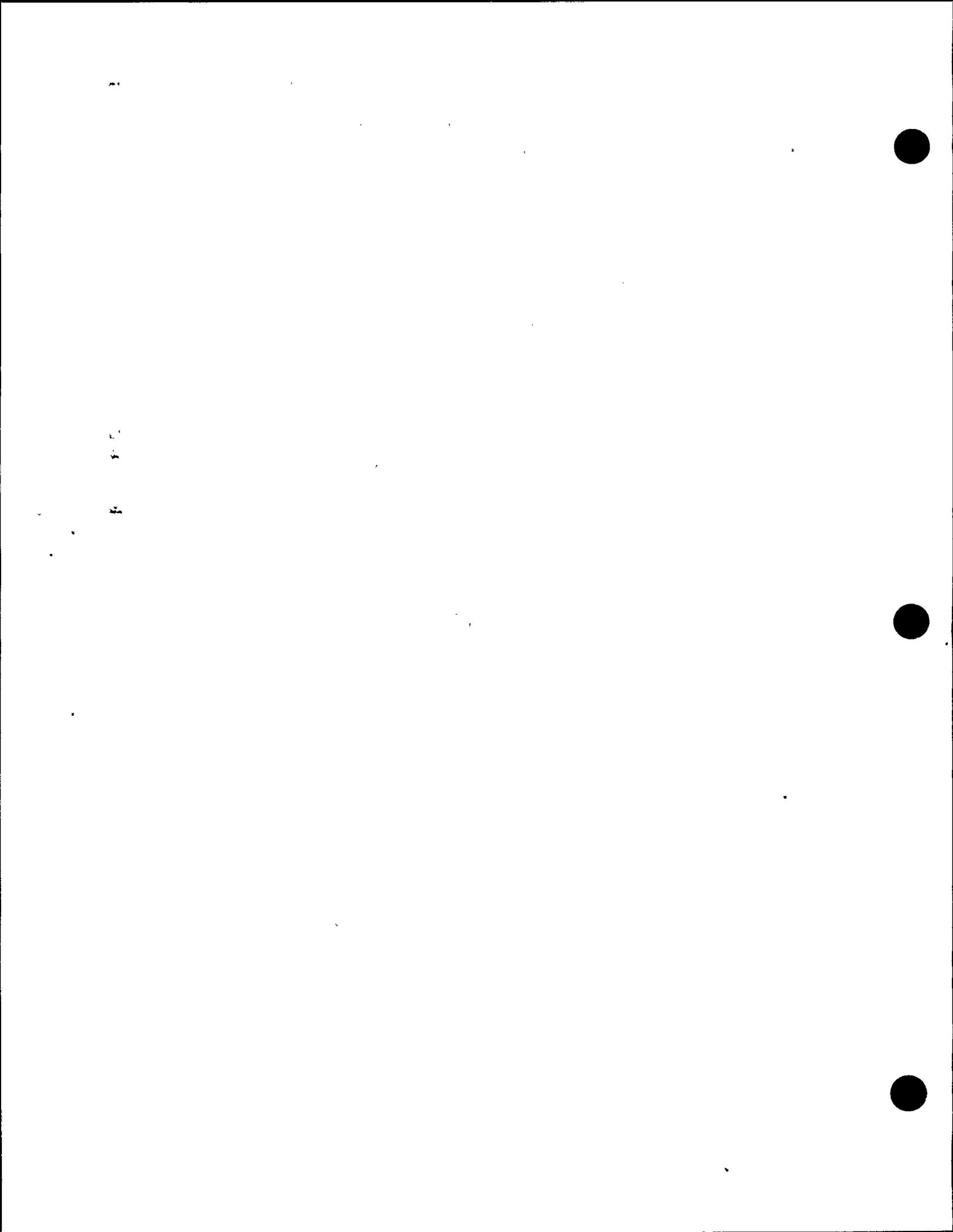


Table 2-11

FACTORS FAVORING REVERSE/THRUST FAULTING ON THE HOSGRI FAULT ZONE

- Unresolved convergence along the North America-Pacific plate margin of about 8 millimeters per year suggests that fold and thrust faulting is an active tectonic process in south-central California.
- Apparent subsurface, east-dipping, listric structures are observed in Tertiary strata on seismic reflection time sections west of the structures that are interpreted as the steeply dipping component of the Hosgri fault zone.
- Curving and overlapping frontal traces of the listric seismic reflectors, and the occurrence of folds in at least a portion of the Miocene and Pliocene stratigraphic section overlying the reflectors are compatible with reverse/thrust faulting.
- Seismic reflection data are interpreted to indicate that several folds west of and subparallel to the Hosgri fault zone are underlain by thrust faults. These structures, including the Lompoc, Purisima, and Queenie folds, have been explored by drilling, and the thrust faults were confirmed in at least the Purisima structure.
- Evidence for northeast compression in south-central coastal California includes reverse faulting focal mechanism solutions (including the 1927 Lompoc earthquake), the presence of onshore reverse faults such as the Los Osos, Pecho, San Luis Bay, Casmalia and Lions Head faults, and the regional stress orientation determination from borehole breakouts (Mount and Suppe, 1988).
- Balanced geologic cross-sections in south-central California indicate that compression has occurred and that there is associated thrust faulting at the base of the sedimentary section.
- Parallel and subparallel trends of folds and faults west of the Hosgri fault zone are compatible with thrust faulting on the Hosgri fault zone.





Table 2-12
ESTIMATED SLIP RATES—SAN SIMEON FAULT ZONE

1. Marine Terrace Investigation

	San Simeon Terrace (105 ka)	Tripod Terrace (120 ka)	Oso Terrace (214 ka)
A. Strandline piercing points based on mapping	1.4 to 8.6 mm/yr	0.8 to 8.8 mm/yr	0.7 to 2.6 mm/yr
B. Horizontal component of slip calculated from vertical separation of terrace and 6° - 7° plunge of slickensides observed along the fault in trenches.	1.2 to 1.8 mm/yr	0.7 to 1.2 mm/yr	0.4 to 0.7 mm/yr

2. Trenching

	Minimum	Maximum
A. Airport Creek Site		
Offset of 9 ka to 11 ka ponded alluvium	1.4 mm/yr	5.4 mm/yr
Estimates based on vertical separation of dated units and plunge of slickensides	1.1 mm/yr	1.4 mm/yr
B. Oak Knoll Trench		
Secondary fault trace	0.2 mm/yr (since ~3,000 yr B.P.)	—

3. Geomorphic Expression

A. Drainage displacement	0.6 to 2.0 mm/yr	6 mm/yr
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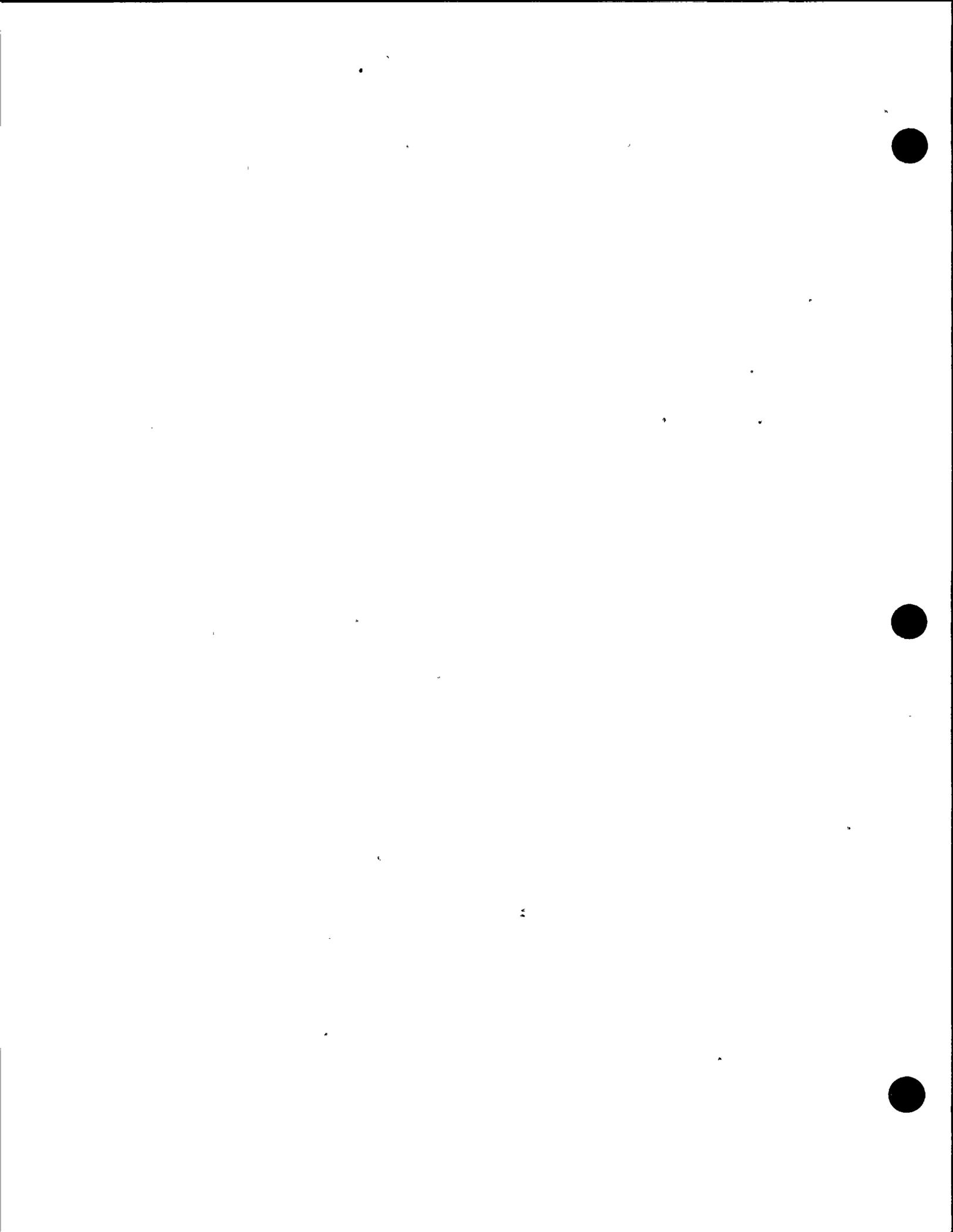




Figure 2-45

Photograph of San Simeon fault zone (view is northwest). The fault zone forms a linear northeast-facing escarpment across a flight of late Quaternary emergent marine terraces.





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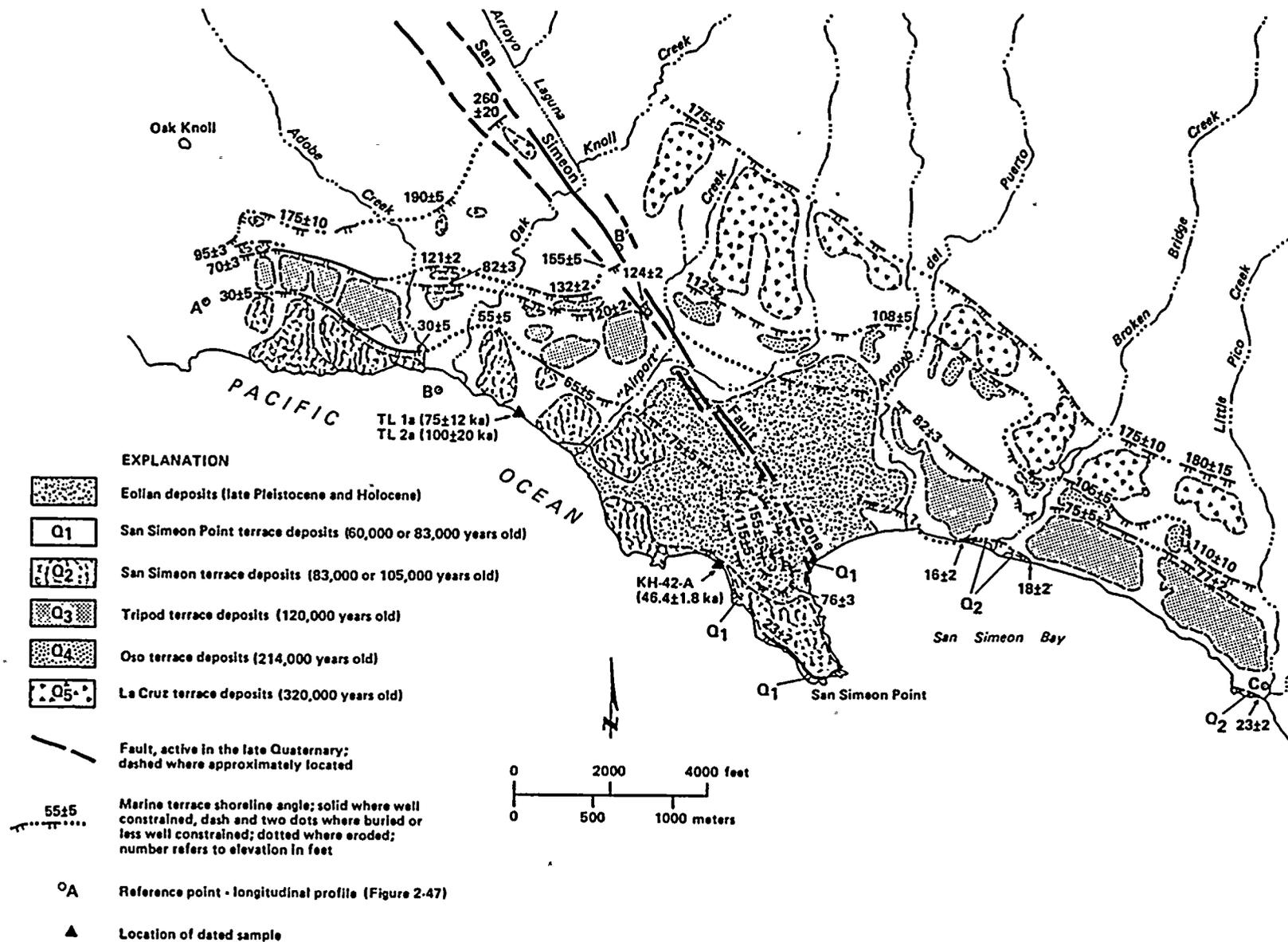


Figure 2-46
Geologic map of marine terraces and shoreline angles along the southern onshore reach of the San Simeon fault zone.



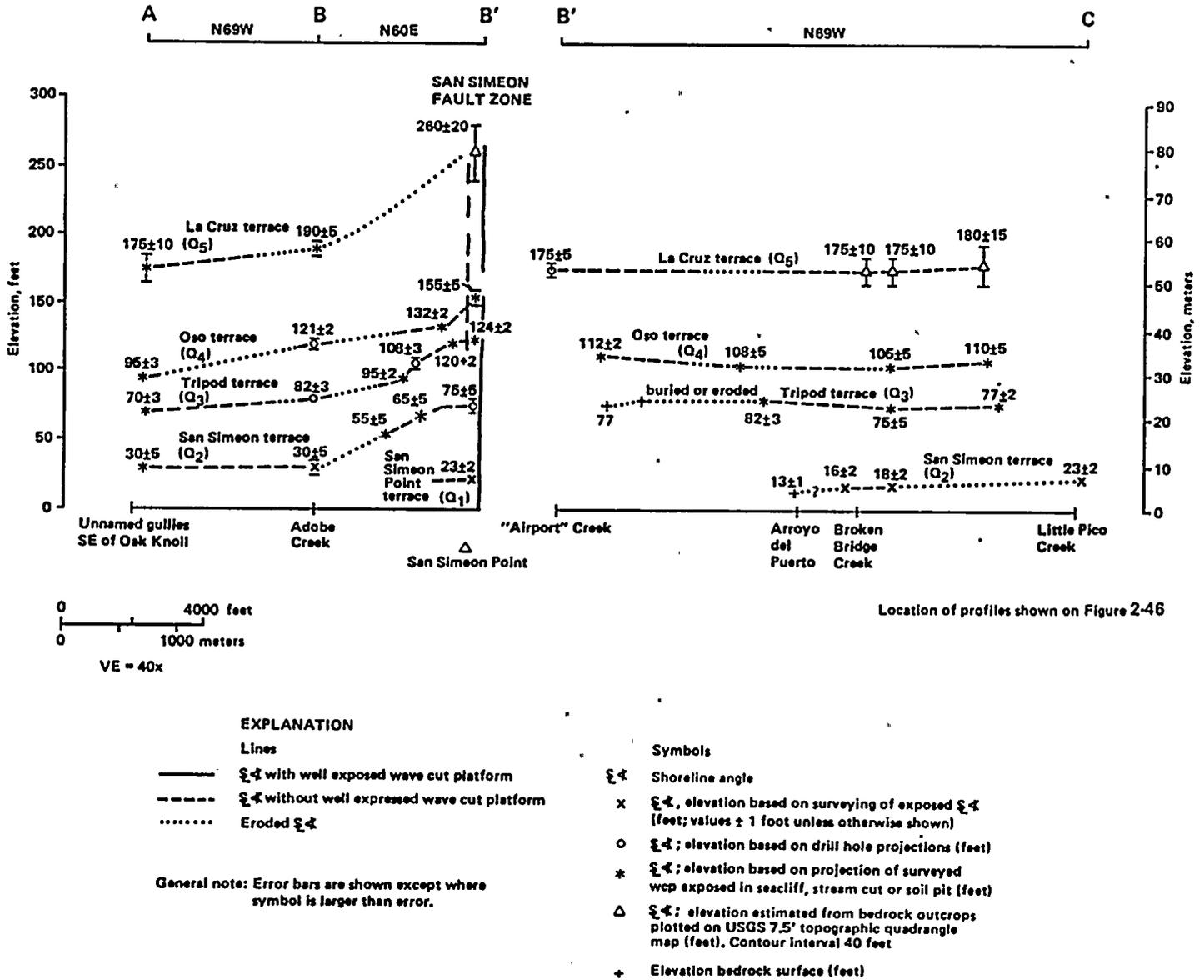


Figure 2-47
 Longitudinal profile of marine terraces along the southern onshore reach of the San Simeon fault zone.

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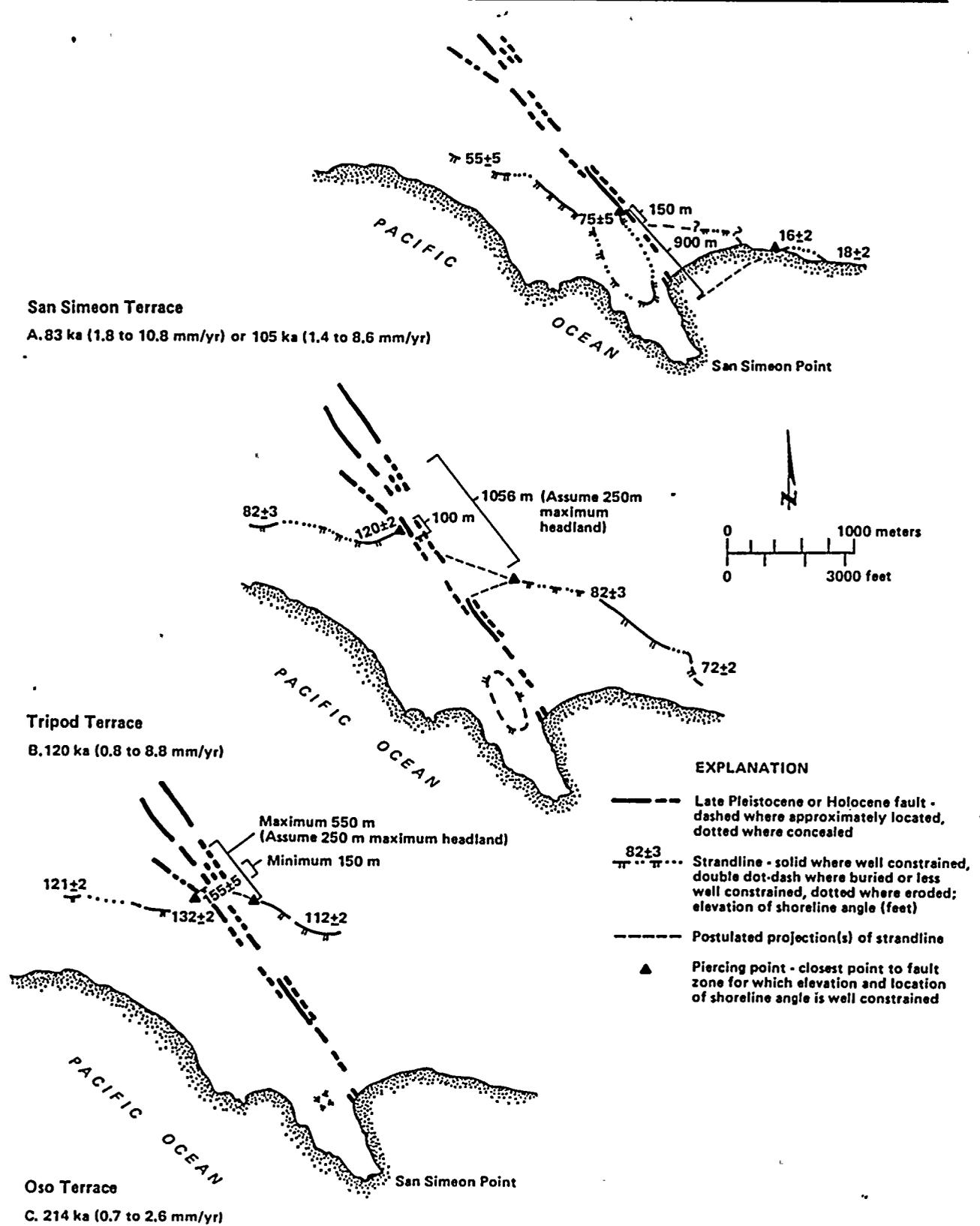


Figure 2-48

Offsets of the San Simeon, Tripod and Oso marine strandlines and estimated late Quaternary slip rates on the San Simeon fault zone.

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separation of the two piercing points on either side of the fault yields a maximum offset of 550 meters (Figure 2-48). Values of 150 to 550 meters for the amount of lateral offset and a preferred age of 214,000 years for the Oso terrace yields a range in slip rate of 0.7 to 2.6 millimeters per year.

Estimates of lateral offset for the Tripod terrace are not as well constrained due to the greater degree of fluvial modification and burial that has occurred northeast of the fault zone subsequent to formation of the terrace. A maximum lateral offset is estimated by assuming that the map pattern of the Tripod strandline was similar to that of the present shoreline. Adding a 600-meter headland comparable to the present San Simeon Point headland yields a lateral offset of 1,056 meters. This value divided by the preferred age of the Tripod terrace of 120,000 years yields a slip rate of 8.8 millimeters per year. This estimate is considered to be poor because it is unlikely that a large headland developed in this area at that time. In the vicinity of the Tripod strandline, the San Simeon fault zone juxtaposes similar bedrock lithologies where it crosses the fault. In contrast, the present San Simeon headland is underlain by resistant Monterey chert while San Simeon bay is underlain by less resistant lithologies of the Franciscan assemblage. Also, this slip rate greatly exceeds the better-constrained range of slip rate based on offset of the Oso terrace. A minimum value of lateral offset of 100 meters is obtained if it is assumed that there was no headland during formation of the Tripod terrace, which yields a minimum slip rate of 0.8 millimeters per year.

The paleogeographic reconstruction of the San Simeon terrace, like the Tripod terrace, is complicated by fluvial modification of the terrace surface and by the presence of thick eolian deposits northeast of the fault zone. The location of the piercing point on the southwest side of the fault is tightly constrained by borehole data (Plate 14). On the northeast side of the fault zone the terrace is clearly observed along the coastline between Arroyo del Puerto and Broken Bridge Creek and may extend further to the northwest based on indirect geomorphic and subsurface borehole and geophysical data (Figure 2-48). A maximum value of lateral offset of approximately 900 meters is obtained if it is assumed that the

shoreline mimicked the curve of the present shoreline and did not extend northwest of Arroyo del Puerto. In this interpretation, the offshore portion of the strandline would have been eroded by fluvial and possibly subsequent marine erosion. An estimated slip rate assuming a 900 meters offset and an age of 105,000 years is 8.6 millimeters per year. This value also greatly exceeds the better constrained slip rates based on the Oso terrace. It seems more likely that the San Simeon strandline extended north of the Arroyo del Puerto area (Figure 2-48). A minimum offset of approximately 150 meters is obtained if the strandline continued along this projection into the fault zone which would indicate a slip rate of 1.4 millimeters per year.

Alternative estimates of net slip on the San Simeon fault are obtained by converting the vertical separation of marine terrace strandlines into cumulative offset using the 6 to 7 degree plunge of slickensides and mullions observed on the fault plane in trenches as the assumed slip direction. This technique has the added benefit that the vertical offsets of terrace strandlines are much more tightly constrained than the lateral offset of strandlines, as discussed above. The initial elevation of the strandline generally approximates former mean sea level and is not significantly affected by paleogeography. Slip rates calculated from vertical offset of the marine terraces range from 0.4 to 1.8 millimeters per year (Table 2-12).

Deflection And Offset Of Drainages. Previous workers (ESA 1974, 1975; Hall, 1975; Weber, 1983; Hamilton, 1984) observed that numerous stream channels are deflected by various strands of the onshore San Simeon fault zone. Between Oak Knoll Creek and Arroyo de la Cruz, two small drainages both exhibit apparent right-lateral deflection of approximately 360 meters across the main trace of the fault (n1 and n2, Figure 2-49). These drainages are incised into elevated surfaces mapped by Weber (1983) as the Oak Knoll and Cinnabar marine terraces. The ages of these surfaces are not precisely known, but based on their elevations with respect to the La Cruz terrace are estimated to be approximately 320,000 (stage 9) and 430,000 or 480,000 years



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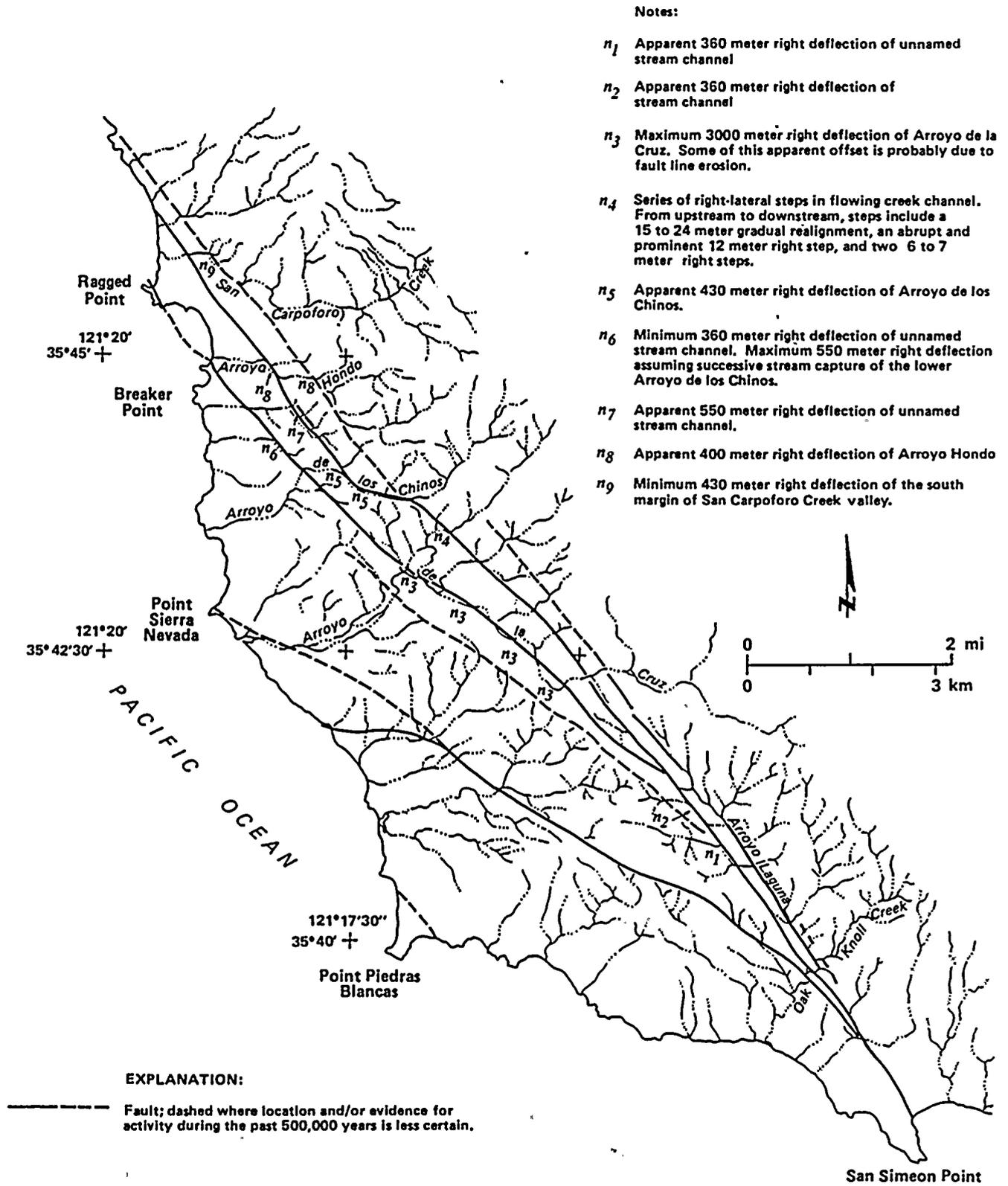


Figure 2-49

Map of drainage pattern in the San Simeon region showing possible stream deflections across traces of the San Simeon fault zone.



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old (stages 11 or 13), respectively. Using these ages and the 360-meter deflections along the fault suggests a minimum right-lateral slip of 0.8 to 1.1 millimeters per year for this strand of the fault.

Higher slip rates are suggested by deflections of streams along the two most active traces of the fault zone north of Arroyo de la Cruz. Along the western trace a minimum deflection of 360 meters (n6, Figure 2-49) is observed for an unnamed creek north of Arroyo de los Chinos. Along the eastern trace, Arroyo Hondo is deflected 400 meters (n8, Figure 2-49). Both of these streams are incised into a surface equivalent to or younger than the Oak Knoll terrace as mapped by Weber (1983). The Oak Knoll terrace is estimated to be on the order of 500,000 years old. Based on these data, minimum slip rates for the western and eastern traces are 0.7 and 0.8 millimeter per year, respectively, or 1.5 millimeters per year for the fault zone. In this area, geomorphic relations also suggest that stream capture has occurred during the evolution of the drainage network. The lower reach of Arroyo de los Chinos appears to have followed a more northerly direction based on extensive alluvial fans near Breaker Point. These fans appear to require a larger source area than is presently provided for by the two unnamed creeks south of Arroyo Hondo. Also, the present stream along one of these drainages (n6, Figure 2-49) is clearly underfit with respect to the size of the channel margins. Assuming capture occurred, the stream has been deflected about 500 meters in the past 320,000 to 500,000 years, which suggests a minimum slip rate of about 1 to 1.6 millimeters per year along this trace.

Maximum lateral slip can be broadly constrained by assuming that the large Arroyo de la Cruz channel reflects actual fault offset on the major fault strand(s) of the San Simeon fault zone. The channel is deflected roughly 3,000 meters and is incised into the oldest marine terrace in the area (480,000 years old), suggesting a slip rate of about 6 millimeters per year (Table 2-12). Offshore to the northwest, the western strand of the San Simeon fault zone deflects the Mill Creek submarine canyon 1 to 2 kilometers. Age of the canyon is not well constrained but may be late Pliocene or early Quaternary suggesting a

long-term slip rate of approximately 1 millimeter per year.

Trenching Investigations. Eighteen trenches and two natural exposures were logged and interpreted at four localities to assess the Holocene behavior of the San Simeon fault zone (Figure 2-43).

Data from exploratory trenches at the Airport Creek locality (Plate 15) show multiple net displacements of Holocene deposits of about 1 to 2 meters per event. These displacements suggest an average recurrence interval of $1,100 \pm 450$ years for surface faulting events. The channel thalweg of Airport Creek is deflected 1.8 meters (Plate 15) and a sand bed exposed in a trench at the Oak Knoll Creek locality is offset in a single event 1.2 meters, both right laterally, also suggesting an average offset of 1 to 2 meters per event.

Plate 15 provides a detailed log of the northeast wall of Airport Creek Trench T-1 illustrating the stratigraphic and structural relationships across the fault zone. The fault plane is vertical to subvertical and splays upward toward the ground surface. Several of these fault splays extend into the modern surface soil indicating late Holocene activity. Four radiocarbon dates have been obtained from a sequence of fine grained fluvial sediments ponded against the northeastern side of the fault and indicate an age from 9,000 to 11,000 years. Subhorizontal slickensides and mullions that plunge 6° to 7° to the southeast are well preserved on the fault plane and indicate that strike-slip is the primary sense of displacement on the fault. Assuming that the ponded sediments are flat-flying, the plunge of the slickensides and the amount of vertical separation across the fault of dated horizons indicates a net Holocene slip rate for this fault strand of about 1.25 ± 0.15 millimeters per year.

In summary, we conclude that the lateral slip rate on the San Simeon fault is in a range between about 0.5 to 6 millimeters per year. Higher values of 7 to 9 millimeters per year shown on Table 2-12 are derived assuming that a large headland persisted through time along the fault, an assumption that we do not believe is geologically reasonable for reasons described above. An estimate of between 1 and



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3 millimeters per year is preferred because the range in slip rate encompasses most of the values shown on Table 2-12 and, in particular, encompasses the minimum slip rate for offset of the San Simeon Terrace and the maximum slip rate for offset of the Oso terrace, our best constrained values of stratigraphic offset.

Vertical Slip Rate. Vertical slip on the Hosgri fault zone in the reach from Estero Bay to San Luis Obispo Bay is constrained by rates of uplift along the onshore San Luis/Pismo block and by rates of subsidence in the offshore Santa Maria Basin west of the fault zone. As described later in this chapter, the San Luis/Pismo block is rising at a late Quaternary rate of 0.1 to 0.2 millimeter per year. Based on seismic reflection data, the offshore Santa Maria Basin is subsiding at a late Pliocene and Quaternary rate of 0.1 to 0.2 millimeter per year. Differential vertical separation across the Hosgri fault zone, therefore, ranges from 0.2 to 0.4 millimeter per year. This rate of vertical separation decreases to the north into Estero Bay and to the south into San Luis Obispo Bay where the coastal structural blocks east of the Hosgri fault zone are not rising and locally may actually be subsiding.

SUMMARY

The following paragraphs summarize the results of our investigations regarding the principal characteristics of the Hosgri fault zone.

The Hosgri fault zone is part of a larger zone of faulting that extends for over 400 kilometers along the central California coast. From north to south this zone includes the San Gregorio, Sur, San Simeon, and Hosgri faults. The zone has been intermittently active since at least early Tertiary time.

The Hosgri fault zone terminates about 35 kilometers north of Point Buchon where it forms an en echelon right step with the southern San Simeon fault zone at the Cambria stepover. From this point, the fault zone extends south-southeast, sub-parallel to the coast line, for a distance of approximately 105 ± 5 kilometers to the area northwest of Point Pedernales where it separates into en echelon strands and dies out.

Seismicity. Earthquakes adjacent to the Hosgri fault zone on the east show right-reverse to strike-slip focal mechanisms. The resolved fault plane, dips steeply and strikes parallel to subparallel with the Hosgri fault zone. Seismicity occurs down to about 12 kilometers in the immediate vicinity of the Hosgri fault zone, and to the east. The spatial distribution of these events requires a near-vertical cutoff of the seismically active east block throughout the vertical extent of the seismogenic crust. Focal mechanisms in the region within a few kilometers to the east of the Hosgri fault zone in Estero Bay and northwest of Point Sal exhibit west-northwest-striking fault planes, consistent with faulting trends along the Los Osos and Casmalia fault zones, respectively.

Segmentation. The Hosgri fault zone consists of several discrete reaches or segments that are defined on the basis of changes in geometry and behavioral characteristics of the fault zone and by intersecting structures. Evidence for segmentation is summarized on Table 2-13. From north to south these are the Northern Reach, San Luis/Pismo Reach, San Luis Obispo Bay Reach, Point Sal Reach, and Southern Reach. Segmentation points are identified where rather abrupt changes occur in the behavior or geometry of the fault zone and in the style of deformation in areas bordering the fault zone. In particular, the relative lateral slip rate decreases southward along the Hosgri fault zone due to north-northeast-directed shortening east of the Hosgri, and interactions with active faults and structural blocks to the east of the fault zone appear to effect the slip rate, trend and lateral continuity of the fault zone.

Style and Rate of Contemporary Deformation. Detailed offshore geophysical investigations strongly indicate that at least the northern three reaches of the Hosgri fault zone are characterized by late Quaternary right-lateral strike-slip displacement. Evidence for strike-slip displacement is summarized on Table 2-10. Onshore geologic studies along the San Simeon fault zone confirm right-lateral displacement along this part of the San Gregorio/Hosgri fault system at a late Quaternary rate of between 1 and





Table 2-13
SUMMARY OF HOSGRI FAULT ZONE SEGMENT CHARACTERISTICS

Fault Segment	Segment Boundaries N: North S: South	Length (km)	Average Trend	Strands	Down Dip Geometry	Near Surface Expression	Adjacent Structures
Southern San Simeon Reach	N: South Arroyo del Oso Fault Intersection S: Cambria Stepover	28 km	N38W	One, or possibly two high-angle traces within 0.5 to 1.5 km of coastline. Low-angle fault approximately 5 km offshore in north only, related to anticlinal fold.	High-angle trace based on bathymetry. Low-angle trace dips 30 to 40NE.	East-facing scarps San Simeon Bay to Cambria rock and west of Point Estero. Straight coastline (west facing scarp) south of Cambria to north of Point Estero.	North of Cambria offshore structures bend west-northwest parallel to south side of Piedras Blancas antiform. South of Cambria structures trend parallel to San Simeon fault.
Northern Reach	N: Cambria Stepover S: Los Osos Fault Intersection	21 ± 1 km	N40W	West trace exists only south of Morro Rock, east trace extends along entire reach. Low-angle fault is not present.	Near vertical with dips ≥ 80NE.	Local seafloor scarps and disruption of late-Wisconsinan sediment basins.	Generally parallel or subparallel to fault zone within 2 km. To east in Estero Bay structures trend more westerly, oblique to fault zone.
San Luis/Pismo Reach	N: Los Osos Fault Intersection S: Pecho Fault Intersection	22 ± 1 km	N25W	Two vertical strands generally within a 2-km wide zone. Low-angle fault parallel and west of vertical traces.	West strand vertical in upper 1 km and dips of 65 to 70E at depths of 3 to 4 km. East strand dips 70 to 80NE. Low-angle fault dips 35 to 45NE in near surface, increases dip to 60NE at 2 to 3 km.	West strand associated with seafloor scarps and inflection points. Central zone contains small sediment-filled grabens. East strand forms boundary between deformed bedrock outcrops on east and sediment-covered basin to west.	West of zone, trends are parallel to fault. Between east and west strands trends are parallel to subparallel to trend of zone. East of east strand trends are N30W to N60W.
San Luis Obispo Bay Reach	N: Pecho Fault Intersection S: Casmalia Fault Intersection	23 km	N20W	West strand relatively continuous, east strand is discontinuous. Two subparallel low-angle faults with tips up to 2 km west of western trace.	West strand is vertical in upper 1 to 2 km, dips 60 to 75NE to depths of 4 km. Low-angle fault(s) dips 30NE ± 10 increasing to 60NE or more at depth.	Sediment covered over entire reach. West strand disrupts post-late Wisconsinan unconformity, some eastern strands do not.	Generally parallel or subparallel to Hosgri fault traces along the zone. In eastern San Luis Bay the few structures observed trend N45W ± 10.



Table 2-13 (Continued)
SUMMARY OF HOSGRI FAULT ZONE SEGMENT CHARACTERISTICS

Fault Segment	Segment Boundaries N: North S: South	Length (km)	Average Trend	Strands	Down Dip Geometry	Near Surface Expression	Adjacent Structures
Point Sal Reach	N: Casmalia Fault Intersection S: Lion's Head Fault Intersection	16 ± 2 km	N20W	West strand continuous, short (6 km) east strand in center of reach. One low-angle fault present generally within 0.5 km of west trace.	West strand dips 70 to 90NE. Low-angle fault steepens with depth and joins west trace.	West strand offsets post-late Wisconsinan sediment basin in manner consistent with right slip movement. Southern 3 km present at seafloor.	East of east trace trends are generally N40W to N70W gradually turning northerly as they approach Hosgri. West of west trace fold axes are parallel or subparallel with Hosgri strands, N20W to N30W.
Southern Reach	N: Lion's Head Fault Intersection S: Southern Termination	25 ± 2 km	N20W N5W south of Purisima Point area	Continuous west strand south past Purisima Point, discontinuous south of change in trend. East strand discontinuous and not present south of change in trend.	West strand dips 75W to 75E but is generally 90 ± 5.	Local seafloor disruption and deformation of post-late Wisconsinan sediments.	West of the fault zone structures generally trend 10 degrees west of Hosgri trend. East of Hosgri fault zone structures trend EW to N45W. Significant variations in trend are noted as structures approach Hosgri fault zone, implying, in some areas, left-lateral displacement. Both up-to-west and up-to-east relative basement offsets are present.

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3 millimeters per year. To the south, the San Simeon fault zone forms an en echelon 5-kilometer right step with the northern Hosgri fault zone. An intervening basin bordered by normal faults and filled with post-late Wisconsinan sediment occurs within the stepover region suggesting that the right slip on the San Simeon fault zone is transferred to the northern Hosgri fault zone across a pull-apart basin. The rate of lateral slip is interpreted to decrease to the south, possibly becoming zero south of Point Sal. The relative vertical component of slip on the Hosgri fault zone along the reach of the fault bordering the San Luis/Pismo block (Figure 2-11) is about 0.2 to 0.4 millimeter per year, but is less than 0.2 millimeter per year along the Northern and San Luis Obispo Bay reaches of the fault zone.

There is an en echelon right stepping pattern from the southern end of the San Simeon fault zone to the northern end of the Hosgri fault zone called the Cambria stepover. The stepover is evidenced by normal faults bounding a small graben. The graben is filled with post-late Wisconsinan sediment indicating late Pleistocene and Holocene pull-apart deformation within a releasing en echelon step along right-lateral fault.

The continuity, linearity and near surface expression of the Hosgri fault zone suggests late Quaternary strike-slip displacement along a high-angle fault. In contrast, associated concealed low-angle faults along the western side of the fault zone are not found in the immediate vicinity of the northern or southern reaches of the fault zone, and have a sinuous subsurface trend that does not cut the Miocene/Pliocene unconformity.

The relative sense of vertical displacement varies along the strike of the high-angle strands. The overall aspect of the fault is west-side down, probably related to an earlier Miocene episode of basin subsidence and/or Pliocene episode of convergence. However, there are local areas where west-side up relative motion is interpreted from the stratigraphy and the potential field data.

Interpretations that the Hosgri fault zone is an east-dipping thrust fault that becomes listric at a

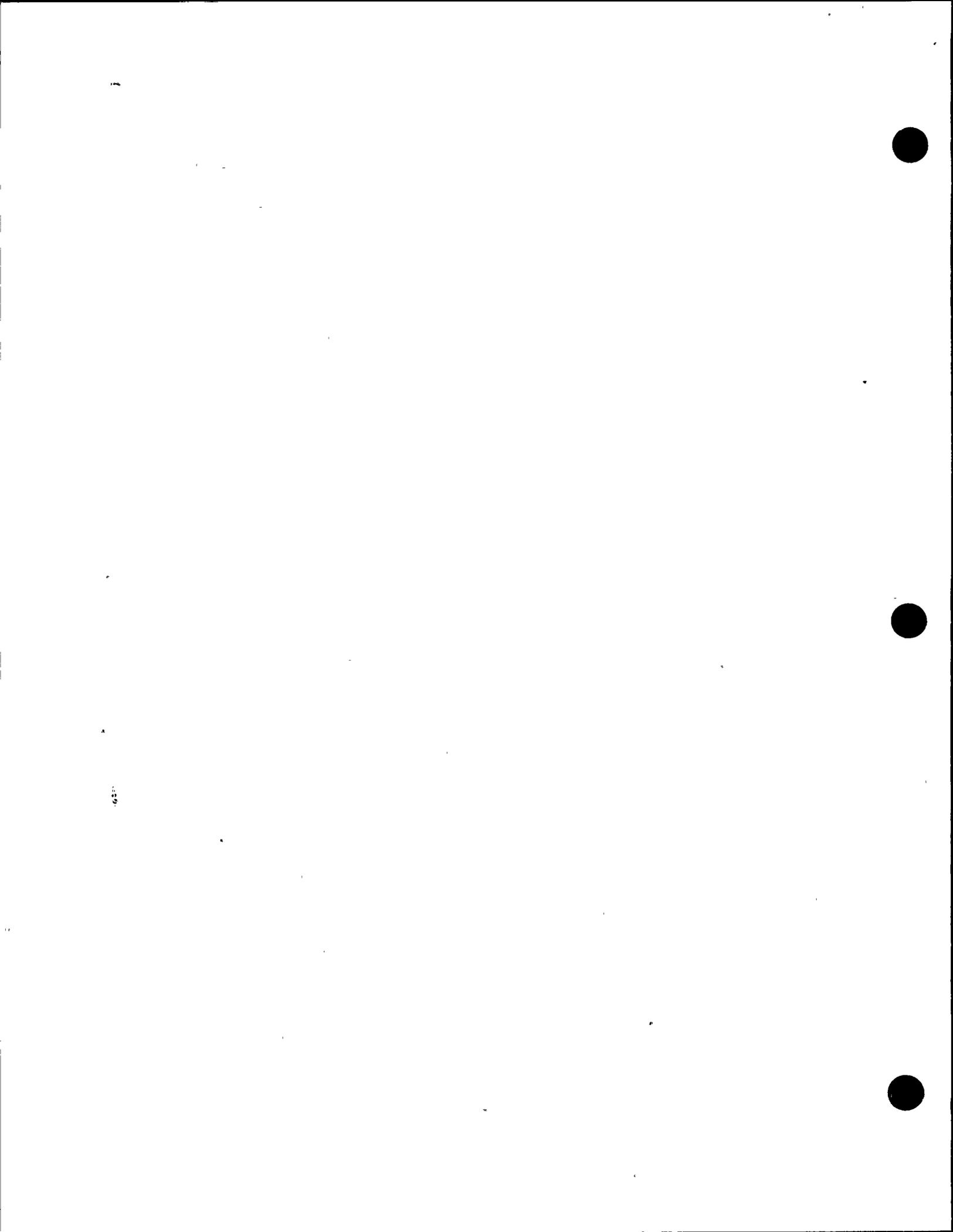
depth of 1.5 to 2.5 kilometers were evaluated during this study. A low-angle fault component, which is prominent in the area immediately northwest of Point Sal, does not show direct evidence of late Quaternary activity and appears to steepen and merge with the steeply dipping component of the Hosgri fault zone at depth.

Los Osos Fault Zone

The Los Osos fault zone lies along the northeastern margin of the San Luis/Pismo structural block (Figure 2-50). Reconnaissance and detailed studies indicate that this fault zone is a northwest-trending zone, of high- and low-angle faults that have a complex history of strike-slip and reverse displacement throughout late Cenozoic time. During the late Quaternary (past 500,000 years), the fault has exhibited primarily reverse displacement. The fault zone has a maximum length of 36 to as much as 57 kilometers, is up to 2 kilometers wide at the surface and consists of discontinuous, subparallel and en echelon fault traces. The primary reverse or thrust fault appears to lie along the northeastern margin of the zone and dip to the southwest; high-angle faults and related deformation are present in the hanging wall of the primary reverse/thrust fault.

The Los Osos fault zone separates the elevated San Luis/Pismo structural block on the southwest from the relatively stable Cambria structural block on the northeast, and is thus interpreted to be the northeastern structural boundary of the San Luis/Pismo structural block (Figure 2-11). At its closest surface approach, the fault is about 9.5 kilometers from the Diablo Canyon Power Plant site. Because of its potential significance as a major block-bounding fault and its proximity to the site, an extensive program of mapping, shallow subsurface exploration, and geophysical investigation was conducted to characterize those aspects of the fault that are important to its behavior as a potential seismic source (for example, geometry, segmentation, slip rate, recurrence).





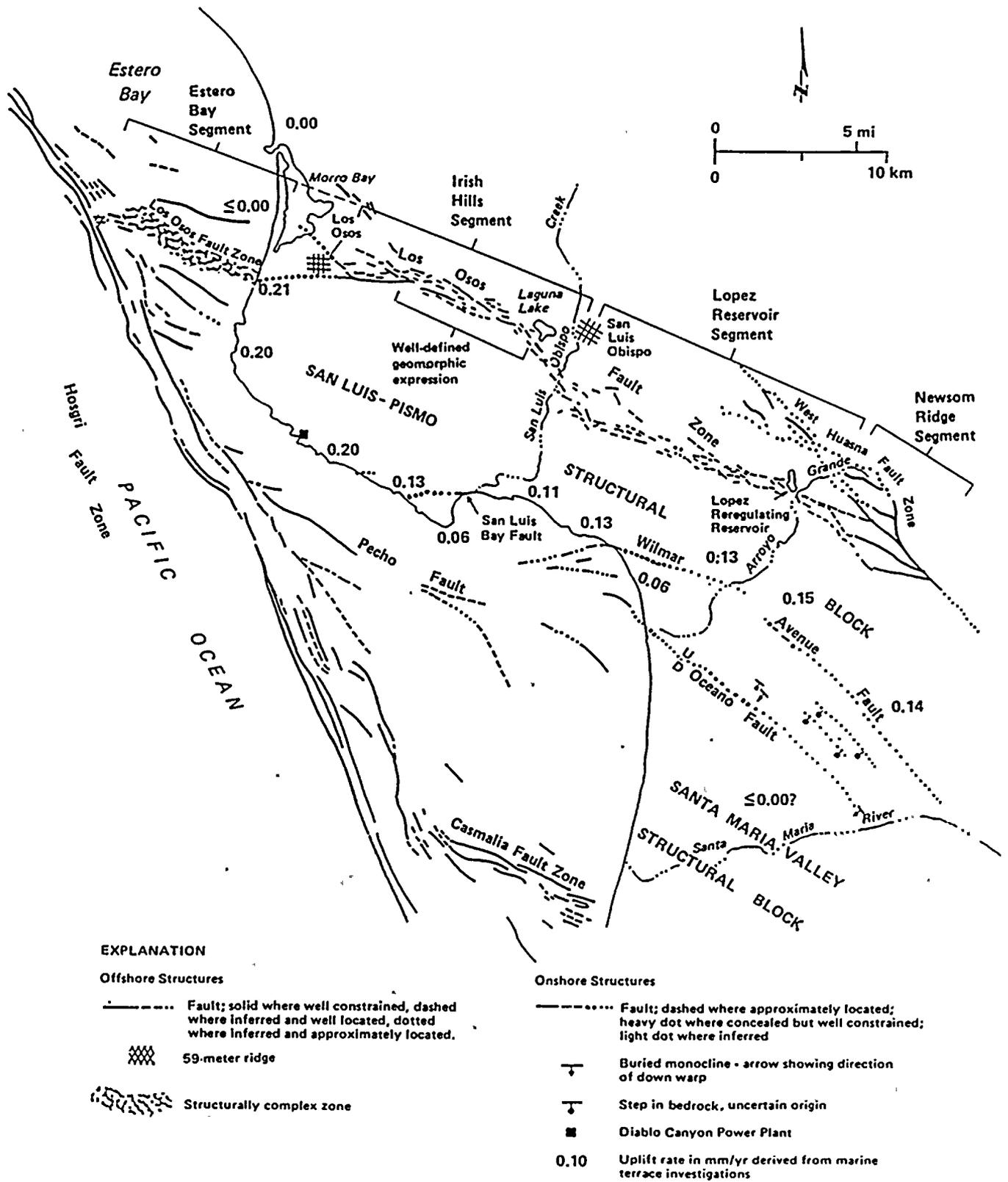


Figure 2-50
Regional map showing segments of the Los Osos fault zone and late Quaternary uplift rates of the San Luis/Pismo structural block.

PREVIOUS STUDIES

The Los Osos fault zone is shown by Hall and others (1979) as a zone of several fault traces that generally bound serpentinite within the Franciscan assemblage along the lower margin of the northeast flank of the Irish Hills. Locally, strands of the fault zone displace Tertiary strata and the Pleistocene Paso Robles Formation. To the southeast, the Los Osos fault zone is coincident with the southeastern part of the Edna fault (Hall, 1973a; Hall and others, 1979). The Edna fault as described by Hall (1981a) had mid-Tertiary right slip displacement and is part of a larger zone of northwest-trending strike-slip faults that are responsible for creating the Miocene Santa Maria, Pismo and Huasna "pull-apart" basins.

Late Quaternary activity has not been described along the Los Osos fault zone in the published literature. Hall and others (1979) show strands of the fault zone locally displacing the Pleistocene Paso Robles Formation. In this study, we have identified and mapped many of the bedrock fault traces mapped by Hall and others (1979) as well as many additional traces within the fault zone. Most of the late Quaternary activity identified during this study occurs on traces of the Los Osos fault zone not mapped by previous investigators.

SEGMENTATION AND LATERAL CONTINUITY

Segmentation and Lateral Continuity. The onshore Los Osos fault zone is a zone of discontinuous, subparallel and en echelon fault traces that extends at least from Morro Bay on the northwest to the Lopez Reregulating Reservoir on the southeast, a distance of about 36 kilometers (Figure 2-50, Plate 16). Reconnaissance studies suggest that the fault may extend to the southeast an additional 8 ± 1 kilometers to an intersection with the West Huasna fault near Twitchell Reservoir. To the northwest, the fault may continue offshore as one or more subparallel traces for another 13 ± 2 kilometers to intersect with the Hosgri fault zone in Estero Bay. If these northwesterly and southeasterly extensions exist, the total fault length would be 57 ± 3 kilometers.

To characterize the late Quaternary behavior of the Los Osos fault zone, field studies and subsequent analyses were focused on defining recognizable segments of the zone. Four fault segments are identified based on differences in physical characteristics such as spatial coincidence with topographic segmentation of the San Luis/Pismo structural block, spatial separation of en echelon fault traces, intersection with known or inferred branching or crossing structures (faults, subsiding basins), and geomorphic character as a range-front fault or intra-range fault, as well as differences in fault behavioral characteristics (recency, slip rate). The segments are referred to as the Estero Bay, Irish Hills, Lopez Reservoir, and Newsom Ridge segments (Figure 2-50, Table 2-14). The Estero Bay segment lies offshore and was investigated using offshore geophysical data. The late Quaternary slip rate on this segment is uncertain (Table 2-14). Detailed and reconnaissance field investigations indicate that the Lopez Reservoir and Newsom Ridge segments (Plate 16) have poor geomorphic expression and late Quaternary slip rates probably less than 0.1 millimeter per year (Table 2-14). The Irish Hills segment displays evidence of late Quaternary activity and was investigated in detail as described below.

Irish Hills Segment. The Irish Hills segment lies along the northeastern flank of the Irish Hills subblock between Morro Bay on the northwest and San Luis Obispo Creek on the southeast, a distance of 19 ± 2 kilometers (Figure 2-50). It is a range-front fault over most of its length, but is obscured by cultural activity and eolian and fluvial deposits along its northwestern and southeastern sections. The surface trace of the segment is about 9.5 kilometers from the Diablo Canyon Power Plant at its closest approach.

Geomorphic features indicative of Quaternary faulting are well expressed along the central 8- to 10-kilometer part of the segment (Figure 2-50, Plate 16). Prominent spring lines, linear and arcuate topographic scarps, and tonal lineaments define numerous northwest-trending lineaments up to several kilometers in length (Plate 16).

The northwestern and southeastern sections of the Irish Hills segment have poor geomorphic





Table 2-14

**FAULT SEGMENT CHARACTERISTICS ALONG THE LOS OSOS FAULT ZONE
 FAULT SEGMENTS SHOWN ON FIGURE 1-8**

<u>Fault Segment</u>	<u>Topographic Segmentation</u>	<u>Range-front Character</u>	<u>Geomorphic Expression</u>	<u>Recency of Slip</u>	<u>Late Quaternary Slip Rate mm/yr</u>	<u>Length</u>	<u>Characteristics at Segment Boundary</u>
Estero Bay (southern and northern traces.	Poorly-defined; deeply eroded bedrock platform with several NW-trending linear ridges.	Southerly trace borders NE flank of "59-meter ridge." Northern trace unknown.	Southerly trace marked by several NE-facing scarps. Northern trace borders several post-Wisconsinan basins but does not have seafloor expression.	Not well constrained. May displace post-Wisconsinan sediment.	Not well constrained.	13 ± 2 km	<p>Northwest—Inferred to intersect Hosgri fault in Estero Bay.</p> <p>Southeast—northerly trace makes 3-5 km en echelon right step or branches from Irish Hills segment across Morro Bay basin. Southerly trace projects into Irish Hills segment along SW margin of Morro Bay basin.</p>
Irish Hills	Coincident with Irish Hills range segment.	Well-defined range front fault. Range front linear, steep, moderately dissected.	Well-defined scarps, spring lines and lineaments. Tectonically impounds Pleistocene and Holocene (?) alluvium.	Multiple late Pleistocene and Holocene events.	Vertical 0.2 to 0.4. Net = 0.25 to 0.5 (60° dip) 0.4 + 0.8 (30° dip)	19 ± 2 km	<p>Northwest—Two alternatives: 1) segment ends at Morro Bay basin coincident with en echelon or branching relationship to northern Estero Bay trace described above; 2) segment bends 15° to 25° to more westerly trend along southern margin of Morro Bay basin and ends at northwestern margin of Irish Hills range segment.</p> <p>Southeast—1 to 2 km en echelon right step to Lopez Reservoir segment. Coincident with SE termination of Irish Hills range segment, 2-4 km right step in range front, and possible intervening basin of subsidence.</p>

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Table 2-14 (Continued)

**FAULT SEGMENT CHARACTERISTICS ALONG THE LOS OSOS FAULT ZONE
FAULT SEGMENTS SHOWN ON FIGURE 1-8**

<u>Fault Segment</u>	<u>Topographic Segmentation</u>	<u>Range-front Character</u>	<u>Geomorphic Expression</u>	<u>Recency of Slip</u>	<u>Late Quaternary Slip Rate mm/yr</u>	<u>Length</u>	<u>Characteristics at Segment Boundary</u>
Lopez Reservoir	Coincident with Edna range segment.	Poorly defined range-front fault along NW part. Range front deeply dissected. Fault crosses rolling foothills along SE part.	Poorly-defined lineaments. Tectonically impounds Pleistocene and Holocene (?) alluvium.	Displaces early (?) Pleistocene alluvium. Late Pleistocene and Holocene activity not observed.	Vertical = < 0.1	17 ± 2 km	<p>Northwest-1 to 2 km en echelon right step to Irish Hills segment (see above). Coincident with NW termination of Edna range segment.</p> <p>Southeast-poorly defined. Coincident with SE termination of Edna range segment and postulated NE-trending Arroyo Grande cross structure partially defined by Arroyo Grande structural basin to SW.</p>
Newsom Ridge	Subparallel to and within Newsome Ridge range segment.	Intra-range fault, range deeply dissected.	No expression. Trace may be defined, in part, by linear drainage.	Quaternary displacement not observed.	Vertical = < 0.1 Probably not active	8 ± 2 km	<p>Northwest—poorly defined (see above). Lies along projection of Lopez Reservoir segment.</p> <p>Southeast—intersects West Huasna fault zone near Twitchell Reservoir.</p>

expression. Quaternary displacement along the southeastern part of the segment is indicated by the following geomorphic relationships: 1) the range front continues as a steep, linear escarpment; 2) the fault truncates a flight of elevated fluvial terraces along San Luis Obispo Creek; and 3) a closed basin, Laguna Lake, may be tectonically impounded by the fault (Plate 16). To the northwest, the Irish Hills segment is overlain by late Pleistocene and Holocene eolian deposits that form a large "sand ramp" against the northeastern margin of the Irish Hills and obscures geomorphic evidence of fault activity. However, Quaternary deformation in this area is suggested by the following indirect geomorphic relationships: 1) the range front continues as a steep, linear escarpment; and 2) the fault separates an area of Quaternary uplift, the San Luis/Pismo structural block, from an area of Quaternary subsidence beneath Morro Bay.

No direct structural basis for defining the northwestern boundary of the Irish Hills segment of the Los Osos fault zone has been recognized. The segment is interpreted to end at Morro Bay coincident with the subsiding Morro Bay structural basin and with the northwestern end of the Irish Hills range segment. The actual location of the boundary, however, is uncertain because of the thick veneer of eolian sand that obscures the fault trace. The Irish Hills segment may terminate at the southeastern margin of the Morro Bay Basin where a more northerly trending fault branches into a possible northern trace of the offshore Estero Bay segments of the Los Osos fault zone (Figure 2-50). Alternatively, the segment may bend sharply 15 to 25 degrees to the west along the southern margin of the Morro Bay Basin where it projects seaward into a possible southern trace of the offshore Estero Bay segment of the Los Osos fault zone.

The southeastern boundary of the Irish Hills segment is relatively well constrained on the basis of physical characteristics. The segment is separated from the Lopez Reservoir segment by a 1- to 2-kilometer en echelon right step and/or a sharp 20 to 30 degree bend in the fault trace to a more northerly trend across San Luis Obispo Creek. This discontinuity is coincident with a similar 2- to 4-kilometer right step in the range

front and with the southeastern termination of the Irish Hills subblock (Figure 2-15). Well data in the San Luis Obispo Creek area show a thickening of late Quaternary deposits near the en echelon step which suggests that a small subsiding basin (informally named the San Luis basin) may be present at the stepover.

DETAILED INVESTIGATIONS

Potentially fault-related geomorphic features along the Irish Hills segment were investigated in detail on the Cuesta, Ingley and Ellsworth properties (Plate 16) to assess fault geometry and late Pleistocene-Holocene behavior. Investigations included detailed mapping of geomorphic features, drilling, seismic refraction profiling, and exploratory trenching (Plate 16).

Two traces of the Los Osos fault zone shown by Hall and others (1979) apparently were mapped primarily from bedrock relationships. These traces border a zone of serpentinite within the foothills of the Irish Hills. Faults and fault-related features identified during this investigation are based mainly on bedrock relationships, geomorphic criteria and/or observed disruption of Quaternary deposits north and northeast of the previously mapped traces.

Trench and natural stream cut exposures on the Ingley property (Plate 16) show a northwest-trending, near vertical to steeply northeast-dipping reverse fault. In the stream cut exposure, warping of beds within older alluvium on the hanging and foot walls is consistent with drag folding along a northeast-dipping reverse fault. In Ingley trench T-1, the fault separates Quaternary alluvium on the southwest from Franciscan sandstone and shale on the northeast. Older alluvium tentatively correlated with the Pleistocene Paso Robles Formation of Hall and others (1979) is extensively sheared and dips steeply to the southwest. These stratigraphic relations indicate northeast-side-up reverse displacement.

A radiocarbon date of $28,450 \pm 550$ years before present from a faulted paleosol in Ingley trench T-1 indicates that there has been late Quaternary (last-40,000 years) activity along the fault. Fine-grained deposits dated at 2420 ± 90 and

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2520 \pm 50 years before present are indicative of ponding on the footwall block and suggest that minor warping possibly related to multiple faulting events continued into the Holocene.

Ingly trench T-2 was excavated at the base of a prominent, northeast-facing, 6-meter-high topographic scarp within the Los Osos fault zone (Plate 17). Four low-angle faults displace a buried soil A horizon with down-to-the-northeast displacement in this trench. Slickensides and mullions on the northeasternmost fault plane trend S42°W to S68°W and plunge 14 to 22 degrees, indicating predominantly dip-slip displacement with some minor left slip. Cumulative vertical separation of the buried A horizon is 0.6 \pm 0.3 meters.

Cumulative net horizontal displacement of the buried A horizon across the four faults is approximately 4.1 \pm 0.2 meters, which suggests shortening of about 15 percent of this stratum. The ratio of cumulative horizontal to vertical separations suggests an average fault dip of about 9 degrees within the upper 3 meters of exposed strata, although maximum fault dip exposed in the trench is 29 degrees (Plate 17). Based on the cumulative net horizontal displacement of 4.1 \pm 0.2 meters and a range in fault dip of 9 to 29 degrees, the cumulative net slip on the fault since development of the buried A horizon ranges from 4.0 to 4.9 meters. The lower value of 4.0 meters (or slightly higher) is preferred because most of the near-surface shears in the trench are low angle.

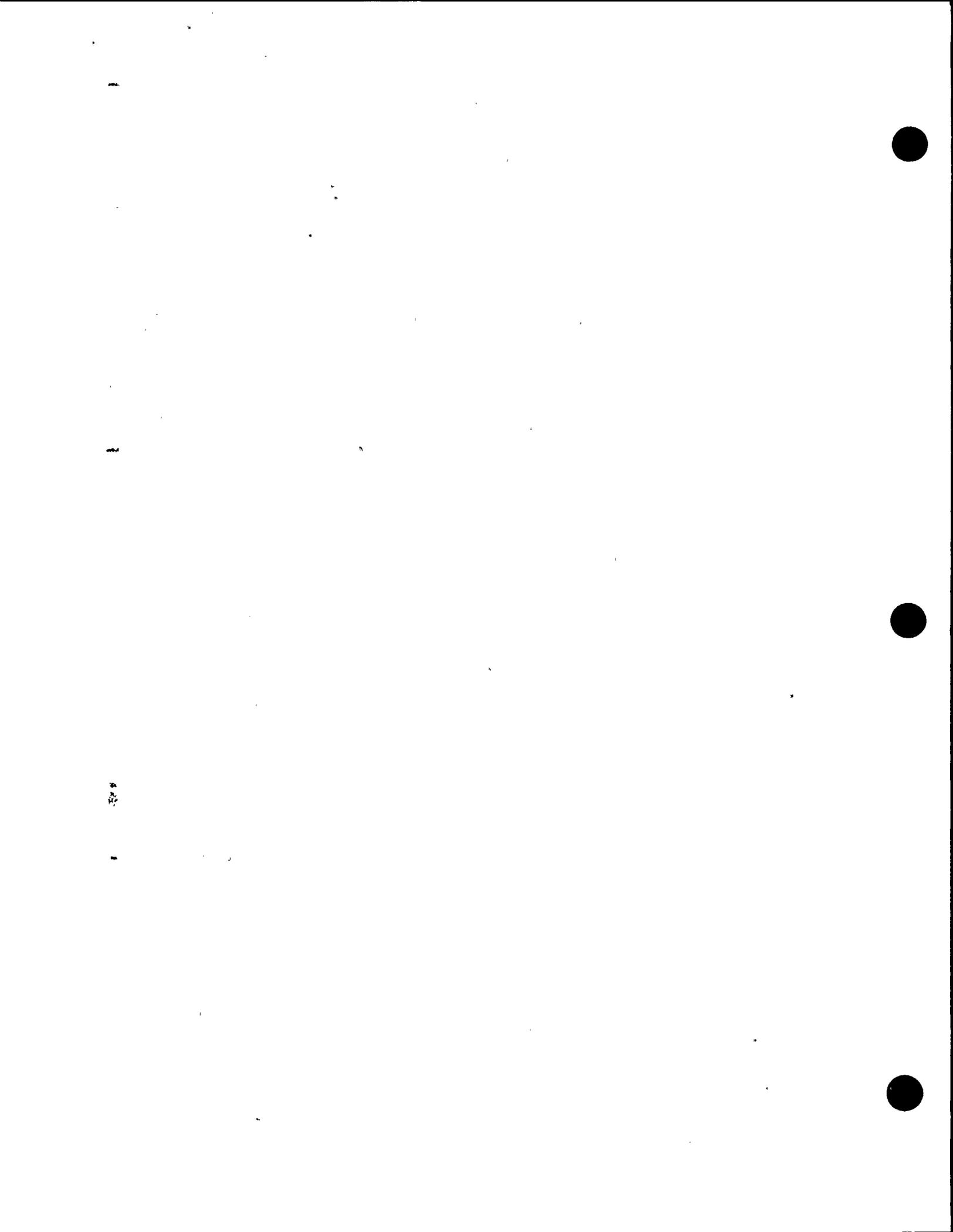
Evidence that several surface-faulting events have occurred on the shears exposed in Ingly trench T-2 includes: 1) numerous shears within a zone approximately 21 meters wide; 2) a thick (0.5 meter) gouge zone within the older alluvium (unit 1, Plate 17) and younger, overlying deposits suggesting that repeated shearing has occurred; and 3) the northeasternmost shear displaces a soil E horizon near station 0 + 10 (Plate 1-17), whereas the southwesternmost shear does not; and 4) soil horizons show smaller vertical separations upsection across the northeasternmost shear. These relations suggest that the southwesternmost shear predates development of the E horizon and was not involved in fault

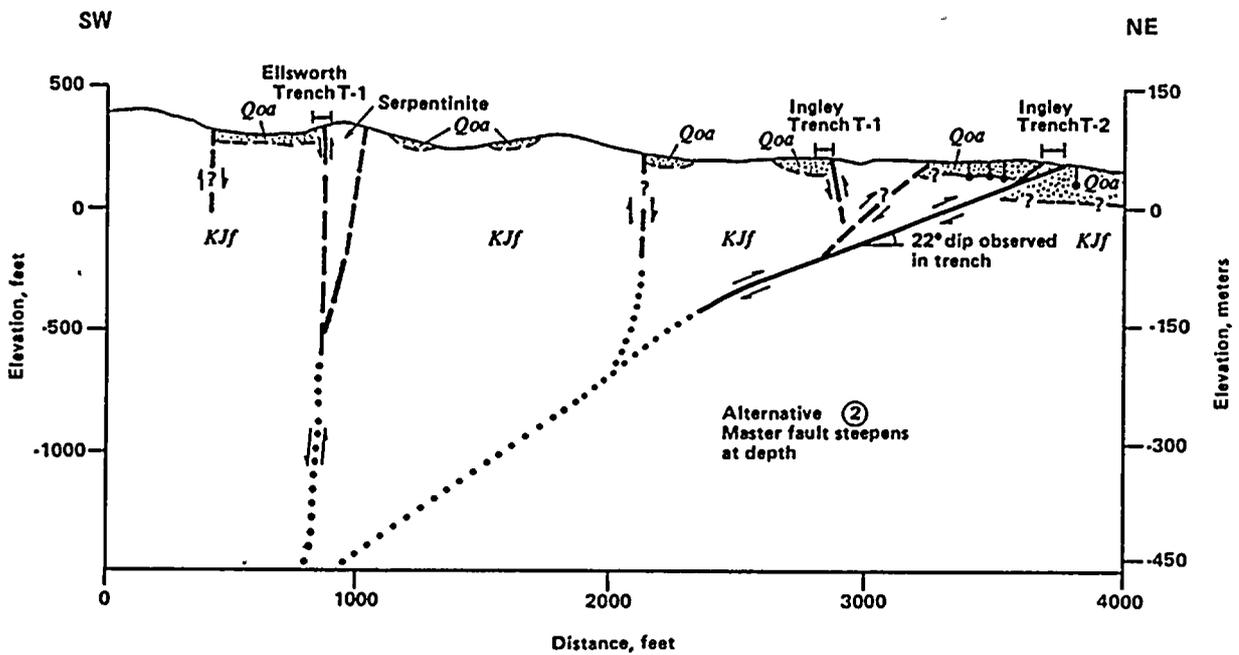
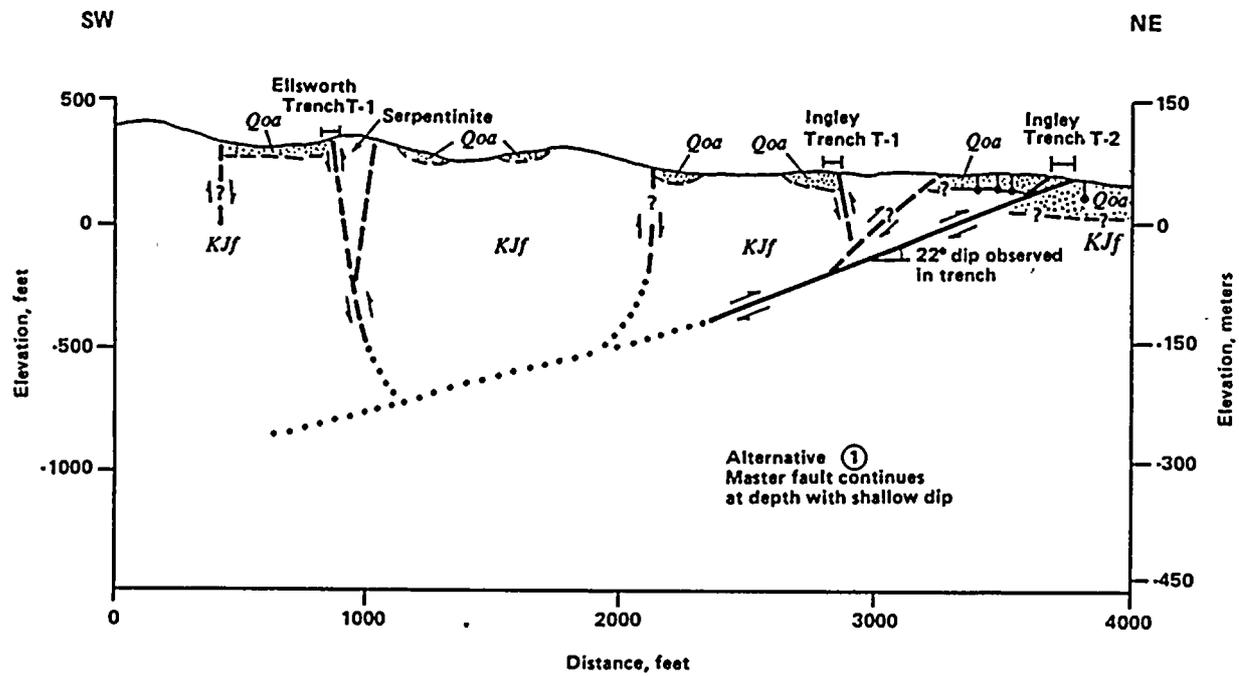
movement during the most recent event. Thus, there are at least two and probably more surface-faulting events recorded in the trench exposure. Assuming a minimum of two events and a net cumulative displacement of 4.0 meters or slightly more, the maximum displacement per event is about 2 meters or slightly more. An age of 1840 \pm 60 years before present of unit 6 (Plate 17) and displacement of the near-surface E horizon strongly suggest that there has been Holocene rupture along at least one of the shears exposed in Ingly trench T-2.

Based on relative soil development and soil-stratigraphic relations, the faulted buried A horizon exposed in Ingly trench T-2 is estimated to be between 15,000 and 30,000 years in age. This age-estimate and the displacements of the buried A horizon suggest a late Pleistocene net vertical slip rate of 0.02 to 0.04 millimeter per year. The late Pleistocene net slip rate ranges from 0.13 to 0.33 millimeter per year, which is consistent with the long-term net slip rate of 0.2 to 0.5 millimeter per year based on block uplift of marine terraces at the coastline to the west along a fault dipping 30 to 60 degrees southwest.

Near-surface fault geometry, sense of displacement and recency of slip suggest that this fault is the primary reverse fault in the Los Osos fault zone. Two alternative down-dip fault geometries are permissible to produce the observed near-surface stratigraphic and structural relationships (Figure 2-51). The faults may continue to depth either as southwest-dipping, low-angle thrusts or as steeper reverse faults that flatten as they approach the surface. The steeper dip model is supported by structural evidence for a previous history of strike slip along the zone and by the geomorphic expression of faults on the Cuesta property (Plate 16). This suggests normal faulting within the upper plate of the Los Osos fault zone, implying that the fault steepens with depth. Alternatively, the high-angle reverse faults or "backthrusts" observed in Ellsworth trench T-1 Ingly trench T-1, and Cuesta trenches suggest compression in the hanging wall of the primary fault, which, in turn, could imply a low-angle thrust geometry for the primary fault at depth. Both dip geometries are considered in







- EXPLANATION**
- Fault: dashed where inferred, dotted where conjectural; arrows indicate sense of displacement
 - Alluvium - Pliocene to Pleistocene
 - Franciscan assemblage
 - Borehole

Figure 2-51

Diagrammatic cross sections illustrating alternative tectonic models to explain stratigraphic and structural relationships observed at the Ingley and Ellsworth properties.

characterizing the fault as a seismic source (Chapter 3).

Marine Terrace Investigations, Montaña de Oro/Morro Bay Area. The Irish Hills segment of the Los Osos fault zone terminates a flight of emergent marine terraces along the coast between Montaña de Oro and the town of Los Osos. Disruption of the terrace sequence clearly demonstrates late Quaternary activity on the fault (Plates 10 and 12). These terraces were mapped in detail in order to 1) provide constraints on the location of the fault through the dune complex south of Morro Bay; 2) evaluate the relationship of the fault to the San Luis/Pismo structural block; and 3) provide a basis for estimating long-term rates of vertical displacement along the fault.

A flight of eleven emergent marine terraces is preserved along the coast from Montaña de Oro to San Luis Obispo Bay. The lower two emergent terraces are well preserved and laterally continuous along the coastline. Based on 28 age dates obtained during this study and comparison with marine terrace sequences worldwide, these two lower terraces are 83,000 or 105,000 years old and 120,000 years old (marine oxygen isotope substages 5a or 5c and 5e, respectively). The higher, older terraces, which are not as well preserved, are present as discontinuous remnants along the coast. Based on terrace elevations and correlation to paleosea-level highstands, these higher terraces range in age from about 214,000 to over 500,000 years.

The flight of marine terraces between Montaña de Oro and the town of Los Osos terminate at the Los Osos fault zone along the northeastern margin of the San Luis/Pismo structural block. The marine terrace shoreline angles are cut into bedrock at elevations ranging from 14 meters to over 198 meters (Figures 2-14, Plates 10 and 12). The shoreline angles maintain a relatively constant elevation laterally, but show a slightly higher uplift rate close to the Los Osos fault zone (Figure 2-11).

Emergent marine terraces are not present in the Morro Bay area northeast of the Los Osos fault zone. Borehole and gravity data indicate that a

deep but locally restricted subsiding basin is present in the southern Morro Bay area directly northeast of the fault. The Los Osos fault zone, therefore, separates the uplifting San Luis/Pismo structural block to the southwest from an area of subsidence, informally referred to here as the Morro Bay Basin, to the northeast. Onshore, the basin is about 6 kilometers long and 3 to 4 kilometers wide at the coast. Gravity data suggest that the basin extends offshore an additional 2 to 3 kilometers to the northwest. The basin thus occupies a local area beneath the southern part of Morro Bay and a small area directly offshore from it. In general, bedrock around the perimeter of the basin is represented by Franciscan assemblage rocks, whereas late Tertiary age rocks and Quaternary deposits occupy the center of the basin. The presence of Pliocene rocks in the basin indicates that subsidence was occurring during the late Tertiary and may have begun even earlier.

The origin of the Morro Bay Basin appears to be tectonic rather than erosional. The surface of Pliocene bedrock is at depths of over 200 meters below sea level. The depth to which bedrock can be scoured by fluvial erosion is limited by the lowest elevation of sea level during sea-level lowstands and by the sill elevations of channels leading to the ocean. Maximum lowering of sea level in the middle to late Pleistocene has been on the order of 130 to 150 meters below modern sea level (Chappell and Shackleton, 1986). Streams draining Morro Bay and the Los Osos Valley established gradients to the lower sea-level stands and, thus, at any point upstream, had an elevation higher than the corresponding sea level. Based on this reasoning, the deepest possible erosional Quaternary valley along the coastline must be shallower than 150 meters below present sea level, provided no subsequent tectonic subsidence has occurred. In fact, the deepest channel eroded into the bedrock floor of Estero Bay only allows for erosion to a depth of about 30 to 40 meters below present sea level 3 kilometers south of Morro Rock and 1.5 kilometers offshore.

Quaternary sediment is interpreted to overlie Pliocene bedrock in the Morro Bay Basin at depths exceeding 200 meters below sea level. Because the depth of scouring is constrained to be



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less than 50 meters below sea level based on the depth of offshore channels or 150 meters below sea level based on sea level lowstand estimates, the Morro Bay Basin has clearly undergone Quaternary subsidence. It is difficult to quantify the rate of subsidence, however, because of the poor age control (post-Pliocene) and the great range in the amount of scouring, and thus subsidence, that may have occurred.

The distribution of marine terraces north of Morro Bay also suggests that southwest-directed tilting and subsidence of the Morro Bay Basin has occurred. Between the towns of Cayucos and Morro Bay, a single well-developed marine terrace is preserved (Weber, 1983). Field reconnaissance indicates that the terrace ranges in elevation from 5 to 6 meters near Cayucos to slightly less than 5 meters near Morro Bay, suggesting a slight tilt to the south. The terrace is approximately 120,000 years old (substage 5e) based on U-series ages, analysis of paleoclimate from faunal assemblages and amino-acid racemization analyses. Coincidence of the substage 5e highstand elevation (about 6 meters) with the present terrace elevation near Cayucos indicates that the coastline in this area has undergone little or no tectonic uplift or subsidence. The slight tilt of the terrace toward Morro Bay suggests that there is slight subsidence of the coastline near Morro Bay and toward the Morro Bay Basin.

Borehole, gravity and field data suggest that a major structural boundary exists beneath eolian deposits along the southwestern margin of the Morro Bay Basin. This boundary is coincident with the northeastern margin of the San Luis/Pismo structural block and is interpreted to be the northwestern extension of the Los Osos fault zone (Figure 2-15).

FLUVIAL TERRACE INVESTIGATIONS— SAN LUIS OBISPO CREEK AREA

The distribution of alluvial deposits along the Los Osos fault zone strongly suggests tectonic impoundment of alluvium along San Luis Obispo, Pismo and Arroyo Grande Creeks upstream of the fault (Plate 16, Figure 2-52). The areal extent of younger and older alluvium supports segmentation

of the fault zone. A larger amount of younger alluvium is ponded along the Irish Hills segment suggesting a relatively higher rate of uplift across the fault in this area. Lesser amounts of younger alluvium are ponded behind the Lopez Reservoir segment suggesting relatively lower rates of activity on the fault in this area. The presence of large amounts of older alluvium (Paso Robles Formation of Hall and others, 1979) at the surface along the Lopez Reservoir segment, however, may suggest a higher rate of activity along the segment during the early Quaternary than at present.

San Luis Obispo Creek flows to the southwest across Los Osos Valley, the Los Osos fault zone and the San Luis/Pismo structural block (Figure 2-52) and is antecedent to uplift of the block. A flight of fluvial strath and fill terraces is preserved along the creek within the elevated structural block. Pleistocene and Holocene valley fill deposits present in the Los Osos Valley suggest that tectonic ponding has occurred behind the rising San Luis/Pismo structural block and/or there has been subsidence of the Los Osos Valley. The fluvial stratigraphy and fluvial terraces along San Luis Obispo Creek thus help constrain the rates and sense of displacement along the Los Osos fault zone. The terraces, which were graded to a former Los Osos Valley surface at the time of their development, now project upstream as much as 34 meters above the valley floor. Based on inferred correlations to marine terraces at the coast, the oldest terrace remnants are estimated to be on the order of 430,000 to 580,000 years old. Disruption of the terrace sequence by the fault indicates late Pleistocene and probable Holocene activity along the Irish Hills segment.

SLIP RATE, IRISH HILLS SEGMENT

Rates of displacement on the Irish Hills segment of the Los Osos fault zone are estimated from the displacement of marine terraces between Montaña de Oro and Morro Bay, the displacement of fluvial terraces along San Luis Obispo Creek, and the displacement history recorded in Ingleigh trench T-2.

The substage 5e (120,000 years old) marine terrace is present in both the Montaña de Oro



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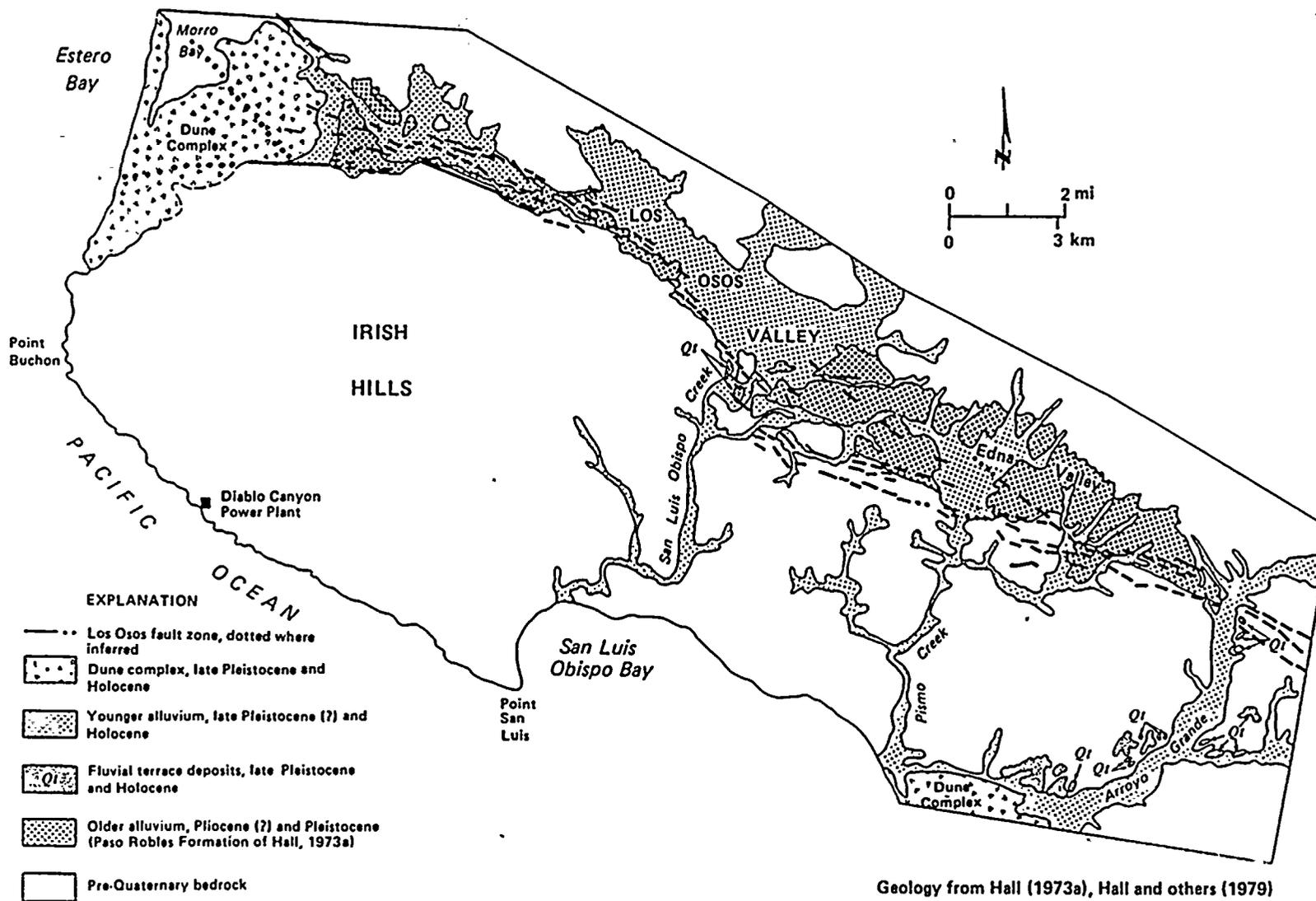


Figure 2-52
Distribution of Pliocene(?) and Quaternary alluvial deposits in the San Luis/Pismo region, illustrating tectonic impoundment of alluvium along the Los Osos fault zone.

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area south of the fault and between the towns of Morro Bay and Cayucos north of the fault. Differential uplift of this terrace is used to assess the minimum vertical component of slip on the Los Osos fault zone. In the Cayucos to Morro Bay area, the shoreline angle is at an elevation of 6 ± 1 meters (Weber, 1979). In the Montaña de Oro area, the shoreline angle for the terrace is at an elevation of 32 ± 1 meters (Plate 7). The minimum amount of vertical separation across the Irish Hills segment of the Los Osos fault zone is thus greater than 26 meters (32 meters - 6 meters) during the past 120,000 years. The minimum vertical component of slip is therefore 0.2 millimeter per year.

Maximum vertical displacement on the Irish Hills segment outside of the Morro Bay Basin is estimated by projecting the southwest-tilted shoreline angle of the substage 5e marine terrace from the Cayucos area across the Morro Bay Basin into the Los Osos fault zone. This projection suggests that the Los Osos Valley outside of the Morro Bay Basin is subsiding at a rate of less than 0.2 millimeter per year and probably less than 0.1 millimeter per year. Uplift of the San Luis/Pismo block based on the elevation of the substage 5e shoreline angle is 0.2 millimeter per year. Therefore, the maximum relative vertical component of slip across the Irish Hills segment is estimated to be 0.4 millimeter per year (Table 2-15).

The well-developed flight of fluvial terraces preserved along San Luis Obispo Creek within the San Luis/Pismo structural block is truncated by the Los Osos fault zone. Upstream of the fault trace, the creek meanders within a broad floodplain that lacks a sequence of fluvial terraces. The presence of extensive deposits of Pleistocene and Holocene valley-fill alluvium suggests that the valley is tectonically quiescent or subsiding at a low rate, and that alluvium is tectonically ponded against the rising Irish Hills subblock along the Los Osos fault zone. The minimum rate of vertical slip on the fault zone is estimated by assuming that the highest fluvial terrace south of the fault correlates with the aggrading valley floor north of the fault. The highest recognized fluvial terrace is approximately

430,000 to 580,000 years old and if projected across (northeast) the Los Osos fault zone would be up to 34 meters above the valley floor. This indicates a minimum component of vertical slip on the Irish Hills segment of 34 meters/580,000 years or 0.06 millimeter per year (Table 2-15).

The maximum rate of vertical slip is estimated by assuming that the highest fluvial terrace south of the fault correlates to the bedrock (pre-Quaternary) erosional surface at the base of the valley fill in the Los Osos Valley. Interpretation of water-well data suggest that the base of Quaternary alluvium is at a depth of 76 meters below the valley surface. This would indicate a maximum component of vertical slip on the Irish Hills fault segment of 110 meters/430,000 years or 0.26 millimeter per year.

Southwestern Boundary Of The San Luis/Pismo Structural Block

The San Luis/Pismo structural block is bounded along its southwestern margin by a diffuse, complex zone of northwest-trending reverse faults and flexures (Figure 2-53). Principal structures within this zone include the San Luis Bay, Wilmar Avenue, Pecho and Oceano faults.

This zone of faulting is 4 to 6 kilometers wide and over 60 kilometers long, although the individual structures within the zone are limited in extent and lateral continuity. None of these faults were recognized by previous workers in the region. A map illustrating the distribution of these faults in relation to faults mapped by previous workers is shown on Plate 13.

Faults along the southwestern boundary of the San Luis/Pismo structural block have had predominantly reverse displacement with little or no strike-slip separation. The rate of vertical separation across the zone of faults is the difference between the rate of uplift of the San Luis/Pismo structural block along its southwestern margin (0.10 to 0.15 millimeter per year) and the rate of subsidence of the northeast side of the Santa Maria Valley structural block (greater than





Table 2-15
 LATE QUATERNARY SLIP RATES, IRISH HILLS SEGMENT
 Los Osos Fault

	Vertical Component of Slip (mm/yr)		Net Slip (mm/yr) ¹			
			30° Fault Plane		60° Fault Plane	
	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>	<u>Max.</u>	<u>Min.</u>	<u>Max.</u>
Montaña de Oro	0.2	0.4	0.4	0.8	0.25	0.5
San Luis Obispo Creek	0.06	≥0.26	0.12	≥0.5	0.07	≥0.3
Ingley Trench T-2	0.02	0.04	0.15	0.3	0.06	0.2

¹Vertical component of slip is converted into net slip, assuming the fault plane dips 30° and 60° at depth.



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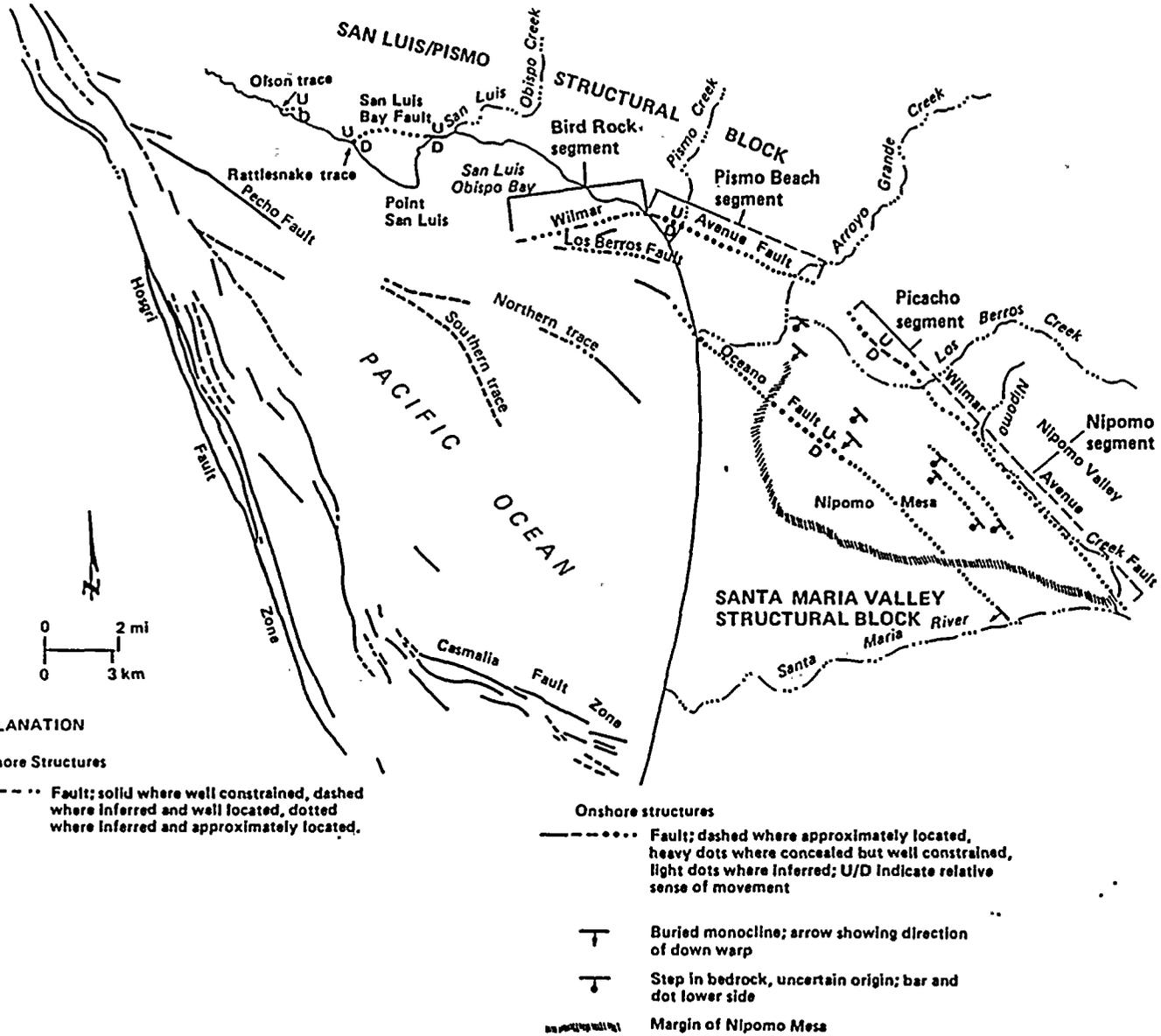


Figure 2-53
Map of the southwestern boundary of the San Luis/Pismo structural block illustrating faults and postulated segments of the Wilmar Avenue fault.

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0.01 millimeter per year). These rates suggest a minimum component of vertical displacement of 0.11 millimeter per year across the boundary zone. Assuming an average fault dip of 45 degrees to the northeast, the net dip-slip rate of displacement for the boundary zone is about 0.2 millimeter per year. The physical and behavioral characteristics of individual faults along this margin of the San Luis/Pismo block are described below.

PECHO FAULT

The northwest-trending Pecho fault lies entirely offshore west and south of Point San Luis (Figure 2-53, Plate 5). The fault is interpreted from offshore geophysical data to dip steeply to the northeast and to have up-to-the-east reverse displacement. To the northwest, the fault ends at the Hosgri fault zone about 4.1 kilometers southwest of the plant site. To the southeast, the fault branches into two traces in southern San Luis Obispo Bay. Both traces die out before intersecting the coast in the Santa Maria Valley area. Southwest of Point San Luis there is a 4.5 kilometer gap in the mapped trace of the fault. The total fault length, including the gap, is 22 kilometers including the northern trace and 19 kilometers including the southern trace (Figure 2-53).

Prior to studies conducted for the Long Term Seismic Program, the Pecho fault was not recognized by previous workers in the region. The postulated Santa Maria River fault of Hall (1982) would lie 1.5 to 3 kilometers north of the Pecho fault and would have a more westerly trend, particularly in the area of Point San Luis. The Santa Maria River fault is interpreted by Hall (1978a, 1982) to be a major late Quaternary right-lateral strike-slip fault with activity from 17 to 3 million years ago related to development of the Santa Maria "pull-apart" basin. This fault was not confirmed in this study. Moreover, its timing and sense of displacement is not consistent with Quaternary reverse displacement interpreted on the Pecho fault.

The Pecho fault is expressed geomorphically by a trend of discontinuous seafloor scarps that extends about 5 kilometers from near the Hosgri

fault zone at the latitude of Pecho Creek southeast toward San Luis Obispo Bay. The trend is featured by irregular, southwest-facing scarps in Franciscan or middle Tertiary bedrock. Because the scarps are located in an area that lacks post-late Wisconsinan on sediments, their presence cannot be used to establish the timing of most recent fault activity.

Evidence of Quaternary activity along the Pecho fault is observed along the southeastern end of its northern trace in San Luis Obispo Bay (Figure 2-53). Sedimentary rocks believed to be of Wheelerian (early Pleistocene) age are separated about 17 meters by what is interpreted on high-resolution seismic reflection profiles to be a vertical fault. The displacement suggests a long-term vertical slip rate for this part of the Pecho fault on the order of 0.01 millimeter per year. Assuming that the fault dips steeply northeast like other faults along the southwestern margin of the San Luis/Pismo block, this vertical component of slip suggests a net dip-slip rate of about 0.01 to 0.02 millimeter per year. Near the junction of the northern and southern traces of the Pecho fault, geophysical records show that the late Wisconsinan unconformity is elevated up to 6 meters across the northern trace. The uplift may be due to faulting which suggests that slip occurred on this part of the northern trace of the Pecho fault within the past 18,000 years.

SAN LUIS BAY FAULT

The San Luis Bay fault is a west-northwest-trending reverse fault that is the northeasternmost element of the zone of faults along the southwestern boundary of the San Luis/Pismo block (Figure 2-53). This fault displaces and locally warps late Quaternary marine terraces and is thus interpreted to be capable. Progressively smaller amounts of displacement of successively younger marine terraces indicate that there have been multiple faulting events along it during the late Pleistocene.

The San Luis Bay fault is poorly exposed and is not well expressed geomorphically suggesting a low rate of activity. It is observed in only one location, a roadcut and seacliff exposure about 0.3 kilometers west of the community of Avila



Beach (Figure 2-54 and Plate 10). The behavior and geometry of this fault is interpreted primarily from detailed investigation of this exposure, supported by interpretation of offshore geophysical data, borehole data from construction of the Union Oil pier in San Luis Obispo Bay, and an investigation and analysis of onshore marine terraces (Figure 2-55, Plates 10 and 12).

The San Luis Bay fault is interpreted to trend west-northwest from the Avila Beach exposure through a large topographic saddle between San Luis Hill and the Irish Hills. Higher marine terrace shoreline angles on opposite sides of the saddle have different elevations and cannot be correlated (Plate 12). In addition, two relatively abrupt changes in elevation or local disruptions of several meters each in the lower marine terrace sequence near Olson Hill and Rattlesnake Canyon have been identified northwest of the topographic saddle (Figure 2-55, Plates 10 and 12). These disruptions are interpreted to be the result of movement along the San Luis Bay Fault, although there is no geomorphic expression or exposure of the fault in these areas.

The San Luis Bay fault was recognized in early 1987 during field investigations for the Long Term Seismic Program. The fault had not been previously mapped or described by investigators in the region. However, Chipping (1979) described deformed marine terraces near the Avila Beach fault exposure but did not describe or map a fault in the area.

Onshore Investigations. The San Luis Bay fault in the Avila Beach exposure is a zone of shearing up to 1 meter wide, that strikes nearly east-west and dips about 15° to 40° to the north, becoming progressively steeper down dip (Figure 2-56). Mullions within the fault zone trend roughly N17°E and indicate predominantly dip-slip displacement on the fault. The fault exhibits up-to-the-north displacement of the substage 5e (120,000 years old) marine terrace and younger colluvial deposits (Figure 2-54).

The late Pliocene angular unconformity at the base of late Pliocene deposits is displaced 13.4 meters by the fault exposed in the roadcut.

Additionally, at least one other strand of the San Luis Bay fault is present directly offshore from the roadcut exposure. Data from exploration borings for the Union Oil Company pier (McClelland Engineers, Inc., 1984) suggest that the minimum post-Pliocene cumulative vertical separation across the fault zone may be 43 meters (Figure 2-57).

The substage 5e marine terrace between Point San Luis and Avila Beach (Figure 2-55, Plate 10) provides a late Pleistocene (120,000 years old) strain gauge from which to estimate the slip rate across the fault zone. The substage 5e strandline lies at an elevation of 18 to 20 meters on the upthrown side of the fault and at an elevation 12 to 14 meters on the downthrown side. These relations indicate a late Pleistocene cumulative vertical separation of 4 to 8 meters across the entire fault zone.

Detailed mapping, drilling and surveying suggest that the two lowest marine terraces are disrupted by faulting and/or tight monoclinical folding near Rattlesnake Canyon and north of Olson Hill (Figure 2-55, Plates 10 and 12). Although a fault has not been observed in available exposures at either of these locations, the terrace disruptions are inferred to be the result of faulting. Both of the lower terraces are disrupted by an inferred fault near Rattlesnake Canyon, herein called the Rattlesnake trace of the San Luis Bay fault. Vertical separation of the substage 5e strandline (Plates 10 and 12) is about 5 to 8 meters. Vertical separation of the substage 5a strandline is about 1.5 to 3 meters.

Detailed field mapping, surveying and drilling suggest that the substage 5a and 5e marine terraces also are displaced near Olson Hill (Figure 2-55, Plates 10 and 12). This inferred fault trace is called herein the Olson trace of the San Luis Bay fault. Seacliff exposures on both sides of the fault trace suggest that the substage 5a shoreline angle has an up-to-the-north vertical separation of 3 to 4 meters. These exposures also constrain the location of the trace to be approximately coincident with a bedrock fault mapped at the coast by Hall and others (1979). Borehole data and field mapping suggest that the



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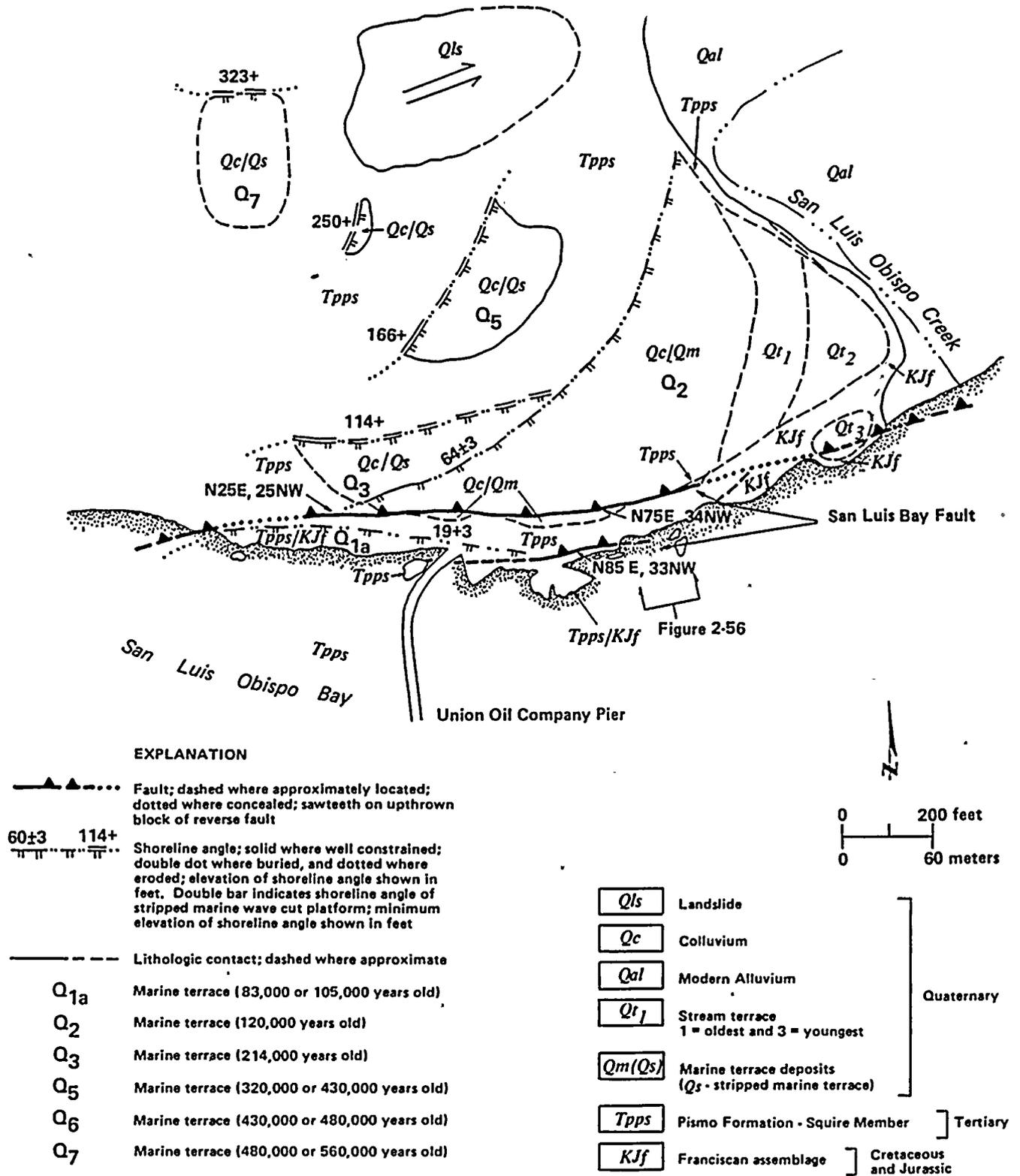


Figure 2-54
Geologic map of the Avila Beach exposure of the San Luis Bay fault.



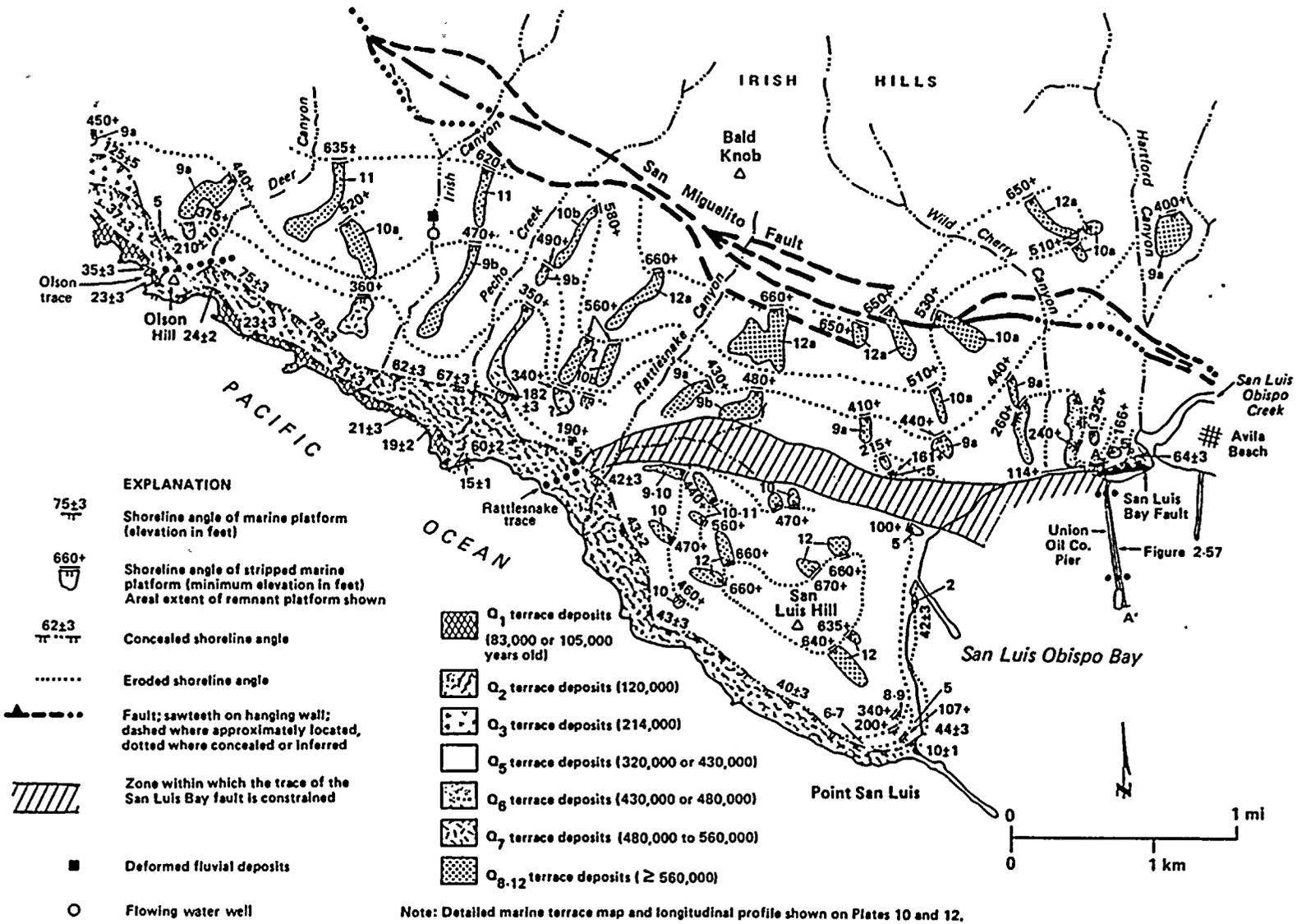


Figure 2-55
Geologic map illustrating distribution and elevation of marine terrace shoreline angles in the Point San Luis to Mallagh Landing area.



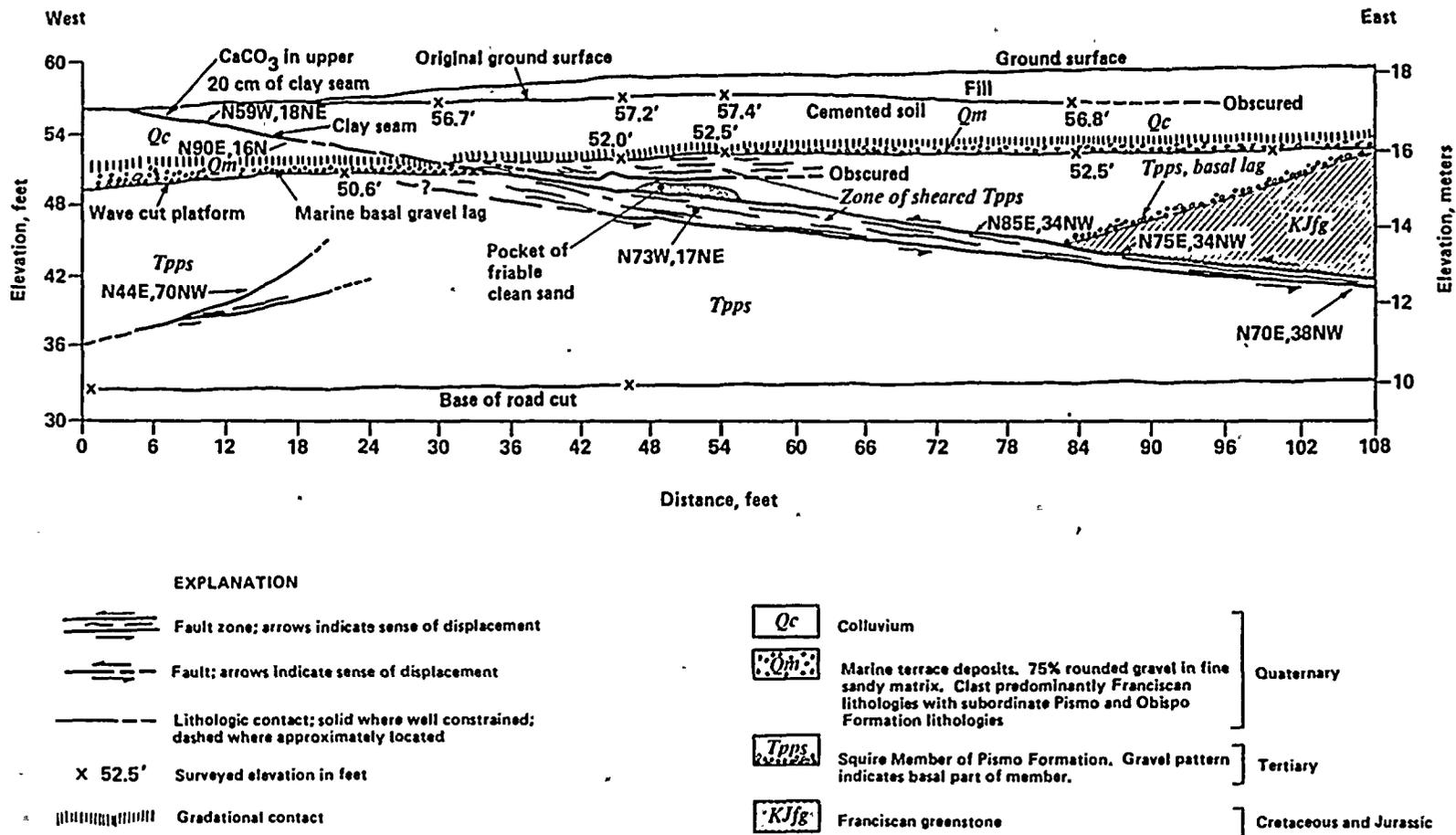


Figure 2-56
Detailed log of a portion of the Avila Beach roadcut exposure illustrating stratigraphic relationships across the upper trace of the San Luis Bay fault.

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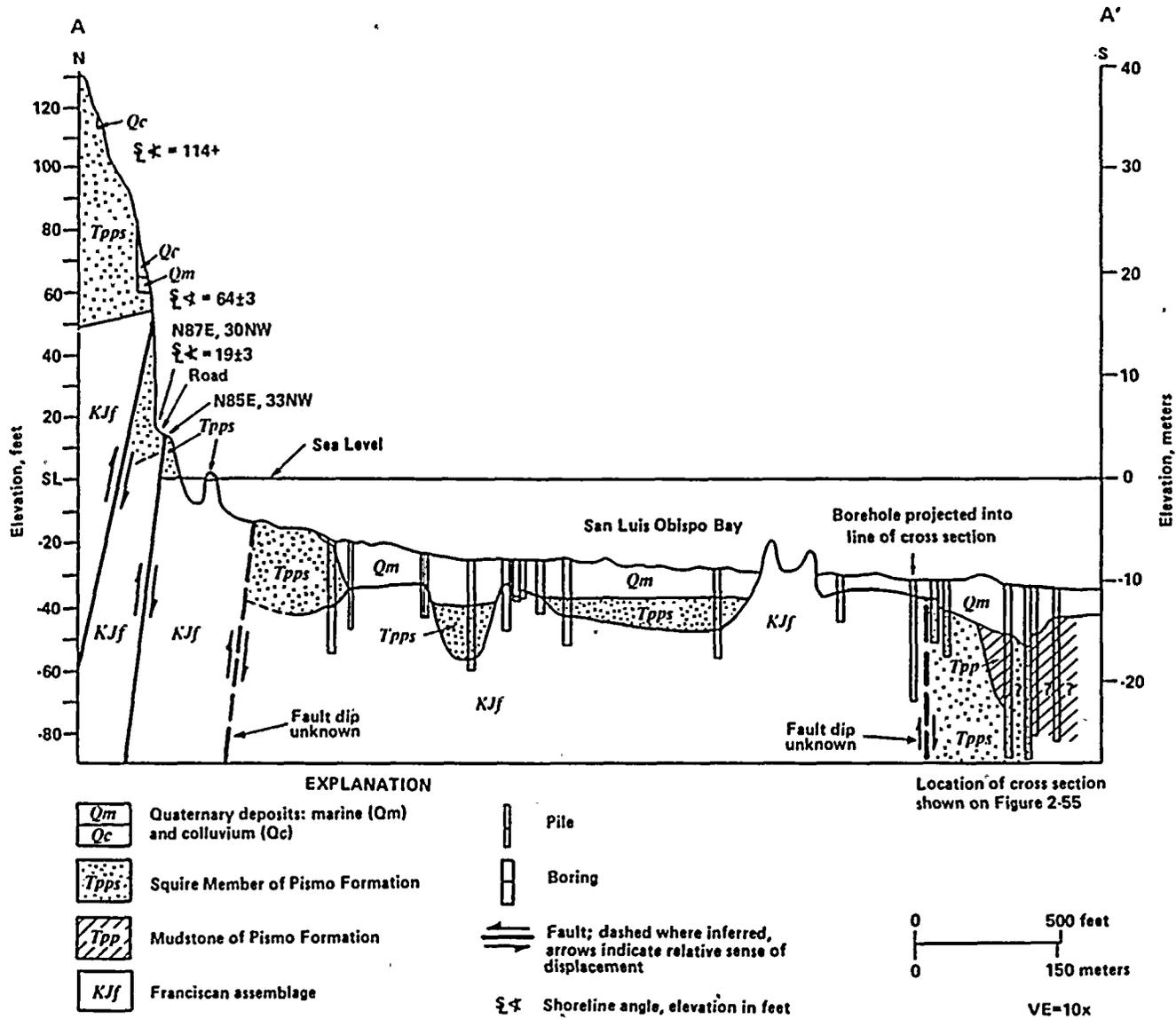


Figure 2-57
Geologic cross section illustrating stratigraphic and structural relationships near the Avila Beach roadcut exposure and the Union Oil Company Pier.

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substage 5e shoreline angle has vertical separation of 1 to 5 meters.

The relationship between the Olson and Rattlesnake traces onshore is poorly constrained. Mapping of high marine terraces along the eastern projection of the Olson trace suggest that the terraces have not been disrupted by faulting or warping (Figure 2-55, Plate 10). However, an approximately 3-meter-high, southwest-facing scarp present on a stripped marine terrace platform just north of Irish Canyon suggests that the Olson trace may project inland with a southeasterly trend. Further to the southeast, there are no apparent disruptions in the marine terrace sequence suggesting that if the scarp is evidence for the continuation of the Olson trace, the fault probably dies out to the southeast, giving an onshore length of only about 1 to 2 kilometers.

Detailed field mapping and drilling demonstrate that the marine terrace sequence has not been disrupted elsewhere along the coast between Point San Luis and Point Buchon (Plates 10 and 12). The Rattlesnake and Olson features, therefore, are the only traces of the San Luis Bay fault that extend to this part of the coastline. These strands probably extend offshore into the area between the coastline and the Hosgri fault zone or die out to the northwest.

Offshore Investigations. Available seismic reflection, side-scan sonar, bathymetric and seafloor sampling data have been interpreted to evaluate the offshore continuation of the San Luis Bay Fault to the southeast into San Luis Obispo Bay from the Avila Beach exposure and to the northwest into the Pacific Ocean along the Rattlesnake and Olson traces. These data are shown on Plate 19.

Features interpreted to be faults or fault-related deformation are imaged on several seismic reflection lines within a 1-kilometer-wide zone east of the Hosgri fault zone (Plate 4, Sheet 2). These geophysical picks align along two general trends that are interpreted to be fault traces. The southern fault trace was mapped over a distance of about 3 kilometers and is imaged on three seismic reflection lines as poorly-defined, terminated reflections in the limb of an anticline

and as localized diffractions. The fault plane is interpreted to dip steeply to the northeast (70 degrees or greater) to a depth of at least 90 m. The northern fault trace was mapped over a distance of about 1 kilometer and is imaged on three seismic reflection lines as a poorly-defined, northeast-dipping reverse fault underlying a small anticline. Evidence for the presence of these fault traces, however, is non-existent or inconclusive on other geophysical lines that cross their projected trend to the east because of factors that do not allow for clear resolution of the data, such as shallow depth of water and acoustic basement with steeply dipping structure at or near the seafloor. Both the northern and southern fault trends are mapped to within 200 meters of the Hosgri fault zone. Similar to most of the structural trends along the Hosgri fault zone's eastern margin, the southern trace bends to the north as it approaches the fault zone and appears to become parallel to it. The southern trace apparently dies out rather than directly merging with or being truncated by the eastern trace of the Hosgri fault zone. Seismic data are not available in the 1.5-to-2-kilometer-wide zone between the coastline and the area of geophysical coverage near the Hosgri fault zone (Plate 2).

To assess the possible westward offshore extension of the Olson and Rattlesnake traces and their relationship to the two small geophysically imaged faults near the Hosgri fault zone, we compiled bathymetry data available for the intervening offshore area and prepared a detailed seafloor contour map (Plate 19). The possible presence of faulting was assessed by identifying and evaluating topographic lineaments such as scarps and inflections on the contoured bathymetric data.

Topographic lineaments with a variety of orientations were identified on the contour map within 7 kilometers of the coastline. As shown on Plate 19, the well-defined, northwest-trending lineaments in the western part of this area are associated with the Hosgri fault zone, the Pecho fault, or low-sealevel stillstands. In the intervening area between the coastline and the Hosgri fault zone, the general trend of lineaments, stratigraphic bedding, and fold axes is west-northwest with subordinant north-northwest and northeast trends. The bathymetric lineaments

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101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150



identified in this area occur in highly deformed rocks of probable Miocene age or older. They may be fault-line scarps, erosion-resistant beds standing higher than surrounding beds, or remnants of now-submerged strandlines carved during sea level lowstands. Parts of the lineaments occur near old shorelines of sealevel lowstands and thus likely have an erosional origin. Most of the lineaments cut across regional bathymetric trends, however, and are not related to former lowstands but reflect changes in bedrock lithology.

Among these lineaments, two well-defined but discontinuous lineaments strike N70 to 80W and trend approximately toward the shoreline location of the Rattlesnake trace. The westernmost of these lineaments is also recognized on side-scan sonar and subbottom profiler data. However, the easternmost lineament is separated from the onshore Rattlesnake trace by about 4.5 kilometers. Within this distance, several other weakly defined northwest- and northeast-trending lineaments cross-cut the eastward projection of the easternmost lineament. Thus there is not a direct connection of the eastward-projecting offshore lineament trend with the Rattlesnake trace. Three short, weakly expressed bathymetric lineaments also trend toward the shoreline location of the Olson trace. However, these are too short and too subtle to infer the presence of a fault.

Because of the low slip rate on the Olson and Rattlesnake fault traces, it is not likely that tectonic scarps would be preserved in areas of shallow water subject to near-shore erosion. At a slip rate of about 0.1 millimeters per year or less, scarps less than 2 meters high would have developed since the late Wisconsinan (18,000 years old) sealevel lowstand. Even if preserved, scarps of this size would be less than the resolution of the available bathymetric data (two-meter contour interval).

The San Luis Bay fault may extend offshore to the southeast from the Avila Beach exposure along the northern margin of San Luis Obispo Bay. The results of detailed mapping of marine terraces and bedrock geology between Avila Beach and Pismo

Beach indicate that the fault does not come back onshore (Figures 2-13 and 2-55, Plates 7 and 8). Geophysical data and seafloor samples suggest that the San Luis Bay fault dies out within about 4 kilometers southeast of the Avila Beach exposure, and thus is not continuous with but forms a 2- to 5-kilometer-wide en echelon right step with the Wilmar Avenue fault.

Fault Characteristics. Marine terrace mapping suggests that the onshore length of the San Luis Bay fault is about 4.5 kilometers. Evidence of the offshore continuity of the fault is weak. If the fault dies out to the northwest and southeast within about 1 kilometer of the coastline, it is about 6 kilometers long. If the fault extends offshore only to the northwest or to the southeast, fault lengths of as much as 15 and 8 kilometers, respectively, are possible. The maximum potential fault length, including both possible extensions of the onshore fault, is about 19 kilometers.

The age of the most recent surface faulting event on the San Luis Bay fault is uncertain. The absence of onshore geomorphic expression strongly suggests little or no Holocene activity. Although the fault at the Avila Beach exposure displaces the substage 5e (120,000 years old) marine terrace and extends into younger colluvium overlying the wave-cut platform, no dateable material was obtained from this colluvium or an overlying warped(?) paleosol.

Recurrent late Pleistocene faulting along the Rattlesnake and Olson traces is indicated by the decreasing displacement of successively younger marine terraces. Vertical separation of the substage 5e (120,000 years old) terrace across the Rattlesnake trace is approximately twice that of the substage 5a (83,000 years old) terrace (Table 2-16) suggesting multiple late Pleistocene surface faulting events.

Estimates of long-term slip rates of the San Luis Bay fault in the vicinity of the Avila Beach exposure and of the Rattlesnake and Olson traces are summarized in Table 2-16. These low rates are indicative of a low degree of activity and long recurrence intervals, estimated to be about 35,000 years for a magnitude 6 earthquake (Chapter 3).





Table 2-16
SUMMARY OF SLIP RATES SAN LUIS BAY FAULT

Locality	Vertical Displacement (m)	Vertical Component (mm/yr)	Slip Rates (mm/yr)	
			70° Fault Plane	35° Fault Plane
Avila Beach Exposure Post-Pliocene unconformity at the base of the Squire Member (1 to 2 Ma)	≥ 43	0.02 to 0.04	0.02 to 0.05	0.04 to 0.07
Late Pleistocene post-substage 5e (120 ka)	4 to 7.5	0.03 to 0.06	0.04 to 0.07	0.06 to 0.11
Rattlesnake Trace Late Pleistocene post-substage 5e (120 ka)	5 to 8 ¹	0.04 to 0.07	0.04 to 0.07	0.07 to 0.11*
	3 to 5 ²	0.02 to 0.04	0.03 to 0.04	0.04 to 0.07
post-substage 5a (83 ka)	1.5 to 3 ¹	0.02 to 0.04	0.03 to 0.06	0.02 to 0.04
Olson Trace Late Pleistocene post-substage 5e (120 ka)	1 to 5	0.01 to 0.04	0.01 to 0.04	0.01 to 0.07*
post-substage 5a (83 ka)	2 to 4	0.02 to 0.05	0.02 to 0.05	0.04 to 0.08

Maximum³
Post-substage 5e
(120 ka)
0.18 mm/yr

NOTES:

¹Amount of vertical deformation due to faulting and downwarping of wave-cut platform.

²Amount of vertical deformation due to faulting only, does not include deformation due to warping.

³Maximum post-substage 5e rate is sum of "starred" (*) values.

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WILMAR AVENUE FAULT

The Wilmar Avenue fault is a northwest-trending, northeast-dipping reverse fault along the southwestern boundary of the San Luis/Pismo structural block (Figure 2-53). Elevated marine terraces on both sides of the fault suggest that the Wilmar Avenue fault is not the primary fault that separates the uplifting San Luis/Pismo block from the subsiding Santa Maria Valley block.

Cumulative displacement of the substage 5e (120,000 years old) terrace suggests that there have been multiple faulting events during the late Pleistocene, but the recurrence interval between faulting events and the timing of the most recent event are uncertain. The Wilmar Avenue fault has poor geomorphic expression, however, suggesting a low rate of activity, possibly with little or no Holocene activity.

The Wilmar Avenue fault is exposed only at the present sea cliff near Wilmar Avenue in Pismo Beach (Figures 2-13, 2-53, Plate 11). Based on data from detailed mapping and drilling, the fault is well constrained southeast of the sea cliff for a distance of 2.3 kilometers.

Detailed mapping of Pleistocene marine terraces and analysis of water well logs suggest that the fault continues at least to Arroyo Grande and may extend along the northeastern margin of the Nipomo Mesa at least to the northern part of the Santa Maria Valley, a distance of 25 kilometers (Figure 2-53). Offshore to the northwest of the sea-cliff exposure, the Wilmar Avenue fault bends to a more westerly trend and continues for a distance of at least 5.1 kilometers. Maximum fault length is thus approximately 30 kilometers.

Prior to 1986, the Wilmar Avenue fault was not recognized as a fault in the area. The Wilmar Avenue fault as defined by this study coincides with part of the Santa Maria Basin fault as shown by Gray (1980) and may include part of the Santa Maria River fault of Hall (1978a, 1982). Nitchman (1987) noted that Pleistocene deposits overlying the marine platform exposed near Wilmar Avenue are displaced by a subsidiary fault associated with the Wilmar Avenue fault.

Fault Characteristics. Four segments of the Wilmar Avenue fault are identified based on variations in fault trend, spatial coincidence with subblocks of the San Luis/Pismo structural block, continuity and distribution of marine terraces and possible relations to Tertiary basin margins (Figure 2-53). Characteristics of these segments are presented below and are summarized on Table 2-17.

Bird Rock segment. The Bird Rock segment lies entirely offshore in San Luis Obispo Bay and extends at least 5.2 kilometers west-southwest from the seacliff exposure of the Wilmar Avenue fault (Figure 2-53). Based on seismic reflection data, the segment ends beneath the bay and does not merge with the Hosgri, Oceano, San Luis Bay, or Pecho faults to the west. The eastern boundary of this segment is defined as the change in the trend of the fault from generally east/west beneath San Luis Obispo Bay to N65°W onshore. Little is known about recency or slip rate for this offshore segment. Seafloor scarps (Plate 19) occur locally along the segment, but these are probably due to differential erosion of bedrock units juxtaposed by the fault. Possible deformation of the post-Wisconsinan ($\leq 18,000$ years old) unconformity is interpreted from some geophysical records, but there is no definitive evidence for post-Wisconsinan fault activity in the data presently available.

Pismo Beach segment. The Pismo Beach segment extends for a distance of approximately 7 kilometers from the Wilmar Avenue seacliff exposure to the vicinity of Arroyo Grande Creek (Figure 2-53). The fault zone exposed in the Wilmar Avenue sea cliff is approximately 4 ± 2 meters wide and contains shears that range in strike from N64°W to east/west and dip 45° to 60° northeast (Plates 20 and 21). Striae along these shear surfaces, as well as the presence of older bedrock overlying younger bedrock, indicate predominantly reverse displacement on the Wilmar Avenue fault.

The substage 5e wave-cut platform exposed in the sea cliff is displaced by the fault and has a net vertical separation of 5.7 meters (Figure 2-13, Plates 11 and 12). However, the wave-cut



Table 2-17
CHARACTERISTICS OF POSTULATED SEGMENTS OF THE WILMAR AVENUE FAULT

Postulated Fault Segment	Topographic Segmentation	Range-Front Character	Geomorphic Expression	Recency of Slip	Slip Rate (mm/yr)	Length	Segment Boundary
Bird Rock	Borders southern margin of east-west trending bedrock ridge that lies below sea level.	—	Trace marked locally by scarps are probably fault-line features.	Late Quaternary. Not well constrained.	Not well constrained	3.2 mi (5.2 km)	NW: Seismic reflection data suggests the segment dies out in southern San Luis Obispo Bay. SE: Apparent bend of approximately 25° or more in near-shore area near Wilmar Avenue, Pismo Beach.
Pismo Beach	Coincident with southern part of the Edna subblock.	Northwest of Pismo Creek, the fault lies close to base of steep range front; southeast of Pismo Creek, fault defines boundary between broad alluvial and eolian plain and rolling upland area.	Poor—abundant cultural modification along fault trace, buried in part by thick late Pleistocene and Holocene alluvium and eolian deposits.	Multiple late Pleistocene and possible Holocene events.	Late Quaternary 0.04 - 0.08	4.8 mi (7.7 km)	NW: Apparent bend of ≥25° (see above). SE: Coincident with SE termination of Edna Range segment and postulated NE-trending Arroyo Grande cross structure; apparent change in fault trend of 20°; marine terrace sequence not disrupted.
Picacho	Roughly coincident with Newsom Ridge subblock.	Located at western margin of rolling foothills.	Poor—discontinuous, lineaments (linear stream segments, saddles, breaks in slope).	Post-mid-Pleistocene; Late Pleistocene unknown; Poor geomorphic expression suggests no Holocene activity.	Post-mid-Pleistocene 0.03 - 0.05	4.7 mi (7.5 km)	NW: Arroyo Grande area described above. SW: poorly defined, may not appear to extend to Summit Station Road area based on water well data.
Nipomo	Located at western margin of rolling foothills.	—	Poor-discontinuous linear stream segments; approximates the northeastern boundary of Nipomo Mesa.	Unknown.	Late Quaternary. Not well constrained.	≥ 6.5 mi (10.6 km)	NW: Summit Station Road area described above. SE: Not investigated as part of the LTSP.

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platform on the downthrown side of the main fault may be a younger (substage 5a or 5c) terrace; if so, the cumulative net vertical separation of the 120,000 years old (substage 5e) terrace is approximately 4.1 meters. Assuming a range in fault dip of 45° to 60° and a range in vertical separation of 4.1 to 5.8 meters, the Wilmar Avenue fault has an average late Quaternary net slip rate of 0.04 to 0.07 millimeter per year.

Along the trend of the Pismo Beach segment 2 kilometers to the southeast, deformed beds within the Squire Member of the Pismo Formation are exposed in a quarry in Pismo Beach informally called the "Farmboy quarry" (Plate 11). Detailed structural observations in the Farmboy quarry suggest that late Quaternary activity along this segment was primarily reverse dip slip. Estimated vertical separation of the substage 5e wave-cut platform (Plate 11) across the Wilmar Avenue fault in the vicinity of the Farmboy quarry ranges from 4 to 6.4 meters, which is comparable to the separation of the substage 5e platform in the Wilmar Avenue sea-cliff exposure. An average late Pleistocene net slip rate of 0.04 to 0.08 millimeter per year is estimated assuming a 45 to 60 degrees northeast-dipping fault plane. The similarity in behavior and probable lateral continuity of the fault between the Farmboy quarry and the seacliff exposure suggests consistent fault behavior along the Pismo Beach segment.

There is no direct evidence for multiple displacement on the Wilmar Avenue fault. The cumulative displacement of between 4 and 6 meters of the substage 5e (120,000 years old) terrace along the Pismo Beach segment of the Wilmar Avenue fault, however, is greater than would be expected to occur in a single faulting event, which suggests that there have been multiple faulting events during the late Quaternary. However, the recurrence interval between faulting events and the timing of the most recent event are uncertain. The lack of geomorphic expression suggests a low rate of activity and probable absence of Holocene displacement.

Picacho Segment. The Picacho segment is defined chiefly by the apparent disruption of the marine terrace sequence southwest of Picacho Hill (Plate 11). The boundaries of this postulated segment, particularly to the southeast, are poorly constrained (Table 2-17). The maximum length of this segment is 7.5 kilometers.

Possible deformation of the 430,000-year-old to 560,000-year-old marine terrace (map unit Q_6 , Plate 11) near Picacho Hill suggests that this segment has been active in the past approximately 500,000 years. Estimated displacement of the terrace suggests a vertical slip rate ranging from 0.03 to 0.05 millimeter per year, which is comparable to that observed along the Pismo Beach segment to the northwest. The age of the most recent faulting event along the Picacho segment is not known, although the lack of geomorphic expression along the segment suggests that it has not been active in Holocene time.

Nipomo Segment. The Wilmar Avenue fault is poorly defined southeast of the Arroyo Grande area. The trace of the Wilmar Avenue fault along the Nipomo segment is inferred by the alignment of several subtle geomorphic and geologic features, including a straight segment of Nipomo Creek and the postulated Tertiary basin margin south of the town of Nipomo (Plate 11). There is no surface expression of the fault and behavioral characteristics such as slip rate and age of most recent faulting are not known.

OCEANO FAULT

The Oceano fault is a major northwest-trending reverse fault that is recognized in the Nipomo Mesa area and in the offshore region west of the town of Oceano (Figure 2-53, Plate 11). This structure is recognized via interpretation of onshore Vibroseis[®] reflection data obtained during the Long Term Seismic Program (Plate 9). The $N45^{\circ}W$ to $N50^{\circ}W$ trend of the structure projects to a previously recognized subsurface fault (California Department of Water Resources, 1970), and to a structure comparable to the onshore Oceano fault observed in geophysical data in the offshore region 1.8 kilometers northwest of the coastline (Figure 2-53). The offshore structure follows a more east-southeast



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trend and appears to terminate in San Luis Obispo Bay approximately 3.3 kilometers from the coastline.

Onshore and offshore geophysical data indicate a minimum length of 15 kilometers for the Oceano fault. Along projection of the Oceano fault to the southeast, the Santa Maria fault, a subsurface fault recognized in the Santa Maria Valley (Canfield, 1939; Worst 1951; Hall, 1982), may be a continuation of the Oceano fault (Plate 13).

Offshore geophysical data suggest that the Oceano fault displaces beds of probable Pleistocene age overlying a late Pliocene(?) unconformity. Along the western end of the Oceano fault, the late Wisconsinan ($\leq 18,000$ years ago) unconformity is not disrupted, indicating that the fault has not been active in the late Pleistocene and Holocene. Onshore, the Oceano fault is not exposed and has poor geomorphic expression. Thick eolian and alluvial deposits and extensive fluvial erosion in the Santa Maria Valley have buried and/or obscured the onshore fault trace.

Estimates of slip rate along the onshore reach of the fault are based on vertical displacement of the Foxen Formation. Vertical slip rate is between about 0.04 and 0.13 millimeter per year in the central part of the Nipomo Mesa and is between about 0.01 and 0.05 millimeter per year near the coastline. These poorly-constrained data suggest that there may be a slight decrease in vertical slip rate to the west, which is consistent with the termination of the fault to the west identified via geophysical data. Offshore, probable displacement of Wheelerian deposits suggests a long-term vertical slip rate of 0.01 to 0.03 millimeter per year.

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Chapter 3

SEISMIC SOURCE CHARACTERIZATION

To Address

Element 2 of the License Condition

ELEMENT 2 OF THE LICENSE CONDITION

PG&E shall reevaluate the magnitude of the earthquake used to determine the seismic basis of the Diablo Canyon Nuclear Plant using the information from Element 1.

INTRODUCTION

Results of the seismic source characterization respond directly to Element 2. We view this element as calling for a full characterization of the Hosgri fault zone as a potential seismic source including other aspects in addition to assessment of maximum magnitude. Therefore, we incorporate the implications of various proposed tectonic models to the fault as a seismic source (for example, implications to activity, geometry, style of faulting, slip rate, etc.). We also characterize other faults that may be important to the seismic hazard at the site, and we address the possibility of seismic sources that may have escaped detection or that may not be directly expressed as faults at the surface.

The purpose of the seismic source characterization activities of the Long Term Seismic Program is to use the geosciences data and interpretations developed in the Program (Chapter 2) to characterize the earthquake environment in the site region. Specifically, we assess the location, magnitude, and rate of occurrence of earthquakes on sources of significance to ground motions at the site.

OBJECTIVES

The objectives of the Seismic Source Characterization activities are:

- To utilize data and interpretations developed in the geosciences investigations (Chapter 2) to define the earthquake environment of the site
- To incorporate fully the range of interpretations advocated in the scientific community and derived from our investigations, with proper emphasis accorded the more strongly supported interpretations and with a full treatment of uncertainty
- To develop, when appropriate, new or improved methods and approaches toward characterizing earthquake sources, in order to understand more fully the physical processes
- To document interpretations of the source characterization and their bases in the geosciences data
- To present the conclusions in ways that are appropriate for subsequent use in probabilistic and deterministic ground-motion analyses.

BACKGROUND AND APPROACH

Characterization of seismic sources is closely linked to the geosciences program and therefore is driven by the data and interpretations developed throughout the course of the Program. The source characterization is a logical extension of the geosciences program due in large part to the Phase II Scoping Study.



The Phase II Scoping Study was designed to assess the relative importance of geologic considerations regarding central coastal California in order to arrive at a plan of work focused on the most important considerations. Preliminary probabilistic and deterministic seismic hazard analyses were conducted that incorporated the range of tectonic interpretations and models advocated in the scientific community. Emphasis was placed on the possible implications of these models to earthquake source characterization (for example, age of deformation; stress state; location, amount, and rate of deformation in the contemporary tectonic environment) and site ground motions (for example, distance to site and maximum magnitude). Tectonic models proposed to explain the Cenozoic evolution and contemporary tectonic setting of the North America-Pacific plate margin were considered important to the Program as they relate to the *current* and *expected* style of deformation, timing, geometry of faults, stress orientation, and rate of crustal deformation in the region. These models are addressed in Chapter 2 of this report. Seismic source characterization focuses on aspects of these tectonic models that relate specifically to the earthquake issue.

As a result of the Phase II Scoping Study, several significant technical considerations were identified (Chapter 2) and a work plan was developed to focus efforts on aspects of crustal deformation important to seismic source characterization, including considerations identified by the NRC staff and its consultants.

During the Long Term Seismic Program, data collection, analysis, and interpretation have emphasized identifying and reducing the uncertainties associated with any particular source characteristic. For example, following identification of Quaternary activity on the Los Osos fault zone, studies were performed to assess its capability, geometry, length, segmentation, slip rate, and other physical and behavioral characteristics. Data were gathered, analyzed, and a range of interpretations were made. Additional work was then performed to constrain or quantify the range of possible interpretations, within the limit of available resources and resolution of the

geologic techniques available. Larger uncertainties are acceptable for sources identified as less significant based on their physical and behavioral characteristics (for example, slip rate on a fault located 50 kilometers from the site). However, large uncertainties in more significant source characteristics were targeted as priority areas for more intensive study. For example, extensive offshore geophysical data were collected to define the location, geometry, and style of faulting along structures proximal to the site such as the Hosgri fault zone and the faults that make up the southern boundary of the San Luis-Pismo block. Intensive field investigations were also conducted to map late Quaternary marine terraces in the site vicinity to assess the locations and amounts of onshore deformation. By monitoring our interpretations and uncertainties during the data collection phase of the Program, we were able to supplement or redirect our ongoing field efforts to reduce uncertainties and solidify interpretations for the most significant seismic sources. This chapter summarizes results of the geosciences activities, with particular focus on results important to earthquake source characterization.

Many aspects for understanding the future behavior of earthquake sources have, through routine use and analysis, become widely accepted (for example, the relationship between fault rupture length and magnitude, the relationship between fault slip rate and earthquake recurrence). Other aspects are being addressed by ongoing research (for example, fault segmentation, and coseismic folding). We have carried out the seismic source characterization using accepted approaches. In some cases, we have developed state-of-the-art methods for assessing certain important characteristics (for example, estimating rupture lengths using segmentation criteria). In all cases, the methods used are documented in this report.

Recent seismic hazard analyses for critical facilities at multiple sites have relied on interpretations developed by experts to assess the range of interpretations and associated earthquake potential in a variety of inter- and intra-plate tectonic environments (for example, LLNL, 1985; EPRI, 1986). A significant aspect of these expert opinion studies is that the range of





opinions and the uncertainties are large and the studies are focused primarily on the present understanding of the problem and not on the gathering of data to resolve or reduce the uncertainties.

In contrast to these other seismic hazard studies, the Long Term Seismic Program was designed to take an active, focused role in gathering, analyzing, and interpreting geosciences data. From the standpoint of evaluating earthquake sources, the Program builds upon and exceeds the level of investigation of any previous studies in south-central coastal California. For the Program, PG&E implemented a large, comprehensive program of data collection and interpretation. Coupled with this program has been the evaluation of existing data and interpretations developed by others, complemented by extensive interactions with the scientific community throughout the course of the work. As a result, data and interpretations developed in the Long Term Seismic Program provide the most complete and scientifically-supportable bases for characterizing the seismic sources of significance to the site.

Scientific peer review of the geoscience findings and interpretations was and is being accomplished through several means. Throughout the course of the Program, PG&E personnel and consultants interacted with a large number of researchers in the field, through personal interviews, and by other discussions and communications. Long Term Seismic Program activities and interim conclusions were presented at professional society meetings and other topical meetings (for example, Geological Society of America, Seismological Society of America, American Geophysical Union, USGS Segmentation Workshop). Numerous meetings and workshops were held with the Long Term Seismic Program Board of Consultants and Technical Advisors. Workshops and field trips were held with the NRC staff and its consultants to review data and interpretations and to discuss methods and progress on the program. As a result of this peer review, the geoscience bases for seismic source characterization incorporated the range of relevant professional opinion in the scientific community in addition to

utilizing results of the Program to specify the earthquake characteristics.

Seismic source characterization includes both probabilistic and deterministic evaluations for use in later phases of the Program, such as ground-motion assessment and seismic margins analysis. For the probabilistic analysis, a broader range of physical characteristics regarding each source is used, such as recurrence-related parameters, multiple sources, and ranges of values. In general, probabilistic treatment provides a fuller representation of both the physics of the source and the associated uncertainties. In the deterministic analysis, a controlling source is selected that leads to the largest site ground motions, parameters are evaluated that are related to maximum magnitude, and a conservative maximum magnitude is selected. For the purpose of evaluating site ground motions, an earthquake of this magnitude is then assumed to occur at the closest approach of the source to the site.

Probabilistic and deterministic approaches are complementary. Probabilistic treatment of uncertainty clearly illustrates and documents the possible discrete scenarios and the relative credibility of each. Sensitivity and uncertainty analyses provide a context for the selected deterministic values and show the sensitivity of the results to the parameters selected.

METHODS FOR CHARACTERIZING SEISMIC SOURCES

In this section we describe the methods used to characterize seismic sources. We specifically focus on methods to incorporate uncertainty in seismic source characterization and to assess maximum earthquake magnitude.

Incorporating Uncertainty in Seismic Source Characterization

Evaluation of the seismic potential of faults, particularly those having no recorded history of earthquake activity, requires the use of indirect measures of the size, frequency, and location of earthquakes that the fault may generate. These indirect measures are based on interpretations of

the fault's behavior in the geologically recent past. This is done by integrating geological, seismological, and geophysical data for the fault as well as analogies with other faults. Such evaluations are usually subject to uncertainty due to incomplete, and/or alternative interpretations of the data. Characterization of the seismic potential of a fault results from synthesis of available data, interpretations, and scientific judgment. The probabilistic approach used in this study to characterize potential seismic sources explicitly incorporates alternative interpretations as a measure of the uncertainty in various source characteristics (such as maximum magnitude and earthquake recurrence). The approach is based on the use of logic trees and provides a convenient, flexible means for assessing multiple interrelated parameters and for quantifying the uncertainty in seismic source characteristics (Kulkarni and others, 1984; Coppersmith and Youngs, 1986; National Academy of Sciences, 1988).

Logic trees are composed of nodes and branches (Figure 3-1). Each node represents a choice between alternative values of that a parameter. Each branch leading from the node represents one possible parameter value. If the variable in question is continuous, it can be discretized at a suitable increment. Nodes of the logic tree are sequenced to provide for conditional aspects or dependencies among the parameters and to provide a logical progression from general to specific fault characteristics.

The example logic tree shown in Figure 3-1(a) displays the uncertainty in assessing the maximum magnitude earthquake that could occur on a fault on the basis of empirical relationships between maximum displacement per event and earthquake magnitude (for example, the relationships of Slemmons, 1982 for strike-slip and reverse faulting). In order to assess the maximum magnitude, two pieces of information are required: the sense of slip (S) of the fault and the maximum rupture length (DE) that could occur in a single event. This logic tree thus contains two levels or nodes, one for each parameter. In the example, values that might be assessed for

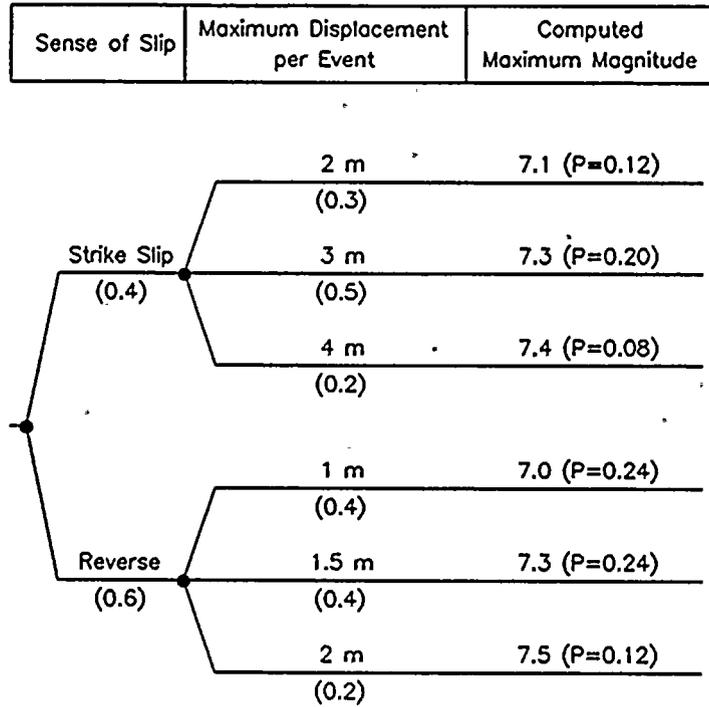
maximum displacement per event are dependent on the assumed sense of slip of the fault (strike-slip earthquakes may tend to have longer rupture lengths than reverse earthquakes, for example) and are thus most easily assessed given knowledge of the sense of slip. Consequently, the node for maximum rupture length is located after the node for sense of slip.

At each node, probabilities are assigned to each branch that represent the relative likelihood of that branch being the correct value or state of the parameter considered. These probabilities are assessed conditionally on the assumption that all branches on the particular path through the logic tree that leads to the node represent the true state or value of the preceding parameters. The probabilities are assessed subjectively because the available data are typically too limited to allow objective statistical treatment, and because scientific judgment is needed to weigh alternative interpretations. The logic tree approach simplifies these subjective assessments because the uncertainty in a single parameter is considered individually assuming that all other parameters are known with certainty.

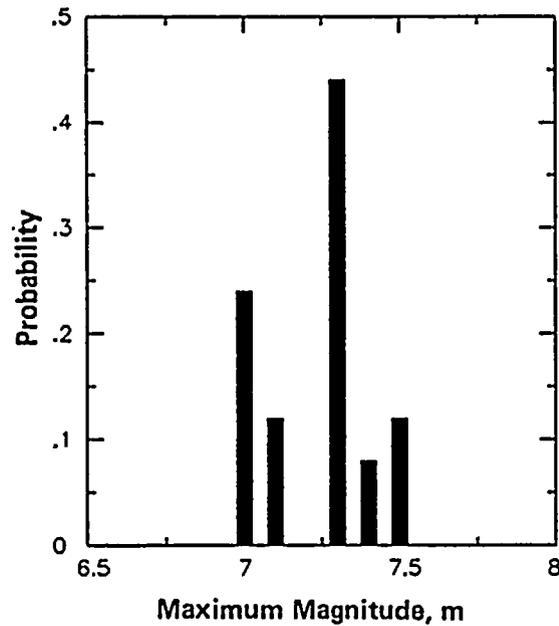
Two sense-of-slip models are considered in Figure 3-1: strike-slip and reverse. In this example, a slight preference for the reverse faulting case is reflected by the relative weights of 0.6 and 0.4 for the reverse and strike-slip cases, respectively. The probability that 2 meters is the correct maximum rupture length is assessed conditionally on which sense of slip is assumed to be correct [that is, the probability of a 2-meter maximum displacement given strike-slip faulting, $P(DE=2m|S=strike\ slip)$, is a separate assessment from $P(DE=2m|S=reverse)$]. As the branches at each node are intended to represent mutually exclusive and collectively exhaustive states of the input parameter, the sum of the conditional probabilities at each node is unity.

The logic tree shown in Figure 3-1(a) defines a discrete distribution for the maximum magnitude, $M_{max}(S,DE)$, considering the uncertainty in sense of slip and maximum rupture length. The resulting distribution is shown in Figure 3-1(b). The probability that $M_{max}(S,DE)$ will take on





a) Logic Tree for evaluating maximum magnitude



b) Discrete distribution for maximum magnitude

Figure 3-1
Example logic tree.

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any particular value $M_{\max}(s_i, de_j)$ is equal to the joint probability of the set of parameters s and de being the true sense of slip and maximum rupture length.

$$P[M_{\max}(S, DE) = M_{\max}(s_i, de_j)] = P(S=s_i) P(DE=de_j | S=s_i) \quad (5-1)$$

The expected or mean value of $M_{\max}(S, DE)$ given the uncertainty in the input parameters S and DE is given by:

$$E[M_{\max}(S, DE)] = \sum_i P(S=s_i) \cdot \sum_j P(DE=de_j | S=s_i) \cdot M_{\max}(s_i, de_j) \quad (5-2)$$

and the variance in $M_{\max}(S, DE)$ is given by:

$$\text{Var}[M_{\max}(S, DE)] = \sum_i P(S=s_i) \cdot \sum_j P(DE=de_j | S=s_i) \cdot M_{\max}(s_i, de_j)^2 - E[M_{\max}(S, DE)]^2 \quad (5-3)$$

Logic Tree for the Long Term Seismic Program

Figure 3-2 shows the logic tree used to characterize seismic sources in the Long Term Seismic Program. The definitions of each node of the logic tree are discussed below and the specific assessments for each fault are discussed later in this chapter. Note that in the logic tree given in Figure 3-2 and those given later in this chapter, those branches that appear to end (such as the "dip 2" branch for the dip node) actually continue on with values identical to those shown for the same node (the "dip 1" branch). Space limitations preclude the inclusion of these redundant branches.

The first node of the logic tree represents the uncertainty in the style of faulting (sense of slip) for the fault. Style of faulting was placed first in the logic tree because many of the other characteristics of a fault are considered dependent on the current mode of deformation. The three general classifications considered in this study are strike-slip, oblique slip, and reverse (thrust) slip.

For this study, these models are defined by the ratio of the horizontal to vertical components of slip: greater than 2:1 for strike-slip, between 2:1 and 1:2 for oblique slip, and less than 1:2 for reverse (thrust) slip.

Nodes 2, 3, and 4 of the logic tree represent the uncertainty in defining the fault geometry. Dip, maximum depth of faulting, and total length were judged to be dependent on the style of faulting. The maximum depth of faulting is the vertical thickness of the seismogenic crust, which, on the basis of earthquake hypocenters, is about 9 to 15 kilometers in California. The down-dip seismogenic width of a fault, then, is a function of its dip and the thickness of the seismogenic crust. These parameters affect the maximum rupture size possible, the distribution of distances from the site to potential earthquakes, and, via seismic moment, the rate of seismic energy release on the fault.

Nodes 5 through 9 relate to the assessment of the maximum earthquake magnitude for the fault. The nodes for maximum rupture length, maximum displacement, and average displacement define the dimensions of rupture for the maximum event. Maximum rupture length is based on an assessment of segmentation of the fault. Maximum displacement and average displacement are the amounts of slip associated with a single earthquake and are derived from geologic data. The rupture dimensions are used to estimate magnitude on the basis of empirical relationships between magnitude and rupture length, rupture area (product of rupture length and maximum down-dip width), maximum surface displacement, and seismic moment (proportional to the product of rupture area and average displacement). The next node (node 8) assesses the largest historical earthquake that has been associated with the fault. Only historical events of magnitude greater than $M_s 6$ were considered as possible maximum events. In the tree we show the uncertainty in whether an example fault may have been associated with a magnitude 6.3 earthquake (50 percent likelihood) or only with earthquakes smaller than 6 (50 percent likelihood).



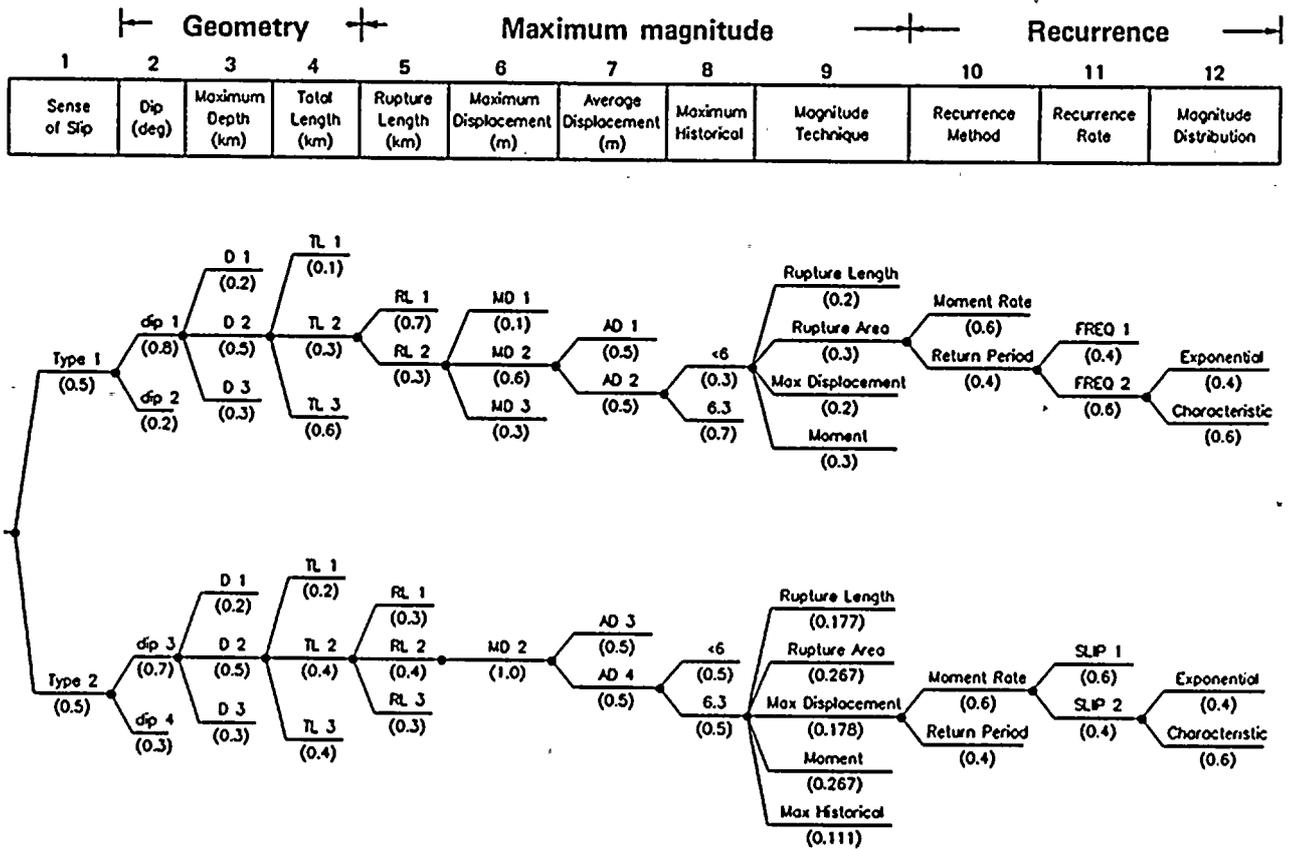


Figure 3-2
Logic tree for seismic sources evaluated in the Long Term Seismic Program.

1 100

100 100

100 100

100

The final node related to the assessment of maximum magnitude (node 9) addresses the selection of the appropriate technique to use for the magnitude assessment. The techniques considered in this study are listed in Table 3-1 and consist of published empirical relationships between magnitude and rupture length, rupture area, total fault length, maximum surface displacement, and seismic moment, as well as use of the maximum historical earthquake associated with the fault. Also given in Table 3-1 are the ranges of values in the data sets upon which the relationships are based. The relative weights assigned to each technique were considered to be the same for all faults. The basis for the weights as well as additional discussion of the maximum magnitude approach is given later in this chapter.

Nodes 10, 11, and 12 specify earthquake recurrence rates. Node 10 presents alternative methods for estimating recurrence rates. Two methods were used in this study, the seismic moment rate approach using fault slip rates, and recurrence rates constrained by geologically estimated recurrence intervals for surface rupturing events. The historical seismicity catalog was not used for recurrence estimation because the limited history and location accuracy do not allow reliable fault-specific recurrence estimates for larger magnitude earthquakes (events of magnitude 5 or greater) as are provided by geologically-constrained moment rates and recurrence intervals.

Node 11 defines the earthquake recurrence rate, either in terms of the fault slip rate or the recurrence intervals for surface rupturing events (assumed to be events within 1/2 magnitude unit of the maximum event). The last node of the logic tree (Node 12) addresses the appropriate form of the earthquake size distribution. The truncated exponential model (Cornell and Vanmarcke, 1969) is commonly used to model earthquake recurrence and has been shown to fit regional seismicity data. However, recent studies (for example, Schwartz and Coppersmith, 1984) have suggested that the magnitude distribution for individual faults may be better represented by a "characteristic" earthquake model that implies relatively more frequent large events than

intermediate size events. For this study, both the truncated exponential magnitude distribution and the characteristic magnitude distribution were used. Recurrence rates based on fault slip rate were obtained using the relationship given by Anderson (1979) for the truncated exponential model and by Youngs and Coppersmith (1985) for the characteristic model.

Approaches to Maximum Earthquake Magnitude Assessment

We assess maximum earthquake magnitudes for each seismic source using a multi-factor approach. That is, a number of fault characteristics that are correlated with magnitude (for example, rupture length, rupture area, maximum displacement per event) and various published empirical relationships are used (for example, Bonilla and others, 1984; Slemmons, 1982; Wesnousky, 1986). The use of multiple relationships leads to more reliable estimates of maximum magnitude than the use of any single relationship (Slemmons, 1982; Schwartz and others, 1984; Slemmons and Depolo, 1986). Such an approach has been used in seismic hazard studies for the San Onofre nuclear generating station (Southern California Edison, 1980), the Hanford nuclear power plant (Power and others, 1982), the southern California coastal region (Slemmons and others, 1982), the San Diego region (Power and others, 1986), the Wasatch corridor, Utah (Youngs and others, 1988) and a number of other site-specific and regional seismic hazard studies.

The selection of a maximum magnitude results from an evaluation of magnitude-related fault characteristics, calculation of magnitudes given these characteristics, and scientific judgment regarding the weight of evidence, applicability of various data sets to the Diablo Canyon site, and experience regarding historical earthquakes. For the probabilistic seismic hazard analysis, we use a full distribution of maximum magnitude for various faults (such as that shown in the example in Figure 3-1). The distribution incorporates the uncertainty in the parameter values, their relative credibility, and multiple techniques for estimating magnitude. For the deterministic analysis we



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Table 3-1
EMPIRICAL RELATIONSHIPS FOR MAGNITUDE ESTIMATION

Rupture Length versus Magnitude

Reverse Faulting:

Bonilla and others (1984) $M_S = 5.71 + 0.916 \log_{10}$ (Rupture Length in km)
(data range: M 6.5-7.7; 18-120 km)

Stemmons (1982) $M_S = 2.021 + 1.142 \log_{10}$ (Rupture Length in m)
(data range: M 5.8-7.7; 4-120 km)

Strike-Slip Faulting:

Bonilla and others (1984) $M_S = 6.24 + 0.619 \log_{10}$ (Rupture Length in km)
(data range: M 6.6-8.3; 11-440 km)

Stemmons (1982) $M_S = 1.404 + 1.169 \log_{10}$ (Rupture Length in m)
(data range: M 5.8-8.25; 6-450 km)

All Styles of Faulting:

Wesnousky (1988) (Slip rate less than 1 cm/yr data set)
 $M_S = 5.133 + 1.153 \log_{10}$ (Rupture Length in km)
(data range: M 6.3-8.1; 11-285 km)

Rupture Area versus Magnitude

Wyss (1979) $M_S = 4.15 + \log_{10}$ (Rupture Area in km²)
(data range: M 5.8-9.5; 30-200,000 km²)

Total Length versus Magnitude for Strike-Slip Faulting

Stemmons (1982) $M_S = 6.618 + 0.00012$ (Total Length in km)
(data range: M 6.8-8.25; 280-1,300 km)

Maximum Displacement versus Magnitude

Reverse Faulting:

Stemmons (1982) $M_S = 6.793 + 1.306 \log_{10}$ (Maximum Displacement in m)
(data range: M 5.9-7.7; 0.3-4 m)

Strike-Slip Faulting:

Bonilla and others (1984) $M_S = 7.00 + 0.782 \log_{10}$ (Maximum Displacement in m)
(data range: M 6.7-8.3; 0.4-9.5 m)

Stemmons (1982) $M_S = 6.974 + 0.804 \log_{10}$ (Maximum Displacement in m)
(data range: M 5.8-8.25; 0.02-9.5 m)

Seismic Moment versus Magnitude

Hanks and Kanamori (1979) $M_W = -10.7 + 0.667 \log_{10}$ (Seismic Moment in dyne-cm)
(data range: M 5.3-7.5)



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select a maximum magnitude for the controlling source.

Generally the historical record is too short to provide strong constraints on the maximum magnitude for a given fault or seismic source (Allen, 1975; McGuire, 1977; Bender, 1988). However, for more active faults, the historical record can provide an estimate of the maximum magnitude. For example, the sizes of the 1857, 1906, and 1966 earthquakes on the San Andreas fault are often considered to represent the maximum magnitudes for segments of this fault.

Studies of faults, including the characteristics of historical and prehistoric ruptures, show that many fault zones are segmented. These studies are leading to evidence for the controls and persistence of segments, as well as the distribution of slip along a segment associated with prehistoric earthquakes. For many faults studied, it appears that segments persist through repeated seismic cycles, that the distribution of slip repeats itself in successive earthquakes, and that past large earthquakes along individual segments are similar in size. This observation of repeated same-size events is embodied in the "characteristic earthquake" concept (Schwartz and Coppersmith, 1984; 1986; Wesnousky and others, 1983). The indications are that these characteristic events, because their size appears to be constrained by physical characteristics of the fault zone, can be considered to be maximum earthquakes.

For example, suppose we are interested in the maximum magnitude on the San Andreas fault near the central part of its south-central segment, which ruptured in 1857. Historical and geologic evidence shows that the length and displacement of the 1857 rupture is characteristic of prehistoric events (Sieh and Jahns, 1984; Schwartz and Coppersmith, 1984). Therefore, it appears that the maximum magnitude on the San Andreas fault along the south-central segment is that associated with the 1857 segment, about moment magnitude 7.9 (Sieh, 1978). Likewise, the observed repeated occurrence of magnitude 6 earthquakes on the Parkfield segment suggests that the maximum magnitude on this segment is that associated with the 1966 Parkfield event. In effect, it appears that the characteristic

earthquake for these segments is also the maximum earthquake.

Of course, for faults that have not experienced large historical earthquakes involving surface rupture, we must rely on geologic evidence about the extent of past ruptures and must estimate future fault behavior from geologic evidence of segmentation. However, the general conclusion that the characteristic earthquake is "at or near the maximum" earthquake (Schwartz and Coppersmith, 1984) remains unchanged. This conclusion provides a basis for the assignment of "expected magnitudes" to segments of the San Andreas and associated faults in a recent study of earthquake probabilistics (USGS, 1988).

RUPTURE LENGTH AND SEGMENTATION

Estimates of the maximum length of future ruptures on a fault are needed to assess maximum magnitude because magnitude increases with rupture length (for example, Tocher, 1958) and that the dimensions of rupture are directly related to earthquake size by seismic moment (Aki, 1966; Hanks and Kanamori, 1979).

It is generally recognized that faults rarely if ever rupture their entire length during individual earthquakes. This fact instigated the use of "fractional fault length" to estimate rupture length. Wentworth and others (1969) noted that faults usually do not rupture more than one-half their length, prompting a common usage of fault half-lengths as potential rupture lengths in conservatively estimating maximum magnitude. A problem with the fractional fault length method is the difficulty in deciding unequivocally on the total length of the fault. Slemmons (1982) analyzed the ratio of rupture length to total length of several historical ruptures along long strike-slip faults. He found that typically these faults rupture about 15 to 30 percent of their total length in a single event. This conclusion motivated his use of 1/5 length as the potential rupture length (Slemmons and others, 1982).

Recent advances in paleoseismologic techniques have been successfully identified the extent of prehistoric fault ruptures, the distribution of slip along them, and the timing of individual events. For example, Machette and others (1988) and

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Schwartz (1988) show that segments of the Wasatch fault differ from one another in the time elapsed since the most recent event. These data suggest that the past ruptures occurred along independent segments. Further, it was concluded that boundaries between segments can be distinguished by several geometric and geologic characteristics, including: changes in the surface trend of the fault zone, major salients in the range front, intersecting structural trends in the bedrock geology, cross faults, transverse trends in gravity data, and geodetic changes (Schwartz and Coppersmith, 1984; 1986). Studies of historical ruptures (for example, King and Nabelek, 1985; Sibson, 1985) and theoretical physical modeling (for example, Segall and Pollard, 1980) suggest that rupture segments persist through repeated seismic cycles and that the end-points of ruptures occur at distinct geologic and geometric changes in the fault zone. The geometric and geologic characteristics that are most indicative of segment boundaries have not yet been identified unequivocally. However, there is a general consensus in the scientific community that the use of segmentation to identify potential future rupture segments is preferred over the use of fractional fault lengths.*

To better define the physical characteristics of a fault zone that might indicate the location of segments and segment boundaries, we collected data on several large historical strike-slip and reverse faulting events (Knuepfer, 1988; Coppersmith and Youngs, 1988). Conclusions from this study are summarized below.

Individual earthquake ruptures were studied in detail to assess the geologic and geometric characteristics at rupture end-points. Only static and spatial aspects of the rupture were considered, not the dynamic aspects such as the

*At the recent USGS Conference on "Fault Segmentation and Controls on Rupture Initiation and Termination," Leon Reller of the NRC conducted an informal poll of the conference participants asking whether segmentation or fractional fault length was their preferred approach to estimating rupture length for maximum magnitude assessments. All of those participants responding indicated a preference for the segmentation approach.

point of rupture initiation, direction of rupture propagation, or point of rupture termination. Several studies have concluded that particular kinds of geologic features are usually present at the ends of ruptures such as releasing stepovers and bends (Sibson, 1985; King and Nabelek, 1985; Barka and Kadinsky-Cade, 1988). If paleoseismic data were available, we would expect to see changes in the age of the most recent event at a segment boundary, perhaps reflected by geomorphic expression (Schwartz and Coppersmith, 1986), and perhaps changes in slip rate or style of faulting.

To evaluate the characteristics that occur at the rupture end-points, we researched the available literature and maps for over 70 historical events involving fault surface ruptures with emphasis on strike-slip and reverse faulting events. Specifically, characteristics identified at rupture end-points include:

- Releasing double bends
- Restraining double bends
- Single bends
- En echelon stepovers
- Changes in sense of slip
- Fault creep
- Changes in slip rate
- Changes in elapsed time (recency of slip)
- Changes in trace complexity
- Fault and fold branches
- Cross faults and folds
- Fault terminations
- Gaps
- Changes in basement terranes
- Basin boundaries

To assess the significance of these characteristics for interpreting segmentation of a fault zone, we examined the historical rupture data to determine the number of cases where a particular characteristic occurred at an end-point and the number of cases where that characteristic occurred within a rupture (that is, was ruptured through). Based on this analysis, it appears that 1) releasing bends and en echelon stepovers, restraining bends, branch or cross-cutting structures, and changes in the sense of slip along an otherwise continuous fault are the most common characteristics of rupture end-points on

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strike-slip faults and are thus the most diagnostic indicators of the ends of segments; 2) restraining features occur as end-points as frequently as releasing features. This contrasts with models (for example, Sibson, 1985) that suggests that releasing features rather than restraining features control the ends of strike-slip ruptures; 3) wide double-bends and en echelon stepovers are more likely to be rupture end-points than small stepovers and double-bends. This is consistent with models by Segal and Pollard (1980) and Sibson (1985) and studies by Wesnousky (1988). This conclusion appears to be particularly true for restraining features. Ruptures through restraining double-bends or stepovers wider than about 5 kilometers have not been observed in the data base (Knuepfer, 1988); 4) in all nine documented cases, rupture on a strike-slip fault appears to end where the primary sense of slip changes from strike-slip to dip-slip, suggesting that a change in sense of slip is a diagnostic indicator of segment boundaries; and 5) fault bends, branching structures, and cross structures appear to be the most common characteristics of features at the ends of ruptures along reverse faults. These conclusions have direct significance and were used to assess segmentation of faults in the present study.

Comparison of the relative frequency that a characteristic occurred at the end of ruptures versus was ruptured through shows that typically, the most diagnostic characteristics of end-points occur at end-points in about 25 to 35 percent of the cases and are ruptured through in the remaining cases. This result "clearly indicates that rupture ends do not follow any single, simple model of fault mechanics and rupture propagation . . . The major implication is that faults behave in complex fashions, that segment boundaries can and are caused by numerous different geologic and geometric features." (Knuepfer, 1988). It is important to note that thus far all studies of historical ruptures have examined fault characteristics *individually* (for example, What is the number of times that restraining bends occur at end-points or are ruptured through?). *Combinations* of characteristics have not yet been examined (for example, How many times do the combination of restraining bends and

cross-structures occur at end-points or are ruptured through?). The first level of analysis, described above, has shown us that apparently no *single* characteristic is highly diagnostic of a segment boundary. However, conclusions 1 through 5 above show that several characteristics have been identified that emerge individually or in combination as most significant in evaluating segmentation. These characteristics serve as a guide for evaluating potential rupture segments for faults in this study.

ONGOING RESEARCH IN SEGMENTATION

The study of fault segmentation is very important to assessments of the earthquake potential of faults and is an active area of research, both by the general scientific community and by PG&E. The results of the historical rupture data base analysis described above go beyond any previous studies as far as improving our understanding of fault segmentation. Assessment of the fault characteristics that are diagnostic of segment boundaries provides a reasonable basis for evaluating fault segmentation. Ongoing efforts by PG&E that will further increase our understanding of fault segmentation are briefly summarized here.

As noted above, the ends of historical ruptures typically occur at the locations of more than a single fault characteristic. For example, several Wasatch fault segment boundaries are marked by multiple characteristics such as changes in fault behavior, change in range height, and cross structures (Machette and others, 1988; Schwartz, 1988). To evaluate the effect of multiple characteristics, we are evaluating combinations of particular characteristics (say, cross structures together with stepovers) and the occurrence of multiple characteristics in any combination. Preliminary analysis shows that the occurrence of two characteristics at a point along a fault significantly increases the frequency that the point is an end-point of rupture.

Studies of historical ruptures have shown that some of the most diagnostic indicators of segmentation are those that consider fault behavior. For example, changes in the long-term sense of slip along strike-slip faults is highly significant as a segment boundary. Age of the



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most recent slip, slip rate, and slip distribution has been used to differentiate segments of the Wasatch fault (Schwartz and Coppersmith, 1986; Machette and others, 1988), the Lost River fault zone, Idaho (Schwartz and Crone, 1985), and the San Andreas fault (Schwartz and Coppersmith, 1984; Schwartz, 1988). At present, however, detailed paleoseismic data of this type are sparse. To supplement the general data base, we have been studying case histories in which paleoseismic data of this type are available.

In order to use the conclusions drawn from the historical data base and the case history analysis, we are developing a quantitative statistical model for evaluating the fault segmentation. At present, available models are qualitative. Quantitative measures of the likelihood that a particular point along a fault will be a segment boundary are being investigated. Further development of a segmentation model that incorporates parameters such as the number of characteristics per kilometer of fault length and the likelihood of rupturing through these points, will allow a more rigorous estimation of the probability of various segments being actual rupture segments.

EMPIRICAL MAGNITUDE RELATIONSHIPS

Several empirical relationships have been published that relate earthquake magnitude to various fault characteristics. To arrive at estimates of maximum magnitude for seismic sources of significance to the Diablo Canyon site, we use a multifactor approach that considers several aspects of fault behavior. Such an approach has been suggested by several researchers (for example, Slemmons, 1982; Schwartz and others, 1985; Slemmons and Depolo, 1986). Subject to availability of data, we estimate maximum magnitude from empirical relationships between earthquake magnitude and fault rupture length, fault rupture area, total fault length, maximum displacement per event, and seismic moment (Table 3-1).

Definitions of various parameters used in these published relations are not always consistent. Definition of "rupture length" is particularly important. Bonilla and others (1984) use rupture length to describe the length *at the surface* of

co-seismic ruptures. Wesnousky's (1986) data set, on the other hand, includes rupture lengths assessed from either the surface rupture or subsurface rupture, as inferred largely from aftershock sequences. Wyss (1979), in assessing the rupture area, also uses data from both the surface and subsurface. These differences in definition can be important in application to this study. Analysis of several historical earthquakes indicates that, on the average, the surface rupture length is shorter than the rupture length at depth. This difference is especially pronounced for smaller magnitude events.

In this study, we estimate the rupture length for various faults by examining the length of segments along the fault zone. For example, a possible rupture length on the Hosgri fault zone may be estimated at 45 kilometers based on a segment extending from an en echelon stepover to a point where the fault is intersected by a cross structure. Assuming that an earthquake were to rupture this segment of the fault, we would expect the rupture *at depth* to extend from one segment boundary to the other. However, the rupture *at the surface* could be significantly less. If we had evidence for the actual prehistoric surface rupture lengths on the Hosgri fault zone, then perhaps we could compare these lengths to those from historical events in the Bonilla and others (1984) data sets. Because we do not have such data, we must use segmentation evidence and estimate magnitudes from the published relationships we have available, knowing that our assessed rupture lengths are probably systematically longer than the expected surface rupture lengths. Because we conservatively assume that segmentation-derived lengths are equivalent to the "surface rupture length" as defined by Bonilla and others (1984), it follows that the resultant maximum magnitude estimate also will be higher and thus more conservative.

The magnitude scale of importance to ground-motion analyses in the Long Term Seismic Program is moment magnitude (M_w). However, nearly all of the empirical relationships are developed using surface-wave magnitude (M_s). Several workers have shown that M_w is essentially equivalent to M_s (for example, Kanamori, 1977, 1983) in the magnitude range of

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about 6 to 8. The magnitude range of interest for this Program falls within this range.

As discussed above, we use logic trees to capture the uncertainty in magnitude-related fault characteristics. A distribution of maximum magnitudes for each source results and these are used in the probabilistic seismic hazard analysis. Development of these distributions involves the combination of magnitude estimates resulting from various characteristics (for example, rupture length and maximum displacement) and from various authors for a given characteristic (for example, Slemmons, 1982 and Bonilla and others, 1984). Further, we also consider the maximum historical earthquake that has been associated with the fault. To combine the calculated magnitudes from the various magnitude relationships, we have adopted a simple weighting scheme, which is given in Table 3-2 and described below.

Examination of the data base for the empirical magnitude relationships suggest that the amount of data density for rupture lengths shorter than about 50 kilometers is less than that for ruptures over 50 kilometers. Therefore, a 50-kilometer rupture length was considered a reasonable break point for developing the relative weights for each magnitude relationship. For faults with rupture lengths of 50 kilometers or greater, all of the techniques that are based on physical dimensions (rupture length, rupture area, total length, maximum displacement, and seismic moment) were judged to be equally credible and were given equal weight. Because the historical record is usually too short to include the maximum event, the largest historical event was judged to have only half of the credibility of any one technique based on physical dimensions. For example, in case 1 of Table 3-2, there are five techniques listed for assessing maximum magnitude that are based on physical dimensions (rupture length, rupture area, total length, displacement per event, and seismic moment) above in addition to the use of the largest historical event. The weight assigned to any one technique based on physical dimensions, such as seismic moment, is thus equal to 1.0/5.5 or 0.182. Where there are several alternative empirical relationships for a particular parameter

(such as the three published relationships for magnitude versus rupture length), they are considered equally credible and the weight assigned to the technique is partitioned accordingly. When a particular piece of data is unavailable, such as maximum displacement in case 5 of Table 3-2, that technique cannot be used and the weight assigned to that technique is redistributed among the remaining techniques.

For faults with rupture lengths less than 50 kilometers, it was judged that the weights assigned to the techniques based on physical dimensions should be reapportioned such that those that incorporate multiple dimensions (fault area and seismic moment) should have 50 percent greater credibility than those based on a single dimension (rupture length). This adjustment was made because the empirical relationships between magnitude and rupture length are based on data sets in which the rupture lengths are generally greater than 50 kilometers, and consequently, are not as well constrained at the smaller dimensions as are rupture area and seismic moment. The weight assigned to the use of the largest historical event remains the same.

KEY FINDINGS

The key findings regarding the seismic sources of significance to the site are summarized below.

Style of Deformation

The dominant style of deformation in the Los Osos and northern Santa Maria Valley area of south-central coastal California is block uplift and subsidence with associated faulting along the block boundaries. Folding is not a significant mode of deformation in the contemporary tectonic environment in this area. Tertiary folds, such as the Pismo syncline, have not been active during late Quaternary time, as demonstrated by a lack of folding of late Quaternary geomorphic surfaces (Chapter 2). The lack of late Quaternary folding in the site region indicates that associated structures such as blind faults if present are not active. The documented lack of activity of faults within the San Luis/Pismo structural block (for



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Table 3-2
WEIGHTS FOR MAXIMUM EARTHQUAKE MAGNITUDE TECHNIQUES

Strike-Slip Faulting—Rupture Length \geq 50 km

Relationship	Case							
	1	2	3	4	5	6	7	8
Bonilla et al (1984)—Rupture Length	0.060	0.067	0.074	0.083	0.074	0.083	0.095	0.111
Slemmons (1982)—Rupture Length	0.061	0.066	0.075	0.084	0.075	0.084	0.095	0.112
Wesnousky (1986)—Rupture Length	0.060	0.067	0.074	0.083	0.074	0.083	0.095	0.111
Wyss (1979)—Rupture Area	0.182	0.2	0.222	0.25	0.222	0.25	0.286	0.333
Slemmons (1982)—Total Length	0.182	0.2	0.222	0.25	0.222	0.25	0.286	0.333
Bonilla et al (1984)—Displacement/Event	0.091	0.1	0.111	0.125	-	-	-	-
Slemmons (1982)—Displacement/Event	0.091	0.1	0.111	0.125	-	-	-	-
Seismic Moment	0.182	0.2	-	-	0.222	0.25	-	-
Maximum Historical	0.091	-	0.111	-	0.111	-	0.143	-

Strike-Slip Faulting—Rupture Length < 50 km

Relationship	Case							
	9	10	11	12	13	14	15	16
Bonilla et al (1984)—Rupture Length	0.050	0.056	0.066	0.074	0.059	0.067	0.082	0.095
Slemmons (1982)—Rupture Length	0.051	0.055	0.065	0.075	0.059	0.066	0.081	0.095
Wesnousky (1986)—Rupture Length	0.050	0.056	0.066	0.074	0.059	0.067	0.082	0.095
Wyss (1979)—Rupture Area	0.227	0.25	0.296	0.333	0.267	0.3	0.367	0.429
Slemmons (1982)—Total Length	0.152	0.167	0.198	0.222	0.178	0.2	0.245	0.286
Bonilla et al (1984)—Displacement/Event	0.076	0.083	0.099	0.111	-	-	-	-
Slemmons (1982)—Displacement/Event	0.076	0.083	0.099	0.111	-	-	-	-
Seismic Moment	0.227	0.25	-	-	0.267	0.3	-	-
Maximum Historical	0.091	-	0.111	-	0.111	-	0.143	-

Reverse Faulting—Rupture Length \geq 50 km

Relationship	Case							
	17	18	19	20	21	22	23	24
Bonilla et al (1984)—Rupture Length	0.074	0.083	0.095	0.111	0.095	0.111	0.133	0.167
Slemmons (1982)—Rupture Length	0.075	0.083	0.095	0.112	0.095	0.112	0.134	0.166
Wesnousky (1986)—Rupture Length	0.074	0.083	0.095	0.111	0.095	0.111	0.133	0.167
Wyss (1979)—Rupture Area	0.222	0.25	0.286	0.333	0.286	0.333	0.4	0.5
Slemmons (1982)—Displacement/Event	0.222	0.25	0.286	0.333	-	-	-	-
Seismic Moment	0.222	0.25	-	-	0.286	0.333	-	-
Maximum Historical	0.111	-	0.143	-	0.143	-	0.2	-

Reverse Faulting—Rupture Length < 50 km

Relationship	Case							
	25	26	27	28	29	30	31	32
Bonilla et al (1984)—Rupture Length	0.059	0.067	0.082	0.095	0.071	0.133	0.107	0.133
Slemmons (1982)—Rupture Length	0.059	0.066	0.081	0.095	0.072	0.134	0.106	0.134
Wesnousky (1986)—Rupture Length	0.059	0.067	0.082	0.095	0.071	0.133	0.107	0.133
Wyss (1979)—Rupture Area	0.267	0.3	0.367	0.429	0.322	0.6	0.48	0.6
Slemmons (1982)—Displacement/Event	0.178	0.2	0.245	0.286	-	-	-	-
Seismic Moment	0.267	0.3	-	-	0.321	-	-	-
Maximum Historical	0.111	-	0.143	-	0.143	-	0.2	-

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example, the San Miguelito and Edna faults) further supports this conclusion. Based on the block-boundary behavior of deformation, the locations of potential seismic sources will be along the margins of blocks, rather than within them or at depth beneath Tertiary folds.

Capable Faults

The following faults (Figure 3-3) are judged to be capable on the basis of investigations conducted during the Long Term Seismic Program: Hosgri, Los Osos, San Luis Bay, and Wilmar Avenue faults. The faults are recognized as capable because they displace late Quaternary or Holocene deposits at one or more locations along their length. Other faults are known to exist along the southwest boundary of the San Luis/Pismo structural block, such as the Pecho fault offshore and the Oceano fault beneath the edge of the Santa Maria Basin. These faults are characterized principally on the basis of subsurface geophysical data. Late Quaternary displacement on the faults has not been directly observed, although their presence along the southwest boundary of an actively rising structural block suggests that they have been active in the past 500,000 years. None of the faults judged to be capable is associated unequivocally with either macroseismicity (earthquakes of magnitude 5 or greater) or microseismicity. The San Miguelito, Edna, and Pismo faults are documented to be not capable because Quaternary deposits overlie and are not displaced by these faults.

Potential for Significant Unknown Faults

The possibility that a fault at the surface may have escaped detection during the geosciences investigations is a function of the resolution of the field investigations. The level of resolution in our study increases with proximity to the site. At distances greater than 10 to 20 kilometers from the Diablo Canyon site, the geosciences investigations were largely reconnaissance in nature (for example, aerial photograph analysis and field and aerial reconnaissance) and were focused on the more active features that are

better-expressed geomorphically. Within about 20 kilometers, detailed mapping, drilling, and trenching were performed across faults and to delineate late Quaternary and Holocene geomorphic surfaces and deposits. Obviously, these investigations can not be carried out everywhere in the site vicinity. However, the field program was designed to provide sufficient data coverage such that projections from known locations constrain on the presence or absence of deformation.

Exposures of faults and stratigraphic relationships in trenches, cuts, and natural exposures can allow resolution on the order of centimeters. Good examples of this level of resolution are the exposure of the San Luis Bay fault in the roadcut near Avila Beach, exposures of the Los Osos fault zone in trenches, and seacliff exposures of the Wilmar Avenue fault. At other locations where exposures are sparse or discontinuous, we rely on mapping and drilling data to define surfaces and stratigraphic units of interest and to interpolate between areas of exposure. The resolution associated with these techniques is on the order of one to two meters. For example, over 200 boreholes were drilled in the Program to define the positions of the shoreline angles of late Quaternary marine terraces in the site region (Chapter 2).

Based on the studies in the site vicinity, we see no evidence of potentially capable faults other than those identified in this report. As described above, our geologic resolution for detecting faults or associated deformation is on the order of centimeters to meters. Assuming an average age of 100,000 years for the late Pleistocene surfaces and deposits investigated, centimeter to meter resolution translates to very low rates of 0.0001 to 0.01 millimeter per year. That is, if a fault is hypothesized to exist, it must have a slip rate that is less than 0.0001 to 0.01 millimeter per year to escape detection. These rates are indicative of a very low degree of activity (Cluff and others, 1982); therefore, these faults are less important from a seismic hazard point of view. Recognition of the San Luis Bay fault, which has a slip rate of about 0.07 to 0.11 millimeter per year, and the Wilmar Avenue fault, which has a slip rate of 0.04 to 0.07 millimeter per year confirms



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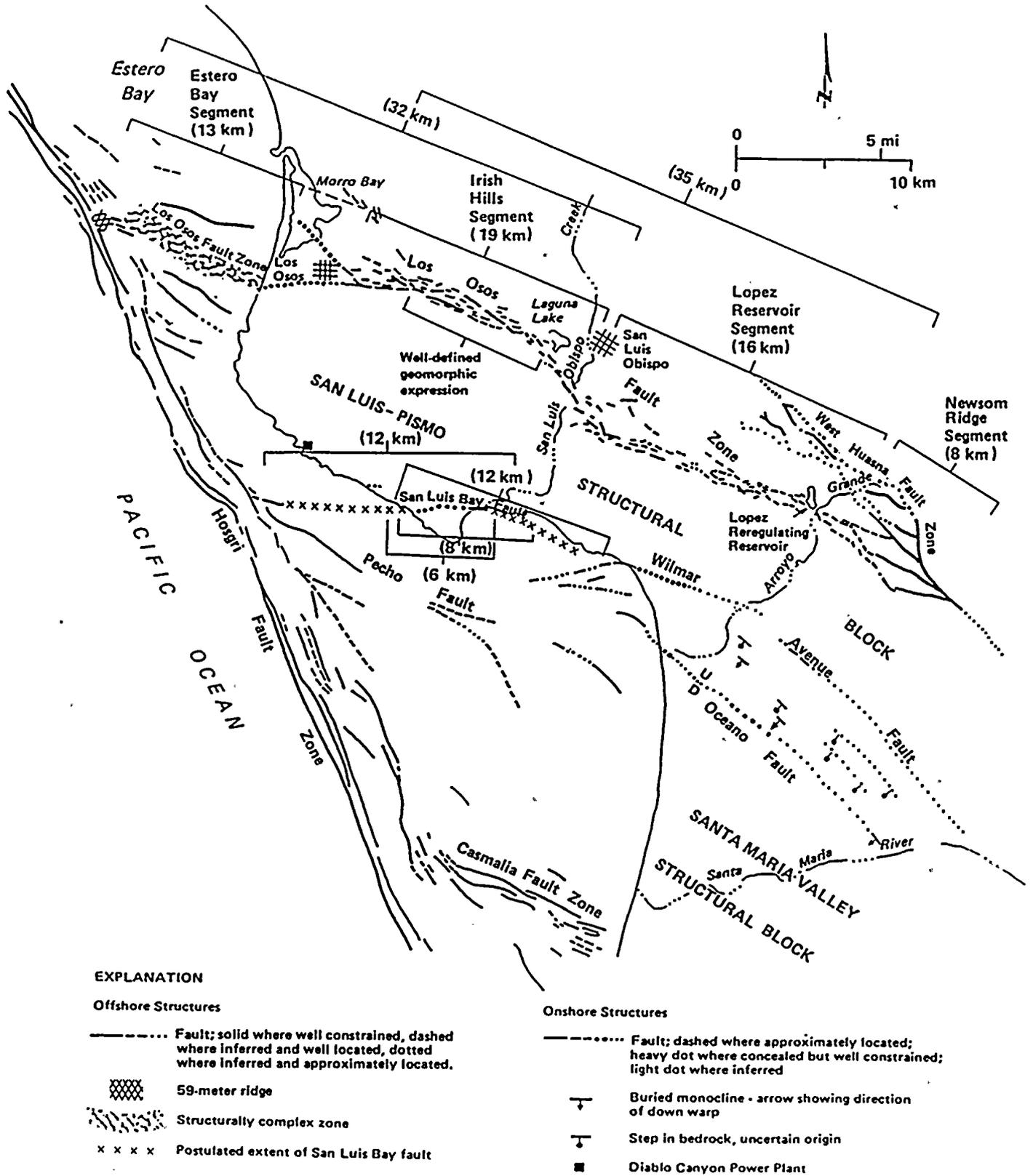


Figure 3-3
Regional map showing rupture lengths considered for the Los Osos fault zone and the San Luis Bay fault zone.

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our ability to recognize faults having very low levels of activity.

Some probabilistic seismic hazard studies have invoked the concept of a "random" nearby source. Random sources are usually included in studies in which the dominant contributions to site ground motions are coming from more distant sources and where the local geologic resolution is not sufficient to rule out local undetected sources. We conclude that the excellent geologic resolution in the site vicinity argues against the existence of an unknown nearby fault that can generate earthquakes of sufficient size to be significant to site ground motions. Earthquakes having magnitudes smaller than those typically associated with geologic deformation at the surface may be postulated to occur in the site vicinity as a random source. However, the observed rate of microseismicity in the area is low (Chapter 2) and does not require the existence of any other source besides those considered to account for the observed rate of seismicity. Therefore, we conclude that the geologic resolution coupled with the existence of known nearby capable faults included in the seismic hazard analysis precludes the need for a random nearby source in the ground-motion analyses.

Blind or Concealed Faults

The Coalinga and Whittier Narrows earthquakes demonstrate that moderate earthquakes can occur on blind thrust or reverse faults that do not break the surface. We, therefore, have considered the possibility of this type of seismic source in the site vicinity.

At Coalinga and Whittier Narrows, the subsurface faults causing rise to the earthquakes are associated with mapped Quaternary anticlines at the surface. Importantly, geodetic studies have shown that these folds are actively growing through coseismic uplift of the axis of the anticline (Stein, 1985). This strongly indicates a genetic association between faulting at depth and near-surface fold deformation. A sequence of deformed Quaternary fluvial terraces documents the longer-term activity of folding (Stein and King, 1983, 1984; Trumm, 1988). The genetic

association of folding at the surface with faulting at depth is consistent with kinematic models of the geometric response of crustal rocks to compression (Suppe, 1983). The fact that active blind faults can be discerned as being associated with active folds in the surface Quaternary geologic record confirms that we can apply Quaternary geologic techniques to identify the locations, ages, and amounts of Quaternary folding. This information can, in turn, be used to infer the existence and activity of blind faults. An example of this approach was the identification of the zone of crustal deformation along which the Coalinga earthquake occurred as a potential seismic source prior to the event (Woodward-Clyde Consultants, 1975, 1978).

The known fold closest to the site is the Pismo syncline, which deforms Miocene and Pliocene strata within the San Luis/Pismo structural block. The syncline does not deform late Quaternary marine terraces, however, indicating that deformation ceased over 500,000 to 1,000,000 years ago (Chapter 2). Detailed mapping documents the absence of folds in the site region that deform late-Quaternary deposits. Davis (1986) has developed a preliminary balanced cross-section through the site region basing structural relations on the surficial and shallow structure developed in upper Tertiary and older rocks. The cross-section does not incorporate the recent mapping of late-Quaternary units and surfaces along the edges and within the San Luis/Pismo structural block that have been developed during this Program.

The balanced cross-section techniques of Suppe (1983) are intended to account for the relations between the structure of the shallow geology and the inferred deeper structure. Using these techniques, if a fold is known at the surface, it may be explained by a fault at depth (for example, fault-bend or fault-propagation fold). The age of the faulting and associated folding is as young or younger than folded units but older than undeformed units. As noted above, we see evidence for no significant folding in the site vicinity during at least the past approximately 500,000 years and possibly the past 1,000,000 years. Therefore, we conclude that a blind late Quaternary fault is not present at depth beneath

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the site area. In addition, any fault that might be inferred to exist in the San Luis/Pismo region on the basis of folding in the Tertiary section, must be considered to be not capable on the basis of a lack of Quaternary surface deformation.

Seismic Source Characteristics

The potential seismic sources of significance to the ground motions at the site are: the Hosgri and Los Osos fault zones, and the San Luis Bay fault, based on the probabilistic seismic hazard analysis; and the Hosgri fault zone, based on the deterministic analysis. Figures 3-3 and 3-4 show the location of these faults.

Hosgri Fault Zone Characterization

The logic tree for the Hosgri fault zone is given on Figure 3-5. Characteristics of the Hosgri fault zone are discussed in Chapter 2 and are summarized here to illustrate the derivation of the values and probabilities given in the logic tree.

- Sense of Slip

The sense of slip on the Hosgri fault zone is assessed based on a large number of observations and interpretations, which are summarized in Table 2-9 and the associated section of Chapter 2. Kinematic models of the Hosgri fault zone and deformation to the east of the fault suggest that the horizontal component of slip on the Hosgri fault zone probably decreases from north to south. However, the logic tree is intended to be most representative of the sense of slip along the reach of the fault that is in the Diablo Canyon region.

The data contained in Table 2-9 lead us to a fairly strong preference (0.65) for strike-slip faulting. Oblique-slip faulting is given a moderate but significant weight (0.3) to account for the evidence of a dip-slip component along the zone opposite the slowly uplifting San Luis/Pismo structural block. Evidence for thrust or reverse faulting is judged to be relatively weak and not representative of the Hosgri fault zone as a whole or for the reach opposite the Plant site in particular.

- Dip

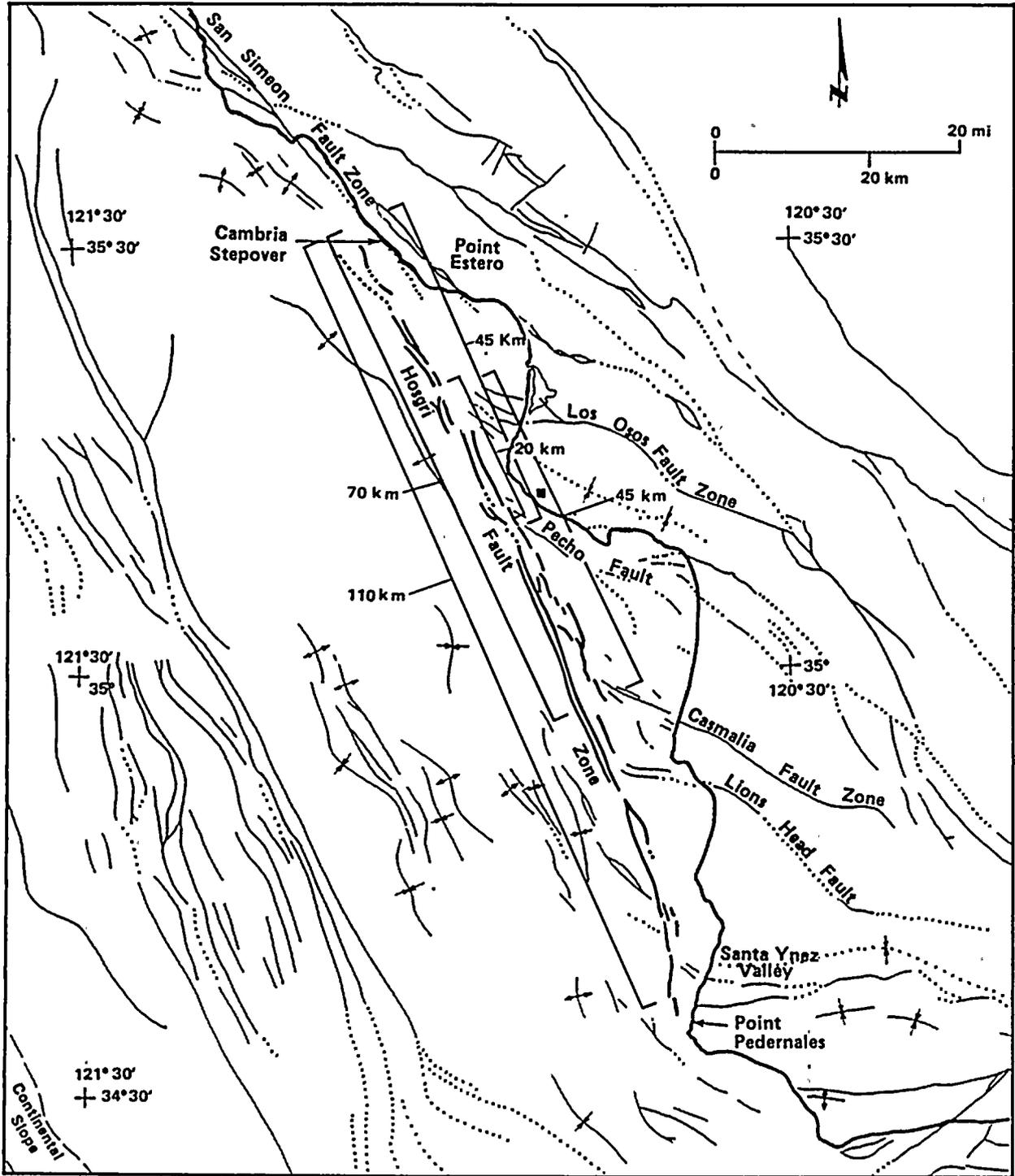
The dip of the Hosgri fault zone, as for the other faults, is an assessment of the geometry of the fault through the seismogenic crust. We have no direct geophysical data that clearly image the fault to seismogenic depths (below about 3 to 5 kilometers). We, therefore, must rely largely on interpretations of the fault in the near-surface (for example, in trenches cut across the San Simeon fault zone, shallow high resolution and 3 to 5 second seismic reflection data). Because the dip of the fault is uncertain and not strongly constrained by observation, its estimated value is a function of the assumed model for the sense of slip.

Assuming that the Hosgri fault zone is a strike-slip fault, we consider two values for its dip as it would extend through the seismogenic crust, 90 degrees and 70 degrees to the east (Figure 3-5). We give a slight preference to the 90 degrees value (0.6 versus 0.4). Steep to vertical dips are supported by the following: the traces of the San Simeon fault zone seen in exploratory trenches are all very steeply dipping to vertical; the high resolution seismic reflection data show dips of about 90 degrees on faults to depths of about one kilometer; depth-corrected seismic reflection profiles show the dips on the Hosgri fault zone to be about 60 degrees to 80 degrees at depths of about three kilometers; the linearity of the Hosgri fault zone suggests that it is steeply dipping; the Hosgri fault zone appears to be a vertical boundary between seismic quiescence in the region to the west and low levels of seismicity to the east extending to depths of 10 to 12 kilometers (for example, Point Sal earthquakes of 1980 and 1985); and, in general, strike-slip earthquake focal mechanisms elsewhere in the world usually indicate that the causative fault is steeply dipping to vertical.

Assuming that the Hosgri fault zone is an oblique-slip fault, we consider three possible dips: 90, 60, and 45 degrees. The relative weights of these values are 0.3, 0.6, and 0.1, respectively (Figure 3-5). The arguments for a vertical dip on the Hosgri fault zone are given above. However, given a significant dip-slip component associated with the oblique case, we would expect the dip to



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■ Diablo Canyon Power Plant

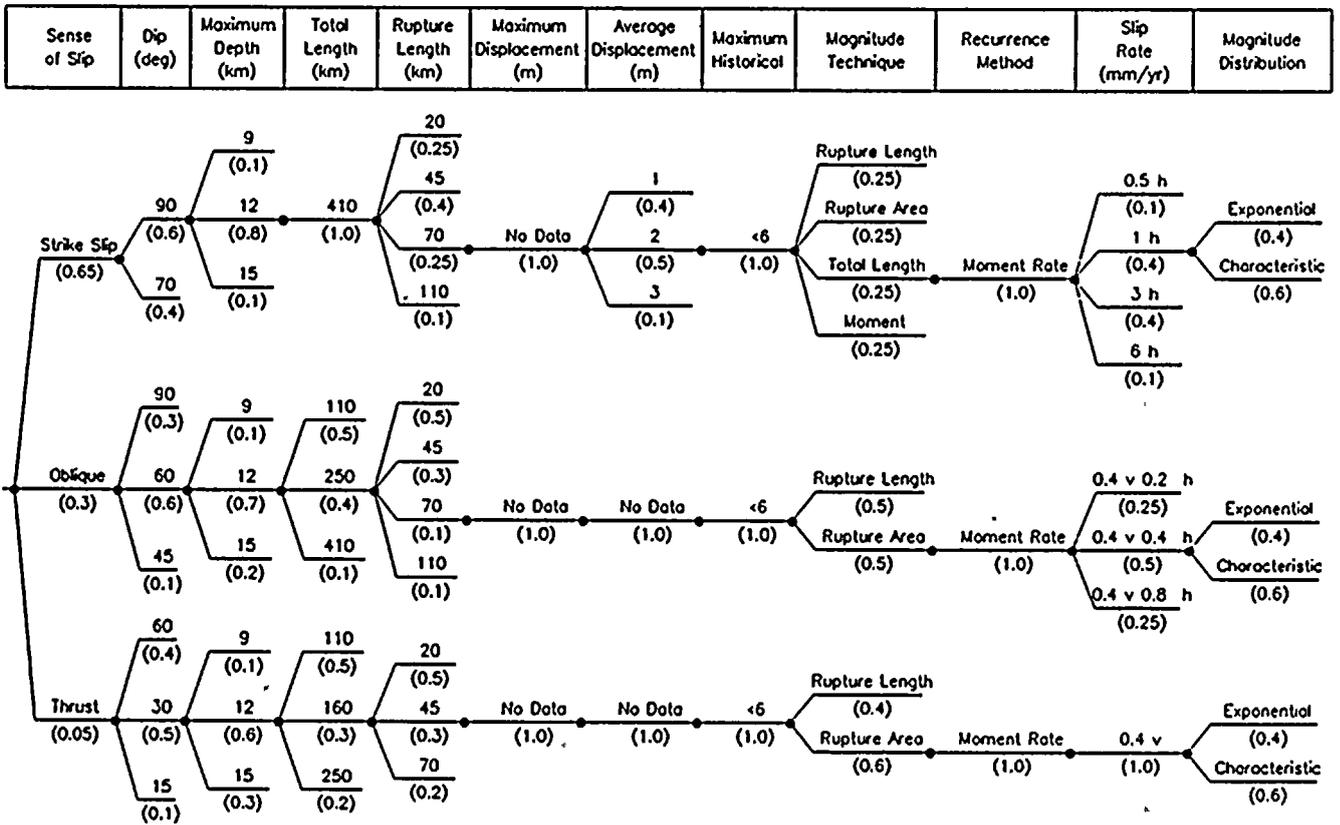
Figure 3-4
Map showing rupture lengths considered for the Hosgri fault zone.



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Notes:
 Values in parentheses are probabilities
 h = horizontal component of slip rate,
 v = vertical component of slip rate

Figure 3-5
 Logic tree for Hosgri fault zone.

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be closer to about 60 degrees based on typical focal mechanisms for oblique-faulting earthquakes. A 60-degree dip is also compatible with most of the deeper geophysical data showing 60- to 80-degree dips to the east. The 45-degree value is given low weight because of the several lines of evidence for steep dips cited previously, which are also applicable to an oblique-slip fault.

Assuming that the Hosgri fault zone is a reverse or thrust fault, we consider three models for dip: 60, 30, and 15 degrees. The 30-degree dip is preferred slightly (0.6) over the 60-degree value (0.4) and the 15-degree value is given a relatively low weight (0.1) (Figure 3-5). A 60-degree dip allows for a mechanism similar to that developed for the 1927 earthquake (Chapter 2). The 30-degree dip is representative of the average dips of the Hosgri fault zone proposed by Crouch and others (1984). For a thrust fault, an approximately 30-degree dip is also predicted by simple failure theory. The 15-degree value is considered unlikely but allows for a scenario in which the Hosgri fault zone is hypothesized to shallow with depth to a listric subhorizontal fault.

• Depth of Faulting

The down-dip width of a fault is a function of fault dip and the thickness of the seismogenic crust. We also consider the depth of faulting to be partially dependent on the sense of slip on the fault. For all slip types, we consider three possible cases: 9, 12, and 15 kilometers. Thickness of the seismogenic crust is estimated on the basis of hypocentral distribution of historical earthquakes in this part of south-central coastal California (Chapter 2). Generally, the maximum depth of seismicity in the region is about 12 kilometers and this depth is given the highest weight (0.6, 0.7, or 0.8) depending on fault dip through the seismogenic crust (Figure 3-5). The 9-kilometer value, which is given relatively low weight (0.1), accounts for the local evidence of a seismicity cut-off at shallower depths. Depending on the sense of slip, the 15-kilometer value is given a weight of 0.1, 0.2, and 0.3 for strike-slip, oblique, and reverse faulting, respectively. These weights account for the observation that historical reverse/thrust earthquakes tend to rupture a

thicker section of crust than strike-slip events. A low weight is given because this observation may merely be the result of the fact that reverse/thrust faults often are present in areas of shortened and thickened crust (such as the Transverse Ranges). Therefore, for all slip types, the 12-kilometer depth based on hypocenter distribution is given relatively higher weight.

• Total Length

The total length of the Hosgri fault zone is considered to be a function of the sense of slip. Assuming that the Hosgri fault zone is a strike-slip fault, we consider it to be a part of the San Gregorio/Hosgri fault zone extending 410 kilometers from an intersection with the San Andreas fault near Bolinas north of San Francisco Bay south to where the Hosgri fault zone terminates in the offshore region northwest of Point Pedernales (Figure 3-4).

Assuming the oblique-slip case, we consider three total length possibilities: 110 kilometers, extending from an en echelon right-step northwest of Point Estero, termed the "Cambria stepover" (Figure 3-4), to northwest of Point Pedernales; 250 kilometers, extending from the north end of the Santa Lucia Range near Cypress Point to opposite the Santa Ynez Valley; and 410 kilometers, extending from Bolinas to northwest of Point Pedernales. The 110-kilometer length is given relatively higher weight (0.5) because onshore investigations of the San Simeon fault zone clearly show that strike slip is the primary sense of displacement in this area and would not be expected to be continuous with an assumed oblique-slip Hosgri fault zone. The 250-kilometer length is given slightly less weight (0.4) on the basis of separation between the strike-slip San Gregorio fault to the north and an assumed oblique-slip Hosgri fault zone to the south. The 410-kilometer length is given relatively low weight (0.1) because this model assumes that the entire San Gregorio/San Simeon Hosgri trend is an oblique-slip fault zone despite studies at Año Nuevo (Weber and Lajoie, 1974) and San Simeon (Chapter 2) that demonstrate strike-slip.

Assuming that the Hosgri fault zone is a reverse or thrust fault, the total lengths considered are:

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110 kilometers, from the Cambria stepover to northwest of Point Pedernales; 160 kilometers, extending from Cape San Martin to northwest of Point Pedernales; and 250 kilometers, extending from Cypress Point to northwest of Point Pedernales. For the same reasons as the oblique-slip case, the 110-kilometer case is favored (0.5) and the 250-kilometer case is given less weight (0.2). The 160-kilometer case accounts for the possibility that, given that the Hosgri fault zone is a reverse or thrust fault, the Piedras Blancas antiform may be considered part of the system.

- Rupture Length

The rupture lengths estimated for the Hosgri fault zone are based on evaluations of the segmentation of the fault zone (Figure 3-4). We have identified specific locations along the Hosgri fault zone where geometrical and geological relationships suggest that a segment boundary should be located. Each of these points is discussed in detail in Chapter 2. The segments of the fault zone between these points are also described in Chapter 2 (for example, Table 2-12). We here consider possible *rupture* segments along the fault, which, because of the uncertainties, may involve more than one of the geologically-defined segments. We arrive at four possible rupture lengths.

The rupture lengths considered are 20, 45, 70, and 110 kilometers. A brief discussion of each follows.

Twenty kilometers, extending between the intersections of the Hosgri fault zone with the Los Osos fault zone on the north and the Pecho fault on the south. The Los Osos fault zone intersection is also associated with an 11-degree bend in the Hosgri fault zone where the number of traces and width of the zone decreases south to north. The Los Osos fault zone is the northeastern border of the San Luis/Pismo structural block and the Pecho fault is a part of the southwestern boundary of this block. This reach of the Hosgri fault zone is the western margin of the San Luis/Pismo structural block.

Forty five kilometers, representing the rupture length for either of two scenarios, either extending from the Harmony stepover to the Pecho fault or from the Los Osos fault zone intersection to the intersection with the Casmalia fault zone. The Cambria stepover is a releasing stepover that is about 5 kilometers wide. Extension within the stepover is verified by the existence of north-trending normal faults bordering a local basin containing late Pleistocene and Holocene sediment. The stepover is also generally coincident with the southern margin of an intersecting Tertiary structure, the Piedras Blancas antiform. At the stepover, the nature and orientation of folding west of the Hosgri fault zone changes south-to-north from a pattern of broad folds parallel to the zone to more westerly trending tighter folds. At the approximate location of the intersection of the Hosgri fault zone with the Casmalia fault zone, the eastern Hosgri trace ends abruptly and the Casmalia fault zone actually extends into the Hosgri fault zone. Deformation west of the Hosgri fault zone changes dramatically from sparse very broad, low-amplitude folds to the north, to numerous tight folds and faults, such as the Purisima trend, to the south. This is also the boundary between the Santa Maria Valley structural block to the north and the Casmalia structural block to the south (Chapter 2).

Seventy kilometers, extending from the Cambria stepover to the intersection with the Casmalia fault zone.

One hundred ten kilometers, extending from the Cambria stepover to the southern termination of the Hosgri fault zone in the region northwest of Point Pedernales.

The relative weight of these rupture length models is a function of the sense of slip. In the strike-slip case, the 45-kilometer length is slightly favored, based on evidence from the analysis of historical ruptures that shows that fault intersections and releasing stepovers of large width are typically segment boundaries. In the cases of oblique and reverse faulting, where the dip-slip component is significant, the 20-kilometer rupture length is favored. The 20-kilometer length is defined by the length of the Hosgri fault zone along which the San Luis/Pismo structural block is being uplifted.

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It is this interaction of the block with the fault zone that gives rise to the greater dip-slip component. Therefore, the San Luis/Pismo structural block interaction is judged to be very important to segmentation; hence, given the dip-slip faulting scenarios (oblique or reverse) it is accorded the highest weight. In all cases of slip, the 110-kilometer case is given little to no weight because this rupture length model assumes that rupture will occur across several segment boundaries marked by distinct geometrical and geological changes.

- Average Displacement Per Event

The data available regarding the average displacement associated with individual surface faulting events along the Hosgri fault zone come from geologic investigations in the San Simeon area. These data indicate only strike-slip offsets and thus are only applicable to the strike-slip case. We do not have displacement per event data for other parts of the fault zone. We assume that the data from the San Simeon fault zone are representative of *average* displacements rather than the *maximum* displacements, because studies of coseismic slip distributions show that the maximum displacement occurs over a limited length of the rupture (for example, Thatcher and Bonilla, 1988). Therefore, a random point along a rupture is more likely to be at a location of average displacement than maximum displacement.

Trenches in the Airport Creek and Oak Knoll Creek localities along the San Simeon fault zone showed evidence for lateral offset of stratigraphic units of about one meter. Right-lateral deflection of stream channels in the area appears to be about two meters. Although it is possible that these displacements are due to multiple events, we consider them to be single events and we give these two estimates the highest weight (Figure 3-5). It is possible but unlikely that the offsets recorded at the exploration localities do not encompass the entire zone of deformation and that the displacement could be larger. Accordingly, we also assume a displacement per event of 3 meters, although this possibility is

considered to be unlikely and given a given weight of 0.1.

- Maximum Historical Earthquake

The Hosgri fault zone has not been associated historically with an earthquake having a magnitude of 6 or larger. Therefore, it is judged that the historical record places no constraints on the size of the maximum earthquake magnitude.

- Magnitude Techniques

The various magnitude estimation relationships and their relative weights are described above (Table 3-2).

- Recurrence Method

The method used to assess earthquake recurrence on the Hosgri fault zone is the seismic moment rate approach, which uses the slip rate, total length, and depth of faulting estimates on the fault.

- Slip Rate

The slip rate estimates on the Hosgri fault zone are given as a function of sense of slip. For the strike-slip case, slip rates are based primarily on detailed mapping of marine terraces in the San Simeon area. In particular, the range of offsets of the Oso terrace (preferred age of 214,000 years) suggests slip rates of one to three millimeters per year. Less definitive geomorphic constraints, including stream offsets, allow possible slip rates as low as 0.5 and as high as 6 millimeters per year. For the oblique-slip and reverse-slip cases, the vertical slip rate is 0.4 millimeter per year and the net slip rate is a function of the range of horizontal to vertical slip assumed. The 0.4 millimeter per year rate comes from the combination of an uplift rate of the San Luis/Pismo block of up to 0.2 millimeter per year and subsidence rate of the offshore Santa Maria Basin west of the Hosgri fault zone of up to 0.2 millimeter per year (Chapter 2).

- Magnitude Distribution

The magnitude distribution models considered are the exponential and characteristic earthquake models. Slightly more weight (0.6) is given to the

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characteristic earthquake model because this model is believed to be more appropriate for individual faults and fault segments than the exponential model (Schwartz and Coppersmith, 1984; 1986).

Los Osos Fault Zone Characterization

The logic tree for the Los Osos fault zone is given on Figure 3-6.

- Sense of Slip

Two alternatives for the sense of slip on the Los Osos fault zone are considered, oblique-slip and reverse or thrust faulting. Several lines of evidence suggest reverse faulting and lead to a significantly higher weight (0.9) than oblique-slip (0.1). The Los Osos fault zone lies at the topographic base of an elevated range, suggesting a significant vertical component of slip. Slickensides and stratigraphic relationships observed in trenches along the fault display nearly pure dip-slip. Arcuate geomorphic lineaments present along the fault zone are typical of reverse faults and the ponding of Laguna Lake is likely a result of tectonic impoundment by dip-slip displacement. Regional stress trajectories developed from borehole breakout data and Neogene fold trends (Mount and others, 1988) and tectonic models of the region (Luyendyk and Hornafius, 1986) also suggest that the Los Osos fault zone is a reverse fault. The slight possibility of oblique-slip faulting is allowed based on locally observed slickensides on fault surfaces within the fault zone that suggest a minor component of possible lateral displacement.

- Dip

The dip of the Los Osos fault zone is considered to be dependent on the sense of slip. Assuming reverse slip, the two dips considered were 60 degrees and 30 degrees, with higher weight assigned to 60 degrees (0.7) than 30 degrees (0.3). The steeper dip is preferred because of structural evidence for a history of strike-slip along the zone and because of tectonic models such as that by Hall (1981) that suggest Tertiary strike-slip displacement. Also, the geomorphic expression of fault scarps preserved along the fault

zone suggest normal faulting within the upper plate of the zone. This implies extension within the hanging wall and steepening of the fault with depth. The Los Osos fault zone appears to be tectonically analogous to the Casmalia fault zone to the south, which forms the northern boundary of the Casmalia structural block. Subsurface studies of the Casmalia fault zone show that it steepens with depth (Krammes and Curan, 1959) and this may also be true of the Los Osos fault zone. Alternatively, stratigraphic relations observed in trenches suggest compression within the upper plate of the Los Osos fault zone. Upper plate compression suggests that the fault maintains the approximately 30-degree dip observed at the surface or becomes shallower with depth.

Assuming that the Los Osos fault is an oblique-slip fault, the values for dip are 45 degrees and 75 degrees. These dips are slightly steeper than those for the reverse-slip case, because of the assumed horizontal component of slip necessary to define this value, but the arguments are the same as for the 30-degree and 60-degree dips in the reverse-slip model.

- Maximum Depth of Rupture

The opposing dip directions and close proximity of the Hosgri and Los Osos fault zones result in geometrical interactions that affect the assessment of maximum depth and total fault length. Within the brittle upper crust, the Hosgri and Los Osos fault planes should intersect at depths that depend on the assessed fault dips. Figure 3-7 shows examples of a fault plane intersection for one possible scenario of fault dip, the Hosgri fault zone having a vertical dip and the Los Osos fault zone dipping southwest at 60 degrees. At the line of intersection either the Hosgri fault zone truncates the Los Osos fault zone or the Los Osos fault zone truncates the Hosgri fault zone. Given that the Hosgri fault zone is a much larger and more through-going structure, it was judged that the Los Osos fault zone would be truncated by the Hosgri fault zone.

The inferred depth of the intersection of the Hosgri and Los Osos fault zones influences the relative weights assigned to values on the logic tree. If the intersection occurs below the





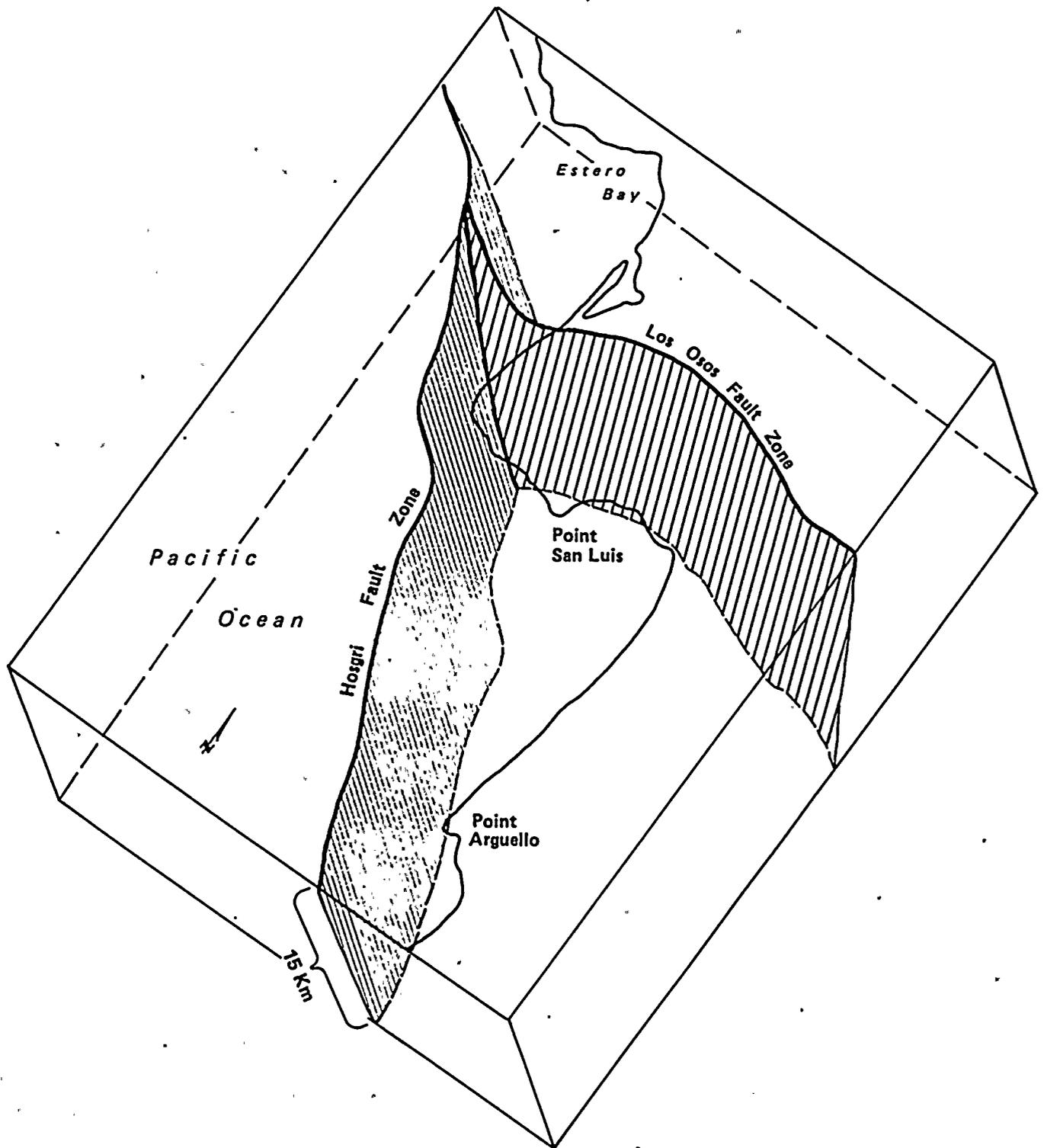


Figure 3-7

Diagram showing the cross-cutting relationship between a vertical Hosgri fault zone and a 60-degree-dipping Los Osos fault zone.

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maximum depth of seismogenic rupture, then the assessments for maximum depth of seismogenic rupture range from 9 to 15 kilometers and the relative weights are the same as those discussed above for the Hosgri fault zone. The maximum depth of rupture for the Los Osos fault zone is considered to be perfectly dependent on the assessment made for the Hosgri fault zone. That is, if the maximum depth for the Hosgri is judged to be 12 kilometers, then the maximum depth for the Los Osos is also 12 kilometers (assuming the depth of the intersection between the two faults is below 12 kilometers). As indicated in the logic tree for the Hosgri fault zone (Figure 3-5), the probability of various maximum depths is dependent on the assumed sense of slip for the fault zone. The marginal distribution over all three slip types results in weights of 0.11, 0.76, and 0.13 being assigned to depths of 9, 12, and 15 kilometers, respectively.

If the fault plane intersection occurs at depths shallower than the maximum depth assessed for the Hosgri fault zone, then this shallower depth becomes the maximum depth of rupture. For example, the logic tree for the Los Osos fault zone (Figure 3-6) shows the assessments of maximum depth conditional on fault dips of 75 degrees and 60 degrees. The differences between the relative likelihoods shown in the logic tree and the marginal distribution for the Hosgri fault zone reflects the fact that shallow dipping models of the Hosgri truncate the Los Osos fault zone at depths shallower than 15 kilometers, resulting in a partial redistribution of the weight assigned to 15 kilometers to shallower depths. As indicated in Figure 3-6, the amount of this redistribution is dependent on the dip of the Los Osos fault zone.

- Total Length

On the basis of the geologic studies, the Los Osos fault is considered to have two possible total lengths of 49 and 57 kilometers with weights of 0.2 and 0.8, respectively. The difference in total length reflects uncertainty in the geologic data of whether the Newsom Ridge segment of the fault is a capable part of the fault zone. The geometric interaction of the Los Osos and Hosgri fault planes also has implications to the assessment of total length for the Los Osos fault zone. For some

fault geometries, parts of the Estero Bay segment of the Los Osos fault zone are truncated by the Hosgri fault zone at relatively shallow depths (Figure 3-7). For these parts of the fault, the depth of truncation is considered to be shallow enough to preclude the segment from being capable of generating significant earthquakes. Studies of the seismicity in California show that essentially all significant earthquakes (magnitudes greater than or equal to 5) initiate at depths greater than 7 kilometers (Sibson, 1984; Chapter 2). This is consistent with rheologic models of the crust that call for the nucleation of large earthquakes near the base of the seismogenic zone where shear resistance is largest (Sibson, 1984). The absence or low rate of seismicity in the upper several kilometers of the crust has been attributed to the stable behavior of shallow unconsolidated fault gouge within well-developed fault zones (Marone and Scholz, 1988). Therefore, it was judged that a maximum fault depth of at least 7 kilometers is needed for a fault to be capable of generating significant earthquakes

For the example schematically shown on Figure 3-7, the Estero Bay segment of the Los Osos fault zone is truncated at depths shallower than 7 kilometers and, therefore, is not considered to be a seismogenic fault segment. The effect of this truncation was modeled by including alternative, shorter total lengths in the logic tree (Figure 3-6). It was judged appropriate to use identifiable segment boundaries along the Los Osos fault zone to define possible total lengths for the fault rather than use the exact point at which the depth of truncation exceeded 7 kilometers. Combining the lengths of the various segments of the Los Osos fault zone results in total fault lengths of 24, 44, and 57 kilometers (where the Newsom Ridge segment is considered capable) and 16, 36, and 49 kilometers (where the Newsom Ridge segment is considered to be not capable). The northwestern segments of the Los Osos fault zone were considered not to be seismogenic if the average depth at which they are truncated by the Hosgri fault zone is less than 7 kilometers.

If the Los Osos fault zone dips 60 degrees to a depth of 12 kilometers (Figure 3-6), there is a

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0.514 probability that the Estero Bay segment is truncated at an average depth of less than 7 kilometers, and is, therefore, not seismogenic. This probability is split between total lengths of 36 and 44 kilometers (at a ratio of 0.2:0.8) reflecting uncertainty in the capability of the Newsom Ridge segment. Alternatively, there is a 0.486 probability that the Estero Bay segment of the Los Osos fault extends to depths greater than 7 kilometers before being truncated by the Hosgri fault zone, and is, therefore, capable of generating earthquakes. This probability is also split between total lengths of 49 and 57 kilometers. Similar assessments were made for each of the dips and maximum depths postulated for the Los Osos fault zone to assign probabilities to each possible total length scenario.

- Rupture Length

The estimates of rupture length for the Los Osos fault zone come from a consideration of the segmentation of the zone. Geologic data, geometric considerations, and fault behavioral interpretations all show very strong evidence for the segmentation of the Los Osos fault, as well as of the entire San Luis/Pismo structural block (Chapter 2). We consider two rupture lengths: 19 kilometers, which is the length of the Irish Hills segment; and 36 kilometers, which represents either the approximate length of a rupture of the Estero Bay segment and the Irish Hills segment, or the rupture of the Irish Hills segment and the Lopez Reservoir segment. Various lines of evidence (Chapter 2), including indications that the Irish Hills segment has pronounced differences in slip rate and recency of slip from adjacent segments, strongly suggest that this segment behaves as a coherent rupture segment. We judge it much less likely that a future rupture will rupture past the segment boundaries at the ends of the Irish Hills segment. Accordingly, we assign a weight of 0.7 to the 19-kilometer case and 0.3 to the 36-kilometer case.

- Maximum Displacement Per Event

Stratigraphic relationships exposed in Ingley trench T-2 show that the cumulative net slip on the fault since development of a buried A soil

horizon ranges from 4.0 to 4.9 meters. Various lines of evidence suggest that there are at least two and probably more surface-faulting events are recorded in the trench exposure. Assuming that the 4.0- to 4.9-meter net slip occurred in two events, we obtain a maximum displacement of about 2 meters. Because these trenches are in a geomorphically well-defined part of the fault zone, we believe that the largest displacements at this location are representative of maximum displacement for the segment as a whole and assign a probability of 1.0 to the 2-meter value.

- Average Displacement Per Event

To arrive at an estimate of the average displacement per event, we use the reasoning of Slemmons (1982) and Slemmons and Depolo (1986), which, based on observations of historical ruptures, assumes that the average displacement is about one-half the maximum. To allow for the variability observed in earthquake ruptures (for example, Thatcher and Bonilla, 1988), we allow a range from 0.5 to 1.5 meters and give both extremes equal weight.

- Maximum Historical Magnitude

No historical earthquakes larger than magnitude 6 have been associated with the Los Osos fault zone. We therefore conclude that the historical record places no constraints on the maximum earthquake magnitude.

- Magnitude Technique

The relative weight or credibility associated with the various magnitude estimation relationships are described previously in this chapter (Table 3-2).

- Recurrence Method

Earthquake recurrence on the Los Osos fault zone was assessed using the seismic moment rate approach incorporating geologic estimates of late Quaternary slip rate. Geologic recurrence intervals are poorly constrained due to lack of good age control and discrete slip events in the trenches.

- Slip Rate

The vertical component of the slip rate is calculated based on topographic separation of



correlative marine terraces across the Los Osos fault zone and accounting for the maximum and minimum amount of possible subsidence of Los Osos Valley. The 0.2-millimeter-per-year value is slightly preferred (0.6) over the 0.4-millimeter-per-year value (0.4) because the former value accounts for the likelihood that bedrock is fairly shallow beneath the valley and the subsidence rate is probably less than 0.1 millimeter per year. For the oblique-slip case, a horizontal component of slip is assumed directly from the definition of an oblique-slip fault used in this analysis, (a range in the horizontal to vertical ratio of from 2:1 to 1:2).

- **Magnitude Distribution**

The assessment for magnitude distribution on the Los Osos fault zone is the same as that for the Hosgri fault zone.

San Luis Bay Fault

The logic tree for the San Luis Bay fault is shown on Figure 3-8.

- **Sense of Slip**

Observations of the San Luis Bay fault in exposures near Avila Beach show slickensides and stratigraphic evidence of the fault being reverse or thrust. Little or no lateral component of slip is detected. Therefore the thrust model is given a weight of 1.0.

- **Dip**

Two values of dip on the San Luis Bay fault are considered: 40 degrees and 70 degrees. The measured values of the dip of the San Luis Bay fault in exposures ranges from about 15 degrees to about 40 degrees. Judging from the exposures near Avila Beach the fault steepens with depth. In addition, stratigraphic relationships interpreted from borehole data across an offshore strand of the fault require the existence of a high-angle, near-vertical fault plane. Seismic reflection data that image the San Luis Bay fault, although poorly constrained, also suggest steep dips. For these reasons, we assign a higher weight to the 70-degree value (0.8) than the 40-degree value (0.2).

- **Maximum Depth of Rupture**

As with the Los Osos fault zone, there are geometrical interactions with other faults that affect the assessment of maximum depth and length for the San Luis Bay fault. This fault lies between the Hosgri and Los Osos fault zones and is affected by the geometries assessed for both faults. The San Luis Bay fault is considered to be a secondary structure compared to the two fault zones and thus is modeled as being truncated by the other fault planes.

The maximum depth of rupture for the San Luis Bay fault was also considered to be perfectly dependent on the assessment of depth of the seismogenic crust made for the Hosgri fault zone, with a marginal distribution of 0.1, 0.76, and 0.14 probabilities assigned to depths of 9, 12, and 15 kilometers, respectively. As described above, a fault or fault segment is considered potentially seismogenic if the maximum depth of rupture is 7 kilometers. Based on the assigned probabilities to the various dips for the Hosgri, Los Osos, and San Luis Bay fault zones, there is a 0.41 probability that the San Luis Bay fault is truncated at depths less than 7 kilometers and therefore is not potentially seismogenic. There is a very low probability that the fault extends to depths of 15 kilometers. The remaining probability is split between depths of 9 and 12 kilometers, with more weight assigned to 9 kilometers.

- **Total Fault Length**

The assessment of the possible total surface lengths are 6, 12, and 19 kilometers with weights of 0.4, 0.25, and 0.35, respectively. The 6-kilometer total length is based on a fault that extends from about 0.5 kilometer west of Rattlesnake Creek southeast into San Luis Bay near Avila Beach. This is the preferred model for total length because this is the length on which we see any substantial evidence of a fault. The 12-kilometer length extends from just west of Rattlesnake Creek southeast to near the Wilmar Avenue fault in San Luis Obispo Bay. This length is based on indirect stratigraphic relationships in San Luis Obispo Bay and the assumption that these relationships are the result of faulting. The



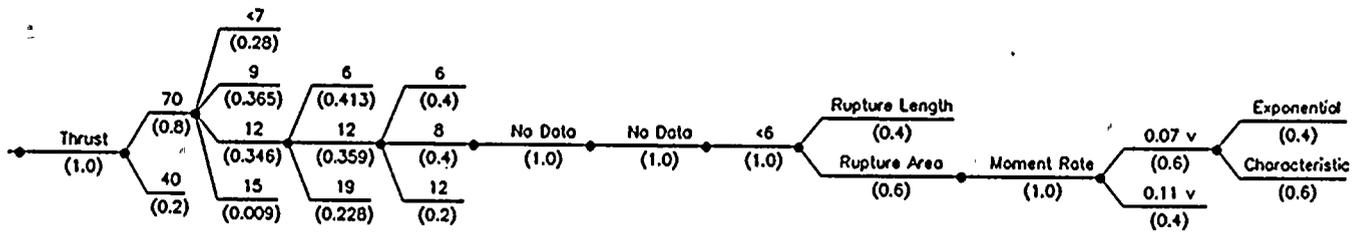


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Sense of Slip	Dip (deg)	Maximum Depth (km)	Total Length (km)	Rupture Length (km)	Maximum Displacement (m)	Average Displacement (m)	Maximum Historical	Magnitude Technique	Recurrence Method	Slip Rate (mm/yr)	Magnitude Distribution
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Notes:
 Values in parentheses are probabilities
 h = horizontal component of slip rate,
 v = vertical component of slip rate

Figure 3-8
 Logic tree for San Luis Bay fault.

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third value is a total length of 19 kilometers, which extends from the Hosgri fault zone southeast to near the Wilmar Avenue fault. The equivocal evidence for the fault in the offshore area west of Rattlesnake Creek causes this value to be given somewhat lesser weight. The geometric interactions with the Hosgri and Los Osos fault zones affect the total length assessments for the San Luis Bay fault. In the same manner as discussed for the Los Osos fault zone, weights were adjusted to reflect those segments of the San Luis Bay fault that are considered potentially seismogenic under various assumptions of fault dip and the values are given in the logic tree on Figure 3-8.

- Rupture Length

Rupture lengths for the San Luis Bay fault are assessed conditionally on the total length of the fault. For a total length of 6 kilometers, an equivalent rupture length is assumed. For total lengths of 12 kilometers and 19 kilometers, rupture lengths of 6, 8, and 12 kilometers are assessed (Figure 3-3) and are given weights of 0.4, 0.4, 0.2, respectively. The 6-kilometer length is the length from just west of Rattlesnake Creek to east of the Avila Beach exposure; 8 kilometers is the distance from just west of Rattlesnake Creek into San Luis Obispo Bay to explain the interpreted stratigraphic relations in the Tertiary section (Chapter 2); and 12 kilometers represents two scenarios, either the distance from west of Rattlesnake Creek to near the Wilmar Avenue fault in San Luis Obispo Bay or the length from the Hosgri fault zone to the Avila Beach exposure. The 12-kilometer rupture length is not preferred because such a rupture length is more than one-half the total fault length. It should be noted that because of uncertainties in the existence of the fault in the offshore region, we do not have information regarding segmentation. If we assume a half-length rupture of our longest length, we arrive at a rupture length (9 kilometers) that is well within those considered.

- Magnitude Technique

The relative weight or credibility associated with the various magnitude estimation relationships are described previously in this chapter (Table 3-2).

- Recurrence Method

The moment rate approach was the method used to estimate earthquake recurrence on the San Luis Bay fault.

- Slip Rate

Based on displacements of the marine terrace wave-cut platform and deposits exposed near Avila Beach, a late Quaternary slip rate ranging from 0.07 to 0.11 millimeter per year was determined. The higher value assumes that associated localized warping is the result of brittle fault displacement while the lower value includes only observed fault displacement. We give a slightly higher weight (0.6) to the directly observed value.

- Magnitude Distribution

The assessment of magnitude distribution for the San Luis Bay fault is the same as that for the Hosgri fault zone.

Maximum Earthquake Magnitudes

Maximum earthquake magnitudes are estimated using empirical relations between magnitude and source characteristics shown in the logic trees. Specifically, we used relations between magnitude and rupture length, rupture area, total length, maximum displacement per event, and seismic moment (Table 3-1). The elements of the logic tree that are important here are the sense of slip, dip, rupture length, total length, down-dip width, maximum displacement per event, and average displacement per event. Particular paths through the logic trees define scenarios that are each associated with a maximum magnitude. For example, one path for the Hosgri fault zone might be for a strike-slip fault dipping 90 degrees, extending down-dip 12 kilometers, and having a total length of 410 kilometers, a rupture length of 45 kilometers, and an average displacement per event of 2 meters (Figure 3-5). This combination represents one of hundreds of scenarios in the logic tree and its relative weight or credibility is simply the product of the probabilities associated with each value on the tree.

Depending on the parameters being considered and on the empirical relationship being used, this

particular scenario would result in the following maximum magnitude estimates:

	<u>M_s</u>
Rupture Length (45 km)	
Slemmons (1982)	6.8
Bonilla and others (1984)	7.3
Wesnousky (1986)	7.0
Total Length (410 km)	
Slemmons (1982)	7.1
Rupture Area (45 km x 12 km)	
Wyss (1979)	6.9
Moment Magnitude	
(45 km x 12 reasonable and km x 2 m x 3 x 10 dyn/cm ²)	
Hanks and Kanamori (1979)	7.0

Tracing this scenario through the Hosgri fault zone logic tree, we see that the relative likelihood of this scenario is 0.062, which is the product of the respective branches: strike-slip (0.65), 90 degrees (0.6), 12-kilometer width (0.8), 410-kilometer total length (1.0), 45-kilometer rupture length (0.4), and 2-meter average displacement per event (0.5). Examination of the logic tree (Figure 3-5) shows that this particular path is given relatively high weight.

By repeating the calculation for all end branches and combining similar estimates, a probability distribution for maximum magnitude for the Hosgri fault zone was obtained (Figure 3-9). The distribution has a mean value of 6.96 and a standard deviation of 0.27 magnitude units. Low values result from the use of the rupture area-magnitude or seismic moment-magnitude relationships, together with the shortest rupture lengths and narrowest fault widths, large values result from the use of rupture length-magnitude relationships and rupture area-magnitude relationships together with the longest rupture lengths and widest fault widths.

Figure 3-10 shows the magnitude distribution for the Hosgri fault zone obtained conditional on the sense of slip. As illustrated, similar distributions are obtained for each style of faulting and the

resulting mean estimates are 6.98, 6.93, and 6.98 for strike-slip, oblique, and thrust faulting, respectively.

Figure 3-11 presents the maximum magnitude distribution for the Los Osos fault. The distribution has a mean value of 6.81 and a standard deviation of 0.28.

Figure 3-12 presents the maximum magnitude distribution for the San Luis Bay fault. The mean value is 6.15 with a standard deviation of 0.22.

These distributions represent the uncertainty in the maximum magnitude estimate. The mean of the distribution is the best estimate of maximum magnitude and the tails of the distribution are unlikely scenarios in the logic tree. For the seismic hazard analysis and probabilistic risk assessment, these full distributions are directly used in the analysis. For the deterministic analysis, a maximum magnitude is selected on the controlling source, as discussed later in this chapter.

Earthquake Recurrence

For the seismic hazard analysis, earthquake recurrence intervals were assessed for each seismic source. Recurrence information also provides a useful vehicle for evaluating the relative degree of fault activity (Cluff and others, 1982; Cluff and Cluff, 1984). Recurrence estimates for the Hosgri, Los Osos, and San Luis Bay fault zones were based on two approaches. The primary method was the moment rate approach (Anderson, 1979; Molnar, 1979) in which estimated slip rate is used to infer the rate of seismic moment release on the fault. Given a relationship between seismic moment and earthquake magnitude and a magnitude-distribution model, we can then translate the estimated rate of seismic moment release into earthquake frequencies, also called recurrence relationships. Two forms of the earthquake magnitude distribution were used in the analysis (Figure 3-13), the truncated exponential distribution (Anderson, 1979) and the characteristic magnitude distribution (Youngs and Coppersmith, 1985). The relationship



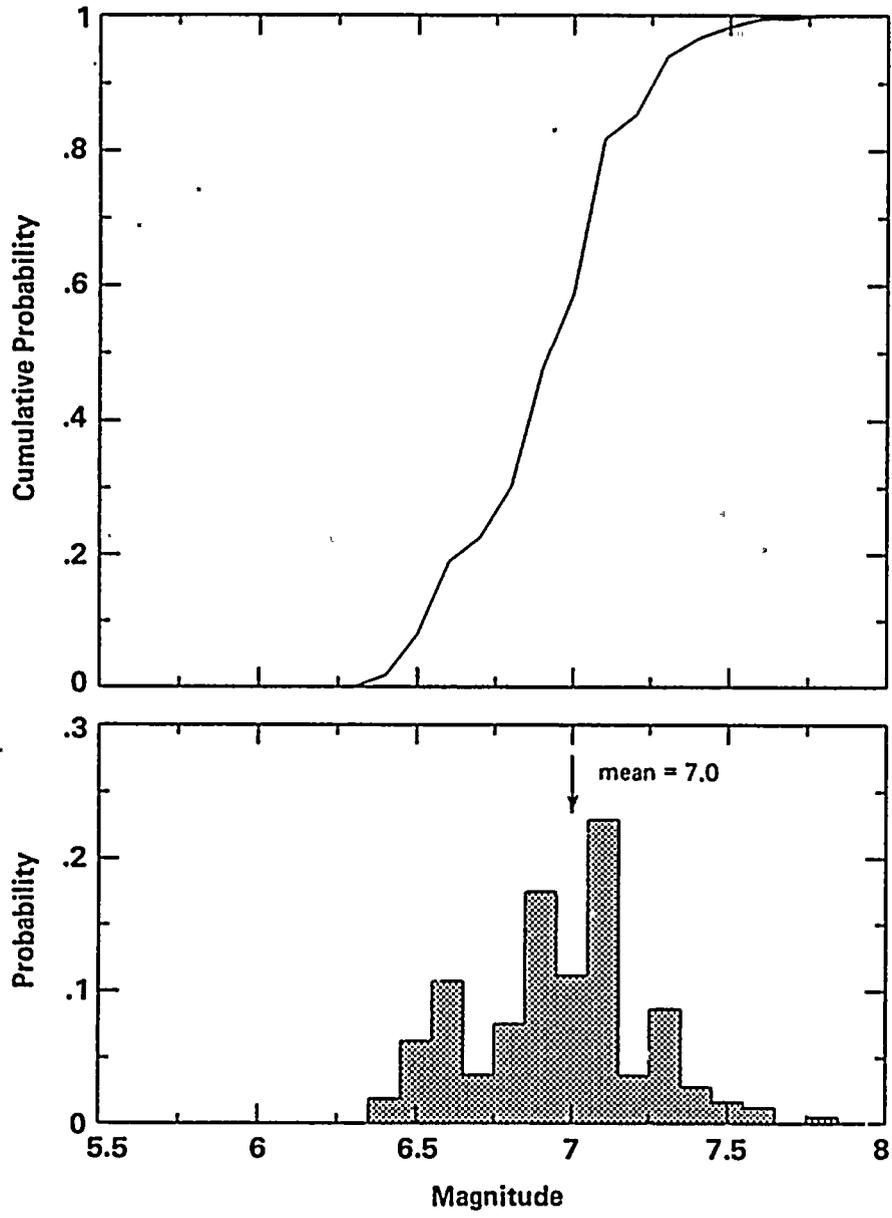


Figure 3-9
Maximum magnitude distribution for Hosgri fault zone.



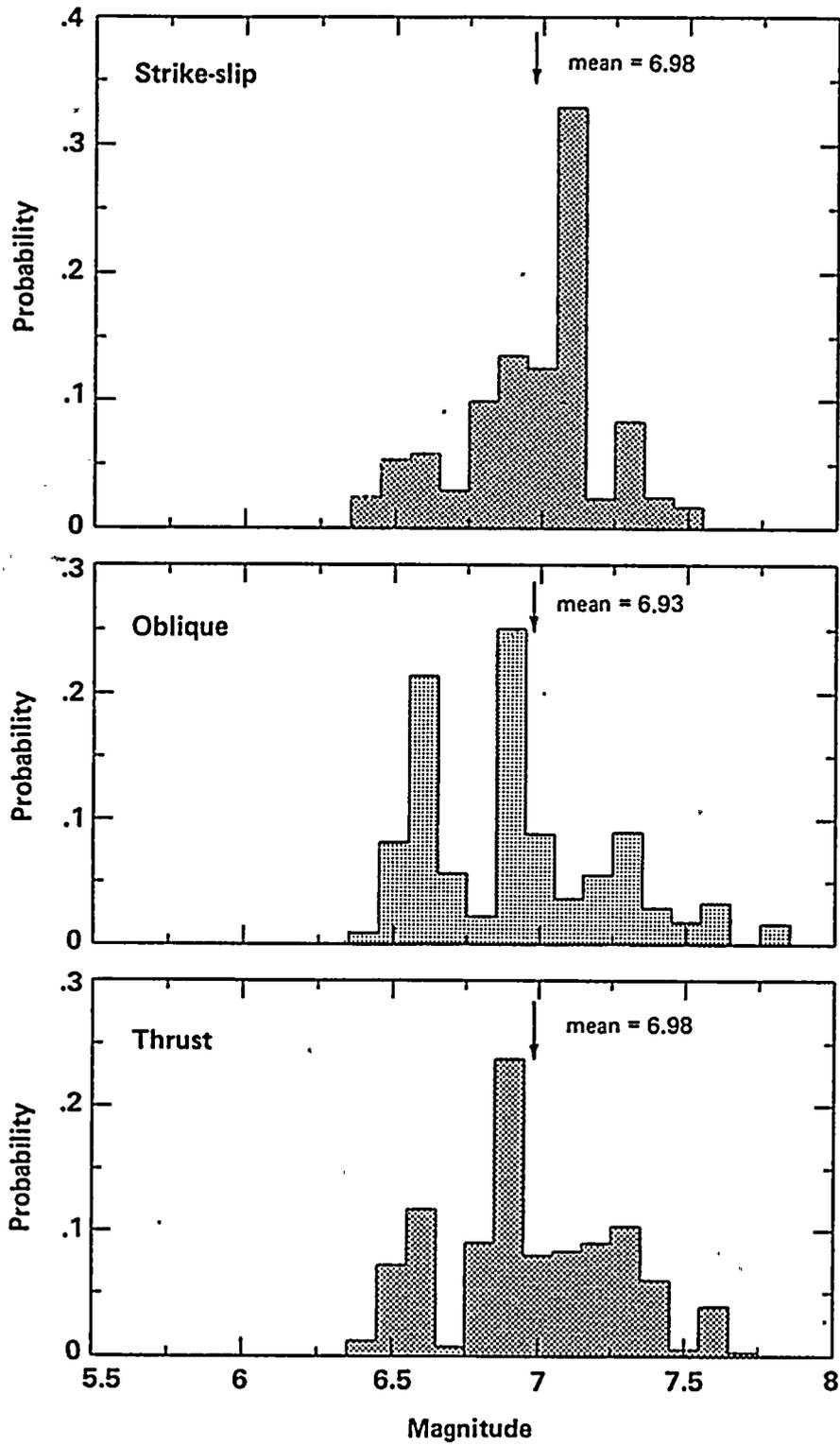


Figure 3-10
Maximum magnitude distributions for the Hosgri fault zone as a function of the sense of slip.



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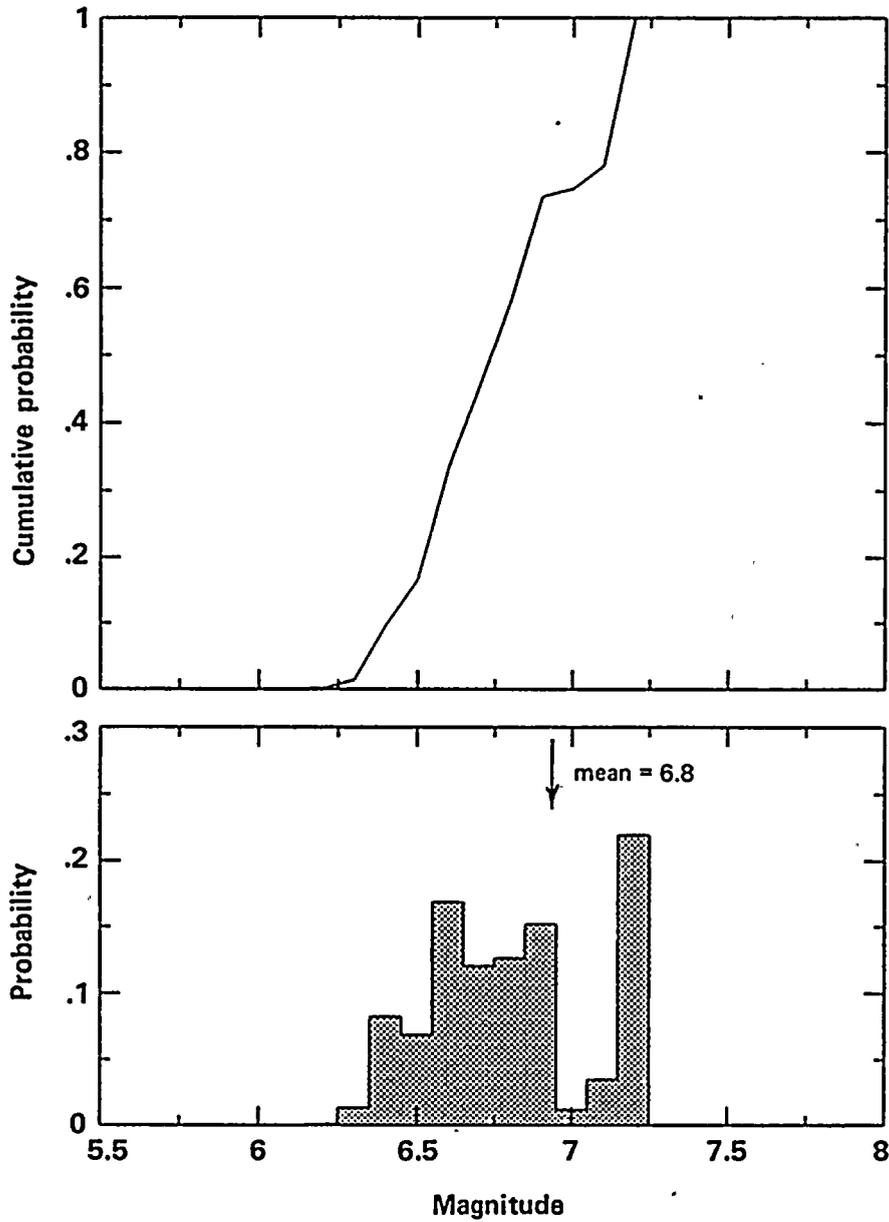
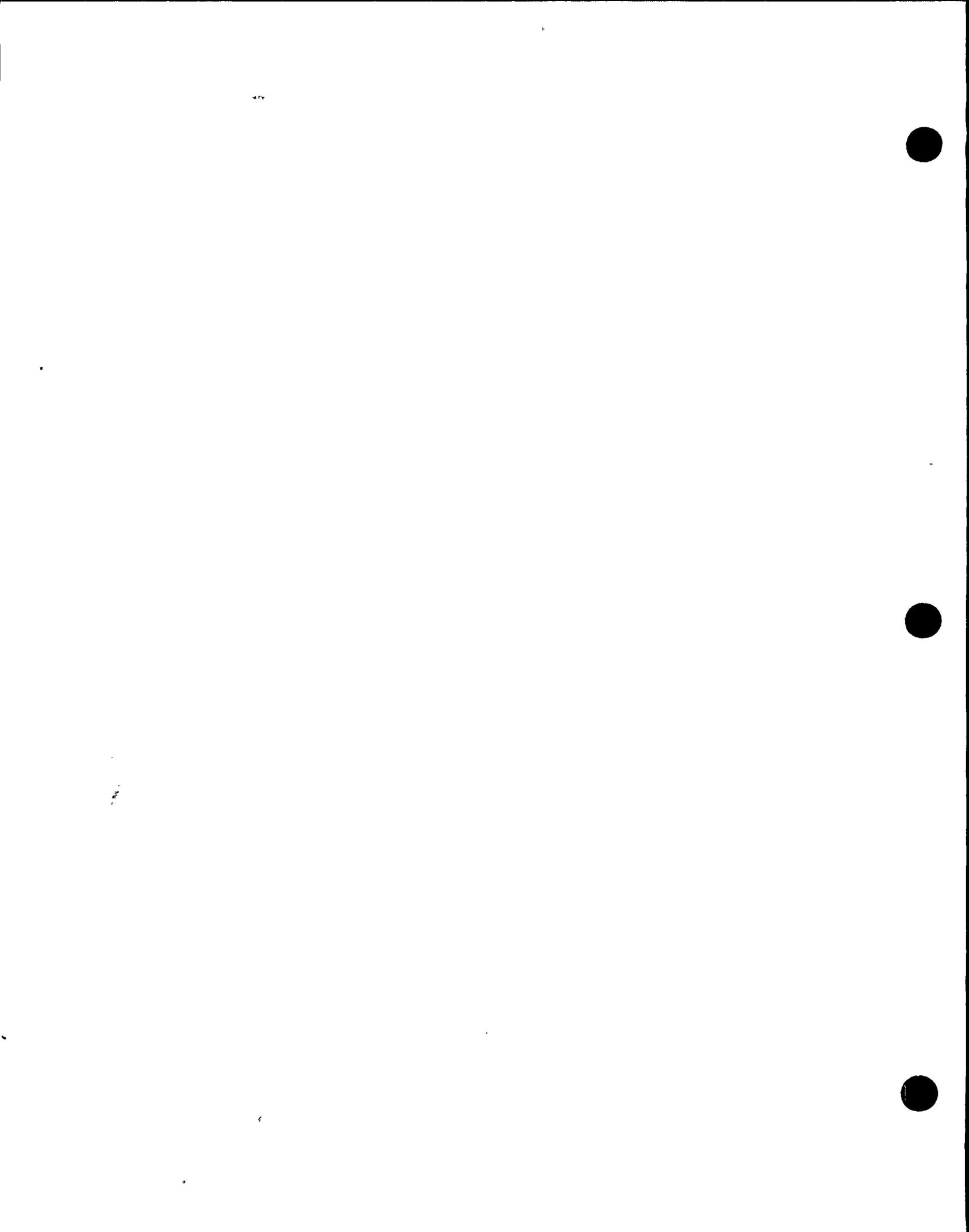


Figure 3-11
Maximum magnitude distribution for Los Osos fault zone.



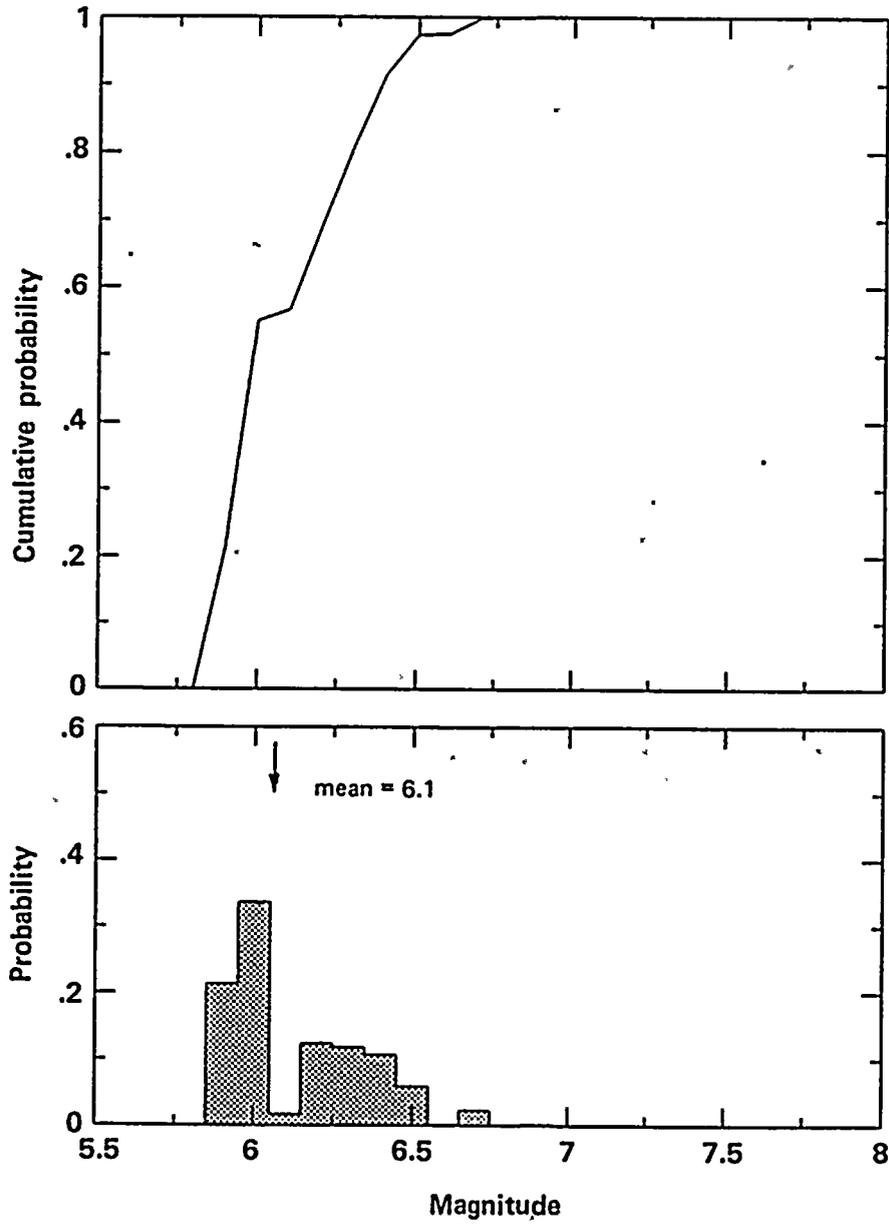


Figure 3-12
Maximum magnitude distribution for San Luis Bay fault zone.



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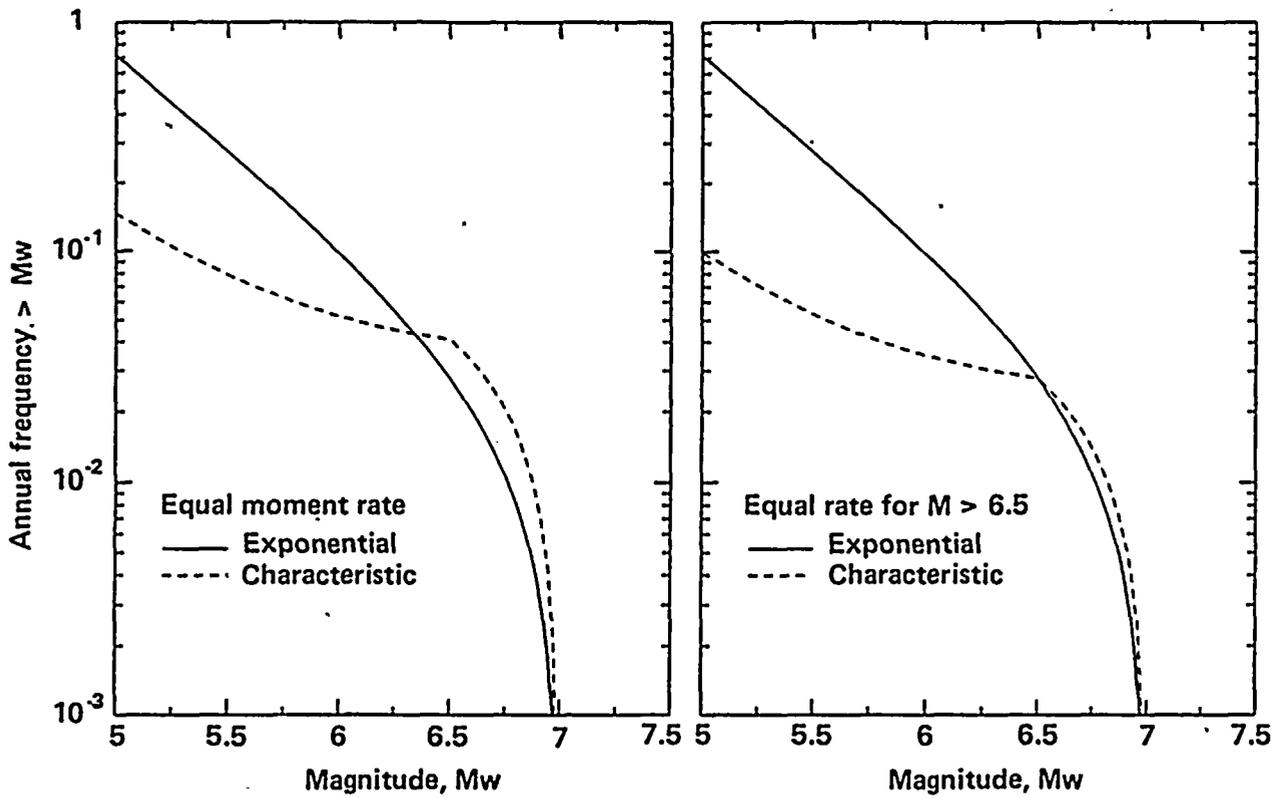


Figure 3-13

Example recurrence relationships showing the effect of the exponential and characteristic earthquake magnitude distributions.

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between seismic moment and earthquake magnitude developed by Hanks and Kanamori (1979) was used in the analysis. The resulting earthquake recurrence estimates are in terms of moment magnitude, M_w , which is considered to be equivalent to M_L in the range of 3 to 7 and equivalent to M_S in the range of 5 to 7.5 (Kanamori, 1977, 1983). In applying the moment rate approach, it was assumed that all fault slip occurred during seismic events. No allowance was made for post-seismic slip or fault creep.

The second approach to recurrence estimation was direct assessment of the frequency of surface-rupturing events based on paleoseismic data. In this study, surface-rupturing events were considered to be events within 0.5 magnitude units of the maximum event. The frequency of smaller earthquakes was then specified by the appropriate form of the magnitude distribution (exponential or characteristic) anchored at the specified frequency of $M_{max}-1/2$ magnitude events.

In both approaches, the frequency of smaller earthquakes is specified by the form of the magnitude distribution and the b -value for the exponential portion of the magnitude distribution. A b -value of 0.8 was used for the exponentially-distributed recurrence curve for all of the faults based on evaluations of the regional seismicity in the central Coast Ranges (for example, Uhrhammer, 1985).

Figure 3-14 shows the mean recurrence moment rates for the Hosgri, Los Osos, and San Luis Bay faults. Recurrence intervals from these relationships are given below:

Fault	Recurrence Intervals for Magnitude (years)				
	5.5	6.0	6.5	7.0	7.2
Hosgri	20	40	125	1,700	11,350
Los Osos	350	850	3,300	-	-
San Luis Bay	1,100	35,000	-	-	-

Comparison of these recurrence intervals and magnitudes with other faults worldwide (for example, Cluff and Cluff, 1984) shows that the Hosgri fault zone has a moderate degree of

activity that is typical of the second-order faults of the San Andreas fault system. In contrast, the San Luis Bay fault has a very low degree of activity. Recurrence intervals for this fault are compatible with the lack of geomorphic evidence suggestive of Holocene displacement.

The historical seismicity record is too short to provide fault-specific recurrence information. However, we can qualitatively compare the *regional* recurrence rates from seismicity data with the rates that we have developed from fault slip rates and geologic data. In general, these comparisons show that we are predicting recurrence rates for larger earthquakes that are higher than those observed historically. For example, within the entire Los Osos/Santa Maria Valley Domain (Figure 2-8) including its borders we have observed seven or eight earthquakes (range due to location uncertainty) having magnitudes greater than or equal to 5 have been observed in the past 90 years. In this area over the same period, no earthquakes greater than or equal to 6 have been observed. Considering *only* the Hosgri, Los Osos, and San Luis Bay faults' recurrence rates, we predict about twelve magnitude 5 or greater events and two magnitude 6 or greater events for the same length of time. Clearly if we included other potentially active faults within this region such as the Casmalia, West Huasna, and Los Alamos faults, our predicted rate of significant earthquakes would exceed the observed rate still more. We therefore conclude that the recurrence rates used for the faults of significance to the site are conservative.

Maximum Earthquake Magnitude on Controlling Source

For deterministic analysis, the controlling seismic source was determined to be the Hosgri fault zone, located at an average distance of 4.5 kilometers from the plant site. Based on fault length, segmentation, potential fault displacement, and other factors discussed above, the best estimate of the maximum earthquake magnitude on this source is equal to about M_S or M_w 7. However, a very conservative evaluation of the maximum magnitude on the Hosgri fault zone



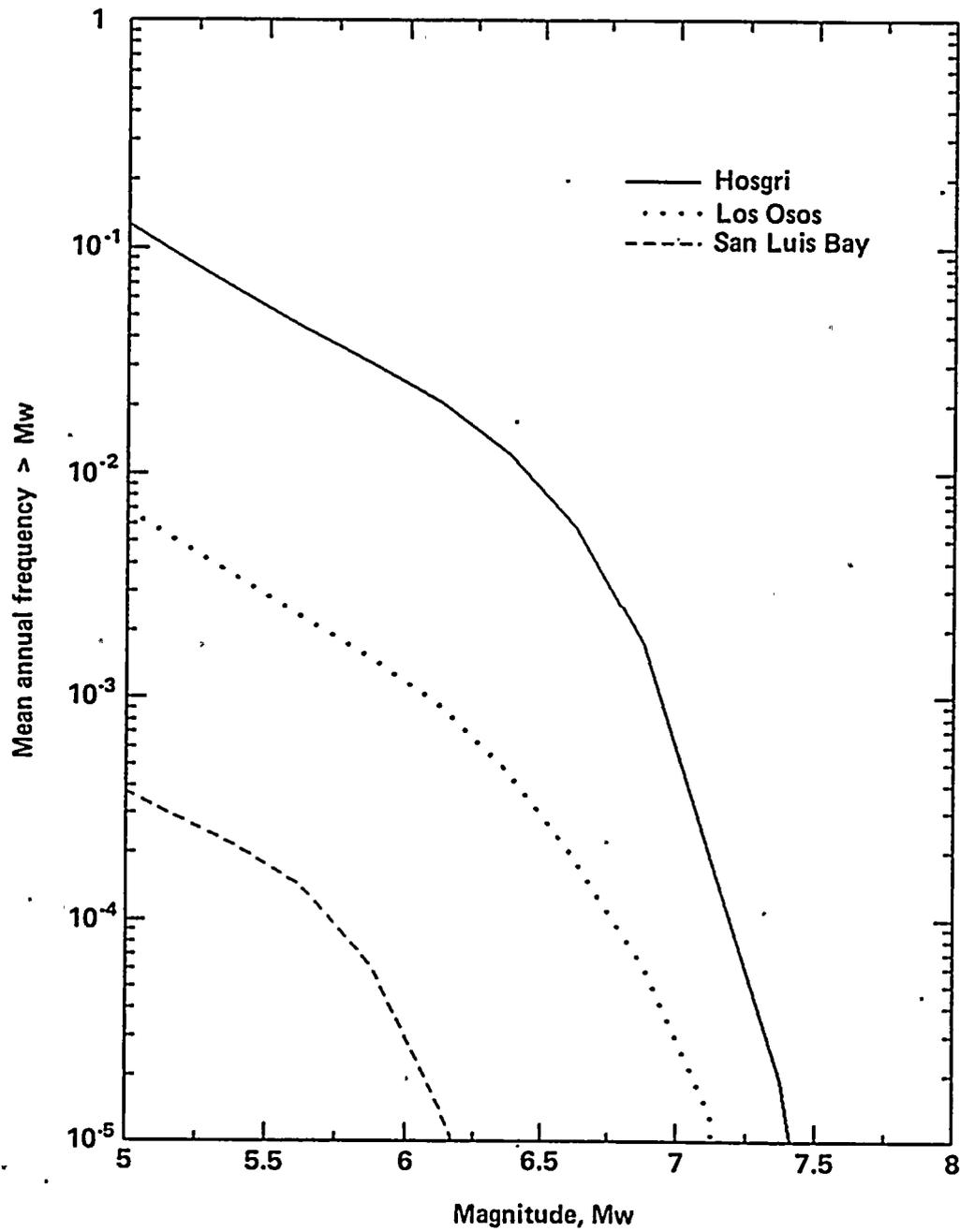


Figure 3-14
Mean recurrence relationships for the Hosgri, Los Osos, and San Luis Bay fault zones.

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adjacent to the plant site is $M_S = M_W = 7.2$. The ground motions associated with an earthquake of this magnitude were selected for deterministic analyses of the plant structures, systems and equipment. While the most likely style of faulting associated with such an event is strike-slip, it was also concluded that to allow for uncertainties, the ground motions should be weighted on the basis of type of faulting included in the logic trees, as follows:

<u>Style of Faulting</u>	<u>Relative Weight</u>
Strike-slip	0.65
Oblique	0.30
Reverse	0.05

These criteria were used to determine appropriate deterministic ground motions at the Diablo Canyon site for seismic margin evaluations.

Input to Subsequent Seismic Hazard Analysis

The logic trees shown in Figures 3-5, 3-6, and 3-8 model all of the uncertainties considered in characterizing the seismic potential of the faults. These logic trees were used directly in the seismic hazard analysis (Chapter 6) in a condensed form. The logic trees were condensed by combining those elements of the logic tree used to estimate various parameters of maximum magnitude and earthquake recurrence into single nodes for maximum magnitude and the frequency of events of moment magnitude 5.0 or greater. Specifically, the nodes for rupture length, maximum displacement, average displacement, maximum historical event, and magnitude technique were combined to produce a discrete distribution for maximum magnitude conditioned on a particular sense of slip, dip, maximum depth, and total length. In a similar fashion, the nodes for recurrence method and slip rate/recurrence rate were combined to produce a discrete distribution for annual frequency of events greater than M_W 5.0 conditional on a particular fault area and maximum magnitude. The remaining levels of the logic trees were retained because they affect the choice of attenuation relationships, the source-to-site distance distribution, and the

magnitude distribution. Figures 3-15 through 3-17 show the resulting seismic source logic trees used in the seismic hazard analysis.

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Sense of Slip	Dip (deg)	Maximum Depth (km)	Total Length (km)	Maximum Magnitude	Magnitude Distribution	Annual Frequency M > 5.0
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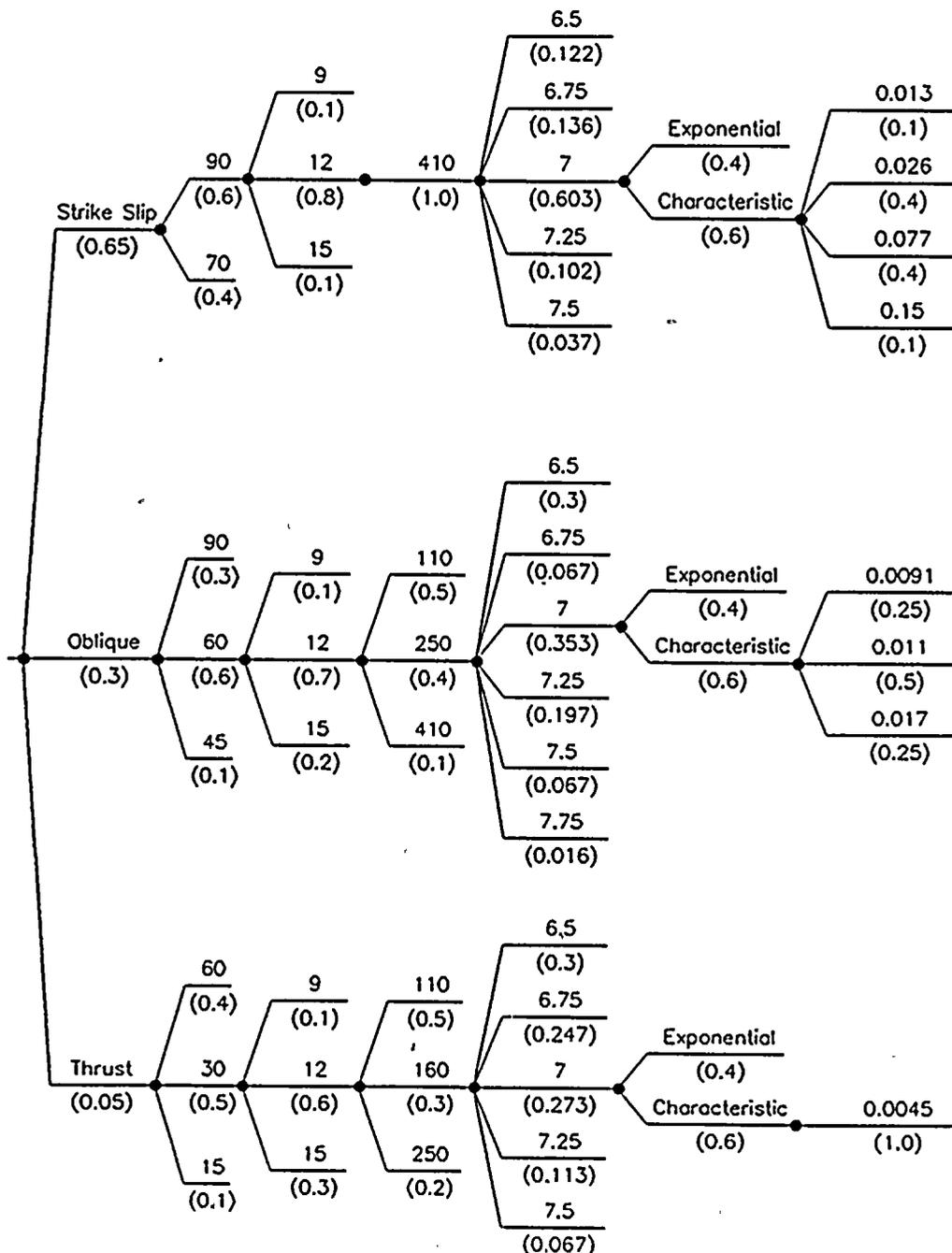


Figure 3-15

Seismic hazard logic tree for Hosgri fault zone illustrating the format for input to seismic hazard analysis.

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Sense of Slip	Dip (deg)	Maximum Depth (km)	Total Length (km)	Maximum Magnitude	Magnitude Distribution	Annual Frequency M > 5.0
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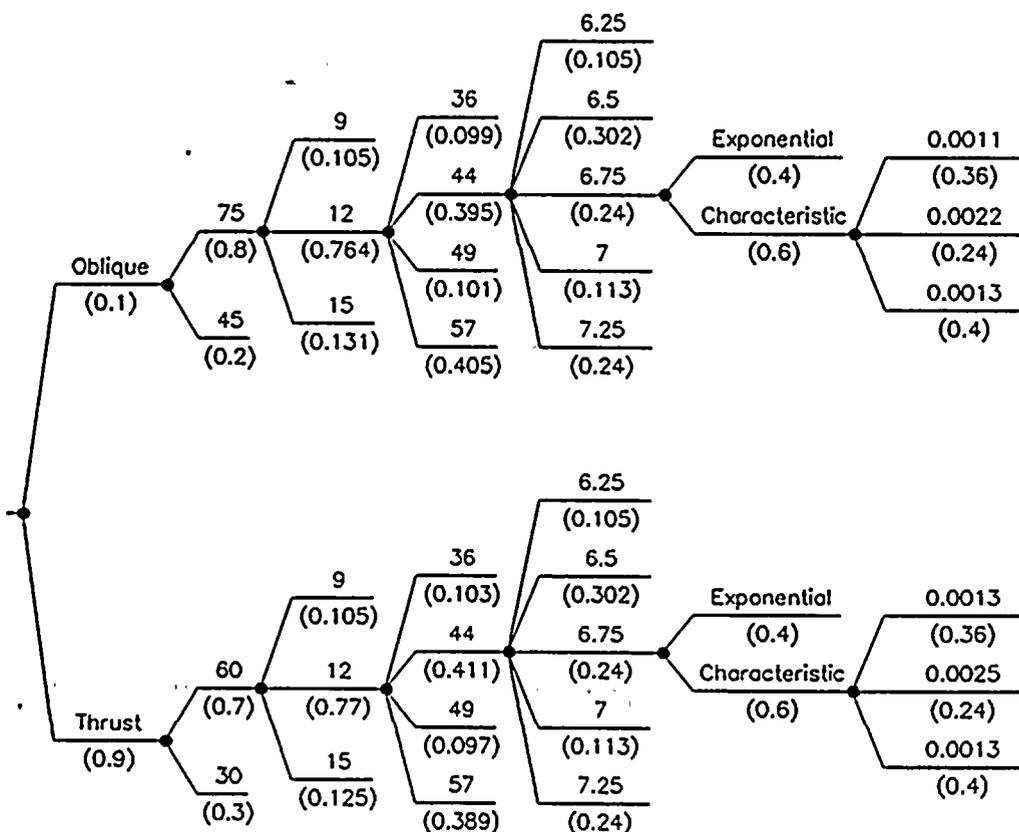


Figure 3-16

Seismic hazard logic tree for Los Osos fault zone illustrating the format for input to seismic hazard analysis.

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Sense of Slip	Dip (deg)	Maximum Depth (km)	Total Length (km)	Maximum Magnitude	Magnitude Distribution	Annual Frequency M > 5.0
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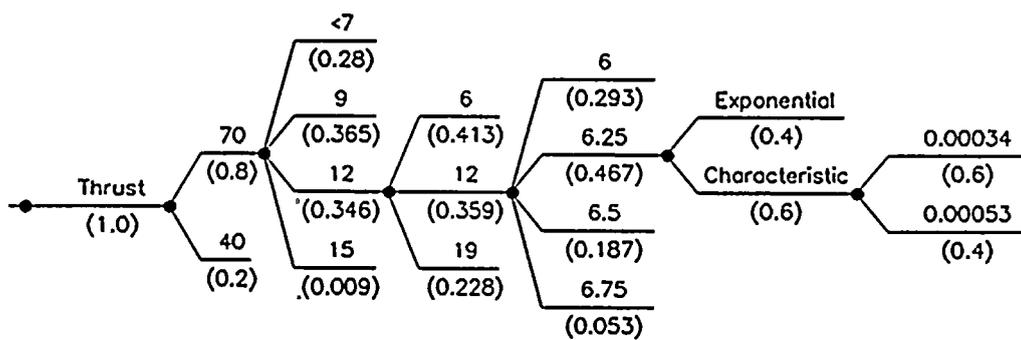


Figure 3-17

Seismic hazard logic tree for San Luis Bay fault zone illustrating the format for input to seismic hazard analysis.

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Chapter 4

CHARACTERIZATION OF GROUND MOTIONS

To Address *Element 3 of the License Condition*

ELEMENT 3 OF THE LICENSE CONDITION

PG&E shall reevaluate the ground motion at the site based on the results obtained from Element 2 with full consideration of site and other relevant effects.

OBJECTIVES

The ground-motion studies in the Long Term Seismic Program had the following objectives:

- To reevaluate the ground motions at the Diablo Canyon site based on the results of the characterization of the seismic sources in the region (Chapter 3), with full consideration of site and other relevant effects. This objective is responsive to Element 3 of the license condition.
- To provide appropriate ground-motion data for the engineering probabilistic risk, and deterministic analyses (Chapters 5, 6 and 7), in response to Element 4 of the license condition.

SCOPE OF WORK

The Long Term Seismic Program ground-motion evaluations began with Phase I, the development of the Program Plan. This plan contains two main components for ground-motion studies:

- *Evaluation of earthquake ground motions by empirical analysis.* In the past decade, the data base of strong ground-motion recordings close to large earthquakes has been greatly enlarged. Regression analyses of this up-

to-date ground-motion data base and statistical analyses of selected near-source strong-motion recordings have been performed.

- *Evaluation of earthquake ground motions by numerical modeling.* Procedures for the simulation of strong ground motions using numerical modeling techniques developed during the past decade have been further refined, extensively validated, and applied to the Diablo Canyon site using site-specific information.

The Program Plan was reviewed and endorsed by the Long Term Seismic Program Consulting Board and was subsequently approved by the Nuclear Regulatory Commission (NRC).

During Phase II, PG&E identified several significant ground-motion considerations, and developed a Work Plan consisting of a set of well-defined tasks to address these considerations. The ground-motion tasks were structured to integrate the results from both the empirical investigations and numerical modeling studies to assess the ground motions at the site, and provide specific ground-motion data needed for the engineering analyses.

Scope of Empirical Investigations

The empirical ground-motion investigations were based on analyses of an up-to-date strong-motion data base applicable to the seismic environment and site conditions at the Diablo Canyon Power Plant. The investigations consisted of:

- Compilation of a primary data base consisting of a large volume of up-to-date



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strong-motion data recorded at rock and rock-like sites from shallow crustal earthquakes. In addition, a supplementary data base from soil sites was also compiled for special studies on the effects of style of faulting, magnitude scaling, and data dispersion.

- Development of attenuation relationships for peak ground acceleration and response spectral acceleration by regression analyses using the strong-motion data base
- Development of site-specific response spectra based on these attenuation relationships, and also based on statistical analysis of near-source, strong-motion recordings
- Development of acceleration time histories from recorded accelerograms appropriate to the magnitude, source-to-site distance, and site conditions.

Scope of Numerical Modeling Studies

Major progress in the use of empirical methods based on available strong-motion data recorded in past earthquakes has been made. It is recognized, however, that past recordings were made at locations having earthquake source characteristics and local site conditions not entirely similar to the Diablo Canyon site, and the number of available recordings from large earthquakes at near-source sites, particularly at near-source rock sites, is still not large. Because the seismic hazards at the Diablo Canyon site are dominated by near-source large earthquakes which are postulated to originate from the Hosgri fault zone, it was considered desirable to supplement and reinforce the empirical studies with ground-motion estimates using numerical modeling methods.

The numerical ground-motion modeling studies were designed to complement the empirical investigations in several important ways. They provided a means for:

- Augmenting the data set of empirical strong-motion recordings close to large earthquakes

- Estimating the dependence of strong ground motions on variations in specific fault parameters
- Including specific information about earthquake source, wave propagation path between the source and the site, and local site response
- Estimating the orientation, wave composition, and spatial incoherence of ground motions at the site.

The numerical ground motions modeling studies consisted of:

- Formulation of a semi-empirical ground-motion simulation procedure
- Validation of the ground-motion simulation procedure against actual strong-motion recordings
- Analysis of wave propagation in the Diablo Canyon site region based on site recordings
- Application of the simulation procedure to study the sensitivity of ground motions to seismic source parameters
- Application of the simulation procedure to simulate ground motions at the Diablo Canyon site
- Application of the simulation procedure to assess spatial incoherence of ground motions at the Diablo Canyon site.

To perform the numerical modeling studies, PG&E acquired (and in some cases digitized) a large volume of seismograms and strong-motion recordings from the Diablo Canyon site and the surrounding region, including approximately 50 earthquake seismograms and 1,000 explosion seismograms. Approximately 100 strong-motion recordings of earthquakes in other regions were also acquired and analyzed in the course of validation of the ground-motion simulation procedures. The analysis of these seismograms and the simulation of synthetic strong-motion seismograms entailed the development, documentation, and application of approximately 65 computer codes.

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METHOD OF STUDY

The ground-motion evaluations consisted of three main components: (1) empirical ground-motion investigations, (2) numerical ground-motion modeling studies, and (3) integration of the results from both the empirical investigations and numerical modeling studies to achieve the objectives of the study.

Method of Empirical Investigations

The empirical ground-motion investigations were based on analyses of actual strong-motion records of past earthquakes. A large up-to-date empirical ground-motion data base was first compiled to form the foundation for this study. This strong-motion data base was continuously updated by incorporating newly available recordings.

It was decided early in the Program not to rely solely on peak ground acceleration for characterizing seismic ground motions at the Diablo Canyon site. The peak ground acceleration in many cases represents isolated spikes having limited engineering significance. Instead, we have chosen response spectral acceleration as the primary ground-motion parameter to properly reflect the frequency content of ground motions, thus enabling more direct prediction of the response of various plant structures, systems, and components with different natural frequencies.

Attenuation relationships for response spectral acceleration were developed using the procedure employed by Sadigh (1983, 1984). This involves developing relationships for the ratio of spectral acceleration to peak ground acceleration (spectral shape) as a function of magnitude and distance, and then applying these to attenuation relationships for peak ground acceleration. The advantages of this approach are that for rock or rock-like sites there is a much larger data base of peak ground acceleration (217) than response spectra (88) for establishing magnitude and distance scaling of absolute levels of ground motions; and the use of spectral shapes results in attenuation relationships for various frequencies that are consistent over the full range of

magnitudes and distances to which the relationships apply.

The procedure involves three steps: first, developing a spectral shape for a reference-size event for which there is abundant data; second, developing relationships to scale this spectral shape to other magnitudes; and third, computing the standard error of the absolute spectral values about the attenuation relationships. For this analysis, a reference magnitude of M_w 6.5 was used, because there is a relatively large number of recordings from rock or rock-like sites for which response spectra are available.

The attenuation relationships for peak ground acceleration and response spectral ordinates were developed using the average of the two horizontal components. As discussed by Campbell (1985), use of the average of the two horizontal components removes the effects of component-to-component correlations that are associated with assuming that each component represents an independent measurement of ground motion.

Attenuation relationships for rock site conditions were developed using a nonlinear regression procedure based on the modified Gauss-Newton method. Attenuation relationships were developed for horizontal peak ground acceleration, horizontal 5 percent damped response spectral acceleration at 15 frequencies in the range 1 to 25 hertz, and for 5 percent damped average response spectral acceleration for two frequency bands: 3 to 8.5 hertz and 5 to 14 hertz.

Site-specific response spectra for horizontal motions were developed using these attenuation relationships, and also by statistical analysis of a suite of 18 near-source strong-motion recordings. Site-specific response spectra for vertical motions were also developed by scaling the site-specific horizontal response spectra using ratios of the vertical to horizontal response spectra values. The site-specific response spectra for horizontal and vertical motions were used as input data to the soil/structure interaction analyses, and the attenuation relationships were used as input data to the seismic hazard analysis.



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Suites of realistic time histories needed for input to the fragility studies and soil/structure interaction analyses were developed by modifying, as necessary, the amplitude spectral content of the recordings to conform to the established site-specific criteria for magnitude, distance, and site conditions.

Method of Numerical Modeling Studies

In conducting the numerical modeling studies, we used techniques for making synthetic seismograms that have been developed during the past two decades. Comparison of synthetic seismograms with recorded seismograms has been widely used in a broad variety of contexts to estimate earthquake or explosion source characteristics and velocity structure models. These synthetic seismogram techniques have been adapted to the specific application of estimating strong ground motions close to large earthquakes by several researchers. We used an approach developed and validated by other investigators (Hadley and others, 1982), and incorporated several modifications and refinements. In addition, we formulated a procedure to estimate site-specific spatial incoherence of ground motions.

The development of the simulation methods used to evaluate ground motions at the site and to provide specific ground-motion inputs into engineering analyses was based on two main considerations. First, it was recognized that there are many effects that influence strong ground motions, especially at high frequencies, that cannot be predicted realistically by deterministic theoretical methods. These effects are related to details of the earthquake rupture process and of wave propagation through complex media. Therefore, empirical data were used directly in place of theoretical models wherever appropriate and feasible.

Second, the ground-motion simulation methods were validated using recorded strong-motion data before the methods were applied to the site. The validation consisted of demonstrating that ground-motion characteristics estimated using these methods, with constraints imposed by known characteristics of the source and path, were

similar to those of the recorded data. Validation studies were performed both for the ground-motion simulation procedure (Wald and others, 1988a,b) and for the procedure used to estimate site-specific spatial incoherence functions (Somerville and others, 1988).

DEVELOPMENT OF SIMULATION PROCEDURE

We have developed a state-of-the-art ground-motion simulation procedure for efficient simulations of ground motions at the Diablo Canyon site. Figure 4-1 shows schematically a general outline of the simulation procedure as formulated by Hadley and others (1982). The rupture surface of the simulated event is discretized into small fault elements. For each element, the source time function is represented by a sequence of empirical source functions that simulate the rise time of the slip on the fault. The source contribution is convolved with a simplified Green's function appropriate for the particular geometry between the fault element and the site. Finally, the responses from all of the elements are summed to yield the simulated accelerogram.

This simulation procedure takes into account the deterministic, stochastic, and empirical aspects of source and propagation effects on ground motions. Gross aspects of fault rupture and wave propagation are modeled deterministically. Stochastic aspects simulate irregularities in rupture velocity and slip velocity as well as minimize the numerical effects of fault discretization. Finally, details of the radiated source spectrum, including frequency dependent radiation pattern (Liu and Helmberger, 1985) and unmodeled propagation phenomena such as scattering, are included empirically by using suites of actual recordings of small earthquakes as source functions. Several key features of the semi-empirical simulation procedure are now described.

Simplified Green's Functions. The empirical source functions are derived from recordings of small earthquakes. The simplified Green's functions allow these empirical source functions to be transferred from the geometrical spreading and receiver function parameters at which they were



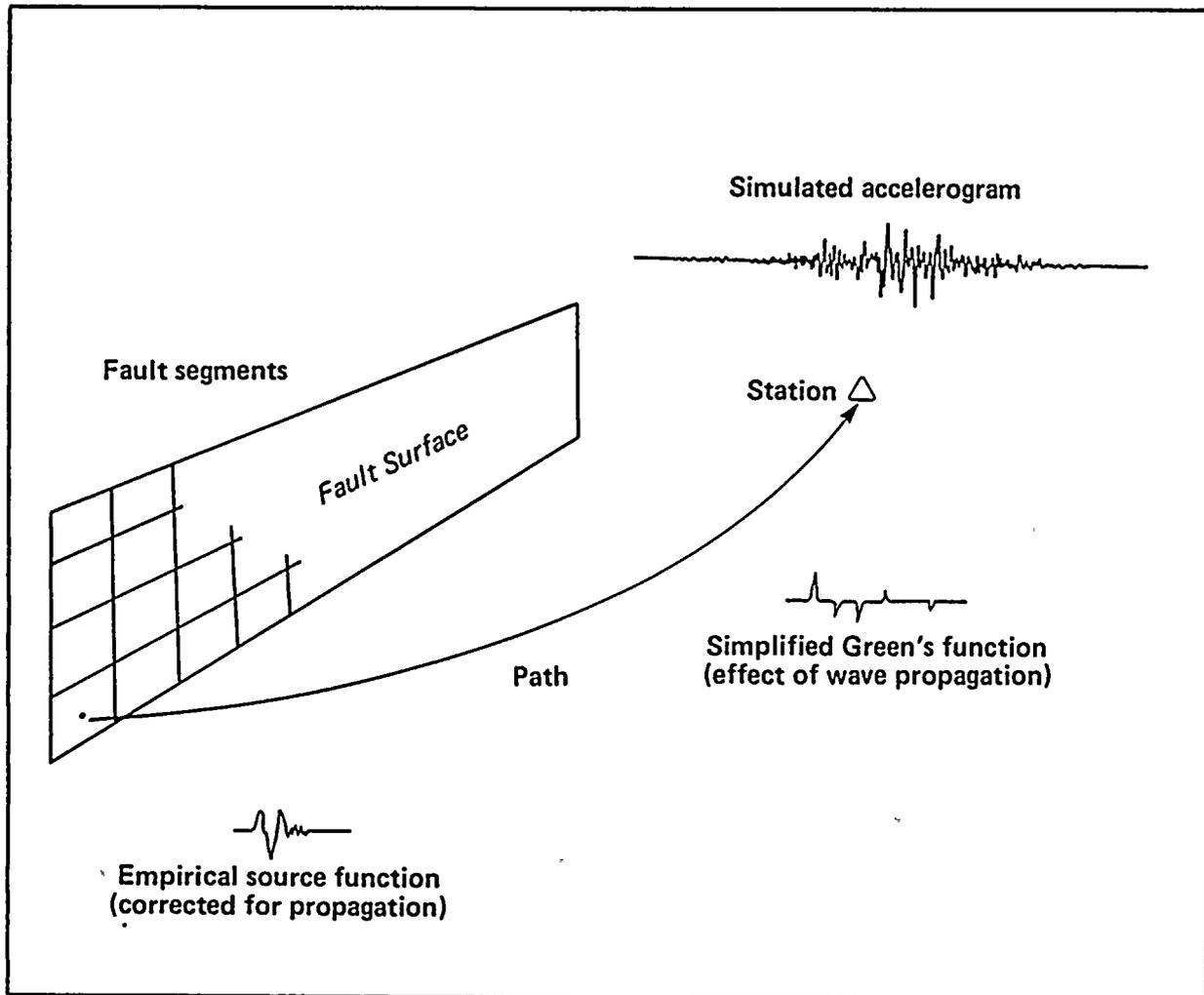
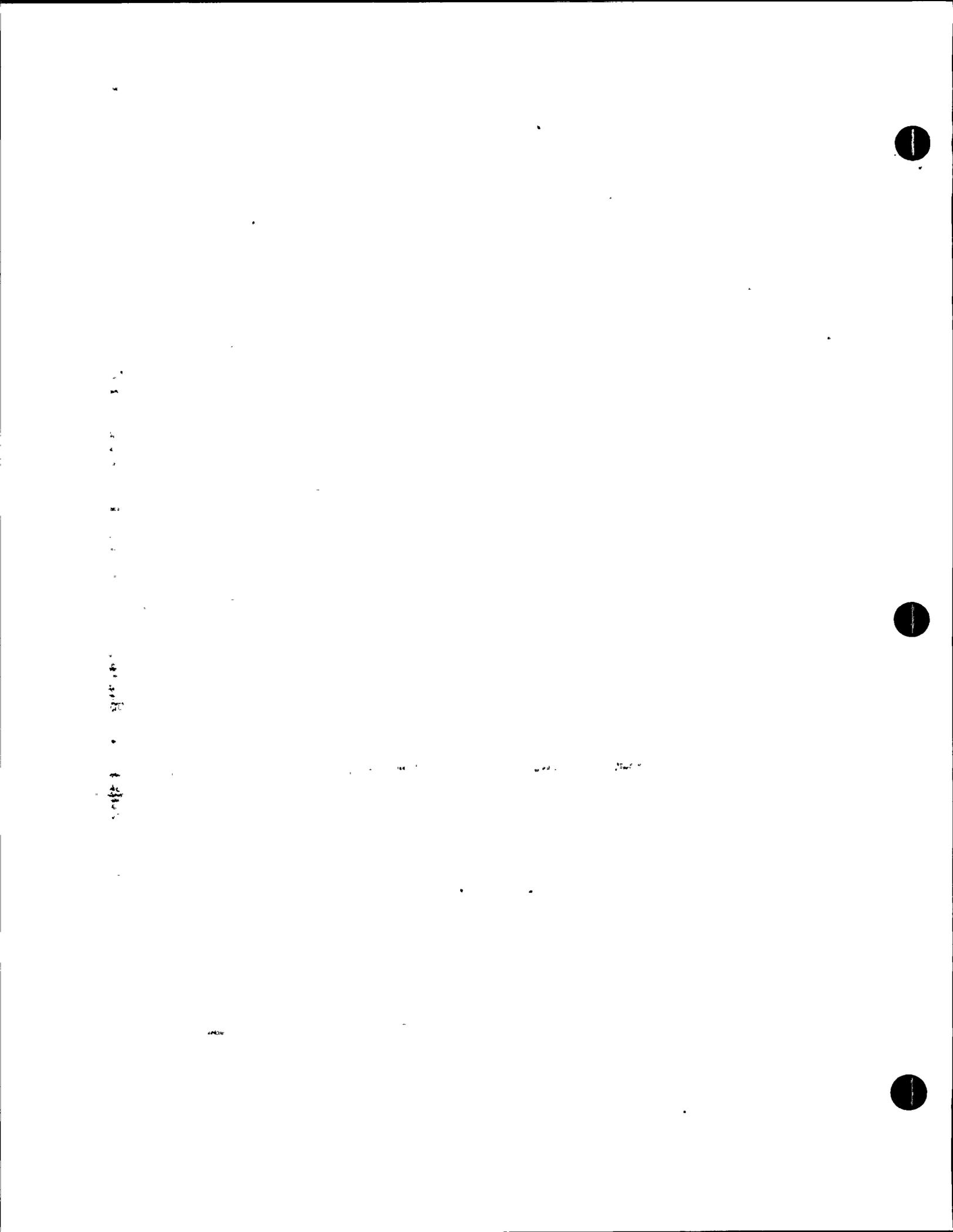


Figure 4-1

Schematic diagram of the semi-empirical ground-motion simulation procedure. For each subfault, an empirical source function with the appropriate radiation pattern is convolved with the simplified Green's function. The ground-motion contributions of each subfault are then time-lagged and summed in accordance with a prescribed geometry of rupture evolution.



recorded to the parameters for which they are used in the simulation. They contain the principal direct, reflected, and refracted rays but no multiples. The receiver function transfer accounts for differences in medium properties and incidence angles between the site and the location in which the source function was recorded. By combining the empirical source functions with the simplified Green's functions, we are able to approximately transfer recordings of small earthquakes from one region to another. This enables us to perform simulations at the Diablo Canyon site, where we do not have sufficient recordings of small earthquakes to use them directly to represent both source and wave propagation effects by the method of Hadley and Helmberger (1980).

Scaling Considerations. The area of the rupture surface of the earthquake is determined by the seismic moment and static stress drop desired. The area of the fault element is determined by the seismic moment and static stress drop of the small earthquake that generated the empirical source function. The dimensions of the fault plane then determine the number of fault elements along strike and down dip. Because the earthquake that generated the empirical source functions resulted from rupture on a smaller fault, its rise time is shorter than that of the larger event being simulated. Accordingly, we lag and sum enough subevents to simulate the rise time of the large event, this number being the ratio of the large event to subevent rise times.

Slip Function. The form of the fault slip function at each fault element was assumed to be a simple ramp following Haskell (1964), parameterized by static slip and rise time. At the same time we also incorporated a stochastic component in the slip function to account for variation in the instantaneous slip rate. The subsources are time lagged with a Gaussian probability distribution centered on equal intervals of the subsource rise time. The probability of a subsource initiating at the boundary between subevent time intervals was set at the three-standard-deviation level.

Empirical Source Functions. An empirical source function, as used in the semi-empirical

simulation procedure, represents a single estimate of the source radiation from a given fault element. The empirical source function includes the detailed source spectrum. It also implicitly includes estimates of other stochastic effects of the source and propagation, such as near-source and near-receiver scattering, near-receiver frequency-dependent attenuation, multipathing and reverberations, and radiation pattern incoherence at high frequencies. The underlying assumption in using the empirical source functions is that these unknown and stochastic effects are similar on average at the Diablo Canyon site to the sites which supplied the empirical source functions.

We applied several criteria in the selection of empirical source functions. First, they must be recorded from an earthquake small enough to be considered a point source for the distance ranges at which we wish to simulate ground motions. Second, they must also be from an earthquake large enough to produce recordings with adequate signal-to-noise ratios and to minimize the amount of scaling required to simulate large earthquakes. Finally, we require an adequate sampling of the source spectrum and the radiation pattern with recordings well-distributed about the hypocenter. We identified the 23:19 aftershock of the October 15, 1979 Imperial Valley earthquake and the May 9, 1983 (02:49) aftershock of the Coalinga earthquake as fitting these criteria.

Rupture Propagation. We assumed the fault rupture to initiate at the hypocenter and propagate outward on an initially circular rupture front at a constant velocity. At the same time we incorporated a stochastic component in rupture velocity to account for local irregularities in rupture propagation. This was done by letting the rupture turn-on time of individual fault elements follow a Gaussian probability distribution centered about the mid-point between the arrival and departure times of the rupture front across each fault element. In the simulations, the probability for the rupture turn-on time to be at the arrival or departure time of the rupture front was set at the three standard deviation level.

Slip-Distribution Models. An important aspect of faulting is the heterogeneous distribution of slip

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that is inferred to occur on the fault plane. For example, models of variable slip on the Imperial Fault during the 1979 earthquake have been derived by Olson and Apsel (1982), Hartzell and Heaton (1983), and Archuleta (1984), and these models are in substantial agreement. This heterogeneity has been modeled as asperities, originally interpreted as regions of high strength on the fault plane from laboratory experiments on rock friction by Byerlee (1970) and Scholz and Engelder (1976). In a dynamical interpretation, Kanamori (1978) regards the occurrence of a large earthquake as being caused by failure of the asperities; the weak zone between asperities may behave aseismically or fail in background seismic activity.

An alternative model of fault heterogeneity is the barrier model proposed by Burridge and Halliday (1971), Das and Aki (1977) and Aki (1979). The failure mode of the barrier model is the converse of that of the asperity model: failure begins in the weaker zone and propagates into a stronger zone which may or may not fail. However, the two models provide closely related descriptions of the heterogeneity of the earthquake rupture process.

If a barrier does fail, it is behaving as an asperity; and if adjacent asperities stop the rupture caused by the failure of an asperity, they are behaving as barriers.

We modeled heterogeneity in slip on the fault plane by assigning to each fault element a weighting factor representing the static slip and normalized to preserve total seismic moment. Asperities are thus represented by areas of the fault with greater than average static slip.

VALIDATION OF THE SIMULATION PROCEDURE

The semi-empirical simulation procedure was validated in two stages before being used to simulate ground motions at the Diablo Canyon site. In the primary stage of validation we selected large earthquakes which were widely recorded by strong-motion instruments at near-source distances, and for which detailed information about source characteristics useful for constraining

the simulation procedure is available. Such earthquakes provide the best available means to validate our procedure. In the second stage of validation we used other large earthquakes which were not so widely recorded by strong-motion instruments at near-source distances, and for which available detailed information about source characteristics is limited. Such earthquakes provide an opportunity to test the reliability of our simulation procedure in estimating ground motions when a number of assumptions must be made about the source characteristics of the earthquakes being simulated.

We selected the 1979 Imperial Valley earthquake (M_w 6.5) for the primary stage of validation for the following reasons:

- The earthquake was widely recorded by near-source strong-motion instruments.
- The faulting process, in particular the distribution of slip on the fault, has been widely studied (Olson and Apsel, 1982; Hartzell and Heaton, 1983; Archuleta, 1984).
- The regional velocity structure is well-known (Fuis and others, 1982).
- A magnitude 5 aftershock provided a large set of accelerograms suitable for use as empirical source functions, and the source parameters of this aftershock are known (Liu and Helmberger, 1985).

This detailed information enabled us to simulate the ground motions in a quasi-deterministic manner, and to compare the simulated against the recorded ground motions at many sites (Wald and others, 1988a). The results show that our simulation procedure is capable of producing ground motions whose acceleration time histories, peak acceleration values, and acceleration response spectra closely match those of the recorded ground motions, as shown on Figures 4-2 and 4-3 for two stations located approximately 4 kilometers from either side of the fault.

Similarly close agreement was obtained in another validation study using the 1987 Whittier Narrows



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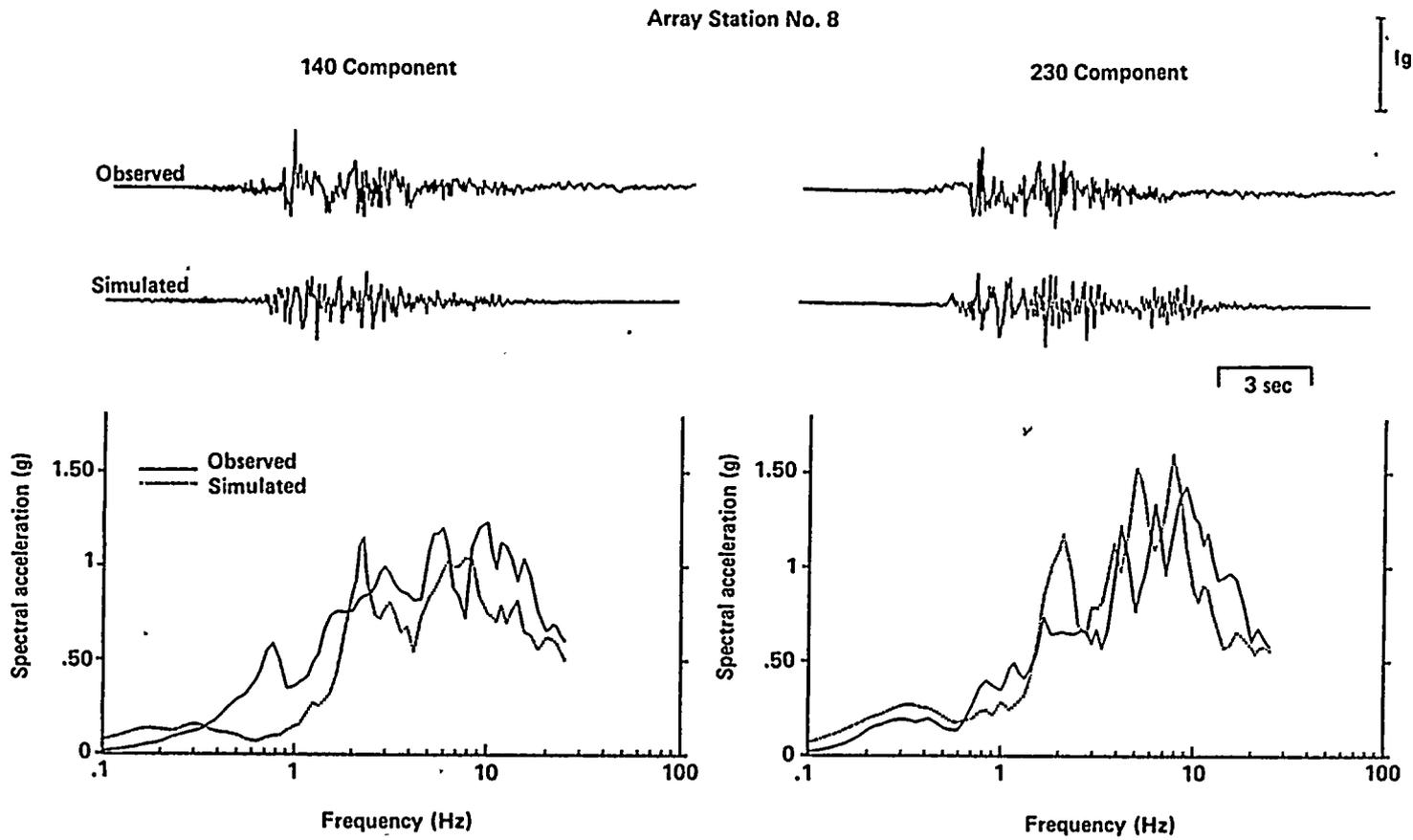
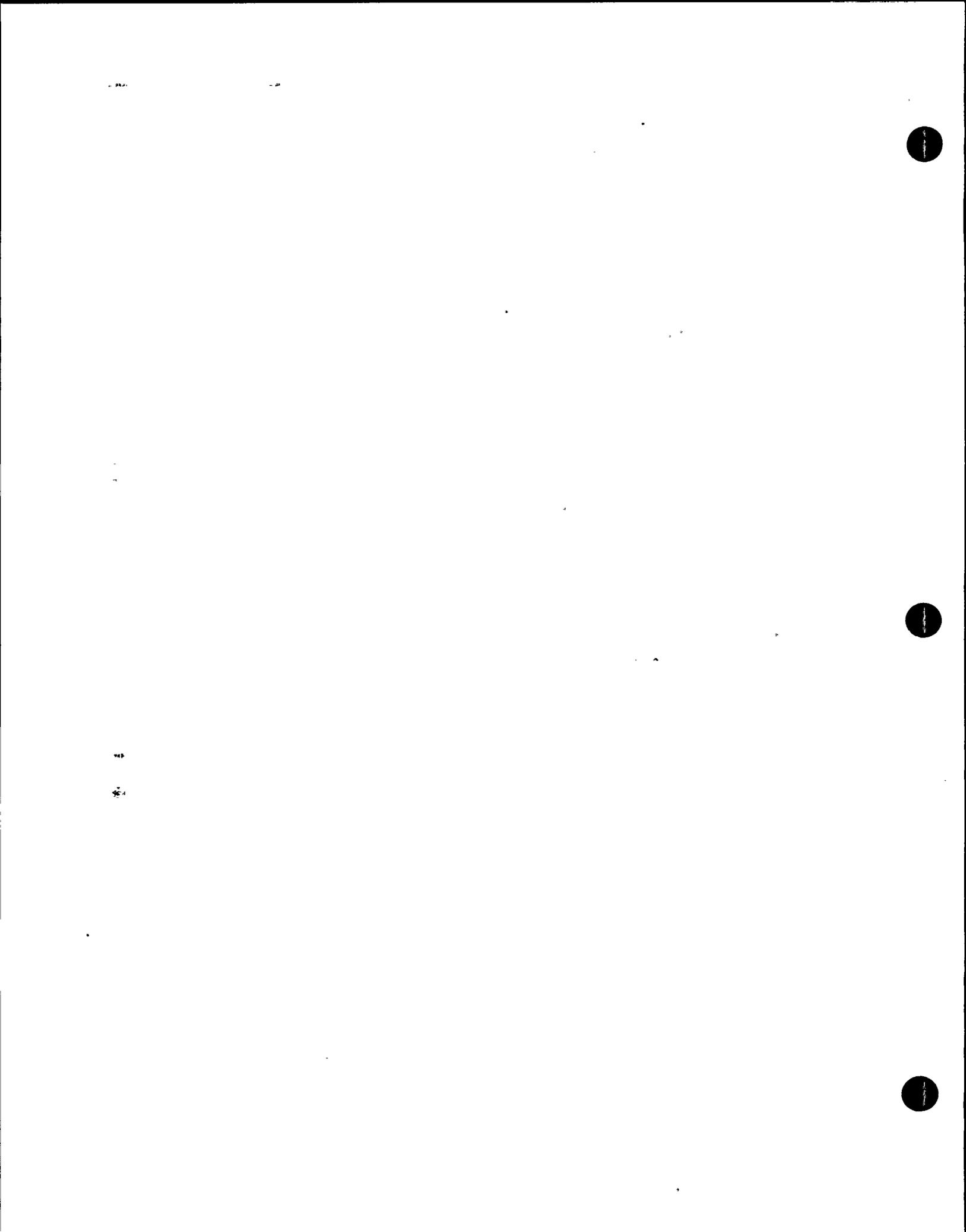


Figure 4-2

Comparison of observed and simulated accelerograms and response spectra with 5 percent damping for the 1979 Imperial Valley earthquake at El Centro array station 8.



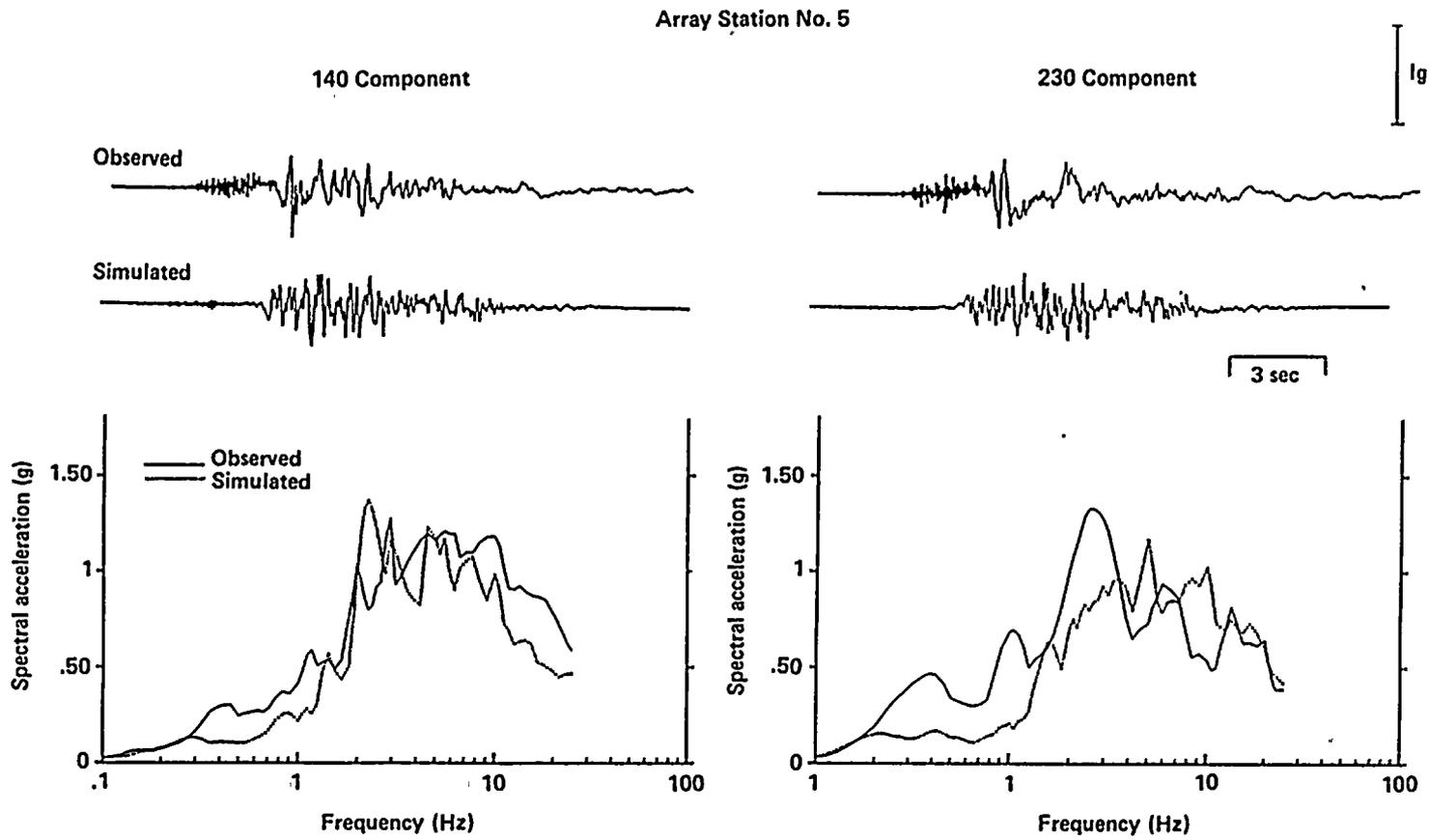


Figure 4-3

Comparison of observed and simulated accelerograms and response spectra with 5 percent damping for the 1979 Imperial Valley earthquake at El Centro array station 5.

earthquake (Wald and others, 1988b). This validation is similar to that of the Imperial Valley earthquake in that many near-source strong-motion recordings were obtained, but dissimilar in that less detailed information about the source characteristics of the Whittier Narrow earthquake was available to constrain the simulation procedure.

In the second stage of validation, our simulation procedure was tested by comparing the simulations against the recorded ground motions of the May 2, 1983 Coalinga earthquake and the December 23, 1985 Nahanni earthquake. In each case, only a few near-source strong-motion recordings were obtained, and little information about the source characteristics was available to constrain the simulation procedure. Nevertheless, generally good agreement between the simulations and the recorded ground motions was obtained for both cases. These tests indicate that our ground-motion simulation procedure is capable of realistically simulating the ground motions from large earthquakes at near-source distances when a number of assumptions must be made about the source characteristics of the earthquakes being simulated.

SENSITIVITY STUDIES

We investigated the ground-motion sensitivity to uncertainties in several aspects of the simulation procedure, including the effects of fault element size, the degree of randomness in fault kinematics, and fault asperities. The principal findings are now described.

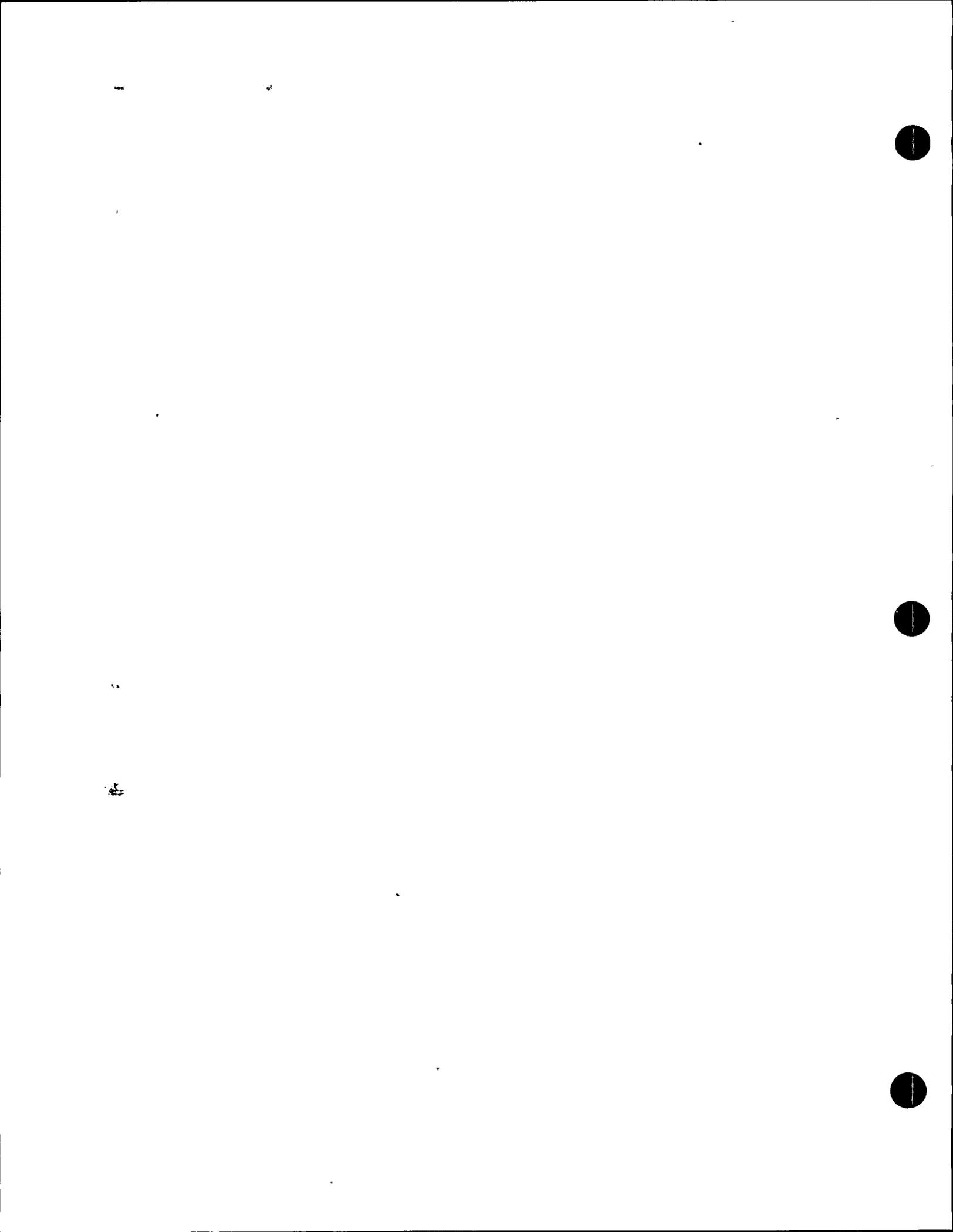
Effect of Fault Element Size. The simulation procedure requires division of the fault plane being modeled into small fault elements. However, there are uncertainties concerning the selection of the fault element size used in the simulation procedure. Ideally, we want to use the fault dimensions of the small earthquake whose recordings are used as empirical source functions to define the fault element size. However, it is difficult to accurately estimate the fault dimensions of the small earthquake. We have adopted the procedure of using fault dimensions

that are characteristic of California earthquakes having the seismic moment of the small event.

For both the Imperial Valley and Coalinga aftershocks, we used a fault element size of 4 x 3 kilometers, which corresponds to a stress drop of about 50 bars. It seems likely that the stress drop of the Imperial Valley aftershock was substantially higher than this value (Liu and Helmberger, 1985), and so we have examined the sensitivity of the ground motions to using a fault element size of 1.5 x 1.5 kilometers, which corresponds to a stress drop of about 400 bars.

We made simulations of a moment magnitude 7 earthquake on a vertical strike-slip fault at a distance of 5.8 kilometers using 4-x-3-kilometer and 1.5-x-1.5-kilometer fault element sizes. The results, as shown on Figure 4-4, indicate that the larger fault element size gives ground motions that are about 10 percent larger. It also gives response spectra that are richer at frequencies of a few hertz. This shows that the 4-x-3-kilometer fault element size used in ground-motion simulations at the Diablo Canyon site has been conservative.

Effect of Randomness in Fault Kinematics. We have used Gaussian random numbers to simulate randomness superposed on a ramp slip function and on a constant rupture velocity. We used a moderate degree of randomness in both rupture velocity and slip function in our simulations. There is no evidence of spectral peaks characteristic of the rupture time across a fault element, or of the rise time of the subevent, in these simulations. Only when we used very low randomness did we find a periodicity of 5.4 hertz in the Fourier spectrum, corresponding to the rise time of the subevent. The periodicity due to rupture time across a fault element, expected at a mean frequency of 1.7 hertz, was not evident in the Fourier spectrum due to fluctuations about this mean. The simulated time histories for this very low randomness case have a more ringing character, as shown on Figure 4-5, and appear to be depleted in Fourier spectra in the frequency range of 5 to 15 hertz when compared with the moderate randomness case. However, the differences are not large, indicating that the sensitivity of the simulated ground motions to the degree of randomness is not large.



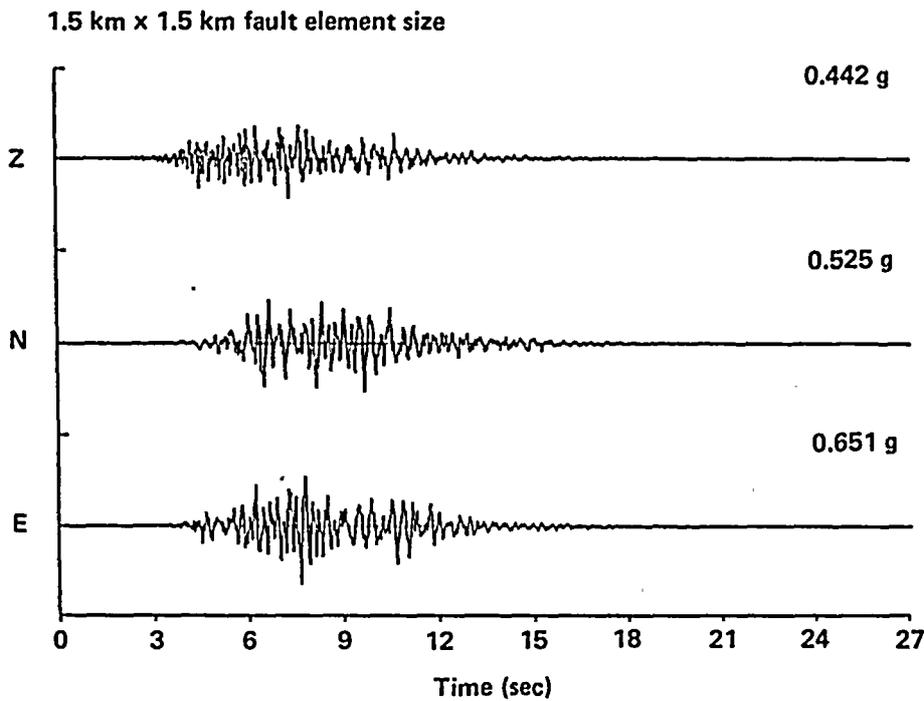
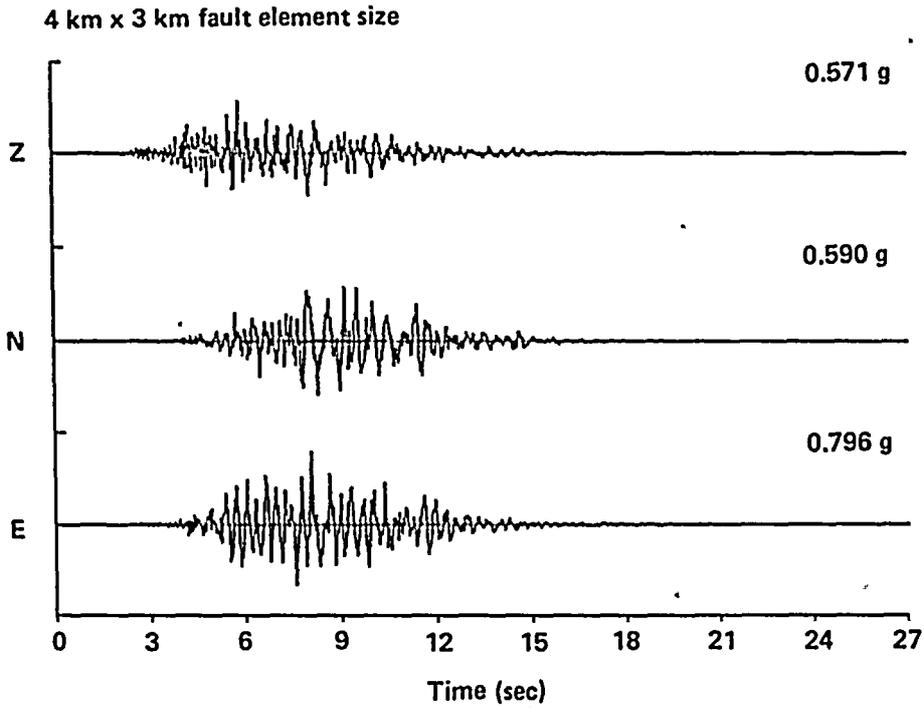


Figure 4-4

Effect of fault element size on simulated acceleration time histories: upper plot is for 4-x-3-kilometer fault element size, lower plot is for 1.5-x-1.5-kilometer fault element size. These accelerograms were simulated for a magnitude 7.0 strike-slip earthquake at 5.8 kilometers.

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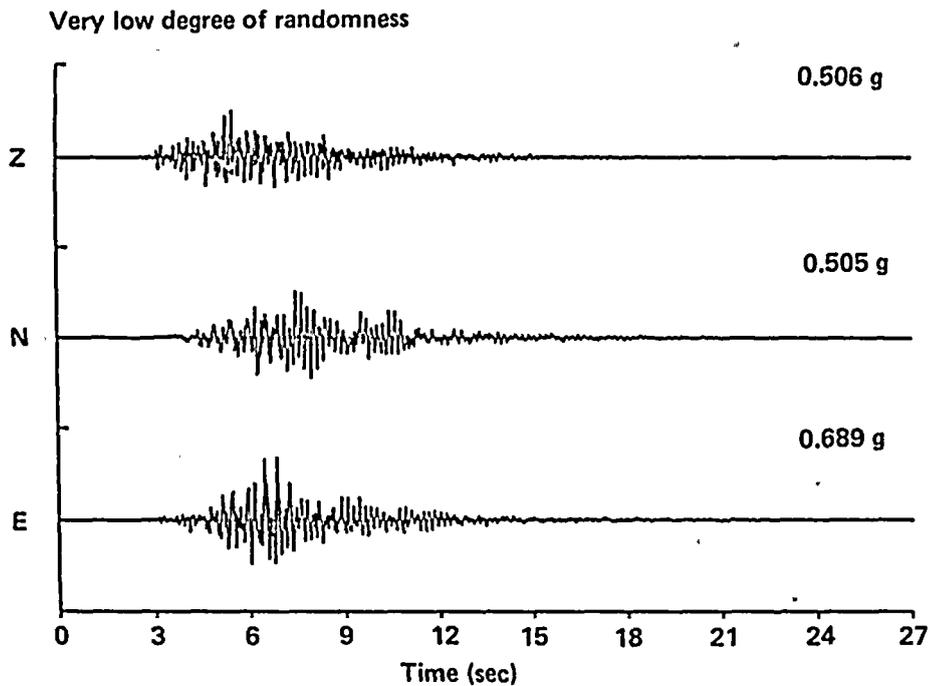
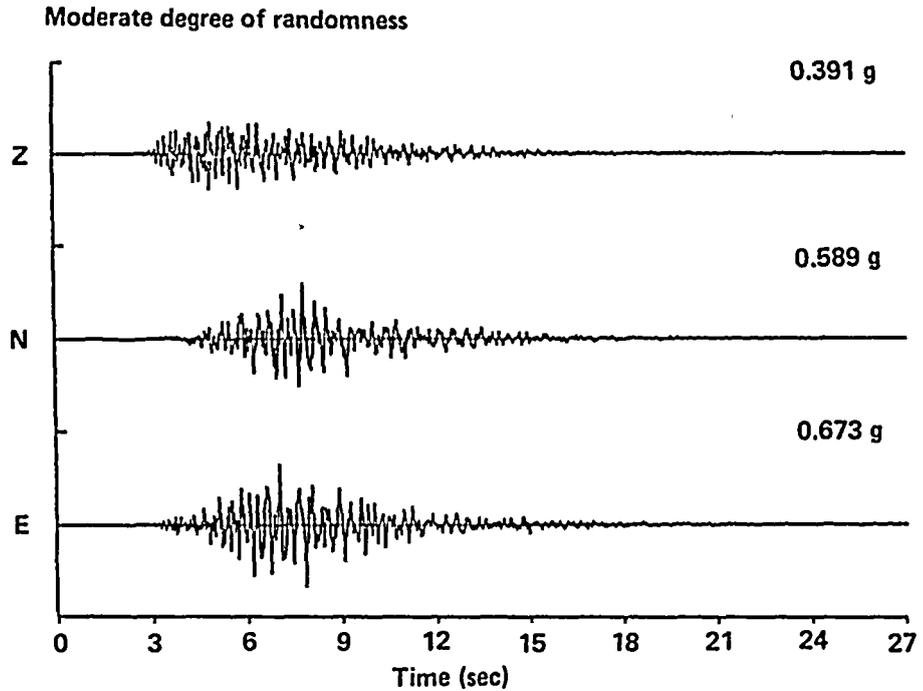


Figure 4-5

Effect of degree of randomness in rupture velocity and slip velocity on simulated acceleration time histories: upper plot is for moderate degree of randomness, lower plot is for very low degree of randomness. These accelerograms were simulated for a magnitude 7.0 strike-slip earthquake at 5.8 kilometers, using 1.5-x-1.5-kilometer fault element size.

Effect of Fault Asperities. We have simulated two sets of acceleration time histories at the El Centro array stations for the 1979 Imperial Valley earthquake using two different slip distribution models (Wald and others, 1988a). One set was based on a fault model having a uniform slip distribution, that is, having no asperities. The other set was based on a fault model with asperities that were broadly characterized using the static slip distribution determined from inversion of local and teleseismic observations (Hartzell and others, 1983). The two sets of simulations were compared with the recorded time histories at individual stations. The results show that the simulations from the fault model with asperities successfully reproduce both the amplitude and arrival time of a large acceleration pulse observed on the recorded time histories. The moveout of this large pulse across the array uniquely identifies the asperity as its origin. On the other hand, the simulations from the fault model without asperities fail to reproduce the large acceleration pulse observed on the recorded time histories. Figure 4-6 compares the peak ground accelerations of the horizontal components of motion recorded at the El Centro array stations with the simulations from the fault models with and without the asperity. It is evident that the asperity model produces peak accelerations more closely matching the observed accelerograms. Although this asperity model was determined from lower frequency near-field velocity and teleseismic records, the same asperity model can also explain the character and content of higher frequency accelerations. Accordingly, we have used this kind of fault asperity model based on static slip distribution in our ground-motion simulations at the Diablo Canyon site.

SUMMARY OF RESULTS

After three years of comprehensive planning and intensive execution of coordinated empirical investigations and numerical modeling studies to characterize the ground motions at the Diablo Canyon site, we have achieved the two objectives of the ground-motion studies of the Long Term Seismic Program. A substantially enlarged data base of strong-motion recordings close to large

earthquakes has been compiled, and a numerical modeling procedure has been extensively refined, validated, and applied to the Diablo Canyon site using site-specific information. By using these new developments in the empirical and numerical methods in an integrated, complementary and site-specific manner, we have obtained ground-motion estimates in whose accuracy we have a high level of confidence. Specifically, we have accomplished the following:

- Compilation of a large up-to-date strong-motion data base applicable to the Diablo Canyon site.
- Reevaluation of the free-field ground motions at the Diablo Canyon site.
- Development of ground-motion data for the seismic hazards analysis.
- Development of ground-motion data for the seismic fragility evaluation.
- Development of ground-motion data for the soil/structure interaction analyses.

Compilation of an Up-to-Date Strong-Motion Data Base

The empirical ground-motion investigations began with the compilation of an up-to-date strong-motion data base applicable to the Diablo Canyon site. Emphasis was placed on the selection of strong ground-motion records obtained from sites having seismic environment and site conditions similar to those at the Diablo Canyon site.

The Diablo Canyon site is classified as a rock site, based on local subsurface geologic conditions and shear wave velocity profiles (Chapter 5). The potential seismogenic zones in the Diablo Canyon site region are confined to the upper crust down to a depth of about 12 kilometers, as evidenced by seismicity data for the region (Chapter 2). Accordingly, the criteria for selecting records to be included in the strong-motion data base were:

- Records from rock or rock-like sites
- Records from shallow crustal earthquakes.





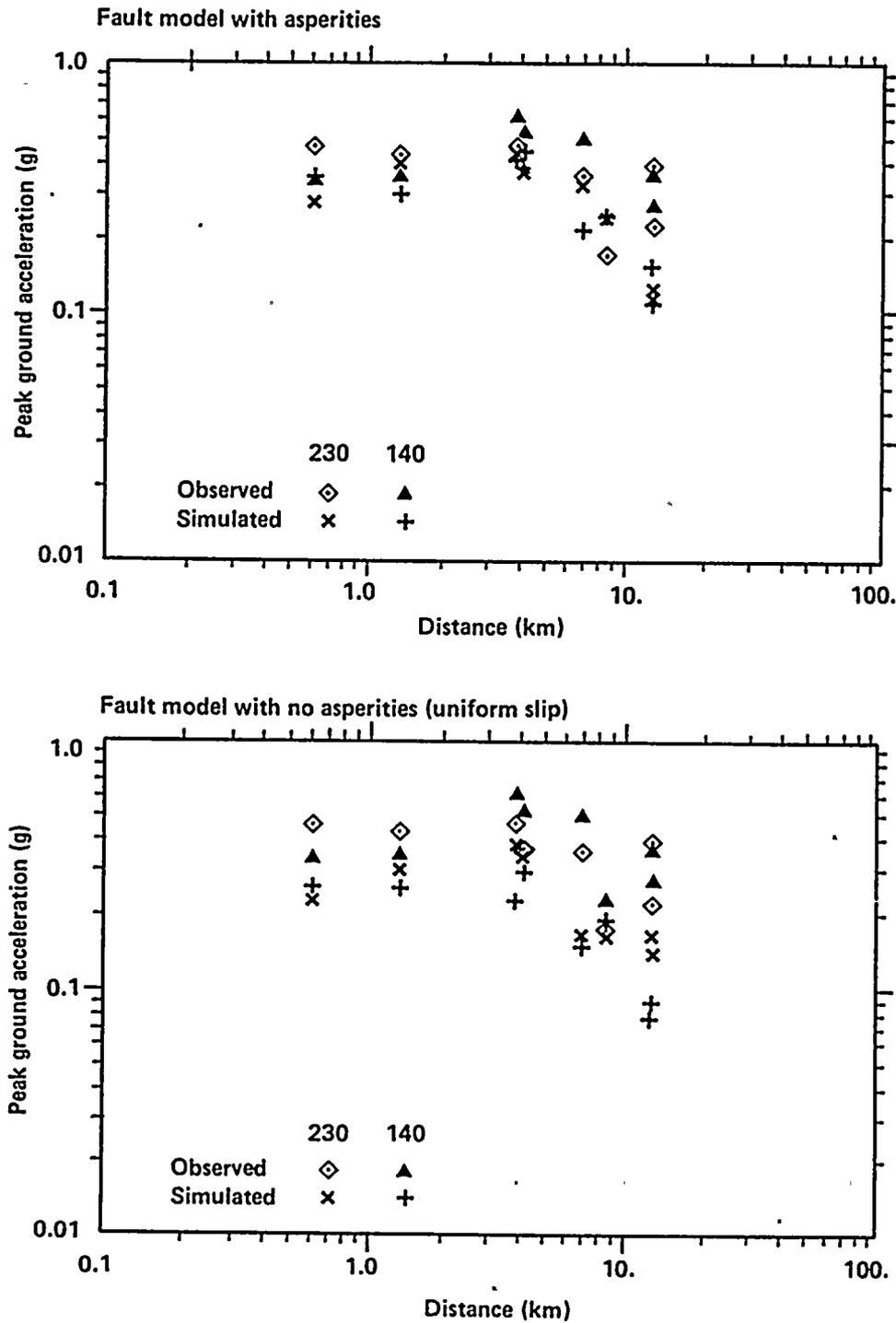


Figure 4-6

Effect of fault asperity on simulated horizontal peak ground acceleration for the 1979 Imperial Valley earthquake (cross symbols): upper plot is based on fault model with asperities, lower plot is based on fault model without asperities (uniform slip). Also shown for comparison is observed horizontal peak ground acceleration (open symbols). Distance is defined as the closest horizontal distance to the surface rupture.

Application of these selection criteria to strong-motion records obtained worldwide between 1935 and 1987 has yielded a large up-to-date ground-motion data base applicable to the Diablo Canyon site, containing:

- 217 records for peak ground acceleration
- 88 records for response spectral acceleration
- 51 shallow crustal earthquakes having magnitudes ranging from 4.6 to 7.4 and various styles of faulting.

Fifty-nine earthquakes provided strong-motion recordings that were chosen for the Long Term Seismic Program data base. (Table 4-1). From these, records that were from instruments close to the earthquake source and on rock sites were selected for the primary data base (Figure 4-7). A larger, supplementary data base was developed that included recordings from soil sites for the purpose of examining trends for magnitude scaling and data dispersion and the effects of style of faulting on ground motions.

Site-Specific Aspects of Free-Field Ground Motions at the Diablo Canyon Site

As a result of seismic source characterization studies (Chapter 3), which were based on analysis and interpretation of a large volume of geologic, geophysical, and seismological information (Chapter 2), the Hosgri fault zone was confirmed as the dominant seismic source in the site region. The maximum magnitude on the Hosgri fault zone was conservatively assessed to be 7.2 M_w . Opposite the Diablo Canyon site, the shortest distance between the site and the fault zone was about 4.5 kilometers (Chapter 3). We used this magnitude and distance for the purpose of the ground-motion assessment. To incorporate the effects of style of faulting, we assessed the relative probabilities of occurrence of three potential styles of faulting on the Hosgri fault zone (Chapter 3)

and used them as weights in the reevaluation of the ground motions:

<u>Style of Faulting</u>	<u>Probability of Occurrence</u>
Strike-slip	0.65
Oblique	0.30
Thrust	0.05

SITE RESPONSE

The response of the site was compared with that at other sites in the region using recordings of small earthquakes from the Central Coast Seismic Network. The locations of earthquakes and recording stations used in this and other site analyses are shown on Figure 4-8, and the earthquakes are listed in Table 4-2. The spectra at the Diablo Canyon site (DC) and at a nearby recording station situated on similar sedimentary rocks (DP) were very similar, as illustrated on Figure 4-9 for event 9 in Table 4-2, and have a spectral decay rate that is more rapid than that of three other stations that are situated on or close to Franciscan rocks. In their study of site amplification of coda waves in the Central California Coast Ranges, Phillips and Aki (1986) found that Franciscan rock sites have low amplification, especially at high frequencies, relative to the average site. The observation that the Diablo Canyon site shows a spectral decay rate at least as great as that of neighboring Franciscan stations suggests that the site is also characterized by relatively low spectral amplification.

In the study of Phillips and Aki (1986), a station at See Canyon (PSE), about 10 kilometers inland from the Diablo Canyon site, was found to have anomalously high amplification at frequencies around 6 hertz. This amplification was extrapolated by Phillips and Aki to the entire San Luis/Pismo synclinorium on the basis of similarity in geologic structure. However, it appears that the anomalous site response at this station was local, probably due to the location of the station on a landslide. For two small offshore earthquakes (events 2 and 3 in Table 4-2), the See Canyon station has a spectrum having a peak in the range of 4 to 8 hertz, as shown on Figure 4-10, in agreement with the observation of Phillips and

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Table 4-1

CHARACTERISTICS OF THE EARTHQUAKES FROM WHICH STRONG-MOTION RECORDINGS HAVE BEEN SELECTED FOR THE LONG TERM SEISMIC PROGRAM DATA BASE

Earthquake	Date	Style of Faulting	Magnitudes			
			M_L	M_S	M_{WV}	M^*
Helena, Mont.; Mainshock	10/31/35	Normal	5.6			5.6
Helena, Mont.; Aftershock	11/28/35	Normal	5.0			5.0
Kern County, Calif.	07/21/52	Reverse	7.2	7.7	7.4	7.4
San Francisco, Calif.	03/22/57	Strike-slip	5.3			5.3
Parkfield, Calif.	06/27/66	Strike-slip	5.6	6.4	6.1	6.1
Koyna, India	12/10/67	Strike-slip		6.3	6.3	6.3
Borrego Mountain, Calif.	04/09/68	Strike-slip	6.4	6.7	6.6	6.6
Santa Rosa, Calif.; Shock A	10/02/69	Strike-slip	5.6			5.6
Santa Rosa, Calif.; Shock B	10/02/69	Strike-slip	5.7			5.7
Lytle Creek, Calif.	09/12/70	Reverse	5.4		5.3	5.3
San Fernando, Calif.	02/09/71	Thrust	6.4	6.6	6.6	6.6
Managua, Nicaragua	12/23/72	Strike-slip	6.1			6.1
Point Mugu, Calif.	02/21/73	Reverse	6.0	5.2	5.6	5.6
Hollister, Calif.	11/28/74	Strike-slip	5.2			5.2
Oroville, Calif.; Mainshock	08/01/75	Normal	5.7		5.9	5.9
Oroville, Calif.; Aftershock R	08/02/75	Normal	5.1			5.1
Oroville, Calif.; Aftershock S	08/02/75	Normal	5.2			5.2
Oroville, Calif.; Aftershock A	08/03/75	Normal	4.6			4.6
Oroville, Calif.; Aftershock F	08/06/75	Normal	4.7			4.7
Oroville, Calif.; Aftershock K	08/08/75	Normal	4.9			4.9
Gazli, USSR	05/17/76	Reverse	6.4	7.0	6.8	6.8
Calipatria, Calif.	11/04/76	Strike-slip	4.9			4.9
Santa Barbara, Calif.	08/13/78	Reverse	5.1	5.6	6.0	6.0
Tabas, Iran	09/16/78	Thrust	6.5	7.4	7.4	7.4
Coyote Lake, Calif.	08/06/79	Strike-slip	5.9		5.7	5.7
Imperial Valley, Calif.; Mainshock	10/15/79	Strike-slip	6.6	6.9	6.5	6.5
Imperial Valley, Calif.; Aftershock 03	10/15/79	Strike-slip	5.2			5.2
Imperial Valley, Calif.; Aftershock 25	10/15/79	Strike-slip	5.1			5.1
Imperial Valley, Calif.; Aftershock 29	10/15/79	Strike-slip	5.1			5.1
Imperial Valley, Calif.; Aftershock 31	10/15/79	Strike-slip	5.5			5.5
Livermore, Calif.; Shock A	01/24/80	Strike-slip	5.5	5.9	5.8	5.8
Livermore, Calif.; Shock B	01/26/80	Strike-slip	5.6	5.0	5.4	5.4
Horse Canyon, Calif.	02/25/80	Strike-slip	5.3	4.7		5.3
Mammoth Lakes, Calif.; Shock A	05/25/80	Strike-slip	6.1		6.2	6.2
Mammoth Lakes, Calif.; Aftershock A01	05/25/80	Strike-slip	5.0			5.0
Mammoth Lakes, Calif.; Shock B	05/25/80	Strike-slip	6.0		5.7	5.7
Mammoth Lakes, Calif.; Shock C	05/25/80	Strike-slip	6.1		6.0	6.0
Mammoth Lakes, Calif.; Aftershock C01	05/25/80	Strike-slip	5.7			5.7
Mammoth Lakes, Calif.; Shock D	05/27/80	Strike-slip	6.2		6.0	6.0
Mexicali Valley, Mexico	06/09/80	Strike-slip	6.1	6.4		6.4
Westmorland, Calif.	04/26/81	Strike-slip	5.6	6.0		5.6
Coalinga, Calif.; Mainshock	05/02/83	Reverse	6.7	6.5	6.4	6.5
Coalinga, Calif.; Aftershock 03	05/09/83	Reverse	5.3		5.1	5.1
Coalinga, Calif.; Aftershock 08	06/10/83	Reverse	5.2		5.3	5.3
Coalinga, Calif.; Aftershock 10	07/09/83	Thrust	5.4		5.2	5.2
Coalinga, Calif.; Aftershock 12	07/21/83	Thrust	6.0		5.9	5.9
Coalinga, Calif.; Aftershock 13	07/21/83	Thrust	5.0		4.9	4.9
Coalinga, Calif.; Aftershock 14	07/25/83	Thrust	5.3		5.2	5.2
Coalinga, Calif.; Aftershock 16	09/09/83	Reverse	5.3			5.3
Morgan Hill, Calif.	04/24/84	Strike-slip	6.2	6.1	6.2	6.2
Bishop, Calif.	11/23/84	Strike-slip	5.9		5.8	5.8
Nahanni, Canada	12/23/85	Thrust		6.9	6.8	6.8



Table 4-1 (Continued)

**CHARACTERISTICS OF THE EARTHQUAKES FROM WHICH STRONG-MOTION
RECORDINGS HAVE BEEN SELECTED FOR THE LONG TERM SEISMIC PROGRAM
DATA BASE**

Earthquake	Date	Style of Faulting	Magnitudes			
			M_L	M_s	M_w	M^*
Hollister, Calif.	01/26/86	Strike-slip	5.5			5.5
North Palm Springs, Calif.	07/08/86	Strike-slip	5.9	6.0	5.9	5.9
Chalfant Valley, Calif.	07/21/86	Strike-slip	6.4	6.2	6.0	6.0
Whittier Narrows, Calif.; Mainshock	10/01/87	Thrust	5.9		6.0	6.0
Whittier Narrows, Calif.; Aftershock	10/04/87	Strike-slip	5.3			5.3
Elmore Ranch, Calif.	11/23/87	Strike-slip	5.8	6.2		6.2
Superstition Hills, Calif.	11/24/87	Strike-slip	6.0	6.6		6.6

NOTES:

Magnitudes

 M_L = Local magnitude M_s = Surface-wave magnitude M_w = Moment magnitude M^* = Magnitude used for Long Term Seismic Program empirical ground-motion studies



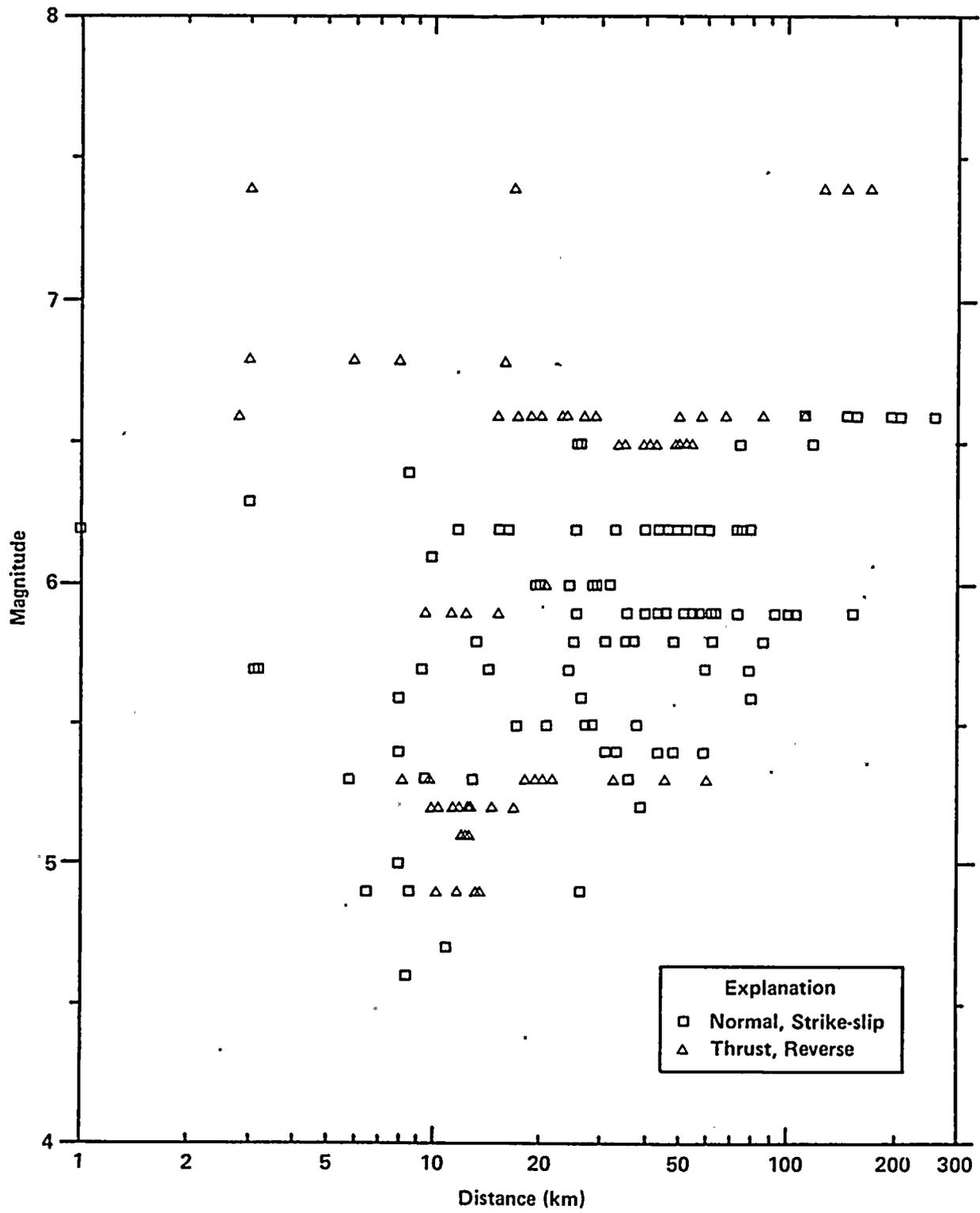
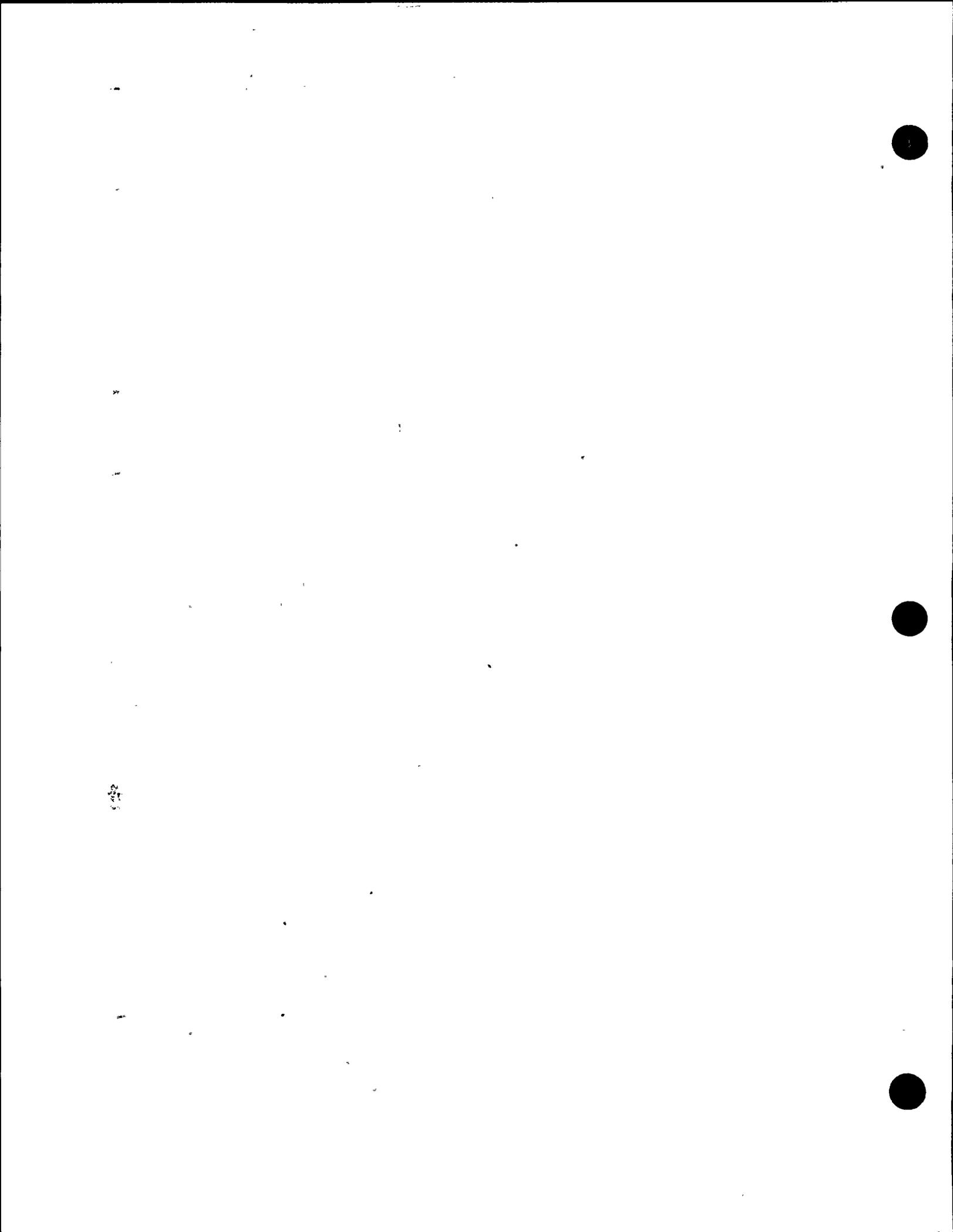


Figure 4-7
Magnitude versus distance relationships for all records from rock sites in the Long Term Seismic Program data base.



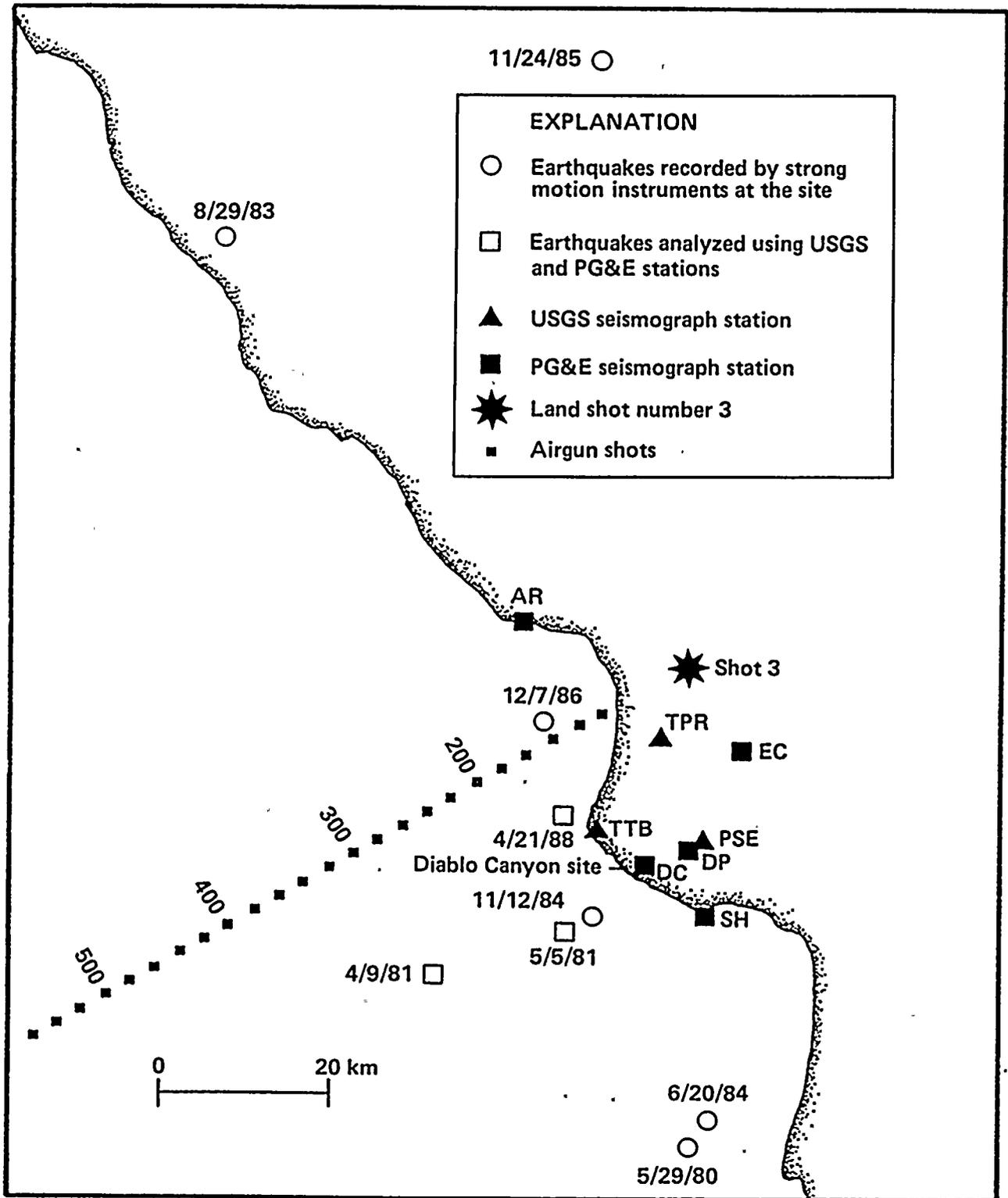


Figure 4-8

Locations of seismic sources and recording stations that provided seismograms for site response analyses.



Table 4-2
HYPOCENTERS OF EARTHQUAKES NEAR THE SITE

<u>No.</u>	<u>Year</u>	<u>Mo.</u>	<u>Day</u>	<u>Hr.</u>	<u>Mln.</u>	<u>Sec.</u>	<u>Lat.</u> <u>(°)</u>	<u>Long</u> <u>(°W)</u>	<u>Depth</u> <u>(km)</u>	<u>Range</u> <u>(km)</u>	<u>Sm.</u>
1	1980	05	29	03	38	47.24	34.935	120.779	9.2	31.05	*
2	1981	04	09	00	18	55.27	35.108	121.083	4.9	23.87	
3	1981	05	05	19	20	19.76	35.152	120.925	1.1	09.39	
4	1983	08	29	10	10	30.80	35.841	121.341	9.2	83.04	*
5	1984	06	20	19	28	06.23	34.962	120.756	9.4	29.39	*
6	1984	11	12	11	09	58.20	35.168	120.893	4.9	06.00	*
7	1985	11	24	19	21	39.30	36.018	120.889	9.1	89.85	*
8	1986	12	07	12	33	08.85	35.362	120.952	8.7	19.26	*
9	1988	04	21	11	20	30.60	35.268	120.938	5.7	09.60	

*Indicates that the event was recorded by the supplemental (free-field) strong-motion instrument network.



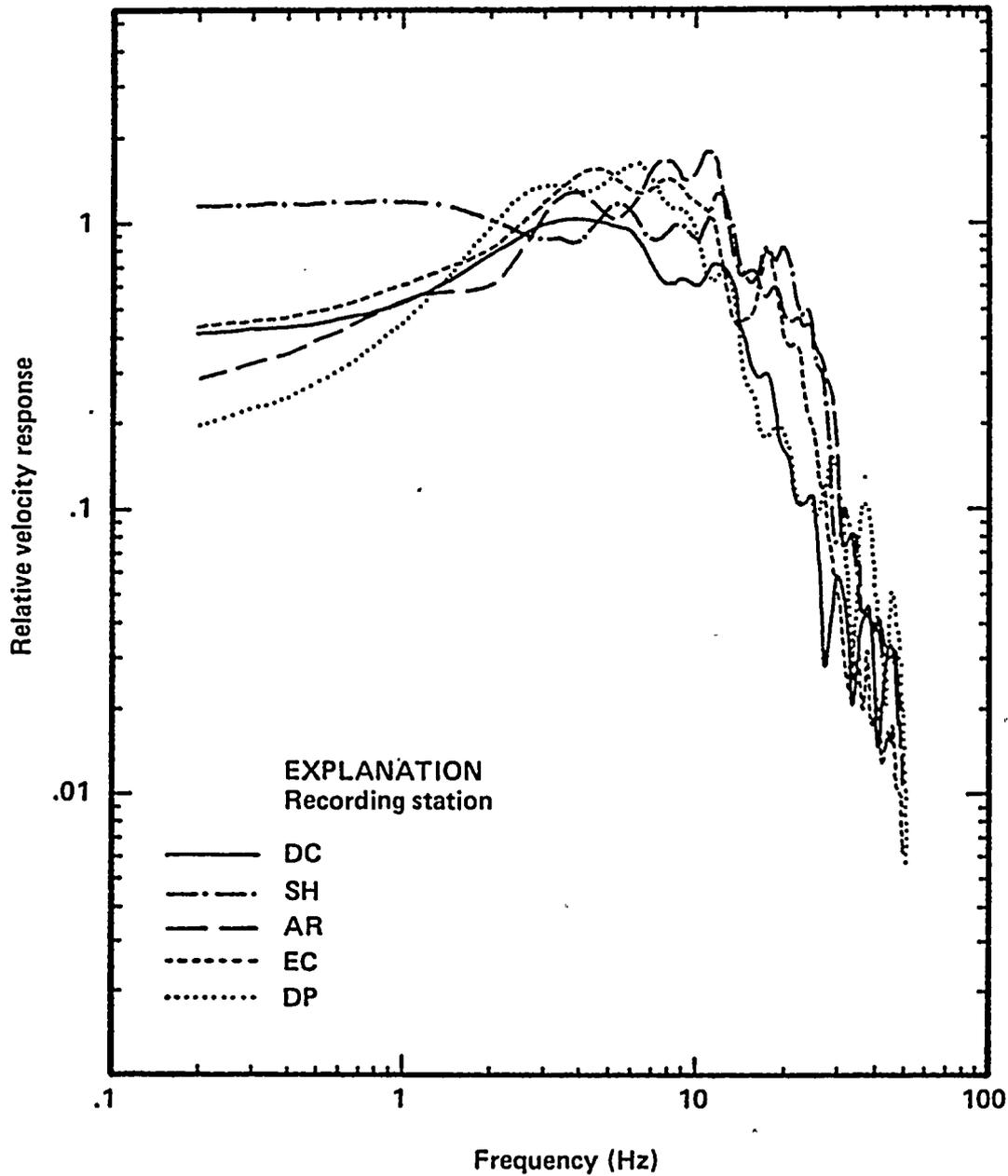
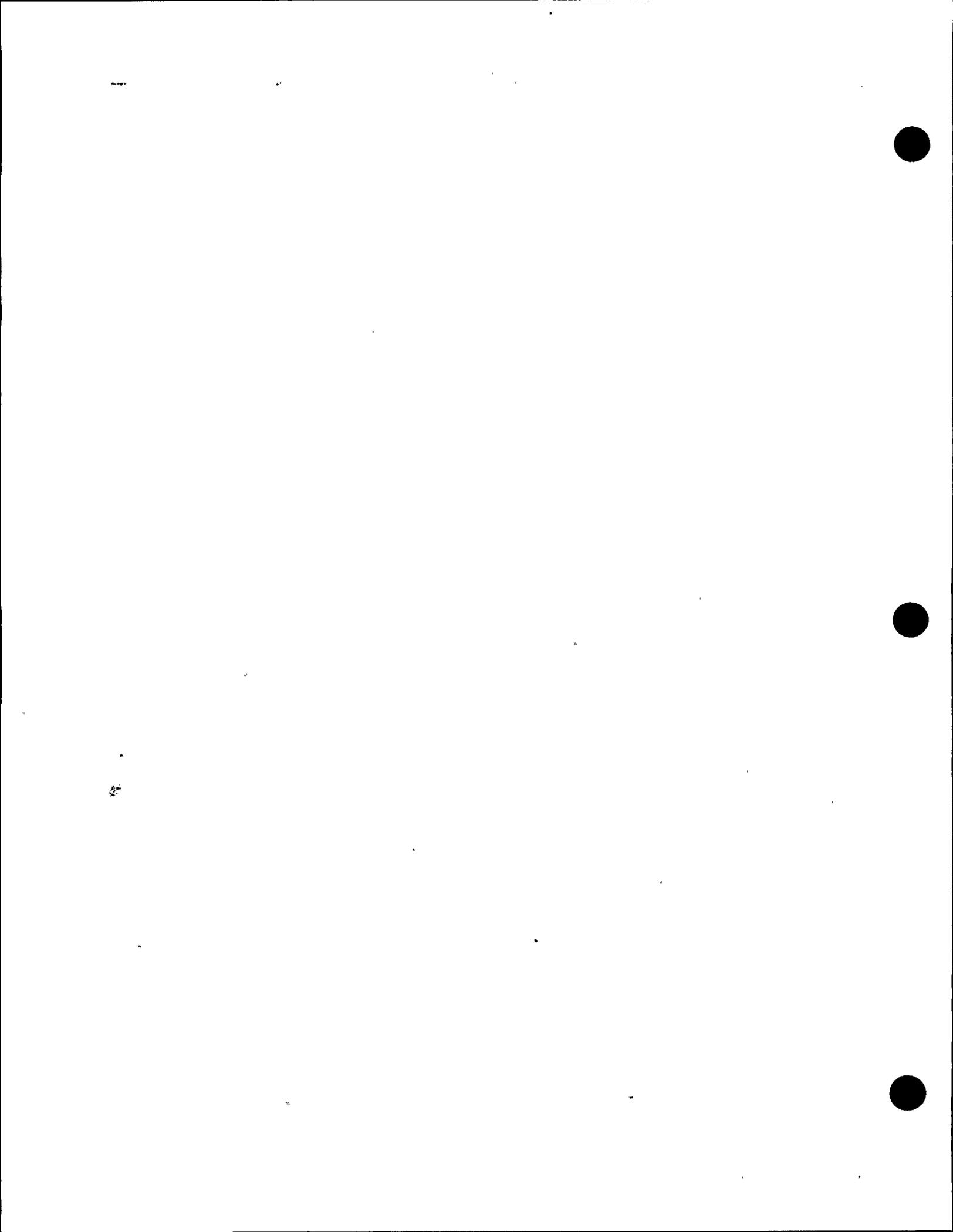


Figure 4-9

Comparison of smoothed Fourier spectral shape of vertical component shear waves at Station DC from a local earthquake with that of other nearby stations.





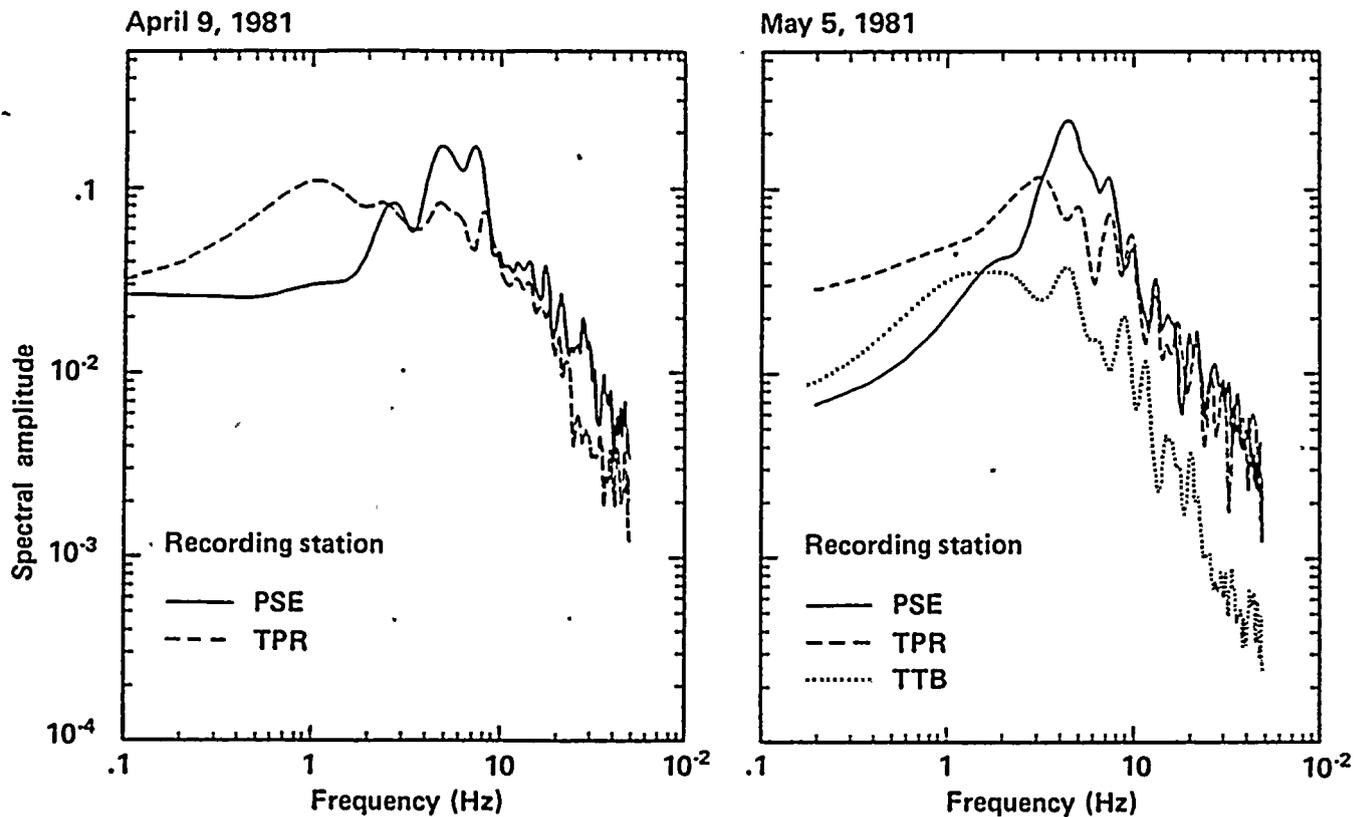


Figure 4-10

Comparison of smoothed Fourier spectral shape of vertical component shear waves at Station PSE from two local earthquakes with those at other nearby stations.

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Aki (1986), while other stations at Point Bouchon (TTB) and near Morro Bay (TPR) have spectra that do not have this peak. It is concluded that the response of this station is not characteristic of the response of the San Luis/Pismo synclinorium, and that the response at the Diablo Canyon site is characterized by a spectral decay rate that is at least as rapid as that of Franciscan sites of the region. Unusual site amplification of ground motions is not evident at the Diablo Canyon site.

The spectral decay rate of site strong ground-motion recording (events 1, 4, and 5 in Table 4-2) is compared with that of the empirical source functions derived from the ground-motion recordings of the 1979 Imperial Valley and the 1983 Coalinga aftershocks on Figure 4-11, and shown to be very similar. This similarity in spectral decay rate provides justification for using the recordings of the two aftershocks as empirical source functions for simulating the ground motions at the Diablo Canyon site.

DEPTH DISTRIBUTION OF SLIP

In our simulations of strong ground motion at the Diablo Canyon site, we have used both site-specific information and information from studies of past California earthquakes to estimate the distribution of slip with depth on the fault plane. The variation of coseismic slip with depth, averaged along the strike of the fault, for four California earthquakes is shown in the upper panel of Figure 4-12. In each case, the slip distribution has been inferred using the same procedure of jointly inverting strong motion and teleseismic velocity seismograms. On average, the slip is small at the surface, increases in an approximately linear manner from a depth of a few kilometers to a maximum value that lies within the bottom half of the fault plane, and then decreases in a linear manner to zero at the base of the seismogenic zone. The average seismic moment release as a function of depth, which is related to the slip distribution with depth via the shear modulus, is shown in the lower panel of Figure 4-12. Because of the low shear modulus at shallow depth, and the generally small values of shallow slip, the seismic moment release from

shallow depths is very small. This is consistent with the observation that close-in strong-motion recordings of earthquakes in California do not contain significant surface wave contributions.

It has been pointed out by Marone and Scholz (1988) that there is a cutoff in seismicity above a depth that varies between 3 and 5 kilometers on well-developed faults in California. They propose that this is caused by a transition from inherently stable velocity strengthening within shallow unconsolidated gouge to velocity weakening within the consolidated material below. The presence of unconsolidated gouge at shallow depths may be related to the nature of the shallow materials. In the case of the 1979 Imperial Valley earthquake, the upper cutoff of seismicity at a depth of about 4 kilometers shows a close correlation with the base of the sediments (Doser and Kanamori, 1986). In the case of the 1979 Coyote Lake and the 1984 Morgan Hill earthquakes on the Calaveras fault, the upper cutoff of seismicity at a depth of about 3 kilometers is correlated with the interface between the sedimentary rocks of the Great Valley sequence and the underlying Franciscan rocks (Blumling and others, 1985). The latter two cases are the most closely analogous to that of the site, where sedimentary rocks of the Obispo Formation overlie Franciscan rocks at a depth of about 3 kilometers on the west side of Hosgri fault in the vicinity of San Luis Bay as shown on Figure 4-13. Although Franciscan rocks are shallower on the east side of the Hosgri fault, the weaker of the two sides of the fault is expected to control the nature of the fault gouge. This suggests that it is appropriate to use a slip model that has little or no slip at depths above 3 kilometers. The maximum depth of seismic faulting, as evidenced by focal depths of earthquakes, is about 12 kilometers in the site region, as described in Chapter 2. Based on the slip distributions of the four earthquakes shown on Figure 4-12, the depth of maximum slip was taken to be at or below the center of the depth interval of seismic faulting.

We have performed sensitivity studies to evaluate the contribution of shallow slip to ground motions at the site. Using depth distributions of slip





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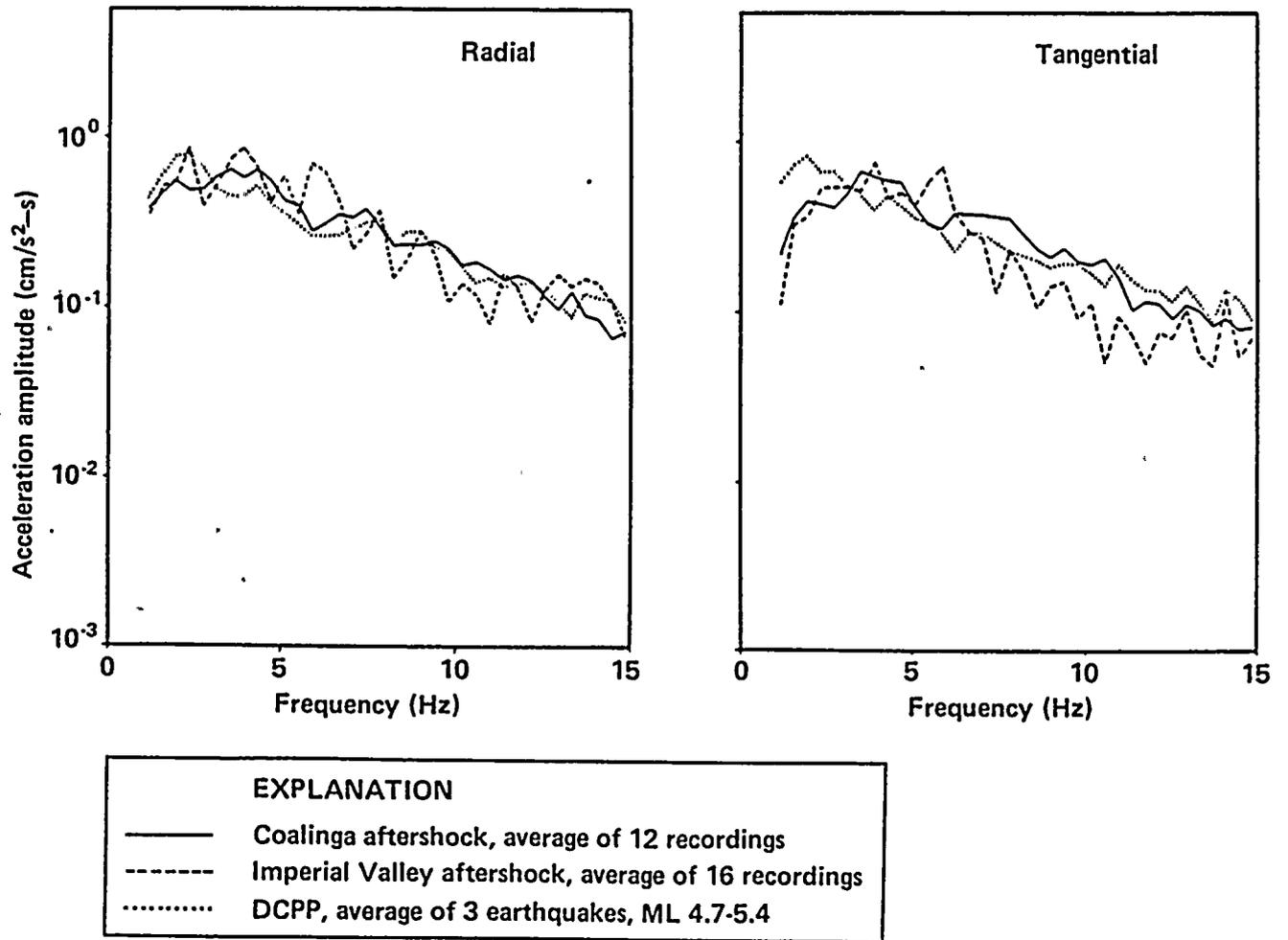
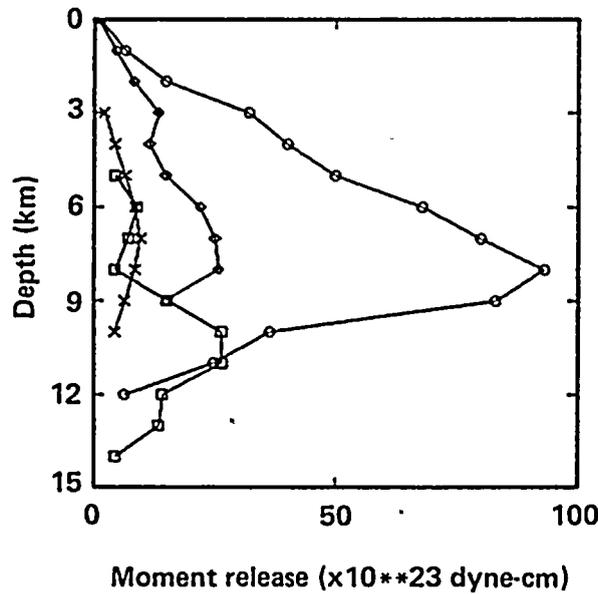
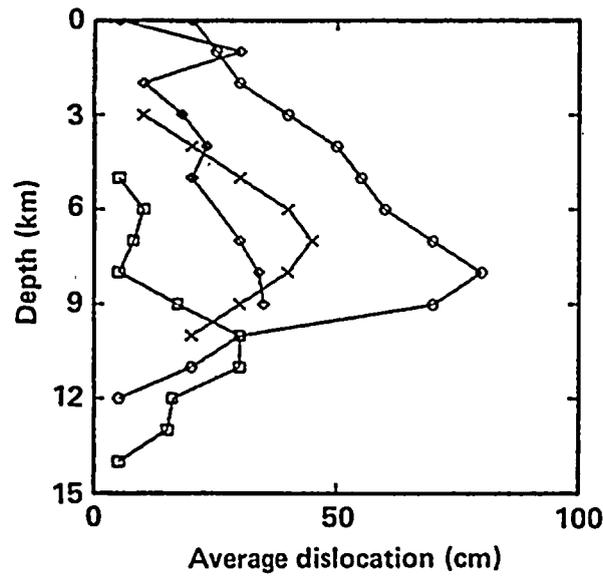


Figure 4-11

Comparison of normalized, smoothed, averaged Fourier spectral shapes of radial (left) and tangential (right) site accelerograms with those of suites of accelerograms from the Imperial Valley and Coalinga aftershocks used as empirical source functions.

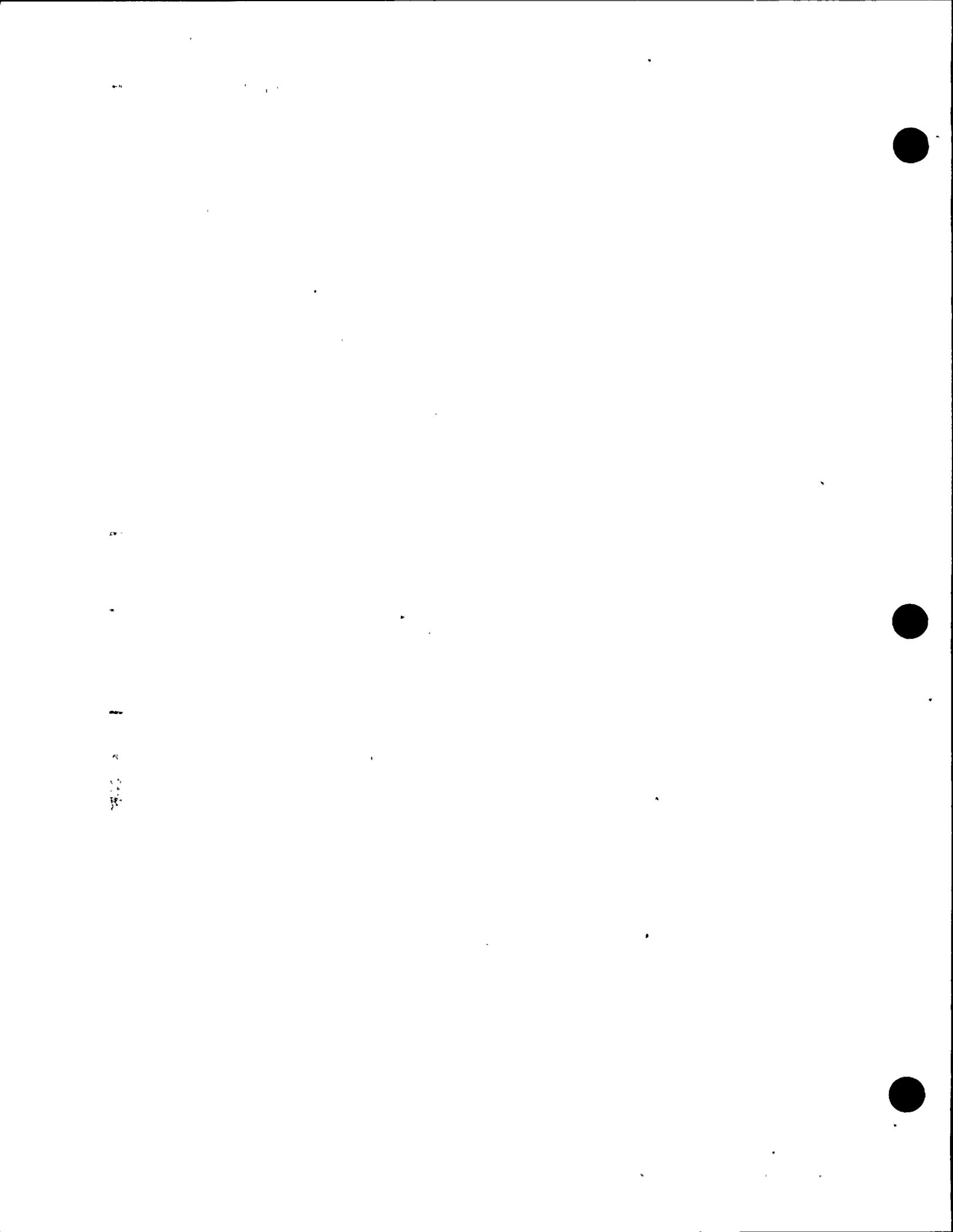




EXPLANATION	
—□—	Palm Springs earthquake, 1986 (Mendoza and Helmberger, 1988)
—×—	Coyote Lake earthquake, 1979 (Liu and Helmberger, 1983)
—○—	Imperial Valley earthquake, 1979 (Hartzell and Heaton, 1983)
—◆—	Morgan Hill earthquake, 1984 (Hartzell and Heaton, 1986)

Figure 4-12

Seismic slip (above) and seismic moment release (below) as a function of depth, averaged along strike, for four California earthquakes.



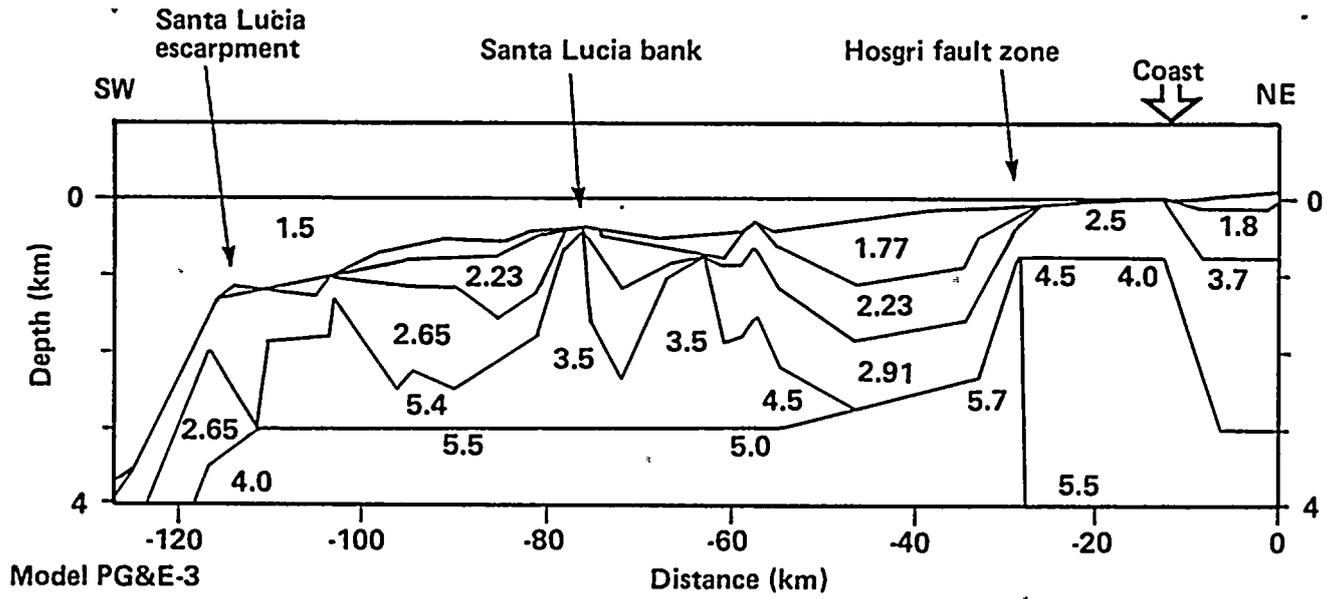


Figure 4-13
 Shallow crustal structure in the San Luis Bay region. Numerals represent compressional wave velocity in kilometers per second.

described on Figure 4-12, we find that the shallow part of the fault contributes very little to the simulated motions. Even if the shallow part of the fault has the same amount of slip as the deeper part, it still contributes little to the ground motions, a result that is due in part to the lower shear modulus of the shallow region. We conclude that ground motions at the site are not sensitive to realistic distributions of slip on the shallow part of the fault.

ASPERITY DIMENSIONS AND SEPARATION

The size of the asperities in the slip-distribution models of the four California earthquakes shown on Figure 4-12 lies in the range of one to ten kilometers. The separation of asperities is in the range of 10 to 20 kilometers. In the site region, the smallest intervals of fault segmentation that have been estimated are approximately 20 kilometers (Chapters 2 and 3). For large earthquakes, we expect that the size and separation of asperities may be larger than for small earthquakes. In the models used in simulations at the site, we have used asperities having dimensions of about 10 kilometers and separated by 20 to 30 kilometers.

CALCULATION OF SIMPLIFIED GREEN'S FUNCTIONS

We calculated simplified Green's functions using the generalized ray method of Helmberger and Harkrider (1978). For this purpose, a crustal structure model for the site region was derived using regional seismograms, including site strong-motion records. The model is a modification of the Eaton (1984) model, and is summarized in Table 4-3. The shear velocity profile was constrained using SP travel times of local earthquakes recorded at the site. The depth at the base of Franciscan (11.5 kilometers) was constrained using post-critically reflected S waves from this interface. The adequacy of the simplified Green's functions calculated by the generalized ray method using this model was confirmed by comparison with site strong-motion recordings and with synthetic seismograms calculated using the frequency-wave number integration method.

Development of Site-Specific Response Spectra

To satisfy Element 3 of the license condition, which calls for reevaluation of the free-field ground motions at the Diablo Canyon site based on the results of an updated seismic source characterization of the region, we developed site-specific horizontal and vertical response spectra at the median and 84th percentile levels. The development of site-specific response spectra was based on direct estimation of the response spectral acceleration at individual frequencies appropriate for the site-specific criteria for earthquake magnitude, source-to-site distance, style of faulting, and local site conditions.

In accord with the characteristics of the maximum earthquake, site-specific response spectra for a site close to a large earthquake were required. Three different approaches were used to obtain the site-specific acceleration response spectra at the Diablo Canyon site. Comparison of the results obtained by these three approaches provides a means of assessing the uncertainty in the response spectrum. The three approaches used were:

- Statistical analysis of near-source strong-motion recordings.
- Peak ground acceleration and response spectral acceleration attenuation relationships from regression analyses.
- Numerical modeling studies.

SITE-SPECIFIC RESPONSE SPECTRA BASED ON STATISTICAL ANALYSIS OF NEAR-SOURCE STRONG-MOTION RECORDINGS

This approach was based on statistical analysis of a suite of strong motion recordings at near-source distance (within 20 kilometers) from large earthquakes (greater than magnitude 6.3) selected from the ground-motion data base for rock sites. As shown on Figure 4-14, 13 recordings from 6 earthquakes in our data base meet these distance and magnitude criteria.

Because the number of available recordings was not very large, and most of the recordings were associated with thrust faulting, we added five





Table 4-3
 REGIONAL CRUSTAL VELOCITY STRUCTURE MODEL
 USED IN GROUND-MOTION SIMULATIONS

<u>P Velocity (km/s)</u>	<u>S Velocity (km/s)</u>	<u>Density (g/cm³)</u>	<u>Thickness (km)</u>	<u>Q_a[*]</u>	<u>Q_b[*]</u>
3.00	1.80	2.40	0.30	50	25
4.80	2.70	2.50	0.60	100	50
5.20	2.90	2.60	1.40	200	100
5.60	3.23	2.70	9.80	1000	500
6.30	3.64	2.80	14.00	2000	1000
8.00	4.62	3.30	∞	3000	1500

*Estimate of Q structure necessary for the computation of frequency wavenumber integration synthetic seismograms.





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recordings associated with strike-slip faulting to obtain a more balanced representation in style of faulting. These recordings were obtained at soil sites 4 to 8.5 kilometers from the causative fault of the 1979 Imperial Valley earthquake. Table 4-4 lists the 18 selected near-source strong-motion recordings and the related information on earthquake magnitude, style of faulting, and source-to-site distance.

To provide site-specific ground motions that are compatible with the seismic environment at the Plant site, each of these near-source records was evaluated for the following conditions:

- Compatibility of tectonic setting.
- Unusual topographic or subsurface conditions.
- Unusual source-site geometry.

Based on such evaluations, each record was assigned a weighting factor that reflects the overall compatibility in seismic environment between the recording station and the Plant site:

Compatibility of Tectonic Setting. There is evidence to suggest that there are differences in strong ground-motion characteristics between tectonically active and stable regions, and that these differences may be most pronounced at high frequencies. The differences may be due to variations in earthquake source, propagation path, or site response, or a combination of these factors. At present, there is no general consensus on which of these factors are most important. We took a simple approach to treating this attribute by dividing the records into one of the two categories: records from tectonically active areas that are close to active plate margins; and records from tectonically stable areas that are remote from such margins. The Diablo Canyon site is in a tectonically active region by this criterion.

Under this classification method, the near-source records considered are divided as follows:

Records from tectonically active areas: San Fernando, Mexicali Valley, Imperial Valley, Tabas; the tectonically compatible conditions were given a weighting factor of unity.

Records from tectonically stable areas: Koyna, Nahanni, Gazli; these tectonically incompatible conditions were taken into account by down weighting the records in the overall evaluation.

Unusual Topographic or Subsurface Conditions. There is strong empirical evidence for significant topographic effects on strong ground-motion amplitudes, and this evidence is supported by numerical studies (Geli and others, 1988; Aki, 1988). The effects of lateral heterogeneities in subsurface seismic velocities are also significant but are generally less well documented.

The Diablo Canyon site is in a location where topographic effect was shown to be insignificant; based on finite difference calculations made as part of the Long Term Seismic Program numerical modeling studies. Although subsurface conditions at the site are characterized by possible small-scale (on the order of several hundred meters) variations of seismic velocities within the San Luis/Pismo synclinorium, it is not near an alluvial basin margin having high lateral velocity contrast. Thus, no unusual subsurface conditions exist at the Diablo Canyon site.

The degree in influence of unusual topographic or subsurface conditions was estimated for each record as follows:

Nahanni site 3; Koyna; Tabas: no significant topographic effect.

Nahanni sites 1 and 2: Presence of unusual topographic conditions (Weichert and Homer, 1988); strong topographic effects indicated by finite difference calculations; treated by down weighting the significance of these records.

Pacoima Dam: strong topographic effects; treated by modification of the response spectrum with a correction function varying linearly on a logarithmic frequency scale from 1.0 at frequencies of 10 hertz and lower, to 2/3 at a frequency of 33 hertz (peak ground acceleration). The modification factors were based on analytical studies by Boore (1973).

Mexicali Valley: insignificant topographic effect, but significant effect due to location of the site on

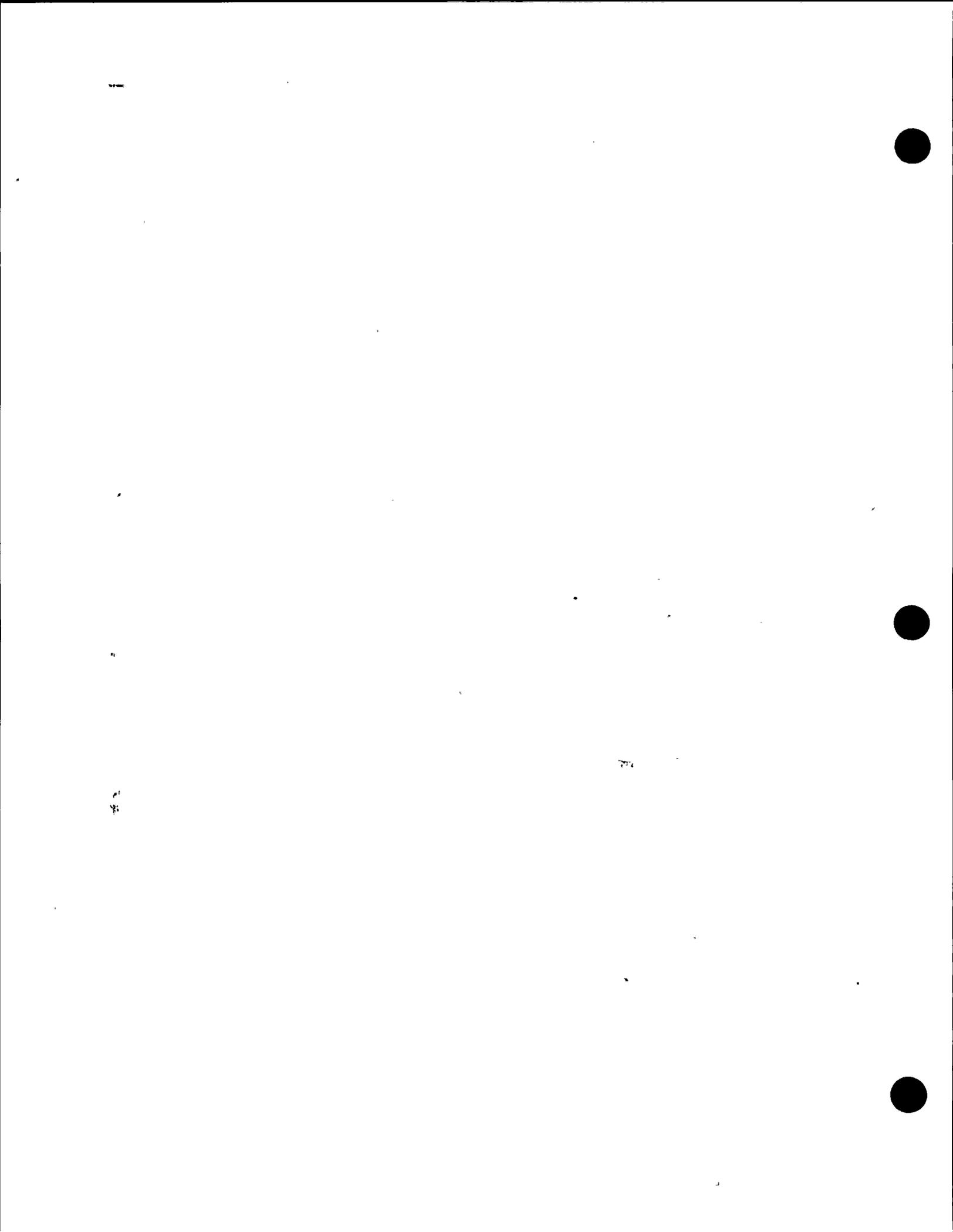


Table 4-4

CHARACTERISTICS OF THE NEAR-SOURCE RECORDINGS USED TO DEVELOP SITE-SPECIFIC RESPONSE SPECTRA BY STATISTICAL ANALYSIS

<u>Earthquake/ Record Name</u>	<u>Style of Faulting</u>	<u>Magnitude (M_w)</u>	<u>Distance (km)</u>	<u>Original PGA (g)</u>	<u>Type of Modification¹</u>	<u>Overall Adjustment Factor for PGA²</u>	<u>Weighting Factor³</u>
ROCK SITES							
1 Gazli/Karakyr Point	Reverse	6.8	3	0.70 0.66	D, M	0.95	0.5
2 Tabas/Tabas	Thrust	7.4	3	0.70 0.81	D, M	0.89	1.0
3 San Fernando/Pacoima Dam	Thrust	6.6	3	1.08 1.17	D, M, T	0.66	1.0
4 Koyna/Koyna Dam	Strike-slip	6.3	3	0.63 0.49	D, M	1.10	0.75
5 Nahanni/Site 1	Thrust	6.8	6	1.35 1.10	D, M	1.20	0.3
6 Nahanni/Site 2	Thrust	6.8	8	0.59 0.42	D, M	1.39	0.3
7 Tabas/Dayhook	Thrust	7.4	17	0.39 0.38	D, M	1.86	1.0
8 Nahanni/Site 3	Thrust	6.8	16	0.19 0.19	D, M	2.30	0.4
9 San Fernando/ Lankershim Boulevard	Thrust	6.6	15	0.18 0.15	D, M	2.39	1.0
10 San Fernando/Griffith Park Observatory	Thrust	6.6	17	0.19 0.18	D, M	2.81	1.0
11 San Fernando/Old Seismology Lab—CIT	Thrust	6.6	19	0.10 0.20	D, M	3.00	1.0
12 San Fernando/Lake Hughes No. 12	Thrust	6.6	20	0.37 0.29	D, M	3.17	1.0
13 Mexicali Valley	Strike-slip	6.4	8.5	0.60 0.61	D, M	1.70	0.5

¹Type of modification: D = for Distance
M = for Magnitude
S = for Site Conditions
T = for Topographic Effects

²Adjusted to: M_w = 7.2, D = 4.5 kilometers, and rock-site condition.

³Based on evaluations of compatibility of tectonic setting, topographic effects or subsurface conditions, and source-site geometry.

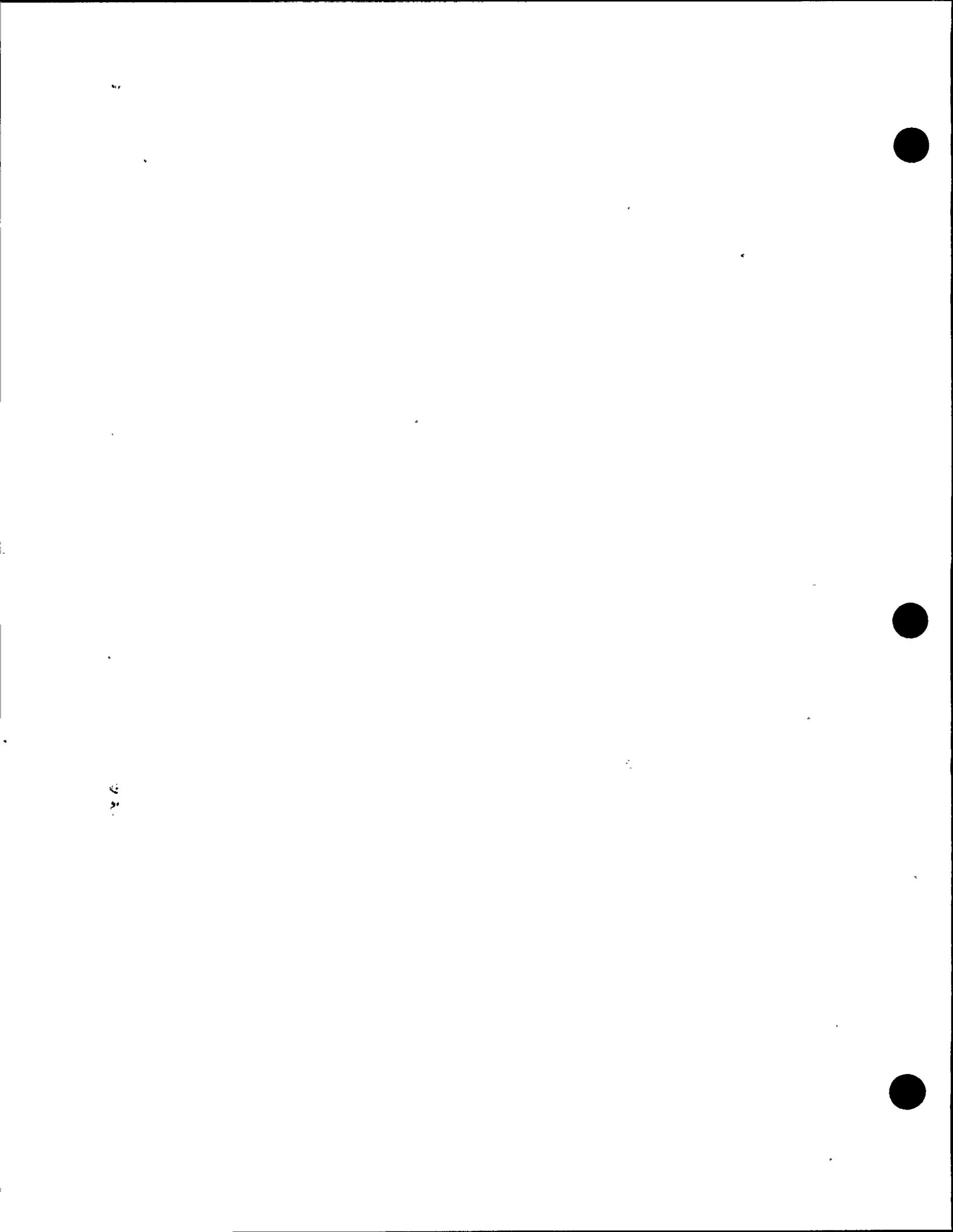


Table 4-4 (Continued)
 CHARACTERISTICS OF THE NEAR-SOURCE RECORDINGS USED TO DEVELOP SITE-SPECIFIC RESPONSE
 SPECTRA BY STATISTICAL ANALYSIS

<u>Earthquake/ Record Name</u>	<u>Style of Faulting</u>	<u>Magnitude (M_w)</u>	<u>Distance (km)</u>	<u>Original PGA (g)</u>	<u>Type of Modification¹</u>	<u>Overall Adjustment Factor for PGA²</u>	<u>Weighting Factor³</u>
SOIL SITES							
14 Imperial Valley/ Differential Array	Strike-slip	6.5	5	0.49 0.35	D, M, S	1.36	1.0
15 Imperial Valley/ El Centro No. 4	Strike-slip	6.5	4	0.49 0.37	D, M, S	1.25	1.0
16 Imperial Valley/ Holtville Post Office	Strike-slip	6.5	7.5	0.26 0.22	D, M, S	1.61	1.0
17 Imperial Valley/ El Centro No. 10	Strike-slip	6.5	8.5	0.23 0.18	D, M, S	1.73	1.0
18 Imperial Valley/ El Centro No. 8	Strike-slip	6.5	4	0.62 0.48	D, M, S	1.25	1.0

¹Type of modification: D = for Distance
 M = for Magnitude
 S = for Site Conditions
 T = for Topographic Effects

²Adjusted to: M_w = 7.2, D = 4.5 kilometers, and rock-site condition.

³Based on evaluations of compatibility of tectonic setting, topographic effects or subsurface conditions, and source-site geometry.

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a volcanic plug penetrating a deep basin (Anderson and others, 1982); treated by down-weighting the significance of the record.

Unusual Source-Site Geometry. There is strong empirical and theoretical evidence of a directivity effect due to rupture propagation on strong ground motions (Aki, 1968; Haskell, 1969; Boore and Joyner, 1978; Boatwright and Boore, 1982). The effect is most pronounced at periods of several seconds, but is not so significant at high frequencies, and does not strongly affect peak accelerations. The Diablo Canyon site is sufficiently distant from the Hosgri fault that the directivity effects at the site are expected to be moderate. This is true for both along-strike directivity from a vertical strike-slip fault and for up-dip directivity from a dipping thrust fault.

The degree of influence of the directivity effect was assessed for each record by the proximity of the recording site to the causative fault.

Mexicali Valley: the site is directly on the strike of this vertical strike-slip earthquake (Frez, 1982), suggesting a strong directivity effect; treated by down-weighting the significance of the record.

All other records: insignificant directivity effect.

The overall effects of these factors are incorporated in a weighting factor for each record, as shown in Table 4-4. In total, six of the 18 near-source records were down-weighted in the statistical analysis by factors ranging from 0.3 for the Nahanni records (affected by tectonic setting and topographic effects) to 0.75 for the Koyna record (affected by tectonic setting only).

The selected records in Table 4-4 were individually modified to conform to moment magnitude 7.2 and distance 4.5 kilometers of the maximum earthquake using appropriate scaling relationships, which are based on results of the empirical regression analyses and the numerical modeling studies, as well as on an evaluation of published studies available in the literature. In addition, modification was made from soil to rock site response for the five records from the 1979 Imperial Valley earthquake. The modification for site response resulted in an increase in peak

ground acceleration and high-frequency spectral acceleration, and a decrease in low-frequency spectral acceleration.

The total scaling factor for converting the peak ground acceleration of each record to that at a rock site 4.5 kilometers from the closest fault rupture of a moment magnitude 7.2 earthquake is given in Table 4-4. A great majority (15 out of 18) of the records were scaled up by factors of as high as 3.17. Only three records were scaled down.

Style of Faulting. Next, the scaling factor for the style of faulting was considered. It has been suggested that ground-motion amplitude may depend on the style of faulting. For example, Boore and Boatwright (1984) showed numerically that at distances within about a focal depth of the source, the ratio of average body wave radiation coefficients between thrust faulting and strike-slip faulting ranges from 1.14 to 1.28. Campbell (1987) obtained empirically a peak ground acceleration ratio between reverse faulting and strike-slip faulting of 1.38. The current Long Term Seismic Program empirical ground-motion studies show a range from 1.08 to 1.27 for the ratio of peak ground acceleration between thrust faulting and strike-slip faulting. As part of the numerical modeling studies, we compared the average peak ground acceleration and spectral acceleration over the frequency band from 3 to 8.5 hertz of 40 simulated acceleration time histories at a site 5.8 kilometers from a moment magnitude 7 earthquake for each of the three styles of faulting, namely, strike-slip, oblique, and thrust. The lognormally averaged peak ground acceleration and spectral acceleration for strike-slip, oblique, and thrust faulting are approximately 10 percent lower than, equal to, and 10 percent higher than the overall average of the total set of 120 simulations, respectively, and the spectral shapes for the three styles of faulting are very similar. On the basis of the above studies, the following relative scaling factors on peak ground acceleration and spectral acceleration for the style of faulting were used to convert the ground motions from one style of faulting to another:

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<u>Style of Faulting</u>	<u>Scaling Factor</u>
Strike-slip	0.83
Oblique	0.91
Thrust	1.0

The above scaling factors were used to convert the individual records in Table 4-4 so that statistical analysis could be performed to obtain representative response spectra for strike-slip, oblique, and thrust faulting. These three sets of response spectra were finally combined to obtain the response spectra for the maximum earthquake using weights proportional to the relative probabilities of occurrence of the three potential styles of faulting.

In total we have 18 near-source recordings for statistical analysis of response spectral acceleration for individual frequencies. Since our site-specific response spectra are expressed in terms of the average peak ground acceleration and spectral acceleration of the two horizontal components, we have performed the statistical analysis on the 18 averaged horizontal peak ground acceleration and spectral acceleration values to obtain the median and the 84th percentile acceleration response spectra. The results are shown on Figure 4-15 for strike-slip faulting, on Figure 4-16 for thrusting faulting, and on Figure 4-17 for the weighted styles of faulting. Comparisons of the response spectra in Figure 4-17 with results from the other two approaches will be made later in this section to select the overall site-specific response spectra representing ground motions at the Diablo Canyon site.

SITE-SPECIFIC RESPONSE SPECTRA BASED ON ATTENUATION RELATIONSHIPS

Horizontal Response Spectra. Sets of updated attenuation relationships for horizontal peak ground acceleration and horizontal response spectral acceleration were developed in the empirical investigations. These relationships were developed for rock sites by multiple-regression analysis of the up-to-date ground-motion data base described earlier. The parameters of the attenuation relationships were estimated using nonlinear least-squares techniques; specifically,

the modified form of the Gauss-Newton method developed by Marquardt (1963) has been employed.

We then developed site-specific horizontal acceleration response spectra for the maximum earthquake at the Plant site using these attenuation relationships.

The attenuation relationships for peak ground acceleration and spectral acceleration at 5 percent damping are represented by the following equations (Sadigh, 1983; Sadigh, 1984):

$$\ln \text{PGA} = C_0 + C_1 M + C_3 \ln [D + C_4 \exp (C_5 M)]$$

$$\ln S_a = C_0' + C_1 M + C_2 (8.5 - M)^{2.5} + C_3 \ln [D + C_4 \exp (C_5 M)]$$

where PGA is horizontal peak ground acceleration in g and S_a is spectral acceleration in g for a given frequency. M is the moment magnitude, D is the closest distance in kilometers to the fault rupture surface, and C_0 , C_0' , C_1 , C_2 , C_3 , C_4 and C_5 are constants to be determined from regression analysis performed on the observed peak ground acceleration and spectral acceleration data contained in the ground motion data base. The dispersion of $\ln \text{PGA}$ or $\ln S_a$ with respect to the best estimate is also obtained as a result of the regression analysis.

As may be seen from Figure 4-7, nearly all available recordings above moment magnitude 6.5 are from thrust faulting. Therefore, well-constrained attenuation relationships for larger earthquakes and near-source distances were first developed for thrust faulting. Table 4-5 summarizes the coefficients for peak ground acceleration and for 5 percent damped response spectra at five individual frequencies corresponding to thrust earthquakes. Attenuation relationships were also developed using 5 percent damped spectral acceleration averaged over frequency bands of 3 to 8.5 hertz and 5 to 14 hertz as ground-motion parameters of interest to this study. The coefficients for these two frequency bands corresponding to thrust earthquakes are also contained in Table 4-5.



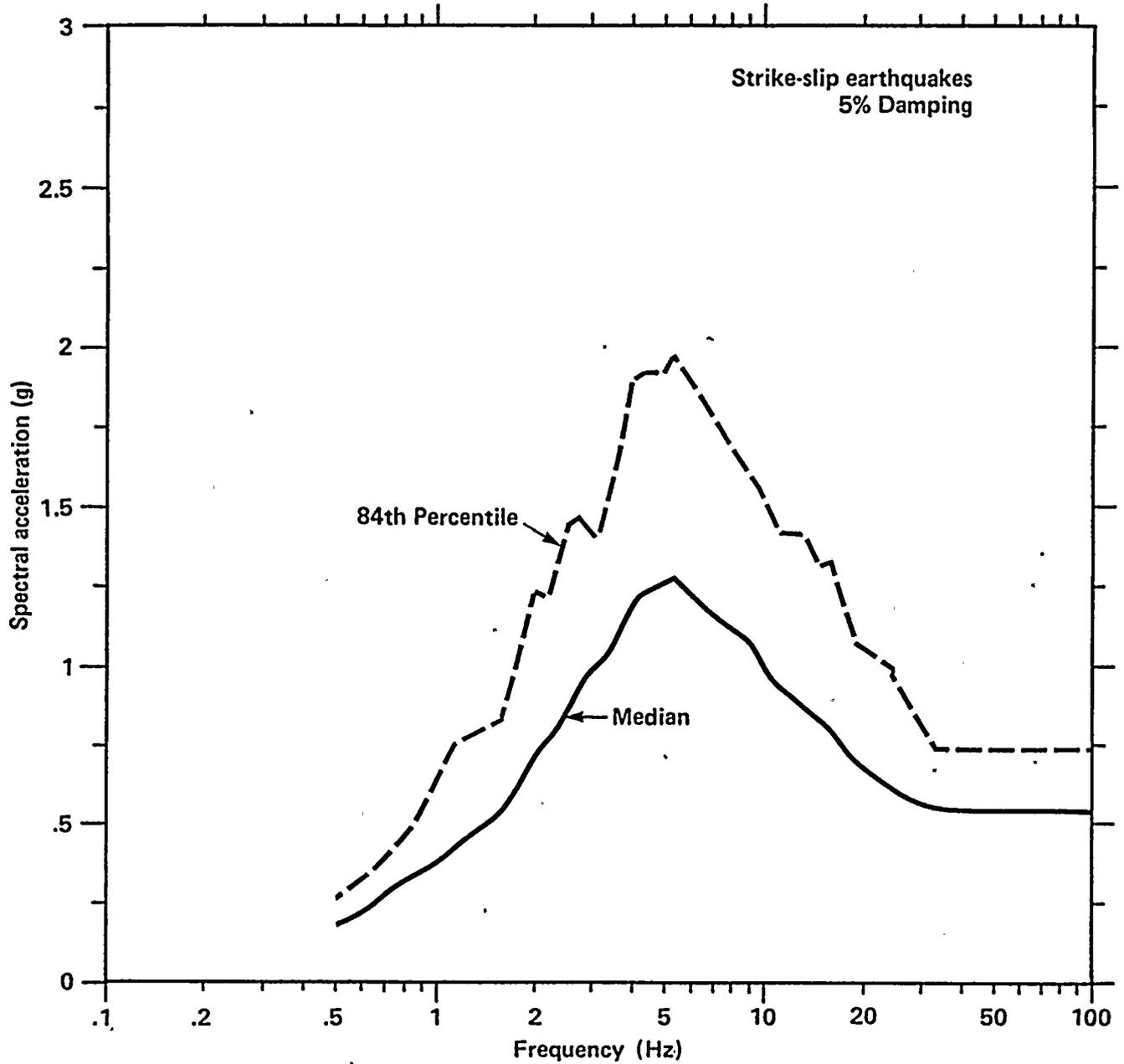


Figure 4-15

Median and 84th percentile horizontal acceleration response spectra for a magnitude 7.2 strike-slip earthquake at 4.5 kilometers based on statistics of 18 near-source records.



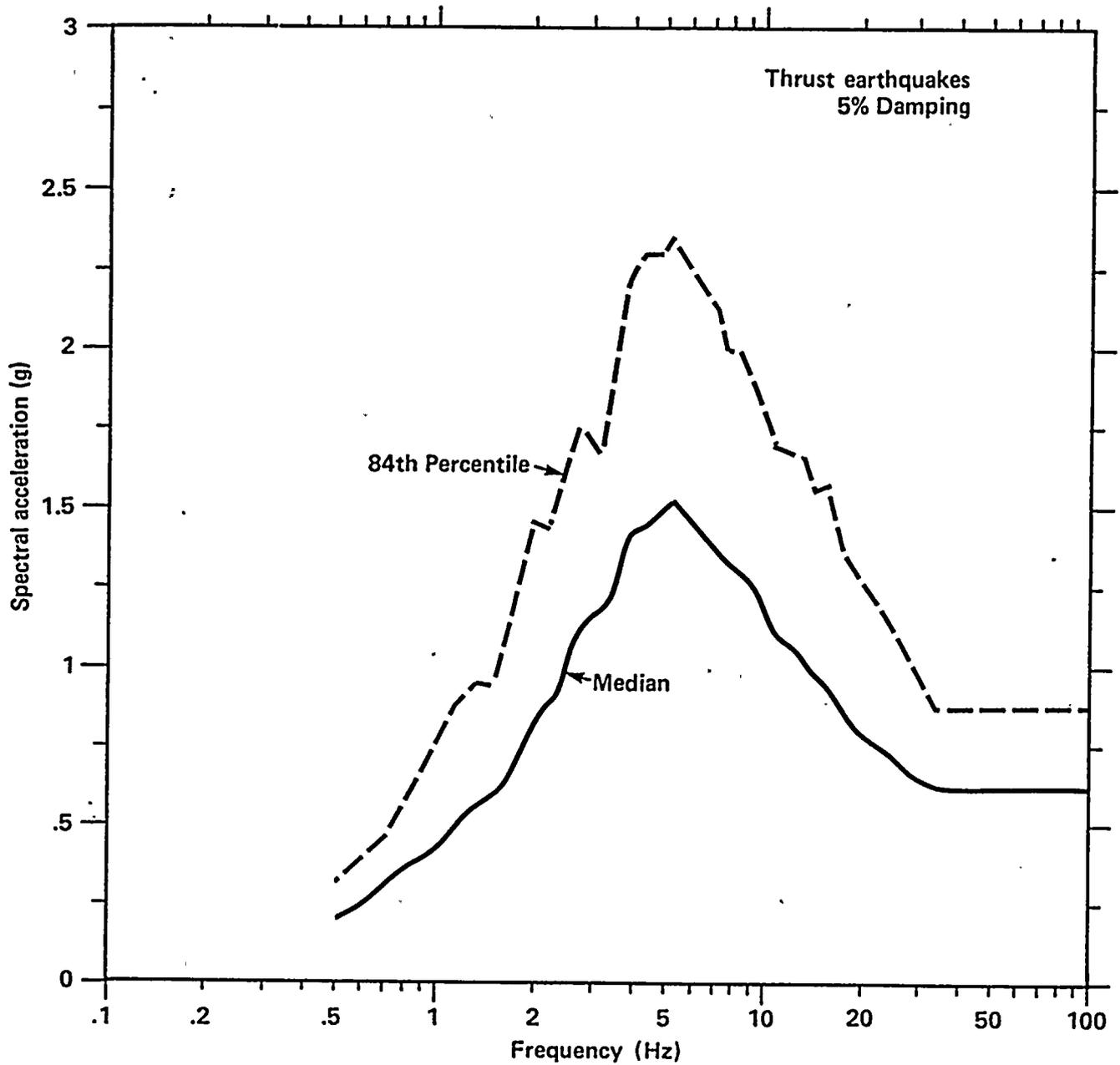
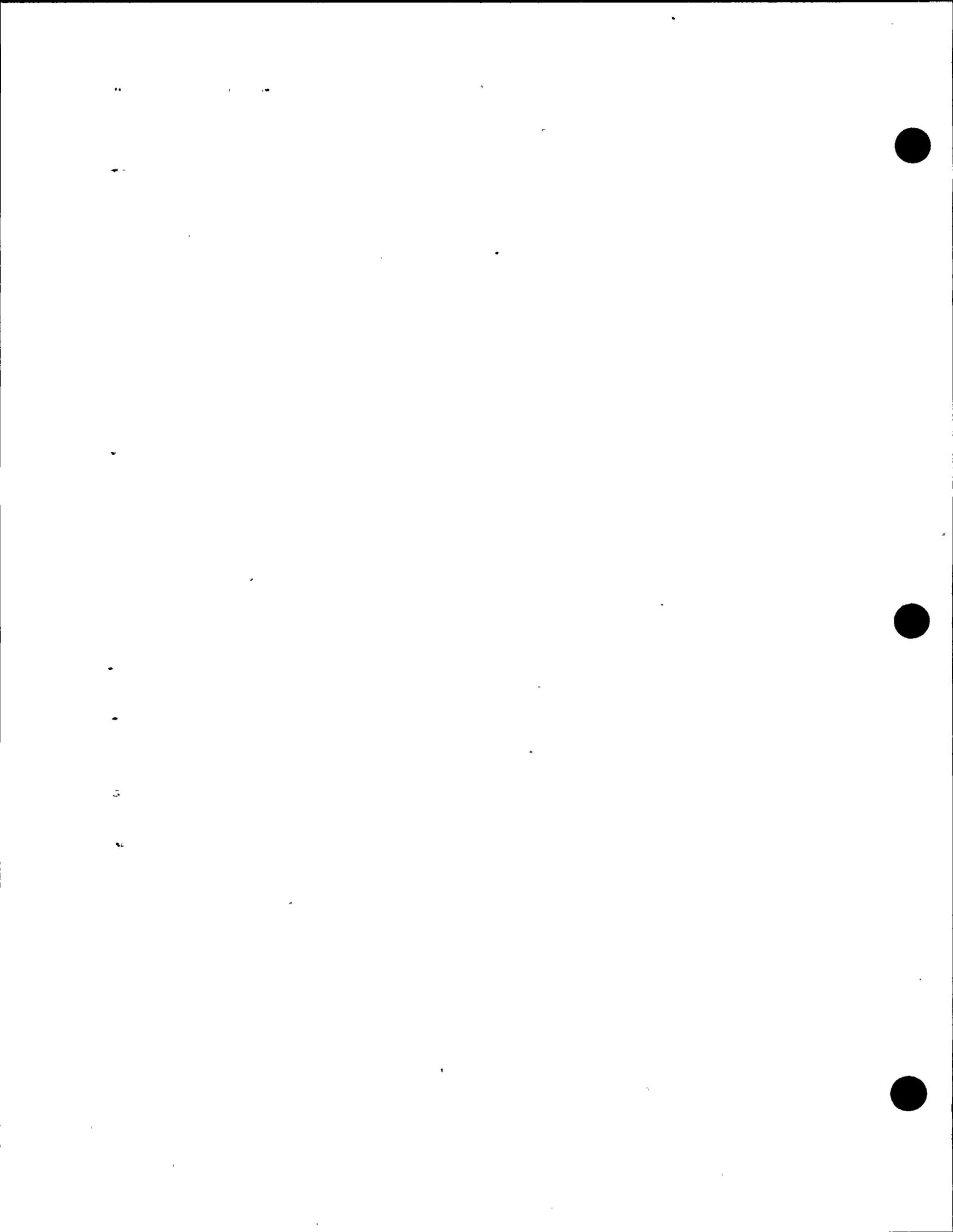
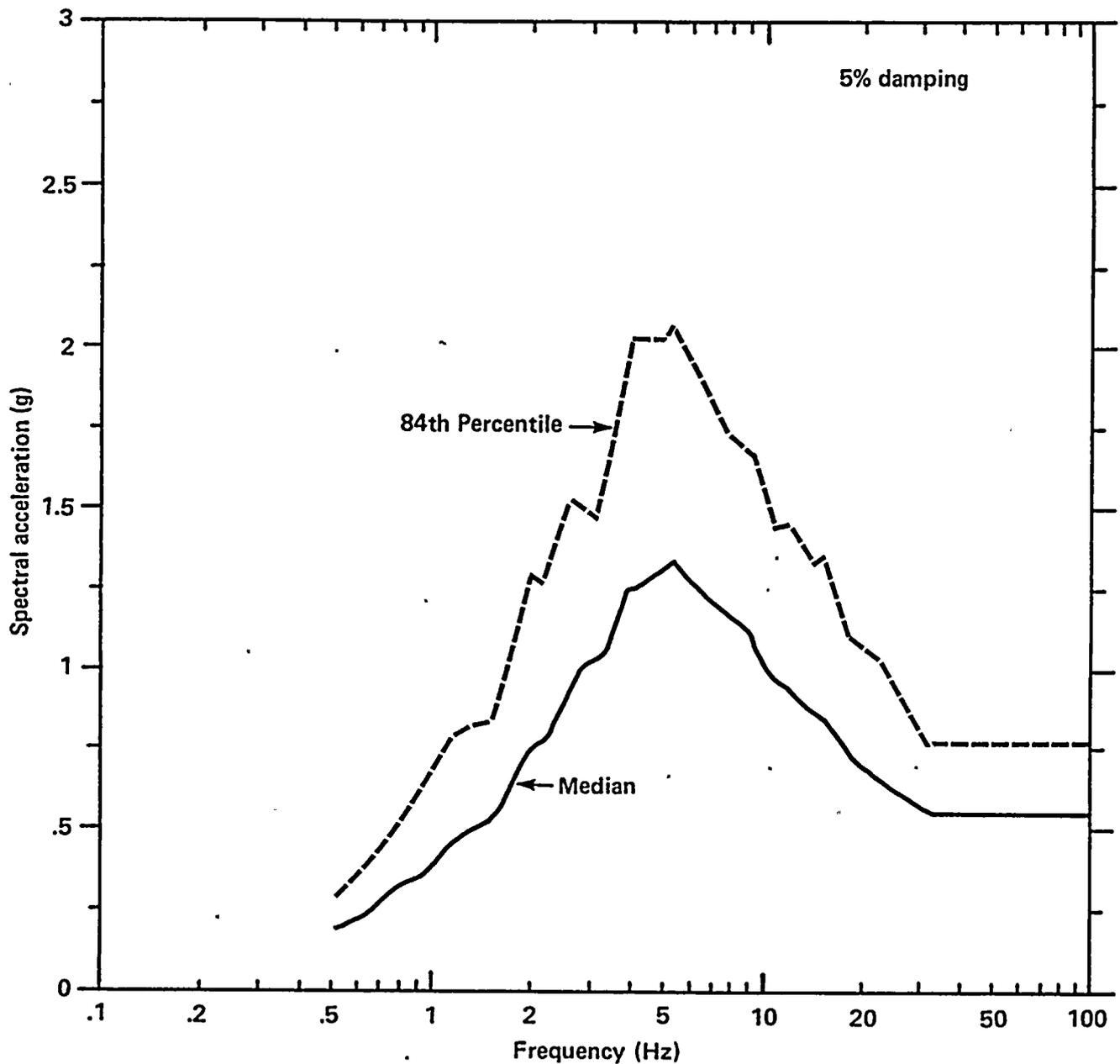


Figure 4-16
Median and 84th percentile horizontal acceleration response spectra for a magnitude 7.2 thrust earthquake at 4.5 kilometers based on statistics of 18 near-source records.





Median and 84th percentile horizontal acceleration response spectra for a records.

Figure 4-17

Median and 84th percentile horizontal acceleration response spectra for a magnitude 7.2 earthquake at 4.5 kilometers, based on statistics of 18 near-source records, weighted for style of faulting: 0.65, strike-slip; 0.30, oblique; 0.05, thrust.

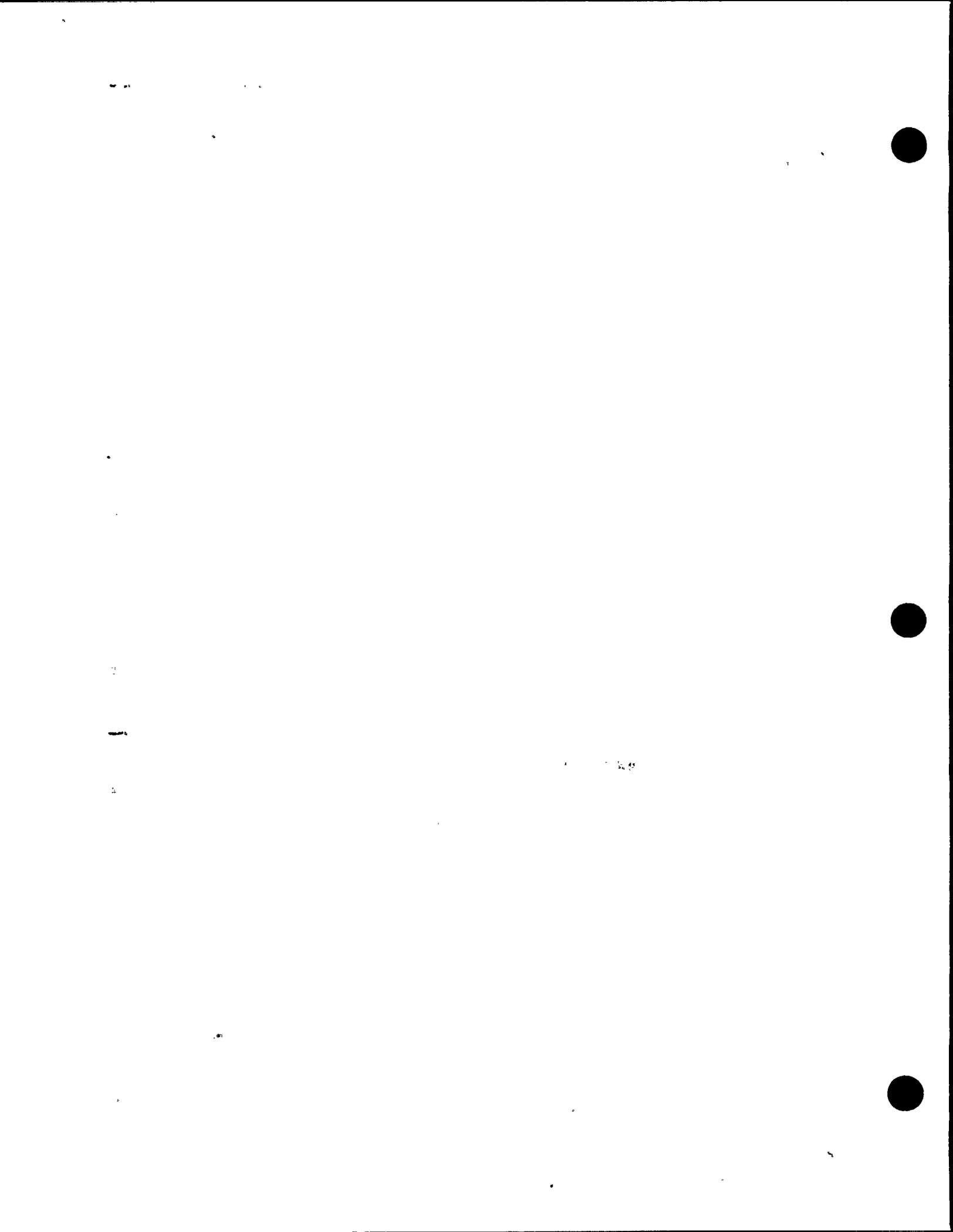


Table 4-5

VALUES OF COEFFICIENTS FOR ATTENUATION RELATIONSHIPS OF HORIZONTAL
PEAK GROUND ACCELERATION AND RESPONSE SPECTRAL ACCELERATIONS
(5% DAMPING) FOR THRUST FAULTING*

FOR $M \geq 6.5$

$$\ln y = c_0 + c_1 M + c_2 (8.5 - M)^{2.5} - 2.1 \ln [D + 0.616 \exp (0.524M)]$$

Ground Motion Parameter, y	Period (sec)	c_0	c_1	c_2	$\sigma_{\ln y}$
Peak Ground Acceleration	—	-1.092	1.10	0	0.36
Spectral Acceleration (5% damping)	0.1	-0.432	1.10	0.006	0.38
	0.2	-0.232	1.10	-0.010	0.40
	0.3	-0.248	1.10	-0.023	0.42
	0.5	-0.469	1.10	-0.040	0.44
	1.0	-1.059	1.10	-0.064	0.45
	(3 - 8.5 Hz)	-0.258	1.10	-0.011	0.36
	(5 - 14 Hz)	-0.384	1.10	0.001	0.36

FOR $M < 6.5$

$$\ln y = c_0 + c_1 M + c_2 (8.5 - M)^{2.5} - 2.1 \ln [D + 3.656 \exp (0.250M)]$$

Ground Motion Parameter, y	Period (sec)	c_0	c_1	c_2	$\sigma_{\ln y}$
Peak Ground Acceleration	—	-0.442	1.00	0	1.27 - 0.14M
Spectral Acceleration (5% damping)	0.1	0.218	1.00	0.006	1.29 - 0.14M
	0.2	0.418	1.00	-0.010	1.31 - 0.14M
	0.3	0.402	1.00	-0.023	1.33 - 0.14M
	0.5	0.181	1.00	-0.040	1.35 - 0.14M
	1.0	-0.409	1.00	-0.064	1.36 - 0.14M
	(3 - 8.5 Hz)	0.392	1.00	-0.011	1.27 - 0.14M
	(5 - 14 Hz)	0.266	1.00	0.001	1.27 - 0.14M

*Relationships for strike-slip faulting are obtained by multiplying the thrust amplitudes by 0.83. Relationships for oblique faulting are obtained by multiplying the thrust amplitudes by 0.91.

NOTES: In the above equations, M is moment magnitude and D is the closest distance to the fault rupture surface. $\sigma_{\ln y}$ is the standard error of estimate of the relationship.

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Attenuation relationships for other styles of faulting such as strike-slip or oblique were scaled from those for thrust faulting using the relative scaling factors for the style of faulting given earlier.

Figures 4-18 and 4-19 show the attenuation relationships for horizontal peak ground acceleration for strike-slip faulting and for thrust faulting, respectively. Figures 4-20 and 4-21 show the attenuation relationships for 5 percent damped horizontal spectral acceleration at 5 hertz for strike-slip faulting and for thrust faulting, respectively. These attenuation relationships contain moderate distance and magnitude saturations in the small distance and large magnitude ranges.

The horizontal acceleration response spectra at the median and 84th percentile levels at a site 4.5 kilometers from a magnitude 7.2 earthquake were derived from the attenuation relationships for strike-slip, oblique, and thrust faulting, respectively. Finally, the acceleration response spectra for the three styles of faulting were combined with weights proportional to their respective probabilities of occurrence to give the overall site-specific response spectra at the Diablo Canyon site for the maximum earthquake on the Hosgri fault zone.

Figure 4-22 shows the median and 84th percentile site-specific horizontal acceleration response spectra (at 5 percent damping) for the maximum earthquake, as obtained from the attenuation relationships. Comparisons of these response spectra with the results from the other two approaches are made later to select the overall site-specific horizontal response spectra representing ground motions at the Diablo Canyon site.

Vertical Response Spectra. For deterministic seismic margin evaluation studies, we also developed corresponding vertical acceleration response spectra. Estimates of site-specific vertical response spectra were made by scaling the horizontal site-specific response spectra by ratios of the vertical to horizontal response spectral values. Statistical analyses of response spectral

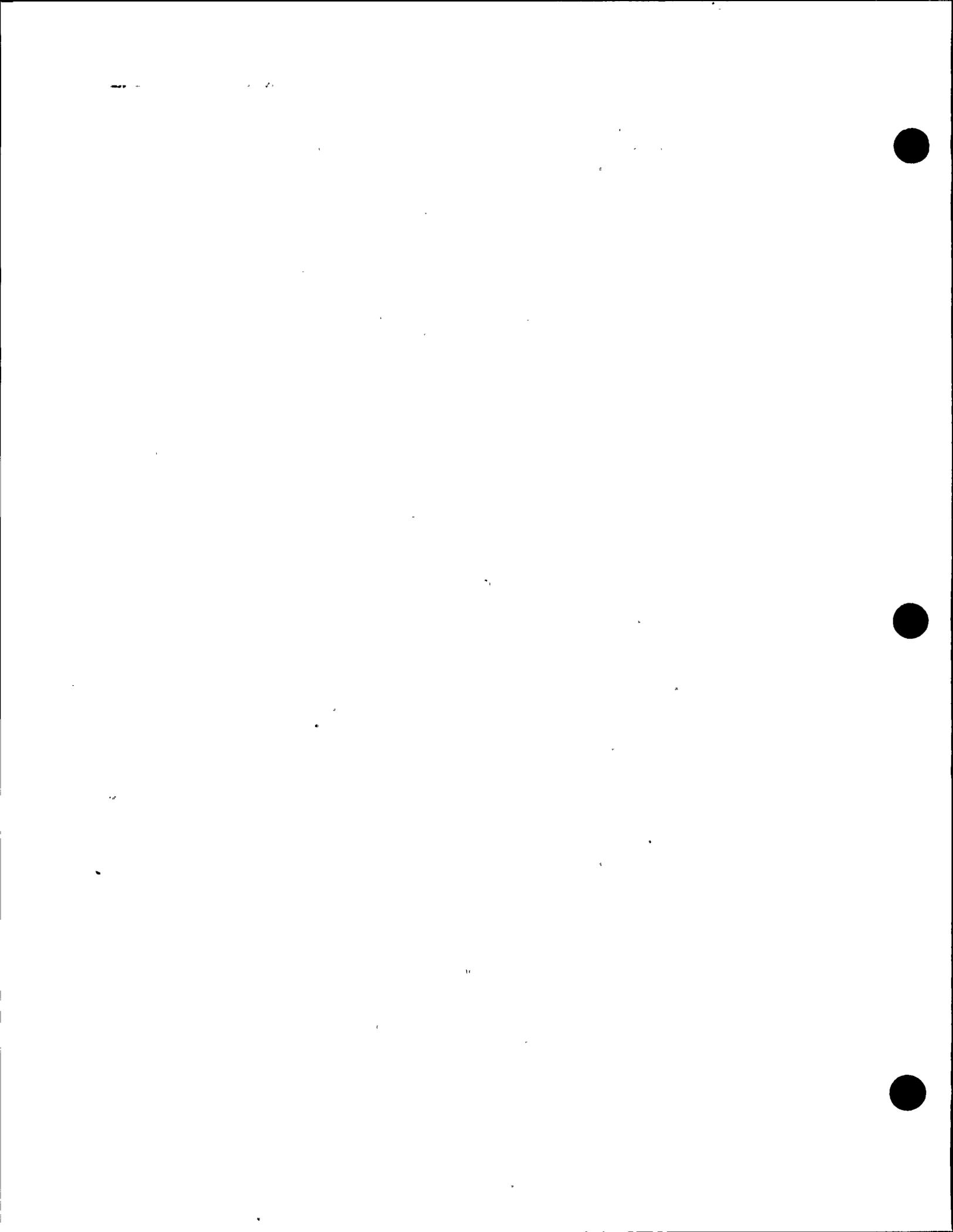
values of vertical ground motions and those of horizontal ground motions show that ratios of vertical to horizontal response spectra are strongly frequency-dependent and distance-dependent.

Using published data supplemented by statistical analysis of a number of near-source rock recordings, estimates of the ratios between vertical and horizontal response spectra were made for use in this study. Using these ratios, an estimate was made of the site-specific vertical response spectra from the corresponding horizontal spectra. Figure 4-23 shows that the vertical response spectra peak at higher frequencies than the corresponding horizontal response spectra.

SITE-SPECIFIC RESPONSE SPECTRA BASED ON NUMERICAL MODELING STUDIES

A suite of 116 simulations was generated using the semi-empirical procedure for the purpose of developing the site-specific response spectra. The source models used were based on updated information on seismic source characterization. First, the magnitude of the earthquakes simulated was 7.2. Second, the stress drop of the earthquakes was 50 bars, based on recent results from Somerville and others (1987) and Boore (1987), and earlier results of Kanamori and Anderson (1975). Third, the strike-slip and oblique fault models included rupture to the surface. Fourth, the slip distribution models included substantial shallow slip on the fault planes.

For each of the fault models, approximately 40 simulations were performed that encompassed bilateral and unilateral rupture, two sets of empirical source functions, and approximately 10 different positions of the fault rupture segment with respect to the site, as summarized in Table 4-6. The average acceleration response spectrum for each fault type was calculated, and these three spectra were combined using weights corresponding to their relative probabilities. The resulting average horizontal acceleration response spectrum and its dispersion is shown in Figure 4-24. The dispersion reflects the estimated variability in ground motions at the site due to the



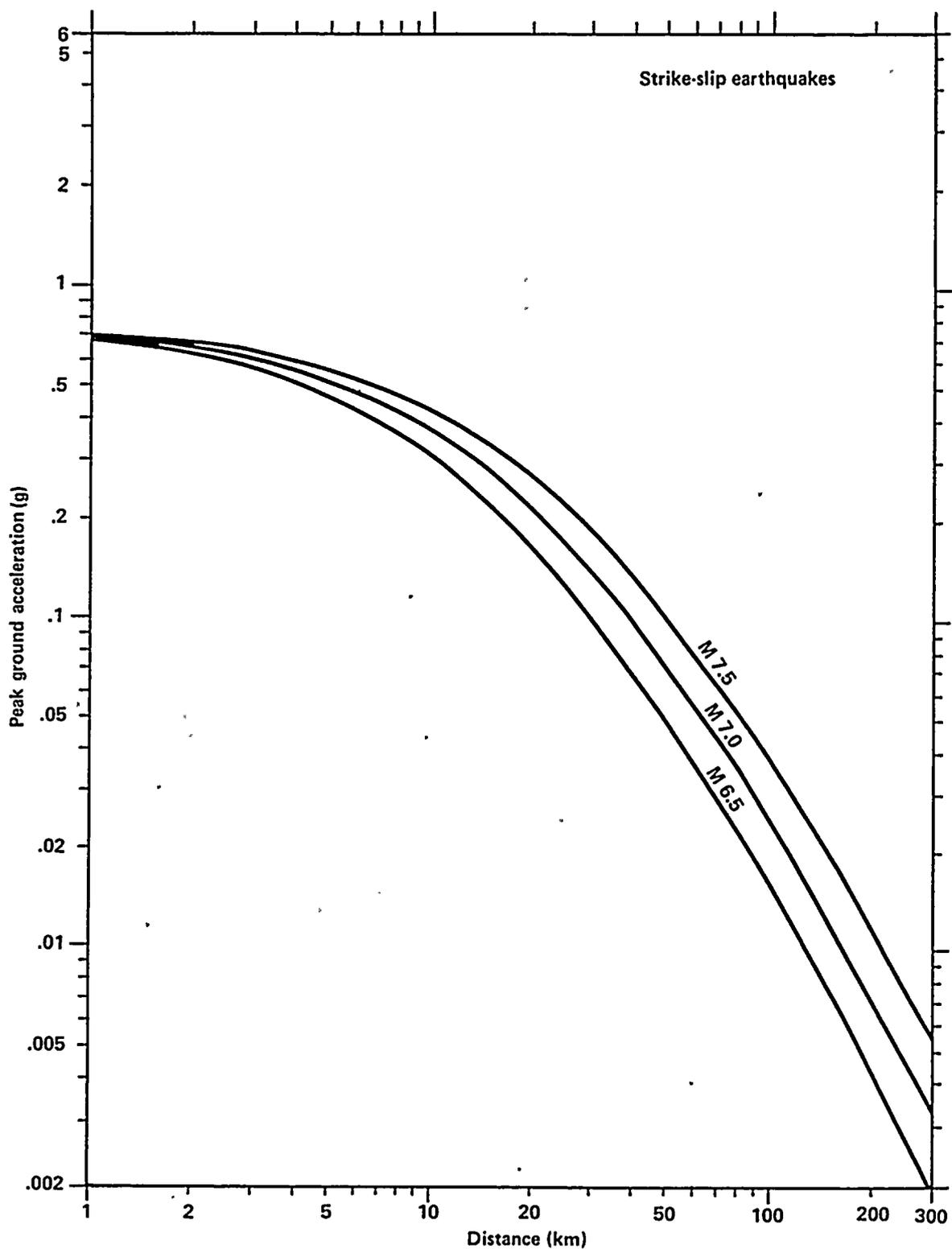


Figure 4-18
Attenuation relationships for median peak ground acceleration for strike-slip earthquakes of magnitudes 6.5, 7.0, and 7.5.



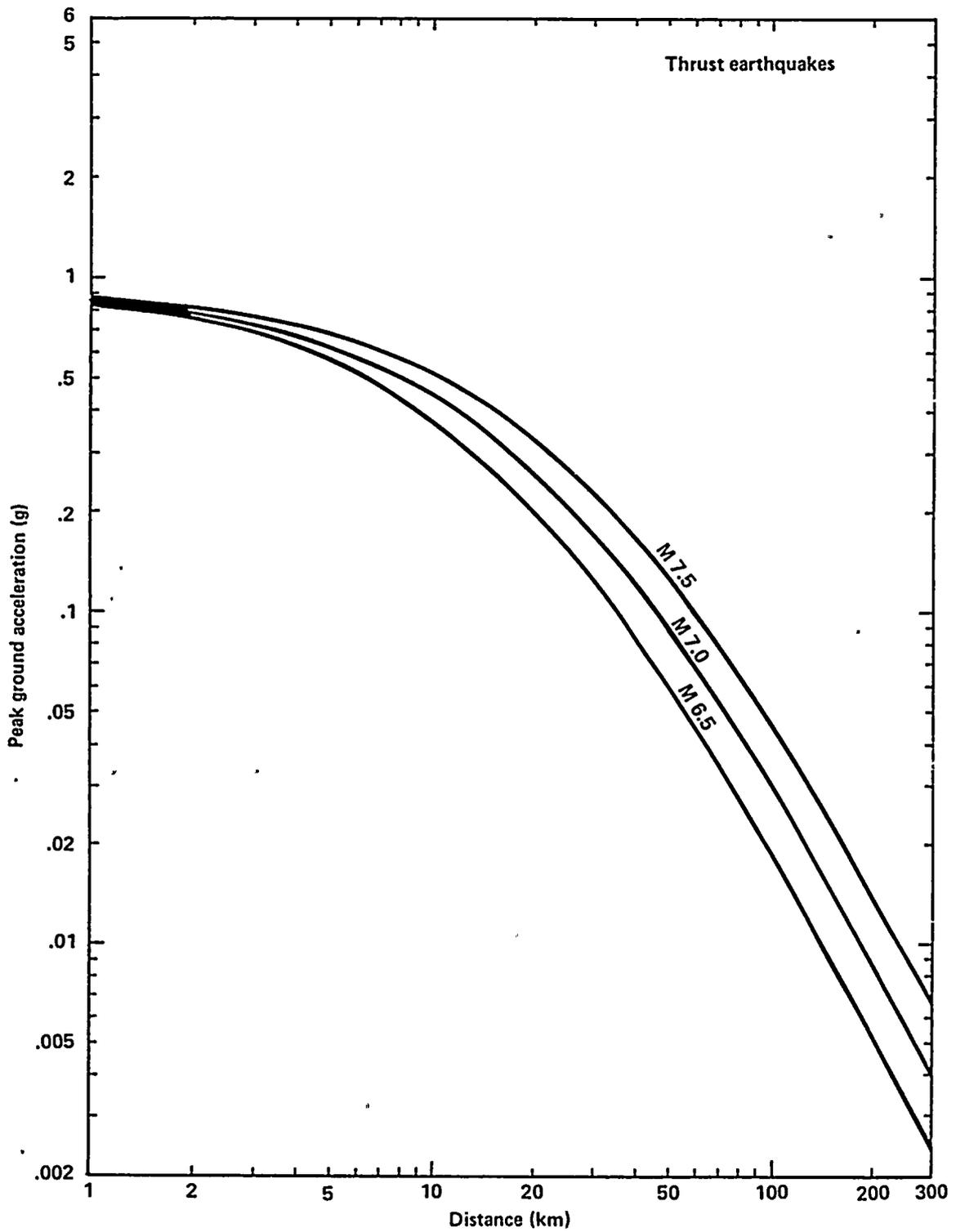


Figure 4-19
Attenuation relationships for median peak ground acceleration for thrust earthquakes of magnitudes 6.5, 7.0, and 7.5.



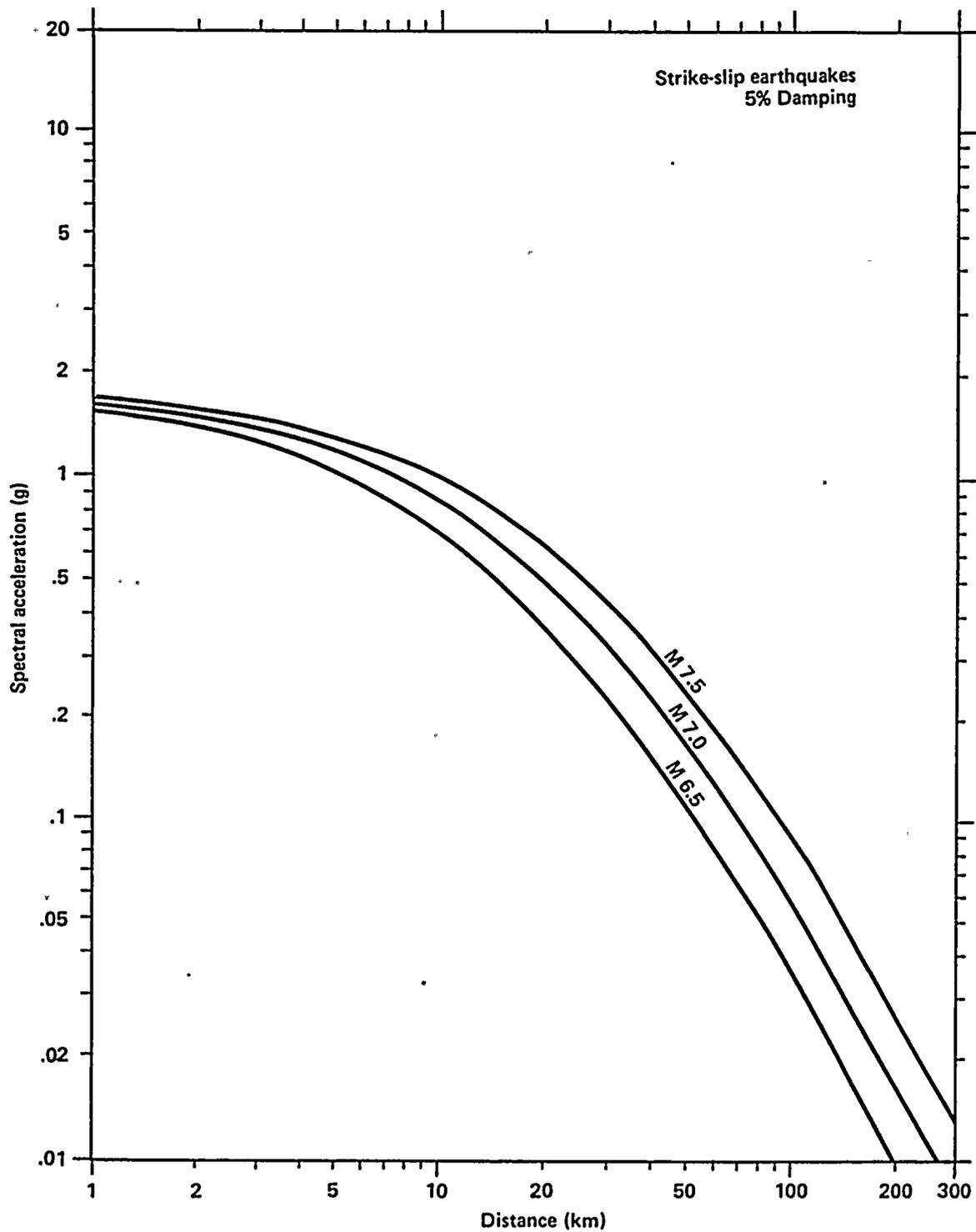
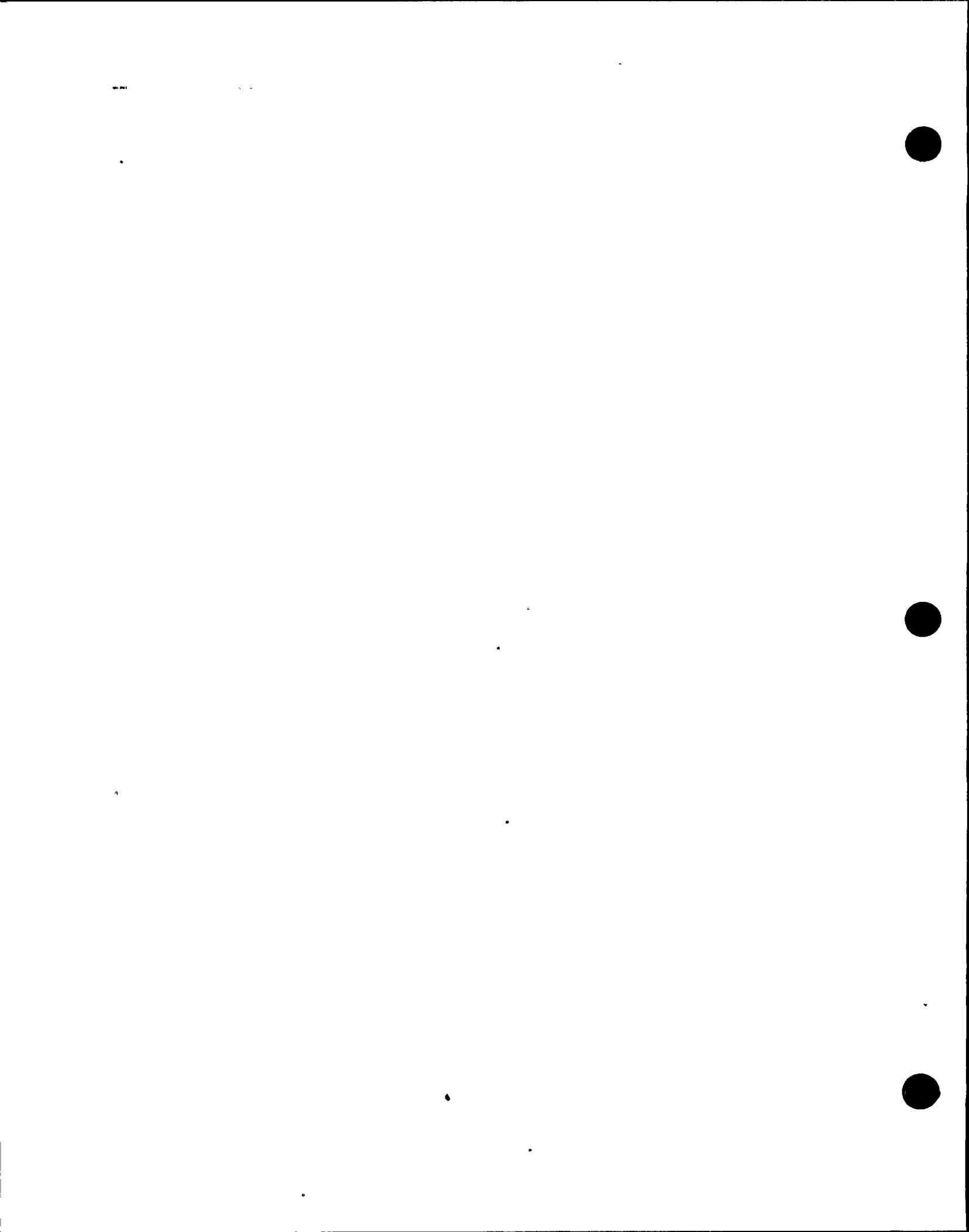


Figure 4-20
Attenuation relationships for median spectral acceleration at 5 hertz for strike-slip earthquakes of magnitudes 6.5, 7.0, and 7.5.



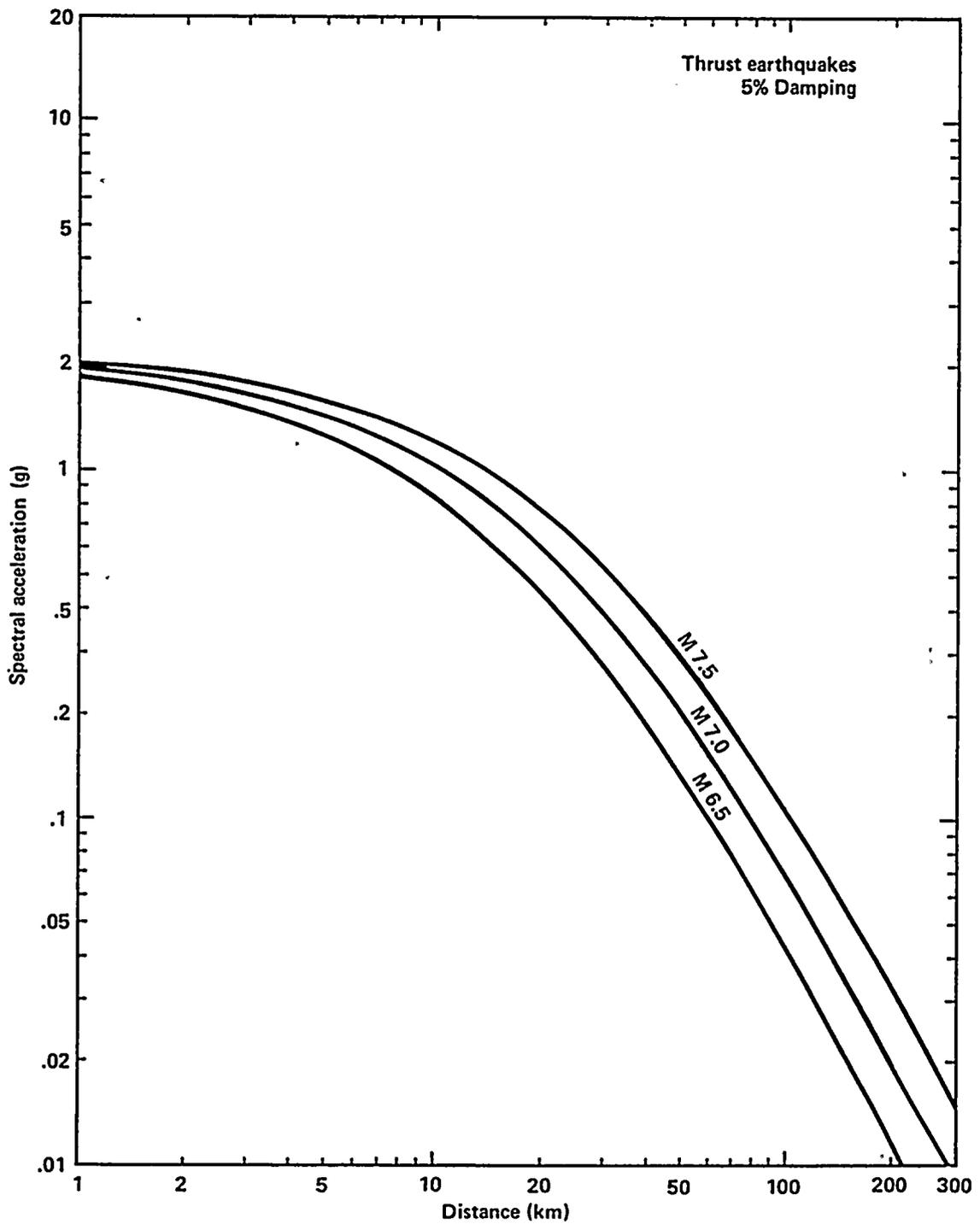
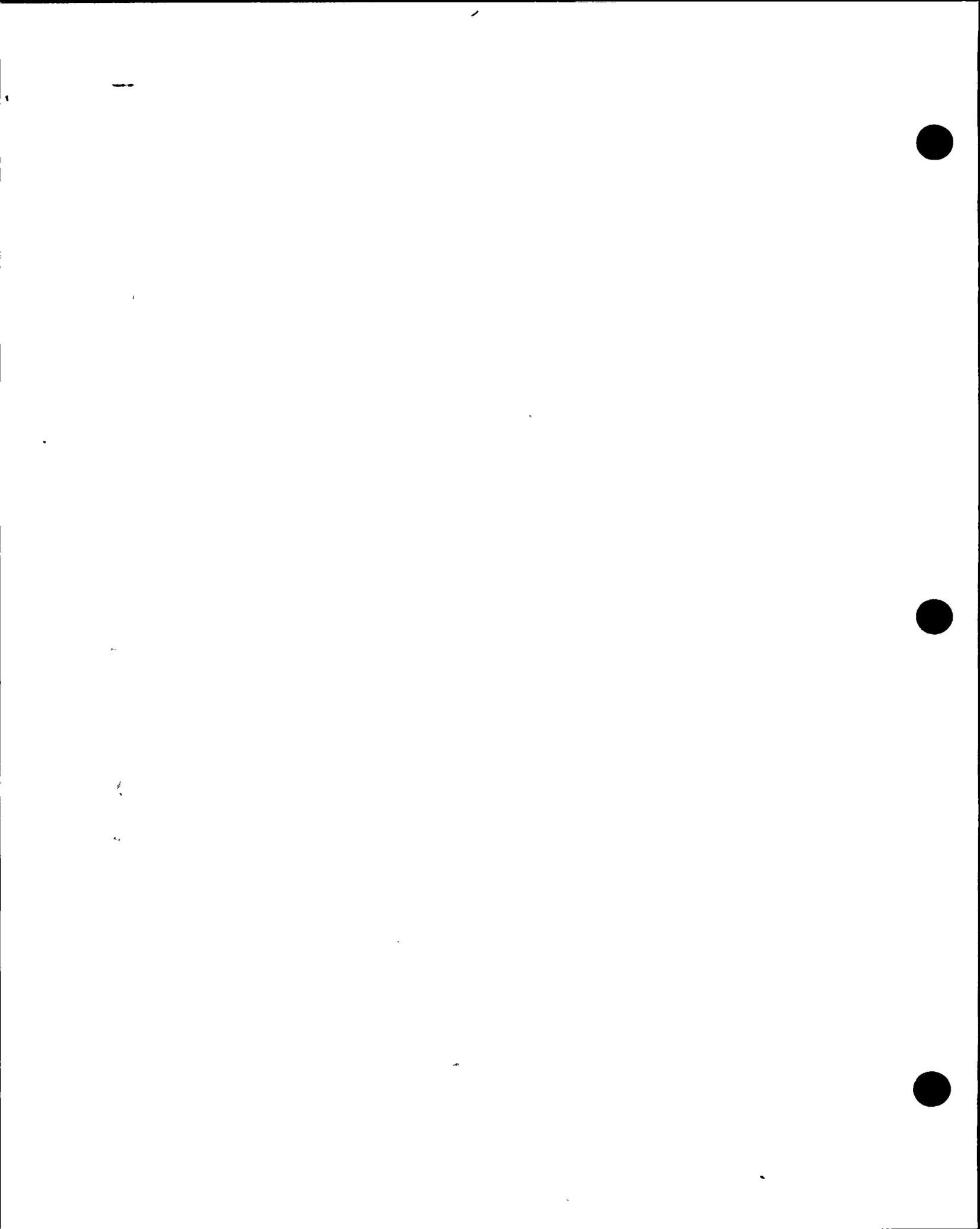


Figure 4-21
Attenuation relationships for median spectral acceleration at 5 hertz for thrust earthquakes of magnitudes 6.5, 7.0, and 7.5.



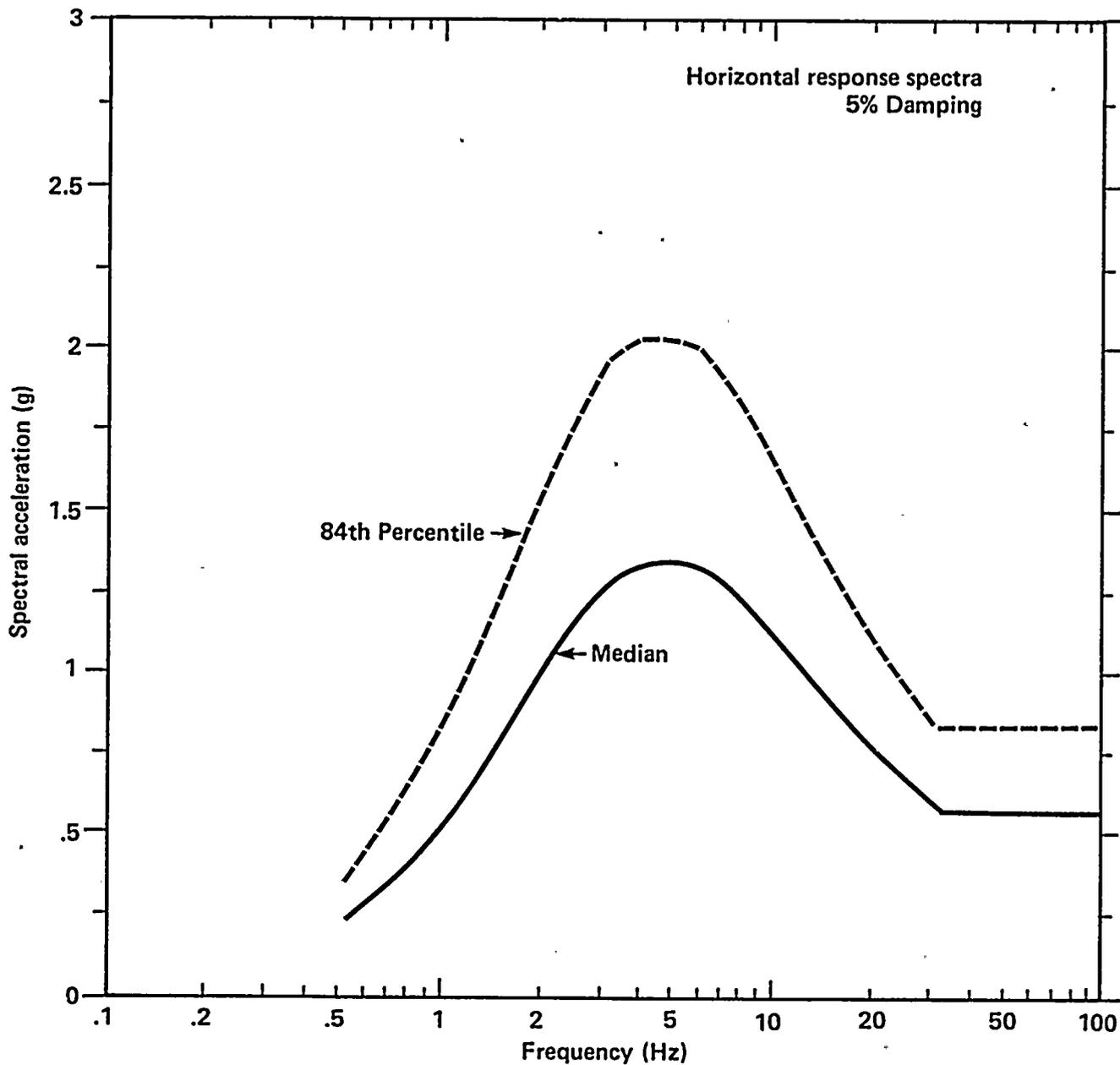


Figure 4-22

Median and 84th percentile horizontal acceleration response spectra for a magnitude 7.2 earthquake at 4.5 kilometers, based on attenuation relationships, weighted for syle of faulting: 0.65, strike-slip; 0.30, oblique; 0.05 thrust.



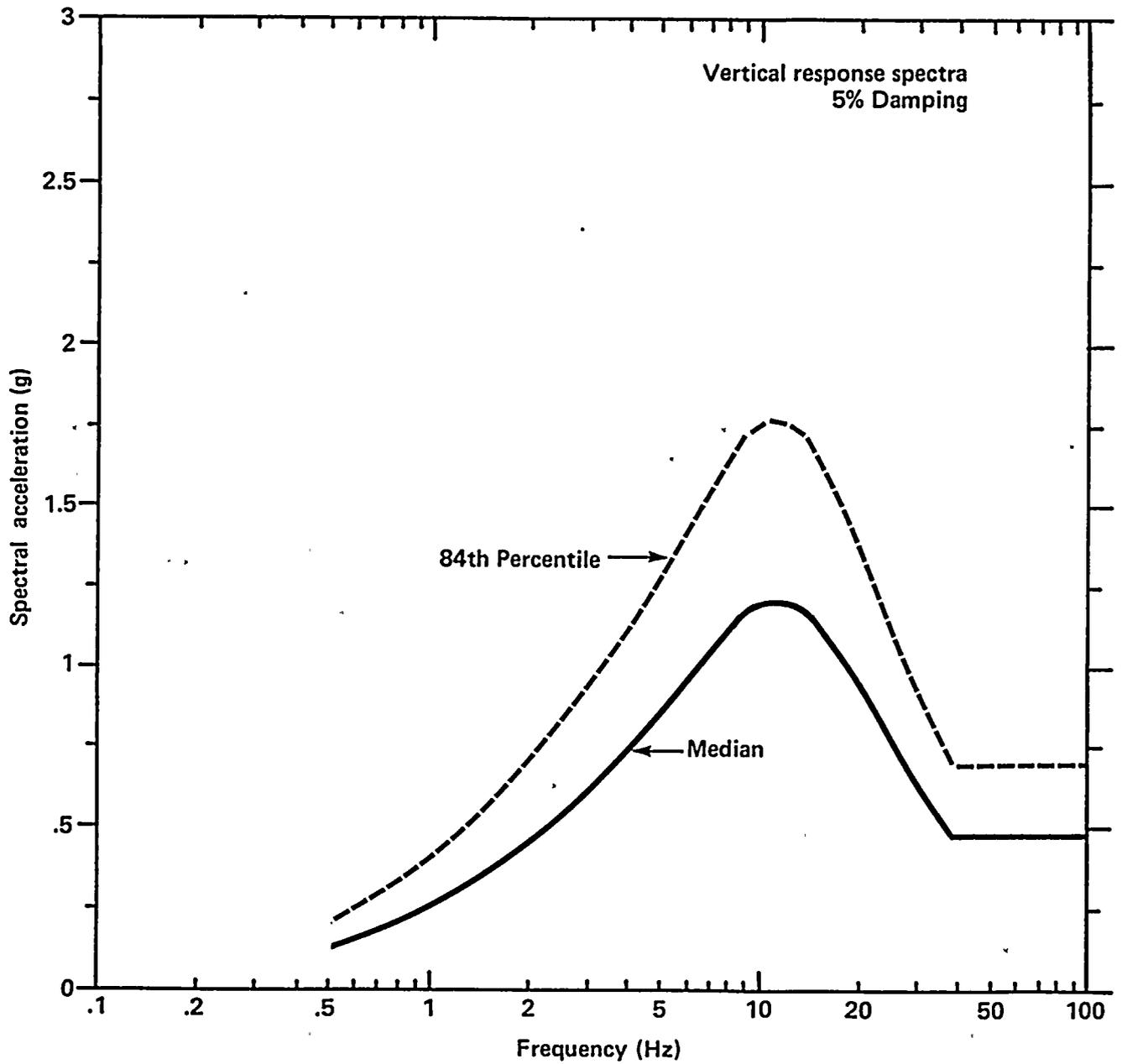


Figure 4-23

Median and 84th percentile vertical acceleration response spectra for a magnitude 7.2 earthquake at 4.5 kilometers, weighted for style of faulting: 0.65, strike-slip; 0.30, oblique; 0.05, thrust.

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Table 4-6

CHARACTERISTICS OF FAULT MODELS FOR SIMULATION OF GROUND MOTIONS AT THE DIABLO CANYON SITE (ALL SIMULATIONS ARE FOR 7.2 M_w)

Styles of Faulting	—	Strike-slip length = 88 km, dip = 90°
	—	Oblique length = 72 km, dip = 60°
	—	Thrust length = 60 km, dip = 35°
Rupture Locations	—	8 to 11 different locations of fault rupture along the Hosgri fault zone
Rupture Modes	—	Bilateral
	—	Unilateral southward
Asperity Models	—	Shallower asperity
	—	Deeper asperity
Source Functions	—	Imperial Valley aftershock
	—	Coalinga aftershock
Components	—	Vertical
	—	Plant north
	—	Plant east

Total of 116 three-component time histories; 44 strike-slip, 40 oblique, and 32 thrust.

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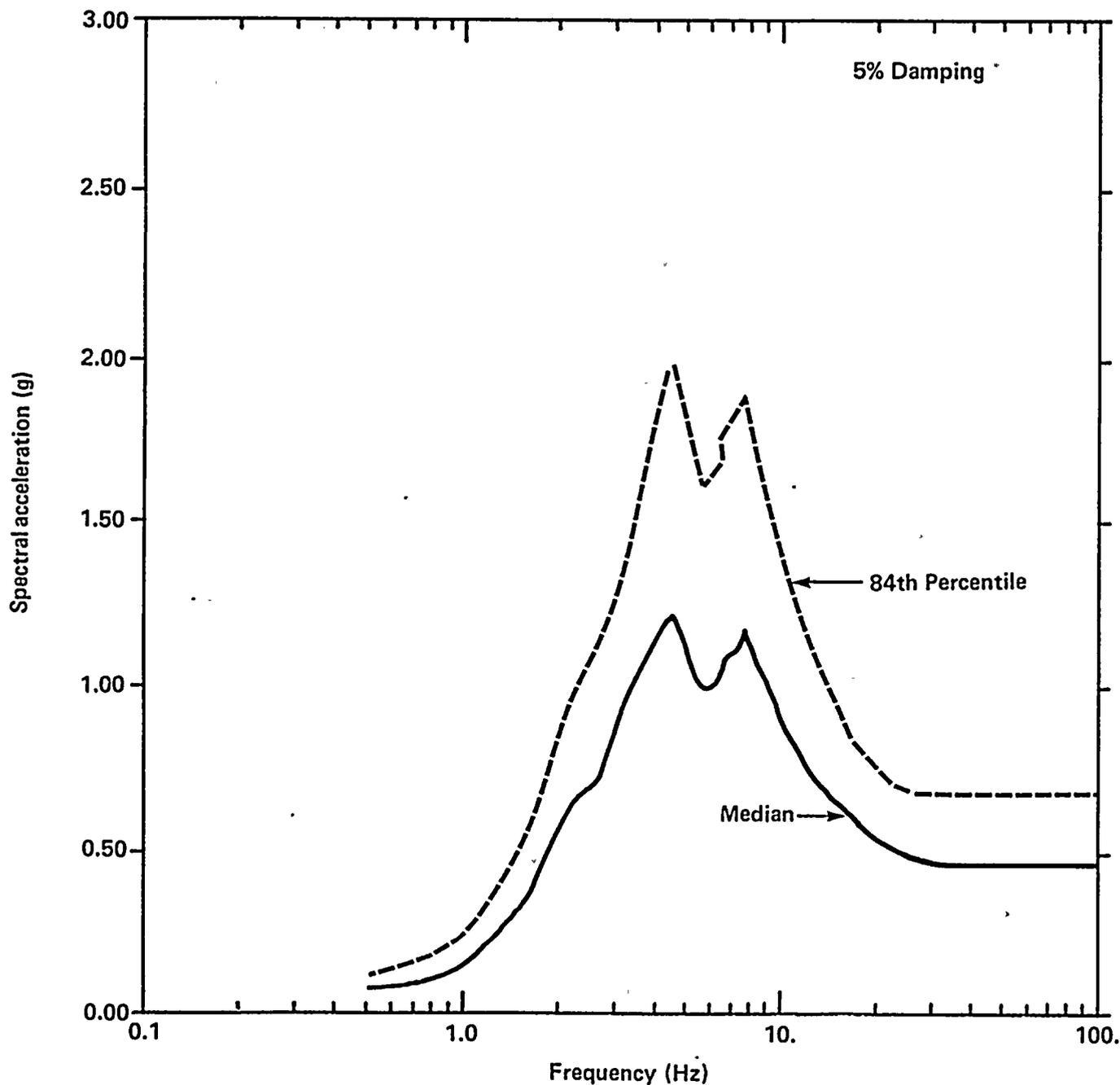


Figure 4-24

Median and 84th percentile horizontal acceleration response spectra from a magnitude 7.2 earthquake at 4.5 kilometers, based on numerical modeling studies, and weighted for style of faulting: 0.65, strike-slip; 0.30, oblique; 0.05, thrust.



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variations in source parameters of the 116 time histories summarized in Table 4-6.

In the course of validation, it was found that the ground-motion simulation procedure produced response spectra that agreed well with empirical data at frequencies above 2 hertz, as shown on Figures 4-2 and 4-3. At lower frequencies, the simulation procedure produces ground-motion amplitudes that are generally lower than are observed. The reasons for this discrepancy are well understood. The simulation procedure does not completely include surface wave contributions: they are not included in the calculated Green's functions, and the small earthquakes that are used as empirical source functions had relatively deep focal depths and thus contain little surface wave energy. Also, it is possible that the summation of source elements results in a depletion of amplitudes at frequencies around the corner frequency of the large event being simulated, as suggested by Joyner and Boore (1986). The response spectrum developed using the empirical approach is expected to provide a more reliable estimate of the response spectral shape at low frequencies.

The response spectral amplitudes at high frequencies are strongly dependent on the rate of spectral decay of the empirical source functions used in the simulation. We found that the spectral decay rate of the empirical source functions used in the simulations is compatible with that of strong motion recordings of small earthquakes at the Diablo Canyon site, as shown on Figure 4-11. To this extent, the response spectrum is site-specific, and may provide a more accurate estimate of the response spectral shape at high frequencies than is obtained from the empirical approach.

While the overall shape of the response spectrum estimated using the simulation procedure is fairly smooth, it has some fluctuations such as the trough centered at about 6 hertz. This trough is mainly attributable to irregularity in the source spectra of the Coalinga aftershocks used as empirical source functions, but is also present in the source spectra of the Imperial Valley aftershocks. This coincidence is believed to be

fortuitous, and thus the fluctuations in the shape of the response spectrum are not considered to have significance for the representation of the response spectral shape at Diablo.

SELECTION OF SITE-SPECIFIC RESPONSE SPECTRA FOR DIABLO CANYON

The response spectra obtained from the three approaches described above (namely, the statistics of near-source records, using the attenuation relationships developed from regression analyses of recorded ground motions, and numerical ground-motion modeling studies) are compared with each other on Figure 4-25 for the median level, and on Figure 4-26 for the 84th percentile level. The response spectra obtained using the attenuation relationships from regression analyses envelop the corresponding response spectra obtained from the statistics of near-source records and those from numerical ground-motion modeling studies.

For frequencies above about 3 hertz, the response spectra from the three approaches are in good agreement. Specifically: (1) the response spectra from the two empirical approaches differ by about 10 percent at the median level and by less than 5 percent at the 84th percentile level, (2) the response spectra obtained from the numerical modeling studies are exceeded by the corresponding spectra from the two empirical approaches by less than 5 to about 20 percent, and (3) in the frequency range of about 3 to 10 hertz, the 84th percentile response spectra from all three approaches are, overall, in good agreement. Because this frequency range is of primary interest for the Long Term Seismic Program seismic margin studies, the close agreement among the results from the three approaches enhances our confidence in the accuracy of the predicted ground motions at the site.

In the frequency range below 3 hertz, the median and 84th percentile response spectra obtained from the attenuation relationships exceeds the corresponding spectra obtained from the statistics of near-source records by as much as about 25 percent. In this frequency range, the response



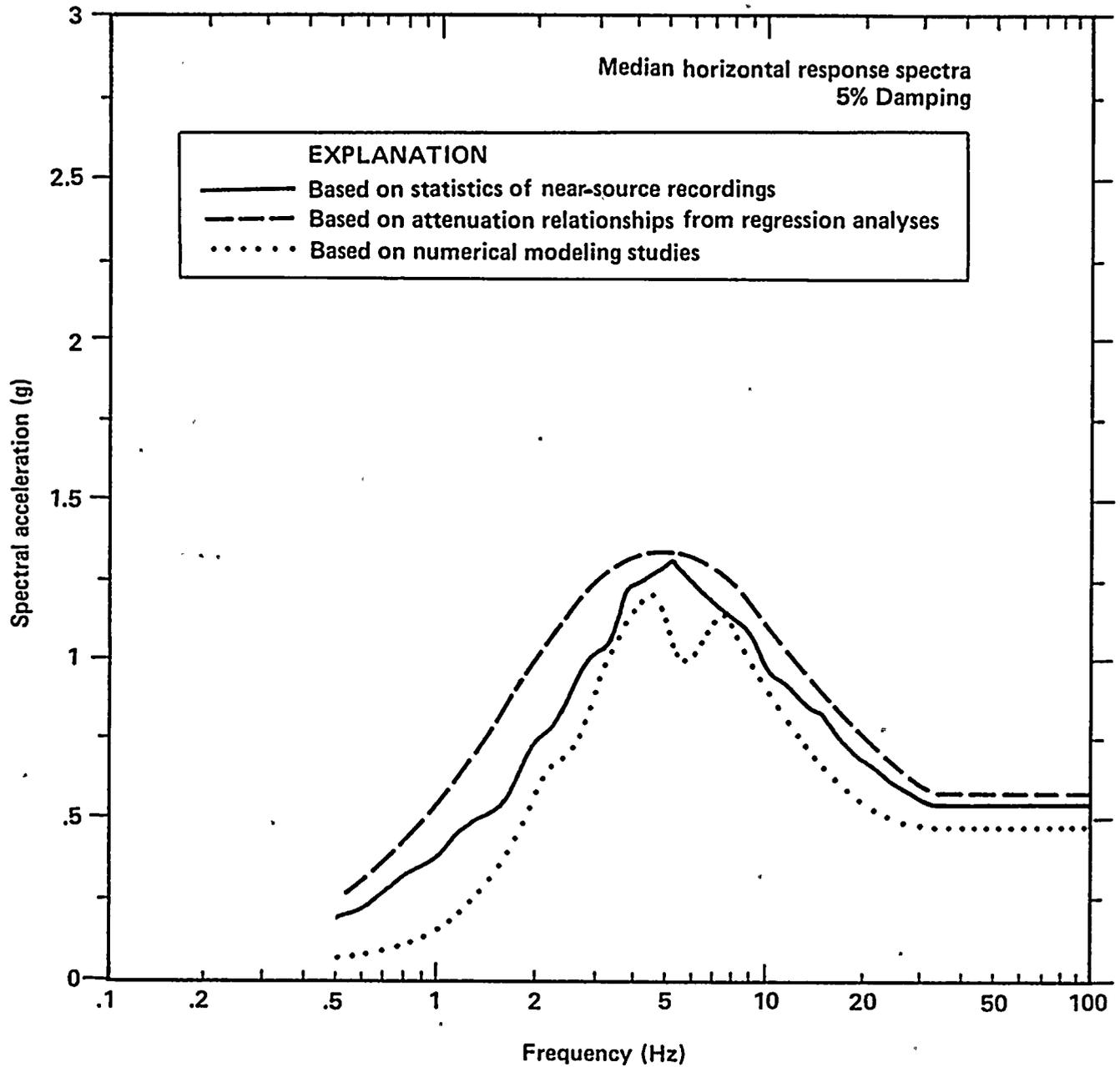


Figure 4-25

Comparison of the site-specific median horizontal acceleration response spectra obtained from three different approaches.

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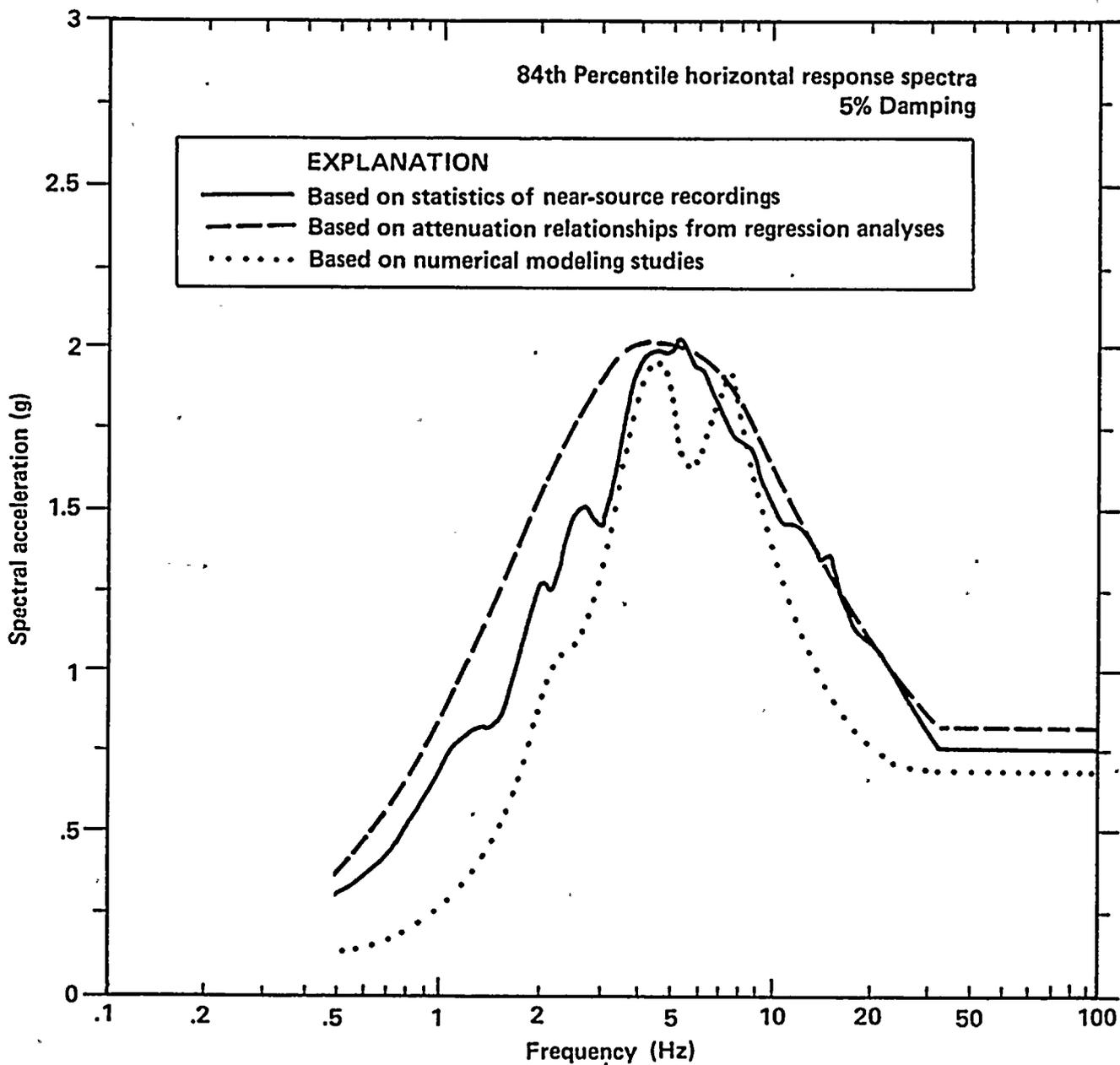


Figure 4-26

Comparison of the site-specific 84th percentile horizontal acceleration response spectra obtained from three different approaches.

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spectra from the two empirical approaches exceed the corresponding spectra from the numerical modeling studies by a substantial margin. Possible causes for this underprediction in the numerical modeling results have been discussed in the preceding section. It should be noted that the discrepancy in ground-motion estimates in this lower frequency range is of little significance to the present seismic margin studies.

For ease of application and to be consistent with past NRC practice, only one set of smoothed response spectra was selected for the present seismic margin studies. Of the three sets of horizontal response spectra, the ones derived from the attenuation relationships not only have smooth spectral shapes but also envelop the other two sets of response spectra throughout the frequency range. Therefore, we have conservatively selected this set of acceleration response spectra for use in the deterministic seismic margin studies. The results of these studies are presented in Chapter 7 of this summary report.

Figure 4-27 shows the normalized spectral shape (S_a/PGA) for the median and 84th percentile horizontal spectra based on attenuation relationships from regression analysis, shown on Figure 4-22. The close similarity between these two curves indicates that we can make direct scaling of the calculated Plant responses from input ground motions at one percentile level to another.

For deterministic seismic margin studies, we have used corresponding vertical acceleration response spectra shown on Figure 4-23. These vertical response spectra were developed from the horizontal response spectra shown on Figure 4-22 using the procedures described previously.

Ground-Motion Input Data for Engineering Analyses

The second objective of the ground-motion studies is to provide appropriate ground-motion input data for engineering analyses. We have achieved this objective by providing specific ground-motion input data needed for the seismic

hazard analysis, the seismic fragility evaluation and the soil/structure interaction analyses.

GROUND-MOTION INPUT DATA FOR SEISMIC HAZARD ANALYSIS

The seismic hazard analysis makes probabilistic estimates of ground motions at the Diablo Canyon site. It uses a logic tree approach requiring seismic source characterization and ground-motion inputs. The ground-motion inputs include the peak ground acceleration and response spectral acceleration attenuation relationships, and the scaling factors for the style of faulting. The ground-motion input data provided for the seismic hazard analysis are described below.

Attenuation Relations. Attenuation relationships were provided for the seismic hazard analysis for peak ground acceleration, for spectral acceleration at five discrete frequencies: 2, 4, 8, 14, 25 hertz, and for average spectral acceleration over two frequency ranges: 3 to 8.5 hertz and 5 to 14 hertz. These relationships were developed from the regression analyses of the Long Term Seismic Program strong-motion data base.

The frequency range of 3 to 8.5 hertz was selected because it encompasses the highest portion of the horizontal acceleration response spectra of the near-source rock recordings from large-magnitude earthquakes. Figure 4-28 shows schematically the definition of the average spectral acceleration over the frequency range of 3 to 8.5 hertz. The average spectral acceleration in the frequency range 5 to 14 hertz was used as a reference ground-motion parameter in the seismic fragility evaluation.

The median attenuation relationships for the averaged S_a over the frequency band 3 to 8.5 hertz are shown on Figure 4-29 for strike-slip faulting and on Figure 4-30 for thrust faulting.

The strong-motion recordings presently available at near-source distances from large earthquakes are not abundant enough to provide strong constraints on the dependence of ground motions on distance in these distance and magnitude ranges. We have applied our simulation procedure



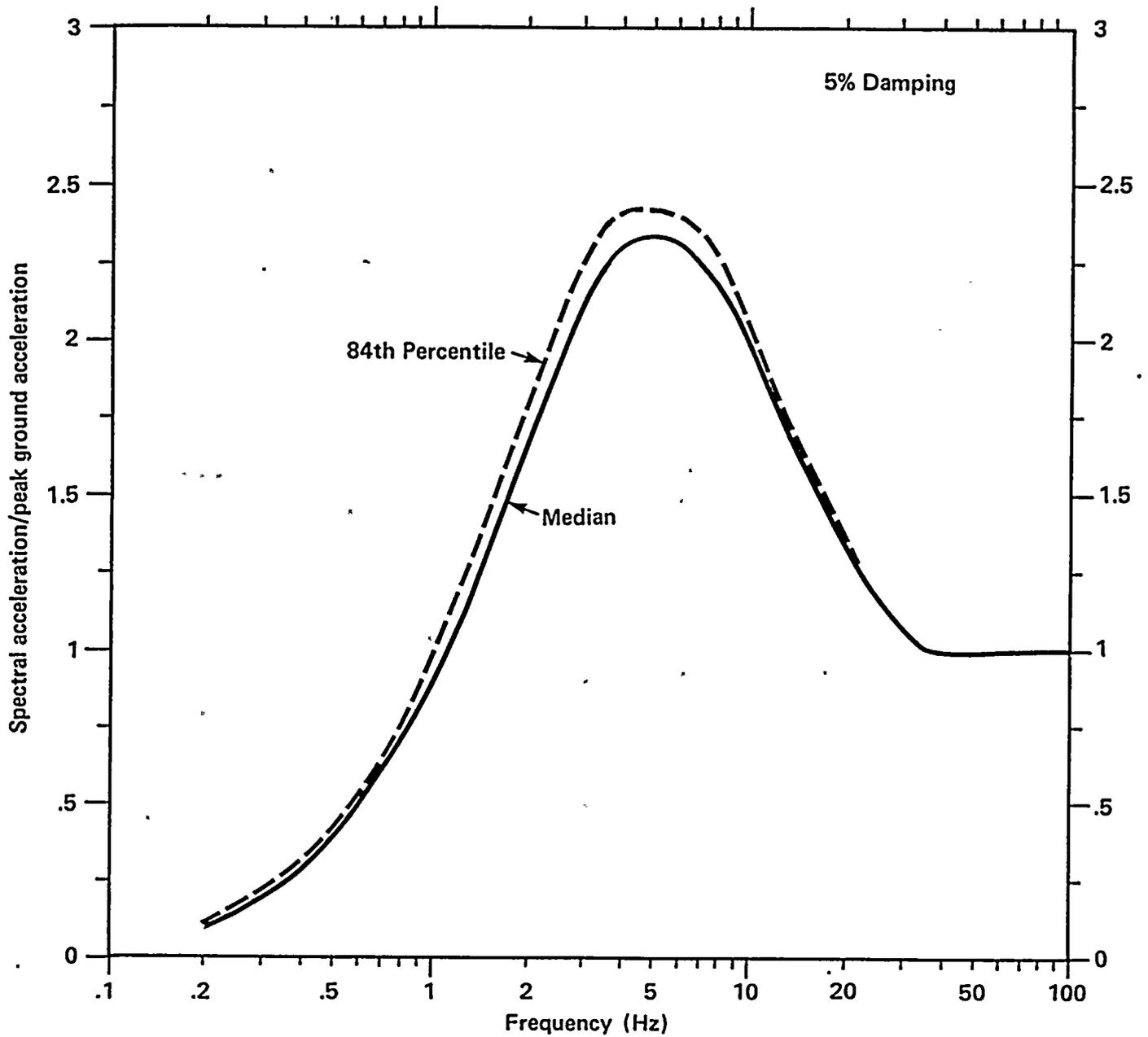


Figure 4-27
Normalized spectral shapes for the median and 84th percentile site-specific horizontal response spectra selected for the deterministic studies.



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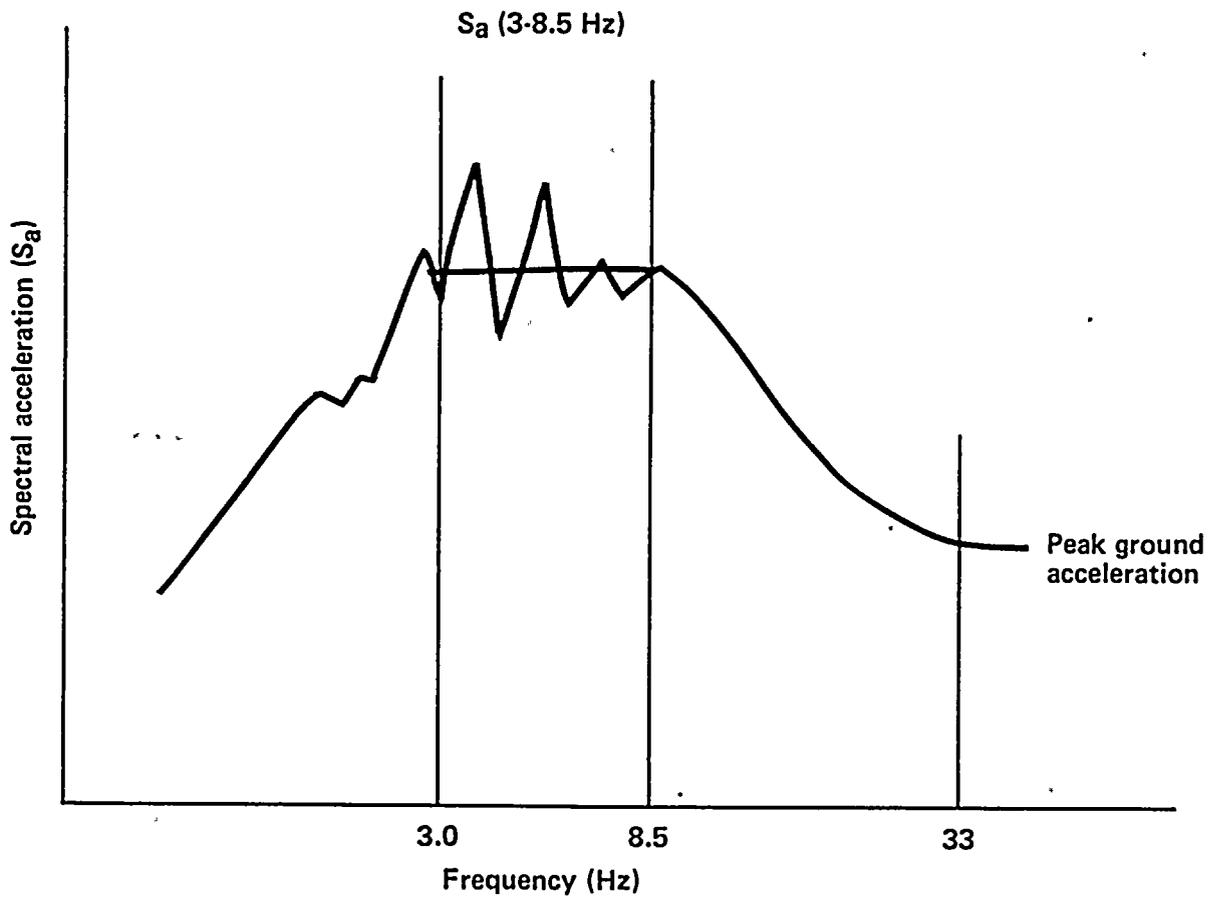


Figure 4-28
Schematic diagram showing definition of spectral acceleration averaged over a frequency range of 3 to 8.5 hertz.



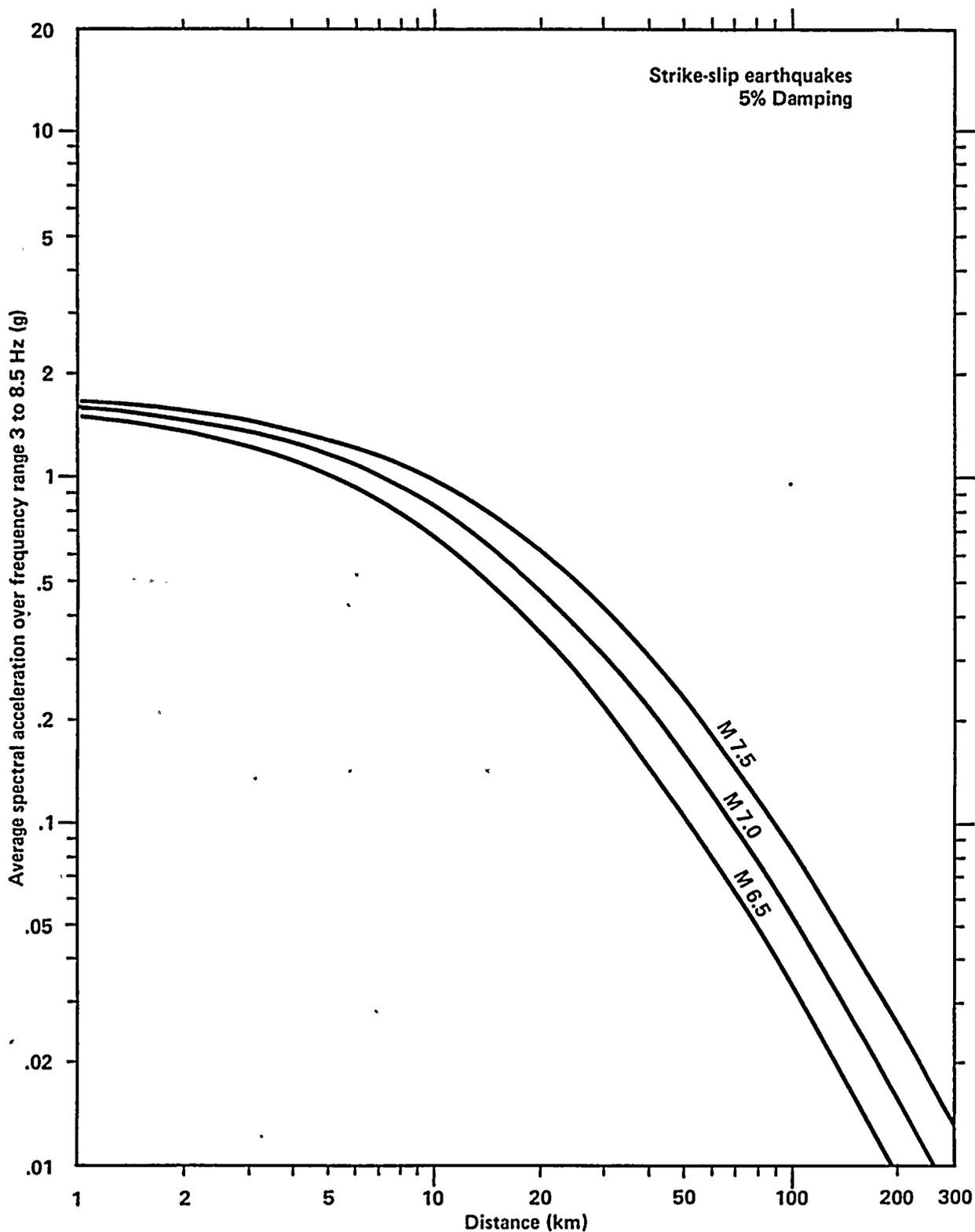


Figure 4-29

Attenuation relationships for response spectral acceleration averaged over frequency range of 3 to 8.5 hertz for strike-slip earthquakes of magnitudes 6.5, 7.0, and 7.5.



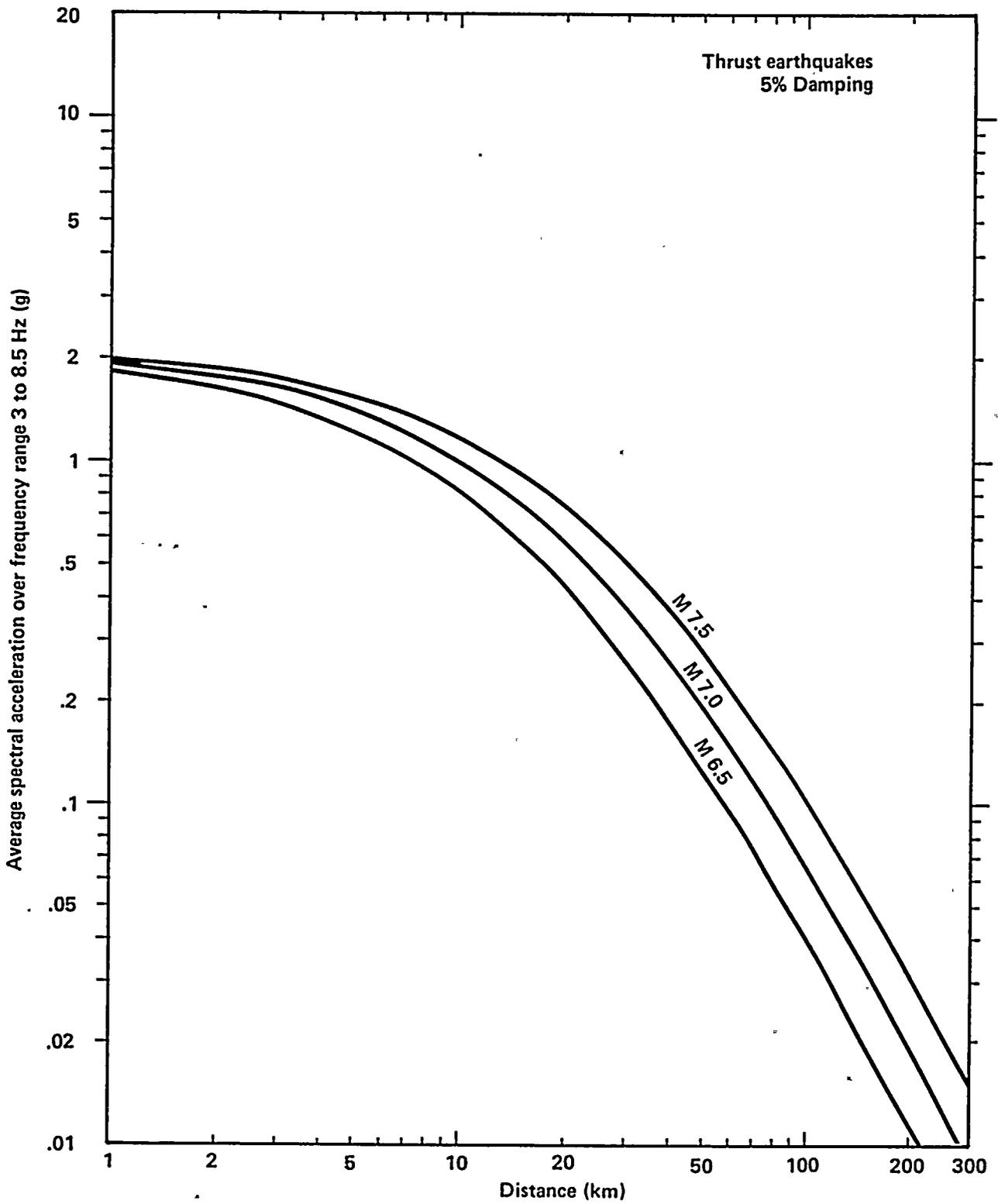


Figure 4-30

Attenuation relationships for response spectral acceleration averaged over frequency range of 3 to 8.5 hertz for thrust earthquakes of magnitudes 6.5, 7.0, and 7.5.

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to evaluate the dependence of ground motions at the Diablo Canyon site on distance. This was done by making simulations at seven locations along a vertical strike-slip fault at each of several fault distances. A moment magnitude 7 earthquake was assumed for these simulations. The logarithms of the peak acceleration and the average spectral acceleration in the frequency band of 3 to 8.5 hertz were averaged over the seven stations for both unilateral and bilateral rupture propagation to provide a median value for each fault distance. The results, as plotted on Figure 4-31, show a gradual decrease of the peak ground acceleration with increasing distance. The trend is in good agreement with the corresponding empirical attenuation relationship obtained from regression analysis, as shown on the same figure.

Style of Faulting. The second category of ground-motion input data for the seismic hazard analysis consists of a set of ground-motion scaling factors for different styles of faulting. The evaluation of these factors is given above in the section describing the development of site-specific response spectra.

GROUND-MOTION INPUT DATA FOR SEISMIC FRAGILITY EVALUATION

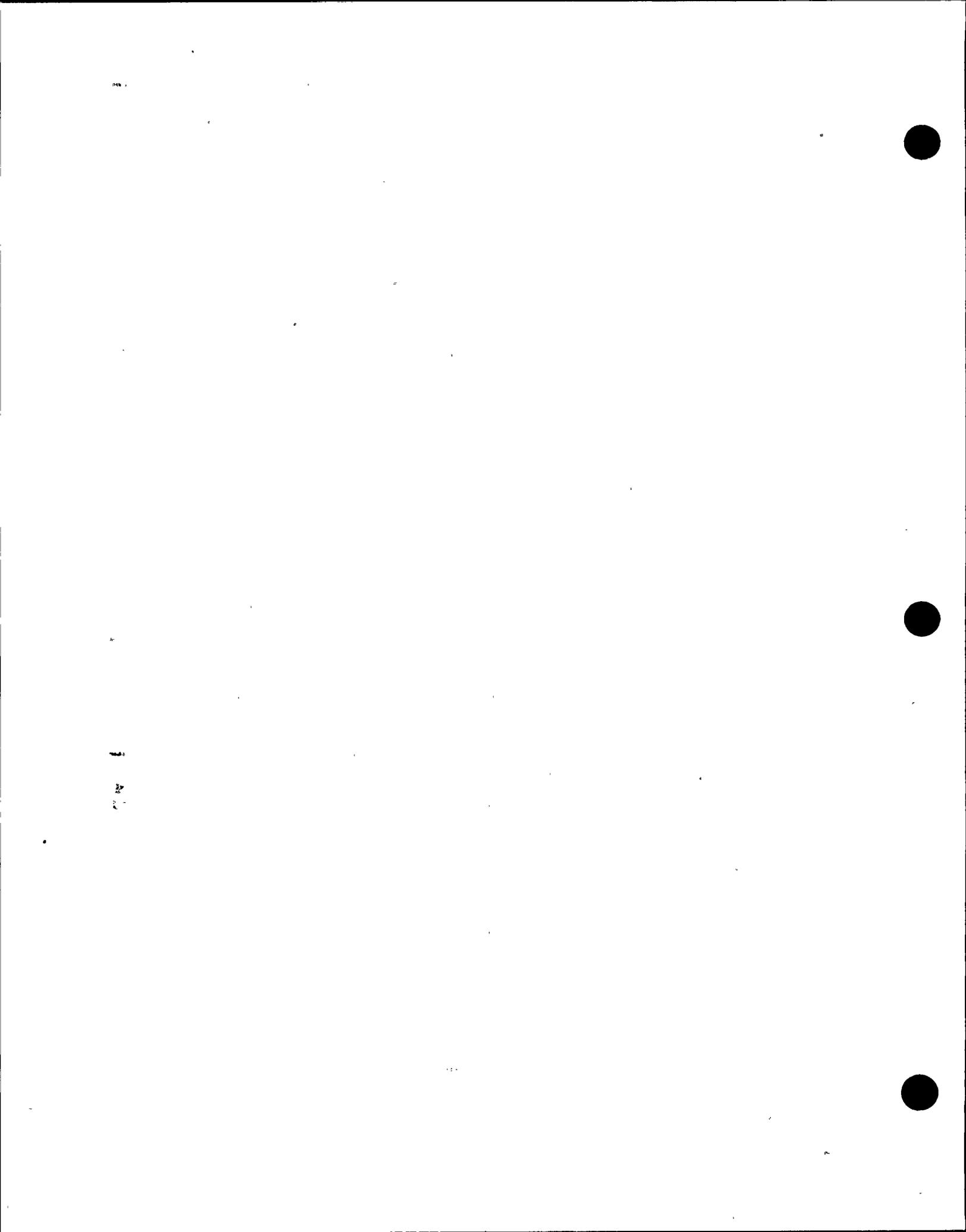
Large suites of acceleration time histories have been provided as input for variability analyses in the seismic fragility evaluation. These time histories were selected to represent ground motions at a rock site within 10 kilometers of the fault rupture surface due to shallow crustal earthquakes having moment magnitudes ranging from 6.5 to 7.5 and having strike-slip, oblique, or thrust fault mechanisms. These selection criteria were guided by the results of the Long Term Seismic Program seismic hazard analysis, as well as by the current seismic source characterization of the Hosgri fault zone. A total of 26 sets of acceleration time histories were developed. They included 12 sets of empirically developed and 14 sets of numerically simulated time histories.

The two horizontal components of the 12 sets of empirical time histories were treated as interchangeable with respect to the orientations of

the Plant structures. The 14 sets of numerically simulated time histories were included not only to increase the total number of time histories but also to provide a more balanced representation of potential styles of faulting. Since these ground-motion simulations were generated by the simulation procedure in a site-specific manner, the two horizontal components of the simulated time histories could be provided specifically in the plant-north and plant-east directions and were not treated as interchangeable with respect to the orientations of the plant structures. This resulted in two separate suites of 38 horizontal time histories: one suite combined the 24 empirical components with the 14 simulated east-west components, and the other combined the 24 empirical horizontal components with the 14 simulated north-south components.

Development of Empirical Time Histories. The 12 empirical acceleration time histories were obtained from actual recordings of eight earthquakes, as shown in Table 4-7. These time histories were selected from records having the largest ground motions. Four of the records met all the selection criteria and were directly adopted for present use. These include the Tabas record of the 1978 Tabas earthquakes, the Site 1 record of the 1985 Nahanni earthquake, the Karakyr Point record of the 1976 Gazli earthquake, and the Pacoima Dam record of the 1971 San Fernando earthquake.

Four other records met all the selection criteria except that their source-to-site distances were 10 kilometers or greater. These include the Dayhook record of the 1978 Tabas earthquake, the Lake Hughes No. 12 and Castaic records of the 1971 San Fernando earthquake, and the Pleasant Valley Pump Station record of the 1983 Coalinga earthquake. These records were adjusted to higher amplitudes by applying a distance scaling factor to bring the records from their original distances to a common distance of 5 kilometers. The distance scaling factor was based on several published relationships (Joyner and Boore, 1981, 1982; Campbell, 1981, 1987; Seed and Schnabel, 1980; Sadigh, 1983; Sadigh and others, 1986).



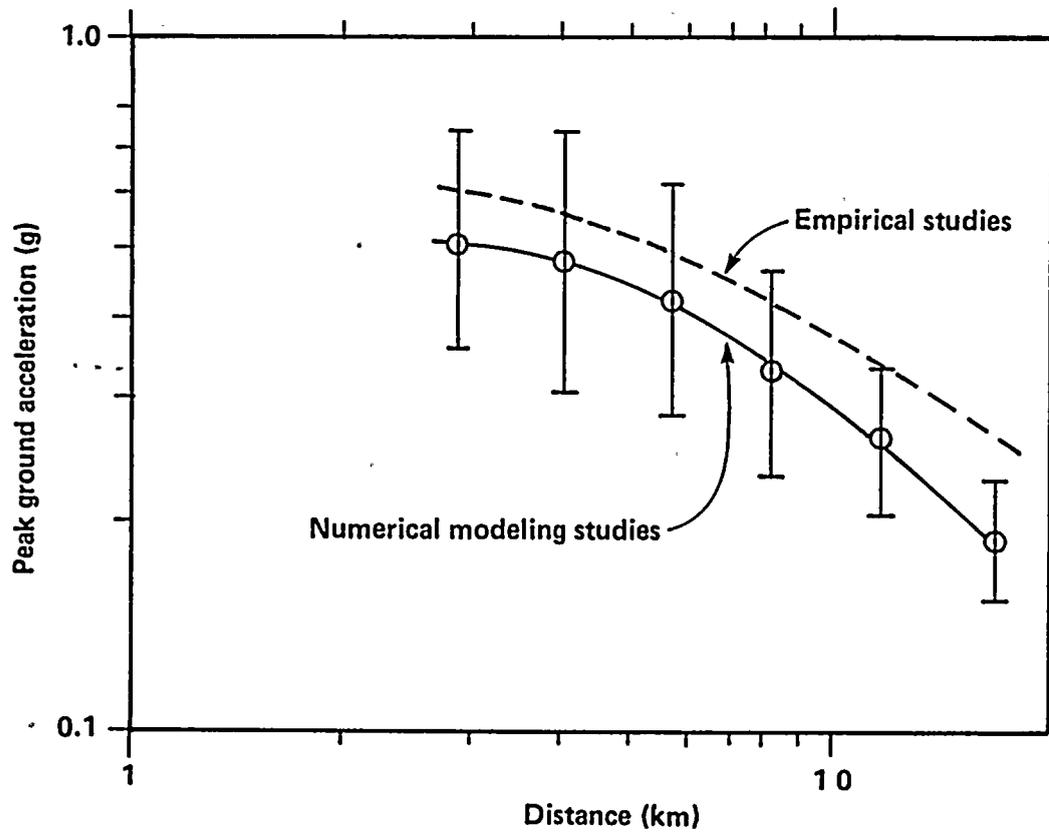


Figure 4-31

Dependence of horizontal peak ground acceleration on source-to-site distance for a magnitude 7.0 strike-slip earthquake. Shown are the median (open circles) and 16th to 84th percentile range (vertical bars) values from numerical modeling studies. Also shown for comparison is the median attenuation relationship from empirical studies.



Table 4-7
EARTHQUAKE RECORDS USED TO DEVELOP TIME HISTORIES FOR
FRAGILITY STUDIES

<u>Earthquake</u>	<u>Recording Station</u>	<u>Magnitude Used</u>	<u>Distance (km)</u>	<u>Style of Faulting</u>	<u>Adjustment</u>
1966 Parkfield	Temblor	6.1	10	Strike-slip	Distance and magnitude
1971 San Fernando	Pacoima Dam	6.6	3	Thrust	None
1971 San Fernando	Lake Hughes No. 12	6.6	20	Thrust	Distance
1971 San Fernando	Castaic	6.6	25	Thrust	Distance
1976 Gazli	Karakyr Point	6.8	3	Reverse	None
1978 Tabas	Tabas	7.4	3	Thrust	None
1978 Tabas	Dayhook	7.4	17	Thrust	Distance
1979 Imperial Valley	Differential Array	6.5	5	Strike-slip	Site response
1979 Imperial Valley	El Centro No. 4	6.5	4	Strike-slip	Site response
1983 Coalinga	Pleasant Valley Pump Station (Switchyard)	6.5	10	Reverse	Distance
1984 Morgan Hill	Coyote Lake Dam	6.2	0.1	Strike-slip	Magnitude
1985 Nahanni	Site 1	6.8	6	Thrust	None

Two records met all the selection criteria except that their recording sites were on alluvium and were included to enhance the representation of strike-slip faulting in the data base. They were the El Centro No. 4 and the Differential Array Station records of the 1979 Imperial Valley earthquake. These two records were adjusted using a frequency-dependent spectral scaling function to modify their characteristics from soil to rock sites. The site-response scaling function was based on the results of empirical studies of response spectra (Seed and others, 1976; Seed and Idriss, 1982; Joyner and Boore, 1982; Sadigh, 1983; Sadigh and others, 1986). This site-response correction resulted higher peak ground acceleration and response spectral acceleration at high frequencies. At the same time, it resulted in lower response spectral acceleration at low frequencies.

The Coyote Lake Dam record of the 1984 Morgan Hill earthquake met all the selection criteria except that the earthquake magnitude was less than 6.5. This record was adjusted by using a frequency-dependent spectral scaling function to increase its magnitude by 3/4 unit. The magnitude scaling function was based on empirical studies of Fourier amplitude (Trifunac, 1976; McGuire, 1978) and response spectra (Joyner and Boore, 1982; Sadigh, 1983; Sadigh and others, 1986). This magnitude adjustment resulted in an increase of response spectral acceleration for all frequencies, with greater increase for low frequencies. The remaining record, the Temblor record of the 1964 Parkfield earthquake, was adjusted to increase the magnitude by 3/4 unit and reduce the distance from 10 kilometers to 5 kilometers to meet the selection criteria.

Combination of the scalings and adjustments resulted in increases in the peak ground acceleration by a factor ranging from about 1.2 to 3.2 for the eight records that were modified for magnitude, distance, site response, or combinations of these factors.

These adjusted time histories were scaled up to different levels of spectral acceleration when used as input for variability studies in the seismic fragility evaluation. The emphasis in developing

these time histories is on providing a measure of the spectral shape and the associated dispersion.

Development of Simulated Time Histories. To provide a larger number of time histories for statistical analysis, and to provide a more balanced representation in the styles of faulting, a suite of 14 time histories was selected from a large set of 120 simulated time histories. These were combined with the 12 empirical time histories for use in the seismic fragility evaluation. Table 4-8 lists these 14 simulated acceleration time histories including a description of the fault rupture type used in the simulations. The 120 time histories from which the 14 were selected constitute a large sample of simulated ground motions at the Diablo Canyon site covering wide ranges of fault type, fault geometry, location of the rupture segment, rupture mode, and asperity distributions in the fault models for the Hosgri fault zone. These model parameters were based on seismic source characteristics of the Hosgri fault zone as well as on knowledge gained from published studies of recent California earthquakes. Empirical source functions derived from both the 1979 Imperial Valley and the 1983 Coalinga aftershocks were used.

Three styles of faulting were simulated: pure strike-slip faulting on a vertical fault plane, oblique faulting on an inclined fault plane dipping 60 degrees east beneath the Diablo Canyon site, and pure thrust faulting on an inclined fault plane dipping 35 degrees east beneath the Diablo Canyon site. A moment magnitude 7 was assumed for all simulations. Different rupture modes were simulated, including bilateral rupture starting at the center, unilateral rupture starting at the north end, and unilateral rupture starting at the south end of the fault.

Of the total of 120 sets of simulated time histories, 40 sets were simulated for each of the three styles of faulting. The 14 time histories listed in Table 4-8 were selected from the above suite of 120 simulations such that: (1) The 14 simulated time histories would offset the imbalance in the styles of faulting in the empirical time histories. Accordingly, simulations for seven oblique, five strike-slip, and two thrust faulting events were



Table 4-8
**FAULT MODELS USED TO GENERATE SIMULATED TIME HISTORIES
 FOR FRAGILITY STUDIES**

<u>Record Number</u>	<u>Style of Faulting</u>	<u>Rupture Mode</u>	<u>Source Functions</u>
1	Strike-slip	Bilateral	Coalinga aftershock
2	Strike-slip	Bilateral	Imperial Valley aftershock
3	Strike-slip	Unilateral-N	Imperial Valley aftershock
4	Strike-slip	Unilateral-S	Coalinga aftershock
5	Strike-slip	Unilateral-S	Imperial Valley aftershock
6	Oblique	Bilateral	Coalinga aftershock
7	Oblique	Bilateral	Coalinga aftershock
8	Oblique	Bilateral	Imperial Valley aftershock
9	Oblique	Unilateral-N	Coalinga aftershock
10	Oblique	Unilateral-N	Imperial Valley aftershock
11	Oblique	Unilateral-S	Coalinga aftershock
12	Oblique	Unilateral-S	Imperial Valley aftershock
13	Thrust	Bilateral	Coalinga aftershock
14	Thrust	Unilateral-N	Coalinga aftershock



selected; (2) The selected cases should have other source parameters spanning the range of the 120 cases; and (3) the median response spectrum and its associated dispersion of the 14 selected time histories should conform to those of the original suite of 120 time histories.

Figure 4-32 shows the median and 84th percentile acceleration response spectra of the combined suite of 38 horizontal time histories consisting of the 24 empirical horizontal components and the 14 simulated Plant east/west components. Figure 4-33 shows a similar plot for the combined suite of 38 horizontal time histories consisting of the 24 empirical horizontal components and the 14 simulated Plant north/south components. Comparison of the two figures indicates that the response spectra for the Plant north/south components of motion are very similar in spectral shape, but slightly higher in spectral level than the Plant east/west component.

Consistency Checks. Consistency checks were made between the spectral shapes of the ground motions used as inputs to the fragility studies and the soil/structure interaction analyses. Figures 4-34 and 4-35 show a comparison between the normalized spectral shapes for the median response spectra based on the two suites of 38 time histories used for the fragility studies and the normalized spectral shape of the 1987 response spectrum (Figure 4-36) used for the soil/structure interaction analyses. For the turbine building nonlinear analyses, a set of 25 horizontal acceleration time histories was developed, mostly from the same empirical records listed in Table 4-7, and was designated Phase IIIA fragility input ground motions. The median spectral shape for this set of time histories is also shown on both Figures 4-34 and 4-35. In both figures, all response spectra were normalized to an average spectral acceleration of 2.25 g in the frequency range 3 to 8.5 hertz to be consistent with the fragility studies (Chapter 6). These comparisons show close agreement in the average spectral shapes of the input ground motions used for the fragility studies and those used for the soil/structure interaction analyses.

GROUND-MOTION INPUT DATA FOR SOIL/STRUCTURE INTERACTION ANALYSES

The ground-motion input data required for the soil/structure interaction analyses are as follows:

- Site-specific acceleration response spectra for soil/structure interaction analyses with coherent ground motions. For this purpose three sets of acceleration time histories, modified to match the site-specific spectra, were also required. These spectra and time histories were developed to represent the ground motions at the Diablo Canyon site.
- Three sets of acceleration time histories for use in soil/structure interaction analyses of containment basemat uplift effects. The same three sets of time histories as those mentioned above were used for this purpose.
- Spatial incoherence functions for soil/structure interaction analyses with incoherent ground motions.
- Power and cross-power spectra for soil/structure interaction analyses with incoherent ground motions.

Site-Specific Response Spectrum for Soil/Structure Interaction Analyses. A normalized horizontal acceleration response spectrum at 5 percent damping was provided for input to the SASSI program to assess the soil/structure interaction effects due to coherent ground motions. This response spectrum was developed to provide a representative response spectral shape of the site-specific ground motions expected at the Diablo Canyon site. At the time when the site-specific response spectrum was developed in 1987, the seismic source characterization studies were still in progress, and detailed assessment of the source characteristics of the maximum earthquake on the Hosgri fault zone was not yet available. So for the purpose of estimating the site-specific response spectrum, we assumed a moment magnitude 7 earthquake rupturing a segment of the Hosgri fault zone with a closest source-to-site distance of 4.5 kilometers. At the same time, the style of faulting of this earthquake was conservatively



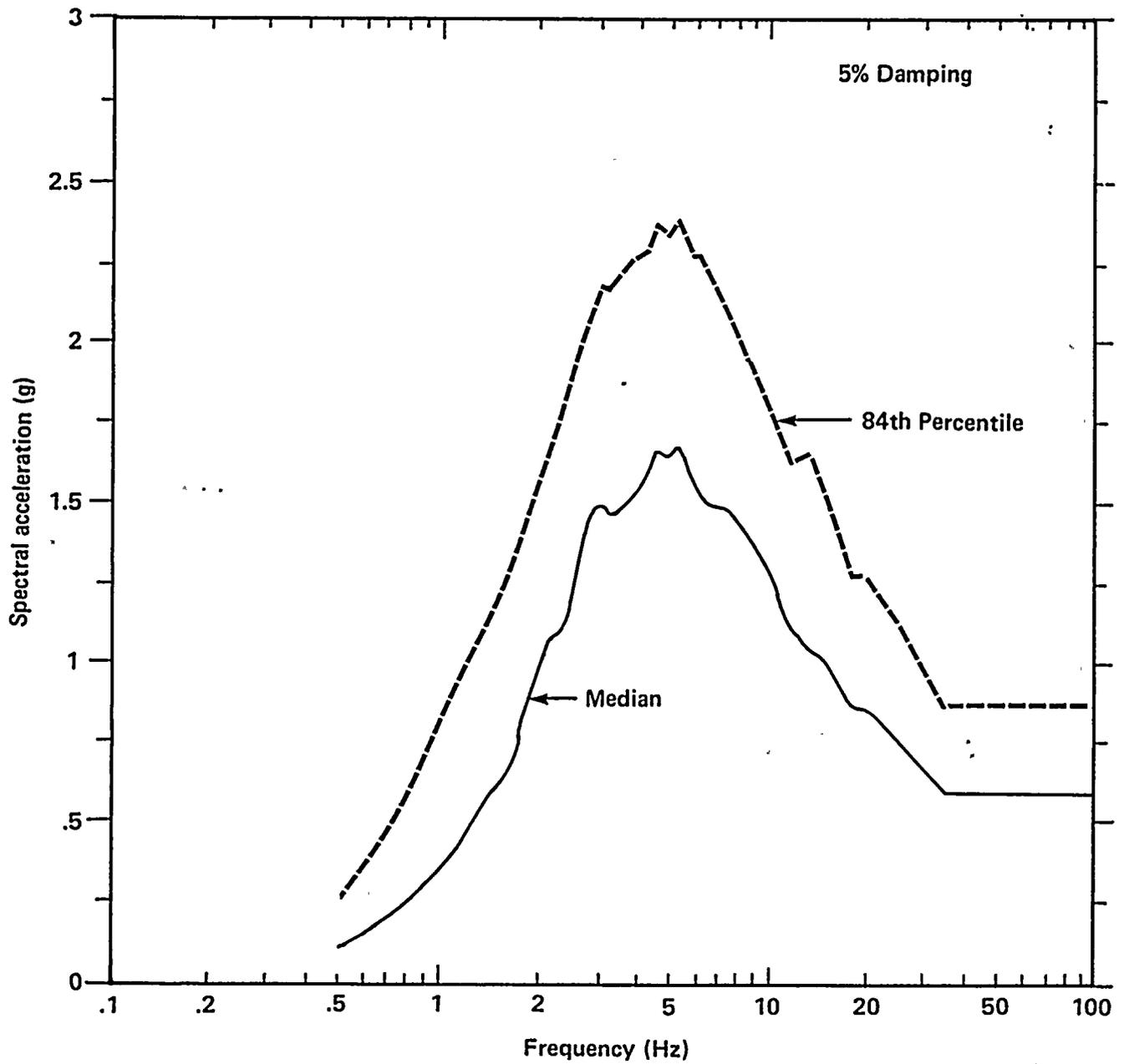


Figure 4-32

Median and 84th percentile acceleration response spectra based on 24 horizontal-component and 14 simulated east-west-component time histories used as input to the fragility studies.



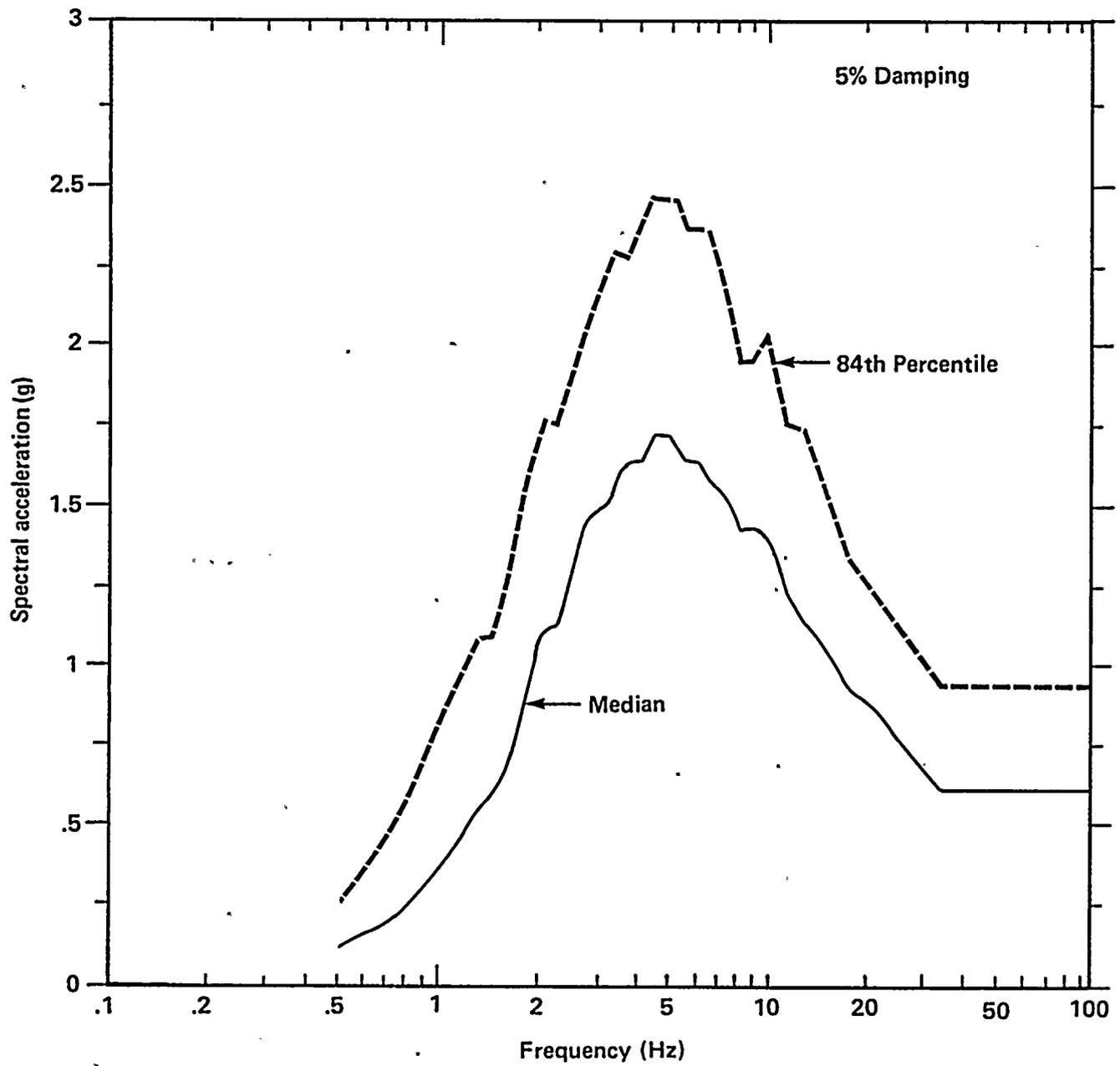
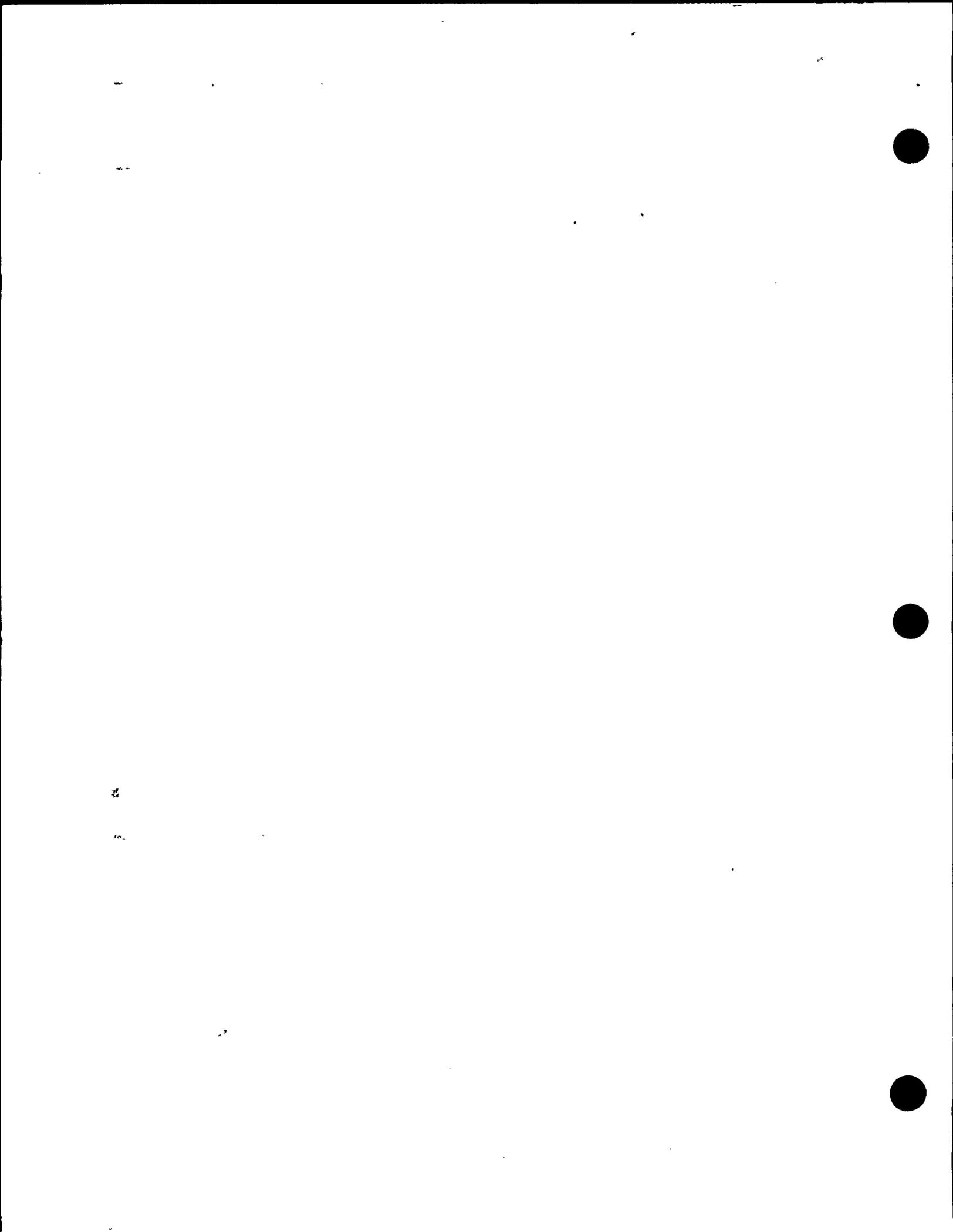


Figure 4-33
 Median and 84th percentile acceleration response spectra based on 24 empirical horizontal-component and 14 simulated north-south-component time histories used as input to the fragility studies.



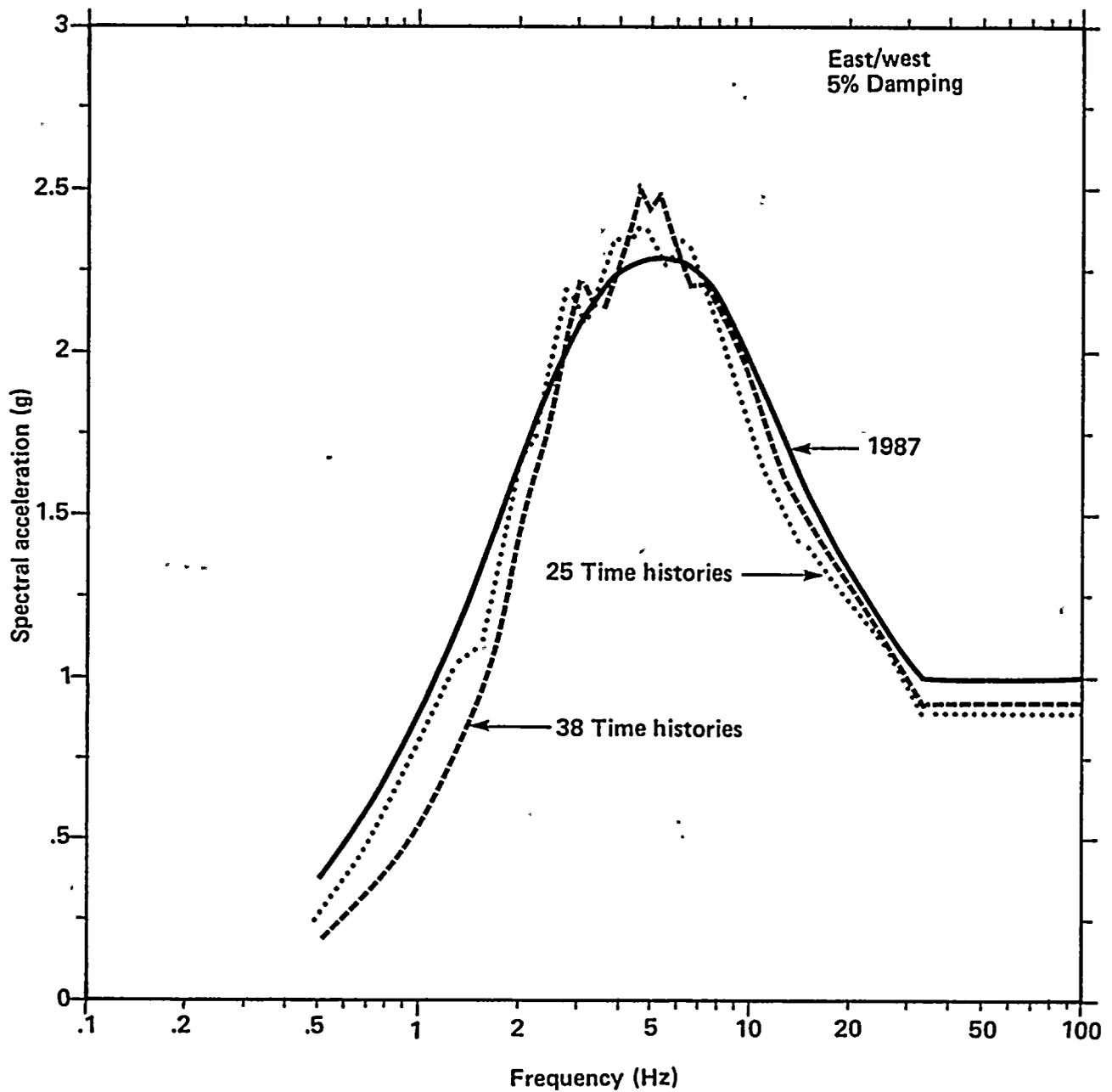


Figure 4-34

Comparison between the normalized spectral shapes of the 1987 response spectrum used for the soil/structure interaction analyses and the median response spectra based on east-west-component time histories used as input to the fragility studies. Also shown is the normalized spectral shape of the median response spectrum based on the time histories for the Phase IIIA fragility studies. All response spectra are normalized to an average spectral acceleration of 2.25g in the frequency range 3 to 8.5 hertz.



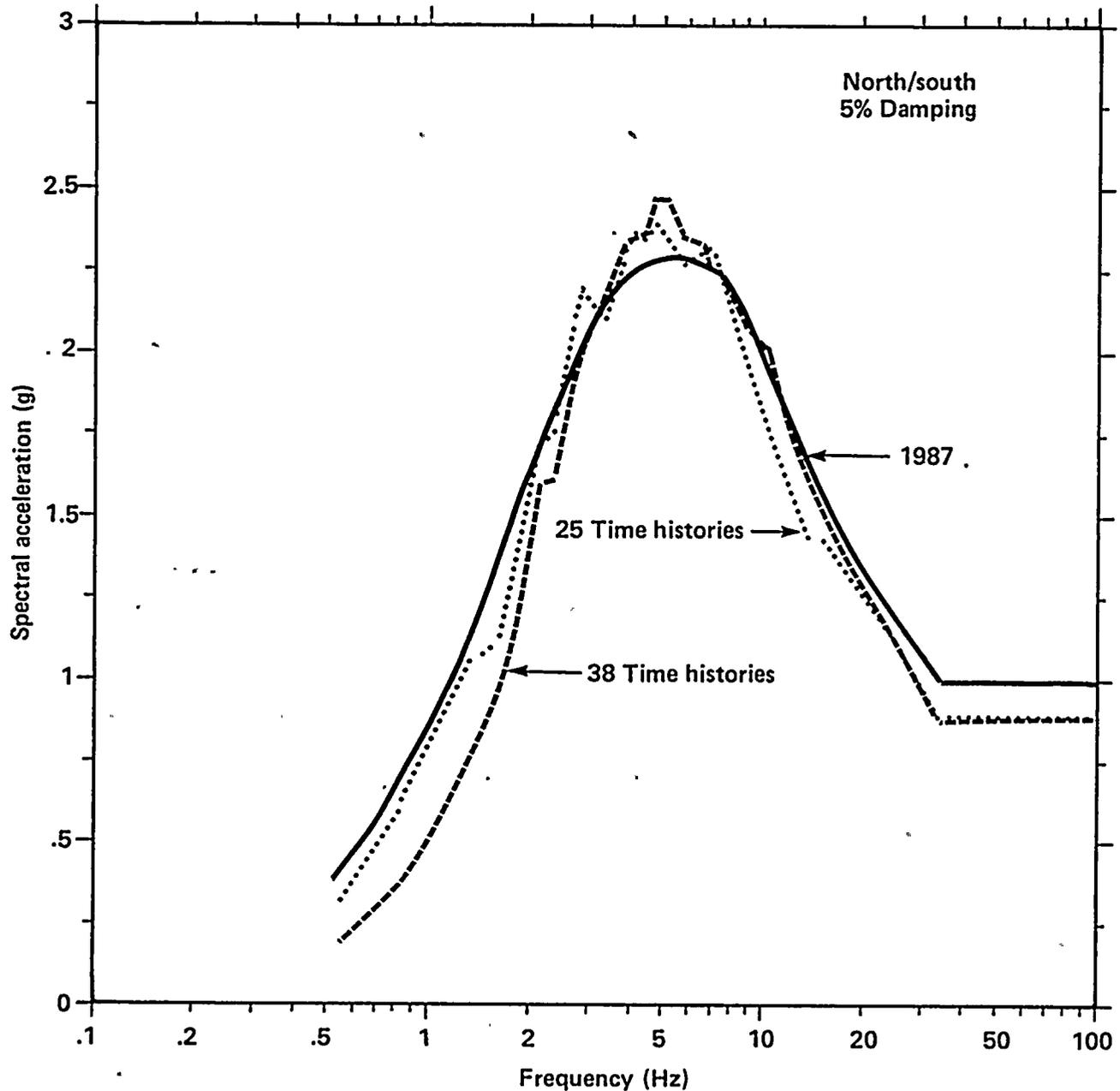


Figure 4-35

Comparison between the normalized spectral shapes of the 1987 response spectrum used for the soil/structure interaction analysis median response spectra based on north-south-component acceleration time histories used as input to the fragility studies. Also shown is the normalized spectral shape of the median response spectrum based on the time histories for the Phase IIIA fragility studies. All response spectra are normalized to an average spectral acceleration of 2.25g in the frequency range 3 to 8.5 hertz.

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assumed to have equal probability of strike-slip and thrust faulting. This acceleration response spectrum was derived from the peak ground acceleration and spectral acceleration attenuation relationships obtained from regression analyses performed on the up-to-date strong-motion data base. The normalized spectral shape (spectral acceleration/peak ground acceleration) of this response spectrum is shown on Figure 4-36. In the same figure, we also show the proposed site-specific response spectrum of 1988. The two are practically indistinguishable. We already showed, on Figure 4-27, the close similarity in spectral shapes of the proposed median and 84th percentile site-specific response spectra of 1988. Based on these similarities in response spectral shape, the results from the soil/structure interaction analyses based on the 1987 site-specific response spectrum can be directly scaled to obtain the Plant floor response spectra corresponding to the proposed site-specific ground-motion spectra of 1988 at the median and 84th percentile levels.

Acceleration Time Histories for Soil/Structure Interaction Analyses. The second category of ground-motion input data required for the soil/structure interaction analyses consisted of three acceleration time histories selected as suitable for modification so that their response spectra matched the site-specific response spectrum. The three sets of time histories selected were the Pacoima Dam record of the 1971 San Fernando earthquake, the Tabas record of the 1978 Tabas earthquake, and the El Centro No. 4 record of the 1979 Imperial Valley earthquake adjusted for site conditions, as shown in Table 4-9. They were selected from the suite of

empirical time histories developed for the seismic fragility evaluation based on a set of selection criteria on source characteristics, site conditions, as well as response spectral levels and shapes judged to be applicable to the Diablo Canyon site. After modification for site response, the peak ground acceleration and high-frequency spectral acceleration of the El Centro No. 4 record were significantly increased.

Figures 4-37, 4-38, and 4-39 show these three sets of time histories in their original orientations. The two horizontal components of each of these three sets of time histories were rotated into components along the directions normal and parallel to the strike of the causative fault. The rotated time histories for the fault-normal and fault-parallel components are shown on Figures 4-40 to 4-42. These rotated horizontal components along with the vertical component of the three sets of time histories were provided for use in the soil/structure interaction analyses of the Plant response to coherent ground motions and the effects of containment basemat uplift.

The response spectra of these time histories fluctuate irregularly and have peaks and valleys. However, it is desired that the soil/structure interaction results represent the average response to a large number of input time histories. Accordingly, these acceleration time histories were first modified to match the smooth site-specific spectrum before being used for input to the soil/structure interaction analyses on Plant responses due to coherent ground motions. In this way, the calculated soil/structure interaction responses can be traced more easily. In the analysis of containment basemat uplift, these time histories were not smoothed in their spectral

Table 4-9
TIME HISTORIES USED FOR SOIL/STRUCTURE INTERACTION ANALYSES

<u>Recording Station</u>	<u>Earthquake</u>	<u>Magnitude (Mw)</u>	<u>Distance (km)</u>	<u>Style of Faulting</u>
Tabas	1978 Tabas	7.4	3	Thrust
Pacoima Dam	1971 San Fernando	6.6	3	Thrust
El Centro No. 4*	1979 Imperial Valley	6.5	4	Strike-slip

*This record was modified for site condition.



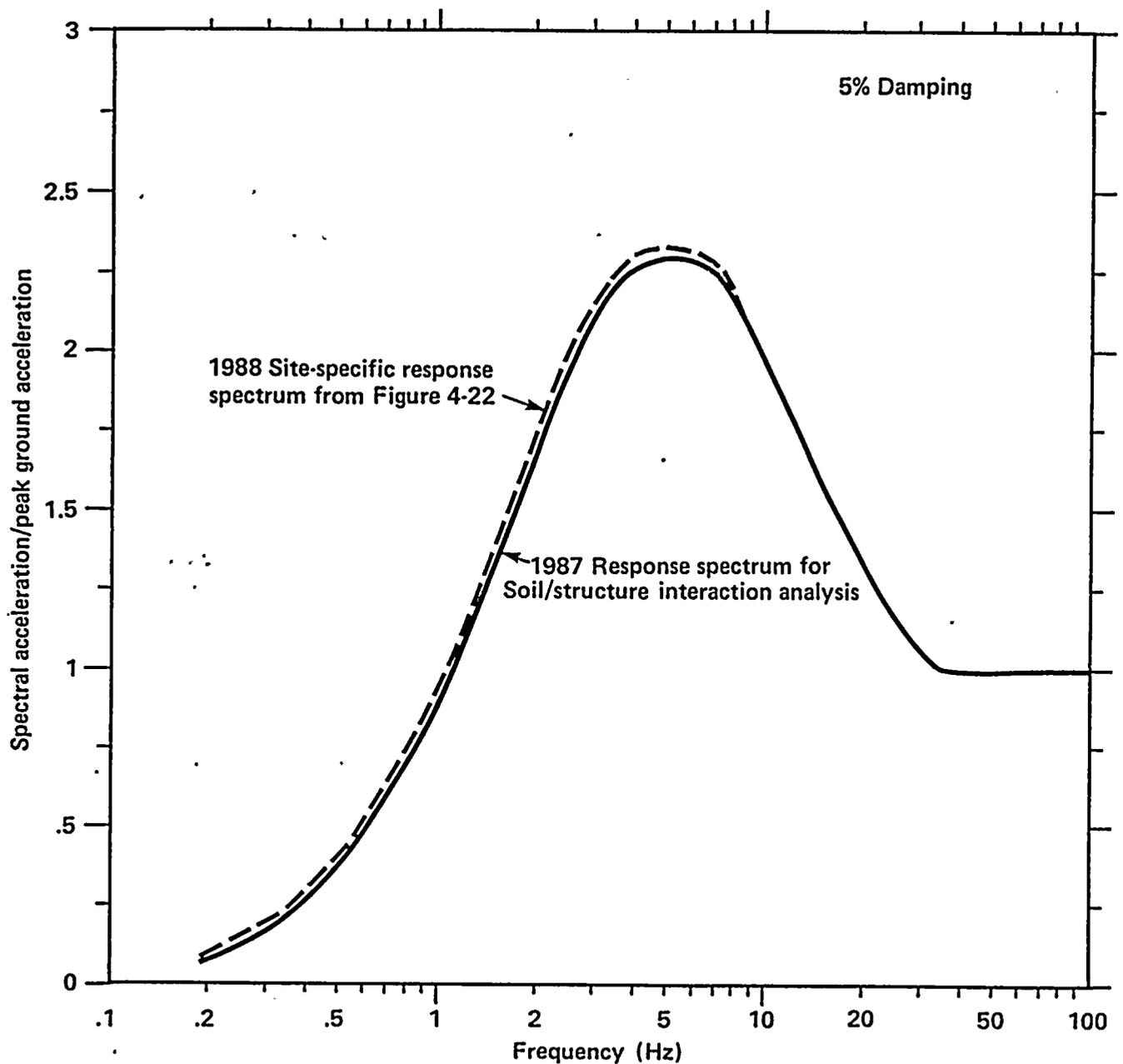


Figure 4-36

Comparison of the shape of the 1987 response spectrum used for the soil/structure interaction analyses and the 1988 site-specific response spectrum. The 1987 spectrum was scaled to peak ground acceleration of 0.96 g for soil/structure interaction analyses (Chapter 5). This exceeds the site-specific 84th percentile peak ground acceleration of 0.83 g.

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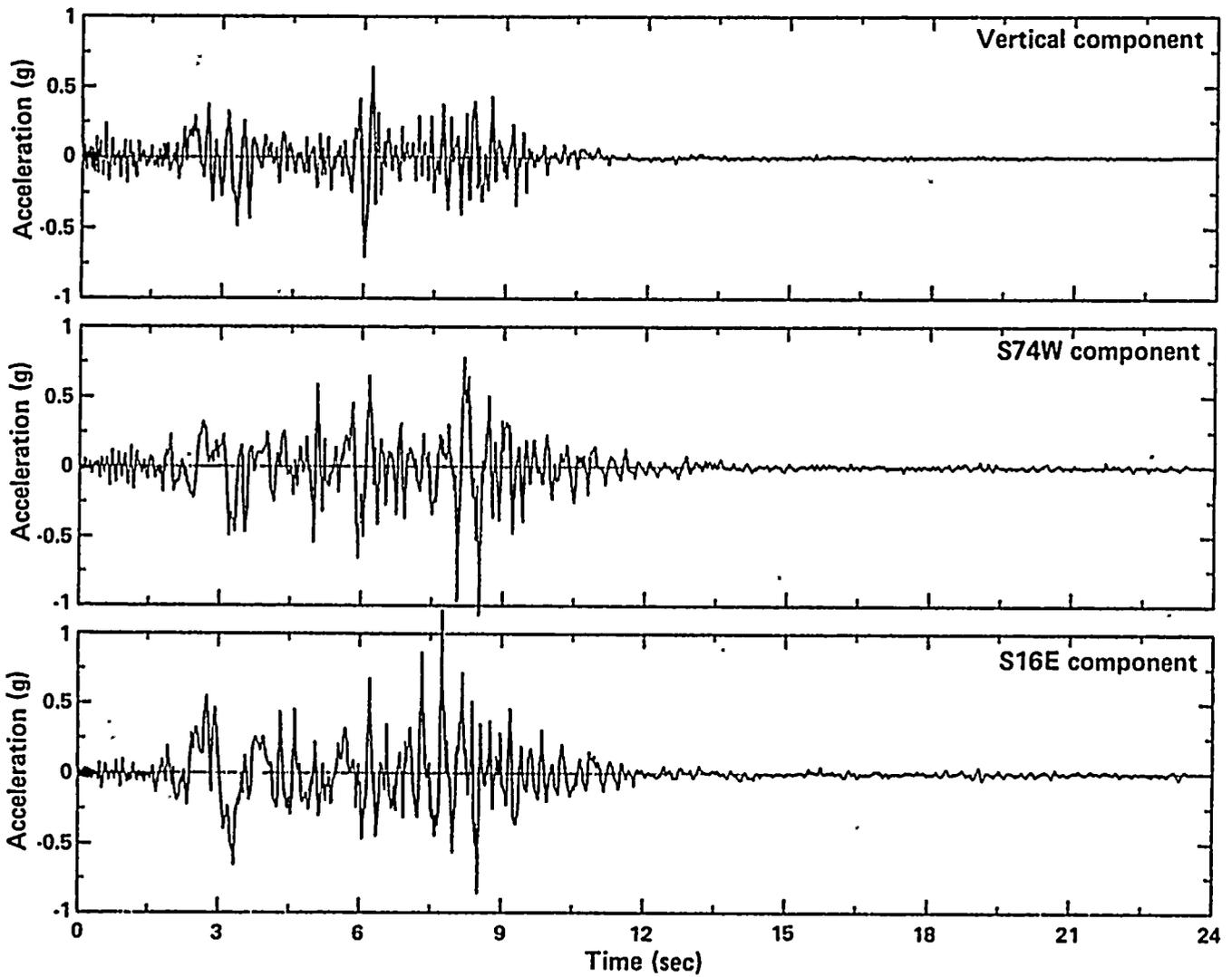


Figure 4-37

Acceleration time histories recorded at Pacoima Dam during the 1971 San Fernando, California, earthquake.

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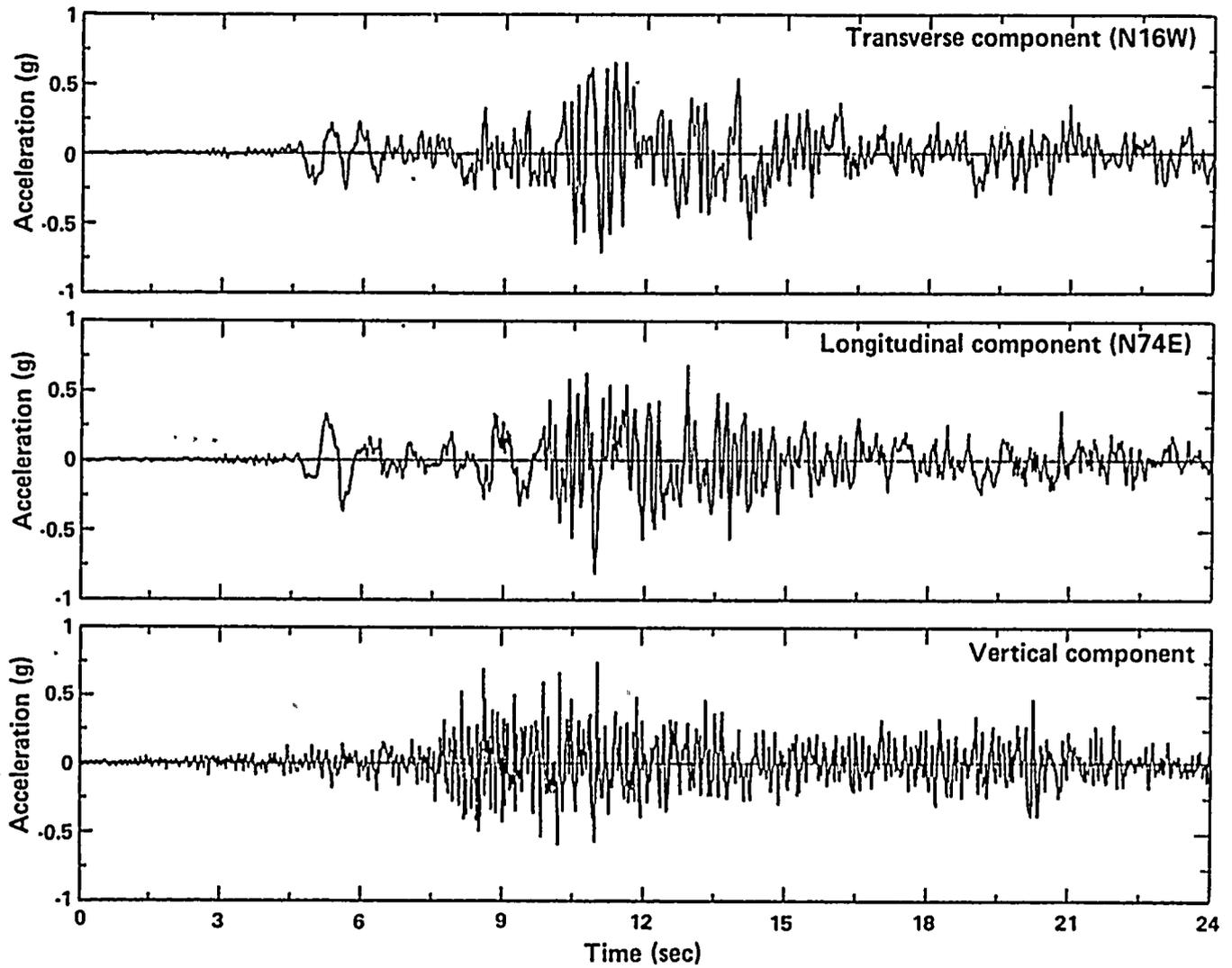


Figure 4-38

Acceleration time histories recorded at Tabas during the 1978 Tabas, Iran, earthquake.

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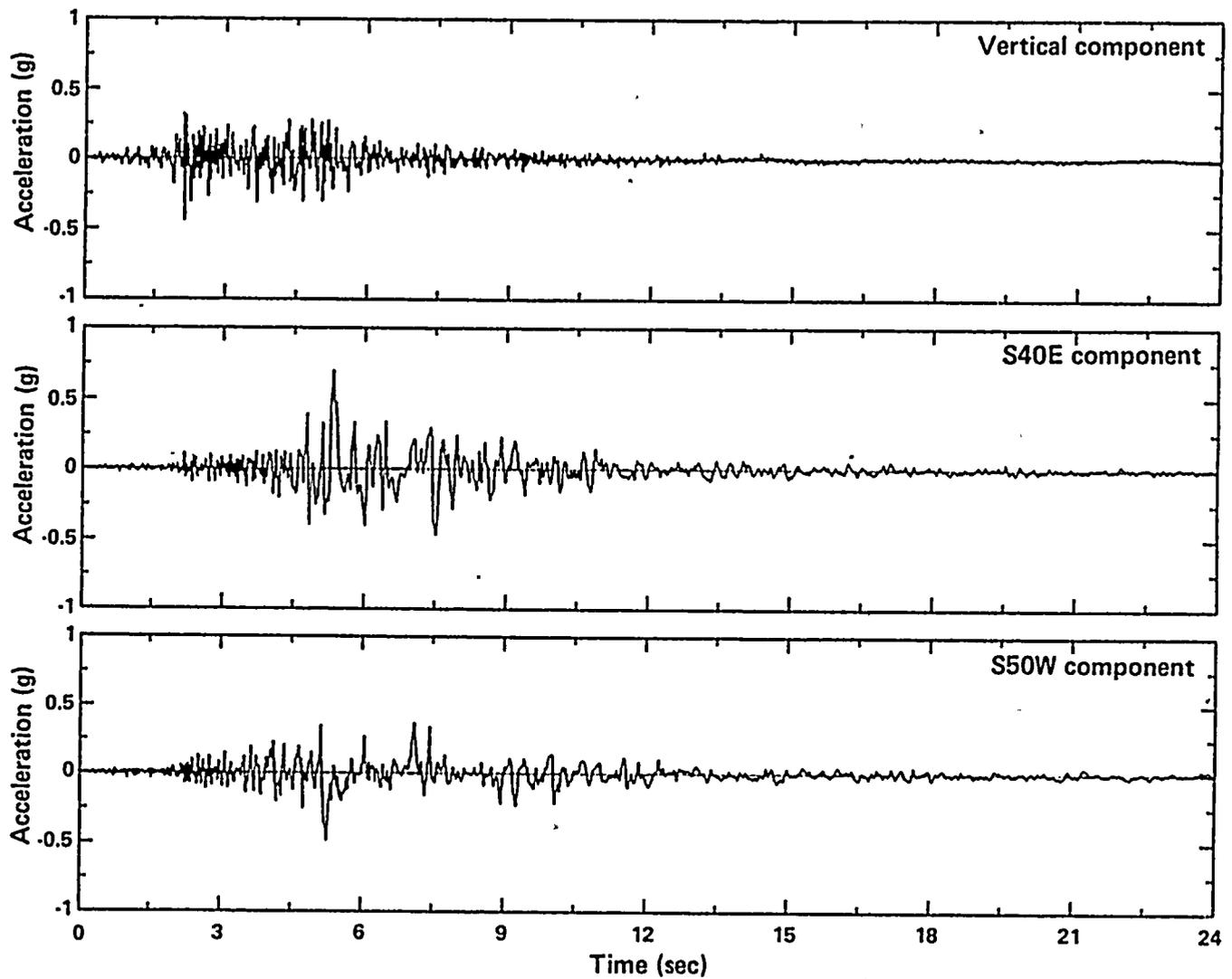


Figure 4-39

Acceleration time histories recorded at the El Centro No. 4 station during the 1979 Imperial Valley, California, earthquake. These accelerograms have been modified for site response (from soil- to rock-site conditions).

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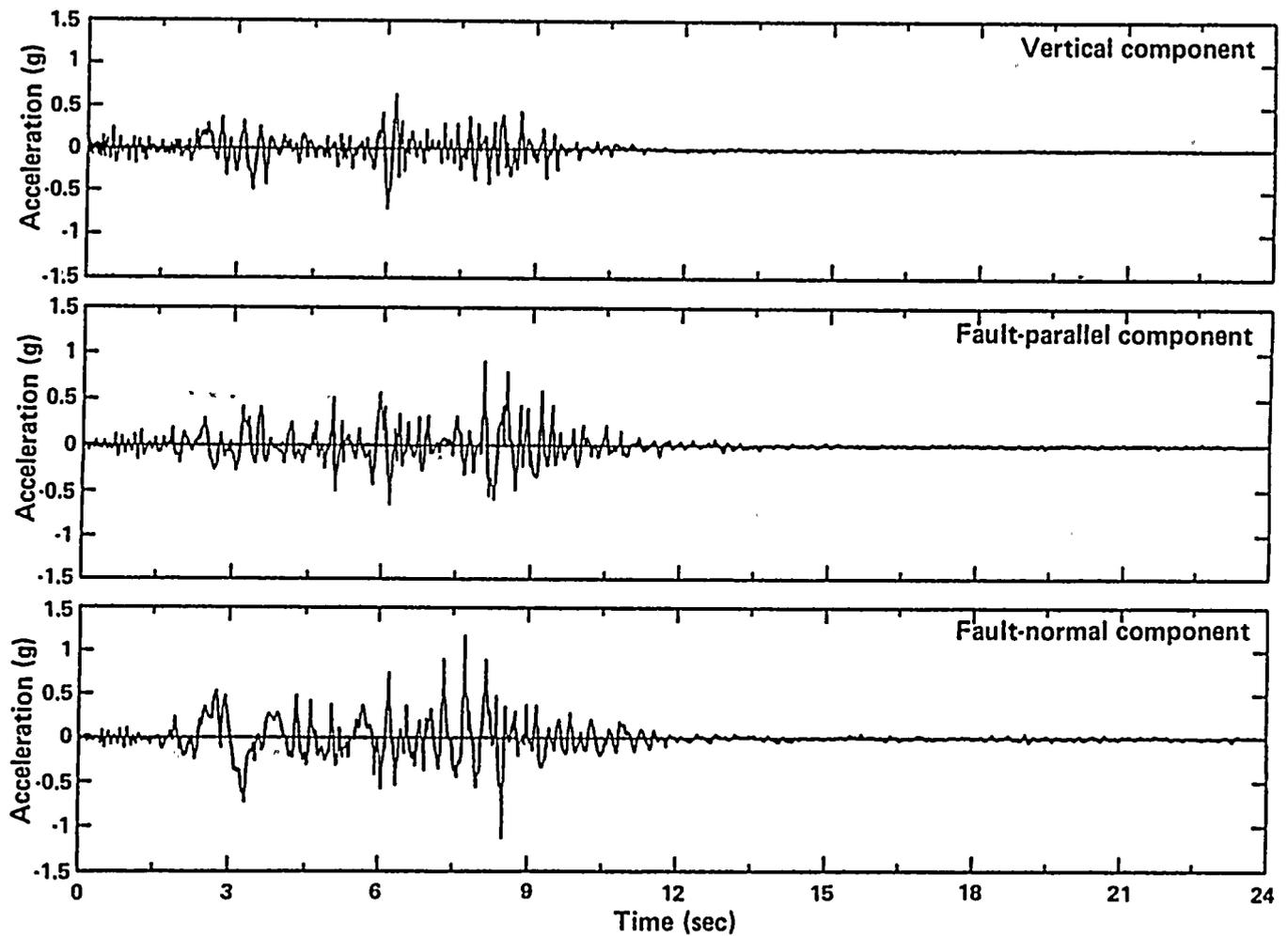


Figure 4-40

Acceleration time histories recorded at Pacoima Dam during the 1971 San Fernando, California, earthquake. The original horizontal components have been rotated in the fault-parallel and fault-normal directions.



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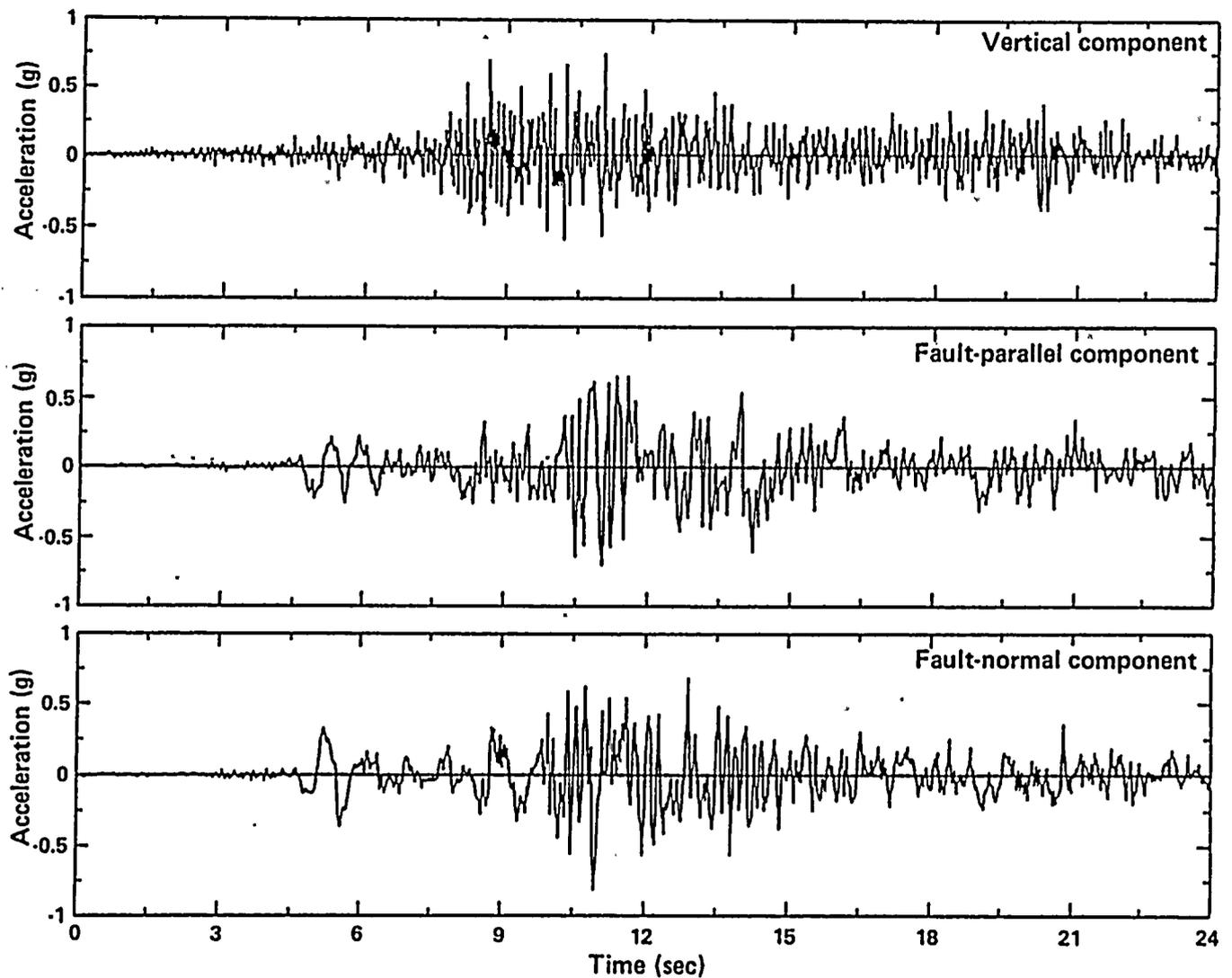


Figure 4-41

Acceleration-time histories recorded at Tabas during the 1978 Tabas, Iran, earthquake. The original transverse and longitudinal horizontal components are redesignated respectively, as fault-parallel and fault-normal components.

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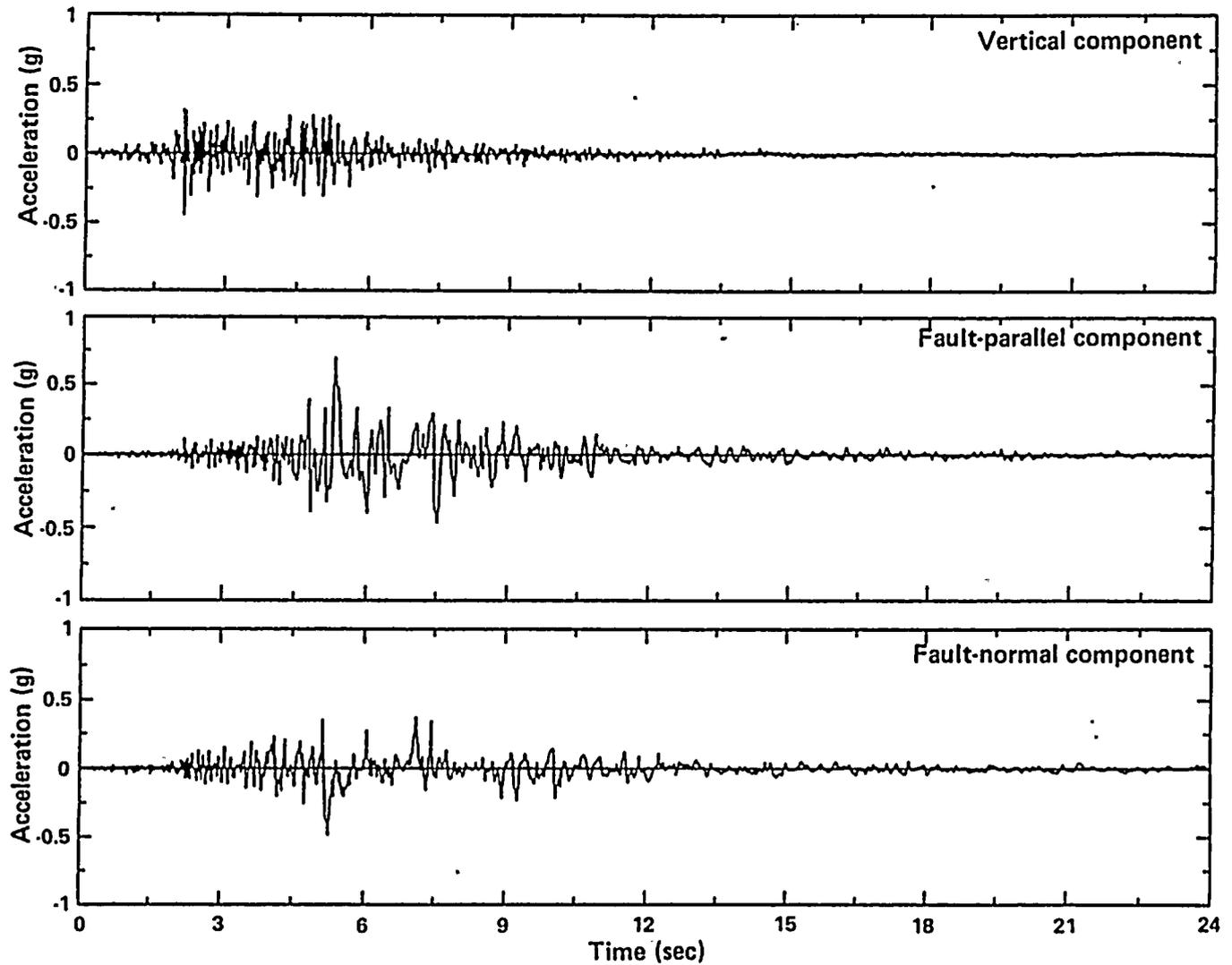


Figure 4-42

Acceleration time histories recorded at the El Centro No. 4 station during the 1979 Imperial Valley, California, earthquake. These accelerograms have been modified for site response (from soil- to rock-site conditions). The original S40E and S50W components are redesignated, respectively, as fault-parallel and fault-normal components.

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shapes. However, they were scaled to higher ground-motion levels to evaluate the possible effects of uplift of the containment basemat on the structural response.

Spatial Incoherence Functions for Soil/Structure Interaction Analyses. The third category of ground-motion input data for the soil/structure analysis is a set of spatial incoherence functions for ground motions at the Diablo Canyon site. These functions were used along with the power spectral density functions in the soil/structure interaction analysis to evaluate the adjustment factors for the Plant floor response spectra due to spatial variations of the free-field ground motions. The development of these spatial incoherence functions is now described.

From the analysis of site ground-motion recordings from small events (Table 4-2, Figure 4-8), we observed significant spatial incoherence in ground motions attributable to irregular wave propagation effects such as scattering incurred along the wave path and near the recording site. Moreover, the Diablo Canyon site is relatively close to the Hosgri fault zone on which a large segment would rupture in case a large earthquake occurs. This extended fault rupture would give rise to a wave field at the Diablo Canyon site containing wide ranges of azimuth and incidence angles. Simultaneous wave arrivals from different parts of the fault would interfere with each other in a complex manner, thus giving rise to spatial incoherence. Furthermore, any departure from vertical incidence in each arriving wave group would also contribute to spatial incoherence due to the wave passage effect.

In summary, the overall spatial incoherence of ground motions at the Diablo Canyon site from a postulated large earthquake on the Hosgri fault zone will consist of two major components:

- Spatial incoherence due to scattering effects of the path and site

- Spatial incoherence due to wave passage and extended source effects.

Ideally, strong motion recordings at the Diablo Canyon site from large earthquakes on the Hosgri fault zone would be used to estimate the spatial incoherence of ground motions at the site. However, this is not possible because no such recordings at the site exist. In fact, no such recordings are available from other sites having comparable source and site conditions (Smith and others, 1982; Abrahamson and others, 1987). Thus, we have developed a procedure to estimate the spatial incoherence of ground motions using site-specific information.

This procedure (Somerville and others, 1988) combines the above two major contributions to ground-motion spatial incoherence. The procedure was validated by showing that combining the incoherence measured from Differential Array recordings of an aftershock of the 1979 Imperial Valley earthquake with the incoherence measured from closely spaced strong-motion simulations of the mainshock agrees closely with the incoherence measured from the mainshock accelerograms recorded at the Differential Array. This validation is described in Somerville and others (1988).

To estimate the spatial incoherence at the Diablo Canyon site, we used the ground-motion recordings obtained at the site from small earthquakes, dynamite explosions in boreholes, and air gun shots fired at sea in the site region (Figure 4-8) to estimate the scattering contribution. At the same time, we used our semi-empirical ground-motion simulation procedure to estimate the contribution due to wave passage and the extended source. These two contributions were then combined to obtain a spatial incoherence model for the site.

The spatial incoherence functions for the free-field ground motions are expressed in the frequency domain as follows:

$$C(\omega, R) = A(\omega, R) e^{i\phi(\omega, R)}$$

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where $C(\omega, R)$ is the complex incoherence function, $A(\omega, R)$ is the amplitude term of the incoherence function, and $\phi(\omega, R)$ is the phase term of the incoherence function. Furthermore, $A(\omega, R)$ and $\phi(\omega, R)$ are evaluated using the functional forms:

$$A(\omega, R) = e^{-(N+M\omega)R}$$

$$\phi(\omega, R) = CR\omega + DR \sin(F\omega) \sin(G\omega)$$

where ω is the angular frequency in radians/sec, R is the separation in meters, and $M, N, C, D, F,$ and G are constants evaluated by fitting coherence measurements.

The values for the constants in the vertical, horizontal, and cross-term incoherence functions have been determined as follows:

Constant	Vertical	Horizontal	Cross-Term
$M (x10^{-4})$	0.85	0.85	0.42
$N (x10^{-2})$	0.10	0.05	0.04
$C (x10^{-3})$	0.10	0.125	0.10
$D (x10^{-2})$	0.05	0.05	0.05
F	0.28	0.36	0.32
$G (x10^{-1})$	0.125	0.125	0.125

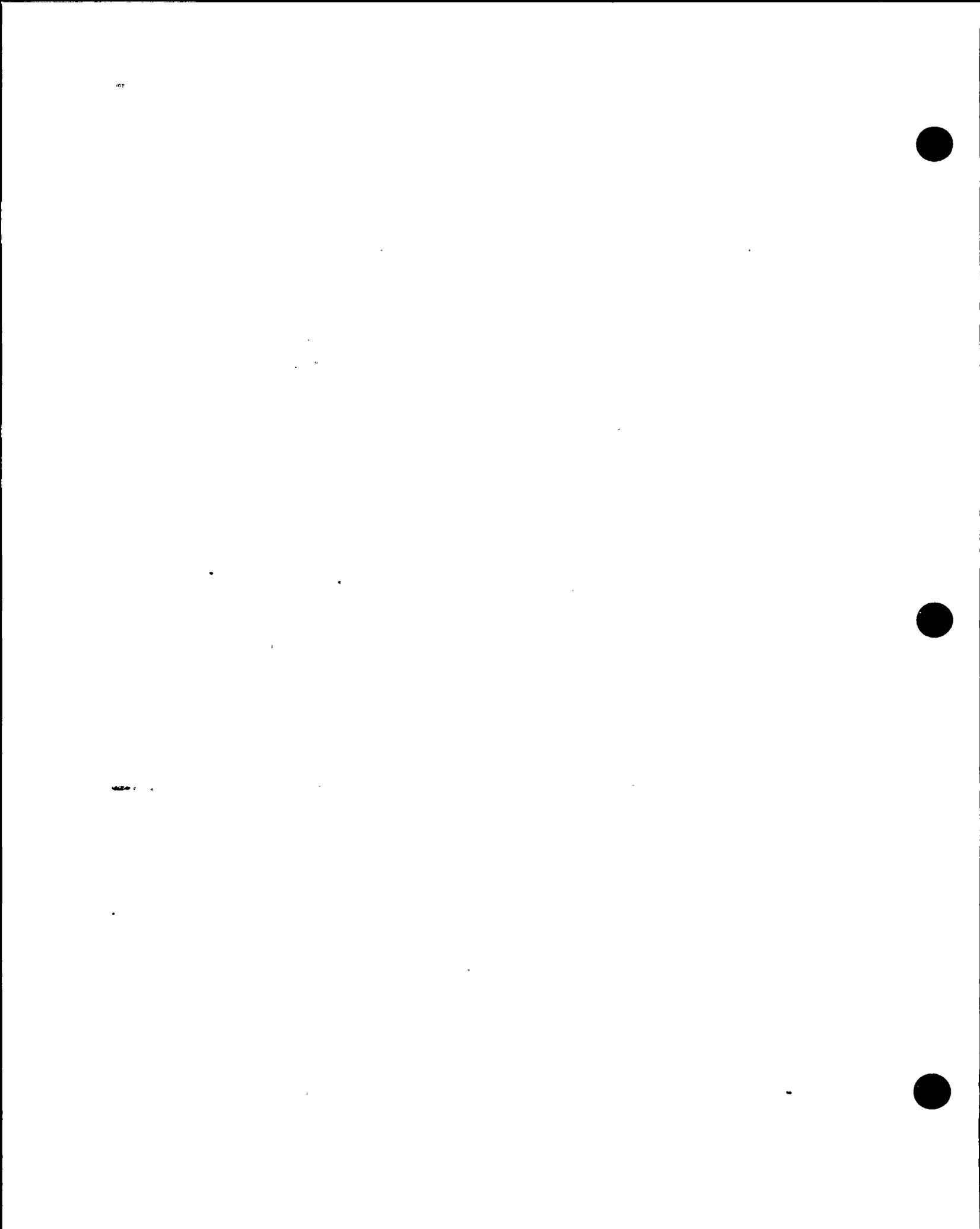
Figure 4-43 shows the amplitude term of the horizontal spatial incoherence function for frequencies of 3.75, 7.50, and 15.00 hertz. Figure 4-44 shows the phase term of the vertical, horizontal, and cross-term spatial incoherence functions for separations ranging from 50 to 300 meters.

Power and Cross-Power Spectra for Soil/Structure Interaction Analyses. The fourth category of ground-motion input data for the soil/structure interaction analysis consisted of a set of power and cross-power spectra of ground motions. These power spectra were estimated from the mean power and cross-power spectra of the empirical time histories developed for the seismic fragility evaluation, listed in Table 4-7. Figure 4-45 shows one of the power spectra provided for the soil/structure interaction analyses. These power and cross-power spectra were divided by an equivalent stationary duration of 11 seconds to give the power and cross-power spectral density functions which were then used in conjunction with the spatial incoherence function

as input to the soil/structure analysis of the effects of ground motions incoherence.

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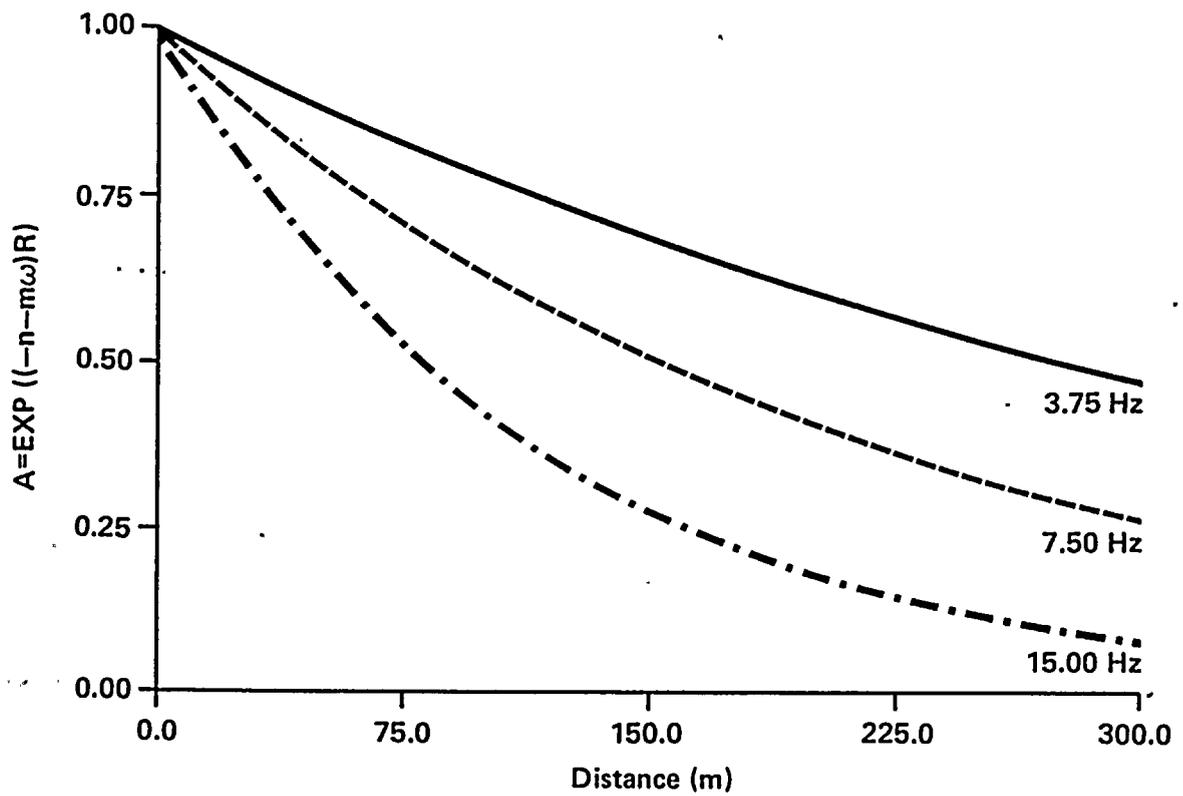


Figure 4-43
Amplitude term of the horizontal spatial incoherence functions.



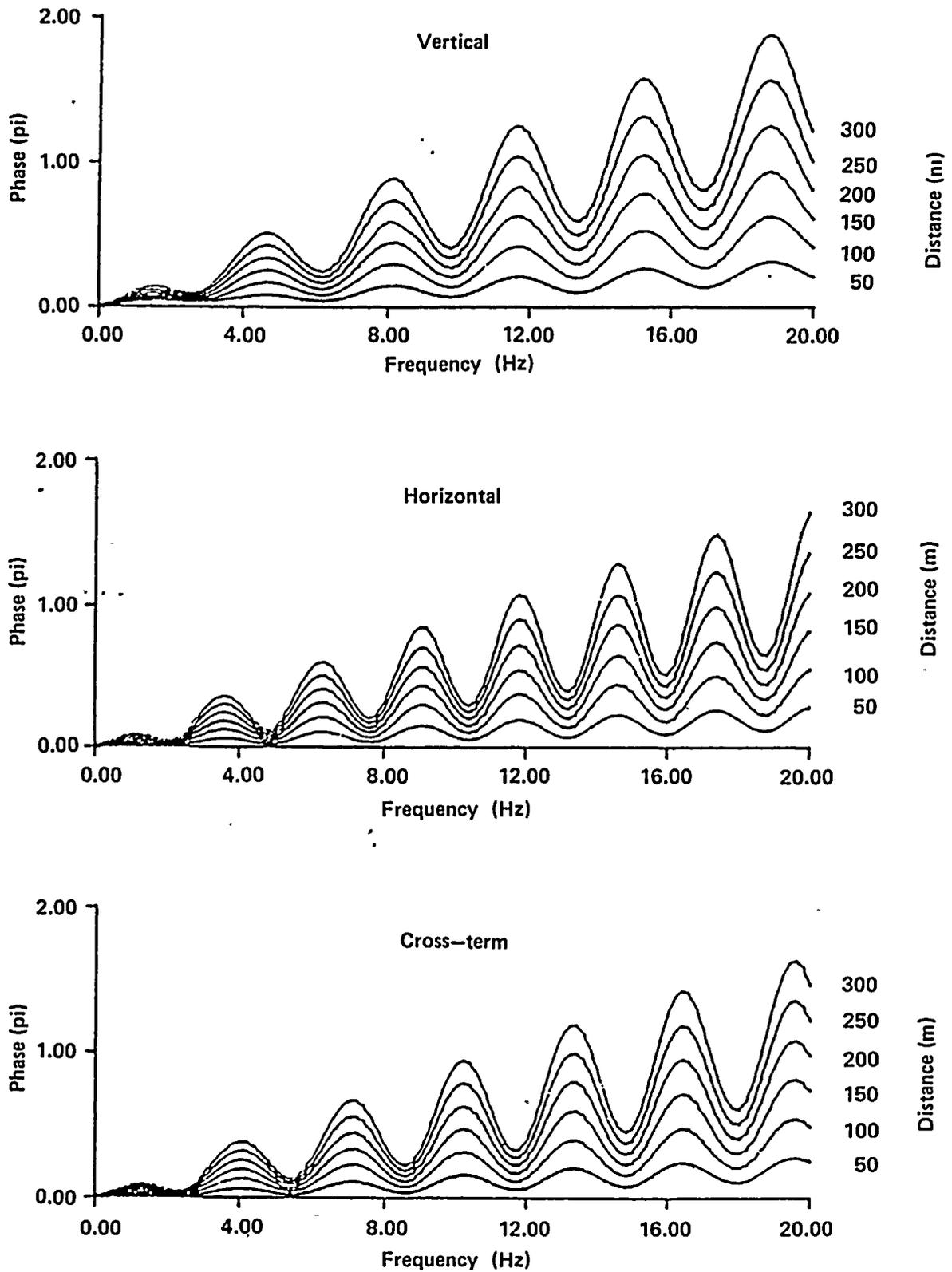


Figure 4-44
Phase terms of the vertical, horizontal, and cross-term spatial incoherence functions.



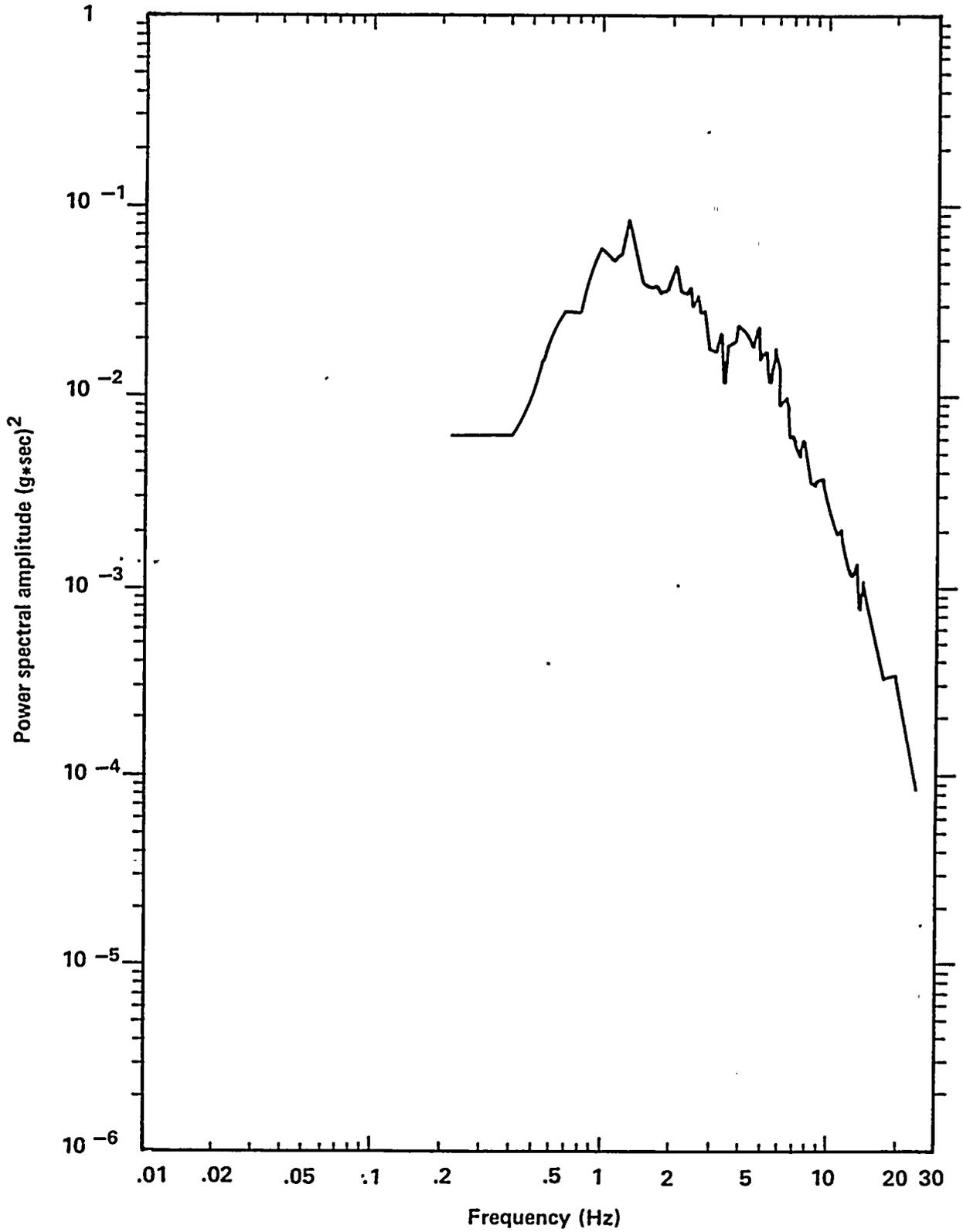


Figure 4-45
Horizontal power spectrum provided for use as input to the soil/structure interaction analyses.

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Chapter 5

SOIL/STRUCTURE INTERACTION ANALYSIS

To Partially Address *Element 4 of the License Condition*

ELEMENT 4 OF THE LICENSE CONDITION

PG&E shall assess the significance of conclusions drawn from the seismic reevaluation studies in Elements 1, 2, and 3, utilizing a probabilistic risk analysis and deterministic studies, as necessary, to assure adequacy of seismic margins.

OBJECTIVES

The objectives of the soil/structure interaction analysis conducted for the Diablo Canyon Power Plant Long Term Seismic Program were to examine the effects of dynamic interaction between the Plant structures and the supporting rock medium on the seismic response of the structures, and to generate seismic responses for the Plant structures required for the seismic fragility evaluation and seismic margin assessment. This analysis was conducted in response to Element 4 of the license condition.

SCOPE

The soil/structure interaction analysis started in late 1984 and continued through mid-1988. The analysis was carried out in three phases, namely, Phase I: Program Plan development; Phase II: preparatory work and Scoping Study; Phase III: method development, implementation, and verification; preliminary results; and final analysis and results.

The progress and results of the soil/structure interaction analysis obtained in various phases were reviewed and discussed with the Nuclear

Regulatory Commission (NRC) Staff and its consultants through several NRC/PG&E meetings, three specific NRC/PG&E workshops on soil/structure interaction analyses, and one NRC audit on soil/structure interaction analysis calculations. The schedule and milestones of the soil/structure analysis program are summarized in Figure 5-1. Comments received to date from the NRC at various stages of review have been incorporated into the program wherever applicable, and they are reflected in the final results of the analysis.

The scope of the soil/structure interaction analysis that has been carried out for the Long Term Seismic Program consists of the following major activities:

- Assemble, review, and determine appropriate site rock profiles and properties.
- Develop suitable three-dimensional dynamic models for the power block structures.
- Implement, modify, and validate dual soil/structure interaction analysis computer programs, CLASSI and SASSI.
- Perform parametric studies to assess the sensitivities of soil/structure interaction response and identify significant parameters to be considered for modeling and analysis.
- Perform analyses of on-site recorded earthquake data and extract information useful for correlation and calibration of model parameters.
- Perform soil/structure interaction analyses to generate the responses for the power block structures subjected to coherent, vertically





Work Phases	Description	1984	1985	1986	1987	1988
Phase I	Program Plan Development					
Phase II	Preparatory and Scoping Studies					
Phase IIIA	Development of Methods, Verification, and Preliminary Studies					
Phase IIIB	Final Analysis and Results					

Milestones:

1. NRC approval of the Long Term Seismic Program Plan, January 31, 1985
2. NRC/PG&E meeting on Long Term Seismic Program, October 21, 1985
3. First NRC/PG&E soil/structure interaction workshop, April 14-16, 1986
4. NRC/PG&E ground-motion workshop to review soil/structure interaction work, October 24, 1986
5. Second NRC/PG&E soil/structure interaction workshop, December 10-12, 1986
6. NRC audit of PG&E soil/structure interaction calculations, June 9-11, 1987
7. Third NRC/PG&E soil/structure interaction workshop, November 4-6, 1987
8. PG&E submittal of Long Term Seismic Program Final Report to NRC, July 31, 1988

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Figure 5-1

Soil/structure interaction assessment schedule and milestones.



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- Develop and validate the method and computer programs for incorporating the spatial incoherence of seismic ground motions for soil/structure interaction analysis; perform analyses to develop the soil/structure interaction response adjustment factors to account for the spatial incoherence of ground motions.
- Modify and validate the method and computer program for nonlinear soil/structure interaction analysis, taking into account the nonlinear base-uplifting response behavior, and perform analyses for the containment structure to assess the effect on soil/structure interaction response due to partial uplifting of the containment base from the rock foundation.
- The effect of spatial variation of free-field seismic ground motion, including the apparent wave passage effect, has been properly evaluated.
- The effect of nonlinear base uplifting behavior on the seismic response of the most critical containment structure under the fragility evaluation strong ground motion input has been assessed.
- Recorded earthquake data at the Diablo Canyon site and on the power block structures have been utilized to the extent practicable to assist in calibrating the low amplitude dynamic characteristics of the site rock and dynamic models.

METHOD OF ANALYSIS AND SUMMARY OF RESULTS

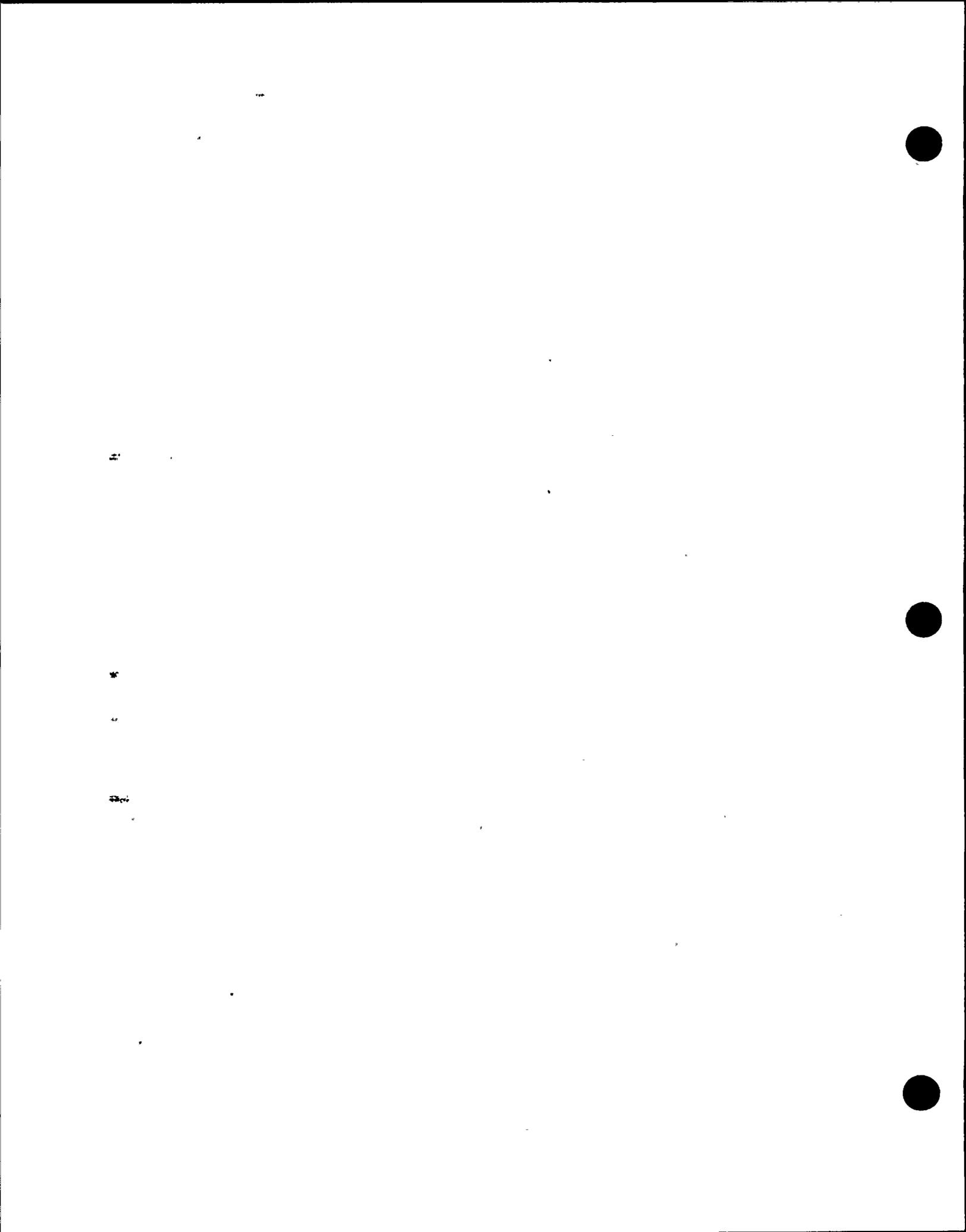
The general configuration of the Plant power block structures, which include the containment structures of both units, the auxiliary building, and the turbine building, is shown schematically in Figure 5-2. An elevation view of a section through the Plant is shown in Figure 5-3. To achieve the objective of the soil/structure interaction analysis, a complete reevaluation of the seismic soil/structure interaction effects on the power block structures was carried out, using state-of-the-art analysis techniques. The analysis has also incorporated all available relevant new information that became available after 1978. This includes the additional site investigation data obtained during 1977 to 1978, and the on-site recorded actual earthquake data available since 1980.

As stipulated in the Program Plan, the Long Term Seismic Program soil/structure interaction analyses have specifically included the following elements:

- Three-dimensional soil/structure analysis methods have been used.
- All components of free-field ground motions at the site have been considered in the determination of seismic response of interest.

The free-field seismic ground-motion inputs for the soil/structure interaction analyses were obtained from the ground-motion studies, as summarized in Chapter 4. The results of the soil/structure interaction analyses provided the Plant responses required for the probabilistic Plant fragility evaluation and the deterministic seismic margin assessment. The overall soil/structure interaction analysis method, from the ground-motion input to the generation of Plant response output, is shown schematically in Figure 5-4.

Prior to performing the soil/structure interaction analysis, an extensive effort was conducted to characterize the soil/structure interaction systems for the power block structures and to prepare the appropriate analytical methods and computer programs required by various phases of analysis. The effort spent on the characterization of the systems includes: (a) the characterization of site rock profile and properties; (b) the development of suitable three-dimensional dynamic models for the power block structures; and (c) parametric studies to evaluate the sensitivities of soil/structure interaction response and identify important soil/structure interaction parameters to be considered. The effort on preparation of appropriate analytical tools for the soil/structure interaction analysis includes: (a) the implementation and validation of the CLASSI and



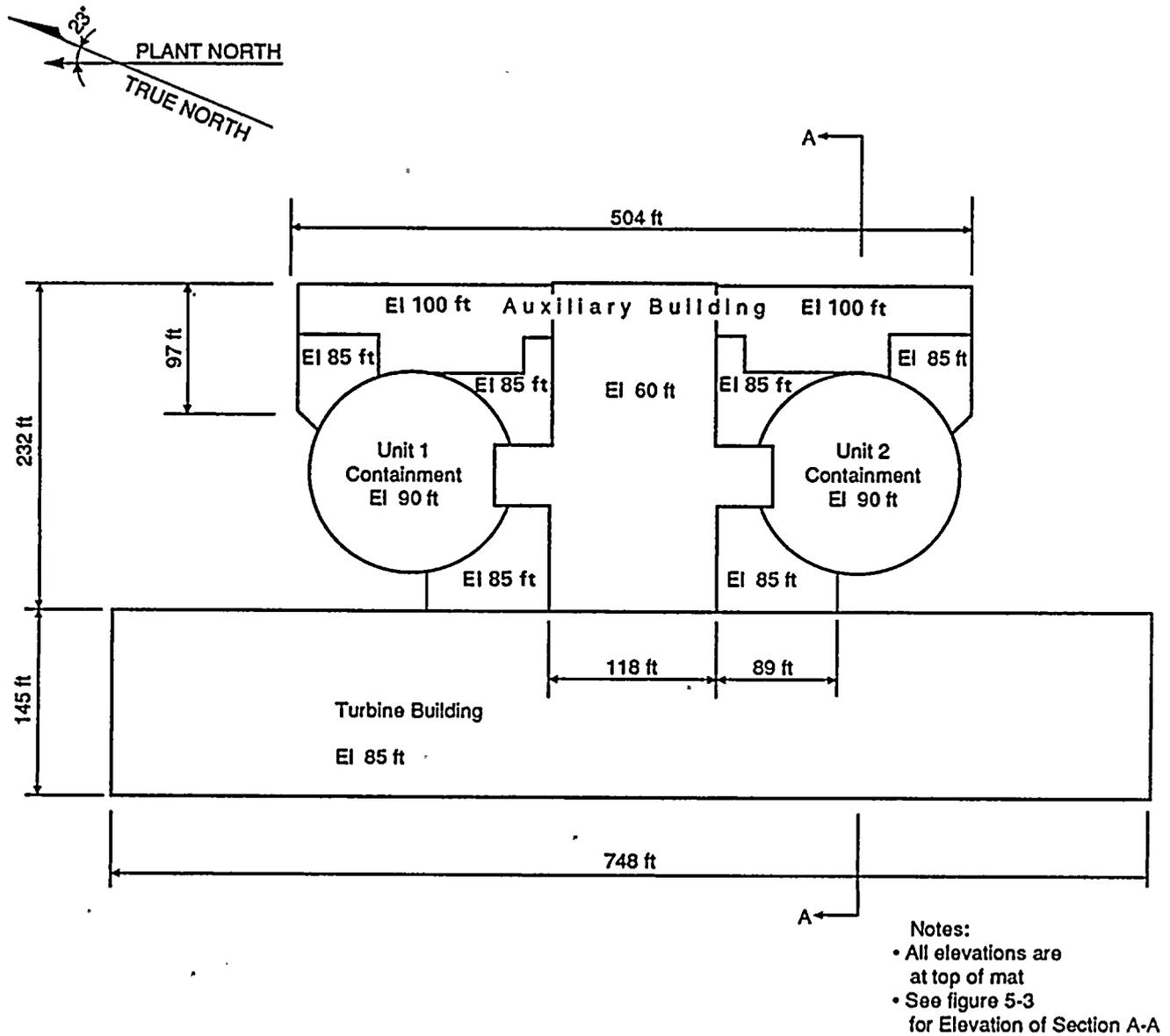


Figure 5-2
 Foundation configuration of power block structures.



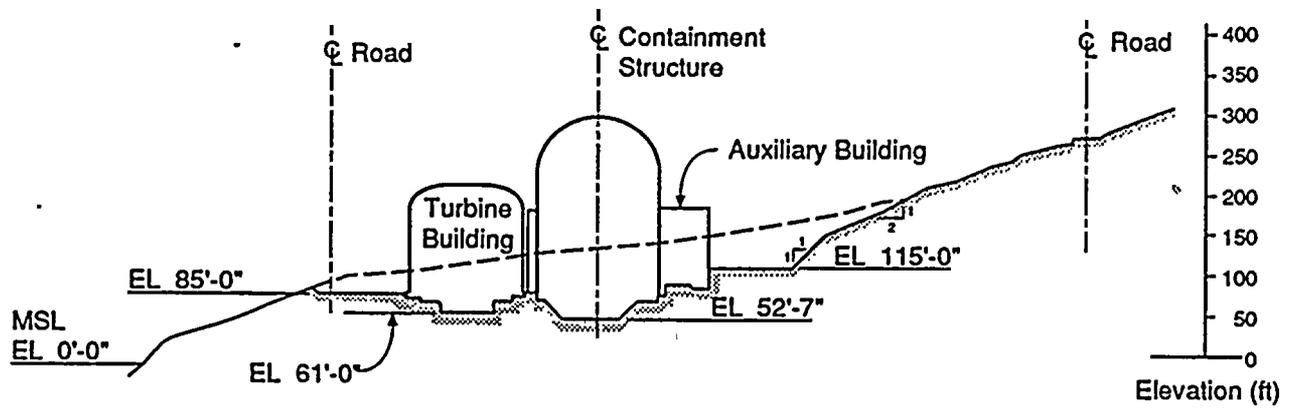


Figure 5-3

Elevation view of section A-A of Figure 5-2.



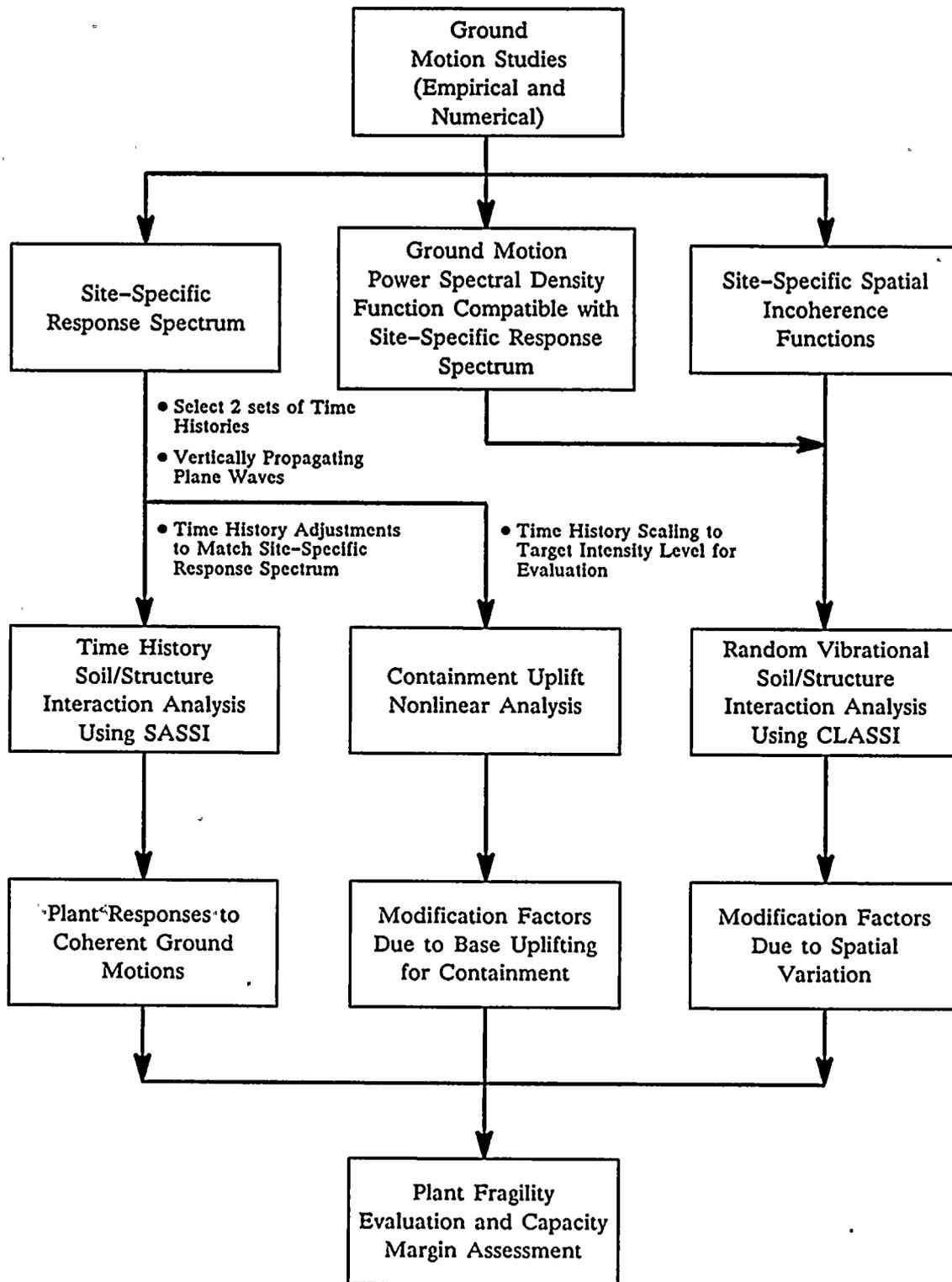


Figure 5-4
Overall soil/structure interaction analysis method.



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SASSI computer programs for three-dimensional analysis; (b) the development, implementation, and validation of analysis method and computer programs for soil/structure interaction analysis incorporating the spatial incoherence of seismic ground motions; and (c) the modification and validation of the soil/structure analysis method and computer program for analyzing the nonlinear dynamic response due to base-uplifting.

Characterization of Site Rock Properties

Recognizing the importance of fixing the site rock properties at the beginning of the Long Term Seismic Program, a priority task was performed to assemble and review all available site rock data and, based on this review, to assess the appropriate rock profile and properties for soil/structure interaction analysis. The rock data that have been assembled include two sets of data: one set consists of data contained in the source references of the Diablo Canyon Power Plant FSAR Section 2.5, which were obtained from the site investigations conducted from 1967 to 1973; the second set consists of data obtained from the additional site investigations conducted from 1977 to 1978. Both sets of data have been reviewed in detail.

The rock data available from the FSAR references consist of data obtained from both field geophysical surveys and laboratory tests of rock samples. These data were applicable mainly for rocks at shallow depths, that is, down to a depth of about 40 feet below the finished grade at El 85 feet. The rock data available from the 1977 to 1978 site investigations consist of data from borehole logging, field geophysical surveys, and laboratory tests of rock samples obtained from four deep boreholes drilled around the Plant to a depth of approximately 300 feet below grade.

Review of data from both sets indicated that the data from field-measured shear and compression wave velocities and rock densities are more mutually consistent and these data are considered to be more representative of the in situ properties of the rock mass below the plant foundation; the laboratory test values represent only very local

rock conditions and the test results are marked with uncertainties resulting from the specimen saturation procedures used and the test equipment flexibilities. Thus, in deriving the low-strain rock property profiles for soil/structure interaction analysis purposes, emphasis was placed on field-measured data, especially the data taken from the depth below El 50 feet, because the foundations of the power block structures are located at elevations between 50 feet and 80 feet.

Based on the review of rock data assembled, representative profiles and the ranges of variation of rock shear wave velocity, Poisson's ratio, rock density, damping ratio at low-strain, and the strain-dependent variations of shear modulus and damping ratio, were derived. Figure 5-5 shows the mean shear wave velocity profile and the upper-bound and lower-bound of data developed from the assembled site rock data.

Because the rock shear wave velocity profiles developed from the assembled data showed relatively large scattering, a study was carried out to assess the sensitivity of soil/structure interaction response due to the variation of rock shear wave velocity profile. The sensitivity study was performed using a simplified soil/structure interaction model for the containment structure and the CLASSI computer program for soil/structure interaction analyses. The results of this sensitivity study indicated that, as the foundation rock shear wave velocity profile varies from the upper-bound to the mean and then to the lower-bound, the fundamental soil/structure interaction frequency for the coupled horizontal translation and rocking mode of the containment shell shifts from 4.6 hertz to 4.0 hertz, and then to 3.3 hertz. Despite the relatively large variation in the rock shear wave velocity profile, the frequency variation was found to be within approximately ± 15 percent.

To provide an independent confirmation of the appropriateness of the rock property profiles developed for soil/structure interaction analysis, the fundamental soil/structure interaction frequency of the containment shell, which was sensitive to the variation of rock shear wave



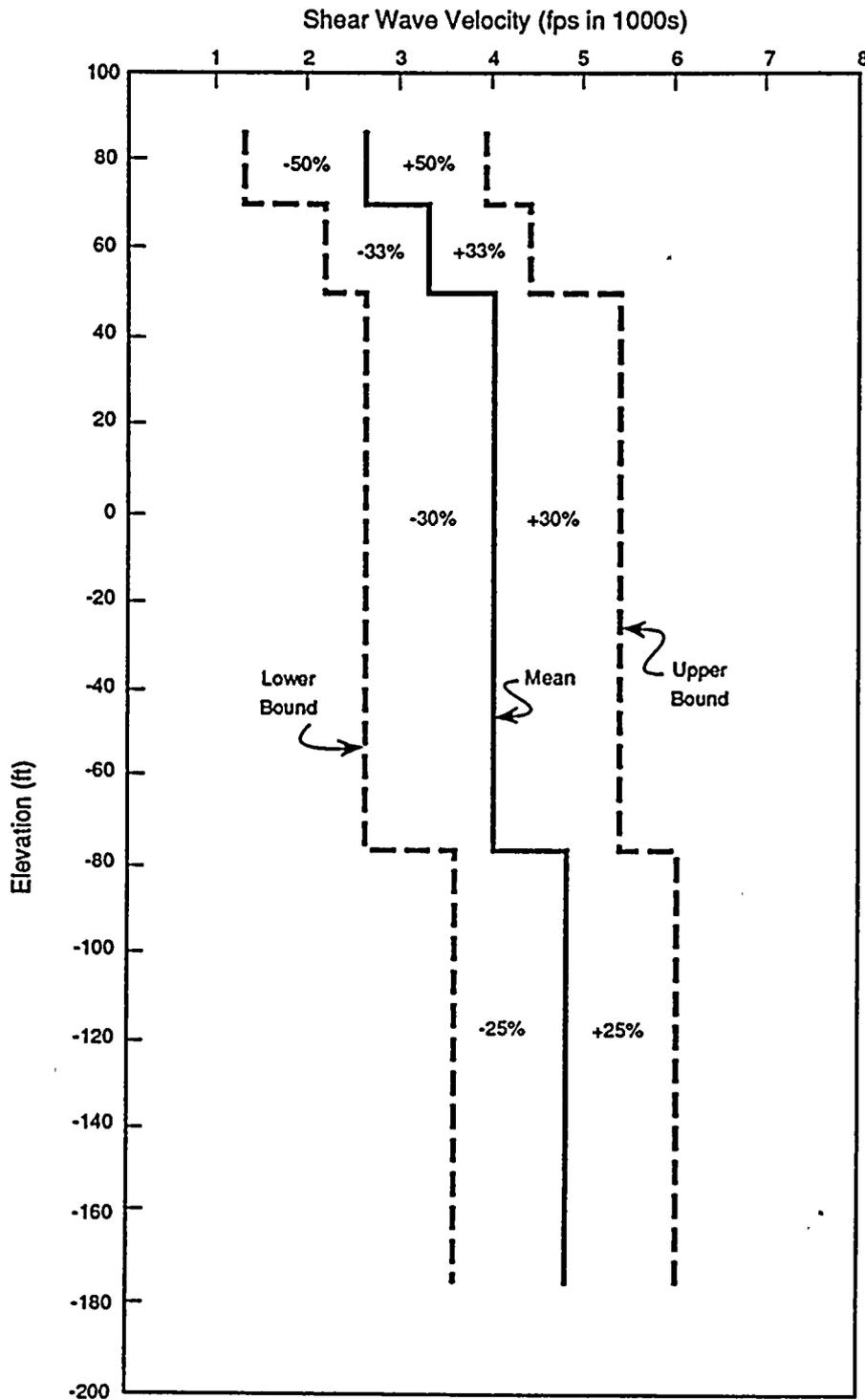


Figure 5-5

Site shear wave velocity profiles (based on 1978 downhole velocity measurements).

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velocity profile, was selected as the parameter for a correlation study using the available on-site recorded earthquake data in the free-field and on the Unit 1 containment structure for three very low intensity earthquakes (the maximum ground accelerations recorded were between 0.01 to 0.03 g). The results of this correlation study showed that the analytical soil/structure interaction frequency based on the mean shear wave velocity profile and the associated properties correlates very well (within ± 5 percent) with the corresponding soil/structure interaction frequencies determined from the analysis of recorded data for all three earthquakes. This good correlation confirms that the mean shear wave velocity profile along with other associated elastic properties of the rock as developed from the assembled rock data provides an appropriate representation of the characteristics of the foundation rock at the Diablo Canyon site for strain levels (2×10^4 percent to 4×10^{-4} percent) consistent with the low-intensity earthquakes considered in the study. It can be concluded from this result that values of shear wave velocity above those represented by the mean profile shown in Figure 5-5 need not be considered for soil/structure interaction analyses with input seismic intensities higher than those considered in this correlation study.

Soil/Structure Interaction Analysis Methods and Computer Programs

To adequately address the issues relating to soil/structure interaction raised in the NRC SER Supplement No. 27, the analysis adopted the newly developed three-dimensional soil/structure interaction analysis methods and the associated computer programs, CLASSI and SASSI. Both these programs are capable of handling three-dimensional soil/structure interaction problems with seismic inputs in the form of general incidence plane wave fields. Although some limitations still exist in the use of the individual computer codes, the effects of these limitations can be evaluated through the concurrent use of both analysis techniques and reconciliation of the results with each other.

In the early stages of the Long Term Seismic Program, both these computer programs (that is, CLASSI and SASSI) were obtained from the program developers and they were implemented to test their suitability for Program applications. As a result of these tests, desirable modifications to both programs were identified to suit the Program application requirements; these modifications were subsequently implemented with the aid of the program developers. At this stage, an extensive code verification program was performed to validate the modified versions of the computer codes. The results of the program modifications and validation for both programs have been fully documented in the Theoretical, User's, and Validation Manuals for CLASSI and SASSI (Bechtel, 1988).

CLASSI (Continuum Linear Analysis for Soil/Structure Interaction) is a linear three-dimensional seismic soil/structure interaction analysis computer code developed at the University of California, San Diego (Wong and Luco, 1976). The analysis method used in CLASSI is based on the substructuring technique that separates the analysis of kinematic interaction (foundation scattering of seismic motions) from that of inertial interaction (dynamic coupling of structure and foundation impedances), as shown schematically in Figure 5-6. The foundation medium is represented in CLASSI by a uniform or a horizontally layered, elastic or viscoelastic continuum halfspace. The most significant limitation of the version of CLASSI implemented for our Program applications is that the structural foundation must be rigid, flat, and founded on the surface of the halfspace. Thus, the foundation embedment and basemat flexibility effect cannot be evaluated. This version of CLASSI has been validated by benchmarking the CLASSI solutions against available published solutions for 18 validation test problems, and by cross-benchmarking with the SASSI solutions available for the common validation test problems.

SASSI (Systems for Analysis of Soil/Structure Interaction) is a finite-element computer program for two- and three-dimensional linear





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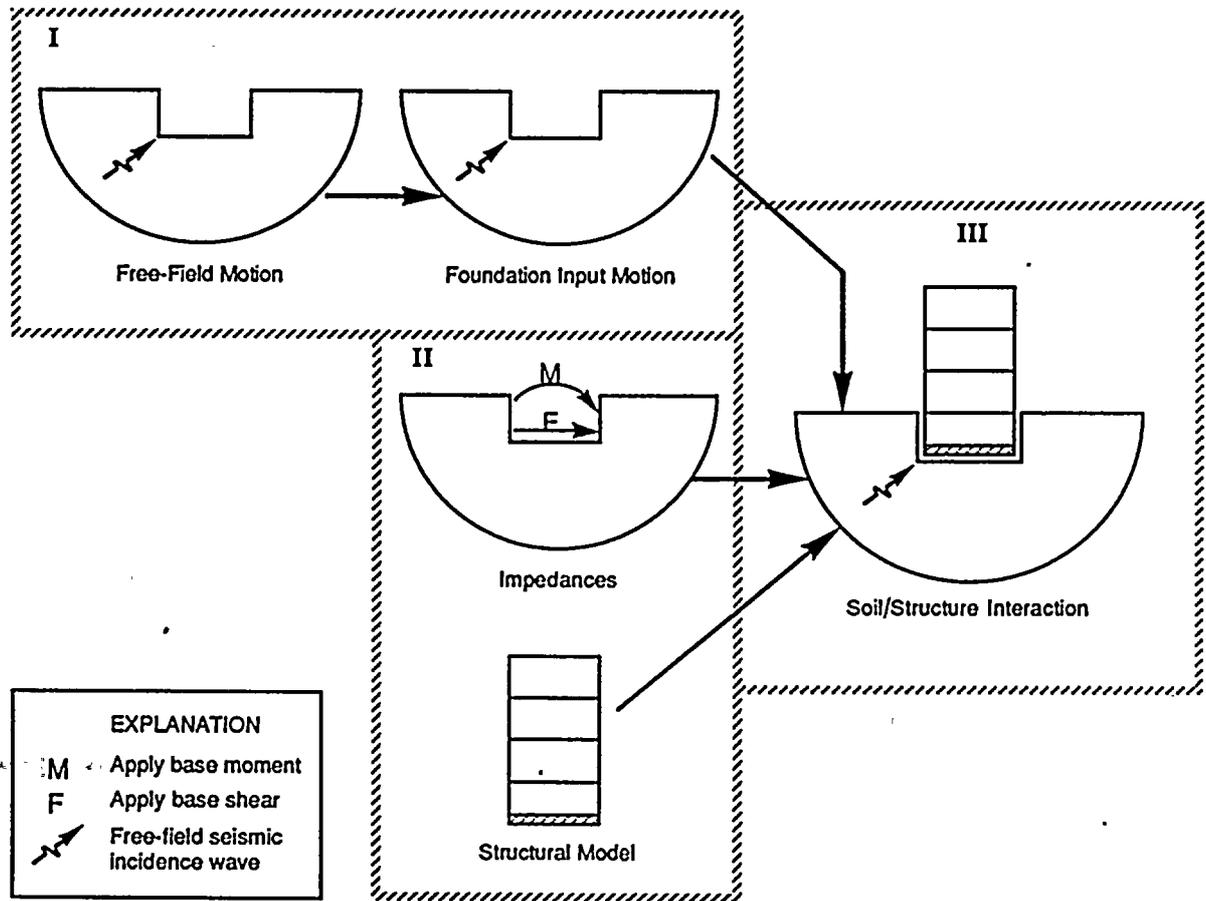


Figure 5-6

CLASSI substructuring technique.

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soil/structure interaction analyses developed at the University of California, Berkeley (Lysmer and others, 1981). The program uses the complex response method and the flexible-volume substructuring technique as shown schematically in Figure 5-7. The soil material is modeled using complex moduli and a hysteretic damping mechanism. The foundation medium is represented by a horizontally layered soil system overlaying an elastic halfspace. Due to the unique flexible-volume substructuring technique employed and the use of finite-element models, SASSI can rigorously handle the soil/structure interaction effects due to foundation embedment and basemat flexibility. However, because of the large number of degrees-of-freedom that usually result from the use of three-dimensional finite-element models, the most significant limitation of the SASSI program is the soil/structure interaction model size and the computational costs. The SASSI version implemented for Program applications has been validated by benchmarking SASSI solutions against available published solutions for 20 validation test problems, and by cross-benchmarking with the CLASSI solutions available for the common validation test problems.

Three-Dimensional Dynamic Models for Power Block Structures

For the purpose of three-dimensional soil/structure interaction analysis for the power block structures using either CLASSI or SASSI, three-dimensional dynamic models were developed for the containment structure, auxiliary building, and turbine building including the turbine pedestal. The development of these models used as much as possible the model data available from the dynamic models used for seismic analysis prior to the Long Term Seismic Program.

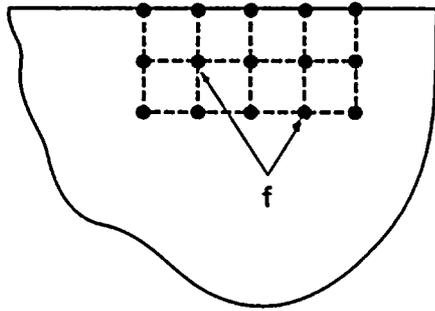
For the containment structure, the three-dimensional dynamic model developed for the analysis is a three-dimensional lumped-mass,

multiple-stick model, as shown in Figure 5-8. The model consists of a 9-lumped-mass, single stick for representing the exterior containment shell and a 16-lumped-mass, multiple-branch single-stick for representing the interior concrete structure. An extra single degree-of-freedom vertical lumped-mass model was developed and attached to the containment shell stick at the containment springline location to represent the fundamental vertical drumming mode of the containment hemispherical dome. Due to its asymmetric configuration, the three-dimensional stick model for the interior concrete structure includes both the mass eccentricities and the proper locations and orientations of the centers of rigidity of the structure.

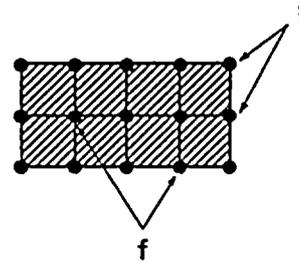
For the auxiliary building, two three-dimensional dynamic models were developed for analysis applications. One of these models was a three-dimensional finite-element dynamic model, which was developed by modifying the three-dimensional finite-element static model that existed prior to the Program. The second model was a three-dimensional, 25-lumped-mass, five-stick model. The three-dimensional finite-element dynamic model was developed primarily for studying the dynamic characteristics of the building in relation to its irregular configuration. The knowledge gained from this study provided a basis for developing the three-dimensional lumped-mass stick model. In addition to this application, the three-dimensional finite-element dynamic model was also used for soil/structure interaction parametric studies to assess the effect of foundation basemat flexibility.

The three-dimensional lumped-mass stick model for the auxiliary building was developed with the specific intent of CLASSI and SASSI analysis applications. The development was based on the conventional dynamic stick model development technique aided with the understanding of the dynamic characteristics of the building obtained from the three-dimensional finite-element dynamic model.

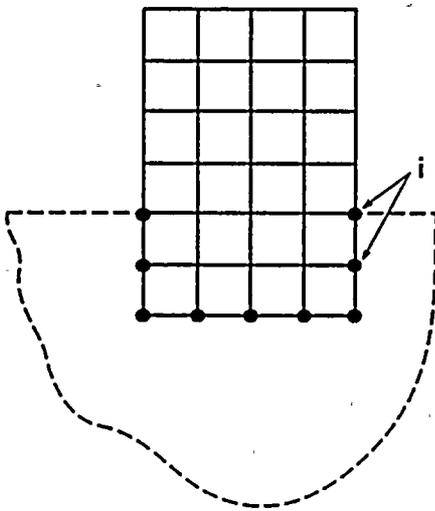




(a) Free-field soil medium



(b) Excavated soil volume



(c) Structure

<p>EXPLANATION</p> <p>i Interaction degrees of freedom at the structure / soil interface</p> <p>f Interaction degrees of freedom in excavated soil volume</p>
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Figure 5-7

SASSI flexible-volume substructuring technique.



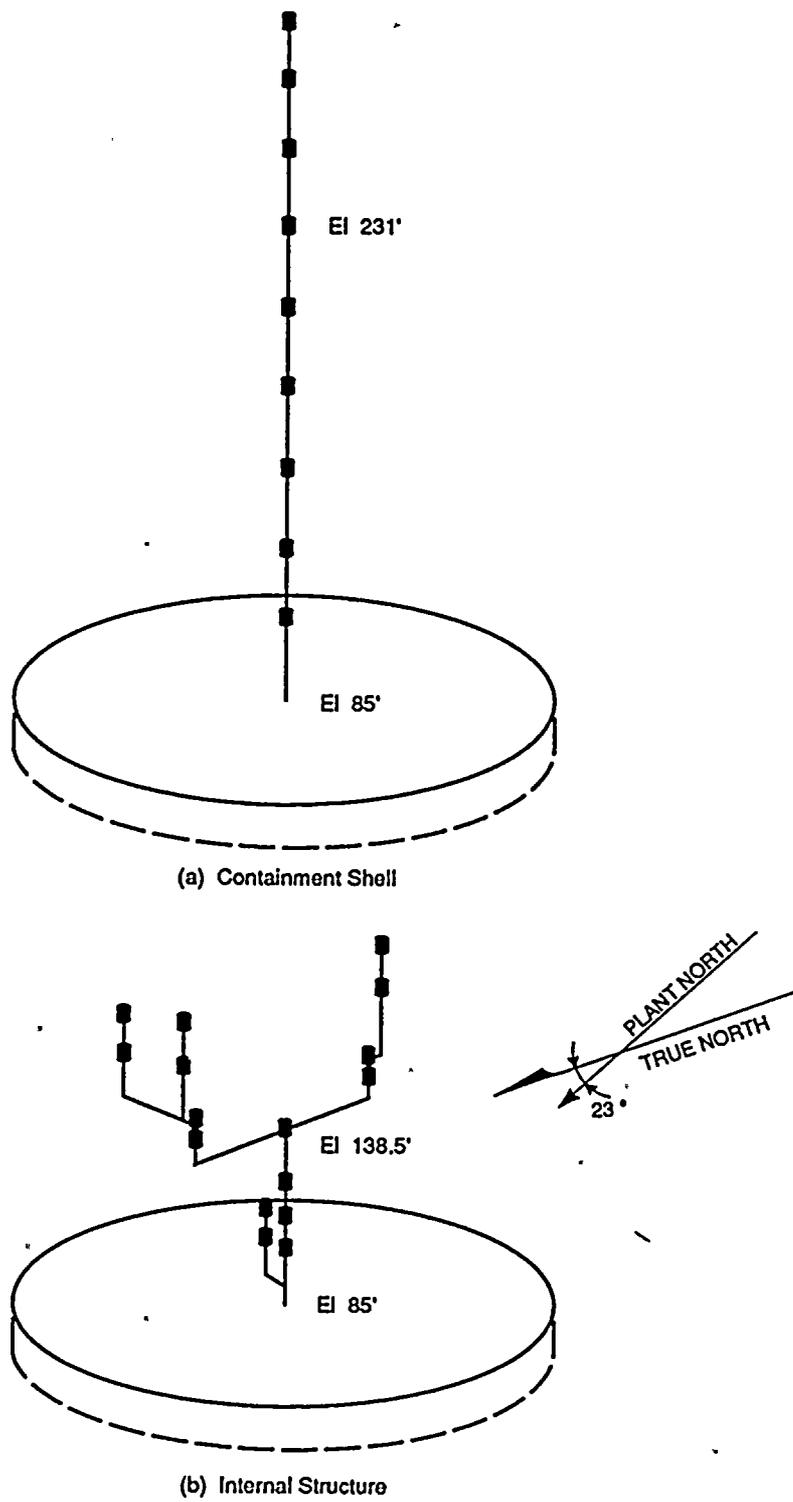


Figure 5-8

Three-dimensional lumped-mass dynamic model for the containment structure.

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The configuration of the three-dimensional lumped-mass stick model developed for the auxiliary building is shown in Figure 5-9. Modal analysis performed using the three-dimensional stick model and the three-dimensional finite-element dynamic model, both with the same fixed-base conditions, showed that they are dynamically equivalent with each other in terms of providing comparable modal characteristics for the significant response modes.

For the turbine building, because of the complexity of the building structural system and the lack of continuous rigid diaphragm action due to the presence of turbine pedestal openings in the floors, the three-dimensional dynamic model selected for analysis applications was a three-dimensional finite-element dynamic model, as shown in Figure 5-10 for the Unit 2 turbine building. This model was developed by modifying the detailed three-dimensional finite-element model used in studies prior to the Program. The three-dimensional dynamic model for the turbine pedestal developed for Program applications is a single lumped-mass stick model. This simple model was considered adequate, because the dynamic characteristics of the turbine pedestal as indicated by the existing refined model were found to be dominated by the fundamental modes in each of the three directions.

Soil/Structure Interaction Parametric Studies

Prior to the development of suitable soil/structure interaction models for the power block structures and the selection of the more appropriate computer programs between CLASSI and SASSI to be applied for final soil/structure interaction analysis, a series of parametric studies were carried out. The objectives of these parametric studies was to assess the soil/structure interaction response sensitivities as affected by various parameters and to identify those parameters which are important for the soil/structure interaction modeling and analysis for power block structures.

The soil/structure interaction parameters studied included the foundation embedment effect, the

multiple-structure-to-structure interaction effect, the effect of nonvertically incident seismic wave inputs, the foundation basemat flexibility effect, and the sensitivity of results to the CLASSI/SASSI solution techniques. In addition, a separate study was performed to assess the importance of strain-dependency of the site rock shear modulus under high intensity earthquake conditions and the effects of variations in Poisson's ratio and material damping ratio for the foundation rock.

For the purpose of the parametric studies, the horizontal soil/structure interaction responses of the containment structure and the auxiliary building were analyzed using either CLASSI or SASSI, or both, for seven parametric cases, each with a different combination of the following parameters: surface-supported versus embedded foundations; single versus multiple foundations; rigid versus flexible foundation. The seismic input for the analysis considered three different type of seismic wave fields, namely, vertical SV plane waves; SV plane waves inclined at a 30-degree angle from the vertical; and horizontally propagating SH plane waves. The seven parametric cases with different types of seismic input analyzed for the parametric studies are summarized in Table 5-1. Except the study for the foundation basemat flexibility effect, for which the analysis was based on the three-dimensional finite-element dynamic model of the auxiliary building coupled with a finite-element foundation model, all analyses for the parametric studies were based on simplified soil/structure interaction models of both the containment structure and the auxiliary building. As an example, the simplified model for the containment structure used for the studies is shown in Figure 5-11. The seismic input time history for the parametric studies was a horizontal acceleration time history with a maximum acceleration of either 0.75 g or 0.96 g, prescribed at the rock surface of the Plant's finished grade at El 85 feet.

Based on the assessment of the soil/structure interaction response sensitivities indicated by the results of the parametric studies, the following conclusions were made:





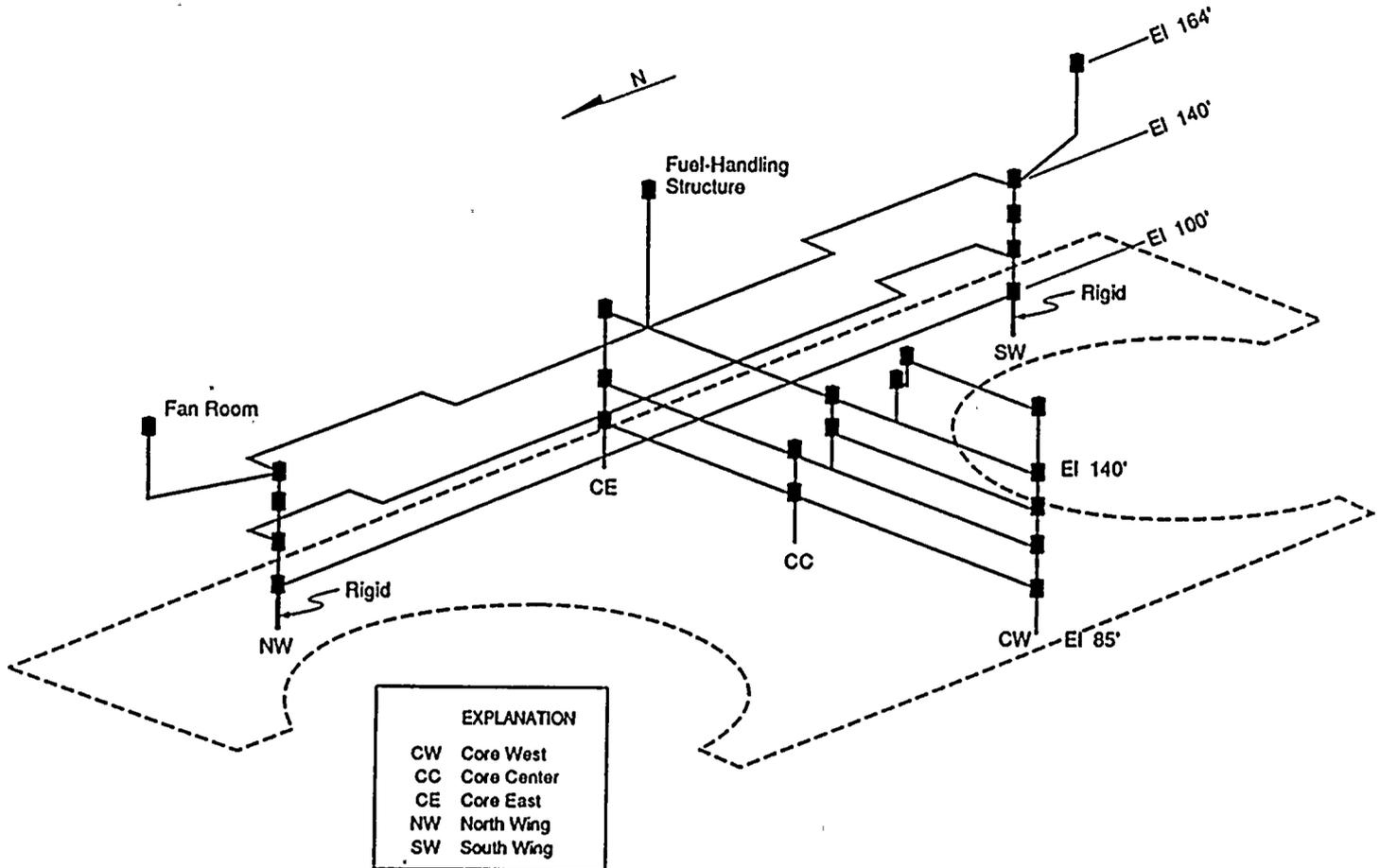


Figure 5-9
Three-dimensional 25-lumped-mass, 5-stick model for auxiliary building.



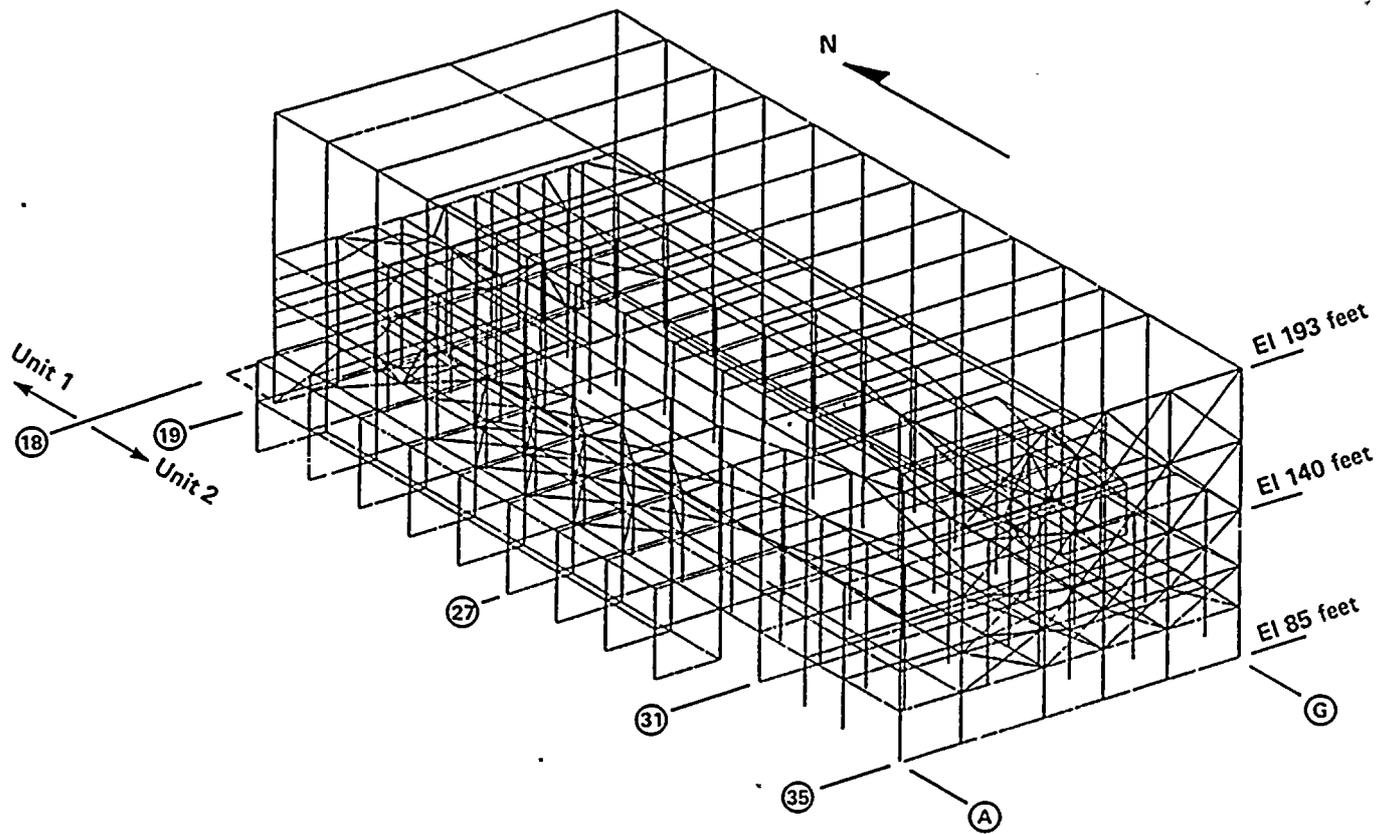


Figure 5-10

Three-dimensional finite-element dynamic model for Unit 2 turbine building above El 85 feet.

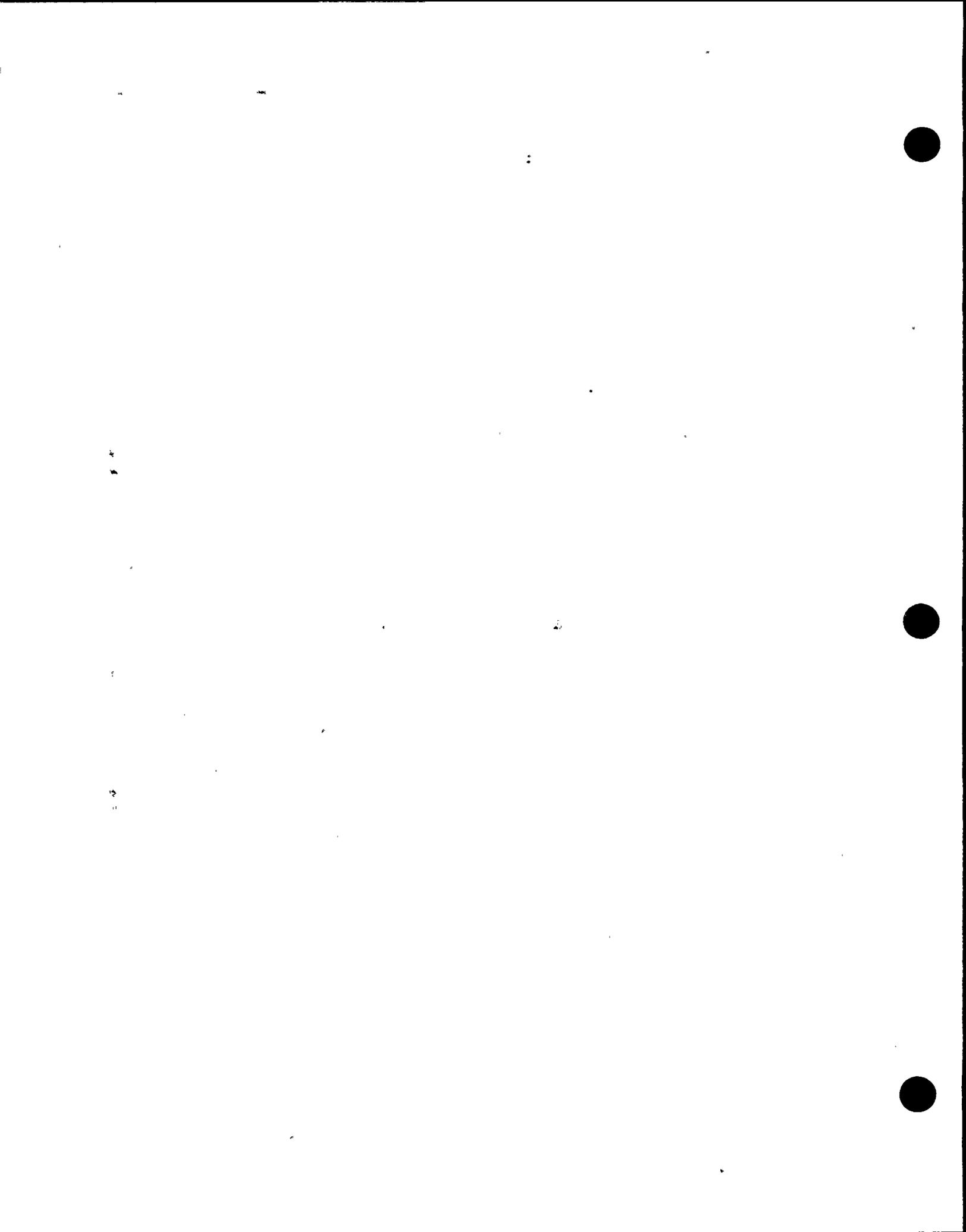


Table 5-1

PARAMETRIC CASES STUDIED AND COMPUTER PROGRAMS USED

Parametric Cases	Ground Motion Input		
	Vertical SV	SV-30 Degrees	Horizontal SH
(1) Fixed-Base Condition for Containment and Auxiliary Building	Standard Structural Dynamics Programs	-	-
(2) Single Surface Rigid Foundation for Containment and Auxiliary Building	CLASSI/SASSI	CLASSI/SASSI	CLASSI
(3) Single Embedded Rigid Foundation for Containment and Auxiliary Building	SASSI	SASSI	-
(4) Containment and Auxiliary Building Surface Rigid Foundation	SASSI/CLASSI	SASSI/CLASSI	CLASSI
(5) Containment and Auxiliary Building Embedded Rigid Foundation	SASSI	SASSI	-
(6) Auxiliary Building Embedded Flexible Foundation	SASSI	-	-
(7) Containment with Embedded Rigid Foundation and Rock Property Variations	SASSI	-	-



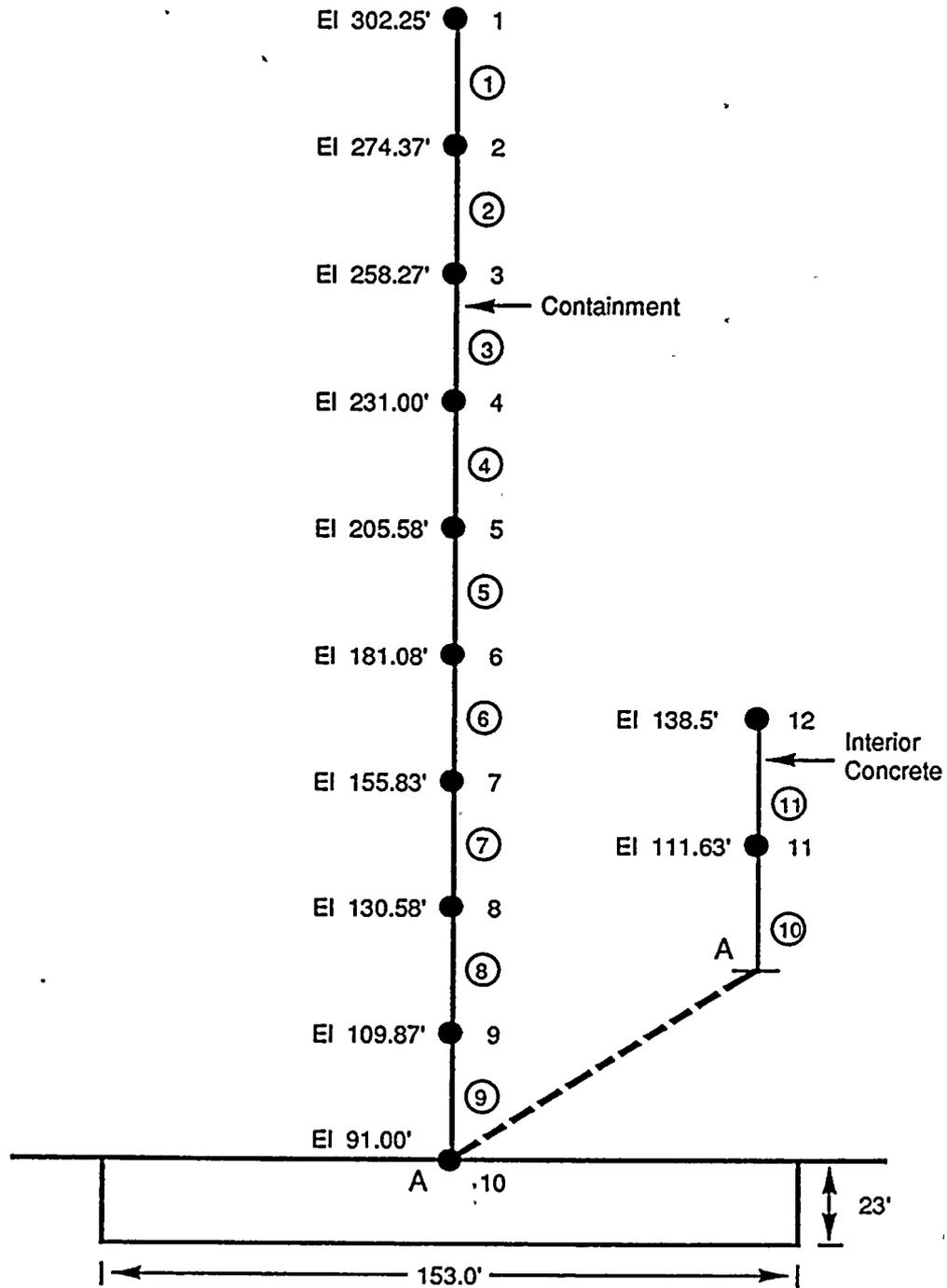


Figure 5-11

Simplified lump-mass stick model of the containment structure used in the parametric studies.

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CLASSI/SASSI Solution Techniques. CLASSI and SASSI produce solutions that are closely comparable with each other so that the choice of either solution method and computer program for a specific application can be based simply on the suitability of foundation model assumptions for the specific application. Representative comparisons of the floor response spectra determined from CLASSI and SASSI analyses for a common parametric case involving the response of the containment base and top of the interior structure to vertically propagating SV wave inputs are shown in Figures 5-12 and 5-13, respectively.

Foundation Embedment Effect. The foundation embedment effect is relatively important and, thus, should be considered in the final soil/structure interaction models for the power block structures. This is demonstrated by the comparison shown in Figure 5-14 of floor response spectra at El 140 feet of the auxiliary building obtained from SASSI analyses assuming surface-supported versus embedded foundation conditions.

Structure-to-Structure Interaction Effect. The through-rock, multiple-structure-to-structure interaction effect is relatively unimportant; thus, it can be neglected in the soil/structure interaction analyses for the power block structures. This is demonstrated by the comparison shown in Figure 5-15 of the floor response spectra at the top of containment interior concrete structure obtained from SASSI analyses assuming single-embedded versus multiple-embedded foundation conditions.

Non-Vertical Wave Propagation Effect. The use of non-vertical seismic wave input motions was found to generally result in reductions in the seismic response; thus, the use of vertical plane wave input for soil/structure interaction analysis is conservative. This is demonstrated by the comparison shown in Figure 5-16 of the floor response spectra at El 140 feet of the auxiliary building obtained from SASSI analyses assuming vertical SV wave versus inclined SV-30-degree wave inputs. Furthermore, the use of vertically propagating wave input precludes double counting of the effect of horizontal spatial variations of ground motions when such a variation is included in the ground-motion spatial incoherence model

and incorporated in the soil/structure interaction analysis.

Basemat Flexibility Effect. The effect of foundation basemat flexibility was shown to be relatively important for the auxiliary building. This is demonstrated by the comparisons shown in Figure 5-17 of the transfer function amplitudes at the core west location of the floor at El 140 feet of the auxiliary building obtained from SASSI analysis assuming five different basemat flexibility conditions as shown in Figure 5-18. Thus, for those structures having basemats of large plan dimensions such as the auxiliary and turbine buildings, the basemat flexibility should be considered in the soil/structure interaction models.

Rock Property Variation Effect. The effect of strain-dependency of site rock shear modulus was found to be insignificant (maximum reduction of containment fundamental soil/structure interaction frequency was less than 8 percent) for seismic input intensities involving maximum ground acceleration as high as 1.0 g. The effects of variations in the Poisson's ration and material damping ration of the rock within the ranges of values considered appropriate was found to be negligible.

Based on the above conclusions, the SASSI computer program was selected for the final soil/structure interaction analysis application because of its capability to include the effects of foundation embedment and basemat flexibility. The SASSI finite-element foundation models developed for the power block structures for the final analysis are shown in Figure 5-19 for the containment structure, in Figure 5-20 for the auxiliary building, and in Figure 5-21 for the turbine building.

Ground-Motion Input for Soil/Structure Interaction Analysis

The basic data of seismic ground-motion input for soil/structure interaction analysis were provided by the ground-motion studies (Chapter 4). These data consisted of the median and 84th percentile, horizontal and vertical site-specific



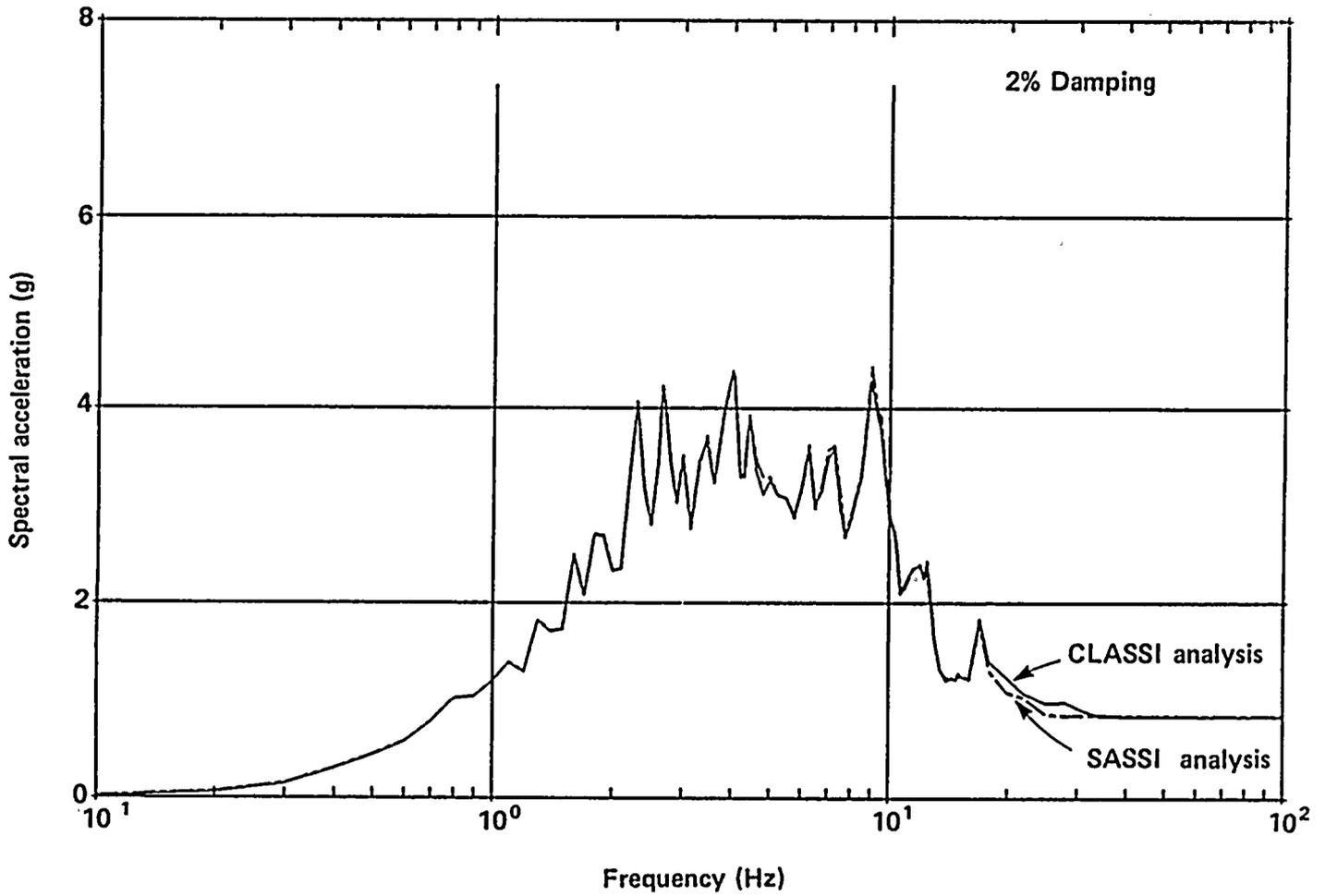


Figure 5-12

Comparisons of floor response spectra obtained from CLASSI and SASSI analysis for the east/west response at the containment base.



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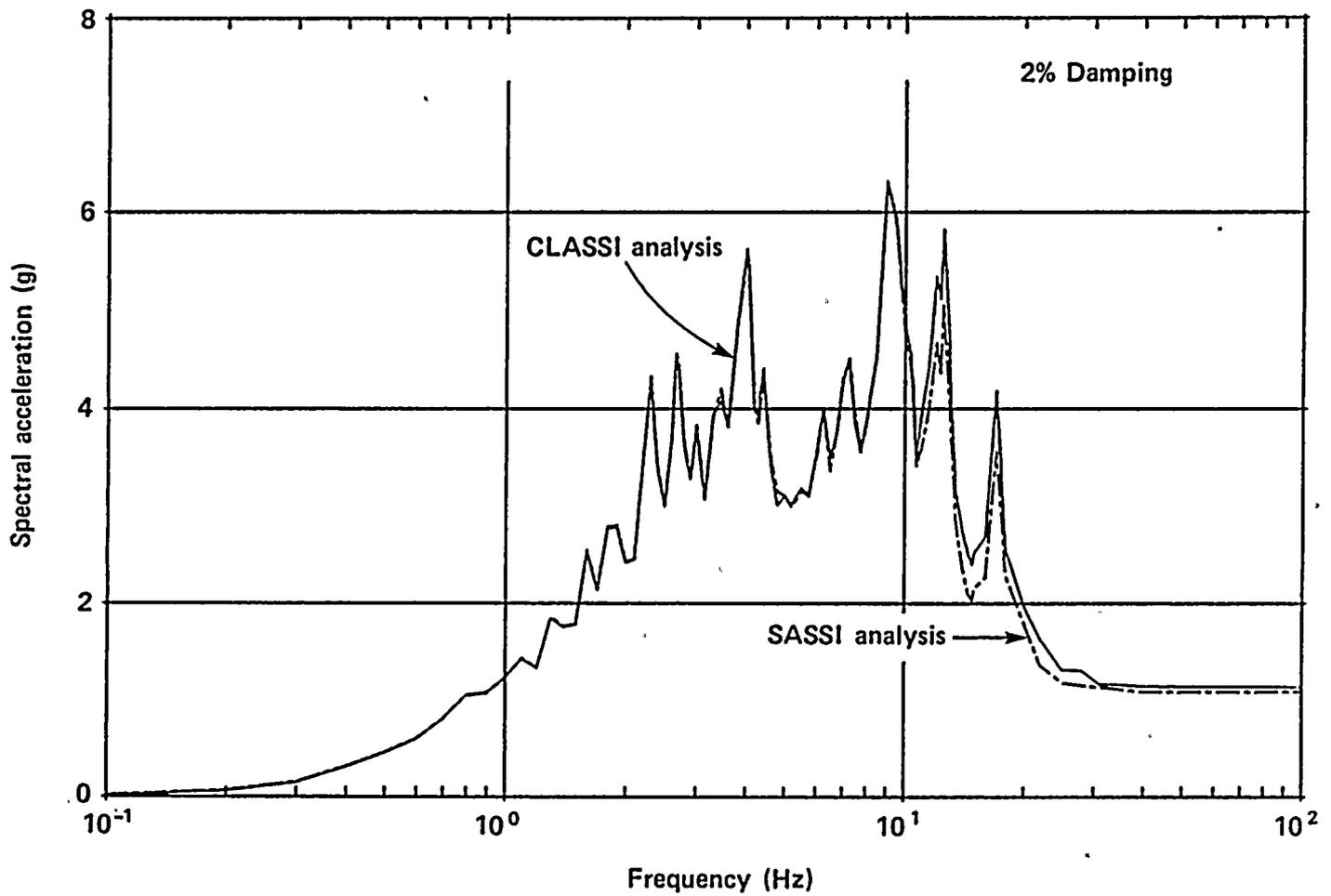
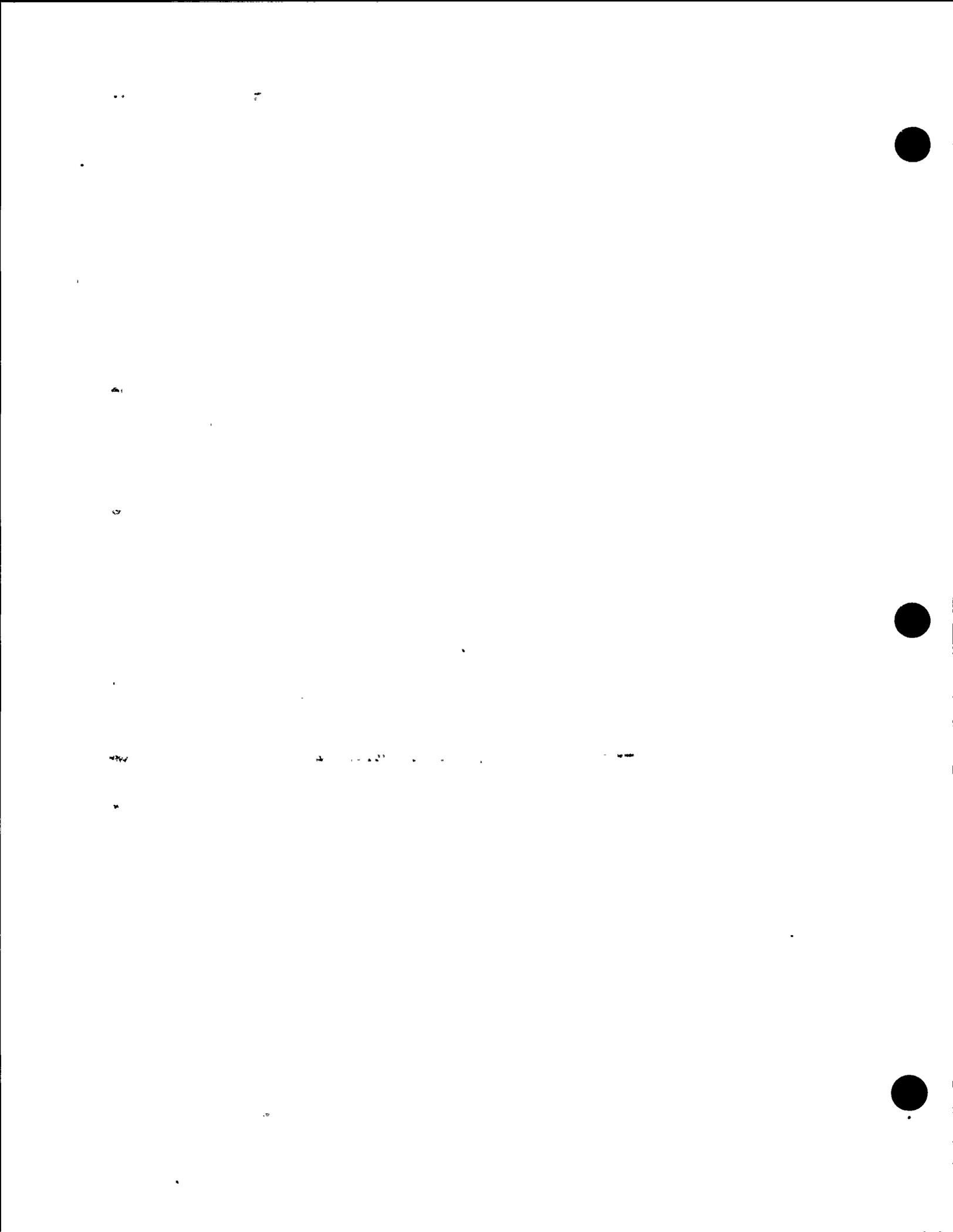


Figure 5-13

Comparisons of floor response spectra obtained from CLASSI and SASSI analyses for the east/west response at the top of interior concrete structure.



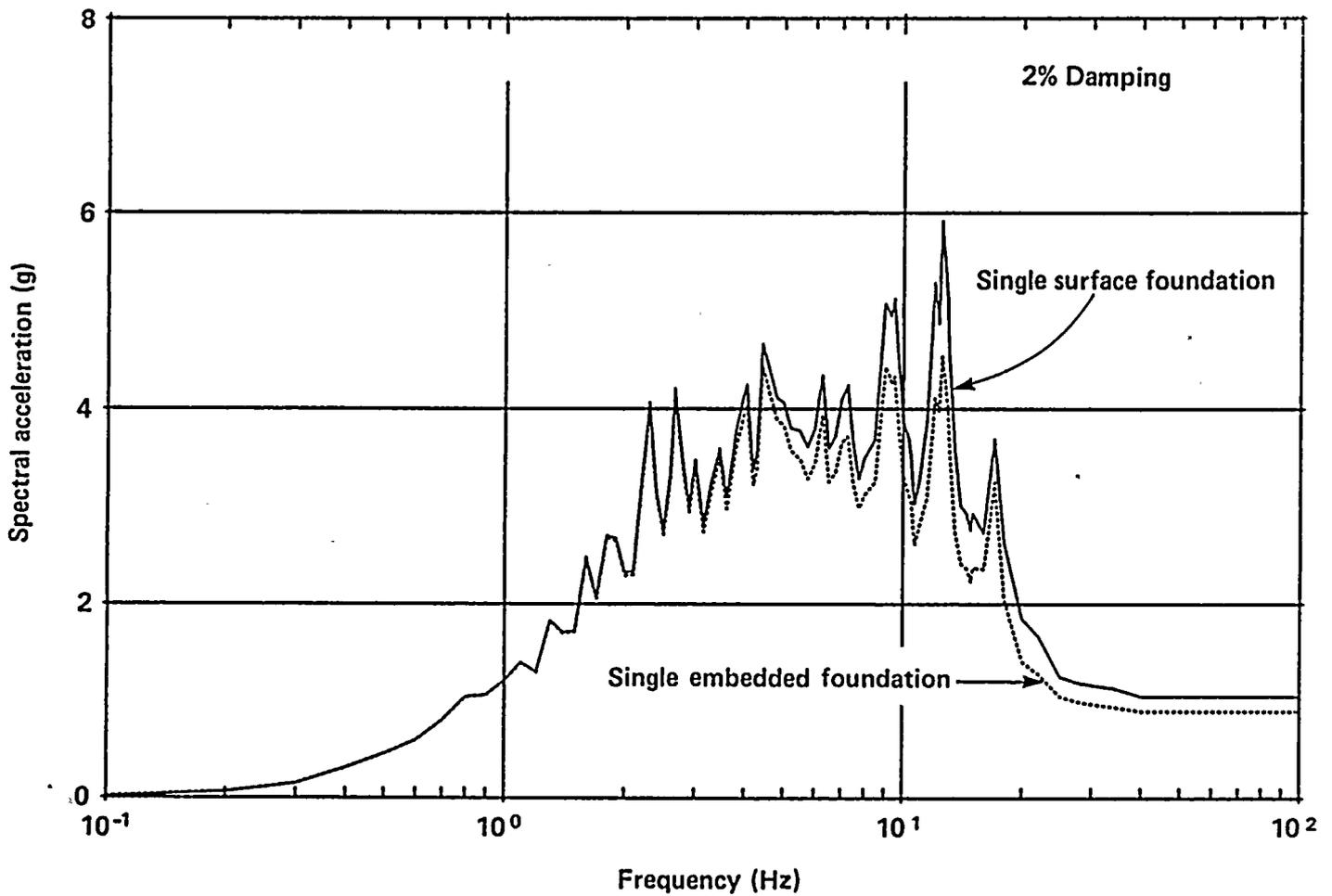


Figure 5-14

Comparison of floor response spectra obtained from SASSI analysis assuming surface-supported versus embedded foundation conditions for the auxiliary building at El 140 feet.



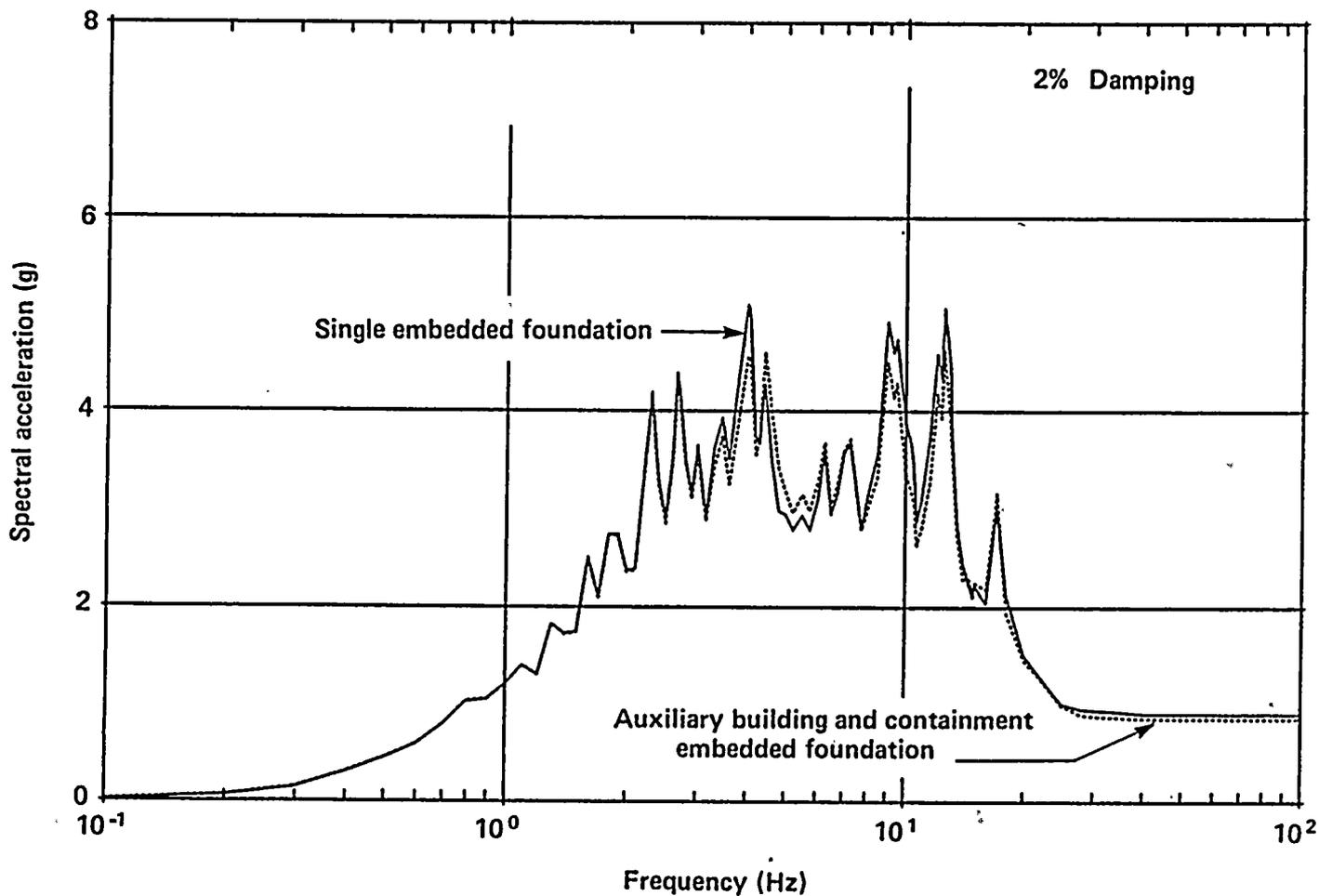
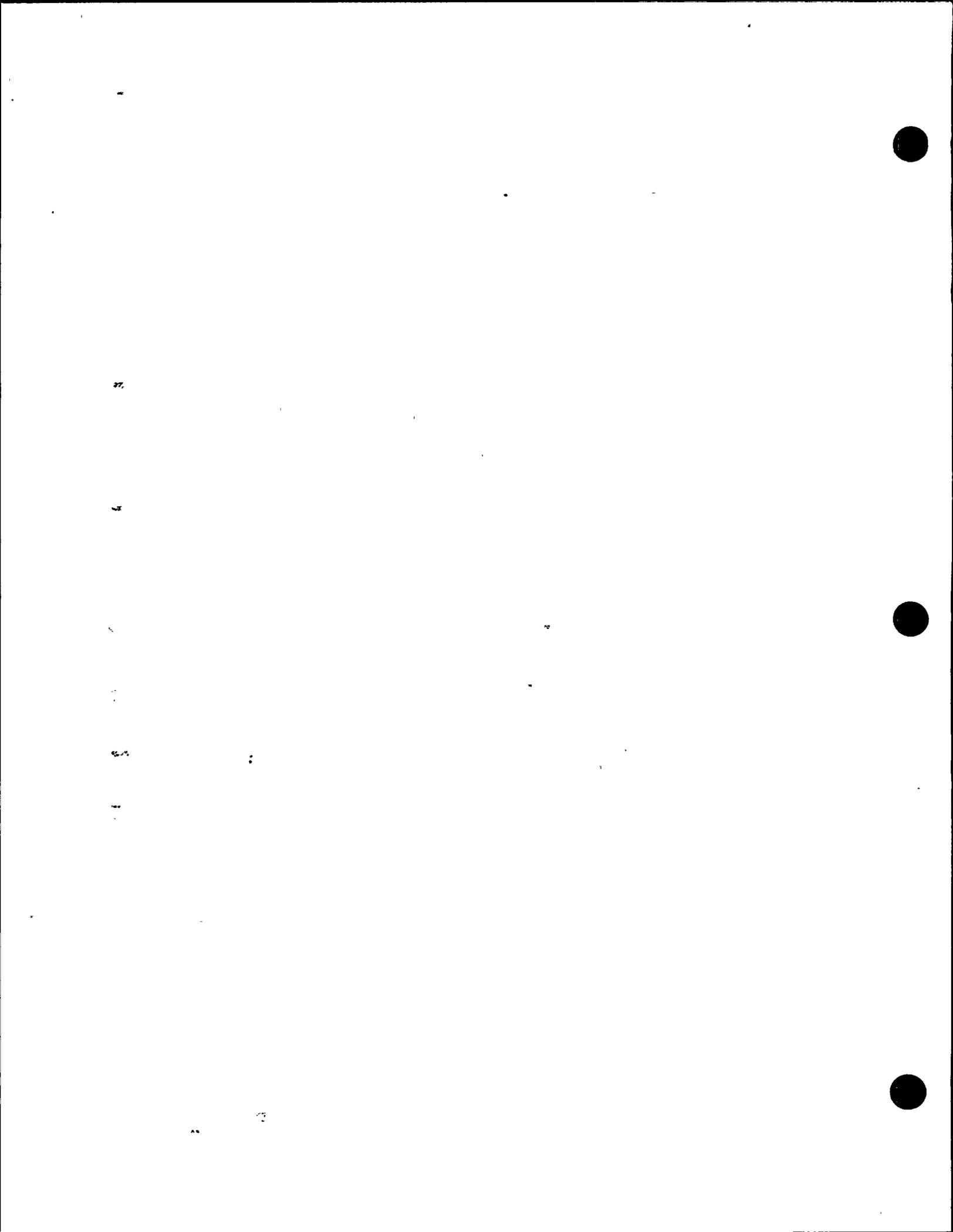


Figure 5-15

Comparison of floor response spectra obtained from SASSI analyses assuming single embedded foundation versus multiple-embedded foundations.



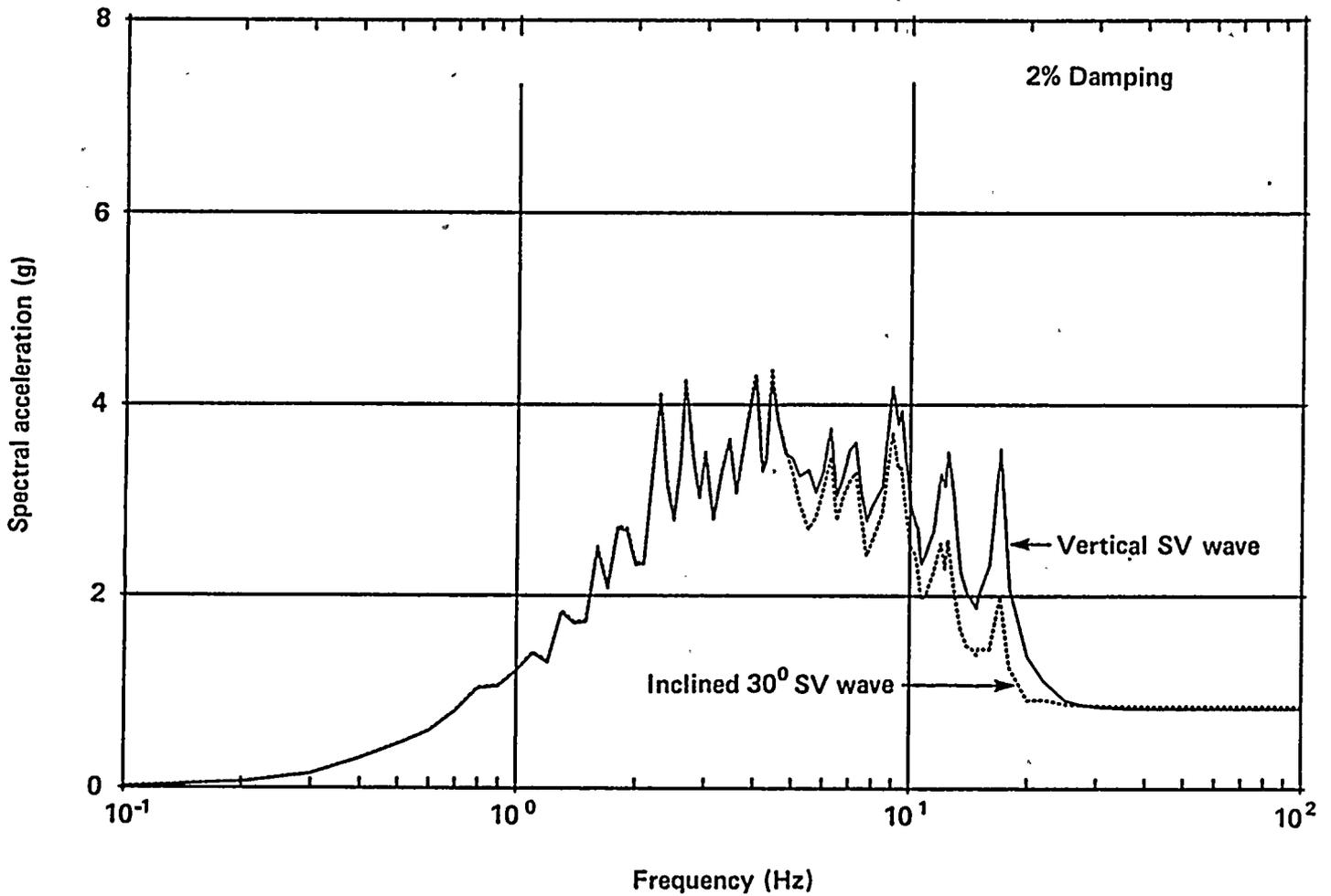


Figure 5-16

Comparison of floor response spectra at El 140 feet of the auxiliary building obtained from SASSI analyses with vertical SV wave input versus inclined SV wave input.

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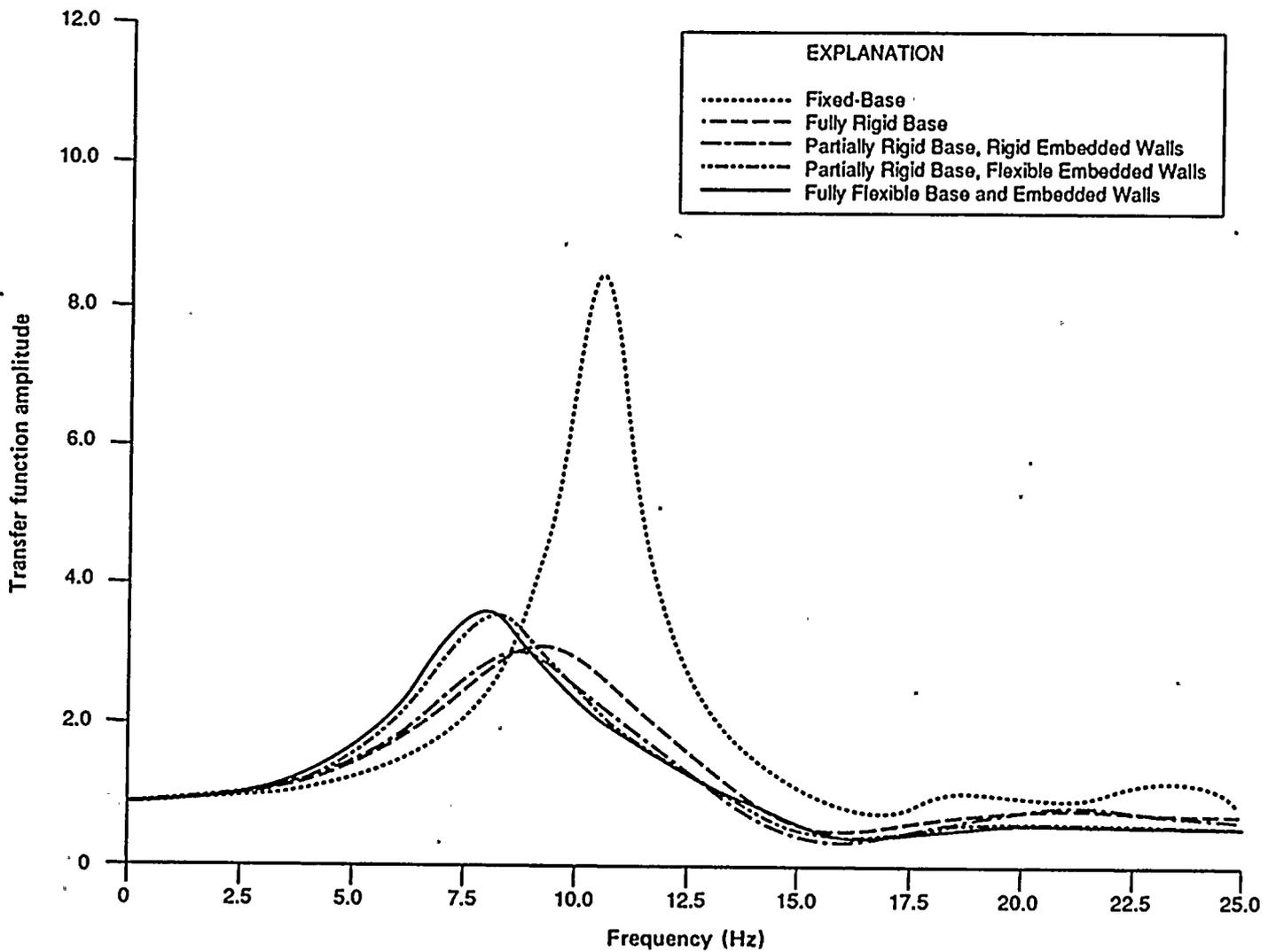


Figure 5-17

Transfer functions for east/west response at core west El 140 feet of the auxiliary building for various conditions of foundation systems.

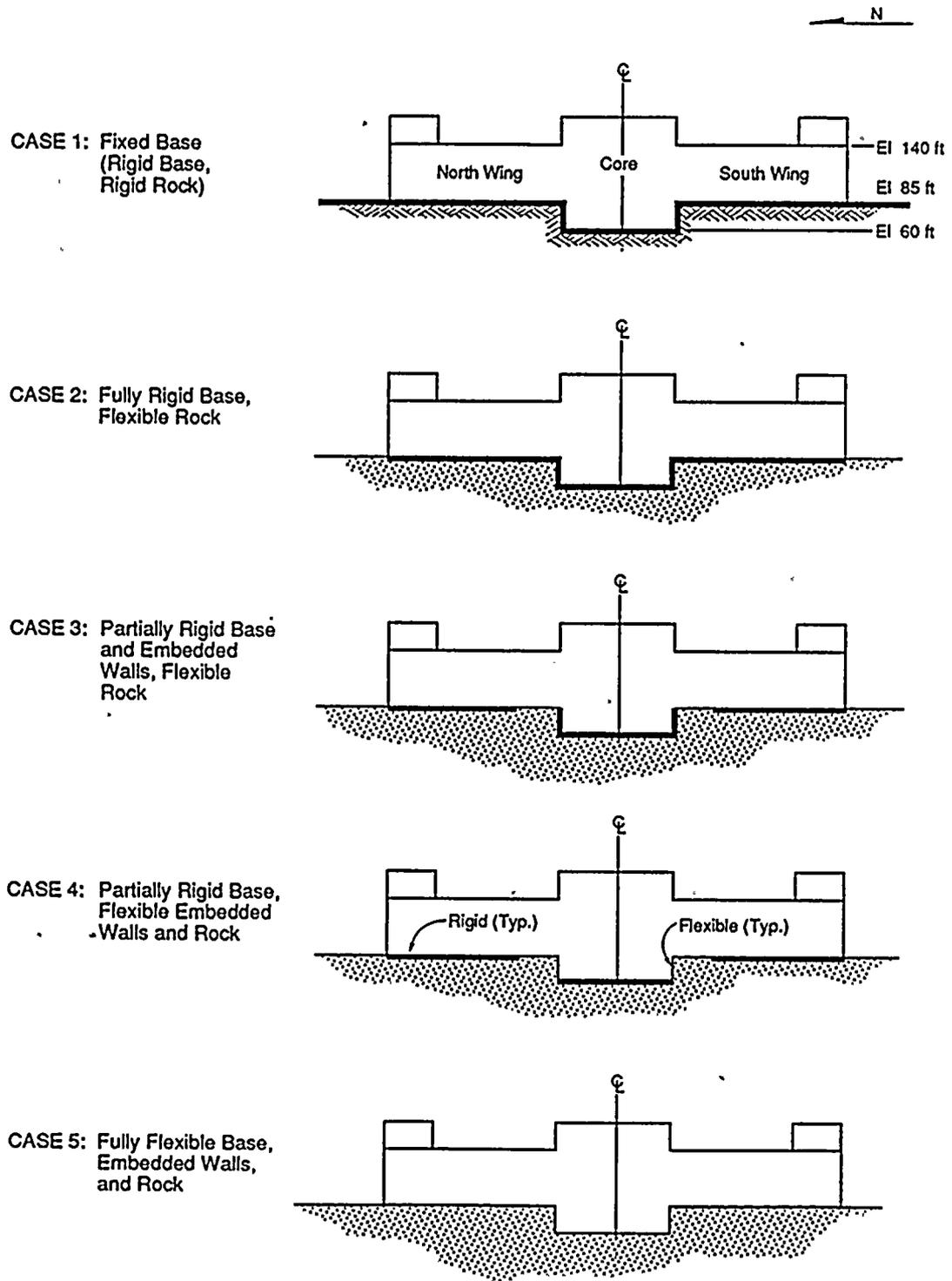
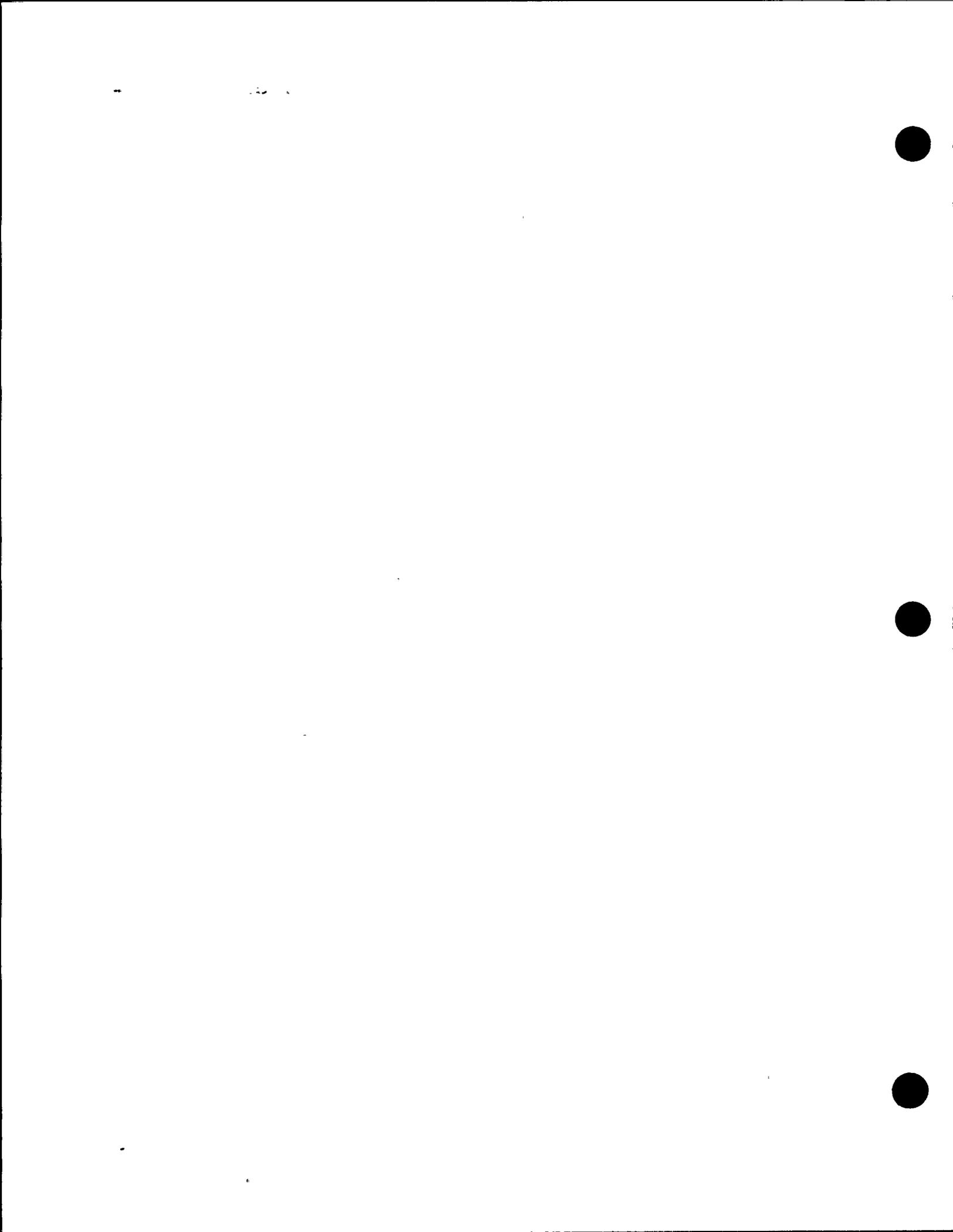


Figure 5-18

Various foundation basemat flexibility assumptions for the auxiliary building considered in the parametric studies.





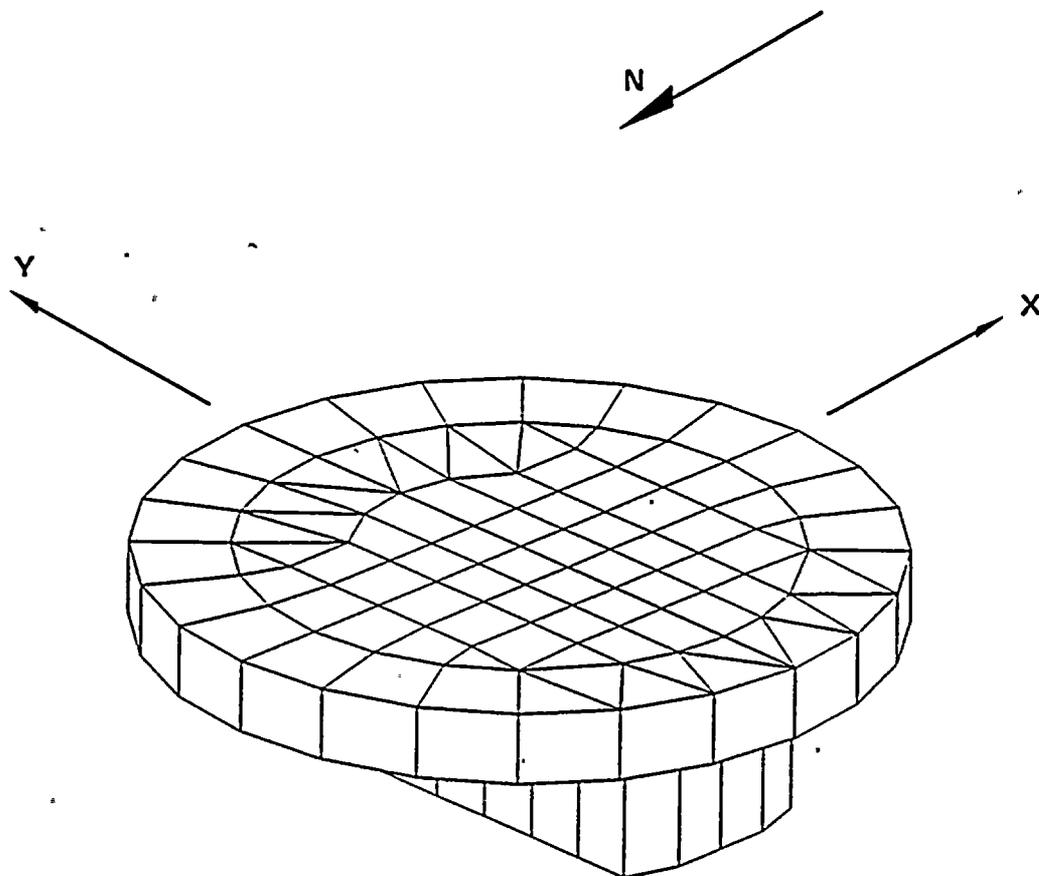


Figure 5-19

SASSI foundation model for containment structure.



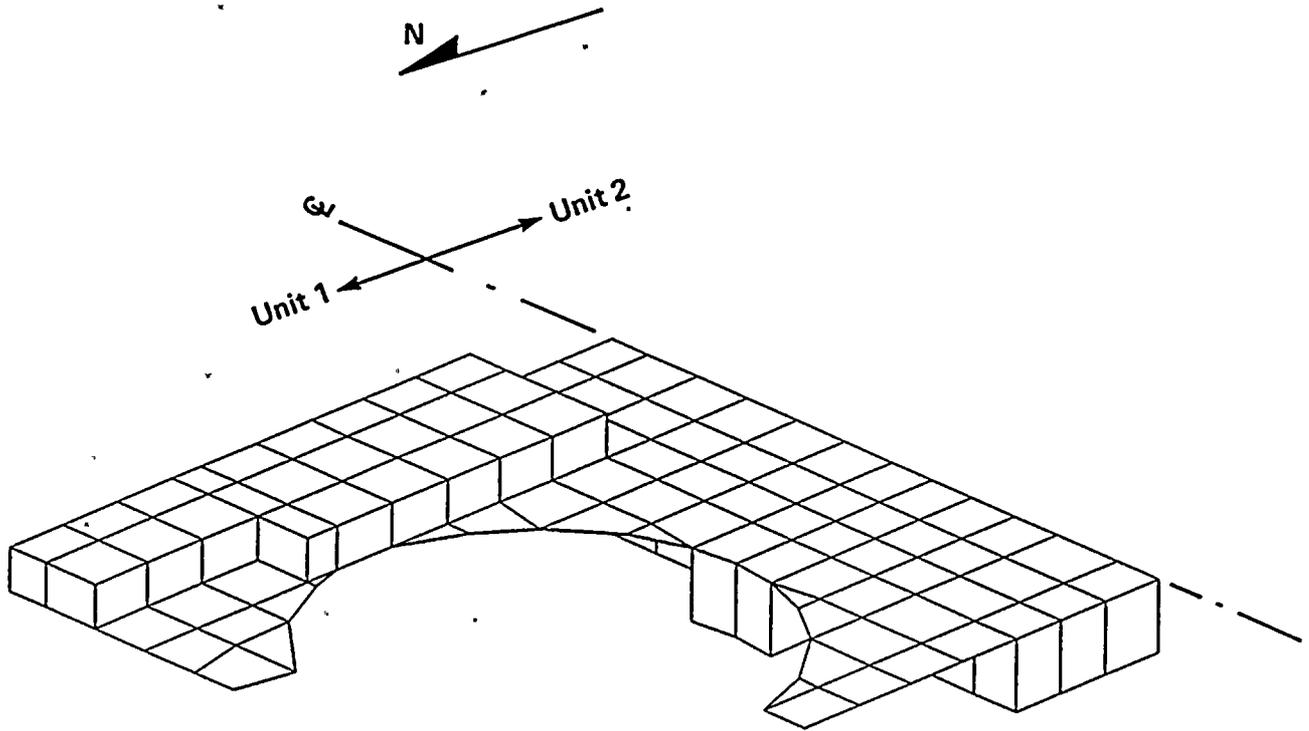
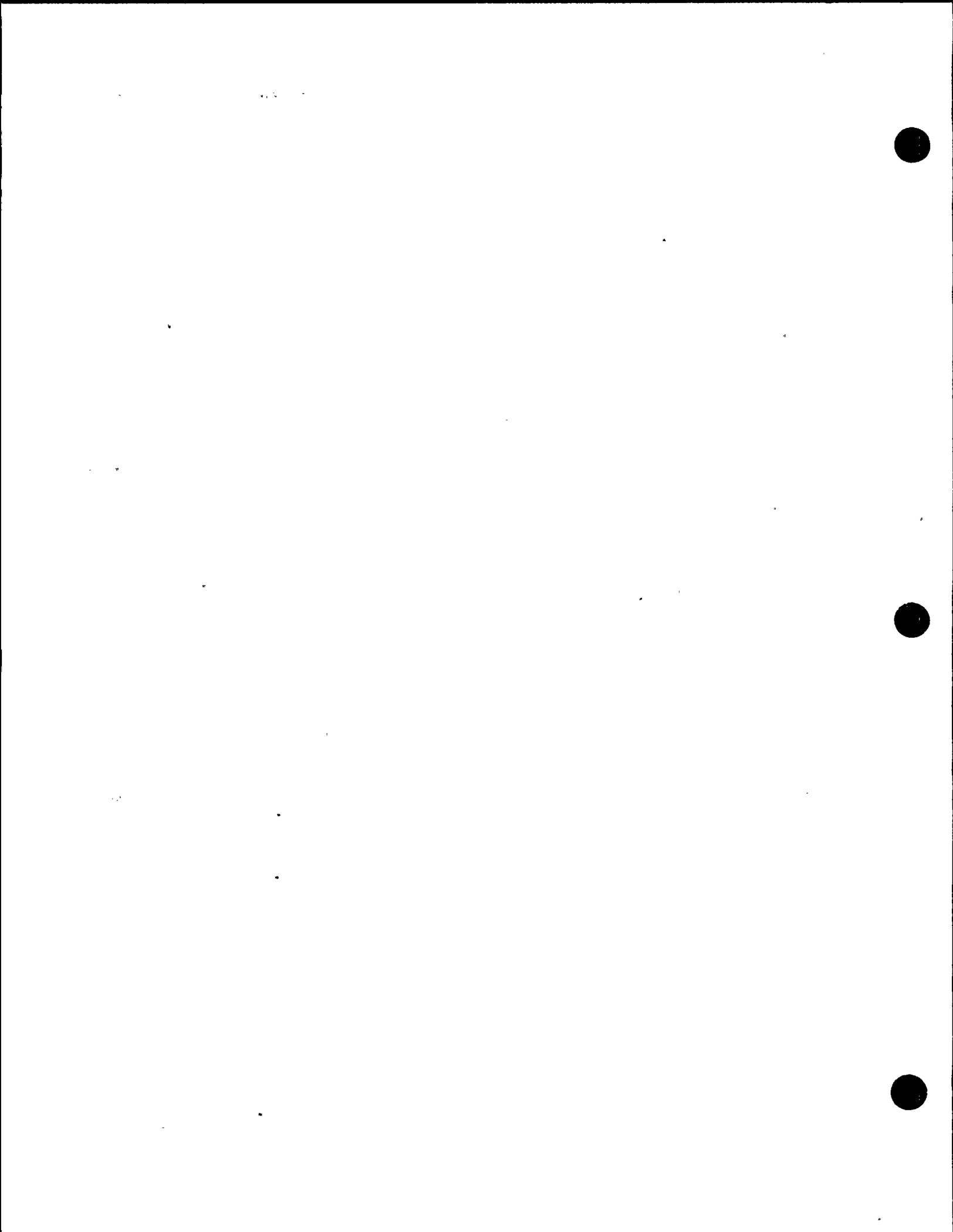
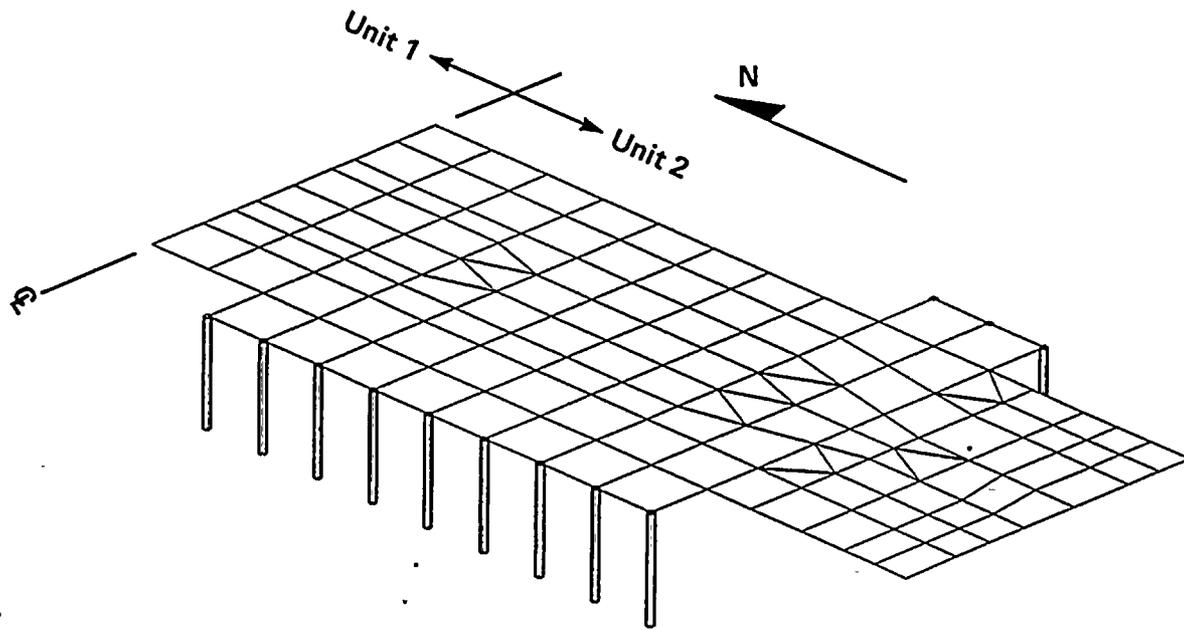


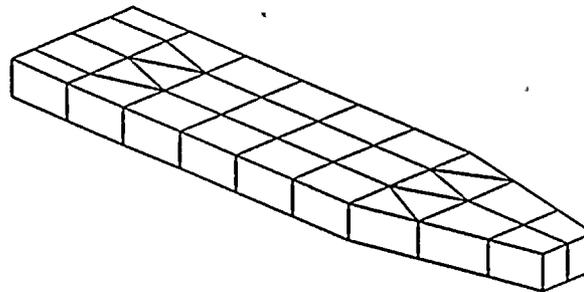
Figure 5-20

SASSI foundation half-model for auxiliary building.





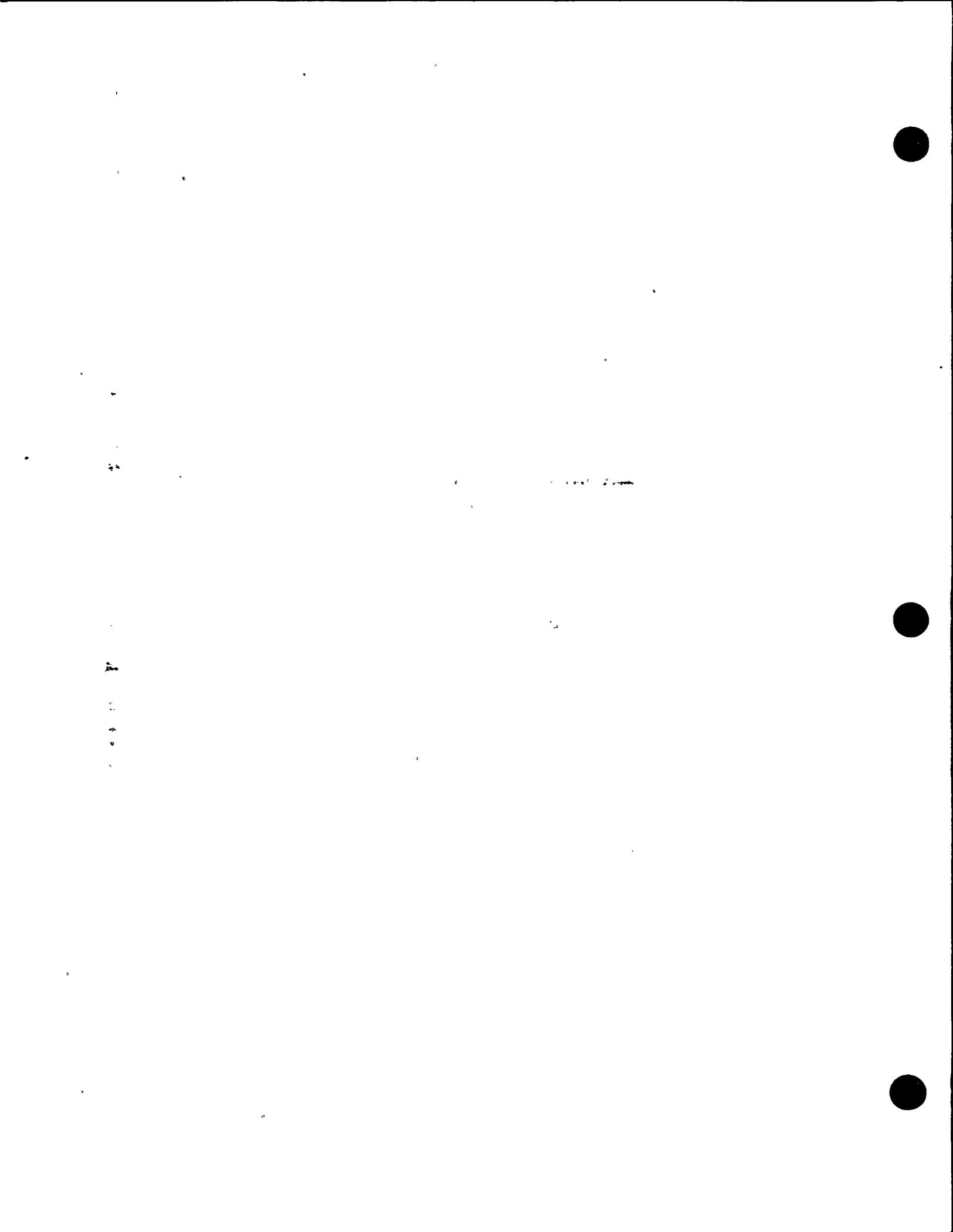
Unit 2 turbine building foundation model



Unit 2 turbine pedestal foundation model

Figure 5-21

SASSI foundation model for Unit 2 turbine building.



earthquake acceleration response spectra for the Diablo Canyon site. Both the median and the 84th percentile spectra, normalized with respect to peak ground acceleration values, have almost the same spectral shape. Thus, it is only necessary to consider one set (median or 84th percentile) of these spectra for linear soil/structure interaction analysis, because the responses so obtained can be linearly scaled up or down, based on the peak ground acceleration ratio, to obtain the soil/structure interaction responses for any desired level of input.

Associated with the site-specific response spectra, three sets of three-component actual earthquake ground-motion time histories were selected and provided by the ground-motion study for soil/structure interaction analysis applications. These three sets of ground-motion records are: (a) the Pacoima Dam records of the 1971 San Fernando earthquake; (b) the Tabas records of the 1978 Tabas earthquake; and (c) the El Centro No. 4 records of the 1979 Imperial Valley earthquake. Two of the three sets of ground-motion records provided (Pacoima and Tabas) were actually used for final soil/structure interaction analyses.

Before these motions were applied for soil/structure interaction analysis, the following step-by-step procedure was used to adjust the motions:

- (1) The original recorded motions were adjusted to conform to site-specific conditions, such as the maximum earthquake magnitude, source-to-site distance, and site condition.
- (2) The two horizontal components of the motions were transformed, as necessary, into the longitudinal and transverse horizontal components to provide motions in the directions normal and parallel to the strike of the causative fault.
- (3) The longitudinal and transverse time histories were both modified by adjusting the Fourier

amplitudes, but keeping the Fourier phase-angles unchanged, so that the resulting time history response spectra closely matched the median site-specific horizontal spectra of several damping values. Likewise, the vertical component time histories were modified to match the median site-specific vertical spectra of several damping values.

- (4) The three-component time histories were scaled upward by a constant scaling factor common to all three components to correspond to a reference seismic input level for Plant fragility evaluation purposes.
- (5) Because the Plant north/south direction is approximately parallel to the strike of the Hosgri fault zone, the modified and scaled three-component time histories were applied as the input for soil/structure interaction analyses; first, with the longitudinal component applied in the Plant north/south direction, and the transverse component in the plant east/west direction; then vice versa, the vertical component was applied in the Plant vertical direction. The interchanging of the two horizontal components for input was done to allow for uncertainties in the time history phasing, because both the Pacoima and Tabas motions were initiated by thrust events.

For Plant fragility evaluation applications, the constant scaling factor used in step (4) above, was derived in such manner that the average spectral value of the 5 percent damped site-specific horizontal spectral acceleration in the frequency range from 4.8 hertz to 14.7 hertz, equal to the fragility evaluation reference spectral acceleration of 2 g. The frequency range was chosen considering the fragility evaluations described in Chapter 6. This procedure is illustrated in Figure 5-22. The resulting scaling factor was 1.6, and the peak spectral acceleration of the resulting horizontal spectrum was about 2.2 g. The fragility evaluation reference spectra so obtained are



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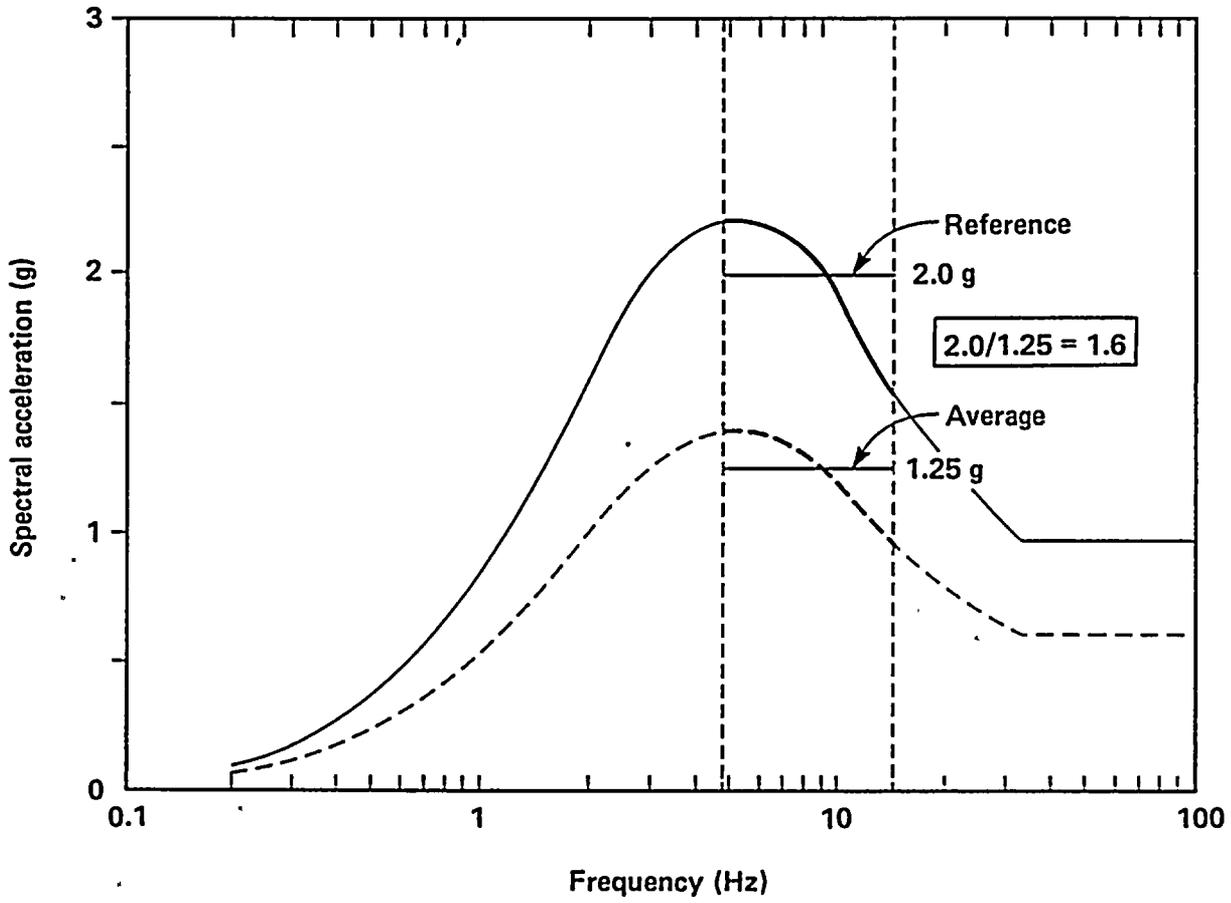
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EXPLANATION

— Median site-specific response spectrum scaled by 1.6

- - - Median site-specific response spectrum

Figure 5-22

Illustrative procedure for obtaining the 5 percent damped horizontal reference spectrum for soil/structure interaction analyses.

slightly higher than the 84th percentile response spectra for the site.

The final three-component Pacoima time histories, which have been modified to match the median spectra shapes and subsequently scaled up by the 1.6 factor, are shown and compared with the unmodified, time histories from step (2) above (but scaled to the maximum acceleration of 0.96 g for the horizontal components) in Figures 5-23, 5-24, and 5-25, respectively for the longitudinal, transverse, and vertical components. The comparisons of the 5 percent damped final Pacoima time history response spectra with the 5 percent damped fragility evaluation reference response spectra are shown in Figures 5-26, 5-27, and 5-28. Similar comparisons for the three-component Tabas time histories are shown in Figures 5-29, 5-30, and 5-31; and similar comparisons for response spectra are shown in Figures 5-32, 5-33, and 5-34.

As shown in these comparisons, the modified final time history response spectra closely match the corresponding reference response spectra, which are about 10 percent higher than the 84th percentile response spectra discussed previously. Furthermore, as a result of keeping the time history Fourier phases unchanged during the time history modifications for spectrum compatibility, the final spectrum-compatible time histories maintain realistic characteristics and appearances, and resemble the time histories of the motions before modifications.

Generation of Soil/Structure Interaction Responses to Coherent Ground-Motion Inputs

To generate the soil/structure interaction responses required for the Plant fragility evaluations, soil/structure interaction analyses were performed using the SASSI computer program, the soil/structure interaction models developed for the power block structures, and the ground motions described previously. Because equipment fragilities are mostly dominated by

horizontal responses (Chapter 6), only the horizontal north/south and east/west responses of the power block structure were generated.

For these analyses, the final scaled-up three-component spectrum-compatible Pacoima and Tabas time histories, shown in Figures 5-23 through 5-25, and Figures 5-29 through 5-31, respectively, were directly used as inputs for analyses. These input motions were assumed in the analyses to be the free-field surface motions prescribed at the plant grade (El 85 feet). The incident seismic wave field was assumed to be coherent, vertically propagating plane seismic shear and compression waves, respectively, for the horizontal and vertical components of the free-field motion. Because only the horizontal north/south and east/west responses were generated, the coupling between the two horizontal responses that exists for non-symmetrical structures was considered by combining the co-directional time history responses or by combining the floor response spectra using the rule of square-root-of-the-sum-of-squares. Under the vertically propagating plane wave assumption, the contributions to the horizontal responses due to the vertical input motion are negligible; thus, they were not considered in the response combinations to obtain the north/south and east/west horizontal responses.

The results of the soil/structure interaction analyses were obtained and provided for use in the Plant fragility evaluation in terms of 5 percent damped horizontal north/south and east/west floor response spectra at selected locations in the power block structures. Floor response spectra for both sets of input motions, namely, the Pacoima and the Tabas inputs, were generated. Representative results obtained from both sets of input motions are shown in Figures 5-35 and 5-36 for the north/south response of the containment at the base (El 85 feet) and at the top of the interior structure (El 138.5 feet), respectively. Similarly, the results for the north/south response of the auxiliary building at El 85 feet and El 140 feet of the core west

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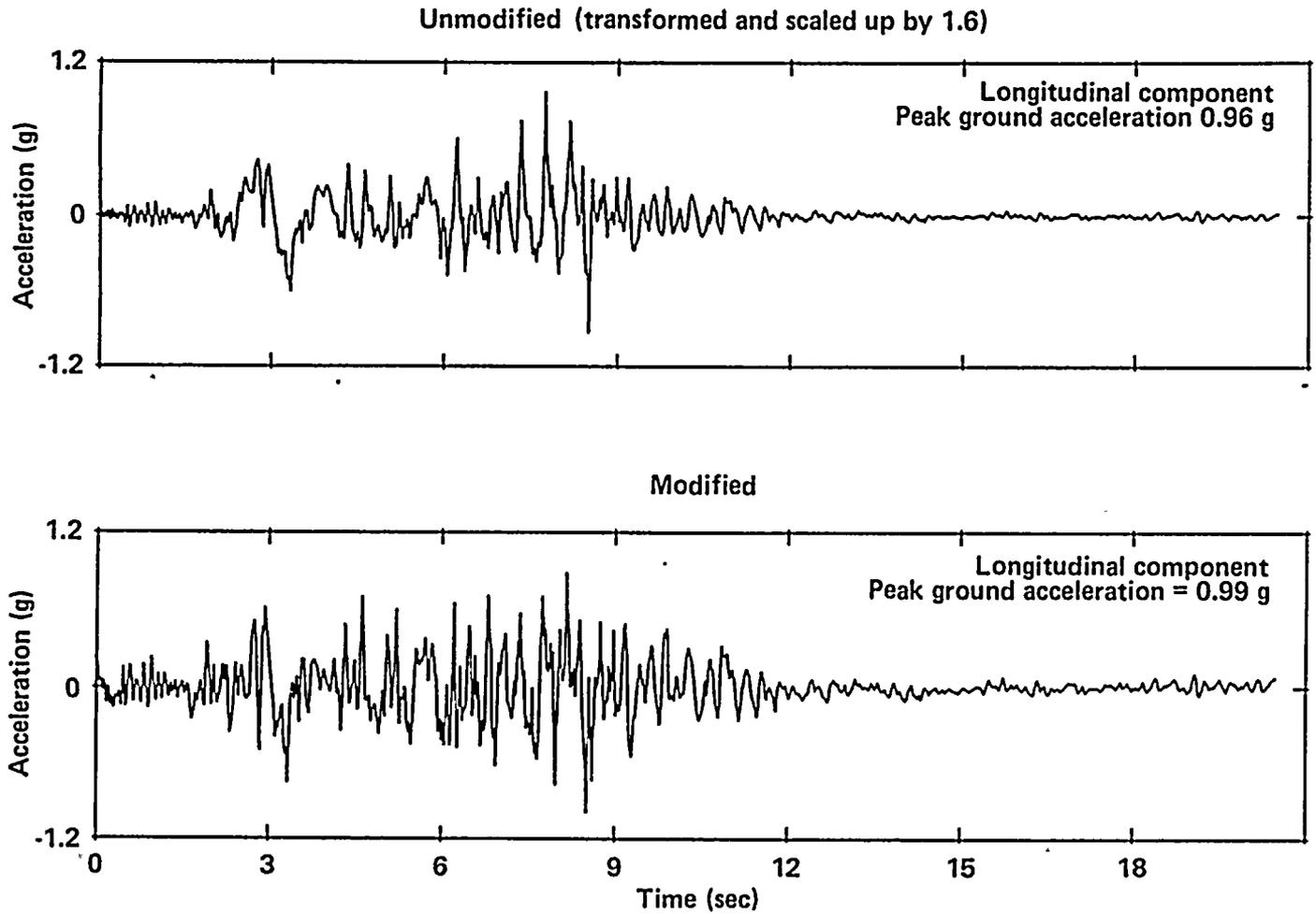
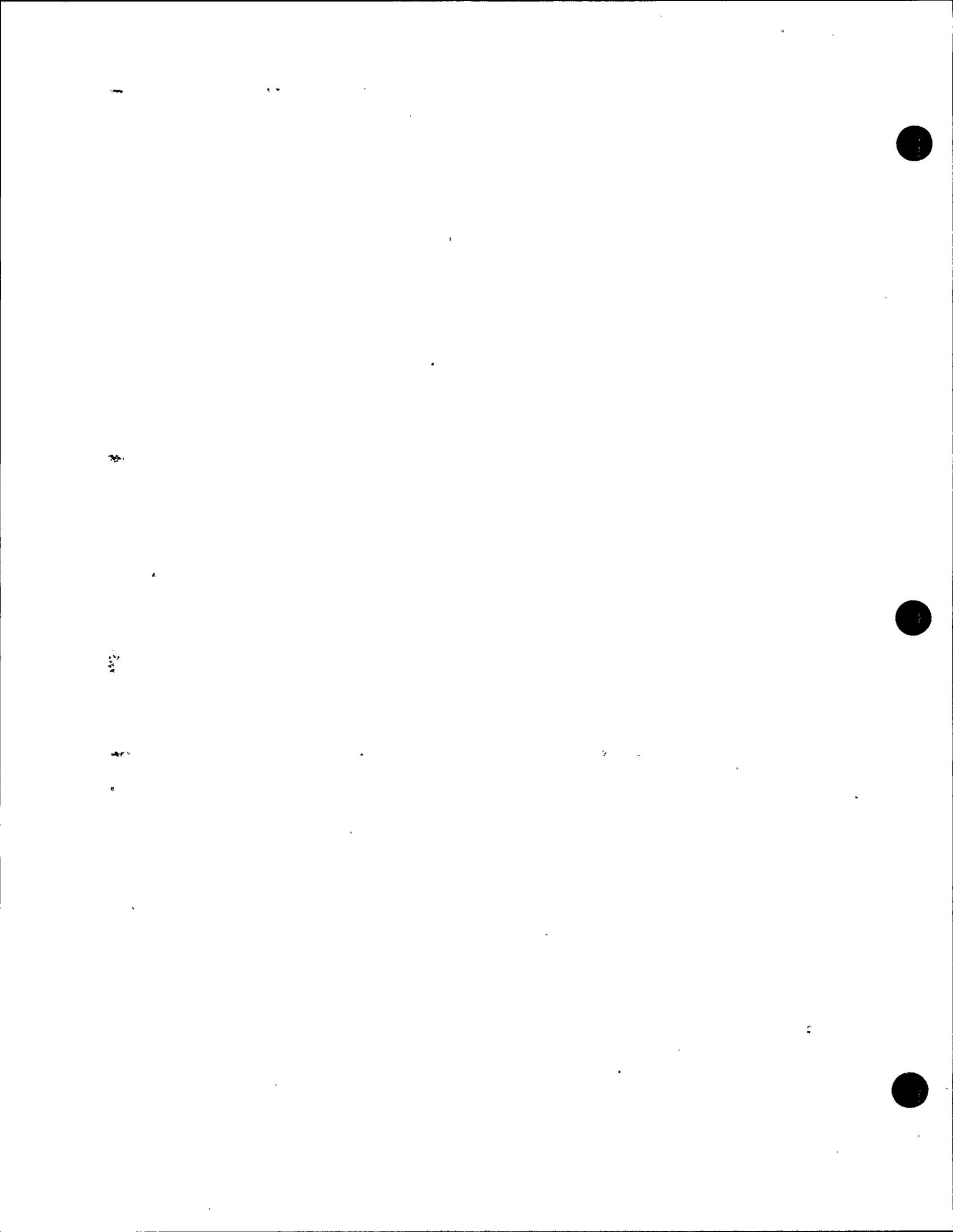


Figure 5-23

Comparisons of unmodified and modified Pacoima acceleration time histories, longitudinal component.



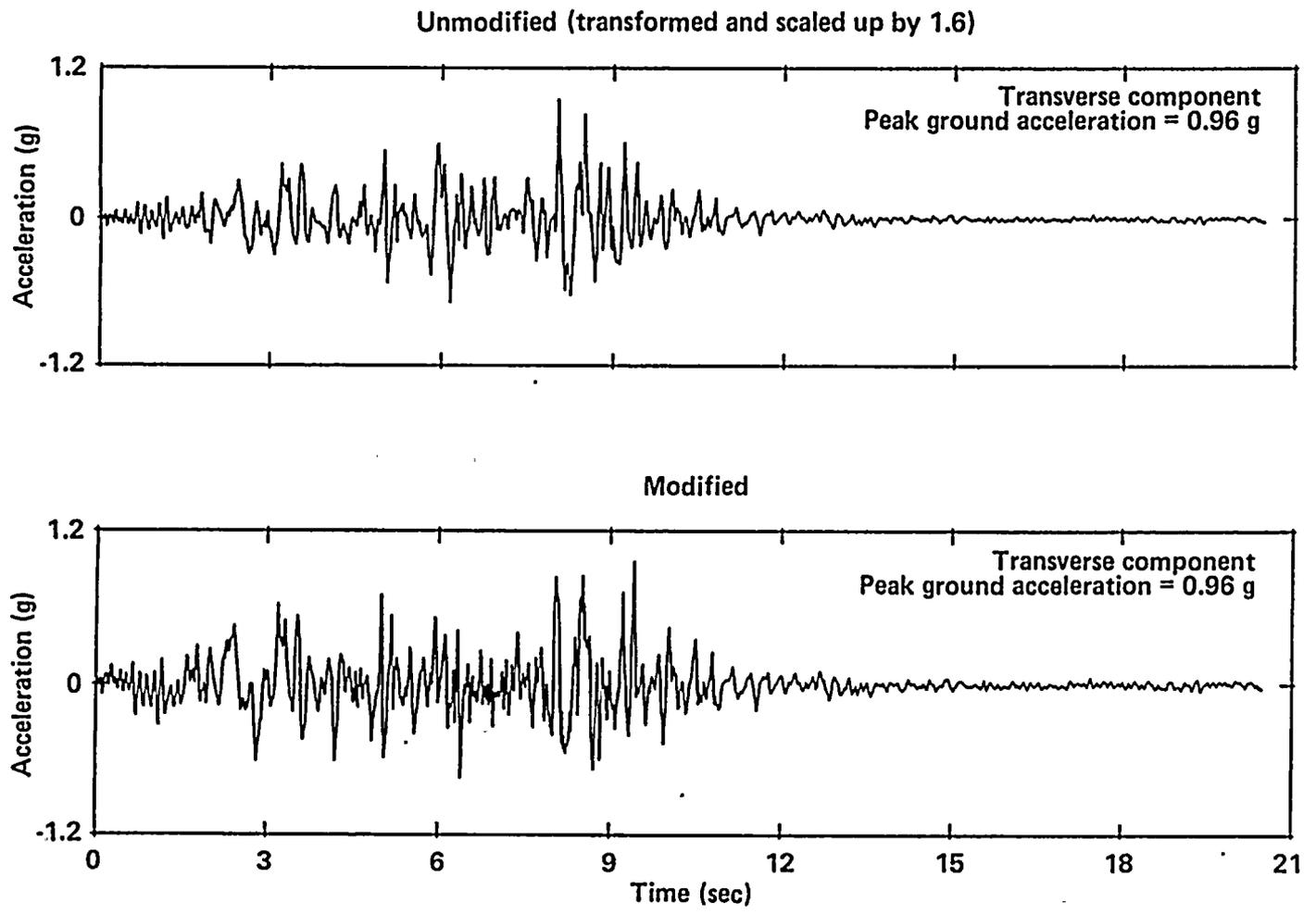


Figure 5-24

Comparisons of unmodified and modified Pacoima acceleration time histories, transverse component.

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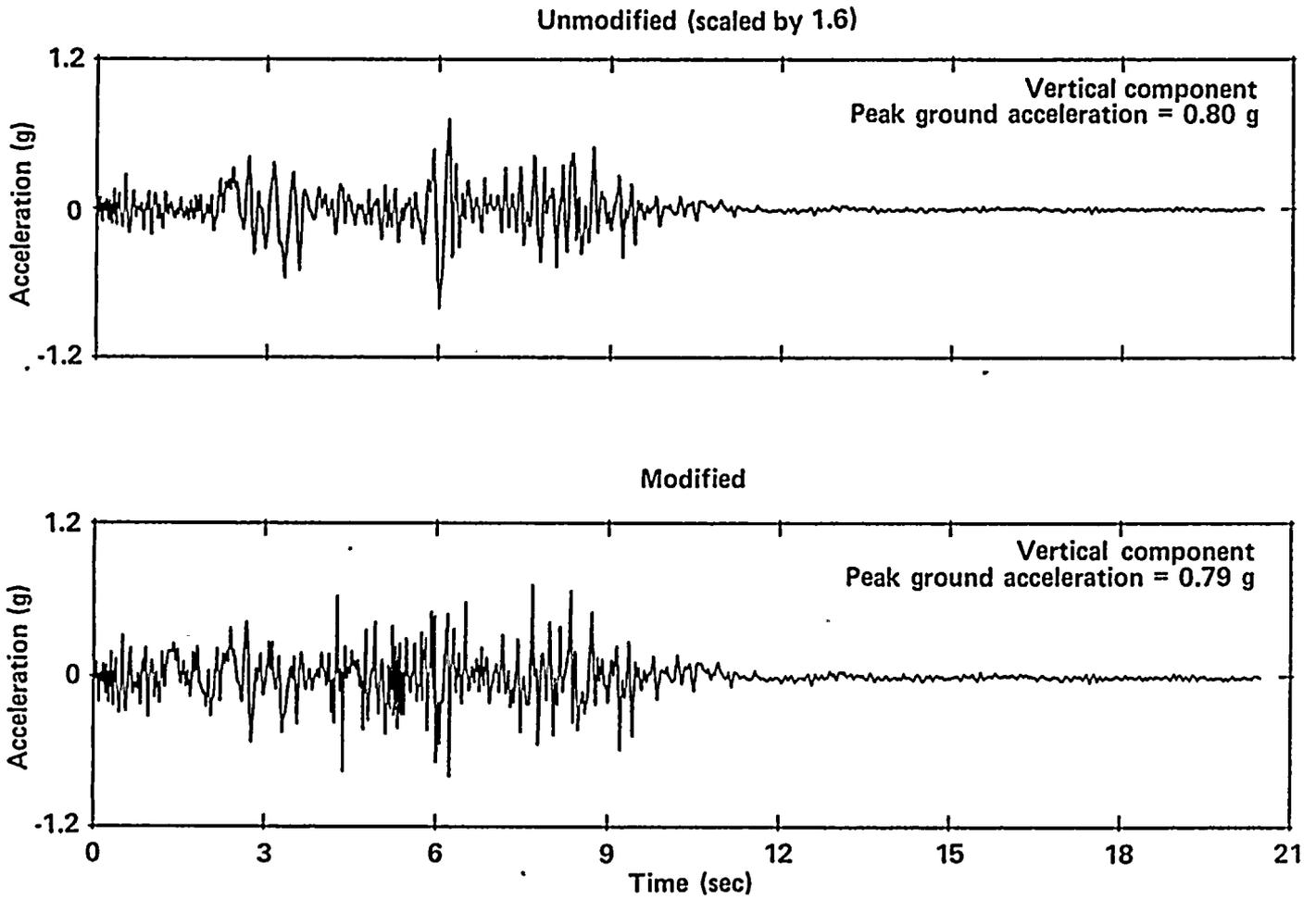
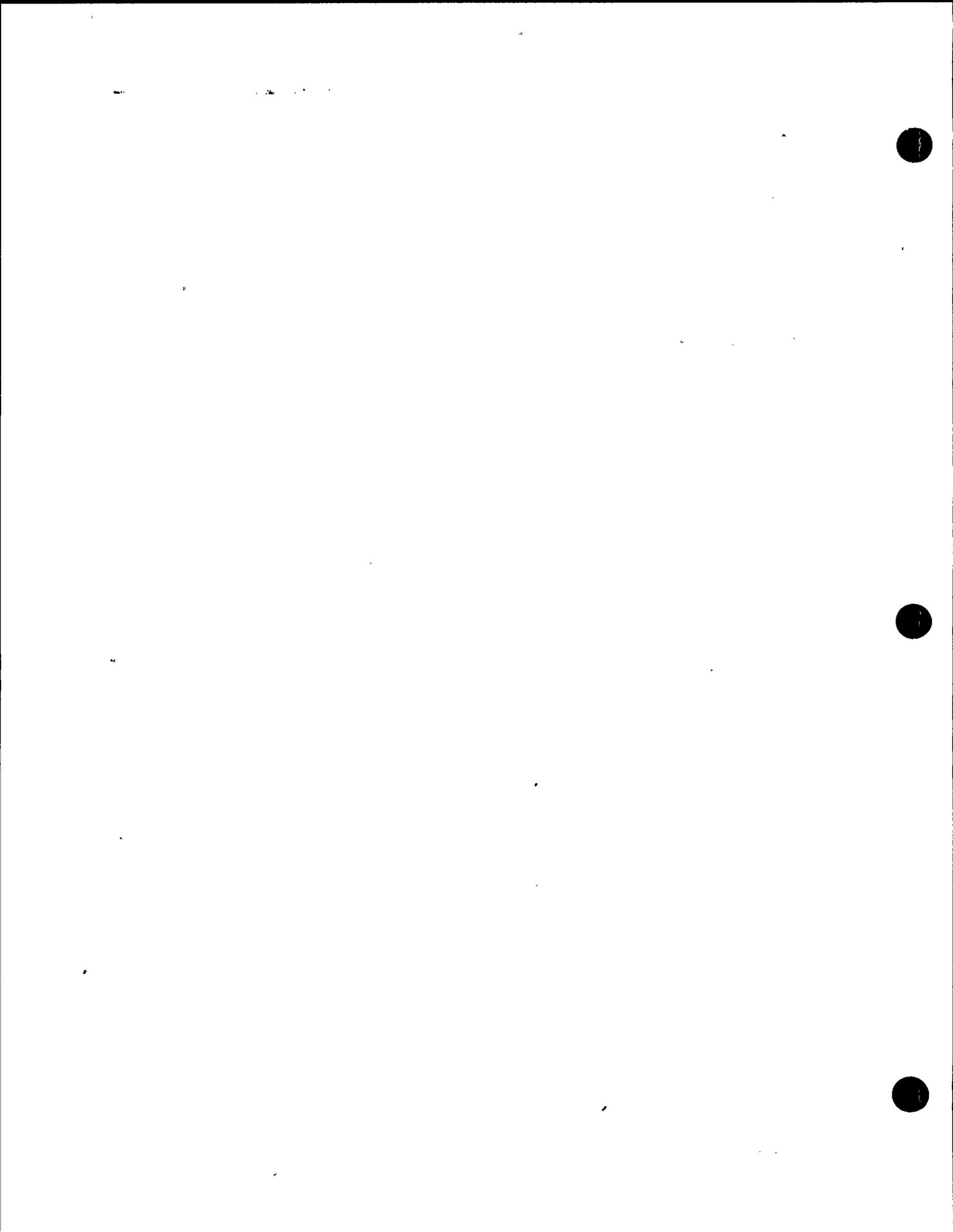


Figure 5-25

Comparisons of unmodified and modified Pacoima acceleration time histories, vertical component.



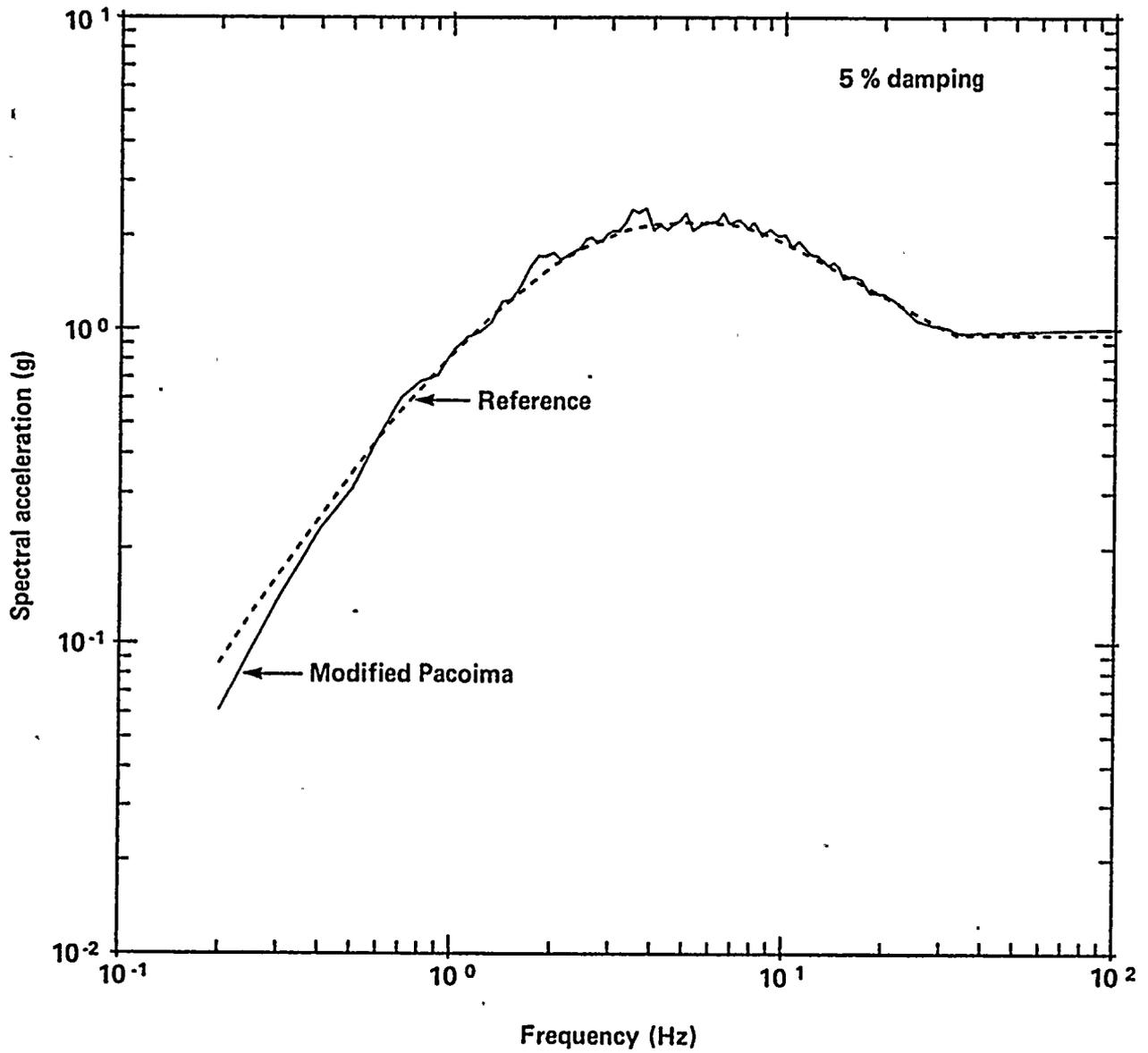
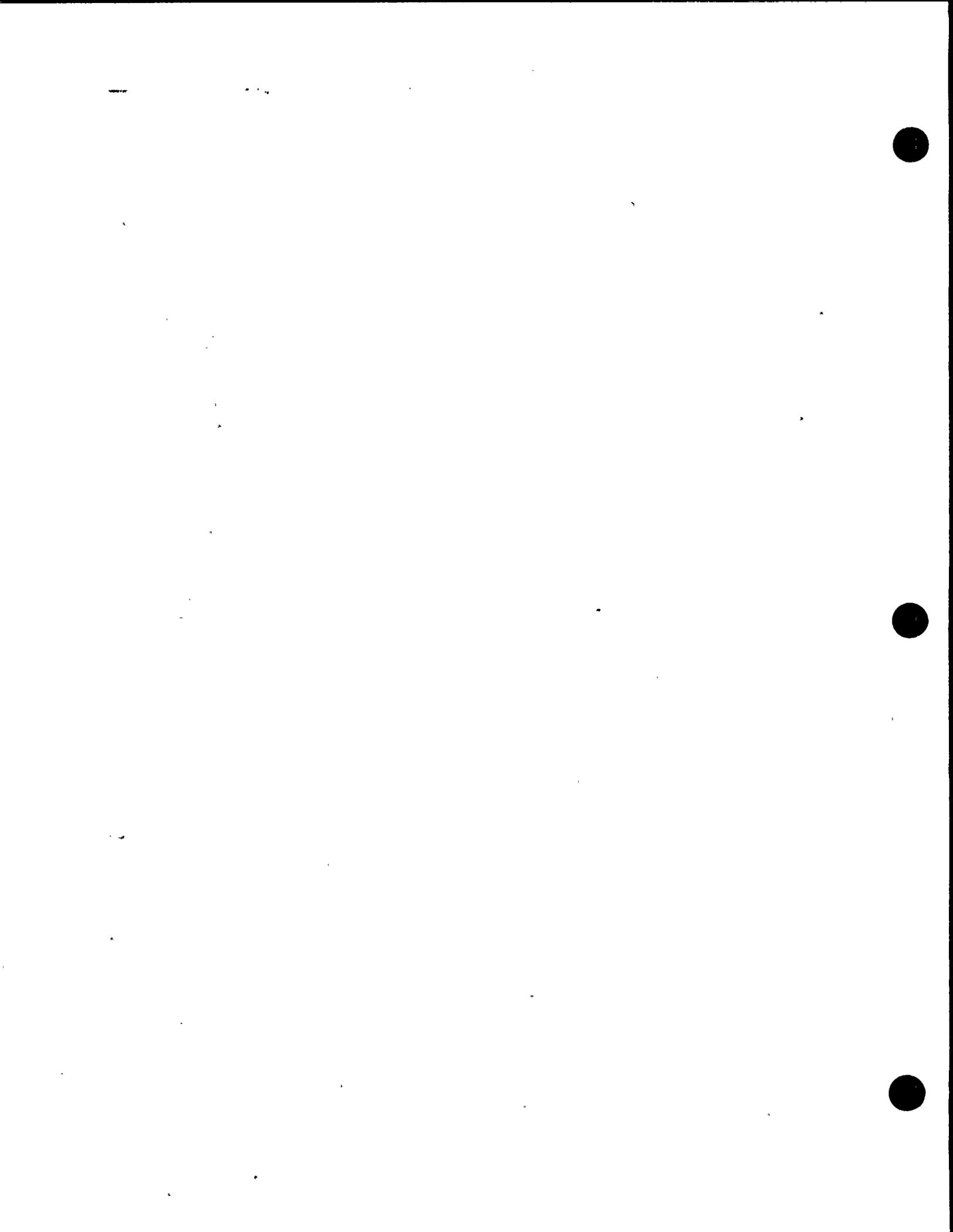


Figure 5-26

Comparisons of modified Pacoima time history response spectrum and fragility evaluation reference response spectrum, longitudinal component.



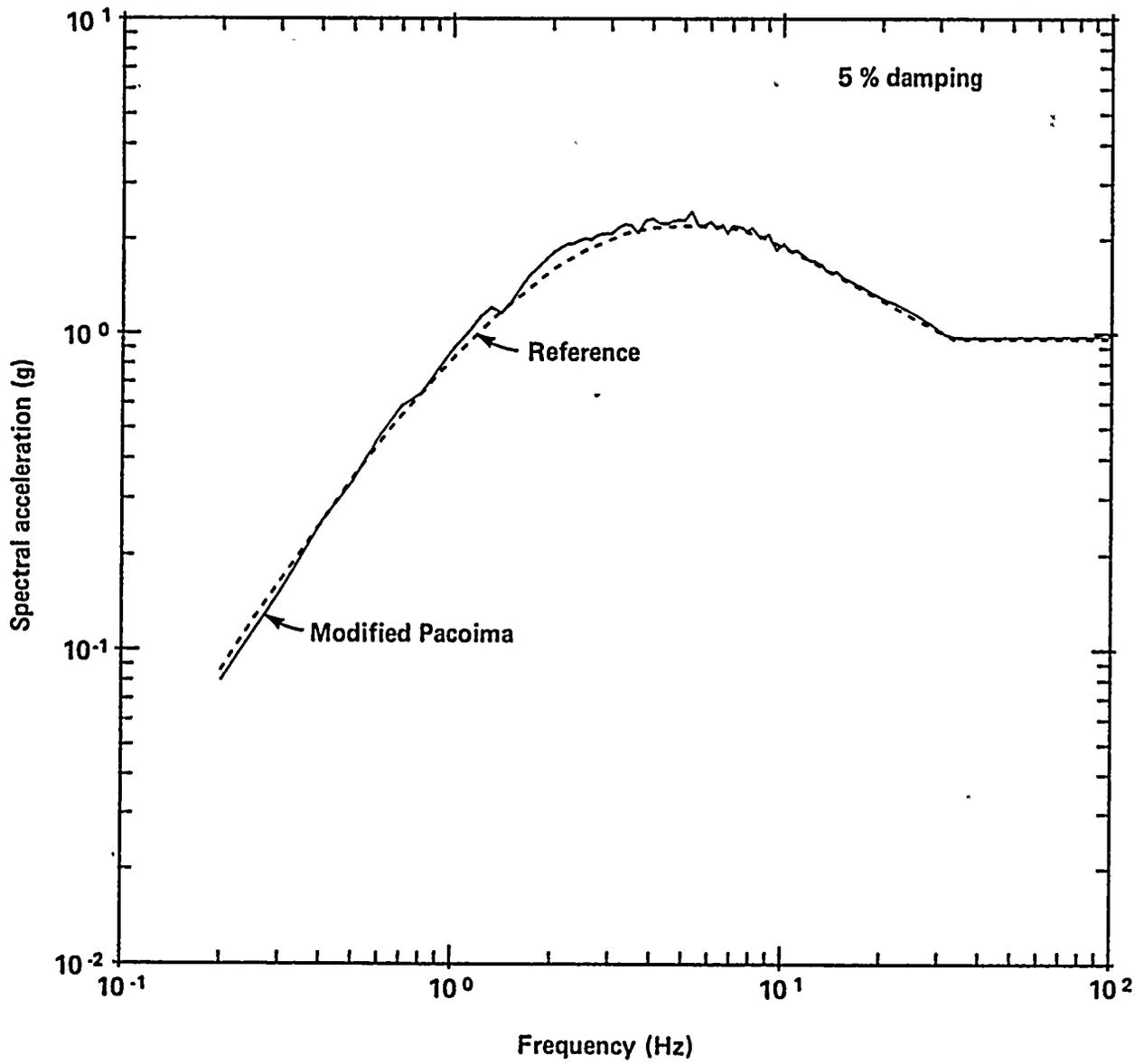
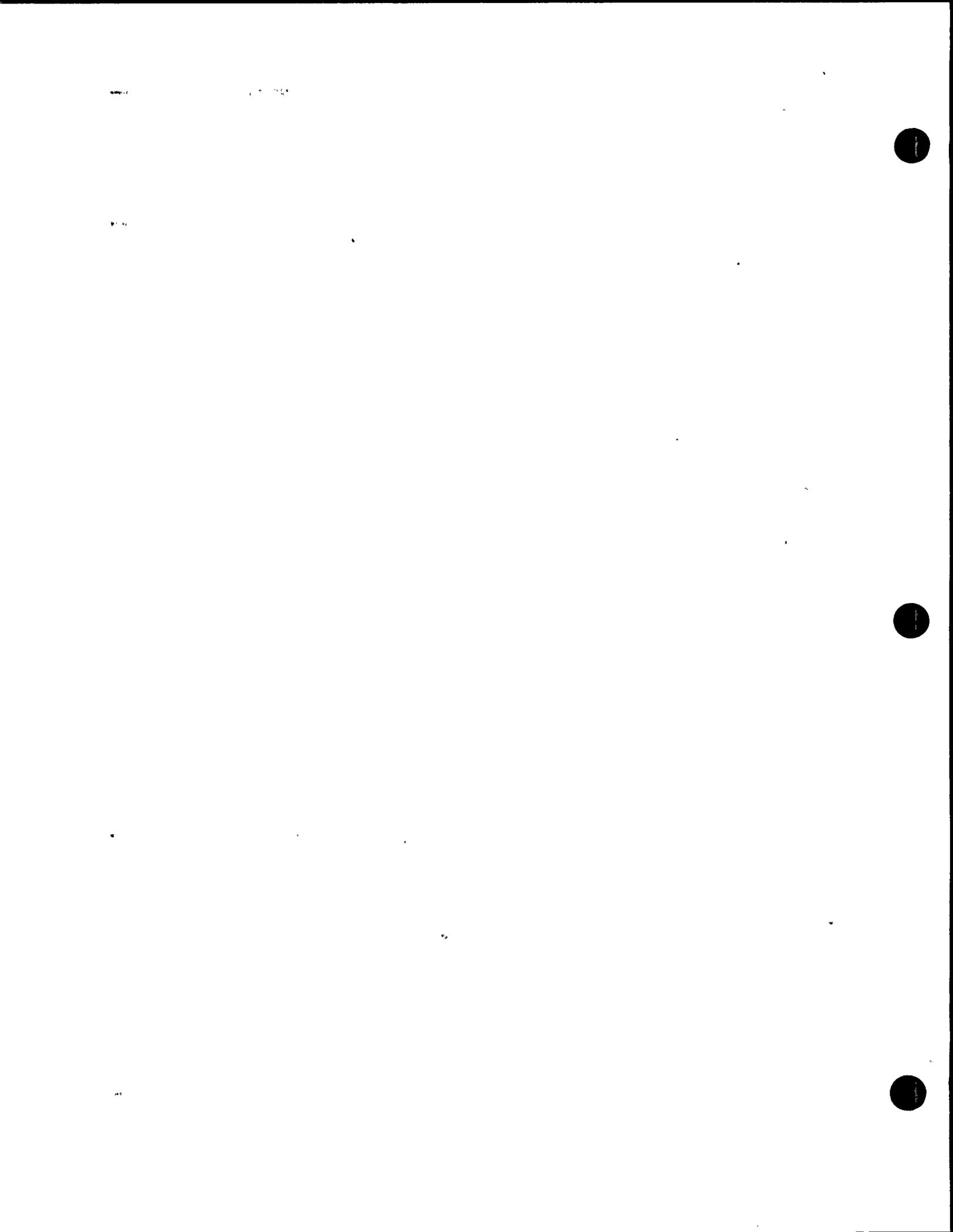


Figure 5-27

Comparisons of modified Pacoima time history response spectrum and fragility evaluation reference response spectrum, transverse component.



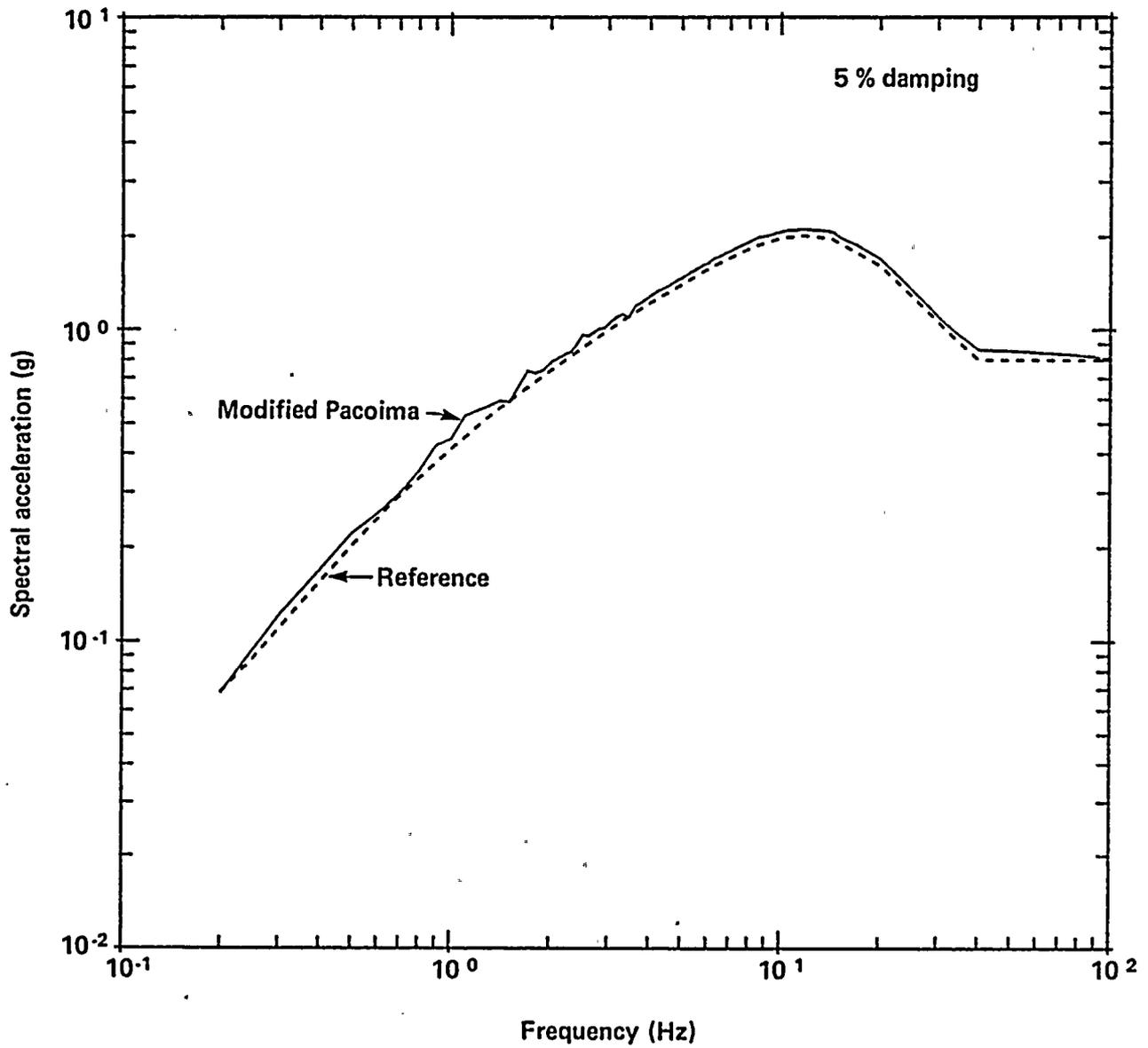


Figure 5-28

Comparisons of modified Pacoima time history response spectrum and fragility evaluation reference response spectrum, vertical component.

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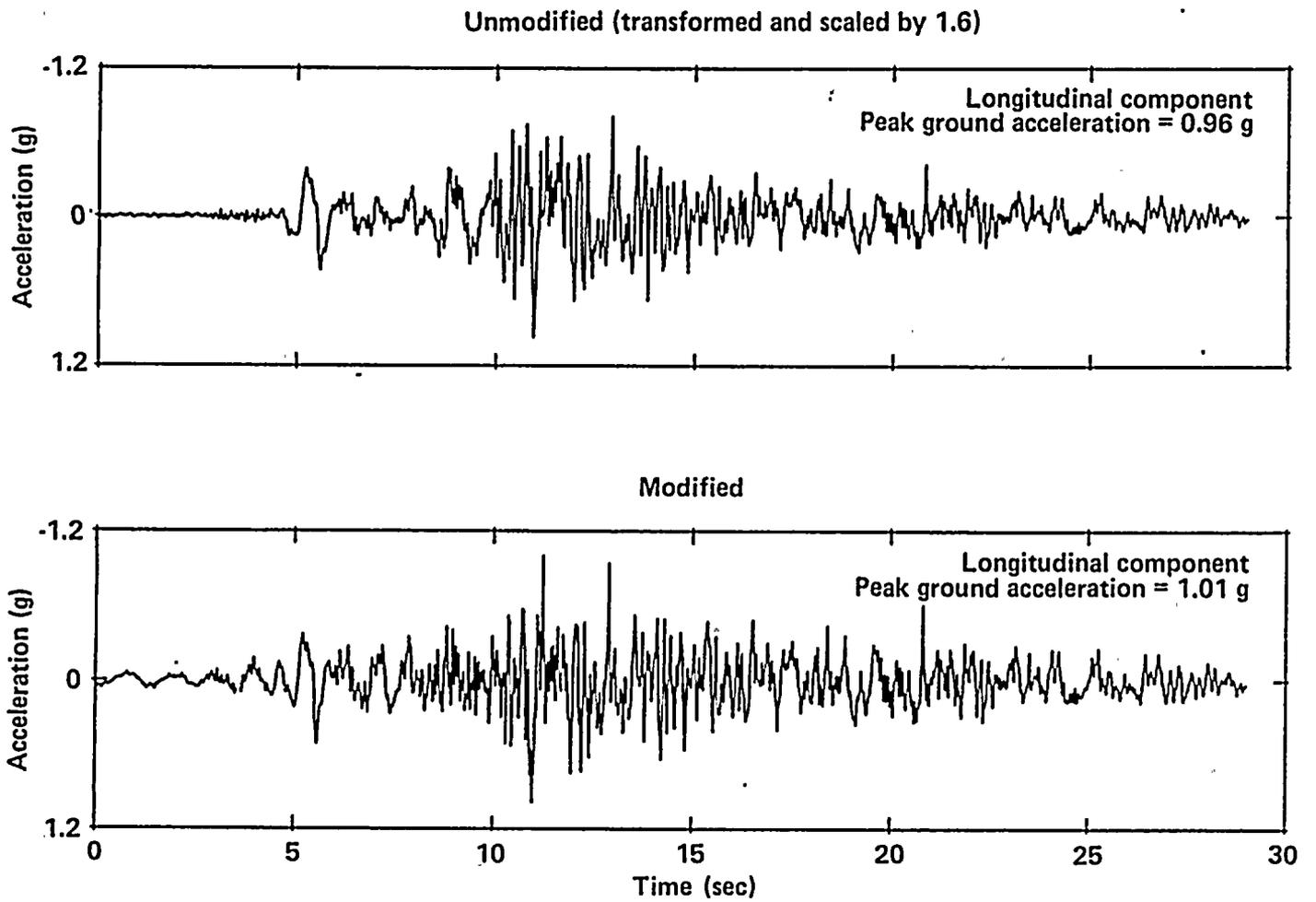


Figure 5-29

Comparisons of unmodified and modified Tabas acceleration time histories, longitudinal component.



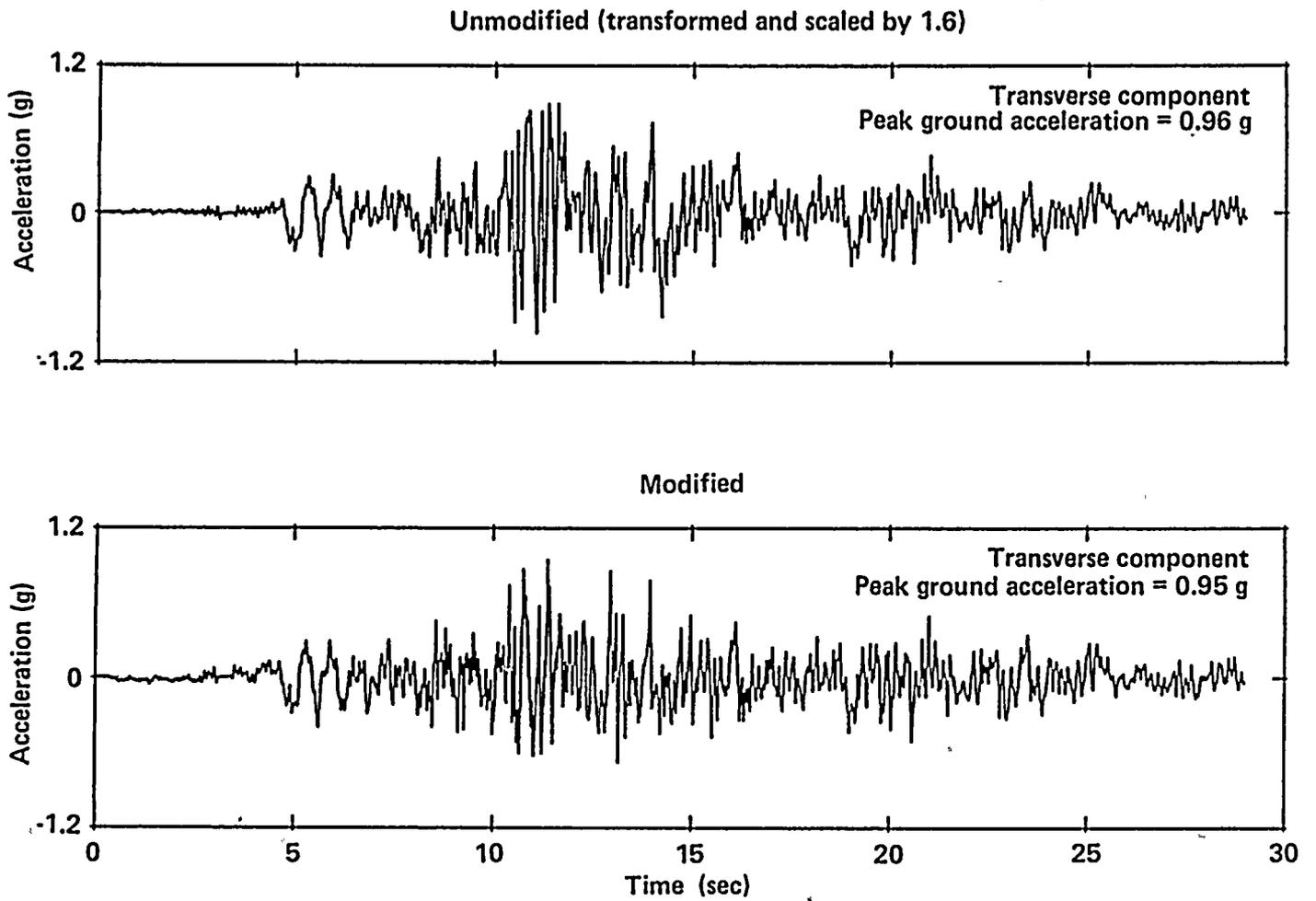
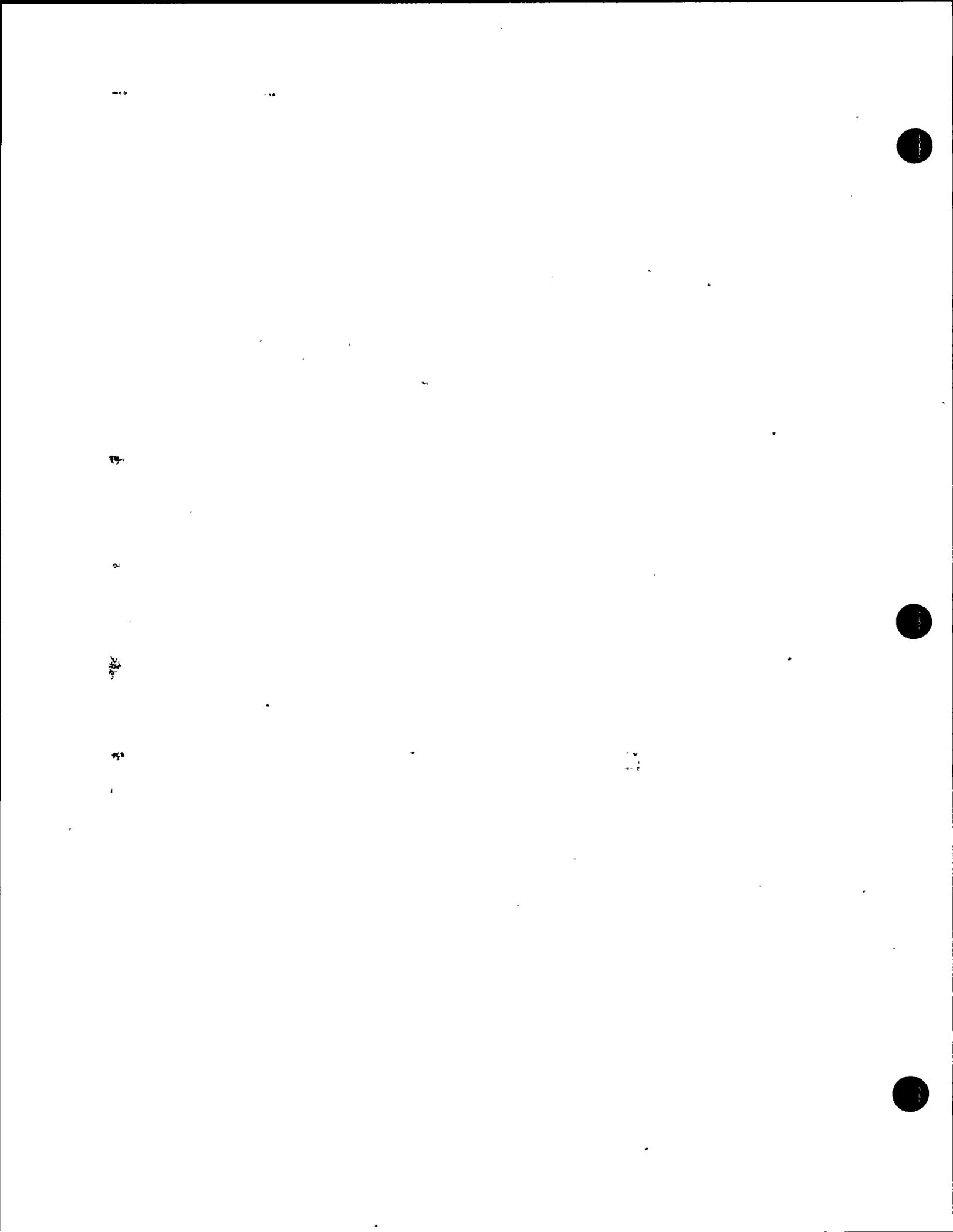


Figure 5-30

Comparisons of unmodified and modified Tabas acceleration time histories, transverse component.



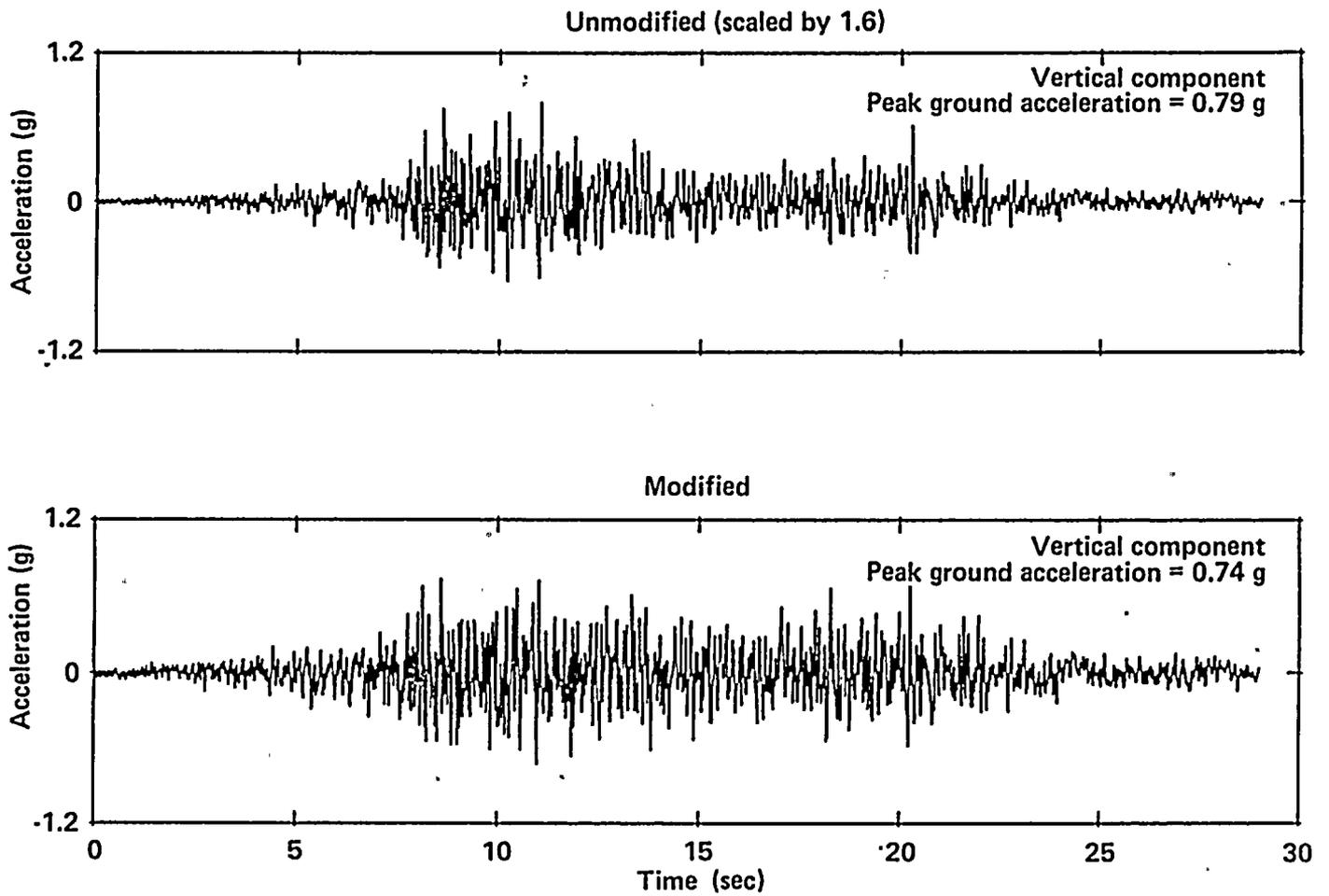


Figure 5-31

Comparisons of unmodified and modified Tabas acceleration time histories, vertical component.

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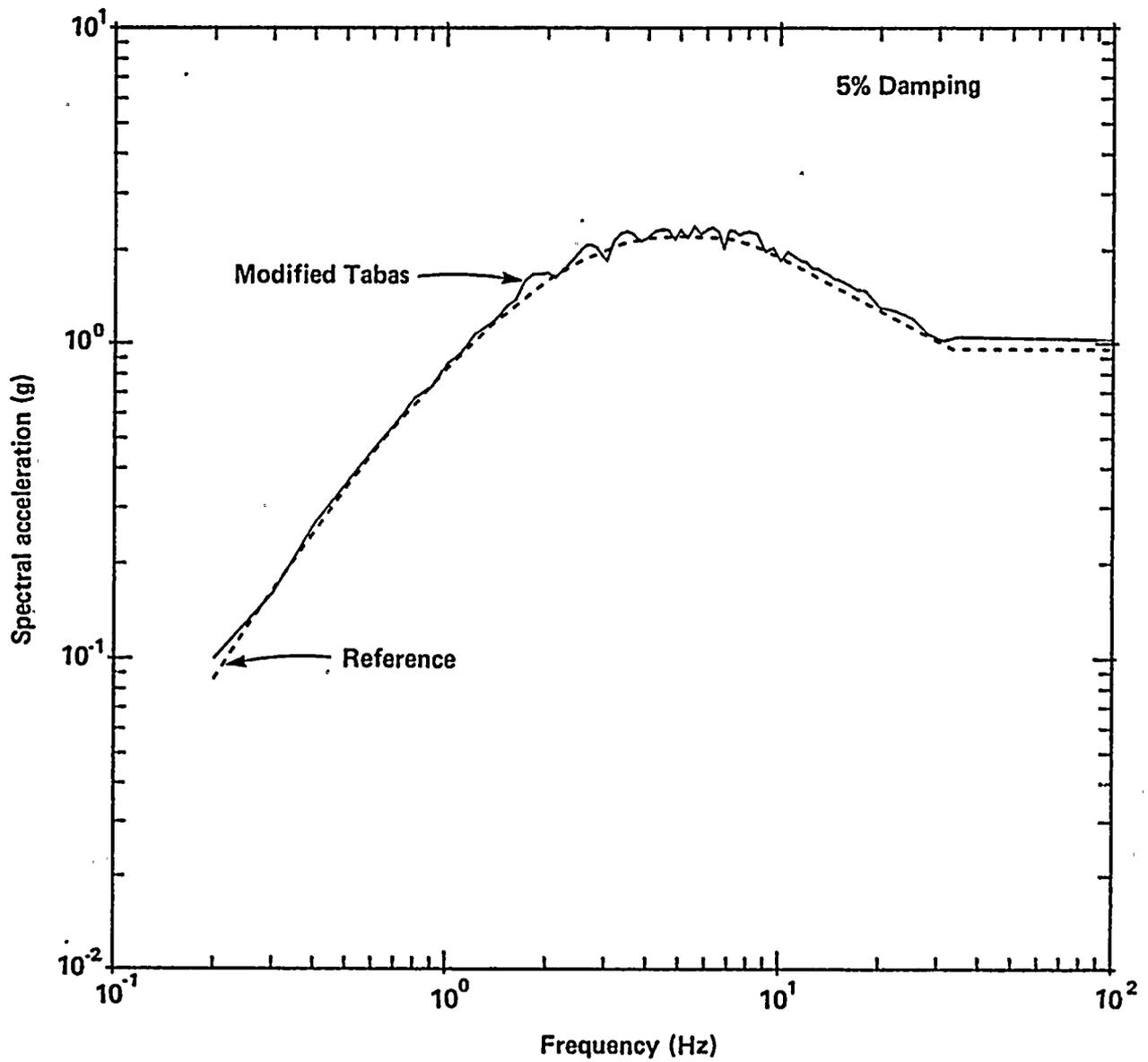


Figure 5-32

Comparisons of modified Tabas time history response spectrum and fragility evaluation reference response spectrum, longitudinal component.

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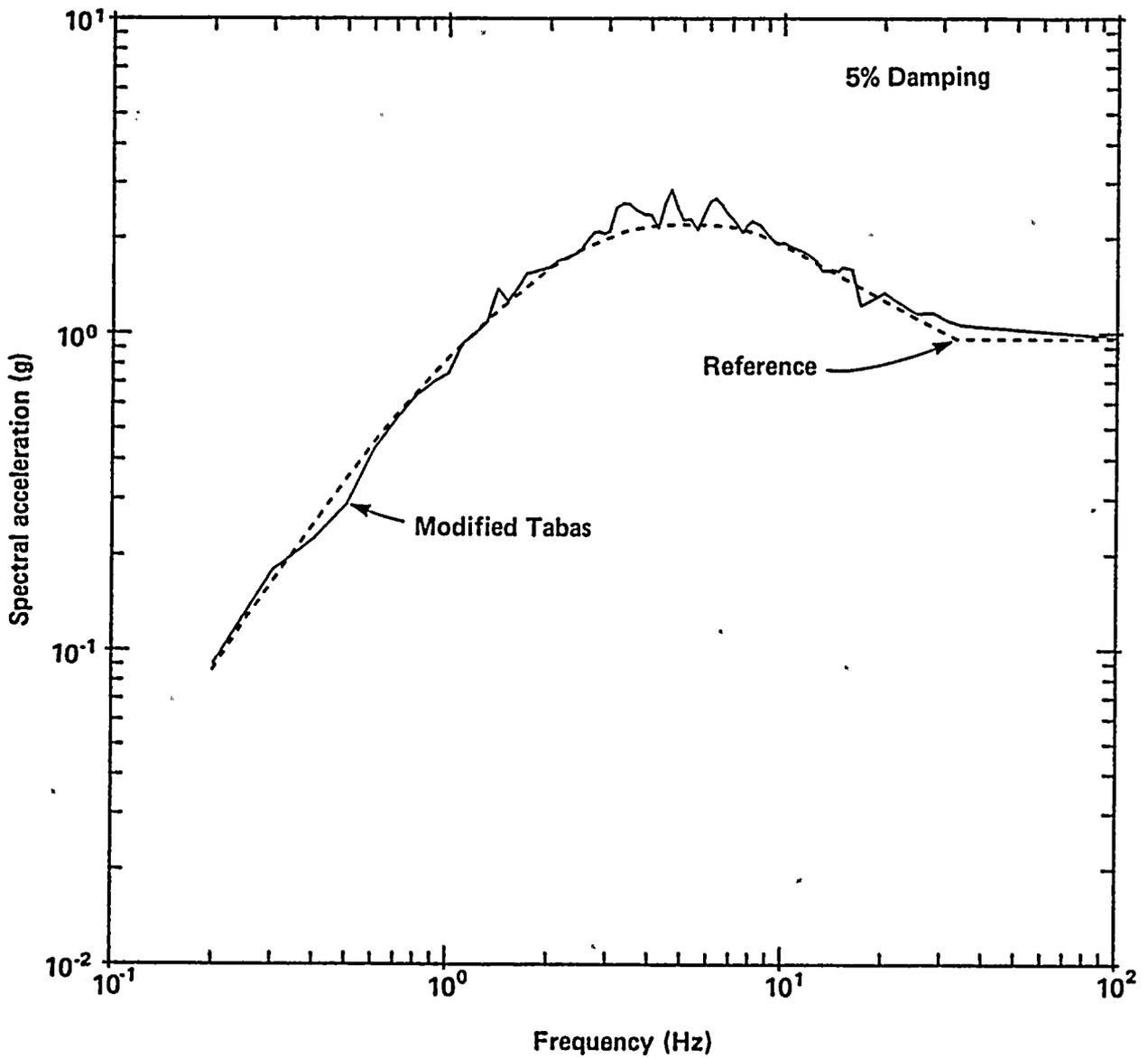


Figure 5-33

Comparisons of modified Tabas time history response spectrum and fragility evaluation reference response spectrum, transverse component.



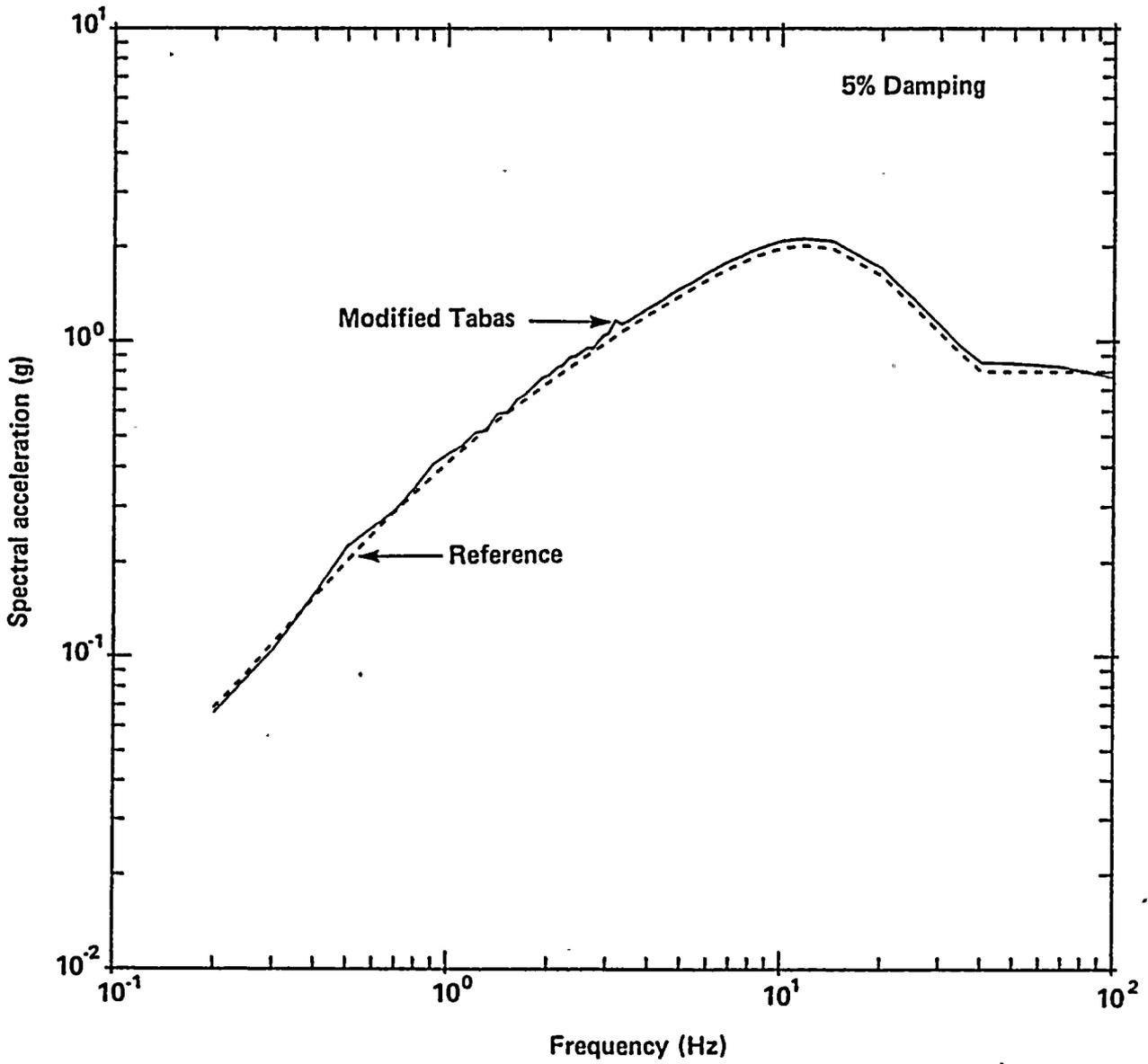
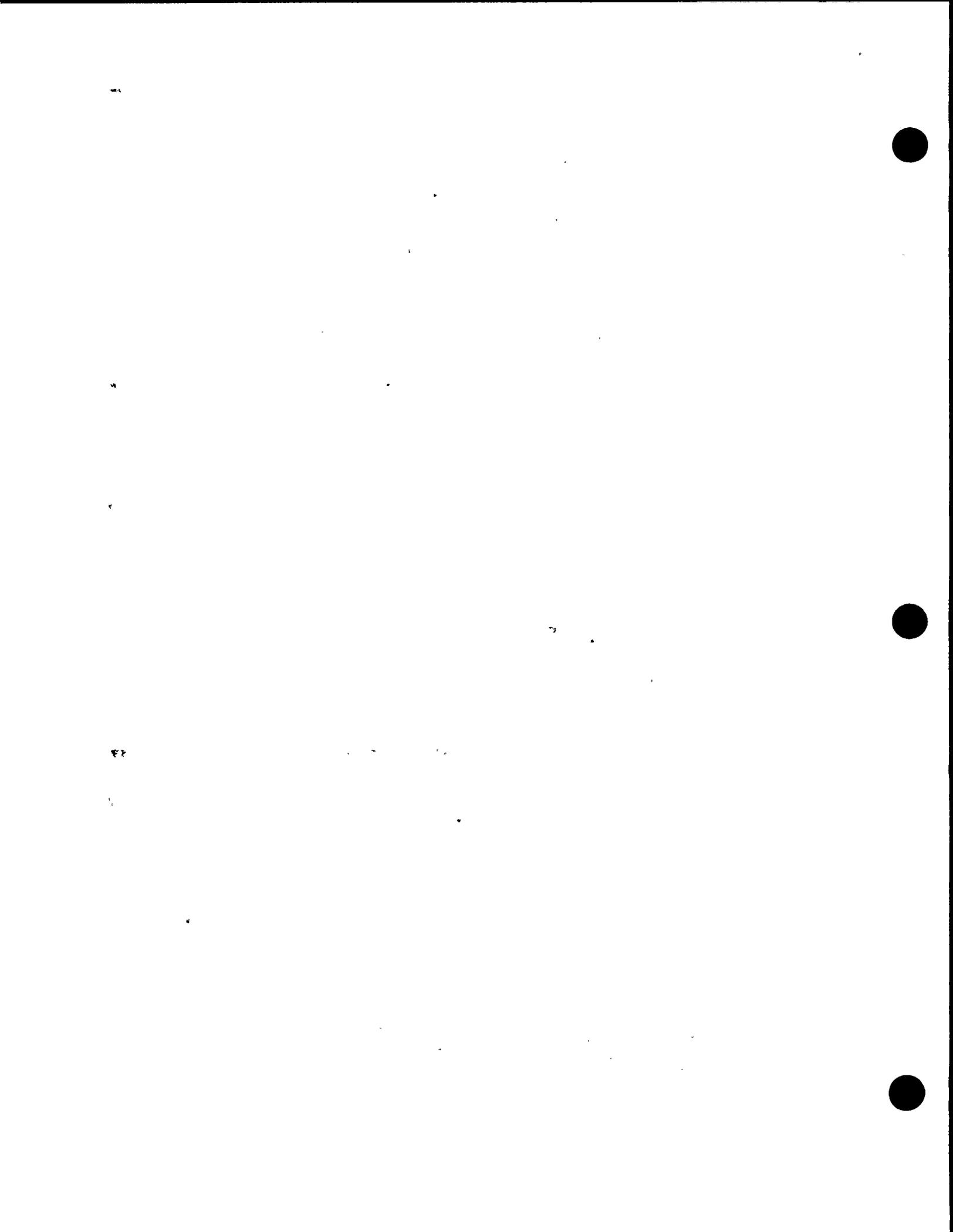


Figure 5-34

Comparisons of modified Tabas time history response spectrum and fragility evaluation reference response spectrum, vertical component.



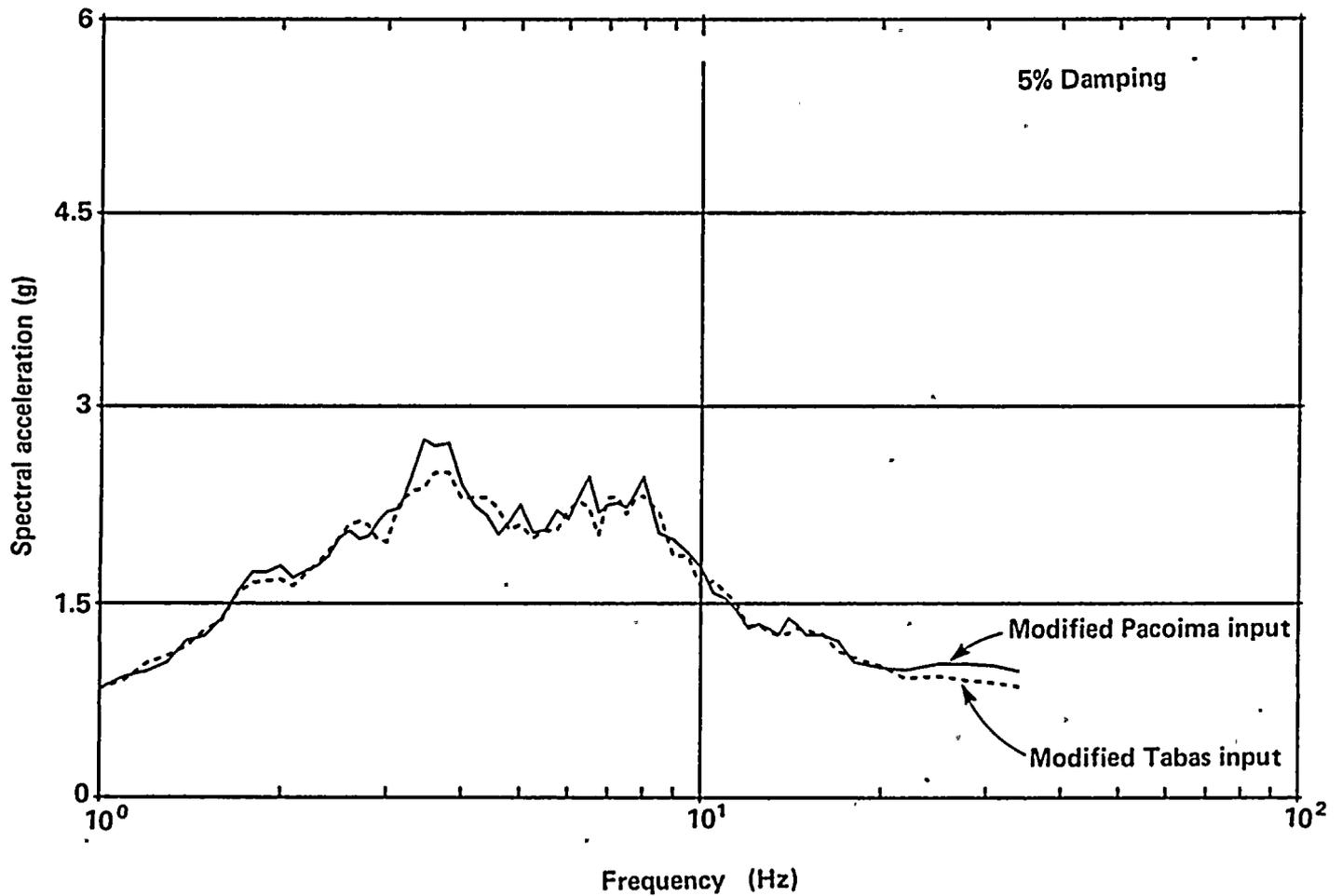
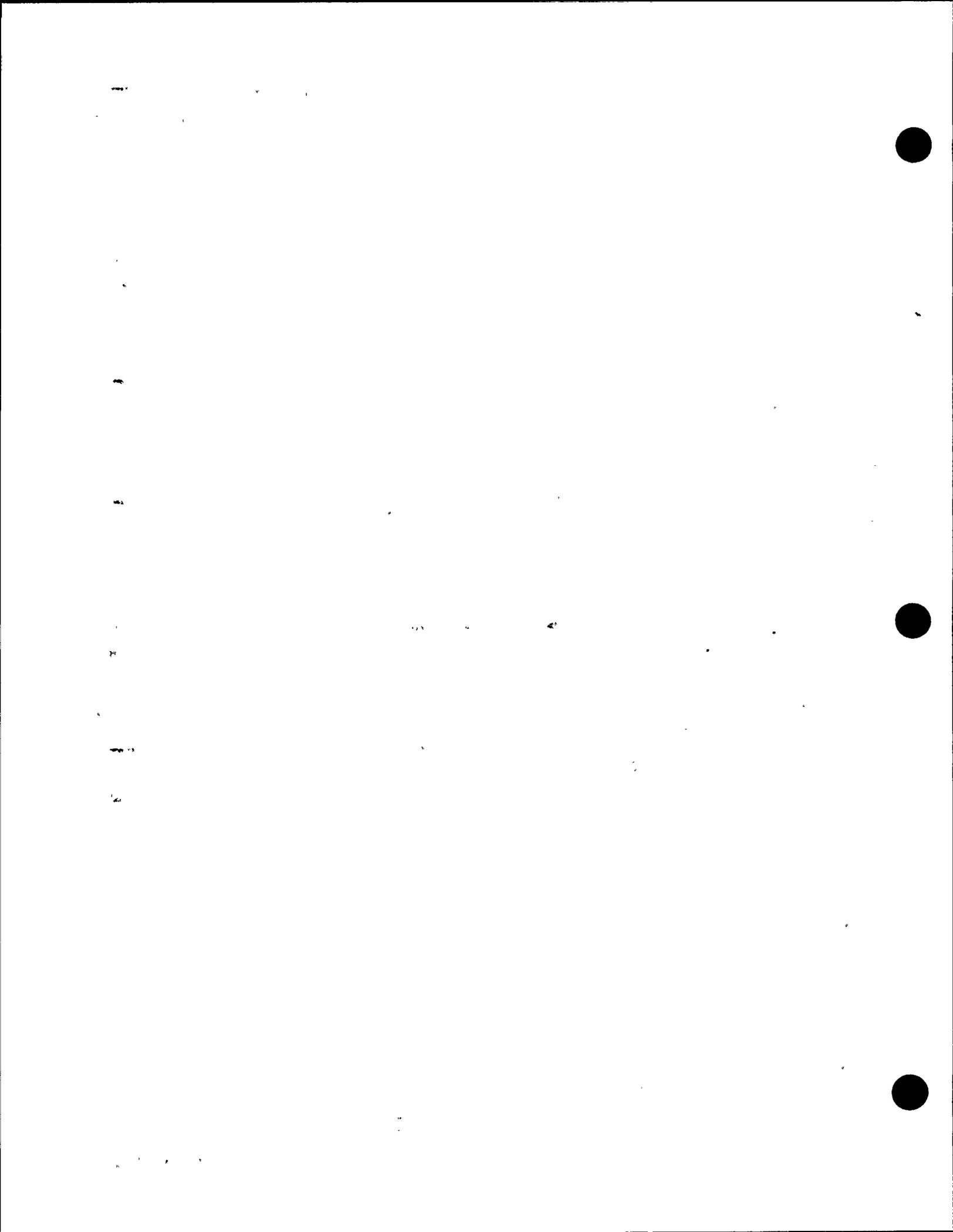


Figure 5-35

Floor response spectra for the north/south response of the containment at the base (El 85 feet) obtained from SASSI analyses with coherent ground motion input.



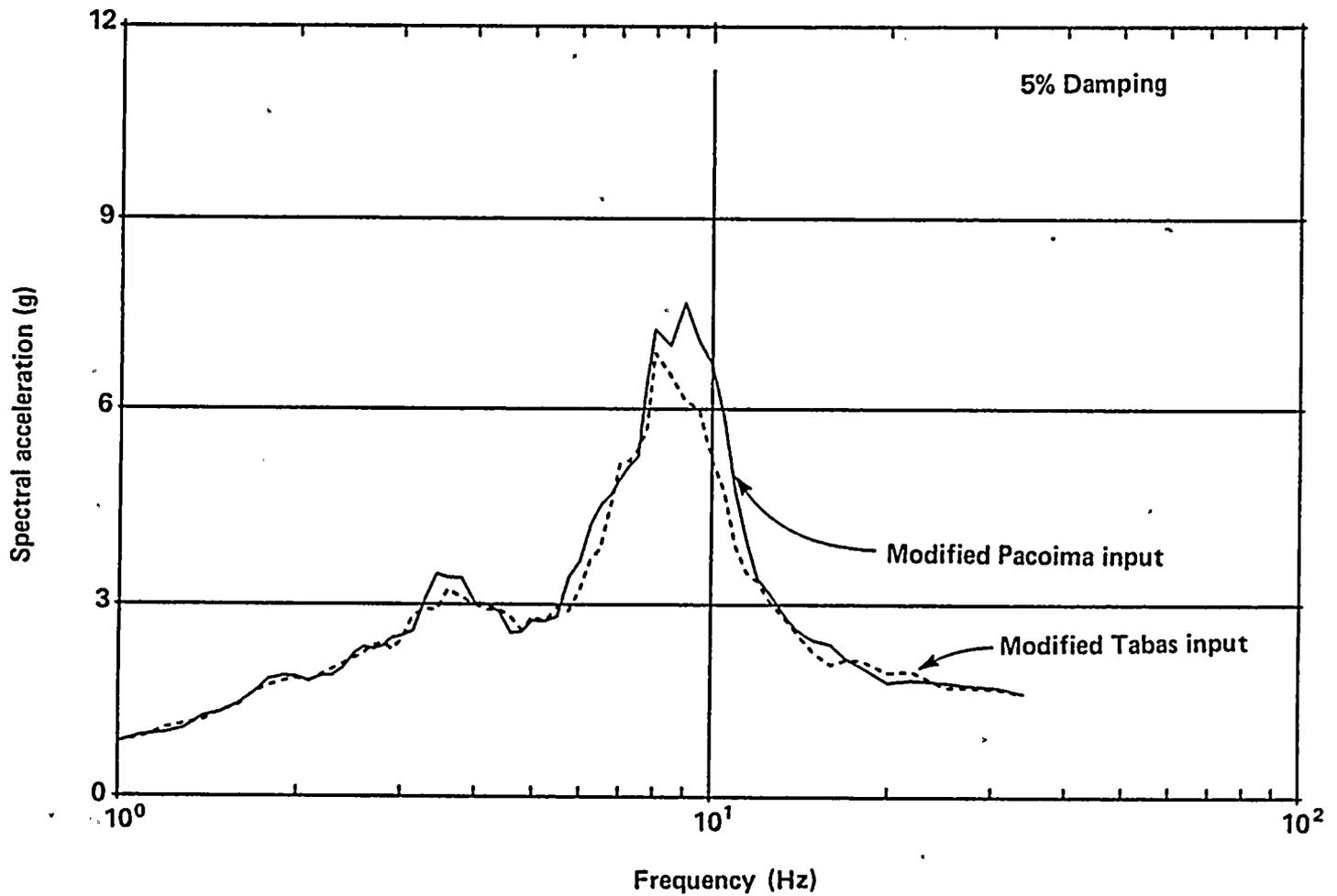


Figure 5-36

Floor response spectra for the north/south response of the containment at the top of interior concrete structure (El 138.5 feet) obtained from SASSI analyses with coherent ground motion input.



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location are shown in Figures 5-37 and 5-38, respectively.

The soil/structure interaction responses resulting from the two sets of input motions (Pacoima and Tabas) were found to be consistent with each other for all response locations, as shown in Figures 5-35 through 5-38. Thus, the use of more sets of such motions as input was considered unnecessary. It was also found that interchanging the directions of the horizontal motion components had no significant effect on structural responses. The soil/structure interaction responses generated using the spectrum-compatible input motions as used herein also can be shown to be consistent with the responses that would be obtained from the ensemble averages of the responses to the individual inputs of the time history ensemble that forms the basis of the site-specific earthquake spectra.

Adjustment of Soil/Structure Interaction Responses Due to Spatial Incoherence of Ground Motions

The soil/structure interaction responses based on the assumption of vertical coherent plane wave input do not consider the effects of horizontal spatial variation of free-field ground motions. Thus, separate soil/structure interaction analyses were performed to develop the response adjustment factors that could be used to adjust the soil/structure interaction responses obtained from the coherent ground-motion input to account for the effect of spatial variations.

The characterization of spatial variation of free-field surface motions at the Diablo Canyon site was achieved using a set of site-specific spatial incoherence functions, as described in Chapter 4. Such functions consist of ground-motion coherency amplitudes (Figure 5-39), and the corresponding phase angles (Figure 5-40). These functions vary with the Fourier frequency of the surface motions and the separation distance between two points on the ground surface.

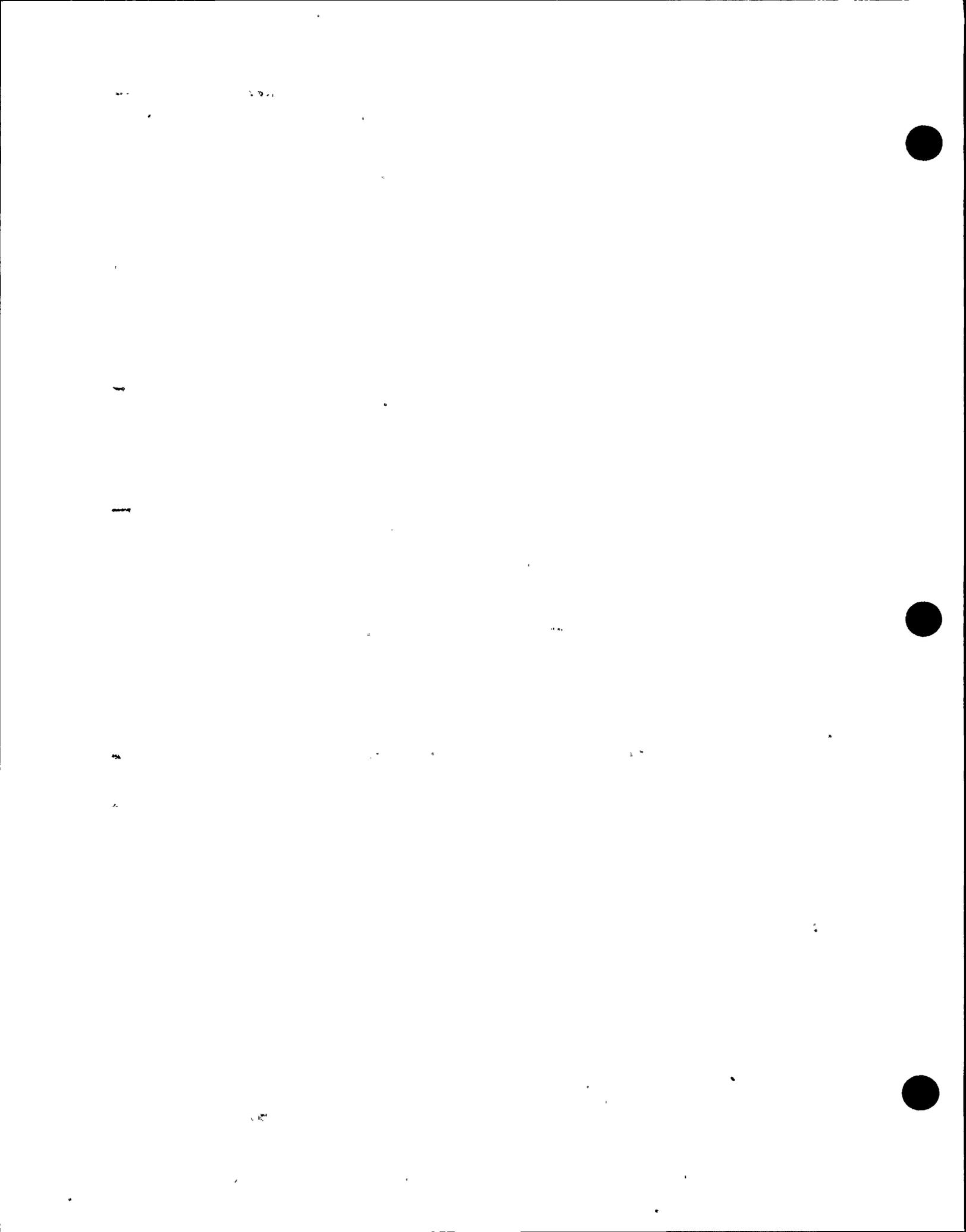
To use such spatial incoherence functions for soil/structure interaction analysis, the free-field ground surface motions at various points of the

site within the foundation region were represented in the frequency domain, using a 3x3 ground-motion covariance matrix in which the on-diagonal elements represent the auto-power spectral density and the off-diagonal elements represent the cross-power spectral density for the three-components of the ground motions.

The ground-motion covariance matrix for the Diablo Canyon site was derived from the time history ensemble used for deriving the site-specific spectra. Thus, it is consistent with the site-specific earthquake spectra. The amplitude of one element of the covariance matrix, scaled-up by the factor of $(1.6)^2$ to correspond to the fragility evaluation reference input, is shown in Figure 5-41.

To incorporate the ground-motion covariance matrix in conjunction with the spatial incoherence functions for soil/structure interaction analyses, an analysis method was developed that is based on the random vibration theory of structural dynamics and uses the covariance matrix of the ground motions directly as the input.

Because the site-specific spatial incoherence functions were developed only for free-field surface motions, only the spatial variations of surface motions need be considered for soil/structure interaction analyses. Consequently, the analysis method developed to incorporate the site-specific spatial incoherence functions used the CLASSI method of soil/structure interaction analysis, which is applicable for surface-supported rigid foundations. The total method, which includes applying the CLASSI computer code for generating the scattered foundation input motions and soil/structure interaction response transfer functions, and the PROSPEC computer code (Lilhanand and Tseng, 1983) for generating the probabilistic floor response spectra based on random vibration theory, is shown schematically in Figure 5-42. Using this method, the spatial incoherence functions are incorporated into the ground-motion input at the step when the ground-motion covariance matrices for various points on the ground surface covered by the CLASSI foundation model are calculated, and then integrated to generate the scattered foundation



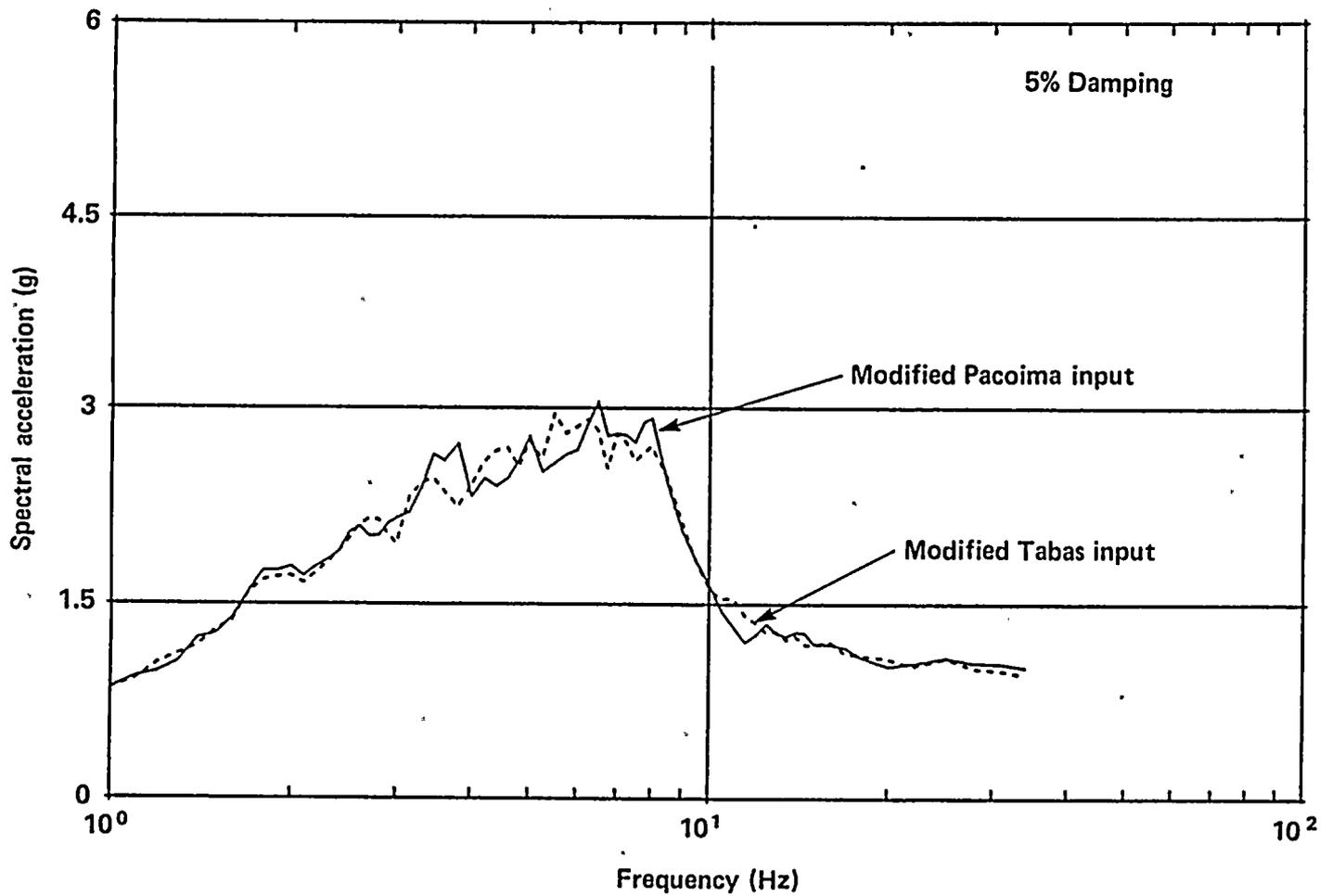
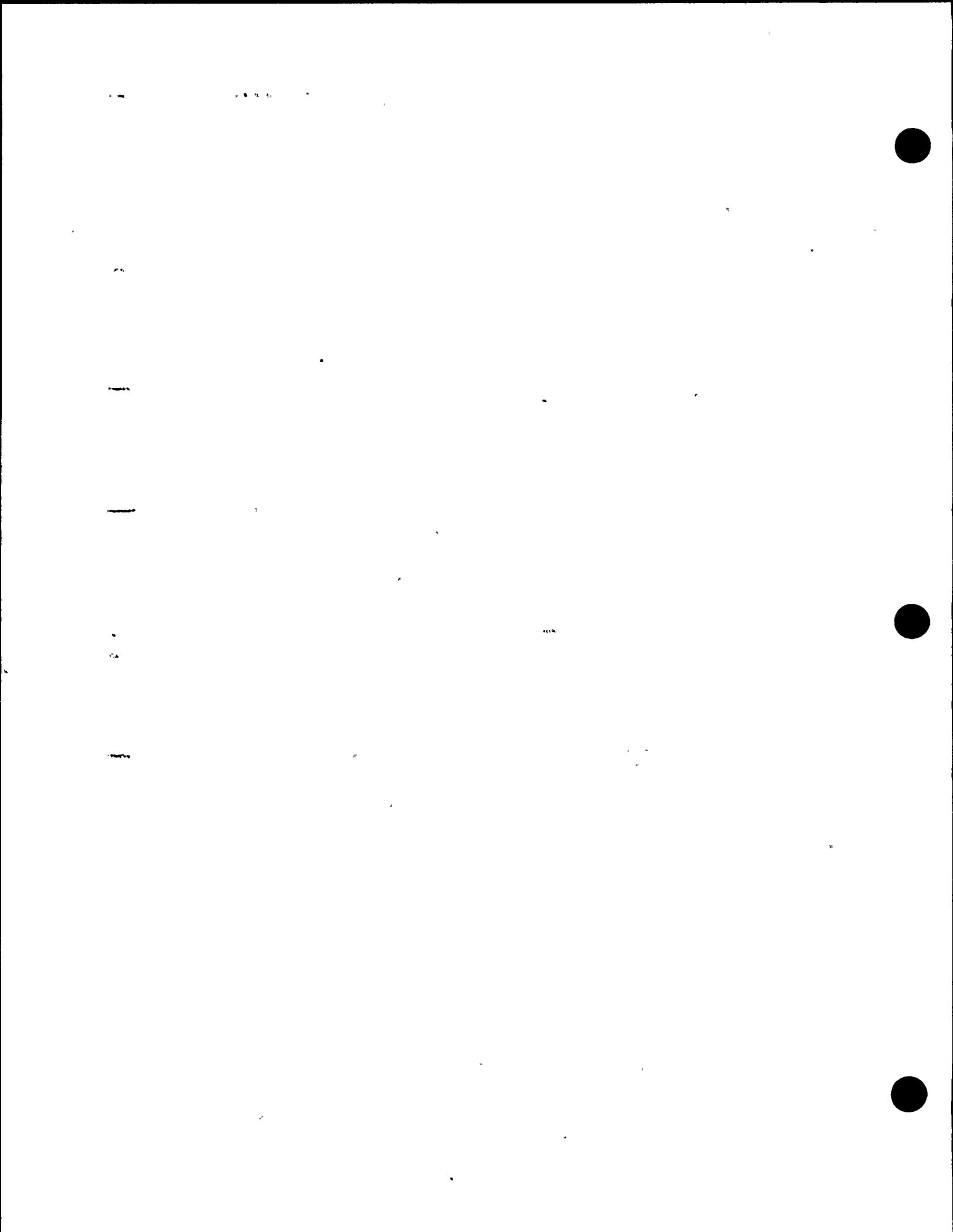


Figure 5-37

Floor response spectra for the north/south response of the auxiliary building at the core west (El 85 feet) obtained from SASSI analyses with coherent ground motion input.





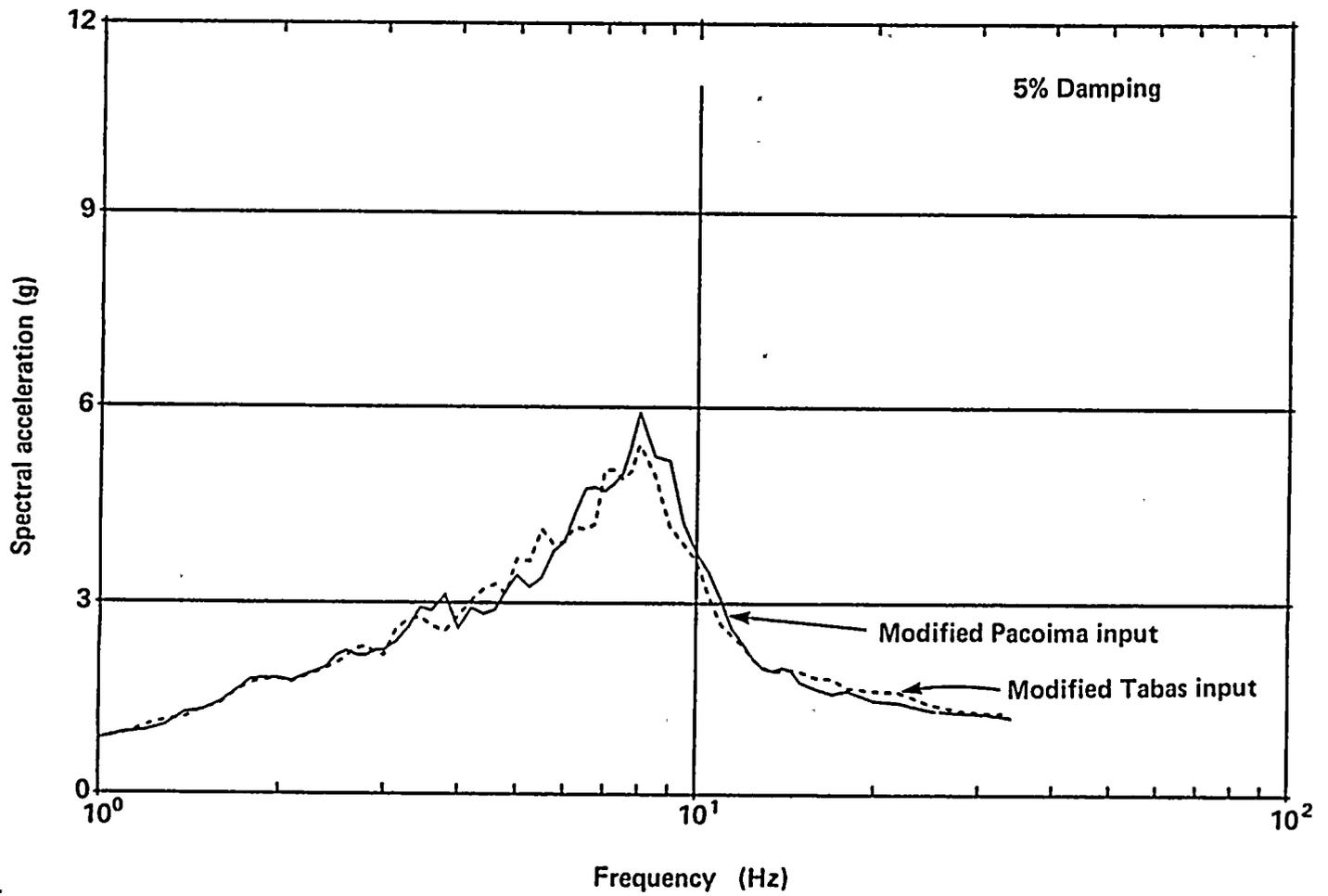


Figure 5-38

Floor response spectra for the north/south response of the auxiliary building at core west (EI 140 feet) obtained from SASSI analyses with coherent ground motion input.



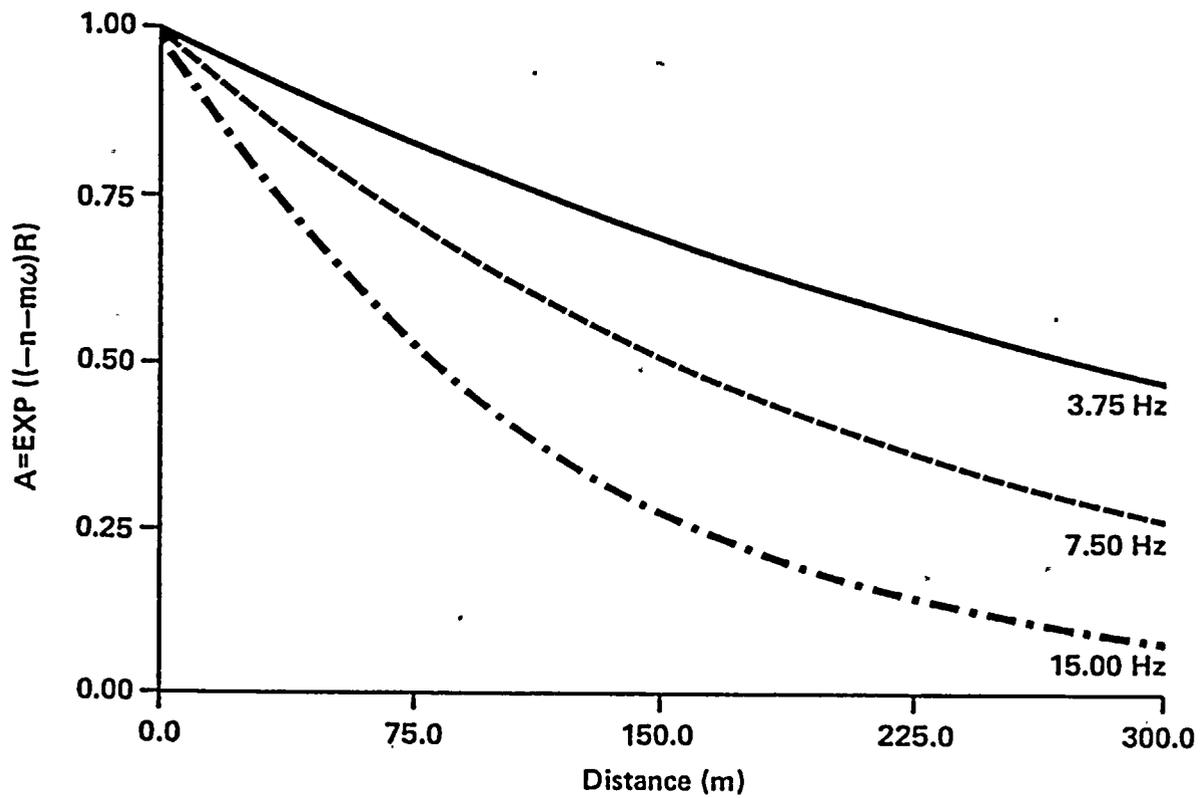


Figure 4-12 Horizontal coherence spectral amplitude functions.

Figure 5-39

Amplitudes of horizontal site-specific spatial incoherence functions.



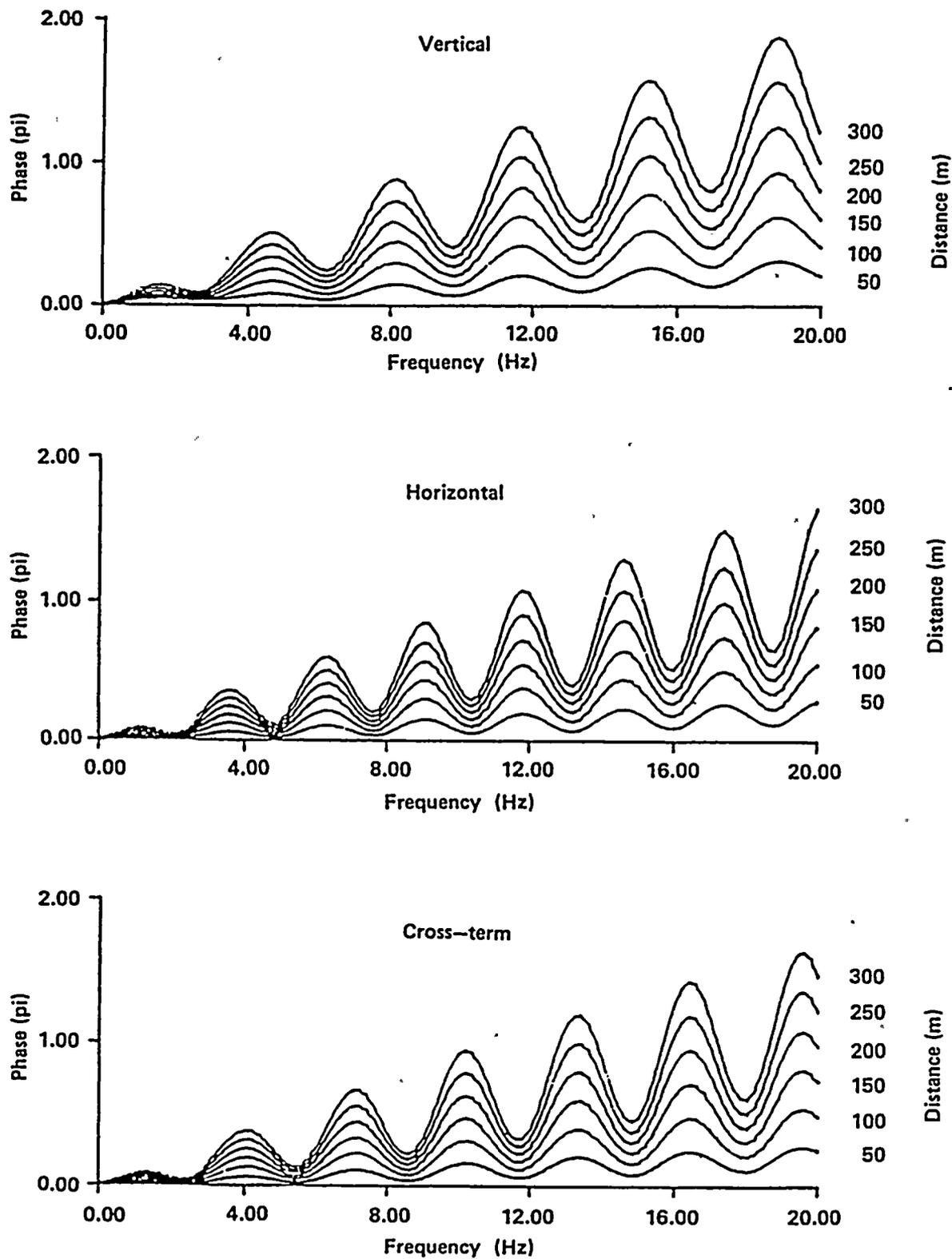
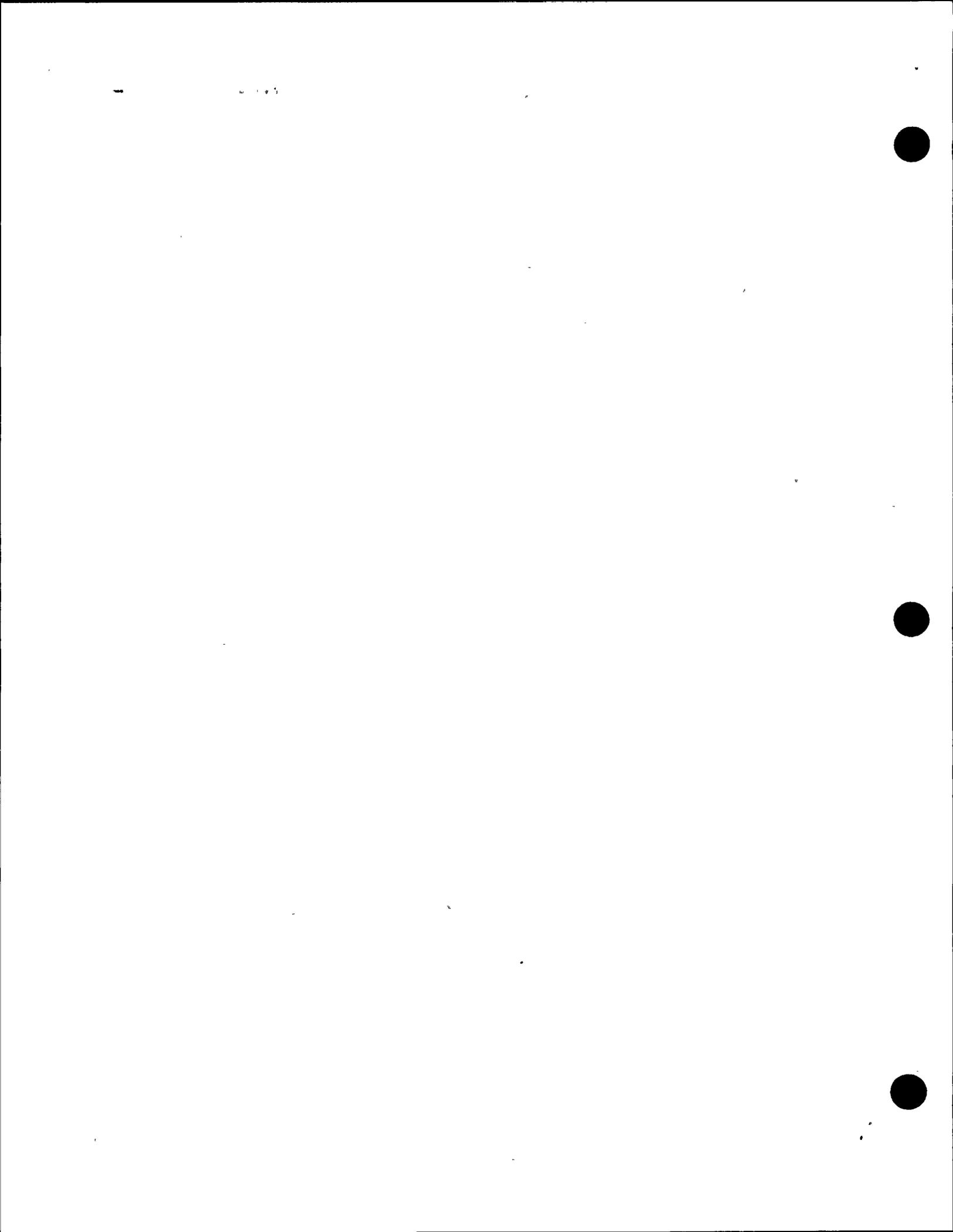


Figure 5-40

Phase angle of site-specific spatial incoherence functions.



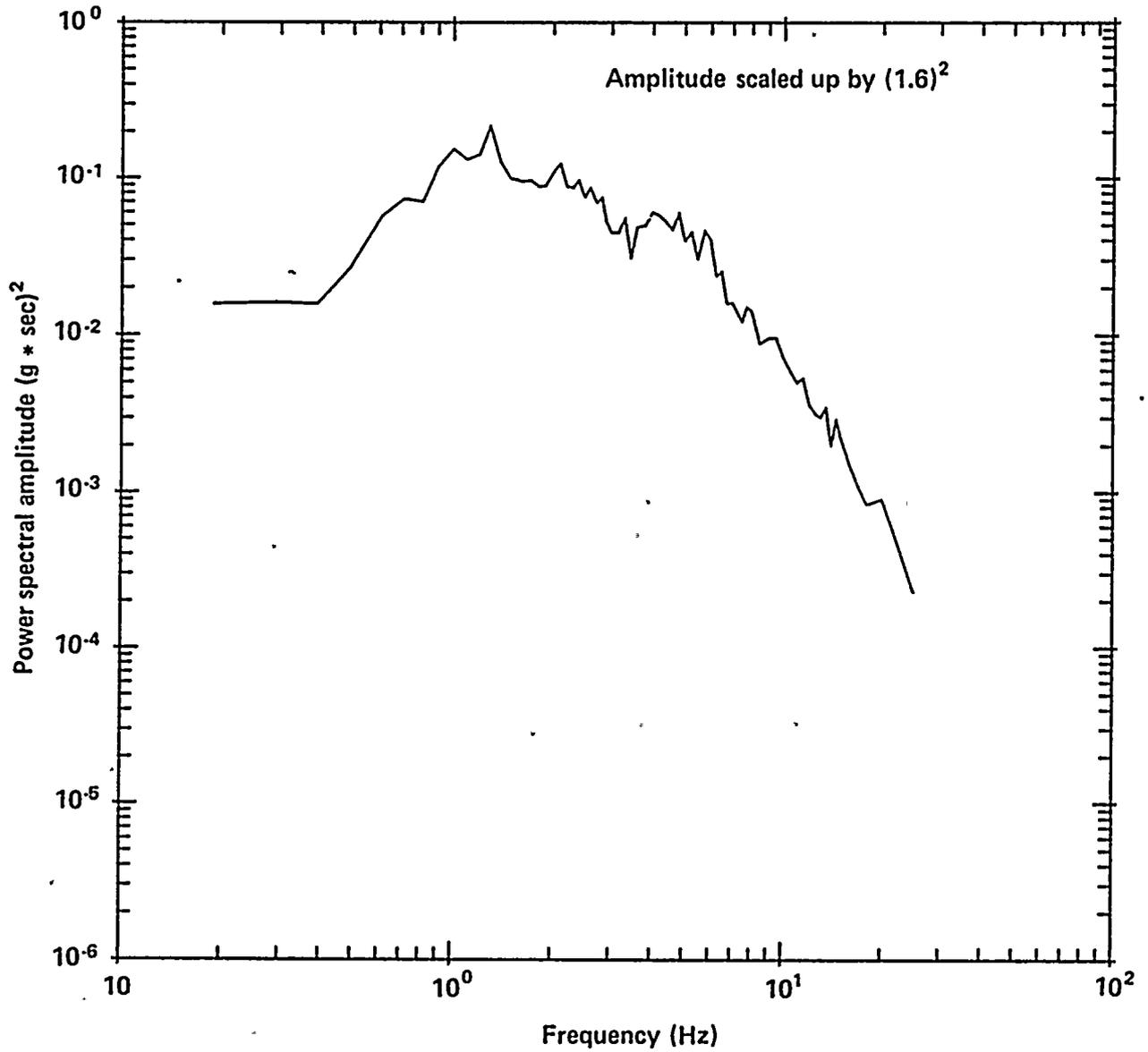
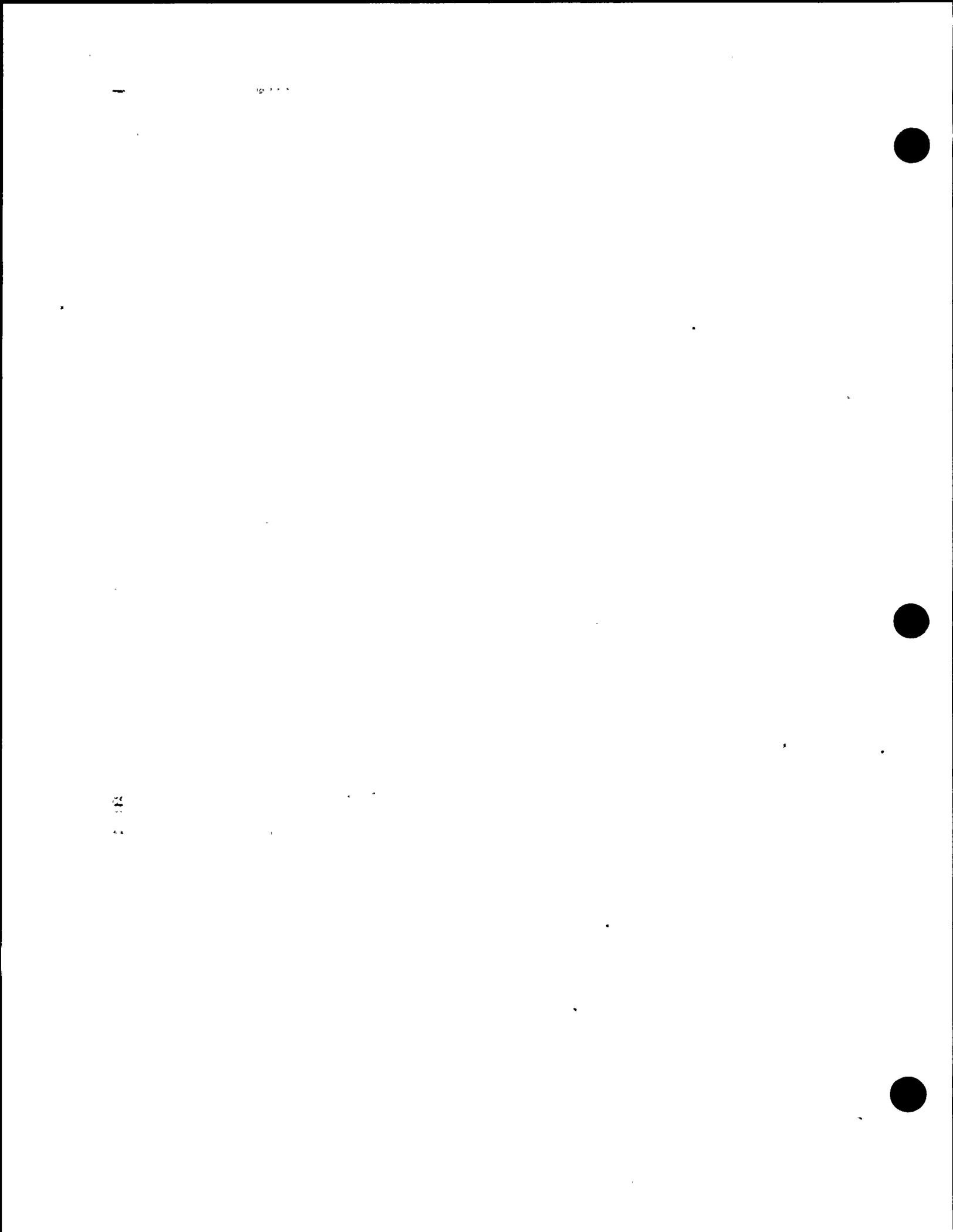


Figure 5-41

Amplitude of one element of the ground motion covariance matrix used for the soil/structure interaction analysis with incoherent ground motion input.



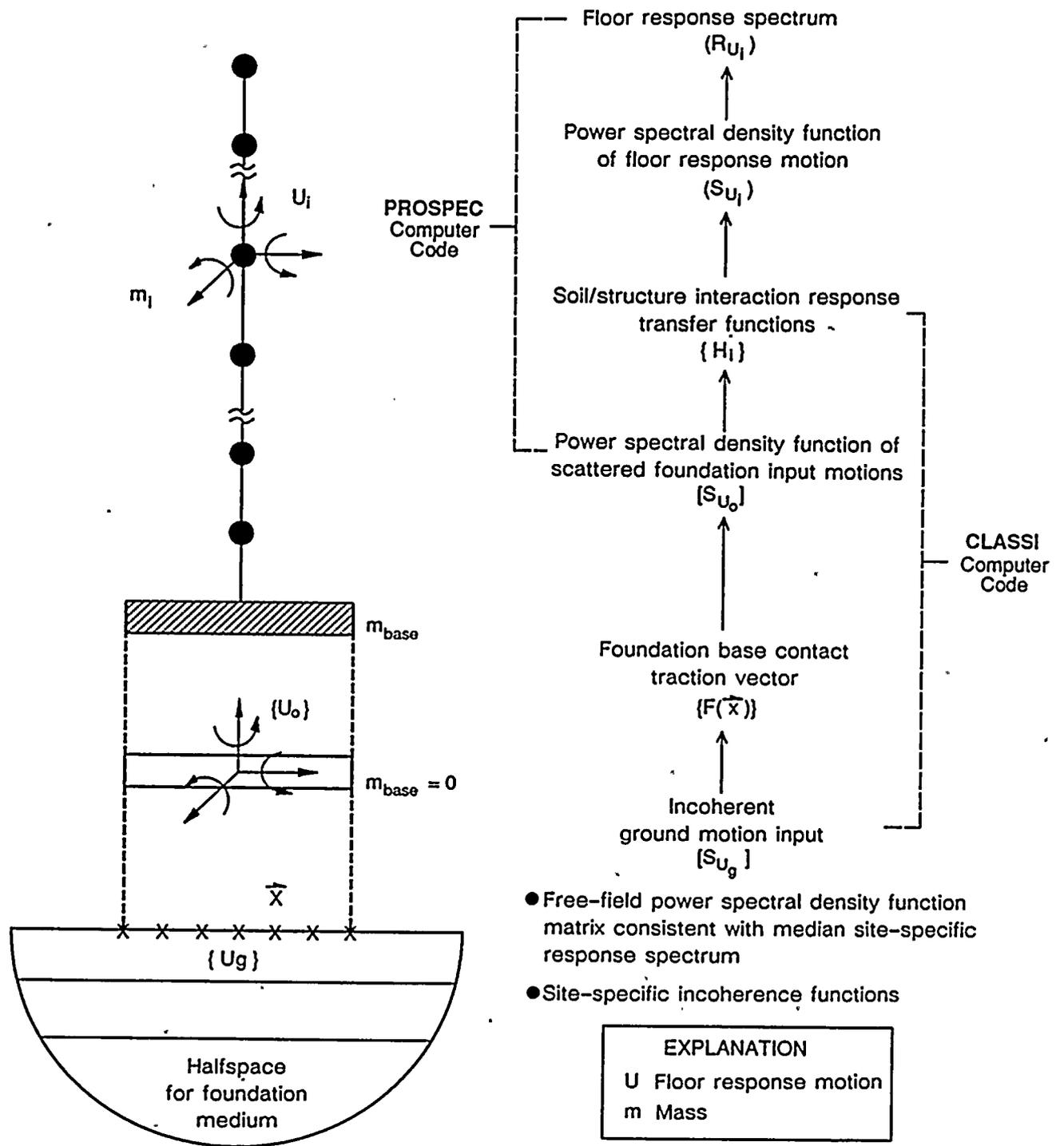


Figure 5-42

Schematic diagram of random vibrational soil/structure interaction analysis for incoherence ground motion input.

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input motions. This method and the associated computer programs have been benchmarked against the available published solutions (Luco and Wong, 1986; Mita and Luco, 1986).

Using this method and the CLASSI soil/structure interaction models for the power block structures, analyses were performed with input conforming to the fragility evaluation reference average spectral acceleration of 2 g, as shown in Figure 5-22. Soil/structure interaction responses (including the effects of spatial incoherence) in terms of 5 percent damped floor response spectra were developed for each of the locations in the power block structures where the responses to the coherent ground-motion inputs were generated earlier. To isolate the effect of spatial incoherence using the same analysis method, soil/structure interaction analyses in which the spatial incoherence functions were set equal to unity, were also performed to generate the responses to the coherent ground motions at the same locations. Values of the floor response spectral ratio, which is the ratio of the 5 percent damped floor response spectral value resulting from the incoherent ground-motion input to the corresponding spectral value resulting from the coherent ground-motion input, were determined. The floor response spectral ratios for various response locations, which represent only the effect on the soil/structure interaction response due to the spatial incoherence of ground motions, were then provided for use in the Plant fragility evaluations. Representative results of the 5 percent damped floor response spectra and the corresponding floor response spectral ratios to be used as the response adjustment factors, obtained from both the coherent and incoherent ground motion inputs consistent with the fragility evaluation reference response spectra, are shown in Figures 5-43 and 5-44 for north/south responses of the containment, in Figures 5-45 and 5-46 for north/south responses of the auxiliary building, and in Figures 5-47 through 5-50 for north/south and east/west responses of the turbine building.

The results obtained from soil/structure interaction analyses of the power block structure,

incorporating site-specific spatial incoherence ground motion effects, indicate the following:

- (1) Spatial incoherence of ground motions generally results in reductions in the foundation base translational motions as indicated by the floor response spectral ratios for the basemat responses shown in Figures 5-43, 5-45, 5-47, and 5-48, and such reductions are proportional to the plan area of the foundation. For the basemats of the power block structures, the magnitudes of these reductions increase gradually with increasing frequency. For frequencies above 10 hertz, these reductions, as indicated by the analytical studies, are about 6 percent for the containment structure, 15 percent for the auxiliary building, and between 0 and 30 percent for the turbine building.
- (2) Due to the accompanying rocking and torsional motions induced as a result of spatial incoherence, the reductions in response are less at the locations within the structures where the response is affected by rocking or torsional response motions, and in the specific frequency ranges of the rocking and torsional response modes of the structure. This is illustrated by comparing the floor response spectral ratios for the north/south and east/west responses as shown, respectively, in Figures 5-49 and 5-50 for the switchgear location near the south end of the Unit 2 turbine building. The comparisons indicate that the spectral ratio for the north/south response, which is close to the north/south centerline of the foundation mat and thus has little contribution from the torsional response, is similar to the spectral ratio of the north/south response near the center of the basemat, as shown in Figure 5-47. The spectral ratio for the east/west response, which is away from the east/west centerline and thus is sensitive to torsional response, is different from that of the east/west response of the basemat, as shown in Figure 5-48.



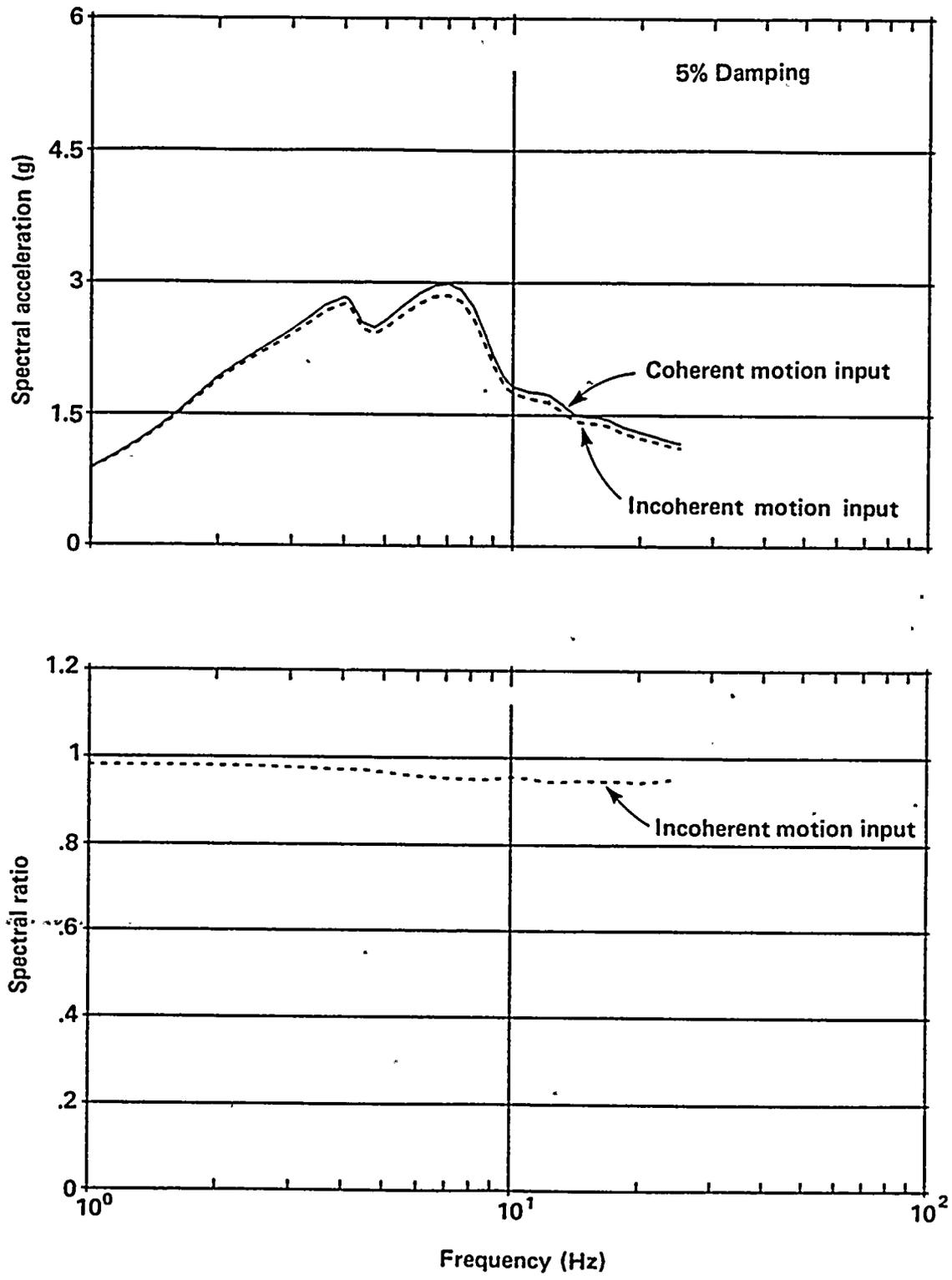


Figure 5-43

Floor response spectra and floor response spectral ratio for the north/south response of the containment at the base, El 85 feet.

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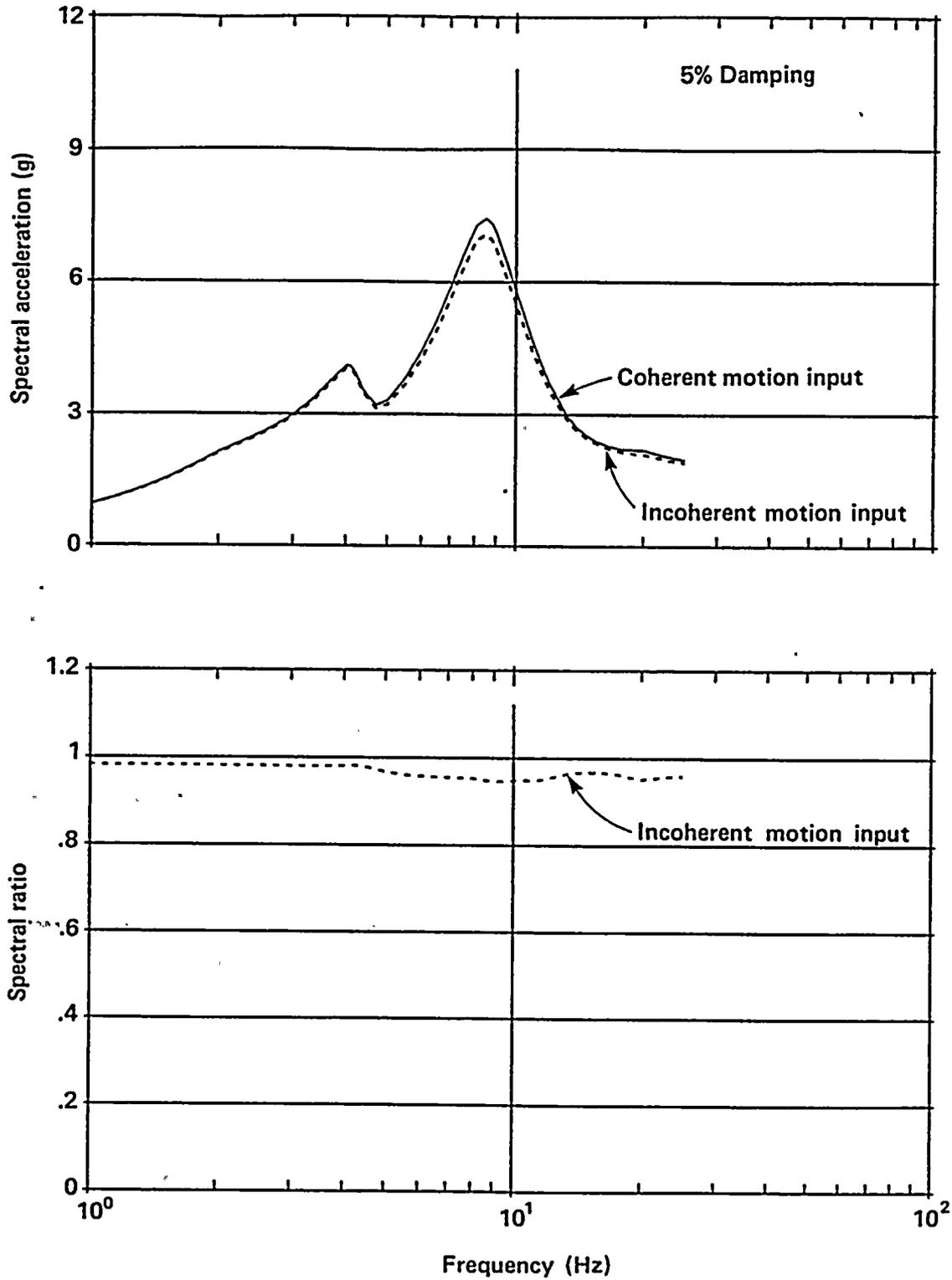


Figure 5-44

Floor response spectra and floor response spectral ratio for the north/south response of the containment at the top of interior concrete structure, El 138.5 feet.

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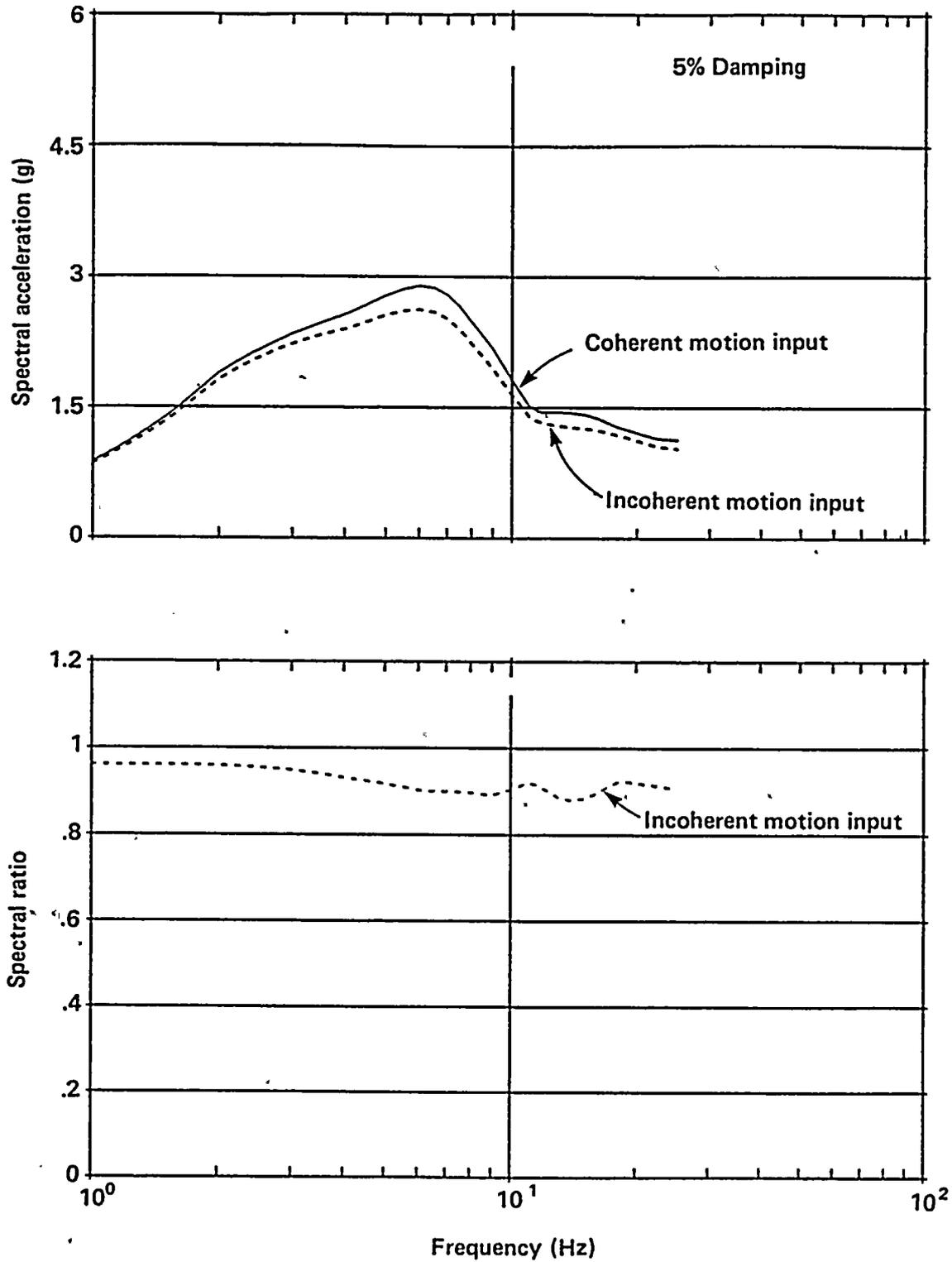


Figure 5-45

Floor response spectra and floor response spectral ratio for the north/south response of the auxiliary building at El 85 feet.

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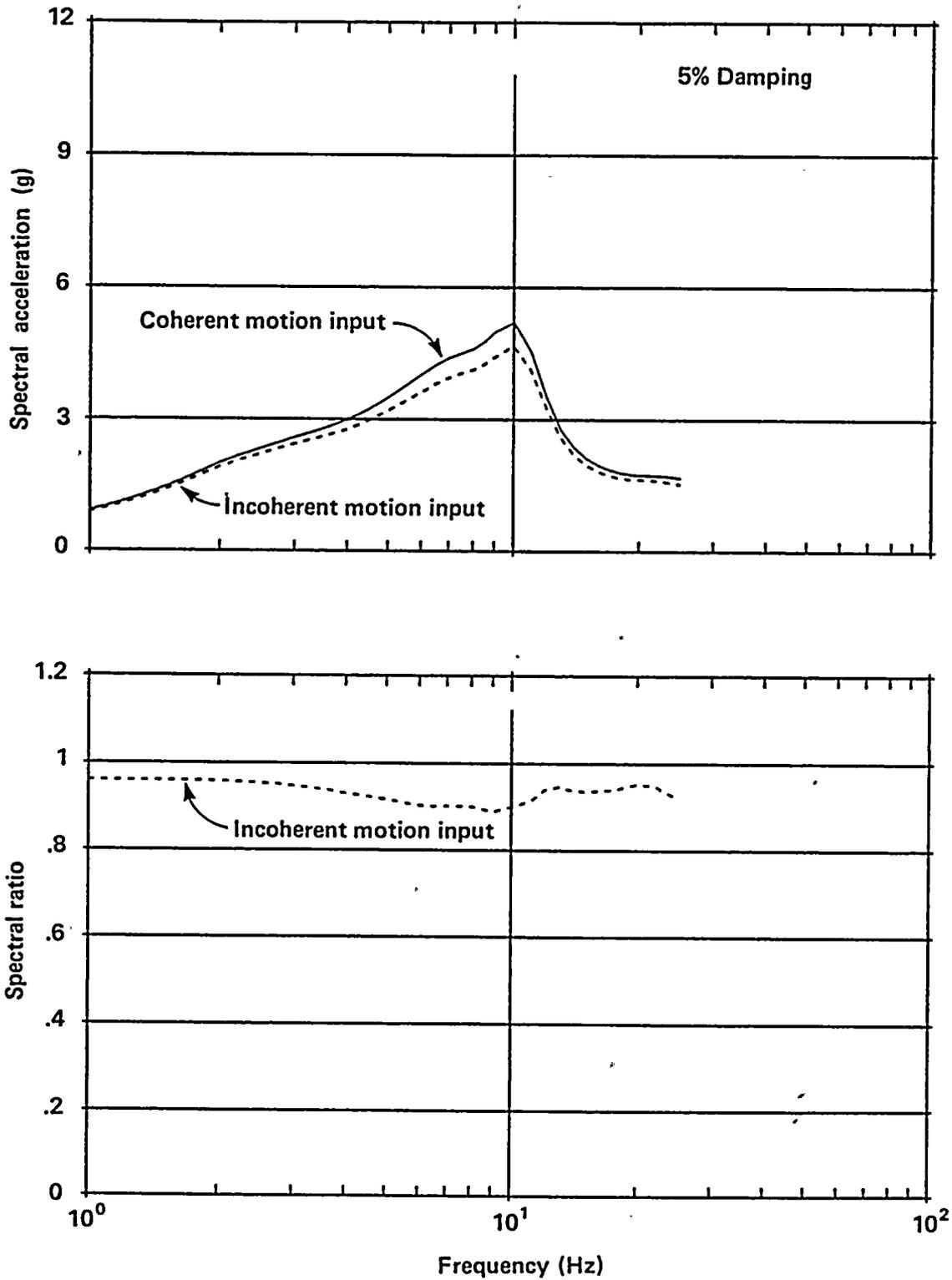


Figure 5-46

Floor response spectra and floor response spectral ratio for the north/south response of the auxiliary building at El 140 feet.



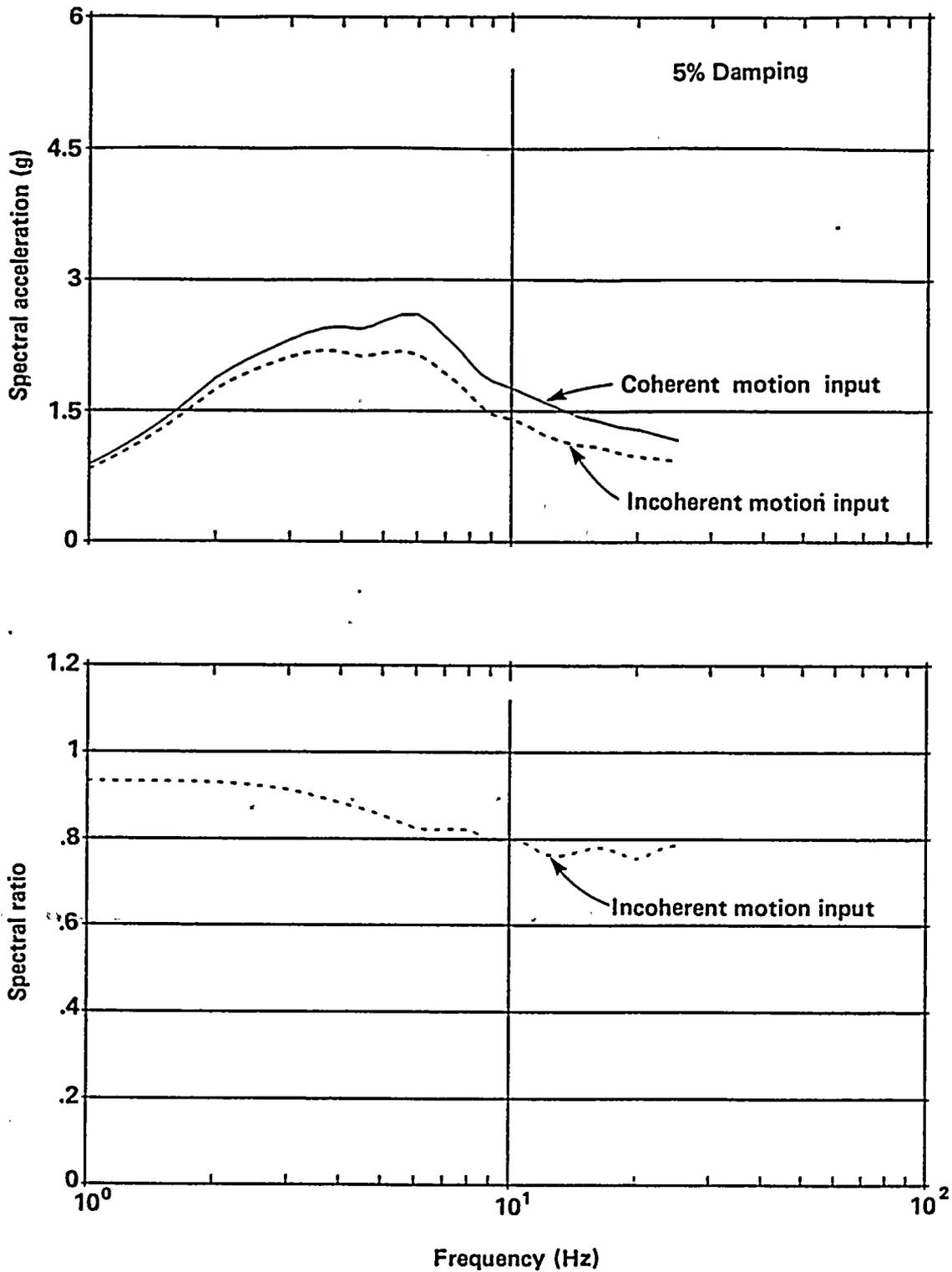


Figure 5-47

Floor response spectra and floor response spectral ratio for the north/south response of the turbine building at CCW heat exchange location, El 85' feet.



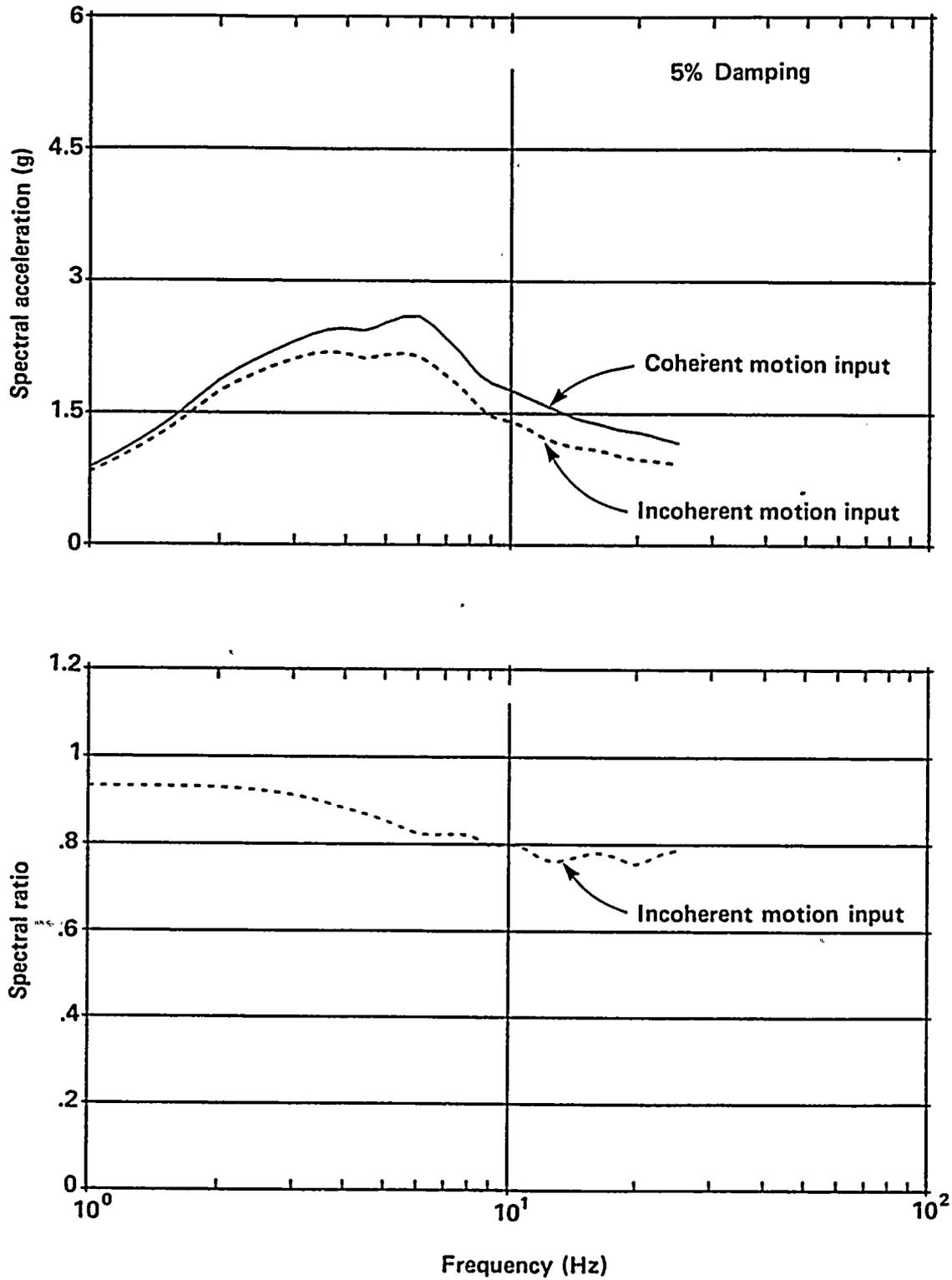


Figure 5-48

Floor response spectra and floor response spectral ratio for the east/west response of the turbine building at CCW heat exchange location, El 85 feet.



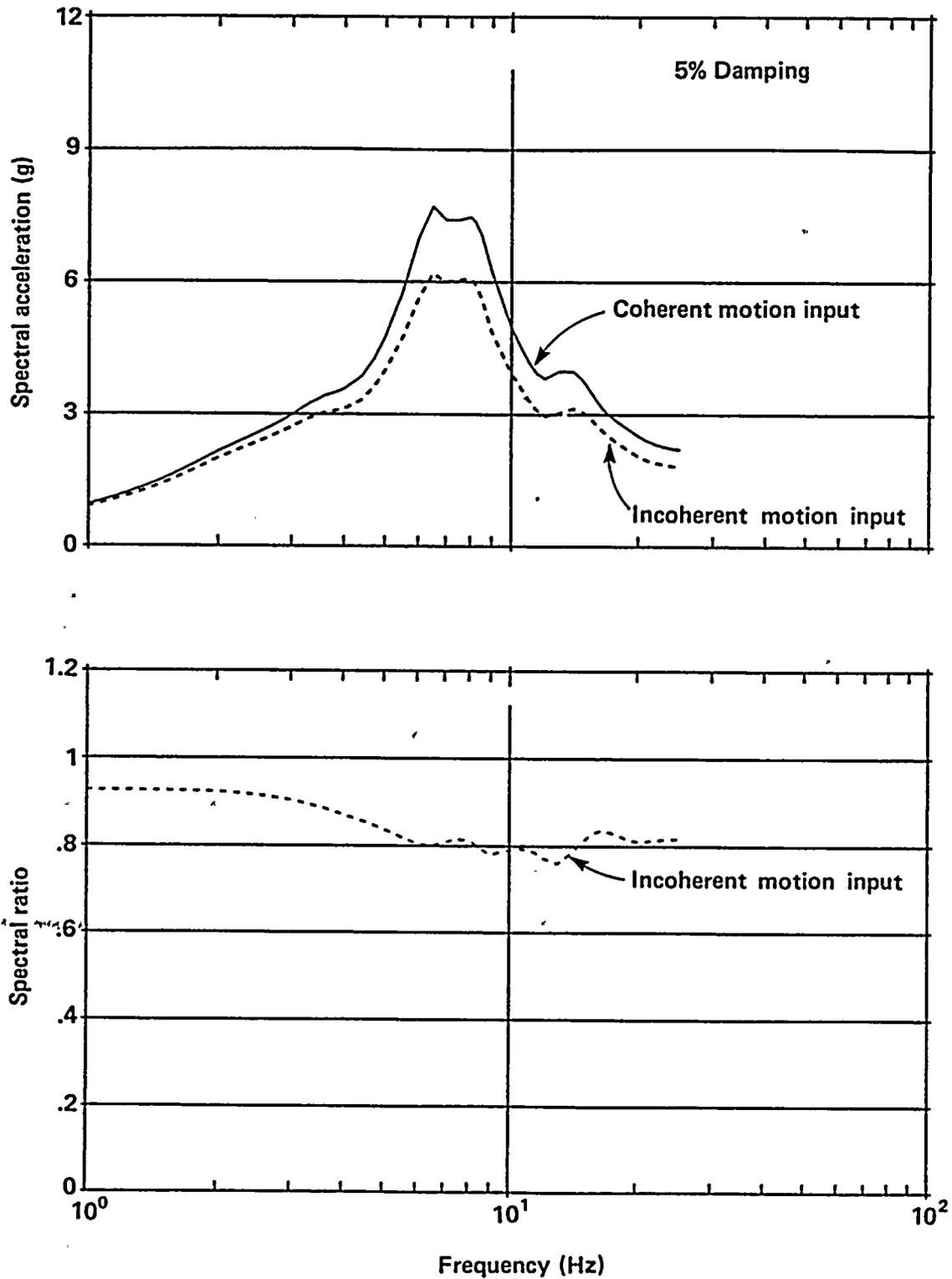
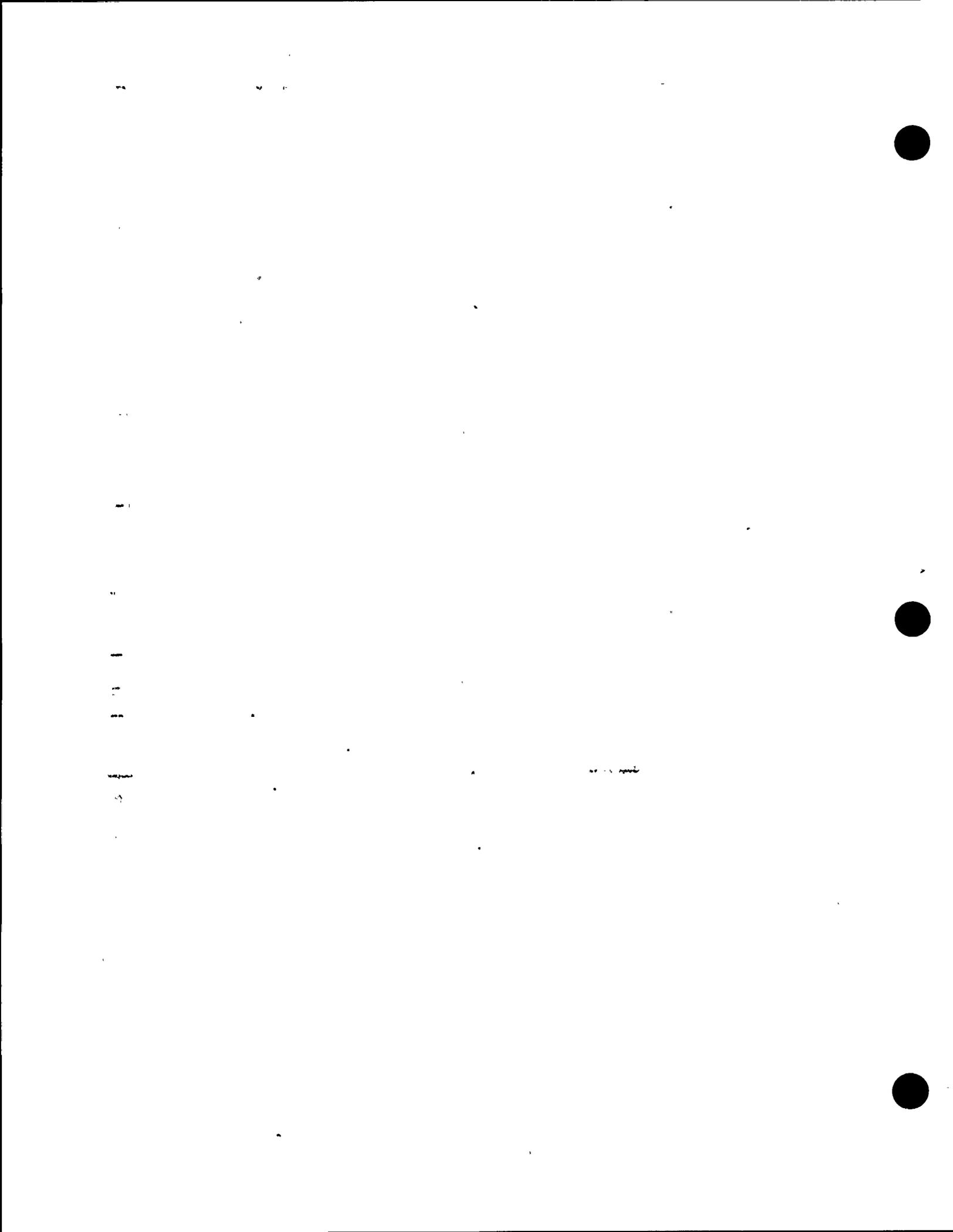


Figure 5-49

Floor response spectra and floor response spectral ratio for the north/south response of the turbine building at switchgear location, El 119 feet.



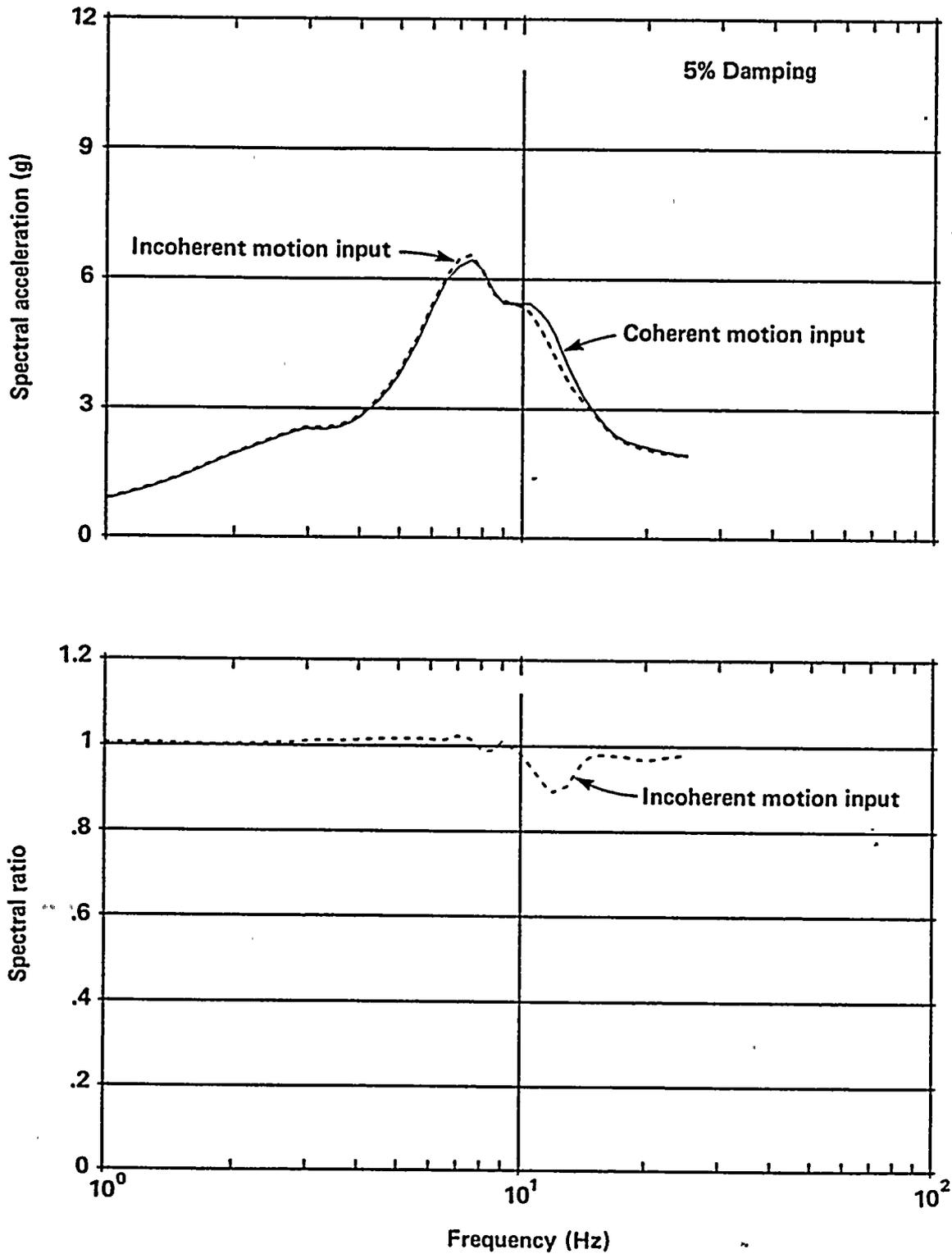


Figure 5-50

Floor response spectra and floor response spectral ratio for the east/west response of the turbine building at switchgear location, El 119 feet.

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Assessment of Soil/Structure Interaction Responses of the Containment Structure Due to Basemat Uplifting

The effect on the containment seismic response due to partial uplift of the containment basemat from the rock foundation under strong seismic ground motions was investigated in a separate study using a two-dimensional nonlinear time history analysis method.

The analysis was based on a soil/structure interaction model for the containment formed by coupling the lumped-mass stick model for the structure with a Winkler foundation model (uniformly distributed discrete foundation springs and dampers) which has no tension capability. This model is shown schematically in Figure 5-51. For the Diablo Canyon Power Plant containment which has foundation embedment, the Winkler foundation model was further extended to simulate the foundation embedment effect by incorporating a set of Winkler-type side-rock springs and dampers. Furthermore, a method was also developed to incorporate the energy dissipation associated with the base "slapdown" which occurs following base uplift. The mechanism of energy dissipation was simulated using an equivalent viscous damping for the foundation model which becomes effective when base uplift occurs.

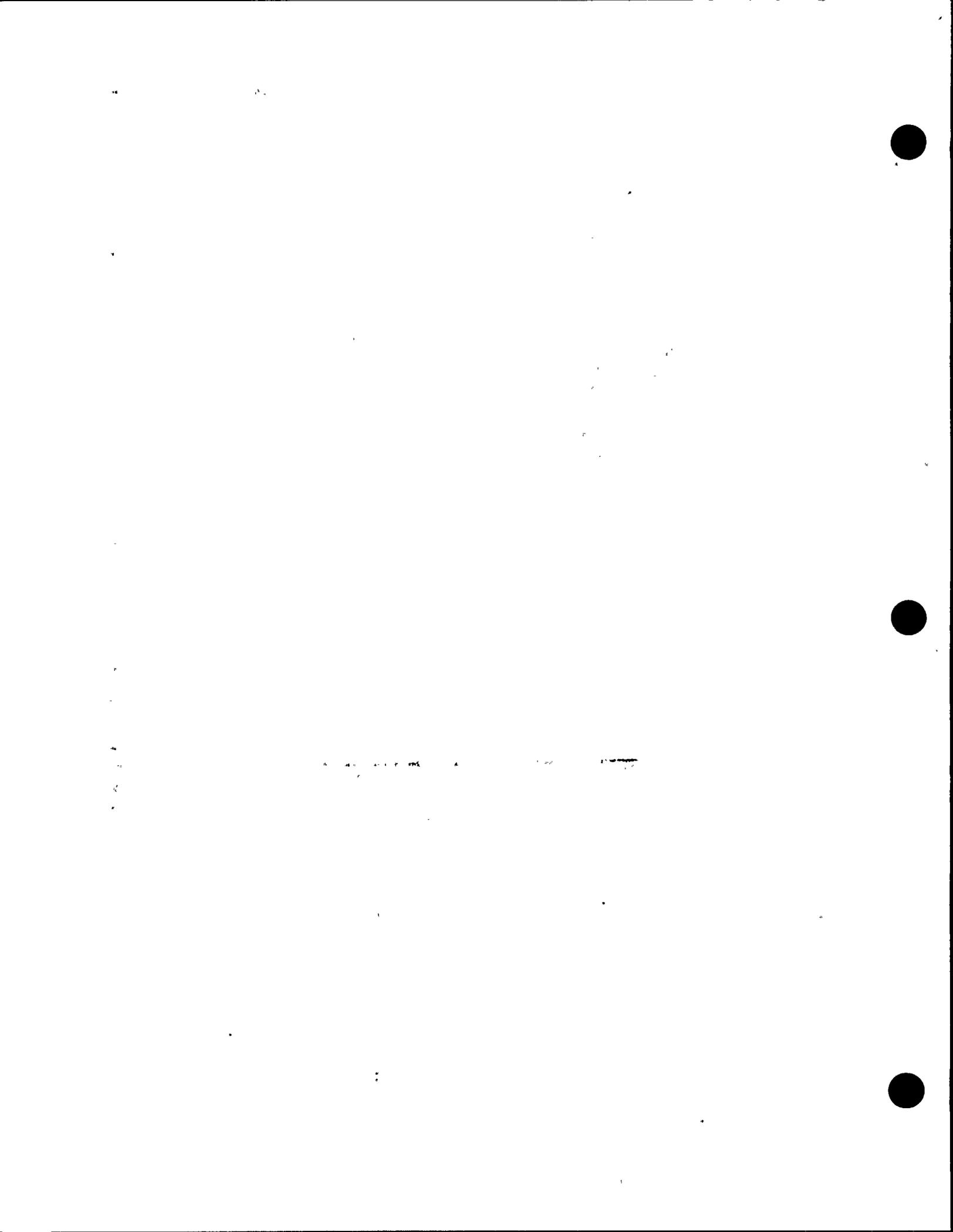
The nonlinear base uplifting analysis methodology and the associated UPLIFT computer program (Tseng and Wing, 1984) used for the analysis of containment have been benchmarked against available published solutions for the effects of base uplifting in dynamic response problems (Psycharis, 1981).

The free-field input motions used for the containment base uplift response analyses were the rock surface motions assumed in the form of coherent, vertically incident, plane waves. Since a two-dimensional analysis was used, one horizontal component together with the vertical component of the three-component prescribed earthquake motions were simultaneously applied as the input for each analysis. Both horizontal components were used in this manner in two separate analyses.

The ground motions that were used as the input for the containment base uplift response analysis consisted of three sets of three-component recorded motions as selected by the ground-motion studies, which are: (a) the Pacoima Dam records of the 1971 San Fernando earthquake; (b) the 1978 Tabas records of the Tabas earthquake; and (c) the El Centro No. 4 records of the 1979 Imperial Valley earthquake. Before applying these as-recorded motions for the analysis, the motions were adjusted in the following manner:

- (1) The original recorded motions were adjusted to conform with the site-specific conditions such as the maximum earthquake magnitude, source-to-site distance, and site condition.
- (2) The two horizontal components of the adjusted three-component motions were transformed, as necessary, into two longitudinal and transverse horizontal components to provide motions in the directions normal and parallel to the strike of the causative fault.
- (3) The three-component time histories were scaled by a constant scaling factor common for all three components, to correspond to the reference seismic input level used for fragility evaluation purposes.
- (4) The scaled three-component time histories were then applied as the input for the base uplift response analyses, first, with the longitudinal component applied in the Plant north/south direction and the transverse component in the Plant east/west direction, and then vice versa; the vertical component was applied in the Plant vertical direction in each case.

To be conservative for the containment base uplift response analyses, the constant scaling factor used for step (3) above was derived such that the average value of the 5 percent damped acceleration response spectral values of the two horizontal time histories in the frequency range of 3 to 8.5 hertz, inclusively, was equal to 2.25 g. This procedure is illustrated in Figure 5-52. The scaling factors as derived for the three sets of



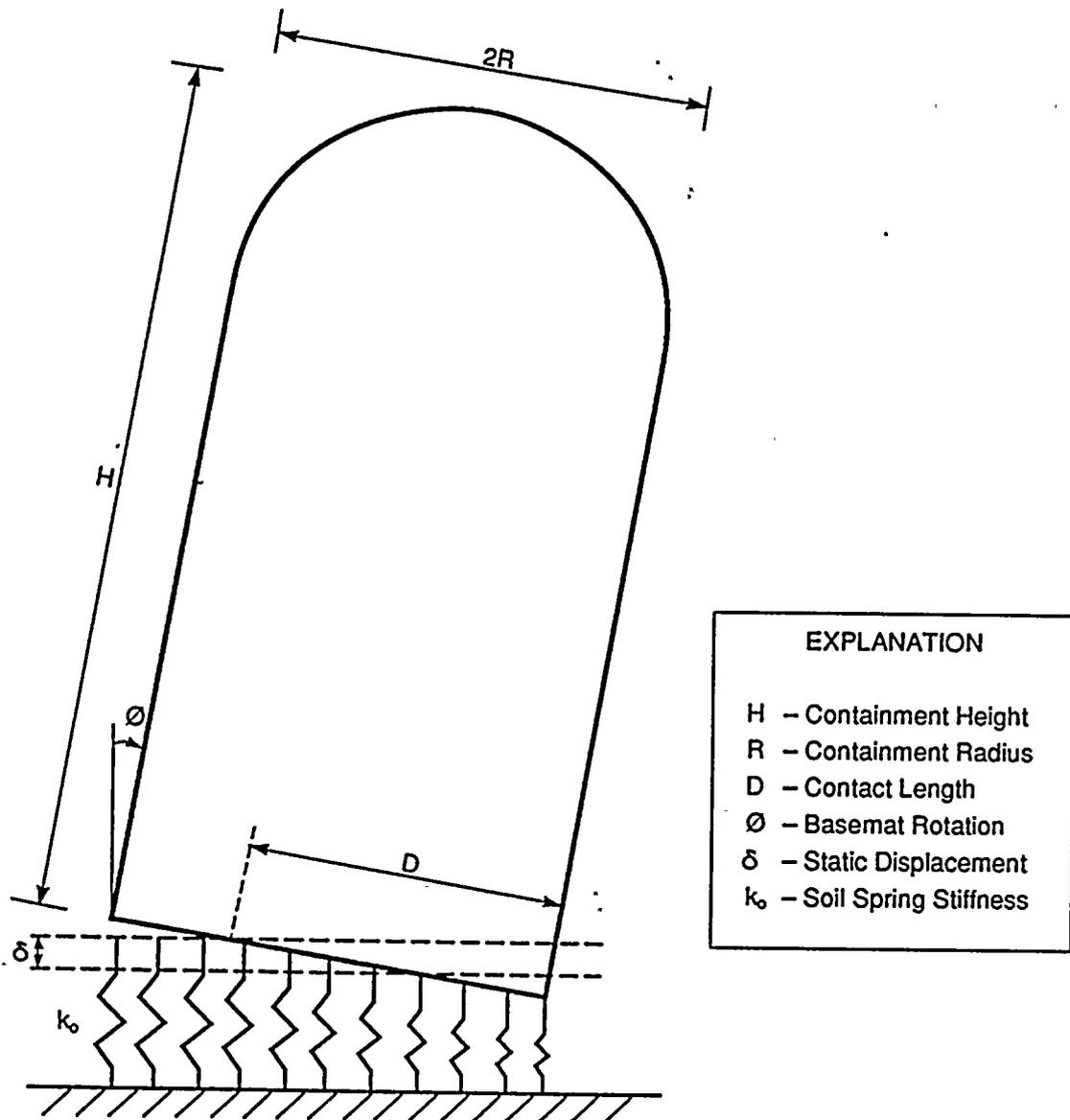
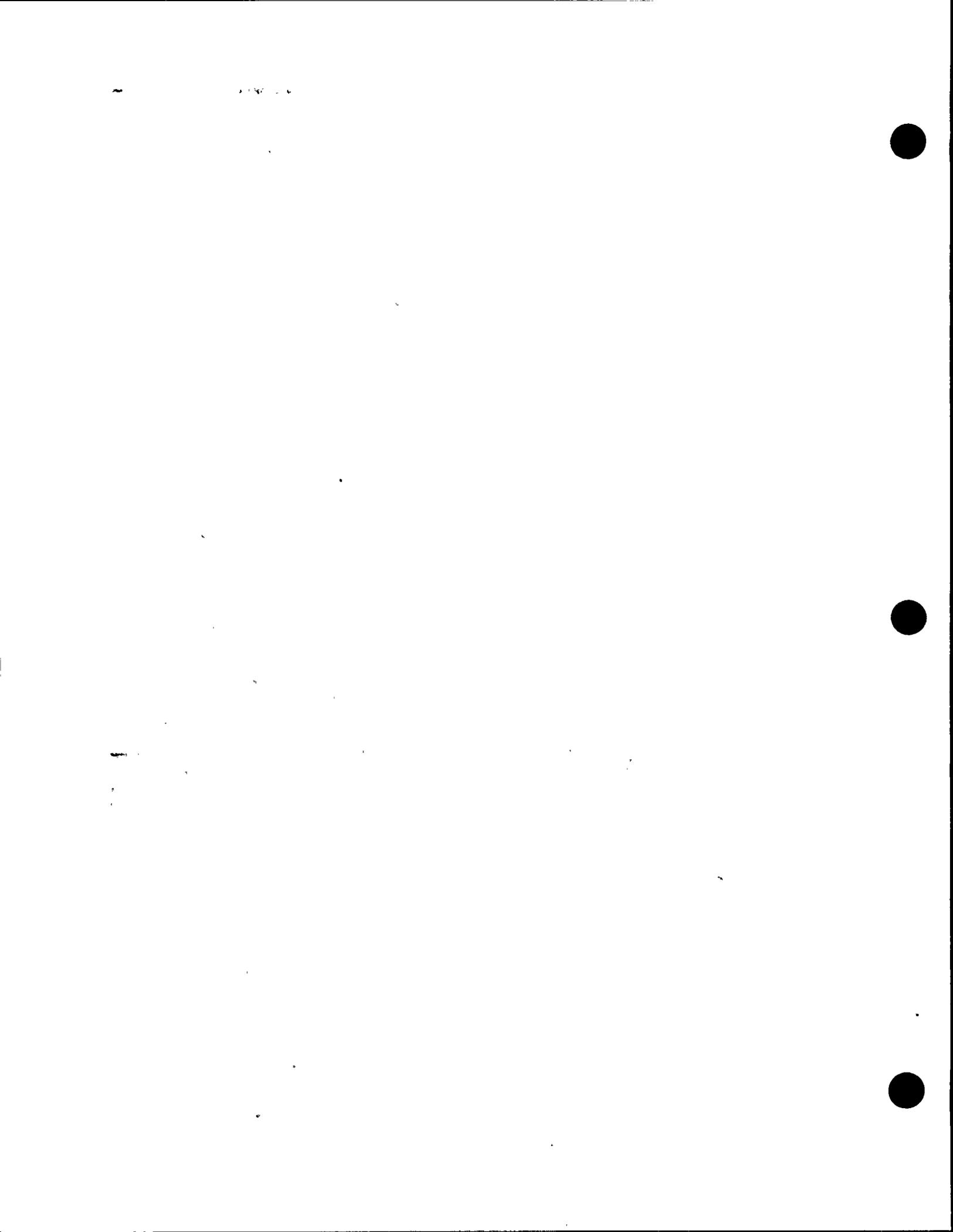


Figure 5-51

Schematic configuration of containment on Winkler foundation with base uplift.



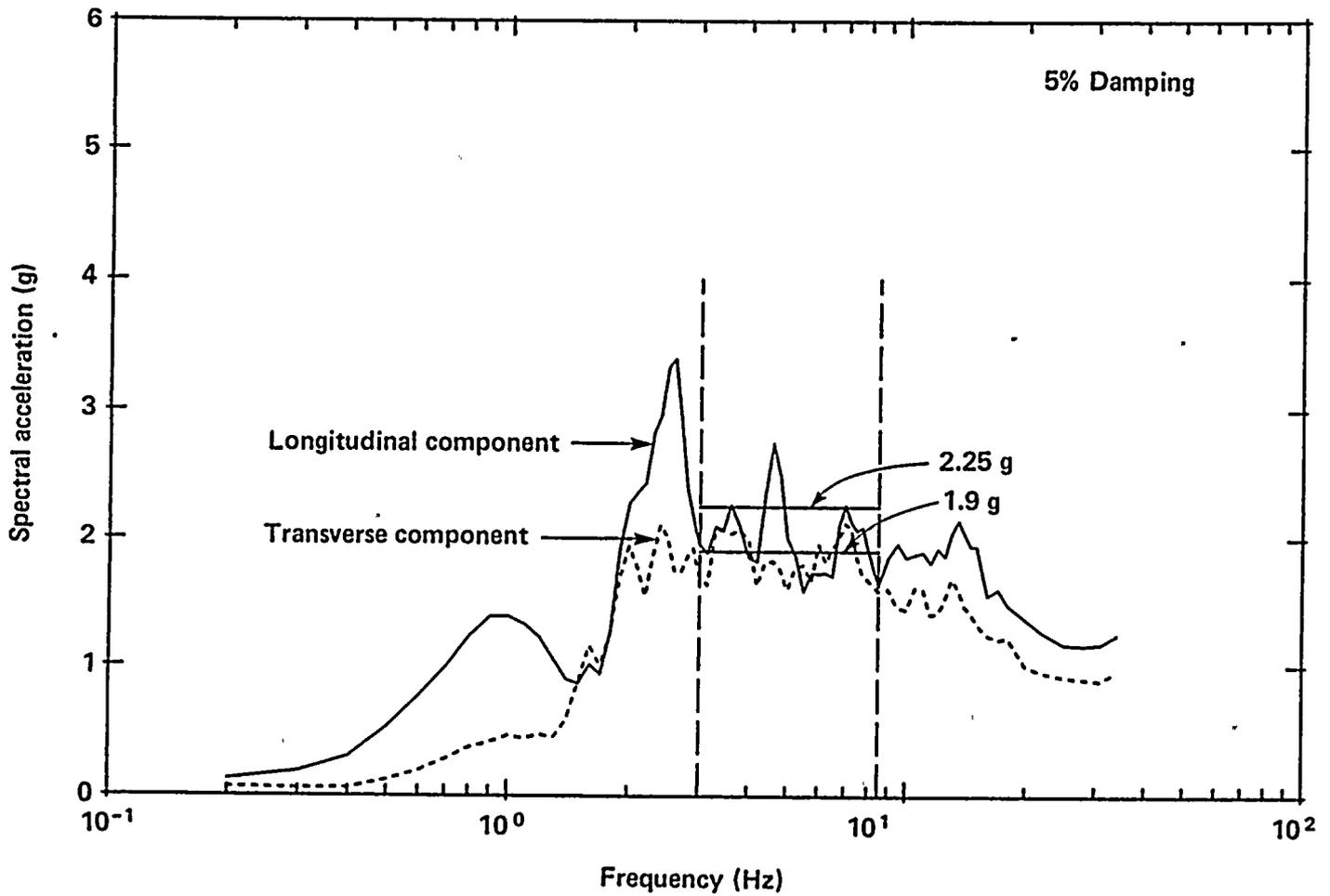


Figure 5-52

Illustration of the procedure used to derive the constant scaling factor for the input motions using the Pacoima motions for containment base uplift analyses.

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ground motion inputs considered were: 1.2 for the Pacoima input; 0.9 for the Tabas input; and 2.5 for the El Centro No. 4 input. The scaled final time histories used for analyses of base uplift effects are shown in Figures 5-53 through 5-55. The 5 percent damped acceleration response spectra of these time histories are shown in Figures 5-56 through 5-58.

Containment base uplift analyses were performed for three foundation model assumptions: (a) a Winkler base foundation model with the full amount of side-rock impedances to simulate the condition of full contact between the side rock and the embedded containment basemat wall; (b) a Winkler base foundation model with one-half the side-rock impedances to simulate the partial loss of side-rock support up to one-half the basemat wall perimeter; and (c) a Winkler base foundation model with one-half the side-rock impedances and with added viscous damping to simulate the base slapdown impact energy dissipation. For comparison purposes, linear response analyses, in which base uplift was suppressed, were also performed for all base uplift analysis cases.

Representative horizontal and vertical response results obtained from the analyses for all three foundation model cases and all three sets of three-component time histories used as input motions, are presented in Figures 5-59 through 5-64 in terms of the 5 percent damped floor response spectra at the containment shell springline location and at the top floor of the containment interior structure.

The results of the containment base uplift analyses, as presented in these figures, show that: (a) allowance for base uplift generally leads to small reductions in the horizontal acceleration response, shear, and overturning moment; and small increases in the horizontal displacement and the vertical acceleration response in the high frequency range, as compared to the response obtained without including base uplift effects; (b) a reduction in the side-rock impedances to one-half the full values, to account for the partial separation of the embedded wall from the surrounding rock over one-half the basemat wall perimeter, produced relatively small variations in

the response; and (c) consideration of the base slapdown impact energy dissipation, as proposed by Psycharis (1981), resulted in further reductions in both horizontal and vertical response; however, the effect was found to be relatively small. In view of these results, it was concluded that base uplift had no significant effects on the dynamic response of the containment structure.

SUMMARY AND CONCLUSIONS

A complete reevaluation of the seismic soil/structure interaction effect on the power block structures was carried out as part of the Long Term Seismic Program. The conclusions from these studies are described below.

CLASSI/SASSI Solution Techniques. The reevaluation used state-of-the-art three-dimensional analysis techniques and computer programs, CLASSI and SASSI. An extensive effort was spent implementing, upgrading, validating, and documenting these two programs for our Program's applications. Plant-specific applications of these two programs have demonstrated that they produce essentially the same solutions for the same soil/structure interaction problems.

Soil/Structure Interaction Parametric Studies. Prior to performing the soil/structure interaction analysis, extensive studies were made to characterize the soil/structure interaction systems for the power block structures. These studies included the assemblage, review, and characterization of the foundation rock profile and properties, the development of appropriate three-dimensional dynamic models for the power block structures, and the performance of a series of soil/structure interaction parametric studies. In these studies, the additional site investigation data that became available in 1978, and the on-site earthquake recordings that became available after 1980 have been used to assist in calibrating the dynamic characteristics of the site rock and the soil/structure interaction systems for the power block structures.

The results of the soil/structure interaction parametric studies indicated that the effects of



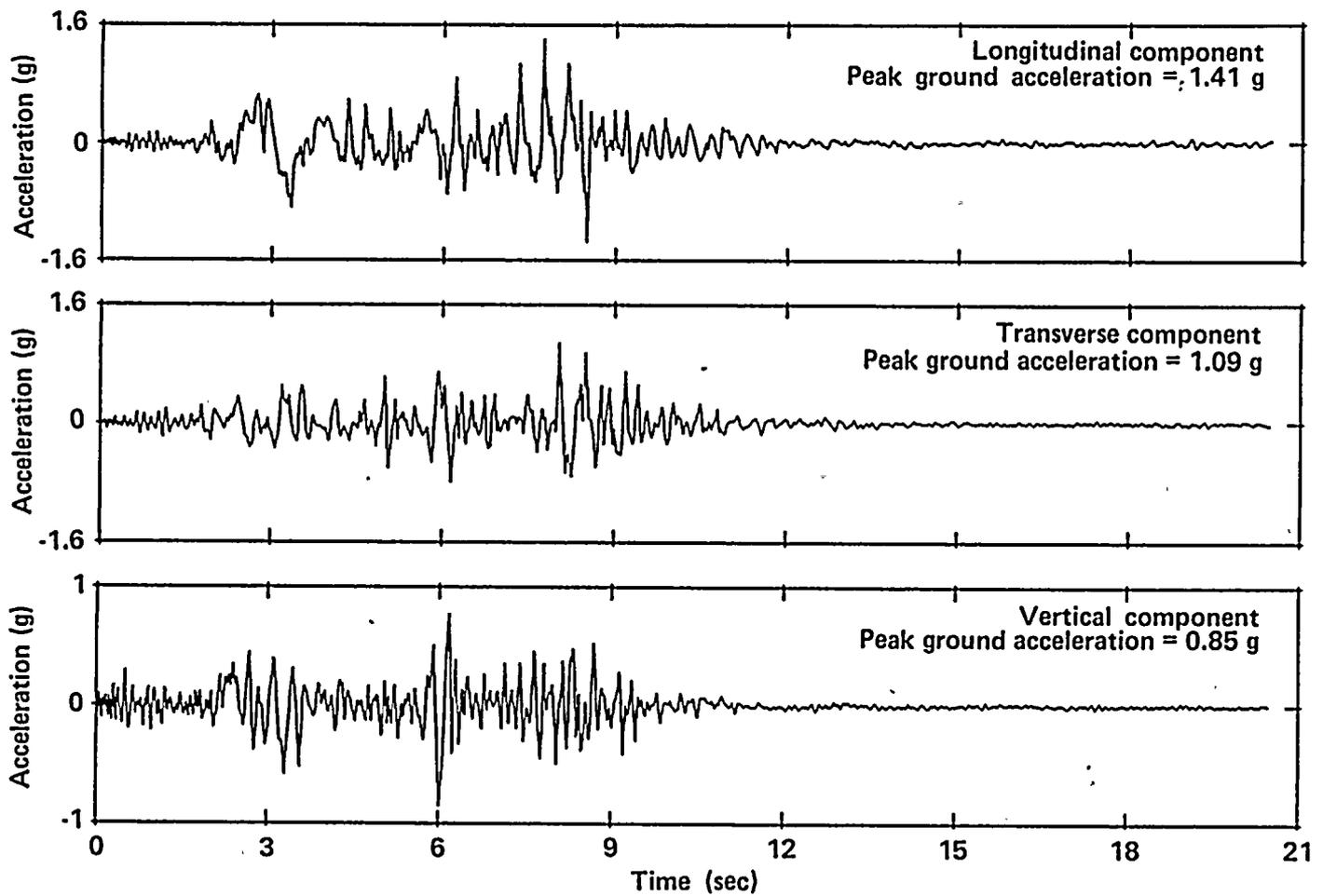


Figure 5-53

Scaled Pacoima acceleration time histories used for containment base uplift analyses, longitudinal, transverse, and vertical components.



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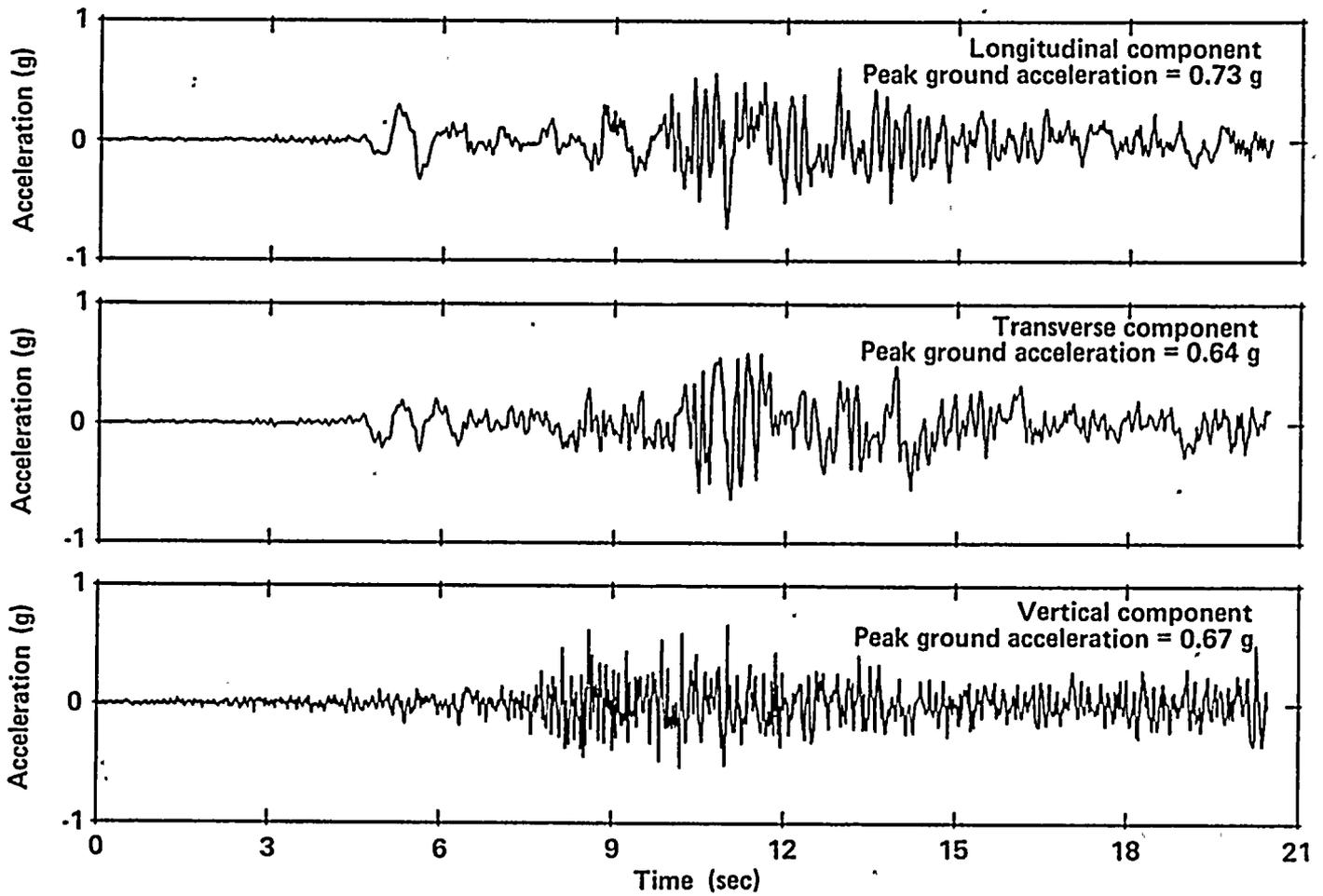


Figure 5-54

Scaled Tabas acceleration time histories used for containment base uplift analyses, longitudinal, transverse, and vertical components.

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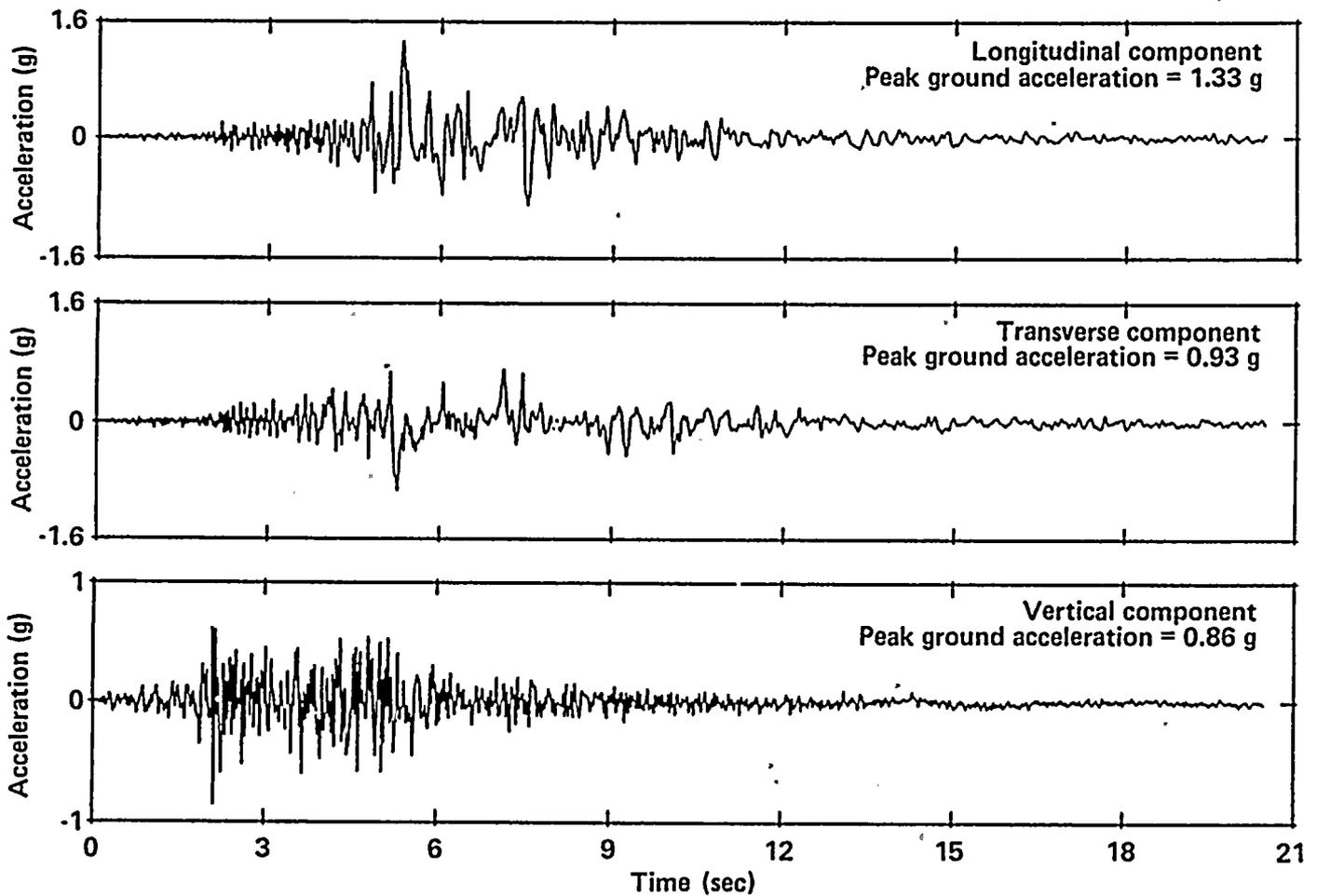
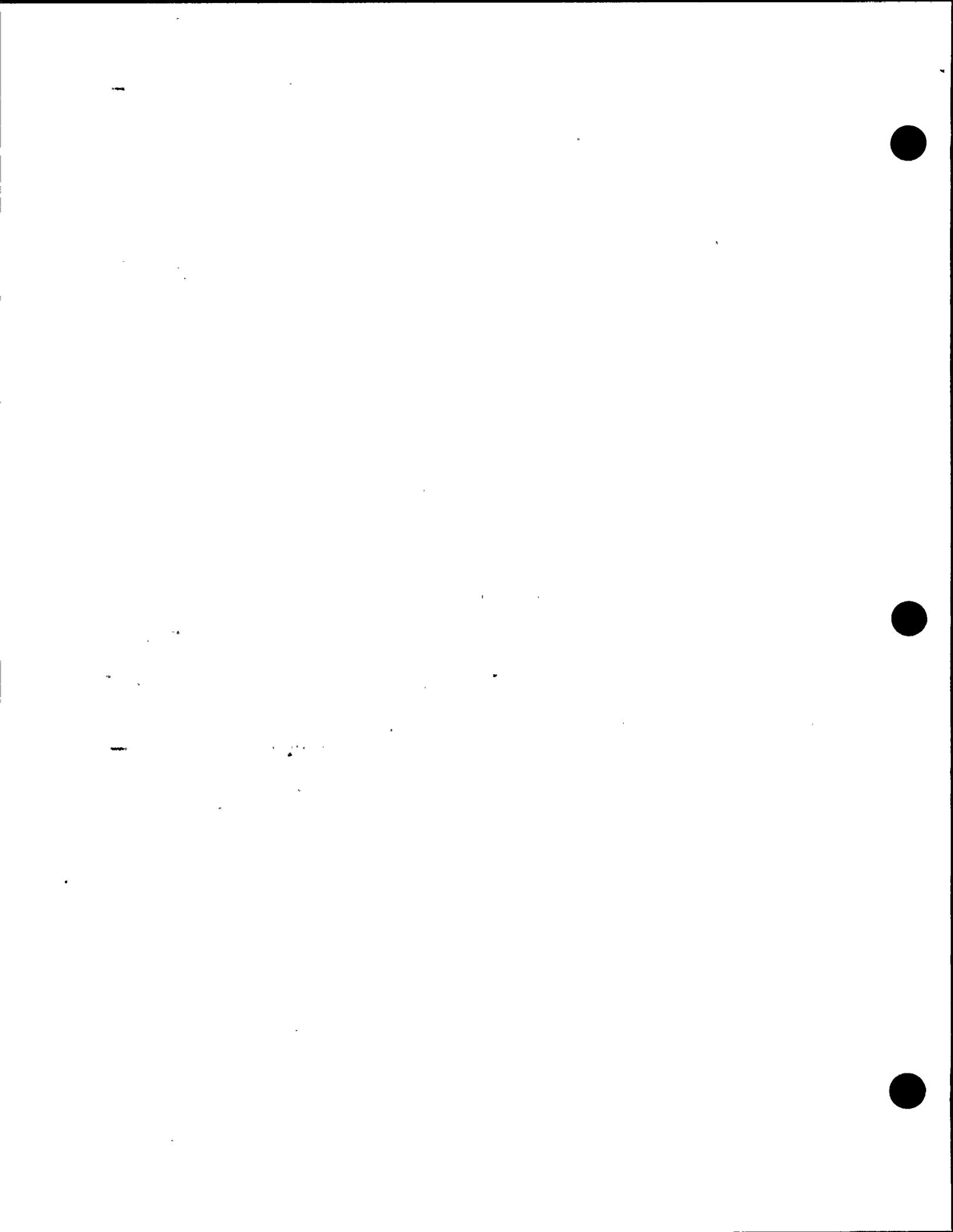


Figure 5-55

Scaled El Centro No. 4 acceleration time histories used for containment base uplift analyses, longitudinal, transverse, and vertical components.



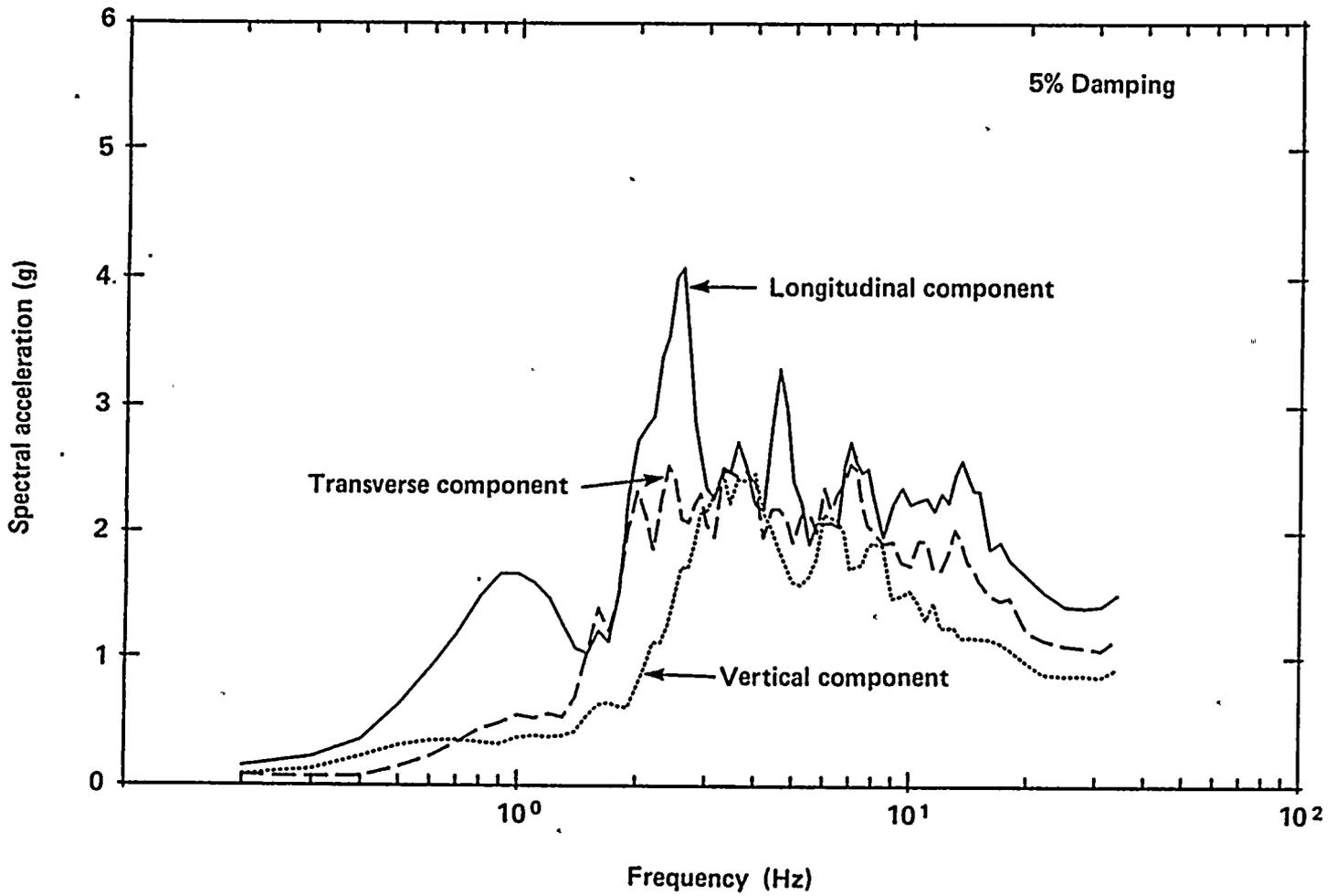


Figure 5-56

Acceleration response spectra of scaled Pacoima time histories used for containment base uplift analyses.



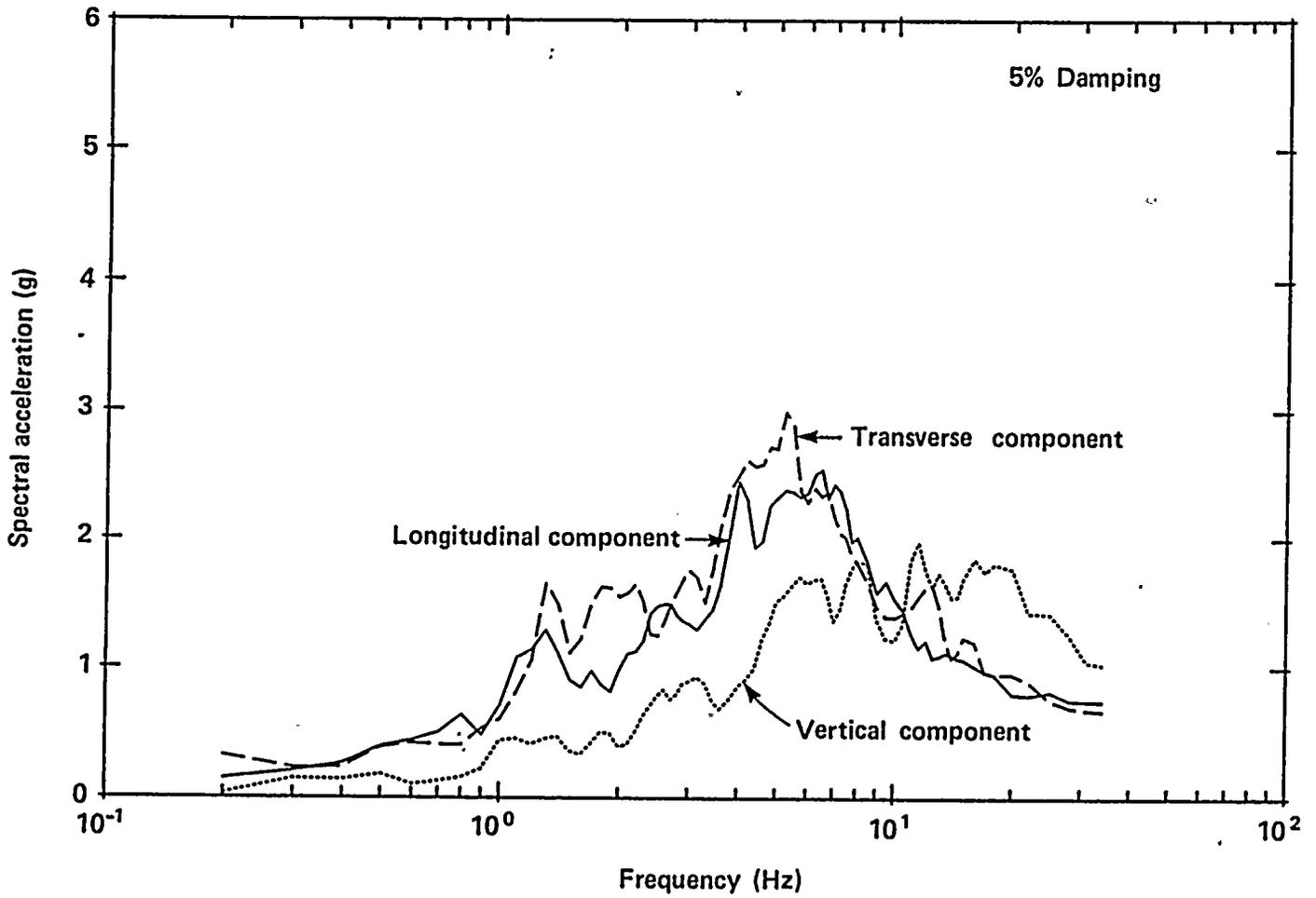
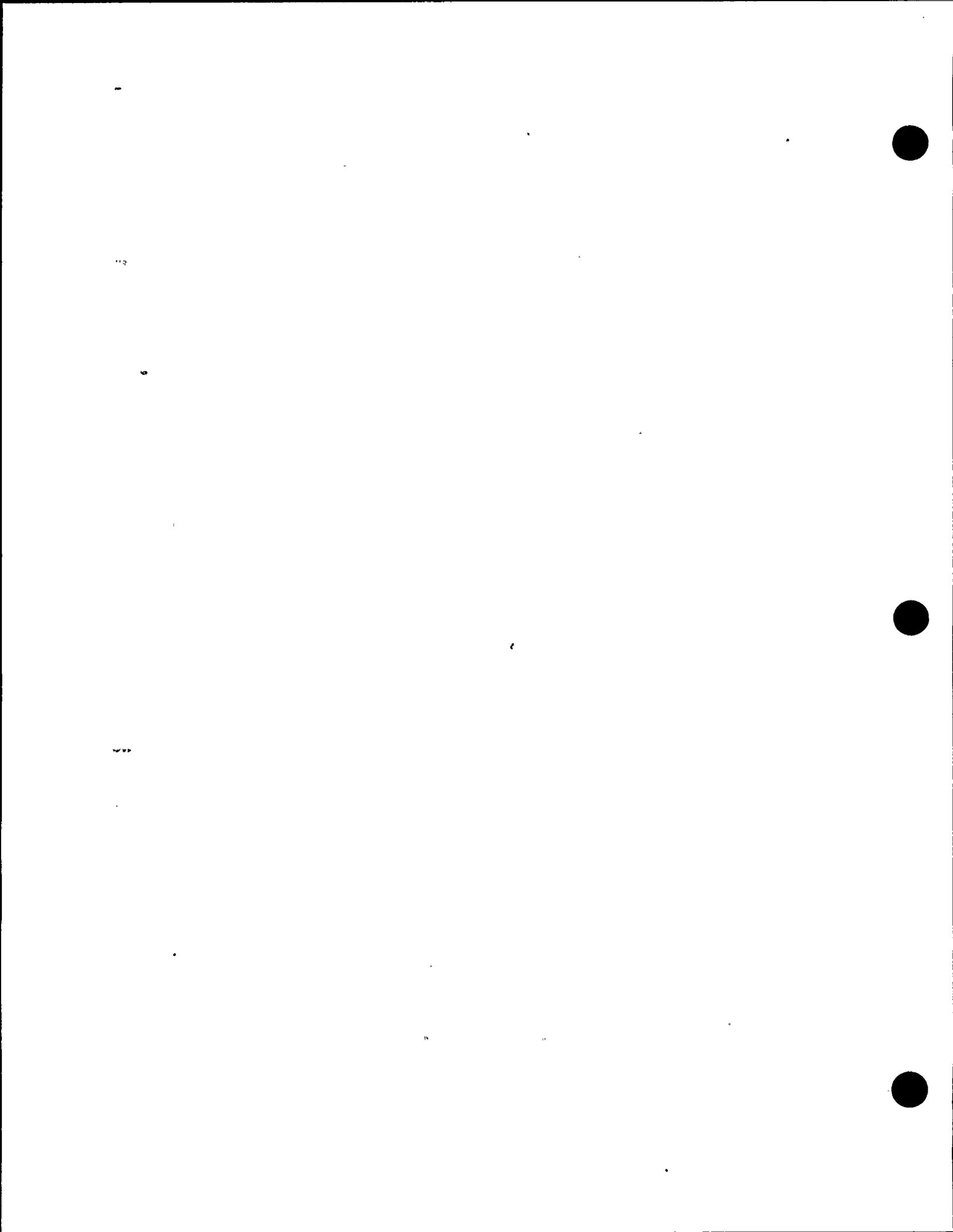


Figure 5-57

Acceleration response spectra of scaled Tabas time histories used for containment base uplift analyses.



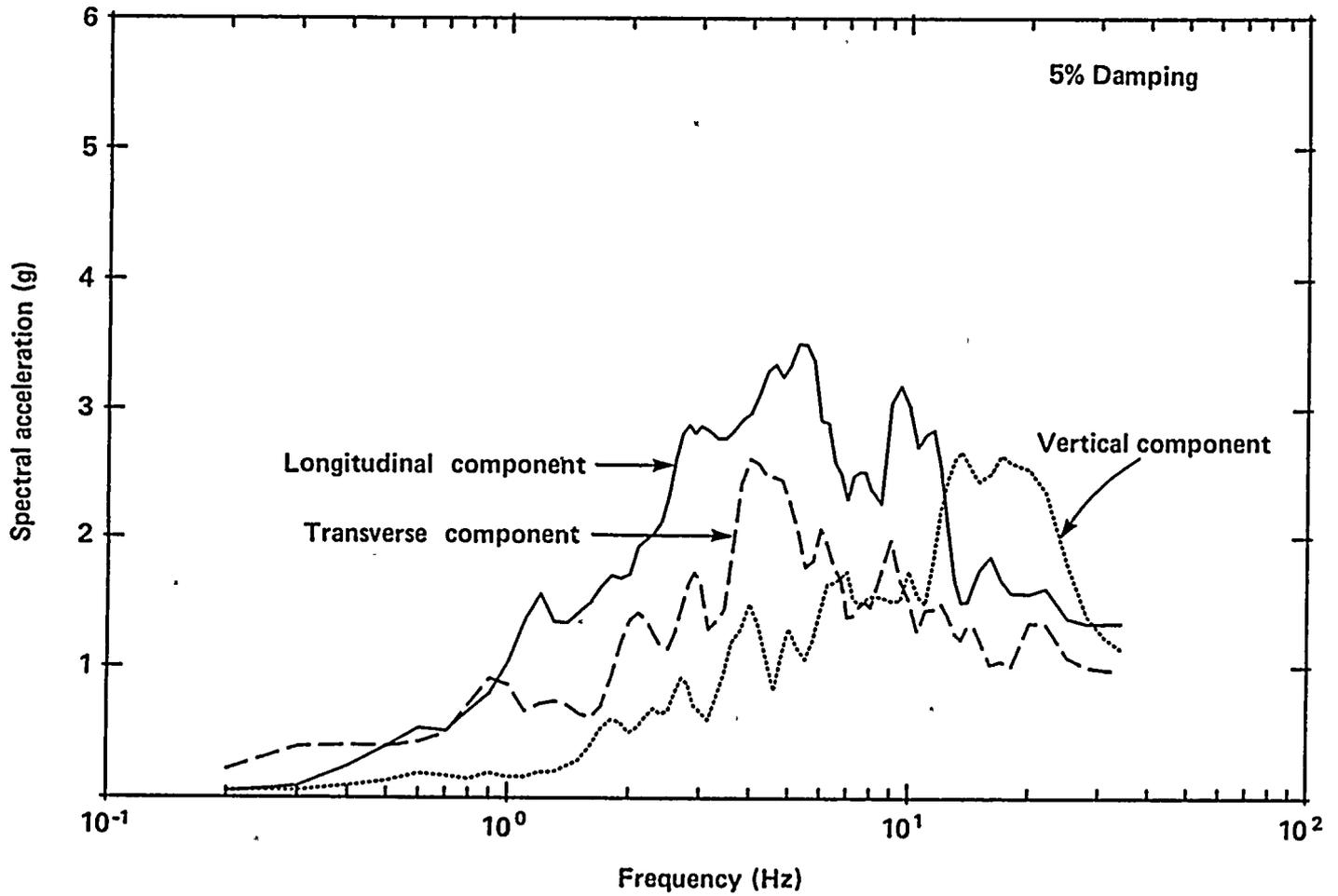


Figure 5-58

Acceleration response spectra of scaled El Centro No. 4 time histories used for containment base uplift analyses.



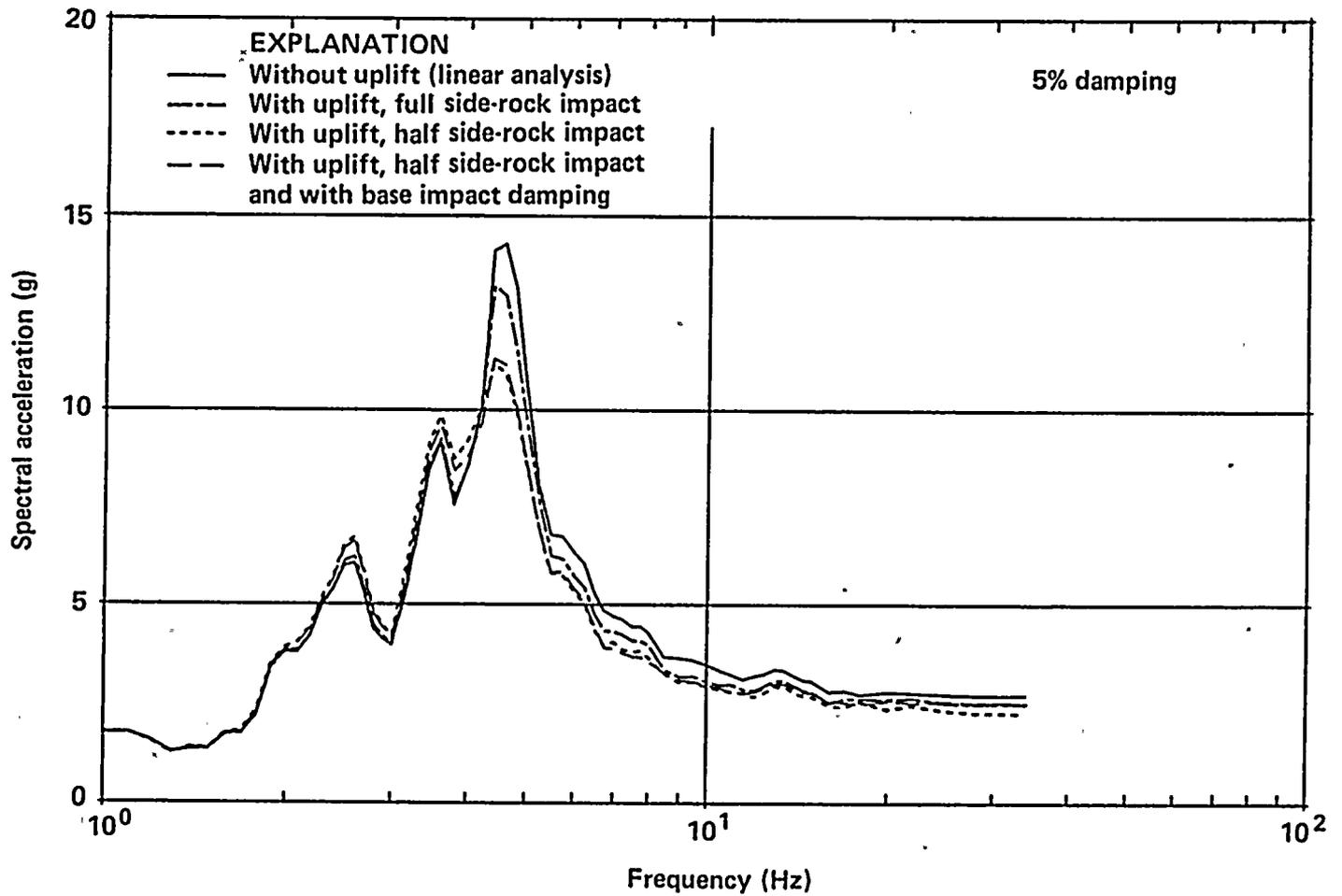


Figure 5-59

Floor response spectra for the north/south response of containment shell at El 231 feet due to scaled Pacoima input.

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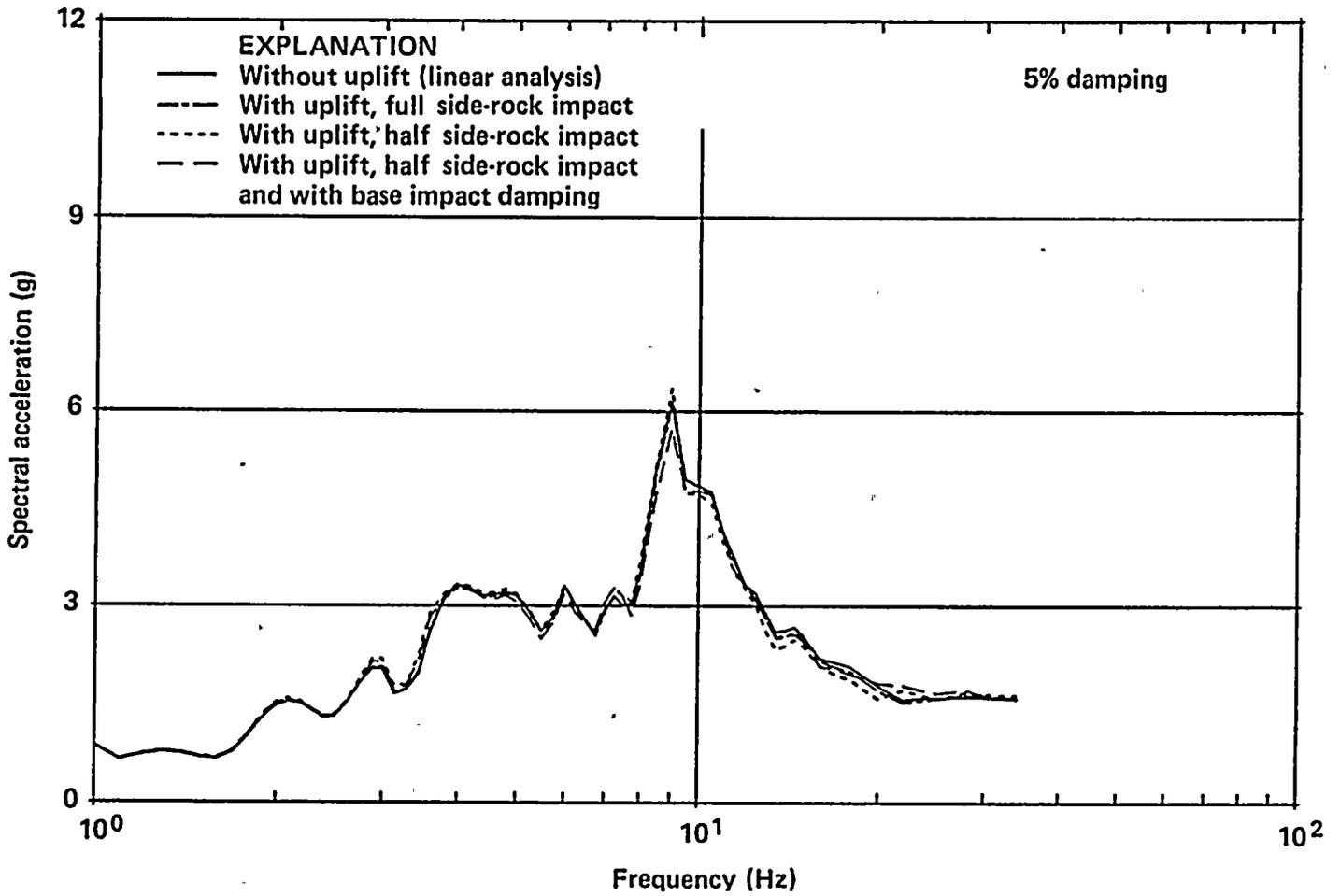


Figure 5-60

Floor response spectra for the east/west response of containment interior structure at El 138.5 feet due to scaled El Centro 4 input.



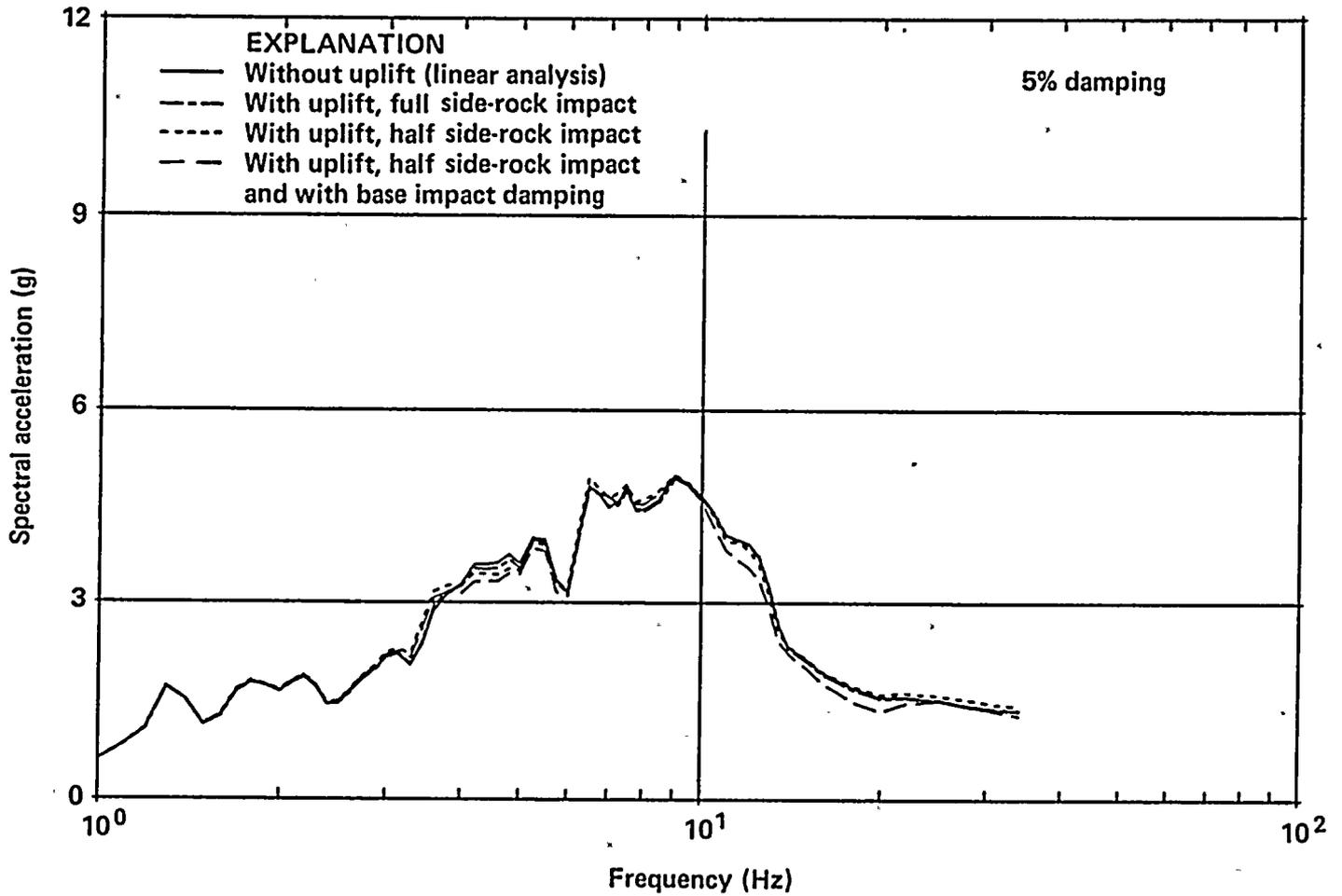


Figure 5-61

Floor response spectra for the east/west response of containment interior structure at El 138.5 feet due to scaled Tabas input.



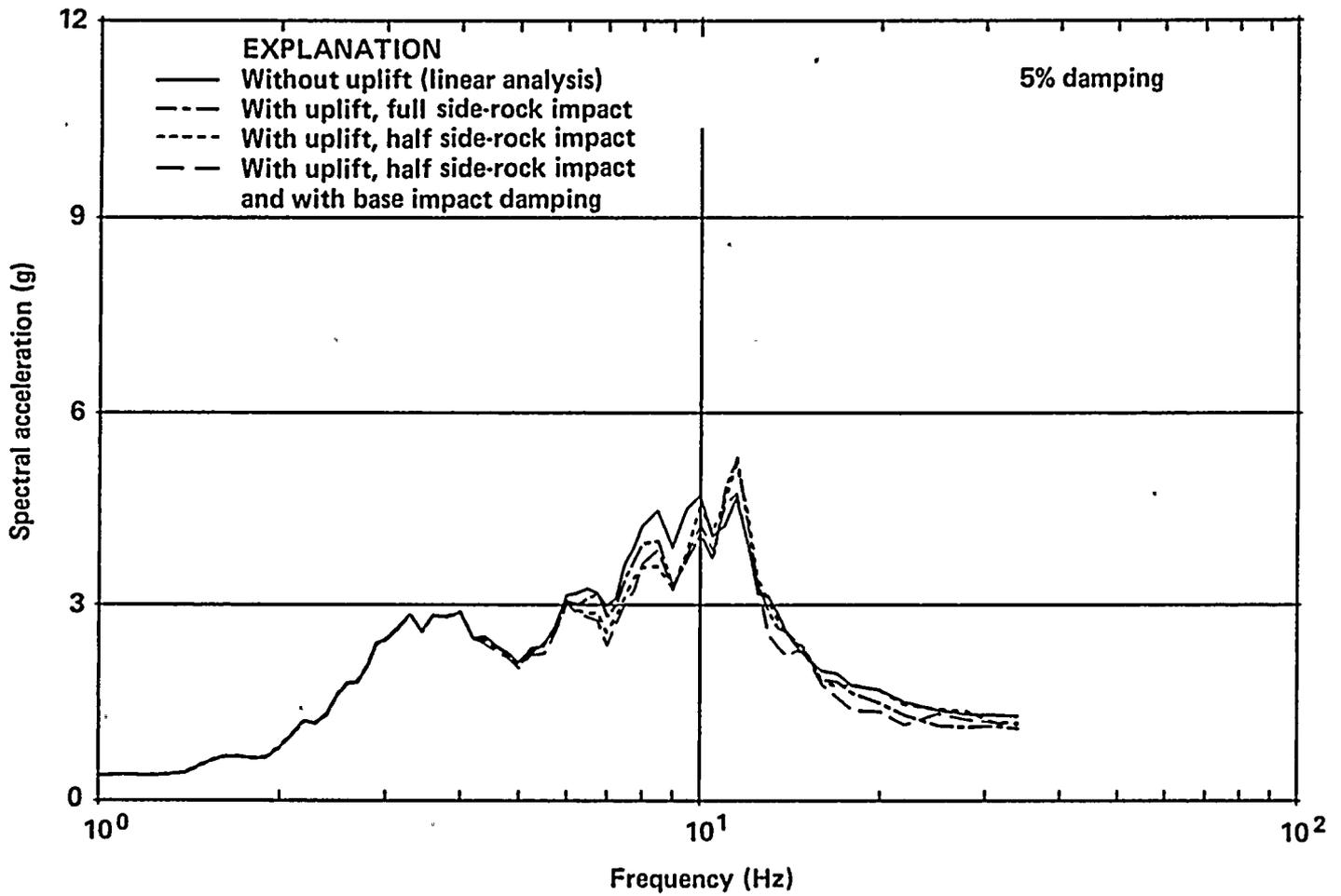


Figure 5-62

Floor response spectra for the vertical response of containment shell at El 231 feet due to scaled Pacoima input.



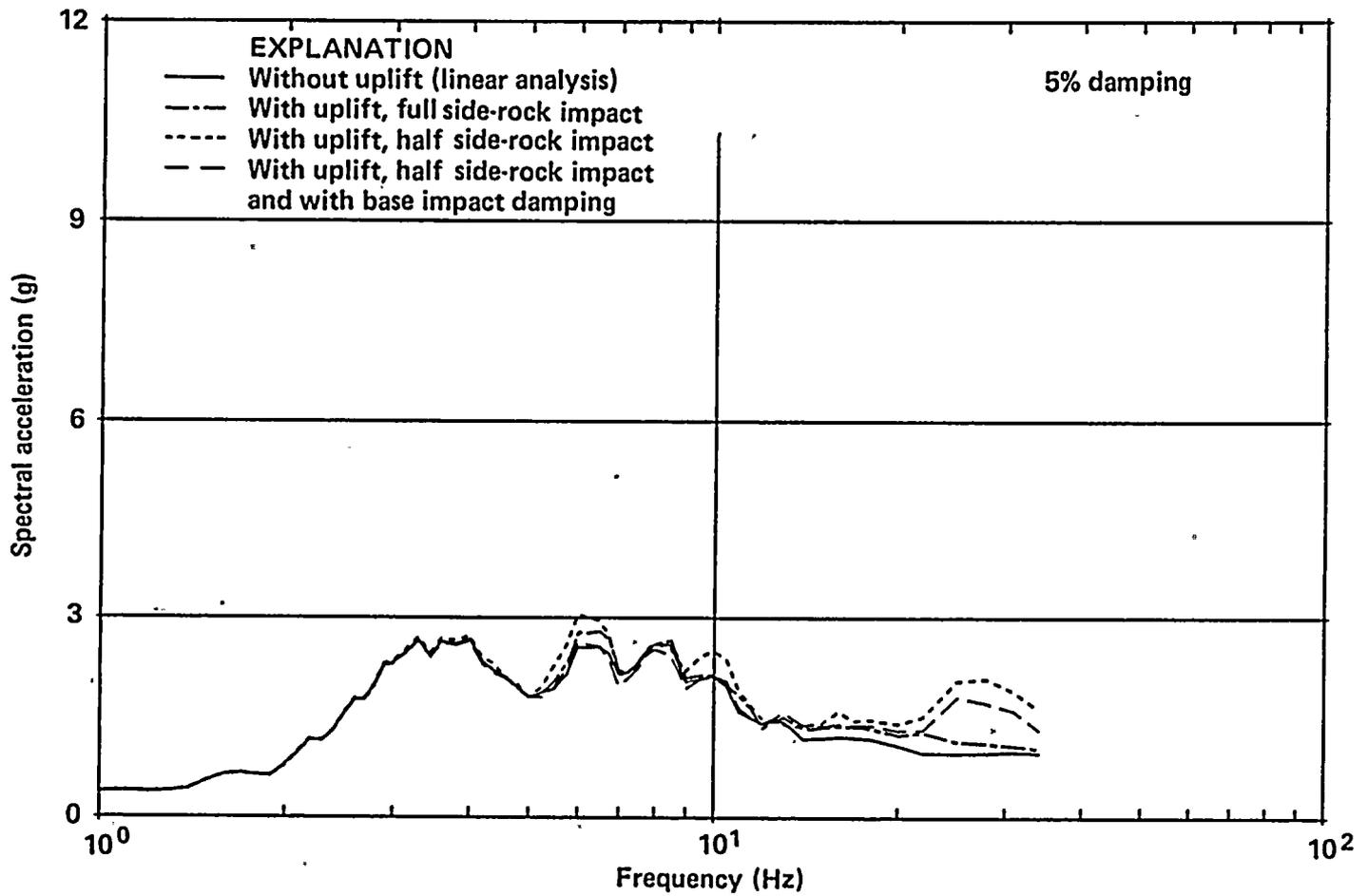


Figure 5-63

Floor response spectra for the vertical response of containment interior structure shell at El 138.5 feet due to scaled Pacoima input.



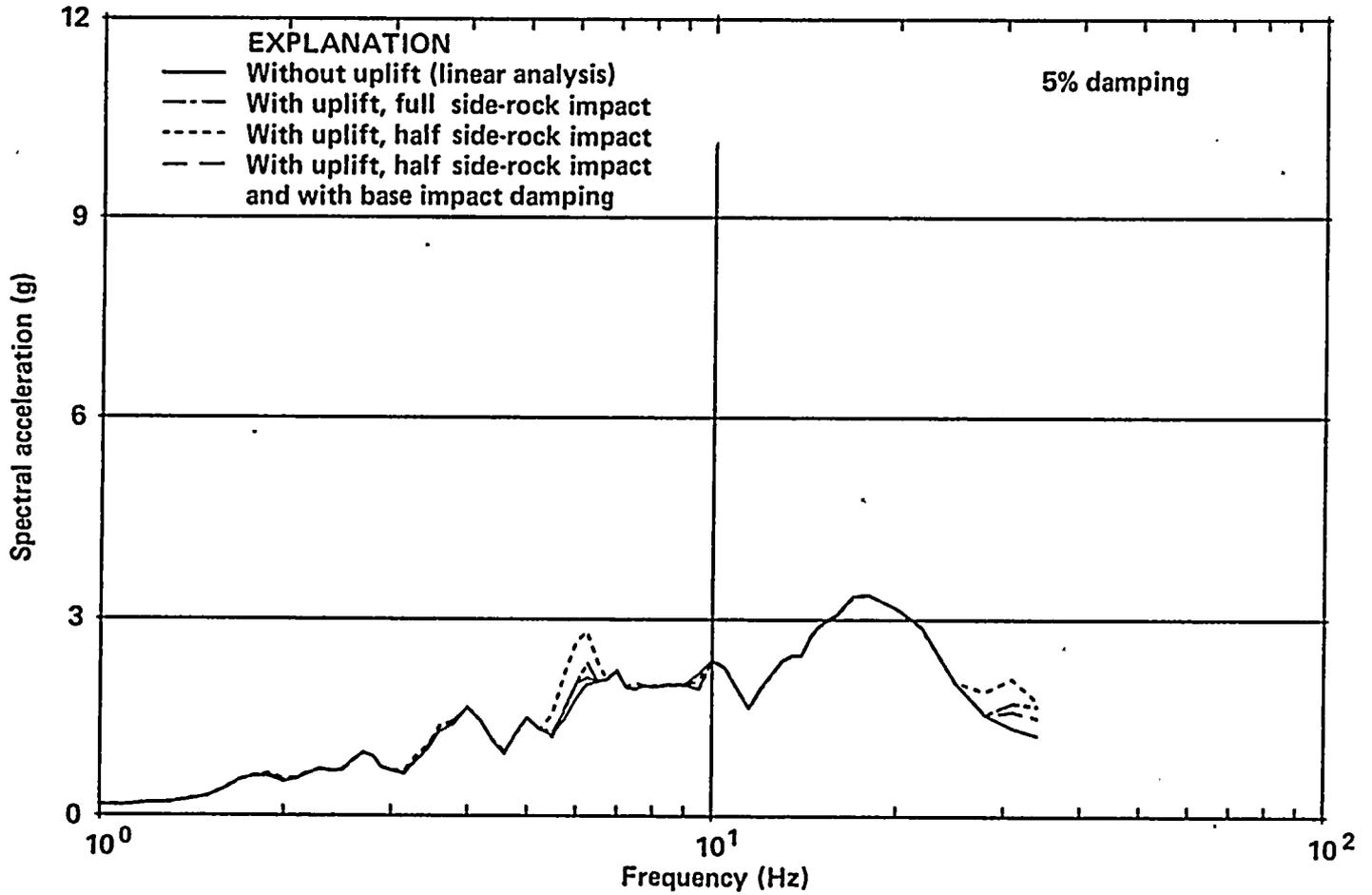


Figure 5-64

Floor response spectra for the vertical response of containment interior structure at El 231 feet due to scaled El Centro No. 4 input.

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structure-to-structure interaction, degradation of rock shear modulus, and variations of Poisson's ratio and material damping ratio of the foundation rock are relatively unimportant; however, the effects of foundation embedment and foundation basemat flexibility are relatively important for the power block structures. The important parameters, such as foundation embedment and basemat flexibility, were incorporated into the models of the power block structures for the final soil/structure interaction analyses.

Soil/Structure Interaction Response to Coherent Ground-Motion Inputs. The basic soil/structure interaction responses of the power block structures required for the Plant fragility evaluations and seismic margin assessment were generated using the three-dimensional SASSI time history response analyses with coherent ground-motion inputs; the input motions were consistent with the site-specific earthquake response spectrum and at a level slightly higher than the site-specific 84th percentile response spectrum. The results of these analyses indicated substantial soil/structure interaction effects, mainly due to inertial interaction, for the short, stiff containment interior structure and the auxiliary building. The soil/structure interaction effects due to coherent ground-motion excitation was, however, found to be relatively small for the taller and more flexible containment shell and the turbine building.

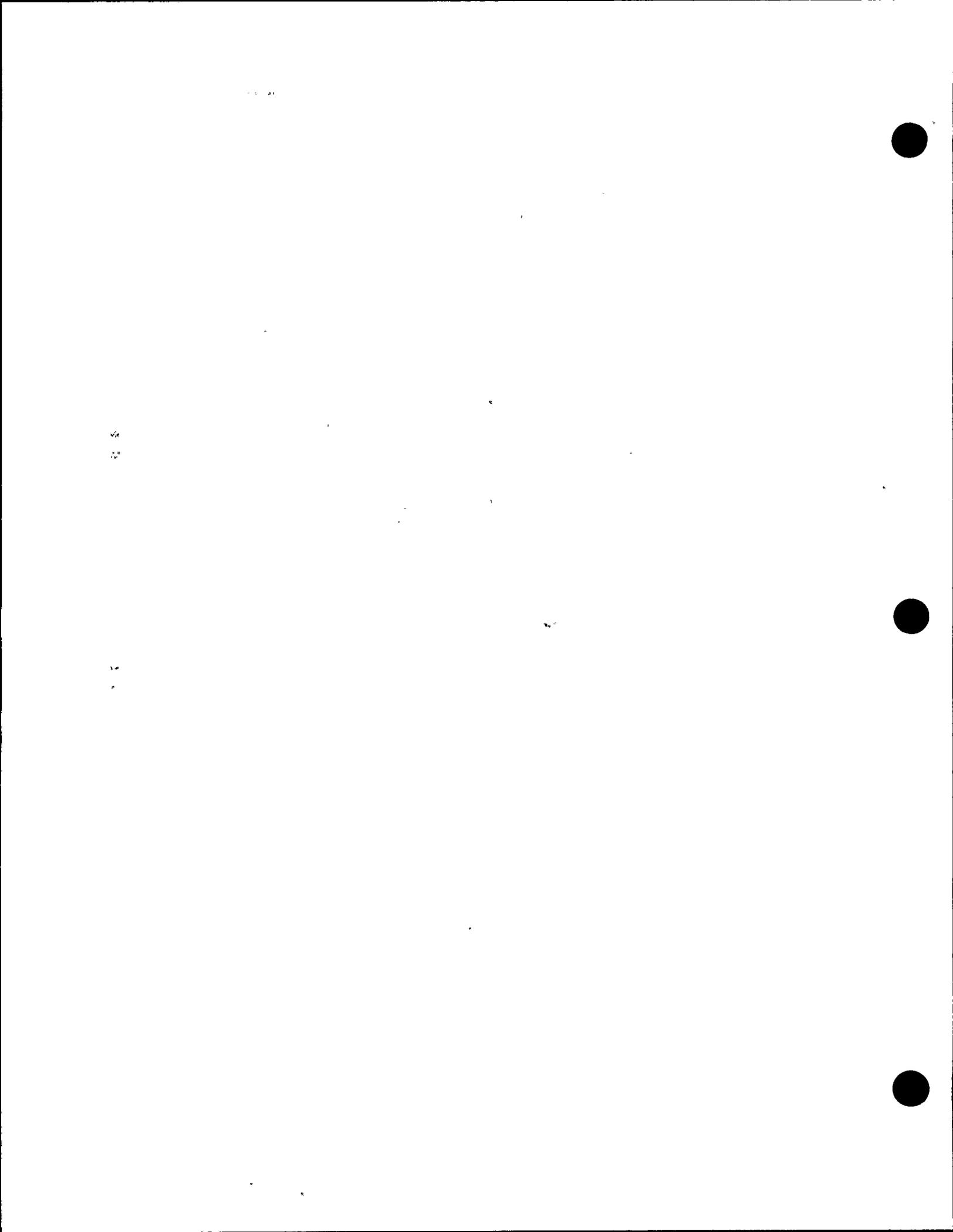
Adjustment of Soil/Structure Interaction Responses Due to Special Incoherence of Ground Motions. To account for the effect of spatial variations of ground motions on soil/structure interaction response, separate analyses, using the CLASSI analysis technique and random vibration theory, were performed incorporating site-specific spatial incoherence functions. Soil/structure interaction response adjustment factors, in the form of floor response spectral ratios applicable to specific response directions and locations, were developed to adjust the floor response spectra resulting from the coherent ground-motion analyses to give the final soil/structure interaction responses for the Plant fragility evaluations. The results of these analyses showed that spatial incoherence of ground

motions generally resulted in a reduction in the soil/structure interaction responses. However, the amount of reduction varied from point to point within the structure. These variations resulted from rocking and torsional response motions induced by spatial incoherence. At the structural base near the center region (which is not affected by rocking and torsion), in the frequency range above 10 hertz, such reductions are about 6 percent for the containment, 15 percent for the auxiliary building, and 20 percent for the turbine building.

Containment Base Uplift Effects. The effect of base uplift on the containment seismic response was investigated using a separate study that used a two-dimensional nonlinear time history base-uplift response analysis procedure. This study considered the seismic input from three sets of three-component actual earthquake ground-motions adjusted to an intensity level higher than the site-specific 84th percentile ground motion level. It also considered foundation model parameter variations including the partial loss of side rock support for embedded basemat wall and the base slapdown impact energy dissipation. The results of the study indicated that base-uplift has no significant effect on the dynamic response of the containment structure, even under the strong input motions considered in the study.

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Chapter 6

PROBABILISTIC RISK ANALYSIS

To Partially Address *Element 4 of the License Condition*

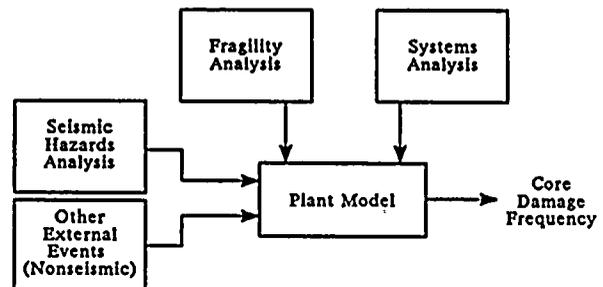
ELEMENT 4 OF THE LICENSE CONDITION

PG&E shall assess the significance of conclusions drawn from the seismic reevaluation studies in Elements 1, 2, and 3, utilizing a probabilistic risk analysis and deterministic studies, as necessary, to assure adequacy of seismic margins.

INTRODUCTION

Element 4 of the license condition calls for an assessment of the significance of conclusions drawn from the seismic studies in Elements 1, 2, and 3, utilizing a probabilistic risk analysis and deterministic studies, as necessary, to assure adequacy of seismic margins. This chapter summarizes our approach to and key findings from the probabilistic risk analysis. The approach and findings related to deterministic studies are summarized in Chapter 7.

The results presented in the earlier chapters have been integrated to develop seismic hazard curves and fragilities of Plant structures and items of equipment that are important to evaluating probabilities of seismic risk. The seismic hazards and fragilities are combined to perform a systems analysis on the Plant risk model as part of the probabilistic risk analysis.



This chapter details the processes and results of each component of the probabilistic risk assessment and how these components are combined to produce the results. The Seismic Hazards Analysis is described first, followed by the Seismic Fragility Analysis. Finally, the remaining components are described in the Probabilistic Risk Assessment.

SEISMIC HAZARDS ANALYSIS

Objectives

The objective of the seismic hazards analysis was to provide a probabilistic representation of the earthquake ground motions at the Diablo Canyon Power Plant site, in a format suitable for use in the probabilistic risk analysis. A secondary objective of the seismic hazards analysis was to calculate constant hazard spectra over the frequency range of interest to Plant structures and equipment.

Scope

The seismic hazards analysis included consideration of all seismic sources that can affect ground motions at the Diablo Canyon Power Plant site. Logic trees were developed for the Hosgri,

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Los Osos, San Luis Bay, Santa Lucia Bank, West Huasna, offshore Lompoc, Rinconada, Nacimiento, and San Andreas faults. Seismic hazards calculations were performed and it was shown that the Hosgri fault dominates the seismic hazard at the site, and that the Los Osos and San Luis Bay faults taken together add only a few percent to the total seismic hazard. Relative contributions to the total hazard from the other faults are insignificant.

The seismic hazards analysis for the Hosgri, Los Osos and San Luis Bay faults was performed in terms of response spectral acceleration, in order to provide consistency with the fragility estimates of Plant structures and equipment.

The development of ground-motion attenuation relationships applicable to the Diablo Canyon Power Plant site is described in Chapter 4. For use in the seismic hazards analysis, attenuation relationships were developed for spectral acceleration at 5 percent damping, at frequencies of vibration of 33, 25, 14, 8, 4, and 2 hertz, and for average spectral acceleration in the ranges of 3 to 8.5 hertz and 5 to 14 hertz. These relationships include factors that represent the different styles of faulting included in the logic tree representation (strike-slip, oblique-slip and thrust) based on results derived from the numerical modeling program, from the empirical ground-motion studies, and from review of available literature.

Seismic hazards analyses for the Hosgri, Los Osos, and San Luis Bay faults were performed for each of the structural frequencies mentioned above (33, 25, 14, 8, 4, and 2 hertz), and for the frequency ranges of 3 to 8.5 hertz, and 5 to 14 hertz. From these multiple hazards analyses, the hazards curves representing the frequency range of 3 to 8.5 hertz were selected for use in the probabilistic risk assessment, and are presented herein. In addition, the analyses at individual frequencies were used to construct constant hazard response spectra as presented herein.

The results of the seismic hazards analyses are presented in terms of fractile hazard curves, which show at each spectral acceleration amplitude the distribution of hazard from the entire family of

hazard curves, and in the form of aggregate hazard curves, which reduce the large number in the total family of hazard curves to a limited number of curves (about 8 to 12) for input into the probabilistic risk assessment.

Method of Analysis

The procedures used to calculate seismic hazard for the case when faults can be identified as the potential sources of earthquakes are documented in detail (for example, Der Kiureghian and Ang, 1977; McGuire, 1978). The steps involved in a seismic hazards analysis are illustrated in Figure 6-1. The calculation of seismic hazard is made with the following equation:

$$\nu(a^*) = \sum_i \nu_i \iint G_{A|m,d}(a^*) f_{M(i)}(m) f_{D(i)}(d|m) dm dd \quad (6-1)$$

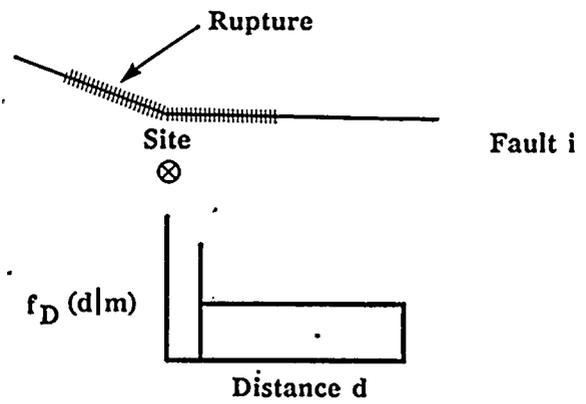
in which the summation is performed over all faults i that affect the site, ν_i is the mean annual rate of damaging earthquakes for fault i . The probability-density function of magnitude and distance for fault i are $f_{M(i)}(m)$ and $f_{D(i)}(d|m)$. (The distance distribution depends on magnitude because the rupture length is explicitly taken into account.) The ground-motion or attenuation model allows calculation of, for a given magnitude m and distance r , the probability $G_{A|m,d}(a^*)$ that a ground motion amplitude a^* is exceeded. The hazard defined in equation 6-1 represents the annual rate ν at which ground-motion amplitude a^* is exceeded at the site; because it is much smaller than unity, this rate can be interpreted as the probability that ground-motion amplitude a^* is exceeded in any one year. As is common in probabilistic risk assessments, we refer to this rate as an "annual frequency of exceedance." The calculation of equation (6-1) is performed for several values of a^* and the resulting values can be plotted as a "hazard curve," illustrated on Figure 6-1(D).

This is a standard formulation of seismic hazard; the application takes proper account of randomness in the following factors:

- Fault geometry in three dimensions,
- All possible locations of the rupture surface, both horizontally and vertically,

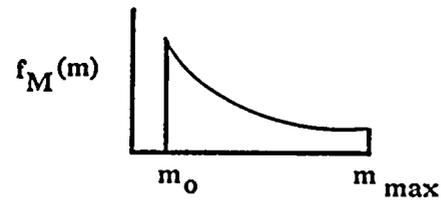


(A) Seismic source i
 (earthquake locations in space lead
 to a distribution of epicentral
 distances $f_D(d|m)$)



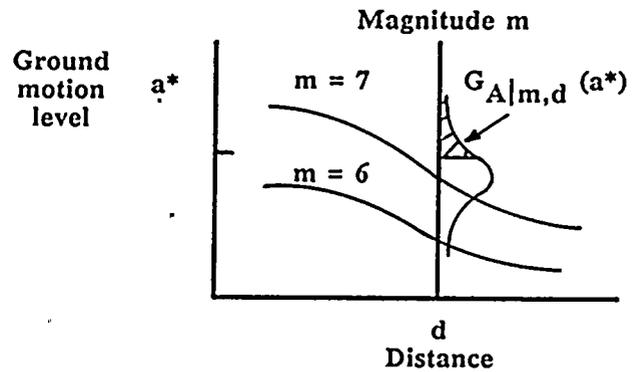
(B) Magnitude distribution and
 rate of occurrence for source i :

$$f_M(m), \nu_i$$



(C) Ground motion estimation:

$$G_{A|m,d}(a^*)$$



(D) Probability analysis:

$$P[A > a^* \text{ in time } t] / t \simeq \sum_i \nu_i \iint G_{A|m,d}(a^*) f_{M(i)}(m) f_{D(i)}(d|m) dm dd = \nu(a^*)$$

$P[A > a^* \text{ in } t]/t$
 (log scale)

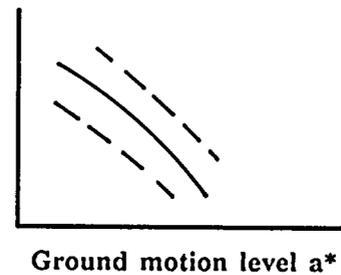


Figure 6-1
 Steps involved in seismic hazard analysis.

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- Sizes (magnitudes of earthquakes that might occur on the fault),
- Size of rupture as a function of earthquake magnitude,
- Closest distance of the site to the rupture, as required by the ground-motion estimation equations,
- Ground motions at the site as a function of the earthquake magnitude and its location relative to the site, and
- Possible amplification or reduction of the ground motions as a result of the sense of fault slip and geometry of the fault.

Thus, for a given fault geometry and style of faulting, the calculation integrates over all possible magnitudes of earthquakes, generates a rupture surface for each magnitude, and integrates over all possible locations of the rupture surface on the fault plane. For each possible rupture location, the procedure calculates the distance to the Plant site; estimates the distribution of site ground motions, accounting for any amplification or reduction caused by faulting style and geometry; and integrates over randomness in ground motions, given the earthquake magnitude and location with respect to the site. The result is a calculation of annual rates (probabilities) that specified levels of ground shaking will be exceeded. The procedure accounts for randomness in the models used to represent earthquake occurrences: earthquake magnitudes, rupture locations, times of occurrence, and ground-motion levels given the occurrence of the event.

Uncertainties are distinct from randomness in the sense that they involve parameters and models that are chosen to describe earthquake occurrences; in concept, uncertainties can be reduced as more data are collected and physical processes are better understood. Uncertainties are treated by performing separate hazard calculations (equation 6-1) for different sets of models and parameter values. Hence, uncertainty in the input results in uncertainty in the hazard curve, which may be represented by a family of

hazard curves or by fractiles of hazard at all ground-motion amplitudes. The uncertainties in input were represented using the logic tree format, an example of which is shown on Figure 6-2. Each element in the logic tree consists of a set of nodes representing an uncertain state of nature, and each branch represents discrete possible values for that state. Probabilities were assigned to each branch using subjective assessments, and the end branch probabilities were calculated as the product of all the intermediate branch probabilities. A single seismic hazard analysis was performed for each end branch resulting in a single hazard curve for the set of assumptions that led to that end branch. The eight hazard curves for the logic tree on Figure 6-2 are illustrated at the right side of the figure. The uncertainty in hazard is represented by this family of hazard curves, the size of the family being equal to the number of end branches.

Typically, large numbers (several thousand) of hazard curves result from practical applications of the logic-tree concept. This large number is reduced to summary curves, both for examination and analysis and for input to other Plant evaluations. One simple representation of the uncertainty in hazard is gained through fractile hazard curves, which show, at each ground-motion amplitude, the distribution of hazard from the family. A second representation is through aggregate hazard curves, which reduce the large number in the total family of hazard curves to a limited number of curves (about 8 to 12) for input into a probabilistic risk assessment of the Plant systems.

The logic tree approach has several important advantages over others that might be pursued. First, the complete enumeration of all possible states of nature ensures that all hypotheses have been accounted for properly, with appropriate weights assigned to each. As a result of the efficient algorithms used to calculate seismic hazard, no compromises need be made to keep the number of combinations small or to reduce the number of hypotheses that can be considered. The procedure allows consideration of all suggestions made about tectonics, fault behavior, seismicity, and ground-motion characteristics,



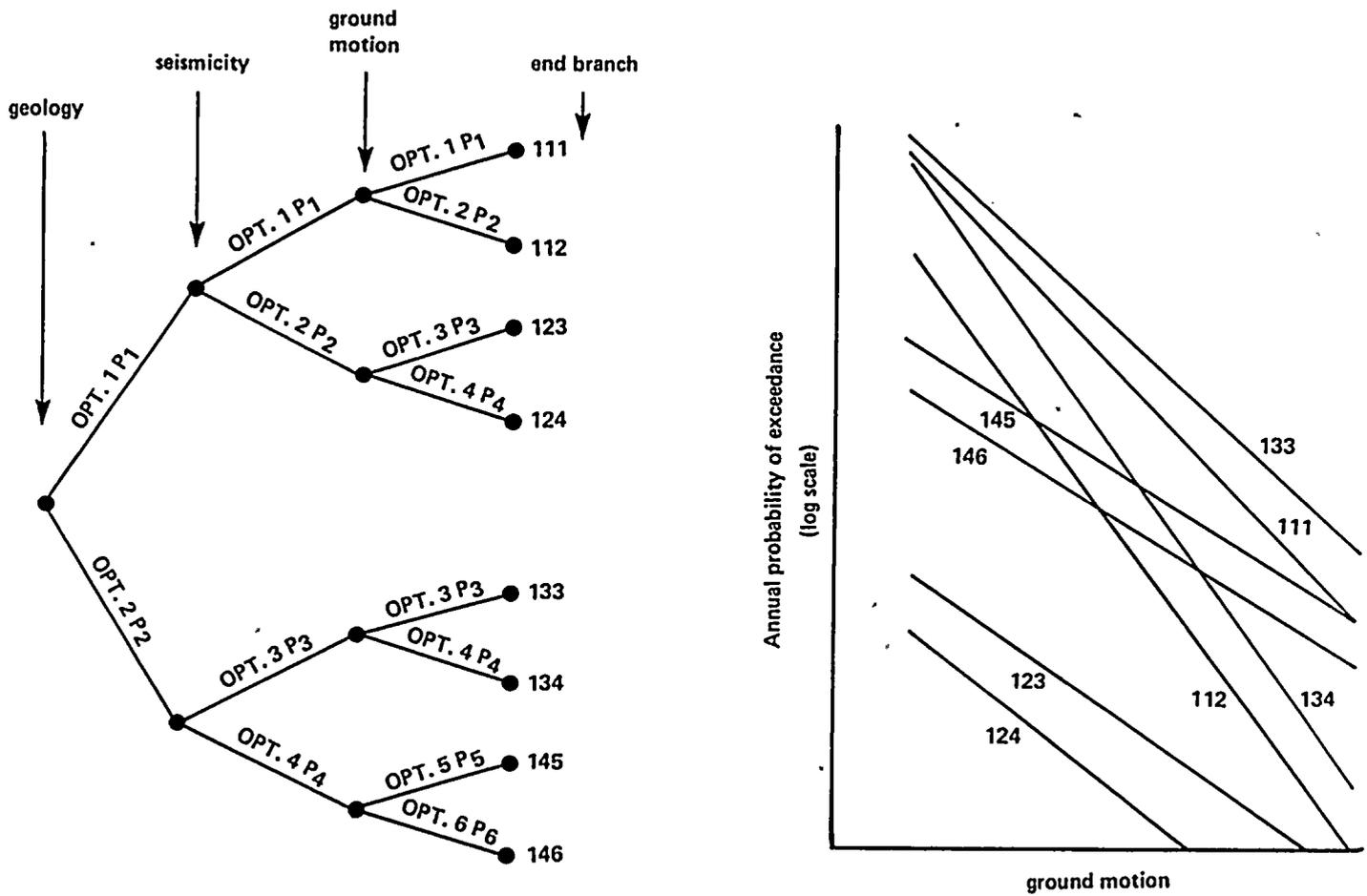


Figure 6-2
 Example of logic tree and resulting family of hazard curves.



however unlikely, and puts them in the proper context along with all other interpretations.

Second, the procedure provides a logical means of identifying those elements that contribute importantly to uncertainty in seismic hazard and those that do not. This allows priorities for investigations on appropriate input models and parameters to be established on a logical basis.

Third, the entire procedure is documentable and trackable, so that decisions (for example, which faults to investigate further can be justified and defended.

The analyses considered here calculated hazard from each fault separately. Although several faults are currently active in south-central coastal California, the Hosgri fault dominates the seismic hazard at the Diablo Canyon site (as will be demonstrated below), so that consideration of multiple faults acting simultaneously is not required. The total hazard can be accurately calculated by considering each fault characterization separately, and combining hazards to evaluate the total hazard.

The logic tree used to represent input for the Hosgri, Los Osos, and San Luis Bay faults is shown on Figure 6-3.

A total of 20,700 end branches of the logic tree resulted from the input specification. The resulting family of hazard curves is too numerous to interpret, or even to illustrate on a single plot. As described above, one summary of this family can be constructed by determining, at each ground motion amplitude, the distribution of annual frequency of exceedance, and identifying the frequencies that are associated with certain preselected fractiles. For example, at each ground-motion amplitude the *median* frequency of exceedance can be determined, meaning that curves below that frequency have 50 percent of the total weight. Constructing a plot of frequency of exceedance versus ground-motion, and drawing these medians, gives an indication of the median seismic hazard for all ground motions. This procedure can be applied to other fractiles as well.

For probabilistic risk analyses, it is necessary to construct a sophisticated representation of the family of hazard curves. The reason is that probabilistic risk assessment procedures treat uncertainty by conditioning on alternative interpretations (in this case seismic hazard curves), convolving these with alternative representations of Plant response, and calculating the resulting uncertainty in Plant state frequency. Therefore, if several hazard curves represent the uncertainty in geological and seismological interpretations, and these curves have different slopes, the character of the curves (slopes) must be maintained for probabilistic risk assessment input. Fractile hazard curves do not transmit this information.

To derive hazard results appropriate for probabilistic risk assessment, an aggregation process is employed that reduces the large number of hazard curves (20,700) to a few (typically 8 to 12), using a procedure that optimally determines how to combine pairs of curves sequentially so that the character of the original curves will be maintained, and the set of aggregate curves will represent as much of the original uncertainty in hazard as possible for each ground-motion amplitude. The procedure uses the following steps:

- 1) A contribution to variance analysis is used to select nodes on the logic tree that do not contribute significantly to uncertainty in hazard. The logic tree is then restructured to reduce the number of end branches by combining hazard results for end branches that are identical except for branches at nodes that contribute little to the uncertainty in hazard. By this mechanism the family of hazard curves is reduced to several hundred in number. These hazard curves typically represent greater than 96 percent of the total uncertainty in hazard.
- 2) The hazard curves are characterized by the frequency of exceedance at three ground-motion amplitudes, chosen as those most critical to the determination of Plant response and system state. The total variance in frequency of exceedance at these three amplitudes is calculated.



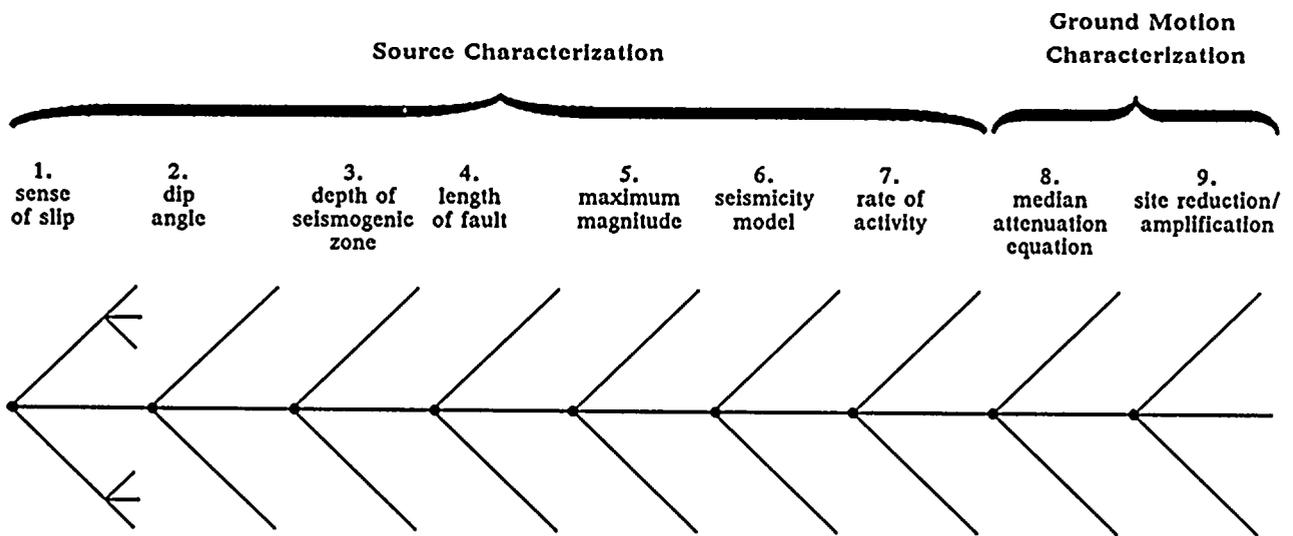


Figure 6-3
Elements in logic tree used for Hosgri, Los Osos, and San Luis Bay faults.

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- 3) A small number of possible aggregate curves (for example, 64) is estimated by dividing the ranges of frequencies of exceedance into intervals and constructing a first set of aggregates at the centers of these intervals.
- 4) Each of the hazard curves is assigned to a tentative aggregate curve, based on its proximity in frequency-of-exceedance for the three amplitudes.
- 5) The tentative aggregate curves are recomputed as the conditional mean or the assigned curves.
- 6) Steps 4 and 5 are repeated, because step 5 may change the assignments based on proximity, until the tentative aggregate curves are stable (that is, until there are no changes in assignments). A weight for each tentative aggregate curve is calculated as the sum of weights of the assigned curves.
- 7) All possible pairs of tentative aggregate curves are examined as candidates for combination; the pair that, when combined, will result in the minimum reduction in variance is selected and combined by computing the weighted average frequency of exceedance for all three amplitudes. The combined curve is assigned a weight equal to the sum of the weights of the two curves used to calculate it.
- 8) Steps 4 through 7 are repeated to reduce sequentially the number of tentative aggregate curves. The process ends when the desired number of aggregate curves is reached.
- 9) The curve assignments are used to calculate aggregate hazard curves for all ground-motion amplitudes; the weight given to each aggregate is the sum of the weights of the assigned curves.

There are no general solution techniques for aggregating a discrete, multidimensional distribution, but the above algorithm has been tested for a number of seismic hazard problems and works well. It is efficient for up to several hundred initial hazard curves (which is the reason

for Step 1). Typically, 8 to 12 aggregate curves can be constructed with this algorithm that replicate about 90 percent of the total variance of the original data set, for all ground-motion amplitudes (that is, the standard deviation of frequency of exceedance is 95 percent of the original). Figure 6-4 illustrates how this procedure would work for the case of reducing nine hazard curves. Three aggregate curves adequately represent the amplitude and slope of the original nine curves.

Input Data

As illustrated schematically on Figure 6-1, input data for the seismic hazards analysis consisted of seismic source characteristics (location and recurrence) and ground-motion attenuation relationships.

SEISMIC SOURCE CHARACTERISTICS

The logic trees for the Hosgri, Los Osos, and San Luis Bay faults are given in Chapter 3. The range of parameters and associated probabilities provide a description of the uncertainties associated with the characteristics of each earthquake source. Included in the analysis of the logic tree are calculations of the distribution of maximum magnitudes and recurrence relationships for each source. In addition, the calculations of seismic hazard include the ranges of fault geometries given in the logic trees in defining source locations.

The input data for the Hosgri, Los Osos, and San Luis Bay faults are summarized as follows:

Hosgri Fault. Geologic data were provided for the first four nodes of the Hosgri fault logic tree (Figure 6-3). These are summarized as follows:

<u>Style of Faulting</u>	<u>Dip (Degrees)</u>	<u>Depth (km)</u>	<u>Fault Length (km)</u>
Strike-slip	90, 70	9, 12, 15	410
Oblique	90, 60, 45	9, 12, 15	110, 250, 410
Thrust	60, 30, 15	9, 12, 15	110, 160, 250



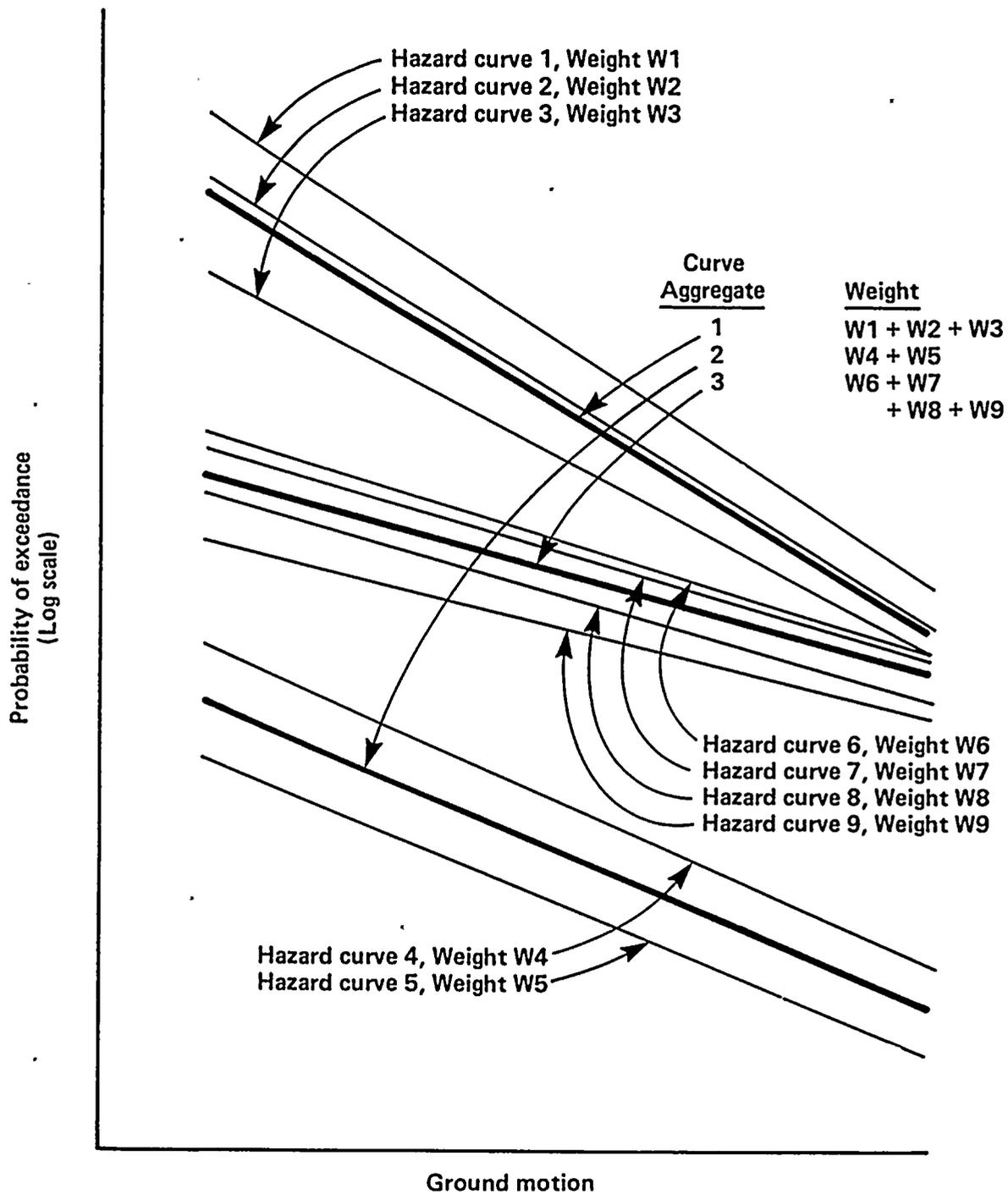


Figure 6-4
 Example of aggregation of nine hazard curves to obtain three curves.

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Weights assigned to the style of faulting interpretations are as follows: strike-slip = 0.65; oblique = 0.30; thrust = 0.05. Weights assigned to the subsequent interpretations are conditional on style of faulting.

Seismological input constituted the next three sets of nodes on the logic tree of Figure 6-3. The assessments of maximum magnitudes (the fifth element of the logic tree) and their probabilities are conditional on previous branches; values chosen for maximum magnitude range from 6.5 to 7.75 M_w . Two seismicity models (logic tree element 6) were used, exponential and characteristic; these were weighted 0.4 and 0.6, respectively, for all faults. The rate of seismic activity (element 7) was discretized and estimated from interpretations of fault slip rate; the values and their probabilities are conditional on previous branches of the logic tree.

Los Osos Fault. The geologic input for the Los Osos fault is summarized as follows:

<u>Style of Faulting</u>	<u>Dip (Degrees)</u>	<u>Depth (km)</u>	<u>Fault Length (km)</u>
Oblique	75, 45	9, 12, 15	16, 24, 36, 44, 49, 57
Thrust	60, 30	9, 12, 15	16, 24, 36, 44, 49, 57

Weights assigned to the style of faulting interpretations are as follows: oblique = 0.1; thrust = 0.9. Weights assigned to the subsequent interpretations are conditional on the style of faulting.

San Luis Bay Fault. The geologic input for the San Luis Bay fault is summarized as follows:

<u>Style of Faulting</u>	<u>Dip (Degrees)</u>	<u>Depth (km)</u>	<u>Fault Length (km)</u>
Thrust	70, 40	9, 12, 15	6, 12, 19

In this case a weight of unity was assigned to the thrust interpretation.

Other Faults. Other faults considered in the hazard analysis are the Santa Lucia Bank fault,

the Rinconada fault, the Nacimiento fault, the offshore Lompoc fault, and the West Huasna fault. Input for these faults was specified using the logic tree format. The hazard from these faults is several orders of magnitude lower than for the Hosgri, as will be documented below. Thus, the total seismic hazard at the Plant can accurately be calculated by considering only the Hosgri, the Los Osos, and the San Luis Bay faults.

GROUND-MOTION CHARACTERISTICS

Ground-motion input constitutes the last two elements of the logic tree. Three median ground-motion attenuation relationships (element 8) were used for all faults. The attenuation equations for the eight frequencies and frequency bands investigated are listed in Table 6-1. Note that for use in probabilistic seismic hazard analyses, the nonlinear magnitude scaling of spectral ordinates (presented in Chapter 4) was simplified into a bilinear form to provide linear magnitude scaling within two magnitude ranges, $M_w < 6.5$ and $M_w \geq 6.5$. The coefficients for this bilinear form provide essentially identical spectral values in the magnitude range M_w 5.5 to 7.5, which is the range of interest to the seismic hazard analysis.

The coefficients given in Table 6-1 represent the average amplitudes for two horizontal components. The variability in amplitude was expressed as the standard deviation of \ln (spectral acceleration) = 0.36 for magnitude greater than or equal to 6.5, and $1.27 - 0.14M$ for magnitude less than 6.5. This is the variability specified for the frequency bands 3 to 8.5 hertz and 5 to 14 hertz, and does not include frequency-to-frequency variations (these variations have been averaged by calculating the average spectral acceleration for a frequency band). Because the amplitudes desired for the probabilistic risk assessment are spectral accelerations (average of two horizontal components, without peak-to-valley variability from frequency to frequency), the above variability was used for all frequencies.

The site factor (element 9) represents the portion of empirical ground-motion variability that can be attributed to variability in site characteristics. As



Table 6-1

**ATTENUATION EQUATIONS* FOR SPECTRAL ACCELERATION (5% DAMPING)
FOR THRUST FAULTING****

$$\ln(S_a [f]) = c_0 + c_1M + c_2 \ln[D + c_3 \exp(c_4M)]$$

$c_2 = -2.1$ for all frequencies and magnitudes

$c_3 = 3.656$ and $c_4 = 0.25$ for $M < 6.5$

$c_3 = 0.616$ and $c_4 = 0.524$ for $M > 6.5$

<u>f(Hz)</u>	<u>c₀(for M ≥ 6.5)</u>	<u>c₀(for M < 6.5)</u>	<u>c₁(for M ≥ 6.5)</u>	<u>c₁(for M < 6.5)</u>
33	-1.092	-0.442	1.1	1.0
25	-0.943	-0.293	1.1	1.0
14	-0.280	+0.695	1.05	0.90
8	-0.327	+0.323	1.1	1.0
4	-0.872	-0.840	1.184	1.179
2	-1.902	-2.624	1.286	1.397
3-8.5	-0.537	-0.154	1.136	1.077
5-14	-0.374	+0.276	1.1	1.0

* Coefficients above represent the best-estimate equation, which is assigned a weight of 0.5; alternative equations, which were assigned weights of 0.25 each, provide acceleration values 1.15 times the above values, and 1/1.15 times the above values.

** Equations for strike-slip faulting are obtained by multiplying the reverse thrust amplitudes by 0.833. Equations for oblique faulting are obtained by multiplying the reverse thrust amplitudes by 0.913.

Note: M is moment magnitude, D is closest distance to rupture surface, in kilometers.

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such, this variability is treated as an uncertainty for any specific site. The variance representing total ground-motion variability discussed above (represented by the variance of \ln [spectral acceleration]) was divided into two parts:

$$\sigma_{\text{tot}}^2 = \sigma_r^2 + \sigma_{\text{site}}^2 \quad (6-2)$$

where σ_{tot}^2 is the total variance of ground-motion amplitude (that is, of response spectral amplitude at a given frequency); σ_r^2 is variance attributed to randomness and σ_{site}^2 is variance attributed to uncertainty in site conditions. As discussed above, σ_{tot} was specified as 0.36 for magnitude greater than 6.5. We divide the total variance equally between σ_r and σ_{site} , so that both are equal to 0.255. As σ_{site} is treated as uncertainty, we represent it with element 10 of the logic tree (Figure 6-3) and use five discrete factors of 0.682, 0.869, 1.00, 1.15, and 1.47, weighted equally, to represent this uncertainty in site response. The total variability in ground motions was truncated at three standard deviations, but this truncation has almost no influence on the final hazard results.

Results of Analysis

Results of the hazard calculations are shown for the Hosgri fault on Figure 6-5 in the form of fractile hazard curves for spectral acceleration in the frequency range 3 to 8.5 hertz (5 percent damping). These fractile curves illustrate the range of uncertainty in hazard that results from uncertainty in the geologic, seismologic, and ground-motion input.

Figure 6-6 compares the mean hazard from the Hosgri fault to mean hazards from the Los Osos fault and the San Luis Bay faults (for spectral acceleration in the same frequency range of 3 to 8.5 hertz), and to approximate mean hazards from the Nacimiento, West Huasna, Rinconada, offshore Lompoc, and Santa Lucia Bank faults. The approximate mean curves were constructed by determining the ratios of hazards from these faults to that of the Hosgri under the same ground-motion assumptions, and applying these

ratios to the current mean Hosgri hazard curve that uses the most current ground-motion assumptions. This approximation is justified in light of the low hazards that these curves indicate, compared to the Hosgri fault. It is clear that the Hosgri fault zone is the dominant contributor to the seismic hazard, with the Los Osos and San Luis Bay faults contributing a minor fraction of this hazard (about 3 to 5 percent in aggregate) and the remaining faults contributing hazards that are several orders of magnitude lower.

To calculate aggregate hazard curves for input to probabilistic assessment, the family of 20,700 Hosgri hazard curves based on spectral acceleration for 3 to 8.5 hertz were aggregated to eight curves, using the method presented in the previous section. For this aggregation process, hazards at 1.5 g, 2.0 g, and 3.0 g spectral acceleration were used, as these levels of ground motions contribute most to Plant seismic risk studied in probabilistic risk assessments and therefore are the most important to represent accurately. To these eight aggregate curves were added the mean hazards from the Los Osos and San Luis Bay faults. This procedure preserves the mean total hazard from all three faults, and incurs almost no loss of accuracy in representing the uncertainty in hazard, because of the low contribution of these faults relative to the Hosgri. Figure 6-7 shows the resulting eight aggregate hazard curves. The seismic hazard is highly skewed, with a high probability at relatively low hazards and a small probability of relatively high hazards. This characteristic is properly portrayed by the aggregate hazard curves. As discussed in the previous section, the amplitudes presented on Figure 6-7 are spectral accelerations for the average of two components, with frequency-to-frequency (peak and valley) variation removed.

A second set of hazard curves is presented on Figure 6-8 as fractile curves of total hazard. These curves were obtained in a manner similar to the aggregate curves; that is, fractile curves were calculated for the Hosgri fault, and mean hazards were added to represent the Los Osos and San Luis Bay faults. Thus, these fractile curves are approximate for the lower fractiles; they are very accurate for fractiles above the median.

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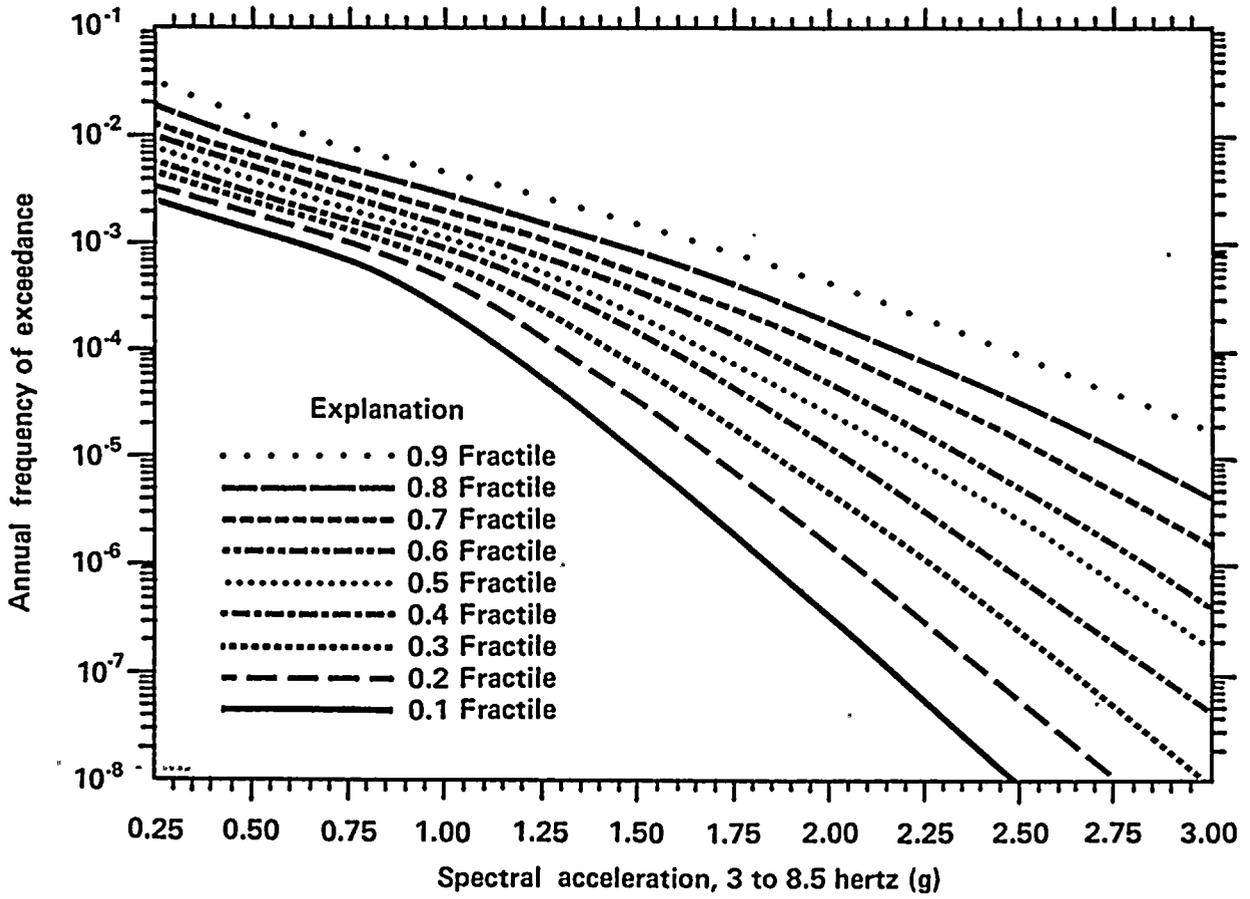


Figure 6-5
Fractile seismic hazard curves for Hosgri fault zone.

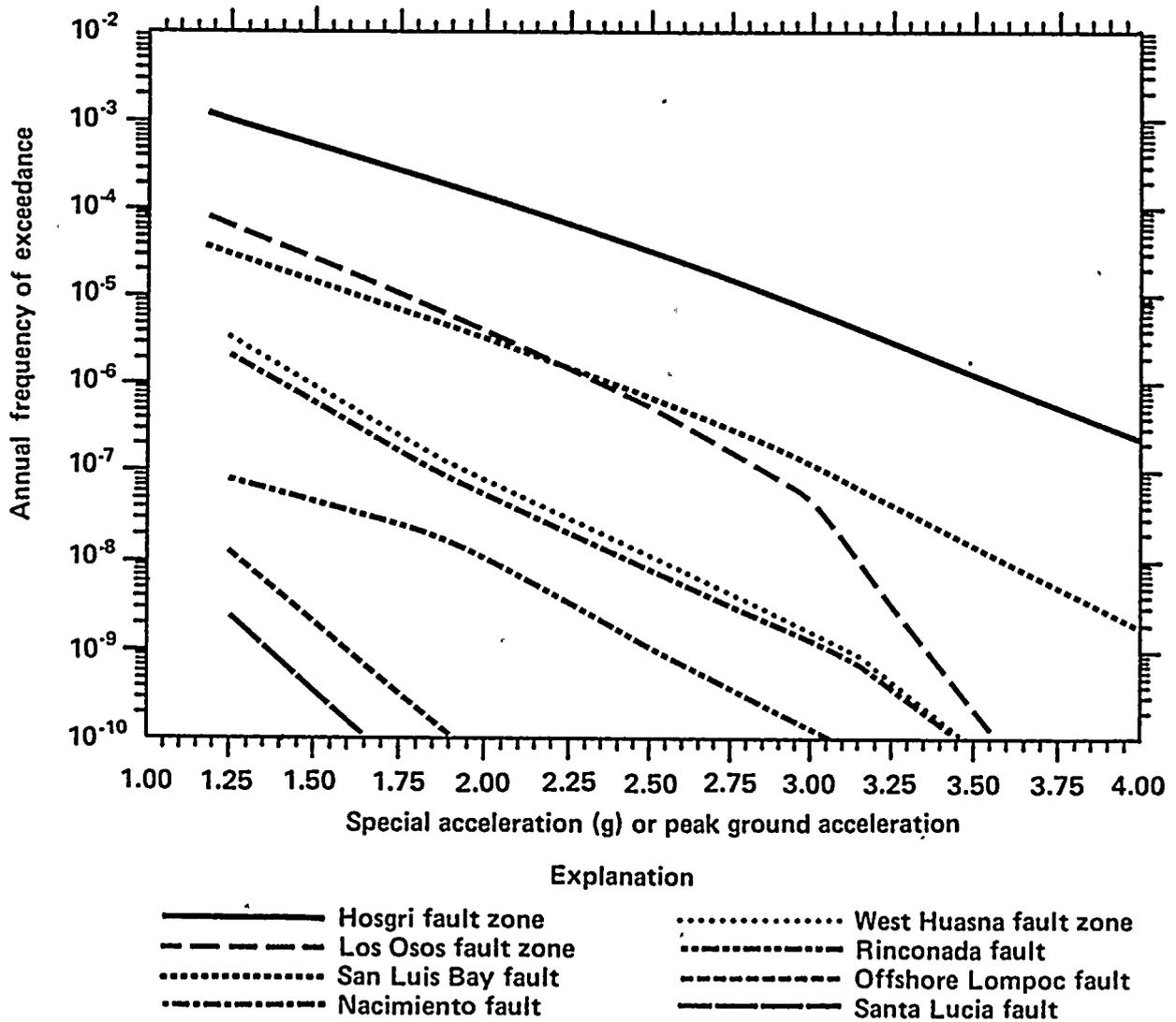


Figure 6-6

Comparison of mean hazard from Hosgri fault zone to mean hazards from Los Osos and San Luis Bay faults, and to approximate mean hazards from other faults.

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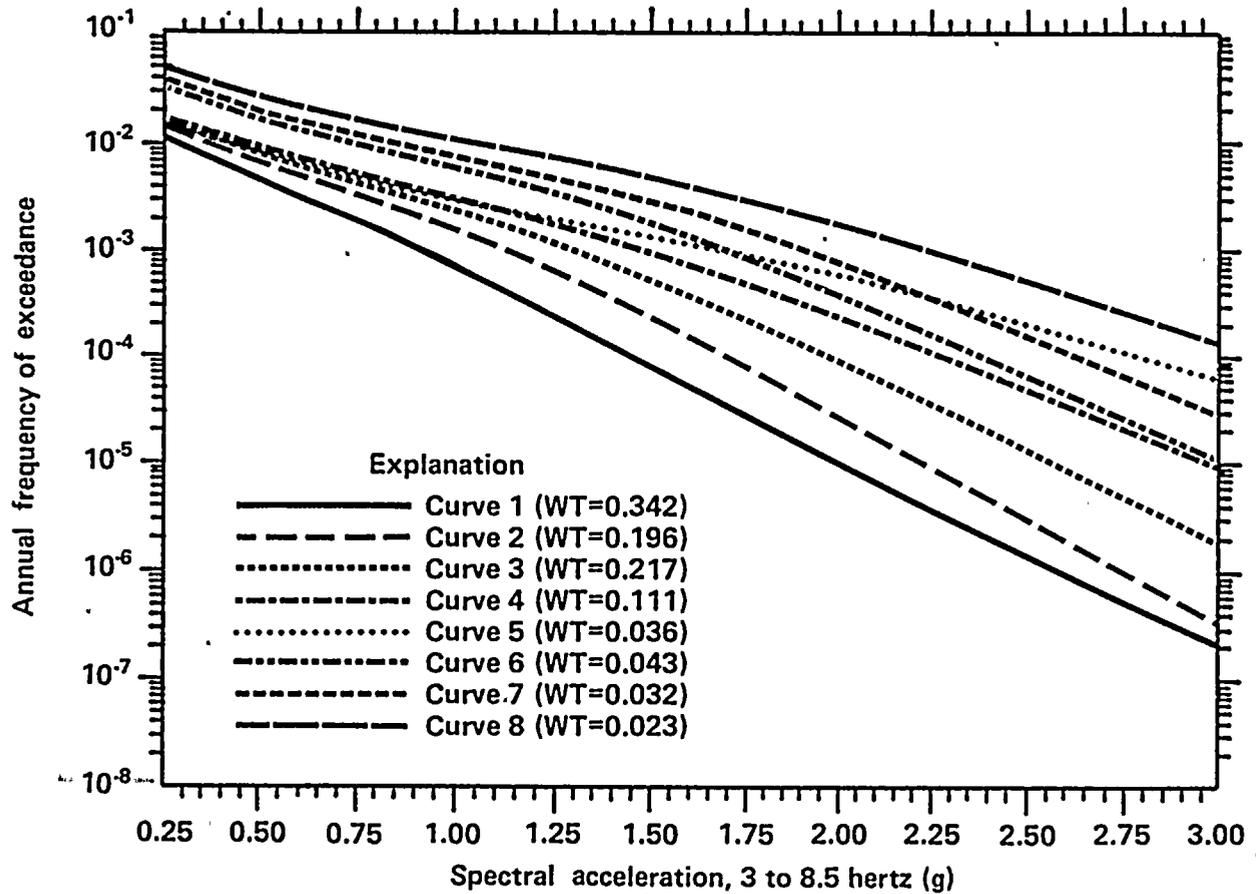


Figure 6-7
Total aggregate hazard curves.

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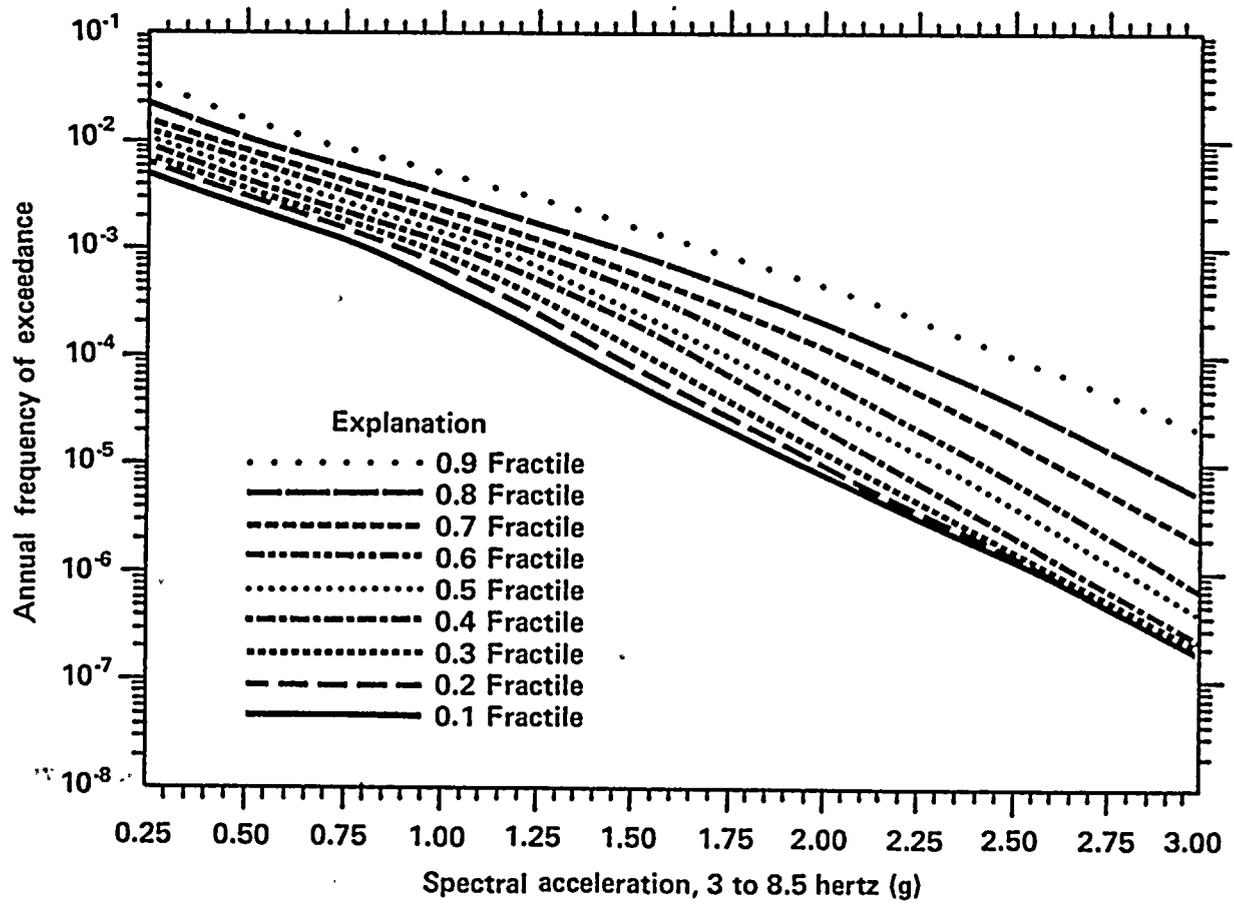


Figure 6-8
Curves representing approximate fractiles of total hazard.

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The final set of results was obtained from the hazard calculations at all six frequencies shown in Table 6-1. For each frequency, total fracture hazard results were prepared (as illustrated on Figure 6-8 for the frequency range 3 to 8.5 hertz) and spectra were calculated for 10^{-3} , 10^{-4} , and 10^{-5} annual frequencies of exceedance, for median results. These spectra are shown on Figure 6-9.

SEISMIC FRAGILITY ANALYSIS

Objectives

As part of the probabilistic risk assessment, a seismic fragility evaluation of key safety related structures and equipment was conducted. The seismic fragility evaluation consisted of a probabilistic definition of seismic capacity which, together with a probabilistic definition of the seismic hazard and an event-tree and fault-tree characterization of the operating system, provided the necessary data for the probabilistic risk assessment. The objective of the fragility analysis was to carefully evaluate each of the structures and components which are included in the risk model to define those failure modes that have the lowest seismic capacities and which, therefore, may constitute the most important or dominant contributors to Plant seismic risk.

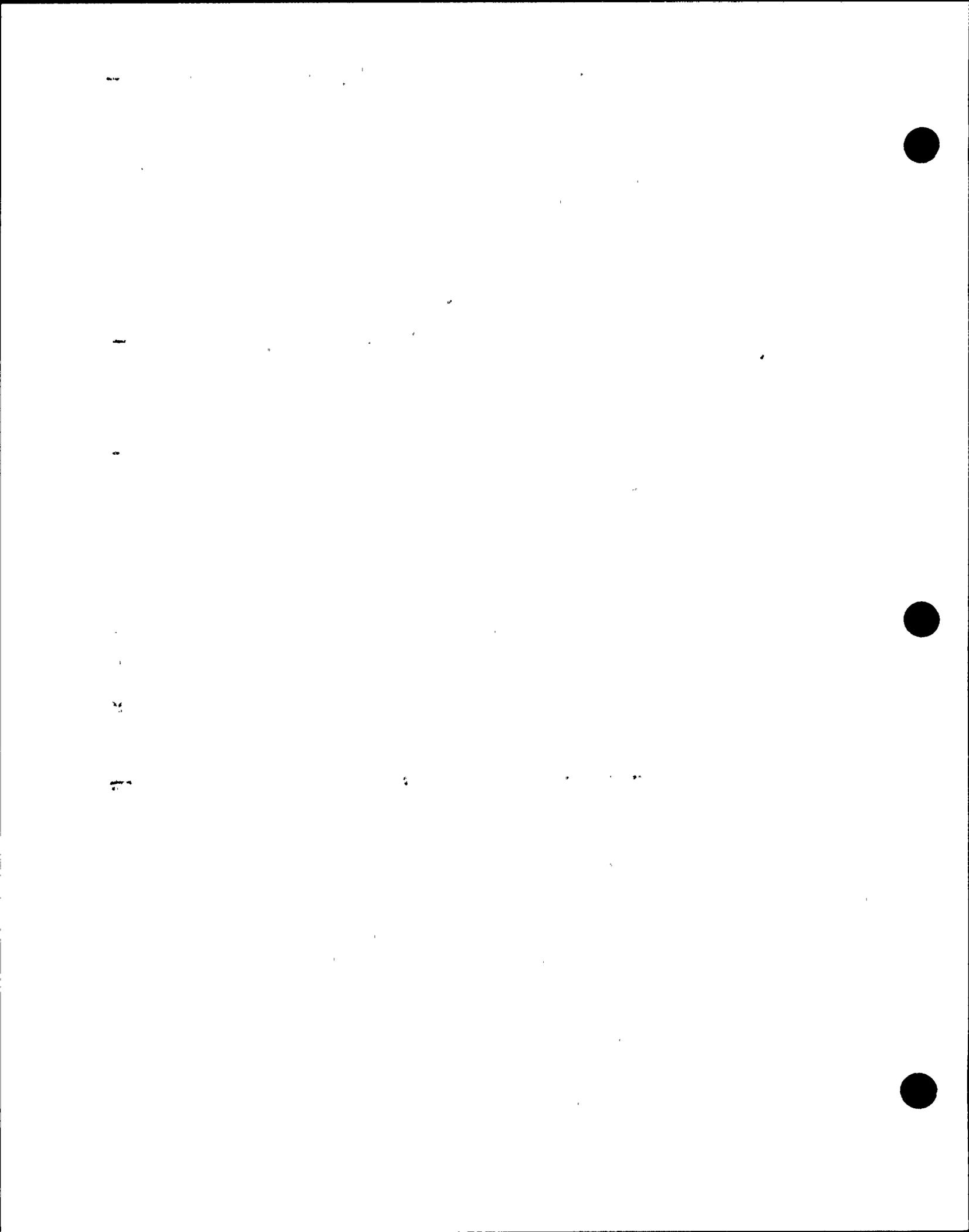
Scope

The Diablo Canyon seismic fragility evaluation studies were conducted over a period of approximately 3 years in a phased approach designed to clearly identify and reevaluate those components whose failure most substantially contribute to plant risk. Appropriate aspects of the various Diablo Canyon Long Term Seismic Program studies, including the site-specific geotechnical and soil/structure interaction investigations, the median in-structure response spectra evaluation, and the structural response variability investigation were incorporated into the fragility evaluations.

The fragility description of structures consisted of the identification and evaluation of controlling failure modes associated with the important structures (Table 6-2). Similarly, the fragility description of mechanical and electrical equipment consisted of the identification and evaluation of controlling failure modes related to elements of the major safe shutdown reactor plant systems (Table 6-3). In every case, the fragility analyses were based upon Plant-specific structure or component seismic qualification analyses directly related to elements in place at the Diablo Canyon Plant. Even the fragility for generic component categories, whose elements are too numerous to evaluate individually, were based upon a sampling of Plant-specific seismic qualification analyses for components in the category. Typical generic component categories are listed in Table 6-4.

Method Of Analysis

The definition of failure is vitally important to the development of median fragilities for structures and equipment. For purposes of this study, Category I structure failure was defined in terms of inelastic lateral drifts generally corresponding to the onset of significant strength degradation of major structural elements. The exception is the containment building where lateral drifts were limited to lower levels consistent with the need of the containment building to remain pressure-tight. Equipment housed in the important structures was assumed to fail when the structure reached lateral drifts corresponding to the onset of significant strength degradation or severe distress. The fragility estimates for structures correspond to distress levels short of partial or total collapse, but are treated as total collapse in the probabilistic risk assessment. The degree of margin between the onset of significant strength degradation and total collapse is uncertain and difficult to estimate. However, the benefits of this margin, which in most cases is likely to be large, has been conservatively ignored.



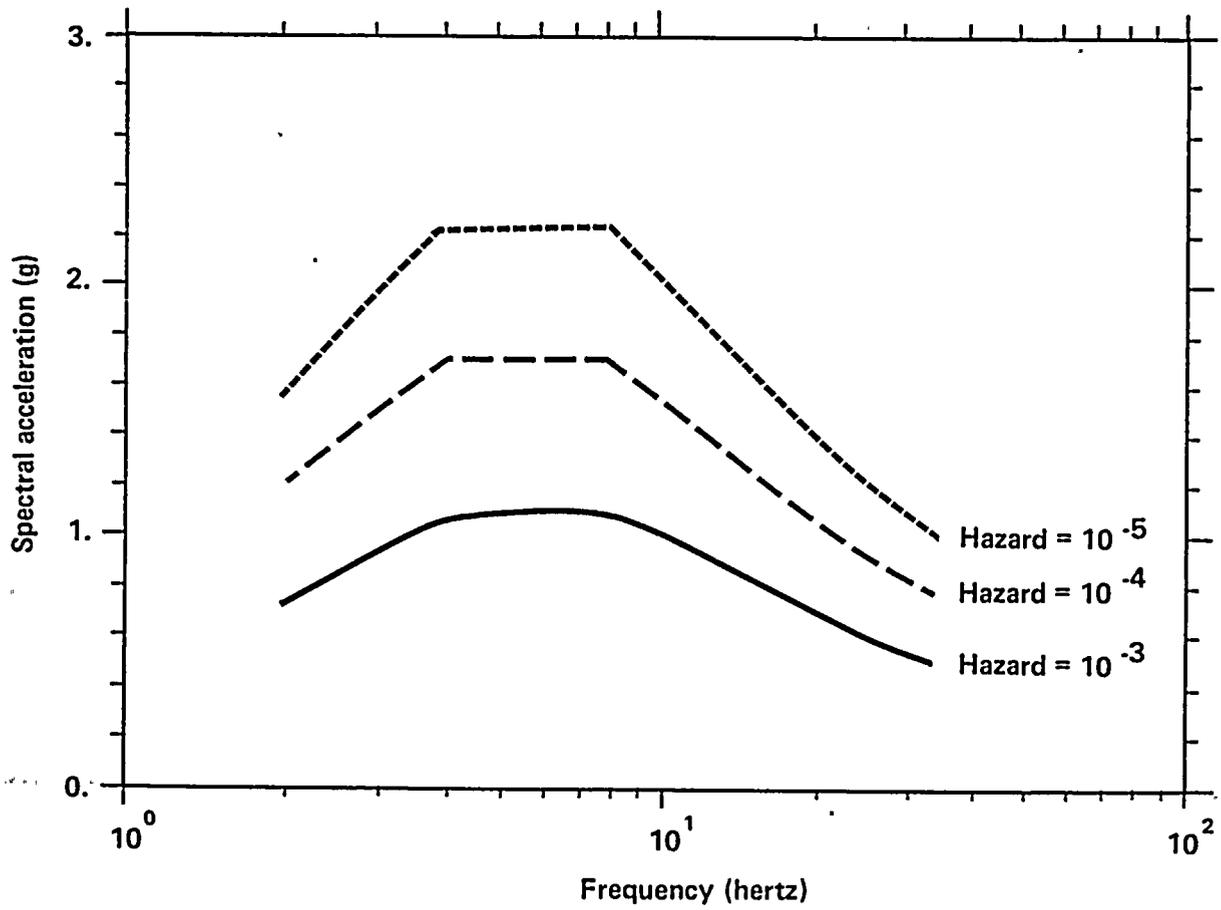


Figure 6-9
Median constant-hazard spectra (5 percent damping).

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Table 6-2

IMPORTANT STRUCTURES

Containment Building
 Concrete Internal Structure
 Auxiliary Building
 Turbine Building
 Intake Structure
 Refueling Water and Condensate Storage Tanks
 Diesel Generator Fuel Oil Storage Tank (Buried)
 Auxiliary Saltwater System Piping (Buried)

Table 6-3

MAJOR REACTOR PLANT SYSTEMS

Nuclear Steam Supply System (NSSS)	Containment Building Ventilation System
Residual Heat Removal System	Control Room Ventilation System
Safety Injection System	Vital Electrical Room Ventilation System
Component Cooling Water System	4160 V (Vital) Electrical System
Chemical and Volume Control System	480 V (Vital) Electrical System
Auxiliary Saltwater System	125 V DC Electrical System
Containment Spray System	120 V AC Electrical System
Main Steam System	Operator Instrumentation and Control System
Auxiliary Feedwater System	NSSS Instrumentation and Control System
Diesel Generator and Auxiliaries	Off-Site Power System

Table 6-4

TYPICAL GENERIC COMPONENT CATEGORIES

Electrical Penetrations
 Balance-of-Plant Piping and Supports
 Air- and Motor-Operated Valves
 Cable Tray, Conduits, and Supports
 HVAC Ducting and Supports

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Piping, electrical, mechanical, and electro-mechanical equipment vital to safe shutdown of the Plant or mitigation of an accident were considered to fail when it was judged they were no longer able to perform their designated functions. Therefore, for mechanical equipment, the fragility definition represents failure to function, loss of anchorage, or rupture of the pressure boundary. For electrical equipment, the fragility represents loss of function due to acceleration-sensitive failure (for example, relay chatter) or loss of function due to structural failure of the cabinet, anchorage, or internals. For ductile systems such as piping, HVAC ducting, and electrical conduits, fragility represents crimping, choking of flow, or rupture due to failure of the supports, as it has been shown that failure of these systems is virtually impossible apart from failure of the supports.

Fragility of a structure or a component is defined as the conditional frequency of its failure for a given value of the ground-motion parameter (for example, spectral acceleration). Thus, the fragility evaluation is based on the estimation of the median ground spectral acceleration value for which the seismic response of a given structure or component exceeds its capacity, resulting in failure. Because there are many sources of variability in the estimation of the median ground spectral acceleration capacity, the component fragility is described by means of a family of fragility curves. Figure 6-10 depicts such curves, showing the best estimate (50 percent confidence, $C_2 = 0$) curve with its shape governed by randomness variability, (β_R), and showing the relative position of the curve for other confidence levels greater than or less than 50 percent. The properties of the fragility curves and the general approach to their development are defined in previous works (Kennedy, 1980; Kennedy, 1984). Employing the characteristics of the lognormal distribution as described in these references, the entire family of fragility curves for any mode of failure is defined in terms of a median estimate of the ground spectral acceleration capacity, \bar{S}_a (Figure 6-10), times the product of randomness and uncertainty variables, ϵ_R and ϵ_U , which have unit median values and are lognormally

distributed with logarithmic standard deviations of β_R and β_U , respectively.

$$\bar{S}_a = \bar{S}_a^v \epsilon_R \epsilon_U \quad (6-3)$$

The spectral ground acceleration capacity, \bar{S}_a , is computed as:

$$\bar{S}_a = F \cdot \bar{S}_{aRef} \quad (6-4)$$

where F equals the overall factor of safety based on response to the reference earthquake, and \bar{S}_{aRef} equals the average spectral ground acceleration of the reference earthquake. The overall factor of safety has a median value, F , and randomness and uncertainty variabilities (β_R and β_U). In contrast, the average reference spectral acceleration is a deterministic quantity determined over a specified frequency range of the reference ground spectrum. Thus, the product of these terms, shown in equation (6-4), results in a spectral acceleration capacity which has a median value, \bar{S}_a , and randomness and uncertainty variabilities which are equal to the corresponding variabilities associated with the overall factor of safety (Figure 6-10). As a result, the spectral acceleration capacity at any point within the family of fragility curves is computed as:

$$\bar{S}_a = \bar{S}_a^v e^{(C_1\beta_R + C_2\beta_U)} \quad (6-5)$$

where C_1 and C_2 are the statistical constants associated with the failure fraction and confidence level of interest (Figure 6-10).

It must be noted then, that the term \bar{S}_a as used in this chapter refers to an average spectral acceleration capacity defined over the same frequency range as \bar{S}_{aRef} . This is in contrast to the normal usage of the term S_a , which refers to a spectral acceleration at a specific frequency.

The Diablo Canyon site-specific median horizontal and vertical ground spectra were established as part of the ground-motion studies documented in Chapter 4. These are shown on Figure 6-11 and define the median spectral shape



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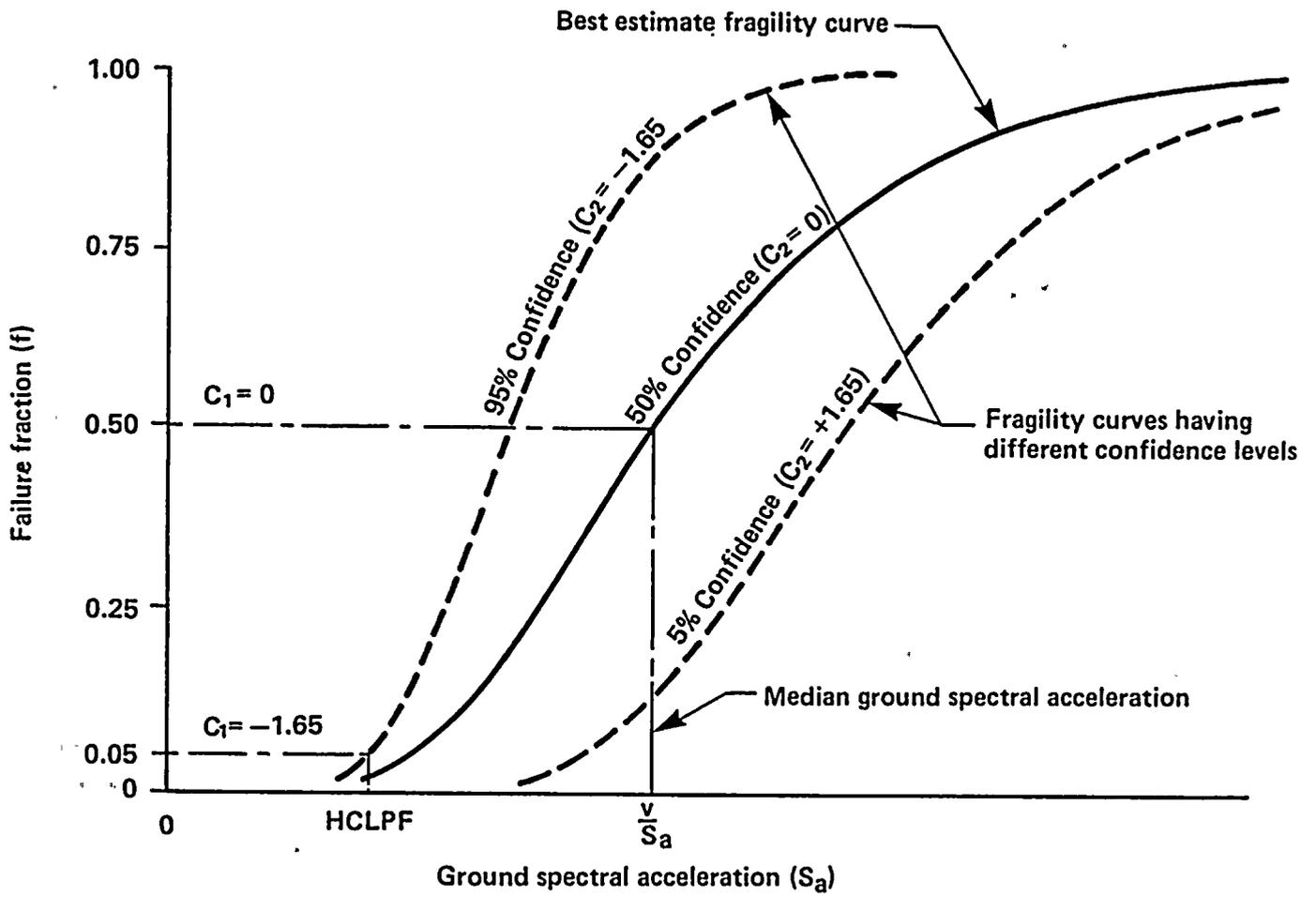


Figure 6-10
Fragility curve representations.

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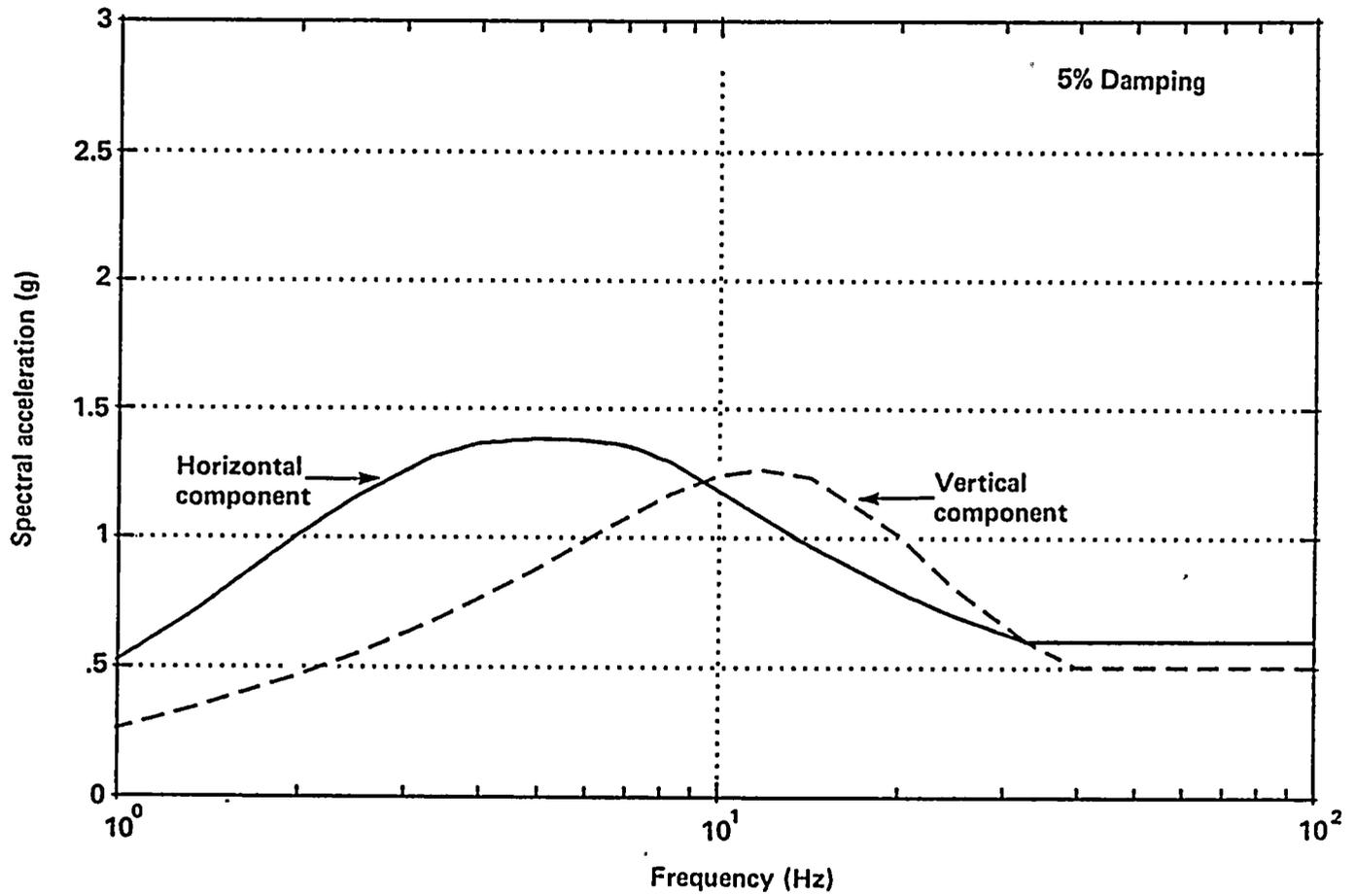


Figure 6-11
Diablo Canyon site-specific median ground-motion acceleration response spectra.



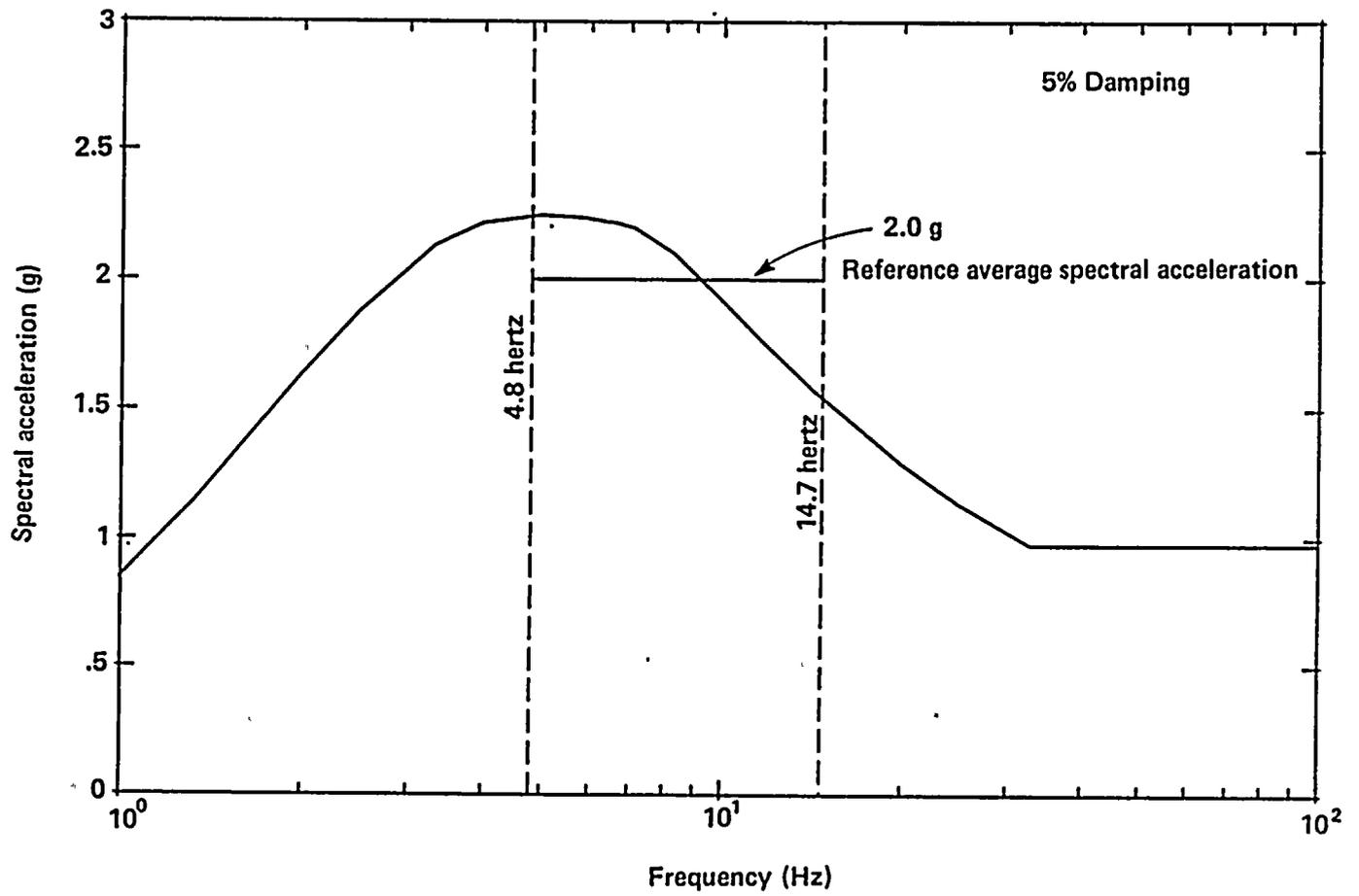


Figure 6-12
Reference horizontal ground-motion response spectrum.

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and relative amplitude between the horizontal and vertical components on a frequency-by-frequency basis. For use in the fragility evaluation of the Diablo Canyon structures and equipment, the reference horizontal ground spectrum (Figure 6-12) was established by scaling the median horizontal ground spectrum such that the average spectral acceleration, \bar{S}_{aRef} , over the frequency range between 4.8 and 14.7 hertz was several key variables together with the randomness and uncertainty variability associated with each. The key factors involved are listed below and were appropriately applied for structures and/or components.

Because seismically induced fragility data are generally unavailable for most Plant components and all structures, fragility curves were developed primarily from design analysis data, equipment qualification test data, and engineering judgment. The overall median factor of safety, \bar{F} , based on these data sources, was established by considering

- 1) The Strength factor, F_s , comparing the median strength available to resist seismic motion (or strength at loss of function) to the response level due to either the reference seismic event or the design seismic event. Where possible, based upon the form of the available seismic qualification data, the Strength factor was based upon a revised calculation of the critical response using the reference spectra, median-centered property values, and median-centered combination methods. For such cases the response factors discussed below were unity and only the associated variabilities were evaluated. This was done to minimize the uncertainty variabilities associated with the various response parameters. Where the form of the available data did not permit recomputation of the median-centered response, the responses from the design event (usually Hosgri reevaluation data) were used to evaluate the Strength factor of safety. For such cases, the response factors were evaluated as necessary.
- 2) The Inelastic Energy Absorption factor, F_{μ} (ductility), accounting for the fact that an earthquake represents a limited energy source and many structures and components are capable of absorbing substantial amounts of energy beyond yield without loss of function.
- 3) The Qualification Method factor, F_{QM} , comparing the acceleration values used in the equipment design analysis (when F_s is based on the design seismic event) to those obtained from the reference floor response spectrum.
- 4) The Damping factor, F_D , comparing response accelerations from the reference floor spectra at structure or equipment design damping to that associated with the damping level expected at or near failure.
- 5) The Modeling factor, F_M , assessing the ability of the design mathematical model to accurately determine the fundamental frequencies and mode shapes of the structures or equipment modeled; for tested components, assessing the similarity of the dynamic test boundary conditions to the in-Plant anchorage.
- 6) The Mode Combination factor, F_{MC} , assessing the conservatism or unconservatism in the mode combination method used in the design process; for components qualified by test, assessing the ability of the test method to simultaneously excite all dynamic modes.
- 7) The Earthquake Component Combination factor, F_{ECC} , evaluating the conservatism or unconservatism in the method used to combine the responses from the various earthquake component directions during the design analysis; for tested equipment, evaluating the unconservatism in the use of uniaxial or biaxial tests to duplicate actual earthquake response.
- 8) The Spectral Shape factor, F_{SS} , evaluating the randomness and uncertainty associated with peaks and valleys in the reference ground spectra.
- 9) The Ground Motion Incoherency factor, F_{GMI} , evaluating the conservatism in assuming coherent ground motion in establishing the reference floor spectra.

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- 10) The Inelastic Structural Response factor, F_{IR} , evaluating the potential for increased high frequency floor acceleration response due to nonlinear structural behavior. This factor is applicable to equipment fragility evaluation only.

The median overall factor of safety and its variabilities are computed as:

$$F = F_S \cdot F_{\mu} \cdot F_{QM} \cdot F_D \cdot F_M \cdot F_{MC} \cdot F_{ECC} \cdot F_{SS} \cdot F_{GMI} \cdot F_{IR} \quad (6-6)$$

$$\beta_R = \left[\beta_{R_S}^2 + \beta_{R_{\mu}}^2 + \beta_{R_{QM}}^2 + \beta_{R_{IR}}^2 \right]^{1/2}$$

$$\beta_U = \left[\beta_{U_S}^2 + \beta_{U_{\mu}}^2 + \beta_{U_{QM}}^2 + \beta_{U_{IR}}^2 \right]^{1/2}$$

Although the Diablo Canyon fragility evaluation of safety-related structures and equipment essentially followed the basic approach used for previous seismic probabilistic risk assessments of nuclear power plants, substantial work went into the more rigorous determination of certain factors and their variabilities. This was accomplished with the intent of minimizing the variabilities associated with the various parameters. A discussion of the important differences between previous fragility estimation efforts and the approaches used for the Diablo Canyon evaluation is included in the following sections.

Reference Ground-Motion Parameter

The fragilities for all Diablo Canyon structures and equipment, except the turbine building, were estimated as a function of the 5 percent damped average spectral acceleration of the horizontal ground-motion components averaged over the frequency range of 4.8 to 14.7 hertz. Most previous seismic probabilistic risk assessments of nuclear plants have defined fragilities as a function of the peak ground acceleration. However, damage to structures and equipment is more a function of the spectral accelerations within the elastic and inelastic frequency ranges of

the structure and equipment than it is a function of the peak ground acceleration. For nearly all of the structures (except the turbine building) and the equipment, the frequency range of primary interest was from about 3.5 hertz to about 35 hertz. From the 38 sets of time histories defined in Chapter 4 and used for the fragility evaluations, it was found that the ratio of spectral acceleration, at any specific frequency of interest in the 3.5 hertz to 35 hertz frequency range, to the average spectral acceleration over the 4.8 to 14.7 hertz range, showed lesser and more consistent variability than did the ratio of spectral acceleration at any specific frequency to peak ground acceleration. Over the entire frequency range of 3.5 hertz to 35 hertz, the ratio of spectral acceleration at any specific frequency to the average spectral acceleration over 4.8 to 14.7 hertz had a nearly constant logarithmic standard deviation that averaged about $\beta_R = 0.18$. However, the ratio of spectral acceleration at a specific frequency to the peak ground acceleration was highly variable over this important frequency range. The logarithmic standard deviation of this ratio ranged from close to zero at 35 hertz to more than 0.25 below 5 hertz. The frequency-dependent nature of spectral peak-and-valley or spectral shape variability is difficult to accommodate in the fragility analysis of a large number of components and equipment so that seismic fragility estimates anchored to peak ground acceleration have tended to use a conservative, frequency-independent spectral shape randomness variability of 0.25 or greater. Anchoring the fragility estimates to the average spectral acceleration from 4.8 to 14.7 hertz eliminates this difficulty and has enabled the use of a lesser β_R for peak-and-valley or spectral shape variability for frequencies equal or greater than about 3.5 hertz.

As will be noted later, the turbine building fragility was initially estimated to be sensitive to spectral accelerations in the 3 to 8.5 hertz frequency range, and was later found to be sensitive to spectral accelerations in the 1.7 to 9.5 hertz frequency range. To enable a better incorporation of spectral shape variability within the frequency range of interest for the turbine building, its fragility estimate was developed as a function of

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the average spectral acceleration in the 3 to 8.5 hertz range.

When convolving the seismic hazard and fragilities together in the seismic probabilistic risk assessment, it is desirable for all fragilities and the seismic hazard to be expressed in terms of one common ground-motion parameter. Because the median and 84 percent nonexceedance probability site-specific spectra, the probabilistic seismic hazard spectra with the annual probability range of interest, and the median horizontal spectrum shape used in the fragility evaluations all showed essentially the same ratio of average spectral acceleration in the 3 to 8.5 hertz range to average spectral acceleration in the 4.8 to 14.7 hertz frequency range, it was immaterial which average spectral acceleration frequency range was used for the common ground-motion parameter. The ratio between these average 5 percent damped spectral accelerations was:

$$\frac{\bar{S}_{a_{3-8.5}}}{\bar{S}_{a_{4.8-14.7}}} = 1.125$$

Because 3 to 8.5 hertz is the frequency range over which spectral accelerations are maximum, it was judged to be most descriptive to define the average spectral acceleration over the 3 to 8.5 hertz range as the common ground motion parameter for convolving hazard and fragility estimates. All fragility median and high-confidence-of-low-probability-of-failure estimates included in this report were converted so as to be defined in terms of the average spectral acceleration in the 3 to 8.5 hertz frequency range using the above defined conversion ratio.

Median Horizontal Floor Spectra

In many previous probabilistic risk assessments, the factors for equipment capacities and equipment responses were based upon the floor spectra used during the Plant design phases. Various factors were then generated in an attempt to account for conservatism or unconservatism in the generation of the design floor spectra due to

differences between the design and median site-specific ground spectra, effects of soil/structure interaction, and differences between design structural damping and structural damping expected at or near failure. In contrast, as discussed in Chapter 5, reference median horizontal floor spectra were generated for selected elevations of the Diablo Canyon safety-related structures corresponding to the location of important safety-related equipment. These floor spectra were generated using the reference ground motion, together with median soil/structure interaction and building structural parameters. Thus, the Strength factor of safety, F_s , is generally based upon the reference median horizontal floor spectra, together with a clear understanding of the associated variabilities.

Relationship Between Horizontal and Vertical Ground Spectra

The vertical ground spectrum used in the design of most nuclear plants is usually based upon some specified factor (for example, 2/3 or 1) times the design horizontal spectrum evaluated on a frequency-by-frequency basis. For the probabilistic risk assessments for such plants, the potential for higher than the designed-for vertical to horizontal ground-motion ratio is either ignored or included as a randomness variability based upon the vertical direction contribution to the response of interest. The Diablo Canyon site-specific horizontal and vertical 5 percent damped median ground spectra are shown on Figure 6-11. As discussed earlier, the reference horizontal ground spectrum for use in the fragility evaluations was established by scaling the median horizontal spectrum such that the average spectral acceleration over the 4.8 to 14.7 hertz range was equal to 2.0 \dot{g} (Figure 6-12). This same scale factor was applied to the median vertical ground response spectrum to establish a reference vertical ground response spectrum that properly corresponded to the reference horizontal spectrum. The resulting 5 percent damped reference vertical ground response spectrum is depicted on Figure 6-13 and is shown in comparison with the Hosgri reevaluation vertical ground spectrum.

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From Figure 6-11 it can be seen that the vertical ground acceleration exceeds the horizontal acceleration over the frequency range of about 9.5 to 30 hertz. In addition, Figure 6-13 shows that the reference vertical ground spectrum exceeds the Hosgri reevaluation vertical spectrum for frequencies greater than about 4.5 hertz. The effects of this reference vertical spectrum were included in the evaluation of equipment fragilities.

Equipment fragilities are mostly dominated by horizontal responses. As discussed above, reference median horizontal floor spectra were developed for the safety-related structures (Chapter 5). Reference median vertical floor spectra were not similarly generated. Reference vertical floor spectra were developed by scaling the Hosgri reevaluation vertical spectral acceleration at the floor by the ratio of the reference vertical ground spectrum to the Hosgri reevaluation vertical ground spectrum (Figure 6-13). Since the vertical direction contribution to seismic fragilities of components is generally small, this approach for the generation of reference vertical floor spectra was considered adequate.

Structural Response Variability

In most previous seismic probabilistic risk assessments of nuclear power plants, the evaluation of the Structural Response factor used in developing fragility descriptions for structures and equipment has employed simplified methods using the separation-of-variables approach. Because of the significant variabilities associated with each of the factors that would make up the Structural Response factor and the uncertainties associated with the simplified approach (how the individual variabilities combine), a more rigorous approach was undertaken to establish structural response variability; as part of the Diablo Canyon Long Term Seismic Program.

The Structural Response factor is a measure of the conservatism introduced in the development of the reference in-structure floor response spectra. The important variables used in the development

of equipment fragilities, which affect the generation of in-structure floor spectra include:

- 1) Ground-motion spectral shape
- 2) Structural damping
- 3) Structural frequency
- 4) Structural mode combination
- 5) Earthquake directional combination
- 6) Soil/structure interaction
- 7) Structural mode shape
- 8) Ground-motion incoherency
- 9) Inelastic structural response

The first six variables, which constitute the majority of the randomness and uncertainty variability, were included in the structural response variability study described herein; the last three variables were added to the structure and component fragility analyses based on the normal separation-of-variables approach.

The variables associated with ground-motion spectral shape (peaks and valleys), structural mode combination, and earthquake directional combination were represented in the variability study using a large suite of 38 sets of two orthogonal horizontal components of earthquake time histories that provided a broad characterization of the ground motions which might occur at the Plant site in the event of a very large earthquake. The 38 sets of earthquake time histories used in the variability study consisted of a set of 24 empirical earthquake time histories and 14 numerically simulated acceleration-time records. The variables associated with structural damping, structural frequency, and rock modulus are model parameters that characterize the behavior of the soil/structure system under a given ground motion. These parameters were represented by employing a random selection procedure (Latin Hypercube simulation) to select model parameter values which were then randomly mixed for use with the suite of earthquake time history input ground motions.

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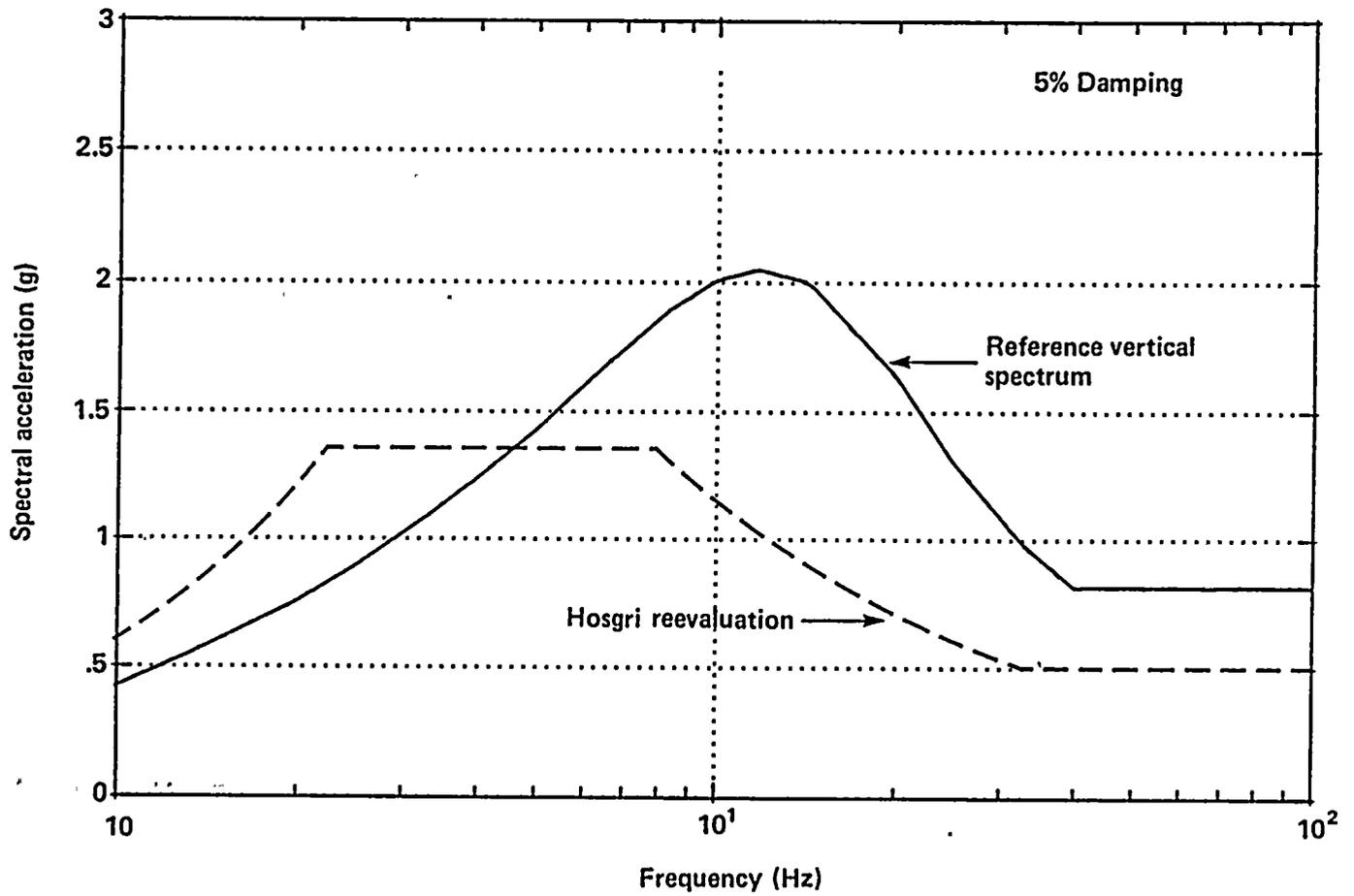


Figure 6-13
Diablo Canyon reference vertical ground spectrum.

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Each set of randomly selected and mixed model parameter values and its associated north/south and east/west earthquake time histories were input into a simplified soil/structure interaction system model of the auxiliary building, which was analyzed using the CLASSI computer code to generate 38 sets of deterministic floor response spectra at various elevations. The floor response spectra from the 38 earthquake runs were then statistically analyzed to generate median and 84th percentile probabilistic floor spectra. At any frequency, the combined variability, β_c , associated with the six variables included in the study was estimated from the ratio of the 50th and 84th percentile spectral accelerations

ANALYSIS MODEL

As noted above, a simplified soil/structure interaction model of the auxiliary building was used in this study. This structure was chosen because it is a large structure that houses a substantial portion of the important Plant equipment. Emphasis in this study was placed upon assessing the response variability of the western core of the auxiliary building because a majority of the Plant safety-related equipment is located in the western core.

As discussed in Chapter 5, detailed soil/structure interaction analyses of the auxiliary building were conducted using the SASSI computer code based upon a three-dimensional, 5-stick representation of the structure above E1 85 feet and a three-dimensional finite element plate representation below E1 85 feet (Figure 6-14, SASSI model). A large number of time-history soil/structure interaction response analyses and varying model parameters were required in the structural response variability study; thus, it was desired that the model be simple and easily amendable to model parameter adjustment. The SASSI 5-stick model was considered too detailed for the structural response variability study, and as a result, a simplified CLASSI model was developed (Figure 6-15). The transformation to the simplified 3-stick model of the auxiliary building superstructure was accomplished by deleting the stick representation of the north and south wings. The north/south stiffnesses of the deleted wings were accounted for by adjusting the

north/south stiffness of the core east stick. Comparison of fixed-base modal properties between the two models, both fixed at E1 85 feet, showed close agreement at the lower modes. The embedded portion of the auxiliary building, the foundation, basement, and the underlying rock medium, were represented by equivalent foundation base mass, mass moments of inertia, and impedances in the simplified model. The frequency-dependent foundation impedances associated with the rigid rectangular base were calculated using the CLASSI code, based on the same rock profile and properties used for the soil/structure interaction study (Chapter 5). The frequency-dependent soil spring stiffnesses and damping coefficients were taken as the CLASSI calculated impedance functions at about 8 hertz, which closely corresponds to the fundamental north/south and east/west frequencies from the soil/structure interaction model. These parameters were then adjusted for the embedment effect of the core structure. The simplified soil/structure interaction model was formed by coupling the 3-stick core structure model, the foundation base mass properties, and the soil spring and damping coefficients into the soil/structure interaction system.

To validate the simplified CLASSI soil/structure interaction model, two response parameters were compared with results from the more detailed SASSI model. The comparison of the north/south and east/west horizontal seismic response transfer functions at E1 140 feet is shown on Figure 6-16 and the comparison of the 2 percent damped north/south and east/west floor response spectra at E1 140 feet (core west) for the same free-field ground-motion time-history input is shown on Figure 6-17. Both show very good agreement.

The effect of concrete cracking on structural response was considered by adjusting the frequencies of the fixed base model by a factor of 0.9 (stiffness reduction of approximately 0.8).

The median fundamental frequencies of the simplified soil/structure interaction model, for both the north/south and east/west directions, were approximately 8 hertz taking concrete cracking into account.



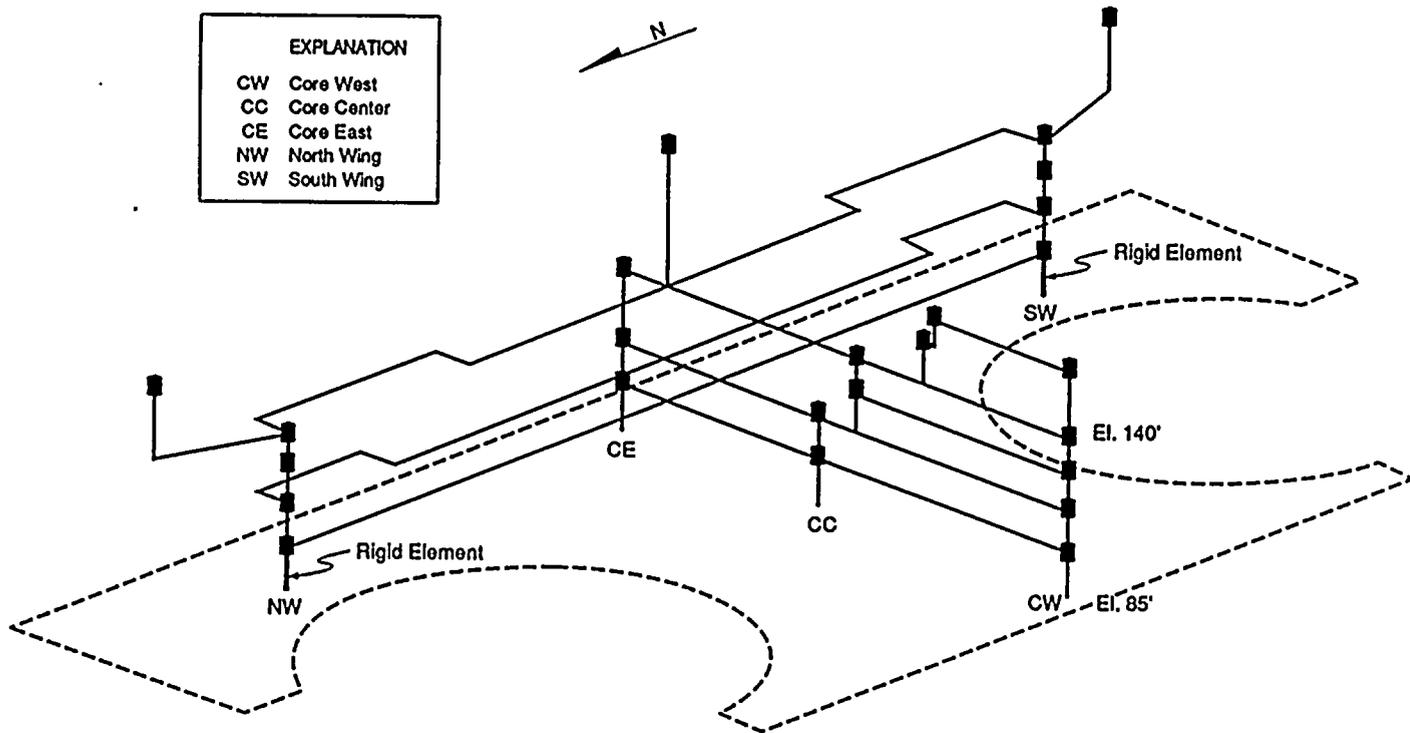


Figure 6-14
SASSI structural model for the auxiliary building.

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EXPLANATION
 CE Core east
 CC Core center
 CW Core west
 □ Node number

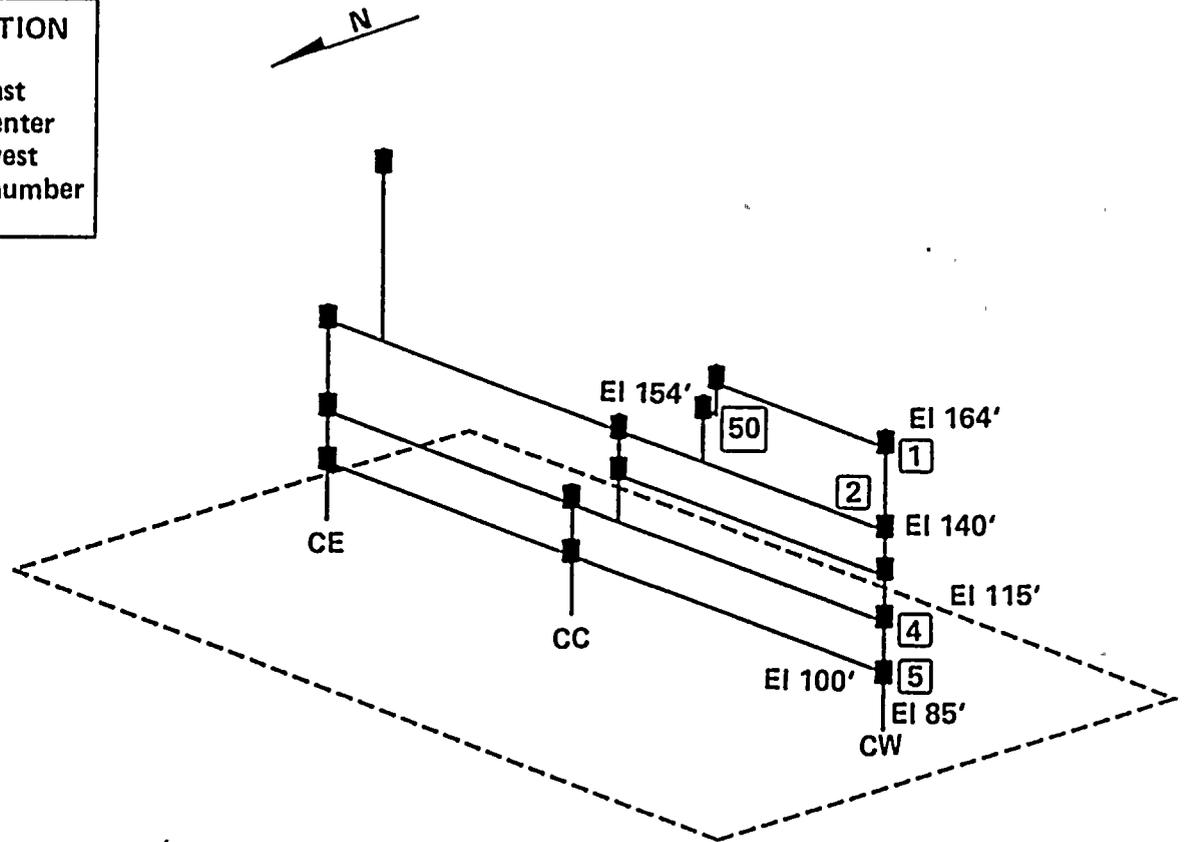


Figure 6-15
 Configuration of the simplified CLASSI model for the auxiliary building core structure.



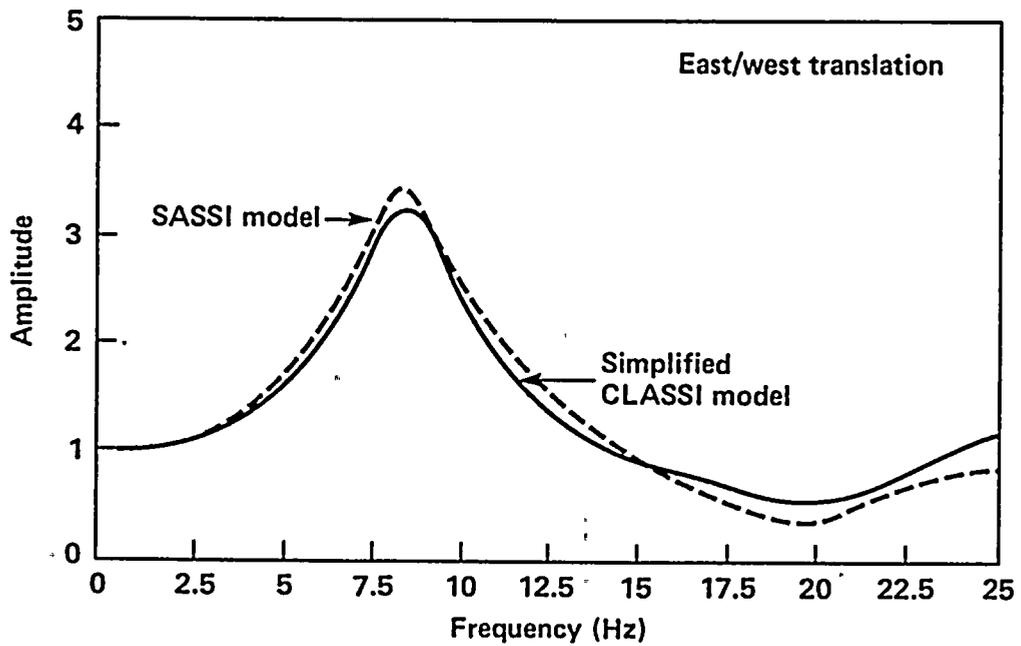
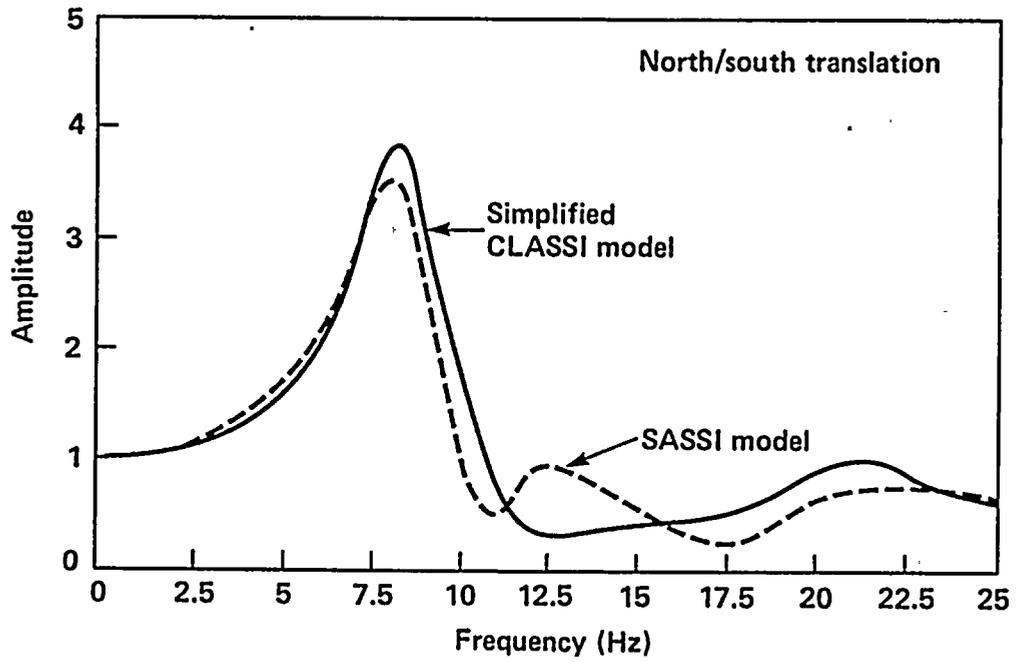


Figure 6-16

Comparison of transfer functions from the simplified CLASSI soil/structure interaction model with those from the SASSI model at El 140 feet (core west).

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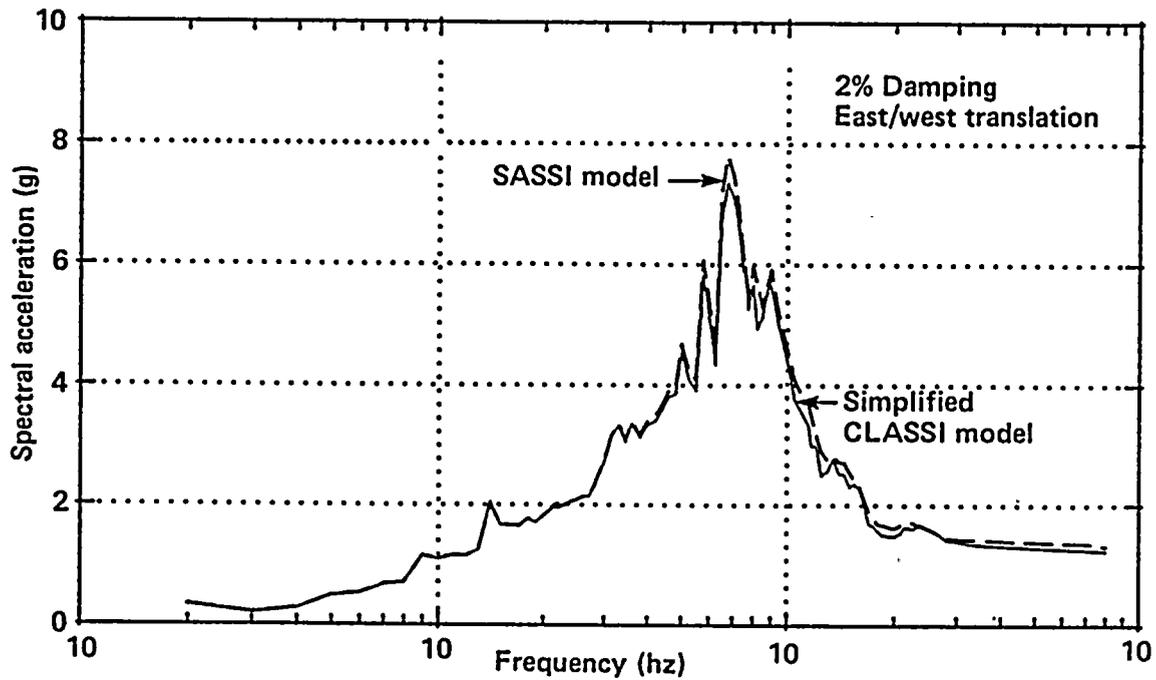
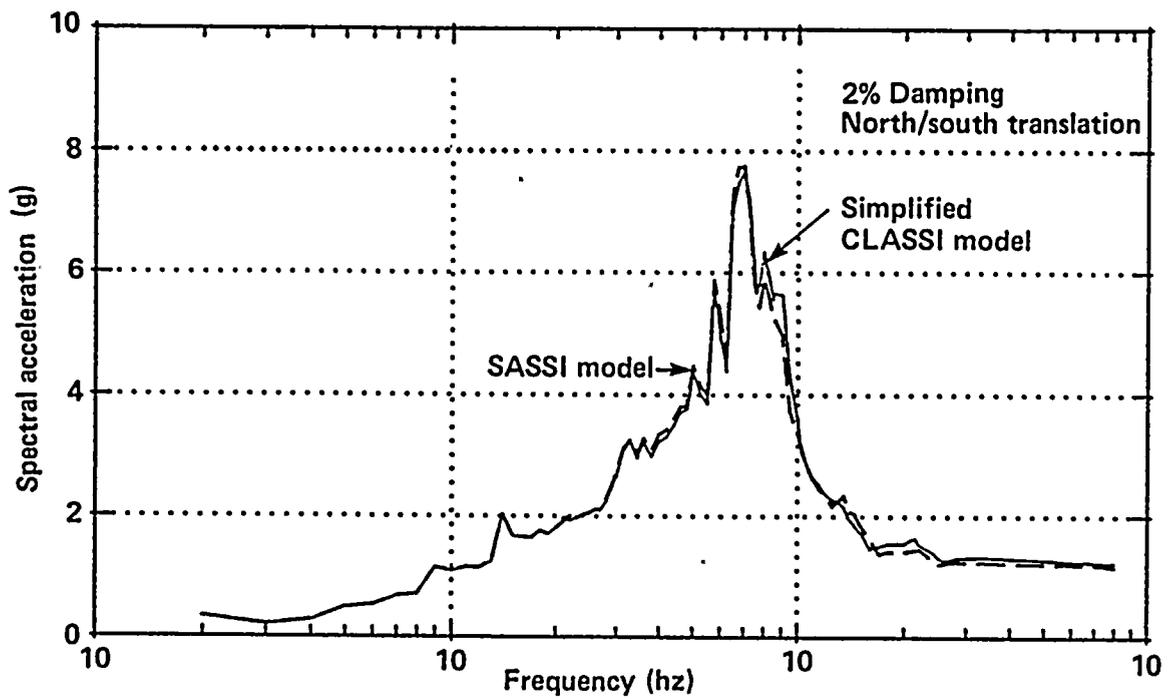


Figure 6-17

Comparison of 2 percent damped response spectra from the simplified CLASSI soil/structure interaction model with those from the SASSI model at El 140 feet (core west).

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INPUT MOTION

Acceleration time histories used in the structural response variability study were developed to represent ground motions that might be expected at a rock site within 10 kilometers of the fault rupture surface due to shallow crustal earthquakes having magnitudes in the range of 6.5 to 7.5 and having strike-slip, oblique, or reverse faulting mechanisms.

A total of 52 horizontal ground-motion time-history records were used in this study. Twelve pairs of orthogonal empirical time histories derived from actual recordings of eight past earthquakes were selected and are shown in Table 6-5. Because directions of ground motions for the suite of empirical time histories are random with respect to the north/south and east/west directions of the Plant, the two components of each of the 12 empirical records were interchanged to produce 24 empirical earthquake time-history sets. To provide a more balanced representation of potential fault mechanisms at the site, and to increase the size of the suite of time histories for a better overall distribution, 14 pairs of orthogonal numerically simulated time histories were also generated. Because the numerical set of earthquake histories (Table 6-6) were specifically generated to correspond to the Plant north/south and east/west directions respectively, they were applied in accordance with their specified directions.

As discussed earlier, average spectral acceleration over a broad frequency range is a substantially better descriptor of damage than is peak ground acceleration. To maintain an approximately uniform variability over the entire frequency range of interest in the earthquake ground motion, each time-history pair was scaled such that the average 5 percent damped spectral acceleration over the frequency range of 4.8 to 14.7 hertz was 2.0 g for the average of the two horizontal components. This scaling method is identical to that used in the detailed soil/structure interaction analyses described in Chapter 5. The scaling factors used are shown in Table 6-5 and Table 6-6. The frequency range of 4.8 to 14.7 hertz covers approximately the median auxiliary building

soil/structure system frequency (about 8 hertz) plus or minus two logarithmic standard deviations. Tables 6-5 and 6-6 present details of each of the empirical and numerical time-history records, respectively, including fault type, scaling factor to achieve an average spectral acceleration of 2.0 g, and the nature of adjustments to the empirical records necessary so that they would be appropriate for the Diablo Canyon site.

VARIABLE MODEL PARAMETERS

Variability in structural response due to variation in structural damping, structural frequency, and rock modulus were included in the auxiliary building variability study. A Latin Hypercube simulation was used to select the random variables (model parameter values) used in the analysis. Since the earthquake time histories selected were assumed to be equally likely, the sample size was set equal to the number of earthquake records provided. The damping ratios, frequencies, and rock modulus values were assumed to be lognormally distributed with medians and variabilities as shown in Table 6-7. Two sets of model parameter samples were created: one for the set of 24 empirical earthquakes, and one for the set of 14 numerically simulated earthquakes.

Table 6-7

MEDIANS AND VARIABILITIES FOR MODEL PARAMETERS

<u>Parameter</u>	<u>Median</u>	<u>β</u>
Structure Frequency Ratio	1.0	0.25
Structure Damping	0.07	0.35
Rock Modulus Ratio	1.00	0.45

The domain of each model parameter was divided into $N + 2$ strata (where N is equal to the number of sample points to be selected, that is, the number of earthquakes) such that each of the strata is of equal probability (Figure 6-18). Parameter values within the first and $(N + 2)$ th strata (that is, the tails of the probability distribution function) were considered to be extreme, unrealistic values; thus sampling was



Table 6-5
EARTHQUAKE RECORDS USED TO DEVELOP TIME HISTORIES FOR
FRAGILITY STUDIES

Time History Number	Earthquake	Recording Station	Record Name	Magnitude Used	Distance (km)	Style of Faulting	Adjustment	Scaling Factor ¹
1 2	1978 Tabas	Tabas	Tabas N74E Tabas N16W	7.4	3	Thrust	None	0.98
3 4	1971 San Fernando	Pacoima Dam	SFPAC S16E SFPAC S74W	6.6	3	Thrust	None	1.12
5 6	1971 San Fernando	Lake Huges No. 12	SFLH12 N21E SFLH12 N69W	6.6	20	Thrust	Distance	1.07
7 8	1971 San Fernando	Castaic	CAS N69W CAS N21E	6.6	25	Thrust	Distance	1.25
9 10	1979 Imperial Valley	Differential Array	IVDA N00E IVDA N90W	6.5	5	Strike-slip	Site response	1.46
11 12	1979 Imperial Valley	El Centro No. 4	IVEC S50W IVEC S40E	6.5	4	Strike-slip	Site response	1.80
13 14	1984 Morgan Hill	Coyote Lake Dam	CLD N75W CLD S15W	6.2	0.1	Strike-slip	Magnitude	1.21
15 16	1983 Coalinga	Pleasant Valley Pump Station (Switchyard)	PVPP 045 PVPP 135	6.5	10	Reverse	Distance	1.31
17 18	1985 Nahanni	Site 1	NAH1 010 NAH1 280	6.8	6	Thrust	None	0.84
19 20	1976 Gazli	Karakyr Point	Gazli EAS Gazli NOR	6.8	3	Reverse	None	1.24
21 22	1966 Parkfield	Temblor	TEM N65W TEM S25W	6.1	10	Strike-slip	Distance and magnitude	2.13
23 24	1978 Tabas	Dayhook	Dayhook N10E Dayhook N80W	7.4	17	Thrust	Distance	1.45

¹This scaling factor was used to bring the empirical records to an average 5 percent damped spectral acceleration of 2.0 g in the 4.8 to 14.7 hertz range and is in addition to the scaling necessary to make the records appropriate for the Diablo Canyon site (Chapter 4).

Table 6-6

**FAULT MODELS USED TO GENERATE SIMULATED TIME HISTORIES
FOR FRAGILITY STUDIES**

<u>Time History Number</u>	<u>Record Name</u>	<u>Style of Faulting</u>	<u>Rupture Mode</u>	<u>Source Functions</u>	<u>Scaling Factor</u>
25	FILE1-C2E	Strike-slip	Bilateral	Coalinga aftershock	1.38
26	FILE1-C2N				
27	FILE1-I3N	Strike-slip	Bilateral	Imperial Valley aftershock	2.06
28	FILE1-I3E				
29	FILE2-I9N	Strike-slip	Unilateral-N	Imperial Valley aftershock	2.53
30	FILE2-I9E				
31	FILE3-C6N	Strike-slip	Unilateral-S	Coalinga aftershock	1.68
32	FILE3-C6E				
33	FILE3-I6N	Strike-slip	Unilateral-S	Imperial Valley aftershock	2.33
34	FILE3-I6E				
35	FILE4-C4N	Oblique	Bilateral	Coalinga aftershock	1.09
36	FILE4-C4E				
37	FILE4-C5N	Oblique	Bilateral	Coalinga aftershock	1.33
38	FILE4-C5E				
39	FILE4-I7N	Oblique	Bilateral	Imperial Valley aftershock	2.63
40	FILE4-I7E				
41	FILE5-C5N	Oblique	Unilateral-N	Coalinga aftershock	1.39
42	FILE5-C5E				
43	FILE5-I6N	Oblique	Unilateral-N	Imperial Valley aftershock	2.25
44	FILE5-I6E				
45	FILE6-C4N	Oblique	Unilateral-S	Coalinga aftershock	1.12
46	FILE6-C4E				
47	FILE6-I1N	Oblique	Unilateral-S	Imperial Valley aftershock	1.96
48	FILE6-I1E				
49	FILE7-C1N	Thrust	Bilateral	Coalinga aftershock	1.23
50	FILE7-C1E				
51	FILE8-C2N	Thrust	Unilateral-N	Coalinga aftershock	1.05
52	FILE8-C2E				

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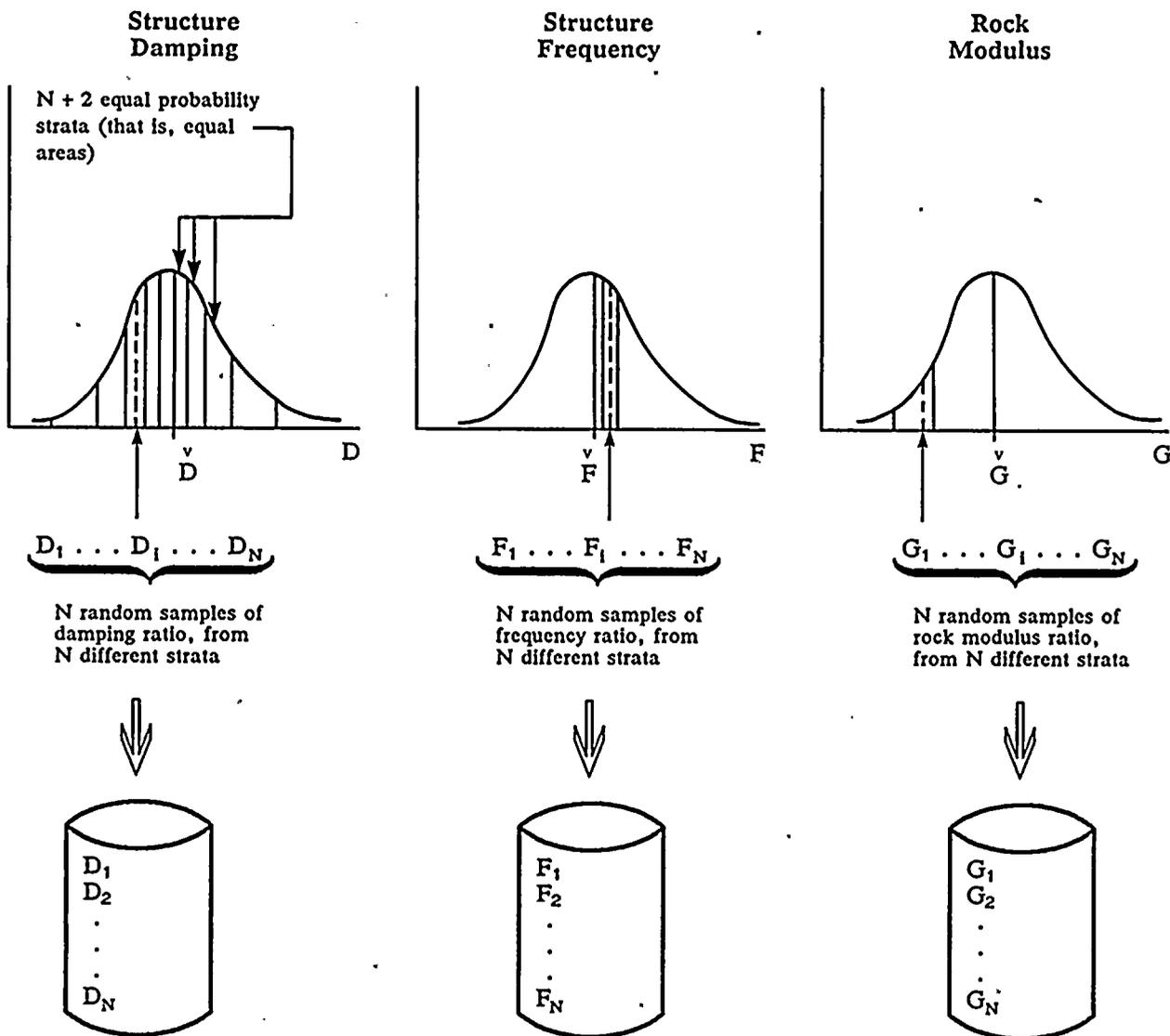


Figure 6-18
Sampling of model parameter values.

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limited to the N strata lying between the first and last strata. For each model parameter, one sample value was chosen at random within each of the N strata (by using the model parameter medians and variabilities given in Table 6-7) based on the properties of the lognormal distribution. The result is a set of model parameter values consisting of N values of damping ratio, N values of frequency, and N values of rock modulus as illustrated schematically on Figure 6-18. The three sets of model parameter values were then randomly mixed. This might be visualized as placing the N damping values, N frequency values, and N rock modulus values into three separate bins, then drawing one damping, frequency, and rock modulus value at random, without replacement, until all values have been chosen. As a result, N sets of model parameter values, each containing a damping, frequency, rock modulus value are obtained as shown on Figure 6-19. Each of the N equally likely parameter values were assigned to one of the N equally likely earthquake pairs; the resulting sets are given in Tables 6-8 and 6-9 for the 24 empirical and 14 numerical records, respectively.

The dynamic properties of the superstructure portion of the simplified soil/structure interaction model were input in each CLASSI run in the form of modal masses, structure damping, and mode shapes and frequencies. A frequency cut-off point of 33 hertz for the superstructure resulted in a total of 56 modes, with cumulative effective modal masses of 87 percent and 95 percent in the north/south and east/west directions, respectively. The balance of the modal masses were treated by the CLASSI program as rigid masses.

From the given set of model parameters, the sampled structure damping was applied to all 56 modes. The frequency ratios, along with the 0.9 concrete cracking factor, were used to scale each of the 56 fixed base frequencies. The rock modulus ratio was applied to the median rock modulus value (that is, the value at the top layer of the soil profile, to which all other layers have been normalized) to determine the input value for each analysis. The shear wave velocity, which is not independent of the rock modulus, must also be specified for the CLASSI program; thus the

rock modulus ratio was also used to compute the corresponding shear wave velocity for each analysis.

One deterministic soil/structure interaction analysis was then performed for each of the 38 earthquake/model parameter value sets.

RESULTS

The time-history output from each of the 38 deterministic analyses was obtained for both horizontal directions for six selected locations in core west of the auxiliary building. Referring to Figure 6-15, the selected locations included El 164 feet (node 1), El 154 feet (node 50), El 140 feet (node 2), El 115 feet (node 4), El 100 feet (node 5), and El 85 feet (structure base). From the floor response time histories, floor response spectra were generated for four specified damping ratios (3, 5, 7, and 15 percent). As an illustration of the results of the 38 CLASSI runs, the 5 percent damped north/south response spectra from all 38 runs, at El 140 feet of the core west stick, were plotted on the same frame on Figure 6-20. The spectral accelerations were arranged in descending order at each of the selected frequency points and the median and 84th percentile values were extracted. The resulting median (50th percentile) and 84th percentile floor spectra were then plotted and digitized for use in the fragility evaluations. The north/south and east/west median and 84th percentile spectra for El 140 feet are depicted on Figures 6-21 through 6-24.

APPLICATION OF RESULTS

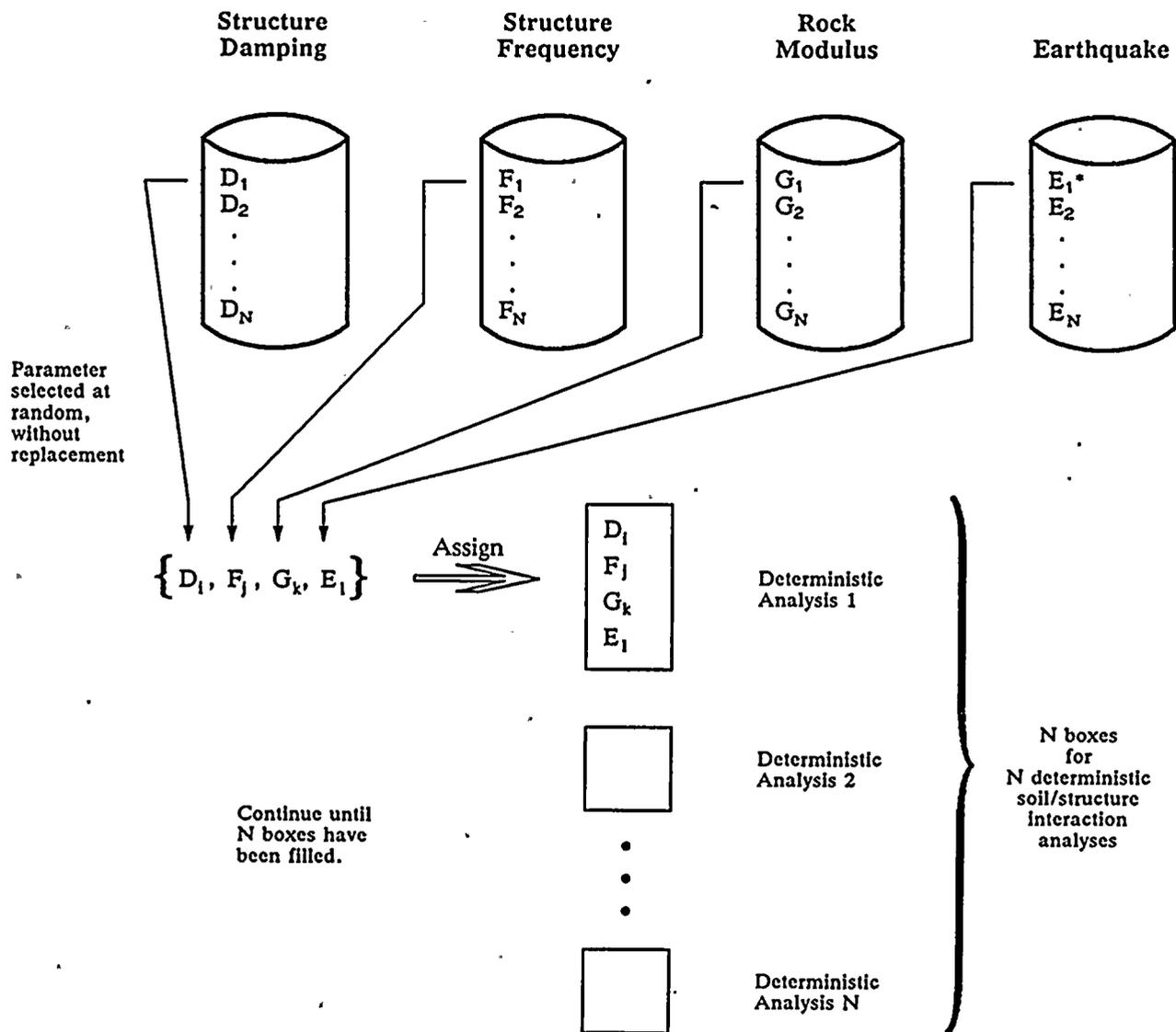
The combined variability associated with variation of the six parameters included in the auxiliary building variability study was determined by comparing the 5 percent damped median and 84th percentile floor spectra.

$$\beta_c = \ln (S_{a,84} / S_{a,50}) \quad (6-7)$$

In a comparison of the 50th and 84th percentile floor spectra for the various auxiliary building core west elevations, it was found that the variabilities tended to be consistent over certain frequency bands. The resulting combined variabilities are shown in Tables 6-10 and 6-11, respectively, for the north/south and east/west directions.

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*The earthquake time histories were randomly mixed by virtue of the random selection of the other three parameters.

Figure 6-19
Random mixing of model parameters.

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Table 6-8

**MODEL PARAMETER VALUES AND SCALING FACTORS FOR THE
EMPIRICAL RECORDS**

Analysis Number	Input Time History Number		Structure Damping (%)	Structure Frequency Ratio ¹	Rock Modulus Ratio	Time History Scaling Factor ²
	NS	EW				
1	1	2	6.80	$0.950 \times 0.9 = 0.855$	1.335	0.98
2	2	1	4.71	$0.915 \times 0.9 = 0.824$	1.124	0.98
3	3	4	9.46	$0.983 \times 0.9 = 0.885$	0.771	1.12
4	4	3	12.45	$0.801 \times 0.9 = 0.721$	1.737	1.12
5	5	6	4.34	$0.903 \times 0.9 = 0.813$	1.081	1.07
6	6	5	5.10	$1.174 \times 0.9 = 1.057$	1.238	1.07
7	7	8	5.82	$0.814 \times 0.9 = 0.733$	1.486	1.25
8	8	7	6.33	$1.009 \times 0.9 = 0.908$	0.618	1.25
9	9	10	10.09	$1.217 \times 0.9 = 1.095$	2.187	1.46
10	10	9	10.71	$1.509 \times 0.9 = 1.358$	0.986	1.46
11	11	12	4.05	$0.644 \times 0.9 = 0.580$	1.434	1.80
12	12	11	8.07	$0.871 \times 0.9 = 0.784$	0.900	1.80
13	13	14	6.28	$0.855 \times 0.9 = 0.770$	0.540	1.21
14	14	13	9.97	$1.344 \times 0.9 = 1.210$	1.033	1.21
15	15	16	7.29	$1.068 \times 0.9 = 0.961$	1.651	1.31
16	16	15	7.68	$0.750 \times 0.9 = 0.675$	0.853	1.31
17	17	18	5.49	$1.428 \times 0.9 = 1.285$	0.934	0.84
18	18	17	8.02	$1.134 \times 0.9 = 1.021$	0.672	0.84
19	19	20	5.33	$0.957 \times 0.9 = 0.861$	1.167	1.24
20	20	19	7.01	$1.121 \times 0.9 = 1.009$	0.512	1.24
21	21	22	6.08	$1.047 \times 0.9 = 0.942$	0.697	2.13
22	22	21	8.57	$0.734 \times 0.9 = 0.661$	0.738	2.13
23	23	24	8.73	$1.264 \times 0.9 = 1.138$	1.311	1.45
24	24	23	6.72	$1.097 \times 0.9 = 0.987$	0.830	1.45

¹0.9 factor accounts for concrete cracking (typical).

²For both north/south and east/west time histories.

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Table 6-9

**MODEL PARAMETER VALUES AND SCALING FACTORS FOR THE
NUMERICAL RECORDS**

Analysis Number	Input Time History Number		Structure Damping (%)	Structure Frequency Ratio ¹	Rock Modulus Ratio	Time History Scaling Factor ²
	NS	EW				
25	26	25	9.28	$0.892 \times 0.9 = 0.803$	0.954	1.38
26	27	28	5.42	$0.865 \times 0.9 = 0.779$	0.566	2.06
27	29	30	8.77	$1.061 \times 0.9 = 0.955$	0.669	2.53
28	31	32	7.90	$1.218 \times 0.9 = 1.096$	1.510	1.68
29	33	34	5.08	$1.265 \times 0.9 = 1.139$	1.693	2.33
30	35	36	10.57	$0.801 \times 0.9 = 0.721$	0.924	1.09
31	37	38	5.56	$0.928 \times 0.9 = 0.835$	1.016	1.33
32	39	40	7.08	$0.811 \times 0.9 = 0.730$	1.190	2.63
33	41	42	9.77	$1.025 \times 0.9 = 0.923$	1.470	1.39
34	43	44	6.05	$1.180 \times 0.9 = 1.062$	0.747	2.25
35	45	46	7.56	$0.712 \times 0.9 = 0.641$	1.299	1.12
36	47	48	6.58	$1.430 \times 0.9 = 1.287$	1.098	1.96
37	49	50	6.75	$0.986 \times 0.9 = 0.887$	0.701	1.23
38	51	52	4.35	$1.129 \times 0.9 = 1.016$	0.864	1.05

¹0.9 factor accounts for concrete cracking (typical).

²For both north/south and east/west time histories.

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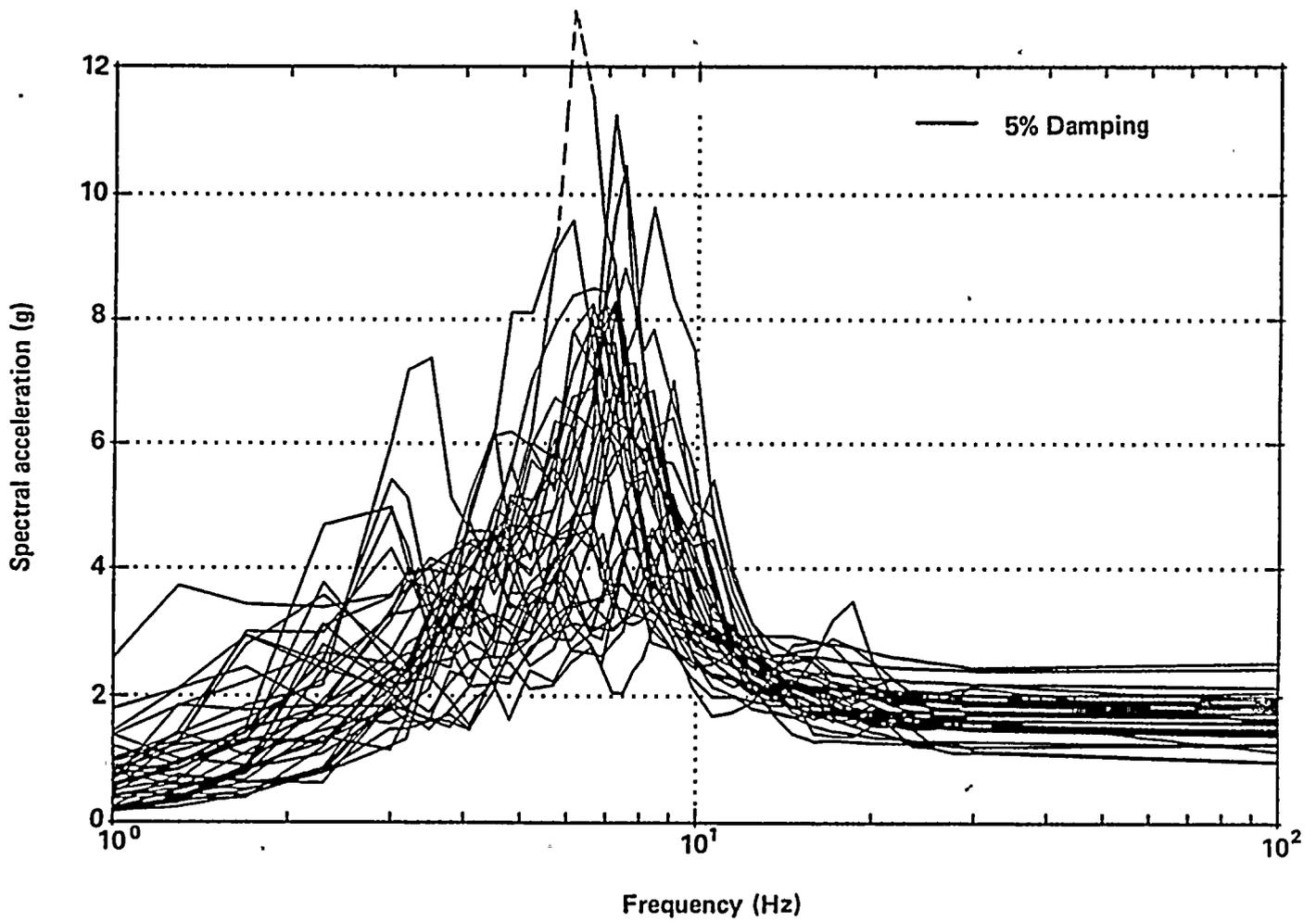


Figure 6-20
North/south response spectra at El 140 feet from all 38 deterministic analyses.

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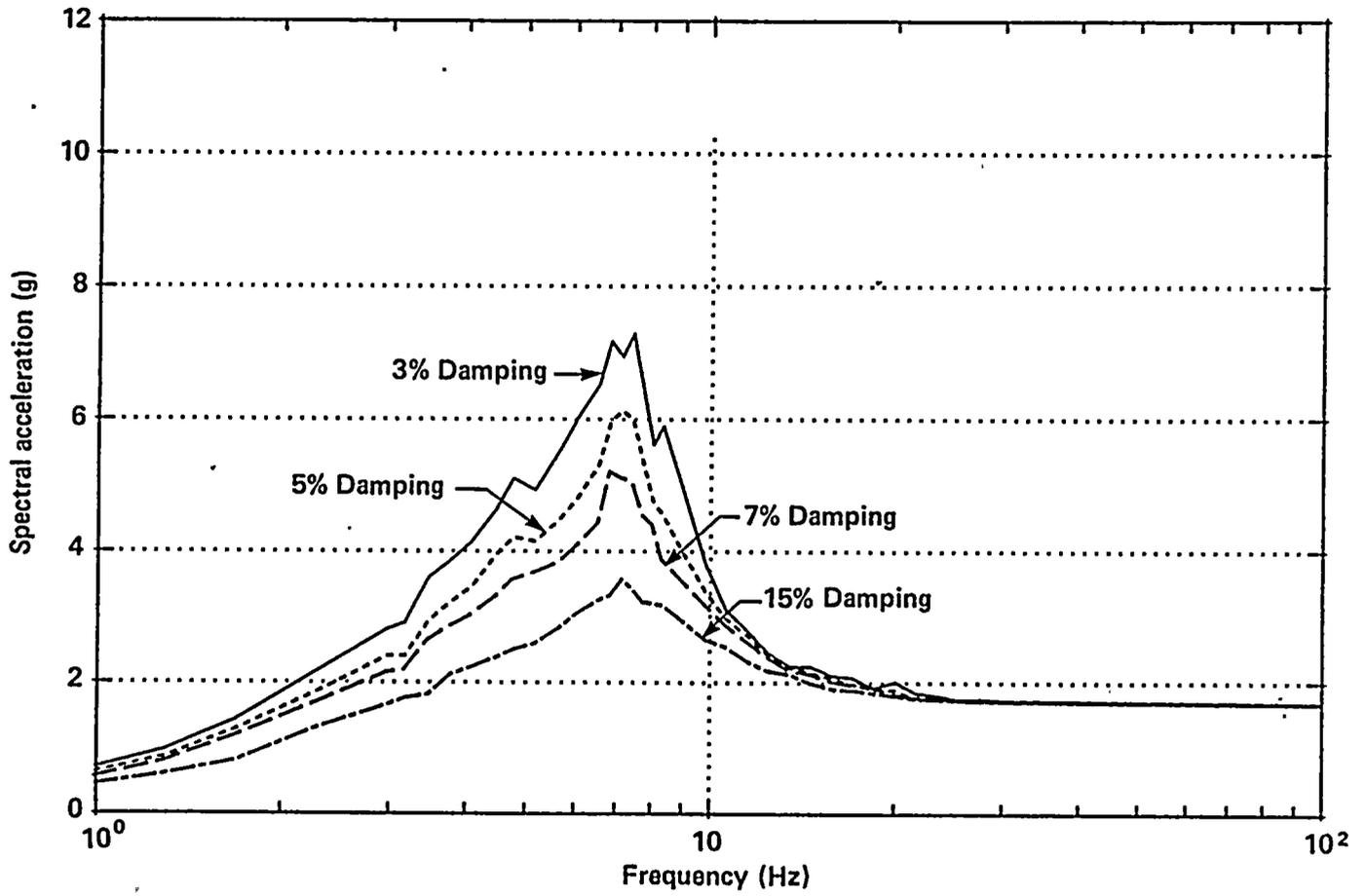


Figure 6-21
50th percentile north/south response spectra for El 140 feet.



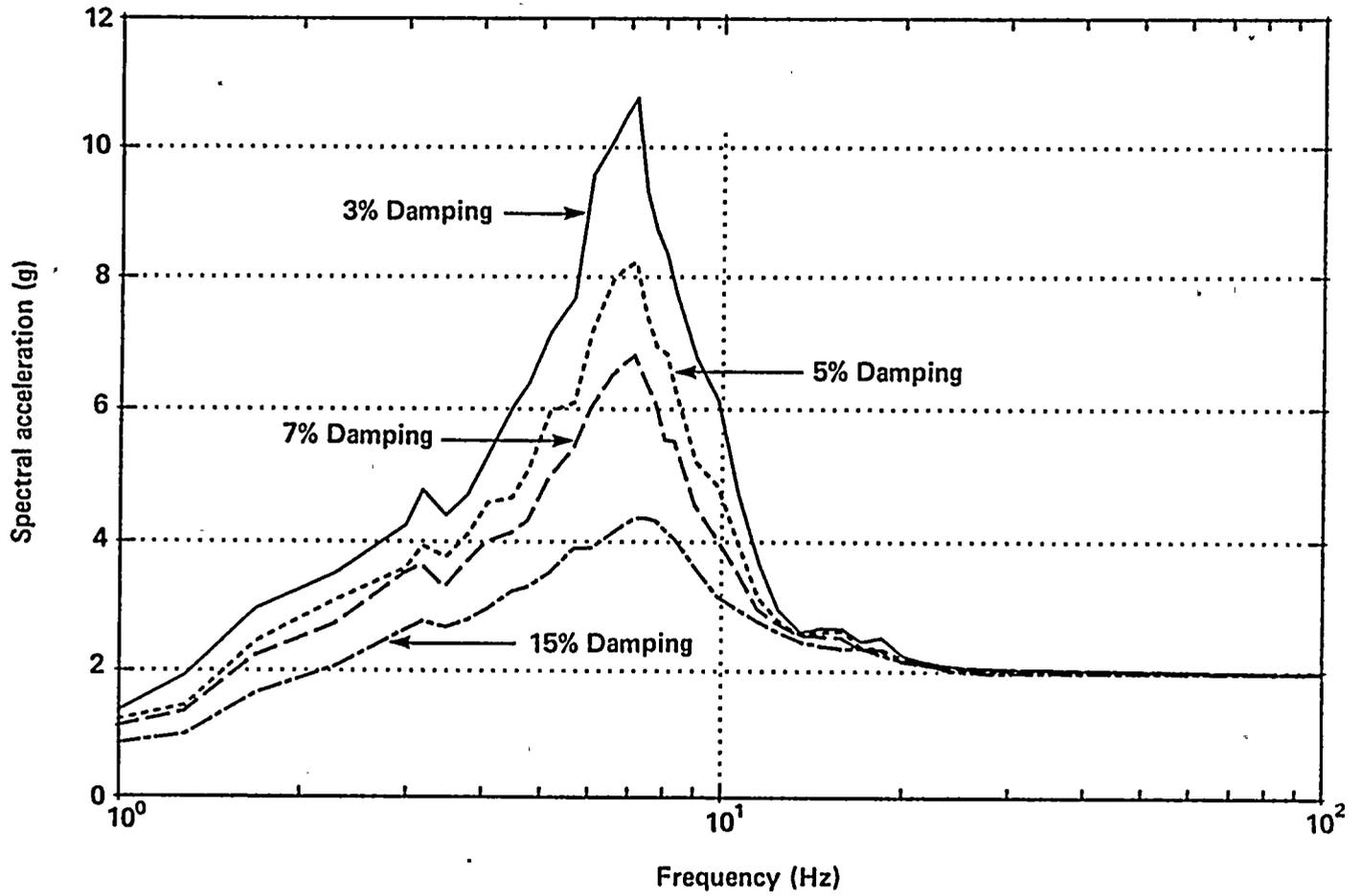


Figure 6-22
84th percentile north/south response spectra for El 140 feet.



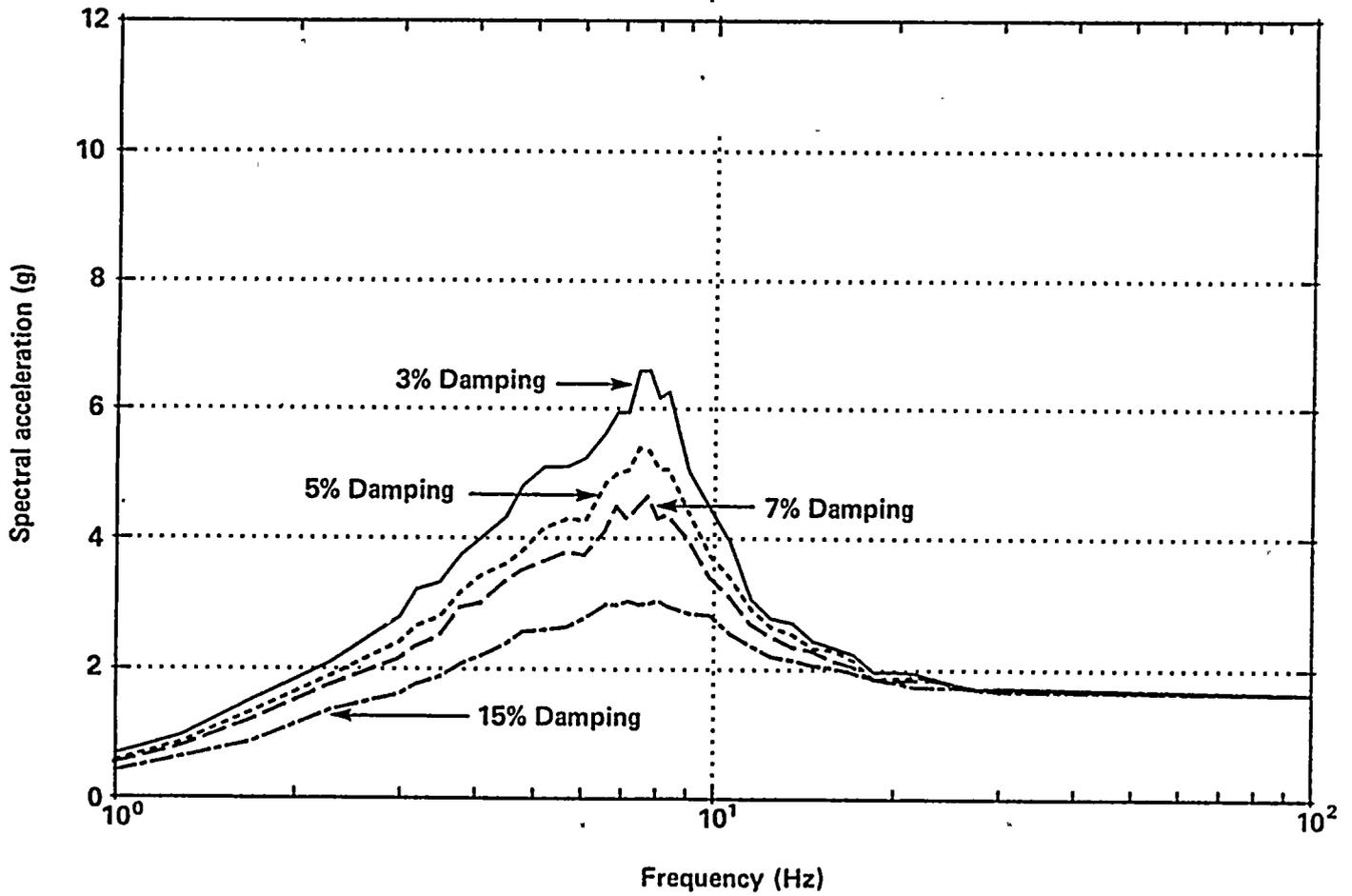


Figure 6-23
50th percentile east/west response spectra for El 140 feet.



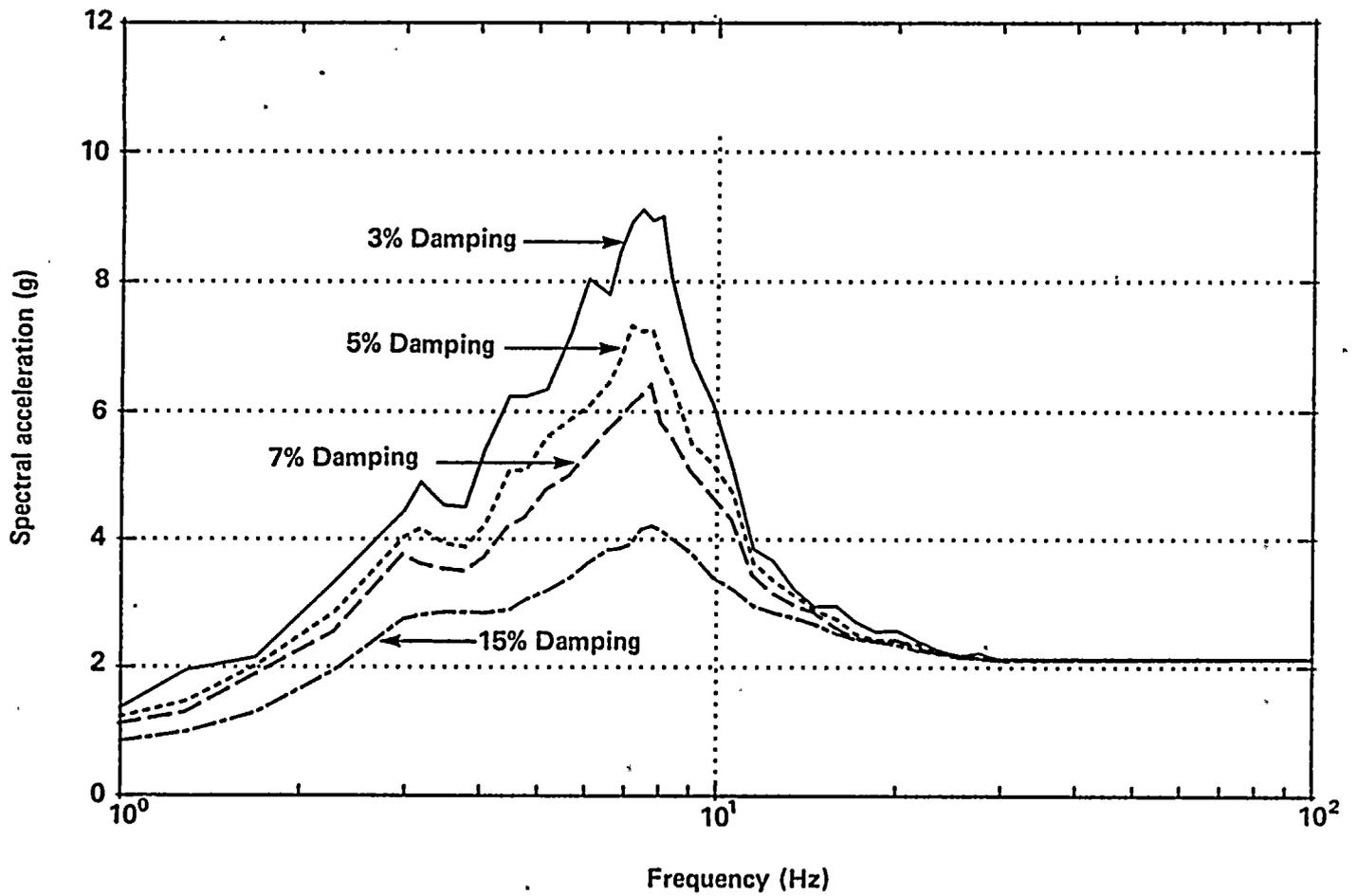


Figure 6-24
84th percentile east/west response spectra for El 140 feet.

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At El 85 feet, corresponding to the basemat of the structure, the entire combined variability over each frequency band is taken to be due to randomness, that is, β_R . It can be seen that the combined variability is relatively insensitive to changes in floor level in the low and high frequency ranges, and thus, in these frequency ranges, the combined variability is also virtually all due to randomness. However, in the frequency bands near the fundamental frequency of the auxiliary building, it can be seen that at higher elevations, the combined variability increases substantially. The majority of the increase in the combined variability is due to the uncertainty associated with the structural property values and is assigned to β_u .

Specific structural response variabilities were not conducted for the containment building, concrete internal structure and the turbine building. The structural response variabilities for equipment located in structures other than the auxiliary building were based upon a conservative application of the result of the auxiliary building evaluation. Referring again to Tables 6-10 and 6-11, the structural variabilities at the basemat (El 85 feet) and high in the structures (approximately El 164 feet) were taken to be as shown below:

ELEVATION	FREQUENCY RANGE		
	Low <0.6 f_n	Mid 0.6 f_n to 1.4 f_n	High >1.4 f_n
BASEMAT	0.24	0.26	0.24
HIGH IN STRUCTURE	0.34	0.41	0.26

where f_n is the median frequency of the appropriate structure, and the low, mid, and high frequency range correspond to the ranges given in Tables 6-10 and 6-11.

Values for other floor levels were interpolated accordingly. The variabilities for equipment located in these other structures were applied as shown above in terms of the ratio of the equipment fundamental frequency to the fundamental frequency of the appropriate structure.

As noted earlier, the factors and variabilities associated with the remaining three structural response parameters not included in the auxiliary building variability study were applied in accordance with the normal separation-of-variables approach.

As part of the soil/structure interactions analysis described in Chapter 5, median reference floor response spectra were developed for various locations of the containment, auxiliary, and turbine building structures. The 5 percent damped median reference floor spectra developed for selected locations in the west core of the auxiliary building from the soil/structure interaction deterministic study were compared with those developed in the structural response variability study. It was found from the comparisons that the spectra showed good agreement. A representative comparison is depicted on Figure 6-25. The peak frequencies of the two spectra were found to be approximately the same, and the spectral accelerations from the soil/structure interaction spectra were found to be only slightly higher than those from the response variability study in the frequency range of interest. Thus, it was judged that the median reference spectra developed in the soil/structure interaction deterministic study were adequate for use in estimating equipment fragilities.

As noted above, the auxiliary building variability study results were used as the basis for the structural response variabilities for the other structures. The median reference floor spectra from the soil/structure interaction study for the containment building, concrete internal structure, and turbine building tended to be somewhat sharply peaked. Therefore, to be certain that the equipment response near the peak of the reference floor spectra was adequately represented for structures other than the auxiliary building, an additional uncertainty variability on the fundamental frequency of the structures was introduced. This additional uncertainty variability of 0.15 was combined with the equipment frequency uncertainty variability in the assessment of the equipment modeling factor.

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Table 6-10
NORTH/SOUTH RESPONSE COMBINED VARIABILITY (β_c)

Floor Elevation (feet)	Frequency Band (Hz)			
	3.5 to 5	5 to 7	7 to 11	11 to 30
85	0.24	0.24		0.18
100	0.24	0.27		0.18
115	0.24	0.32	0.27	0.18
140	0.24	0.37	0.29	0.18
154	0.25	0.40	0.29	0.18
164	0.26	0.41	0.30	0.18

Table 6-11
EAST/WEST RESPONSE COMBINED VARIABILITY (β_c)

Floor Elevation (feet)	Frequency Band (Hz)		
	3.5 to 6	6 to 11	11 to 30
85	0.24	0.28	0.25
100	0.24	0.30	0.25
115	0.24	0.30	0.25
140	0.31		0.25
154	0.32		0.26
164	0.35 *		0.26

*Except for 6.9 to 7.5 hertz, where $\beta_c = 0.47$

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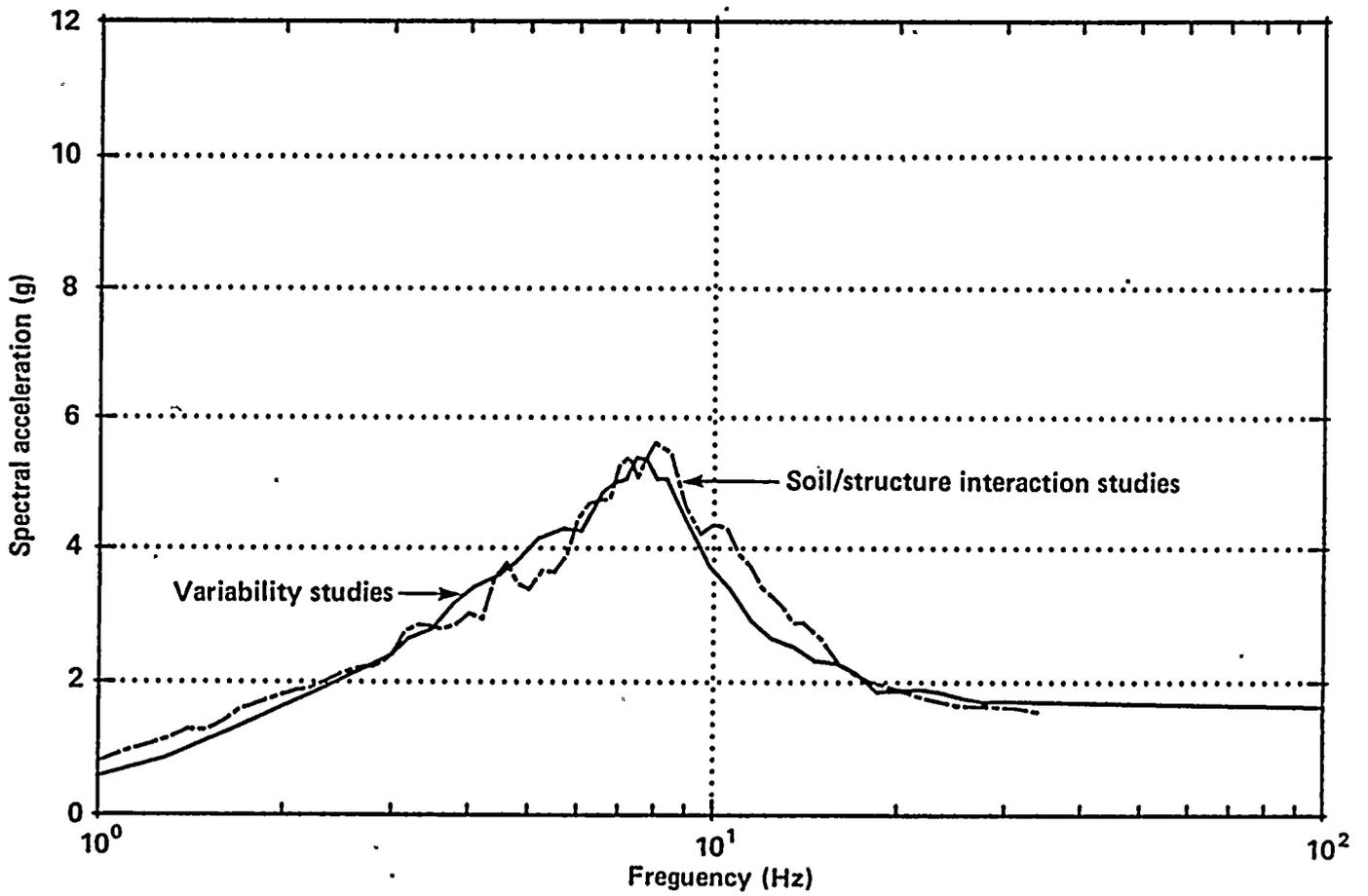


Figure 6-25
Representative comparison of median reference response spectra from the soil/structure interaction and structural response variability studies.

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Turbine Building Nonlinear Analysis

In the Diablo Canyon Long Term Seismic Program, the fragilities (probabilistic seismic capacities) of all major structures (Table 6-2) were obtained using the standard separation-of-variables approach (Kennedy, 1980; Kennedy and Ravindra, 1984) as summarized earlier. From these analyses, it was found that the turbine building has the lowest seismic capacity of the structures and is the only one that could possibly be a significant contributor to the seismically induced risk of core damage. Thus, it was determined that a probabilistically based, nonlinear evaluation of the turbine building would be extremely valuable for the purposes of:

- Improving the probabilistic seismic capacity (fragility) estimates for severe overall distress of the turbine building for use in the seismic probabilistic risk assessment.
- Comparing the fragility estimate based upon multiple nonlinear analyses with the estimate extrapolated from a single median-centered elastic response spectrum analysis obtained using the standard separation-of-variables fragility evaluation method.

As a by-product, it was found that the nonlinear analysis provided an understanding of the relationship between turbine building shear wall distress and various earthquake ground-motion characteristics.

It should be noted that the nonlinear evaluation of the Diablo Canyon turbine building provided both probabilistic and deterministic estimates of the turbine building capacity. It is the intention of this portion of the report to only briefly summarize those aspects of the study leading to the development of the fragility parameters. Details are included in the full report entitled "Probabilistic Evaluation of the Diablo Canyon Turbine Building Seismic Capacity Using Nonlinear Time-History Analysis" (Kennedy and others, 1988).

In a manner similar to that used for the auxiliary building variability study, the variables associated with ground motions spectral shape were represented using a suite of 25 earthquake time histories that provide a broad characterization of the ground motions which might occur at the Diablo Canyon site. Further, the variables associated with structural damping, stiffness, and strength were represented by randomly selecting model parameters for use with the suite of earthquake time-history ground motions.

The 25 earthquake time histories used in the turbine building nonlinear analysis consisted of 21 actual recorded ground motions, some of which have been scaled and modified to correspond to Diablo Canyon magnitude, source-to-site distance, and site conditions, and four semi-numerically generated ground-motion records developed to simulate the magnitude of a strike-slip earthquake on the Hosgri fault.

A total of 200 deterministic nonlinear analyses (25 each at average spectral accelerations of 3.0 g and 6.0 g with median structural properties, and 50 each at average spectral accelerations of 3.0 g, 4.0 g, and 6.0 g using variable structural properties) was performed using a simplified model of the turbine building, which was analyzed using the DRAIN-2D computer code (Kanaan and Powell, 1975). The resulting inelastic structure drift from each deterministic run was compared with a criterion relating inelastic drift to the probability of severe distress and strength degradation. The probabilities of severe distress were then statistically evaluated as a function of the three average spectral acceleration levels and the median seismic capacity and variabilities were estimated. The structural response variables associated with structural modeling, earthquake directional effects, and ground-motion incoherency were then added using the normal separation-of-variables approach.

It should be emphasized again that this study is concerned with the prediction of ground-motion levels associated with the onset of severe structural distress and significant strength degradation of the turbine building and not the prediction of failure capacity. In the Diablo Canyon seismic probabilistic risk assessment, the onset of severe

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structural distress was conservatively used as a surrogate for a structure-induced failure of *all* safety equipment housed in the turbine building.

ANALYSIS MODEL

During Phase II of the Long Term Seismic Program, several possible failure modes that could lead to overall severe distress of the turbine building were investigated using the standard fragility evaluation method. It was concluded that the most probable cause of overall severe distress was substantial inelastic drift and strength degradation of the two major east/west load-carrying shear walls spanning from the foundation level (El 85 feet) to the operating floor (El 140 feet). Thus, the nonlinear analyses consisted of an assessment of the east/west response of the Unit 2 turbine building, with emphasis on the two major east/west load-carrying shear walls below the operating floor.

Figure 6-26 shows a plan view of the Unit 2 turbine building; Figure 6-27 presents a schematic elevation view, emphasizing the major east/west shear walls at column lines 19 and 31 (herein called wall 19 and wall 31), which support the heavy operating floor at El 140 feet. Essentially, walls 19 and 31 are the only two major walls available to resist east/west drift of the heavy operating floor. In turn, nearly all the in-plane lateral loads imposed on these two walls come from the east/west inertial loads of the operating floor, plus their own weight. Although some additional in-plane loads enter due to east/west inertial loads from the intermediate floors, these floor masses are small compared with that of the operating floor, and much of their east/west inertial load is carried by external buttresses added to the turbine building. The inertial loads transferred into Walls 19 and 31 from the superstructure above the operating floor are also small; they were approximated by a slight increase in the weight at the operating floor level. Each wall is 55 feet high by approximately 137 feet long, and contains several openings (particularly wall 19). The thickness of wall 19 varies from 20 inches to about 36 inches over its height. Wall 31 is 24 inches thick over its entire

height. Thus, these walls are long relative to their height and are rather thick.

The operating floor consists of a 12-inch concrete slab supported on a steel beam framing system. It is 139 feet wide and 267 feet long between Walls 19 and 31, plus a 77-foot overhang beyond Wall 31. The slab contains a cutout for the independently supported turbine pedestal which is approximately 59 feet wide by 212 feet long. Thus, for east/west lateral forces, the operating floor was treated as two independent 267-foot-long by about 40-foot-deep beams between Walls 19 and 31.

A minimum gap of 3.375-inch exists between the turbine pedestal and the operating floor. This gap is insufficient to preclude impact between the turbine pedestal and the operating floor at the high ground-motion levels of interest in the fragility evaluation. Furthermore, the effective inertial mass to be lumped at the top of the turbine pedestal exceeds the entire inertial mass supported by wall 19 plus wall 31; therefore, impact of the turbine pedestal potentially could lead to additional distress in the shear walls. Thus, the turbine pedestal was included in the nonlinear model together with a gap element interconnecting it to the operating floor beam elements on each side.

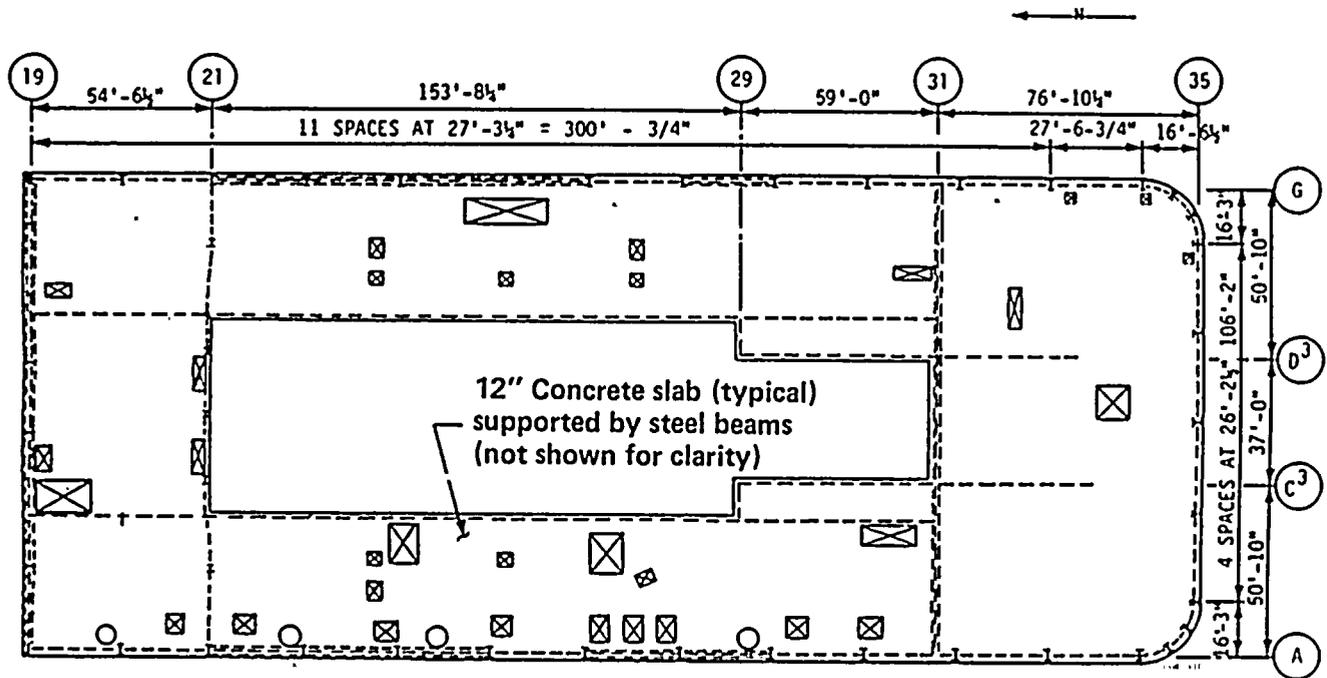
Due to their relative ductility, severe distress of the shear walls was expected to occur well before failure of either the operating floor beam elements or the turbine pedestal. For this reason, walls 19 and 31 were modeled in more detail than either the operating floor beam elements or the turbine pedestal. The operating floor and turbine pedestal were only modeled in sufficient detail to approximate their potential for distributing inertial loads to the shear walls. The shear walls were modeled into three segments each along their height, corresponding to points where both the stiffness and strength of the walls greatly change. Because of the low height-to-length ratio, the wall shear stiffness is generally greater than the flexural stiffness and the shear capacity is generally less than the flexural capacity. Each shear wall segment was modeled with both a nonlinear shear element and a nonlinear flexural element combined in series, because each element has different nonlinear properties.

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EXPLANATION

- Continuous chord beams
- ===== Shear wall

Figure 6-26

Turbine building Unit 2 concrete outline at El 140 feet.

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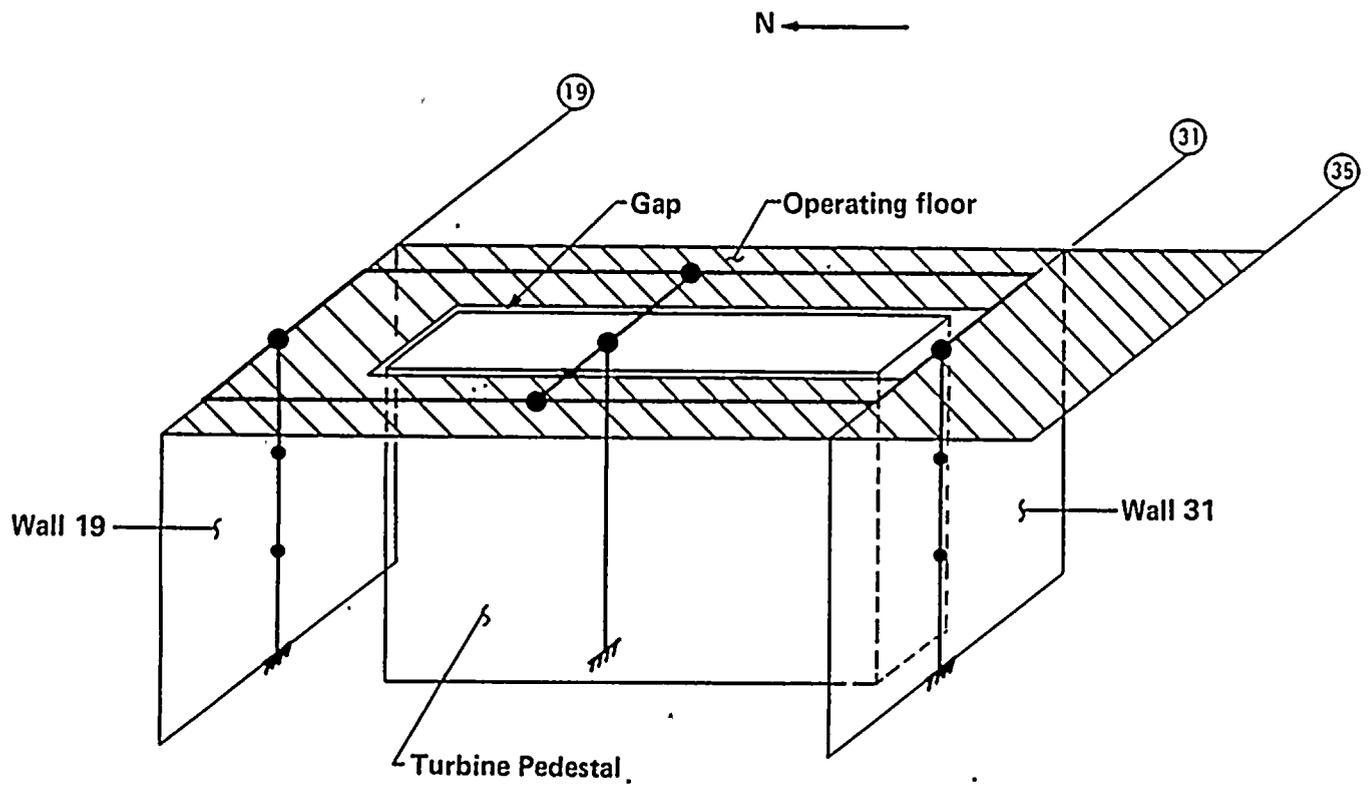


Figure 6-27
Schematic illustration of turbine building nonlinear model.

The analysis was concerned only with east/west response due to an east/west input; therefore, the schematic model (Figure 6-27) was simplified into a two-dimensional model (Figure 6-28). This model consists of the two shear walls subdivided into three segments (stories) each, two operating-floor beam elements, and the turbine pedestal with a 3.375-inch separation gap between the pedestal and the operating floor beam elements. Model properties, including

masses, element strengths, and stiffnesses are summarized in Tables 6-12 through 6-14, respectively. Elastic modal characteristics of this model are summarized in Table 6-15.

FORCE-DEFLECTION DIAGRAM FOR SHEAR DRIFT

Reinforced concrete walls resist shear through various mechanisms. Initially, the wall is elastic and shear resistance is developed according to elastic beam theory. Inclined shear cracks develop when the principal tensile stresses exceed the concrete tensile strength. Once shear cracks open, the shear force is resisted mainly by the reinforcing bars and aggregate interlock. Other mechanisms such as dowel action, truss action, and the flexural compression zone also contribute

to the shear resistance. The opening and closing of cracks under load reversals causes a pinching behavior to be noted in the hysteresis loops. Also, as shear cracks open wider and damage to the concrete increases, the contribution of concrete, through aggregate interlock, to shear resistance decreases. This effect causes strength degradation under large displacement cycles. A typical shear force-shear distortion diagram obtained during a structural wall test is shown on Figure 6-29 (Wang, 1975), which illustrates the reverse-cycle loading behavior characterized by stiffness degradation and pinching of the hysteresis loops. This behavior was approximated by the 10 Rule hysteretic model shown on Figure 6-30. The shear force-deformation curves used for the operating floor beams and the turbine pedestal are shown on Figures 6-31 and 6-32, respectively.

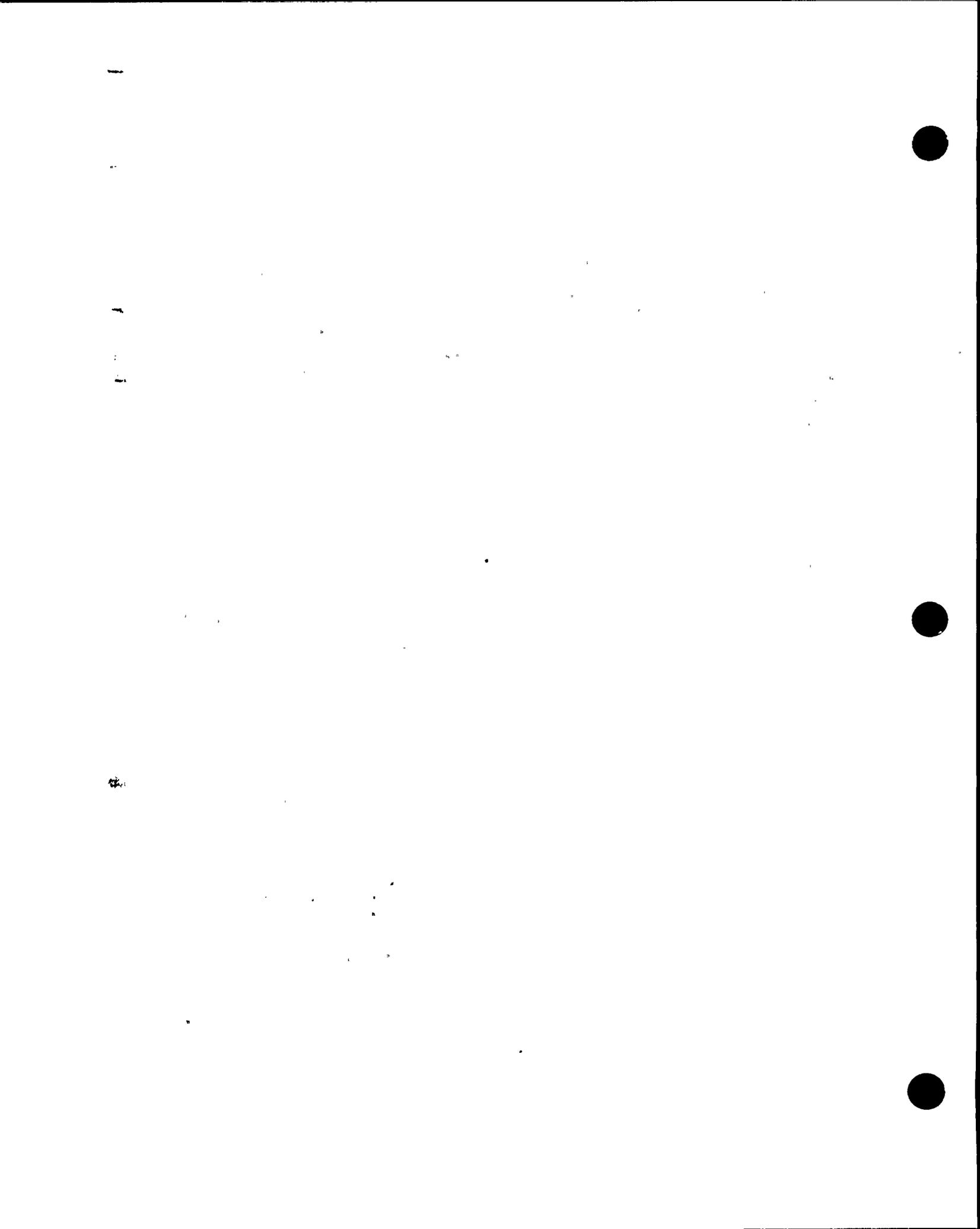
VARIABLE STRUCTURE PROPERTIES

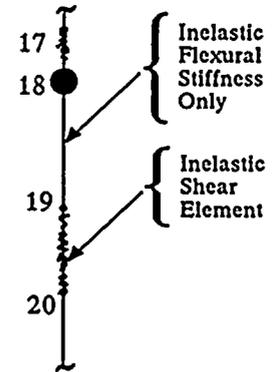
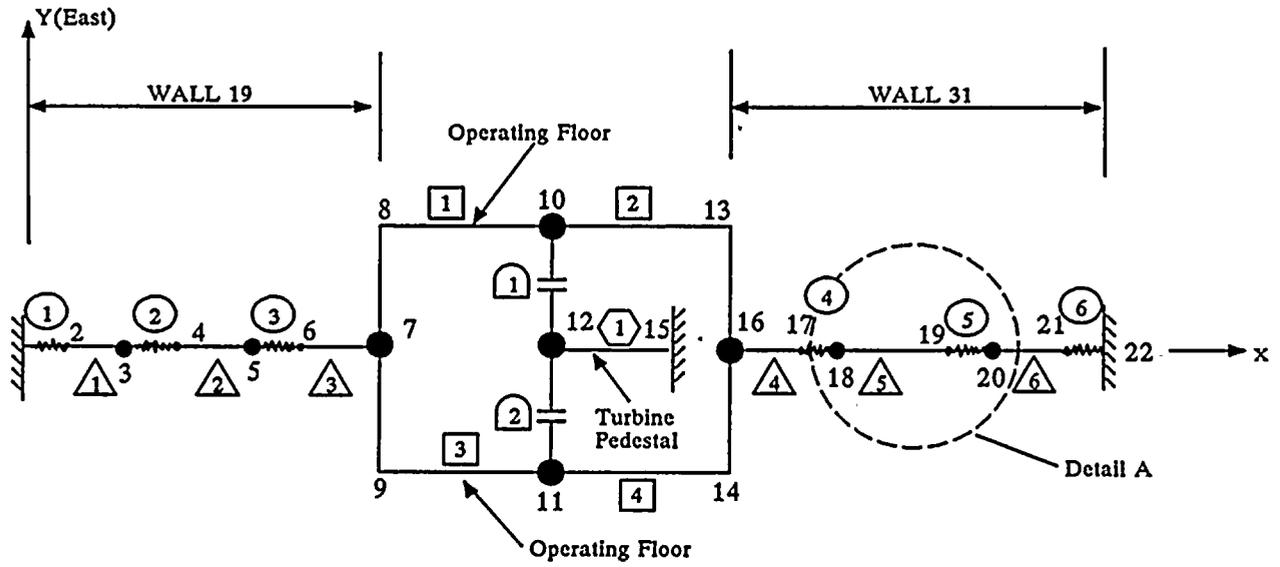
To study the dispersion in the response due to uncertainty in structure properties, a Monte Carlo technique was used in the turbine building nonlinear analysis. Important structure variables affecting structure response (damping, stiffness, and strength), were assumed to be lognormally distributed with median and logarithmic standard deviations as shown below:

Variable	Median Value	Logarithmic Standard Deviation		
		Random	Uncertainty	Composite
Damping	7%	0	0.35	0.35
Stiffness Ratio	1.0	0	0.50	0.50
Strength Ratio	1.0	0	0.25	0.25

Note that the stiffness and strength ratios were used to scale the median stiffnesses and median strengths of each of the structural elements of the nonlinear model. For each nonlinear analysis, the median stiffnesses and strengths of the shear walls, operating floor, and turbine pedestal were multiplied by a probabilistically defined stiffness and strength ratio. Stiffness and strength ratios were independently defined for each element type (shear walls, operating floors, and turbine pedestals). Thus, a given element could

simultaneously have a high stiffness ratio and a low strength ratio. Similarly, shear walls could have a low strength ratio and the operating floor have a high strength ratio. However, all six shear wall elements in shear and flexure had the same stiffness and strength ratios in a given analysis. Similarly, the four operating floor elements had the same stiffness and strength factors in a given analysis. The 50 sets of stiffness ratios, strength ratios and damping shown in Table 6-16 were independently selected.





DETAIL A

- ⊙ i - Inelastic Shear Elements (Shear Deformation Only)
- △ i - Inelastic Flexural Beam Element (Flexural Deformation Only)
- i - Operating Floor Element
- ⬡ i - Turbine Pedestal
- ⊞ i - Gap Element

Figure 6-28
Turbine building DRAIN-2D model.

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Table 6-12
NODAL MASSES OF TURBINE BUILDING NONLINEAR MODEL

<u>Node No.</u>	<u>Weight (kips)</u>	<u>Comment</u>
3	1,573	Wall 19 and Floor at El 104
5	832	Wall 19 and Floor at El 123
7	4,219	Wall 19 and Operating Floor
10	2,250	Operating Floor
11	2,250	Operating Floor
12	25,000	Turbine Pedestal
16	6,331	Wall 31 and Operating Floor
18	2,130	Wall 31 and Floor at El 119
20	2,460	Wall 31 and Floor at El 107

Table 6-13
MEDIAN CAPACITIES OF SHEAR WALL ELEMENTS

<u>Concrete Shear Wall</u>	<u>Shear Capacities</u>		<u>Flexural Capacities</u>	
	<u>Concrete Only V_C (kips)</u>	<u>Ultimate V_U (kips)</u>	<u>Yield Moment M_U (kip-ft)</u>	<u>Equivalent Yield Shear V_M (kips)</u>
WALL 19				
El 140 to El 123	10,600	12,800	0.23×10^6	13,700
El 123 to El 104	11,000	13,300	0.39×10^6	11,200
El 104 to El 85	9,200	13,500	0.71×10^6	14,100
WALL 31				
El 140 to El 119	13,200	16,600	0.64×10^6	30,700
El 119 to El 107	17,000	21,700	0.72×10^6	24,800
El 107 to El 85	15,000	19,200	1.04×10^6	22,300

Table 6-14
EFFECTIVE ELASTIC SHEAR AND FLEXURAL STIFFNESS OF SHEAR WALLS

<u>Concrete Shear Wall</u>	<u>Effective Shear Stiffness (kips/ft)</u>	<u>Effective Flexural Stiffness (kips/ft)</u>
WALL 19		
El 140 to El 123	1.14×10^6	6.13×10^7
El 123 to El 104	1.22×10^6	7.55×10^7
El 104 to El 85	2.25×10^6	5.05×10^7
WALL 31		
El 140 to El 119	1.71×10^6	24.2×10^7
El 119 to El 107	3.10×10^6	99.0×10^7
El 107 to El 85	1.60×10^6	16.0×10^7

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Table 6-15

**ELASTIC MODAL PROPERTIES OF THE TURBINE BUILDING MODEL WITH MEDIAN
STRUCTURE PROPERTIES**

(A) MODAL FREQUENCIES

<u>Mode</u>	<u>Natural Frequency (Hz)</u>	<u>Remarks</u>
1	3.1	Turbine Pedestal
2	4.0	Operating Floor
3	8.6	Wall at Line 31
4	9.5	Wall at Line 19

(B) MODAL SHEARS, AND MOMENTS

<u>Element</u>	<u>Modal Shears (klps/g)</u>					<u>Modal Moments (klp-ft/g)</u>				
	<u>Mode 1</u>	<u>Mode 2</u>	<u>Mode 3</u>	<u>Mode 4</u>	<u>Total Higher Modes</u>	<u>Mode 1</u>	<u>Mode 2</u>	<u>Mode 3</u>	<u>Mode 4</u>	<u>Total Higher Modes</u>
Turbine Pedestal	25,000	—	—	—	—	—	—	—	—	—
WALL 19										
Operating Floor (Per Beam)	—	1,410	-20	-260	0	—	—	—	—	—
EI 123+	—	3,470	-390	3,820	-420	—	59,000	-7,000	65,000	-7,000
EI 104+	—	3,550	-430	4,360	-160	—	126,000	-15,000	148,000	-10,000
EI 85+	—	3,600	-460	4,740	1,010	—	195,000	-24,000	238,000	9,000
WALL 31										
Operating Floor (Per Beam)	—	1,460	-310	-40	0	—	—	—	—	—
EI 119+	—	3,660	5,580	160	-840	—	77,000	117,000	4,000	-18,000
EI 107+	—	3,820	7,020	230	-380	—	123,000	201,000	6,000	-22,000
EI 85+	—	3,950	8,190	280	740	—	210,000	381,000	12,000	-6,000

(C) MODAL DISPLACEMENTS

<u>Location</u>	<u>Drifts (Inches/g)</u>			
	<u>Mode 1</u>	<u>Mode 2</u>	<u>Mode 3</u>	<u>Mode 4</u>
Top of Turbine Pedestal	1.040	—	—	—
Center of Operating Floor		0.768	-0.019	-0.015
WALL 19				
EI 140	—	0.098	-0.011	0.111
EI 123	—	0.056	-0.007	0.070
EI 104	—	0.020	-0.003	0.026
WALL 31				
EI 140	—	0.071	0.129	0.004
EI 119	—	0.044	0.090	0.003
EI 107	—	0.030	0.062	0.002



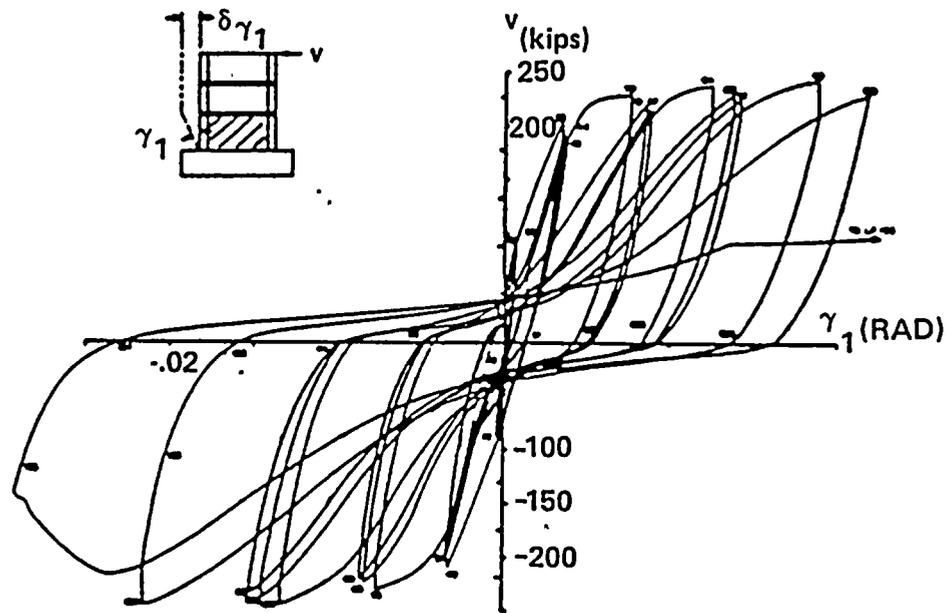


Figure 6-29

Cyclic load-deflection behavior of concrete shear walls (Wang, 1975).



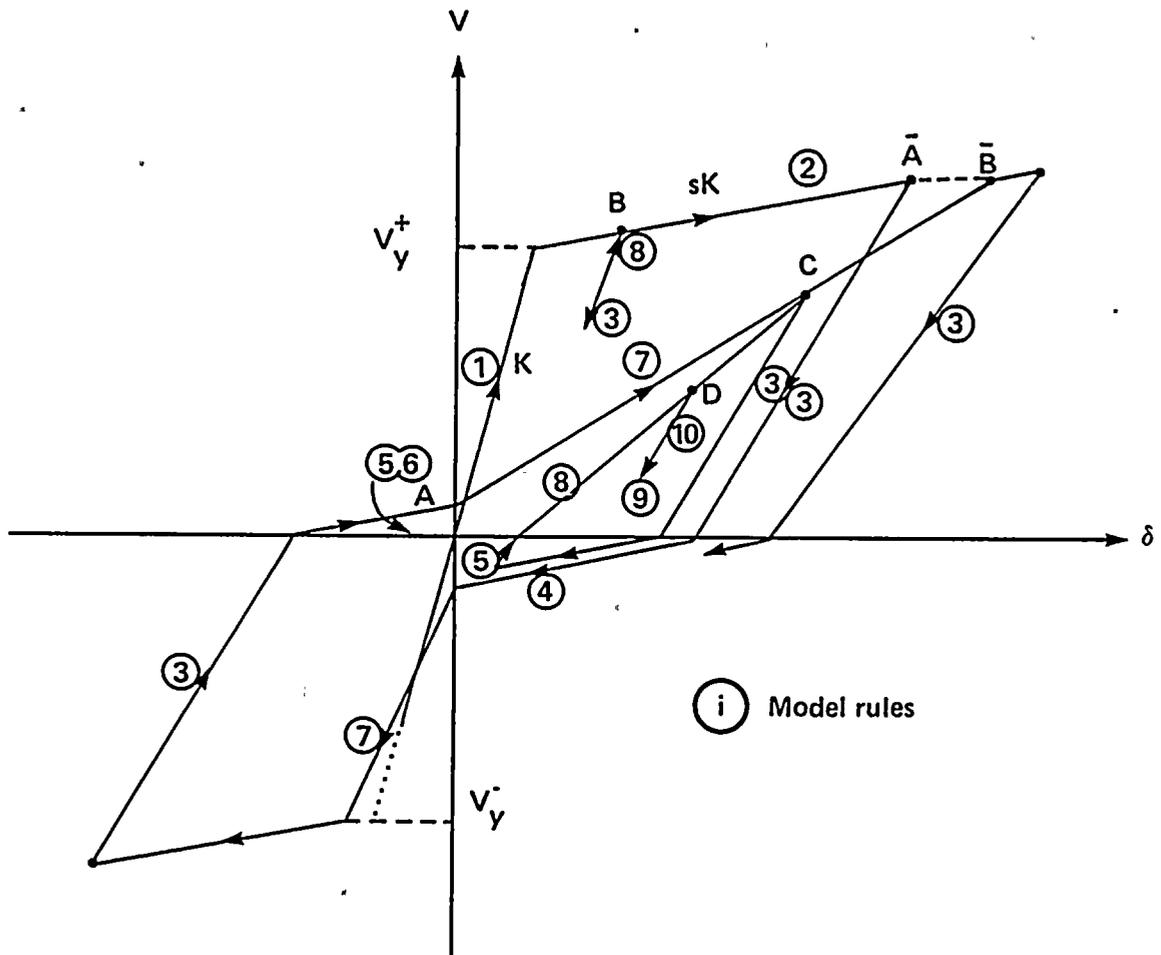
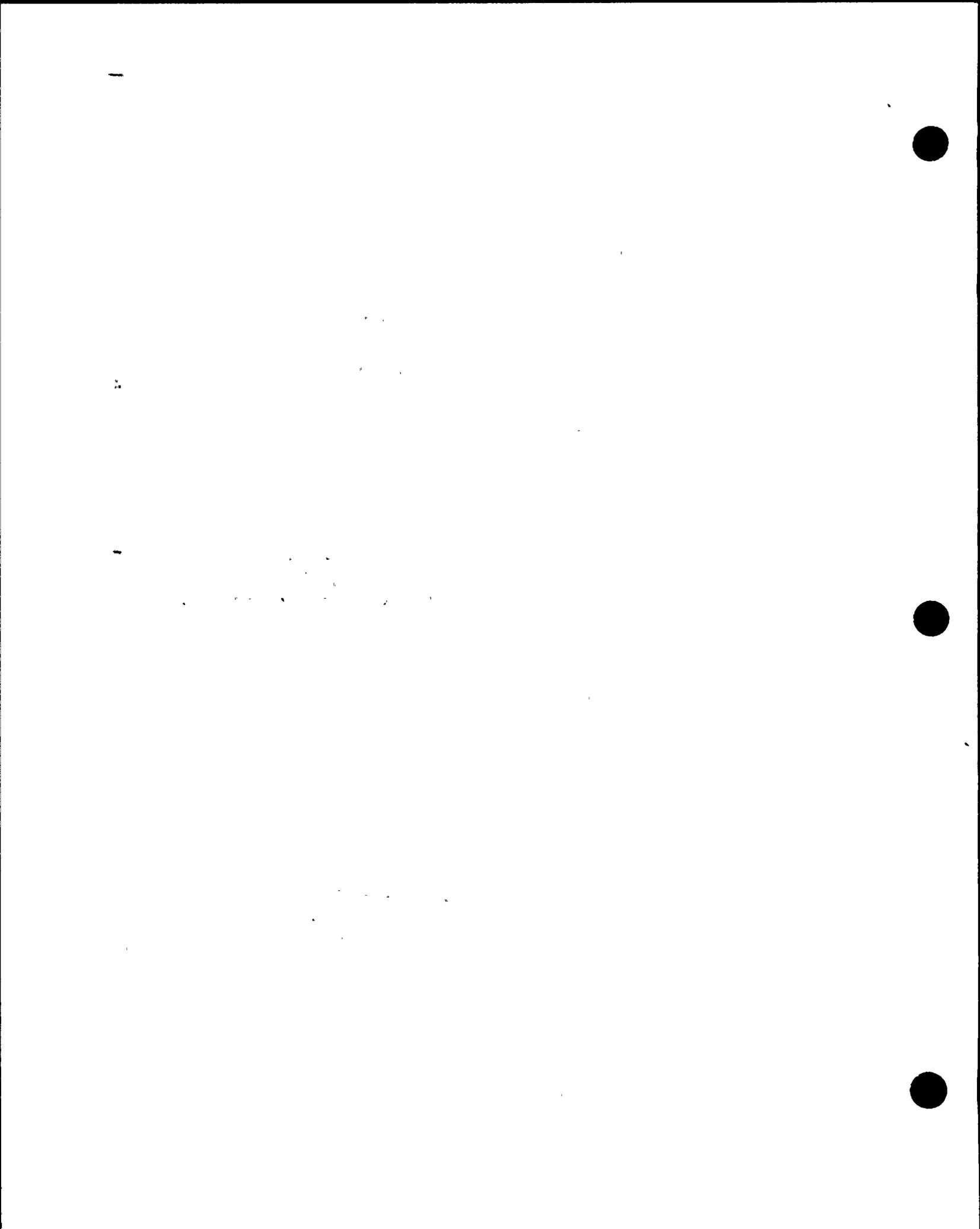


Figure 6-30

Shear deformation hysteretic behavior.



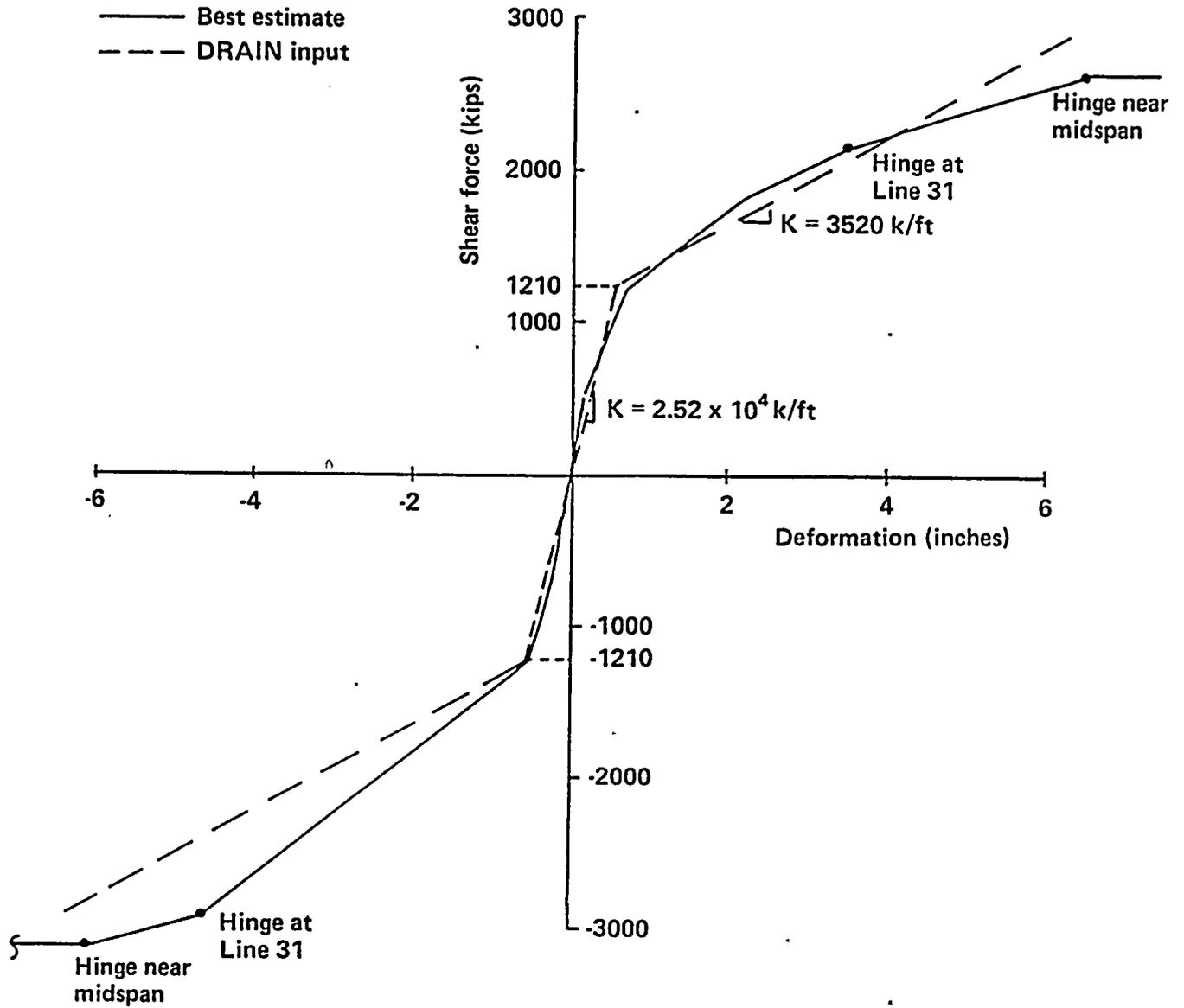


Figure 6-31

Shear deformation curve of the beam-like portion of the operating diaphragm at the midspan for each of four beam elements.



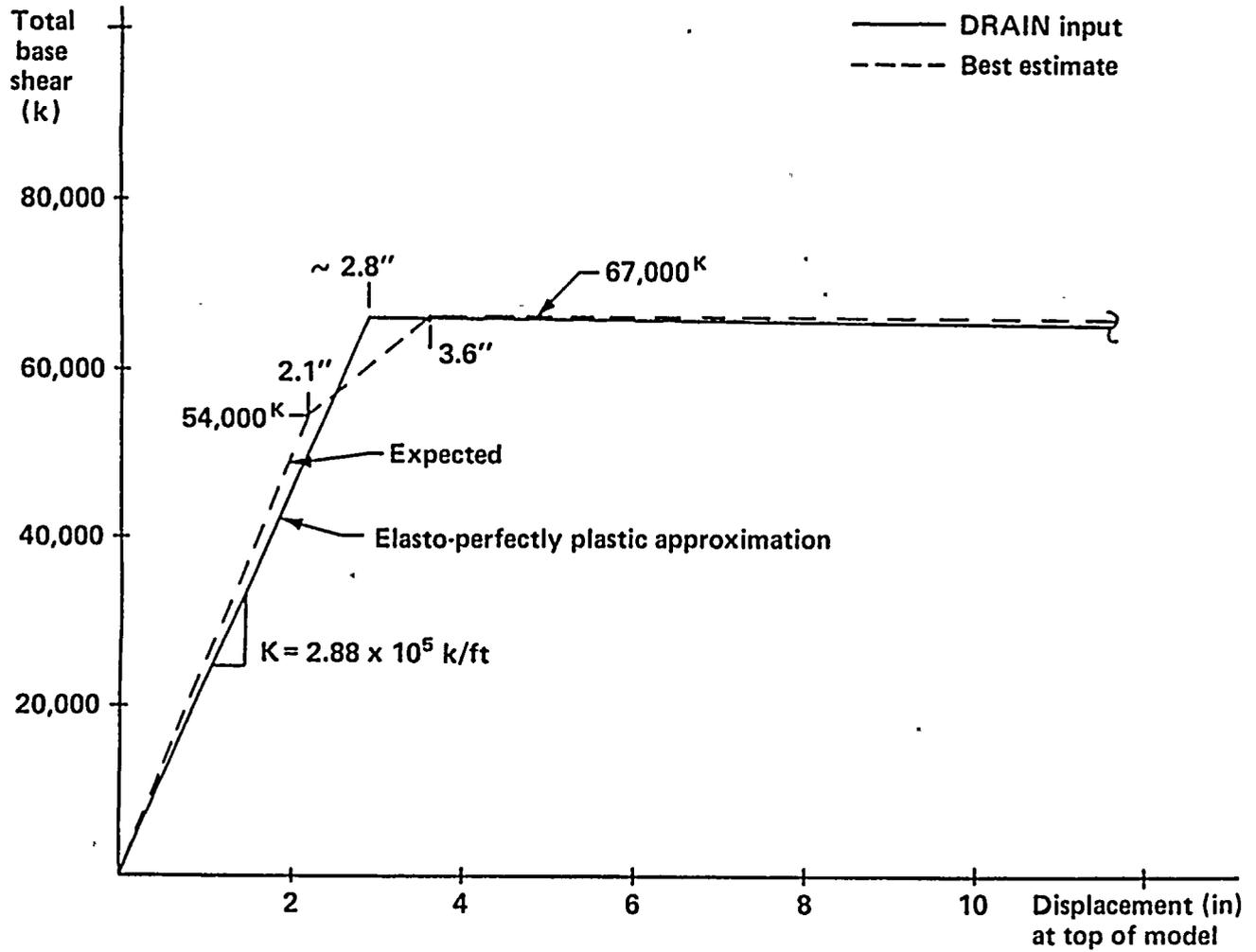


Figure 6-32

Shear-deformation curve of the turbine pedestal.

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Table 6-16
 VARIABLES OF MODEL STRUCTURE PROPERTIES

Trial Number	System Damping Value	Stiffness Ratio			Strength Ratio		
		Shear Walls	Operating Floor	Turbine Pedestal	Shear Walls	Operating Floor	Turbine Pedestal
1	.0601	.9343	.8421	1.4495	1.1481	.9319	1.1148
2	.0793	1.0607	.9839	.6679	1.0732	.9263	1.2484
3	.1155	.9275	1.0205	.4355	.9692	1.8888	1.0005
4	.1009	1.0914	1.7003	.7948	.8729	1.2734	1.0282
5	.1023	2.1317	1.5155	1.2248	1.4069	1.1721	1.1336
6	.0582	3.0935	.6578	1.3189	.6618	1.3248	1.4670
7	.0585	1.0504	1.1815	.5977	1.0734	.7686	1.4773
8	.0568	.9974	1.5550	1.0877	1.2396	.7181	.7032
9	.0684	1.5548	.5104	.8385	1.3007	1.2217	1.5525
10	.0698	1.1254	1.3876	2.2731	1.4946	.8750	.7939
11	.0704	.4634	1.1817	.4356	.7953	1.0006	1.1623
12	.1493	1.4327	1.3365	1.3245	.9122	1.0389	1.5407
13	.0572	.6004	1.3288	1.0898	.7238	.8229	1.1988
14	.0927	1.5996	.9293	2.1709	.9210	1.3397	1.3248
15	.1123	.4682	1.0784	.6464	.8982	.6652	.8286
16	.0652	1.2137	1.0849	1.1087	.7419	1.4439	.8299
17	.1053	1.1349	1.7651	2.0897	.6416	1.1718	.9177
18	.0609	2.1395	.9588	.5845	1.0878	.8770	.9039
19	.1096	1.2604	1.6396	2.5241	1.1662	1.6452	1.1995
20	.1074	1.6790	.8242	2.5171	.8942	.8675	1.0032
21	.0596	.6275	.7439	.6320	.8245	.7250	.7423
22	.0760	1.0896	1.0855	.5099	.8584	1.4128	1.0756
23	.1369	3.5920	.8568	1.3599	1.2019	.9804	1.1332
24	.0831	1.0797	.9291	.6403	1.5220	.5480	1.0474
25	.1240	1.0087	.9222	1.8344	.6911	.6206	1.0911
26	.0772	.5653	.8310	.8607	1.0071	.8561	.8499
27	.1136	1.3648	.5680	.6208	1.3277	.7726	1.3637
28	.0910	.6796	1.1320	1.4513	.9571	1.0147	.7058
29	.0496	2.2296	1.8930	1.1704	1.0630	1.1235	1.3609
30	.0486	.9323	3.7765	2.3605	1.4893	.6491	1.6148
31	.0538	.4250	.5502	2.0228	1.1503	.6496	.9712
32	.1009	1.1350	.5983	2.5905	.8772	.8909	.6511
33	.0949	.8769	2.0427	.9961	.7191	1.2164	.6773
34	.0365	1.1243	1.9010	.7875	1.5064	.7779	1.0995
35	.1507	1.6397	3.7699	1.4291	.9167	1.0773	1.2275
36	.0334	.8274	.9919	.5106	.9336	1.0267	.6908
37	.0523	.6222	1.4331	.9317	.9753	.8322	1.2863
38	.0357	.6568	1.4558	1.4051	.9462	1.0556	1.5023
39	.0603	1.0507	1.2858	1.2992	1.0741	.6953	.8159
40	.0753	.9401	1.7601	1.0112	.7298	.7261	1.5294
41	.0637	1.2890	.8582	.8481	.8885	.7238	.8793
42	.0391	.5772	.8199	.9413	.5133	.8863	1.2748

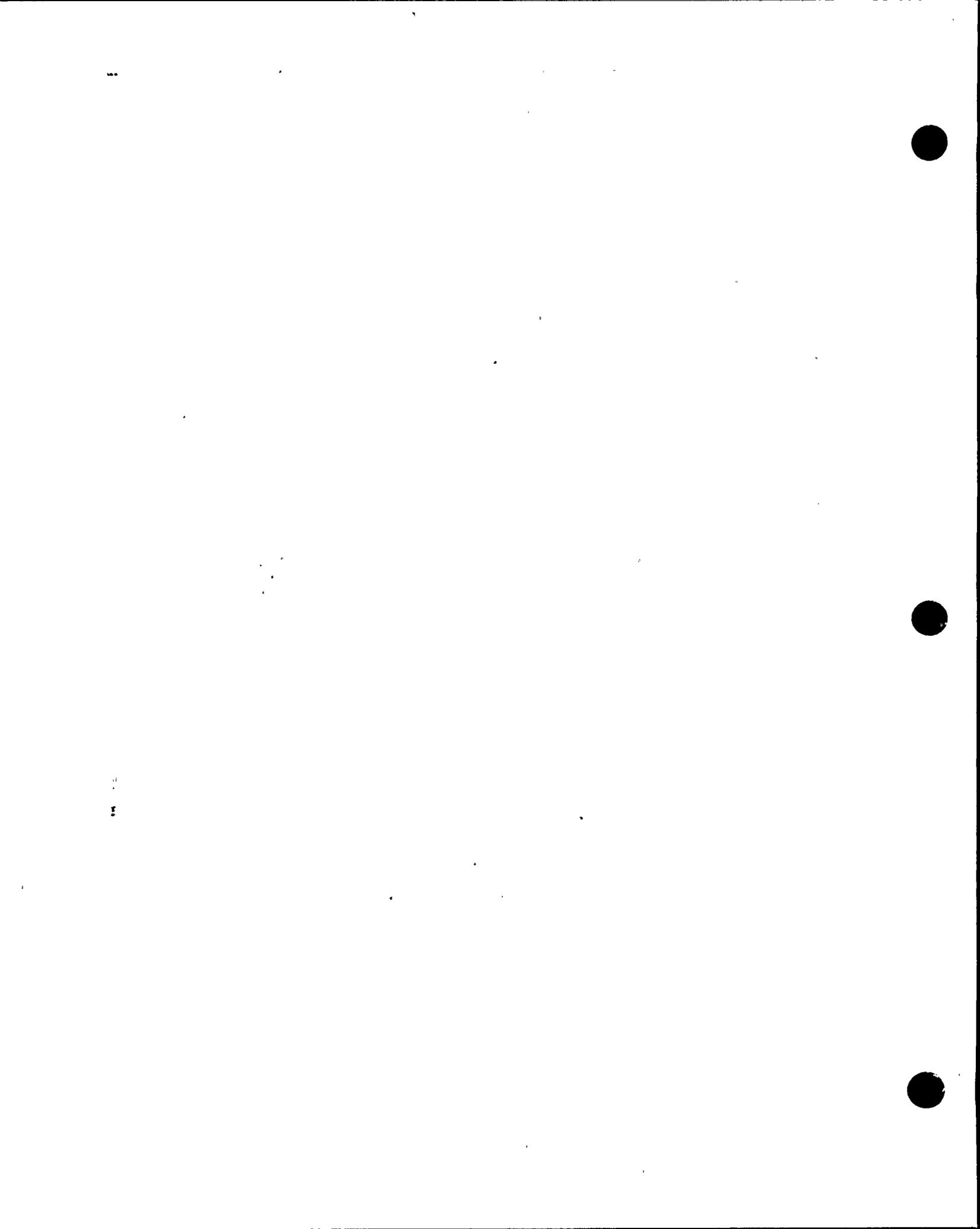


Table 6-16 (Continued)
 VARIABLES OF MODEL STRUCTURE PROPERTIES

Trial Number	System Damping Value	Stiffness Ratio			Strength Ratio		
		Shear Walls	Operating Floor	Turbine Pedestal	Shear Walls	Operating Floor	Turbine Pedestal
43	.1107	1.1182	1.3084	.4553	.9878	1.1935	1.1383
44	.1180	2.6135	.8649	1.0102	.7662	1.1832	.9608
45	.1142	3.3185	1.5687	.8905	1.1715	.9960	.9420
46	.1162	.8227	1.1182	.7581	.8490	1.6054	.7599
47	.0783	1.0485	3.6193	.9812	1.0399	1.2617	.8452
48	.0538	1.3866	.6226	.5341	.8526	1.0049	.9262
49	.0403	.6810	1.2759	.5473	1.1852	1.0856	1.2072
50	.0616	.3445	.4155	.8854	1.1008	1.1917	1.2165

INPUT MOTION

A single ground-motion parameter was used to define the fragilities of Diablo Canyon structures and equipment. The 5 percent damped average spectral acceleration over the 3 to 8.5 hertz range was chosen to convolve the seismic hazard and seismic fragilities for use in the probabilistic risk assessment.

Twenty-one earthquake time-history records (Table 6-17) representing actual recorded events were selected for use in this study based upon the following selection criteria:

- 1) The records should be appropriate for shallow crustal earthquakes in the magnitude range from 6.5 to 7.5 with recording distances appropriate for the Hosgri fault zone.
- 2) The records should be appropriate for rock-site conditions.
- 3) The records should represent, in the aggregate, about a 50-50 mixture of thrust and strike-slip faulting.
- 4) The records should be appropriate for ground motions having very high average spectral accelerations (defined as the average 5 percent damped spectral acceleration in the 3 to 8.5 hertz range), of 2.0 g or greater. Ground motions with average spectral acceleration less than about 2.0 g are undamaging to the turbine building and are thus of little interest.

Only the Tabas and Pacoima Dam records (Records 3 through 6) met the above criteria in their original unmodified form. Although average spectral acceleration was too low, the Gazli records (Records 1 and 2) clearly met Criteria 1 and 2. All other empirical records had to be modified for distance (frequency-independent scaling) and/or magnitude and site conditions (non-constant, frequency-dependent correction). After modification, all 21 empirical records met Criteria 1 and 2. Table 6-17 lists the characteristics of both the original and the modified records and the average spectral acceleration for each record after modification.

Even after modification, only a few of the empirical records met Criterion 4; it was assumed the records could be further modified by frequency-independent upward scaling to achieve desired values of average spectral acceleration. Due to the paucity of near-source, strong-motion records from rock sites for magnitude approximately 7.0 strike-slip earthquakes, records 22 through 25 were added (Criterion 3). These are simulated ground-motion records generated by semi-numerical methods to represent a magnitude 7.0 M_s strike-slip earthquake on the Hosgri fault.

To study the randomness variability of the ground motions on the shear wall drifts, each of the 25 modified earthquake ground-motion time histories listed in Table 6-17 were constant-amplitude (frequency-independent) scaled to obtain the same average spectral acceleration in the frequency range of 3 to 8.5 hertz. Using median structural properties, shear wall drifts were computed from the nonlinear analyses for average spectral acceleration values of 3.0 g and 6.0 g (25 trials each). Figure 6-33 presents the 5 percent damped response spectra for three of the records, each scaled to an average spectral acceleration of 3.0 g to illustrate the diversity of spectral shapes included. Figure 6-34 depicts the mean, median, 84 percent probability of non-exceedance, and upper-bound spectra for the ensemble of 25 records scaled to an average spectral acceleration of 2.25 g.

To study the combined influence of the randomness variability associated with the ground motions and the uncertainty variability associated with the structural properties, each of the 25 modified ground-motion records was scaled to average spectral acceleration values of 3.0 g, 4.0 g, and 6.0 g, and each was used twice (Trials 1 through 25 and Trials 26 through 50), in combination with the 50 sets of variable structural properties shown in Table 6-16 (150 total trials).

SHEAR WALL DRIFT LIMIT

The drifts associated with Walls 19 and 31 were established from each of the 200 nonlinear trials using median and variable structural properties. To calculate the corresponding probability of

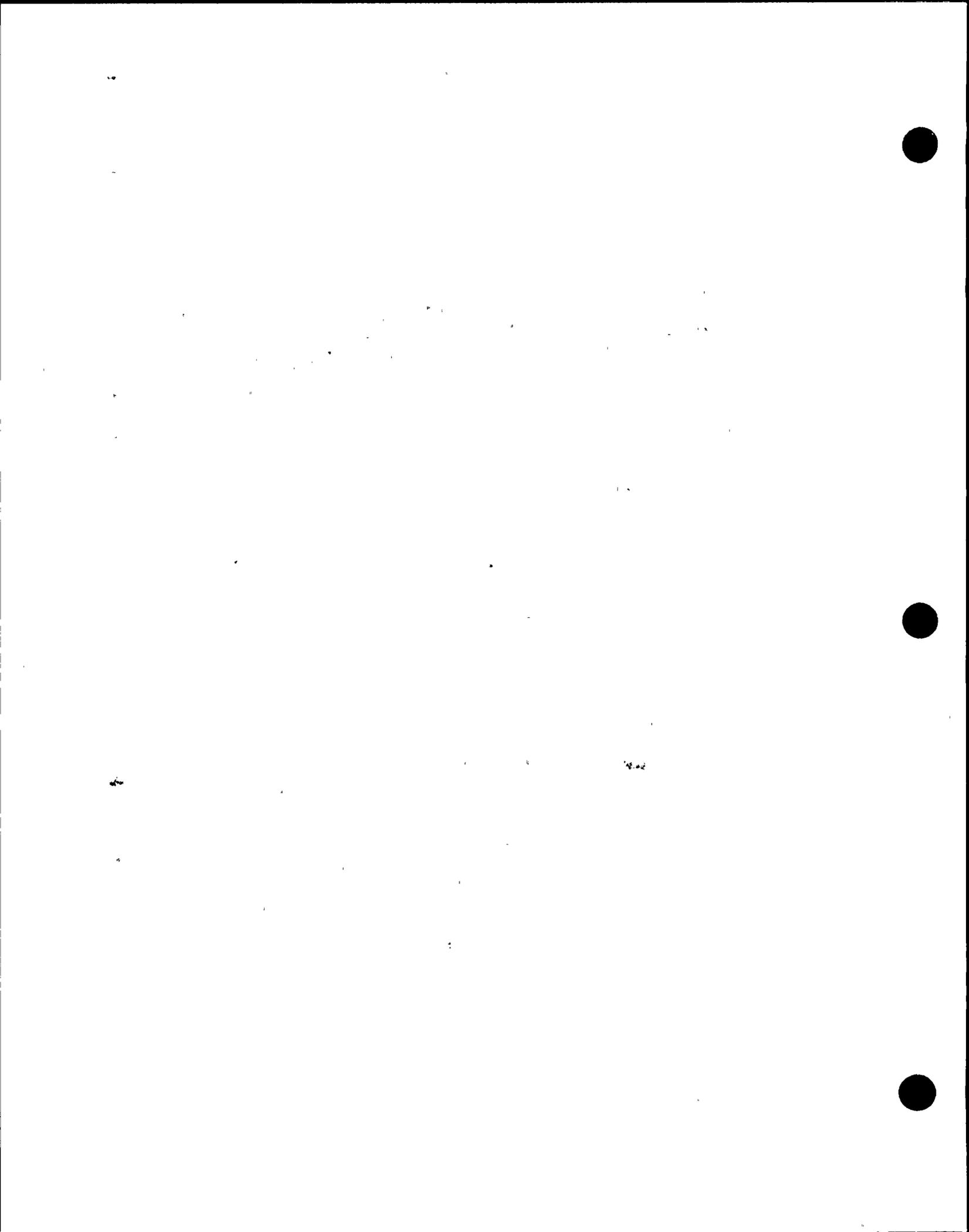


Table 6-17
EARTHQUAKE TIME HISTORIES

<u>Earthquake Date</u>	<u>Magnitude</u>	<u>Style of Faulting</u>	<u>Recording Station Distance</u>	<u>Time History Number</u>	<u>Component</u>	<u>Site Conditions</u>	<u>Time History Adjustments</u>	$\frac{\bar{S}}{S} _{3-8.5 \text{ Hz}}$ (g)
Gazli, U.S.S.R. May 17, 1976	6.8	Reverse	Karakyr Point 3 km	2	East	Rock/stiff alluvium	None	1.33
				1	North			1.31
Tabas, Iran Sept. 16, 1978	7.4	Thrust	Tabas 3 km	4	N16W	Stiff alluvium/rock	None	2.48
				3	N74E			2.27
San Fernando, CA Feb. 9, 1971	6.6	Thrust	Pacolma Dam 3 km	5	S16E	Rock	None	2.00
				6	S74W			1.89
			Lake Hughes No. 12 20 km	7	N21E	Rock	Distance	2.38
				8	N69W			2.27
			9	N69W	Stiff alluvium	Distance	1.69	
Imperial Valley, CA Oct. 15, 1979	6.5	Strike-Slip	Differential Array 5 km	10	N00E	Deep alluvium	Site response	1.38
				11	N90W			1.55
			El Centro No. 4 4 km	12	S50W	Deep alluvium	Site response	0.75
				13	S40E			1.16
			Parkfield, CA Jun. 27, 1966	6.1	Strike-Slip	Temblor 10 km	14	N65W
15	S25W	1.33						
Morgan Hill, CA Apr. 24, 1984	6.2	Strike-Slip	Coyote Lake Dam 0.1 km	16	N75W	Rock	Magnitude	2.29
				17	S15W			1.95
Coalinga, CA May 2, 1983	6.5	Reverse	Pleasant Valley Pump Station (Switchyard) 10 km	18	N45E	Stiff alluvium/rock	Distance	1.63
				19	S45E			2.38
Tabas, Iran Sep. 16, 1978	7.4	Thrust	Dayhook 17 km	20	N10E	Rock	Distance	1.12
				21	N80W			1.67
Hosgrl Simulations	7.0	Strike-Slip Bilateral	-	22	North	-		1.16
				23	East			1.47
		Strike-Slip Unilateral	-	24	North	-	0.98	
25	East	-	1.56					



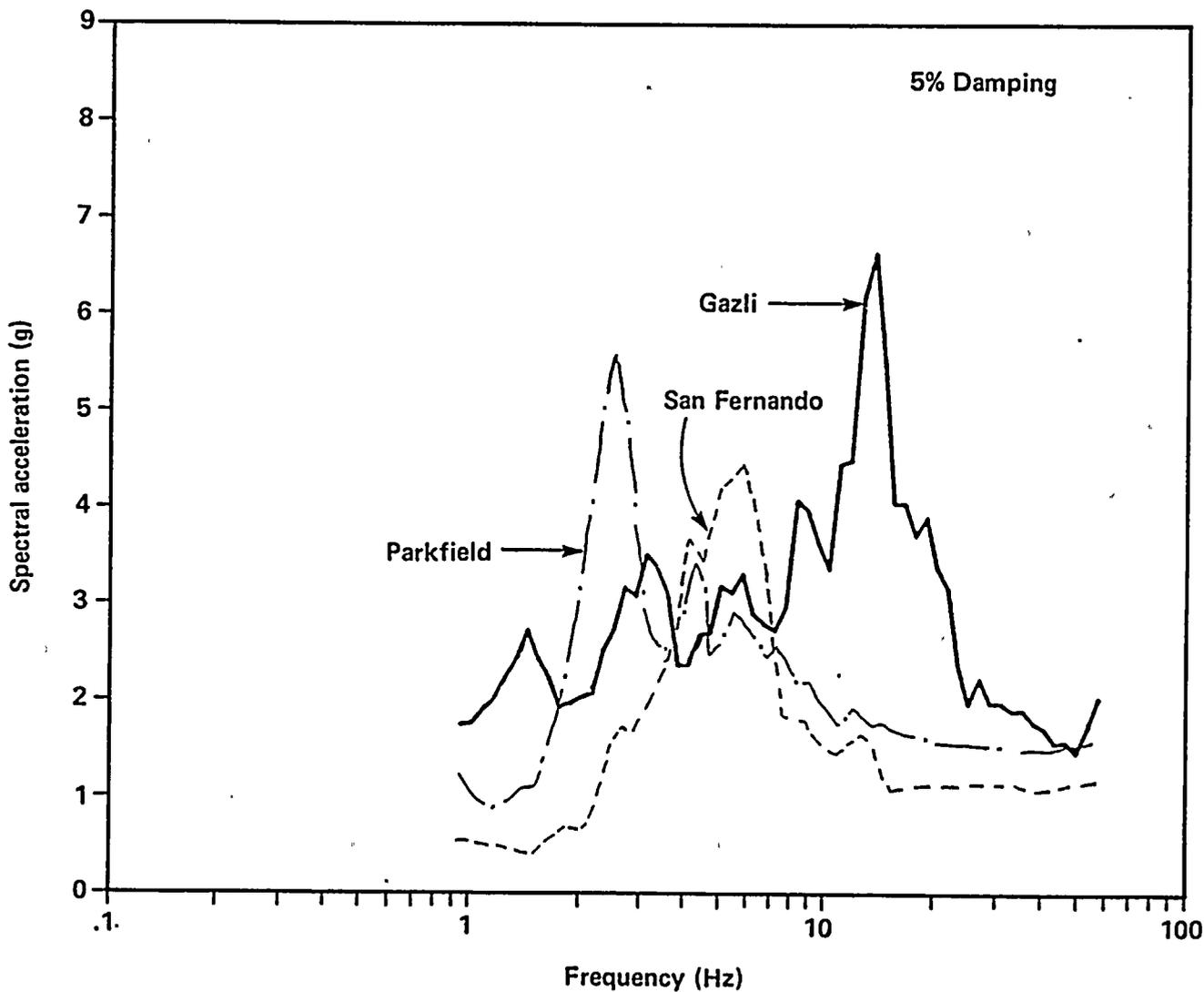


Figure 6-33

Acceleration response spectra for three empirical records scaled to an average spectral acceleration of 3.0 g over the frequency range of 3.0 to 8.5 hertz.



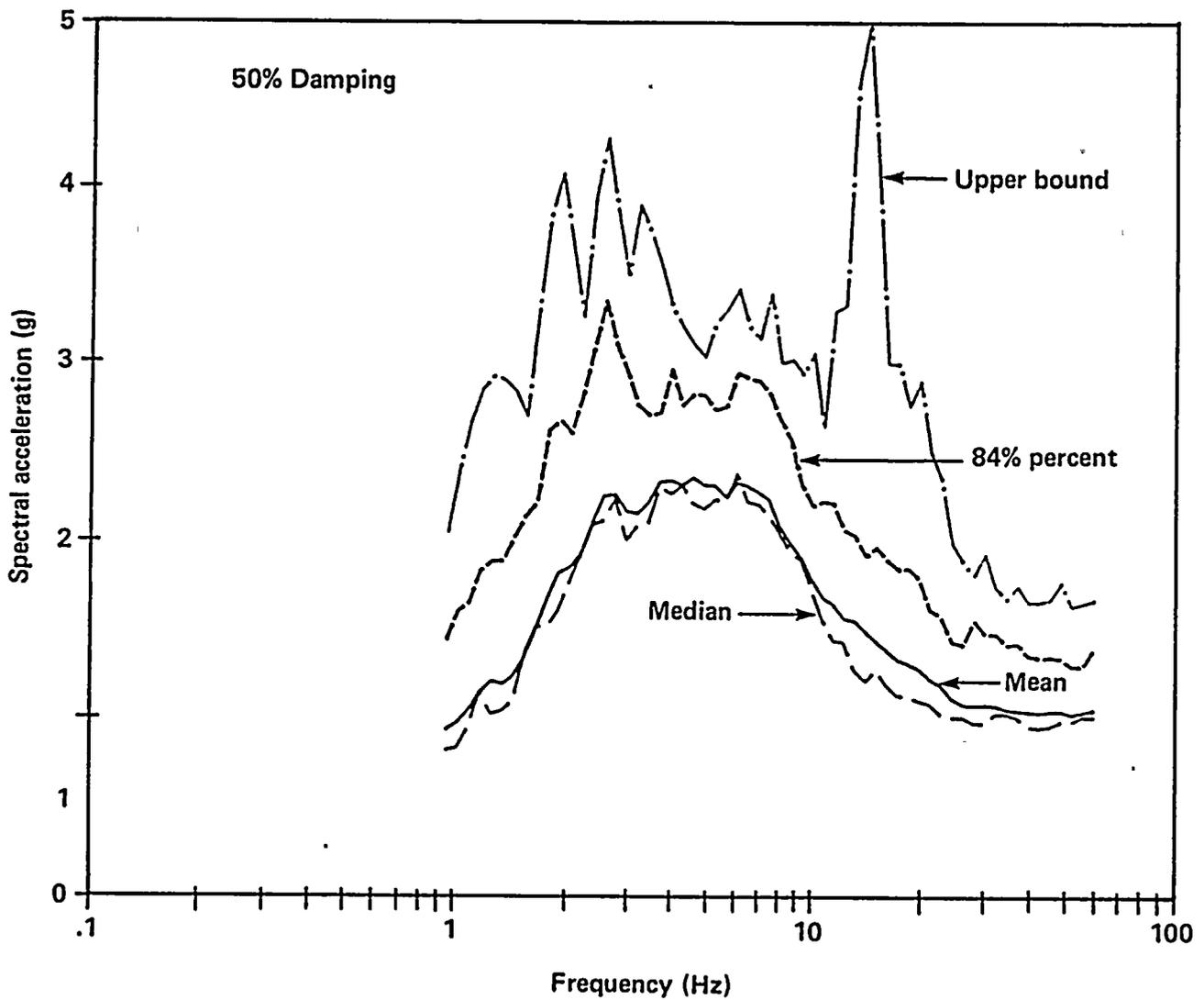


Figure 6-34

Mean, median, 84 percent probability of nonexceedance, and upper-bound spectra for 25 records scaled to an average spectral acceleration of 2.25 g over the frequency range of 3.0 to 8.5 hertz.

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severe distress, the onset of severe shear wall damage (significant strength degradation) was defined in terms of shear wall drift limits. Based upon a study of the results of a number of shear wall strength investigations, both in the United States and Japan, the median estimate of shear wall drift (expressed as a percentage of wall height) corresponding to the onset of significant strength degradation and the associated logarithmic standard deviations were taken as:

$$\overset{v}{D} \doteq 0.7\% \quad (\text{median drift limit})$$

$$\beta_R = 0.15$$

$$\beta_U = 0.30$$

$$\beta_C = 0.335$$

When treated on a composite basis (using β_C), there is about a 16 percent probability of severe distress at 0.5 percent drift and about an 84 percent probability of severe distress at 1.0 percent drift. These estimates might be more conservative than necessary.

Both walls 19 and 31 were segmented into three elements along their height because of changing capacities and stiffnesses. With the shear capacities listed in Table 6-13, drift percentages tend to be greatest within the lower element in wall 19 or within the lower or upper element of wall 31. It was conservatively decided to limit the element having the greatest drift percentage to the limits specified above. Thus, the probability of severe distress was based upon the shear element having the largest drift percentage obtained as a percent of the element height, such that the limit criterion was essentially treated as an element drift criterion. The total drift of either wall 19 or 31 was less than the maximum element drift percentage times the total wall height of 55 feet (often substantially less).

ANALYSIS RESULTS

First, an elastic response spectrum analysis was performed using the 5 percent damped median response spectrum scaled to an average spectral acceleration of 2.25 g (Figure 6-34) and median structural properties (note that 7 percent median

damping was used in this analysis). The results of this analysis are presented in Table 6-18. Based upon these results, it was concluded that the lower segment of both wall 19 and wall 31 will yield slightly in shear at an average spectral acceleration of 2.25 g because the elastic demand to yield capacity ratios (V_R/V_Y) are slightly greater than unity. Based on the median ground spectrum shape and median structural properties, inelastic behavior is expected to initiate at about an average spectral acceleration of 1.90 g and 2.05 g for the lower segment of walls 19 and 31, respectively. However, at an average spectral acceleration of 2.25 g, with median properties, yielding in the shear walls will be slight and limited to the lowest segment of each wall. With median properties, the turbine pedestal is expected to remain elastic up to an average spectral acceleration of 3.30 g. At an average spectral acceleration of 2.25 g, the median drift of the turbine pedestal was estimated to be about 1.9 inches; that for the operating floor was estimated to be about 2.0 inches. Combining the drift responses by square-root-sum-of-the-squares, the gap closure between the pedestal and operating floor was estimated to be about 2.75 inches, which is less than the available gap of 3.375 inches. Thus, at an average spectral acceleration of 2.25 g, it is not expected that the turbine pedestal will impact the operating floor for the median spectrum shape case.

Each of the 25 modified time histories, scaled to an average spectral acceleration of 3.0 g and 6.0 g, were applied to the nonlinear structure model with median strength, stiffness, and damping properties. Tables 6-19 and 6-20 list the maximum total drift at the top of both Walls 19 and 31, and for the operating floor and turbine pedestal for the two acceleration levels. Also shown are the maximum story drifts for each wall defined as a percentage of the wall segment (story) height. In nearly every case, the maximum story drifts occurred in the lowest segment of each wall. These tables also indicate for which cases the turbine pedestal impacted the operating floor. Lastly, the probability of severe shear wall distress is estimated for each trial using the random shear wall distress criteria defined above. Defining P_{F1} as the probability P_F of severe distress for



Table 6-18

ELASTIC COMPUTED RESPONSE FOR FIGURE 6-28 MEDIAN SPECTRUM SCALED
TO AN AVERAGE 5 PERCENT DAMPED SPECTRAL ACCELERATION OF 2.25 G

(A) DRIFTS

<u>Location</u>	<u>Drifts (inches)</u>
Top of pedestal	1.89
Center of operating floor	1.57* (2.00)
Wall 19	
El 140	0.26
El 123	0.16
El 104	0.06
Wall 31	
El 140	0.27
El 119	0.18
El 107	0.12

* The operating floor is actually highly inelastic, so this elastic computed drift is too small. Value in parenthesis is more realistic for the inelastic operating floor.

(B) SHEARS AND MOMENTS

<u>Element</u>	<u>Shear V_R (kips)</u>	<u>$\frac{V_R}{V_Y}$</u>	<u>Moment M_R (kip-ft) $\times 10^6$</u>	<u>$\frac{M_R}{M_Y}$</u>
Turbine pedestal	45,400	0.68	—	—
Wall 19				
Operating Floor (Per Beam)	2,910	2.41	—	—
El 123+	9,520	0.90	0.16	0.70
El 104+	10,240	0.93	0.36	0.91
El 85+	10,820	1.18	0.56	0.79
Wall 31				
Operating Floor (Per Beam)	3,030	2.50	—	—
El 119+	12,330	0.93	0.26	0.40
El 107+	14,560	0.86	0.43	0.60
El 85+	16,460	1.10	0.79	0.76



Table 6-19

**NONLINEAR RESULTS FOR MEDIAN STRUCTURAL MODEL AT AN AVERAGE
SPECTRAL ACCELERATION OF 3.0 G**

Trial No.	Wall 19		Wall 31		Operating Floor Drift (Inches)	Turbine Pedestal Drift (Inches)	Pedestal Impact Cases ¹	Probability of Severe Wall Distress (%)
	Top Drift (Inches)	Max Story Drift (%)	Top Drift (Inches)	Max Story Drift (%)				
1	0.58	0.18	0.60	0.18	3.06	3.22		0
2	1.01	0.35	1.30	0.42	5.15	2.47	Y	0
3	0.36	0.09	0.61	0.18	2.29	1.86		0
4	0.24	0.04	0.29	0.06	1.58	2.20		0
5	0.52	0.17	0.83	0.26	3.54	2.35	Y	0
6	0.79	0.26	0.79	0.26	4.57	2.40	Y	0
7	0.22	0.04	0.43	0.11	1.98	1.58		0
8	0.20	0.04	0.24	0.05	1.81	2.12		0
9	0.89	0.30	1.18	0.38	4.00	2.70	Y	0
10	0.64	0.20	0.70	0.22	2.71	2.45		0
11	0.54	0.16	0.74	0.24	1.70	1.37		0
12	0.36	0.10	0.52	0.17	2.84	2.24		0
13	0.59	0.18	0.58	0.18	3.78	2.81		0
14	0.28	0.06	0.25	0.05	3.18	3.43		0
15	1.39	0.43	1.81	0.61	7.03	4.80	Y	17.9
16	1.03	0.35	1.10	0.37	3.71	2.28		0
17	0.65	0.20	0.89	0.28	5.39	3.50		0
18	1.69	0.53	2.36	0.69	5.77	2.48	Y	46.0
19	0.24	0.04	0.25	0.05	2.57	3.47		0
20	1.62	0.51	2.11	0.59	5.37	3.12	Y	12.7
21	0.25	0.03	0.48	0.15	1.66	1.86		0
22	0.41	0.11	0.62	0.19	3.47	3.07	Y	0
23	0.65	0.21	0.97	0.32	4.18	3.76	Y	0
24	1.13	0.43	0.90	0.29	2.95	1.88		0
25	0.23	0.04	0.62	0.19	3.84	3.88		0

$$\Sigma = 76.6$$

$$P_F = \frac{\Sigma}{25} = \frac{76.6}{25} = 3.1\%$$

¹Y indicates that the turbine pedestal did impact the operating floor. For all other cases, no impact occurred.



Table 6-20

**NONLINEAR RESULTS FOR MEDIAN STRUCTURAL MODEL AT AN AVERAGE
SPECTRAL ACCELERATION OF 6.0 G**

Trial No.	Wall 19		Wall 31		Operating Floor Drift (Inches)	Turbine Pedestal Drift (Inches)	Pedestal Impact Cases ¹	Probability of Severe Wall Distress (%)
	Top Drift (Inches)	Max Story Drift (%)	Top Drift (Inches)	Max Story Drift (%)				
1	4.8	0.89	5.9	1.46	8.8	6.1		100
2	6.4	0.97	7.7	2.05	14.0*	10.6		100
3	2.1	0.59	4.2	0.97	7.4	4.0		99
4	2.4	0.66	3.1	0.90	7.3	4.6		95
5	3.2	0.84	5.8	1.20	8.6	5.2		100
6	4.6	0.82	6.3	1.50	11.5*	8.1		100
7	1.5	0.48	2.0	0.65	4.4	3.1		31
8	1.3	0.43	1.9	0.64	3.6	3.5	N	27
9	7.2	1.16	9.1	1.89	13.1*	9.7		100
10	2.8	0.71	4.0	1.13	7.3	5.4		100
11	1.5	0.48	1.8	0.57	3.9	2.8	N	9
12	3.6	0.81	5.9	1.45	9.3*	5.9		100
13	3.8	0.74	5.6	1.41	10.7*	7.3		100
14	3.0	0.73	4.2	1.21	8.8*	6.3		100
15	6.6	1.05	9.4	2.08	11.8*	9.9		100
16	6.6	1.00	8.2	1.67	11.8*	8.4		100
17	6.1	1.09	8.1	1.72	10.3	8.3		100
18	10.1	1.82	12.2	2.76	18.5*	15.1		100
19	1.6	0.55	2.8	0.95	5.6	5.3	N	98
20	7.7	1.23	8.8	1.91	14.2*	10.8		100
21	1.7	0.55	2.0	0.65	4.9	4.0		31
22	4.3	0.77	5.3	1.33	10.0*	6.6		100
23	3.8	0.82	5.2	1.45	9.6*	6.2		100
24	4.2	0.81	5.2	1.33	7.9	5.0		100
25	2.2	0.68	5.0	1.28	8.0	6.8		100

$$\Sigma = 2190$$

$$P_F = \frac{\Sigma}{25} = \frac{2190}{25} = 87.6\%$$

* Relative diaphragm drift exceeds the limits of applicability of the bilinear force-deflection relationship used for the operating floor so that diaphragm drifts are likely to be underpredicted and wall drifts are likely to be overpredicted to some extent for these cases.

¹N indicates that the turbine pedestal *did not* impact the operating floor. For all other cases there was impact.

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Trail i , the median estimate of the probability each average spectral acceleration value is obtained from:

$$P_{F_i} = \frac{\sum_{i=1}^N P_{F_i}}{N} \quad (6-8)$$

where N is the number of trials.

In a similar manner, 50 nonlinear analyses were conducted at average spectral acceleration values of 3.0 g, 4.0 g, and 6.0 g, incorporating the randomly selected structure damping, stiffness, and strength ratios shown in Table 6-16. These analyses include both input motion randomness variability and structural property uncertainty. Table 6-21 tabulates the maximum story drift as a percentage of the wall segment height for both walls 19 and 31. Again, in nearly every case, the maximum story drifts occurred in the lowest segment of each wall and again the composite probability of severe wall distress for each trial was estimated based upon the median drift limit of 0.7 percent and composite $\beta_c = 0.335$. The overall composite probability of severe wall distress is computed using equation (6-8) for each average spectral acceleration level as shown in Table 6-21. Those trials in which turbine pedestal and operating floor impact occurred are also indicated.

The overall probability estimates for each case studied (randomness only at an average spectral acceleration of 3.0 g and 6.0 g, and randomness plus uncertainty at an average spectral acceleration of 3.0 g, 4.0 g, and 6.0 g) are presented in Tables 6-19 through 6-21. These results were then fit by a "best-fit" lognormally distributed fragility estimate using linear regression (least-square error fitting). The result is a lognormally distributed fragility estimate defined in terms of the median, \bar{S}_a , and logarithmic standard deviations for randomness variability, β_R , composite variability, β_C , and uncertainty variability, β_U . The high-confidence-low-probability-of-failure (HCLPF) capacity, defined as a 95 percent confidence of less than 5 percent probability of failure, is calculated from:

$$\text{HCLPF } \bar{S}_a = \frac{V}{\bar{S}_a} e^{-1.65(\beta_R + \beta_U)} \quad (6-9)$$

Thus, the turbine building fragility estimate becomes:

$$\frac{V}{\bar{S}_a} = 4.59 \text{ g}$$

$$\beta_C = 0.37 \quad (\text{from randomness and uncertainty runs})$$

$$\beta_R = 0.23 \quad (\text{from randomness only runs})$$

$$\beta_U = (0.37^2 - 0.23^2)^{1/2} = 0.29$$

$$\text{HCLPF } \bar{S}_a = 4.59 e^{-1.65(.23 + .29)} = 1.95 \text{ g}$$

As noted earlier, three structural response factors were not included in the nonlinear time-history analyses and their effects were added by means of the separation-of-variables approach.

- 1) *Modeling*: Only a single mathematical model was used. Structure properties were varied, but the model was not varied. The model which was used is judged to be median-centered. It is further judged that modeling uncertainty is about $\beta_{UM} = 0.15$, which is equivalent to stating that the 95 percent nonexceedance probability responses near the base of the shear walls are estimated to be as much as 1.28 times those reported herein if differing models had been used.
- 2) *Earthquake Component Variation*: Within this study, the fragility of east/west shear walls were defined in terms of average spectral acceleration associated with east/west ground motions. However, in the seismic probabilistic risk assessment, the seismic hazard was defined in terms of the average horizontal component (\bar{S}_a). The east/west component is expected to have the same median value as the average horizontal component ($\bar{F}_{DIR}^V = 1.0$); however, the random variability (β_{RDIR}) for the east/west component, given an average horizontal component spectral acceleration, is estimated to be about 0.12.
- 3) *Incoherence of Ground Motion*: At any instant in time, the ground acceleration is not the same at every location under the turbine building foundation. The soil/structure

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Table 6-21
NONLINEAR RESULTS FOR UNCERTAIN STRUCTURAL PROPERTIES MODEL

Trial No.	Average Spectral Acceleration 3.0 g				Average Spectral Acceleration 4.0 g				Average Spectral Acceleration 6.0 g			
	Max Story Drift (%)		Prob. Severe Distress (%)	Pedestal Impact (1)	Max Story Drift (%)		Prob. Severe Distress (%)	Pedestal Impact (1)	Max Story Drift (%)		Prob. Severe Distress (%)	Pedestal Impact (1)
	Wall 19	Wall 31			Wall 19	Wall 31			Wall 19	Wall 31		
1	0.19	0.15	0	Y	0.29	0.64	39.4	Y	0.94	1.27	96.2*	Y
2	0.45	0.37	9.3		1.10	0.65	91.1	Y	1.76	1.62	99.7*	Y
3	0.19	0.23	0		0.40	0.46	10.6	Y	1.23	0.99	95.4	Y
4	0.04	0.05	0		0.18	0.25	0		0.63	0.86	72.9	Y
5	0.02	0.04	0		0.06	0.11	0		0.37	0.60	67.4	Y
6	0.19	0.33	1.3	Y	0.47	0.52	18.7	Y	1.68	0.92	99.5*	Y
7	0.03	0.09	0		0.16	0.29	0.4		0.42	0.66	57.1	
8	0.02	0.05	0		0.05	0.09	0		0.27	0.44	8.2	
9	0.06	0.31	0.8	Y	0.24	0.40	4.7	Y	1.15	1.09	93.1*	Y
10	0.03	0.06	0		0.06	0.20	0		0.47	0.66	42.9	Y
11	0.22	0.19	0		0.75	0.35	58.3		0.72	0.86	72.9	Y
12	0.14	0.16	0		0.29	0.44	8.2		0.53	0.97	83.4	Y
13	0.42	0.71	51.6	Y	0.67	1.24	95.6	Y	1.20	1.97	99.9*	Y
14	0.09	0.06	0		0.28	0.40	4.7	Y	0.53	0.90	77.3	Y
15	0.72	0.96	82.6		1.18	1.84	99.8		1.97	2.81	100.0	Y
16	0.45	0.63	37.8		0.87	0.99	84.8	Y	1.44	1.51	98.9	Y
17	0.51	0.83	69.5	Y	0.73	0.96	82.6	Y	1.11	1.42	98.3	Y
18	0.45	0.26	9.3	Y	0.38	0.79	63.7*	Y	1.46	1.15	98.6*	Y
19	0.02	0.04	0		0.20	0.17	0		0.45	0.71	51.6	Y
20	0.40	0.46	10.6	Y	0.45	0.70	50.0	Y	0.80	1.21	94.8*	Y
21	0.24	0.31	0.8		0.45	0.45	9.3	Y	0.69	1.02	86.9	Y
22	0.33	0.52	18.7	Y	0.58	0.74	56.8	Y	0.84	1.25	95.8	Y
23	0.01	0.01	0		0.02	0.03	0		0.24	0.35	2.0	Y
24	0.05	0.24	0		0.32	0.36	2.3	Y	0.86	0.78	72.9*	Y
25	0.31	0.43	7.4	Y	0.49	0.82	68.1	Y	0.71	1.15	93.1	Y

(1) Y indicates that turbine pedestal did impact the operating floor. For all other cases, no impact occurred.

* Relative diaphragm drift exceeds the limits of applicability of the bilinear force-deflection relationship used for the operating floor so that wall drifts and probability of severe wall distress are likely to be overpredicted to some extent for these cases.

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Table 6-21 (Continued)
NONLINEAR RESULTS FOR UNCERTAIN STRUCTURAL PROPERTIES MODEL

Trial No.	Average Spectral Acceleration 3.0 g				Average Spectral Acceleration 4.0 g				Average Spectral Acceleration 6.0 g			
	Max Story Drift (%)		Prob. Severe Distress (%)	Pedestal Impact (1)	Max Story Drift (%)		Prob. Severe Distress (%)	Pedestal Impact (1)	Max Story Drift (%)		Prob. Severe Distress (%)	Pedestal Impact (1)
	Wall 19	Wall 31			Wall 19	Wall 31			Wall 19	Wall 31		
26	0.17	0.41	5.6		0.69	0.85	71.9	Y	1.36	1.76	99.7	Y
27	0.37	0.17	2.9		0.30	0.40	4.7	Y	0.57	0.76	59.9	Y
28	0.18	0.20	0		0.43	0.46	10.6		0.79	1.12	65.5	Y
29	0.05	0.18	0		0.06	0.13	0		0.35	0.43	7.4	Y
30	0.06	0.11	0		0.25	0.27	0.2*		0.87	1.07	89.8*	Y
31	0.14	0.45	9.3	Y	0.79	1.37	97.7	Y	1.71	2.54	100.0*	Y
32	0.03	0.12	0		0.17	0.29	0.4		0.41	0.62	35.9	
33	0.33	0.30	1.3		0.40	0.51	17.1		0.50	0.66	42.9	
34	0.08	0.09	0	Y	0.35	0.40	4.7	Y	0.80	1.11	91.6*	Y
35	0.12	0.15	0		0.27	0.39	4.0		0.70	0.67	50.0	
36	0.19	0.23	0		0.30	0.35	2.0		0.51	0.61	34.1	
37	0.16	0.28	0.3		0.51	0.90	77.3	Y	1.31	1.99	99.9*	Y
38	0.25	0.36	2.4	Y	0.51	0.99	84.8	Y	2.11	1.90	100.0*	Y
39	0.04	0.05	0		0.13	0.27	0.2		0.91	1.17	93.7*	Y
40	0.75	1.10	91.1	Y	1.20	1.70	99.6	Y	1.70	2.20	100.0*	Y
41	0.31	0.43	7.4	Y	0.53	0.90	77.3	Y	1.03	1.41	98.2*	Y
42	0.67	0.98	84.1	Y	1.50	1.72	99.6	Y	2.86	3.14	100.0*	Y
43	0.41	0.67	44.8	Y	0.74	1.20	94.6	Y	1.69	2.30	100.0*	Y
44	0.08	0.06	0		0.14	0.20	0		0.35	0.46	10.6	Y
45	0.11	0.13	0		0.22	0.39	4.0		0.51	0.67	44.8*	
46	0.06	0.15	0		0.22	0.32	1.0		0.57	0.76	59.9	
47	0.35	0.25	1.9		0.80	0.92	79.4	Y	1.23	1.42	98.3*	Y
48	0.15	0.36	2.4		0.51	0.79	63.7	Y	0.59	1.15	93.1*	Y
49	0.27	0.29	0.4	Y	0.58	0.51	28.8	Y	1.14	1.73	99.7*	Y
50	0.11	0.22	0	Y	0.43	1.04	88.1	Y	1.49	2.00	100.0	Y
		$\Sigma =$	553.6			$\Sigma =$	1860.8			$\Sigma =$	3833.8	

$$P_F = 553.6/50 = 11.1\%$$

$$P_F = 1860.8/50 = 37.2\%$$

$$P_F = 3833.8/50 = 76.7\%$$

(1) Y indicates that turbine pedestal did impact the operating floor. For all other cases, no impact occurred.

* Relative diaphragm drift exceeds the limits of applicability of the bilinear force-deflection relationship used for the operating floor so that wall drifts and probability of severe wall distress are likely to be overpredicted to some extent for these cases.

interaction analysis considered this aspect for Diablo Canyon, and it was estimated that east/west shear wall responses are reduced by a median factor of $F_{GMI} = 1.06$, with estimated randomness $\beta_{RGMI} = 0.02$, and uncertainty $\beta_{UGMI} = 0.06$.

Table 6-22 includes the effects of these three additional parameters on the fragility estimate for the turbine building. The final fragility estimate for the turbine building for use in the seismic probabilistic risk assessment is:

$$\begin{aligned}\frac{v}{\bar{S}_a} &= 4.87 \text{ g} \\ \beta_C &= 0.26 \\ \beta_R &= 0.33 \\ \text{HCLPF } \bar{S}_a &= 1.84 \text{ g}\end{aligned}$$

The median and HCLPF capacities are in terms of an average 5 percent damped spectral acceleration averaged over the 3 to 8.5 hertz range.

Results and Conclusions

The fragility evaluation established that the Diablo Canyon safety-related structures and equipment that are important to evaluating the probability of

core damage, generally have high median seismic capacities relative to the median reference ground motion. In addition, the important structures and equipment have HCLPF capacities that are generally in excess of 2.25 g average spectral acceleration. (The exceptions are noted below.)

The following summarizes the findings of the fragility evaluation with regard to several categories of structures and equipment, and highlights those items that may contribute to seismic risk due to relatively low demonstrated capacity. Only the salient information that is specific to the Diablo Canyon fragility evaluation is summarized. Details are included in the comprehensive technical reports (Kennedy, 1988; Kipp, 1988) where descriptions of the methods used, example calculations, interpretation of the fragilities, and failure consequences are discussed. Again, it should be noted that the reported median fragility capacities, $\frac{v}{\bar{S}_a}$, are in terms of the 5 percent damped average spectral acceleration averaged over the 3 to 8.5 hertz range.

STRUCTURAL FRAGILITY RESULTS

The fragility parameters associated with the important structures are presented in Table 6-23. The fundamental frequency of the structure, failure mode, fragility parameters (\bar{S}_a , β_R , and β_U), and HCLPF capacity are included in the table.

Table 6-22
TURBINE BUILDING FRAGILITY ESTIMATE INCORPORATING ADDITIONAL
VARIABLE PARAMETERS

	Median $\frac{v}{\bar{S}_a}$, (g) or F	Randomness β_R	Uncertainty β_U	HCLPF \bar{S}_a (g)
Nonlinear Time History Results	4.59 g	0.23	0.29	1.95 g
Modeling	1.0	—	0.15	—
Directional Effects	1.0	0.12	—	—
Incoherence of Ground Motion	1.06	0.02	0.06	—
Fragility Estimate	4.87 g	0.26	0.33	1.84 g

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Table 6-23

DIABLO CANYON STRUCTURE FRAGILITIES

(Based on hazard defined over 3 to 8.5 hertz range.)

Structure	Fundamental Frequency Hertz	Failure Mode	Spectral Acceleration Capacity			
			$\frac{v}{S_a}$ (g)	β_R	β_U	HCLPF (g)
Containment Building	4.1	Exterior Shell Shear	8.42	0.26	0.30	3.34
Concrete Internal Structure	8.9	Internal Structure Shear	6.91	0.20	0.31	2.98
Intake Structure	23.3	North Wall Shear	8.55	0.28	0.31	3.23
Auxiliary Building	8.2	North/South Shearwalls	5.79	0.21	0.26	2.66
Turbine Building	8.6	Shear Wall, Column 31	4.87	0.26	0.33	1.84
	9.0	Block Wall	>10.0	—	—	—
Refueling Water Storage Tank	7.6	Concrete/Bedrock Flexure	9.92	0.29	0.36	3.40
Condensate Storage Tank	—	Comparison to RWST	>10.0	—	—	—
DG Fuel-Oil Storage Tank	Buried	Rupture	>10.0	—	—	—
Auxiliary Saltwater Piping	Buried	Rupture	9.23	0.18	0.21	4.85

The containment building, concrete internal structure and intake structure all have very high median and HCLPF capacities, and thus contribute very little to overall Plant risk. The auxiliary building fragility evaluation shows median and HCLPF capacities of 5.79 g and 2.66 g, respectively, which, although not as high as the three concrete structures identified above, are sufficiently high so as not to contribute significantly to Plant seismic risk.

The turbine building has the lowest median seismic capacity of all the civil structures. The median spectral acceleration capacity for the turbine building is estimated to be 4.87 g, based upon a shear-wall failure due to east/west response, with randomness and uncertainty variabilities of 0.26 and 0.33, respectively. The resulting HCLPF spectral acceleration capacity is 1.84 g. Because the turbine building houses the diesel generators, the component cooling water heat exchanger, and the 4160 V (vital) electrical system, the potential for severe distress of the turbine building is likely to be a significant contributor to overall Plant risk. However, it should be noted that in searching for actual earthquake records for use in the turbine building

nonlinear analysis, very few were found that met Criterion 4 (see page 6-64), related to high spectral acceleration in the 3.0 to 8.5 hertz range. This fact alone demonstrates the lack of seismic vulnerability of the Diablo Canyon turbine building. Two of strongest ground motions that have ever been recorded anywhere in the world (Tabas and Pacoima Dam) only have a slight potential of causing measureable damage to the turbine building. It should be further noted that the fragility estimate of the turbine building was heavily influenced by the selection and equal weighting of the 25 time histories used in the study. The highest probability of severe distress was related to those records that required substantial frequency-dependent modifications to scale them up to the level required for the Diablo Canyon site. In contrast, those very strong motion records requiring only minor frequency-independent scaling resulted in relatively small potential for severe distress. Thus, the turbine building fragility estimate is likely to be conservatively biased. Particularly, both β_R and β_U are likely to be too large.

The main outdoor storage tanks for refueling water and condensate, the buried diesel generator

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fuel oil storage tank, and buried piping all have very high seismic capacities, and thus are negligible contributors to overall Plant risk.

EQUIPMENT FRAGILITY RESULTS

Table 6-24 contains fragility descriptions for all the equipment that was included in the probabilistic risk assessment. The table includes the component location, frequency, method of seismic qualification, critical failure mode, sources of information, and fragility parameters (\bar{S}_x , β_R , and β_U). As a means of reference, the resulting HCLPF capacity is also listed. Fragility derivations were conducted for each of the components and are reported for those items that have a median spectral ground acceleration capacity less than 10.0 g. Based upon a review of the seismic capacity of a sample of such equipment, it was determined that equipment that possessed median spectral ground acceleration capacities greater than about 10.0 g also possessed HCLPF capacities in excess of 3.0 g. Due to the fact that there is an extremely low frequency of occurrence of a 3.0 g average spectral acceleration earthquake at the Diablo Canyon site, and that other lower capacity equipment would govern the Plant seismic risk, it was judged that the high capacity equipment would not contribute to the overall Plant risk. Therefore, detailed fragility descriptions were not included for components having median capacities greater than 10.0 g based on the capacity factor alone. Equipment in this category are labeled with a ">10.0" in the spectral acceleration capacity column.

The seismic capacity for most of the safety-related equipment items is relatively high with respect to the median reference ground motion. In all cases, the equipment fragilities were based upon Plant-specific component analyses or qualification test data and involved the use of very little generic information. Even for generic component categories, the fragilities were based upon the review of sample calculations from specific Diablo Canyon qualification analyses. The piping and major equipment components associated with the reactor coolant loop have generally high capacities with respect to the reference ground-motion spectra demands. The

most critical component is the steam generator, which has a median spectral acceleration capacity of 6.96 g, based upon the failure of the upper lateral support due to the formation of a plastic hinge in the ring band. The fundamental frequency of the steam generator is 8.8 hertz, which corresponds closely to the frequency of the concrete internal structure. Excessive movement of the steam generator after loss of the upper support is assumed to result in rupture of the main steam system piping and other attached lines.

The components for the major balance-of-Plant safety systems, such as the residual heat removal, safety injection, and component cooling water systems were found to have high capacities. The failure modes for these components were generally associated with anchorage. Pumps, piping, and valves are estimated to have median capacities greater than 7.7 g and HCLPF capacities greater than 3.4 g. Similarly, tanks and vessels have high capacities, with median capacities and HCLPF values estimated to be greater than 6.7 g and 3.0 g, respectively. The component cooling water heat exchanger was found to be the weakest of all mechanical system components, based upon the failure of the longitudinal strut anchor bolts. The median seismic capacity of the heat exchanger was estimated to be 6.31 g, with randomness and uncertainty variabilities of 0.27 and 0.28, respectively, providing a HCLPF capacity of 2.55 g.

Components of the diesel generator system exhibit high seismic capacities. For the diesel generator itself, fragility is based upon failure of the skid anchor bolts and seismic stays, which occur at a spectral acceleration of 7.79 g. The most critical element of the diesel generator system is the diesel generator control panel which was computed to have median and HCLPF capacities of 4.55 g and 2.24 g, respectively, based upon a generic structural failure. This fragility is based upon the seismic qualification dynamic testing of the cabinet and, as such, is not based on actual fragility testing leading to an actual failure state. Because the control panel is situated on the basemat of the turbine building, the demand acceleration for the seismic qualification test was relatively low. Thus, the reported fragility may be



Table 6-24
DIABLO CANYON EQUIPMENT FRAGILITIES
 (Based on hazard defined over 3 to 8.5 hertz range.)

System and Component	Location	Fundamental Frequency	Method of Seismic Qualification	Failure Mode	Information Source	Spectral Acceleration Capacity			
						$\frac{V}{S_a}(g)$	β_R	β_U	HCLPF (g)
NUCLEAR STEAM SUPPLY									
Reactor Pressure Vessel	Containment - (107')	12-14 Hz (H)	Dynamic Analysis	Support Pin Shear	\bar{W} Summary Data	8.71	0.25	0.33	3.34
Reactor Internals	Containment - (107')	16-20 Hz (V)	Dynamic Analysis	Lower Core Plate	\bar{W} Summary Data	10.54	0.40	0.26	3.55
Steam Generators	Containment - (140')	9 Hz (H)	Dynamic Analysis	Upper Lateral Support	\bar{W} Summary Data	6.96	0.31	0.29	2.55
Pressurizer	Containment - (140')	15 Hz (H)	Dynamic Analysis	Seismic Support Lug	\bar{W} Summary Data	11.46	0.31	0.44	3.33
Pressurizer Safety Valves	Containment - (169')	Flexible Piping	Static Analysis/Test	Generic Function	M397, M401	>10.0	-	-	-
Power Operated Relief Valves	Containment - (169')	Flexible Piping	Static Analysis/Test	Generic Function	M397, M401	7.62	0.30	0.42	2.32
Reactor Coolant Pumps	Containment - (114')	7 Hz (H)	Dynamic Analysis	Lower Motor Stand	M355, M428, M429	8.82	0.37	0.32	2.83
Reactor Rod Drives	Containment - (140')	7-10 Hz (H)	Dynamic Analysis	Head Adapter Yield	\bar{W} Summary Data	11.71	0.41	0.34	3.40
NSSS Piping	Containment - (140')	7-9 Hz (H&V)	Dynamic Analysis	Rupture	\bar{W} Summary Data	>10.0	-	-	-
RESIDUAL HEAT REMOVAL									
RHR Pumps	Auxiliary (58')	Flexible Piping	Dynamic Analysis	Pump Hold Down Bolts	\bar{W} Summary Data	8.31	0.33	0.22	3.35
RHR Heat Exchangers	Auxiliary (100')	12 Hz (H)	Static Analysis	Anchor Bolts & Upper Lateral Support	\bar{W} Summary Data, M462, M474	8.09	0.24	0.27	3.48
SAFETY INJECTION									
SI Accumulators	Containment (91')	23-34 Hz (H)	Static Analysis	Anchor Studs	\bar{W} Summary Data, M316	10.01	0.29	0.19	4.53
SI Pumps	Auxiliary (85')	>33 Hz (H)	Static Analysis	Pump Hold Down Bolts	\bar{W} Summary Data	10.94	0.34	0.18	4.64
Boron Injection Tank	Auxiliary (73')	15-17 Hz (H)	Static Analysis	Anchor Bolts	\bar{W} Summary Data	8.46	0.27	0.19	3.96
COMPONENT COOLING WATER									
CCW Pumps	Auxiliary (73')	Flexible Piping	Static Analysis	Pump Hold Down Bolts	M006, M007, M318	8.53	0.29	0.21	3.74
CCW Heat Exchangers	Turbine (85')	13 Hz (H)	Dynamic Analysis	Longitudinal Strut Bolts	M008, M336, M475	6.31	0.27	0.28	2.55
CCW Surge Tank	Auxiliary (163')	32 Hz (H)	Static Analysis	Seismic Lateral Brace	M319	7.22	0.33	0.22	2.91
CHEMICAL AND VOLUME CONTROL									
Charging Pumps (centrifugal)	Auxiliary (73')	>33 Hz (H)	Static Analysis	Motor Hold Down Bolts	\bar{W} Summary Data	10.16	0.31	0.19	4.45
Charging Pumps (reciprocal)	Auxiliary (73')	>33 Hz (H)	Static Analysis	Pump Hold Down Bolts	\bar{W} Summary Data	>10.0	-	-	-
AUXILIARY SALTWATER									
Auxiliary Saltwater Pumps	Intake (2'-2")	43 Hz (H)	Static Analysis	Pump Mounting Bolts	M009	>10.0	-	-	-
CONTAINMENT SPRAY									
CS Pumps	Auxiliary (73')	>33 Hz (H)	Static Analysis	Foundation Bolts	\bar{W} Summary Data	8.65	0.29	0.20	3.85
Spray Additive Tank	Auxiliary (73')	24 Hz (H)	Static Analysis	Support Pad/Shell	\bar{W} Summary Data	6.78	0.30	0.18	3.07

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Table 6-24 (Continued)
DIABLO CANYON EQUIPMENT FRAGILITIES
 (Based on hazard defined over 3 to 8.5 hertz range.)

System and Component	Location	Fundamental Frequency	Method of Seismic Qualification	Failure Mode	Information Source	Spectral Acceleration Capacity			
						$\frac{V}{S_a}(g)$	β_R	β_U	HCLPF (g)
MAIN STEAM									
MS Isolation Valves	Outside Containment (127')	Flexible Piping	Dynamic Analysis/Test	Actuator Support	M067, M463, M469	>10.0	-	-	-
MS Safety Valves	Auxiliary (140')	Flexible Piping	Dynamic Analysis/Test	Generic Function	M397	>10.0	-	-	-
MS PORV'S	Auxiliary (140')	Flexible Piping	Dynamic Analysis/Test	Generic Function	M397	11.51	0.34	0.38	3.51
AUXILIARY FEEDWATER									
AFW Pumps (Motor Driven)	Auxiliary (100')	42 Hz (H)	Static Analysis	Pump Hold Down Bolts	M320A	>10.0	-	-	-
AFW Pumps (Turbine Driven)	Auxiliary (100')	43 Hz (H)	Static Analysis	Pump Hold Down Bolts	M320, M321	7.71	0.29	0.21	3.38
DIESEL GENERATOR									
D.G. Fuel Oil Day Tank	Turbine (85')	10 Hz (V)	Static Analysis	Bottom Plate Rupture	M323	>10.0	-	-	-
D.G. Fuel Oil Pumps/Filters	Underground Vault (77')	Flexible Piping	Static Analysis	Filter Anchor Bolts	M324, M326	8.33	0.27	0.23	3.65
D.G. Fuel Oil Shutoff Valve	Underground Vault (77')	Flexible Piping	None	Fusible Link	Data Base	>10.0	-	-	-
D.G. Air Start Compressor	Turbine (85')	>33 Hz (H)	Generic Anchorage Analysis	Hold Down Bolts	M323	>10.0	-	-	-
D.G. Air Start Receiver	Turbine (85')	26 Hz (H)	Dynamic Analysis	Hold Down Bolts	M329	>10.0	-	-	-
Diesel Generators	Turbine (85')	17 Hz (H)	Dynamic Analysis	Skid Anchor Bolts	M423-M426	7.79	0.26	0.20	3.64
D.G. Radiator/Water Pump	Turbine (85')	17 Hz (H)	Dynamic Analysis	Anchor Bolting	M323	8.78	0.29	0.24	3.66
D.G. Inlet Silencer/Air Filter	Turbine (104')	Flexible Piping	Dynamic Analysis	Filter Support Rod Weld	M271, M449	>10.0	-	-	-
D.G. Excitation Cubical	Turbine (85')	13 Hz (H)	Test	Structural	M346, M364	7.40	0.29	0.35	2.57
D.G. Control Panel	Turbine (85')	8 Hz (H)	Test	Chatter	M347, M364, M464, M482	7.77	0.25	0.14	4.08
D.G. Main Lead Terminal/Box	Turbine (85')	10 Hz (H)	Test Static Analysis	Structural Attachment-Fillet Weld	M348	4.55 >10.0	0.30	0.13	2.24
CONTAINMENT BUILDING VENTILATION									
Containment Fan Cooler	Containment (140')	23 Hz (H)	Dynamic Analysis	Foot Plate/Embed. Weld	M399, M499, M420, M421, M448	8.10	0.31	0.33	2.82
CONTROL ROOM VENTILATION									
Supply Fans	Auxiliary (154'-6")	>33 Hz (H)	Static Analysis	Support Bolting	M056	9.79	0.33	0.24	3.82
AC Units/Compressors	Auxiliary (154'-6")	>33 Hz (H)	Static Analysis	Anchor Bolt	M288, M312	>10.0	-	-	-
Control Cabinets	Auxiliary (157')	21 Hz (H)	Test	Structural	M455	>10.0	-	-	-
480V SWITCHGEAR/INVERTER/DC SWITCHGEAR/SPREADING ROOM VENTILATION									
Supply/Return Fans	Auxiliary (163')	>33 Hz (H)	Static Analysis	Expansion Anchor	M310	11.16	0.33	0.30	3.95
Backdraft and Shut-Off Dampers	Auxiliary (163')	>33 Hz (H)	Static Analysis	Structural	M388	>10.0	-	-	-

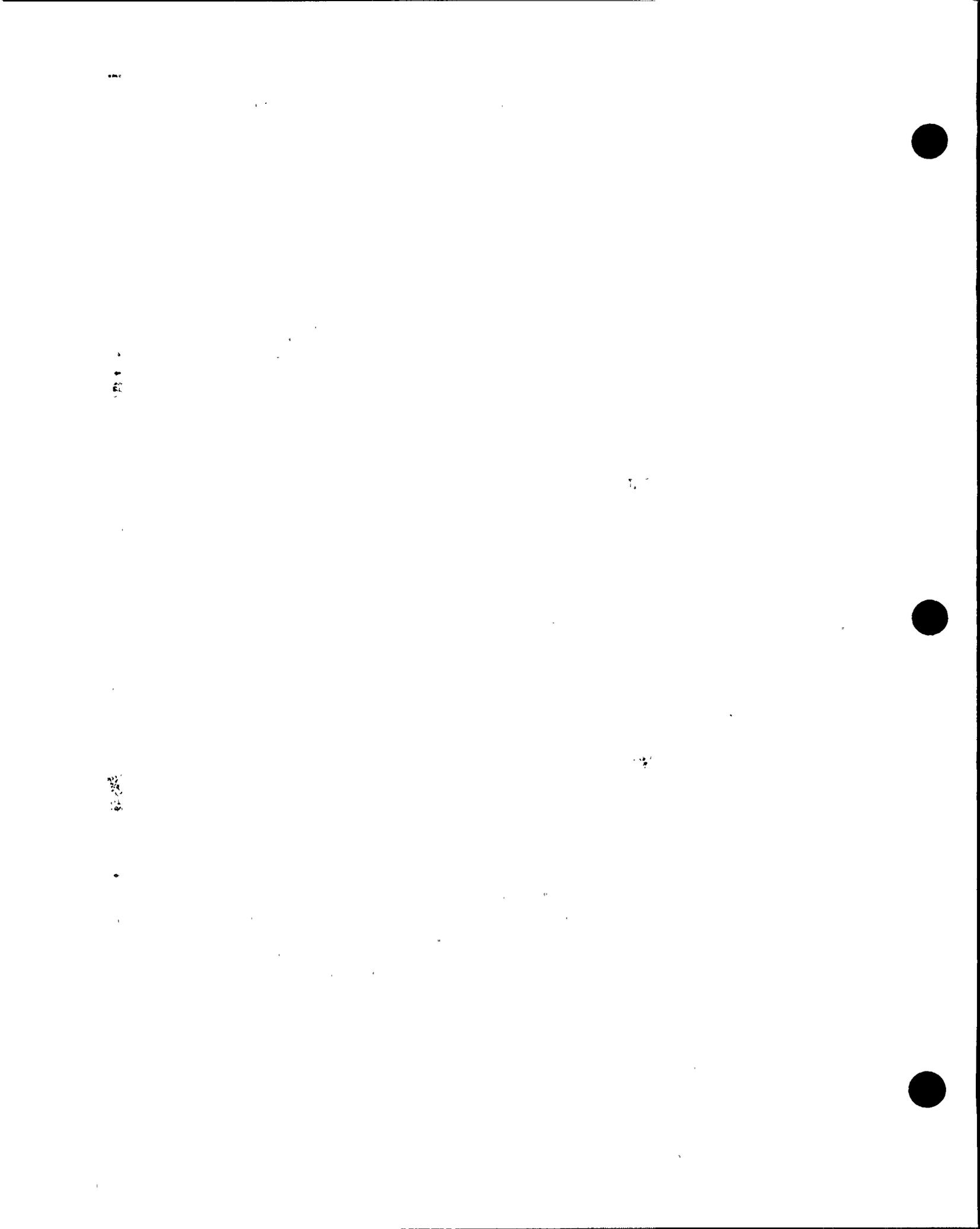


Table 6-24 (Continued)
DIABLO CANYON EQUIPMENT FRAGILITIES
 (Based on hazard defined over 3 to 8.5 hertz range.)

System and Component	Location	Fundamental Frequency	Method of Seismic Qualification	Failure Mode	Information Source	Spectral Acceleration Capacity			
						$\frac{V}{S_a}(g)$	β_R	β_U	HCLPF (g)
4160V (VITAL) ELECTRIC POWER									
Switchgear	Turbine (119')	7 Hz (H)	Test Static Analysis	Chatter Guide Rod Bending	M049, M315, M356, M373, M377-380, M482	3.53 7.44	0.35 0.31	0.25 0.25	1.31 2.95
Potential Transformers (Bus F)	Turbine (119')	21 Hz (H)	Static Analysis	Support Leg/Embed. Weld	M049, M375, M416, M450	10.83	0.31	0.38	3.47
(Bus G & H)	Turbine (119')	35 Hz (H)	Static Analysis	Support Leg/Embed. Weld	M049, M375, M416, M450	>10.0	-	-	-
Safeguard Relay Panel	Turbine (119')	11 Hz (H)	Static Analysis	Anchor Welds	M012, M373, M414, M430	10.76	0.34	0.36	3.39
125V DC ELECTRIC POWER									
Batteries	Auxiliary (115')	>33 Hz (H)	Test	Structural	M050, M054, M364	6.04	0.30	0.18	2.74
Battery Racks	Auxiliary (115')	>33 Hz (H)	Static Analysis	Longitudinal End Restraint	M013, M032, M050, M207	11.91	0.26	0.22	5.40
Battery Chargers	Auxiliary (115')	12 Hz (H)	Test	Structural	M054, M364, M453, M462	9.93	0.34	0.40	2.93
Switchgear/Breaker Panels	Auxiliary (115')	7 Hz (H)	Test	Structural	M014, M051, M364	6.67	0.35	0.28	2.36
120V AC ELECTRIC POWER									
Instrument Breaker Panels	Auxiliary (115')	>20 Hz (H)	Static Analysis	Slip-Nut Failure	M051A	>10.0	-	-	-
Inverters	Auxiliary (115')	5 Hz (H)	Test	Structural	M015, M016, M355, M415, M436, M451, M467	6.82	0.31	0.24	2.75
480V (VITAL) ELECTRIC POWER									
4160V/480V Transformers	Auxiliary (100')	3 Hz (H)	Static Analysis	Structural	M052, Walkdown	5.34	0.28	0.20	2.42
Breaker Cabinets (Load Centers)	Auxiliary (100')	13 Hz (H)	Static Analysis	Anchor Stitch Weld	M017, M364	>10.0	-	-	-
Auxiliary Relay Panel	Auxiliary (100')	29 Hz (H)	Test	Structural	M315, M364	7.25	0.28	0.15	3.57
CONTROL ROOM									
Main Control Boards	Auxiliary (140')	>33 Hz (H)	Test Dynamic Analysis	Switch Function Structural	W Summary Data, M456, M482	>10.0 7.77	- 0.31	- 0.27	- 2.98
Hot Shutdown Panel	Auxiliary (100')	>33 Hz (H)	Test Static Analysis	Switch Function Structural	M317, M383, M342, M479, M482	7.60 7.27	0.27 0.30	0.25 0.14	3.22 3.52
Auxiliary Safeguards Cabinet	Auxiliary (128')	9-13 Hz (H)	Test	Structural	M317, M354, M359	>10.0	-	-	-



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Table 6-24 (Continued)
DIABLO CANYON EQUIPMENT FRAGILITIES
 (Based on hazard defined over 3 to 8.5 hertz range.)

System and Component	Location	Fundamental Frequency	Method of Seismic Qualification	Failure Mode	Information Source	Spectral Acceleration Capacity			
						$\frac{v}{S_a}(g)$	β_R	β_U	HCLPF (g)
NSSS CONTROL									
Process Control and Protection System	Auxiliary (128')	8-10 Hz (H)	Test	Structural	M317, M355	10.78	0.39	0.28	3.57
Solid State Protection System	Auxiliary (140')	8-11 Hz (H)	Test	Structural	M317, M355	12.63	0.37	0.28	4.32
Reactor Trip Switchgear	Auxiliary (115')	8 Hz (H)	Test	Structural	M317, M354	7.90	0.30	0.26	3.14
Resistance & Temperature Detectors	Auxiliary (140')	Not Given	Test	Structural	M345	>10.0	-	-	-
Pressure & ΔP Transmitters	Containment (117')	>33 Hz (H)	Test	Structural	M341	8.93	0.27	0.20	4.11
MISCELLANEOUS COMPONENTS									
Auxiliary Relay Rack	Auxiliary (128')	12-20 Hz (H)	Static Analysis	Anchor Bolts	M317, M350, M359	>10.0	-	-	-
Local Starter Boards	Various	18 Hz (H)	Test	Structural	M454	>10.0	-	-	-
Molded Case Circuit Breakers	Auxiliary (115')	>33 Hz (H)	Test	Structural	M476	>10.0	-	-	-
Valve Limit Switches	Auxiliary (Various)	>33 Hz (H&V)	Test	Generic Function	M344	>10.0	-	-	-
Impulse Lines	Containment (Various)	5-20 Hz (H&V)	None	Rupture From Impact	Data Base	7.09	0.28	0.32	2.63
Containment Purge Valves	Containment (132')	>33 Hz (H&V)	Static Analysis	Actuator Attach. Bolts	M432	>10.0	-	-	-
GENERIC COMPONENTS									
Off-Site Power 230KV 500KV	Yard	Flexible	None	Generic Failure	Data Base	1.69	0.24	0.20	0.82
Penetrations/Penetration Boxes	Containment (135')	24 Hz (H)	Test	Generic Structural	M054	7.38	0.31	0.27	2.83
BOP Piping and Supports	Various	Flexible Piping	Dynamic Analysis	Generic Support	M020, M381	11.03	0.40	0.39	3.00
Hand, Relief, Solenoid, & Check Valves	Various	Flexible Piping	Dynamic Analysis	Generic Function	Data Base	>10.0	-	-	-
Air and Motor Operated Valves	Various	Flexible Piping	Dynamic Analysis	Generic Function	M067, M401	17.10	0.35	0.60	3.57
Cable Trays and Supports	Various	Flexible Trays	Static Analysis	Generic Support	M209-M213	>10.0	-	-	-
HVAC Ducting and Supports	Various	Flexible Ducting	Static Analysis	Generic Support	M214-M218	9.78	0.35	0.48	2.49

excessively conservative; however, it is difficult to justify higher values based upon qualification test data alone.

The fragility description of electrical cabinets was based upon the documented results of their corresponding seismic qualification tests. The loss of function due to acceleration-sensitive failures (for example, relay chatter), when important, and the loss of function due to generic structural failure were generally based upon a conservative factor applied to the qualification acceleration test level. The structural capacities of the important electrical components are high, and have adequate factors of safety. The weakest of the electrical elements is the 4160 V/480-V transformer which has median and HCLPF capacities estimated to be 5.34 g and 2.42 g, respectively.

Loss of function due to acceleration-sensitive failures were considered to be of sufficient importance to warrant fragility estimates for the following electrical cabinets:

Diesel Generator Control Panel

4-kV Switchgear

4-kV Safeguard Relay Panel

Main Control Boards

Hot Shutdown Panel

Except for the 4-kV switchgear, the chatter failure mode capacities, when evaluated by means of relay-specific Generic Equipment Ruggedness Spectra, are sufficiently high so as not to contribute significantly to Plant seismic risk. The 4-kV switchgear, however, contains a large number of overcurrent relays, which are primarily sensitive to vertical excitation. The median and HCLPF chatter failure capacities were estimated to be 3.53 g and 1.31 g, respectively. The 4-kV switchgear chatter failure mode is recoverable by operator action, and the probabilities associated with operator action were included in the model of the system.

The main components of the various critical safety-related ventilation supply systems have relatively high seismic capacities. The failure of the heating, ventilating, and air conditioning (HVAC) ducting is based upon the generic failure of the ducting supports. The supports have a median spectral acceleration capacity of 9.78 g. Bending or slight buckling of the HVAC ducts is likely at accelerations less than the support capacity, but is not expected to result in failure of the ventilation systems.

The fragility of offsite power is based upon the failure of ceramic insulators, transformers, and circuit breakers, and is generated from a data base pertaining to the performance of power transmission components for both nuclear and non-nuclear power stations in real earthquakes. Review of these data shows clear evidence of superior performance of the lighter 230-kV systems over the 500-kV systems. This is particularly true where live-tank, air-blast circuit breakers are used in the 500-kV systems. The median capacities for the 230-kV and 500-kV switchyards are 1.69 g and 0.81 g, respectively.

Several items were treated in a generic manner due to the quantity of such items in the Plant. These included balance-of-Plant piping, air and motor-operated valves, cable trays, and heating, ventilating, and air conditioning ducting and supports. In general, these had relatively high capacities, with median spectral acceleration capacities of approximately 6.0 g or greater. The basis for the fragility of balance-of-Plant piping is generic failure of the piping supports.

Conclusion

In summary, based upon the estimated fragility capacities of the important safety-related structures and equipment, it is judged that the largest individual contributor to seismic risk is the turbine building, because the probable loss of function of the 4-kV switchgear due to acceleration-sensitive failure is recoverable by operator action. Several other components constitute much lesser contributors to overall Plant risk, and no other structures contribute to the seismic risk.

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PROBABILISTIC RISK ASSESSMENT

The Diablo Canyon Probabilistic Risk Assessment is a Level 1 probabilistic risk assessment. That is, it evaluates the frequency of core damage due to all causes including seismically initiated scenarios.

The risk assessment integrates the results produced by the seismic hazards and seismic fragility studies of the Long Term Seismic Program to quantify the risk due to seismic events. The objective of the probabilistic risk assessment is to "assess the significance of the conclusions drawn from the seismic reevaluation studies . . . utilizing a probabilistic risk analysis . . ." as stated in the license condition. In addition to the license requirement, the risk assessment provides for a quantitative estimate of the seismic risk in operating the Plant, and permits a comparison with other more traditional risks that we are subjected to in our daily lives. The quantitative risk assessment further provides a basis for managing risk through use of models that identify the key contributors to risk. These models also allow the evaluation of the impact on risk from changes in design and procedures.

This chapter is a summary of a comprehensive 3,500-page Diablo Canyon probabilistic risk assessment report. Sections pertinent to the Long Term Seismic Program form the basis for this chapter. Computer output, calculations, and data bases not specifically addressing seismic issues are not always included. However, most of this material has been submitted to the NRC in preliminary form. The analysis and data necessary to support the Long Term Seismic Program results and conclusions are included in this chapter.

The Diablo Canyon Probabilistic Risk Assessment was managed and largely performed by Pickard, Lowe and Garrick, Inc. (PLG), with support and participation by Pacific Gas and Electric Company (PG&E) personnel. PG&E provided design and operation information, performed transient analyses, participated in systems analysis and other analytical parts of the risk assessment, and had the lead role in seismic relay chatter analysis.

Assumptions and Limitations

The Diablo Canyon Probabilistic Risk Assessment analyzes the risk from operation of Diablo Canyon Nuclear Power Plant Unit 1. It is based on Diablo Canyon as it exists in the summer of 1988. Changes in Plant design completed through April 1988 and additional changes to hardware and procedures that are scheduled to be complete in 1988 have been incorporated in the model.

Several minor modifications have been implemented as part of the probabilistic risk assessment process:

- *Diesel Generator Fuel-Oil Transfer System.* Constant recirculation paths have been designed to eliminate multiple pump starts. Connections for a backup portable fuel oil pump will be added.
- *Charging Pump Backup Cooling.* Hose connections will be added to allow use of the firewater system for emergency cooling in the event of a total loss of component cooling water.
- *Substation Spare Parts.* Dedicated spare parts will be stored at the 230-kV substation to allow rapid recovery of offsite power in the event of a substation failure.
- *Overcurrent Relay Remote Reset.* The 4-kV overcurrent relays will have the seal-in contact removed to allow the operators to reset the relay from the control room.

Several options were considered to address issues highlighted by the risk assessment process. In some instances such as relay chatter and thermal fragility, testing or additional analysis was appropriate. In other cases, modification of procedures or design was a more beneficial approach. Although the plant risk was acceptable before the modifications, the changes enhance the existing plant safety and provide more flexibility for the operators.

The risk is calculated for Unit 1 only. However, the probabilistic risk assessment models interactions between the two units such as the possibility that the swing diesel generator may

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align to Unit 1 or Unit 2 and the capability to cross tie auxiliary saltwater between the units. Although there are competing factors, especially during two-unit events, the frequency of core damage from the two-unit site should be approximately double the results calculated here for Unit 1.

Every attempt has been made to provide realistic models within the schedule and budget of the project. The central element of the probabilistic risk assessment is the Plant event sequence model discussed in later sections. The general event sequence diagram model was developed to accurately represent the unfolding of scenarios in the Plant and is keyed to specific steps in the emergency procedures. Areas of significant uncertainty are discussed and the few cases of conservative modeling are identified. More extensive conservatisms are introduced when the event sequence diagrams are abstracted into event trees to support quantification. These are clearly indicated in the event tree discussions. Further simplifying approximations (conservatisms) were added during the quantification process as discussed in the results and the systems analysis sections. The simplifying approximations were selected with an awareness of their potential impact; only approximations that significantly reduced the computational complexity of the probabilistic risk assessment were selected, and then only if it appeared that they would have no significant impact on the quantitative results. The results have been reviewed on a sequence by sequence basis to ensure that none of the conservative approximations contribute substantially to the results.

The recovery analysis evaluates the top 80 to 90 percent of the sequences and incorporates approximate recovery factors. However, time was not available to delve deeper and consistently recover all similar sequences. On the other hand, more than 60 human response and recovery actions are imbedded in the systems analyses of the event tree split fractions. For important sequences contributing to risk, a limited number of actions are involved, and the dependencies are modeled correctly. For the rare sequences deep in

the event trees with multiple failures, the human factors may be optimistically quantified. Although these conditions have little impact on current results, they can affect the interpretation of some of the less significant scenarios.

Plant Systems and Site

The Plant is located on the central California coast in San Luis Obispo County, approximately 12 miles west-southwest of the city of San Luis Obispo. Owned and operated by PG&E, the Plant consists of two separate but substantially identical nuclear power units (Unit 1 and Unit 2).

THE PHYSICAL PLANT

Each unit employs a 4-loop pressurized water reactor nuclear steam supply system (NSSS) furnished by Westinghouse Electric Corporation. The NSSS for each unit is contained within a steel-lined reinforced concrete structure that is capable of withstanding the pressure that might be developed as a result of the most severe design basis loss of coolant accident (LOCA).

Table 6-25 briefly lists some Plant-specific features. The vital 4-kV, 480V, and DC systems are arranged to provide 3 redundancies, except for the instrument AC system which has 4 trains and 6 inverters. Emergency power for the two units is supplied by 5 diesel generators. One of these generators is a "swing" unit that is automatically transferred to the unit with the first need. The diesel generators are 3 MVA ALCO units with self-contained automotive-style radiators that do not require Plant cooling water. Each diesel generator has two dedicated starting air systems that are independent of Plant air systems. Each generator has an integral day tank that supplies fuel for 2 to 3 hours of operation. For long-term operation, the fuel to the day tanks is replenished by the 2 redundant fuel oil transfer pump trains supplied from underground fuel oil storage tanks.

The component cooling water/auxiliary saltwater system is important to risk because of the large number of components that are dependent on the system. Two redundant auxiliary saltwater system

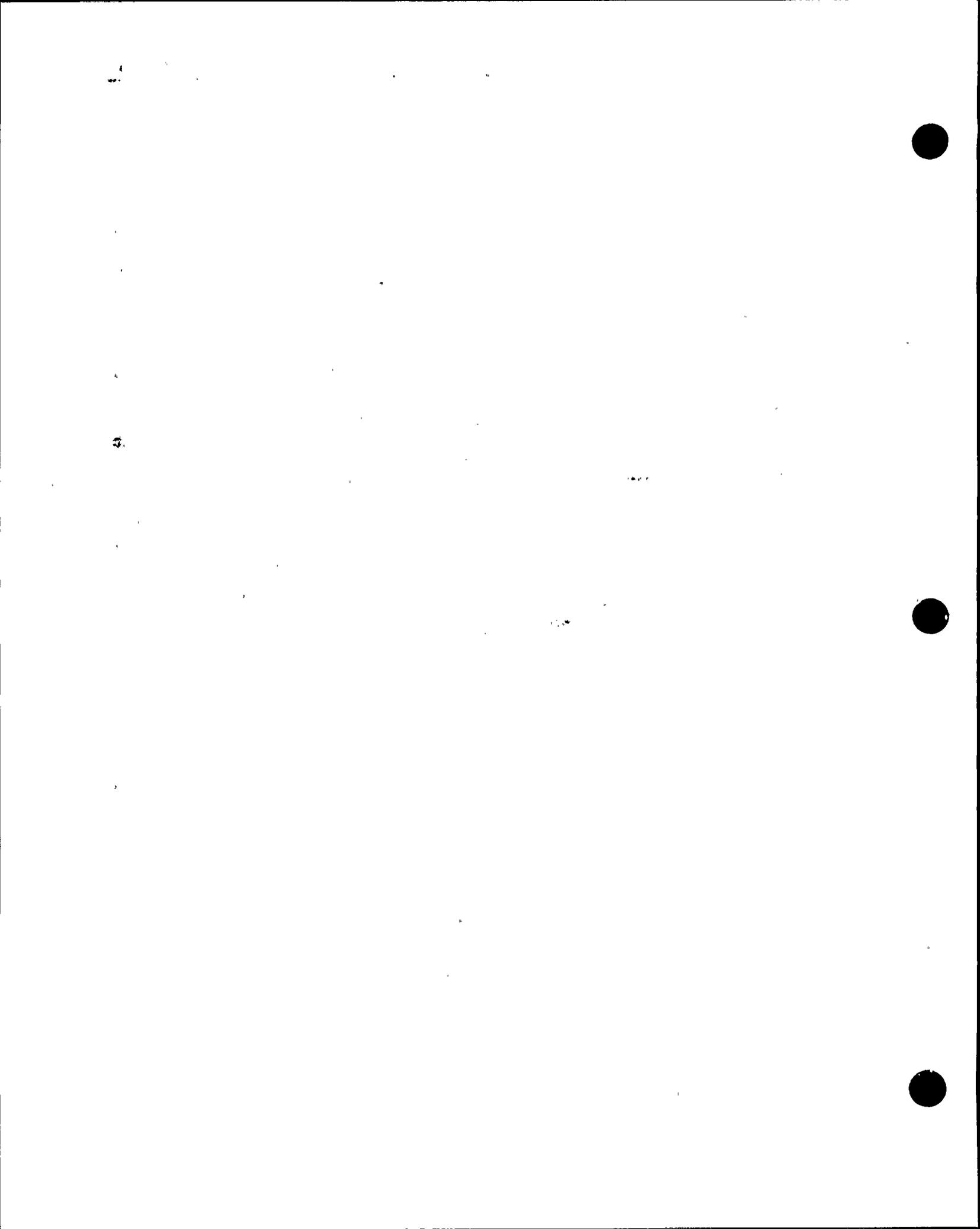


Table 6-25
FEATURES OF DIABLO CANYON

- Three component cooling water pumps and auxiliary saltwater cross-tie
- Two auxiliary saltwater trains
- Three vital power buses
- Swing diesel generator
- Two-train fuel oil system
- Mild climate (minimal) air conditioning requirements
- Nuclear steam supply system pumps and 4-kV switchgear not susceptible to room heatup
- Protective relays not susceptible to room heatup
- 480-V switchgear/inverter room heatup
- Relay chatter easily recovered, no "lockup" and no restart restrictions
- Reliable plant with fewer startup problems than most
- Diesel generator has a self-contained heat exchanger for cooling
- Isolated site
- Seismic design
- Large battery capacity

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pumps at the intake pump seawater to the component cooling water heat exchangers. Three redundant component cooling water pumps are crosstied to the 2 component cooling water heat exchangers which feed 3 headers. The 3 headers provide component cooling water to the fan coolers, reactor coolant pump seals, charging pump, and other systems requiring heat removal. The auxiliary saltwater system and component cooling water systems may be crosstied between units if necessary.

The mild seaside climate eliminates the need for air conditioning except in the control room. Room heatup analyses and thermal fragility tests were performed to determine the success criteria for ventilation systems. To be successful, the component had to continue to operate without the ventilation system (at higher than normal temperatures) until the operator recovered the ventilation.

The instrument air and nitrogen systems are nonvital and were assumed to fail; therefore, vital air-operated equipment that must operate is furnished with backup air bottles. These systems were analyzed to determine the amount of time that the operator could use the equipment before the backup air was exhausted. The recovery for these systems was manual operation of a valve or replenishment of the backup air.

The reactor charging system is important because it provides seal water to the reactor coolant pumps. Loss of seal water will lead to failure of the seals and a resulting seal loss of coolant accident. The charging system is dependent on component cooling water for pump cooling. However, the dependence on component cooling water may be mitigated by an emergency pump cooling system fed from the fire mains.

Although the reactors, structures, and all auxiliary equipment are substantially identical for the two units, there is a difference in the capability of the turbine generators. The licensed reactor rating is 3,338 MWt for Unit 1 and 3,411 MWt for Unit 2, with a corresponding estimated net electrical output of 1,084 MWe and 1,106 MWe, respectively.

The Unit 1 full power operating license was issued by the USNRC on November 2, 1984 and commercial operation began on May 7, 1985. The full power operating license for Unit 2 was issued on August 26, 1985, and commercial operation began on March 13, 1986.

LOCATION AND TOPOGRAPHY

The Plant site consists of approximately 750 acres adjacent to the Pacific Ocean and roughly equidistant from San Francisco and Los Angeles. The minimum distance from either reactor to the nearest site boundary on land is one-half mile, the minimum exclusion distance. On land, there are no activities unrelated to Plant operation within the exclusion area, and it is not traversed by public highway or railroad.

The low population zone (LPZ), as defined in 10CFR100, is the area immediately surrounding the exclusion area. The Plant's LPZ is an area encompassed by a radius of 6.2 miles. This zone contains approximately 80 residents for whom there is reasonable probability that appropriate protective measures, as described in the Emergency Plan, can be taken in the event of a serious accident.

The Plant site occupies a coastal terrace that ranges in elevation from 60 to 150 feet above sea level and is approximately 1,000 feet wide. Plant grade is at El 85 feet. The seaward edge of the terrace is a near-vertical cliff. Back from the terrace and extending for several miles inland are the rugged Irish Hills, an area of steep, brush-covered hillsides and deep canyons that are part of the San Luis Mountains and attain El 1,500 feet within about a mile of the site.

METEOROLOGY

The climate of the site area is typical of that along the central California coast. In the dry season, mainly May through September, the Pacific Anticyclone stays off the California coast and prevents Pacific storms from moving eastward across the state. In the winter wet season, November through March, the Pacific Anticyclone moves southward, weakening in intensity, and allows Pacific storms to enter the state. More than 80 percent of the average annual

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rainfall of 16 inches occurs during this 5-month period. The prevailing wind is from the northwest, and the average annual wind speed is 10 miles per hour. However, the wind direction in many areas results from local terrain. The average annual temperature of the site area is about 55°F, which reflects the strong maritime influence. Maximum summer temperatures of 85°F and minimum winter temperatures of 35°F are exceeded only 1 percent of the time. Severe weather conditions, such as tornadoes and hurricanes, have not been recorded in the area. Thunderstorms are also a rare phenomenon, and the average occurrence of lightning is less than 3 days per year.

Method of the Study

The purpose of this section is to summarize the technical approach and method used in the development of the risk model.

The overall probabilistic risk assessment method closely follows the series of analytical tasks and methods PLG has developed and implemented in performing more than 20 full-scope and phased probabilistic risk assessments of U.S. nuclear power plants. The original exposition of the theoretical and mathematical bases for the approach is given in the PLG methodology document (Kaplan S. and others, 1981).

The purpose of this probabilistic risk assessment is to model scenarios leading to reactor core damage, analyze the probability of such scenarios occurring, and assess the consequences should they occur. The application of PLG's method to Diablo Canyon constitutes a full-scope Level 1 probabilistic risk assessment as defined in the IEEE/ANS probabilistic risk assessment Procedures Guide (NUREG/CR-2300, 1983).

While the method of risk assessment is somewhat improved over previous assessments in many areas, the differences generally are obvious evolutionary steps. However, many aspects of the seismic analysis represent a substantial departure from existing work. The seismic hazard is based on extensive site-specific study far beyond that accomplished for any other risk assessment. The fragility analysis is more thorough, with more

careful attention to conservatisms and site specific factors than has been attempted in previous studies. Finally, the study is the first to include a comprehensive analysis of the impact of seismically induced relay chatter.

STRUCTURE OF THE RISK ASSESSMENT

Core damage may be initiated either by internal events such as a loss of coolant accident or external events such as fires, earthquakes, etc.,. The goal of risk assessment is to identify all sources of initiating events, determine the possible ensuing chains of events, and quantify the likelihood of Plant damage.

The tasks necessary to perform a full-scope Level 1 probabilistic risk assessment include:

1. Definition of all potential initiating events and the resulting sequence-of-event scenarios.
2. Calculation of the frequency for each scenario (because there is uncertainty, a probability distribution over frequency must be determined).
3. Reporting of the results, including quantification of the probability of frequency of reactor core damage and a relative ordering of the specific scenarios (initiating events, system failures, human actions, etc.) leading to it.

A probabilistic risk assessment is basically a listing and analysis of scenarios, and a full-scope probabilistic risk assessment can contain literally billions of scenarios, depending on how narrowly they are described. Assembling a probabilistic risk assessment of workable size, therefore, takes advantage of several "pinch points" that help limit the total number of scenarios requiring separate calculation. At a given pinch point, event sequences are coalesced into groups (states) that are indistinguishable in terms of future behavior; that is, accident sequences emanating from a pinch point state depend only on that state and not on the path up to that point. Major pinch points in the Level 1 Diablo Canyon Probabilistic Risk Assessment are initiating events, the definitions of support system states, early response end states, and Plant damage states, as shown on Figure 6-35. Using these pinch points facilitates

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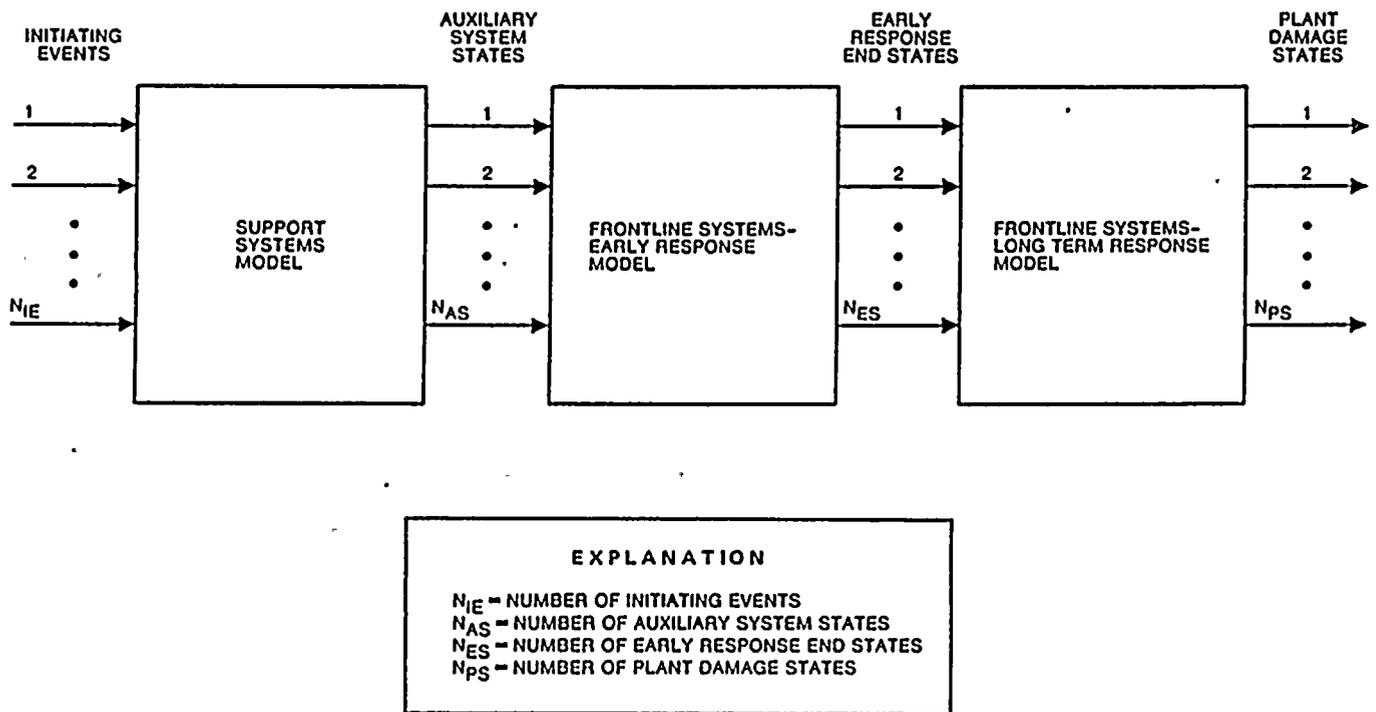


Figure 6-35
 Three-stage plant model with intermediate pinch points.

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the analysis of a large number of accident sequences and the efficient determination of the contributors to risk. One result of the Plant damage state pinch point, for instance, is determination of core damage frequency.

THE PLANT MODEL

A great variety of possible scenarios must be enumerated in the Plant model. To do this requires detailed modeling of the Plant, its systems, its components, and their interdependencies. Physical and human interactions with the Plant that can affect the frequency of occurrence of an accident scenario must also be included.

Event frequencies and their associated uncertainties are quantified using historical evidence in both nuclear and nonnuclear experience, when applicable. The Plant model contains the reliability aspects of all the systems, including the engineered safety features of the containment.

With risk defined fundamentally as a list of scenarios or event sequences, the key requirement of a risk assessment method is an orderly procedure for defining the scenarios. For this purpose, we use a number of logic methods, most notably the master logic diagram, event sequence diagrams, event trees, fault trees, and cause tables. These methods are described and applied by Kaplan and others (1981). Underlying the logic methods used for organizing results are fundamental engineering analyses.

Initiating Events. The completeness in coverage of accident sequences in a probabilistic risk assessment model is determined by the completeness of the choice of initiating events. No matter how completely and accurately detailed the event tree/fault tree logic model is constructed, incomplete or ill-defined initiating events can lead to inaccuracies in the results. Therefore, a great deal of emphasis was placed on selecting a comprehensive and uniquely appropriate set of initiating events. Taken into account in this selection were design-specific factors as well as generic insights from operating experiences, previously published probabilistic risk

assessments, and other safety analyses performed on Diablo Canyon. The three methods that were used to define, evaluate, and group initiating events for the probabilistic risk assessment are described in later sections. The result of applying these methods was the selection of 50 initiating events for full risk model quantification, including 7 loss of coolant accidents, 14 transients, 6 common cause (support system) failures, and 23 external events (including 6 levels of earthquakes).

The primary reason for the unusually large number of initiating events, more than in many other probabilistic risk assessments, is the strong degree of emphasis placed on common cause initiating events. These particular initiating events arise from causes that result not only in a Plant transient event, but also in failure or degradation of one or more Plant systems that are needed to respond to the initiating event. Common cause initiating events include support and control system faults, external events, and spatially dependent physical interactions, such as fires and floods.

Another reason for the selection of initiating event categories is that some have received special attention in recent years. All such events are treated explicitly and in appropriate context in the probabilistic risk assessment. Initiating events receiving special attention include:

- *PWR Steam Generator Tube Rupture.* This event is complicated in terms of the operator actions required to mitigate the consequences. It is discussed in detail and treated explicitly in its own event tree.
- *Loss of Support Systems.* These initiating events are analyzed explicitly. At multiunit plants, loss of common support systems can impact systems success criteria. Because of its far reaching impact, loss of electric power has always drawn interest. Loss of service water and component cooling water are of more recent interest in PWR analysis because they might lead to both reactor coolant pump seal leakage and also HPI pump failure.
- *External Events.* All external events (that is, events that create adverse conditions in the

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Plant at the same time that they perturb the reactor coolant system) are treated explicitly. External events judged to be of possible significance to risk are analyzed in the context of the full Plant model developed for "internal" events. Among the possible external events considered are earthquakes, fire, flood, hazardous materials, and turbine missiles.

Certain scenarios are of special concern because they are unresolved NRC safety issues, and others have been shown to be significant contributors to risk in other probabilistic risk assessments. These include:

- **Station Blackout.** This type of scenario can result from any initiating event if the offsite grid and the outside AC power completely fail. The logical framework of the probabilistic risk assessment places this scenario into perspective.
- **Failure to Trip the Reactor.** The possibility of the reactor failing to trip on demand is considered for every event from which the trip actuation setpoints can be reached. The "no trip" scenarios are considered explicitly.
- **Reactor Coolant Pump Seal LOCAs.** Scenarios that lead to reactor coolant pump seal degradation are possible if seal cooling is lost. These scenarios are particularly troublesome, because the same failures that cause loss of seal cooling can often disable the injection system that could mitigate the leak.
- **Primary Relief Valves Open and Fail To Reclose.** Event trees for which additional leakage is significant are used to model failure of the primary relief valves or primary safety valves to open and successfully reclose. For a PWR, failure of the valves to reclose can lead to a loss of RCS inventory, such as would occur following a pipe break. If isolation of the stuck open valve is not immediate, operator actions are required to mitigate the consequences of the two types of events.
- **Bleed and Feed Cooling.** The event trees for PWR transients consider the possibility of heat

removal from the RCS using the RCS relief valves and high pressure injection flow. This cooling mode is called "bleed and feed." The viability of bleed and feed cooling for removing decay heat has been confirmed by transient analysis. In some event trees, bleed and feed will also be considered as a method for cooling the RCS to decay heat removal system entry conditions; that is, as a way of removing both decay heat and latent heat (the heat stored in the RCS).

- **PWR Pressurized Thermal Shock.** If scenarios leading to high RCS pressure and relatively low RCS temperatures occur, the likelihood of crack propagation in the reactor vessel may increase. This is because exposure of the reactor vessel to neutron flux raises the nil ductility transition temperature; that is, the temperature at which the carbon steel would suffer a sharp increase in brittleness. Usually, the transition temperature is outside the normal operating range for nuclear power plants. However, concerns about the transition temperature after years of reactor operation have caused strict pressure and temperature limits to be established for operation of the reactor coolant system.

Event Sequence Models. Once the initiating events are identified, the scenarios or accident sequences that could result are identified. The basic scenario model of the Plant is in the form of event sequence diagrams (a high level event sequence diagram is shown on Figure 6-36 for illustration purposes). The event sequence diagrams were developed in cooperation with licensed operators at the Plant. Such diagrams mimic success and failure of Plant equipment and identify applicable emergency procedure steps at key points along each sequence. These event sequence diagrams are abstracted into event trees with early and late modules for quantification.

The Plant event tree is actually a network of event tree modules. The top events of each event tree represent the responses of the various Plant systems or operator action, so that each path through the tree represents an event sequence. In this way, the event tree embodies a truth table of all possible success and failure combinations of

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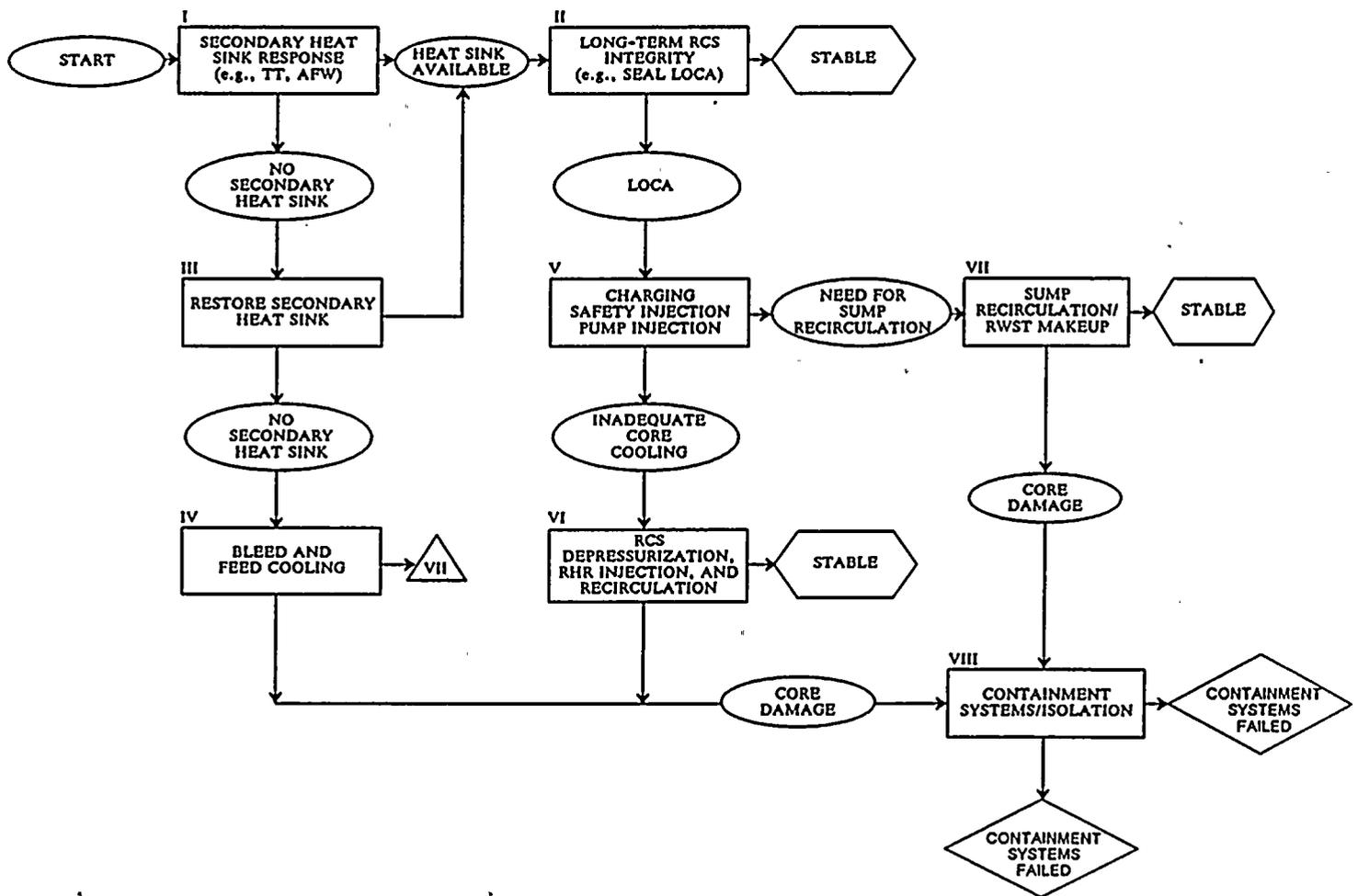


Figure 6-36

General transient event sequence diagram overview.

the Plant systems. At the end of each sequence, the Plant is either in a stable, recovered condition or has suffered some core damage. A set of Plant states, y_j , is defined, and each path through the tree is assigned to one of these states. These Plant damage states are defined in terms of the conditions in the reactor vessel at the time of melt, and the status of the containment safety/mitigation systems. These states are chosen and defined with sufficient specificity that once such a state has occurred, the subsequent events in the containment are the same irrespective of the path by which that state was reached. As a result of this definition, a coalescence of scenarios occurs at this point, which structures the scenarios list and greatly simplifies the computational labor involved in the analysis.

Figure 6-37 is a symbolic representation of an event tree diagram. Arrayed across the top are various systems or safety functions in the Plant, for example, the reactor protection system, the auxiliary cooling system, etc. At the left we enter the tree with the initiating event and then ask, "Does system A work or not?" Thus, the tree branches at this point, with the upper branch representing "system A works" and the lower branch representing "system A fails." At system B there is another branching, and so on.

The basic process used for determining the split fractions (chance of failure at an event tree branch-point) is to perform an analysis of the system to which that branch point relates. That is, we break the system down into its components and determine the relationship between the performance of the components and the performance of the system. From this relationship, and from the likelihood of various component failures and combinations of component failures, the split fractions for the system are calculated.

Thus the risk assessment is structured as shown in Figure 6-38. The top level (that is, the Plant level) is the event tree diagram. This level shows which combinations of system failures, together with which initiating events, could result in any given Plant state.

At the next level down, the system level, there are fault trees or other models expressing the relationship of the system to its components. The component level shows which combinations of component failures result in failure of the systems. Below this level is the cause level, showing which causes could result in component failure and which combinations of causes could result in those combinations of component failures that cause system failure. Particular interest centers, at this level, on single causes that by themselves could fail more than one component or more than one system.

Systems Analysis Techniques. The determination of the split fractions for each system in the Plant event trees is done by a process called systems analysis. This task assesses the likelihood that a system will fail to meet its functional success criteria as defined by the Plant response event tree models. System failures may result from independent or dependent equipment hardware failures, human error, or from combinations of equipment failure, human errors, maintenance actions, and testing activities. Specific system failures may affect the availability of other systems (for example, support system failures), or they may directly affect the ability to mitigate the consequences of accidents or transient events; for example, frontline system failures. The systems analysis defines physical and functional dependencies among the systems and is used in constructing the Plant event tree models. The logical structure of the event trees, in turn, defines scenario-specific success criteria for system performance and boundary conditions within which the system is required to operate. Therefore, the systems analysis task provides:

- Engineering knowledge about the Plant systems needed to develop the Plant risk model; that is, dependency matrices and event tree models.
- Input for quantification of the integrated Plant event tree models; that is, failure frequency of each system top event split fraction for specified boundary conditions.

It is important to recognize that the system models developed in these analyses include only those



EVENT TREE DIAGRAM

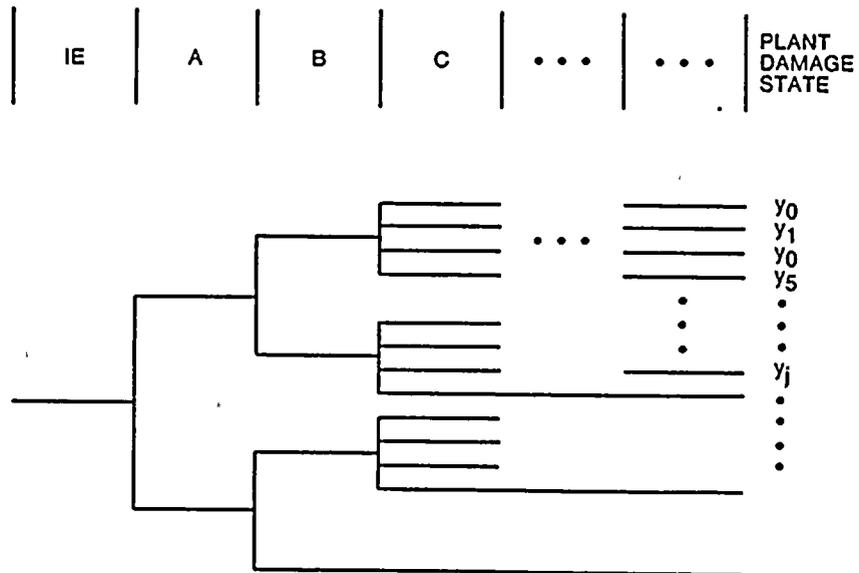


Figure 6-37

Structuring the scenario list: the Plant event tree.

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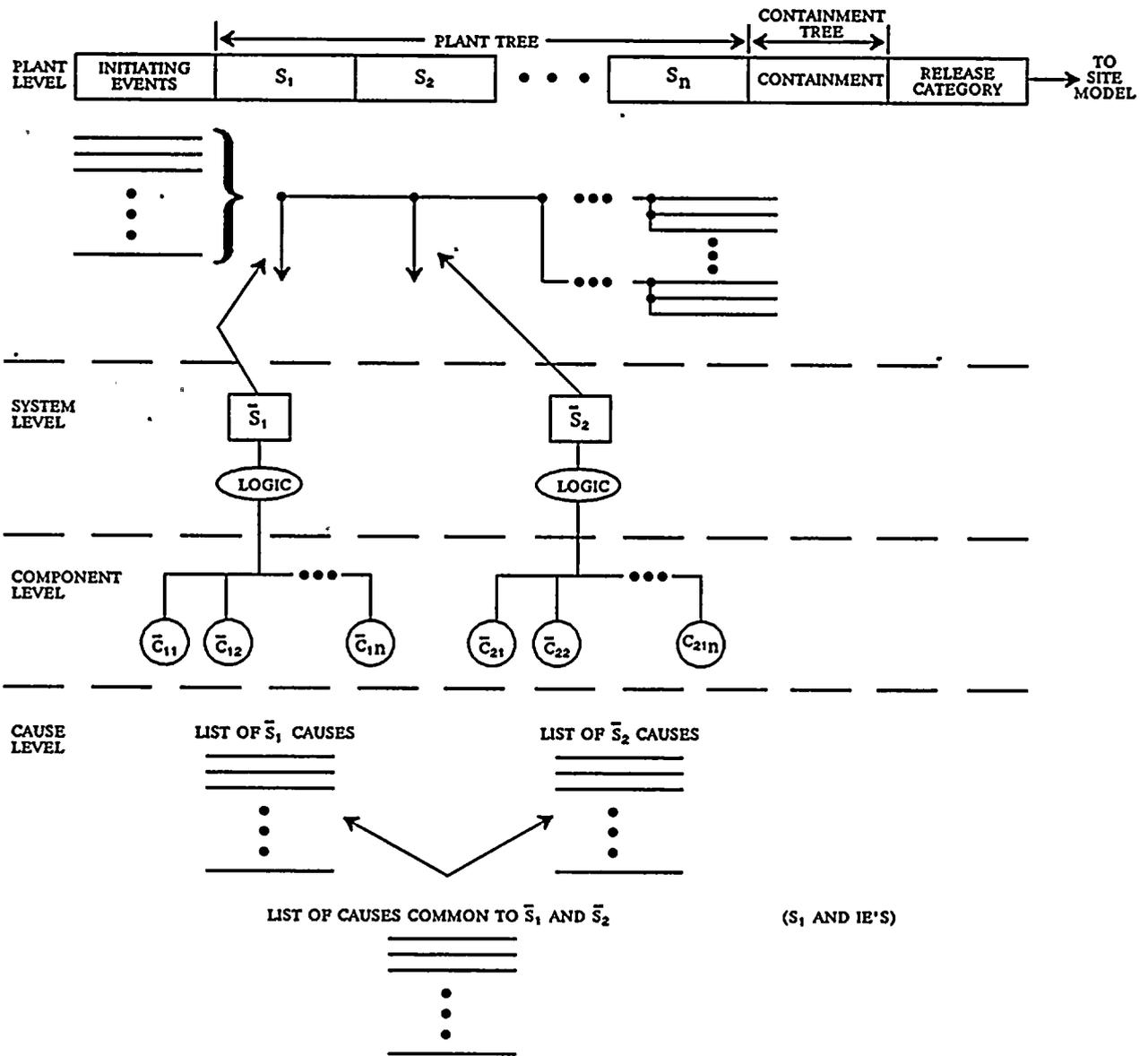


Figure 6-38
Structuring scenarios.

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components necessary to quantify system unavailability for the split fraction boundary conditions for this study.

Each system analysis contains all major components required for system success as defined by the event tree system split fractions. The contribution to system unavailability from common cause dependent failures is treated by the basic parameter model for each system analysis according to the general methodology described by Fleming (1985). The Plant-specific operating and test procedures were reviewed during the systems analysis task.

Human errors during testing that could contribute to system unavailability are included in the systems models when considered significant.

Once the system information is documented and the event sequence diagram developed, the next step is to define the top event split fractions for the quantitative systems analysis. The split fraction definitions identify the success criteria for each system under a specific set of boundary conditions. These definitions include the major components (or systems) required to operate, the operating mission time, and the support systems available. The grouping of system equipment within each top event is performed in the support and frontline event tree development task. The event tree top events model the effects from system and subsystem successes and failures. These provide efficient event logic models for the Plant response to various initiating events and also preserve all important physical and functional dependencies among the Plant systems. Scenario-specific boundary conditions may affect the number of available components or the detailed success criteria for a system. These effects are evaluated by defining one or more conditional split fraction under each top event. Top event success criteria and quantification boundary conditions are determined and provided as input to the systems analysis. The important Plant systems are assumed to be operated and maintained in accordance with the Plant technical specifications except for explicitly modeled system misalignments and maintenance errors.

To incorporate common cause events into the systems analysis, the analyst must understand the factors that determine the dependence or independence among the components in the system. Such factors include how groups of components are used, the extent of their diversity (if any), the physical proximity or separation of redundant components, and the susceptibilities of system components to varied environmental stresses. In addition, the potential for human errors associated with operation, maintenance, or testing systems shared by two or more system components should also be considered as an important factor. Similarity in design, manufacture, and type among components of different trains implies the existence of strong dependencies. On the other hand, common cause effects would not be expected for dissimilar equipment. To account for these factors, the analyst must identify those components in the system that will be included or eliminated from the common cause analysis and categorize common cause groups of components for systems of interest. A common cause group is a group of components having a significant likelihood of experiencing one or more common cause events affecting two or more components in that group.

The outcome of this part of the analysis is a list of the various groups of similar components that are judged to be subject to common cause failures. It should be noted that, due to practical limitations, one may not be able to model all possible ways that similar components within a system can be grouped for common cause analysis.

The top event split fractions are quantified using component failure data, maintenance frequency and duration data, human error rates, and common cause parameter data stored in the data base file. Monte Carlo techniques were used to combine the discrete probability distributions for the data base elements modeled in each split fraction equation. This results in a mean or point estimate value and a discrete probability distribution for the conditional unavailability of each split fraction. The mean or point estimate values are used initially to quantify the support and frontline event trees. Subsequently, the discrete probability distribution for each split

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fraction is used in the Plant model uncertainty analysis for the important sequences identified.

It must be emphasized that the systems analysis methodology outlined in the preceding paragraphs provided a set of general guidelines for the systems analysis task. Each system analysis follows these general guidelines. Individual analyses may not have all of these elements documented in the same style or detail. Some systems may have greater detail in the equations to provide more clarity. These variations in model structure are expected, depending on the system configuration and split fraction quantification requirements.

SEISMIC ANALYSIS

The main elements of a seismic risk analysis are the seismic hazard evaluation, structure and component fragility analysis, Plant logic analysis, and quantification. The general method for the analysis of each of these elements is further discussed here and is represented on Figure 6-39. The hazards and fragility analysis were discussed in earlier sections of this chapter.

Interface with Fragility and Hazards Elements. Because of new approaches to the definition of ground motions used by the Long Term Seismic Program, care was taken to make sure that the information supplied by the hazards and fragility analysts was compatible and that the information was used properly in the probabilistic risk assessment. The fragility curves were defined by median ground spectral acceleration capacities (S_a), times the product of randomness and uncertainty variables which have unit median values and are lognormally distributed with logarithmic standard deviations of β_R and β_U respectively. The aggregate total hazard curves are based on the free-field response spectra averaged over a spectral acceleration range of 3 to 8.5 hertz (vibration). This acceleration frequency range was chosen to be consistent with the fragility calculations. The failure modes that govern the seismic capacity of structures and components were explicitly defined to ensure that the failures were properly categorized in the probabilistic risk assessment. For instance, a pump may fail in several different modes: binding that stops the pump, leakage, or a large breach of the pressure

boundary. These modes are important in characterizing the seismic risk.

Seismic Plant Logic Analysis. The Plant logic analysis determines the consequence of various building and plant component failures. The approach used in the risk assessment relies on the logic expressed by the event trees used in the general event sequence model developed for the analysis of all Plant events.

The Plant logic analysis process is represented in graphic form on Figure 6-40. The first step is to identify the components whose seismic failure could initiate an accident scenario. This identifies the event tree, or trees (initially developed in an internal events analysis), that can be used in the seismic analysis. For example, if failure of a number of components will cause the reactor and/or turbine to trip, a general transient initiating event tree would contain all the possible scenarios of interest. Other component failures could generate other initiating events and also require the use of additional event trees. Once the appropriate event tree is identified, it is necessary to expand it for use in a seismic analysis by adding the passive components (such as buildings, cable trays, conduits, and HVAC ducts) typically not included in the trees developed for the internal events analysis.

Also, it is necessary to develop a matrix that relates the seismic failure of each component to the unavailability of one or more systems reflected in the top events in each event tree.

Seismic Point Estimate Quantification. The initial point estimate quantification is begun by selecting discrete earthquake acceleration levels in the range of interest, and determining the mean annual frequency of each acceleration level. Typically, 5 or 6 such discrete values are selected. When a greater number of values is chosen, the quantitative result is refined but often not significantly so.

As seen on Figure 6-40, a table is developed to indicate, at each of these discrete accelerations, the calculated mean conditional failure fraction of each seismically failed top event. In addition to seismic failures, components might also be unavailable because of nonseismic causes (for

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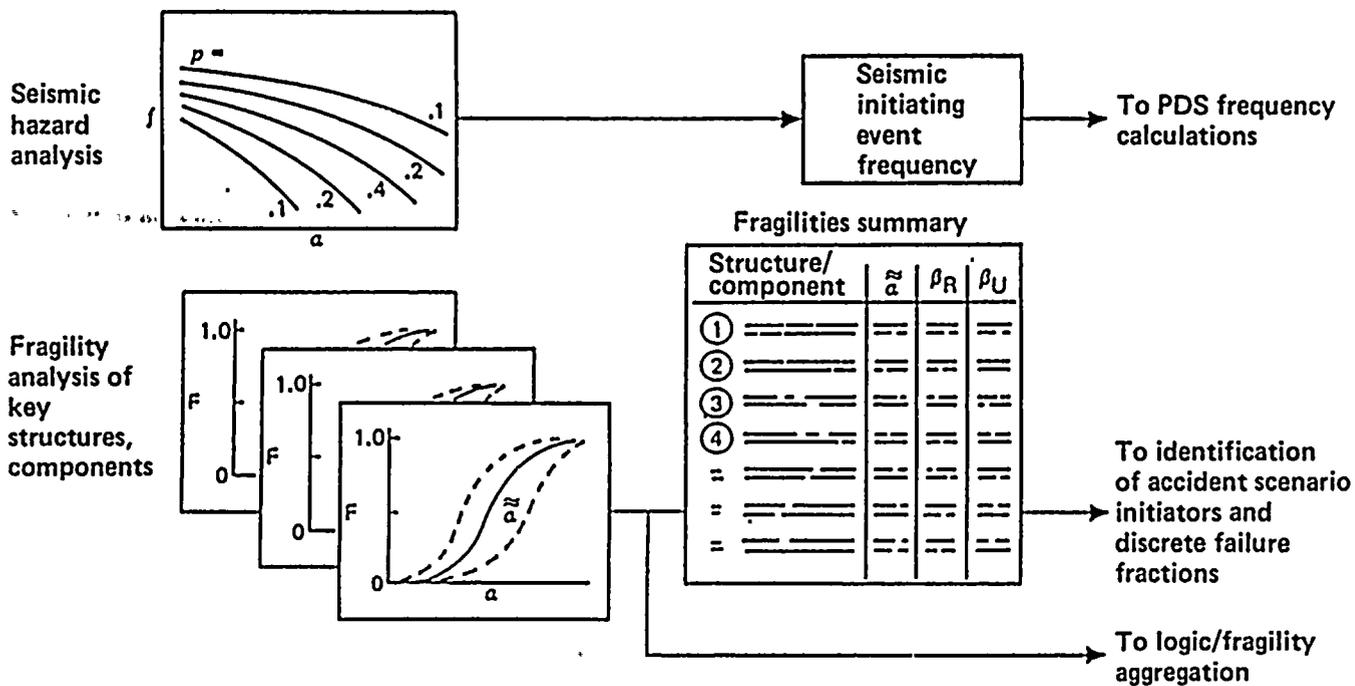


Figure 6-39
Seismic hazard and fragility analysis.

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example, random failures, maintenance, testing). The mean conditional nonseismic unavailabilities (which are constant over all accelerations) are added to the conditional seismic failure frequencies at each discrete acceleration to comprise the top event branch point split fractions for use in the seismic event tree quantification.

First, the conditional frequency of being in each support system end state must be calculated. Each conditional end state frequency is then input to each frontline event tree to determine the conditional frequency of each scenario. Then, the mean frequency of each discrete acceleration is combined with each conditional scenario frequency. This provides an unconditional point estimate of each scenario frequency in rank order of their contributions to the total core damage frequency. After comparing the seismic and nonseismic scenario frequencies and determining the seismic scenario significance, refinement of the scenario analysis (including, for example, the addition of recovery actions) may be warranted.

Seismic Final Quantification. In the cases in which uncertainty calculations for seismic scenarios are warranted, a Boolean logic expression is developed for the significant component failures (those with the highest frequencies) contributing to each major scenario. These Boolean expressions are used in the uncertainty analysis.

In the first step, it is necessary to determine the Plant level fragility for each Boolean expression using the full family of fragility curves for each component in the expression. The family of curves for a component is aggregated with that of another independent component so that the probability of either component failing is given by

$$p(A \text{ or } B) = p(A) + p(B) - p(A) \times p(B)$$

Following this form, a discrete probability distribution is developed by first using each of a number of individual curves for each of two components, and then aggregating these into a number of new curves. These in turn are

aggregated with the curves of the next component in the Boolean, and so on. Eventually, a Plant-level fragility is obtained, complete with its uncertainty (represented by a family of curves).

The next step in the final quantification process is to convolve the full set of seismic hazard curves with the full set of Plant-level fragility curves. Here, each weighted hazard curve is convolved with each weighted Plant-level fragility curve at discrete accelerations. The total is the probability of frequency distribution for all seismic initiated scenarios leading to core damage, and provides a clear picture of the dominant component contributors and the uncertainty in the results. This distribution can then be combined with the distributions of the other initiating events to yield a distribution of the total core damage. From the Boolean and component fragilities, one can determine the components that dominate core damage.

NONSEISMIC EXTERNAL EVENTS

"External" initiating events belong to an important class of common cause initiating events that includes such events external to the Plant as earthquakes, tornadoes, and aircraft crashes, as well as various in situ hazards that occur within the plant, such as fires, steam, and pipe whip. External events analysis is a major task in this risk assessment. An integral part of this analysis is the identification of physical interactions (often called spatial interactions) that cause one or more initiating events and potential additional damage to one or more Plant systems.

Twenty-three categories of external initiating events are quantified. The distinctions made by specifying different categories of initiating events are necessary to account for the influence of the initiating events on the development or unfolding of event sequences and to isolate key factors of importance in quantifying these event sequences. The 23 external initiating events are listed below by major class.

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<u>External Events and Spatial Interactions Class</u>	<u>Number of Initiating Event Categories</u>
Seismic	6
Fires	14
Flooding/jets/sprays	3
Total	23

The approach to seismic events was discussed earlier. Fourteen fire categories cover 24 fire locations and degrees of damage done by the fire in 7 of these locations. The three flooding categories include events in eight different locations.

Summary of Spatial Interactions Analysis (Including Fires, Internal Flooding, and Other Spatially-Dependent Events). This analysis of the environmental (in situ) hazards began with what is known as spatial interactions analysis. The primary objective of spatial interactions analysis is to use information on spatial commonalities to identify those physical interactions involving power plant environmental (in situ) hazards (such as fire, flood, and steam) that can cause an initiating event and intersystem dependent failures that would contribute significantly to risk. The spatial interactions analysis task can be divided into two parts: (1) the identification of Plant environmental hazard scenarios for every location in the Plant and (2) the assessment of their relative importance to risk. Several data bases were developed to cross-reference equipment items, hazard sources, mitigative features, and their associated locations to support the identification and analysis of spatial interactions scenarios. Systematic data collection and scenario identification methods were used to ensure a high level of rigor and completeness in the results.

Fire Analysis. In this section, the effects of fires on Plant safety systems is investigated. Evaluation of fire events follows the scenario approach in which a large list of scenarios is envisioned that may take place. By scenario, we mean a chain of events starting with the ignition of a combustible. A scenario includes the initiation of a fire, its growth, the ignition of other combustibles, its detection, its suppression, and its impact (either

by heating, smoke, or activation of the fire suppression systems) on Plant equipment.

This analysis was started on the basis of results of the spatial interaction study. As part of spatial interaction study, a large set of internal fire scenarios was generated by that analysis. Final results of that analysis include an estimation of the scenario frequency, the extent of impact to Plant systems of each scenario, and a screening of all scenarios judged to be of significant importance to overall Plant risk.

After analyzing the list of important fire scenarios that were screened by the spatial interaction analysis, two separate scenario categories were identified on the basis of their impact on Plant damage states. The first category of scenarios would produce a limited amount of equipment damage as a result of the postulated fire. For most scenarios, the extent of impact on Plant systems should not lead to core damage, assuming the remaining emergency core cooling systems operate in accordance to their design requirements. The second category is for fire scenarios that have the potential for producing a more serious level of Plant damage. Fire incidents of this category generally introduce multiple system failures, and could limit the operators' functional capability inside the control room. Core damage might occur in this type of fire scenario if the recovery actions cannot be conducted successfully.

This analysis is a more detailed evaluation of the results generated by the spatial interaction study. It is conducted by a more in-depth investigation of Plant equipment locations and cable routings to better estimate event frequencies and equipment damage for a given fire scenario. In the spatial interaction analysis, it was conservatively assumed that a fire could disable all equipment and cables within a fire area, independent of the severity of the given fire. For this, analysis layout arrangement of Plant components and cables were examined and the appropriate geometric and severity factors for scenario frequency quantification were developed. Based on these additional efforts, it enabled the analysis to more realistically estimate both the scenario frequency and the Plant damage description.

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For fire scenarios that have the potential to result in serious Plant damage additional consideration was given to the following aspects of the analysis:

- *Operators' Recovery Actions.* Fire-induced Plant hardware damage could be extensive for this type of scenario; therefore, recovery actions need to be started to prevent the initiation of core damage. The scenarios normally involve evacuation from the main control room (control room fire) or loss of the access to key Plant control features inside the control room (cable spreading room fire). Such parameters as the available time window for operator actions and location of the hot shutdown panel outside the control room are critical factors considered in the recovery analysis. A detailed evaluation of operators' response to carry out the necessary recovery tasks was conducted by using a human engineering analysis.
- *Uncertainties of the Frequencies.* To account for the uncertainty associated with the scenario development, a probability distribution was assigned with the scenario development, a probability distribution was assigned for each of the critical parameters, and a Monte Carlo simulation calculation based on these probability distributions was performed.

Analysis of Internal Floods and Other Environmental Hazards. The focus of this section is on hazards other than fire. The term hazard used in this section refers to internal flood, pipe whip, jet spray, explosion, missile (other than those generated by the main turbine generator), and caustic attack.

The scenarios considered in this analysis can be classified into 10 categories according to the hazard types. The hazard types are floodwater (FW), high energy steam line break (HS), high energy water line break (HW), jet steam (JS), jet water (JW), spray steam (SS), spray water (SW), caustic attack (CA), explosion (EX), and missile (MI). A floodwater hazard is a break of water pipe that would lead to a pool. A high energy steam line break or a high energy water line break is a rapid breach in a pipe with a pressure of 275

psia or more or a temperature of 200°F or more. If a pipe section does not comply with these criteria, it is considered as a moderate energy line. A jet steam or jet water hazard consists of small breaks in steam or water pipes with a higher pressure than 1,000 psia. A spray steam hazard is judged as a small steam line break with a pressure less than 1,000 psia that would lead to a steam environment. A spray water hazard is envisioned as a situation for which equipment at high elevations in a location are sprayed with water from a breach. Caustic attack is considered as the potential for reactive chemical release and chemical impact on equipment. An explosion is caused by either an explosive mixture of gases or flammable vapors or combustible gases. For missiles, the condition had been considered as disintegration of runaway rotating equipment and breach of pressurized canisters. Missiles generated from the main turbine generator have not been included.

The internal hazard analysis is an extension of the spatial interactions analysis. The important scenarios from the spatial interactions are analyzed in great detail. The methodology used in this analysis is basically the same as the one used in the spatial interactions analysis except for the depth of the analysis. The approach of the analysis can be divided into two major aspects: the scenario impact justification and the scenario quantification. The main reason for repeating the process used in the spatial interactions analysis is that a given scenario may need to be divided into several subscenarios, to properly account for multiple hazard sources that may be contained in the original spatial interaction scenario, or different types of Plant impact may be possible.

Other External Events Analyses. There is a long list of other potential sources of hazards external to the Plant systems that were considered as candidates for externally initiated accident scenarios. Among these sources, there were several that could not be screened out based on a high level qualitative and quantitative screening. Those external hazards, therefore, were selected for a more detailed analysis to determine the likelihood of the corresponding accident initiators

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and their potential Plant impact and consequences. The selected events are:

- Aircraft crash and other falling objects
- External fire
- Turbine missiles
- Ship impact
- Hazardous chemicals
- Hurricane winds and tornadoes
- External flooding

The basic approach of analysis for all these events is to first perform a conservative screening in the area of initiator frequency as well as for the conditional likelihood of core damage. If such conservative screening resulting in core damage frequencies smaller than 10^{-7} per year, no further detailed analysis was performed. If, on the other hand, the event could not be dismissed via a conservative assessment, a more realistic estimate of initiator frequency and/or conditional core damage probability was made based on a more detailed analysis of the hazard source and the accident scenarios involved.

Initiating Event Identification And Classification

This section presents the initiating events that were identified and selected for quantification in the probabilistic risk model, the set of initiating events uniquely appropriate to Diablo Canyon.

The 50 initiating event categories that were selected for quantification are listed in Table 6-26. The term "category" is used in the sense that many specific events can be identified for each category by breaking the category down by cause, failure mode, and degree of severity. The distinctions made by specifying different categories are those necessary to account for the influence of the initiating events on the development of the accident sequences in the event sequence model and to isolate key factors of importance in quantifying accident sequence frequencies and damage levels. For this reason, discrete seismic hazard intensity levels and distinct fire locations and magnitudes are counted as separate initiating event categories in the tabulation below.

<u>Major Class</u>	<u>Number of Initiating Event Categories</u>
Loss of coolant inventory	7
Transients	14
Common cause initiating event	
● Support system faults	6
● External events and spatial interactions (including fires)	23
Total	50

INITIATING EVENT IDENTIFICATION

The methods used to actually identify candidate initiating events include the following:

- Master logic diagram
- Heat balance fault tree
- Failure modes and effects analysis

The master logic diagram method accounted for the identification of most initiating event categories that were finally selected for quantification. The heat balance fault tree method resulted in a finer structure for defining initiating event categories and enhanced completeness. Failure modes and effects analysis (FMEA) was used here to systematically identify support system failure modes that result in common cause initiating events. The FMEAs are not only used to generate additional initiating event categories but also to subdivide the original set to facilitate the treatment of dependence in event tree quantification.

Data Analysis

To make the risk model as representative of the Plant as possible, a Plant-specific data base was developed.

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Table 6-26
 INITIATING EVENT CATEGORIES SELECTED FOR QUANTIFICATION
 OF THE DIABLO STATION RISK MODEL

Sheet 1 of 2

Group	Initiating Event Categories Selected for Separate Quantification	Code Designator
Loss of Coolant Inventory	1. Excessive LOCA	ELOCA
	2. Large LOCA	LLOCA
	3. Medium LOCA	MLOCA
	4. Small LOCA, nonisolable	SLOCN
	5. Small LOCA, isolable	SLOCI
	6. Interfacing systems LOCA	
	6a. At RHR pump suction	VS
6b. At RHR pump discharge	VD	
	7. Steam generator tube rupture	SGTR
Transients	8. Reactor trip	RT
	9. Turbine trip	TT
	10. Loss of condenser vacuum	LCV
	11. Closure of all MSIVs	AMSIV
	12. Steam line break inside containment	SLBI
	13. Steam line break outside containment	SLBO
	14. Inadvertent safety injection	ISI
	15. Main steam relief valve opening	MSRV
	16. Total main feedwater loss (includes feedwater line break)	TLMFW
	17. Partial main feedwater loss	PLMFW
	18. Excessive feedwater	EXFW
19. Closure of one main steam isolation valve (MSIV)	IMSIV	
20. Core power excursion	CPEXC	
21. Loss of primary flow	LOPF	
Common Cause Initiating Events		
Support System Faults	22. Loss of offsite power	LOSP
	23. Loss of one DC bus	L1DC
	24. Total loss of auxiliary saltwater	LOSW
	25. Total loss of component cooling water	LOCC
	26. Loss of 480-V switchgear ventilation	LOSWV
	27. Loss of control room ventilation	LOCV
Seismic Events	28. 0.2 g to 1.25 g	SEIS1
	29. 1.25 g to 1.75 g	SEIS2
	30. 1.75 g to 2.0 g	SEIS3
	31. 2.0 g to 2.5 g	SEIS4
	32. 2.5 g to 3.0 g	SEIS5
	33. 3.0 g to 4.0 g	SEIS6

Table 6-26 (Continued)

INITIATING EVENT CATEGORIES SELECTED FOR QUANTIFICATION
OF THE DIABLO STATION RISK MODEL

Sheet 2 of 2

Group	Initiating Event Categories Selected for Separate Quantification	Code Designator
Fire and Smoke	34. Loss of both motor-driven AFW pumps	FS1
	35. Loss of all charging pumps and MSIV closure	FS2
	36. Loss of component cooling	FS3
	37. Loss of control ventilation	FS4
	38. Loss of auxiliary saltwater	FS5
	39. Loss of 4-kV buses HF and HG	FS6
	40. Loss of 4-kV buses HG and HH	FS7
	41. Loss of 4-kV buses HF, HG, and HH	FS8
	42. Control room fire at vertical board VB-1	CR1
	43. Control room fire at vertical board VB-2	CR2
	44. Control room fire at the interface of vertical boards VB-2 and VB-3	CR3
	45. Control room fire at vertical board VB-4	CR4
	46. Cable spreading room fire one	CS1
	47. Cable spreading room fire two	CS2
Flood, Jets, and Sprays (pipe breaks)	48. Loss of all auxiliary feedwater	FS9
	49. Loss of both motor-driven AFW pumps	FS10
	50. Loss of auxiliary saltwater	FS11

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Four general categories define the scope of the data analysis task:

1. Component failure rates
2. Common cause failure parameters
3. Component maintenance frequency and duration
4. Internal initiating event frequencies

Several other types of data such as component fragility curves used in the seismic analysis, fire frequencies used in the fire analysis, and human actions were also developed, but evaluated in separate areas of this analysis.

The data were developed by combining, in a Bayesian update, the experience from a large population of nuclear power plants documented in the PLG proprietary data base (plant-to-plant variability distribution) with the plant-specific data developed from a review of the Diablo Canyon Unit 1 records of Plant operation.

The following sections describe the data analysis method and data base. The resulting distributions are presented in tabular form for each of the four data categories. All Plant-specific distributions are stored in a computer data base that includes a brief summary of the collected data, the generic distributions used, and several important characteristics of the distributions.

DATA ANALYSIS APPROACH

This section provides a discussion of the techniques used in developing the Diablo Canyon Unit 1 data base. As mentioned earlier, the data was developed by updating generic information with Plant-specific information, using Bayesian techniques.

The Diablo Canyon Unit 1 Plant began commercial operation on May 7, 1985. The data collection effort covered the period from slightly before the beginning of commercial operation through July 31, 1986. Although Unit 1 was in preoperational testing before May 1985, some of the failure data are considered relevant to this

study. Table 6-27 lists the primary documents and operating records used during the Plant data collection task.

For component failure data, the entire period from November 8, 1984, through July 31, 1986, was covered. Maintenance data was limited to the noncold shutdown periods. Table 6-28 provides the history of Diablo Canyon Unit 1 and Unit 2 cold shutdown outages. The initiating events data were collected for the period May 7, 1985, through February 8, 1988 for Unit 1 and the period February 22, 1986 through February 8, 1988 for Unit 2.

The method used to develop the data for this study is based on the Bayesian interpretation of probability and the concept of "probability of frequency" (Lindley, 1970). In this context, for example, component failure rates are treated as measurable quantities whose uncertainty is dependent on the state of knowledge of the investigation. The "state of knowledge" is presented in the form of a probability distribution over the range of possible values of that quantity. The probability associated with a particular numerical value of an uncertain but measurable quantity indicates the likelihood that the numerical value is the correct one.

A key issue in developing state-of-knowledge distributions for the parameters of the probabilistic risk assessment models is to assure that the information regarding each parameter, its relevance, and its value as viewed by the analyst are presented correctly and that various pieces of information are integrated coherently. "Coherence" is preserved if the final outcome of the process is consistent with every piece of information used and with all assumptions made. This is done by utilizing the fundamental tool of probabilistic influence; that is, Bayes' theorem.

DEVELOPMENT OF GENERIC FAILURE RATE DISTRIBUTIONS

Developing a generic data base requires a thorough review, analysis, and tabulation of the available generic data for each of the identified component failure modes. The PLG generic data

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Table 6-27
DIABLO CANYON UNIT 1 RECORDS CONSIDERED IN DATA SEARCH

<u>Source</u>	<u>Data</u>
Monthly narrative report	Plant power history, forced and scheduled shutdowns, initiating events, and vital equipment failures
Licensee event reports	Initiating events
Mechanical equipment maintenance history	Component failures and component maintenance events
Electrical equipment maintenance history	Component failures and component maintenance events
Clearance requests	Component failures and component maintenance events
Component run-time record (P250 logs)	Component operating hours

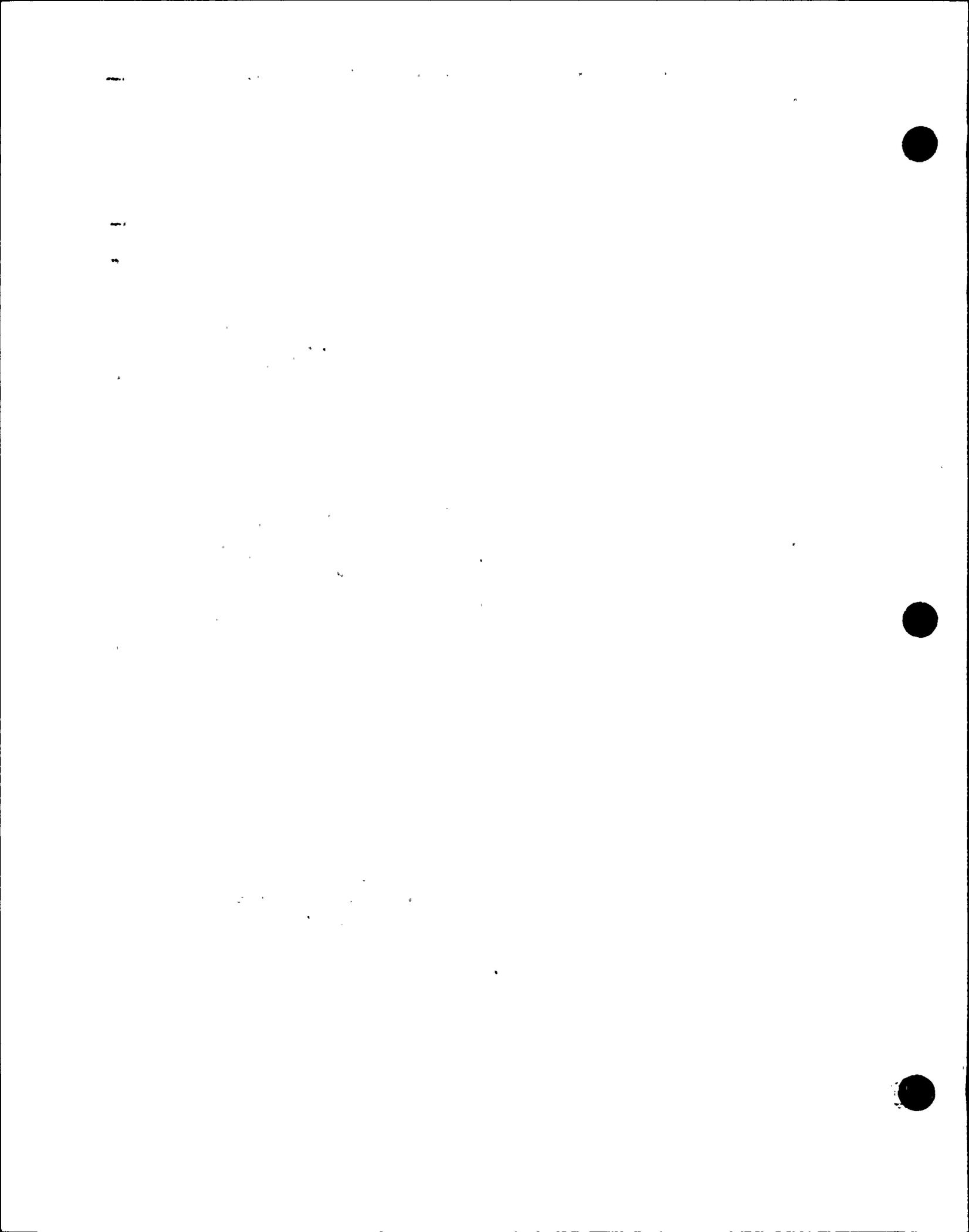


Table 6-28

**COLD SHUTDOWN HOURS FOR DIABLO CANYON UNIT 1 FROM THE START OF
COMMERCIAL OPERATION THROUGH JULY 31, 1986**

<u>Month</u>	<u>Date</u>		<u>Hours</u>		<u>Total Noncold Shutdown Hours</u>
	<u>From</u>	<u>To</u>	<u>Total</u>	<u>Cold Shutdown</u>	
1985					
May	18	19	600	26.0	529.2
	20	20		10.4	
	20	21		14.4	
June			720	—	1,269.2
July			744	—	2,013.2
August	27	28	744	18.6	2,737.2
	28	28		1.4	
September			720	—	3,457.2
October	25	26	744	27.5	4,136.2
	30	31		37.5	
November	01	10	720	240.8	4,615.4
December	02	09	744	150.5	5,208.9
1986					
January			744	—	5,952.9
February			672	—	6,624.9
March	14	17	744	57.0	7,311.9
April			720	—	8,031.9
May			744	—	8,775.9
June			720	—	9,495.9
July			744	—	10,239.9

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base is proprietary. It was updated to its current form during the Seabrook PRA (Pickard, Lowe, and Garrick, 1983, and it is documented in Mosleh, 1987, a PLG proprietary report). This PLG generic data base was used as the generic data bases for the Diablo Canyon Unit 1 PRA. In a few cases additional generic distributions had to be developed for some specific types of equipment. In addition to generic data sources, several well-documented site-specific failure rate data from power plants examined in previous or ongoing risk studies were used in the development of the generic data base. This assures that the final failure rate distributions accurately reflect all information currently available.

Updated Component Failure Rate Distributions

As described earlier, the Diablo Canyon Unit 1 component failure rate distributions were developed by combining two pieces of information; namely, the generic distributions described and the Plant-specific failure data. Data specialization or the development of Plant-specific failure rate distribution is achieved by applying Bayes' theorem. The magnitude of the effect of adding Plant-specific data depends on the relative strength of the data compared with the prior level of confidence expressed in the form of the spread of the prior distribution. Typically both the location and the spread of the posterior or updated distribution is affected by the Plant-specific evidence. The mean value of the updated distribution could be higher or lower than the mean of the generic prior but adding the Plant-specific data normally reduces the spread of the distribution.

Basic characteristics of the resulting distributions are listed in Table 6-29. Also presented in the table are the Plant-specific failure and success data for each component, as well as the mean values of the generic distributions. In cases for which no Plant-specific data were collected, no updating was performed and the listed distributions are generic.

Common Cause Failure Parameters

Dependent failures such as common cause failures at the systems level are treated either explicitly by means of identifying causes of dependent failure and incorporating them into the system or event sequence models or implicitly by using parametric models to account for their contribution to the unavailability of the system. Examples of the first category are the sharing of common components, fires, floods, and certain types of human error during test or maintenance. This section deals with the second category, of common cause failures, such as design errors, construction errors, procedural deficiencies, and unforeseen environmental variations.

The parametric model used in this study to quantify the effect of the second category of dependent failures is known as the alpha factor method. The alpha-factor model develops estimates for the common cause parameters in terms of the total component failure rate typically available from generic sources of data and a set of parameters obtainable from component failure data. Using this method, the unavailability of a system due to common cause failures can be written in terms of a set of basic frequencies.

The common cause failure rate distributions listed in Table 6-30 were also developed by combining the generic and Plant-specific data.

Component Maintenance Data

Maintenance activities that remove components from service and alter the normal configurations of mechanical or electrical systems can provide a significant contribution to the overall system unavailability. This section describes how generic and Plant-specific maintenance data were used to develop distributions for component maintenance unavailability.

These distributions apply to maintenance performed during normal operation or in some cases at hot shutdown (but not during cold shutdown). These include both regularly scheduled preventive maintenance activities and also unplanned maintenance events. The specific causes leading to these maintenance activities can

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Table 6-29
DIABLO CANYON UNIT 1 COMPONENT FAILURE RATES

Designator	Component Description - Failure Mode	Diablo Canyon Unit 1		Distribution			
		Failures	hours/ demands	Mean	5th Percentile	50th Percentile	95th Percentile
ZTBATD	125V DC BATTERY - FAILURE OF OUTPUT ON DEMAND		*	4.84E-04	7.51E-05	3.26E-04	1.15E-03
ZTBATR	BATTERIES - FAIL DURING OPERATION	0	43,992	7.09E-07	5.75E-08	3.72E-07	1.71E-06
ZTBCHR	BATTERY CHARGER - FAIL DURING OPERATION	0	73,320	6.50E-06	5.75E-07	3.97E-06	1.67E-05
ZTBS1R	BUSSES - FAIL DURING OPERATION	0	249,288	4.48E-07	7.39E-08	3.19E-07	1.01E-06
ZTCB1C	CIRCUIT BREAKER (480 VAC AND ABOVE) - FAIL TO CLOSE ON DEMAND		*	1.61E-03	2.80E-04	1.22E-03	3.23E-03
ZTCB10	CIRCUIT BREAKER (480 VAC AND ABOVE) - FAILURE TO OPEN ON DEMAND		*	6.49E-04	5.95E-05	3.67E-04	1.41E-03
ZTCB1T	CIRCUIT BREAKER (480VAC AND ABOVE)-TRANSFER OPEN DURING OPER.		*	8.28E-07	5.08E-08	3.99E-07	2.36E-06
ZTCB2C	CIRCUIT BKR(AC OR DC,LT.480V) - FAILURE TO CLOSE ON DEMAND		*	2.27E-04	6.48E-06	8.89E-05	6.52E-04
ZTCB2O	CIRCUIT BKR(AC OR DC,LT. 480V) - FAILURE TO OPEN ON DEMAND		*	8.39E-04	2.39E-05	3.28E-04	2.40E-03
ZTCB2T	CIRCUIT BREAKER (480V DC) TRANSFER OPEN/CLOSED DUR. OPER.		*	2.68E-07	2.50E-08	1.41E-07	9.11E-07
ZTCB3D	REACTOR TRIP BREAKER MECHANISM - FAIL TO OPERATE ON DEMAND	0	88	1.64E-03	4.14E-04	1.28E-03	3.37E-03
ZTCPPR	COMPRESSOR FREON - FAIL TO RUN		*	3.36E-05	2.75E-06	1.64E-05	9.00E-05
ZTCPPS	COMPRESSOR - FREON - FAIL TO START		*	2.35E-03	2.51E-04	1.44E-03	6.42E-03
ZTCRAD	SINGLE CONTROL ROD - FAIL TO INSERT ON DEMAND		*	3.20E-05	2.00E-06	1.02E-05	9.12E-05
ZTDO1L	RANDOM FAILURE OF DISK LEADING TO LEAK RATE OF 150 GPM		*	4.67E-04	1.64E-05	1.70E-04	1.70E-03
ZTDO2L	RANDOM FAILURE OF DISK LEADING TO LEAK RATE OF 1700 GPM		*	8.15E-05	1.49E-06	2.17E-05	3.05E-04
ZTDO3L	RANDOM FAILURE OF DISK LEADING TO LEAK RATE OF 800 GPM		*	1.38E-04	2.51E-06	3.67E-05	5.14E-04
ZTDAOD	AIR OPERATED DAMPER - FAIL TO OPERATE ON DEMAND	1	2,282	7.81E-04	2.40E-04	6.71E-04	1.40E-03
ZTDAOF	AIR OPERATED DAMPER - FAILURE TO TRANSFER TO FAILED POSITION		*	2.66E-04	7.57E-06	1.04E-04	7.62E-04
ZTDAOT	AIR OPERATED DAMPER - TRANSFER OPEN/CLOSED	0	439,920	4.55E-06	1.08E-06	3.69E-06	9.41E-06
ZTDBDD	BACKDRAFT DAMPER - FAILURE TO OPEN ON DEMAND		*	2.69E-04	5.56E-05	1.50E-04	5.43E-04
ZTDBDT	BACKDRAFT DAMPER - TRANSFER CLOSED		*	1.04E-08	2.43E-09	7.80E-09	2.19E-08
ZTDFRI	FIRE DAMPER - INADVERTENT ACTUATION		*	4.20E-08	1.69E-09	1.41E-08	1.31E-07
ZTDGS1	DIESEL GENERATOR - FAIL TO RUN DURING FIRST HR. OF OPERATION	2	240	8.76E-03	3.65E-03	7.72E-03	1.41E-02
ZTDGS2	DIESEL GENERATOR - FAIL TO RUN AFTER FIRST HOUR OF OPERATION	0	69	2.10E-03	2.14E-04	1.43E-03	4.64E-03
ZTDGSS	DIESEL GENERATOR - FAIL TO START	3	240	1.59E-02	6.95E-03	1.37E-02	2.72E-02
ZTDHOT	MANUAL DAMPER - TRANSFER OPEN/SHUT DURING OPERATION		*	4.20E-08	1.69E-09	1.41E-08	1.31E-07
ZTDMOD	MOTOR OPERATED DAMPER - FAIL TO OPERATE ON DEMAND	3	1,194	2.87E-03	1.03E-03	2.49E-03	4.83E-03
ZTDMOT	MOTOR OPERATED DAMPERS - TRANSFER OPEN/CLOSED	2	85,340	9.54E-07	7.37E-08	4.86E-07	2.37E-06
ZTDryp	AIR DRYER - FAILURE DURING OPERATION	0	14,003	1.00E-06	3.04E-08	4.12E-07	2.91E-06
ZTDSKD	DISK FAILURE ON DEMAND		*	2.13E-04	2.97E-05	1.37E-04	6.14E-04
ZTFL1P	VENTILATION FILTER - PLUGGED	0	28,006	9.45E-07	3.04E-08	4.07E-07	2.76E-06
ZTFL2P	VENTILATION LOUVRE PLUGGED		*	1.07E-07	3.04E-09	4.16E-08	3.05E-07
ZTFL3P	FUEL OIL FILTER - PLUGGED	0	234	1.06E-06	3.04E-08	4.16E-07	3.05E-06
ZTFN1R	CONTAINMENT FAN COOLERS - FAIL TO OPERATE	2	59,105	1.27E-05	3.86E-06	9.29E-06	2.89E-05
ZTFN1S	CONTAINMENT FAN COOLERS - FAIL TO START	0	341	1.62E-03	3.25E-04	1.22E-03	3.35E-03
ZTFN2R	VENTILATION FANS - FAIL TO RUN	1	71,486	8.61E-06	2.54E-06	6.89E-06	1.50E-05
ZTFN2S	VENTILATION FANS - FAIL TO START	1	178	9.59E-04	1.22E-04	5.52E-04	2.42E-03
ZTFU1R	FUSE - FAIL OPEN DURING OPERATION		*	9.20E-07	2.83E-08	3.16E-07	2.83E-06
ZTHXRB	HEAT EXCHANGER - EXCESSIVE LEAK, PLUGGING	0	190,632	1.54E-06	3.16E-07	1.13E-06	3.29E-06
ZTIINVR	INVERTER - FAILURE DURING OPERATION	2	58,656	2.19E-05	6.03E-06	1.68E-05	4.09E-05
ZTLC1D	TRIP LOGIC MODULE - FAILURE TO TRIP ON DEMAND		*	8.52E-05	2.43E-06	3.33E-05	2.44E-04
ZTLC1R	TRIP LOGIC MODULE - FAILURE DURING OPERATION		*	2.93E-06	8.35E-08	1.15E-06	8.39E-06

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Table 6-29(Continued)
 DIABLO CANYON UNIT 1 COMPONENT FAILURE RATES

Designator	Component Description - Failure Mode	Diablo Canyon Unit 1					
		Failures	hours/ demands	Mean	Distribution		
				5th	50th	95th	
				Percentile	Percentile	Percentile	
ZTPAMR	MOTOR OPERATED AFW PUMP - FAIL TO RUN	0	3,305	2.84E-05	2.83E-06	1.70E-05	6.65E-05
ZTPAMS	MOTOR OPERATED AFW PUMP - FAIL TO START	0	111	2.18E-03	1.83E-04	1.24E-03	5.36E-03
ZTPASR	AUX. SALTWATER PUMP- FAIL TO RUN	0	14,152	1.97E-05	2.00E-06	1.20E-05	4.75E-05
ZTPASS	AUX. SALTWATER PUMP - FAIL TO START	1	69	2.05E-03	2.39E-04	1.30E-03	5.21E-03
ZTPATR	TURBINE DRIVEN AFW PUMP - FAIL TO RUN	0	65	8.67E-04	5.89E-05	4.32E-04	2.43E-03
ZTPATS	TURBINE DRIVEN AFW PUMP - FAIL TO START	1	39	2.88E-02	7.37E-03	2.43E-02	4.91E-02
ZTPCCR	COMPONENT COOLING WATER PUMP - FAIL TO OPERATE	1	27,986	2.88E-05	4.24E-06	2.14E-05	5.44E-05
ZTPCCS	COMPONENT COOLING WATER PUMP - FAIL TO START	0	159	1.76E-03	2.28E-04	1.16E-03	4.00E-03
ZTPCCR	CENTRIFUGAL CHARGING PUMP - FAIL TO RUN	0	9,731	2.20E-05	2.17E-06	1.30E-05	5.15E-05
ZTPCCS	CENTRIFUGAL CHARGING PUMP - FAIL TO START	0	68	2.05E-03	2.39E-04	1.30E-03	5.19E-03
ZTPCSR	CONTAINMENT SPRAY PUMP - FAIL TO RUN	0	9	3.41E-05	2.83E-06	1.80E-05	8.19E-05
ZTPCSS	CONTAINMENT SPRAY PUMP - FAIL TO START	0	52	2.63E-03	2.00E-04	1.43E-03	6.93E-03
ZTPFUR	FUEL OIL TRANSFER PUMP - FAIL TO RUN	0	117	3.39E-05	2.83E-06	1.80E-05	8.13E-05
ZTPFUS	FUEL OIL TRANSFER PUMP - FAIL TO START	1	461	2.44E-03	3.68E-04	1.73E-03	5.08E-03
ZTPP1B	PIPE ,GREATER THAN THREE INCH, PER PIPE SECTION	*	*	8.60E-10	1.98E-12	1.80E-10	2.02E-09
ZTPP2B	PIPE,LESS THAN THREE INCH, PER PIPE SECTION	*	*	8.60E-09	1.98E-11	1.80E-09	2.02E-08
ZTPPDR	P. D. CHARGING PUMP - FAIL TO RUN	0	3,506	2.73E-05	2.49E-06	1.49E-05	7.04E-05
ZTPPDS	P. D. CHARGING PUMP - FAIL TO START	0	19	2.26E-03	2.48E-04	1.40E-03	6.10E-03
ZTPRHR	RHR PUMPS 1-1, 1-2 - FAIL TO RUN	0	1,750	3.06E-05	2.83E-06	1.75E-05	7.33E-05
ZTPRHS	RHR PUMP - FAIL TO START	0	87	2.33E-03	1.89E-04	1.31E-03	5.65E-03
ZTPS1R	POWER SUPPLY - FAIL DURING OPERATION	*	*	1.71E-05	1.18E-06	7.25E-06	4.39E-05
ZTPS1R	SAFETY INJECTION PUMP - FAIL TO RUN	0	9	3.41E-05	2.83E-06	1.80E-05	8.19E-05
ZTPS1S	SAFETY INJECTION PUMP - FAIL TO START	0	84	2.76E-03	2.05E-04	1.47E-03	7.76E-03
ZTRL1D	RELAY - FAILURE TO OPERATE ON DEMAND	*	*	2.41E-04	1.41E-05	1.35E-04	6.40E-04
ZTRL1R	RELAY - FAILURE DURING OPERATION	*	*	4.20E-07	2.83E-08	1.90E-07	1.41E-06
ZTSC1P	STRAINER, OTHER THAN AUX. SALTWATER - FAIL DURING OPERATION	*	*	6.22E-06	8.08E-07	3.90E-06	1.58E-05
ZTSC3P	TRAVELLING SCREEN - FAILURE DURING OPERATION	0	102,648	4.07E-06	6.48E-07	2.91E-06	9.11E-06
ZTSC4P	SUMP SCREEN PLUGGING AFTER LARGE LOCA	*	*	8.07E-04	9.51E-05	4.89E-04	2.43E-03
ZTSC5P	SUMP SCREEN PLUGGING AFTER CORE MELT	*	*	4.84E-02	5.71E-03	2.94E-02	1.46E-01
ZTSEQD	ESFAS/LOP SEQUENCER - DEMAND	*	*	2.40E-06	6.83E-08	9.37E-07	6.87E-06
ZTSPNP	SPRAY NOZZLES TRAIN - PLUGGED	*	*	7.06E-08	2.70E-09	3.02E-08	2.00E-07
ZTSPRI	FIRE SPRINKLER HEAD INADVERTENT ACTUATION	*	*	9.99E-07	1.18E-07	6.06E-07	3.01E-06
ZTSTCD	R.T. BREAKER SHUNT TRIP COIL - FAIL TO OPERATE ON DEMAND	0	88	1.39E-04	3.27E-05	1.05E-04	2.91E-04
ZTSWBD	BISTABLE FAILURE TO OPERATE ON DEMAND	*	*	3.89E-07	5.98E-08	2.58E-07	9.16E-07
ZTSWBI	BISTABLE SPURIOUS OPERATION	*	*	2.21E-06	2.56E-09	4.01E-07	4.61E-06
ZTSWLD	LEVEL SWITCH - FAIL TO OPERATE ON DEMAND	*	*	2.69E-04	1.41E-05	1.25E-04	7.69E-04
ZTSWPD	PRESSURE SWITCH - FAIL TO OPERATE ON DEMAND	*	*	2.69E-04	1.41E-05	1.25E-04	7.69E-04
ZTTK1B	STORAGE TANK -- RUPTURE DURING OPERATION	*	*	2.66E-08	7.59E-10	1.04E-08	7.63E-08
ZTTRFR	FLOW TRANSMITTER - FAIL DURING OPERATION	*	*	6.25E-06	6.03E-07	4.18E-06	1.41E-05
ZTTRLR	LEVEL TRANSMITTER - FAILURE DURING OPERATION	*	*	1.57E-05	3.51E-06	1.12E-05	3.34E-05
ZTTRPR	PRESSURE TRANSMITTER - FAILURE DURING OPERATION	*	*	7.60E-06	8.11E-07	4.69E-06	1.79E-05
ZTTRTR	TEMPERATURE TRANSMITTER - FAIL TO OPERATE ON DEMAND	*	*	1.57E-05	3.51E-06	1.12E-05	3.34E-05

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Table 6-29(Continued)
 DIABLO CANYON UNIT 1 COMPONENT FAILURE RATES

Designator	Component Description - Failure Mode	Diablo Canyon Unit 1					
		Failures	hours/ demands	Mean	5th Percentile	50th Percentile	95th Percentile
ZTUVCD	R.T. BREAKER UNDERVOLTAGE COIL - FAIL TO OPERATE ON DEMAND	0	88	2.46E-03	6.43E-04	1.95E-03	4.92E-03
ZTVAOD	AIR OPERATED VALVE - FAIL TO OPERATE ON DEMAND	0	2,058	6.22E-04	1.58E-04	5.09E-04	1.23E-03
ZTVAOF	AIR OPERATED VALVE FAIL TO TRANSFER TO FAILED POSITION ON DEMAND	*	*	2.66E-04	7.57E-06	1.04E-04	7.62E-04
ZTVAOT	AIR OPERATED VALVE TRANSFER OPEN/CLOSED	0	189,608	2.29E-07	1.74E-08	1.14E-07	5.91E-07
ZTVCOD	CHECK VALVE (OTHER THAN STOP) - FAIL TO OPERATE ON DEMAND	0	4,300	1.70E-04	4.05E-05	1.41E-04	2.84E-04
ZTVCOL	CHECK VALVE (OTHER THAN STOP) - GROSS LEAKAGE DURING OPERATION	*	*	5.36E-07	8.21E-08	3.46E-07	1.37E-06
ZTVCOO	NORMALLY OPEN CHK. VALVE (OTHER THAN STOP) - FAIL TO RESEAT	*	*	4.26E-04	1.10E-05	1.34E-04	1.58E-03
ZTVCOP	CHECK VALVE (OTHER THAN STOP) - TRANSFER CLOSED/PLUGGED	0	379,847	1.04E-08	2.43E-09	7.80E-09	2.18E-08
ZTVCSD	STOP CHECK VALVES - FAIL TO OPERATE ON DEMAND	0	88	7.65E-04	6.87E-05	4.02E-04	1.97E-03
ZTVCSL	STOP CHECK VALVES - EXCESSIVE LEAKAGE	*	*	5.36E-07	8.21E-08	3.46E-07	1.37E-06
ZTVCST	STOP CHECK VALVES - TRANSFER OPEN/CLOSED	*	*	1.04E-08	2.43E-09	7.80E-09	2.19E-08
ZTVE1D	ELECTRO-HYDRAULIC VALVE (EXCEPT TSV,TCV) FAIL TO OPER. ON DEMAND	0	1,364	8.12E-04	1.66E-04	6.36E-04	1.53E-03
ZTVE1T	ELECTROHYDRAULIC VALVES - TRANSFER OPEN/CLOSED	0	6,610	2.65E-07	1.78E-08	1.20E-07	6.68E-07
ZTVE21	TURBINE STOP/CONTROL VALVE - TRFR CLOSED DURING OPERATION	*	*	2.88E-05	8.23E-07	1.13E-05	8.25E-05
ZTVE22	TURBINE STOP/CONTROL VALVE TRANSFER OPEN DURING OPERATION	*	*	1.24E-05	3.54E-07	4.85E-06	3.55E-05
ZTVE2D	TURBINE STOP/CONTROL VALVE FAILURE TO OPERATE ON DEMAND	0	1,104	1.17E-04	2.92E-05	9.08E-05	2.41E-04
ZTVHOT	MANUAL VALVE TRANSFERS CLOSED/OPEN	0	1,983,168	3.32E-08	1.65E-09	1.39E-08	1.04E-07
ZTVMCX	VALVE (MOTOR-OPERATED OR CHECK) - DISC RUPTURE	*	*	1.55E-08	1.03E-10	4.09E-09	4.18E-08
ZTVMOD	MOTOR OPERATED VALVE - FAIL TO OPERATE ON DEMAND	3	2,372	1.65E-03	5.64E-04	1.47E-03	2.83E-03
ZTVMOE	MOV FAILURE TO CLOSE ON DEMAND WHILE SHOWING CLOSED	*	*	1.07E-04	1.51E-05	6.60E-05	2.45E-04
ZTVMOT	MOTOR OPERATED VALVES TRANSFER OPEN/CLOSED	1	402,031	2.66E-07	2.51E-08	1.08E-07	1.04E-06
ZTVPCOT	PRESSURE CONTROL VALVE, SELF CONTAINED FAILURE DURING OPERATION	*	*	3.90E-06	2.49E-08	6.05E-07	1.41E-05
ZTVPRO	FUEL OIL PRESSURE REGULATING VALVE, FAILURE TO OPEN ON DEMAND	*	*	1.74E-06	5.65E-08	6.11E-07	6.34E-06
ZTVPRT	FUEL OIL PRESSURE REGULATING VALVE, TRANSFER CLOSED DURING OPERA	*	*	2.72E-06	1.74E-08	4.22E-07	9.83E-06
ZTVR10	PRIMARY SAFETY VALVE - FAILURE TO OPEN ON DEMAND	*	*	3.28E-04	1.34E-05	1.41E-04	1.08E-03
ZTVR15	PRIMARY SAFETY VALVE FAILURE TO RESEAT ON DEMAND (STEAM)	*	*	2.87E-03	8.84E-05	1.15E-03	8.21E-03
ZTVR1W	PRIMARY SAFETY VALVE - FAILURE TO RESEAT AFTER WATER RELIEF	*	*	1.01E-01	2.88E-03	1.20E-01	2.50E-01
ZTVR20	RELIEF VALVE (EXCEPT PORV,SAFETY) FAILURE TO OPEN ON DEMAND	*	*	2.42E-05	7.55E-07	9.72E-06	6.92E-05
ZTVR2T	RELIEF VALVE (EXCEPT PORV, SAFETY) - PREMATURE OPEN	*	*	6.06E-06	1.08E-06	3.94E-06	1.73E-05
ZTVR30	PORV FAILURE TO OPEN ON DEMAND	0	6	4.21E-03	9.95E-04	3.18E-03	8.84E-03
ZTVR3S	PORV - FAILURE TO RESEAT AFTER STEAM RELIEF	*	*	2.50E-02	5.85E-03	1.87E-02	5.25E-02
ZTVR3W	PORV - FAILURE TO RESEAT AFTER WATER RELIEF	*	*	1.01E-01	2.88E-03	1.20E-01	2.50E-01
ZTVSOD	SOLENOID VALVE (DIRECT ACTING) - FAILURE TO OPERATE ON DEMAND	*	*	2.43E-03	7.64E-05	9.79E-04	6.94E-03
ZTVSOT	SOLENOID VALVE (DIRECT ACTING) - TRANSFER OPEN/CLOSED DURING OPER.	*	*	1.27E-06	5.21E-08	4.91E-07	3.59E-06
ZTVSWO	VALVE OPEN BUT SHOWING CLOSED DUE TO LIMIT SWITCH	*	*	1.08E-04	1.75E-05	7.36E-05	3.00E-04
ZTVICD	AIR OPER. PRESSURE CONTROL VALVE - FAIL TO OPERATE ON DEMAND	*	*	1.52E-03	2.83E-04	1.14E-03	3.16E-03
ZTVICF	AIR OPER. PRESSURE CONTROL VALVE - FAIL TO TRFR TO FAILED POS.	*	*	2.66E-04	7.57E-06	1.04E-04	7.62E-04
ZTVICT	AIR OPER. PRESSURE CONTROL VALVE - TRFR OPEN/SHUT DUR. OPERATION	*	*	2.67E-07	1.78E-08	1.20E-07	6.71E-07
ZTXR1R	TRANSFORMER (MAIN, STARTUP, AUXILIARY) - FAILURE DURING OPERATION	0	10,824	1.53E-06	2.83E-07	1.09E-06	3.10E-06
ZTXR2R	TRANSFORMER (LOAD CENTER) - FAILURE DURING OPERATION	0	54,120	6.66E-07	1.31E-07	4.41E-07	1.39E-06
ZTXR3R	INSTRUMENT TRANSFORMER (480V TO 120V) - FAIL DUR. OPER.	*	*	1.55E-06	7.44E-08	6.57E-07	4.18E-06

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Table 6-30
DIABLO CANYON UNIT 1 COMPONENT COMMON CAUSE FAILURE RATES

Item	Designator	Component and Failure Mode	Distribution			
			Mean	5th Percentile	50th Percentile	95th Percentile
1	S2CB1C	1 OF 2 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO CLOSE	1.50E-03	2.62E-04	1.09E-03	2.99E-03
2	D2CB1C	2 OF 2 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO CLOSE	1.12E-04	8.43E-06	5.52E-05	2.80E-04
3	S3CB1C	1 OF 3 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO CLOSE	1.50E-03	2.60E-04	1.10E-03	2.99E-03
4	D3CB1C	2 OF 3 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO CLOSE	4.86E-05	5.38E-07	2.35E-05	1.22E-04
5	T3CB1C	3 OF 3 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO CLOSE	1.65E-05	2.25E-07	6.79E-06	4.46E-05
6	S5CB1C	1 OF 5 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO CLOSE	1.50E-03	2.60E-04	1.09E-03	2.99E-03
7	D5CB1C	2 OF 5 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO CLOSE	3.19E-05	3.30E-07	1.52E-05	8.02E-05
8	T5CB1C	3 OF 5 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO CLOSE	4.33E-06	4.89E-08	1.82E-06	1.20E-05
9	G5CB1C	4/5 OR 5/5 C.B.BREAKER (480VAC AND ABOVE) FAIL TO CLOSE	2.86E-06	2.00E-08	9.00E-07	8.22E-06
10	S2CB10	1 OF 2 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO OPEN	6.05E-04	5.53E-05	3.43E-04	1.32E-03
11	D2CB10	2 OF 2 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO OPEN	4.50E-05	2.01E-06	2.00E-05	1.22E-04
12	S3CB10	1 OF 3 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO OPEN	6.05E-04	5.50E-05	3.43E-04	1.32E-03
13	D3CB10	2 OF 3 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO OPEN	1.94E-05	1.84E-07	7.74E-06	5.43E-05
14	T3CB10	3 OF 3 CIRCUIT BREAKER (480VAC AND ABOVE) FAIL TO OPEN	6.44E-06	5.62E-08	2.25E-06	1.83E-05
15	S2CB3D	1 OF 2 REACTOR TRIP BREAKERS FAIL ON DEMAND	1.53E-03	3.88E-04	1.20E-03	3.03E-03
16	D2CB3D	2 OF 2 REACTOR TRIP BREAKERS FAIL ON DEMAND	1.14E-04	1.51E-05	7.25E-05	2.71E-04
17	S2CPFR	1 OF 2 FREON COMPRESSORS FAIL TO RUN	3.34E-05	2.69E-06	1.65E-05	8.88E-05
18	D2CPFR	2 OF 2 FREON COMPRESSORS FAIL TO RUN	3.39E-07	1.04E-08	1.12E-07	9.88E-07
19	S2CPFS	1 OF 2 FREON COMPRESSORS FAIL TO START	2.35E-03	2.50E-04	1.45E-03	6.38E-03
20	D2CPFS	2 OF 2 FREON COMPRESSORS FAIL TO START	2.26E-06	4.97E-08	7.75E-07	7.09E-06
21	S2DAOD	1 OF 2 AIR OPERATED DAMPERS FAIL ON DEMAND	7.26E-04	2.37E-04	6.07E-04	1.35E-03
22	D2DAOD	2 OF 2 AIR OPERATED DAMPERS FAIL ON DEMAND	5.46E-05	6.58E-06	3.55E-05	1.33E-04
23	SKDAOD	1 OF 20 AIR OPERATED DAMPERS FAIL ON DEMAND	7.27E-04	2.35E-04	6.09E-04	1.35E-03
24	DKDAOD	2 OF 20 AIR OPERATED DAMPERS FAIL ON DEMAND	1.53E-05	1.66E-07	9.53E-06	3.82E-05
25	TKDAOD	3 OF 20 AIR OPERATED DAMPERS FAIL ON DEMAND	2.15E-06	2.48E-08	1.13E-06	5.95E-06
26	GKDAOD	4 OR MORE OF 20 AIR OPERATED DAMPERS FAIL ON DEMAND	1.40E-06	1.46E-08	5.60E-07	4.30E-06
27	S2DBDD	1 OF 2 BACKDRAFT DAMPERS OPEN/CLOSE ON DEMAND	2.52E-04	5.16E-05	1.45E-04	5.02E-04
28	D2DBDD	2 OF 2 BACKDRAFT DAMPERS OPEN/CLOSE ON DEMAND	1.85E-05	1.73E-06	9.70E-06	4.50E-05
29	S5DGSS	1 OF 5 DIESEL GENERATORS FAIL TO START	1.58E-02	7.48E-03	1.45E-02	2.70E-02
30	D5DGSS	2 OF 5 DIESEL GENERATORS FAIL TO START	8.27E-06	9.46E-07	5.59E-06	1.95E-05
31	T5DGSS	3 OF 5 DIESEL GENERATORS FAIL TO START	5.23E-07	8.71E-09	2.22E-07	1.59E-06
32	G5DGSS	4 OR MORE OF 5 DIESEL GENERATORS FAIL TO START	6.17E-07	7.57E-09	2.30E-07	1.85E-06
33	S5DGS1	1 OF 5 DIESEL GENERATORS FAIL TO RUN DURING 1ST HR.	8.63E-03	3.66E-03	7.62E-03	1.41E-02
34	D5DGS1	2 OF 5 DIESEL GENERATORS FAIL TO RUN DURING 1ST HR.	3.48E-05	7.78E-06	2.66E-05	7.28E-05
35	T5DGS1	3 OF 5 DIESEL GENERATORS FAIL TO RUN DURING 1ST HR.	4.65E-06	3.75E-07	2.61E-06	1.22E-05
36	G5DGS1	4 OR 5 OF 5 DIESEL GENERATORS FAIL TO RUN DURING 1ST HR.	6.15E-06	3.65E-07	3.08E-06	1.68E-05
37	S5DGS2	1 OF 5 DIESEL GENERATORS FAIL TO RUN AFTER 1ST HR.	2.07E-03	2.11E-04	1.41E-03	4.37E-03
38	D5DGS2	2 OF 5 DIESEL GENERATORS FAIL TO RUN AFTER 1ST HR.	5.06E-06	2.38E-07	2.37E-06	1.44E-05
39	T5DGS2	3 OF 5 DIESEL GENERATORS FAIL TO RUN AFTER 1ST HR.	1.27E-06	4.63E-08	5.27E-07	3.74E-06
40	G5DGS2	4 OR 5 OF 5 DIESEL GENERATORS FAIL TO RUN AFTER 1ST HR.	1.48E-06	4.79E-08	5.99E-07	4.31E-06
41	S2DMOD	1 OF 2 MOTOR OPERATED DAMPERS FAIL ON DEMAND	2.67E-03	9.93E-04	2.31E-03	4.66E-03
42	D2DMOD	2 OF 2 MOTOR OPERATED DAMPERS FAIL ON DEMAND	2.00E-04	2.56E-05	1.31E-04	4.81E-04
43	S8DMOD	1 OF 8 MOTOR OPERATED DAMPERS FAIL ON DEMAND	2.67E-03	9.82E-04	2.32E-03	4.65E-03

Table 10 (Continued)

DIABLO CANYON UNIT 1 COMPONENT COMMON CAUSE FAILURE RATES

Item	Designator	Component and Failure Mode	Distribution			
			Mean	5th Percentile	50th Percentile	95th Percentile
44	D8DMOD	2 OF 8 MOTOR OPERATED DAMPERS FAIL ON DEMAND	5.79E-05	1.78E-06	3.79E-05	1.41E-04
45	T8DMOD	3 OF 8 MOTOR OPERATED DAMPERS FAIL ON DEMAND	7.77E-06	7.67E-08	4.13E-06	2.16E-05
46	G8DMOD	4 OR MORE OF 8 MOTOR OPERATED DAMPERS FAIL ON DEMAND	5.08E-06	5.90E-08	2.10E-06	1.52E-05
47	S5FN1R	1 OF 5 CONTAINMENT FAN COOLERS FAIL TO RUN	1.26E-05	4.18E-06	9.55E-06	2.77E-05
48	D5FN1R	2 OF 5 CONTAINMENT FAN COOLERS FAIL TO RUN	7.96E-09	7.33E-10	5.02E-09	1.98E-08
49	T5FN1R	3 OF 5 CONTAINMENT FAN COOLERS FAIL TO RUN	2.46E-10	1.07E-12	7.62E-11	7.88E-10
50	G5FN1R	4 OR 5 OF 5 CONTAINMENT FAN COOLERS FAIL TO RUN	6.55E-10	3.03E-11	3.10E-10	1.91E-09
51	S5FN1S	1 OF 5 CONTAINMENT FAN COOLERS FAIL TO START	1.60E-03	3.23E-04	1.22E-03	3.30E-03
52	D5FN1S	2 OF 5 CONTAINMENT FAN COOLERS FAIL TO START	7.15E-06	7.63E-07	4.31E-06	1.82E-05
53	T5FN1S	3 OF 5 CONTAINMENT FAN COOLERS FAIL TO START	6.24E-07	3.04E-08	2.81E-07	1.79E-06
54	G5FN1S	4 OR 5 OF 5 CONTAINMENT FAN COOLERS FAIL TO START	4.18E-07	9.01E-09	1.42E-07	1.25E-06
55	S4FN2R	1 OF 4 ROOM VENT. FANS FAIL TO RUN	8.65E-06	2.80E-06	6.93E-06	1.55E-05
56	D4FN2R	2 OF 4 ROOM VENT. FANS FAIL TO RUN	5.53E-09	5.48E-10	3.63E-09	1.32E-08
57	T4FN2R	3 OF 4 ROOM VENT. FANS FAIL TO RUN	1.63E-10	8.98E-13	4.94E-11	5.00E-10
58	G4FN2R	4 OF 4 ROOM VENT. FANS FAIL TO RUN	4.36E-10	2.11E-11	2.11E-10	1.22E-09
59	S4FN2S	1 OF 4 ROOM VENT. FANS FAIL TO START	9.54E-04	1.26E-04	5.63E-04	2.40E-03
60	D4FN2S	2 OF 4 ROOM VENT. FANS FAIL TO START	4.33E-06	3.30E-07	2.18E-06	1.22E-05
61	T4FN2S	3 OF 4 ROOM VENT. FANS FAIL TO START	3.67E-07	1.35E-08	1.44E-07	1.07E-06
62	G4FN2S	4 OF 4 ROOM VENT. FANS FAIL TO START	2.44E-07	4.36E-09	6.91E-08	7.40E-07
63	S2LC1D	1 OF 2 LOGIC CONTROL (TRIP) MODULE FAIL ON DEMAND	8.77E-05	2.49E-06	3.33E-05	2.62E-04
64	D2LC1D	2 OF 2 LOGIC CONTROL (TRIP) MODULE FAIL ON DEMAND	8.25E-08	6.72E-10	1.64E-08	2.41E-07
65	S2PAMR	1 OF 2 AUX FEEDWATER PUMPS FAIL TO RUN	2.86E-05	2.81E-06	1.72E-05	6.50E-05
66	D2PAMR	2 OF 2 AUX FEEDWATER PUMPS FAIL TO RUN	2.69E-07	1.26E-08	1.17E-07	7.50E-07
67	S2PAMS	1 OF 2 AUX FEEDWATER PUMPS FAIL TO START	2.04E-03	1.79E-04	1.16E-03	5.50E-03
68	D2PAMS	2 OF 2 AUX FEEDWATER PUMPS FAIL TO START	1.59E-04	9.84E-06	7.58E-05	4.38E-04
69	S4PASR	1 OF 4 ASW PUMP FAIL TO RUN	1.99E-05	2.14E-06	1.22E-05	5.14E-05
70	D4PASR	2 OF 4 ASW PUMP FAIL TO RUN	1.28E-08	6.08E-10	6.09E-09	3.49E-08
71	T4PASR	3 OF 4 ASW PUMP FAIL TO RUN	3.73E-10	1.20E-12	8.30E-11	1.24E-09
72	G4PASR	4 OF 4 ASW PUMP FAIL TO RUN	2.38E-10	5.85E-13	4.20E-11	7.56E-10
73	S4PASS	1 OF 4 ASW PUMP FAIL TO START	2.05E-03	2.44E-04	1.31E-03	5.07E-03
74	D4PASS	2 OF 4 ASW PUMP FAIL TO START	5.42E-06	2.58E-07	2.43E-06	1.56E-05
75	T4PASS	3 OF 4 ASW PUMP FAIL TO START	7.88E-07	2.71E-08	3.12E-07	2.36E-06
76	G4PASS	4 OF 4 ASW PUMP FAIL TO START	5.24E-07	8.88E-09	1.60E-07	1.56E-06
77	S3PCCR	1 OF 3 CCW PUMP FAIL TO RUN	2.91E-05	5.85E-06	2.23E-05	5.89E-05
78	D3PCCR	2 OF 3 CCW PUMP FAIL TO RUN	1.34E-08	1.76E-10	5.25E-09	3.90E-08
79	T3PCCR	3 OF 3 CCW PUMP FAIL TO RUN	2.06E-09	8.53E-12	5.38E-10	6.61E-09
80	S3PCCS	1 OF 3 CCW PUMP FAIL TO START	1.76E-03	2.29E-04	1.15E-03	4.14E-03
81	D3PCCS	2 OF 3 CCW PUMP FAIL TO START	7.46E-06	3.57E-07	3.56E-06	2.04E-05
82	T3PCCS	3 OF 3 CCW PUMP FAIL TO START	2.54E-06	1.00E-07	1.06E-06	7.42E-06
83	S2PCGR	1 OF 2 CHARGING PUMPS FAIL TO RUN	2.20E-05	2.30E-06	1.29E-05	5.58E-05
84	D2PCGR	2 OF 2 CHARGING PUMPS FAIL TO RUN	1.92E-07	8.85E-09	8.16E-08	5.39E-07
85	S2PCGS	1 OF 2 CHARGING PUMPS FAIL TO START	1.92E-03	2.26E-04	1.22E-03	4.77E-03
86	D2PCGS	2 OF 2 CHARGING PUMPS FAIL TO START	1.45E-04	1.04E-05	7.35E-05	3.97E-04
87	S2PCSR	1 OF 2 SPRAY PUMPS FAIL TO RUN	3.48E-05	2.86E-06	1.79E-05	9.32E-05
88	D2PCSR	2 OF 2 SPRAY PUMPS FAIL TO RUN	3.38E-07	1.33E-08	1.33E-07	9.06E-07

Table 6-30 (Continued)
 DIABLO CANYON UNIT 1 COMPONENT COMMON CAUSE FAILURE RATES

Item	Designator	Component and Failure Mode	Distribution			
			Mean	5th Percentile	50th Percentile	95th Percentile
89	S2PCSS	1 OF 2 SPRAY PUMPS FAIL TO START	2.54E-03	2.02E-04	1.38E-03	6.74E-03
90	D2PCSS	2 OF 2 SPRAY PUMPS FAIL TO START	1.20E-04	6.14E-06	5.00E-05	3.49E-04
91	S2PFUR	1 OF 2 FUEL OIL PUMP FAIL TO RUN	3.46E-05	2.86E-06	1.79E-05	9.17E-05
92	D2PFUR	2 OF 2 FUEL OIL PUMP FAIL TO RUN	3.52E-07	1.38E-08	1.35E-07	9.35E-07
93	S2PFUS	1 OF 2 FUEL OIL PUMP FAIL TO START	2.28E-03	4.33E-04	1.66E-03	5.38E-03
94	D2PFUS	2 OF 2 FUEL OIL PUMP FAIL TO START	1.72E-04	1.41E-05	9.40E-05	4.65E-04
95	S2PRHR	1 OF 2 RHR PUMPS FAIL TO RUN	3.11E-05	2.82E-06	1.76E-05	7.21E-05
96	D2PRHR	2 OF 2 RHR PUMPS FAIL TO RUN	2.79E-07	1.22E-08	1.18E-07	7.44E-07
97	S2PRHS	1 OF 2 RHR PUMPS FAIL TO START	2.22E-03	1.90E-04	1.25E-03	5.62E-03
98	D2PRHS	2 OF 2 RHR PUMPS FAIL TO START	1.43E-04	8.21E-06	6.49E-05	4.04E-04
99	S2PSIR	1 OF 2 SAFETY INJECTION PUMPS FAIL TO RUN	3.48E-05	2.86E-06	1.79E-05	9.32E-05
100	D2PSIR	2 OF 2 SAFETY INJECTION PUMPS FAIL TO RUN	3.14E-07	1.30E-08	1.18E-07	8.70E-07
101	S2PSIS	1 OF 2 SAFETY INJECTION PUMPS FAIL TO START	2.59E-03	1.99E-04	1.40E-03	7.13E-03
102	D2PSIS	2 OF 2 SAFETY INJECTION PUMPS FAIL TO START	1.93E-04	1.04E-05	8.49E-05	5.61E-04
103	S2RL1D	1 OF 2 RELAYS FAIL TO OPERATE ON DEMAND	2.28E-04	1.55E-05	1.23E-04	6.20E-04
104	D2RL1D	2 OF 2 RELAYS FAIL TO OPERATE ON DEMAND	1.67E-05	6.38E-07	5.71E-06	5.00E-05
105	S3RL1D	1 OF 3 RELAYS FAIL TO OPERATE ON DEMAND	2.28E-04	1.54E-05	1.23E-04	6.21E-04
106	D3RL1D	2 OF 3 RELAYS FAIL TO OPERATE ON DEMAND	7.84E-06	8.56E-08	2.73E-06	2.32E-05
107	T3RL1D	3 OF 3 RELAYS FAIL TO OPERATE ON DEMAND	1.18E-06	3.15E-09	2.80E-07	3.45E-06
108	S4RL1D	1 OF 4 RELAYS FAIL ON DEMAND	2.27E-04	1.54E-05	1.23E-04	6.19E-04
109	D4RL1D	2 OF 4 RELAYS FAIL ON DEMAND	5.40E-06	5.19E-08	1.75E-06	1.56E-05
110	T4RL1D	3 OF 4 RELAYS FAIL ON DEMAND	2.70E-07	7.35E-10	6.22E-08	8.24E-07
111	G4RL1D	4 OF 4 RELAYS FAIL ON DEMAND	3.54E-07	7.20E-10	7.16E-08	1.03E-06
112	S5RL1D	1 OF 5 RELAYS FAIL ON DEMAND	2.28E-04	1.54E-05	1.23E-04	6.19E-04
113	D5RL1D	2 OF 5 RELAYS FAIL ON DEMAND	5.23E-06	4.35E-08	1.74E-06	1.52E-05
114	T5RL1D	3 OF 5 RELAYS FAIL ON DEMAND	2.82E-07	7.50E-10	6.35E-08	7.83E-07
115	G5RL1D	4 OR 5 OF 5 RELAYS FAIL ON DEMAND	3.38E-07	8.20E-10	7.08E-08	9.70E-07
116	S8RL1D	1 OF 8 RELAYS FAIL ON DEMAND	2.28E-04	1.56E-05	1.23E-04	6.20E-04
117	D8RL1D	2 OF 8 RELAYS FAIL ON DEMAND	5.16E-06	4.62E-08	1.76E-06	1.48E-05
118	T8RL1D	3 OF 8 RELAYS FAIL ON DEMAND	2.94E-07	6.27E-10	6.52E-08	8.75E-07
119	G8RL1D	4 OF 8 RELAYS FAIL ON DEMAND	3.38E-07	7.66E-10	7.28E-08	9.23E-07
120	SBRL1D	1 OF 11 RELAYS FAIL ON DEMAND	2.28E-04	1.55E-05	1.23E-04	6.17E-04
121	DBRL1D	2 OF 11 RELAYS FAIL ON DEMAND	5.21E-06	5.81E-08	1.74E-06	1.44E-05
122	TBRL1D	3 OF 11 RELAYS FAIL ON DEMAND	2.98E-07	6.07E-10	6.26E-08	8.56E-07
123	GBRL1D	4 OR MORE OF 11 RELAYS FAIL ON DEMAND	3.14E-07	8.18E-10	7.00E-08	9.72E-07
124	SMRL1D	1 OF 22 RELAYS FAIL ON DEMAND	2.28E-04	1.56E-05	1.23E-04	6.18E-04
125	DMRL1D	2 OF 22 RELAYS FAIL ON DEMAND	5.29E-06	4.92E-08	1.76E-06	1.55E-05
126	TMRL1D	3 OF 22 RELAYS FAIL ON DEMAND	3.16E-07	7.07E-10	6.63E-08	9.22E-07
127	GMRL1D	4 OR MORE OF 22 RELAYS FAIL ON DEMAND	3.40E-07	8.04E-10	6.75E-08	9.89E-07
128	S2STCD	1 OF 2 RT SHUNT TRIP COILS FAIL ON DEMAND	1.31E-04	3.28E-05	9.85E-05	2.78E-04
129	D2STCD	2 OF 2 RT SHUNT TRIP COILS FAIL ON DEMAND	9.26E-06	9.18E-07	5.35E-06	2.35E-05
130	S2SWBD	1 OF 2 BISTABLES FAIL ON DEMAND	3.66E-07	6.14E-08	2.42E-07	8.75E-07
131	D2SWBD	2 OF 2 BISTABLES FAIL ON DEMAND	2.65E-08	1.98E-09	1.38E-08	7.24E-08
132	S3SWBD	1 OF 3 BISTABLES FAIL ON DEMAND	3.65E-07	6.14E-08	2.41E-07	8.73E-07
133	D3SWBD	2 OF 3 BISTABLES FAIL ON DEMAND	1.29E-08	2.67E-10	6.60E-09	3.44E-08

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Table 6-30 (Continued)
 DIABLO CANYON UNIT 1 COMPONENT COMMON CAUSE FAILURE RATES

Item	Designator	Component and Failure Mode	Distribution			
			Mean	5th Percentile	50th Percentile	95th Percentile
134	T3SWBD	3 OF 3 BISTABLES FAIL ON DEMAND	1.90E-09	7.50E-12	6.74E-10	5.71E-09
135	S4SWBD	1 OF 4 BISTABLES FAIL ON DEMAND	3.66E-07	6.07E-08	2.42E-07	8.72E-07
136	D4SWBD	2 OF 4 BISTABLES FAIL ON DEMAND	8.42E-09	1.75E-10	4.15E-09	2.30E-08
137	T4SWBD	3 OF 4 BISTABLES FAIL ON DEMAND	4.52E-10	1.94E-12	1.53E-10	1.36E-09
138	G4SWBD	4 OF 4 BISTABLES FAIL ON DEMAND	5.51E-10	2.12E-12	1.75E-10	1.67E-09
139	S2SWLD	1 OF 2 LEVEL SWITCHES FAIL TO OPERATE ON DEMAND	2.54E-04	1.51E-05	1.16E-04	7.46E-04
140	D2SWLD	2 OF 2 LEVEL SWITCHES FAIL TO OPERATE ON DEMAND	1.91E-05	5.44E-07	5.50E-06	5.97E-05
141	SDSWLD	1 OF 10 LEVEL SWITCHES FAIL TO OPERATE ON DEMAND	2.54E-04	1.49E-05	1.16E-04	7.48E-04
142	DDSWLD	2 OF 10 LEVEL SWITCHES FAIL TO OPERATE ON DEMAND	5.81E-06	6.98E-08	1.61E-06	1.78E-05
143	TDSWLD	3 OF 10 LEVEL SWITCHES FAIL TO OPERATE ON DEMAND	3.08E-07	6.57E-10	5.99E-08	9.60E-07
144	GDSWLD	4 OR MORE OF 10 LEVEL SWITCHES FAIL TO OPERATE ON DEMAND	3.72E-07	7.59E-10	6.95E-08	1.13E-06
145	S4SWPD	1 OF 4 PRESSURE SWITCHES FAIL TO OPERATE ON DEMAND	2.54E-04	1.51E-05	1.16E-04	7.47E-04
146	D4SWPD	2 OF 4 PRESSURE SWITCHES FAIL TO OPERATE ON DEMAND	5.95E-06	6.58E-08	1.65E-06	1.75E-05
147	T4SWPD	3 OF 4 PRESSURE SWITCHES FAIL TO OPERATE ON DEMAND	3.22E-07	7.33E-10	6.13E-08	1.00E-06
148	G4SWPD	4 OF 4 PRESSURE SWITCHES FAIL TO OPERATE ON DEMAND	4.12E-07	7.85E-10	6.84E-08	1.11E-06
149	S2UVCD	1 OF 2 R.T. UV COILS FAIL ON DEMAND	2.18E-03	5.79E-04	1.73E-03	4.35E-03
150	D2UVCD	2 OF 2 R.T. UV COILS FAIL ON DEMAND	2.91E-04	5.87E-05	2.07E-04	6.59E-04
151	S2VAOD	1 OF 2 AIR OPERATED VALVES FAIL ON DEMAND	5.83E-04	1.84E-04	4.68E-04	1.20E-03
152	D2VAOD	2 OF 2 AIR OPERATED VALVES FAIL ON DEMAND	4.29E-05	4.74E-06	2.60E-05	1.09E-04
153	S3VAOD	1 OF 3 AIR OPERATED VALVES FAIL ON DEMAND	5.82E-04	1.82E-04	4.68E-04	1.20E-03
154	D3VAOD	2 OF 3 AIR OPERATED VALVES FAIL ON DEMAND	1.87E-05	3.58E-07	1.11E-05	4.77E-05
155	T3VAOD	3 OF 3 AIR OPERATED VALVES FAIL ON DEMAND	6.23E-06	9.08E-08	3.06E-06	1.76E-05
156	S4VAOD	1 OF 4 AIR OPERATED VALVES FAIL ON DEMAND	5.82E-04	1.83E-04	4.68E-04	1.20E-03
157	D4VAOD	2 OF 4 AIR OPERATED VALVES FAIL ON DEMAND	1.26E-05	2.64E-07	7.55E-06	3.24E-05
158	T4VAOD	3 OF 4 AIR OPERATED VALVES FAIL ON DEMAND	1.74E-06	2.52E-08	8.24E-07	4.94E-06
159	G4VAOD	4 OF 10 AIR OPERATED VALVES FAIL ON DEMAND	1.12E-06	1.36E-08	4.34E-07	3.35E-06
160	SDVAOD	1 OF 10 AIR OPERATED VALVES FAIL ON DEMAND	5.82E-04	1.83E-04	4.67E-04	1.19E-03
161	DDVAOD	2 OF 10 AIR OPERATED VALVES FAIL ON DEMAND	1.25E-05	2.54E-07	7.43E-06	3.23E-05
162	TDVAOD	3 OF 10 AIR OPERATED VALVES FAIL ON DEMAND	1.70E-06	2.38E-08	8.49E-07	4.68E-06
163	GDVAOD	4 OR MORE OF 10 AIR OPERATED VALVES FAIL ON DEMAND	1.16E-06	1.45E-08	4.35E-07	3.36E-06
164	S2VCOD	1 OF 2 CHECK VALVES FAIL ON DEMAND	1.67E-04	4.07E-05	1.40E-04	2.78E-04
165	D2VCOD	2 OF 2 CHECK VALVES FAIL ON DEMAND	1.56E-06	1.33E-07	9.64E-07	3.99E-06
166	S3VCOD	1 OF 3 CHECK VALVES FAIL ON DEMAND	1.67E-04	4.07E-05	1.40E-04	2.78E-04
167	D3VCOD	2 OF 3 CHECK VALVES FAIL ON DEMAND	6.98E-07	5.80E-08	4.24E-07	1.78E-06
168	T3VCOD	3 OF 3 CHECK VALVES FAIL ON DEMAND	2.37E-07	1.56E-08	1.25E-07	6.59E-07
169	S4VCOD	1 OF 4 CHECK VALVES FAIL ON DEMAND	1.67E-04	4.06E-05	1.40E-04	2.78E-04
170	D4VCOD	2 OF 4 CHECK VALVES FAIL ON DEMAND	4.57E-07	3.91E-08	2.87E-07	1.15E-06
171	T4VCOD	3 OF 4 CHECK VALVES FAIL ON DEMAND	5.76E-08	3.51E-09	2.93E-08	1.57E-07
172	G4VCOD	4 OF 4 CHECK VALVES FAIL ON DEMAND	6.81E-08	3.46E-09	3.17E-08	1.95E-07
173	S6VCOD	1 OF 6 CHECK VALVES FAIL ON DEMAND	1.67E-04	4.07E-05	1.40E-04	2.78E-04
174	D6VCOD	2 OF 6 CHECK VALVES FAIL ON DEMAND	4.61E-07	3.99E-08	2.79E-07	1.19E-06
175	T6VCOD	3 OF 6 CHECK VALVES FAIL ON DEMAND	5.54E-08	3.51E-09	2.79E-08	1.52E-07

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Table 6-30 (Continued)
 DIABLO CANYON UNIT 1 COMPONENT COMMON CAUSE FAILURE RATES

Item	Designator	Component and Failure Mode	Distribution			
			Mean	5th Percentile	50th Percentile	95th Percentile
176	G6VCOD	4 OR MORE OF 6 CHECK VALVES FAIL ON DEMAND	6.78E-08	3.30E-09	3.21E-08	1.87E-07
177	SDVCOD	1 OF 10 CHECK VALVES FAIL ON DEMAND	1.67E-04	4.07E-05	1.40E-04	2.78E-04
178	DDVCOD	2 OF 10 CHECK VALVES FAIL ON DEMAND	4.61E-07	3.99E-08	2.79E-07	1.19E-06
179	TDVCOD	3 OF 10 CHECK VALVES FAIL ON DEMAND	5.54E-08	3.51E-09	2.79E-08	1.52E-07
180	GDVCOD	4 OR MORE OF 10 CHECK VALVES FAIL ON DEMAND	6.78E-08	3.30E-09	3.21E-08	1.87E-07
181	SSVCOD	1 OF 2 AFW STEAM SUPPLY LINE VALVES FAIL ON DEMAND	1.66E-04	4.04E-05	1.40E-04	2.77E-04
182	DSVCOD	2 OF 2 AFW STEAM SUPPLY LINE VALVES FAIL ON DEMAND	2.52E-06	3.67E-07	1.76E-06	5.58E-06
183	S4VE2D	1 OF 4 TURBINE CONTROL/STOP VALVES FAIL ON DEMAND	1.08E-04	2.73E-05	8.34E-05	2.13E-04
184	D4VE2D	2 OF 4 TURBINE CONTROL/STOP VALVES FAIL ON DEMAND	2.33E-06	3.91E-08	1.35E-06	6.06E-06
185	T4VE2D	3 OF 4 TURBINE CONTROL/STOP VALVES FAIL ON DEMAND	3.18E-07	4.52E-09	1.53E-07	8.86E-07
186	G4VE2D	4 OF 4 TURBINE CONTROL/STOP VALVES FAIL ON DEMAND	2.08E-07	1.47E-09	7.31E-08	6.15E-07
187	S2VMOC	1 OF 2 MOTOR OPERATED VALVES FAIL TO CLOSE ON DEMAND	1.52E-03	6.56E-04	1.35E-03	2.53E-03
188	D2VMOC	2 OF 2 MOTOR OPERATED VALVES FAIL TO CLOSE ON DEMAND	1.12E-04	3.95E-05	9.54E-05	1.99E-04
189	S2VMOO	1 OF 2 MOTOR OPERATED VALVES FAIL TO OPEN ON DEMAND	1.55E-03	6.67E-04	1.38E-03	2.57E-03
190	D2VMOO	2 OF 2 MOTOR OPERATED VALVES FAIL TO OPEN ON DEMAND	8.43E-05	2.95E-05	7.08E-05	1.53E-04
191	S2VPRO	1 OF 2 PRESSURE REGULATING VALVES FAIL TO OPEN ON DEMAND	1.66E-06	5.19E-08	4.98E-07	5.05E-06
192	D2VPRO	2 OF 2 PRESSURE REGULATING VALVES FAIL TO OPEN ON DEMAND	1.63E-08	2.38E-10	3.75E-09	5.04E-08
193	S3VR10	1 OF 3 RELIEF VALVES FAIL TO OPEN	3.19E-04	1.39E-05	1.34E-04	1.02E-03
194	D3VR10	2 OF 3 RELIEF VALVES FAIL TO OPEN	1.67E-06	4.36E-08	4.84E-07	4.88E-06
195	T3VR10	3 OF 3 RELIEF VALVES FAIL TO OPEN	2.42E-07	1.63E-09	5.10E-08	7.00E-07
196	S5VR10	1 OF 5 SAFETY VALVES FAIL TO OPEN	3.19E-04	1.39E-05	1.34E-04	1.02E-03
197	D5VR10	2 OF 5 SAFETY VALVES FAIL TO OPEN	1.13E-06	2.80E-08	3.21E-07	3.44E-06
198	T5VR10	3 OF 5 SAFETY VALVES FAIL TO OPEN	6.87E-08	3.30E-10	1.35E-08	2.20E-07
199	G5VR10	4 OR MORE OF 5 SAFETY VALVES FAIL TO OPEN	4.60E-08	1.39E-10	6.95E-09	1.36E-07
200	S3VR1S	1 OF 3 RELIEF VALVES FAIL TO RESEAT	2.77E-03	9.48E-05	1.11E-03	7.76E-03
201	D3VR1S	2 OF 3 RELIEF VALVES FAIL TO RESEAT	1.04E-05	1.52E-07	2.87E-06	3.00E-05
202	T3VR1S	3 OF 3 RELIEF VALVES FAIL TO RESEAT	7.18E-06	1.07E-07	1.69E-06	2.05E-05
203	S3VR1W	1 OF 3 SAFETY VLVS. FAIL TO RESEAT AFTER PASSING WATER	9.93E-02	3.09E-03	8.30E-02	2.39E-01
204	D3VR1W	2 OF 3 SAFETY VLVS. FAIL TO RESEAT AFTER PASSING WATER	3.66E-04	6.12E-06	1.51E-04	1.05E-03
205	T3VR1W	3 OF 3 SAFETY VLVS. FAIL TO RESEAT AFTER PASSING WATER	2.57E-04	3.34E-06	8.38E-05	7.74E-04
206	S3VR30	1 OF 3 PORVS FAIL TO OPEN ON DEMAND	3.88E-03	9.52E-04	2.93E-03	7.97E-03
207	D3VR30	2 OF 3 PORVS FAIL TO OPEN ON DEMAND	1.23E-04	2.94E-06	6.86E-05	3.25E-04
208	T3VR30	3 OF 3 PORVS FAIL TO OPEN ON DEMAND	4.09E-05	5.87E-07	1.94E-05	1.14E-04
209	S3VR3S	1 OF 3 PORVS FAIL TO RESEAT AFTER PASSING STEAM	2.30E-02	5.66E-03	1.73E-02	4.78E-02
210	D3VR3S	2 OF 3 PORVS FAIL TO RESEAT AFTER PASSING STEAM	7.38E-04	1.90E-05	4.26E-04	1.93E-03
211	T3VR3S	3 OF 3 PORVS FAIL TO RESEAT AFTER PASSING STEAM	2.46E-04	3.40E-06	1.18E-04	6.86E-04
212	S3VR3W	1 OF 3 PORVS FAIL TO RESEAT AFTER PASSING WATER	9.31E-02	2.90E-03	7.69E-02	2.24E-01
213	D3VR3W	2 OF 3 PORVS FAIL TO RESEAT AFTER PASSING WATER	3.09E-03	2.74E-05	1.24E-03	8.49E-03
214	T3VR3W	3 OF 3 PORVS FAIL TO RESEAT AFTER PASSING WATER	9.78E-04	7.42E-06	3.30E-04	2.95E-03
215	S2VSOD	1 OF 2 SOLENOID OPERATED VALVES FAIL ON DEMAND	2.21E-03	7.72E-05	8.91E-04	6.19E-03
216	D2VSOD	2 OF 2 SOLENOID OPERATED VALVES FAIL ON DEMAND	1.61E-04	3.39E-06	4.60E-05	4.75E-04
217	S3VSOD	1 OF 3 SOLENOID VALVES FAIL TO OPERATE ON DEMAND	2.20E-03	7.70E-05	8.90E-04	6.18E-03
218	D3VSOD	2 OF 3 SOLENOID VALVES FAIL TO OPERATE ON DEMAND	7.62E-05	6.70E-07	2.14E-05	2.16E-04
219	T3VSOD	3 OF 3 SOLENOID VALVES FAIL TO OPERATE ON DEMAND	1.18E-05	2.36E-08	2.09E-06	3.35E-05

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include repairs of component failures experienced during operation, repairs of failures discovered during periodic testing, removal of components from service for unplanned testing or inspection, minor adjustments, and hardware modifications.

To quantify maintenance unavailabilities, both the frequency and the mean duration of maintenance are necessary. The frequency defines the rate at which components are removed from service, while the mean duration is the average amount of time that the component will be out of service.

In order to obtain a state-of-knowledge distribution for the maintenance-related unavailability, state-of-knowledge distributions for both the maintenance frequency and maintenance mean duration must be developed.

The component maintenance frequency distributions for this study were developed by updating generic maintenance frequency distributions using Plant-specific maintenance frequency data from Diablo Canyon Unit 1. The method of updating was the same as that used in updating failure rates. Generic maintenance frequency distributions were developed for 17 categories of components based on the component type and normal service duty (that is, operating or standby). The basis for these distributions is described in the PLG proprietary data book, and the component categories are presented on Figure 6-41. The results of the updated process are presented in Table 6-31.

Maintenance duration is defined to be the period starting when the component is originally isolated or otherwise removed from service and ending when the component is returned to service in an operable state. In many cases, this duration may be only weakly dependent on the actual time required for maintenance personnel to effect the needed repairs.

Generic distributions for mean maintenance duration were developed for 12 categories of components based on the component type and the allowed outage time specified by Plant technical specifications. The basis for these distributions is described in the PLG proprietary

data book, and the component categories are presented on Figure 6-42. The distributions for Plant-specific mean maintenance durations were developed by updating these generic distributions with Diablo Canyon maintenance duration data. The maintenance duration distributions are presented in Table 6-32.

Initiating Event Frequencies

The initiating events are divided into two groups according to the method used for quantifying their frequencies. The first set is composed of those events for which the available data from other nuclear power plants are judged to be relevant. This included essentially all initiating events except those involving failure of systems that have configurations unique to the Diablo Canyon Unit 1 which require a Plant-specific analysis of those systems.

The method used to develop the generic and Plant-specific distribution of the frequencies of the initiating events in the first group is similar to that used for component failure rates. The details of the development of the generic frequencies and the compiled raw data are described in Mosleh, 1987.

The initiating events in the second group (that is, those requiring Plant-specific analysis of the systems involved) are:

- Interfacing system LOCA
- Total loss of auxiliary saltwater
- Total loss of component cooling water
- Loss of 480-V switchgear ventilation
- Loss of control room ventilation

Table 6-33 lists the internal initiating event groups chosen for this. Each group contains one or more specific initiating event believed to result in the same general plant response, as modeled in the Plant event trees.

Event Sequence Models

An event sequence model is used to identify the many possible plant response sequence to each initiating event. Depending on various

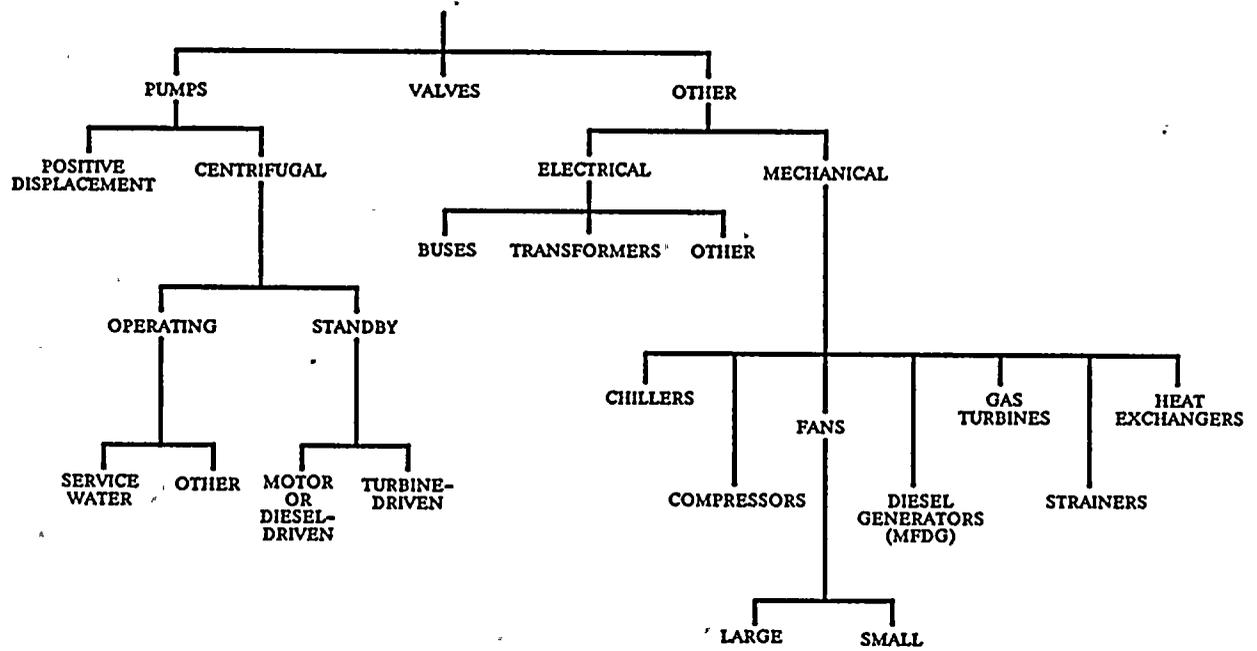


Figure 6-41

Categorization of component types for generic maintenance frequency distributions.

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Table 6-31
 DIABLO CANYON UNIT 1 COMPONENT MAINTENANCE FREQUENCIES

Item	Designator	Component	Diablo Canyon Unit 1 Experience		Generic Mean events per million hours	Diablo Canyon Unit 1 Plant-Specific Distribution (events per million hours)			
			Events	Hours		Mean	5th Percentile	Median	95th Percentile
1	ZMBCHF	Battery Charger	1	51,200	25	22	2	19	50
2	ZMBS1F	Buses, MCCs, Panels	0	112,640	3	2	0.1	1	4
3	ZMCB1F	Breakers	0	348,160	25	5	1	3	12
4	ZMCONF	Condenser Fan	2	20,480	209	100	23	82	201
5	ZMCPFF	Freon Compressor	*	*	156	156	13	86	387
6	ZMDGSF	Diesel Generator	24	30,720	1030	774	525	752	966
7	ZMFN1F	Containment Fan Cooling Unit	3	51,200	147	60	15	51	111
8	ZMFN2F	Ventilation Fans	8	40,960	209	183	82	171	282
9	ZMFNCF	Control Room Fans	8	20,480	209	348	162	319	525
10	ZMGNAF	Electrical Components Very Infrequent Maint.	*	*	3	3	0.1	1	7
11	ZMGNBF	Electrical Components Infrequent Maintenance	*	*	25	24	2	19	50
12	ZMGNCF	Instrument Transformers	*	*	4	4	0.1	1	13
13	ZMGNDF	Valves	9	450,560	27	20	11	19	30
14	ZMHXCF	CCW Heat Exchanger	12	20,480	42	490	245	450	738
15	ZMHXRF	RHR Heat Exchanger	0	20,480	42	19	2	12	46
16	ZMINVF	Inverter	3	40,960	25	37	13	28	72
17	ZMPAMF	AFW Motor-Driven Pump	13	20,480	117	553	313	523	790
18	ZMPASF	Aux. Salt Water Pump	6	20,480	335	280	118	255	436
19	ZMPATF	Turbine-Driven AFW Pump	10	10,240	419	808	399	746	1190
20	ZMPCCF	CCW Pump	10	30,720	158	290	137	274	425
21	ZMPCCF	Centrifugal Charging Pump	7	20,480	158	289	110	264	466
22	ZMPCSF	Containment Spray Pump	6	20,480	117	240	94	218	397
23	ZMPFUF	Fuel Oil Transfer Pump	4	20,480	637	238	81	215	408
24	ZMPPDF	Positive Displacement Charging Pump	3	10,240	637	348	106	314	598
25	ZMPRHF	RHR Pump	8	20,480	117	326	131	298	519
26	ZMPSIF	Safety Injection Pump	9	20,480	117	371	162	342	549
27	ZMVAFV	AFW Valves DC Level Controllers	4	40,960	27	59	19	49	116
28	ZMVASF	Aux. Salt Water Cross-tie	7	51,200	27	93	36	83	156
29	ZMVBOF	ECCS System Valves	21	440,320	27	44	28	42	60
30	ZMVMSF	Mainsteam Atmospheric Dump Valves	22	163,840	27	119	78	114	160
31	ZMVR3F	Primary PORV	2	30,720	27	38	9	31	79
32	ZMXFRF	Transformers (other than instrument)	0	61,440	4	3	0.1	1	7

* No plant-specific data collected.

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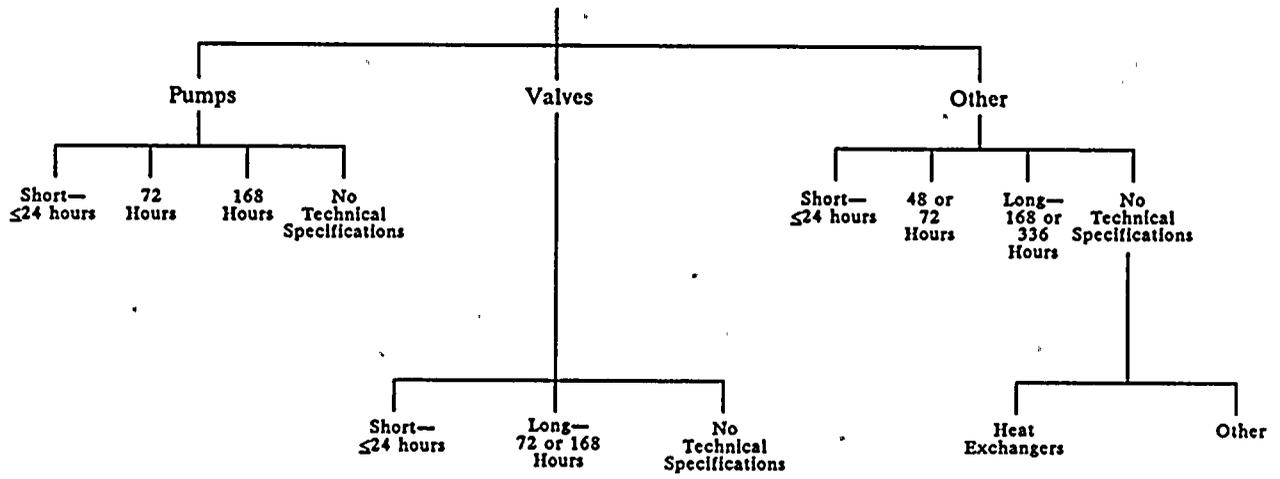


Figure 6-42

Categorization of components by technical specification for generic mean maintenance duration distributions.

Table 6-32
DIABLO CANYON UNIT 1 MEAN MAINTENANCE DURATION DISTRIBUTIONS
 (In Hours)

Item	Designator	Component	Generic Mean (Hrs)	Diablo Canyon Unit 1 Plant Specific Distribution			
				Mean	5th Percentile	Median	95th Percentile
1	ZMBCHD	Battery Charger	38	61	39	59	82
2	ZMCOND	Condenser Fan	37	21	8	19	36
3	ZMDGSD	Diesel Generator	17	10	7	10	13
4	ZMFN1D	Containment Fan Cooling Unit	37	21	9	19	32
5	ZMFN2D	Ventilation Fans	37	64	20	50	120
6	ZMFNCD	Control Room Fans	37	34	15	31	52
7	ZMGN2D	Valves Tech. Spec. Limits Of 24 Hrs.	4	4 *	1	3	10
8	ZMGN3D	Valves Tech. Spec. Limits Of 72 Hrs.	13	19 *	2	11	51
9	ZMGN4D	Equipment other than Valves,Pumps,HXRs 72 Hrs Tech. Spec. Limits	13	13 *	1	6	40
10	ZMGN5D	Equipment other than Valves,Pumps,HXRs Tech. Spec. Limits of 24 Hrs.	6	6 *	1	3	20
11	ZMGN6D	Equipment other than Valves,Pumps,HXRs Tech. Spec. Limits of 168 Hrs.	37	37 *	8	28	74
12	ZMGN7D	Equipment other than Valves,Pumps,HXRs No Technical Specifications	38	38 *	1	14	117
13	ZMGN8D	Freon Compressor 7 Days Tech. Spec. Limits	29	29 *	3	16	73
14	ZMGN9D	RHR Heat Exchanger 72 Hr. Tech. Spec. Limits	21	21 *	12	19	28
15	ZMHXCD	CCW Heat Exchanger 72 Hr. Tech. Spec. Limits	13	16	8	15	24
16	ZMINVD	Inverters	6	8	2	7	18
17	ZMPAMD	Motor-Driven AFW Pump	11	21	14	21	28
18	ZMPASD	AUX. Salt Water Pump	11	12	4	10	22
19	ZMPATD	Turbine-Driven AFW Pump	11	17	11	16	23
20	ZMPCCD	CCW Pump	266	35	24	34	46
21	ZMPCGD	Centrifugal Charging Pump	11	14	9	14	20
22	ZMPCSD	Containment Spray Pump	11	16	7	14	23
23	ZMPFUD	Fuel Oil Transfer Pump	11	17	9	16	23
24	ZMPDD	Positive Displacement Charging Pump	266	85	22	71	158
25	ZMPRHD	RHR Pump	11	15	7	14	21
26	ZMPSID	Safety Injection Pump	11	15	7	14	23
27	ZMVAFD	AFW DC Control Valves	132	13	11	13	15
28	ZMVASD	ASW Crosstie Valves	132	17	12	16	22
29	ZMVBOD	ECCS System Valves	19	12	11	12	13
30	ZMVMSD	Mainsteam Atmospheric Dump Valves	132	55	37	54	72
31	ZMVNTD	Valves with no Technical Specifications	132	18	7	17	27
32	ZMVR3D	Primary PORV	132	110	1	16	412



Table 6-33
DIABLO CANYON UNITS 1 AND 2 INITIATING EVENTS FREQUENCIES

Item	Designator	Description	Generic+ Mean	Specific Data		Distribution			
				# of Events	# of Years	MEAN	5TH XILE	MEDIAN	95TH XILE
1	RT	Total Reactor Trip Frequency	1.53+00	4	4.63	1.14E+00	5.98E-01	1.06E+00	1.73E+00
2	ELOCA	Excessive LOCA	2.66-07*	0	4.63	2.66E-07	7.10E-09	8.76E-08	8.07E-07
3	LLOCA	Large LOCA	2.03-04	0	4.63	2.02E-04	6.72E-06	8.10E-05	5.73E-04
4	MLOCA	Medium LOCA	4.65-04	0	4.63	4.63E-04	1.86E-05	1.99E-04	1.11E-03
5	SLOCAN	Small LOCA, Nonisolable	5.83-03	0	4.63	5.26E-03	1.12E-04	1.73E-03	1.57E-02
6	SLOCAI	Small LOCA, Isolable	2.30-02	0	4.63	1.61E-02	3.76E-04	7.47E-03	4.09E-02
7	SLBI	Steamline Break Inside Containment	4.65-04	0	4.63	4.63E-04	1.86E-05	1.99E-04	1.11E-03
8	SLBO	Steamline Break Outside Containment	6.04-03	0	4.63	5.53E-03	1.15E-04	2.10E-03	1.48E-02
9	LOOP	Loss Of Offsite Power Frequency	1.40-01	0	4.63	9.10E-02	1.08E-02	5.86E-02	2.15E-01
10	LIDC	Loss Of One DC Bus	3.35-02	0	4.63	2.56E-02	1.26E-03	1.48E-02	6.35E-02
11	ISI	Inadvertent Safety Injection Signal	3.03-02	1	4.63	7.39E-02	4.29E-03	3.04E-02	1.60E-01
12	LOPF	Loss Of Primary Flow	1.66-01	1	4.63	1.60E-01	1.93E-02	1.07E-01	3.83E-01
13	TT	Turbine Trip	1.08+00	5	4.63	1.05E+00	5.48E-01	9.57E-01	1.55E+00
14	PLMFW	Partial Loss Of Main Feedwater	1.13+00	3	4.63	7.49E-01	2.64E-01	6.36E-01	1.23E+00
15	TLMFW	Total Loss Of Main Feedwater	1.64-01	0	4.63	9.98E-02	1.50E-02	7.01E-02	2.26E-01
16	LCV	Loss Of Condenser Vacuum	1.16-01	0	4.63	8.73E-02	1.55E-02	6.29E-02	1.86E-01
17	CPEXC	Core Power Excursion	2.72-02	0	4.63	2.19E-02	8.15E-04	1.38E-02	4.61E-02
18	IMSIV	Closure Of One MSIV	8.43-02	1	4.63	1.07E-01	1.58E-02	7.62E-02	2.53E-01
19	AMSIV	Inadvertent Closure Of All MSIVs	1.95-02	0	4.63	1.74E-02	5.17E-04	1.03E-02	4.76E-02
20	SGTR	Steam Generator Tube Rupture	2.88-02	0	4.63	1.71E-02	1.89E-04	5.10E-03	4.64E-02
21	MSRV	Inadvertent Opening Of Main Steam Relief Valves	4.23-03	0	4.63	3.59E-03	7.57E-05	1.10E-03	1.07E-02
22	EXFW	Excessive Feedwater Flow	1.71-01	2	4.63	2.79E-01	4.98E-02	1.97E-01	6.13E-01
23	LOSW	Total Loss of Auxiliary Salt Water	**			1.94E-04	3.34E-05	9.95E-05	4.65E-04
24	LPCC	Total Loss of Component Cooling Water	**			1.99E-04	3.05E-05	1.23E-04	4.90E-04
25	LOSWV	Loss of 480v Switchgear Ventilation	**			6.51E-05	5.84E-07	1.06E-05	2.11E-04
26	LOCV	Loss of Control Room Ventilation	**			7.70E-02	3.39E-02	6.40E-02	1.31E-01
27	VDI	Interfacing LOCA (Discharge Side Valve)	**			3.86E-06	1.33E-08	2.68E-07	7.97E-06
28	VSI	Interfacing LOCA (Suction Side Valve)	**			1.01E-06	5.03E-09	8.40E-08	2.14E-06

+ All frequencies per calendar year.

* Exponential notation is indicated in abbreviated form: i.e. 2.66-07 = 2.66E-07.

** Frequencies for these initiating events are based on system analysis.



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combinations of Plant equipment and operator response success or failure states, the event sequences will either be terminated with no core damage or will lead to core damage and various degrees of Plant damage, defined as Plant damage states.

The event sequence model is divided into four parts as shown on Figure 6-43, the electrical support system event tree, the actuation and mechanical support system event tree, the early response frontline system event tree, and the long-term response frontline system event tree. For each of the 50 initiating event categories that were identified, the Plant response to each one of these was evaluated by using the event sequence model. Since the Plant response to many of these initiating event categories is quite similar, common event tree modules or structures were developed and quantified with different boundary conditions and system top event data specific to each initiator. The event tree modules are shown on Figure 6-43. The electrical and actuation/mechanical support system event trees are common to all initiating events. These modules simply identify different support system states; that is, combinations of support system equipment successes and failures that affect the frontline systems in similar ways. Next are the early response frontline system event trees. These are specific to particular initiating events depending on the required success criteria of the responding systems. There are six early response frontline trees. They are:

- *General Transient*. Covers most initiating event groups that require active nuclear shutdown, heat removal, or coolant injection.
- *Large LOCA*. Covers large breaks in the reactor coolant system pressure boundary (6-inch diameter up to a full design basis guillotine break of cold leg pipe) that requires high capacity makeup but no immediate cooling or reactor trip.
- *Steam Generator Tube Rupture*. Similar to the general transient, with special requirements for operator response to eliminate the flow of reactor coolant through the ruptured steam generator, bypassing containment.
- *Interfacing System LOCA*. Covers cases where the boundary to low pressure systems fail such that containment can be bypassed and equipment needed for control of LOCA can be damaged.
- *Seismic Events*. Very similar to the general transient model, covering the same functional initiating events; additional detail added to more easily account for earthquake-induced dependent failures and specially required human actions.
- *Any Transient Without Trip (ATWT)*. Covers all the above initiating events that require reactor trip if the trip was identified as failed in the support system model; considers potential ensuing overpressure events and special actions to provide long-term shutdown of the nuclear reaction.

Finally, if the event sequence has not yet reached a successful conclusion, sequences branch to one of the long-term event trees. Sequences requiring long-term cooling branch to LT1. Sequences that have already reached melt branch to LT2 and LT3 for an examination of containment safeguards.

SUPPORT SYSTEM EVENT TREES

The intersystem dependencies of the support systems are modeled in two detailed support system event trees. A detailed electric power event tree is developed that models only the electric power support systems. A second support system event tree is used to represent the remaining support systems; for example, 120V AC, component cooling water, ventilation, solid state protection system. Two support model event trees are required because one tree would be too large to include all the systems in one tree.

Intersystem Dependencies

Before embarking on the development of the support system event trees representing the Plant systems, a thorough knowledge of the Plant intersystem dependencies is necessary. Only

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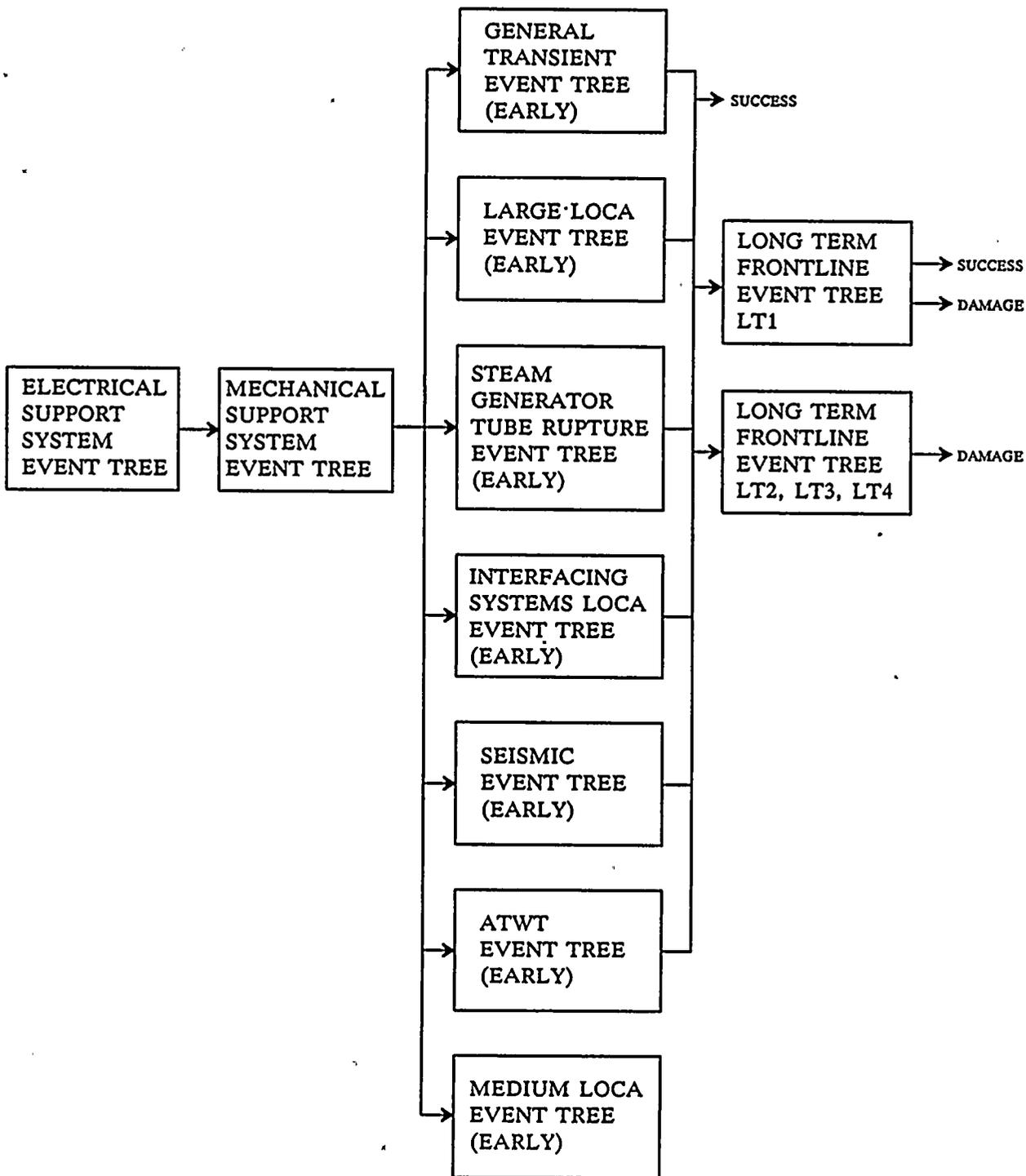


Figure 6-43

The four-module event sequence model.

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functional dependencies, not dependencies arising from spatial relationships, are considered in this review.

The understanding of intersystem functional dependencies was acquired by reviewing system design descriptions, drawings, and other documents of the Plant design. The results of this review are summarized in Tables 6-34 and 6-35. Table 6-34 indicates the intersystem dependencies between support systems. Table 6-35 indicates the intersystem dependencies between support and frontline systems. The vertical axis in Tables 6-34 and 6-35 lists individual trains of support systems, including the electric power systems, systems supplying the control signals, cooling water systems, ventilation systems, and the instrument air system. Although not a support system, the reactor trip system is also listed. For modeling purposes, it is convenient to model reactor trip as a support system. In Table 6-34, the impact of failure of any one train of the indicated support systems on other support systems is indicated.

A single support system failure can give rise to multiple failures in other support systems because of these functional dependencies. An "X" in the table indicates that the support system train in that row has failed.

The table only indicates direct functional dependencies. Consequently, no dependency is shown between 4.16-kV bus HF and 125V DC distribution 11. The 4.16-kV bus does indirectly supply power via 480-V bus 1F to DC distribution 11, but not directly. Eliminating these indirect dependencies simplifies the table without a loss of information. The cascaded impacts are, however, considered in all subsequent modeling efforts.

In Table 6-35, the frontline system trains are listed across the top of the table. As with Table 6-34, this table indicates the dependencies on a per train basis. The redundant features of the frontline systems make it essential that the dependencies be displayed at the train level. This table is read in the same manner as Table 6-34. Cascaded dependencies are not shown. Only direct intersystem dependencies are noted.

Together, Tables 6-34 and 6-35 provide a complete record of the plant intersystem dependencies that are considered in the Diablo Canyon integrated Plant model. The next step in the development of the Plant model is the construction of the electric power event tree.

ELECTRIC POWER EVENT TREE

Tables 6-34 and 6-35 identify the intersystem functional dependencies as they exist at the Diablo Canyon Plant. These dependencies must now be interpreted in a dichotomous manner, suitable for computer modeling using event trees, without creating models excessively large. To accomplish this, groups of electric power support system trains are collected into top events for the electric power event tree. This collection of support system trains into top events must be careful to preserve the dependencies of support systems on one another and of the impacts of failed support systems on frontline systems. The newly defined top events must then be ordered so that subsequent top events only depend on preceding ones. This ordering is to facilitate quantification of the split fractions needed to quantify the support model event trees.

Top Event Definitions. The top events that appear in the electric power event tree are defined below. In some cases, the analysis of a given electric power system is divided into two or three subsystems to facilitate the treatment of intersystem dependencies; for example, 4.16-kV buses HF, HG, and HH are analyzed in separate top events. Separating the systems into separate subsystems simplifies the process of estimating the event tree conditional split fractions; that is, branching ratios.

- *Top Event OG.* This top event questions the availability of offsite power to the three 4.16-kV vital buses in response to a plant initiating event. This event may fail as a result of the grid disturbance associated with the initiating event or, a consequential loss of power may result due to failures of the equipment supplying power to the 4.16-kV vital buses, given offsite power is available at the switchyard buses. Also, this top event is

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guaranteed failed for a loss of offsite power initiating event. Success of this top event ensures the supply of power from the switchyard to the 4.16-kV vital buses. Failure of this top event results in a need for the emergency diesel generators to start and supply power for the Class 1E 4.16-kV buses.

- **Top Event DF.** This top event questions the availability of 125-V vital DC power on bus 11 and at distribution panel 11. Two sources of power are modeled: one from the battery charger if AC power is available from bus 1F or from the battery itself. No credit is given for the backup battery charger 121. Success of this top event ensures DC control power for emergency diesel generator 13 for Unit 1 and the breakers that must function for success of 4.16-kV vital bus HF.
- **Top Event DG.** This top event is similar to Top Event DF, but involves battery 12, 125V DC bus 12 and distribution panel 12. Success of this top event assumes DC control power for emergency diesel generator 12 and the breakers that must function for success of 4.16-kV vital bus HG.
- **Top Event DH.** This top event is similar to Top Event DF, but involves battery 13, 125V DC distribution panel 13 and battery charger 132. Success of this top event ensures DC control power for emergency diesel generator 11 and the breakers that must function for success of 4.16-kV vital bus HH.
- **Top Event NV.** This top event questions the availability of nonvital power on 12-kV buses D and E, given the Unit 1 startup bus is energized. Success of this top event ensures a supply of power to 12-kV bus D or E and, thus, at least two of the reactor coolant pumps. Failure of Top Event OG is assumed to cause failure of Top Event NV.
- **Top Event AF.** This top event questions the availability of vital AC power on 4.16-kV bus HF on Unit 1 and 480-V bus 1F. Given that an offsite source of power is available to the 4.16-kV bus, success of this top event requires that the 4.16-kV feeder breaker from the auxiliary transformer open. DC power is required to open this breaker. Success of this event and of Top Event OG implies that power is available to all equipment and buses supplied from 4.16-kV bus HF and 480-V bus 1F. Success of this event and failure of Top Event OG imply that the corresponding diesel generator must start and load to power the equipment supplied from this bus.
- Failure of this event means that vital AC power on 4.16-kV bus HF on Unit 1 and 480-V bus 1F is not available. Even if operable, neither startup transformer 12 nor diesel generator 13 could supply the loads fed from these buses.
- **Top Event AG.** This top event is similar to Top Event AF, but involves 4.16-kV bus HG and 480-V bus 1G on Unit 1.
- **Top Event AH.** This top event is similar to Top Event AF, but involves 4.16-kV bus HH and 480-V bus 1H on Unit 1.
- **Top Event SF.** This top event questions the closure of circuit breaker 52HF14 supplying 4.16-kV bus HF on Unit 1 from the startup transformer following a plant trip. DC control power from 125V DC panel 11 is required to close the breaker. This top event is only asked if Top Event AF is successful. Success of this top event and of OG implies that power is available from offsite to 4.16-kV bus HF and to 480-V bus 1F on Unit 1. If this top event is not asked and OG fails, this implies that diesel generator 13 must start and load to power the equipment from these buses.
- **Top Event SG.** This top event is similar to Top Event SF, but involves circuit breaker 52HG14, on Unit 1.
- **Top Event SH.** This top event is similar to Top Event SF, but involves circuit breaker 52HH14, on Unit 1.
- **Top Event BF.** This top event models 125V DC distribution Panel 21 and vital AC buses 480-V 2F and 4.16-kV bus HF on Unit 2. If offsite power is available, power is assumed available to the indicated buses. If offsite

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power is not available but Top Event BF is successful, then, if swing diesel 13 aligns to Unit 2, power is available at the indicated buses. Top Event BF models the equivalent of the combined actions of Top Events DF and AF except that BF is for the analogous equipment on Unit 2. If offsite power is available, the Unit 2 buses are assumed to be powered from the auxiliary transformer on Unit 2; no transfer to the startup transformer is required.

- *Top Event BG.* This top event is similar to Top Event BF, but involves 125V DC distribution 22, 480-V bus 2G, and 4.16-kV bus HG on Unit 2.
- *Top Event BH.* This top event is similar to Top Event BF, but involves 125V DC distribution 23, 480-V bus 2H, and 4.16-kV bus HH on Unit 2.
- *Top Event GF.* This top event questions the availability of emergency diesel generator 13 after a loss of power to 4.16-kV vital bus HF on Unit 1. Success of this top event requires that diesel generator 13 starts automatically when a bus undervoltage condition exists, diesel generator breaker 52HF7 closes and reenergizes 4.16-kV bus HF. Success of this top event ensures a source of emergency power to the equipment supplied from 4.16-kV bus HF on Unit 1. Failure of the emergency diesel generator fails all equipment that receives power from this bus.
- *Top Event GG.* This top event is similar to Top Event GF, but involves diesel generator 12 and its associated equipment.
- *Top Event GH.* This top event is similar to Top Event GG, but involves diesel generator 11 and its associated equipment.
- *Top Event 2G.* This top event questions the availability of vital AC power from diesel generator 22 to 4.16-kV bus HG on Unit 2.

If offsite power and Top Event BG are successful, this event is not questioned because AC power is assumed available from offsite via the auxiliary transformer on Unit 2.

- *Top Event 2H.* This top event is similar to Top Event 2G, but involves diesel generator 21 and power to Unit 2 4.16-kV bus HH.
- *Top Event FO.* This top event questions the availability of the diesel fuel oil system for the emergency diesel generators. Success is when either fuel oil transfer pump supplies fuel to all five diesel generator day tanks. Failure of this top event is assumed to result in failure of the operating diesels within a couple of hours due to the depletion of fuel. Failure of the fuel oil system to deliver fuel oil is modeled as failure of fuel oil to all the operable diesels.
- *Top Event SW.* This top event questions the alignment of diesel generator 13. Success of this top event represents that diesel generator 13 is lined up with the 4.16-kV bus HF of Unit 1. Failure of this top event, or a down branch in the event tree, indicates that diesel generator 13 is aligned to the 4.16-kV bus HF of Unit 2. If offsite power is lost to both units and no safety injection signal is present, the diesel is assumed to have an equal chance of being aligned to Unit 1 or Unit 2. If a safety injection signal is present, the swing diesel aligns to the affected unit. If no safety injection signal is present and one unit has fewer operable vital buses than the other, the operators are assumed to try and align the swing diesel to that unit.

Event Tree Construction. The electric power event tree is provided as Figure 6-44. Figure 6-44 presents the reduced event tree. The reduced tree uses subtree transfers to describe the event tree branches. The complete event tree structure (that is, with all transfers expanded into the corresponding subtree logic) is used to quantify the electric power end states. The decisions about whether to branch or not at each point in the event tree are based on the functional dependencies among top events, as described in Table 6-34. The reasons for not branching at selected positions in the tree are noted below.

If power is available from the offsite grid to Unit 1, it is assumed that power is also available at all

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6		6
7	XFR22	7
8	XFR22	8
9	XFR1	10
10	XFR22	12
11		15
12	XFR2	17
13	XFR1	18
14	XFR22	22
15	XFR22	25
16	XFR3	27
17	XFR2	29
18	XFR2	32
19	XFR2	36
20	XFR1	40
21		44
22	XFR3	47
23	XFR4	48
24	XFR5	51
25	XFR6	54
26	XFR7	55
27		61
28	XFR4	65
29	XFR8	75
30	XFR9	76
31	XFR6	79
32		93
33	XFR10	97
34	XFR11	101
35	XFR12	102
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64	XFR24	415
65	XFR24	417
66		421
67	XFR19	429
68	XFR19	437
69	XFR25	438
70	XFR25	441
71	XFR19	444
72		450
73	XFR22	456
74	XFR22	459
75	XFR26	460
76	XFR26	462
77		464
78	XFR20	468
79	XFR20	472
80	XFR20	473
81	XFR27	479
82	XFR23	485
83	XFR23	491
84	XFR23	495
85		499
86	XFR19	503
87	XFR19	507
88	XFR19	508
89		511
90	XFR29	514
91	XFR55	517
92	XFR24	518
93	XFR23	525
94	XFR22	541
95		549
96	XFR30	553
97	XFR59	555
98	XFR26	556
99	XFR22	561

Figure 6-44

Electric power support event tree.

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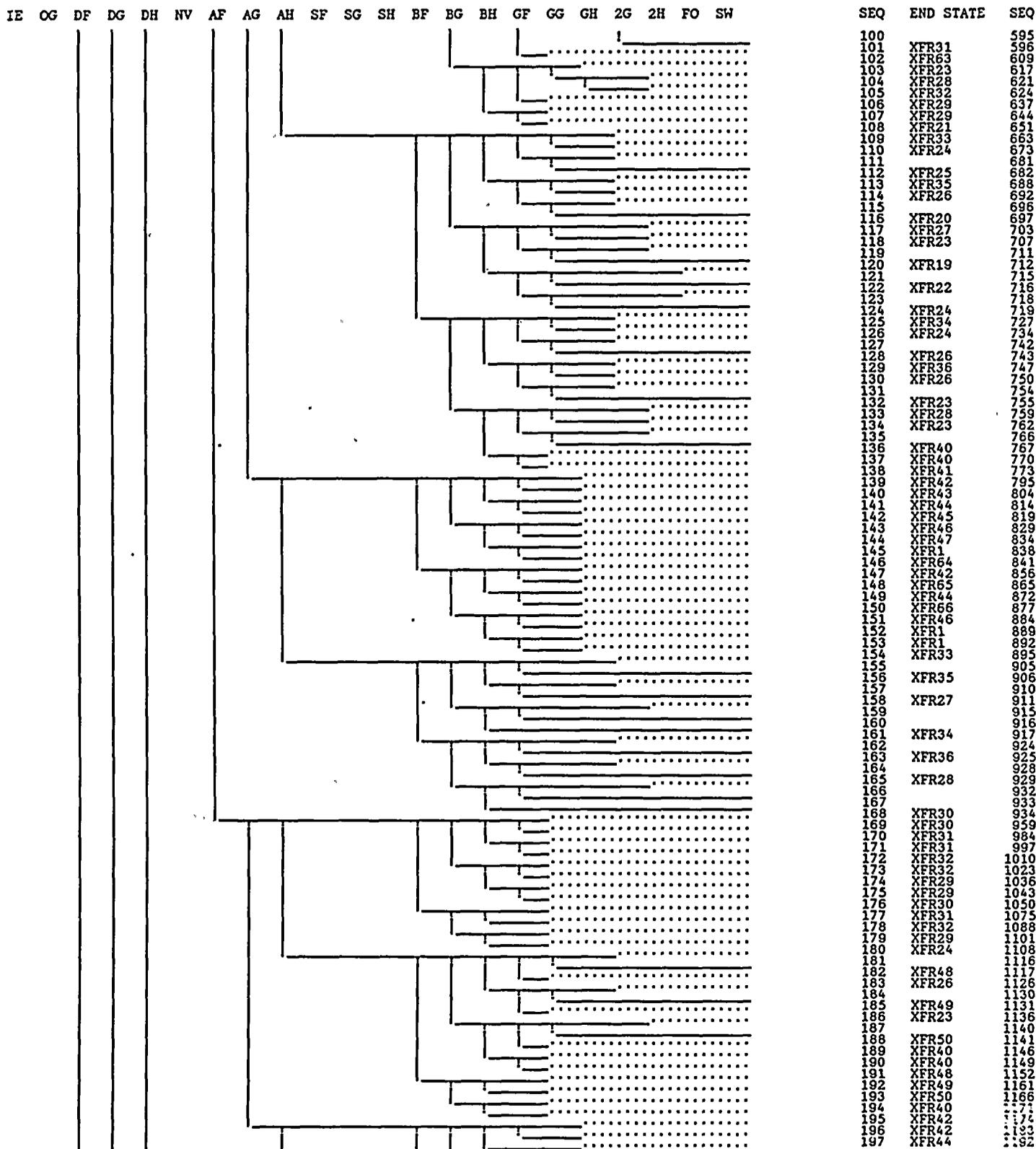


Figure 6-44 (Continued)

Electric power support event tree.

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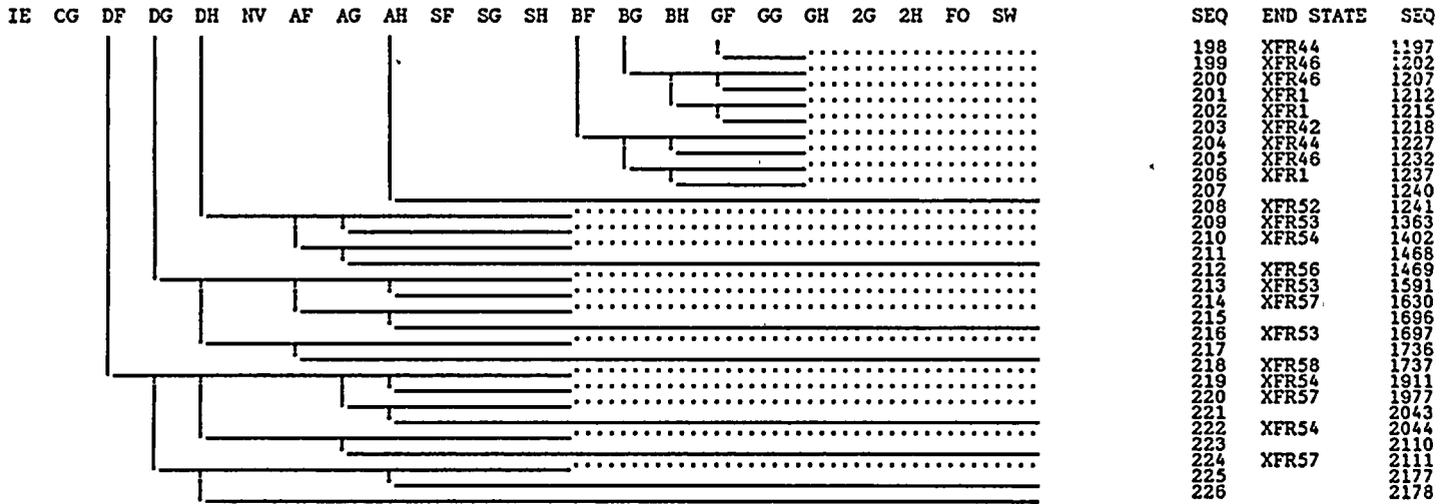


Figure 6-44 (Continued)

Electric power support event tree.



DEFINITION OF SUBTREES (TRANSFERS)

SUBTREE (XFR)	FIRST SEQUENCE	LAST SEQUENCE
*****	*****	*****
1	2	4
2	7	8
3	5	6
4	10	11
5	14	16
6	1	4
7	10	13
8	1	9
9	21	22
10	1	32
11	21	24
12	27	28
13	34	37
14	25	28
15	31	32
16	39	40
17	29	32
18	36	37
19	51	53
20	51	54
21	51	55
22	6	3
23	61	62
24	61	63
25	67	69
26	73	74
27	59	60
28	94	95
29	7	6
30	61	66
31	73	77
32	82	83
33	36	60
34	33	95
35	71	72
36	99	100
37	1	1
38	1	1
39	1	1
40	122	123
41	57	60
42	65	66
43	70	72
44	76	77
45	80	81
46	84	85
47	88	89
48	180	181
49	183	184
50	186	187
51	1	1
52	108	137
53	154	167
54	180	194
55	61	64
56	138	153
57	195	206
58	168	179
59	73	75
60	91	95
61	97	100
62	102	104
63	82	83
64	92	95
65	98	100
66	103	104

Figure 6-44 (Continued)

Electric power support event tree.

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of the 4.16-kV buses of Unit 2. Consequently, in sequence 1 there are no branches under Top Events BF, BG, and BH because power is assumed available to the Unit 2 buses from the Unit 2 generator if Unit 2 is initially operating or from the offsite grid if Unit 2 was previously shut down; that is, Unit 2 is not assumed to trip within 24 hours of the first unit. Also, if power is available to the Unit 1 4.16-kV buses from the startup transformer, the status of the diesels is unimportant. Therefore, those top events associated with the diesels (that is, Top Events GF, GG, GH, 2G, 2H, FO, and SW) are also not asked in sequence 1. If one of the breaker transfers to the startup bus fails (for example, Top Event SH fails), but the corresponding 4.16-kV bus succeeds (for example, Top Event AH success), then the corresponding diesel top events (for example, Top Events GH and FO) are asked as a backup source of power. Sequences 2, 5, and 10 in the reduced tree are examples of this situation. The other diesel generator-related top events need not be asked because power is already known to be available from the startup transformer; that is, the transfer to the startup bus worked for each of the other buses on Unit 1.

If the top event that models a vital 4.16-kV bus itself fails (for example, Top Event AH), then the top events representing the transfer to the startup transformer (Top Event SH) and the corresponding diesel generator top events (Top Events GH and FO) are not asked because they cannot succeed. Examples of this situation are seen in sequences 21, 25, and 29 in the reduced tree.

If one of the 125V DC buses fails (for example, Top Events DF, DG, or DH), then the corresponding vital 4.16-kV bus cannot be energized. DC power is required to effect the transfer to the startup transformer and also to load the diesel. Therefore, if a DC bus fails (for example, Top Event DH), the corresponding top events representing the bus itself (Top Event AH), the startup bus transfer (for example, Top Event SH), and the corresponding diesel (Top Events GH and FO) are not asked. Sequences 34, 39, and 44 in the reduced tree are examples of this situation. Success of Top Event NV only requires that one of the two nonvital 12-kV buses

transfers to offsite power following a plant trip. The control power for the transfer of the two 12-kV buses comes from different DC power sources. Therefore, the tree branches under Top Event NV unless both Top Events DG and DH fail; that is, see sequences 42 and 50.

If power from the offsite grid is lost (that is, Top Event OG fails), no power from the startup transformer is possible. Therefore, there are no branches under Top Events NV, SF, SG, and SH for this part of the tree. Instead, power must be provided by the diesel generators. The loss of offsite power is also assumed to affect Unit 2. Therefore, all of the top events needed to determine whether power is available from the diesels at each of the six vital 4.16-kV buses on Units 1 and 2 are asked.

Top Event SW, which determines to which unit the swing diesel aligns, is not asked if the swing diesel fails (for example, Top Event GF fails) if there is no fuel oil available to run it (that is, Top Event FO fails, such as in sequence 53) or if power is provided to bus HF on both units from offsite; for example, sequence 3.

As with the Unit 1 buses, the Unit 2 diesels (for example, Top Event 2G) are not asked if the corresponding DC or AC bus fails; for example, Top Event BG fails. Examples of this situation are sequences 67 and 78. The swing diesel is asked even if the Unit 2 DC bus that provides control power to it fails because it may still align to Unit 1.

ACTUATION AND MECHANICAL SUPPORT EVENT TREE

The actuation and mechanical support event tree follows the electric power event tree. As with the electric power tree, groups of the remaining support system trains are collected into top events for the second stage support tree.

Top Event Definitions. The top events that appear in the actuation and mechanical support event tree are defined below.

- *Top Event 11.* This top event questions the availability of 120-V vital instrument AC distribution channel I.

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- *Top Event I2.* This top event questions the availability of 120-V vital instrument AC distribution channel II.
- *Top Event I3.* This top event questions the availability of 120-V vital instrument AC distribution channel III.
- *Top Event I4.* This top event questions the availability of 120-V vital instrument AC distribution channel III.
- *Top Event SA.* This top event considers the operability of train A of the solid state protection system. Success of this top event ensures that the appropriate train A actuation signals are provided to the safeguard equipment. The signals required from SSPS depend on the specific initiating event; for example, safeguards actuation, MSIV closure, AFW startup, containment isolation, containment spray actuation. Failure of SSPS train A implies that the associated ECCS equipment and containment isolation valves are not actuated. In addition, failure of Top Event SA prevents the associated reactor trip breakers from receiving an automatic trip signal.
- *Top Event SB.* This top event is similar to Top Event SA, but involves SSPS train B.
- *Top Event CV.* This top event questions the availability of control room HVAC to supply cool air to the instrument safeguard room; that is, SSPS room. Failure of this top event implies that the equipment in the SSPS room will, if ventilation is not recovered, eventually overheat. Failure of Top Event CV is assumed to result in the failure of both SSPS trains. However, a reactor trip signal can still be generated prior to the overheating and is therefore assumed unaffected.
- *Top Event RT.* This top event considers the automatic reactor trip system function and the backup operator action to manually trip the reactor. Success of this top event requires that at least 1 of 2 reactor trip breakers open and that 52 of 53 rod cluster control assemblies are inserted into the reactor core.

Successful operation of at least one SSPS train, manual operator action, or a loss of offsite power is required for the success of RT.
- *Top Event OS.* This top event considers the manual actuation of safety equipment normally actuated by SSPS, given that one or both trains of SSPS has failed. Success of Top Event OS means that the operators have manually actuated the required safety equipment in time for the equipment to still perform its safety function. The equipment required to be actuated and the amount of time available are a function of the initiating event being quantified; that is, large LOCA, small LOCA, steamline break, or general transient.
- *Top Event IA.* This top event questions the availability of the instrument air system. It is conservatively assumed that instrument air is unavailable under all conditions.
- *Top Event AS.* This top event questions the availability of the auxiliary saltwater system supplying cooling water to the Unit 1 CCW heat exchangers. At least one auxiliary saltwater pump must supply cooling water to both Unit 1 CCW heat exchangers. The operator recovery action to crosstie the Unit 2 ASW pump header to the Unit 1 ASW system when both Unit 1 ASW pumps have failed is included in the analysis. If the Unit 2 ASW system is crosstied to Unit 1, one ASW pump is sufficient to supply ASW to both units. Failure of this top event results in a loss of cooling water to the CCW heat exchangers.
- *Top Event CC.* This top event questions the availability of the component cooling water system. Success of this top event requires that cooling flow is provided to both CCW headers A and B. CCW header C is modeled as part of frontline Top Event SE, given Top Event CC is successful. Two of three CCW pumps are required to operate to provide adequate cooling and flow to the cooling loads of all three headers. Only one of three CCW pumps is required if (1) the operator intervenes to reduce flow to header C or the containment fan coolers, or (2) header C is isolated

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automatically. Failure of this top event results in a loss of cooling water to the residual heat removal pumps, reactor coolant pumps, safety injection pumps, centrifugal charging pumps, and the containment fan coolers.

- *Top Event SV.* This top event questions the availability of the 480-V switchgear ventilation system. Success requires at least one supply fan and its associated discharge damper and exhaust fan to be available. Failure of this top event is assumed to result in the eventual overheating of the three Unit 1 480-V vital AC switchgears (1F, 1G, and 1H), 125V DC battery chargers (11, 12, 132, 121, and 131), and the vital instrument AC inverters (11, 11A, 12, 13, 13A, and 14) that supply power to vital instrument channels I, II, III, and IV.

Event Tree Construction. The actuation and mechanical support tree is provided as Figure 6-45. The reasons for not branching at selected positions in the tree are noted below.

If both trains of SSPS succeed (that is, Top Events SA and SB are successful) and the control room ventilation system functions to prevent a heatup of the SSPS cabinets (that is, Top Event CV success), it is assumed for the tree that a manual start of the SSPS-actuated equipment is unnecessary. Therefore, the tree does not branch under Top Event OS for sequence 1.

If control room ventilation fails (that is, Top Event CV fails), the tree still branches under Top Event OS even if the SSPS equipment is available because SSPS may overheat due to the loss of ventilation prior to the time that automatic actuation of safeguards equipment takes place. Sequence 7 in the reduced tree illustrates this branching.

If both trains of SSPS fail, the tree does not branch under Top Event CV. The only assumed impact on the plant due to loss of control room ventilation is failure of SSPS. Since SSPS is already known to be failed (that is, for sequence

13), there is then no reason to branch at Top Event CV.

If power is unavailable from instrument channel 4, the tree does not branch at Top Event SB because SSPS train B requires power for the slave relays to actuate the supported equipment. Similarly, SSPS train A requires power from instrument channel 1. Therefore, the tree does not branch at Top Event SA if Top Event I1 fails. These situations are illustrated by sequences 14 and 24 in the reduced tree.

The actuation and mechanical support model event tree only branches at Top Event IA (that is, for instrument air) if all preceding top events in the tree are successful. In all other sequences, instrument air is conservatively assumed unavailable.

The auxiliary saltwater system only supplies the component cooling water heat exchangers. Therefore, failure of auxiliary saltwater only affects the component cooling water system. The tree does not branch at Top Event CC then if Top Event AS fails. This situation is illustrated in sequence 4.

GENERAL TRANSIENT EVENT TREES

This section describes the event tree models that are used to quantify the accident sequence frequencies. For general transients, two stages of frontline event trees are used sequentially to represent the important actions during the event. Hereafter, these trees are referred to as the early and late event trees for the general transient initiators.

General Transient Early Event Tree. The general transient early event tree (Figure 6-46) covers the events that determine that secondary heat sink response, bleed and feed cooling if the secondary heat sink is unavailable, long-term RCS integrity, and charging and safety injection pump high-pressure injection, if needed.

The early tree top event definitions and success criteria are provided below:

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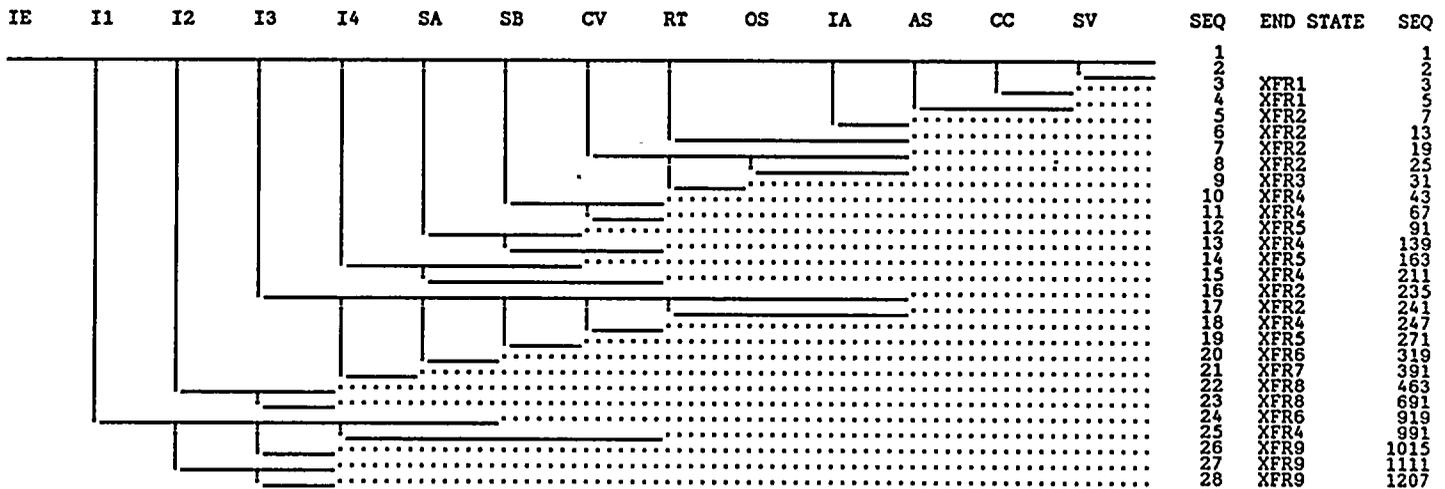
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DEFINITION OF SUBTREES (TRANSFERS)

SUBTREE (XFR)	FIRST SEQUENCE	LAST SEQUENCE
1	1	2
2	1	4
3	7	8
4	7	9
5	10	11
6	12	13
7	14	15
8	16	21
9	24	25

Figure 6-45
Actuation and mechanical support event tree.

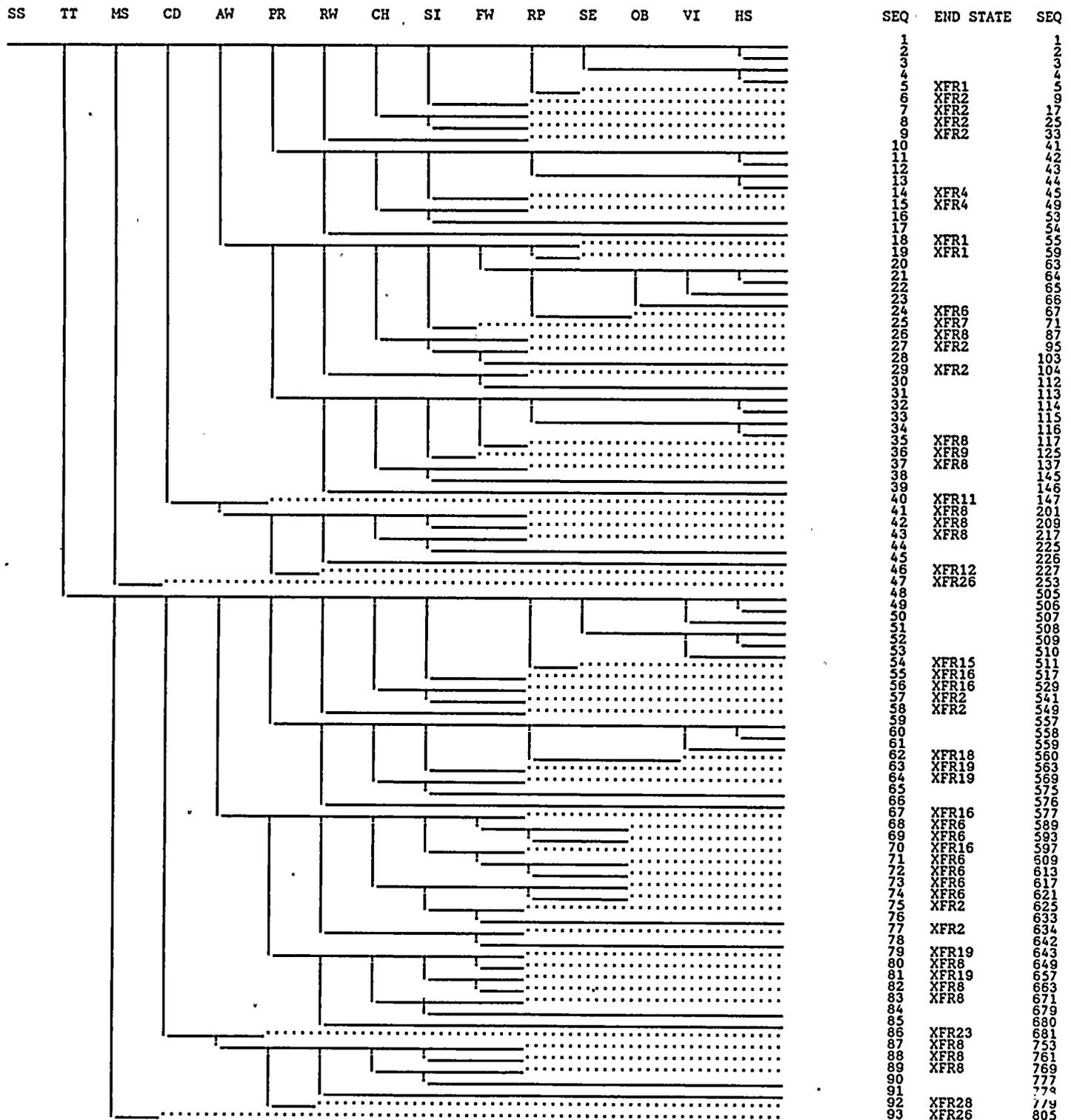


Figure 6-46
General transient early event tree.



DEFINITION OF SUBTREES (TRANSFERS)

SUBTREE (XFR)	FIRST SEQUENCE	LAST SEQUENCE
1	1	4
2	1	5
3	1	9
4	10	13
5	10	17
6	20	23
7	18	24
8	20	24
9	31	35
10	31	39
11	1	17
12	41	45
13	1	6
14	40	46
15	48	53
16	48	54
17	48	58
18	59	61
19	59	62
20	59	66
21	67	78
22	79	85
23	48	66
24	1	2
25	18	30
26	1	46
27	10	11
28	87	91

Figure 6-46 (Continued)
General transient early event tree.

- *Top Event TT.* This top event models the reliability of successful automatic or manual turbine trip, given a successful reactor trip. The backup operator action to manually trip the turbine, given failure of the automatic trip signal, must be in time to prevent MSIV closure on a high steam flow safety injection signal. Each of the four steam lines must be isolated by either the stop valve or the control valve. All four lines must be isolated for success. Failure of Top Event TT means that the MSIVs will be challenged to close to limit a resulting pressurized thermal shock challenge to the reactor vessel.
- *Top Event MS.* Top Event MS represents the 40 percent steam dump valves for cases when turbine trip is successful and represents the MSIVs for turbine trip failure cases. If turbine trip is successful, all 12 of the 40 percent steam dump valves must reclose. If turbine trip fails, three of the four main steam isolation valves must close. Success of Top Events MS (that is, across in the event tree) is interpreted as the valves remaining open. Failure of Top Event MS means that at least three of the valves have successfully closed. Closure of the MSIVs results in the elimination of the steam flow path to the condenser.
- *Top Event CD.* This top event models the availability of the condenser and the condensate system. If the MSIVs are open (that is, Top Event MS success), then success of the Top Event CD implies that a steam flow path from the steam generators through the 40 percent condenser steam dump valves to the main condenser, which is operable, is available. The systems required to maintain condenser vacuum (that is, circulating water, condensate, condenser air removal, gland steam, and service cooling water) and the 40 percent steam dump valves are represented by this top event. Success of both Top Events MS and CD then implies that, following plant trip, the 10 percent steam dump valves and the steam generator safety valves are not challenged and that subsequent

AFW operation can rely on the steam flow path to the condenser.

If Top Event MS fails (that is, the MSIVs are closed), the flow path to the condenser is isolated. Under this condition, Top Event CD models the availability of the condensate system. Together with success of Top Event FW (discussed later), Top Event CD success provides a backup means of feeding the steam generators if AFW fails. However, this top event is conservatively treated as unavailable.

- *Top Event AW.* This top event represents the availability of feedwater pumped from the condensate storage tank to at least one intact steam generator by the auxiliary feedwater system. One of three steam generators is assumed to be required for steam line break events inside the containment because one steam generator will have depressurized. The operators are instructed to isolate flow to the affected steam generator unless no other steam generators are intact. Therefore, for a steam line break outside the containment and the MSIVs failing to close, the operators would establish flow to one of the depressurized steam generators. In this case, the operator action to reestablish flow is modeled, and any one of the four steam generators is assumed required. Also, for steam line break events, one steam supply path to the turbine-driven AFW pump is assumed to be unavailable 50 percent of the time; that is, the steam line break is assumed to occur on either steam generator 1-2 or 1-3 50 percent of the time.

At least 460 gpm of flow is required. One of three AFW pumps is therefore needed for success. Event AW also represents the main steam valves needed for cooling. The 10 percent atmospheric steam dump valves and steam generator relief valves on each steam generator are assumed necessary for cooling the respective steam generator.

- *Top Event PR.* This top event models the RCS pressure relief function. At least one of three pressurizer PORVs must open to relieve RCS pressure, if required, and all three PORVs must reseal. Failure of Top Event PR implies

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that a PORV train is open and a small LOCA has developed. The operator action to isolate a stuck-open PORV by closing the PORV block valve is also considered in this top event. The likelihood that a PORV block valve is closed initially is also considered. If all three PORVs fail to open when challenged, the pressurizer safety valves are then assumed challenged and all three must reset.

For an inadvertent actuation of ECCS or for a steam line break when a safety injection signal is expected, the operator action to secure charging once the safety injection termination criteria are satisfied and prior to the PORV lifting is included in the analysis. If the operator fails to secure charging, the PORVs or the safety valves are assumed to have passed water.

For loss of offsite power events, the pressurizer PORVs are assumed to be challenged.

For all transients, the pressurizer PORVs would not be challenged, if automatic reactor trip is successful. Successful reactor trip is also assumed if the operators manually trip the reactor in the first minute after a failure of an automatic reactor trip. However, for these cases of successful reactor trip, the PORVs would likely be challenged. Therefore, it is model assumed that all three PORVs would be challenged if automatic reactor trip fails, even if the operator successfully trips the reactor as a backup.

- *Top Event RW.* This top event models the availability of the refueling water storage tank. The RWST must maintain its structural integrity, contain the minimum inventory required by technical specifications (i.e., 400,000 gallons), and be properly vented.
- *Top Event CH.* One of two centrifugal charging pumps starts automatically on a safety injection signal, taking suction from the RWST. High pressure flow from the charging pumps is used for either RCP seal injection or for reactor vessel makeup. The analysis for Top Event CH considers the flow paths

through the boron injection tank to the RCS cold legs. Cooling of the RCP seals is considered in Top Event SE.

No credit is given to the positive displacement charging pump for RCS injection because it has limited capacity and is not normally operated. The positive displacement pump is considered in Top Event SE, however, for seal injection.

- *Top Event SI.* This top event models the safety injection pumps starting automatically on a safety injection signal to provide injection to the RCS. At least one of two pumps starts and operates, taking suction from the RWST. This top event is asked, even if Top Event CH is successful, to determine whether two high pressure recirculation paths from the discharge of the RHR pumps are available in the long-term.
- *Top Event FW.* No credit is given for cooling through the normal feedwater system.
- *Top Event RP.* The reactor coolant pumps should continue to run unless CCW has failed, power is lost to the 12-kV buses, or the operator is instructed to turn them off by procedures. The operator action to turn them off is included in this action. Success of Top Event RP means the pumps are running. Failure of Top Event RP means all four pumps are off, and natural circulation cooling is necessary. The operator is instructed to turn the pumps off if (1) there is no secondary cooling (2) a Phase B safety injection signal has occurred, or (3) if RCS pressure is less than 1,275 psig due to an uncontrolled depressurization and at least one safety injection or centrifugal charging pump is running. If CCW cooling to header C is lost and the positive displacement charging pump is initially providing RCP seal injection, the operators must stop the RCPs within 5 minutes to prevent damage to the pump's seals and maintain the RCS boundary. This action is modeled in Top Event RP. Except for loss of CCW, it is assumed for this analysis that the procedural actions to trip the

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RCPs are successful, since natural circulation cooldown is then required.

- *Top Event SE.* This top event models RCP seal integrity. If CCW flow to headers A and B is successful, RCP pump thermal barrier cooling is also assumed successful if flow through CCW header C continues. Therefore, if CCW flow to headers A and B is successful, Top Event SE models the availability of cooling to header C of the CCW system.

If a Phase B safety injection signal occurs (for example, due to a steam line break inside containment), CCW flow to header C is isolated, which isolates cooling to the positive displacement charging pump and RCP thermal barrier cooling. Then, Top Event SE can only be successful if the operators successfully stop the RCPs in time; that is, Top Event RP is successful. Then to protect the RCP seals, the operator must use one of the centrifugal charging pumps. The seal injection path from the charging pumps is then modeled in this top event. If CCW header C is isolated, Top Event CH must have succeeded for this path to be viable.

For success without any CCW cooling, the operators must provide alternate cooling from the fire main to a charging pump heat exchangers for RCP seal injection as described in plant procedures. The pump suction may be from either the VCT or the RWST. A makeshift system for temporary cooling of the positive displacement charging pump (that is, wet rags and portable fans) could also be established, although such actions are not currently covered by procedures.

This top event is not asked in the event tree if Top Event PR fails (that is, a PORV opened and failed to reseat) because a LOCA is then already known to have occurred. The consequential failure of the RCP seals is judged to be unimportant.

- *Top Event OB.* This top event represents the operators initiating bleed and feed cooling, provided all secondary cooling fails, by

manually initiating safety injection signal, then resetting it, and by restoring instrument air to the containment. This cooling path also requires that at least two PORVs are available and are held open for 6 hours; that is, the time it takes to reduce RCS pressure to allow closed loop RHR cooling. The operator also trips the RCPs by procedure. Cooling through the pressurizer safety valves alone, without the PORVs, is assumed unsuccessful because of insufficient makeup flow at their pressure relief setpoint. The procedural actions to open the reactor vessel head vents and depressurize one steam generator to atmospheric pressure, if only two PORV trains are available, are assumed unnecessary. Only two PORVs are connected to a nitrogen supply header supplied by backup nitrogen accumulators. Instrument air must be restored to the containment for operation of the third PORV. The PORVs are qualified for the environment after a steam line break inside the containment and therefore are expected to remain functional during bleed and feed sequences.

- *Top Event VI.* This top event models continued reactor vessel integrity following selected accident sequences, including bleed and feed, depressurization following loss of all AC power, or a sequence involving failure of both the turbine to trip and the MSIVs to close. The possibility that the operator may successfully reduce flow from the charging pumps and safety injection to minimize the PTS conditions posed by these sequences is also considered. For bleed and feed cooling, the operators are assumed to have stopped the RCPs, which minimizes the amount of mixing during ECCS injection. Failure of Top Event VI is assumed to result in a LOCA that cannot be mitigated; one for which the ECCS systems cannot maintain core cooling. Therefore, core damage is assumed if Top Event VI fails.
- *Top Event HS.* This top event models whether hot standby conditions can be maintained successfully. If Top Events HS fails, it is assumed that long-term actions to control AFW, provide AFW makeup, or establish

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closed loop RHR cooling have failed and damage has occurred. There is plenty of time for a successful operator response if something does go wrong in the long-term after conditions have stabilized. Plant operations may decide to cooldown to cold shutdown conditions or to return to power after the cause of the Plant trip is identified and resolved. This analysis assumes that they would only attempt to cool down to cold shutdown if a LOCA is in progress. If a LOCA is not in progress, the Plant would return to power from hot standby.

If all vital instrumentation power is lost as a result of a failure of the 480-V switchgear ventilation system or seismic failure of the inverters, core damage is then assumed.

General Transient Late Event Trees. Those events that are not modeled in the early tree are modeled in late trees described in this section. The late trees are combined with the sequences through the early tree and the support model event trees to form a complete sequence through the plant model. Each sequence through the early tree is then assigned to one of the late trees described in this section.

The top event definitions and success criteria for the LT1, LT2, and LT3 trees are not described in this summary.

LT1 Event Tree. The LT1 late tree models the long-term events, including recirculation and containment systems, for those sequences in the early tree in which a small LOCA has occurred, either as the initiator or as a consequence of the sequence of events, and the charging or safety injection pumps function to initially control RCS inventory. For these sequences, the LT1 tree determines if the cold leg recirculation path is successfully established.

If recirculation is not available, the LT1 tree questions whether closed-loop RHR or secondary cooling can successfully eliminate the need for cold leg recirculation. Cold leg recirculation is not necessary if the RCS leak rate is effectively stopped or if a continuous source of makeup,

together with secondary cooling or closed-loop RHR cooling, maintains RCS inventory.

If the cooling paths mentioned above are unsuccessful and core damage occurs, the LT1 tree then questions whether containment heat removal, radioactivity removal, and containment isolation are successful.

If the containment is successfully isolated or if, at least, there are no leak areas greater than 3 inches in diameter, successful fission product removal is provided by containment spray recirculation via the RHR pumps. If the containment fails to isolate and the leak area is greater than 3 inches in diameter, both automatic containment spray injection initiated at the time of vessel melt-through and long-term containment spray recirculation using flow from the RHR pumps are assumed to be required for successful fission product removal. However, with such a large hole in the containment (that is, from 10 inches to 30 inches in diameter), containment pressure is not expected to reach the 22-psig setpoint for containment spray actuation. Therefore, in the assignment of plant damage states, fission product removal is assumed unavailable if a large leak path through the containment is not isolated.

LT2 Event Tree. The LT2 late tree is transferred to from the early tree if a LOCA has occurred, but high pressure injection fails because the RWST is not available. For these sequences, core damage is assured, and the RHR pumps would not have sufficient water for recirculation after melt. Consequently, the LT2 late tree is substantially simpler than the LT1 tree. The LT2 tree determines whether the containment fan coolers operate to provide containment heat and radioactivity removal and whether the containment isolates.

LT3 Event Tree. The early tree transfers to the LT3 event tree whenever core damage is assured because of a failure to provide high pressure injection with the RWST available. Failure of high pressure injection may result from a failure of both the charging pumps and the safety injection pumps, from an operator error (that is, failure of Top Event OB or HS in the early tree), or from loss of reactor vessel integrity (that is, Top Event

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VI fails in the early tree. The LT3 tree determines whether containment heat removal, radioactivity removal, and containment isolation are successful. Containment heat removal and radioactivity removal may be provided by either the containment fan coolers or by low pressure recirculation from the sump and containment spray.

Seismic Event Trees. The occurrence of a seismic event could initiate a sequence at Diablo Canyon, such as causing turbine trip, which, in turn, results in a demand for reactor trip. A review of the fragilities and the failure modes indicate that some failures can cause a general transient and some a LOCA and, therefore, a number of varied system responses may be called on to mitigate the possible scenarios.

The event trees that closely model the course of scenarios initiated by turbine trip are the support systems and general transient early and late frontline trees. Their development was discussed previously. However, the structure of the early frontline tree was modified to incorporate additional events and to be able to ask additional questions. As seen on Figure 6-47, the seismic early frontline tree has the following added events:

- **ID.** Represents a loss of indications to the operators, and this is assumed to lead directly to core damage.
- **CT.** Represents the summation of all relay chatter fragilities resulting in a loss of all AC power.
- **EL.** This is the summation of all LOCAs greater than a small LOCA. Such LOCAs are all conservatively assumed to be excessive, that is, modeled as if the ECCS systems are not effective at mitigating them.
- **TD.** Represents the turbine-driven AFW pump in order to ask if, under the condition of relay chatter causing loss of the motor-driven AFW pump, the turbine-driven AFW pump is operational. Failure of all AFW shortens the time available for successful recovery from relay chatter.

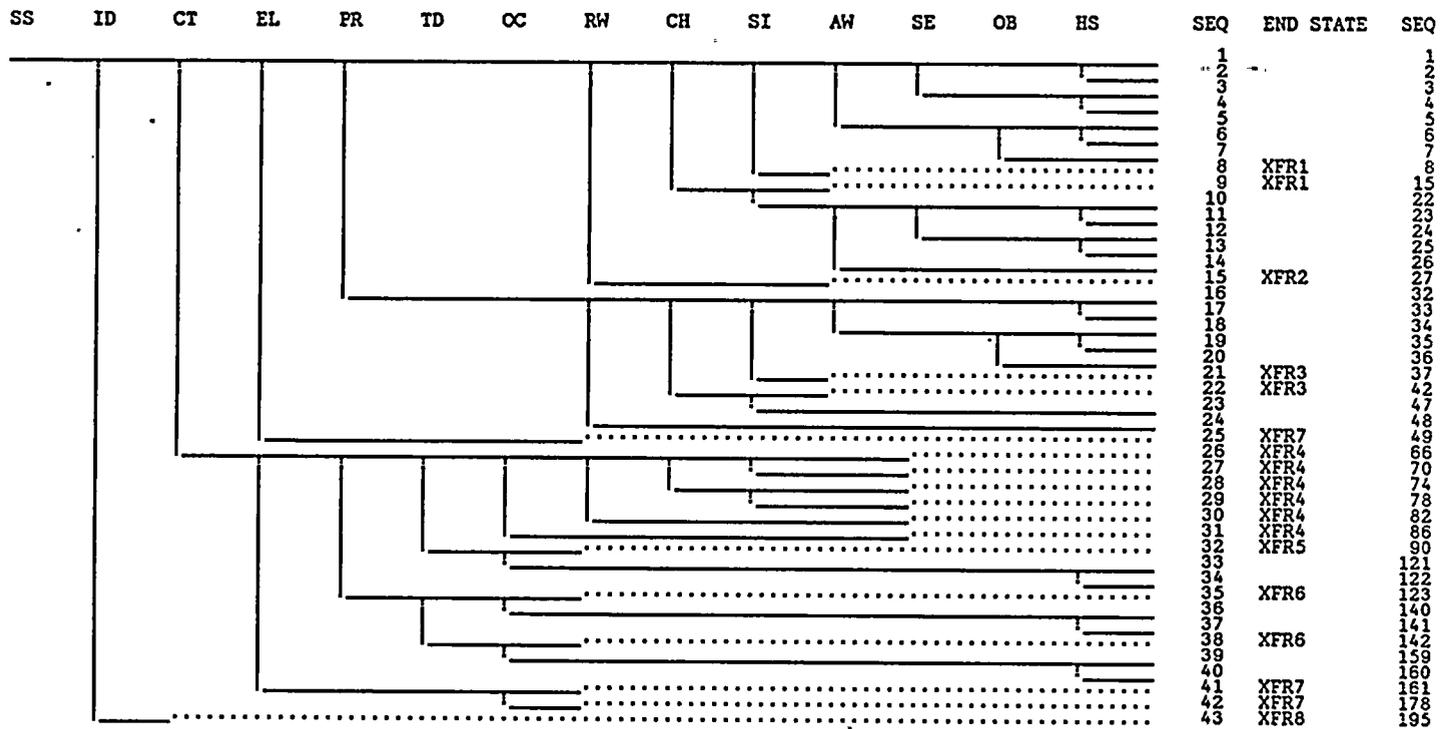
- **OC.** Represents operator recovery from relay chatter. This event is only asked if Top Event CT fails. Different human error rates are used depending on the status of auxiliary feedwater and whether a LOCA has occurred. Failure of this event is assumed to result in a continued loss of all vital AC.

SYSTEM ANALYSES

The Plant frontline systems are standard for most Westinghouse pressurized water reactors, except for the Plant-specific auxiliary feedwater system. The support systems, except for solid state protection systems and reactor trip, are specific to Diablo Canyon. In contrast with other designs, with Diablo Canyon systems are designed with more intertrain, intersystem, and interunit crossies. These crossies make system operation more flexible and tend to give operators more options to bypass failed components or systems. For instances, control power for each diesel generator is supplied from two different batteries through a manual transfer switch, thereby ensuring all diesels have control power to start even though one battery may have failed.

Table 6-36 lists the systems that were included in the model. As discussed previously, the Plant systems were analyzed as a series of top events modeled in the support or frontline event trees. The grouping of these top events into the various support or frontline systems is also given in Table 6-36. The definitions and success criteria of these top events can be found in the event sequence model section.

Each top event is evaluated under a set of boundary conditions. These boundary conditions are determined by the initiating event and successes and failures of the preceding top events in the particular sequence under considerations. For each boundary condition, a set of algebraic equations is developed to model the unavailability contributions from independent hardware failures, common cause failures, testing, maintenance, and human error. A separate split fraction is defined for the top event unavailability derived for each boundary condition. Table 6-37 provided the quantification results for all the top event split fractions. Also included in Table 6-37 are the



DEFINITION OF SUBTREES (TRANSFERS)

SUBTREE (XFR)	FIRST SEQUENCE	LAST SEQUENCE
1	1	7
2	10	14
3	16	20
4	1	4
5	1	15
6	16	24
7	16	24
8	1	42

Figure 6-47

Seismic early frontline event tree.

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Table 6-36
SCOPE OF SYSTEMS ANALYSES

	System	Top Event
Support Systems	Nonvital electric power	OG, NV
	Vital 125V DC power, Unit 1	DF, DG, DH
	Vital AC power, Unit 1	AF, AG, AH, SF, SG, SH
	Vital AC and DC power, Unit 2	BF, BG, BH
	Diesel generators	GF, GG, GH, 2G, 2H, SW
	Diesel fuel oil transfer	F0
	Instrument AC power	I1, I2, I3, I4
	Solid state protection system	SA, SB
	Reactor protection system	RT
	Control room ventilation	CV
	480V switchgear ventilation	SV
	Auxiliary saltwater	AS
	Component cooling water	CC
	Instrument air	IA
Frontline Systems	Turbine trip and main steam isolation	TT, MS
	Auxiliary feedwater system	AW, TD
	Primary RCS pressure relief	PR, PO, OB
	ECCS, high pressure	CH, SI, HR, RC, RF
	ECCS, low pressure	LA, LB, LV, RW, VA, VB, AC, LI, MU
	Containment fan cooling units	FC
	Containment spray	CS, SR
	Containment isolation	CI, CP, WL
	Top event for SGTR tree	SL
	Top events for interfacing LOCA	VD, VS, VO, VC, VR, IT, LW, ME, SM, OT
	Miscellaneous	OS, CD, FW, SE, VI, RP, OI, OP, OE, HS, RS, PL, MC, SS, OD

Table 6-37

SYSTEM SPLIT FRACTION QUANTIFICATION FOR NONSEISMIC INITIATING EVENTS

CSF	BOUNDARY CONDITION	MEAN	5TH XILE	MEDIAN	95TH XILE
SUPPORT SYSTEMS					
SPLIT FRACTIONS FOR TOP EVENT OG					
OG1	Given Offsite Grid success.	7.63E-04	4.20E-04	5.78E-04	1.35E-03
OGF	Given Offsite Grid fails (guaranteed failure OG).	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT NV					
NV1	Given all support available.	1.63E-04	2.60E-05	1.03E-04	3.76E-04
NV2	Given DC 13 or DC 12 failed and OG succeeded.	2.46E-03	8.29E-04	1.87E-03	4.60E-03
NVF	Given DC 13 and DC 12 failed or, OG failed.	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT DF					
DF1	480 V vital bus 1F available.	7.05E-04	2.28E-04	5.56E-04	1.36E-03
SPLIT FRACTIONS FOR TOP EVENT DG					
DG1	480 V vital bus 1G available, DF succeeded.	7.05E-04	2.28E-04	5.56E-04	1.36E-03
DG2	480 V vital bus 1G available, DF failed.	7.02E-04	2.26E-04	5.53E-04	1.35E-03
DGF	Guaranteed failure.	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT DH					
DH1	480 V 1H available, DF-S, DG-S	7.00E-04	2.24E-04	5.51E-04	1.35E-03
DH2	480 V 1H available, DF-S, DG-F	6.98E-04	2.22E-04	5.49E-04	1.35E-03
DH3	480 V 1H available, DF-F, DG-S	6.98E-04	2.22E-04	5.49E-04	1.35E-03
DH4	480 V 1H available, DF-F, DG-F	6.96E-04	2.20E-04	5.47E-04	1.35E-03
SPLIT FRACTIONS FOR TOP EVENT AF					
AF1	All support available with recovery.	6.92E-04	1.34E-04	4.43E-04	1.40E-03
AFA	All support available no recovery.	7.40E-04	1.63E-04	4.91E-04	1.45E-03
AFF	Guaranteed failure.	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT AG					
AG1	DF-S, AF-S with recovery	6.92E-04	1.34E-04	4.43E-04	1.40E-03
AG2	DF-S, AF-F with recovery	8.37E-04	1.94E-04	5.63E-04	1.70E-03
AG3	DF-F with recovery	6.92E-04	1.34E-04	4.43E-04	1.40E-03
AGA	DF-S, AF-S no recovery	7.13E-04	1.47E-04	4.66E-04	1.42E-03
AGB	DF-S, AF-F no recovery	5.18E-02	3.92E-03	2.57E-02	1.48E-01
AGC	DF-F no recovery	7.40E-04	1.63E-04	4.91E-04	1.45E-03
AGF	GUARANTEED FAILURE	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT AH					
AH1	DF-S, DG-S, AF-S, AG-S with recovery	6.92E-04	1.34E-04	4.43E-04	1.40E-03
AH2	DF-S, DG-S, AF-S, AG-F, or DF-S, DG-S, AF-F, AG-S w.r.	8.01E-04	1.80E-04	5.32E-04	1.63E-03
AH3	DF-S, DG-S, AF-F, AG-F with recovery	4.72E-02	9.06E-04	7.96E-03	1.71E-01
AH4	DF-S, DG-F, AF-S or DF-F, DG-S, AG-S with recovery	6.92E-04	1.34E-04	4.43E-04	1.40E-03
AH5	DF-S, DG-F, AF-F or DF-F, DG-S, AG-F with recovery	8.37E-04	1.94E-04	5.63E-04	1.70E-03
AH6	DF-F, DG-F with recovery	6.92E-04	1.34E-04	4.43E-04	1.40E-03
AHA	DF-S, DG-S, AF-S, AG-S no recovery	6.92E-04	1.34E-04	4.43E-04	1.40E-03
AHB	DF-S, DG-S, AF-S, AG-F, or DF-S, DG-S, AF-F, AG-S n.r.	4.42E-02	1.16E-03	1.52E-02	1.37E-01
AHC	DF-S, DG-S, AF-F, AG-F no recovery	3.03E-01	6.28E-03	1.70E-01	8.17E-01
AHD	DF-S, DG-F, AF-S or DF-F, DG-S, AG-S no recovery	7.13E-04	1.47E-04	4.66E-04	1.42E-03
AHE	DF-S, DG-F, AF-F or DF-F, DG-S, AG-F no recovery	5.18E-02	3.92E-03	2.57E-02	1.48E-01
AHG	DF-F, DG-F no recovery	7.40E-04	1.63E-04	4.91E-04	1.45E-03
AHF	GUARANTEED FAILURE	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT SF					
SF1	All support available with recovery.	1.60E-03	3.51E-04	1.15E-03	3.11E-03
SFA	All support available no recovery.	1.71E-03	4.34E-04	1.24E-03	3.22E-03
SPLIT FRACTIONS FOR TOP EVENT SG					
SG1	SF-S with recovery	1.60E-03	3.51E-04	1.15E-03	3.11E-03
SG2	SF-F with recovery	1.74E-03	4.70E-04	1.24E-03	3.30E-03
SG3	SF-B with recovery	1.60E-03	3.51E-04	1.15E-03	3.11E-03
SGA	SF-S no recovery	1.65E-03	3.92E-04	1.19E-03	3.15E-03
SGB	SF-F no recovery	5.31E-02	6.81E-03	3.08E-02	1.36E-01
SGC	SF-B no recovery	1.71E-03	4.34E-04	1.24E-03	3.22E-03
SPLIT FRACTIONS FOR TOP EVENT SH					
SH1	SF-S, SG-S with recovery	1.60E-03	3.51E-04	1.15E-03	3.11E-03
SH2	SF-S, SG-F or SF-F, SG-S with recovery	1.70E-03	4.35E-04	1.21E-03	3.24E-03
SH3	SF-F, SG-F with recovery	3.03E-02	1.54E-03	6.44E-03	9.56E-02
SH4	SF-S, SG-B or SF-B, SG-S with recovery	1.60E-03	3.51E-04	1.15E-03	3.11E-03
SH5	SF-F, SG-B or SF-B, SG-F with recovery	1.74E-03	4.70E-04	1.24E-03	3.30E-03
SH6	SF-B, SG-B with recovery	1.60E-03	3.51E-04	1.15E-03	3.11E-03
SHA	SF-S, SG-S no recovery	1.60E-03	3.51E-04	1.15E-03	3.11E-03
SHB	SF-S, SG-F or SF-F, SG-S no recovery	4.42E-02	2.24E-03	2.07E-02	1.23E-01
SHC	SF-F, SG-F no recovery	2.90E-01	1.34E-02	1.83E-01	7.59E-01
SHD	SF-S, SG-B or SF-B, SG-S no recovery	1.65E-03	3.92E-04	1.19E-03	3.15E-03

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Table 6-37 (Continued)

CSF	BOUNDARY CONDITION	MEAN	5TH XILE	MEDIAN	95TH XILE
SHE	SF-F, SG-B or SF-B, SG-F no recovery	5.31E-02	6.81E-03	3.08E-02	1.36E-01
SHG	SF-B, SG-B no recovery	1.71E-03	4.34E-04	1.24E-03	3.22E-03
SPLIT FRACTIONS FOR TOP EVENT BF					
BF1	OG-F	1.44E-03	5.56E-04	1.14E-03	2.67E-03
SPLIT FRACTIONS FOR TOP EVENT BG					
BG1	OG-F, BF-S	1.44E-03	5.56E-04	1.14E-03	2.67E-03
BG2	OG-F, BF-F	1.49E-03	6.07E-04	1.18E-03	2.73E-03
SPLIT FRACTIONS FOR TOP EVENT BH					
BH1	OG-F, BF-S, BG-S	1.44E-03	5.56E-04	1.14E-03	2.67E-03
BH2	OG-F, BF-S, BG-F or OG-F, BF-F, BG-S	1.48E-03	5.96E-04	1.17E-03	2.71E-03
BH3	OG-F, BF-F, BG-F	1.19E-02	1.13E-03	3.14E-03	3.31E-02
SPLIT FRACTIONS FOR TOP EVENT CF					
CF1	All support available.	4.52E-02	2.90E-02	4.18E-02	6.28E-02
SPLIT FRACTIONS FOR TOP EVENT CG					
CG1	GF-S	4.48E-02	2.85E-02	4.13E-02	6.24E-02
CG2	GF-F	5.56E-02	3.91E-02	5.23E-02	7.33E-02
CG3	GF-B	4.52E-02	2.90E-02	4.18E-02	6.28E-02
SPLIT FRACTIONS FOR TOP EVENT CH					
CH1	GF-S, GG-S	4.44E-02	2.82E-02	4.09E-02	6.20E-02
CH2	GF-S/F, GG-F/S	5.41E-02	3.75E-02	5.08E-02	7.17E-02
CH3	GF-F, GG-F	8.27E-02	6.00E-02	7.72E-02	1.11E-01
CH4	GF-S/B, GG-B/S	4.48E-02	2.85E-02	4.13E-02	6.24E-02
CH5	GF-F/B, GG-B/F	5.56E-02	3.91E-02	5.23E-02	7.33E-02
CH6	GF-B, GG-B	4.52E-02	2.90E-02	4.18E-02	6.28E-02
SPLIT FRACTIONS FOR TOP EVENT 2G					
2G1	GF-S, GG-S, GH-S	4.40E-02	2.77E-02	4.05E-02	6.16E-02
2G2	GF-S/S/F, GG-S/F/S, GH-F/S/S	5.36E-02	3.70E-02	5.03E-02	7.14E-02
2G3	GF-S/F/F, GG-F/F/S, GH-F/S/F	6.25E-02	4.62E-02	5.95E-02	7.91E-02
2G4	GF-F, GG-F, GH-F	2.90E-01	1.28E-01	2.48E-01	5.02E-01
2G5	GF-S/S/B, GG-S/B/S, GH-B/S/S	4.44E-02	2.82E-02	4.09E-02	6.20E-02
2G6	GF-S/S/F/F/B/B, GG-F/B/S/S/S/F, GH-B/F/S/B/F/S	5.41E-02	3.75E-02	5.08E-02	7.17E-02
2G7	GF-F/F/B, GG-F/B/F, GH-B/F/F	8.27E-02	6.00E-02	7.72E-02	1.11E-01
2G8	GF-S/B/B, GG-B/S/B, GH-B/B/S	4.48E-02	2.85E-02	4.13E-02	6.24E-02
2G9	GF-F/B/B, GG-B/F/B, GH-B/B/F	5.56E-02	3.91E-02	5.23E-02	7.33E-02
2GA	GF-B, GG-B, GH-B	4.52E-02	2.90E-02	4.18E-02	6.28E-02
SPLIT FRACTIONS FOR TOP EVENT 2H					
2H1	GF-GG&GH-2G:SS&SS	4.36E-02	2.73E-02	4.01E-02	6.12E-02
2H2	GF-GG&GH-2G:SS&SF/FS, SF/FS&SS	5.32E-02	3.64E-02	4.99E-02	7.12E-02
2H3	GF-GG&GH-2G:FS/SF&SF/FS, SS&FF, FF&SS	6.21E-02	4.59E-02	5.90E-02	7.86E-02
2H4	GF-GG&GH-2G:SF/FS&FF, FF&SF/FS	6.92E-02	5.21E-02	6.62E-02	8.69E-02
2H5	GF-GG&GH-2G:FF&FF	7.73E-01	4.25E-01	7.95E-01	9.39E-01
2H6	GF-GG&GH-2G:SS&SB/BS, SB/BS&SS	4.40E-02	2.77E-02	4.05E-02	6.16E-02
2H7	GF-GG&GH-2G:SF/FS&SB/BS, SB/BS&FS/SF, FB/BF&SS, SS&FB/BF	5.36E-02	3.70E-02	5.03E-02	7.14E-02
2H8	GF-GG&GH-2G:SF/FS&FB/BF, FB/BF&SF/FS, BS/SB&FF, FF&SB/BS	6.25E-02	4.62E-02	5.95E-02	7.91E-02
2H9	GF-GG&GH-2G:FF&FB/BF, FB/BF&FF	2.90E-01	1.28E-01	2.48E-01	5.02E-01
2HA	GF-GG&GH-2G:SB/BS&BS/BS, SS&BB, BB&SS	4.44E-02	2.82E-02	4.09E-02	6.20E-02
2HB	GF-GG&GH-2G:BF/FB&SB/BS, BS/SB&FB/BF, FS/SF&BB, BB&FS/SF	5.41E-02	3.75E-02	5.08E-02	7.17E-02
2HC	GF-GG&GH-2G:FB/BF&BF/FB, FF&BB, BB&FF	8.27E-02	6.00E-02	7.72E-02	1.11E-01
2HD	GF-GG&GH-2G:SB/BS&BB, BB&SB/BS	4.48E-02	2.85E-02	4.13E-02	6.24E-02
2HE	GF-GG&GH-2G:FB/BF&BB, BB&FB/BF	5.56E-02	3.91E-02	5.23E-02	7.33E-02
2HG	GF-GG&GH-2H:BB&BB	4.52E-02	2.90E-02	4.18E-02	6.28E-02
SPLIT FRACTIONS FOR TOP EVENT SW					
SW0	All branch points for LOCA initiating event.	0.00E-01	0.00E-01	0.00E-01	0.00E-01
SW1	LOSP with equal number of DG operating on each unit.	5.00E-01	2.50E-02	2.50E-01	4.75E-01
SW2	LOSP with more DGs aligned to unit 2 than unit 1.	1.77E-03	9.55E-05	7.30E-04	6.82E-03
SW3	LOSP with more DGs aligned to unit 1 than unit 2.	9.98E-01	9.93E-01	9.98E-01	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT FO					
FO1	All support available.	2.16E-04	4.28E-05	1.40E-04	5.29E-04
FO2	Support available to one train only.	7.04E-03	3.49E-03	6.33E-03	1.11E-02
FO3	1/2 normal support unavailable, recover backup.	3.51E-04	1.02E-04	2.70E-04	7.18E-04
FO4	2/2 normal support unavailable, recover backups.	2.26E-02	5.70E-03	1.67E-02	4.90E-02
FO5	2/2 normal and 1/2 backup support unavail., rec. backup	5.08E-02	1.73E-02	3.95E-02	1.01E-01
FOF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT I1					
I11	Given: DF-S,AF-S,AG-S or DF-S,AF-F,AG-S.	1.15E-03	4.16E-04	9.05E-04	2.11E-03
I12	Given: DF-S,AF-S,AG-F or DF-S,AF-F,AG-F.	1.74E-03	7.16E-04	1.49E-03	3.01E-03
I1F	Given: DF-F (guaranteed failure).	1.00E+00	1.00E+00	1.00E+00	1.00E+00

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Table 6-37 (Continued)

CSF	BOUNDARY CONDITION	MEAN	5TH XILE	MEDIAN	95TH XILE
SPLIT FRACTIONS FOR TOP EVENT I2					
I21	Given: AG-S.	5.76E-04	2.08E-04	4.53E-04	1.05E-03
I22	Given: DG-S, AG-F.	8.68E-04	3.58E-04	7.43E-04	1.51E-03
I23	Given: AG-S, I1-F	5.76E-04	2.08E-04	4.53E-04	1.05E-03
I24	Given: DG-S, AG-F, I1-F	8.68E-04	3.58E-04	7.43E-04	1.51E-03
I2F	Given: DG-F (guaranteed failure).	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT I3					
I31	Given: DH-S,AH-S,AG-S or DH-S,AH-F,AG-S.	1.15E-03	4.16E-04	9.05E-04	2.11E-03
I32	Given: DH-S,AH-S,AG-F or DH-S,AH-F,AG-F.	1.74E-03	7.16E-04	1.49E-03	3.01E-03
I3F	Given: DH-F (guaranteed failure).	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT I4					
I41	Given: DG-S,AH-S,AG-S, or DG-S,AH-F,AG-S.	5.76E-04	2.08E-04	4.53E-04	1.05E-03
I42	Given: DG-F,AH-S or AG-F,DG-S,(AH-S or AH-F)	8.68E-04	3.58E-04	7.43E-04	1.51E-03
I4F	Given: DG-F, AH-F (guaranteed failure).	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT SA					
SA1	General Transient	7.58E-03	2.62E-03	5.43E-03	1.55E-02
SA2	Large Loss of Coolant Accident All 4 Channels Available	1.14E-02	3.82E-03	8.02E-03	2.40E-02
SA3	LLOCA with loss of power to two CP H-H channels (not I)	1.78E-02	6.71E-03	1.39E-02	3.49E-02
SA4	Steam Generator Tube Rupture	1.19E-02	3.61E-03	8.11E-03	2.56E-02
SA5	Steam Line Break Inside Containment All 4 Channels Availb	1.40E-02	4.46E-03	9.72E-03	2.96E-02
SA6	SLBIC with loss of power to two CP H-H channels (not I)	2.04E-02	7.59E-03	1.58E-02	3.96E-02
SA7	Steam Line Break Outside Containment	1.19E-02	3.61E-03	8.11E-03	2.56E-02
SA8	Small Loss of Coolant Accident	1.19E-02	3.61E-03	8.11E-03	2.56E-02
SAF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT SB					
SB1	GT given Train A success	7.48E-03	2.58E-03	5.32E-03	1.54E-02
SB2	GT given Train A failure	2.40E-02	5.32E-03	1.58E-02	5.63E-02
SB3	GT given AC I unavailable (same as SA1)	7.58E-03	2.62E-03	5.43E-03	1.55E-02
SB4	LLOCA given Train A success, all AC channels available	1.08E-02	3.33E-03	7.37E-03	2.32E-02
SB5	LLOCA given Train A success, AC II&III unavailable	1.09E-02	3.35E-03	7.42E-03	2.33E-02
SB6	LLOCA given Train A failure, all AC channels available	8.43E-02	2.11E-02	7.39E-02	1.53E-01
SB7	LLOCA given Train A failure, AC II&III unavailable	4.10E-01	1.22E-01	3.65E-01	7.19E-01
SB8	LLOCA given AC I and II(or III)unavailable (same as SA3)	1.78E-02	6.71E-03	1.39E-02	3.49E-02
SB9	SGTR given Train A success	1.17E-02	3.50E-03	7.86E-03	2.53E-02
SBA	SGTR given Train A failure	3.55E-02	6.54E-03	2.27E-02	8.65E-02
SBB	SGTR given AC I unavailable (same as SA4)	1.19E-02	3.61E-03	8.11E-03	2.56E-02
SBC	SLBIC given Train A success, all AC channels available	1.34E-02	3.95E-03	9.06E-03	2.89E-02
SBD	SLBIC given Train A success, AC II&III unavailable	1.35E-02	3.97E-03	9.12E-03	2.91E-02
SBE	SLBIC given Train A failure, all AC channels available	7.43E-02	1.88E-02	6.48E-02	1.36E-01
SBC	SLBIC given Train A failure, AC II&III unavailable	3.71E-01	1.03E-01	3.22E-01	6.79E-01
SBH	SLBIC given AC I and II(or III)unavailable (same as SA6)	2.04E-02	7.59E-03	1.58E-02	3.96E-02
SBI	SLBOC given Train A success	1.17E-02	3.50E-03	7.86E-03	2.53E-02
SBJ	SLBOC given Train A failure	3.49E-02	6.07E-03	2.20E-02	8.60E-02
SBK	SLBOC given AC I unavailable (same as SA7)	1.19E-02	3.61E-03	8.11E-03	2.56E-02
SBL	SLOCA given Train A success	1.17E-02	3.50E-03	7.86E-03	2.53E-02
SBM	SLOCA given Train A failure	3.49E-02	6.07E-03	2.20E-02	8.60E-02
SBN	SLOCA given AC I unavailable (same as SA8)	1.19E-02	3.61E-03	8.11E-03	2.56E-02
SBF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT RT					
RT1	1/2 Trains (both SSPS signals generated)	6.58E-06	3.57E-08	5.17E-07	1.30E-05
RT2	1/2 Trains (DC power lost to one shunt trip)	6.59E-06	3.76E-08	5.28E-07	1.30E-05
RT3	1/2 Trains (DC power lost to both shunt trip coils)	7.24E-06	8.49E-08	8.59E-07	1.44E-05
RT4	1/1 Train (only one SSPS signal generated)	1.60E-05	6.13E-07	4.70E-06	4.49E-05
RT5	1/1 Train (one SSPS signal, LOP to shunt trip coil)	2.10E-05	8.62E-07	6.57E-06	6.37E-05
RT6	Gravity Insertion (insufficient power to prevent insert)	6.30E-06	5.60E-09	3.33E-07	1.25E-05
RT7	Operator initiated (DC power lost to both shunt coils)	1.93E-03	1.16E-04	7.74E-04	5.82E-03
RTF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT CV					
CV1	1/2 subtrains: All support available (OSP,2F,1G,1H,2H)	7.60E-04	2.15E-04	4.68E-04	1.36E-03
CV2	1/2 subtrains: Normal power for subtrain F unavail. (2F)	2.06E-02	6.81E-03	1.59E-02	4.24E-02
CV3	1/1 subtrain: No support for subtrain F (2F,1G)	5.68E-02	3.24E-02	5.11E-02	8.56E-02
CV4	1/1 subtrain: No support for subtrain H (1H,2H)	2.00E-02	8.56E-03	1.70E-02	3.34E-02
CV5	1/2 subtrains:LOSP, all vital buses avail. (2F,1G,1H,2H)	3.65E-03	1.63E-03	3.07E-03	5.99E-03
CV6	1/1 subtrains:LOSP, no support for subtrain H (1H,2H)	3.88E-02	2.21E-02	3.51E-02	5.60E-02
CVF	Guaranteed Failure: 480V 2F,1G,1H,2H unavailable	1.00E+00	1.00E+00	1.00E+00	1.00E+00
LOCV	Initiating Event frequency for 1 year	7.98E-02	3.56E-02	6.64E-02	1.35E-01

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Table 6-37 (Continued)

SYSTEM SPLIT FRACTION QUANTIFICATION FOR NONSEISMIC INITIATING EVENTS

CSF	BOUNDARY CONDITION	MEAN	5TH XILE	MEDIAN	95TH XILE
SPLIT FRACTIONS FOR TOP EVENT SV					
SV1	1/2 trains; OSP, 480V 1F,1H available	1.70E-06	4.70E-08	4.92E-07	5.47E-06
SV2	1/1 train start and run; 480V Bus 1F unavailable	1.80E-04	5.05E-06	4.99E-05	5.69E-04
SV3	1/1 train continue to run; 480 V Bus 1H unavail.	1.33E-04	3.02E-06	3.40E-05	4.17E-04
SV4	1/2 trains start and run; LO SP, 480V Bus 1F,1H availab.	2.57E-05	8.14E-07	7.84E-06	7.93E-05
SV5	Only recovery possible, Bus 1F,1H unavailable	5.62E-03	2.38E-04	1.78E-03	2.17E-02
SVF	Guaranteed failed, all inverters already failed	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SVI	Initiating Event frequency for 1 year	6.29E-05	4.56E-07	9.12E-06	2.02E-04
SVO	Station Blackout, guaranteed success.	0.00E-01	0.00E-01	0.00E-01	0.00E-01
SPLIT FRACTIONS FOR TOP EVENT AS					
AS1	All Pump Trains Available: 2 Running, 2 Standby (OP1)	1.85E-06	3.74E-07	1.14E-06	4.17E-06
AS2	3 Pump Trains Available: Fail Train 11 (OP2)	3.55E-04	1.69E-04	3.10E-04	5.84E-04
AS3	3 Pump Trains Available: Fail Train 12 (OP1)	1.22E-04	4.38E-05	9.62E-05	2.34E-04
AS4	2 Pump Trains Available: Fail Trains 11 and 12 (OP2)	1.69E-02	6.58E-03	1.33E-02	3.16E-02
AS5	LOSP: 3 Pump Trains Available: Fail Train 11 (OP2)	3.58E-04	1.71E-04	3.13E-04	5.88E-04
AS6	LOSP: 3 Pump Trains Available: Fail Train 21 (OP1)	7.86E-06	3.04E-06	6.30E-06	1.47E-05
AS7	LOSP: 2 Pump Trains Available: Fail Trains 11 & 12 (OP2)	1.69E-02	6.66E-03	1.34E-02	3.17E-02
AS8	LOSP: 2 Pump Trains Available: Fail 11 & 21(or 22) (OP2)	4.71E-04	2.43E-04	4.12E-04	7.54E-04
AS9	LOSP: 2 Pump Trains Available: Fail Trains 12 & 21 (OP1)	2.74E-04	1.02E-04	2.13E-04	5.30E-04
ASA	LOSP: 2 Pump Trains Available: Fail Trains 21 & 22 (OPF)	1.83E-04	7.00E-05	1.52E-04	3.39E-04
ASB	LOSP: 1 Pump Train Available: Fail 11,12 & 21(or 22) (OP2)	2.70E-02	1.54E-02	2.37E-02	4.22E-02
ASC	LOSP: 1 Pump Train Available: Fail 11(or 12),21 & 22(OPF)	1.07E-02	6.68E-03	9.68E-03	1.57E-02
ASI	Loss of ASW Supply to Unit 1 Initiating Event Frequency	9.73E-05	2.47E-05	6.23E-05	1.97E-04
ASF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT CC					
CC1	All Support Available(N/3 pumps starts and/or runs)	1.88E-05	5.69E-06	1.31E-05	4.33E-05
CC2	Loss of 4KV Bus H (N/2 pumps runs)	5.69E-04	2.25E-04	4.79E-04	9.65E-04
CC3	Loss of 4KV Bus G (N/2 pumps starts and/or runs)	5.85E-04	2.32E-04	4.93E-04	9.99E-04
CC4	Loss of 4KV Buses G and H (1/1 pump runs)	2.67E-02	1.09E-02	2.07E-02	5.06E-02
CC5	Loss of 4KV Buses F and G (1/1 pump starts and runs)	2.87E-02	1.24E-02	2.27E-02	5.26E-02
CC6	LOSP - All Support Available(N/3 pumps starts and runs)	2.43E-05	8.65E-06	1.89E-05	4.89E-05
CC7	LOSP - Loss of one 4KV bus (N/2 pumps starts and runs)	6.63E-04	2.74E-04	5.55E-04	1.14E-03
CCI	Initiating Event Frequency (All pumps fail)	1.97E-04	3.05E-05	1.23E-04	4.84E-04
CCF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT IA					
IAF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
FRONTLINE SYSTEMS					
SPLIT FRACTIONS FOR TOP EVENT TT					
TT0	Turbine Trip - TT Initiator	0.00E-01	0.00E-01	0.00E-01	0.00E-01
TT1	Turbine Trip - All Support Available	1.55E-05	8.85E-07	5.20E-06	3.86E-05
TT2	Turbine Trip ATWT - All Support Available	3.27E-03	4.59E-04	1.84E-03	8.48E-03
TT3	Turbine Trip ATWT, Man. Rx trip - All Support	8.92E-03	6.22E-04	3.70E-03	2.58E-02
TT4	Turbine Trip - 1 Train of Support Avail.	2.98E-03	5.02E-04	1.67E-03	7.39E-03
TT5	Turbine Trip ATWT - 1 Train of Support Avail.	6.12E-03	1.44E-03	4.07E-03	1.38E-02
TT6	Turbine Trip ATWT, Man. Rx trip-1 Support Train	1.17E-02	1.79E-03	6.19E-03	3.16E-02
TTF	Turbine Trip - Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT MS					
MS0	Main Steam Isolation, TT failed, fire scenario 2	0.00E-01	0.00E-01	0.00E-01	0.00E-01
MS1	Main Steam Isolation, TT succeeds- All Support Avail.	7.51E-03	2.41E-03	6.13E-03	1.71E-02
MS2	MS Isolation - TT fails, All Support Avail.	1.00E+00	1.00E+00	1.00E+00	1.00E+00
MSF	MS Isolation - Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT AW					
AW1	All Support Sys Available, Lo Power	3.73E-05	8.78E-06	2.56E-05	8.10E-05
AW2	All Support Sys Available, Hi Power	1.17E-01	7.28E-02	1.07E-01	1.71E-01
AW3	Support for 1 MDP Unavail, Lo Power	1.24E-03	4.10E-04	9.65E-04	2.36E-03
AW4	Support for 2 MDP's Unavail, Lo Power	7.25E-02	3.73E-02	6.27E-02	1.18E-01
AW5	Support for All 10% Stm Dumps Unavail, Lo Power	3.30E-02	1.38E-05	2.10E-04	1.04E-01
AW6	Support for All 10% Stm Dumps Unavail, Hi Power	2.01E-01	7.86E-02	1.27E-01	5.31E-01
AW7	Support for All 10% SD's and TDP Unavail, Lo Power	3.50E-04	8.72E-05	2.23E-04	6.91E-04
AW8	Support for All 10% SD's and 1 MDP Unavail, Lo Power	8.00E-03	3.86E-04	9.39E-04	2.37E-03
AW9	Support for All 10% SD's and 2 MDP's Unavail, Lo Power	1.41E-01	4.34E-02	8.34E-02	3.70E-01
AWA	Support for All 10% SD's, 1 MDP & TDP Unavail, Lo Power	9.59E-02	1.66E-02	3.49E-02	3.28E-01
AWB	One SG depressurizes, All Support Sys Avail., Lo Power	2.41E-02	1.47E-02	2.21E-02	3.50E-02
AWC	ATWS; All Support Systems Available, TT Success	2.45E-03	7.98E-04	1.90E-03	4.69E-03
AWF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00

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Table 6-37 (Continued)

CSF	BOUNDARY CONDITION	MEAN	5TH XILE	MEDIAN	95TH XILE
SPLIT FRACTIONS FOR TOP EVENT TD					
TD1	Support for 2 MDP's Unavail., Seismic events	7.11E-02	3.68E-02	6.16E-02	1.16E-01
TD2	Support for all 10X SD's & 2 MDP's unavail., Seismic IE	1.41E-01	4.34E-02	8.34E-02	3.70E-01
TDF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT PR					
PRO	Guaranteed Success	0.00E-01	0.00E-01	0.00E-01	0.00E-01
PR1	1/2 PORV's or (1/3 SRV's), LOSP or SGTR	5.03E-04	5.26E-05	1.95E-04	9.51E-04
PR2	1/2 PORV's and 3/3 SRV's	1.00E-02	1.25E-03	4.86E-03	2.55E-02
PR3	2/2 PORV's and 3/3 SRV's	2.59E-02	6.45E-03	1.60E-02	5.75E-02
PR4	2/2 PORV's and 2/3 SRV's or(3/3 SRV'S)	8.86E-03	6.56E-04	3.76E-03	2.43E-02
PR5	1/2 PORV's or (1/3 SRV's), HPI or SLB	2.18E-05	1.24E-07	2.91E-06	4.51E-05
PR6	1/1 PORV or (1/3 SRV's), LOSP or SGTR	2.36E-04	3.49E-05	1.25E-04	5.33E-04
PR7	1/1 PORV and 3/3 SRV's	1.83E-02	3.95E-03	1.09E-02	4.15E-02
PR8	3/3 SRV's	9.45E-03	9.45E-04	4.42E-03	2.45E-02
PR9	1/1 PORV or (1/3 SRV's), HPI or SLB	2.92E-05	3.85E-07	6.19E-06	7.17E-05
PRA	1/3 SRV's	8.23E-03	3.44E-04	3.34E-03	2.32E-02
PRB	3/3 SRV's	9.31E-03	7.89E-04	4.28E-03	2.43E-02
PRC	1/3 SRV's	2.84E-03	3.18E-05	6.89E-04	8.47E-03
PRD	1/2 PORV's or (1/3 SRV's), LOSP/SGTR, no blk vlvs	4.88E-02	1.37E-02	3.81E-02	9.74E-02
PRE	1/2 PORV's and 3/3 SRV's blk vlvs not avail.	5.90E-02	1.91E-02	4.64E-02	1.15E-01
PRF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
PRG	2/2 PORV's and 3/3 SRV's blk vlvs not avail.	7.47E-02	2.79E-02	5.98E-02	1.42E-01
PRH	2/2 PORV's and 2/3 SRV's or(3/3 SRV'S) no blk vlvs	5.74E-02	1.80E-02	4.49E-02	1.13E-01
PRI	1/2 PORV's or (1/3 SRV's), HPI or SLB no blk vlvs	2.13E-03	2.38E-05	5.03E-04	6.28E-03
PRJ	1/1 PORV or (1/3 SRV's), LOSP/SGTR, no blk vlvs	2.53E-02	5.90E-03	1.87E-02	5.41E-02
PRK	1/1 PORV and 3/3 SRV's no blk vlvs	4.33E-02	1.53E-02	3.35E-02	8.35E-02
PRL	3/3 SRV's no blk vlvs	3.41E-02	1.01E-02	2.58E-02	6.97E-02
PRM	1/1 PORV or (1/3 SRV's), HPI or SLB no blk vlvs	1.11E-03	1.04E-05	2.54E-04	3.19E-03
PRN	1/1 Block valve closes, All support available	7.66E-03	1.98E-03	4.96E-03	1.76E-02
PRP	1/2 PORV's or (1/3 SRV's), Manual reactor trip	6.11E-08	2.07E-09	1.60E-08	1.32E-07
PRQ	1/1 PORV or (1/3 SRV's), Manual reactor trip	2.73E-08	1.51E-09	9.91E-09	6.64E-08
PRR	1/3 SRV's, Manual reactor trip	9.57E-07	2.05E-08	2.48E-07	2.68E-06
PRS	1/2 PORV's or (1/3 SRV's), Manual reactor trip	5.69E-06	5.19E-07	2.97E-06	1.52E-05
PRT	1/1 PORV or (1/3 SRV's), Manual reactor trip	2.85E-06	2.50E-07	1.43E-06	7.67E-06
SPLIT FRACTIONS FOR TOP EVENT PO					
PO1	1/2 PORVs ATWT, boration, all support, AFW avail.	7.19E-04	1.44E-04	3.93E-04	1.24E-03
PO2	2/2 PORVs ATWT, boration, no block valves, no AFW	6.54E-02	2.30E-02	5.15E-02	1.25E-01
PO3	1/2 PORVs ATWT, boration, no block valves, AFW avail.	4.89E-02	1.39E-02	3.82E-02	9.72E-02
POF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT OB					
OB1	Loss of Instrument air	2.89E-02	6.25E-03	1.71E-02	6.46E-02
OB2	Loss of Instrument air, charging failed	2.89E-02	6.25E-03	1.71E-02	6.46E-02
OB3	Loss of 1 DC bus Initiating event	3.75E-01	3.48E-01	3.65E-01	4.14E-01
OBF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT CH					
CH1	All support available.	6.23E-04	3.01E-04	5.57E-04	9.65E-04
CH2	One standby pump train available only	1.41E-02	9.12E-03	1.32E-02	1.97E-02
CH3	Normally running pump train available only.	1.16E-02	7.46E-03	1.10E-02	1.61E-02
CH4	LOSP ; All support available	7.95E-04	4.17E-04	7.12E-04	1.22E-03
CHF	Guaranteed failure.	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT SI					
SI1	All support available (1/2)	3.25E-03	6.25E-04	1.62E-03	1.04E-02
SI2	One safety injection pump train available only(1/1)	1.60E-02	7.49E-03	1.31E-02	2.99E-02
SI3	Medium LOCA; All support available, CH failed. (2/2)	2.89E-02	1.40E-02	2.44E-02	5.16E-02
SIF	Guaranteed failure.	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT HR					
HR1	All support available	2.11E-04	1.11E-04	1.94E-04	3.22E-04
HR2	Top event CH or SI failed	1.91E-03	1.11E-03	1.59E-03	3.57E-03
HR3	Top event LA or LB failed	4.01E-03	2.55E-03	3.68E-03	5.86E-03
HR4	Top event CH or SI and top events LA or LB failed	4.33E-03	2.77E-03	3.99E-03	6.28E-03
HR5	4KV Bus F failed	2.29E-03	1.36E-03	2.11E-03	3.35E-03
HR6	4KV Bus F failed, top event CH or SI failed	3.99E-03	2.55E-03	3.65E-03	5.89E-03
HR7	4KV Bus F failed, top event LA or LB failed	6.08E-03	4.16E-03	5.74E-03	8.24E-03
HR8	4KV Bus F failed, top event CH or SI & LA or LB failed	6.40E-03	4.39E-03	6.04E-03	8.64E-03
HR9	4KV Bus F and 4KV Bus G failed	6.08E-03	4.16E-03	5.74E-03	8.24E-03
HRA	4KV Bus F and 4KV Bus H failed	2.36E-03	1.39E-03	2.19E-03	3.42E-03
HRB	4KV Bus G failed	4.01E-03	2.55E-03	3.68E-03	5.86E-03

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Table 6-37 (Continued)

SYSTEM SPLIT FRACTION QUANTIFICATION FOR NONSEISMIC INITIATING EVENTS

CSF	BOUNDARY CONDITION	MEAN	5TH XILE	MEDIAN	95TH XILE
HRC	4KV Bus G failed, top event CH or SI failed	6.43E-03	4.03E-03	6.01E-03	9.06E-03
HRD	4KV Bus H failed	4.56E-03	3.07E-03	4.36E-03	6.07E-03
HRE	4KV Bus H failed, top event CH or SI failed	8.66E-03	5.87E-03	8.24E-03	1.15E-02
HRF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT RC					
RC1	Both RHR pump trains operable	4.43E-05	5.88E-06	2.72E-05	1.10E-04
RC2	One RHR pump train operable	1.18E-03	6.84E-04	1.07E-03	1.83E-03
SPLIT FRACTIONS FOR TOP EVENT RF					
RF1	Switchover after SLOCA or B/F with CS failed	3.16E-03	4.78E-04	1.80E-03	8.26E-03
RF2	Switchover after SLOCA or B/F with CS success	3.37E-03	5.07E-04	1.92E-03	8.84E-03
RF3	Switchover after LLOCA or MLOCA initiating event	4.93E-03	9.22E-04	3.07E-03	1.21E-02
RF4	Switchover to recirculation after core melt	5.47E-02	9.54E-03	3.41E-02	1.34E-01
SPLIT FRACTIONS FOR TOP EVENT LA					
LA1	All support available. (SLOCA Case)	2.04E-02	1.13E-02	1.80E-02	3.22E-02
LA2	All support available. (Bleed & Feed case)	2.04E-02	1.12E-02	1.78E-02	3.23E-02
LA3	All support available. (LLOCA/MLOCA Case)	1.58E-02	9.03E-03	1.41E-02	2.42E-02
LAF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT LB					
LB1	All support available. Top event LA successful. (SLOCA)	1.56E-02	8.78E-03	1.38E-02	2.39E-02
LB2	All support available. Top event LA failed. (SLOCA)	2.32E-01	6.20E-02	1.79E-01	4.83E-01
LB3	Top Event LA Guaranteed Failure (SLOCA)	2.04E-02	1.13E-02	1.80E-02	3.22E-02
LB4	All support available. Top event LA successful. (B & F)	1.56E-02	8.78E-03	1.38E-02	2.39E-02
LB5	All support available. Top event LA failed. (B & F)	2.30E-01	6.04E-02	1.78E-01	4.73E-01
LB6	Top Event LA Guaranteed Failure (B & F)	2.04E-02	1.12E-02	1.78E-02	3.23E-02
LB7	All support available. Top event LA successful. (LLOCA)	1.55E-02	8.74E-03	1.37E-02	2.38E-02
LB8	All support available. Top event LA failed. (LLOCA)	3.75E-02	1.66E-02	2.81E-02	7.16E-02
LB9	Top Event LA Guaranteed Failure (LLOCA)	1.58E-02	9.03E-03	1.41E-02	2.42E-02
LBF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT LV					
LV1	All conditions(No support required)	4.59E-04	1.32E-04	3.00E-04	1.20E-03
SPLIT FRACTIONS FOR TOP EVENT RW					
RW1	All conditions(No support required)	3.94E-05	3.44E-06	1.78E-05	1.09E-04
SPLIT FRACTIONS FOR TOP EVENT VA					
VA1	All support available.	4.38E-03	2.87E-03	4.17E-03	5.83E-03
VAF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT VB					
VB1	All support available. Top event VA successful.	4.18E-03	2.69E-03	3.98E-03	5.64E-03
VB2	All support available. Top event VA failed.	5.00E-02	2.52E-02	4.51E-02	7.85E-02
VB3	Top Event VA Guaranteed Failure	4.38E-03	2.87E-03	4.17E-03	5.83E-03
VBF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT AC					
AC1	All conditions(No support required)	6.27E-03	1.44E-03	3.30E-03	1.92E-02
SPLIT FRACTIONS FOR TOP EVENT LI					
LI1	All conditions except large LOCA;(No support required)	4.03E-06	7.90E-07	1.98E-06	1.25E-05
LI2	LLOCA initiating event: Given failure of top event AC	5.55E-04	1.99E-04	3.59E-04	9.43E-04
SPLIT FRACTIONS FOR TOP EVENT MU					
MU1	Power available at AC buses G and H	7.98E-03	3.67E-03	6.51E-03	1.41E-02
MUF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
MU2	Power avail at AC buses G and H (Make-up Via RFW Pump)	1.54E-02	5.48E-03	1.09E-02	3.16E-02
MUV	Makeup to RWST	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT FC					
FC1	2 OF 5 CFCUs start rate 24 hours	1.86E-06	1.72E-07	1.00E-06	4.88E-06
FC2	2 OF 4 CFCUs start and operate 24 hours	4.83E-06	9.90E-07	3.32E-06	1.09E-05
FC3	2 OF 3 CFCUs start and operate 24 hours	6.07E-05	1.84E-05	4.73E-05	1.19E-04
FC4	2 OF 2 CFCUs start and operate 24 hours	6.59E-03	2.88E-03	5.72E-03	1.11E-02
FCF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT CS					
CS1	1/2 Trains Operates(All Support Available)	5.91E-04	2.24E-04	4.59E-04	1.12E-03
CS2	1/1 Train Operates(Loss of One Vital Bus or SSPS train)	1.43E-02	7.29E-03	1.24E-02	2.35E-02
CSF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT SR					
SR1	1/2 Trains Operates(All Support Available)	3.80E-03	4.33E-04	1.76E-03	1.02E-02
SR2	1/1 Train Operates(Loss of 1 Bus or SSPS or RHR train)	9.47E-03	4.15E-03	7.18E-03	1.85E-02
SRF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT CI					
CI1	Either inboard or outboard isol. valve(s) must close	4.06E-03	3.37E-04	1.93E-03	1.07E-02
CI2	Inboard vlves(pen 45) and 1/2 vlves(pen 50,51,52) close	5.77E-03	1.61E-03	3.69E-03	1.24E-02

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Table 6-37 (Continued)

SYSTEM SPLIT FRACTION QUANTIFICATION FOR NONSEISMIC INITIATING EVENTS

CSF	BOUNDARY CONDITION	MEAN	5TH XILE	MEDIAN	95TH XILE
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CI3	Inboard isolation valves (pen 45,50,51,52) must close	7.31E-03	2.84E-03	5.29E-03	1.40E-02
CI4	Inbd. or Outbd. Isolation vlvs close - Excessive LOCA	4.06E-03	3.37E-04	1.93E-03	1.07E-02
CI5	Inbd.pen.45 & 1/2 vlvs pen.50,51,52 close - ELOCA	5.77E-03	1.61E-03	3.69E-03	1.24E-02
CI6	Inbd.isol.vlvs.pen.45,50,51,52 close - ELOCA	7.31E-03	2.84E-03	5.29E-03	1.40E-02
CIF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT CP					
CP1	Either inboard or outboard isolation valve(s) must close	9.05E-07	1.51E-07	5.95E-07	2.06E-06
CP2	Outboard isolation valves must close	1.01E-05	3.66E-06	8.29E-06	1.95E-05
CP3	Fraction of time penetration 61, 62, or 63 is open	8.41E-03	8.41E-03	8.41E-03	8.41E-03
CP4	Same as CP1 with VI failed seismicy	9.05E-07	1.51E-07	5.95E-07	2.06E-06
CP5	Same as CP2 with VI failed seismicy	1.01E-05	3.66E-06	8.29E-06	1.95E-05
CP6	Same as CP3 with VI failed seismicy	8.41E-03	8.41E-03	8.41E-03	8.41E-03
SPLIT FRACTIONS FOR TOP EVENT WL					
WL1	Either FCV-500 (inboard) or FCV-501(outboard) must close	4.32E-05	5.17E-06	2.60E-05	1.11E-04
WL2	Inboard vlv FCV-500 (or outboard vlv FCV-501) must close	6.34E-04	2.19E-04	5.31E-04	1.23E-03
WL3	Fraction of time containment sump discharge line is open	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT SL					
SL1	All Support Available	6.06E-03	1.29E-03	3.67E-03	1.56E-02
SL2	Loss of support to 10X steam dump valves	6.52E-03	1.32E-03	3.88E-03	1.68E-02
SPLIT FRACTIONS FOR TOP EVENT VD					
VDI	Initiating event frequency (discharge side valves)	3.86E-06	1.33E-08	2.68E-07	7.97E-06
SPLIT FRACTIONS FOR TOP EVENT VS					
VSI	Initiating event frequency (suction side valves)	1.01E-06	5.03E-09	8.40E-08	2.14E-06
SPLIT FRACTIONS FOR TOP EVENT VO					
VO1	Pressure relief valves open 3/3 for VSI IE	6.99E-05	4.14E-06	2.90E-05	2.60E-04
VO2	Pressure relief valves open 2/2 for VDI IE	4.66E-05	2.76E-06	1.93E-05	1.73E-04
SPLIT FRACTIONS FOR TOP EVENT VC					
VC1	Leak rate of 1700 gpm for VSI IE	1.48E-01	5.98E-04	1.18E-02	2.96E-01
VC2	Leak rate of 800 gpm for VDI IE	6.93E-02	2.43E-04	4.83E-03	1.36E-01
SPLIT FRACTIONS FOR TOP EVENT VR					
VR1	Pressure relief valves reclose 3/3 for VSI IE	2.44E-01	1.17E-02	2.28E-01	6.39E-01
VR2	Pressure relief valves reclose 2/2 for VDI IE	1.80E-01	7.82E-03	1.58E-01	4.96E-01
SPLIT FRACTIONS FOR TOP EVENT IT					
ITI	RHR piping intact; VO successful	9.90E-01	4.95E-02	4.95E-01	9.40E-01
SPLIT FRACTIONS FOR TOP EVENT LW					
LW1	RCS flow to RWST for VSI IE	4.14E-04	1.15E-05	1.17E-04	1.32E-03
LW2	Guaranteed success	0.00E-01	0.00E-01	0.00E-01	0.00E-01
LW3	MOV support power not available	4.13E-04	1.44E-05	1.17E-04	1.81E-03
SPLIT FRACTIONS FOR TOP EVENT ME					
ME1	Medium LOCA; for VSI IE	5.00E-01	2.50E-02	2.50E-01	4.75E-01
ME2	Medium LOCA; for VDI IE	6.00E-03	3.00E-04	3.00E-03	5.70E-03
SPLIT FRACTIONS FOR TOP EVENT SM					
SM1	Small LOCA; for VSI IE	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SM2	Small LOCA; for VDI IE	5.00E-01	2.50E-02	2.50E-01	4.75E-01
SPLIT FRACTIONS FOR TOP EVENT OT					
OT1	Failure to isolate break, stops leakage; Initiates E-1	9.99E-02	5.00E-03	5.00E-02	9.50E-02
OTF	Operator fails to isolate break	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT OS					
OS1	Manual SI Actuation	1.89E-03	1.94E-04	1.04E-03	5.97E-03
OSF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT CD					
CDF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT FW					
FWF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT SE					
SE1	RCP Seal Cooling, CCW unavailable	9.91E-03	2.83E-03	7.42E-03	2.43E-02
SE2	RCP Seal Cooling, CCW available	0.00E-01	0.00E-01	0.00E-01	0.00E-01
SE0	Guaranteed Success	0.00E-01	0.00E-01	0.00E-01	0.00E-01
SEF	Guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT VI					
VI0	Vessel Integrity Guaranteed success	0.00E-01	0.00E-01	0.00E-01	0.00E-01
VI1	Vessel Integrity (TT & MS Failed)	1.10E-04	5.50E-06	5.50E-05	1.04E-04
VI2	Vessel Integrity Loss of Secondary Heat Sink	2.20E-02	1.10E-03	1.10E-02	2.09E-02
VI3	Vessel Integrity Medium LOCA Events	2.00E-03	1.00E-04	1.00E-03	1.90E-03
VI4	SGTR; With Successful ECCS Termination	1.80E-06	9.00E-08	9.00E-07	1.71E-06
VI5	SGTR; With Delayed ECCS Termination	8.99E-03	4.50E-04	4.50E-03	8.55E-03

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Table 6-37 (Continued)

SYSTEM SPLIT FRACTION QUANTIFICATION FOR NONSEISMIC INITIATING EVENTS

CSF	BOUNDARY CONDITION	MEAN	5TH XILE	MEDIAN	95TH XILE
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SPLIT FRACTIONS FOR TOP EVENT RP					
RP0	Guaranteed Success	0.00E-01	0.00E-01	0.00E-01	0.00E-01
RP1	RCS pressure $\geq 1275\#$	1.00E+00	1.00E+00	1.00E+00	1.00E+00
RP2	CCW lost, operator must trip to prevent seal loca	9.96E-01	9.82E-01	9.98E-01	1.00E+00
RPF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT OI					
OIF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
OI1	when WL fails	1.00E+00	1.00E+00	1.00E+00	1.00E+00
OI2	when CP fails	1.00E+00	1.00E+00	1.00E+00	1.00E+00
OI3	when CI fails	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT OP					
OP1	SGTR when SL S, terminate SI	4.16E-03	4.29E-04	2.28E-03	1.32E-02
OP2	SGTR when SL F,B; terminate SI	4.16E-03	4.29E-04	2.28E-03	1.32E-02
SPLIT FRACTIONS FOR TOP EVENT OE					
OE1	initiate boration in 10 minutes given ATWT	2.32E-03	2.40E-04	1.28E-03	7.35E-03
OE2	initiate boration in 20 minutes given ATWT	2.32E-03	2.40E-04	1.28E-03	7.35E-03
OE3	initiate boration in 30 minutes given ATWT	2.32E-03	2.40E-04	1.28E-03	7.35E-03
SPLIT FRACTIONS FOR TOP EVENT HS					
HS1	hot standby, all available	4.71E-06	2.37E-07	1.91E-06	1.73E-05
HS2	hot standby, with small LOCA	3.09E-06	3.18E-07	1.70E-06	9.77E-06
HS3	hot standby, instrumentation lost	5.06E-03	2.54E-04	2.05E-03	1.86E-02
HS4	hot standby, LOCA and instrumentation lost	1.00E+00	1.00E+00	1.00E+00	1.00E+00
HSF	guaranteed failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT RS					
RS1	43 of 53 inserted within 10 minutes	1.00E+00	1.00E+00	1.00E+00	1.00E+00
RSF	reactor trip failed	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT PL					
PL1	power level greater than 80%	0.00E-01	0.00E-01	0.00E-01	0.00E-01
SPLIT FRACTIONS FOR TOP EVENT MC					
MC1	moderator coefficient less negative than -7	1.00E-02	5.00E-04	5.00E-03	9.50E-03
SPLIT FRACTIONS FOR TOP EVENT SS					
SSF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
SPLIT FRACTIONS FOR TOP EVENT OD					
ODF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
OV1	Failure to diagnoses a LOCA to RHR; Initiates ECA 1.2	1.00E+00	1.00E+00	1.00E+00	1.00E+00
OL1	Operator fails to depressurizes RCS	1.00E+00	1.00E+00	1.00E+00	1.00E+00
CT1	Seismic Failure of relays chattering givne /OP	0.00E-01	0.00E-01	0.00E-01	0.00E-01
CT2	Seismic Failure of relays chattering given OP	0.00E-01	0.00E-01	0.00E-01	0.00E-01
CTF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
EL1	Excessive LOCA	1.00E+00	1.00E+00	1.00E+00	1.00E+00
ELF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00
ID1	Identification of operator	0.00E-01	0.00E-01	0.00E-01	0.00E-01
IDF	Guaranteed Failure	1.00E+00	1.00E+00	1.00E+00	1.00E+00

Table 6-37 (Continued)

SYSTEM SPLIT FRACTION QUANTIFICATION FOR NONSEISMIC INITIATING EVENTS

AC I	INSTRUMENT AC CHANNEL I
AC II	INSTRUMENT AC CHANNEL II
AC III	INSTRUMENT AC CHANNEL III
AC IV	INSTRUMENT AC CHANNEL IV
AFW	AUXILIARY FEEDWATER
ATWT	ANY TRANSIENT WITHOUT TRIP
B&F	BLEED AND FEED COOLING
B/F	BLEED AND FEED COOLING
CCW	COMPONENT COOLING WATER
CP	CHARGING PUMP
DG	DIESEL GENERATOR
E-1	EMERGENCY PROCEDURE STEP 1
ECA	EMERGENCY PROCEDURE
ECCS	EMERGENCY CORE COOLING SYSTEM
ELOCA	EXCESSIVE LOSS OF COOLANT ACCIDENT (BEYOND EECS CAPABILITIES)
GT	GENERAL TRANSIENT INITIATING EVENT
HI POWER	REACTOR HIGH POWER OUTPUT (REACTOR TRIP FAILURE)
HPI	HIGH PRESSURE INJECTION
I.E.	INITIATING EVENT
INBD.	INBOARD ISOLATION VALVE
LLOCA	LARGE LOSS OF COOLANT ACCIDENT
LO POWER	REACTOR LOW POWER OUTPUT (SUCCESSFUL REACTOR TRIP)
LOSP	LOSS OF OFFSITE POWER INITIATING EVENT
MDP	MOTOR DRIVEN PUMP
OUTBD.	OUTBOARD ISOLATION VALVE
PEN	CONTAINMENT PENETRATIONS
PORV	POWER OPERATED RELIEF VALVE
RCP	REACTOR COOLANT PUMP
RCS	REACTOR COOLANT SYSTEM
RFW	REFUELING WATER
RHR	RESIDUAL HEAT REMOVAL
RWST	REFUELING WATER STORAGE TANK
SD	STEAM DUMP VALVES
SG	STEAM GENERATOR
SCTR	STEAM GENERATOR TUBE RUPTURE INITIATING EVENT
SI	SAFETY INJECTION
SLB	STEAM LINE BREAK
SLBIC	STEAM LINE BREAK INSIDE CONTAINMENT
SLBOC	STEAM LINE BREAK OUTSIDE CONTAINMENT
SLOCA	SMALL LOSS OF COOLANT ACCIDENT
SRV	SAFETY RELIEF VALVE
SSPS	SOLID STATE PROTECTION SYSTEM
TDP	TURBINE DRIVEN PUMP
TT	TURBINE TRIP INITIATING EVENT OR TOP EVENT TT
VDI	INTERFACING LOCA INITIATING EVENT, DISCHARGE SIDE
VSI	INTERFACING LOCA INITIATING EVENT, SUCTION SIDE
N/M	N OUT OF M COMPONENTS

BOUNDARY CONDITIONS WITH ABBREVIATIONS OF THE FORM XX-F, XX-S, OR XX-B ARE INTERPRETED AS FOLLOWS:

XX-F, TOP EVENT XX FAILED
 XX-S, TOP EVENT XX SUCCESSFUL
 XX-B, TOP EVENT XX BYPASS (I.E., NO BRANCH IN EVENT TREE)

BOUNDARY CONDITIONS WITH ABBREVIATIONS OF THE FORM XX-S/F/B, YY-F/B/S, AND ZZ-B/S/F ARE INTERPRETED AS FOLLOWS:

TOP EVENTS XX-S AND YY-F AND ZZ-B OR
 TOP EVENTS XX-F AND YY-B AND ZZ-S OR
 TOP EVENTS XX-B AND YY-S AND ZZ-F

BOUNDARY CONDITIONS WITH ABBREVIATIONS OF THE FORM XX-YY&ZZ-AA: SF/FS&SB/BS, SB/BS&FS/SF ARE INTERPRETED AS FOLLOWS:

TOP EVENTS XX-S AND YY-F AND ZZ-B AND AA-B OR
 TOP EVENTS XX-S AND YY-F AND ZZ-B AND AA-S OR
 TOP EVENTS XX-F AND YY-S AND ZZ-S AND AA-B OR
 TOP EVENTS XX-F AND YY-S AND ZZ-B AND AA-S OR,
 TOP EVENTS XX-S AND YY-B AND ZZ-F AND AA-S OR
 TOP EVENTS XX-S AND YY-B AND ZZ-S AND AA-F OR
 TOP EVENTS XX-B AND YY-S AND ZZ-F AND AA-S OR
 TOP EVENTS XX-B AND YY-S AND ZZ-S AND AA-F

description of boundary conditions associated with the split fractions.

Seismic Analysis

Earthquakes can initiate potential accident scenarios, such as causing the turbine to trip and buildings, equipment, or other Plant components to fail or fail to function. Therefore, it is important to evaluate the frequency with which various levels of ground accelerations might occur, the likelihood that important Plant components could fail at these accelerations, and the core damage consequences of component failure combinations. In general, the seismic risk analysis consists of four main steps.

- 1) **Seismic Hazard Analysis.** Determination of the frequency of occurrence of ground motions of various acceleration levels at the site.
- 2) **Fragility Analysis.** Determination of the failure probability of Plant structures and components for different seismically initiated ground accelerations.
- 3) **Plant Logic Analysis.** Development of a logic model that evaluates the Plant's response to the seismic events which may cause one or more different classes of initiating events and one or more failures of components or systems needed to respond to the initiating event; the logic model also considers nonseismic failures that can combine with seismically induced failures to produce an accident sequence.
- 4) **Quantification.** Quantification and assembly of the seismicity, component fragility, and Plant impacts to obtain point estimates of the frequencies of core damage due to seismic initiating events. The important seismic failure contributors are identified and, the probability distribution of core damage frequency is developed.

SEISMIC HAZARD

As mentioned in the method section, it is necessary for the hazard curves used in the

seismic analysis to be characterized by the same parameter as the fragilities; in this case, peak spectral acceleration. Figure 6-7 and Table 6-38 represent the hazard curves used in the seismic analysis for the quantification process. These were obtained from the hazard analysis. They reflect the annual exceedance frequency versus peak spectral acceleration. Table 6-39 reflects mean values of frequencies at discrete spectral accelerations.

SEISMIC FRAGILITIES

Using the models developed for internal initiating events as a basis, a total list of equipment and other Plant components and the buildings that house them was provided to the fragility analysts. Necessarily, this list of equipment lumped much similar equipment into convenient categories, rather than identifying each of the thousands of possible risk-related components in the Plant. The results of the fragility analysis for the structures and Plant components are given in earlier sections of this chapter. Many of the components are noted as having median spectral acceleration capacities greater than 10.0 g. One can look at the hazard curves and note that the mean annual frequency of 4 g acceleration is 2.37×10^{-7} . The frequencies of 10 g acceleration, therefore, is much too low to be of interest even if the failed component independently leads to core damage. However, we have chosen to retain for the seismic analysis all components with median spectral acceleration capacities less than about 10.0 g. These components are listed in Table 6-40 and have been included in the seismic Plant damage state quantifications.

TRUNCATION OF FRAGILITY CURVES

The fragility descriptions are based on a logarithmic distribution because the data generally fits this type of distribution well. However, in the tails of the distribution, the curves are considered to be conservative. The following is the basis for truncation of the fragility curves in this project:

- 1) The uncertainty variability, β_u , should not be truncated.

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Table 6-38
AGGREGATE SEISMIC HAZARD CURVES

Curve	Weight	Spectral Acceleration (3-8.5 Hz, 5% Damping)									
		0.2	0.5	0.8	1.0	1.2	1.5	2.0	2.5	3.0	4.0
1	0.342	.128-1	.436-2	.157-2	.699-3	.293-3	.781-4	.976-5	.136-5	.184-8	.174-8
2	0.196	.165-1	.628-2	.282-2	.166-2	.788-3	.235-3	.271-4	.297-6	.320-8	.227-8
3	0.217	.186-1	.749-2	.371-2	.231-2	.135-2	.030-3	.901-4	.131-4	.172-6	.167-7
4	0.111	.186-1	.837-2	.440-2	.297-2	.185-2	.858-3	.240-3	.602-4	.920-6	.146-6
5	0.036	.149-1	.682-2	.381-2	.275-2	.204-2	.132-2	.581-3	.204-3	.584-4	.296-5
6	0.043	.384-1	.158-1	.850-2	.578-2	.382-2	.192-2	.397-3	.695-4	.108-4	.133-6
7	0.032	.418-1	.188-1	.105-1	.745-2	.527-2	.291-2	.814-3	.168-3	.285-4	.285-6
8	0.023	.526-1	.280-1	.145-1	.106-1	.789-2	.490-2	.183-2	.526-3	.124-3	.432-5

NOTE: Exponential notation is indicated in abbreviated form; i.e., .128-1 = $.128 \times 10^{-1}$.

Table 6-39
SEISMIC HAZARD EVENT MEAN FREQUENCIES

Mean Peak Spectral Acceleration (g)									
0.2	0.5	0.8	1.0	1.2	1.5	2.0	2.5	3.0	4.0
1.52-2	6.24-3	3.12-3	1.97-3	1.23-3	5.82-4	1.53-4	3.59-5	7.67-6	2.37-7

NOTE: Exponential notation is indicated in abbreviated form; i.e., 1.52-2 = 1.52×10^{-2} .

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Table 6-40
KEY SEISMIC FRAGILITIES

<u>Component/Structures</u>	<u>Median Acceleration</u>	<u>Beta R</u>	<u>Beta U</u>	<u>Beta C</u>	<u>HCLPF Value</u>
1. Containment building	8.42	0.260	0.300	0.397	3.342
2. Concrete internal biostructure	6.91	0.200	0.310	0.369	2.979
3. Intake structure	8.55	0.280	0.310	0.418	3.230
4. Auxiliary building	5.79	0.210	0.260	0.334	2.666
5. Turbine building shear wall	4.87	0.260	0.330	0.420	1.840
6. Refueling water storage	9.92	0.290	0.360	0.462	3.394
7. Auxiliary saltwater piping	9.23	0.180	0.210	0.277	4.850
8. Reactor pressure vessel	8.71	0.250	0.330	0.414	3.345
9. Reactor internals	10.54	0.400	0.260	0.477	3.547
10. Steam generators	6.96	0.310	0.290	0.424	2.586
11. Power-operated relief valves	7.62	0.300	0.420	0.516	2.323
12. Reactor coolant pumps	8.82	0.370	0.320	0.489	2.825
13. RHR pumps	8.31	0.330	0.220	0.397	3.353
14. RHR heat exchangers	8.09	0.240	0.270	0.361	3.487
15. Safety injection accumulators	10.01	0.290	0.190	0.347	4.534
16. Boron injection tank	8.46	0.270	0.190	0.330	3.960
17. CCW pumps	8.53	0.290	0.210	0.358	3.738
18. CCW heat exchangers	6.31	0.270	0.280	0.389	2.546
19. CCW surge tank	7.22	0.330	0.220	0.397	2.913
20. Containment spray pmps	8.65	0.290	0.200	0.352	3.854
21. Spray additive tank	6.78	0.300	0.180	0.350	3.071
22. AFW pumps	7.71	0.290	0.210	0.358	3.379
23. Diesel generator fuel oil pumps/filter	8.33	0.270	0.230	0.355	3.650
24. Diesel generators	7.79	0.260	0.200	0.328	3.647
25. Diesel generator radiator/ water pump	8.78	0.290	0.240	0.376	3.662

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Table 6-40 (Continued)
KEY SEISMIC FRAGILITIES

<u>Component/Structures</u>	<u>Median Acceleration</u>	<u>Beta R</u>	<u>Beta U</u>	<u>Beta C</u>	<u>HCLPF Value</u>
26. Diesel generator excitation cubicle	7.40	0.290	0.350	0.455	2.574
27. Diesel generator control panel	4.55	0.300	0.130	0.327	2.238
28. Containment fan cooler	8.10	0.310	0.330	0.453	2.818
29. Supply fans	9.79	0.330	0.240	0.408	3.822
30. Supply/return fans	11.16	0.330	0.300	0.446	3.947
31. 4-kV switchgear	7.44	0.310	0.250	0.398	2.953
32. Bus G and H potential transformer	10.83	0.310	0.380	0.490	3.469
33. Safeguard relay panel	10.76	0.340	0.360	0.495	3.390
34. Batteries	6.04	0.300	0.180	0.350	2.736
35. Battery chargers	9.93	0.340	0.400	0.525	2.929
36. Switchgear/breaker panel	6.67	0.350	0.280	0.448	2.359
37. Inverters	6.82	0.310	0.240	0.392	2.752
38. 4,160V/480V transformers	5.34	0.280	0.200	0.344	2.419
39. Auxiliary relay panel	7.25	0.280	0.150	0.318	3.566
40. Main control boards	7.77	0.310	0.270	0.411	2.984
41. Hot shutdown panel	7.60	0.270	0.250	0.368	3.222
42. Process control and protection	10.78	0.390	0.280	0.480	3.569
43. Reactor trip switchgear	7.90	0.300	0.260	0.397	3.136
44. Pressure and ΔP transmitter	8.93	0.270	0.200	0.336	4.112
45. Impulse lines	7.09	0.280	0.320	0.425	2.634
46. Offsite power, 230 kV	1.69	0.240	0.200	0.312	0.818
47. Offsite power, 500 kV	0.81	0.240	0.200	0.312	0.392
48. BOP piping and supports	11.22	0.390	0.400	0.559	3.047
49. Penetrations/penetration boxes	7.38	0.310	0.270	0.411	2.834
50. HVAC ducting and supports	9.78	0.350	0.480	0.594	2.486
51. Switchgear/strut	7.07	0.310	0.250	0.398	2.806

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Table 6-40 (Continued)
KEY SEISMIC FRAGILITIES

<u>Component/Structures</u>	<u>Median Acceleration</u>	<u>Beta R</u>	<u>Beta U</u>	<u>Beta C</u>	<u>HCLPF Value</u>
52. Chatter, main control board	10.00	0.010	0.010	0.014	9.675
53. Chatter, DG control panel	7.77	0.250	0.140	0.287	4.083
54. Chatter, 4-kV switchgear	3.53	0.350	0.250	0.430	1.312
55. Chatter, safeguards relay panel	10.00	0.010	0.010	0.014	9.675
56. Strut for turbine building	6.71	0.250	0.320	0.406	2.620
57. Bus F potential transformer	5.85	0.310	0.380	0.490	1.874
58. Safeguard relay panel	5.81	0.340	0.360	0.495	1.830
59. Centrifugal charging pump	10.16	0.310	0.190	0.364	4.452

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2) For relatively ductile component failure modes, such as in piping systems and in civil structures, the random variability, β_R , should be truncated at about 1 percent failure fraction. In addition to the civil structures and piping, components in the Plant that are in this category are:

- Reactor internals
- Pressurizer
- Reactor coolant pumps
- Control rod drives
- CCW surge tank
- Battery racks
- Impulse lines
- Cable trays and supports
- HVAC ducting and supports

3) For all other Plant components, the truncation point should be at a significantly lower failure fraction, 0.1 percent. Therefore, fragility truncations were performed in the seismic quantification process in accordance with the foregoing guidelines.

Component Seismic Dependencies

It has been noted that because the response spectra from a given earthquake is common to all of the Plant components to some degree, we can expect some correlation between components having similar vibrational frequencies. Studies to assess these correlations (Kennedy, 1988) concluded the following:

- Except at high frequencies (greater than about 18 hertz), responses of identical components with the same frequencies should be treated as totally dependent, even when mounted at different elevations in different structures located at the site.
- Responses of components with different vibrational frequencies are essentially

uncorrelated even when mounted on the same floor.

- Fragilities of components with different vibrational frequencies and mounted adjacently should be treated as independent.
- The piping fragility indicated in Table 6-40 should be treated such that each segment between rigid supports or equipment is considered to be independent of the other segments).
- The fragility of conduits and cable trays indicated in Table 6-40 is considered to be that of all the conduits and cable trays as a whole, largely because of the natural flexibility existing in cables; that is, individual cable trays and conduits are not considered independently. By their very nature, large physical movements do not mean cable failure.
- The fragility of HVAC ducts, as indicated in Table 6-40, is considered to represent that of all the ductwork supporting a single safety system.

Using these guidelines, the plant model assumes total dependency for identical equipment at the site (that is, if one fails, all of the same type fail). All other equipment situations follow the definitions above or otherwise are considered independent.

SEISMIC LOSS OF OFFSITE POWER

Offsite power loss from earthquakes is seen from Table 6-40 to be the most vulnerable equipment. Given the loss of offsite power, the diesel generators are expected to have to function (with some chance of not functioning) for at least 24 hours. Recovery of seismically failed offsite power within 24 hours of the earthquake was assumed in the quantification.

Based on previous California earthquake experience, the 230-kV line is expected to survive an earthquake. However, the porcelain insulators and bushings in the 230-kV substation are likely to fail. Plant procedures detail the actions required to repair the substation, and repair

materials such as spare insulators, bushings, and cable are stored near the substation. If damage is not easily repairable, the procedure provides for completely bypassing the substation and directly feeding the Plant startup transformer from Morro Bay or Mesa substations. Response time is minimal because substation operators are stationed in the nearby 500-kV substation, and substation repair crews are located in nearby south San Luis Obispo.

A group of PG&E operations and engineering personnel with over 75 years of combined restoring experience evaluated the probability of restoring the 230-kV substation after a major earthquake. All of these people either work in the substation or are directly involved with design of the Plant. The mean repair time estimated by the evaluators was approximately 12 hours. The evaluators considered 24 hours as a worst-case estimate and 9 hours as a best case. Based on expert judgment and Plant-specific recovery procedures, recovery of offsite power was assumed to occur in 24 hours or less.

SEISMIC-INITIATED FIRES

Consideration was given to the possibility of seismic events initiating a fire at the Plant. Historically, where fires have occurred in commercial facilities as a result of earthquakes, they were initiated by sparks to a failed gas line or were caused by operational activities, such as welding at the time of the earthquake that resulted in the welder accidentally initiating the fire. There is no evidence that seismic-initiated shorts in electrical cabinets have caused fires.

On the other hand, electrical cabinet fires and cable insulation fires have already been considered in the fire analysis. That analysis used historical data regardless of underlying cause and, therefore, if seismic-initiated fires occurred and were reported, they have been included. Additionally, it is conceivable that a fuel line to the diesels might be severed during an earthquake and that a spark might be generated, igniting the fuel leak, and thereby causing a fire. This scenario would result in failure of the diesel, but would be no more probable than the diesel failing directly

from the earthquake; the fragility of the diesel already considers the probability of the diesel failing from all direct seismic-initiated causes.

HUMAN ACTIONS UNDER SEISMIC EVENTS

Human errors that might occur during and immediately after seismic initiating events as well as human recovery actions are discussed later in this chapter. Discussed here is an evaluation of pathways to critical areas of the Plant after an earthquake large enough to cause significant damage in the Plant, but not building collapse. The evaluation is based on walkdowns of alternative paths between specific areas of interest.

The following areas potentially to be accessed after an earthquake are:

1. Intake structure for local crosstie of Unit 1 and Unit 2 auxiliary saltwater systems.
2. 480V switchgear rooms 1G and 1H for realignment of the fuel oil transfer pumps' supplies to backup sources.
3. Inverter room 12 for connection of a portable generator to the backup transformer regulator to provide instrument power.
4. 480V rooms 1F, 1G, 1H, 2F, 2G, and 2H for opening of room doors after loss of ventilation.
5. Diesel generator rooms for manual operation of the level control valves.
6. Buttress area of the turbine building for alignment of a portable fuel oil transfer train.
7. 4-kV switchgear rooms for recovery of AC power.
8. Hot shutdown panel for plant shutdown.
9. Radiation control areas for:
 - a. Local isolation of component cooling water to the containment fan coolers.
 - b. The establishment of firewater cooling to the centrifugal charging pump lube/seal oil coolers.

- c. The provision of makeup water to the condensate storage tank.

The following criteria were used in considering the loss of accessibility to the above locations:

1. Weak doors with the potential for jamming.
2. Equipment that could fill and block pathway.
3. Fire and smoke hazards.
4. Flooding.
5. Electrical hazards.
6. Chemical hazards.
7. Steamline breaks.
8. Waterline breaks (jets).

The conclusion from these evaluations is that each of the areas that may require access after a severe earthquake has multiple access paths. Due to the absence of hazards that could block paths, at least one of the paths should be passable after a seismic event.

DESIGN AND CONSTRUCTION ERRORS

Consideration was given in this study to potential design and construction errors at the Plant. It was concluded that if undetected errors exist, they would have to be very substantial to impact the plant seismic fragility. The conclusion was that small errors or errors involving local areas of construction in the Plant could not substantially reduce the seismic capacity. Extensive errors in design or construction could, at least theoretically, impact the capacity particularly under the occurrence of rare events, but the extensive quality assurance and quality control programs used in nuclear power plant projects and the extensive design verification program at the Plant are highly likely to have discovered any large design and construction errors. Based on this logic, seismic design and construction errors are assumed to have negligible effect on risk.

SYSTEM INTERACTION

The systems interaction program (seismic Category 2 over Category 1) at Diablo Canyon closely examined all nonsafety related components that could fail and fall on critical equipment, thereby possibly failing that equipment. All such Category 2 components were reinforced and/or analyzed to show that they will not fail under predicted accelerations.

During the seismic fragility Plant walk-through by the fragility and PRA analysts, no Category 2 items were seen that were considered to have a chance of failing and putting a safety risk-related component out of service.

RELAY CHATTER EFFECTS

During an earthquake, relay chatter could impact the availability of components required to maintain the reactor in a safe shutdown condition. In a nuclear plant subjected to some earthquakes, certain relays normally opened or closed, and normally energized or deenergized, have a possibility of chattering and causing circuit breakers to change valve alignments from a desired mode or could prevent pumps from starting when required. The consequence might be that recovery actions from the control room would be necessary or that it may be necessary for an operator to access local controls in order to return to the desired mode.

PG&E performed a relay chatter analysis to determine which relays are of interest by their possible unplanned change in state. The objectives in that analysis were to:

- Identify contacts that affect components required for safe shutdown.
- Determine which contacts are subject to seismic relay chatter.
- Determine the consequences, if any, of contact chatter.
- If contact chatter is possible, determine how the operator can diagnose the problem.
- When the problem is diagnosed, determine the means available for the operator to

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correct the problem, such as resetting the control.

The process involved reviewing electrical schematic diagrams and other information and identifying each type of relay related to the systems of interest in risk assessment: relay contact type, its location within a building, as well as the normal and directed contact position, the possible result of chatter, and the consequences in terms of affected equipment. From this information, it was possible to screen the very large group of relays for those that were considered susceptible to chatter and negative consequences. The resultant list of relays that can affect safe shutdown is presented in Table 6-41.

SEISMIC FAILURE MODES

The possible structure and Plant component seismic failures reflected in Table 6-40 can affect one or more systems. Failures could lead directly to system unavailability in some cases, and in other cases the seismic or nonseismic failures of additional components could be necessary before the system is unavailable. However, in either case, it is important to understand the failure mode of the component in order to properly assign the impact of its failure on a given system or event tree top in the model. These failure modes and, in some cases, the consequence of the failure are presented in Table 6-42.

Equipment might fail due to earthquakes but also might be unavailable from such nonseismic causes as random failures, testing, or maintenance. These other causes of unavailability were also included in the seismic analysis. Further, several Plant components generally considered to be passive (and therefore of low enough failure frequency to be neglected) when structuring the systems analyses for internal initiating events needed to be considered in the systems analysis for seismic initiated events. Therefore, the systems analyses for each top event in the seismic event trees include the impact of the respective component seismic failure modes, seen in Table 6-42, on the system availability.

The relationship between seismic component failures and plant systems as represented by the top event in the seismic event trees are seen in Table 6-43. Also noted are the relationships to initiating events that were the basis for the analysis. The mean fragility for each component at each discrete acceleration is seen in Table 6-44 and was used to obtain point estimate system failure and sequence frequencies. Note that Table 6-44 also provides the unconditional frequency of groups of components contributing to top events as either sums or products. The mean seismic failure frequency (mean fragility \times mean hazard frequency) for each of these components at discrete accelerations is seen in Table 6-45. The table also indicates the frequency contribution of each component to the top event seismic unavailability frequency. As will be seen, this table enables identification of the components having major contributions to the dominant scenario frequencies.

The seismic failure modes were added to the system analysis equations for each top event quantified for each discrete acceleration, combining the seismic failure fractions (see Table 6-44) with the nonseismic unavailabilities. The results are seen on Table 6-46. The split fraction definitions are found in Table 6-37.

Nonseismic External Initiating Events

Fires, internal floods, and other external events have been analyzed.

SUMMARY OF THE FIRE ANALYSIS RESULTS

The results of the fire study can be divided into two categories based on the impact of fire-induced Plant damages. The first category of fire scenarios would lead to a limited Plant damage state. Core damage is not expected, for most scenarios, if the remaining Plant safety systems (that is, systems not affected by the fire scenario) can be operated according to their design specification. The second category of the scenarios have the potential of introducing a more serious Plant damage state.

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Table 6-41
RELAYS OF INTEREST TO THE PRA AS A RESULT OF CHATTER BY SYSTEM

<u>System</u>	<u>Relay ID</u>	<u>Chatter Result</u>	<u>Relay Location</u>	
1. Auxillary Feedwater	51HH8/A,B,C	Prevent start of pump 1-2	SHH8 - 4-kV Switchgear cubicle 8	
	51HF9/A,B,C	Prevent start of pump 1-3	SHF9 - 4-kV Switchgear cubicle 9	
2. Auxillary Saltwater	51HF8	Pump 1-1 stops	SHF8 - Switchgear 4-kV bus F cubicle	
	C-52HF8/CS	Pump 1-1 stops	CNAS - Control board ASW (VB1)	
	R-52HF8/CS	Pump 1-1 stops	H01 - Hot shutdown panel 1	
	27XHFT	Pump 1-1 stops	SHF13 - Switchgear 4-kV bus F cubicle	
	43RHF88	Pump 1-1 stops	H01 - Hot shutdown panel 1	
	51HG6	Pump 1-2 stops	SHG6 - Switchgear 4-kV bus G cubicle	
	C-52HG6/CS	Pump 1-2 stops	CNAS - Control board ASW (YB1)	
	R-52HG6/CS	Pump 1-2 stops	H01 - Hot shutdown panel 1	
	27XHGT	Pump 1-2 stops	SHG13 - Switchgear 4-kV bus G cubicle	
	43RHG6B	Pump 1-2 stops	H01 - Hot shutdown panel 1	
	3. Component Cooling Water	51HF12	Stop pump 1-1	SHF12 - 4-kV bus F switchgear cubicle
		43HF12	Stop pump 1-1	CNCC - Control board CCW
		C-52HF12/CS	Stop pump 1-1	CNCC - Control board CCW
		R-52HF12/CS	Stop pump 1-1	H01 - Hot shutdown panel 1
27XHFT		Stop pump 1-1	SHF13 - 4-kV bus F switchgear cubicle	
51HG12		Stop pump 1-2	SHG12 - 4-kV bus G switchgear	
43HG12/CS		Stop pump 1-2	CNCC - Control board CCW	
C-52HG12/CS		Stop pump 1-2	CNCC - Control board CCW	
R-52HG12/CS		Stop pump 1-2	H01 - Hot shutdown panel 1	
27XHGT		Stop pump 1-2	SHG13 - 4-kV bus G switchgear cubicle	
51HH12		Stop pump 1-3	SHH12 - 4-kV bus H switchgear cubicle	
43HH12/CS		Stop pump 1-3	CNCC - Control board CCW	
C-52HH12/CS		Stop pump 1-3	CNCC - Control board CCW	
R-52HH12/CS		Stop pump 1-3	H01 - Hot shutdown panel 1	
27XHHT		Stop pump 1-3	SHH13 - 4-kV bus H switchgear cubicle	
421F-11CS		Close FCV-430, stop all flow	CNCC - Control board CCW	
421F-11/Close		Close FCV-430, stop all flow	SPF - 480V MCC bus section 1F	
421G-28/CS	Open FCV-431, alter success criteria	CNCC - Control board CCW		
421G-28/Open	Open FCV-431, alter success criteria	SPG - 480V MCC bus section 1G		
421H-16/CS	Close FCV-355, Isolate Header C	CNCC - Control board CCW		
421H-16/Close	Close FCV-355, Isolate Header C	SPH - 480V MCC bus section 1H		
421G-36/CS	Close FCV-356, Isolate flow to RCPs	CNCC - Control board CCW		

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Table 6-41 (Continued)
RELAYS OF INTEREST TO THE PRA AS A RESULT OF CHATTER BY SYSTEM

System	Relay ID	Chatter Result	Relay Location
3. Component Cooling Water (continued)	421G-36/Close	Close FCV-356, isolate flow to RCPs	SPG - 480V MCC bus section 1G
	421H-18/CS	Close FCV-749, lube oil cooling	CNCC - Control board CCW
	421H-18/Close	Close FCV-749, lube oil cooling	SPH - 480V MCC bus section 1H
	421F-23/CS	Close FCV-750, lose thermal barrier	CNCC - Control board CCW
	421F-23/Close	Close FCV-750, lose thermal barrier	SPP - 480V MCC bus section 1F
	421G-23/CS	Close FCV-363, lube oil cooling	CNCC - Control board CCW
	421G-23/Close	Close FCV-363, lube oil cooling	SPG - 480V MCC bus section 1G
	421H-17/CS	Close FCV-357, lose thermal barrier	CNCC - Control board CCW
	421H-17/Close	Close FCV-357, lose thermal barrier	SPH - 480V MCC bus section 1H
	4. Containment Spray	51HG7	Prevent pump 1-1 from starting
51HH9		Prevent pump 1-2 from starting	SHH9 - Switchgear 4-kV bus H cubicle
42-1G-48/CS		9003A to intermediate position	CNCS - Control board containment
42-1H-6/CS		9003B to intermediate position	CNCS - Control board containment
42-1G-48/aux		9003A to intermediate position	SPG - 480V MCC
42-1H-6/aux		9003B to intermediate position	SPH - 480V MCC
5. Diesel Generator	OPT1-11	Lockout DG start (1)	GQD11 - DG control panel
	OCT-11	Lockout DG start (1)	GQD11 - DG control panel
	OPR-11	Lockout DG start (1)	GQD11 - DG control panel
	JWTR-11	Lockout DG start (1)	GQD11 - DG control panel
	ESR-11	Lockout DG start (1)	GQD11 - DG control panel
	OCR-11	Lockout DG start (1)	GQD11 - DG control panel
	OCR-11	Lockout DG start (1)	GQD11 - DG control panel
	SDR-11	Lockout DG start (1)	GQD11 - DG control panel
	51HF7	Block auto-start (1)	SHF7 - 4-kV switchgear bus F cubicle (one in each unit)
NOTE: (1) similar relays are of interest for the other diesel generators (that is, for diesels 12, 13, 21, and 22).			
6. Reactor Coolant System	PCV 474/CS	Start to open, automatically reclose	CNC2 - Main control boards
	PCV 456/CS	Start to open, automatically reclose	CNC2 - Main control boards
	PCV 455C/CS	Start to open, automatically reclose	CNC2 - Main control boards
NOTE: Block valve closure is not complete; valves may start to close but never close all the way.			
7. Reactor Trip	NONE		
NOTE: Reactor trip breakers will be tripped by seismic sensors; breakers may attempt to reclose but will be kept open by seismic trip signal and chatter in trip circuit.			

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Table 6-41 (Continued)
RELAYS OF INTEREST TO THE PRA AS A RESULT OF CHATTER BY SYSTEM

System	Relay ID	Chatter Result	Relay Location
8. RHR	51HG8	RHR Pump 11 prevented from starting	SHG8 - Switchgear 4-kV bus G Cubicle
	51HH11	RHR Pump 12 prevented from starting	SHH9 - Switchgear 4-kV bus H Cubicle
NOTE: Starting of pump does not hurt since nothing prevents miniflow recirculation. Also, all valves return to initial state so valve changes are not significant. The RWST low level relays are assumed not to lock in so that after the seismic event the RHR pumps would not be prevented from starting even if chatter involving these relays occurs.			
9. Safety Injection/ Charging (1,2)	51HF11	CH Pump 11 prevented from starting	SHF11 - Switchgear 4-kV bus F cubicle
	51HG9	CH Pump 12 prevented from Starting	SHG9 - Switchgear 4-kV bus G cubicle
	51HF15	SI Pump 11 prevented from Starting	SHF15 - Switchgear 4-kV bus F cubicle
	L-52HF15/CS	SI Pump 11 starts	SHF15 - Switchgear 4-kV bus F cubicle
	C-52HF15/CS	SI Pump 11 starts	CNSI - Control board SI (VBI)
	2HF15	SI Pump 11 starts	SHF15 - Switchgear 4-kV bus F cubicle
	51HH15	SI Pump 12 prevented from starting	SHH15 - Switchgear 4-kV bus H cubicle
	L-52HH15/CS	SI Pump 11 starts	SHH15 - Switchgear 4-kV bus H cubicle
	C-52HH15/CS	SI Pump 11 starts	CNSI - Control board SI (VBI)
	2HH15	SI Pump 11 starts	SHH15 - Switchgear 4-kV bus H cubicle
	42-1F-63/CS	VLV 8923A loss of RWST suction (3)	CNSI - Control board SI and a
	42-1H-71/CS	VLV 8923B loss of RWST suction (3)	CNSI - Control board SI and a
	42-1F-49/CS	VLV 8821A prevent successful injection (4)	CNSI - Control board SI and a
	42-1F-31/CS	VLV 8821B prevent successful injection (4)	CNSI - Control board SI and a
NOTE: (1) Valves 8835, 8974A, 8974B, and 8976 are not powered so they cannot change state. (2) Charging pumps have oil pumps driven off motor shaft so it does not matter if auxiliary lube oil pump starts. (3) Loss of RWST suction can fall pump if pump starts. (4) Need to recover for successful injection at a later time.			
10. 4 kV/480V	51HF10	Breaker tripped; loss of 480V	SHF10 - Switchgear 4-kV bus F cubicle
	51HG10	Breaker tripped; loss of 480V	SHG10 - Switchgear 4-kV bus G cubicle
	51HH10	Breaker tripped; loss of 480V	SHH10 - Switchgear 4-kV bus H cubicle
	51HF13	Breaker tripped; loss of 4 kV	SHF13 - Switchgear 4-kV bus F cubicle
	51HG13	Breaker tripped; loss of 4 kV	SHG13 - Switchgear 4-kV bus G cubicle
	51HH13	Breaker tripped; loss of 4 kV	SHH13 - Switchgear 4-kV bus H cubicle
	51HF14	Breaker tripped; loss of 4 kV	SHF14 - Switchgear 4-kV bus F cubicle
	51HG14	Breaker tripped; loss of 4 kV	SHG14 - Switchgear 4-kV bus G cubicle
	51HH14	Breaker tripped; loss of 4 kV	SHH14 - Switchgear 4-kV bus H cubicle

Table 6-42.
PLANT COMPONENT FAILURE MODES

Component	Failure Mode
Containment building	Concrete shell cracking, liner break.
Containment internal structure	Shield wall shear cracks, attached components fail to function, reactor vessel failure, and reactor trip failure.
Intake structure	Shear wall fails, intake pumps fail to function.
Auxiliary building	North-South shear wall fails, structure fails, attached components fail to function.
Turbine building	Shear wall at column 31 fails, 4-kV switchgear fails to function, bracing strut fails, electrical panels fail to function.
Refueling water storage tank	Failure of tank integrity, loss of contents.
Auxiliary saltwater piping	Pipe rupture, loss of contents.
Reactor pressure vessel	Line break, loss of coolant, excessive LOCA.
Reactor internals	Failure of reactor trip and of core cooling geometry.
Steam generator	Main steam and other line breaks, excessive LOCA.
PORVs	Fails as is, binding.
Reactor coolant pumps	Excessive seal leak, small LOCA.
RHR pumps	Failure to function, line break.
RHR heat exchangers	Intake and discharge line ruptures.
Safety injection accumulators	Line break, loss of contents.
Boron injection tank	Line break, failure of charging pump system.
CCW pumps	Loss of pump function (not a line break).
CCW heat exchangers	Line break, loss of CCW and auxiliary saltwater.
CCW surge tank	Loss of surge tank and possibly surge line low pressure leak.
Containment spray pumps	Line break, loss of contents.
Spray additive tank	Loss of contents and one pump.
Auxiliary feedwater pumps	Line break, loss of contents.
Diesel fuel oil pumps	Line break, loss of contents.

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Table 6-42 (Continued)
PLANT COMPONENT FAILURE MODES

Component	Failure Mode
Diesel generators	Failure to function.
Diesel-generator radiator/water pump	Line break, loss of cooling, failing diesel.
Diesel-generator excitation cubicle	Failure to function.
Diesel-generator control panel	Failure to function.
Containment fan cooler	Failure to function, rupture of CCW piping.
Control room ventilation supply fans	Failure to function.
Electrical rooms ventilation dampers (that is, 480V)	Failure to remain open.
4-kV switchgear—structure	Circuit disconnect.
4-kV switchgear—chatter	Circuit interruption.
4-kV potential transformers	Failure to function, bus F only.
4-kV safeguard relay panel	Failure to function.
125V DC batteries	Failure to function.
Battery chargers	Failure to function.
125V DC switchgear/breaker panels	Failure to function.
120V AC inverters	Failure to function.
4,160/480V transformers	Failure to function.
Auxiliary relay panel	Loss of function, structural failure.
Main boards	Failure to function of all instrumentation readout (controls remain operable).
Hot shutdown panel	Failure to function.
NSSS process control and protection system	Failure to function, loss of indicators and control.
Reactor trip switchgear	Failure to function.
Pressure and Δ transmitters	Loss of indicators.
Local starter boards	Electrical disconnects.
Impulse lines	Line break, small LOCA.
Auxiliary transformers	Insulator failure, failure to function.
Electrical penetrations/boxes	Instrumentation failure to function.

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Table 6-42 (Continued)
 PLANT COMPONENT FAILURE MODES

Component	Failure Mode
HVAC ducting and supports	Duct joint break, loss of air, one segment per system.
BOP above ground piping and supports	Line break, loss of contents.
Segments per system:	
Fuel Oil	6
ASW	4
CCW	29
Small LOCA	2
Medium LOCA	1
Large LOCA	1
RWST	18
	(Including SI, RHR, and Spray Segments)
Charging	3
AFW	3
Main steam outside containment	3
Fire water system to charging pump rooms	4
Loss of offsite power	230-kV substation function fails. 500-kV substation function fails.

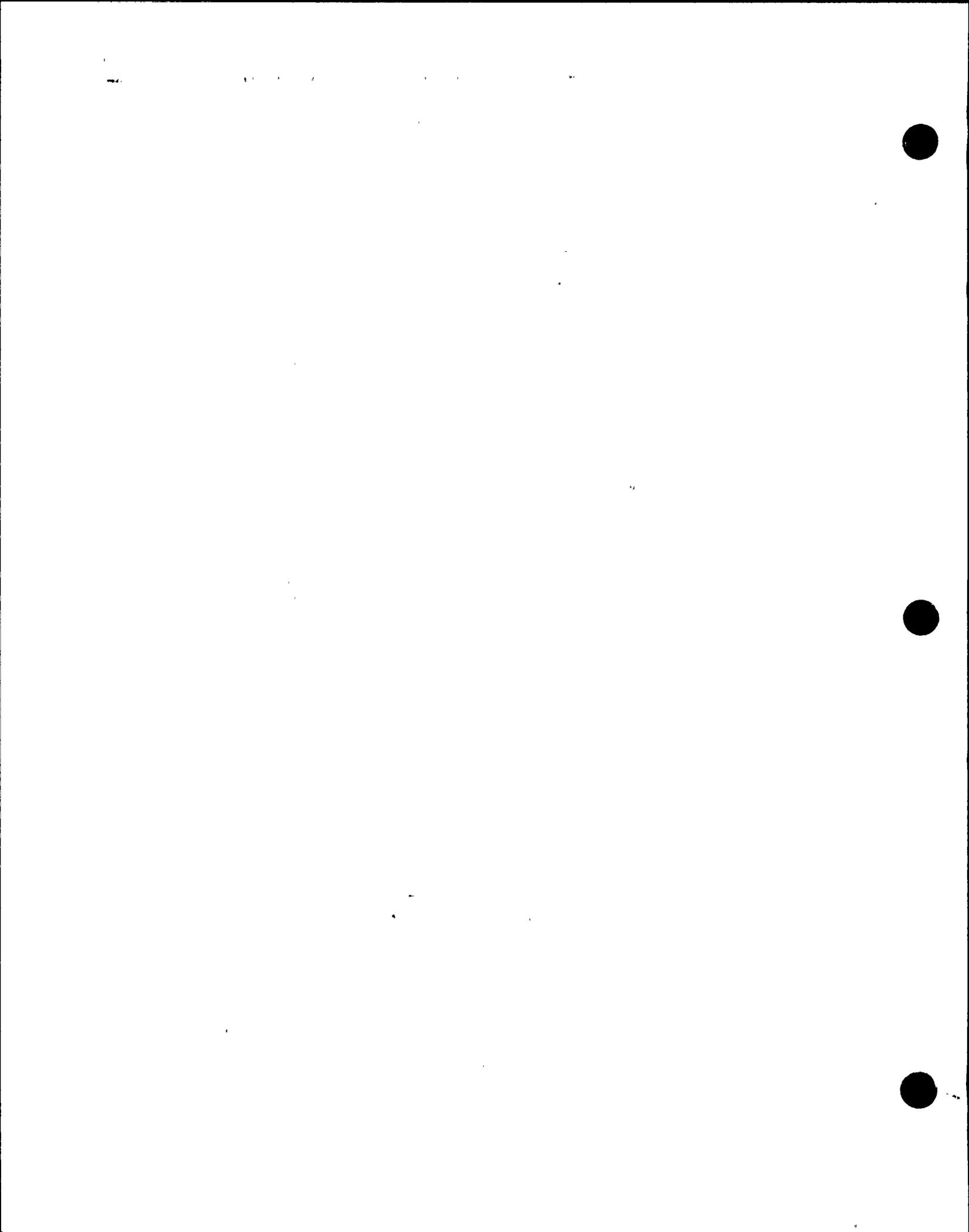


Table 6-43
SEISMIC FAILURE IMPACTS

Sheet 1 of 4

Component/Structures	Top Event Impacted																				Notes						
	OP	DF	AF	AG	AF	GF	FO	II-14	RT	RT	CY	CC	AS	SV	CT	EL	CI	ID	RW	PR		SE	CH	AW	FC	CS	CP
	DH	AH			2H				Partial				Partial											Partial			
Containment Building																										X	
Concrete Internal Biostructure																X											
Intake Structure												X															
Auxiliary Building			X																								
Turbine Building Shear Wall				X																							
Refueling Water Storage																		X									
Auxiliary Saltwater Piping												X															
Reactor Pressure Vessel																X											
Reactor Internals								X																			
Steam Generators																X	X										(a)
Power-Operated Relief Valves																				X							
Reactor Coolant Pumps																					X						
RHR Pumps																			X								
RHR Heat Exchangers											X																
Safety Injection Accumulators																			X								(b)

- a. CI impacted only if EL has failed.
- b. No impact.
- c. Not modeled, high capacity.
- d. Applies only if turbine building strut has not failed.
- e. Only if OP is successful.
- f. Not modeled, 230-kV has higher capacity.
- g. See following table:

System	Number of Fragility Segments
FO	2 for System
CCW	29 for System
ASW	4 for System
CH	1 for EL, 1 for PR, 3 for System
RHR/SI	1 Common for LOCA
RWST	18 (3 for RWST, 6 for SI system, 4 for RHR system, 5 for CS system)
SE	4 for Firewater System
AW	3 for AFW System, 3 for Main Steam System

- h. No cable failure impact.
- i. Switchgear ventilation ducting recoverable by opening doors.
- j. Applies only if turbine building strut has failed.

LEGEND:

OP	Offsite Power
DF, DG, DH	125V DC Power (3 trains)
AF, AG, AH	4,160V Vital AC (3 trains)
AF	4,160V Bus F Potential Transformer
GF-2H	Five Diesel Generators for Units 1 and 2
FO	Fuel Oil Transfer System
II-14	Four Vital Instrument Channels
RT	Reactor Trip
RT (Partial)	Reactor Trip Function Given Offsite Power Success
CY	Control Room Ventilation
CC	Component Cooling Water
AS	Auxiliary Saltwater
SV (Partial)	480V Switchgear Ventilation System
CT	Relay Chatter
EL	Excessive LOCA
CI	Containment Isolation
ID	Control Room and Hot Shutdown Panel Indication
RW	Refueling Water Storage Tank
PR	Pressurizer Relief/Small LOCAs
SE	RCP Seal Cooling
CH	Centrifugal Charging Pumps
AW	Auxiliary Feedwater
CS (Partial)	Containment Spray Pump 12
CP	Large Hole in Containment





Table 6-43 (Continued)
SEISMIC FAILURE IMPACTS

Sheet 3 of 4

Component/Structures	Top Event Impacted																			Notes								
	OP	DF	AF	AG	AF	GF	FO	11-14	RT	RT	CV	CC	AS	SV	CT	EL	CI	ID	RW		PR	SE	CH	AW	FC	CS	CP	
	DH	AH		2H				Partial	Partial				Partial											Partial				
Bus F Potential Transformer					X																						(d)	
Safeguard Relay Panel					X																							(d)
Batteries					X																							
Battery Chargers					X																							
DC Switchgear/Breaker Panel					X																							
Inverters									X																			
4,160/480V Transformers					X																							
Auxiliary Relay Panel																									X			
Main Control Boards																											X	
Hot Shutdown Panel																											X	
Process Control and Protection									X																			
Reactor Trip Switchgear																										X		(e)
Pressure and ΔP Transmitter									X																			
Impulse Lines																											X	
Offsite Power, 230 kV																										X		

- a. CI impacted only if EL has failed.
 b. No impact.
 c. Not modeled, high capacity.
 d. Applies only if turbine building strut has not failed.
 e. Only if OP is successful.
 f. Not modeled, 230-kV has higher capacity.
 g. See following table:

System	Number of Fragility Segments
FO	2 for System
CCW	29 for System
ASW	4 for System
CH	1 for EL, 1 for PR, 3 for System
RHR/SI	1 Common for LOCA
RHST	18 (3 for RHST, 6 for SI system, 4 for RHR system, 5 for CS system)
SE	4 for Firewater System
AW	3 for AFW System, 3 for Main Steam System

- h. No cable failure impact.
 i. Switchgear ventilation ducting recoverable by opening doors.
 j. Applies only if turbine building strut has failed.

LEGEND:	OP	Offsite Power
	DF, DG, DH	125V DC Power (3 trains)
	AF, AG, AH	4,160V Vital AC (3 trains)
	AF	4,160V Bus F Potential Transformer
	GF-2H	Five Diesel Generators for Units 1 and 2
	FO	Fuel Oil Transfer System
	11-14	Four Vital Instrument Channels
	RT	Reactor Trip
	RT (Partial)	Reactor Trip Function Given Offsite Power Success
	CV	Control Room Ventilation
	CC	Component Cooling Water
	AS	Auxiliary Saltwater
	SV (Partial)	480V Switchgear Ventilation System
	CT	Relay Chatter
	EL	Excessive LOCA
	CI	Containment Isolation
	ID	Control Room and Hot Shutdown Panel Indication
	RW	Refueling Water Storage Tank
	PR	Pressurizer Relief/Small LOCAs
	SE	RCP Seal Cooling
	CH	Centrifugal Charging Pumps
	AW	Auxiliary Feedwater
	CS (Partial)	Containment Spray Pump 12
	CP	Large Hole in Containment

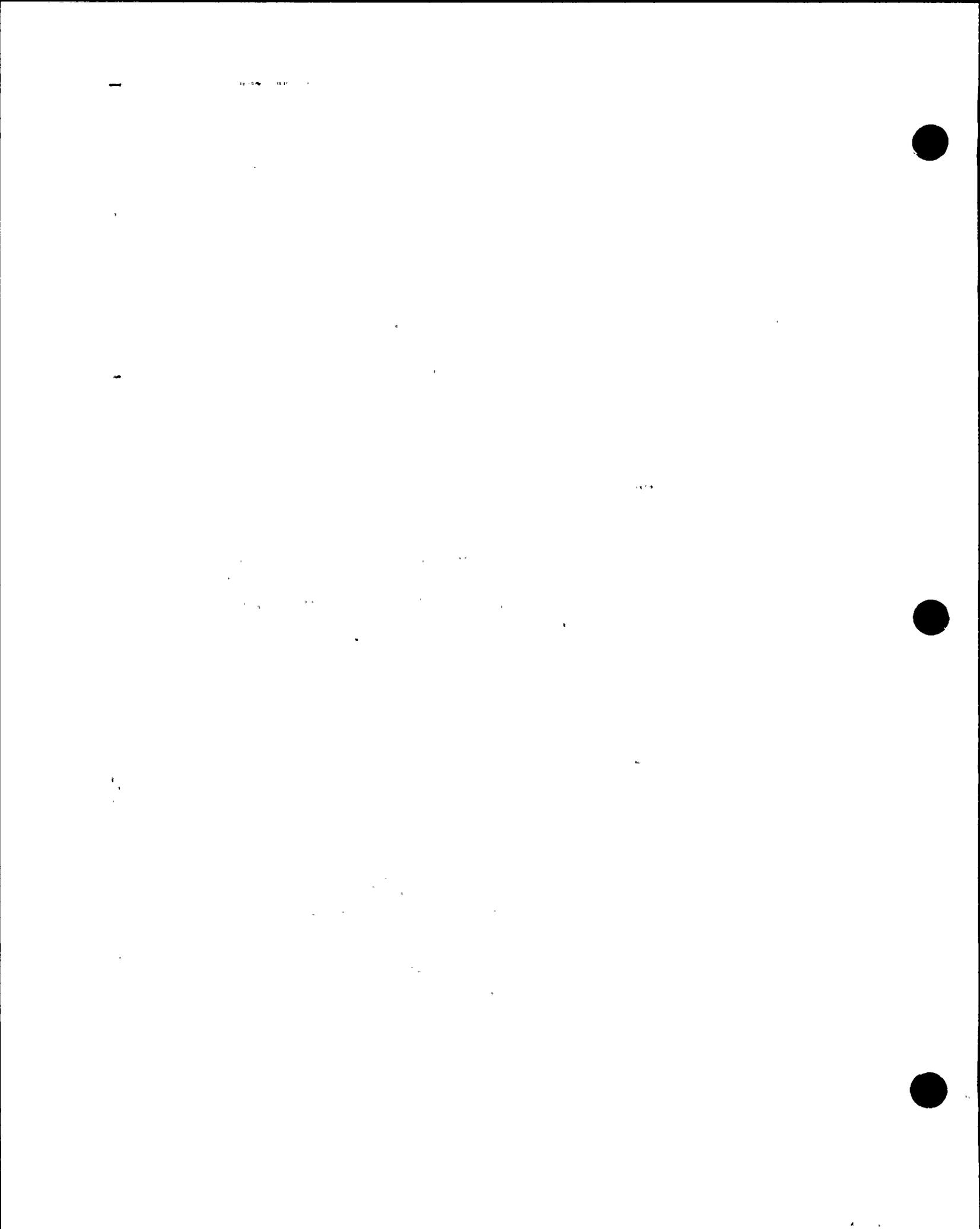


Table 6-43 (Continued)
SEISMIC FAILURE IMPACTS

Sheet 4 of 4

Component/Structures	Top Event Impacted																				Notes						
	OP	DF	AF	AG	AF	GF	FO	I1-14	RT	RT	CV	CC	AS	SY	CT	EL	CI	ID	RW	PR		SE	CH	AW	FC	CS	CP
	DH	AH		2H					Partial				Partial											Partial			
Offsite Power, 500 kV																											(f)
BOP Piping and Supports						X					X	X				X			X	X	X						(g)
Penetrations/Penetration Boxes																											(h)
HVAC Ducting and Supports											X		X														(i)
4-kV Switchgear/Strut Falls				X																							(j)
Chatter, Main Control Board																X											
Chatter, Diesel Generator Control Panel																X											
Chatter, 4-kV Switchgear																X											
Chatter, Safeguard Relay Panel																											(b)
Turbine Building Strut				X																							
Bus F Potential Transformer/Strut Falls					X																						(j)
Safeguard Relay Panel/Strut Falls				X																							(j)
Centrifugal Charging Pump																											(c)

- a. CI impacted only if EL has failed.
 b. No impact.
 c. Not modeled, high capacity.
 d. Applies only if turbine building strut has not failed.
 e. Only if OP is successful.
 f. Not modeled, 230-kV has higher capacity.
 g. See following table:

System	Number of Fragility Segments
FO	2 for System
CCW	29 for System
ASW	4 for System
CH	1 for EL, 1 for PR, 3 for System
RHR/SI	1 Common for LOCA
RWST	18 (3 for RWST, 6 for SI system, 4 for RHR system, 5 for CS system)
SE	4 for Firewater System
AW	3 for AFW System, 3 for Main Steam System

- h. No cable failure impact.
 i. Switchgear ventilation ducting recoverable by opening doors.
 j. Applies only if turbine building strut has failed.

LEGEND:

OP	Offsite Power
DF, DG, DH	125V DC Power (3 trains)
AF, AG, AH	4,160V Vital AC (3 trains)
AF	4,160V Bus F Potential Transformer
GF-2H	Five Diesel Generators for Units 1 and 2
FO	Fuel Oil Transfer System
I1-14	Four Vital Instrument Channels
RT	Reactor Trip
RT (Partial)	Reactor Trip Function Given Offsite Power Success
CV	Control Room Ventilation
CC	Component Cooling Water
AS	Auxiliary Saltwater
SY (Partial)	480V Switchgear Ventilation System
CT	Relay Chatter
EL	Excessive LOCA
CI	Containment Isolation
ID	Control Room and Hot Shutdown Panel Indication
RW	Refueling Water Storage Tank
PR	Pressurizer Relief/Small LOCAs
SE	RCP Seal Cooling
CH	Centrifugal Charging Pumps
AW	Auxiliary Feedwater
CS (Partial)	Containment Spray Pump 12
CP	Large Hole in Containment

Table 6-44

CONDITIONAL MEAN FAILURE FRACTIONS OF KEY STRUCTURES OR COMPONENTS

: (sheet 1 of 2)

COMPONENT/STRUCTURES	*	DISCRETE ACCELERATION RANGE <G>					
		* 0. 725	1. 500	1. 875	2. 250	2. 750	3. 500
1. CONTAINMENT BUILDING	* 1. 06E-08	8. 17E-06	7. 82E-05	4. 03E-04	2. 18E-03	9. 16E-03	
2. CONCRETE INTERNAL BIOSTRUCTURE	* 3. 06E-08	2. 06E-05	2. 01E-04	1. 08E-03	5. 65E-03	2. 24E-02	
3. INTAKE STRUCTURE	* 4. 24E-08	1. 71E-05	1. 37E-04	6. 38E-04	3. 00E-03	1. 13E-02	
4. AUXILIARY BUILDING	* 3. 71E-08	3. 33E-05	3. 72E-04	2. 15E-03	1. 17E-02	4. 56E-02	
5. TURBINE BUILDING SHEAR WALL	* 1. 94E-05	2. 47E-03	1. 14E-02	3. 01E-02	8. 03E-02	1. 71E-01	
6. REFUELING WATER STORAGE TANK	* 9. 20E-08	2. 29E-05	1. 51E-04	6. 07E-04	2. 51E-03	8. 54E-03	
7. AUXILIARY SALTWATER PIPING	* 0. 00E-01	0. 00E-01	0. 00E-01	1. 38E-07	5. 89E-06	1. 34E-04	
8. REACTOR PRESSURE VESSEL	* 2. 50E-08	1. 21E-05	1. 05E-04	4. 88E-04	2. 43E-03	9. 50E-03	
9. REACTOR INTERNALS	* 1. 01E-07	2. 26E-05	1. 42E-04	5. 51E-04	2. 21E-03	7. 38E-03	
10. STEAM GENERATORS	* 7. 02E-07	1. 54E-04	1. 00E-03	3. 56E-03	1. 31E-02	3. 85E-02	
11. POWER OPERATED RELIEF VALVES	* 8. 53E-06	7. 89E-04	3. 27E-03	8. 29E-03	2. 23E-02	5. 10E-02	
12. REACTOR COOLANT PUMPS	* 1. 02E-06	1. 43E-04	7. 72E-04	2. 39E-03	7. 88E-03	2. 17E-02	
13. RHR PUMPS	* 1. 30E-08	9. 25E-06	8. 79E-05	4. 48E-04	2. 40E-03	9. 94E-03	
14. RHR HEAT EXCHANGERS	* 0. 00E-01	2. 03E-06	2. 65E-05	1. 82E-04	1. 27E-03	6. 66E-03	
15. SI ACCUMULATORS	* 0. 00E-01	0. 00E-01	7. 15E-07	8. 19E-06	8. 62E-05	7. 52E-04	
16. BORDON INJECTION TANK	* 0. 00E-01	8. 61E-08	2. 70E-06	2. 93E-05	2. 98E-04	2. 34E-03	
17. CCH PUMPS	* 0. 00E-01	7. 86E-07	1. 21E-05	9. 07E-05	7. 10E-04	4. 14E-03	
18. CCH HEAT EXCHANGERS	* 3. 72E-07	1. 18E-04	9. 10E-04	3. 65E-03	1. 49E-02	4. 67E-02	
19. CCH SURGE TANK	* 1. 07E-07	4. 13E-05	3. 32E-04	1. 50E-03	6. 77E-02	2. 38E-02	
20. CONTAINMENT SPRAY PUMPS	* 0. 00E-01	4. 23E-07	7. 48E-06	6. 12E-05	5. 16E-04	3. 26E-03	
21. SPRAY ADDITIVE TANK	* 7. 62E-09	1. 03E-05	1. 17E-04	7. 49E-04	4. 47E-03	1. 98E-02	
22. AFW PUMPS	* 0. 00E-01	3. 18E-06	4. 01E-05	2. 68E-04	1. 80E-03	9. 02E-03	
23. DO FUEL OIL PUMPS/FILTERS	* 0. 00E-01	8. 85E-07	1. 36E-05	1. 03E-04	8. 05E-04	4. 67E-03	
24. DIESEL GENERATORS	* 0. 00E-01	3. 53E-07	7. 51E-06	7. 19E-05	6. 81E-04	4. 64E-03	
25. DO RADIATOR/WATER PUMP	* 0. 00E-01	1. 69E-06	2. 10E-05	1. 36E-04	9. 24E-04	4. 77E-03	
26. DO EXCITATION CUBICAL	* 1. 36E-06	2. 23E-04	1. 26E-03	4. 02E-03	1. 35E-02	3. 69E-02	
27. DO CONTROL PANEL	* 8. 04E-07	3. 91E-04	3. 37E-03	1. 42E-02	5. 60E-02	1. 57E-01	
28. CONTAINMENT FAN COOLER	* 5. 15E-07	9. 83E-05	6. 14E-04	2. 13E-03	7. 77E-03	2. 32E-02	
29. SUPPLY FANS	* 0. 00E-01	2. 56E-06	2. 59E-05	1. 42E-04	8. 42E-04	3. 90E-03	
30. SUPPLY/RETURN FANS	* 3. 93E-09	3. 83E-06	3. 18E-05	1. 48E-04	7. 64E-04	3. 17E-03	

Table 6-44 (Continued)

CONDITIONAL MEAN FAILURE FRACTIONS OF KEY STRUCTURES OR COMPONENTS

(sheet 2 of 2)

COMPONENT/STRUCTURES	*	DISCRETE ACCELERATION RANGE <G>					
		0.725	1.500	1.875	2.250	2.750	3.500
31. 4KV SWITCHGEAR	*	7.97E-08	3.24E-05	2.65E-04	1.22E-03	5.64E-03	2.04E-02
32. BUS F POTENTIAL TRANSFORMER	*	1.47E-07	2.83E-05	1.68E-04	6.18E-04	2.37E-03	7.59E-03
33. SAFEGUARD RELAY PANEL	*	1.97E-07	3.51E-05	2.01E-04	7.20E-04	2.68E-03	8.37E-03
34. BATTERIES	*	6.10E-08	4.11E-05	4.14E-04	2.19E-03	1.11E-02	4.13E-02
35. BATTERY CHARGERS	*	1.36E-06	1.53E-04	7.44E-04	2.14E-03	6.64E-03	1.75E-02
36. SWITCHGEAR/BREAKER PANELS	*	2.84E-06	4.32E-04	2.31E-03	6.98E-03	2.20E-02	5.66E-02
37. INVERTERS	*	1.69E-07	6.04E-05	4.98E-04	2.14E-03	9.30E-03	3.15E-02
38. 4160/480V TRANSFORMERS	*	2.49E-07	1.28E-04	1.19E-03	5.47E-03	2.43E-02	7.88E-02
39. AUXILIARY RELAY PANEL	*	0.00E-01	5.23E-07	1.10E-05	1.08E-04	1.03E-03	6.91E-03
40. MAIN CONTROL BOARDS	*	9.86E-08	3.46E-05	2.66E-04	1.18E-03	5.22E-03	1.84E-02
41. HOT SHUTDOWN PANEL	*	3.85E-09	6.45E-06	7.27E-05	4.30E-04	2.59E-03	1.17E-02
42. PROCESS CONTROL AND PROTECTION SYSTEM	*	9.27E-08	2.07E-05	1.29E-04	5.02E-04	2.02E-03	6.77E-03
43. REACTOR TRIP SWITCHGEAR	*	3.13E-08	1.63E-05	1.42E-04	7.15E-04	3.56E-03	1.39E-02
44. PRESSURE & DP TRANSMITTERS	*	0.00E-01	4.53E-08	1.82E-06	1.99E-05	2.04E-04	1.65E-03
45. IMPULSE LINES	*	5.95E-07	1.33E-04	8.81E-04	3.17E-03	1.18E-02	3.52E-02
46. OFF-SITE POWER, 230kv	*	8.37E-03	3.19E-01	6.23E-01	7.93E-01	9.29E-01	9.80E-01
47. OFF-SITE POWER 500 KV	*	1.61E-01	9.63E-01	9.96E-01	9.99E-01	1.00E+00	1.00E+00
48. BOP PIPING AND SUPPORTS	*	1.59E-06	1.50E-04	6.77E-04	1.84E-03	5.45E-03	1.39E-02
49. PENETRATIONS/PENETRATION BOXES	*	1.86E-07	5.60E-05	4.31E-04	1.76E-03	7.42E-03	2.47E-02
50. HVAC DUCTING AND SUPPORTS	*	1.17E-05	7.58E-04	2.69E-03	6.16E-03	1.52E-02	3.28E-02
51. SWITCHGEAR /STRUT	*	1.54E-07	5.29E-05	4.32E-04	1.85E-03	8.04E-03	2.74E-02
52. CHATTER, MAIN CONTROL BOARD	*	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01
53. CHATTER, DO CONTROL PANELS	*	0.00E-01	0.00E-01	3.12E-07	8.08E-06	1.32E-04	1.61E-03
54. CHATTER, 4KV SWITCHGEAR PANEL	*	3.35E-04	2.18E-02	6.97E-02	1.37E-01	2.65E-01	4.25E-01
55. CHATTER, SAFEGUARDS RELAY BOARD	*	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01
56. STRUT FOR TBLDO	*	4.36E-07	1.17E-04	8.49E-04	3.25E-03	1.28E-02	3.94E-02
57. BUS F POTENTIAL TRANSFORMER /STRUT	*	3.24E-05	2.63E-03	1.01E-02	2.36E-02	5.75E-02	1.18E-01
58. SAFEGUARD RELAY PANEL /STRUT	*	3.85E-05	2.97E-03	1.11E-02	2.54E-02	6.07E-02	1.23E-01
59. CENTRIFUGAL CHARGING PUMP	*	0.00E-01	5.76E-08	1.78E-06	1.62E-05	1.44E-04	1.06E-03

Table 6-45

UNCONDITIONAL FAILURE FRACTIONS FOR TOP EVENTS

Sheet 1 of 3

Set	Component t/Structures	Discrete Acceleration Level (g)*					
		0.725	1.500	1.875	2.250	2.750	3.500
1	DF, DG, DH 125V DC Power - SUM	4.15-08	3.99-07	4.50-07	1.32-06	1.25-06	1.02-06
	ZABLDG Auxiliary Building	5.24-10	2.62-08	5.41-08	2.52-07	3.30-07	3.39-07
	ZBATRY Batteries	8.61-10	3.24-08	6.03-08	2.56-07	3.13-07	3.07-07
	ZSWGEP Switchgear/Breaker Panel	4.01-08	3.40-07	3.36-07	8.18-07	6.22-07	4.21-07
2	AF, AG, AH - TB Strut OK - SUM	2.83-07	2.12-06	1.93-06	4.44-06	3.17-06	1.96-06
	ZTBSHR Turbine Building Shear Wall	2.73-07	1.95-06	1.66-06	3.53-06	2.27-06	1.27-06
	ZSWGER 4-kV Switchgear	1.12-09	2.55-08	3.85-08	1.43-07	1.59-07	1.51-07
	ZTFKFF Bus F Potential Transformer	2.08-09	2.23-08	2.44-08	7.24-08	6.68-08	5.64-08
	ZSFGRP Safeguard Relay Panel	2.78-09	2.76-08	2.92-08	8.43-08	7.56-08	6.23-08
	ZTRANS 4,160/480V Transformers	3.52-09	1.01-07	1.73-07	6.41-07	6.87-07	5.86-07
3	AF, AG, AH - TB Strut Failure - SUM	1.00-06	4.44-06	3.12-06	5.87-06	3.44-06	1.84-06
	ZTFRF2 Bus F Potential Transformer	4.57-07	2.07-06	1.46-06	2.76-06	1.62-06	8.77-07
	ZSFGR2 Safeguard Relay Panel	5.44-07	2.34-06	1.61-06	2.98-06	1.72-06	9.14-07
	XSWGE2 Switchgear/Strut	2.17-07	4.17-08	6.29-08	2.16-07	2.27-07	2.04-07
4	AF, AG, AH - W/Strut Failure - PRD	4.37-13	5.22-10	2.65-09	1.91-08	4.39-08	7.25-08
	AF, AG, AH - TB Strut Failure	1.00-06	4.44-06	3.12-06	5.87-06	3.44-06	1.84-06
	ZSTRUT Strut for Turbine Building	6.15-09	9.25-08	1.23-07	3.80-07	3.60-07	2.93-07
5	Onsite AC Supply - SUM	4.98-08	6.05-07	7.85-07	2.39-06	2.16-06	1.56-06
	ZOSLGN Diesel Generators	0.00-01	2.78-10	1.09-09	8.42-09	1.92-08	3.45-08
	ZDGRWP Diesel Generator Radiator/Water Pump	0.00-01	1.33-09	3.06-09	1.59-08	2.61-08	3.55-08
	ZDGEXC Diesel Generator Excitation Cubicle	1.92-08	1.75-07	1.83-07	4.70-07	3.80-07	2.74-07
	ZDGCPN Diesel Generator Control Panel	1.13-08	3.08-07	4.91-07	1.66-06	1.58-06	1.17-06
	ZBATCH Battery Chargers	1.93-08	1.20-07	1.08-07	2.51-07	1.87-07	1.30-07
	Onsite AC W/OP Failure - PRD	4.17-10	1.93-07	4.89-07	1.90-06	2.00-06	1.53-06
Onsite AC Supply	4.98-08	6.05-07	7.85-07	2.39-06	2.16-06	1.56-06	
ZOSPWR Offsite Power, 230 kV	1.18-04	2.52-04	9.06-05	9.29-05	2.62-05	7.29-06	
7	IN Instrument and Inverters - SUM	3.69-09	6.39-08	9.14-08	3.11-07	3.25-07	2.94-07
	ZINVTR Inverters	2.38-09	4.76-08	7.23-08	2.50-07	2.63-07	2.34-07
	ZPCAPS Process Control and Pro	1.31-09	1.63-08	1.88-08	5.88-08	5.71-08	5.03-08
	ZPADPT Pressure and ΔP Transmitters	0.00-01	3.57-11	2.65-10	2.33-09	5.76-09	1.23-08

*Fragilities are summed in the following way: SUM = FRAGILITY1 + FRAGILITY2 - (FRAGILITY1) * (FRAGILITY2)

NOTE: Exponential notation is indicated in abbreviated form; i.e., 4.15-08 = 4.15 x 10⁻⁰⁸.

Table 6-45 (Continued)

UNCONDITIONAL FAILURE FRACTIONS FOR TOP EVENTS

Sheet 2 of 3

Set	Component/Structures		Discrete Acceleration Level (g)*					
			0.725	1.500	1.875	2.250	2.750	3.500
8	RT Reactor Trip	- SUM	1.87-09	3.06-08	4.14-08	1.48-07	1.63-07	1.57-07
	ZRXINT Reactor Internals		1.43-09	1.78-08	2.07-08	6.46-08	6.25-08	5.49-08
	ZRTSWG Reactor Trip Switchgear		4.42-10	1.28-08	2.07-08	8.37-08	1.00-07	1.03-07
9	AS Auxiliary Saltwater	- SUM	2.31-08	1.31-07	1.18-07	2.91-07	2.38-07	1.87-07
	ZINSTR Intake Structure		5.99-10	1.35-08	1.99-08	7.47-08	8.47-08	8.37-08
	ZASPIP Auxiliary Saltwater Piping		0.00-01	0.00-01	0.00-01	1.61-11	1.66-10	9.93-10
	ZBOPPS BOP Piping and Supports		2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
10	CC Component Cooling Water	- SUM	1.71-07	1.03-06	9.61-07	2.38-06	1.90-06	1.37-06
	ZRRHX RHR Heat Exchangers		0.00-01	1.59-09	3.86-09	2.13-08	3.60-08	4.95-08
	ZCCWPP CCH Pumps		0.00-01	6.19-10	1.76-09	1.06-08	2.00-08	3.07-08
	ZCCWHX CCH Heat Exchangers		5.25-09	9.32-08	1.32-07	4.28-07	4.20-07	3.47-07
	ZCCWTK CCH Surge Tank		1.51-09	3.25-08	4.83-08	1.76-07	1.91-07	1.77-07
	ZCONFC Containment Fan Cooler		7.28-09	7.74-08	8.93-08	2.49-07	2.19-07	1.72-07
	ZBOPPS BOP Piping and Supports		2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
	ZBOPPS BOP Piping and Supports		2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
	ZBOPPS BOP Piping and Supports		2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
	ZBOPPS BOP Piping and Supports		2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
	ZBOPPS BOP Piping and Supports		2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
	ZBOPPS BOP Piping and Supports		2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
11	Fire Water Backup	- SUM	3.69-08	2.31-07	2.11-07	4.97-07	3.79-07	2.71-07
	ZRCPMP Reactor Coolant Pumps		1.44-08	1.13-07	1.12-07	2.80-07	2.22-07	1.62-07
	ZBOPPS BOP Piping Supports		2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
	ZCHPMP Centrifugal Charging Pumps		0.00-01	4.54-11	2.58-10	1.90-09	4.07-09	7.88-09
12	Excess LOCA-RHR Injection	- SUM	2.25-09	1.18-08	9.83-09	2.16-08	1.53-08	1.03-08
	ZBOPPS BOP Piping and Supports		2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
	ZBOPPS BOP Piping and Supports		2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
13	EL Excessive LOCA	- SUM	1.29-08	1.59-07	2.00-07	6.21-07	6.09-07	5.22-07
	ZBISTR Concrete Internal Biostructure		4.32-10	1.62-08	2.92-08	1.27-07	1.60-07	1.66-07
	ZRXPVR Reactor Pressure Vessel		3.53-10	9.52-09	1.52-08	5.71-08	6.86-08	7.06-08
	ZSTMGN Steam Generators		9.91-09	1.21-07	1.46-07	4.16-07	3.69-07	2.86-07
	Excess LOCA-RHR Injection Pipe		2.25-09	1.18-08	9.83-09	2.16-08	1.53-08	1.03-08

*Fragilities are summed in the following way: SUM = FRAGILITY1 + FRAGILITY2 - (FRAGILITY1) * (FRAGILITY2)

NOTE: Exponential notation is indicated in abbreviated form; i.e., 1.87-09 = 1.87 x 10⁻⁰⁹.

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Table 6-45 (Continued)

UNCONDITIONAL FAILURE FRACTIONS FOR TOP EVENTS

Sheet 3 of 3

Set	Component/Structures	Discrete Acceleration Level (g)*					
		0.725	1.500	1.875	2.250	2.750	3.500
14	RW Refuel Water Storage Tank - SUM	9.14-08	4.97-07	4.29-07	9.91-07	7.60-07	5.57-07
	ZRWSTK Refueling Water Storage	1.30-09	1.80-08	2.20-08	7.11-08	7.09-08	6.35-08
	ZRHRPP RHR Pumps	1.83-10	7.28-09	1.28-08	5.25-08	6.77-08	7.39-08
	ZCSPMP Containment Spray Pumps	0.00-01	3.33-10	1.09-09	7.17-09	1.46-08	2.42-08
	ZBOPPS BOP Piping and Supports	2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
	ZBOPPS BOP Piping and Supports	2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
	ZBOPPS BOP Piping and Supports	2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
	ZBOPPS BOP Piping and Supports	2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
15	Small LOCA - SUM	1.88-07	1.07-06	9.11-07	2.04-06	1.47-06	9.60-07
	ZPORVL Power-Operated Relief Valves	1.20-07	6.21-07	4.76-07	9.71-07	6.30-07	3.79-07
	ZRCPMP Reactor Coolant Pumps	1.44-08	1.13-07	1.12-07	2.80-07	2.22-07	1.62-07
	ZIPLNS Impulse Lines	8.40-09	1.04-07	1.28-07	3.71-07	3.33-07	2.62-07
	ZBOPPS BOP Piping and Supports	2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
	ZBOPPS BOP Piping and Supports	2.25-08	1.18-07	9.84-08	2.16-07	1.54-07	1.04-07
16	ID Operator Indications - SUM	1.45-09	3.23-08	4.92-08	1.88-07	2.20-07	2.22-07
	ZMCNTB Main Control Boards	1.39-09	2.72-08	3.86-08	1.38-07	1.47-07	1.37-07
	ZHSPNL Hot Shutdown Panel	5.43-11	5.08-09	1.06-08	5.04-08	7.32-08	8.73-08
17	Relay Chatter - SUM	4.72-06	1.71-05	1.01-05	1.60-05	7.49-06	3.17-06
	ZMCBCH Chatter, Main Control Board	0.00-01	0.00-01	0.00-01	0.00-01	0.00-01	0.00-01
	ZSGPCH Chatter, 4-kV Switchgear	4.72-06	1.71-05	1.01-05	1.60-05	7.48-06	3.16-06
	ZDCPCH Chatter, DG Control Panel	0.00-01	0.00-01	4.54-11	9.46-10	3.72-09	1.20-08

*Fragilities are summed in the following way: $SUM = FRAGILITY1 + FRAGILITY2 - (FRAGILITY1) * (FRAGILITY2)$

NOTE: Exponential notation is indicated in abbreviated form; i.e., 9.14-08 = 9.14×10^{-08} .

1000

1000

1000

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1000

1000

Table 6-46

SYSTEM SPLIT FRACTION QUANTIFICATION AS A FUNCTION OF SEISMIC LEVEL

Split Fraction ID	Seismic Level (spectral acceleration, g)						
	0.0-0.2	0.2-1.25	1.25-1.75	1.75-2.0	2.0-2.5	2.5-3.0	3.0-4.0
OS1	1.5000E-03	1.5000E-03	1.5000E-03	8.0000E-03	8.0000E-03	5.0000E-02	5.0000E-02
OSF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
IAF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
CDF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
FWF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
SE1	1.2700E-02	1.2700E-02	1.2990E-02	7.1350E-02	7.3930E-02	4.0800E-01	4.2120E-01
SE2	1.0220E-06	1.0220E-06	1.4330E-04	7.7190E-04	2.3870E-03	4.8780E-03	2.1750E-02
SE0	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01
SEF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
V10	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01
V11	1.9000E-05	1.9000E-05	1.9000E-05	1.9000E-05	1.9000E-05	1.9000E-05	1.9000E-05
V12	7.6000E-03	7.6000E-03	7.6000E-03	7.6000E-03	7.6000E-03	7.6000E-03	7.6000E-03
V13	4.7000E-04	4.7000E-04	4.7000E-04	4.7000E-04	4.7000E-04	4.7000E-04	4.7000E-04
V14	3.1000E-07	3.1000E-07	3.1000E-07	3.1000E-07	3.1000E-07	3.1000E-07	3.1000E-07
V15	4.5000E-03	4.5000E-03	4.5000E-03	4.5000E-03	4.5000E-03	4.5000E-03	4.5000E-03
RP0	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01
RP1	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
RP2	9.9630E-01	9.9630E-01	9.9630E-01	9.8000E-01	9.8000E-01	8.0000E-01	8.0000E-01
RPF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OI1	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OI2	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OI3	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OIF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OP1	2.8000E-03	2.8000E-03	2.8000E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OP2	2.8000E-03	2.8000E-03	2.8000E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OE1	1.7000E-03	1.7000E-03	1.7000E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OE2	1.7000E-03	1.7000E-03	1.7000E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OE3	1.7000E-03	1.7000E-03	1.7000E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
HS1	4.4000E-06	4.4000E-06	4.4000E-06	3.0000E-05	3.0000E-05	2.0000E-04	2.0000E-04
HS2	2.5000E-06	2.5000E-06	2.5000E-06	2.0000E-05	2.0000E-05	8.0000E-05	8.0000E-05
HS3	5.0000E-03	5.0000E-03	5.0000E-03	3.0000E-02	3.0000E-02	2.0000E-01	2.0000E-01
HS4	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
HSF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
RS1	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
RSF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
PL1	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01
MC1	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-02
SSF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
ODF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
CT1	2.1040E-04	2.1040E-04	1.5900E-02	5.7130E-02	1.2300E-01	2.6180E-01	4.4790E-01
CT2	2.1040E-04	2.1040E-04	1.5900E-02	5.7130E-02	1.2300E-01	2.6180E-01	4.4810E-01
EL1	1.1910E-06	1.1910E-06	2.4640E-04	1.5880E-03	5.7340E-03	2.1650E-02	6.5740E-02
ELF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
ID1	9.8020E-08	9.8020E-08	3.5150E-05	2.7880E-04	1.3140E-03	6.5360E-03	2.6920E-02
IDF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OC1	2.0000E-03	2.0000E-03	2.0000E-03	1.0000E-02	1.0000E-02	6.0000E-02	6.0000E-02
OC2	4.0000E-03	4.0000E-03	4.0000E-03	2.0000E-02	2.0000E-02	2.0000E-01	2.0000E-01
OC3	4.0000E-03	4.0000E-03	4.0000E-03	2.0000E-02	2.0000E-02	2.0000E-01	2.0000E-01
OC4	8.0000E-03	8.0000E-03	8.0000E-03	4.0000E-02	4.0000E-02	3.0000E-01	3.0000E-01
OCF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
AW1	4.3420E-05	4.3420E-05	2.6920E-04	1.0980E-03	3.0790E-03	9.9980E-03	2.9640E-02
AW2	1.2380E-01	1.2380E-01	1.2400E-01	1.2480E-01	1.2650E-01	1.3260E-01	1.4980E-01
AW3	1.2450E-03	1.2450E-03	1.4710E-03	2.2980E-03	4.2770E-03	1.1190E-02	3.0810E-02
AW4	9.0730E-02	9.0730E-02	9.0930E-02	9.1690E-02	9.3490E-02	9.9780E-02	1.1760E-01
AW5	4.3000E-03	4.3000E-03	4.5250E-03	5.3500E-03	7.3230E-03	1.4210E-02	3.3780E-02
AW6	2.1790E-01	2.1790E-01	2.1810E-01	2.1870E-01	2.2020E-01	2.2570E-01	2.4100E-01
AW7	6.2720E-03	6.2720E-03	6.4960E-03	7.3190E-03	9.2880E-03	1.6160E-02	3.5690E-02
AW8	7.7610E-03	7.7610E-03	7.9850E-03	8.8070E-03	1.0770E-02	1.7640E-02	3.7130E-02
AW9	1.5350E-01	1.5350E-01	1.5370E-01	1.5440E-01	1.5610E-01	1.6190E-01	1.7860E-01
AWA	7.9310E-02	7.9310E-02	7.9520E-02	8.0280E-02	8.2110E-02	8.8480E-02	1.0660E-01
AWB	1.8680E-02	1.8680E-02	1.8910E-02	1.9720E-02	2.1660E-02	2.8450E-02	4.7730E-02
AWC	2.4530E-03	2.4530E-03	2.6790E-03	3.5050E-03	5.4810E-03	1.2380E-02	3.1980E-02
AWF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
TD1	9.0730E-02	9.0730E-02	9.0930E-02	9.1690E-02	9.3490E-02	9.9780E-02	1.1760E-01
TD2	1.5350E-01	1.5350E-01	1.5370E-01	1.5440E-01	1.5610E-01	1.6190E-01	1.7860E-01
TDF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OG1	9.1960E-03	9.1960E-03	3.2160E-01	6.2480E-01	7.9450E-01	9.2980E-01	9.8030E-01

Table 6-46 (Continued)

SYSTEM SPLIT FRACTION QUANTIFICATION AS A FUNCTION OF SEISMIC LEVEL

Split Fraction ID	Seismic Level (spectral acceleration, g)						
	0.0-0.2	0.2-1.25	1.25-1.75	1.75-2.0	2.0-2.5	2.5-3.0	3.0-4.0
OGF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
NV1	1.6290E-04	1.6290E-04	1.6290E-04	1.6290E-04	1.6290E-04	1.6290E-04	1.6290E-04
NV2	2.4620E-03	2.4620E-03	2.4620E-03	2.4620E-03	2.4620E-03	2.4620E-03	2.4620E-03
NVF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
DF1	7.1990E-04	7.1990E-04	1.2210E-03	3.7950E-03	1.1930E-02	4.4580E-02	1.3670E-01
DG1	7.1700E-04	7.1700E-04	7.1700E-04	7.1700E-04	7.1700E-04	7.1700E-04	7.1700E-04
DG2	4.7900E-03	4.7900E-03	4.1370E-01	8.1180E-01	9.4060E-01	9.8460E-01	9.9550E-01
DGF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
DH1	7.1240E-04	7.1240E-04	7.1240E-04	7.1240E-04	7.1240E-04	7.1240E-04	7.1240E-04
DH2	7.1180E-04	7.1180E-04	7.1170E-04	7.1190E-04	7.0990E-04	7.0700E-04	7.2230E-04
DH3	7.1180E-04	7.1180E-04	7.1170E-04	7.1190E-04	7.0990E-04	7.0700E-04	7.2230E-04
DH4	8.5110E-01	8.5110E-01	9.9900E-01	9.9980E-01	1.0000E+00	1.0000E+00	1.0000E+00
AF1	7.1070E-04	7.1070E-04	2.5500E-03	1.1040E-02	3.3040E-02	1.0460E-01	2.6080E-01
AFA	7.5590E-04	7.5590E-04	2.5960E-03	1.1040E-02	3.3040E-02	1.0460E-01	2.6080E-01
AFF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
AG1	6.9980E-04	6.9980E-04	6.9980E-04	7.1920E-04	7.1920E-04	7.1920E-04	7.1930E-04
AG2	1.5950E-02	1.5950E-02	7.2630E-01	9.3560E-01	9.7890E-01	9.9380E-01	9.9800E-01
AG3	7.1070E-04	7.1070E-04	2.5500E-03	1.1040E-02	3.3040E-02	1.0460E-01	2.6080E-01
AGA	7.1920E-04	7.1920E-04	7.1920E-04	7.1920E-04	7.1920E-04	7.1920E-04	7.1930E-04
AGB	4.9200E-02	4.9200E-02	7.2360E-01	9.3560E-01	9.7890E-01	9.9380E-01	9.9800E-01
AGC	7.5590E-04	7.5590E-04	2.5960E-03	1.1040E-02	3.3040E-02	1.0460E-01	2.6080E-01
AGF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
AH1	6.9980E-04	6.9980E-04	6.9980E-04	6.9980E-04	6.9980E-04	6.9980E-04	6.9990E-04
AH2	7.6460E-04	7.6460E-04	7.6450E-04	2.7710E-02	2.7710E-02	2.7700E-02	2.7690E-02
AH3	9.5280E-01	9.5280E-01	9.9970E-01	9.9810E-01	9.9940E-01	9.9980E-01	9.9990E-01
AH4	6.9980E-04	6.9980E-04	6.9980E-04	7.1920E-04	7.1920E-04	7.1920E-04	7.1930E-04
AH5	1.5950E-02	1.5950E-02	7.2630E-01	9.3560E-01	9.7890E-01	9.9380E-01	9.9800E-01
AH6	7.1070E-04	7.1070E-04	2.5500E-03	1.1040E-02	3.3040E-02	1.0460E-01	2.6080E-01
AHA	6.9980E-04	6.9980E-04	6.9980E-04	6.9980E-04	6.9980E-04	6.9980E-04	6.9990E-04
AHB	2.7710E-02	2.7710E-02	2.7710E-02	2.7710E-02	2.7710E-02	2.7700E-02	2.7690E-02
AHC	4.6440E-01	4.6440E-01	9.8940E-01	9.9810E-01	9.9940E-01	9.9980E-01	9.9990E-01
AHD	7.1920E-04	7.1920E-04	7.1920E-04	7.1920E-04	7.1920E-04	7.1920E-04	7.1930E-04
AHE	4.9200E-02	4.9200E-02	7.2360E-01	9.3560E-01	9.7890E-01	9.9380E-01	9.9800E-01
AHG	7.5590E-04	7.5590E-04	2.5960E-03	1.1040E-02	3.3040E-02	1.0460E-01	2.6080E-01
AHF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
SF1	1.5830E-03	1.5830E-03	1.5830E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03
SFA	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03
SG1	1.5830E-03	1.5830E-03	1.5830E-03	1.6320E-03	1.6320E-03	1.6320E-03	1.6320E-03
SG2	1.6790E-03	1.6790E-03	1.6790E-03	3.9940E-02	3.9940E-02	3.9940E-02	3.9940E-02
SG3	1.5830E-03	1.5830E-03	1.5830E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03
SGA	1.6320E-03	1.6320E-03	1.6320E-03	1.6320E-03	1.6320E-03	1.6320E-03	1.6320E-03
SGB	3.9940E-02	3.9940E-02	3.9940E-02	3.9940E-02	3.9940E-02	3.9940E-02	3.9940E-02
SGC	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03
SH1	1.5830E-03	1.5830E-03	1.5830E-03	1.5830E-03	1.5830E-03	1.5830E-03	1.5830E-03
SH2	1.6540E-03	1.6540E-03	1.6540E-03	3.1320E-02	3.1320E-02	3.1320E-02	3.1320E-02
SH3	1.6610E-02	1.6610E-02	1.6610E-02	2.4730E-01	2.4730E-01	2.4730E-01	2.4730E-01
SH4	1.5830E-03	1.5830E-03	1.5830E-03	1.6320E-03	1.6320E-03	1.6320E-03	1.6320E-03
SH5	1.6790E-03	1.6790E-03	1.6790E-03	3.9940E-02	3.9940E-02	3.9940E-02	3.9940E-02
SH6	1.5830E-03	1.5830E-03	1.5830E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03
SHA	1.5830E-03	1.5830E-03	1.5830E-03	1.5830E-03	1.5830E-03	1.5830E-03	1.5830E-03
SHB	3.1320E-02	3.1320E-02	3.1320E-02	3.1320E-02	3.1320E-02	3.1320E-02	3.1320E-02
SHC	2.4730E-01	2.4730E-01	2.4730E-01	2.4730E-01	2.4730E-01	2.4730E-01	2.4730E-01
SHD	1.6320E-03	1.6320E-03	1.6320E-03	1.6320E-03	1.6320E-03	1.6320E-03	1.6320E-03
SHE	3.9940E-02	3.9940E-02	3.9940E-02	3.9940E-02	3.9940E-02	3.9940E-02	3.9940E-02
SHG	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03	1.6970E-03
BF1	1.4530E-03	1.4530E-03	1.4530E-03	1.4980E-03	1.4980E-03	1.4980E-03	1.4980E-03
BG1	1.4530E-03	1.4530E-03	1.4530E-03	1.4720E-03	1.4720E-03	1.4720E-03	1.4720E-03
BG2	1.4930E-03	1.4930E-03	1.4930E-03	1.8720E-02	1.8720E-02	1.8720E-02	1.8720E-02
BH1	1.4530E-03	1.4530E-03	1.4530E-03	1.4530E-03	1.4530E-03	1.4530E-03	1.4530E-03
BH2	1.4830E-03	1.4830E-03	1.4830E-03	1.4640E-02	1.4640E-02	1.4640E-02	1.4640E-02
BH3	8.6280E-03	8.6280E-03	8.6280E-03	2.3280E-01	2.3280E-01	2.3280E-01	2.3280E-01
GF1	8.5100E-02	8.5100E-02	8.5660E-02	9.3020E-02	1.0550E-01	1.7000E-01	2.8270E-01
GG1	8.4170E-02	8.4170E-02	8.4170E-02	8.7670E-02	8.7670E-02	1.0560E-01	1.0560E-01
GG2	9.5020E-02	9.5020E-02	1.0150E-01	1.4510E-01	2.5700E-01	4.8460E-01	7.3210E-01
GG3	8.5100E-02	8.5100E-02	8.5660E-02	9.3020E-02	1.0550E-01	1.7000E-01	2.8270E-01
GH1	8.3340E-02	8.3340E-02	8.3340E-02	8.6700E-02	8.6700E-02	1.0430E-01	1.0430E-01
GH2	9.3290E-02	9.3290E-02	9.3290E-02	9.7810E-02	9.7810E-02	1.1630E-01	1.1630E-01

Table 6-46 (Continued)

SYSTEM SPLIT FRACTION QUANTIFICATION AS A FUNCTION OF SEISMIC LEVEL

Split Fraction ID	Seismic Level (spectral acceleration, g)						
	0.0-0.2	0.2-1.25	1.25-1.75	1.75-2.0	2.0-2.5	2.5-3.0	3.0-4.0
SB6	7.2830E-02	7.2830E-02	7.2830E-02	7.2830E-02	7.2830E-02	7.2830E-02	7.2830E-02
SB7	4.1060E-01	4.1060E-01	4.1060E-01	4.1060E-01	4.1060E-01	4.1060E-01	4.1060E-01
SBB	1.7830E-02	1.7830E-02	1.7830E-02	1.7830E-02	1.7830E-02	1.7830E-02	1.7830E-02
SB9	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02
SBA	3.6850E-02	3.6850E-02	3.6850E-02	3.6850E-02	3.6850E-02	3.6850E-02	3.6850E-02
SBB	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02
SBC	1.3140E-02	1.3140E-02	1.3140E-02	1.3140E-02	1.3140E-02	1.3140E-02	1.3140E-02
SBD	1.3230E-02	1.3230E-02	1.3230E-02	1.3230E-02	1.3230E-02	1.3230E-02	1.3230E-02
SBE	6.3750E-02	6.3750E-02	6.3750E-02	6.3750E-02	6.3750E-02	6.3750E-02	6.3750E-02
SBG	3.6280E-01	3.6280E-01	3.6280E-01	3.6280E-01	3.6280E-01	3.6280E-01	3.6280E-01
SBH	2.0340E-02	2.0340E-02	2.0340E-02	2.0340E-02	2.0340E-02	2.0340E-02	2.0340E-02
SBI	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02
SBJ	3.6530E-02	3.6530E-02	3.6530E-02	3.6530E-02	3.6530E-02	3.6530E-02	3.6530E-02
SBK	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02
SBL	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02	1.1460E-02
SBM	3.6530E-02	3.6530E-02	3.6530E-02	3.6530E-02	3.6530E-02	3.6530E-02	3.6530E-02
SBN	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02	1.1750E-02
SBF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
CV1	5.8300E-04	5.8300E-04	1.3330E-03	1.3330E-03	6.9680E-03	1.7230E-02	3.7810E-02
CV2	1.5060E-02	1.5060E-02	1.5800E-02	7.4740E-02	7.8070E-02	4.1100E-01	4.2340E-01
CV3	5.1070E-02	5.1070E-02	5.1780E-02	1.0860E-01	1.1180E-01	4.3260E-01	4.4450E-01
CV4	2.0060E-02	2.0060E-02	2.0790E-02	2.2720E-02	2.6230E-02	3.5770E-02	5.5970E-02
CV5	3.3130E-03	3.3130E-03	4.0610E-03	7.1050E-03	1.0670E-02	2.6570E-02	4.6960E-02
CV6	3.8870E-02	3.8870E-02	3.9590E-02	4.1470E-02	4.4920E-02	5.4280E-02	7.4090E-02
CVF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
CVI	7.5140E-02	7.5140E-02	7.5140E-02	1.0200E-01	1.0200E-01	2.5650E-01	2.5650E-01
RT1	5.1170E-06	5.1170E-06	4.3900E-05	4.3900E-04	1.3300E-03	5.8900E-03	2.1280E-02
RT2	5.1290E-06	5.1290E-06	4.3910E-05	3.5080E-04	1.3330E-03	5.8960E-03	2.1290E-02
RT3	5.7560E-06	5.7560E-06	4.4540E-05	5.0000E-04	1.4820E-03	6.1930E-03	2.1580E-02
RT4	1.4440E-05	1.4440E-05	5.3230E-05	2.5710E-03	3.5510E-03	1.0310E-02	2.5630E-02
RT5	1.9610E-05	1.9610E-05	5.8400E-05	3.8020E-03	4.7800E-03	1.2760E-02	2.8040E-02
RT6	4.8130E-06	4.8130E-06	2.7300E-05	1.4670E-04	5.5570E-04	2.2170E-03	7.3810E-03
RT7	1.6060E-03	1.6060E-03	1.6440E-03	5.0020E-01	5.0070E-01	1.0000E+00	1.0000E+00
RTF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
AS1	2.0330E-06	2.0330E-06	4.7950E-05	2.5570E-04	8.2060E-04	3.0520E-03	9.6710E-03
AS2	3.2120E-04	3.2120E-04	3.6710E-04	1.0010E-03	1.5650E-03	6.4220E-03	1.3020E-02
AS3	1.0580E-04	1.0580E-04	1.5170E-04	6.5630E-04	1.2210E-03	5.2640E-03	1.1870E-02
AS4	1.3230E-02	1.3230E-02	1.3270E-02	5.4220E-02	5.4750E-02	3.0730E-01	3.1190E-01
AS5	3.2420E-04	3.2420E-04	3.7010E-04	1.0040E-03	1.5680E-03	6.4250E-03	1.3020E-02
AS6	7.7160E-06	7.7160E-06	5.3630E-05	2.6350E-04	8.2840E-04	3.0720E-03	9.6910E-03
AS7	1.3290E-02	1.3290E-02	1.3340E-02	5.4280E-02	5.4810E-02	3.0740E-01	3.1200E-01
AS8	4.2960E-04	4.2960E-04	4.7550E-04	1.1030E-03	1.6670E-03	6.4880E-03	1.3080E-02
AS9	2.5110E-04	2.5110E-04	2.9700E-04	9.3290E-04	1.4970E-03	6.3180E-03	1.2920E-02
ASA	1.8060E-04	1.8060E-04	2.2650E-04	4.2960E-04	9.9440E-04	3.1970E-03	9.8150E-03
ASB	2.3520E-02	2.3520E-02	2.3560E-02	6.3580E-02	6.4110E-02	3.1190E-01	3.1650E-01
ASC	1.0740E-02	1.0740E-02	1.0790E-02	1.0990E-02	1.1550E-02	1.3730E-02	2.0270E-02
ASI	9.2930E-05	9.2930E-05	9.2930E-05	1.9190E-04	1.9190E-04	7.9230E-04	7.9230E-04
ASF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
CC1	3.1720E-05	3.1720E-05	1.3660E-03	6.8080E-03	2.0770E-02	6.8710E-02	1.8740E-01
CC2	6.8760E-04	6.8760E-04	2.0210E-03	8.7030E-03	2.2630E-02	7.7190E-02	1.9480E-01
CC3	7.1310E-04	7.1310E-04	2.0470E-03	8.8390E-03	2.2770E-02	7.7910E-02	1.9550E-01
CC4	2.4150E-02	2.4150E-02	2.5460E-02	8.7110E-02	9.9940E-02	4.4770E-01	5.1810E-01
CC5	2.6060E-02	2.6060E-02	2.7360E-02	8.8890E-02	1.0170E-01	4.4880E-01	5.1910E-01
CC6	3.8320E-05	3.8320E-05	1.3730E-03	6.8230E-03	2.0780E-02	6.8770E-02	1.8750E-01
CC7	7.9080E-04	7.9080E-04	2.1240E-03	9.0270E-03	2.2950E-02	7.8690E-02	1.9610E-01
CCI	1.8910E-04	1.8910E-04	1.8910E-04	2.2500E-04	2.2500E-04	4.3110E-04	4.3110E-04
CCF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
SV1	2.6140E-06	2.6140E-06	8.7450E-06	1.2010E-04	2.5890E-04	4.6560E-03	9.9520E-03
SV2	2.6320E-04	2.6320E-04	2.6910E-04	1.3880E-03	1.5220E-03	1.4040E-02	1.9170E-02
SV3	1.9590E-04	1.9590E-04	2.0190E-04	1.0610E-03	1.1960E-03	1.1620E-02	1.6790E-02
SV4	3.8370E-05	3.8370E-05	4.4480E-05	2.9410E-04	4.3220E-04	5.9440E-03	1.1220E-02
SV5	8.2000E-03	8.2000E-03	8.2000E-03	4.0000E-02	4.0000E-02	3.0000E-01	3.0000E-01
SVF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
SVI	7.8160E-04	7.8160E-04	7.8160E-04	3.8130E-03	3.8130E-03	2.8600E-02	2.8600E-02
SVO	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01
FC1	1.8790E-06	1.8790E-06	2.4080E-06	1.3000E-05	1.1120E-04	1.0400E-03	6.9510E-03
FC2	4.7820E-06	4.7820E-06	5.3100E-06	1.5900E-05	1.1410E-04	1.0430E-03	6.9540E-03

Table 6-46 (Continued)

SYSTEM SPLIT FRACTION QUANTIFICATION AS A FUNCTION OF SEISMIC LEVEL

Split Fraction ID	Seismic Level (spectral acceleration, g)						
	0.0-0.2	0.2-1.25	1.25-1.75	1.75-2.0	2.0-2.5	2.5-3.0	3.0-4.0
FC3	5.7510E-05	5.7510E-05	5.8040E-05	6.8630E-05	1.6680E-04	1.0960E-03	7.0060E-03
FC4	6.6520E-03	6.6520E-03	6.6520E-03	6.6630E-03	6.7610E-03	7.6840E-03	1.3560E-02
FCF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
CS1	5.7410E-04	5.7410E-04	5.7420E-04	5.7500E-04	5.8000E-04	6.0920E-04	7.2950E-04
CS2	1.4400E-02	1.4400E-02	1.4410E-02	1.4520E-02	1.5130E-02	1.8780E-02	3.3810E-02
CSF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
SR1	2.8310E-03	2.8310E-03	2.8310E-03	2.8310E-03	2.0230E-02	2.0230E-02	8.0230E-02
SR2	8.5180E-03	8.5180E-03	8.5180E-03	2.5920E-02	2.5920E-02	8.5920E-02	8.5920E-02
SRF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
MS0	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01
MS1	7.4590E-03	7.4590E-03	7.4590E-03	7.4590E-03	7.4590E-03	7.4590E-03	7.4590E-03
MS2	9.9990E-01	9.9990E-01	9.9990E-01	9.9990E-01	9.9990E-01	9.9990E-01	9.9990E-01
MSF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
TT0	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01
TT1	1.2960E-04	1.2960E-04	1.2960E-04	1.2960E-04	7.1920E-05	1.3860E-05	1.3860E-05
TT2	2.1950E-03	2.1950E-03	2.1950E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
TT3	6.4950E-03	6.4950E-03	6.4950E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
TT4	3.1670E-03	3.1670E-03	3.1670E-03	3.1100E-03	3.1100E-03	3.0520E-03	3.0520E-03
TT5	5.1520E-03	5.1520E-03	5.1520E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
TT6	9.4520E-03	9.4520E-03	9.4520E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
TTF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
CH1	6.2750E-04	6.2750E-04	7.1660E-04	1.0370E-03	1.7800E-03	4.3380E-03	1.2330E-02
CH2	1.4110E-02	1.4110E-02	1.4200E-02	1.4520E-02	1.5250E-02	1.7770E-02	2.5660E-02
CH3	1.1610E-02	1.1610E-02	1.1690E-02	1.2010E-02	1.2750E-02	1.5280E-02	2.3180E-02
CH4	7.9800E-04	7.9800E-04	8.8710E-04	1.2080E-03	1.9500E-03	4.5080E-03	1.2500E-02
CHF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
SI1	3.1890E-03	3.1890E-03	3.1890E-03	3.1890E-03	3.1890E-03	3.1890E-03	3.1890E-03
SI2	1.5950E-02	1.5950E-02	1.5950E-02	1.5950E-02	1.5950E-02	1.5950E-02	1.5950E-02
SI3	2.8880E-02	2.8880E-02	2.8880E-02	2.8880E-02	2.8880E-02	2.8880E-02	2.8880E-02
SIF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
HR1	2.0970E-04	2.0970E-04	2.0970E-04	2.0970E-04	2.0970E-04	2.0970E-04	2.0970E-04
HR2	1.8920E-03	1.8920E-03	1.8920E-03	1.8920E-03	1.8920E-03	1.8920E-03	1.8920E-03
HR3	3.9880E-03	3.9880E-03	3.9880E-03	3.9880E-03	3.9880E-03	3.9880E-03	3.9880E-03
HR4	4.2980E-03	4.2980E-03	4.2980E-03	4.2980E-03	4.2980E-03	4.2980E-03	4.2980E-03
HR5	2.2820E-03	2.2820E-03	2.2820E-03	2.2820E-03	2.2820E-03	2.2820E-03	2.2820E-03
HR6	3.9640E-03	3.9640E-03	3.9640E-03	3.9640E-03	3.9640E-03	3.9640E-03	3.9640E-03
HR7	6.0550E-03	6.0550E-03	6.0550E-03	6.0550E-03	6.0550E-03	6.0550E-03	6.0550E-03
HR8	6.3670E-03	6.3670E-03	6.3670E-03	6.3670E-03	6.3670E-03	6.3670E-03	6.3670E-03
HR9	6.0540E-03	6.0540E-03	6.0540E-03	6.0540E-03	6.0540E-03	6.0540E-03	6.0540E-03
HRA	2.3700E-03	2.3700E-03	2.3700E-03	2.3700E-03	2.3700E-03	2.3700E-03	2.3700E-03
HRB	3.9880E-03	3.9880E-03	3.9880E-03	3.9880E-03	3.9880E-03	3.9880E-03	3.9880E-03
HRC	6.3960E-03	6.3960E-03	6.3960E-03	6.3960E-03	6.3960E-03	6.3960E-03	6.3960E-03
HRD	4.5530E-03	4.5530E-03	4.5530E-03	4.5530E-03	4.5530E-03	4.5530E-03	4.5530E-03
HRE	8.6390E-03	8.6390E-03	8.6390E-03	8.6390E-03	8.6390E-03	8.6390E-03	8.6390E-03
HRF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
RC1	4.3890E-05	4.3890E-05	4.3890E-05	4.3890E-05	4.3890E-05	4.3890E-05	4.3890E-05
RC2	1.1750E-03	1.1750E-03	1.1750E-03	1.1750E-03	1.1750E-03	1.1750E-03	1.1750E-03
RF1	2.1490E-03	2.1490E-03	2.1490E-03	1.0150E-02	1.0150E-02	6.0140E-02	6.0140E-02
RF2	7.3480E-03	7.3480E-03	7.3480E-03	4.0140E-02	4.0140E-02	3.0010E-01	3.0010E-01
RF3	3.8050E-03	3.8050E-03	3.8050E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
RF4	5.9360E-02	5.9360E-02	5.9360E-02	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
LA1	1.9620E-02	1.9620E-02	1.9620E-02	3.5820E-02	3.5820E-02	2.1580E-01	2.1580E-01
LA2	1.9620E-02	1.9620E-02	1.9620E-02	3.5820E-02	3.5820E-02	2.1580E-01	2.1580E-01
LA3	1.5820E-02	1.5820E-02	1.5820E-02	1.5820E-02	1.5820E-02	1.5820E-02	1.5820E-02
LAF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
LB1	1.5550E-02	1.5550E-02	1.5550E-02	1.5810E-02	1.5810E-02	1.9440E-02	1.9440E-02
LB2	2.2310E-01	2.2310E-01	2.2310E-01	5.7450E-01	5.7450E-01	9.2940E-01	9.2940E-01
LB3	1.9620E-02	1.9620E-02	1.9620E-02	3.5820E-02	3.5820E-02	2.1580E-01	2.1580E-01
LB4	1.5550E-02	1.5550E-02	1.5550E-02	1.5810E-02	1.5810E-02	1.9440E-02	1.9440E-02
LB5	2.2310E-01	2.2310E-01	2.2310E-01	5.7450E-01	5.7450E-01	9.2940E-01	9.2940E-01
LB6	1.9620E-02	1.9620E-02	1.9620E-02	3.5820E-02	3.5820E-02	2.1580E-01	2.1580E-01
LB7	1.5490E-02	1.5490E-02	1.5490E-02	1.5490E-02	1.5490E-02	1.5490E-02	1.5490E-02
LB8	3.6410E-02	3.6410E-02	3.6410E-02	3.6410E-02	3.6410E-02	3.6410E-02	3.6410E-02
LB9	1.5820E-02	1.5820E-02	1.5820E-02	1.5820E-02	1.5820E-02	1.5820E-02	1.5820E-02
LBF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
LV1	4.6850E-04	4.6850E-04	4.6850E-04	4.6850E-04	4.6850E-04	4.6850E-04	4.6850E-04
RW1	4.6900E-05	4.6900E-05	7.0990E-04	3.1620E-03	8.9700E-03	2.8270E-02	7.7990E-02

Table 6-46 (Continued)

SYSTEM SPLIT FRACTION QUANTIFICATION AS A FUNCTION OF SEISMIC LEVEL

Split Fraction ID	Seismic Level (spectral acceleration, g)						
	0.0-0.2	0.2-1.25	1.25-1.75	1.75-2.0	2.0-2.5	2.5-3.0	3.0-4.0
VA1	4.3690E-03	4.3690E-03	4.3690E-03	4.3690E-03	4.3690E-03	4.3690E-03	4.3690E-03
VAF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
VB1	4.1750E-03	4.1750E-03	4.1750E-03	4.1750E-03	4.1750E-03	4.1750E-03	4.1750E-03
VB2	4.8550E-02	4.8550E-02	4.8550E-02	4.8550E-02	4.8550E-02	4.8550E-02	4.8550E-02
VB3	4.3690E-03	4.3690E-03	4.3690E-03	4.3690E-03	4.3690E-03	4.3690E-03	4.3690E-03
VBF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
AC1	6.4320E-03	6.4320E-03	6.4320E-03	6.4320E-03	6.4320E-03	6.4320E-03	6.4320E-03
LI1	3.3800E-06	3.3800E-06	3.3800E-06	3.3800E-06	3.3800E-06	3.3800E-06	3.3800E-06
LI2	4.2630E-04	4.2630E-04	4.2630E-04	4.2630E-04	4.2630E-04	4.2630E-04	4.2630E-04
MU1	6.8790E-03	6.8790E-03	6.8790E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
MU2	1.5400E-02	1.5400E-02	1.5400E-02	4.7160E-02	4.7160E-02	3.0520E-01	3.0520E-01
MUF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
PRO	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01
PR1	2.5630E-04	2.5630E-04	1.2230E-03	5.2670E-02	6.0010E-02	8.2650E-02	1.3360E-01
PR2	9.7760E-03	9.7760E-03	1.0730E-02	6.2460E-02	6.9730E-02	9.2130E-02	1.4260E-01
PR3	2.6130E-02	2.6130E-02	2.7080E-02	7.8560E-02	8.5700E-02	1.0770E-01	1.5730E-01
PR4	8.6200E-03	8.6200E-03	9.5790E-03	6.1120E-02	6.8400E-02	9.0830E-02	1.4130E-01
PR5	6.2730E-05	6.2730E-05	1.0300E-03	1.9350E-01	1.9970E-01	2.1900E-01	2.2660E-04
PR6	1.9360E-04	1.9360E-04	1.1600E-03	2.9400E-02	3.6930E-02	6.0120E-02	1.1230E-01
PR7	1.7850E-02	1.7850E-02	1.8800E-02	4.6980E-02	5.4380E-02	7.7150E-02	1.2840E-01
PR8	9.4330E-03	9.4330E-03	1.0390E-02	3.8600E-02	4.6060E-02	6.9030E-02	1.2070E-01
PR9	1.5300E-04	1.5300E-04	1.1200E-03	1.0760E-01	1.1450E-01	1.3580E-01	1.8380E-01
PRA	8.3350E-03	8.3350E-03	9.2940E-03	1.2690E-02	2.0350E-02	4.3940E-02	9.7040E-02
PRB	9.3190E-03	9.3190E-03	1.0280E-02	1.3670E-02	2.1320E-02	4.4890E-02	9.7930E-02
PRC	1.4110E-02	1.4110E-02	1.5060E-02	2.6780E-01	2.7340E-01	2.9090E-01	3.3030E-01
PRD	4.8400E-02	4.8400E-02	4.9320E-02	5.2580E-02	5.9930E-02	8.2570E-02	1.3350E-01
PRE	5.8240E-02	5.8240E-02	5.9150E-02	6.2380E-02	6.9650E-02	9.2050E-02	1.4250E-01
PRF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
PRG	7.4410E-02	7.4410E-02	7.5300E-02	7.8470E-02	8.5620E-02	1.0760E-01	1.5720E-01
PRH	5.6870E-02	5.6870E-02	5.7790E-02	6.1020E-02	6.8300E-02	9.0740E-02	1.4120E-01
PRI	1.0110E-02	1.0110E-02	1.1070E-02	1.9310E-01	1.9940E-01	2.1870E-01	2.6210E-01
PRJ	2.5080E-02	2.5080E-02	2.6020E-02	2.9360E-02	3.6890E-02	6.0080E-02	1.1230E-01
PRK	4.2740E-02	4.2740E-02	4.3660E-02	4.6940E-02	5.4330E-02	7.7110E-02	1.2840E-01
PRL	3.4320E-02	3.4320E-02	3.5250E-02	3.8560E-02	4.6020E-02	6.8990E-02	1.2070E-01
PRM	5.5230E-03	5.5230E-03	6.4840E-03	1.0740E-01	1.1430E-01	1.3560E-01	1.8360E-01
PRN	6.1610E-03	6.1610E-03	7.1220E-03	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
PRP	9.7150E-06	9.7150E-06	9.7650E-04	4.4070E-03	1.2130E-02	3.5910E-02	8.9460E-02
PRQ	9.7080E-06	9.7080E-06	9.7650E-04	4.4050E-03	1.2130E-02	3.5910E-02	8.9460E-02
PRR	1.0650E-05	1.0650E-05	9.7750E-04	4.4040E-03	1.2130E-02	3.5910E-02	8.9460E-02
PRS	1.5290E-05	1.5290E-05	9.8210E-04	4.4070E-03	1.2130E-02	3.5910E-02	8.9460E-02
PRT	1.2590E-05	1.2590E-05	9.7940E-04	4.4050E-03	1.2130E-02	3.5910E-02	8.9460E-02
PO1	4.5850E-04	4.5850E-04	4.5850E-04	4.8480E-02	4.8480E-02	4.8480E-02	4.8480E-02
PO2	6.5090E-02	6.5090E-02	6.5090E-02	6.5090E-02	6.5090E-02	6.5090E-02	6.5090E-02
PO3	4.8400E-02	4.8400E-02	4.8400E-02	4.8400E-02	4.8400E-02	4.8400E-02	4.8400E-02
POF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OB1	7.1490E-02	7.1490E-02	7.1490E-02	4.6590E-02	4.6590E-02	2.1660E-01	2.1660E-01
OB2	7.1490E-02	7.1490E-02	7.1490E-02	4.6590E-02	4.6590E-02	2.1660E-01	2.1660E-01
OB3	4.3140E-01	4.3140E-01	4.3140E-01	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
OBF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
CI1	4.0040E-03	4.0040E-03	4.0040E-03	4.0040E-03	4.0040E-03	4.0040E-03	4.0040E-03
CI2	5.7140E-03	5.7140E-03	5.7140E-03	5.7140E-03	5.7140E-03	5.7140E-03	5.7140E-03
CI3	7.2560E-03	7.2560E-03	7.2560E-03	7.2560E-03	7.2560E-03	7.2560E-03	7.2560E-03
CI4	6.8350E-01	6.8350E-01	7.0650E-01	7.0680E-01	6.8540E-01	6.5910E-01	6.2960E-01
CI5	6.8410E-01	6.8410E-01	7.0700E-01	7.0730E-01	6.8590E-01	6.5970E-01	6.3020E-01
CI6	6.8450E-01	6.8450E-01	7.0740E-01	7.0770E-01	6.8640E-01	6.6020E-01	6.3080E-01
CIF	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
CP1	1.1460E-06	1.1460E-06	4.9990E-05	3.0580E-04	1.1420E-03	4.3970E-03	1.3940E-02
CP2	1.0290E-05	1.0290E-05	5.9130E-05	3.1490E-04	1.1510E-03	4.4060E-03	1.3950E-02
CP3	8.4160E-03	8.4160E-03	8.4640E-03	8.7180E-03	9.5470E-03	1.2770E-02	2.2240E-02
CP4	1.1460E-06	1.1460E-06	4.9990E-05	3.0580E-04	1.1420E-03	4.3970E-03	1.3940E-02
CP5	1.0290E-05	1.0290E-05	5.9130E-05	3.1490E-04	1.1510E-03	4.4060E-03	1.3950E-02
CP6	8.4160E-03	8.4160E-03	8.4640E-03	8.7180E-03	9.5470E-03	1.2770E-02	2.2240E-02
WL1	4.3250E-05	4.3250E-05	4.3250E-05	4.3250E-05	4.3250E-05	4.3250E-05	4.3250E-05
WL2	6.3140E-04	6.3140E-04	6.3140E-04	6.3140E-04	6.3140E-04	6.3140E-04	6.3140E-04
WL3	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
SL1	1.0480E-02	1.0480E-02	1.0480E-02	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00
SL2	1.4260E-02	1.4260E-02	1.4260E-02	1.0000E+00	1.0000E+00	1.0000E+00	1.0000E+00

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Scenarios given in Table 6-47 are selected based on the impact on Plant systems and the associated scenario frequency, and are the fire events included as initiating events in the Plant risk quantification. As shown in Table 6-47, designators FS1 through FS8 are established to represent all fire scenarios addressed in that table.

Fire scenarios that could lead to more severe Plant damage states are summarized in Table 6-48. The designators for these scenarios are FS9 through FS14. These scenarios are not incorporated in the model as initiating events; they are modeled separately as direct core damage sequences after the application of human action factors which account for recovery of the fire scenario.

These fire scenarios represent initiating events fed into the complete Plant model for risk quantification.

Over 100 internal flood and other environmental hazard scenarios were identified by the spatial interactions analysis. Of these significant scenarios were identified as those having a significant contribution to the overall risk of the Plant or participating in a significant group of scenarios. This significant group of scenarios is a group of scenarios that has a similar impact with a comparatively low frequency on an individual basis, but the total frequency (that is, the sum of the frequencies for the participant scenario) is relatively significant (say, more than 10 percent) to the associated initiating events. These significant scenarios can be grouped as three categories. They are: (1) auxiliary feedwater fails, (2) loss of two motor-driven auxiliary feedwater pumps, and (3) loss of auxiliary saltwater. The third group, loss of auxiliary saltwater, is the same as loss of component cooling water in our study since the resulting impact from the two events is identical. For each group, a unique designator is given for entering the support model event tree. A summary table in terms of scenario designator, scenario description, scenario frequency, and support model event tree designator is given in Table 6-49.

Finally, for the wide range of other external event scenarios examined, all of the hazard sources

were shown to be negligible contributors to the core damage frequency, with contributions ranging from 10^{-8} per year for aircraft crashes to 3.5×10^{-7} per year for hazardous chemicals.

Human Action Analysis

This section analyzes those operator actions that occur after an initiating event. Actions that are not (that is, those that occur prior to event initiation) are described in the data analysis report and listed in Table 6-50. Scenario-specific operator actions evaluated in this report are listed in Table 6-51 and include:

- Manual actuation of manually actuated systems.
- Manual actuation of systems that are normally automatically actuated.
- Repair of failed systems.
- Manual alignment of equipment, which backs up automatically actuated systems.

Data for equipment failure rates and for testing and maintenance errors that occur prior to event initiation may be extracted from Plant records and historical data. Data on the reliability of scenario-specific operator actions, are usually much less readily available. The difficulty of predicting the success likelihood of operator response from historical data necessitates the use of a different methodology than that used for predicting the success likelihood of systems and related Plant equipment. The method of evaluation uses a set of 23 performance shaping factors to measure the effects that influence the operators' likelihood of successfully accomplishing an action. Information about each factor is collected from operators using a survey form, and is weighted to determine the likelihood of success for each phase of the action.

All of the human error rates analyzed in this section were used in split fractions. These split fractions in turn were used to evaluate scenario frequencies, as presented elsewhere.

RESULTS OF HUMAN ACTIONS ANALYSIS

The failure frequency estimate from each of the operators were combined assuming that they were

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Table 6-47
FIRE SCENARIOS FOR RISK QUANTIFICATION

<u>Scenario Designation</u>	<u>Scenario Impact on Plant Equipment</u>	<u>Estimate Frequency</u>	<u>Designator to Support Model Event Tree</u>
3-Q-2-FS-1	Loss of both motor-driven auxiliary feedwater pumps	4.0-4	FS1
14-A-FS-1	Loss of both motor-driven auxiliary feedwater pumps	1.0-4	FS1
14-A-104-FS-1	Loss of both motor-driven auxiliary feedwater pumps	1.1-4	FS1
3-BB-100-FS-1	Loss of both motor-driven auxiliary feedwater pumps	5.2-5	FS1
6-A-5-FS-1	Loss of both motor-driven auxiliary feedwater pumps	3.0-4	FS1
5-A-4-FS-1A	Loss of both motor-driven auxiliary feedwater pumps	3.0-4	FS1
S-3-FS-1	Loss of both motor-driven auxiliary feedwater pumps	1.4-4	FS1
12-A-FS-1	Failure to start both motor-driven auxiliary feedwater pumps	3.3-5	FS1
5-A-4-FS-1B	Loss of both motor-driven auxiliary feedwater pumps plus all 10% dump valves	5.0-5	FS1
Total Frequency of FS1		1.485-3	
3-H-1-FS-1	Loss of all three charging pumps	2.0-3	FS2
3-C-FS-5	Loss of all charging pumps	4.0-4	FS2
3-AA-FS-1	Loss of all charging pumps and loss of two MSIVs	3.8-5	FS2
3-J-2-FS-1A	Loss of all charging pumps	4.5-4	FS2
Total Frequency of FS2		2.89-3	

NOTE: Exponential notation is indicated in abbreviated form; that is, 7.5-6 = 7.5×10^{-6} .

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Table 6-47 (Continued)
 FIRE SCENARIOS FOR RISK QUANTIFICATION

<u>Scenario Designation</u>	<u>Scenario Impact on Plant Equipment</u>	<u>Estimate Frequency</u>	<u>Designator to Support Model Event Tree</u>
3-J-2-FS-1B	Loss of all CCW pumps	3.05-6	FS3
8-B-3-FS-1	Loss of control room venting failing all three fans	2.0-3	FS4
4-A-FS-1B	Loss of both ASW pumps	3.0-5	FS5
4-B-FS-1	Loss of both ASW pumps	2.82-6	FS5
14-E-FS-1	Loss of all ASW and CCW	1.0-5	FS5
	Total Frequency of FS5	4.28E-5	
4-A-FS-1A	Loss of buses F and G	7.5-6	FS6
5-A-1-FS-3	Loss of buses F and G	1.0-6	FS6
5-A-2-FS-3	Loss of buses F and G	1.0-6	FS6
12-A-FS-2	Loss of buses F and G	1.3-7	FS6
12-B-FS-2	Loss of buses F and G	1.3-7	FS6
13-A-FS-3	Loss of two buses (F and G)	6.0 -6	FS6
13-B-FS-2	Loss of two buses (F and G)	6.0-6	FS6
	Total Frequency of FS6	2.18-5	
5-A-2-FS-4	Loss of buses G and H	1.0-6	FS7
5-A-3-FS-3	Loss of buses G and H	1.0-6	FS7
13-C-FS-2	Loss of two buses (G and H)	6.0-6	FS7
13-B-FS-3	Loss of two buses (G and H)	6.0-6	FS7
	Total Frequency of FS7	1.4-5	
14-D-FS-3	Delayed failure of all three buses F, G, and H	5.0-6	FS8

NOTE: Exponential notation is indicated in abbreviated form; that is, 7.5-6 = 7.5×10^{-6} .

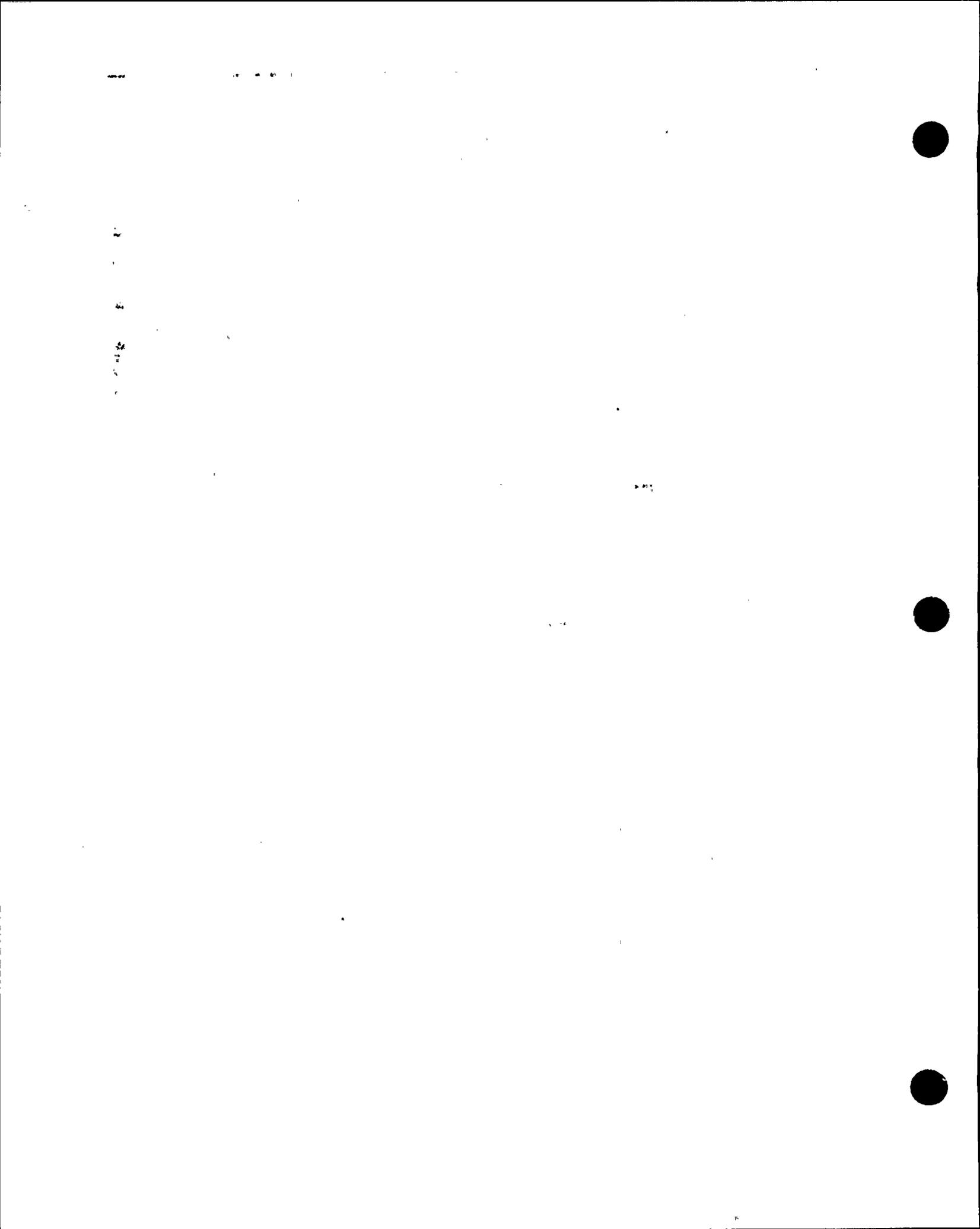


Table 6-48

**SUMMARY OF FIRE SCENARIOS LEADING TO CORE DAMAGE—CONTROL ROOM
AND CABLE SPREADING ROOM FIRE**

<u>Scenario Designation</u>	<u>Scenario Impact on Plant Equipment</u>	<u>Mean</u>	<u>5th Percentile</u>	<u>Median</u>	<u>95th Percentile</u>
Control Room VB-1	Loss of ASW and CCW control on board VB-1	1.25-6	7.72-10	5.29-8	5.02-6
Control Room VB-2	Loss of PORVs and charging pumps control on board VB-2	1.16-6	6.90-10	5.20-8	3.89-6
Control Room VB-2/3	Loss of PORVs and auxiliary feedwater system control on boards VB-2 and VB-3 interface	3.15-6	2.52-9	1.62-7	1.01-5
Control Room VB-4	Loss of 4-kV buses, F, G, and H on board VB-4	6.01-6	3.16-9	2.07-7	1.7 1-5
Summation of Control Room Fire Scenario Frequencies		1.16-5	1.26-8	6.19-7	4.52-5
Cable Spreading Room Scenario 1	Loss of ASW and CCW control	7.90-6	1.03-8	5.34-7	2.48-5
Cable Spreading Room Scenario 2	Loss of PORVs control	1.23-5	2.00-8	1.03-6	4.88-5
Summation of Cable Spreading Room Fire Scenario Frequencies		2.02-5	4.08-8	1.87-6	7.93-5
Summation of Control Room and Cable Spreading Room Fire Scenario Frequencies		3.18-5	2.61-7	5.01-6	1.22-4

NOTE: Exponential notation is indicated in abbreviated form; that is, 1.25-6 = 1.25×10^{-6} .

Table 6-49

SUMMARIES OF SIGNIFICANT SCENARIOS

Scenario Designator	Scenario Description	Estimate Frequency (per year)	Designator To Support Model Event Tree
3-Q-1-SS-2(A)	Loss of AFW	8.0-7	FS9
3-Q-1-SS-2(B)	Loss of AFW	1.6-7	FS9
3-Q-2-SS-2	Loss of AFW	8.0-7	FS9
3-BB-115-HS-1	Loss of AFW	4.0-6	FS9
3-Q-2-SS-1	Loss of Two Motor-Driven Pumps	8.0-6	FS10
14-E-SW-1(A)	Loss of CCW	4.8-5	FS11
3-J-1-SW-1	Loss of CCW	1.6-5	FS11
3-J-2-SW-1	Loss of CCW	1.6-5	FS11
3-J-3-SW-1	Loss of CCW	1.6-5	FS11
3-L-SW-1(A)	Loss of CCW	3.2-5	FS11
3-Q-2-SW-1(A)	Two Motor-Driven Pumps Failed	8.0-7	FS10
3-Q-2-SW-1(B)	Two Motor-Driven Pumps Failed	3.2-6	FS10
3-Q-2-SW-1(C)	Two Motor-Driven Pumps Failed	8.0-7	FS10
3-L-JW-1(A)	Loss of CCW	3.2-5	FS11
3-Q-1-JW-2(A)	Loss of AFW	8.0-8	FS9
3-Q-1-JW-2(B)	Loss of AFW	1.6-8	FS9
3-Q-1-JW-2(C)	Loss of AFW	8.0-7	FS9
3-Q-1-JW-2(D)	Loss of AFW	8.0-8	FS9
3-Q-2-JW-1(A)	Two Motor-Driven Pumps Failed	8.0-7	FS10
3-Q-2-JW-1(B)	Loss of Two Motor-Driven AFW Pumps	3.2-6	FS10
3-Q-2-JW-1(C)	Two Motor-Driven Pumps Failed	8.0-7	FS10
3-Q-2-JW-2(A)	Loss of AFW	8.0-8	FS9
3-Q-2-JW-2(B)	Loss of AFW	3.2-7	FS9
3-Q-2-JW-2(C)	Loss of AFW	8.0-8	FS9
3-Q-1-JS-2(A)	Loss of AFW	8.0-7	FS9
3-Q-1-JS-2(B)	Loss of AFW	1.6-7	FS9
3-Q-2-JS-1	Loss of Two Motor-Driven AFW Pumps	8.0-6	FS10
3-Q-2-JS-2	Loss of AFW	8.0-7	FS9
3-J-1-FW-1	Loss of CCW	1.6-5	FS11
3-J-2-FW-1	Loss of CCW	1.6-5	FS11
3-J-3-FW-1	Loss of CCW	1.6-5	FS11
3-L-FW-1	Loss of CCW	1.6-5	FS11

NOTE: Exponential notation is indicated in abbreviated form; i.e., 8.0-7 = 8.0×10^{-7} .

Table 6-50
HUMAN ACTIONS THAT OCCUR BEFORE EVENT INITIATION

<u>Action</u>	<u>System</u>	<u>Description</u>
ZHEDG1	EPDGS	Fails to return diesel control to "auto" during diesel generator surveillance test and coincident initiating event.
ZHEDG2	EPDGS	Fails to return diesel control to "auto" after completion of a diesel generator surveillance test.
ZHEDG3	EPDGS	Fails to restore fuel transfer pump and level control valve controls to "auto" after monthly diesel generator surveillance.
ZHDDG1	EPDGS	Discovery time for failure to return diesel generator controls to "auto."
ZHDDG3	EPDGS	Discovery time for failure to return fuel transfer pump and level control valves to "auto" after monthly diesel generator surveillance test.
ZHEF01	EPDF0	Fails to realign train after pump performance test of fuel oil transfer system or particulate contamination test (three manual valves).
ZHDF01	EPDF0	Discovery time for misalignment after pump performance test or particulate contamination test of fuel oil transfer train (maximum of 10 days when next diesel generator is tested).
ZHEF02	EPDF0	Fails to return LCV control switch to "auto" position after valve stroke test (1/2 switches).
ZHDF02	EPDF0	Discovery time for control switch not returned to "auto" after valve stroke test - level control valves.
ZHESSR	SSPS	Unavailability due to recoverable calibration error.
ZHESSN	SSPS	Unavailability due to unrecoverable calibration error.
ZHDSS2	SSPS	Test duration for SSPS logic test (2 hours for testing). (In frontline, early response systems.)
ZHEAW1	AFW	Fails to restore system alignment after monthly pump recirculation test. (In frontline, later response systems.)
ZHECS1	Containment Spray	Fails to realign last train tested after test (STP-P-4B and STP-M-16H concurrent).

Table 6-51
DEFINITION OF OPERATOR ACTIONS AND POINT
ESTIMATE MEANS USED TO CHOOSE DOMINANT SCENARIOS

Action	Description
ZHEAC1 N/A	Probability of not recovering from common cause failure of auxiliary or startup feeder breakers to close (or open) on demand.
ZHEAC2	Probability of not recovering from an earthquake induced failure of the battery chargers by replacing the chargers.
ZHEAI1 N/A	Isolate a stuck-open 10% steam dump valve to prevent water loss such that cooldown on closed-loop RHR before RWST low level is not possible and cold leg recirculation is required.
ZHEAS1	Remotely crosstie to Unit 2 ASW system when Unit 1 pumps fail because of loss of offsite power.
ZHEAS2	Locally crosstie to Unit 2 ASW system or crosstie electric power and remotely open crosstie valve.
ZHEAS3	Remotely crosstie to Unit 2 ASW system when Unit 1 pumps fail.
ZHEAW3 N/A	Manually restart turbine driven AFW pump locally after a loss of one DC bus initiating event which makes remote starting unavailable.
ZHEAW4 N/A	Close level control valves to effected steam generator after a steam line break outside containment and before AFW pumps become unavailable due to runoff.
ZHECC1 S.O	Locally isolate containment fan coolers to allow only one CCW pump to deliver enough flow to cool other SI components.
ZHECH1 E	Restore RCP seal injection from the charging pumps by reestablishing cooling to the charging pumps from the fire water system.
ZHECT1 E	Resetting the control room annunciator boards and control power circuits which are tripped off as a result of relay chatter during an earthquake.
ZHECT2 E	Resetting the control room annunciator boards and control power circuits which are tripped off as a result of relay chatter during an earthquake without the turbine driven AFW pump available.
SHECT3 E	Resetting the control room annunciator boards and control power circuits which are tripped off as a result of relay chatter during an earthquake with a small break in the RCS.
SHECT4 E	Resetting the control room annunciator boards and control power circuits which are tripped off as a result of relay chatter during an earthquake with a small break in the RCS without the turbine driven AFW pump available.
ZHECV1	Align the standby control area ventilation train within 60 minutes given the exhaust fan of the operating train fails.
ZHEF04	Realign power to the fuel oil transfer pumps from the other unit.
ZHEF05 E N/A	Realign power to the fuel oil transfer pumps from the other unit given that only one transfer pump has lost power, while the other has failed independently.

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Table 6-51 (Continued)
**DEFINITION OF OPERATOR ACTIONS AND POINT
 ESTIMATE MEANS USED TO CHOOSE DOMINANT SCENARIOS**

Action	Description
ZHEF06 E	Reestablish fuel oil transfer to the affected day tanks by aligning a dedicated, protable fuel oil transfer pump and by controlling the day tank level control valves manually.
During a fire at board VB-1:	
ZHEF11 N/A	Trip the RCPs from the switchgear within 20 minutes.
ZHEF12 N/A	Restore ASW and CCW flow from Hot Shutdown panel.
ZHEF13 N/A	Start RHR pumps at the 4kV switchgear.
ZHEF21 N/A	During a fire at control board VB-2 that spreads to control board VB-3 close PORVs from the Hot Shutdown Panel.
During a fire at the interface of control boards VB-2 and VB-3:	
ZHEF31 N/A	Close PORVs from the Hot Shutdown Panel.
ZHEF32 E N/A	Start and control AFW flow from the Hot Shutdown Panel.
During a fire at control board VB-4:	
ZHEF41 N/A	Trip RCPs within 15 minutes after loss of CCW.
ZHEF42 N/A	Restore 4kV power supply and start charging pumps, CCW pumps, and ASW pumps.
During a fire in the cable spreading room (trips ASW/CCW):	
ZHEF51 N/A	Trip RCPs from the switchgear within 20 minutes.
ZHEF52 N/A	Restore ASW and CCW flow from Hot Shutdown Panel.
ZHEF53 N/A	Start RHR pumps at the 4kV switchgear.
ZHEF61 N/A	During a fire in the cable spreading room which causes the PORVs to open, close PORVs from the Hot Shutdown Panel.
ZHEHS1	Long-term actions to either maintain hot standby or cool down to RHR entry conditions and beyond to cold shutdown. Failure results in loss of RCS heat removal by the secondary system. The CST is assumed to empty in about 8 hours.

Table 6-51 (Continued)
**DEFINITION OF OPERATOR ACTIONS AND POINT
 ESTIMATE MEANS USED TO CHOOSE DOMINANT SCENARIOS**

<u>Action</u>	<u>Description</u>
ZHEHS2	Installing a portable generator to work through a regulated transformer to provide vital 120 VAC following an earthquake.
ZHEHS3	Same as ZHEHS1, but after a LOCA.
ZHEHS4 N/A	Same as for ZHEHS1 except ATWT occurred and has been mitigated.
Stop RHR in short term if RCS pressure is high:	
ZHELA1	For feed and bleed cooling (not in procedures).
ZHELA2	For small LOCA.
ZHEMU1 N/A	Initiate closed loop cooling and depressurize RCS.
ZHEMU2 E	Reduce injection flow to the RCS and provide makeup to the RWST as an alternative to switching over to closed loop RHR cooling or to recirculation from the containment sump.
ZHEOB1	Operator action to initiate bleed and feed cooling.
ZHEOB2 E N/A	Establish instrument air to the containment in order to allow the third PORV to be used for bleed and feed cooling.
ZHEOE1 N/A	Initiate boration of RCS within 10 minutes; i.e., step 4 of FR-S.1 (scenarios = AFW fails or a PORV sticks open).
ZHEOM1 N/A	For SGTR events, control AFW flow to the ruptured SG to prevent challenge to the 10% steam dump to lift, passing water.
ZHEOP1 N/A	Secure ECCS pumps following a SGTR to prevent challenge to the pressurizer PORVs, to the vessel, or to the steam generator relief and safety valves.
ZHEOR1 N/A	Cooldown and depressurize the RCS to less than the ruptured SG pressure and sufficiently to prevent a challenge to the SG 10% steam dumps and safeties to relieve water, within about 30 minutes, assuming RCPs are available; if RCPs are not available, operators open the PORVs.
ZHEOS1	Manual actuation of safety injection equipment, given failure of one or two trains of SSPS.
ZHEOX1 N/A	Identify SGTR and decide to isolate the ruptured SG in time. The available time is governed by the point at which the operators must initiate the SGTR actions or additional challenges to the steam generator valves will occur (that is, about 10 minutes). The operators are assumed to subsequently identify the leak outside containment in time to initiate recirculation.
ZHEPR1 N/A	Throttle centrifugal charging pumps actuated by SI signal to prevent challenge to the PORVs (for example, steam line break).

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Table 6-51 (Continued)
**DEFINITION OF OPERATOR ACTIONS AND POINT
 ESTIMATE MEANS USED TO CHOOSE DOMINANT SCENARIOS**

Action	Description
ZHEPR2	Remotely close a block valve to isolate a stuck open PORV, before SI after reactor trip and PORV demand (about 4 minutes available).
ZHEPR3 N/A	Remotely isolate a block valve to isolate a stuck open PORV, before reactor trip (about 3 minutes available).
ZHEPR4 N/A	Same as ZHEPR2 except reactor trip failed.
ZHEPR5 N/A	Remotely close a block valve to isolate a stuck open PORV following inadvertent safety injection actuation.
ZHERE2	Cross-tie two vital buses following recovery of a diesel generator during station blackout so that two power trains are available.
ZHERE4	Cross-tie a vital power source to an operable bus to restore power to a fuel oil transfer pump whose normal and backup power supplies are both unavailable.
ZHERES5	Depressurize the steam generators to 260 psig during station blackout to reduce RCP seal leak rates.
ZHERE6 E	Install a portable power supply for essential loads during station blackout induced by an earthquake.
Complete sump recirculation alignment and open the CCW valves to the RHR heat exchangers (timing is dependent on CS status and LOCA size).	
ZHERF1	For small LOCA without CS.
ZHERF2 N/A	For medium or large LOCA with CS.
ZHERF3 N/A	After core melt-through with CS.
ZHERF4	For bleed and feed without CS.
ZHERF5	For small LOCAs with CS.
ZHERP1	Trip the RCPs remotely within 15 minutes to prevent seal damage, given a loss of CCW or if CCW is lost and an SI signal occurs.
ZHERP2 N/A	Trip the RCPs locally within 10 minutes because DC power train G is not available for remote tripping.
ZHERS1 N/A	Shut down reactor with rods within 10 minutes of reactor trip signal.

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Table 6-51 (Continued)
DEFINITION OF OPERATOR ACTIONS AND POINT
ESTIMATE MEANS USED TO CHOOSE DOMINANT SCENARIOS

<u>Action</u>	<u>Description</u>
	Manual reactor trip within about 15 seconds to prevent a challenge to the pressurizer PORVs. (See Note 1.)
ZHERT1	Given manual scram, button will trip reactor (logic failure).
ZHERT2	Given that breakers have failed and power must be interrupted to the motor-generator sets.
ZHES01 N/A	Isolate a stuck open safety valve.
ZHESR2	Align RHR for containment spray given successful sump recirculation.
ZHESV1	Open doors to room serviced by 480V switchgear ventilation.
ZHESV2 E	Open doors to room serviced by 480V switchgear ventilation prior to plant trip, about 6 hours available.
ZHESV3 N/A	Establish an alternate ventilation system if both trains of 480V switchgear ventilation fail to open doors earlier.
ZHESW1	Realign the swing diesel to the unit where it is more urgently needed (no SI signal).
	Trip turbine within 30 seconds after demand for reactor trip, when reactor trip initially fails (that is, to limit the RCS pressure rise).
ZHETT1 N/A	Trip turbine manually following ATWT.
ZHETT2 N/A	Given that automatic reactor trip failed and operators successfully attempted manual reactor trip.
ZHETT3 N/A	Manual turbine trip prior to MSIV closure following successful reactor trip.

Key:

E (Under the action column.) Indicates that the operator action failure rates were estimated rather than calculated using the human action analysis methodology.

N/A (Under the action column.) Indicates that the action is not of interest for seismic events therefore no estimate of the failure rate were made.

S.O. (Under the action column.) Indicates that this is a seismic action outside the control room.

Notes:

1. These are special cases where the time is so short that the operator is knocked to the floor and cannot physically get up to hit the scram button in time.

part of a lognormal distribution to develop a single distribution for each operator action error rate. Table 6-52 contains the vital distribution parameters as used in the calculation of scenario frequencies using the dominant scenarios and each human error rate. Mean values only were estimated for the operator actions which occurred following an earthquake.

Distributions of parameters were calculated for all the human error rates, however, not all the error rates were predicted based on operator estimates. The nonseismic error rates indicated in Table 6-51 with an "E" and all of the seismic error rates were estimated based on their similarity to actions for which operator estimates did exist.

ELECTRIC POWER RECOVERY FOLLOWING A LOSS OF ALL AC POWER

Following a loss of all offsite power initiating event, the principal concerns will be to:

- Restore AC power to at least two Unit 1 vital buses.
- Maintain and control auxiliary feedwater flow from the turbine-driven auxiliary feedwater pump.
- Monitor core subcooling and reactor coolant inventory.
- Monitor DC power availability and take action to extend battery life.

The frequency of electric power failure and recovery was analyzed for a number of conditions depending on the systems available for recovery (for example, one of three diesels, one of two diesels, only one diesel, offsite power) and the availability of auxiliary feedwater; that is, heat removal via the steam generators.

Integrated Model for Electric Power Failure and Recovery (Nonseismic). The electric power system analysis evaluates the unavailability of power at the vital buses. These are AC buses F/1F, G/1G, and H/1H and DC buses 11, 12, and 13. Systems analyses analyze the automatic

startup and operation of the emergency diesel generators and the fuel oil transfer system, respectively, after loss of offsite power. An operating mission time of 6 hours is used to quantify the unavailability of onsite power (that is, diesel generators or fuel oil transfer system) before the application of a detailed recovery model. In this analysis, the mission time is extended to 24 hours because operator recovery is explicitly incorporated.

The event tree model defines the nature of the actions that must be taken to restore normal Plant response. For each scenario, there is also a fairly well-defined time window for successful system recovery.

A realistic model for the recovery of electric power during a specific event scenario must account for the causes and timing of the power failure events, the sequencing of failures and recovery actions, and the available time window for success before the onset of core damage. Equipment failures and recovery can occur at any time during the 24-hour study period after event initiation. Thus, a time-integrated model for failures and recovery actions was developed.

Recovery of failure of the diesel fuel oil transfer system is modeled only for the case in which one or both normal power supplies for fuel oil transfer trains are lost. Operator action to realign power to the fuel oil transfer pumps from the alternate source in Unit 2 is included in the system model. Successful recovery requires completion of this action prior to the depletion of diesel fuel in the day tanks. In addition, recovery of fuel oil transfer by installing a portable fuel pump is also considered in the dominant sequence model. In this section, however, only offsite power recovery is modeled in the event that the fuel oil transfer system is unavailable either due to loss of normal power supplies in conjunction with failure of power realignment or due to other types of system failures. Since no other recovery of failure of the diesel fuel oil transfer system is assumed, the frequency of power recovery after a loss of the diesel fuel oil transfer system following loss of all offsite power is simply the frequency of offsite power recovery.

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Table 6-52
HUMAN ACTION ANALYSIS RESULTS

Designation	Operator Error Rate			
	5 %	50%	95 %	Mean
ZHEAC1	0.00010	0.0011	0.0081	0.0023
ZHEAC2	0.00011	0.0011	0.011	0.0030
ZHEAI1	0.0035	0.011	0.032	0.013
ZHEAS1	0.0013	0.0065	0.032	0.010
ZHEAS2	0.0035	0.011	0.032	0.013
ZHEAS3	0.00078	0.0039	0.019	0.0063
ZHEAW3	0.00050	0.0038	0.028	0.008
ZHEAW4	0.00031	0.0024	0.018	0.005
ZHECC1	0.00097	0.0049	0.024	0.0079
ZHECT1	0.00012	0.00094	0.0070	0.002
ZHECT2	0.00025	0.0019	0.014	0.004
ZHECT3	0.00025	0.0019	0.014	0.004
ZHECT4	0.00050	0.0038	0.028	0.008
ZHECV1	0.0049	0.015	0.044	0.018
ZHEF11	0.0035	0.0026	0.035	0.0055
ZHEF12	0.00099	0.0050	0.025	0.0080
ZHEF13	0.00044	0.0033	0.025	0.007
ZHEF21	0.00055	0.0028	0.014	0.0044
ZHEF31	0.00043	0.0022	0.011	0.0035
ZHEF32	0.00041	0.0031	0.023	0.0065
ZHEF41	0.0010	0.0051	0.025	0.0082
ZHEF42	0.00013	0.0010	0.0075	0.0075
ZHEF51	0.00084	0.0063	0.047	0.0135
ZHEF52	0.00047	0.0035	0.027	0.0075
ZHEF53	0.00043	0.0032	0.024	0.0068
ZHEF61	0.00042	0.0031	0.023	0.0066
ZHEF04	0.026	0.079	0.24	0.022
ZHEF05	0.0053	0.016	0.048	0.02
ZHEF06	0.0050	0.025	0.12	0.04
ZHEHS1	0.00029	0.0022	0.0165	0.0047
ZHEHS2	0.00031	0.0024	0.018	0.0050
ZHEHS3	0.00038	0.0019	0.0095	0.0031
ZHEHS4	0.00019	0.0019	0.019	0.0051
ZHEHS5	0.00030	0.0030	0.0300	0.008
ZHELA1	0.00058	0.0029	0.014	0.0047
ZHELA2	0.00058	0.0029	0.014	0.0047
ZHEMU1	0.00046	0.0023	0.012	0.0037
ZHEMU2	0.00050	0.0038	0.028	0.008
ZHEOB1	0.00072	0.0054	0.040	0.011
ZHEOB2	0.021	0.064	0.19	0.08
ZHEOE1	0.00029	0.0014	0.0072	0.0023
ZHEOM1	0.00069	0.0052	0.039	0.011
ZHEOP1	0.00051	0.0026	0.013	0.0041
ZHEOR1	0.0024	0.018	0.13	0.038

Table 6-52 (Continued)
HUMAN ACTION ANALYSIS RESULTS

Designation	Operator Error Rate			
	5%	50%	95%	Mean
ZHEOS1	0.00023	0.0012	0.0058	0.0019
ZHEOX1	0.00062	0.0031	0.016	0.0050
ZHEPR1	0.00067	0.0050	0.038	0.011
ZHEPR2	0.00061	0.0031	0.015	0.0050
ZHEPR3	0.00076	0.0038	0.019	0.0061
ZHEPR4	0.00052	0.0026	0.013	0.0043
ZHEPR5	0.00056	0.0028	0.014	0.0045
ZHERE2	0.00066	0.0033	0.016	0.0053
ZHERE4	0.0011	0.0057	0.028	0.0092
ZHERE5	0.0011	0.0053	0.026	0.0085
ZHERE6	0.00063	0.0047	0.035	0.01
ZHERF1	0.00037	0.0018	0.0092	0.0030
ZHERF2	0.00051	0.0025	0.013	0.0041
ZHERF3	0.00088	0.0044	0.022	0.0071
ZHERF4	0.00042	0.0021	0.010	0.0034
ZHERF5	0.00040	0.0020	0.0099	0.0032
ZHERP1	0.00027	0.0020	0.015	0.0042
ZHERP2	0.00063	0.0047	0.035	0.01
ZHERS1	0.000084	0.00063	0.0047	0.0013
ZHERT1	0.00012	0.00089	0.0067	0.0019
ZHERT2	0.000087	0.00087	0.0087	0.0023
ZHESE1	0.0027	0.0080	0.024	0.01
ZHES01	0.0018	0.0088	0.044	0.014
ZHESR1	0.00023	0.0017	0.013	0.0036
ZHESV1	0.000006	0.00013	0.0026	0.0007
ZHESV2	0.00021	0.0021	0.021	0.0056
ZHESV3	0.00023	0.0018	0.013	0.0037
ZHESW1	0.00022	0.0017	0.013	0.0035
ZHETT1	0.00039	0.0020	0.0098	0.0032
ZHETT2	0.00056	0.0042	0.031	0.0088
ZHETT3	0.0023	0.017	0.13	0.036

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The evaluation requires a quantitative model for the time behavior of electric power failures. The analyses of the diesel generators and the fuel oil transfer system are used to provide this time dependent failure function after an initiating event and to consider the sequencing and details of each recovery option.

The electric power recovery scenarios evaluated in this analysis all include a loss of offsite power (including those caused by nonseismic external events). Offsite power failure could be the initiating event itself, or it could result from power grid instabilities when the Diablo Canyon Unit 1 trips off-line from another initiating event. However, each sequence for this model assumes offsite power is lost at time $t = 0$. Demand failures, such as circuit breaker operations and failures such as short circuits and diesel generator operating problems, contribute to the cumulative unavailability function based on the mission time of the analysis. After the cumulative failure function has been quantified in this manner, it can be differentiated to provide the time-dependent power failure function used in the recovery analysis.

Two types of power recovery actions were evaluated. Depending on the cause for its failure, offsite power may be restored at any time during the 24 hours after the initiating event. When offsite power is recovered, the diesel generators can be stopped. The second type of recovery is the restoration of the failed diesel generators. This is considered only for the period after the onsite diesel generators fail. No repairs of diesel fuel oil transfer failures are evaluated in this section.

Offsite Power Recovery

A review of data from more than 50 complete losses of offsite power at U.S. nuclear plants indicates that the total time to restore onsite power is almost always dominated by the length of time required to restore stable power at the plant switchyard. In other words, once the switchyard is reenergized, experience has shown that plant personnel quickly reconnect onsite buses and restart deenergized equipment.

The detailed forced outage data compiled for the PG&E transmission lines are used in this study to develop a distribution for the likelihood of offsite power recovery as a function of time after its failure. For this analysis, successful offsite power recovery required at least one of the 230-kV lines to the Diablo Canyon startup transformers be reenergized.

Diesel Generator Power Recovery

Each diesel generator requires a supply of 125V DC from its respective DC bus for generator field flashing and generator start and control. The effect of the unavailability of DC power on diesel generator recovery is accounted for in the integrated recovery model.

The causes of diesel generator hardware failures can range from the spurious operation of a trip solenoid to major physical damage of mechanical or electrical components. Recovery from these failures may involve the simple resetting of a local trip interlock and restarting of the diesel generator, or it may require disassembly and repair of the engine, generator, or their control systems. If the time available for electric power recovery is relatively short (for example, less than approximately 2 hours), review of generic diesel generator failure and maintenance data indicate that only the diesel generator startup failures present a significant potential for rapid recovery. Diesel generator failure during operation generally involves more severe problems that require detailed troubleshooting, repairs, or replacement of parts, which are difficult to complete in less than 2 hours.

Finally, because most maintenance events require at least partial reassembly of the diesel generator before it can be started, it is assumed for this analysis that the maintenance contribution to unavailability is also irrecoverable within 2 hours after the initiating event.

The recovery time distribution summarized below applies to situations involving a high urgency for diesel generator repairs.

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Time To Recover A Failed Diesel Generator

<u>Time Following Operator Response (hours)</u>	<u>Probability</u>
0.0 to 0.5	0.20
0.5 to 1.0	0.10
1 to 2	0.15
2 to 4	0.15
4 to 8	0.20
8 to 24	0.10
> 24	0.10

The station auxiliary operators are responsible for operating the diesel generators and for initial problem troubleshooting. The following distribution is used to model the response time for an auxiliary operator. It applies to the elapsed time from failure of the diesel generator until the operator begins local troubleshooting activities in the diesel generator room.

Time For First Operator Response To Failed Diesel Generator

(Includes Detection Time, Notification Time, and Transit Time)

<u>Response Time (minutes)</u>	<u>Probability</u>
0 to 5	.01
5 to 10	.25
10 to 15	.50
15 to 20	.20
20 to 30	.03
30 to 60	.01

Scenario Specific Calculations. Within the framework of the complete loss of AC power, the status of the turbine-driven auxiliary feedwater pump and the status of the reactor coolant pump seals determine the time available before the onset of core damage.

Based on recorded Plant operating data, PG&E electrical design personnel estimated an extended battery availability of more than 12 hours with no reduction in DC loads during a station blackout (Smith, 1988). The diesel generators are assumed

in this analysis to be unrecoverable after depletion of the DC batteries. The restoration of offsite power and operation of the turbine-driven AFW pump, however, are assumed to continue after loss of DC power if a portable generator is successfully installed to provide vital 120 VAC power for instrumentation.

The time-dependent model was developed to compute the ratio of the conditional frequency of onsite power system failure in a mission time of 24 hours with failure to recover diesel generators or offsite electric power before core damage to the conditional frequency of onsite power system failure in a 6-hour period without including recovery.

The human action failure rate for cross tying two vital buses after a diesel generator is recovered is:

Mean Value:	.0053
5th Percentile:	.00063
50th Percentile:	.0032
95th Percentile:	.016

The human action failure rate for depressurizing the steam generators when the turbine-driven AFW pump is operating during a station blackout event is:

Mean Value:	.0085
5th Percentile:	.0010
50th Percentile:	.0052
95th Percentile:	.026

The human action failure rate for installing a portable generator to provide vital 120 VAC instrument power is estimated by the following distribution:

Mean Value:	.0050
5th Percentile:	.0003
50th Percentile:	.0023
95th Percentile:	.0170

The specific scenarios evaluated in this analysis are shown in Table 6-53. Also listed in this table are the analysis results for the electric power recovery factors in these scenarios. These recovery factors are applied to specific event sequences after the complete event tree models are assembled.

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Table 6-53
ELECTRIC POWER RECOVERY SCENARIOS AND RESULTS

Recovery Scenario Designator	Number of Failed Diesel Generators	Number of DC Trains Available to Diesel Generators	Diesel Generator Recovery	AFW Available	Recovery Factor*				Remarks
					Mean	5th Percentile	50th Percentile	95th Percentile	
RESLC1	3	5	Yes	No	0.46	0.21	0.41	0.87	Core damage scenario: core uncoverly due to seal LOCA and RCS inventory loss through PORVs.
RESLC2	3	5	Yes	Yes	0.038	0.0047	0.027	0.11	Core damage scenario: core uncoverly due to seal LOCA.
RESLC3	**	N/A	Not	Yes	0.086	0.013	0.080	0.15	Core damage scenario: core uncoverly due to seal LOCA.
REAC06	2	5	Not†	No	0.28	0.11	0.27	0.46	Core damage scenario: stuck open PORVs (or small LOCA); safety injection lost in 6-8 hours due to depletion of RHST inventory, RHR lost due to diesel generator failure.
REAC12	2	5	Not††	No	0.21	0.055	0.20	0.38	Core damage scenario: PORVs close due to depletion of DC batteries in 12 hours; bleed and feed capability lost.

*The uncertainty distributions presented in this table do not reflect uncertainty in battery lifetime after loss of all AC power and time delay for manual operation of onsite breakers following loss of DC power.

**Fuel oil transfer system failure.

†Recovery of fuel oil transfer by installing portable fuel pump and hoses is considered separately.

††Electric power recovery by restoring diesel generator is assumed to be unsuccessful due to failure to crosstie vital buses.

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Quantification and Results

The Plant event sequence model was quantified for all identified initiating event groups accounting for all identified sources of uncertainty in the model and the data. The results are summarized on Figure 6-48 where we see the probability distributions for core damage frequency at Diablo Canyon Unit 1.

Several important conclusions are evident on Figure 6-48. The risk of core damage is driven by the internal initiating events. Seismic events contribute about 18 percent on a mean basis. The uncertainty in seismic risk is quite broad ($\frac{95\text{th percentile}}{5\text{th percentile}} = 100$) compared to the overall frequency of the core damage ($\frac{95\text{th percentile}}{5\text{th percentile}} = 5$).

The best estimate core damage frequency is the median value of 1.5×10^{-4} event per year; that is, approximately one damaged core every 7,000 years. Summary statistics from all three sources are shown in Table 6-54.

Here we see that the contributions from seismic events; internal events, and other external events (primarily fires) are reasonably consistent at the mean and most likely estimates, seismic events being somewhat more important to the results on a mean value basis. To put these results in terms more familiar to many readers, the last column shows the most likely recurrence rates ($\frac{1}{50\text{th percentile frequency}}$) for core damage events due to seismic, internal, and other external causes.

Looking a little deeper, Table 6-55 shows the contributors within the categories of Table 6-54 on a mean value basis. Of the 63 percent of the core damage frequency due to internal events, only a small fraction results from LOCAs. A variety of general transient events contribute 26 percent due simply to their high frequency of occurrence. (More thorough recovery analysis is likely to reduce this contribution.) Two single initiators, loss of offsite power and loss of a single DC bus are the largest individual contributors at 20 percent and 5 percent respectively. The external events are dominated by a variety of earthquakes at 18 percent and several fire scenarios at 16 percent.

SUMMARY OF SEISMIC RISK RESULTS

The first objective of the Diablo Canyon Probabilistic Risk Assessment has been to support the Long Term Seismic Program by calculating the risk of core damage due to seismic events. In this way, the true impact of seismic events and the seismic design can be understood. Incorporating the seismic PRA within the framework of full-scope Level 1 risk assessment, allows the seismic risk results to be placed in proper perspective. Within this framework, it is important to recognize that improvements to the seismic design can reduce core damage frequency by no more than 18 percent on a mean basis. In the remainder of this section, we look at the contributors to seismic risk.

We can approach the contributors to core damage frequency from three directions. The first is to identify the contribution of each earthquake (spectral acceleration category). This viewpoint is of primary interest to geologists and structural engineers. The second develops a scenario-by-scenario ranking. From this direction the focus is on functional failures, an operational approach and perhaps the best viewpoint for understanding risk and how to control it. The third approach, more traditional to systems and structural analysts, focuses on contributions from specific component failures due to the earthquake.

The complete probabilistic risk assessment model was quantified for six discrete ranges of spectral acceleration:

Discrete Spectral Acceleration Level (g)
0.725
1.500
1.875
2.250
2.750
3.500

The contribution of each earthquake is shown on Figure 6-49 where we see that 55 percent of the core damage frequency comes from accelerations spanning 2.0 to 3.0 g spectral. Only 14 percent comes from the highest range because there is little chance of earthquakes this large (that is, the



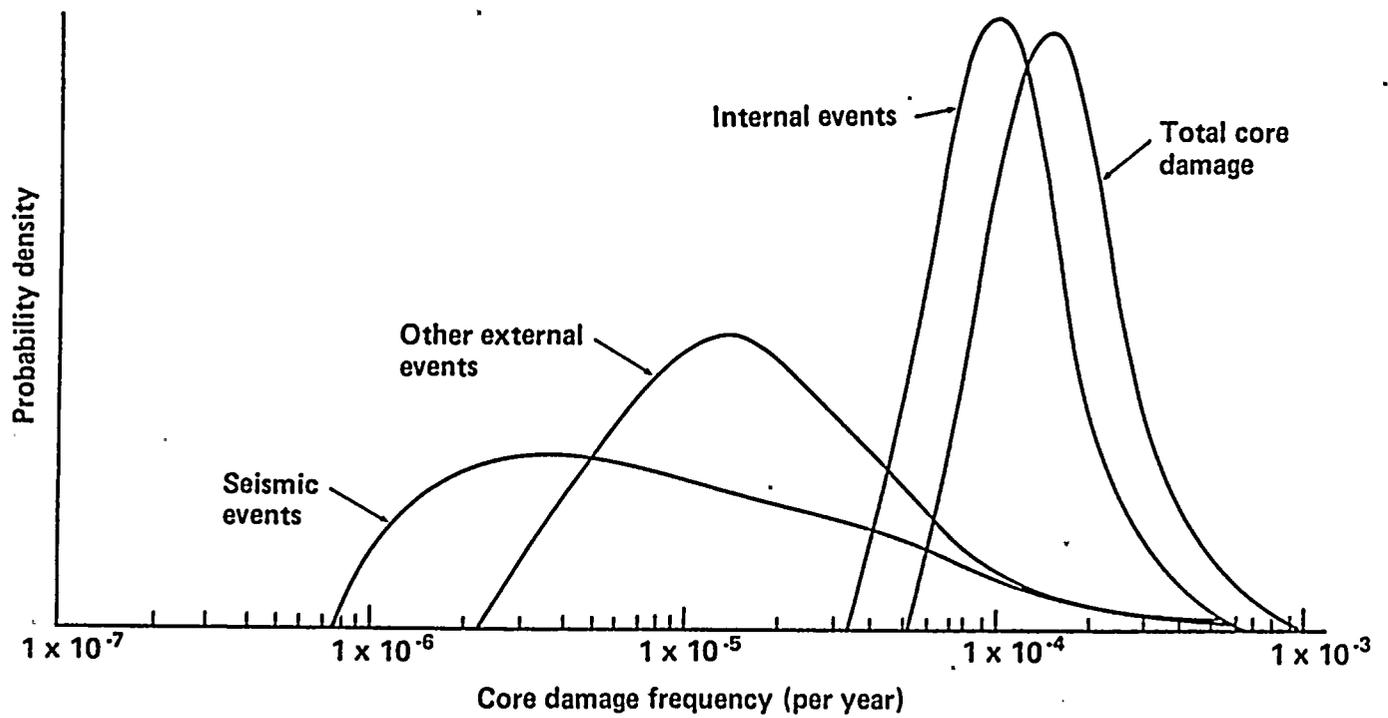
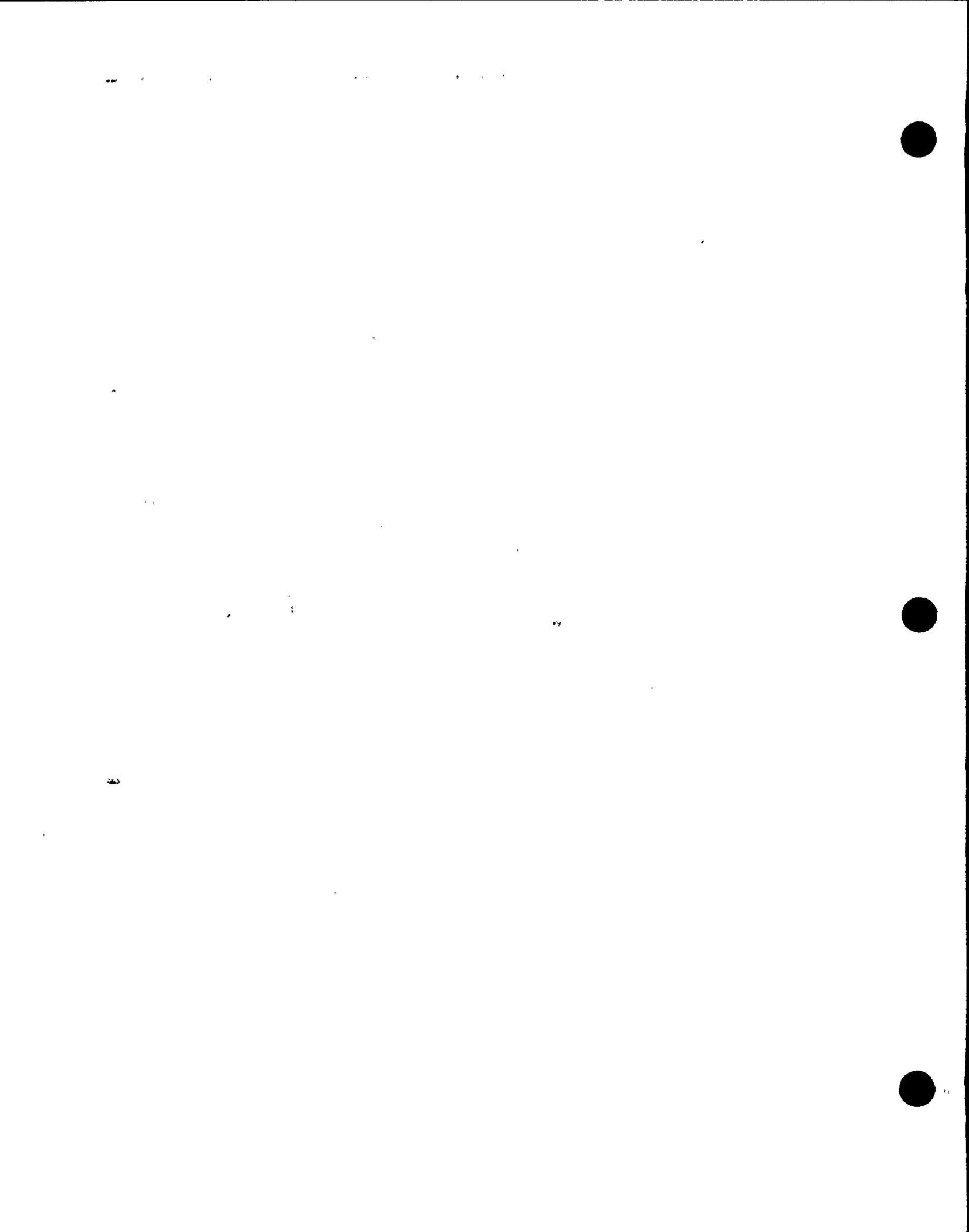


Figure 6-48

Results of the Diablo Canyon probabilistic risk assessment.



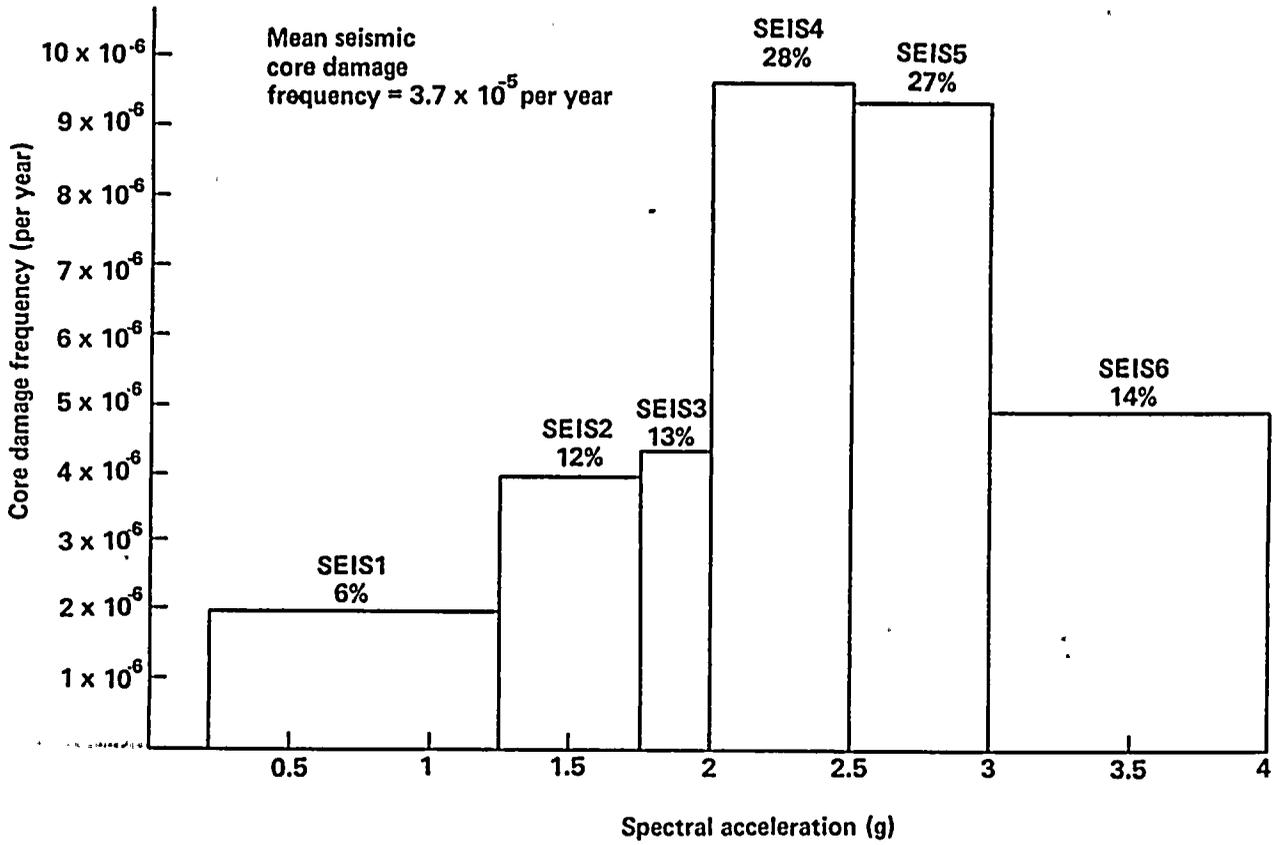


Figure 6-49

Contribution of each earthquake range to the seismic core damage frequency.

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Table 6-54

**DIABLO CANYON PROBABILISTIC RISK ASSESSMENT
SUMMARY STATISTICS**

Contributor	Core Damage Frequency				Most Likely Recurrence Rate
	5th Percentile	50th Percentile	Mean	95th Percentile	
Seismic Events	9.3×10^{-7}	6.2×10^{-6} (5%)	3.7×10^{-5} (18%)	1.1×10^{-4}	1 in 160,000 years
Internal Events	5.2×10^{-5}	1.3×10^{-4} (82%)	1.3×10^{-4} (63%)	2.3×10^{-4}	1 in 10,000 years
Other External Events	4.1×10^{-6}	1.5×10^{-5} (13%)	3.9×10^{-5} (19%)	1.0×10^{-4}	1 in 65,000 years
TOTAL	7.7×10^{-5}	1.5×10^{-4} (100%)	2.0×10^{-4} (100%)	4.0×10^{-4}	1 in 7,000 years



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Table 6-55

CONTRIBUTORS TO MEAN CORE DAMAGE FREQUENCY

<u>Initiating Event Category</u>	<u>Mean Core Damage Frequency (Per Year)</u>	<u>Contribu- tion (Percent)</u>
LOCAs	1.1-5	6
Interfacing system LOCAs	5.6-7	1
Steam generator tube rupture	3.0-6	2
Transients	5.3-5	26
Loss of offsite power	4.1-5	20
Loss of one DC bus	9.2-6	5
Loss of auxiliary saltwater or component cooling water	4.3-6	2
Loss of ventilation	2.7-6	1
TOTAL INTERNAL EVENTS	1.3-4	63
Seismic events	3.7-5	18
Fires	3.2-5	16
Floods, jets, and sprays	6.6-6	3
Chemical hazards	3.5-7	<1
TOTAL EXTERNAL EVENTS	7.6-5	37
TOTAL	2.02-4	100

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hazard curve is falling off sharply above 3.0 g spectral). There is a contribution of 31 percent coming from earthquakes of less than 2.0 g spectral. It is important to realize that these earthquake levels are substantially below the HCLPF values for most of the affected equipment, and this contribution to core damage might be eliminated if we had better knowledge of the chance of equipment failure at very low accelerations.

From the viewpoint of scenarios, seismically induced loss of station electrical power scenarios are in the forefront of the seismic contributors. Furthermore, many of these scenarios involve failure of the turbine building. Note that, although the fragility of offsite power is poorer than the turbine hall or other components, for many of these scenarios (as high as 2.25 g) offsite power has not failed. In other words, the uncertainty in the fragility has a strong impact on the results. Finally, although further recovery is possible for some of the scenarios, the only recourse is to recover offsite power. Substantial time will be required for that activity, enough so that the chance of timely recovery is not especially high; that is, very little conservatism is introduced by our failure to model that recovery.

The final look at the seismic risk contributors is in terms of the significance of individual components. First in Table 6-56, we present the fragilities of key components in rank order, weakest first. However, as indicated in the accompanying notes, this ordering is not directly correlated to risk. Because of the overall systems design, the impact of some failures is more direct than others. As a closer approximation of importance, Table 6-57 looks at key groups of equipment, which have direct impact on core damage. For each group, the table gives the mean frequency of failure found by convolving the seismic hazard curve with the equipment fragility curves. Consistent with the scenario results, the most likely failures of key equipment groups involve vital electrical power. Figure 6-50 gives a

combined fragility curve for the entire Plant obtained by passing the individual curves through the logic of the Plant model. Please note that random nonseismic failures are included in these curves, and that the uncertainty presentation on Figure 6-50 is different than the β_U and β_R formulation described in the fragility section. The uncertainty treatment used for the full Plant fragility curve should be interpreted as the percentiles of the failure fraction associated with any acceleration, a .

Finally, in Table 6-58, the leading individual contributors are ranked by their risk improvement importance, that is, by how much the total seismic risk would improve if each component were individually made impervious to seismically induced failure. The most important components are those for which failure guarantees that core damage will occur. The single greatest contributor is the turbine building. Not only is it the leading contributor, but it is one of the least amenable to improvement. The table also shows the importance of key aspects of the current design by looking at the degradation in core damage frequency if several key component had very low seismic strength.

Overall, the seismic PRA shows that the Plant design is well-balanced. There are no overwhelmingly weak links. The components and structures are strong and the seismic risk is quite low.

SUMMARY OF NONSEISMIC RESULTS

To provide a perspective for the seismic results, the nonseismic risk was quantified. The mean nonseismic core damage frequency is 1.7×10^{-4} .

The bulk of the risk is calculated to come from the internal events as was shown on Figure 6-48. A complete breakdown of the contribution to core damage frequency of all the internal initiating events is given in Table 6-59. Here we see that



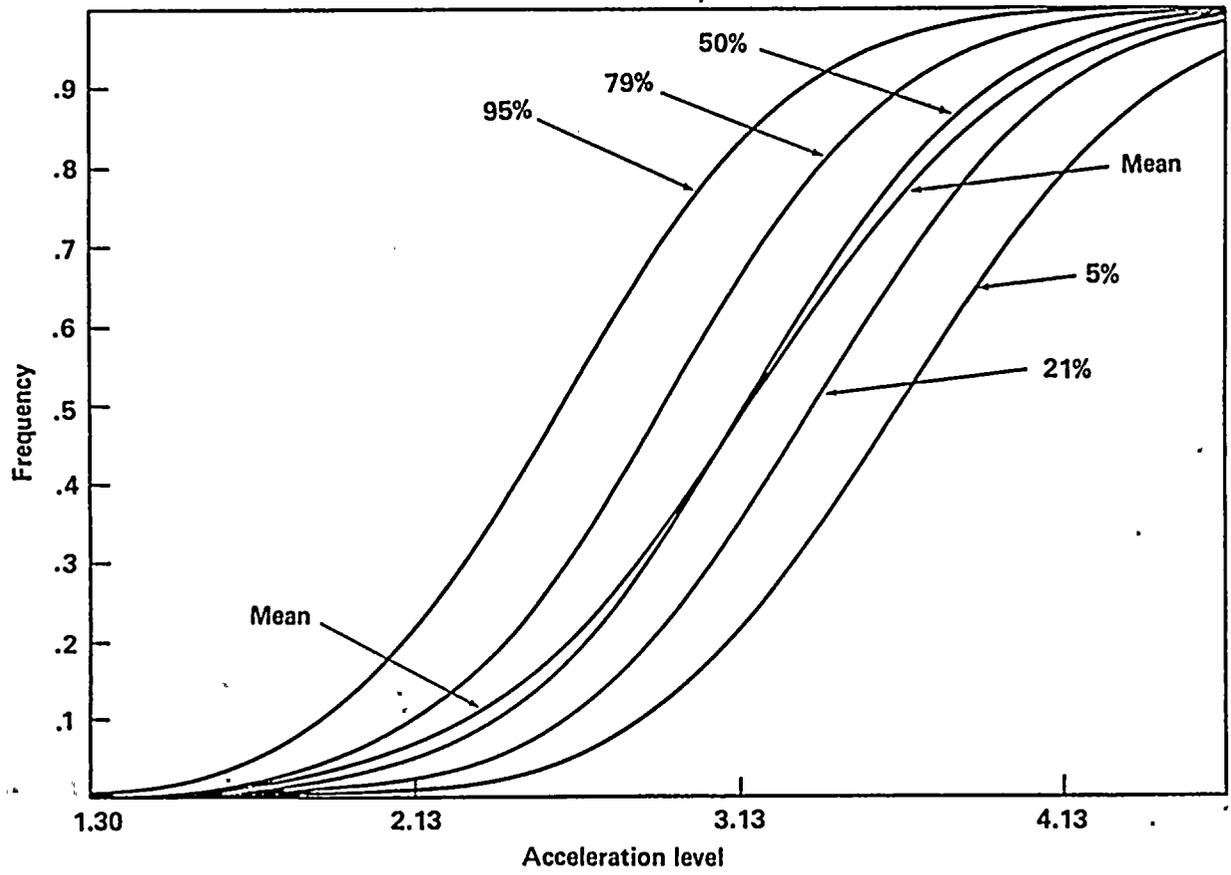


Figure 6-50

Plant fragility curve, including random and nonseismic failures.

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Table 6-56

FREQUENCY OF SEISMIC COMPONENT FAILURES GREATER THAN 1.0×10^{-6} PER YEAR

Component	Frequency of Component Failure (Per Year)	Comment on Failure Impact
1. 500-kV offsite power grid (Z05PR2)	3.34-3	Plant automatically switches to 230-kV grid every plant trip.
2. 230-kV offsite power grid (Z08PWR)	5.87-4	Challenges onsite emergency power system.
3. Chatter of 4-kV switchgear (ZSGPCH)	5.86-5	Interrupts 4.16-kV vital AC, recoverable at switchgear.
4. Turbine building shear wall (ZTBSHHR)	1.10-5	Assumed failure of all AC, unrecoverable.
5. 4.16-kV safeguard relay panel given turbine building strut fails.	1.01-5	Strut has greater capacity; impact is failure of vital AC transfer to 230-kV grid.
6. Potential transformer for bus HF (ZTFRF2) given turbine building strut fails	9.24-6	Strut has greater capacity; impact is failure of vital 4.16-kV bus HF.
7. Diesel generator control panel (ZDGCPN)	5.22-6	If offsite power fails, all five onsite diesel generators assumed failed.
8. Pressurizer PORV (ZPORVL)	3.20-6	Assumed that valves stick open; isolable by closing block valves.
9. 125V DC switchgear/breaker panels (ZSWGBP)	2.58-6	Fails all three trains of 125V DC.
10. HHVAC ducting and supports (ZHHVDAS)	2.55-6	Fails 480V switchgear ventilation and control room ventilation; recoverable by opening doors.
11. 4-kV/480V transformers (ZTRANS)	2.19-6	Conservatively modeled as unrecoverable failure of all 4-kV vital AC.
12. Diesel generator excitation cubicle (ZDGEXC)	1.50-6	If offsite power fails, all five onsite diesel generators assumed failed.
13. CCW heat exchangers (ZCCWX)	1.43-6	Failure leads to draining CCW system; fire water system provides backup cooling for RCP seal injection.
14. Steam generator (ZSTMGN)	1.35-6	Failure assumed to result in excessive LOCA.
15. Turbine building strut (ZSTRUT)	1.26-6	Lowers seismic capacity of safeguard relay panel, bus HF potential transformer and 4-kV switchgear.
16. Impulse lines (ZIPLNS)	1.21-6	Unisolable small LOCA.
17. Auxilliary building (ZABLDG)	1.00-6	Assumed to fail all building contents; modeled as failure of all 125V DC.

NOTE: Exponential notation is indicated in abbreviated form, i.e., 3.34-3 = 3.34×10^{-6} .

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Table 6-57

GROUPS OF RELATED SEISMIC FAILURES
CONTRIBUTING TO THE CORE DAMAGE

<u>Sequences Evaluated</u>	<u>Failure Frequency (Per Year)</u>
Total seismic core damage	3.7-5
All 4.16kV vital AC switchgear fail	1.7-5
Loss of offsite power	1.2-5
Excessive LOCAs	7.8-6
All vital 125V DC fails	5.6-6
All 120V vital instrumentation fails	1.4-6
Relay chatter with failure to recover	1.2-6
Control room boards hot shutdown panel fail	9.7-7

NOTE: Exponential notation is indicated in abbreviated form, i.e., 3.7-5 = 3.7×10^{-5} .



Table 6-58

SEISMIC FAILURES OF COMPONENTS CONTRIBUTING TO CORE DAMAGE

Component	Does Failure Guarantee Core Damage?	Importance			
		Impact If Very Strong, that is, If Impervious to Earthquake		Impact If Very Weak, that is, If Guaranteed to Fail	
		Core Damage Frequency	Percent(1) Improvement in Mean Seismic Core Damage Frequency	Core Damage Frequency	Percent(1) Degredation in Mean Seismic Core Damage Frequency
Original core damage frequency	--	3.7-5	--	3.7-5	--
Turbine building sheerwall	Yes	2.6-5	30.5		
230-kV offsite power	No	2.8-5	24.4		
Vital DC	No				
Excessive LOCA	Yes				
Diesel generator control Panel	No	3.3-5	10.0		
4,160-kV/480V transformers	Yes	3.5-5	5.0		
Steam generators	Yes	3.5-5	3.4		
Relay chater (main control, diesel generator control, 4-kV switchgear)	No	3.6-5	2.4		
BOP piping and supports	No	3.6-5	2.2		
Pressurizer PORV	No	3.6-5	0.7	1.4-4	291
Strut for turbine building	No	3.7-5	0.4		
Small LOCA (PORV, RCPs, impulse lines, BOP piping and supports)	No			1.4-4	291
Human action to recovery relay chatter	No			1.0-4	173
Centrifugal charging pump	No			3.7-5	0.2

(1) Percentages have been carried to the indicated significant digits; core damage frequency has been rounded to two significant digits.

NOTE: Exponential notation is indicated in abbreviated form, that is, 3.67-5 = 3.67×10^{-5} .

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Table 6-59

INTERNAL INITIATING EVENT CONTRIBUTION TO CORE DAMAGE FREQUENCY

Initiating Event Category	Core Damage Frequency (Per Year)	Contribution (Percent)
1. Excessive LOCA	2.7-7	0.2
2. Large LOCA	2.5-6	2.0
3. Medium LOCA	5.8-6	4.6
4. Small LOCA, nonsolable	9.0-7	0.7
5. Small LOCA, isolable	1.7-6	1.4
6. Interfacing systems LOCAs		
6.a. At RHR pump suction	5.0-7	0.4
6.b. At RHR pump discharge	5.8-8	<0.1
7. Steam generator tube rupture	3.0-6	2.4
8. Reactor trip	1.6-5	12.5
9. Turbine trip	1.4-5	11.2
10. Loss of condenser vacuum	7.0-7	0.6
11. Closure of all MSIVs	2.4-7	0.2
12. Steamline break inside containment	2.3-6	1.8
13. Steamline break outside containment	2.7-6	2.2
14. Inadvertent safety injection	6.0-7	0.5
15. Main steam relief valve opening	5.0-8	<0.1
16. Total MFW loss	8.0-7	0.6
17. Partial MFW loss	1.1-5	8.8
18. Excessive feedwater	3.0-6	2.4
19. Closure of one main steam isolation valve	9.0-7	0.7
20. Core power excursion	3.0-7	0.2
21. Loss of primary flow	1.0-6	0.8
22. Loss of offsite power	4.1-5	32.4
23. Loss of one DC bus	9.2-5	7.3
24. Total loss of auxiliary saltwater	1.3-6	1.0
25. Total loss of CCW	3.0-6	2.4
26. Loss of 480V switchgear ventilation	1.5-6	1.2
27. Loss of control room ventilation	1.2-6	1.0
 TOTAL	 1.3-4	 100

NOTE: Exponential notation is indicated in abbreviated form, i.e., 2.7-7 = 2.7×10^{-7} .

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only four specific initiating events yield substantial individual contributions:

<u>Initiating Event</u>	<u>Contribution to Internal Core Damage Frequency</u>	<u>Initiating Event Frequency (Per Year)</u>
Loss of offsite power	32.5%	0.14
Reactor trip	12.5%	1.05
Turbine trip	11.2%	0.75
Partial loss of main feedwater	8.4%	0.03
Loss of 1 DC bus	7.3%	0.09
TOTAL	71.8%	

The remaining 28 percent is distributed among a great many events. The reason for the high contributions from the five events presented above are straightforward. The loss of offsite power event is important because of the challenge it places on the Plant, combined with the moderate frequency of the initiator. Reactor trip and turbine trip are mild transients, but occur more often. The remaining two events have fairly high initiating event frequencies and are somewhat more severe than simple trip. Finally, the most severe events have modest contributions because they are very unlikely. In the remainder of this section, we examine the scenarios leading from initiating event to core damage.

The analysis of scenarios includes consideration of human actions, both routine actions and recovery actions. Recovery, where feasible, has been analyzed for the highest frequency scenarios identified during quantification of the complete Plant model.

Before examining the identified scenarios, we should discuss several caveats that apply to these results at the time of this writing. The results are conservative in the sense that recovery actions have been modeled only for the most significant sequences. Therefore, the ranked list of scenarios may be somewhat misleading in that the highest ranking contributors may be overstated. In another sense, the results for low frequency scenarios may be optimistic. Some human action analysis results have been imbedded in the

systems analysis for event tree top events. Thus, low frequency scenarios exist in which there is an implicit, but incorrect, assumption of independence among several competing human responses. It is believed that this effect would only be significant if the currently significant contributors were much reduced in frequency. Despite these two caveats, much can be learned by reviewing the scenarios of Table 6-60.

SUMMARY OF OTHER EXTERNAL EVENT RESULTS

The contributions to the "other external events" category of Figure 6-48 come primarily from fire and flood scenarios arising within the Plant. Altogether, they are responsible for 19 percent of the core damage frequency (16 percent fires, 3 percent floods). From the large number of potential fire and flood scenario identified by the spatial interactions analysis, 17 were significant enough to warrant more thorough analysis and propagation through the full Plant model. The results for these fire and flood scenarios are summarized in Table 6-61.

A number of additional external initiating events were also considered. The results are summarized in Table 6-62. None of these event contribute substantially to the core damage frequency. All these results are conservative upperbound calculations, except for the hazardous chemical release for which a greater depth of study was performed.

Conclusions

Figure 6-51 compares the results of the Diablo Canyon PRA with other Westinghouse PWRs evaluated for seismic risk by Pickard, Lowe, and Garrick. The total core damage frequency and upper and lower bounds are comparable with other similar Westinghouse PWRs that are located in low seismic hazard zones.

Overall, the seismic probabilistic risk assessment shows that the Diablo Canyon design is well-balanced. There are no outstanding weak links. The components and structures are strong and the seismic risk is quite low.

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Table 6-60

FUNCTIONAL INTERNAL EVENT SCENARIOS CONTRIBUTING TO CORE DAMAGE

Scenario	Frequency (Per Year)	Contribution (Percent)	Initiator	Direct Failures	Further Recovery Possible	Dependent Failures
1	5.36-6	3.1	RT	Failure to maintain hot standby	Yes	Unspecified Operator Errors
2	4.96-6	2.9	TT	Failure to maintain hot standby	Yes	Unspecified Operator Errors
3	3.53-6	2.0	PLMFW	Failure to maintain hot standby	Yes	Unspecified Operator Errors
4	2.28-6	1.3	MLOCA	Manual switchover to recirculation	No	Failure of Recirculation
5	2.13-6	1.2	LOCC	Fail to align backup cooling to charging pumps for RCP seal injection	No	Component Cooling Water, Charging SI Pumps, RCP Seal LOCA
6	1.72-6	1.0	LIDC	DC power train H, one AFW motor-driven pumps	Yes	Instrument Channels I2, I3, I4; 2 AFW Pumps; Bleed and Feed Cooling
7	1.71-6	1.0	MLOCA	Both RHR pump trains	No	Failure of Injection
8	1.70-6	1.0	LIDC	4-kV vital bus HH and one AFW motor-driven pumps	Yes	Instrument Channels I2, I4; 2 AFW Pumps; Bleed and Feed Cooling
9	1.40-6	0.8	EXFW	Failure to maintain hot standby	Yes	Unspecified Operator Errors
10	1.27-6	0.7	LLOCA	Accumulators	No	Failure of Injection
11	1.25-6	0.7	RT	Instrument channel I3, auxiliary feedwater, bleed and feed cooling	Yes	None
12	1.25-6	0.7	RT	Instrument channel I1, auxiliary feedwater, bleed and feed cooling	Yes	None
13	1.24-6	0.7	LOOP	Swing diesel goes to Unit 2, auxiliary feedwater, vessel integrity fails due to PTS	No	None
14	1.16-6	0.7	TT	Instrument channel I3, auxiliary feedwater, bleed and feed cooling	Yes	None

NOTE: Exponential notation is indicated in abbreviated form, i.e., 5.36-6 = 5.36 x 10⁻⁶.

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Table 6-60 (Continued)

FUNCTIONAL INTERNAL EVENT SCENARIOS CONTRIBUTING TO CORE DAMAGE

<u>Scenario</u>	<u>Frequency (Per Year)</u>	<u>Contribution (Percent)</u>	<u>Initiator</u>	<u>Direct Failures</u>	<u>Further Recovery Possible</u>	<u>Dependent Failures</u>
15	1.16-6	0.7	TT	Instrument channel I1, auxiliary feedwater, bleed and feed cooling	Yes	None
16	1.16-6	0.7	RT	Auxiliary feedwater, bleed and feed cooling	Yes	None
17	1.14-6	0.7	TT	Auxiliary feedwater, bleed and feed cooling	Yes	None
18	1.13-6	0.7	LOOP	Diesel for bus HH, PORV sticks open and is not isolated, RHR pump train A fails, failure to recover AC before recirculation required	Yes	Failure of Recirculation

NOTE: Exponential notation is indicated in abbreviated form, i.e., 1.16-6 = 1.16×10^{-6} .



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Table 6-61

CORE DAMAGE SEQUENCES INITIATED BY FIRES AND FLOODS

<u>Initiator</u>	<u>Fire-Related Failures</u>	<u>Independent Failures</u>	<u>Sequence Frequency (Per Year)</u>
1. CS2 (Cable Spreading Room Fire)	Pressurizer PORV sticks open	Operators abandon control room and fail to isolate PORV from hot shutdown panel. No credit for establishing recirculation from outside the control room.	1.20-5
2. CS1 (Cable Spreading Room Fire)	Auxiliary saltwater and component cooling water	Operators fail to either trip the RCPs or reestablish CCW.	7.7-6
3. FS8 (Turbine Building Fire)	Fail of all three trains of vital 4-kV switchgear	Core damage assumed from resulting RCP seal LOCA.	6.0-6
4. CR4 (Control Room Fire)	Failure of all vital 4-kV breakers; 4-kV buses, HF, HG, and HH deenergized	Operators fail to trip RCPs or to reestablish vital AC before core uncover due to RCP seal LOCA.	5.8-6
5. FS11 (Pipe Break in CCW Pump Room)	CCW fails	Operators fail to align fire water cooling to charging pumps to avoid RCP seal LOCA.	4.0-6
6. All Other Fires and Floods	--	--	3.1-6

NOTE: Exponential notation is indicated in abbreviated form, that is, 1.20-5 = 1.20×10^{-5} .

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Table 6-62

OTHER EXTERNAL EVENTS CONTRIBUTING TO CORE DAMAGE

<u>Core Damage</u>	<u>Upper Bound Frequency of Core Damage</u>
Aircraft crash and falling objects	$<10^{-8}$
Ship impact	2.1×10^{-8}
External flooding	2.1×10^{-8}
Hurricane and tornado wind and missile	3.2×10^{-7}
Hazardous chemical	3.5×10^{-7}
Turbine missile	$\approx 10^{-7}$
External fire	$<10^{-8}$

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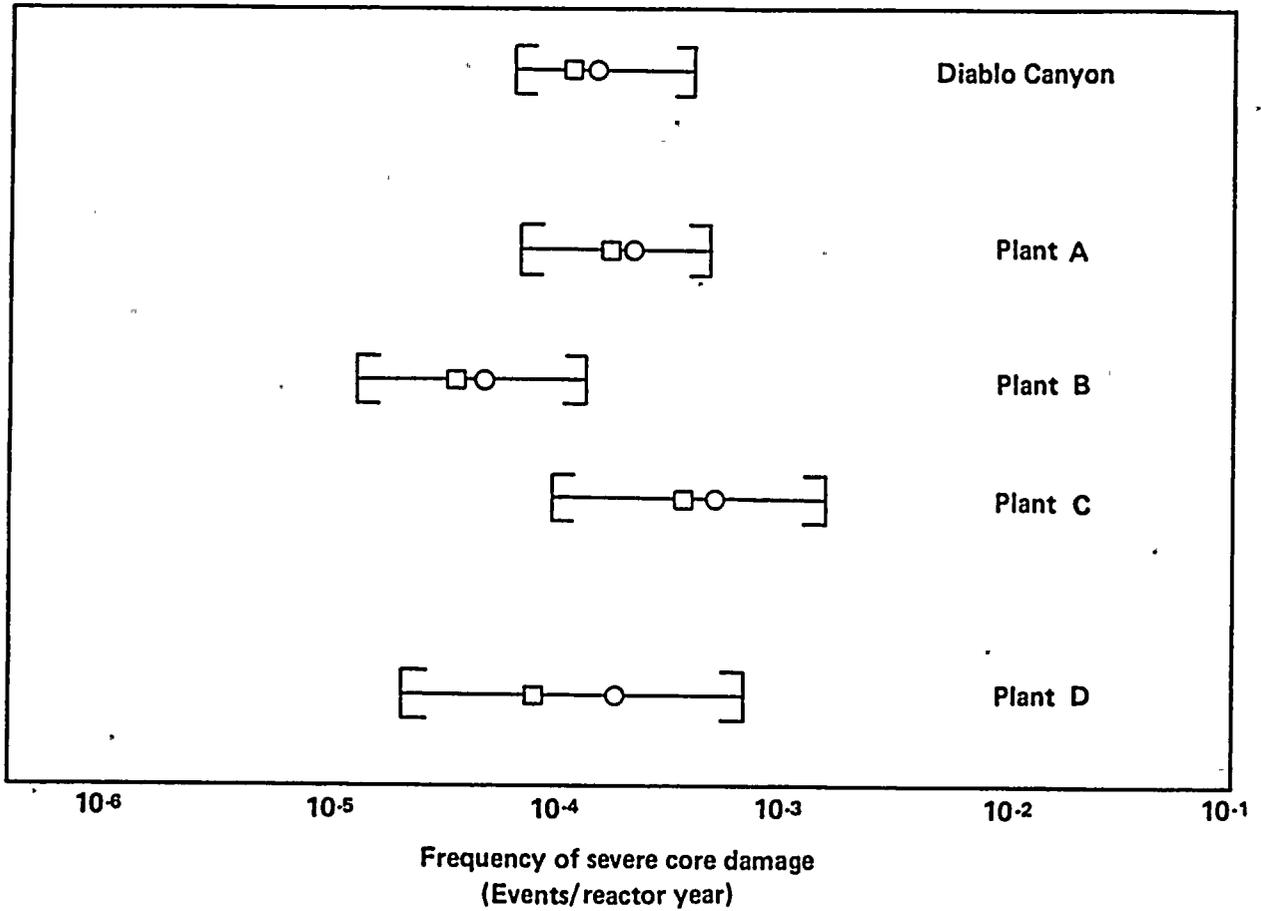
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EXPLANATION

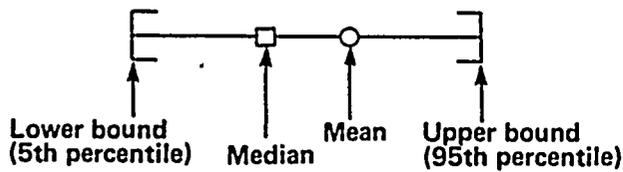


Figure 51

Other probabilistic risk assessments.

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Chapter 7

DETERMINISTIC EVALUATIONS

To Partially Address

Element 4 of the License Condition

ELEMENT 4 OF THE LICENSE CONDITION

PG&E shall assess the significance of conclusions drawn from the seismic reevaluation studies in Elements 1, 2, and 3, utilizing a probabilistic risk analysis and deterministic studies, as necessary, to assure adequacy of seismic margins.

OBJECTIVE

The objective of the deterministic evaluations was to augment the probabilistic risk assessment to assure the adequacy of Plant seismic margins, as specified by Element 4 of the license condition. This objective was achieved by:

- Comparing Plant responses as calculated from the site-specific ground motions due to the maximum earthquake on the Hosgri fault zone with those used as the bases for Plant design or for the earlier Hosgri evaluation, as appropriate (note that we will use the term "qualification basis" to mean the combination of the original design basis and the subsequent Hosgri evaluation basis).
- Assessing the Plant capacity margins over the demands (Plant responses) resulting from the 84th percentile ground motions due to the maximum magnitude earthquake.

SCOPE

The deterministic evaluation of the Plant drew from essentially all activities of the Long Term Seismic Program (Figure 7-1). The evaluation consisted of six steps. In Step 1, the maximum

earthquake magnitude was quantified, as described in Chapter 3. Step 2, which is described in Chapter 4, involved the development of the site-specific ground motions for the 50 percent and 84 percent probability of nonexceedance levels. Step 3 used information from the soil/structure interaction studies (Chapter 5) and applied it to develop Plant responses resulting from the site-specific ground motions. Step 4 compared these responses with the seismic qualification basis responses for the Plant. It also addressed the effects of responses due to the site-specific ground motions that exceed those for the seismic qualification basis. Step 5 involved the determination of the capacities for plant structures and components. These capacities were derived from the fragility evaluations described in Chapter 6. Finally, in Step 6, the capacities were compared with the demands (Plant responses) to assess the seismic margin of the Plant above the demand resulting from the 84th percentile ground motions due to the maximum magnitude earthquake.

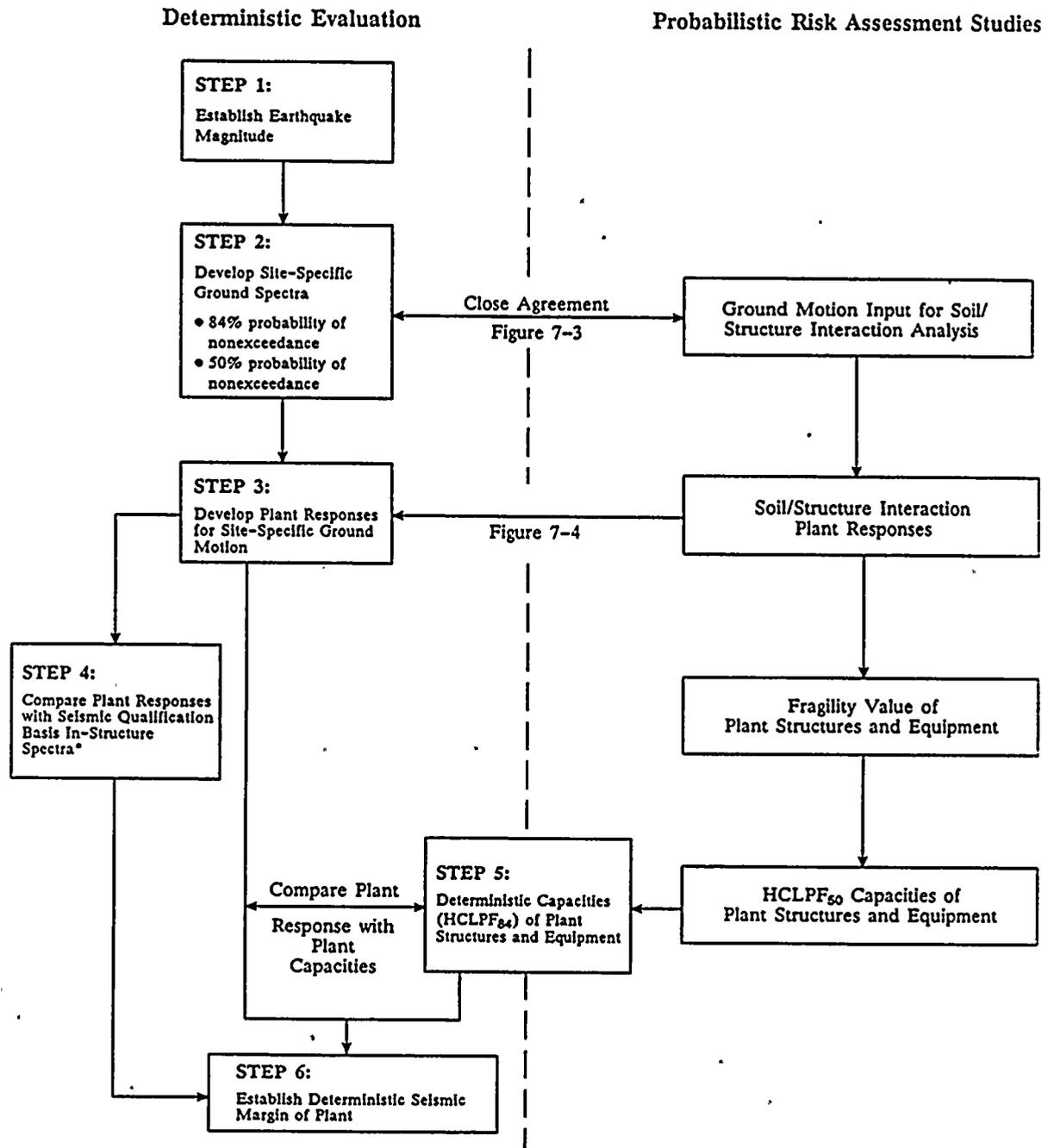
DETERMINISTIC COMPARISONS

Plant Responses to Site-Specific Ground Motions

DEVELOPMENT OF SITE-SPECIFIC GROUND MOTIONS

The confirmation of the controlling seismic source and its tectonic environment are described in Chapter 2 of this report. The source was identified as the Hosgri fault located at a distance of about 4.5 kilometers from the Plant site. The maximum





*Seismic qualification basis is a combination of original design and Hosgri evaluation basis.

Figure 7-1
Deterministic evaluation process.

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magnitude earthquake on this source, as established in Chapter 3, is an earthquake of magnitude 7.2 M_w .

This earthquake was used in the ground-motion study to develop appropriate ground response spectra. Because there is a lack of agreement in the nuclear industry on the selection of the level of ground motions for Plant reevaluations, the site-specific ground motions have been specified at both the 50 percent and 84 percent probability of nonexceedance levels. The details of the development of those ground motions are provided in Chapter 4. Site-specific horizontal and vertical ground-motion response spectra for 5 percent damping corresponding to the maximum earthquake magnitude are shown in Figures 4-22 and 4-23, respectively.

A comparison of the site-specific response spectra (for 5 percent damping) corresponding to the horizontal ground motions due to the maximum magnitude earthquake and the 1977 Hosgri (Newmark) evaluation spectrum is shown in Figure 7-2. It may be seen that the Hosgri evaluation spectrum envelops the site-specific 50th percentile spectrum at all frequencies and the 84th percentile spectrum at all frequencies less than about 15 hertz. The magnitude of the exceedance at frequencies above 15 hertz is approximately 10 percent.

DEVELOPMENT OF PLANT RESPONSES

To generate in-structure response spectra for use in the fragility evaluations for the probabilistic risk assessment, detailed soil/structure interaction analyses were performed, as described in Chapter 5. These soil/structure interaction analyses were performed deterministically, using the most current site-specific acceleration response spectra available at the time.

Although the primary purpose of these analyses was to generate inputs to the fragility analysis and the probabilistic risk assessment, it was recognized that they could also provide data useful in the Plant deterministic evaluation, if the

ground-motion spectral shape used for the deterministic evaluation was similar to that used in the probabilistic risk assessment. At the time the soil/structure interaction analyses were performed, the site-specific ground-motion spectra had not been finalized. To support the fragility analyses, a "best estimate" spectrum was established, recognizing that the soil/structure interaction analysis results could be adjusted for compatibility with the site-specific ground spectra, as appropriate, at a later stage in the Program.

Figure 7-3 shows a comparison of the ground-motion spectral shape used in the soil/structure interaction analyses with the site-specific ground-motion spectrum at the 84 percent probability of nonexceedance level. To permit a meaningful comparison of the shapes of these two ground-motion spectra, the ground response spectrum used in the soil/structure interaction analyses (Figure 5-22) has been scaled uniformly (frequency-independent scaling) such that the average spectral acceleration between 3 and 8.5 hertz is the same as that of the 84 percent probability of nonexceedance site-specific ground-motion spectrum (1.94 g). A comparison of these spectra shows that the site-specific ground-motion spectrum closely matches the soil/structure interaction analysis input spectral shape. Because the soil/structure interaction analyses are linear elastic, their results can be scaled uniformly. Accordingly, the soil/structure interaction analysis results can be used with small adjustment factors, to obtain Plant responses to the selected final site-specific ground motions.

The procedure used to convert the results of the soil/structure interaction analyses into Plant responses for the site-specific ground motions is illustrated in Figure 7-4. It requires the use of two factors:

- 1) A spectral shape factor (F_{ss}) that accounts for the minor variations between the site-specific ground-motion spectrum and the soil/structure interaction input spectrum. This factor is determined from the ratio of the



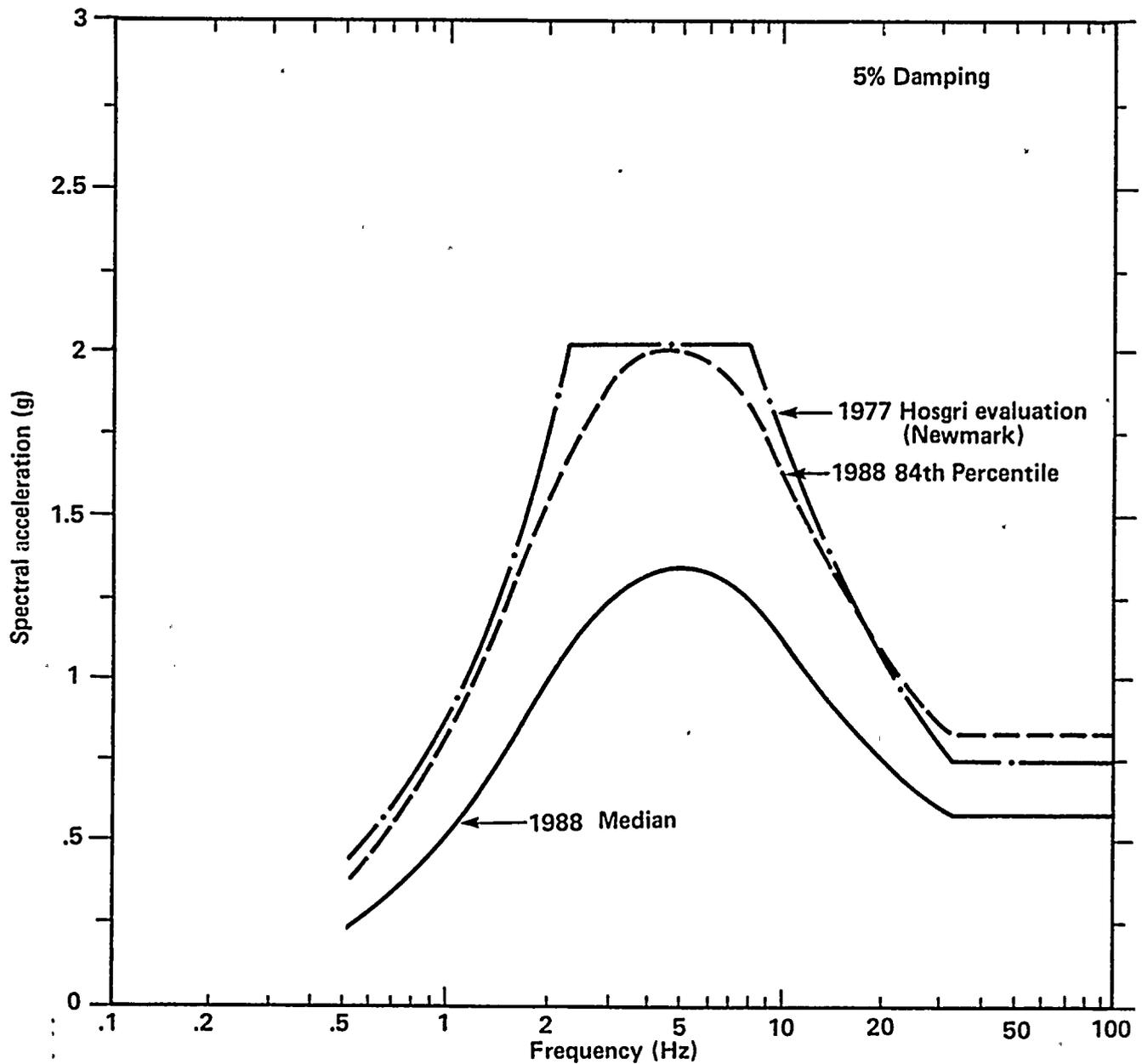


Figure 7-2

Comparison of the 1988 site-specific median and 84th percentile horizontal response spectra with the 1977 Hosgri evaluation (Newmark) response spectrum.

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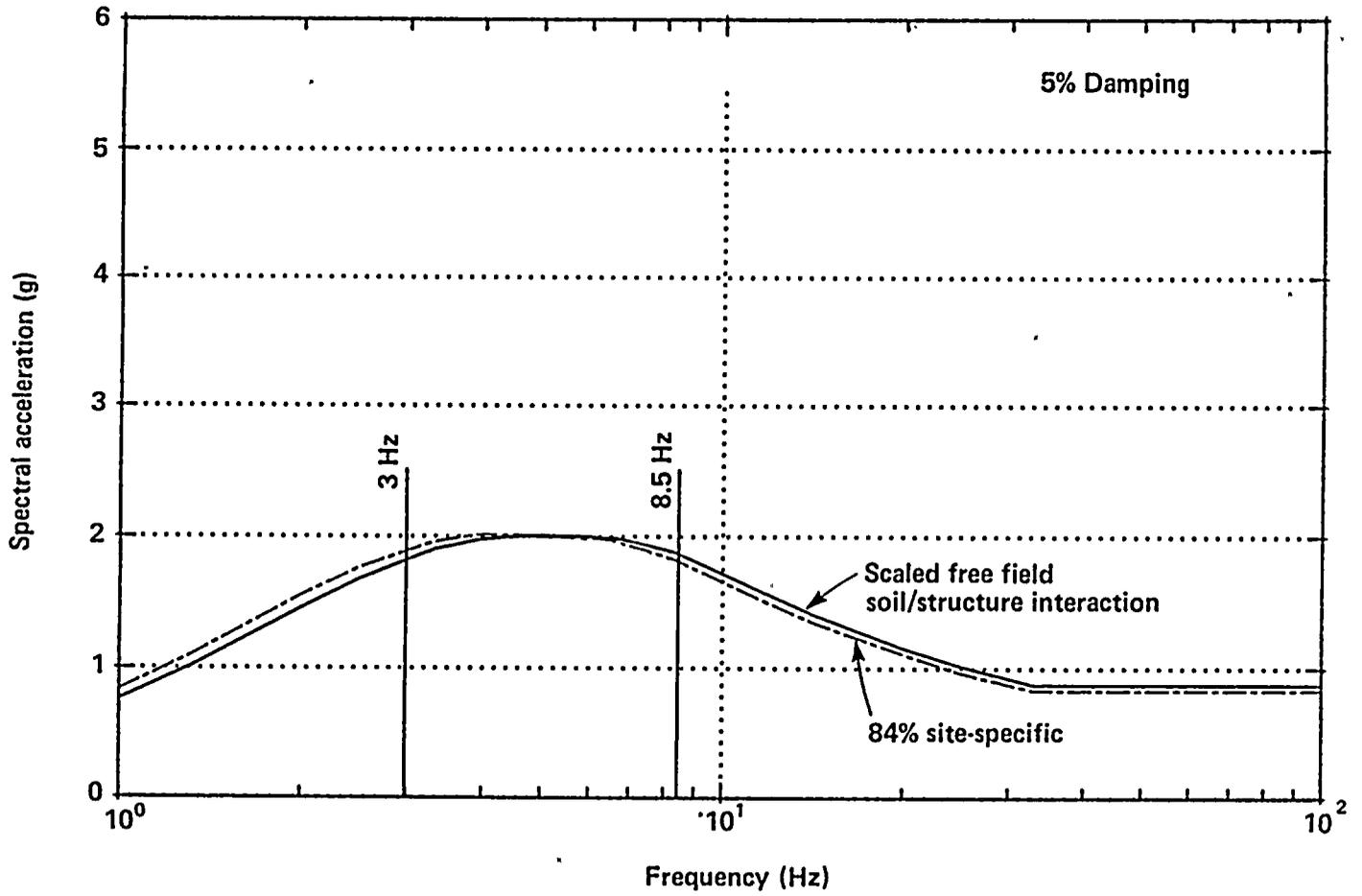


Figure 7-3
Comparison of scaled soil/structure interaction input spectrum with 84 percent probability of nonexceedance site-specific spectrum.

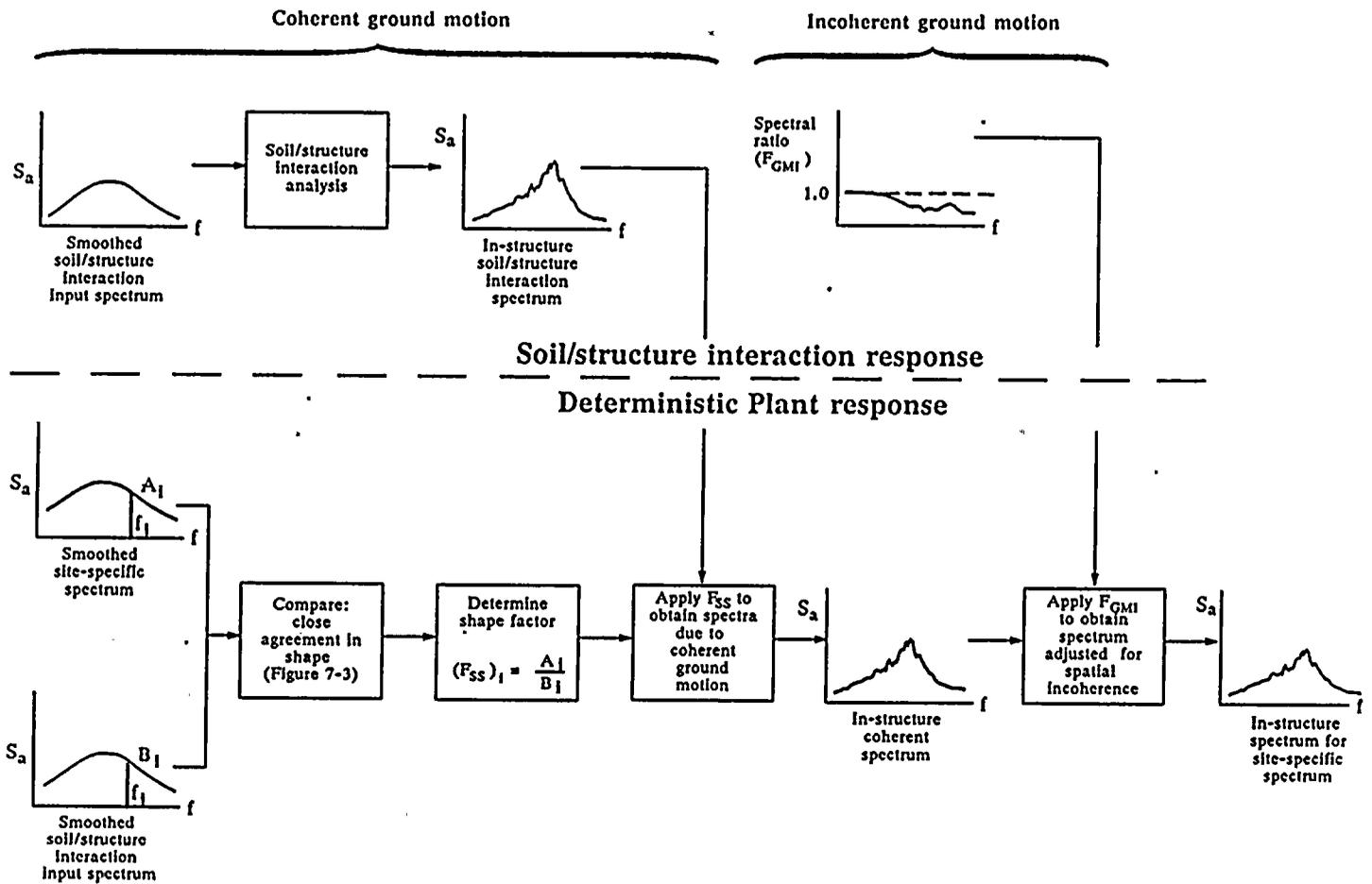


Figure 7-4
Overall process of developing plant responses.



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response spectral ordinates of the free-field site-specific ground-motion spectrum (Figure 7-2) and the spectral ordinates of soil/structure interaction analysis smoothed input spectrum (Figure 5-22). For the 84 percent probability of nonexceedance site-specific ground-motion spectrum, this factor ranges from about 0.86 to 1.0.

The factors F_{SS} are applied to the soil/structure interaction in-structure response spectra to obtain the Plant responses at various floor levels due to coherent site-specific ground motions. Figures 7-5 through 7-10 show plots of the site-specific free-field ground-motion spectrum (at the 50 and 84 percent probability of nonexceedance levels) with the corresponding basemat response spectra (El 85 feet) of the major structures.

For frequencies above about 10 hertz, the soil/structure interaction effect (coherent motion) results in a reduction of the input motion to the basemat from the free-field motion. For the frequencies lower than 10 hertz, that basemat motion is slightly amplified.

- 2) A spatial incoherence factor (F_{GMI}) that accounts for the spatial variations of ground motion. The development of this factor is discussed in Chapter 5. For a specific site, this factor, in general, results in a reduction of building responses and is dependent on the plan area of the building foundation and the frequency of vibration of the building, among other parameters. For the frequency range above about 5 hertz, the reduction in translational motion is about 6 percent for the containment, 15 percent for the auxiliary building, and 20 percent for the turbine building. When considered in conjunction with rocking and torsional motions, there is generally a decrease in the above effects.

The F_{GMI} factors are applied to the response spectra developed for coherent site-specific ground motions to obtain the composite effect

of soil/structure interaction. Figures 7-11 through 7-18 show comparisons of free-field and basemat spectra, including the effects of ground-motion incoherence.

Comparisons of Plant Responses for Site-Specific Ground Motions and Seismic Qualification Bases Motions

The Plant seismic qualification basis events included two large earthquakes: the double design earthquake and the Hosgri earthquake. The seismic design and qualification requirements associated with those two earthquakes were developed at different times during the plant-licensing process. As a result, the corresponding analysis parameters, method, and criteria (for example, structural damping, modeling assumptions, treatment of soil/structure interaction, and so forth), differ not only from those used in the current deterministic evaluations, but also from one another. Because of these differences, one-to-one comparison of response spectra due to the site-specific ground motions with the governing seismic qualification bases spectra is not always appropriate. However, comparisons of response spectra are provided, in response to a request from Nuclear Regulatory Commission (NRC) Staff.

FREE-FIELD AND BASEMAT RESPONSE SPECTRA

During the previous Hosgri evaluations, Plant response was evaluated for both a Hosgri spectrum recommended by Newmark and a Hosgri spectrum recommended by Blume. Seismic evaluations were based on whichever of these spectra proved to be more conservative for any given structure or equipment item at any given frequency. Figure 7-19 shows comparisons of the enveloped Hosgri (Newmark and Blume) 0.75 g free-field response spectrum with the site-specific ground-motion spectra, at the 50 percent and 84 percent probability of nonexceedance levels. This figure shows that the 50 percent probability of nonexceedance of site-specific ground-motion



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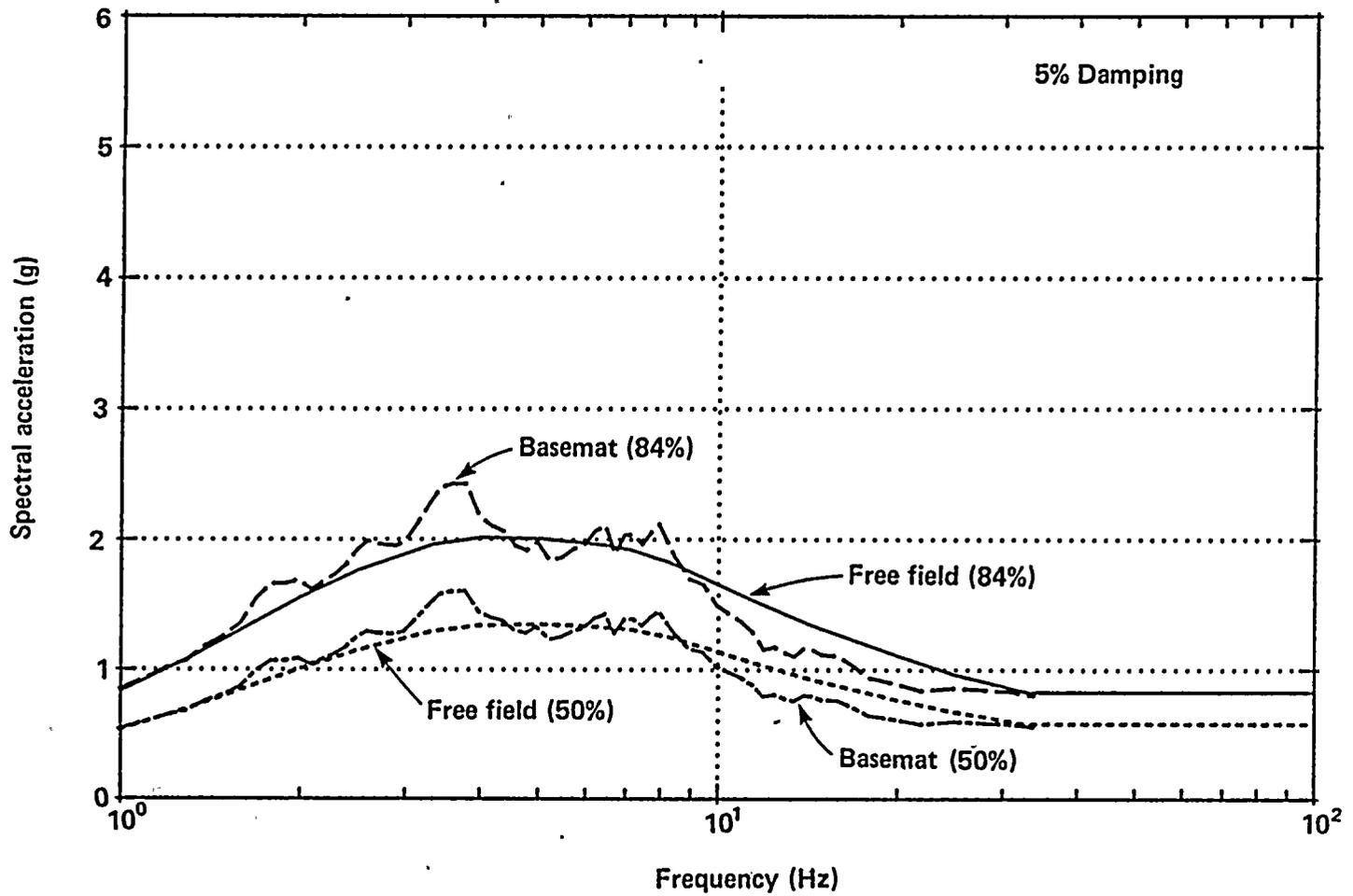


Figure 7-5

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, containment building, north/south response, using coherent ground motions.

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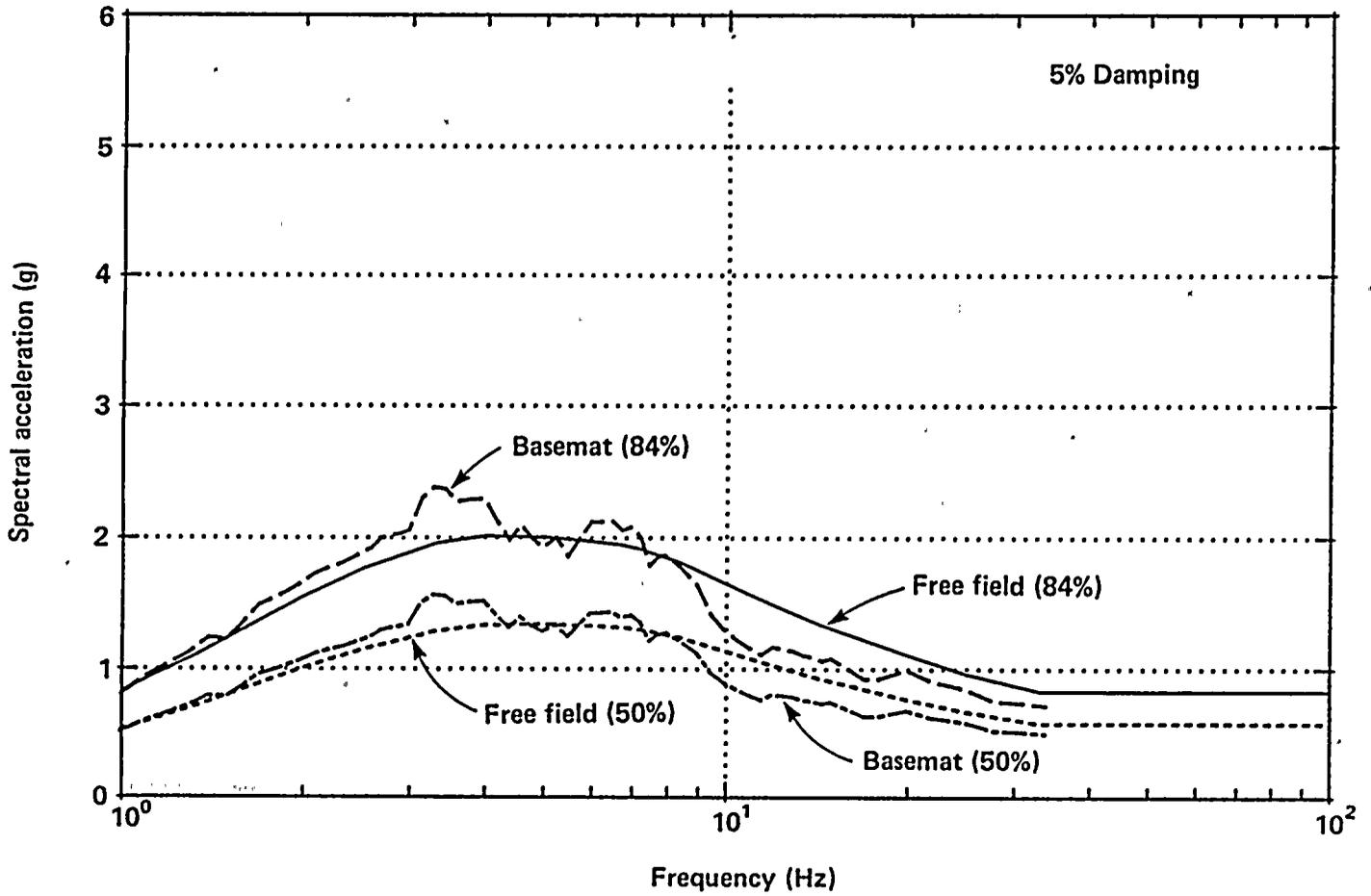


Figure 7-6

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, containment building, east/west response, using coherent ground motions.



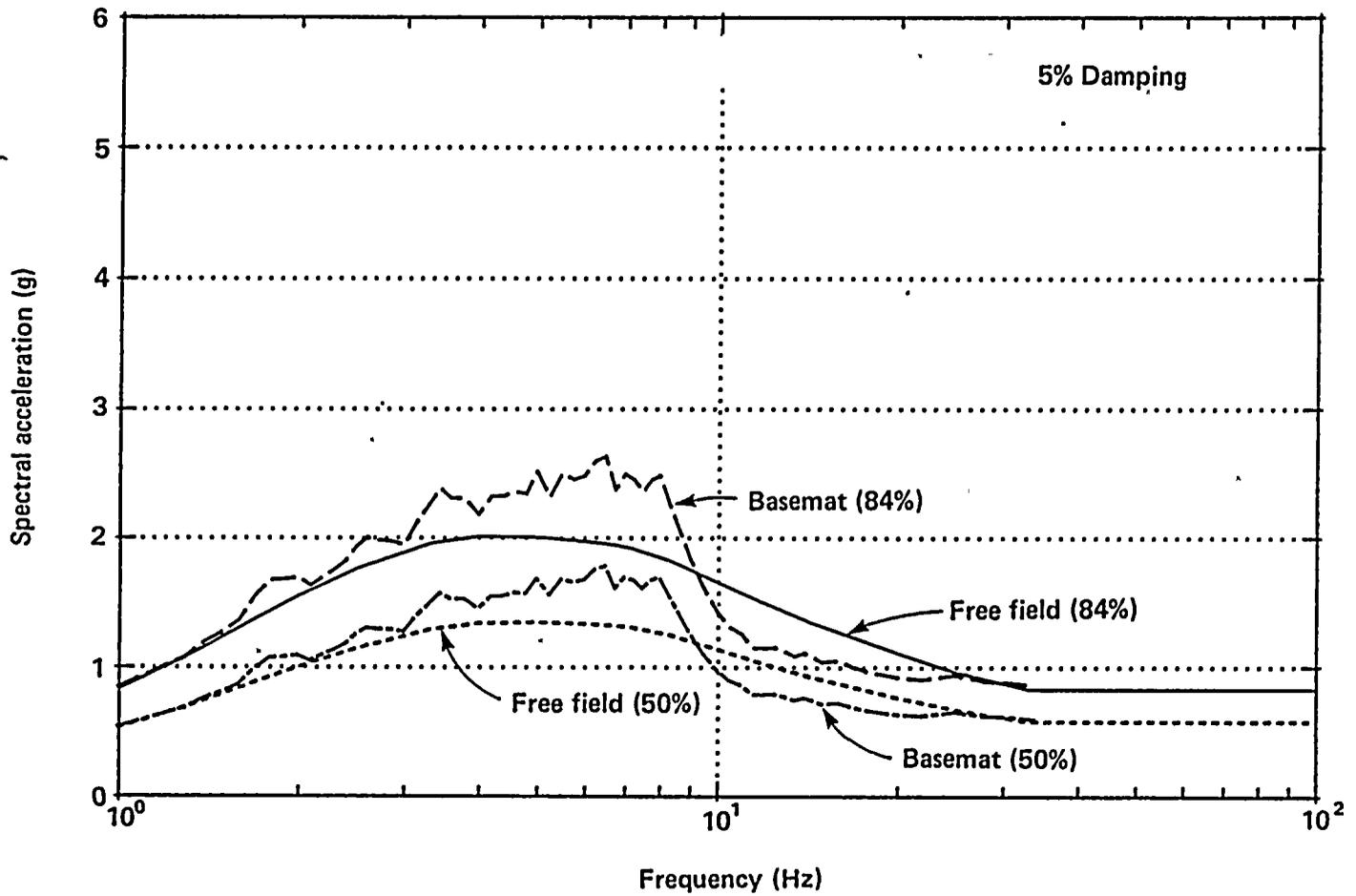


Figure 7-7

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, auxiliary building, north/south response, using coherent ground motions.



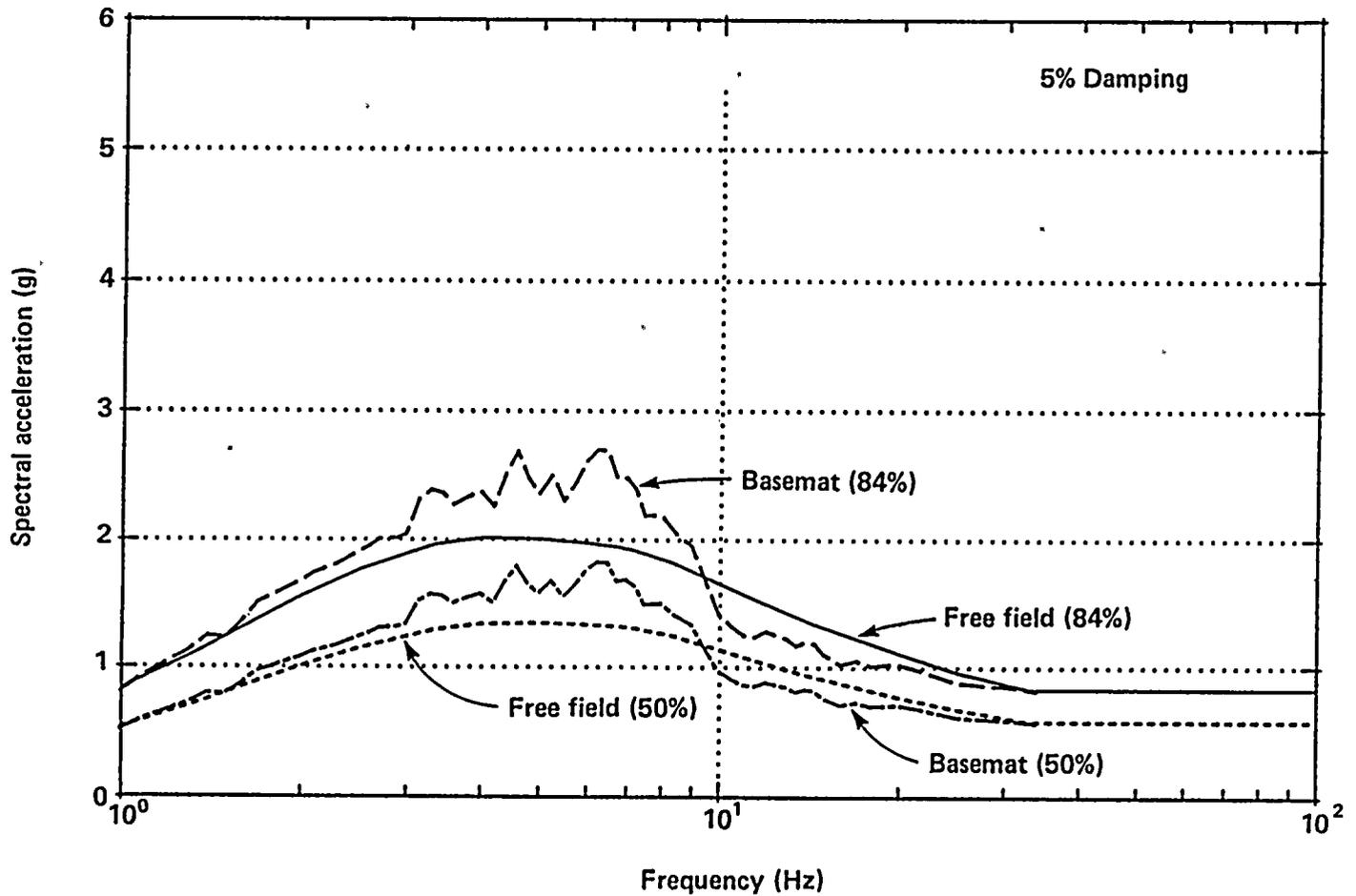


Figure 7-8

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, auxiliary building, east/west response, using coherent ground motions.

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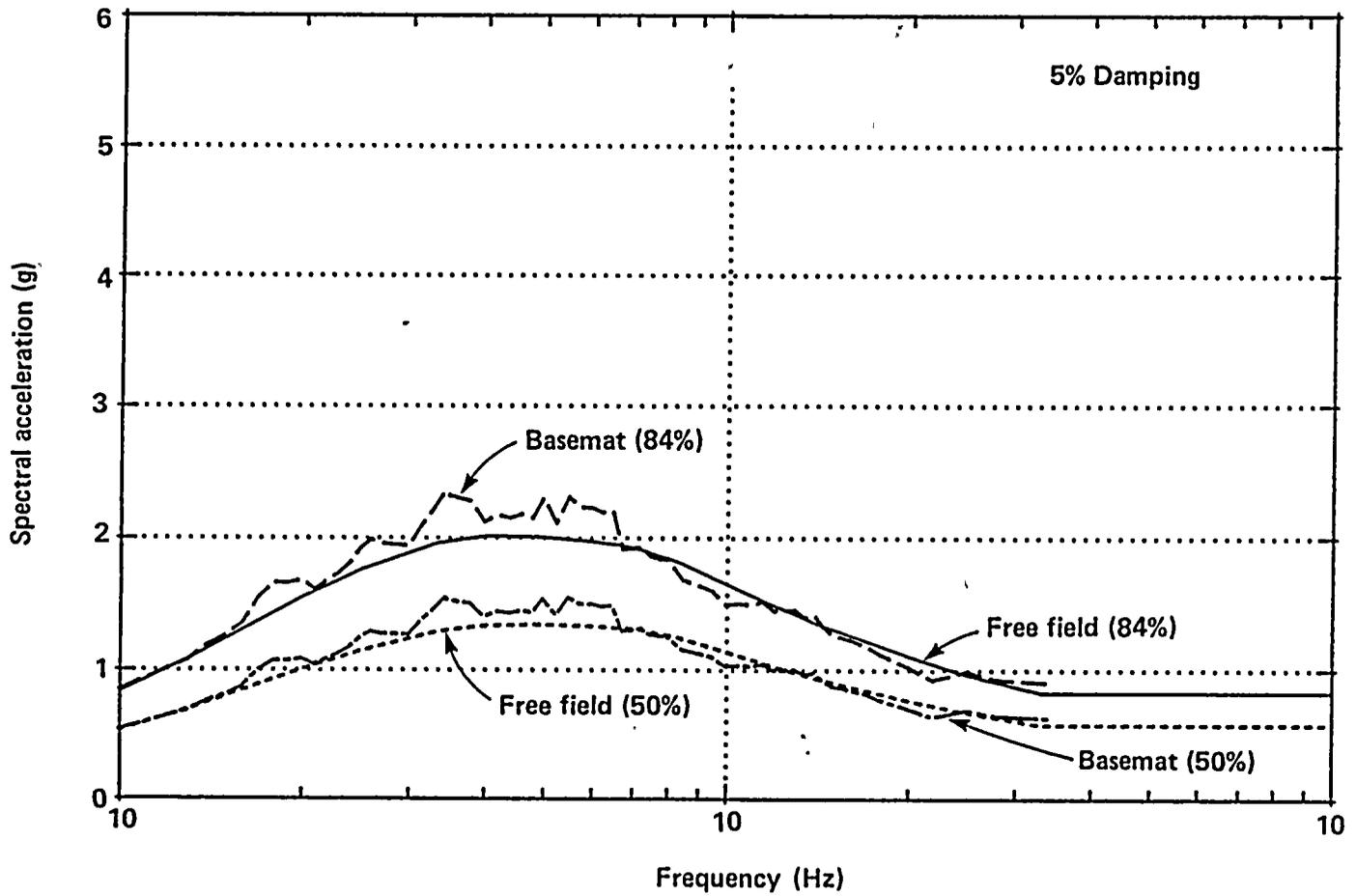


Figure 7-9

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, turbine building, north/south response, using coherent ground motions.



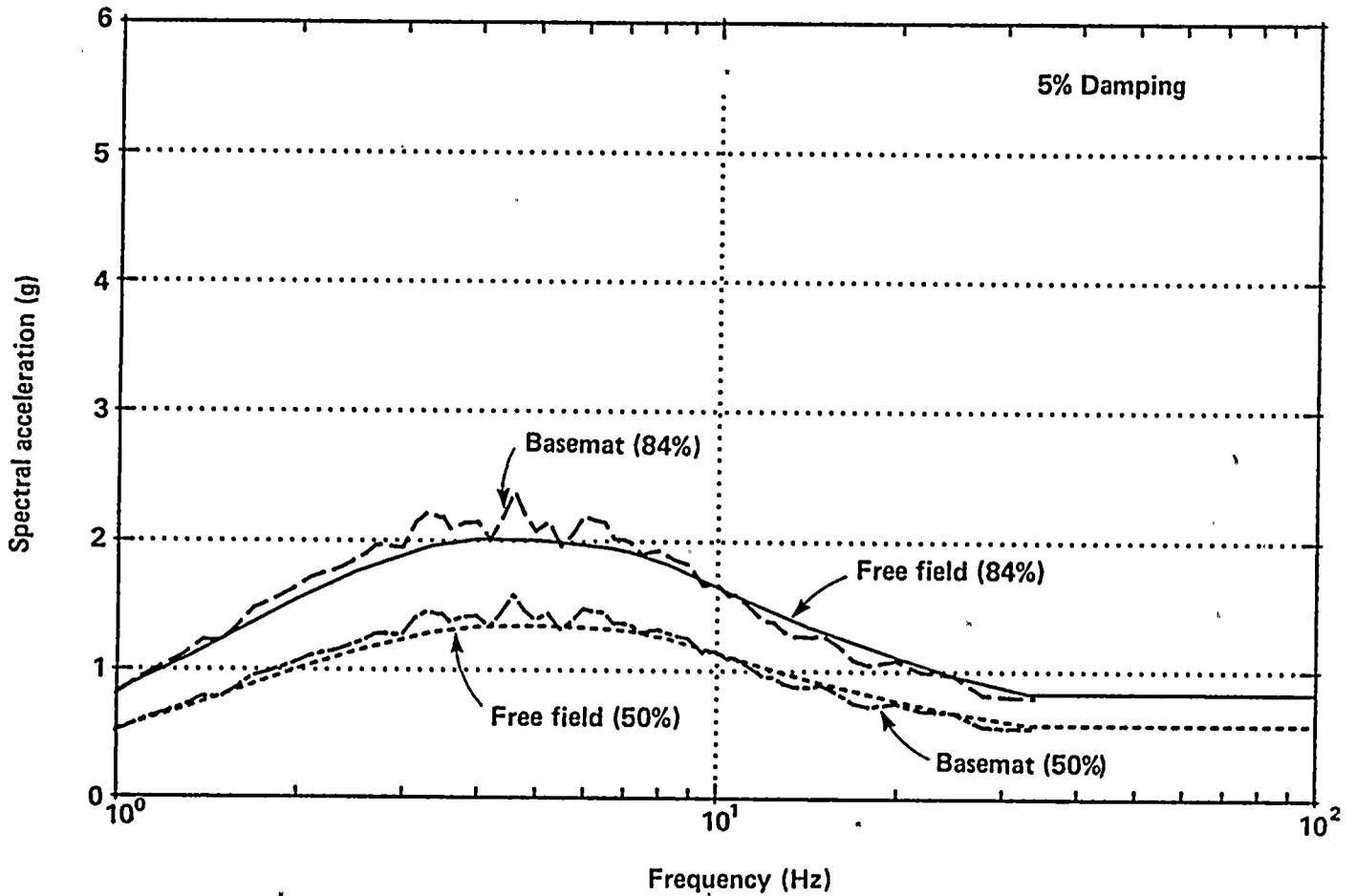


Figure 7-10

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, turbine building, east/west response, using coherent ground motions.

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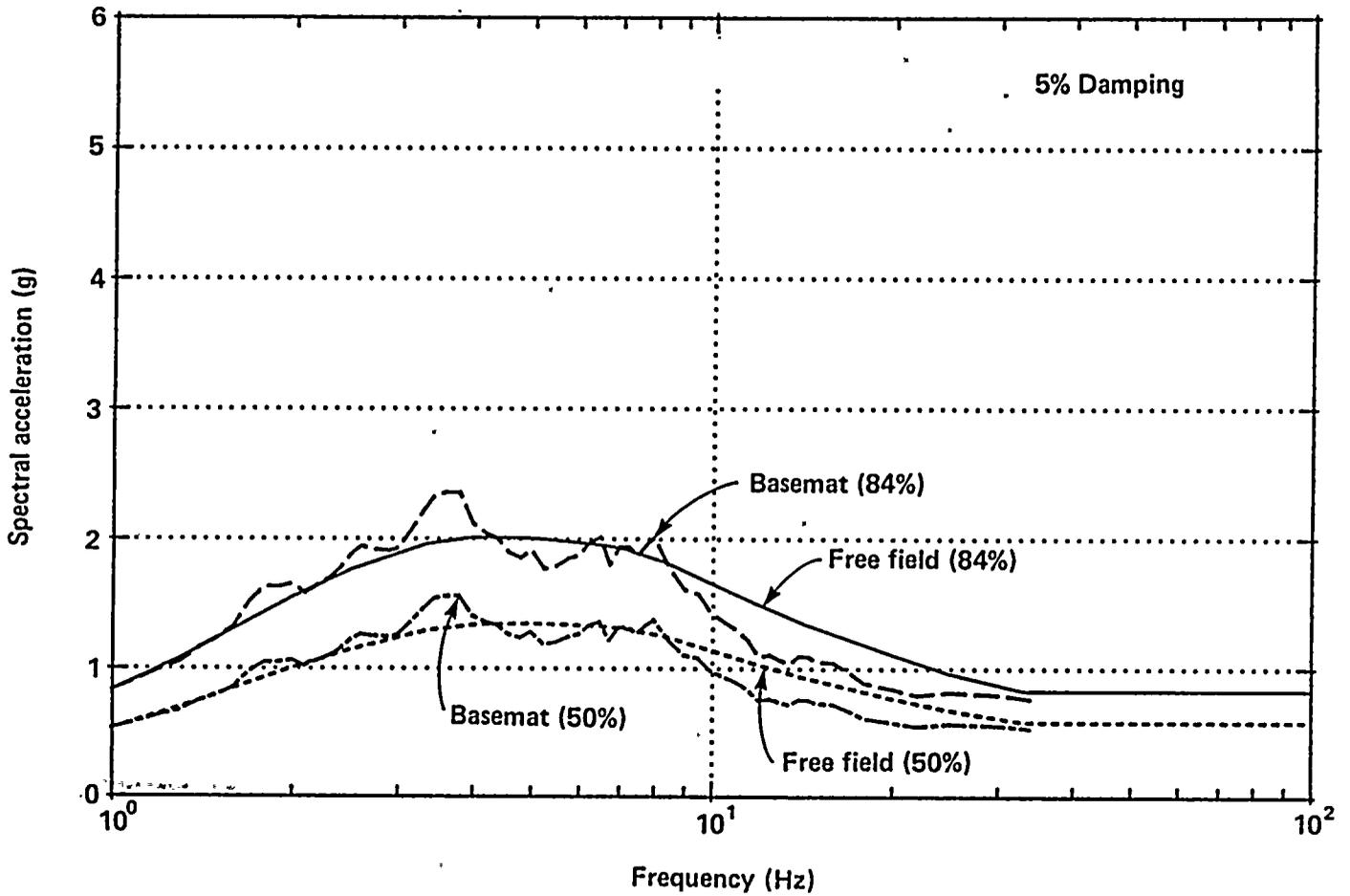


Figure 7-11

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, containment building, north/south response, using incoherent ground motions.



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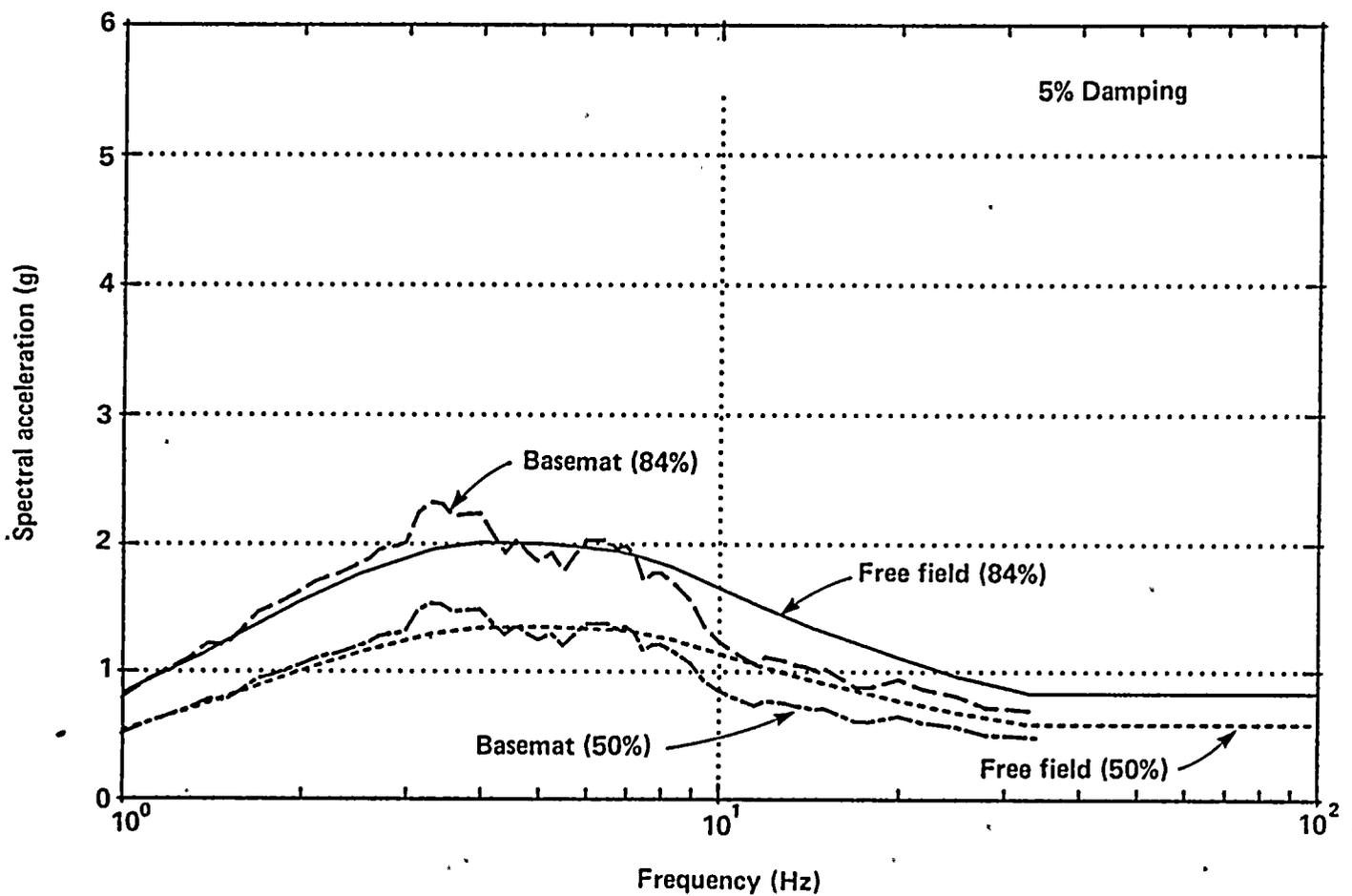


Figure 7-12

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, containment building, east/west response, using incoherent ground motions.

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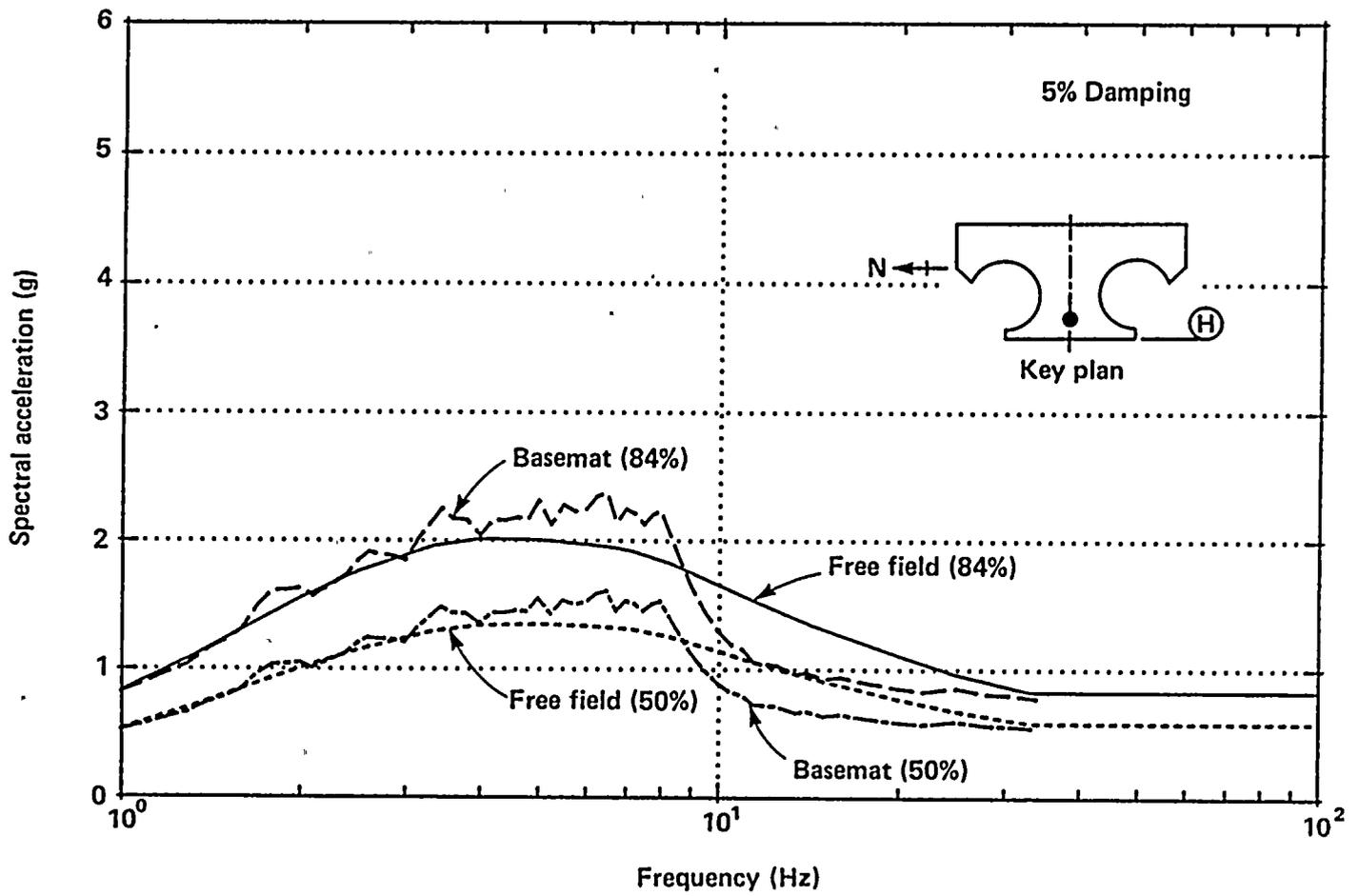


Figure 7-13

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, auxiliary building, north/south response, using incoherent ground motions.

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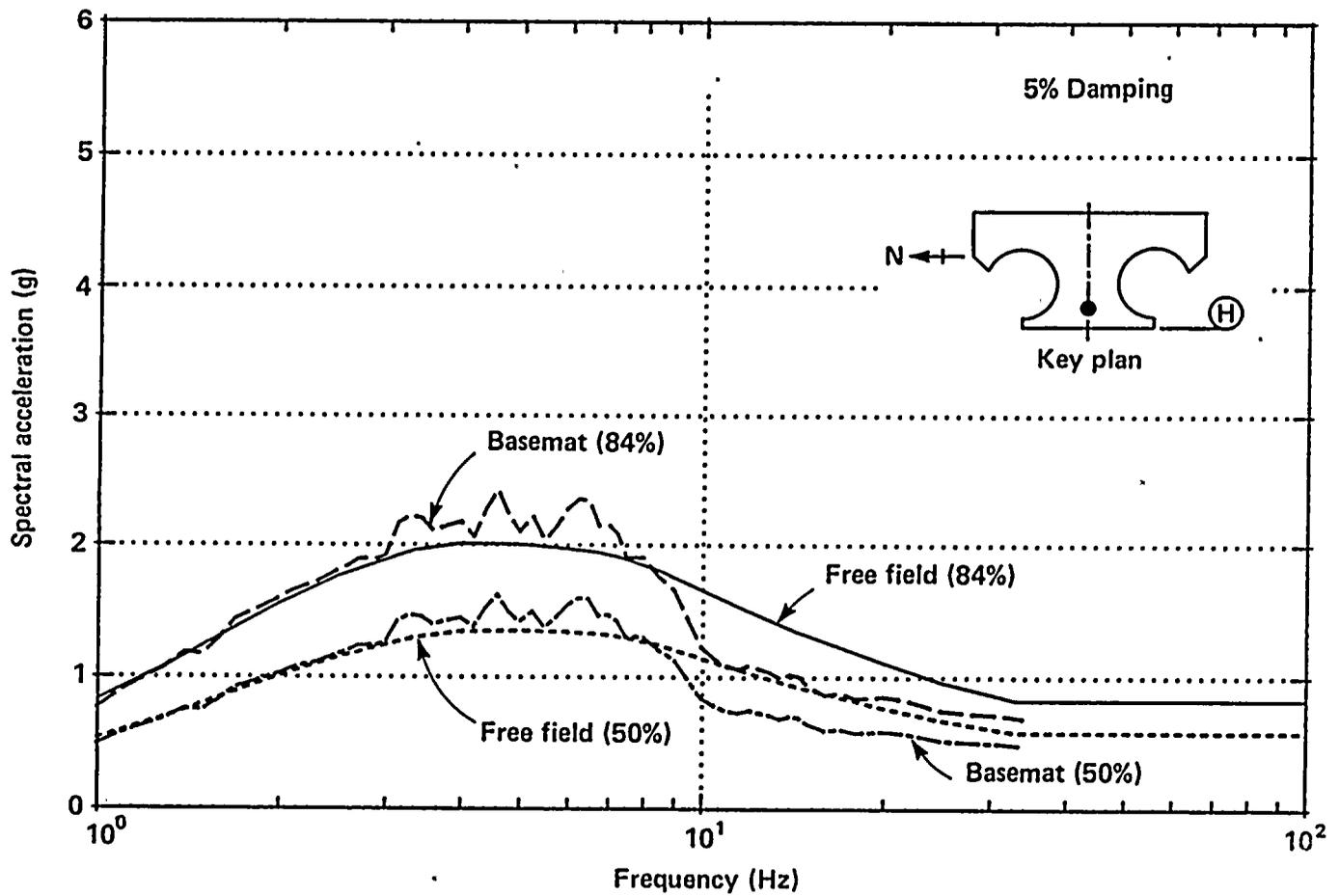


Figure 7-14

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, auxiliary building, east/west response, using incoherent ground motions.

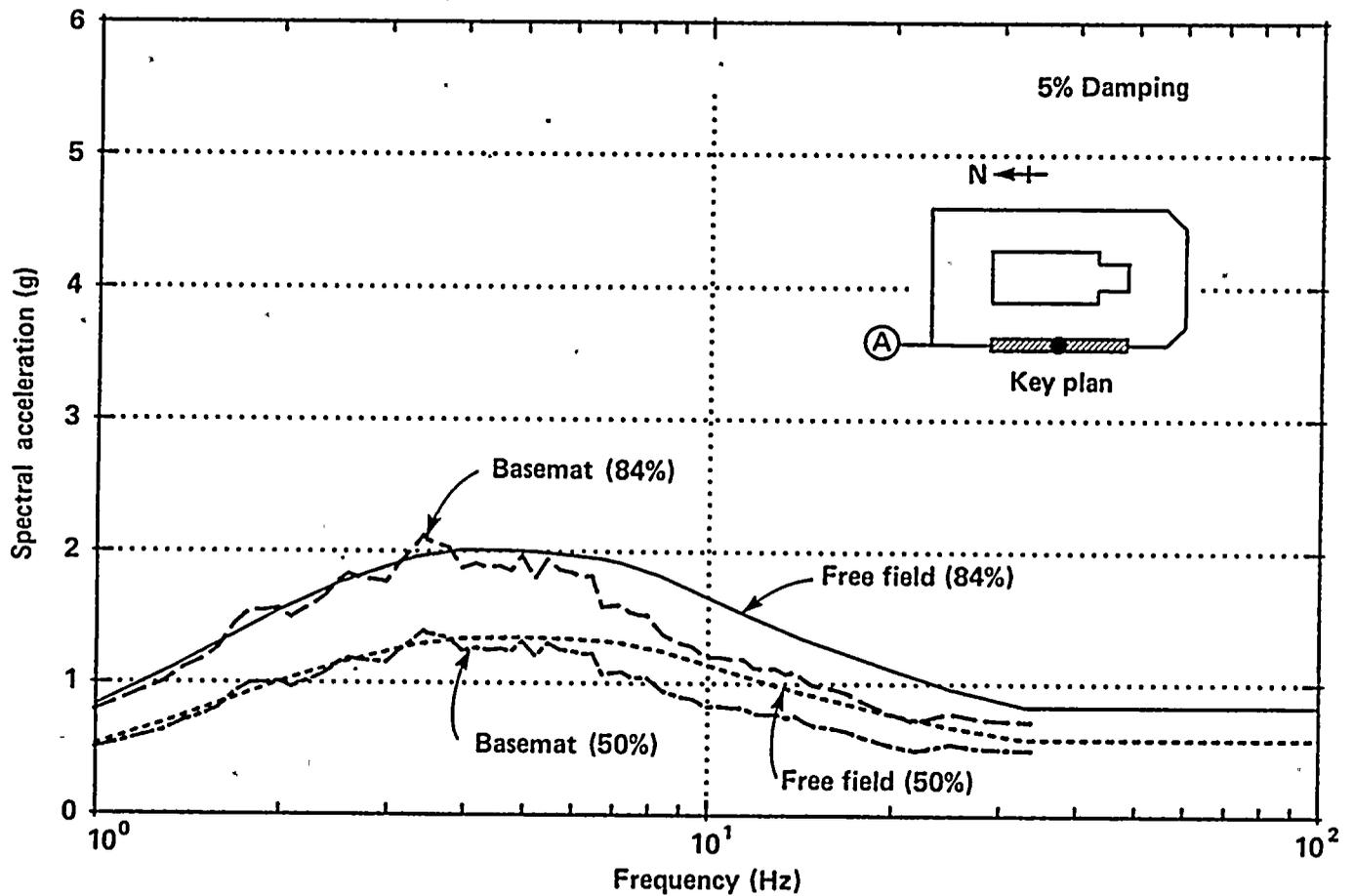


Figure 7-15

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, turbine building, wall A area, north/south response, using incoherent ground motions.



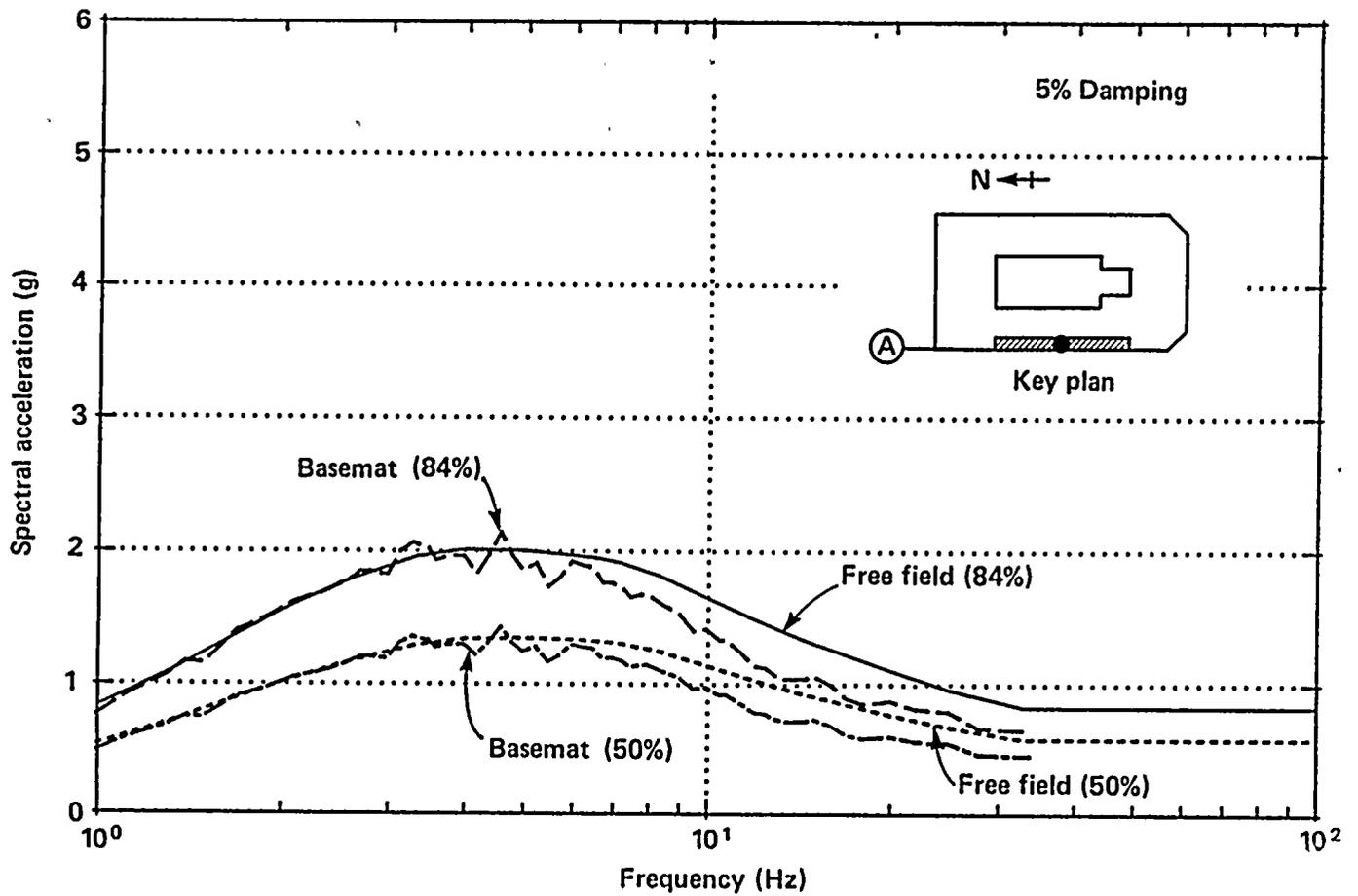


Figure 7-16

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, turbine building, wall A area, east/west response, using incoherent ground motions.

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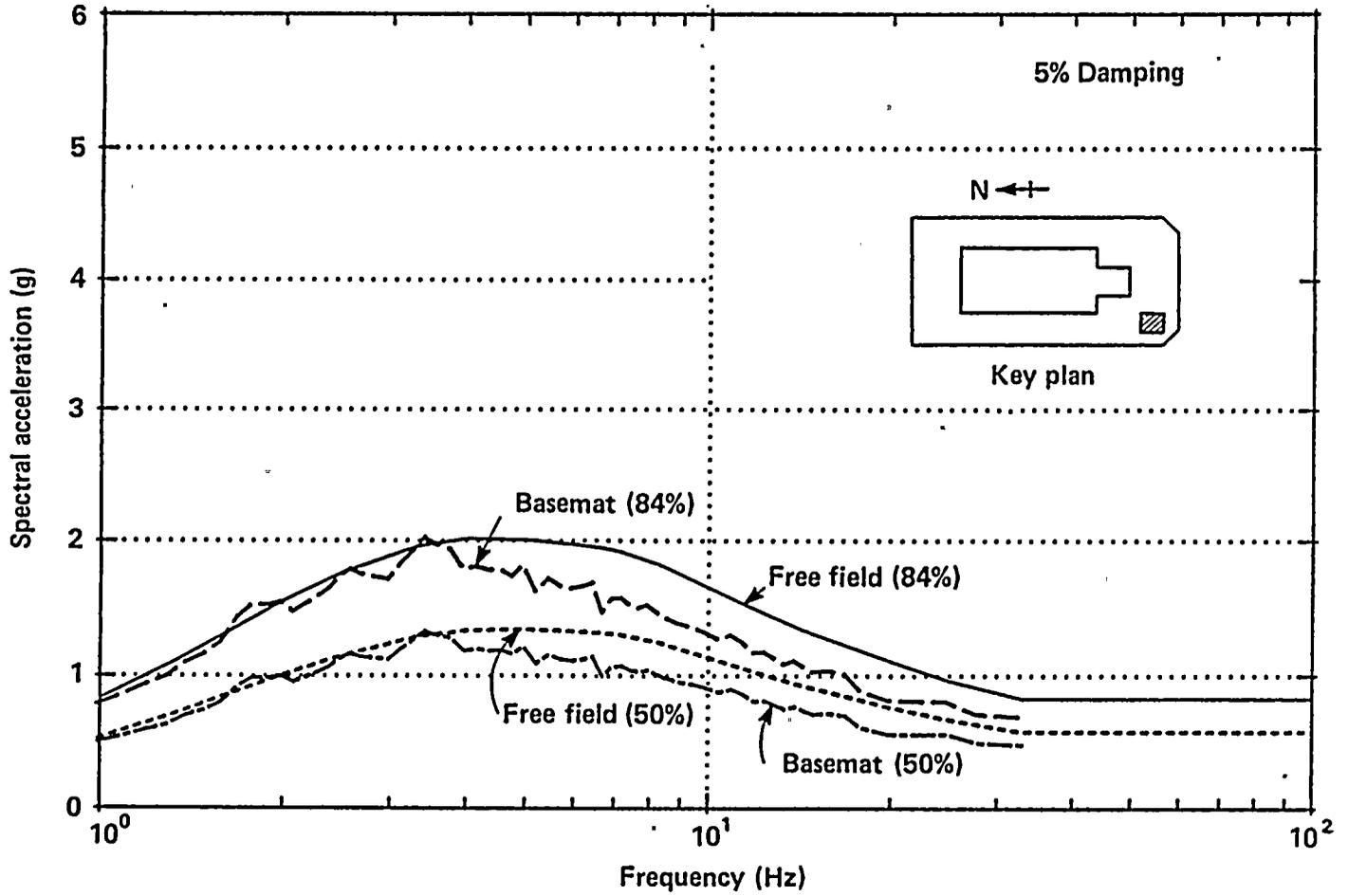


Figure 7-17

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, turbine building, diesel generator area, north/south response, using incoherent ground motions.

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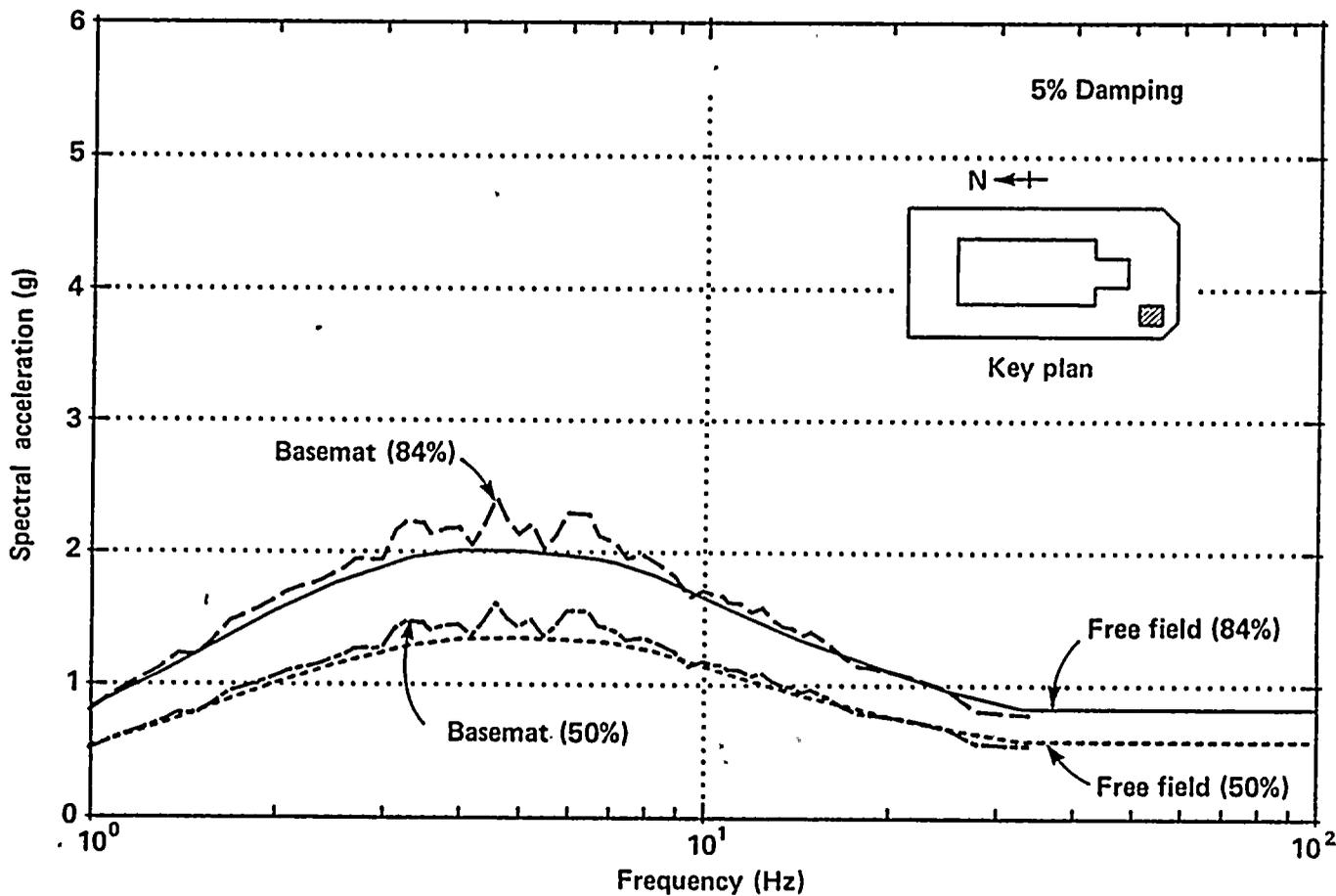


Figure 7-18

Comparison of spectra for free-field ground motions with basemat spectra determined by soil/structure interaction analysis, turbine building, diesel generator area, east/west response, using incoherent ground motions.

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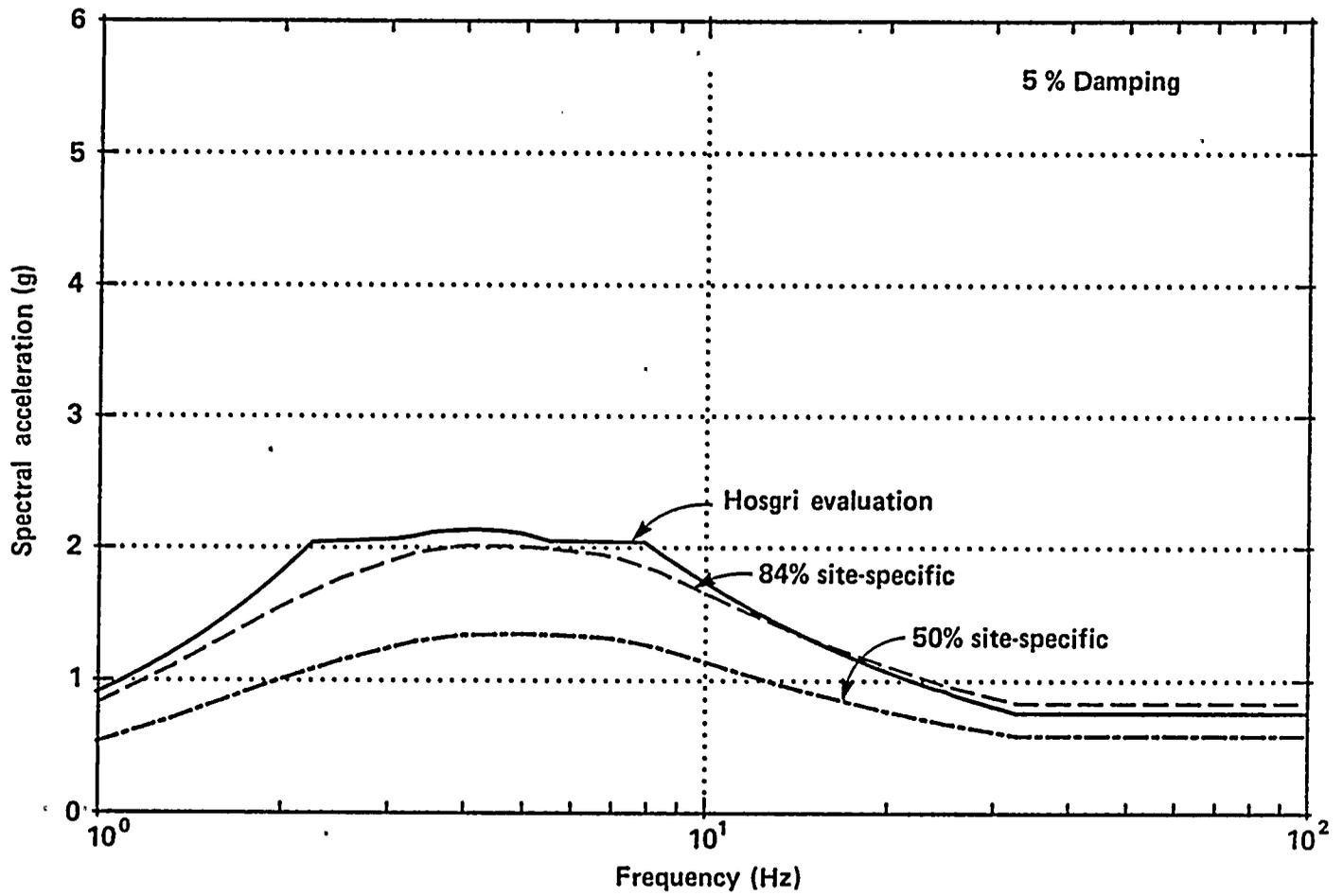


Figure 7-19

Comparison of free-field, site-specific spectra with 1977 Hosgri evaluation spectrum for horizontal ground motion.

spectrum is enveloped by the Hosgri evaluation spectrum. The 84 percent probability of nonexceedance site-specific ground spectrum exceeds the Hosgri evaluation spectrum only at frequencies greater than about 15 hertz, and the exceedance is only about 10 percent.

Figures 7-20 through 7-29 show a comparison of the Hosgri (envelope of Newmark and Blume spectra) evaluation basemat (El 85 feet) response spectra, which had been reduced from the free-field spectra to account for the tau-filtering effect (USNRC, 1976), with the basemat spectra computed from the site-specific ground motions in this study including soil/structure interaction incoherence effects.

It should be noted that the effects of tau-filtering in the Hosgri evaluation studies were generally analogous to the combined effect of soil/structure interaction, foundation embedment, and incoherent ground-motion effects in the current soil/structure interaction analysis. However, these effects vary from point to point on the foundation basemats in the current study results. This is reflected in the difference in spectral amplitudes shown in Figures 7-20 through 7-29 for different locations on a building structure. For the Hosgri evaluation, the dynamic models used for analysis were considered to be fixed at the base and, therefore, the variations in the tau-filtering reduction for different locations on the basemat could not be considered. Instead, an average motion was assumed for all points on the foundation of a building. Because of this, a one-to-one comparison of basemat motions for the Hosgri evaluation spectra with those due to the site-specific ground motions in this study will show some differences.

The comparison shows that the responses to the 84th percentile site-specific spectra exceed the responses to the Hosgri evaluation spectra at various structural frequencies. The average values of these exceedances at key frequencies range from about 5 percent for the containment building interior structure to about 10 percent for the

auxiliary building. These exceedances are not significant as they can be accommodated by the existing design margin, as discussed later.

IN-STRUCTURE RESPONSE SPECTRA

In-structure response spectra at selected locations in the major structures are shown in Figures 7-30 through 7-39. These spectra include the effects of soil/structure interaction, foundation embedment, and spatial incoherence of ground motions, and are compared with Plant seismic qualification basis (Hosgri or double design earthquake) in-structure response spectra. The locations for which these comparisons are shown were based on their importance in terms of structural design, or locations of critical safety-related components. These spectra are for:

- Containment interior structure at El 140 feet (operating floor level)
- Auxiliary building at El 100, 115, and 140 feet (various equipment of interest)
- Turbine building at El 119 feet (4-kV switchgear area)

The primary purpose of these spectral comparisons is to assess the effect of the site-specific ground motion in-structure response spectra on seismic qualification of equipment. Comparison of the spectra shows the following:

- For the containment building operating floor at El 140 feet (Figures 7-30 and 7-31), the seismic qualification basis spectra are well above (by up to 100 percent) the site-specific ground motion in-structure spectra between 8 and 18 hertz. For other frequencies that are significant for qualification of equipment (5 to 8 hertz), the site-specific ground-motion in-structure spectra, in general, exceed the seismic qualification basis spectra by approximately 15 percent. This exceedance is not significant and can be accommodated in design margin.

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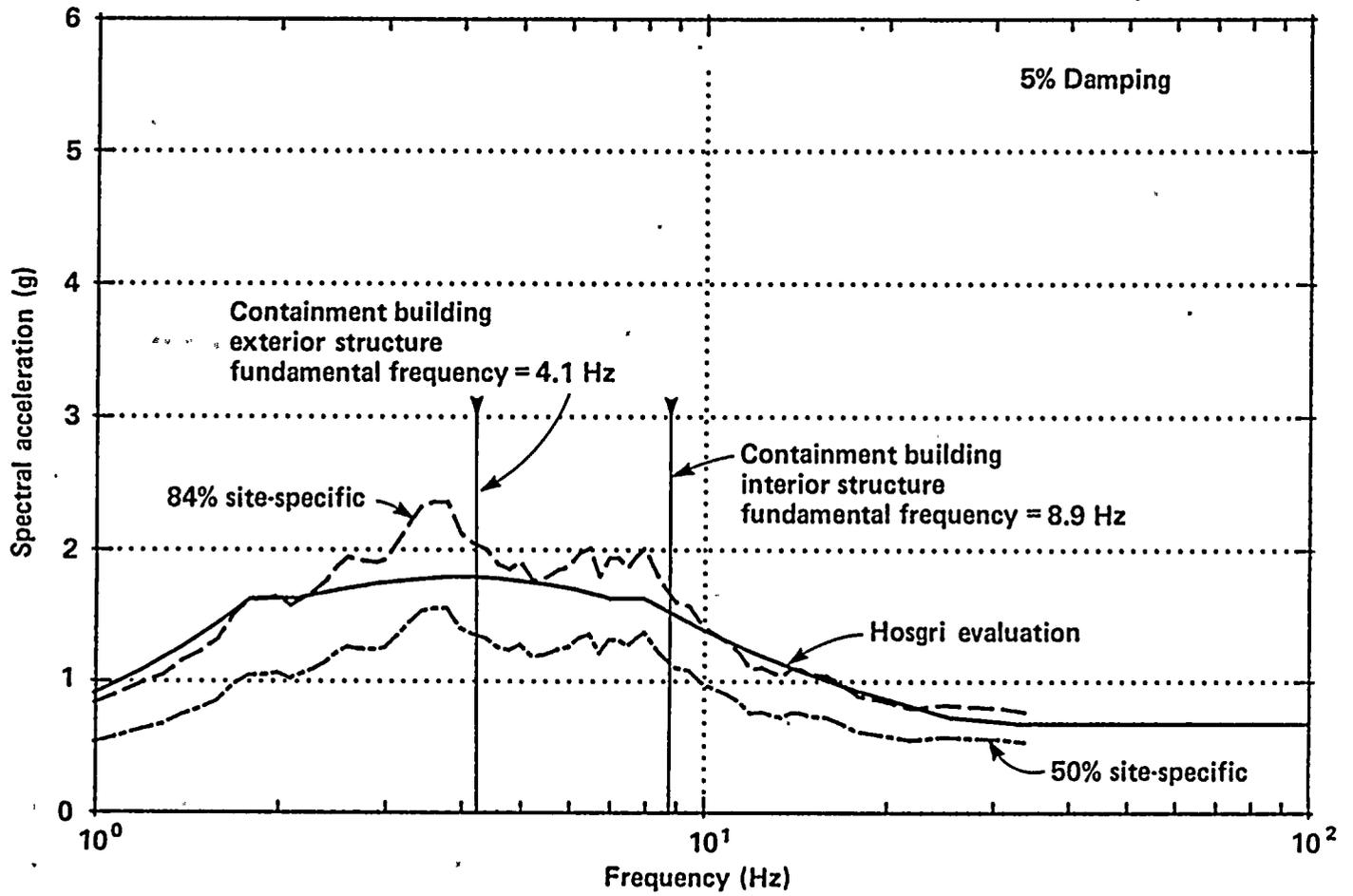


Figure 7-20

Comparison of spectra for motion at top of basemat, containment building, north/south response.



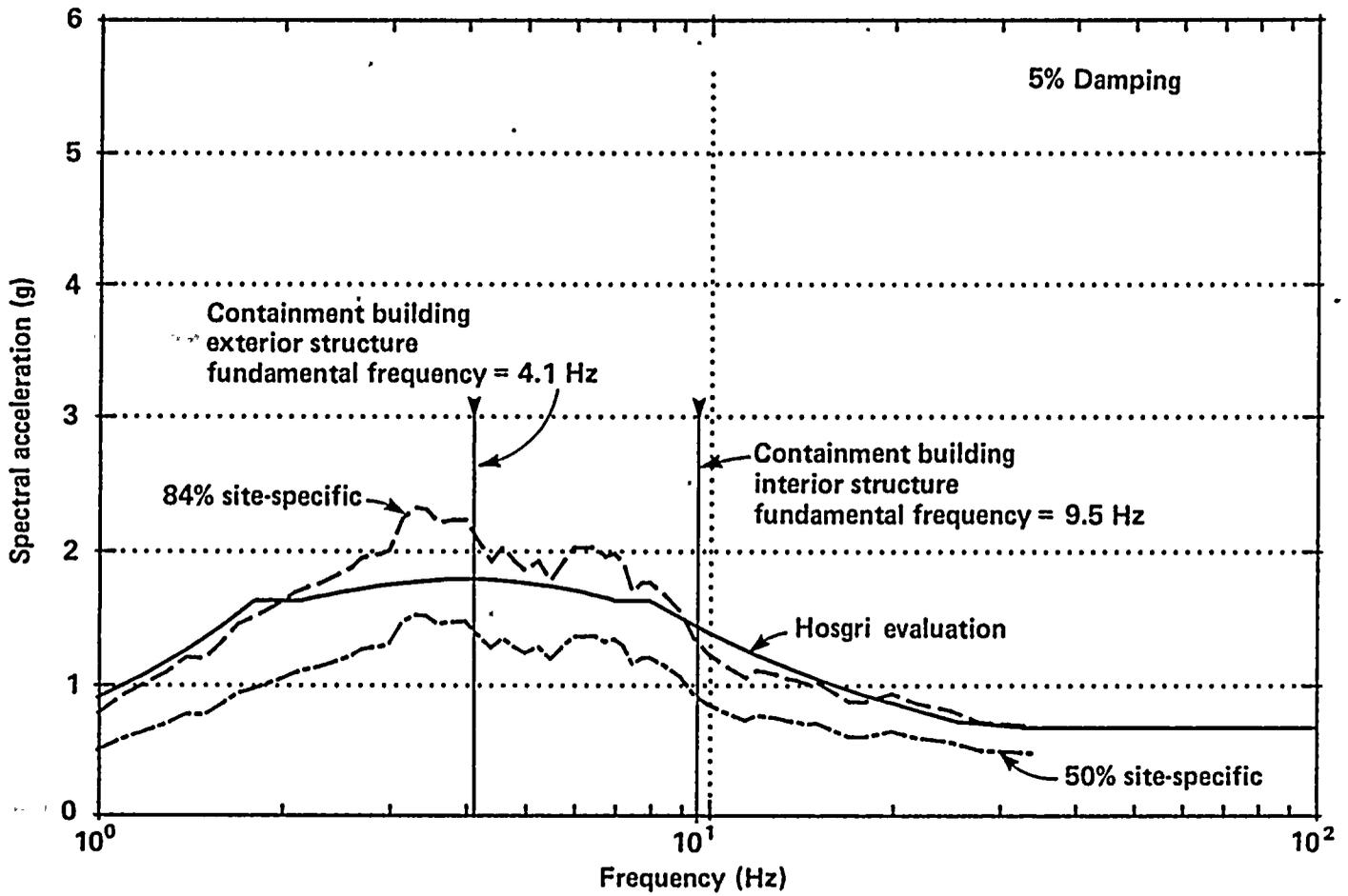


Figure 7-21, Comparison of spectra for motion at top of basemat, containment building, east/west response.

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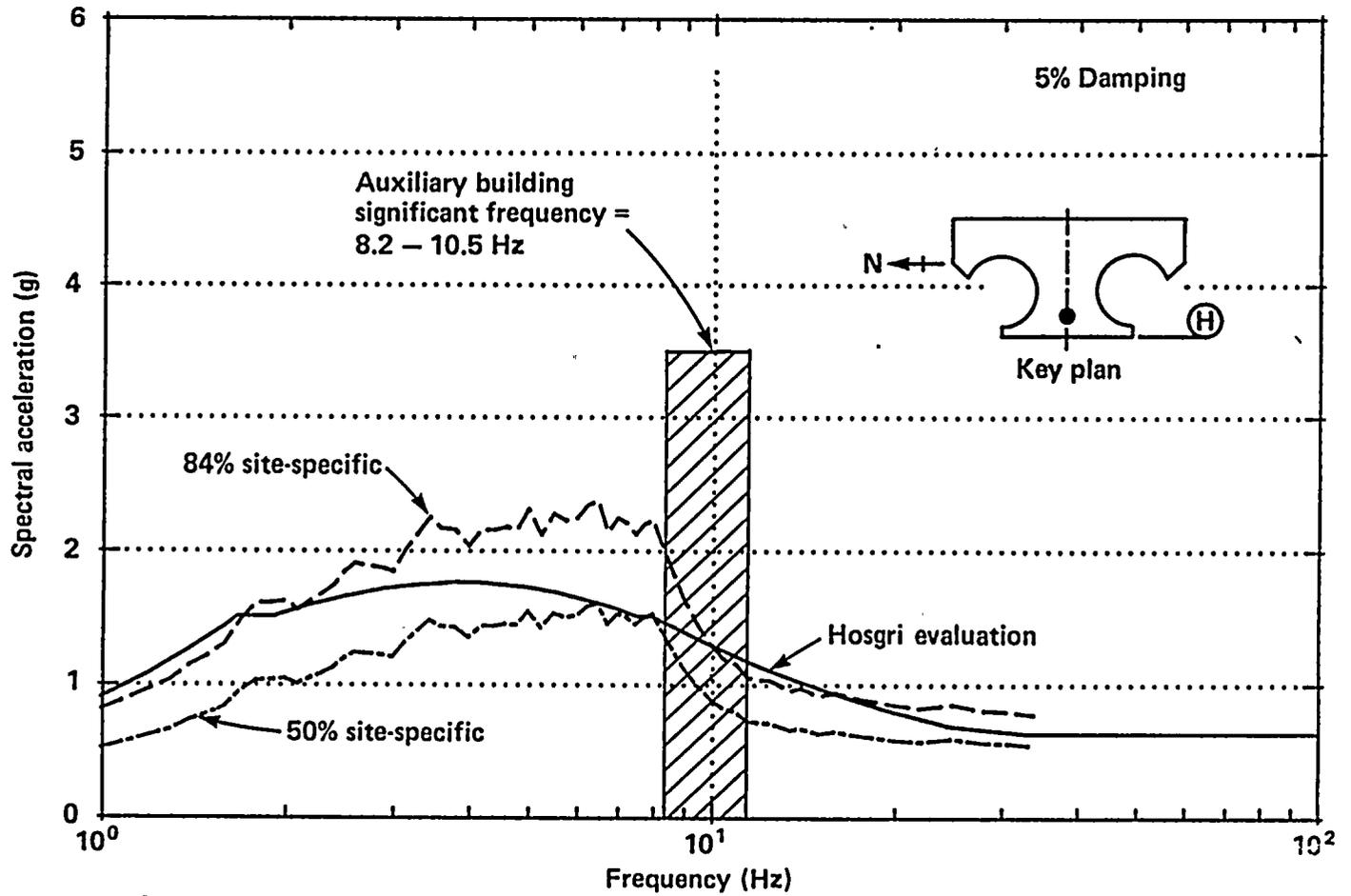


Figure 7-22
Comparison of spectra for motion at top of basement, auxiliary building, north/south response.

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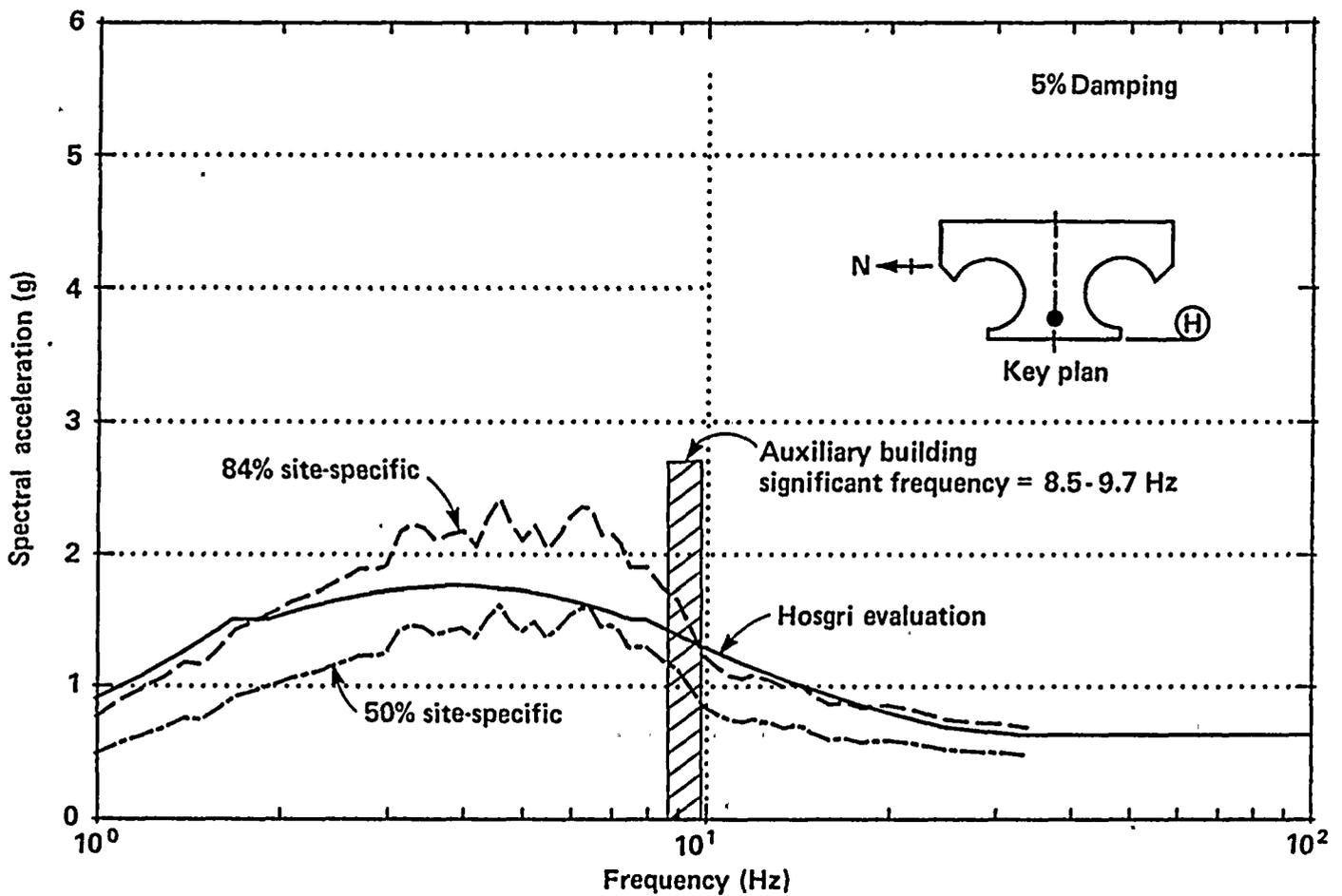


Figure 7-23
 Comparison of spectra for motion at top of basemat, auxiliary building, east/west response.

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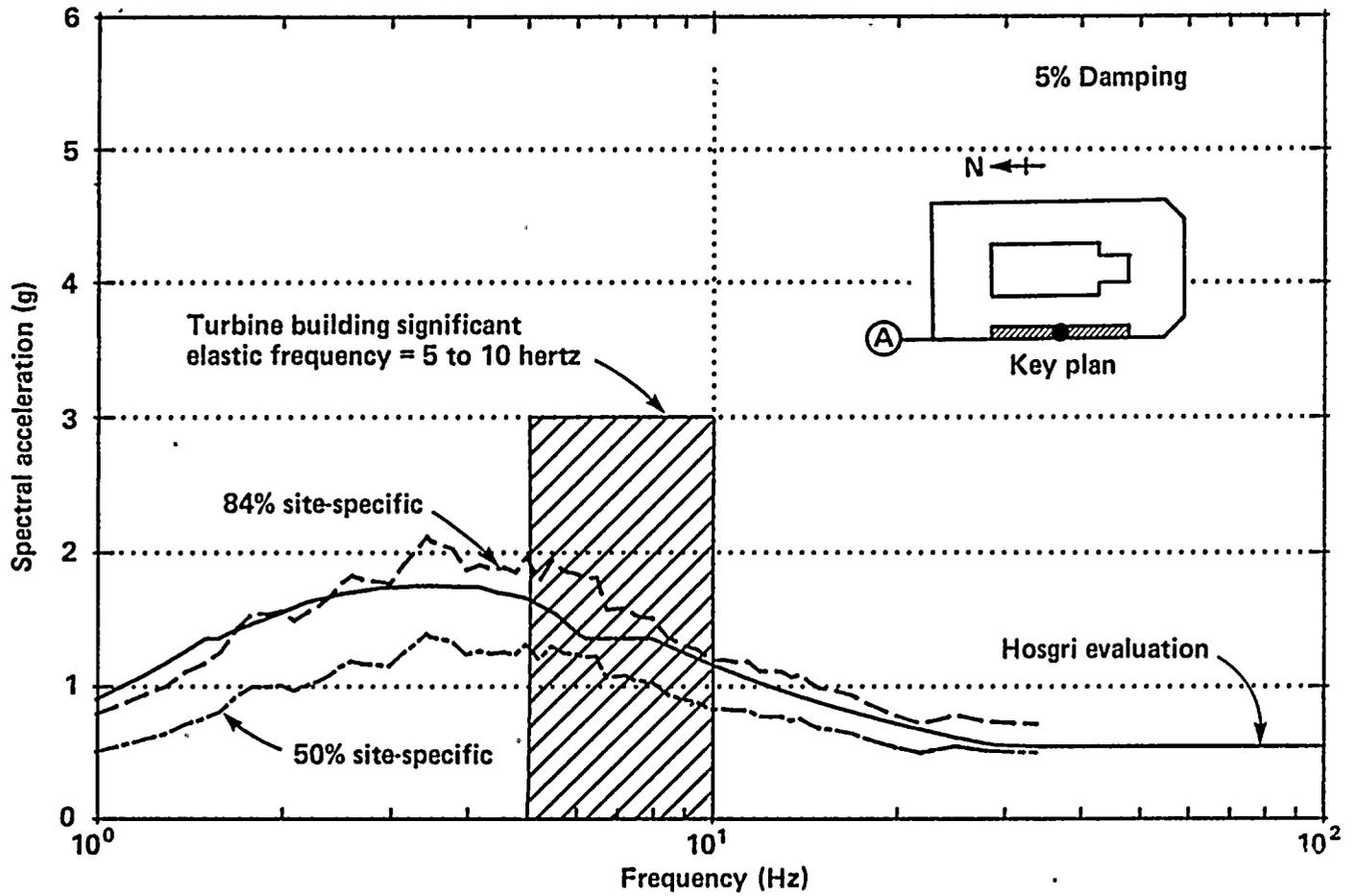


Figure 7-24

Comparison of spectra for motion at top of basemat, turbine building, wall A area, north/south response.

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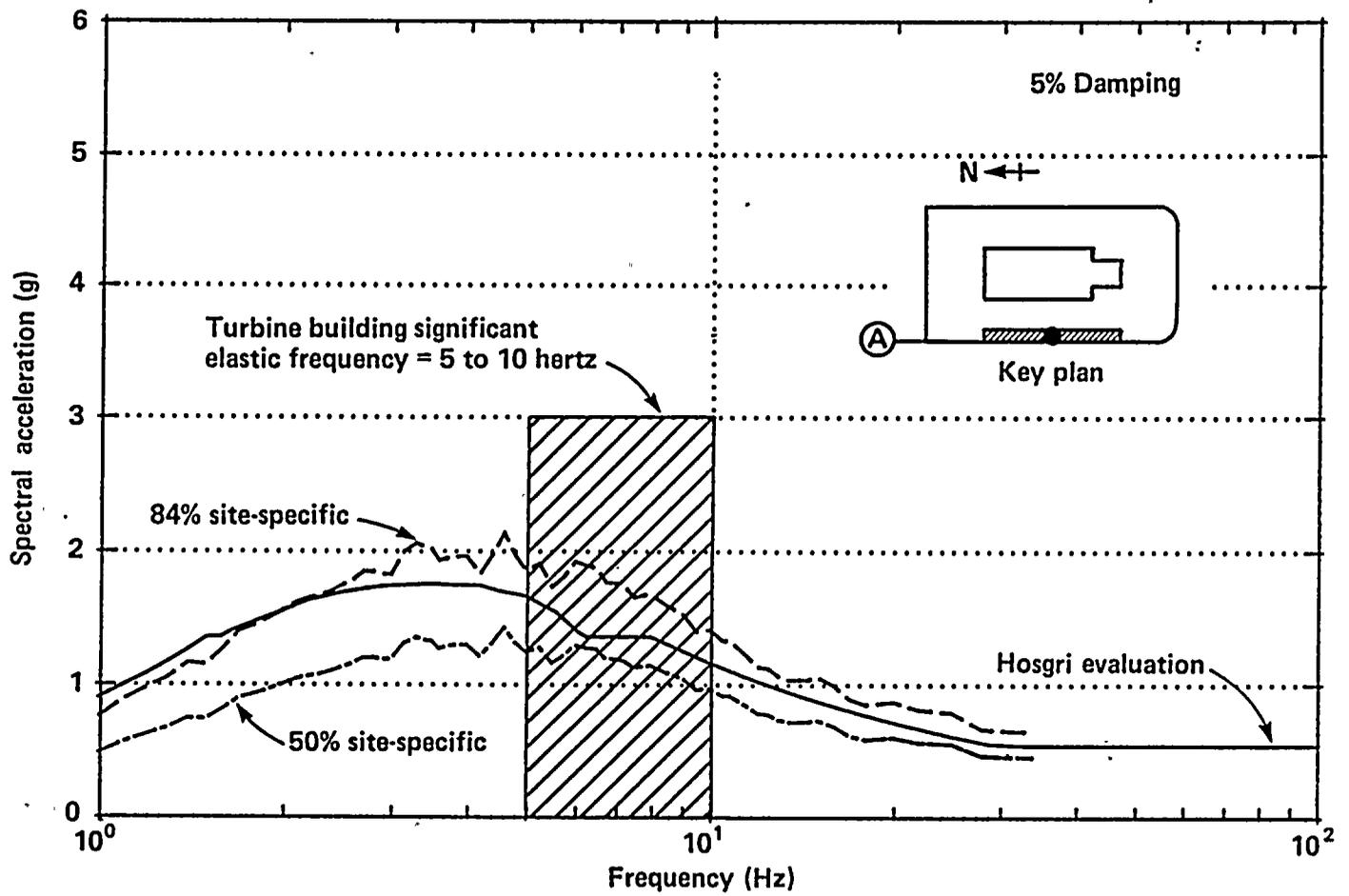


Figure 7-25

Comparison of spectra for motion at top of basemat, turbine building, wall A area, east/west response.

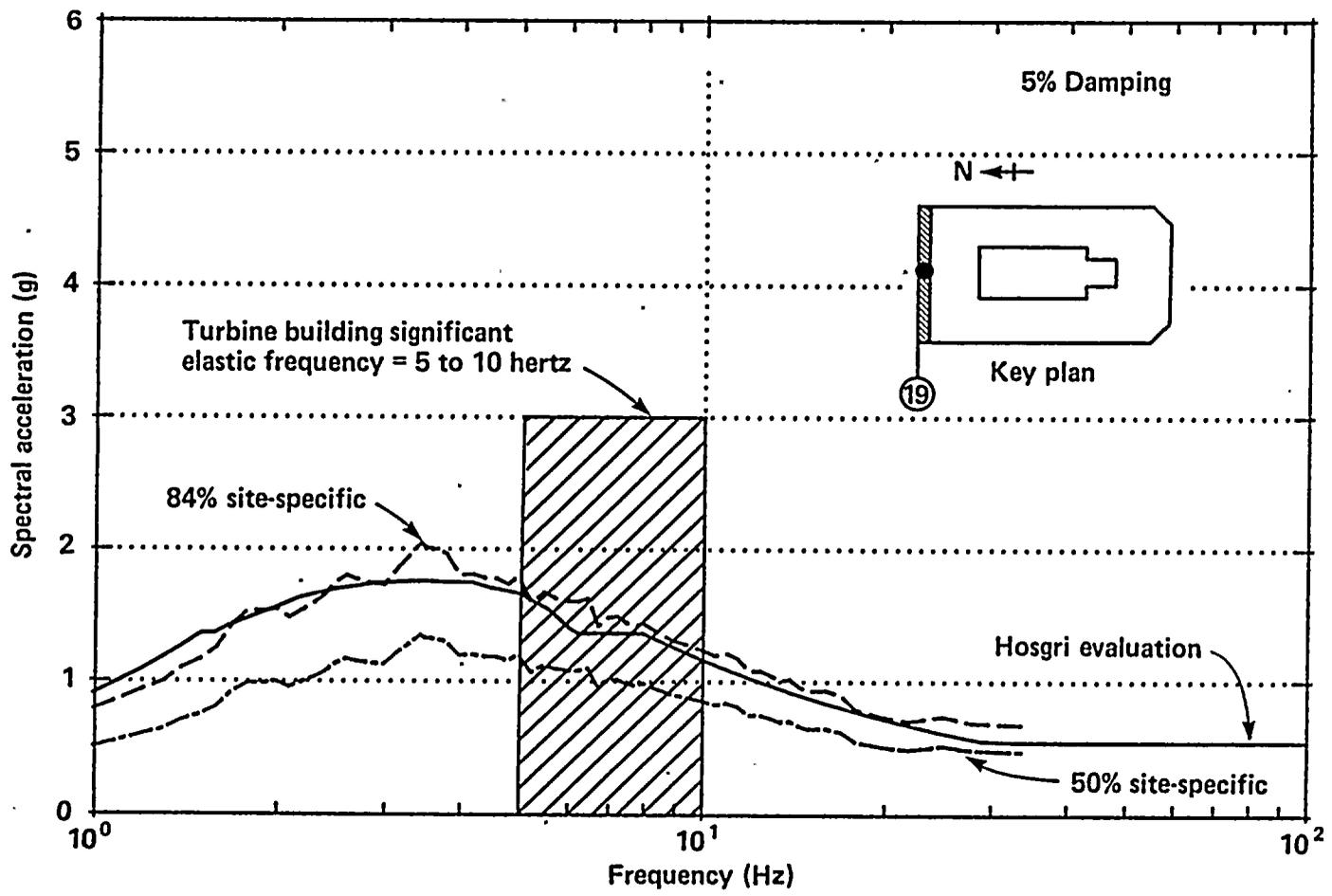


Figure 7-26

Comparison of spectra for motion at top of basemat, turbine building, wall 19 area, north/south response.

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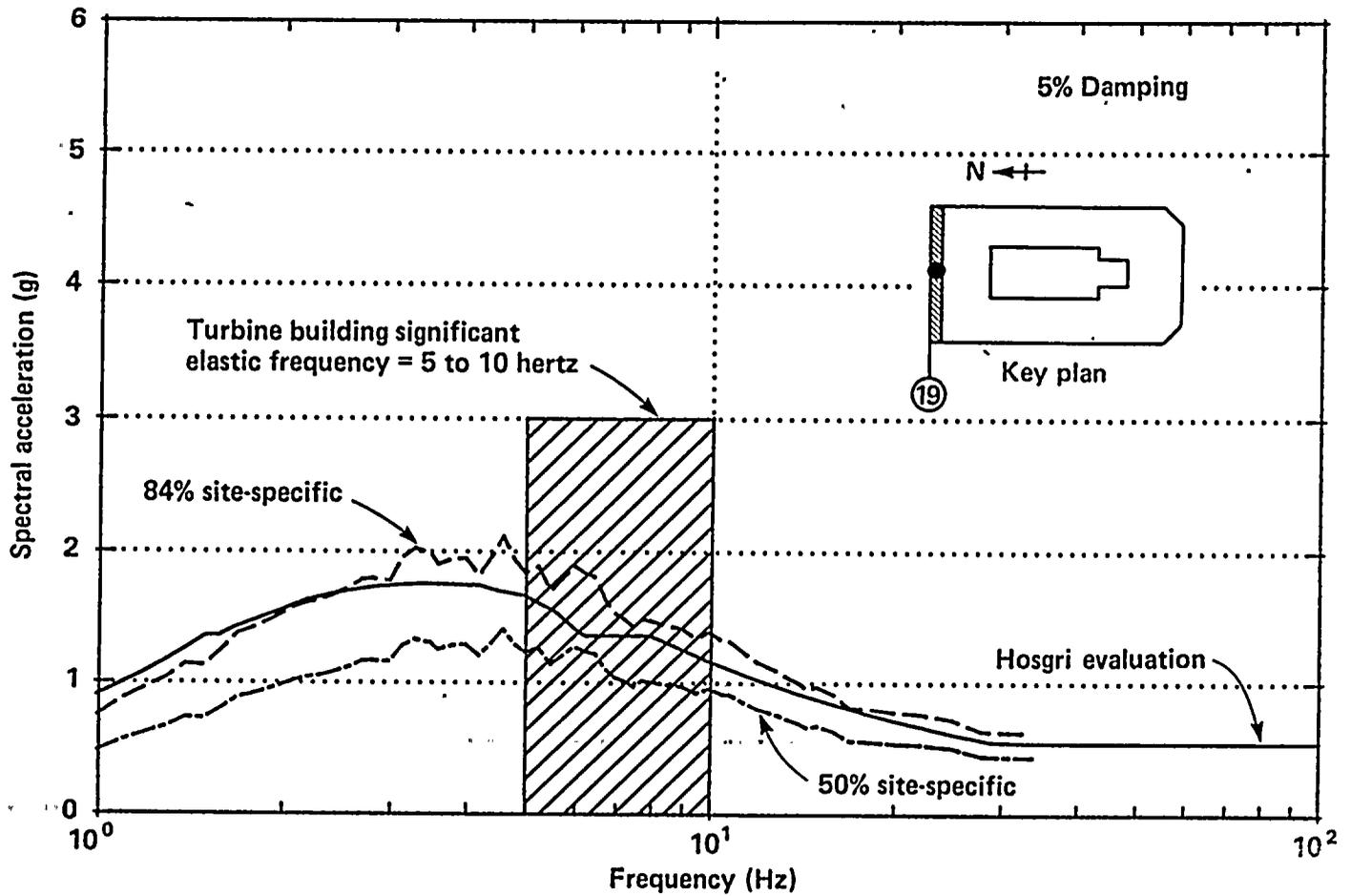


Figure 7-27

Comparison of spectra for motion at top of basemat, turbine building, wall 19 area, east/west response.

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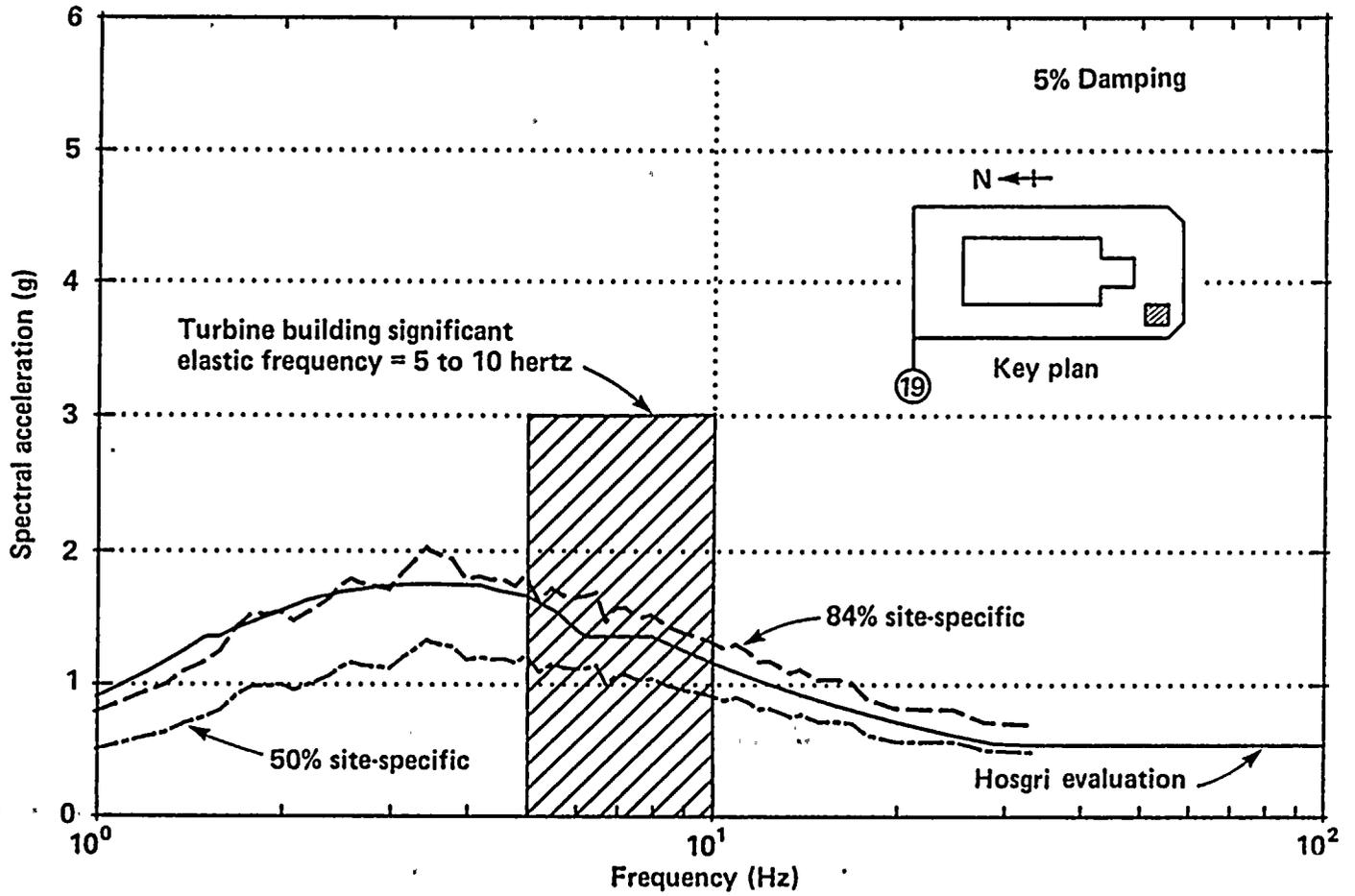


Figure 7-28

Comparison of spectra for motion at top of basemat, turbine building, diesel generator area, north/south response.

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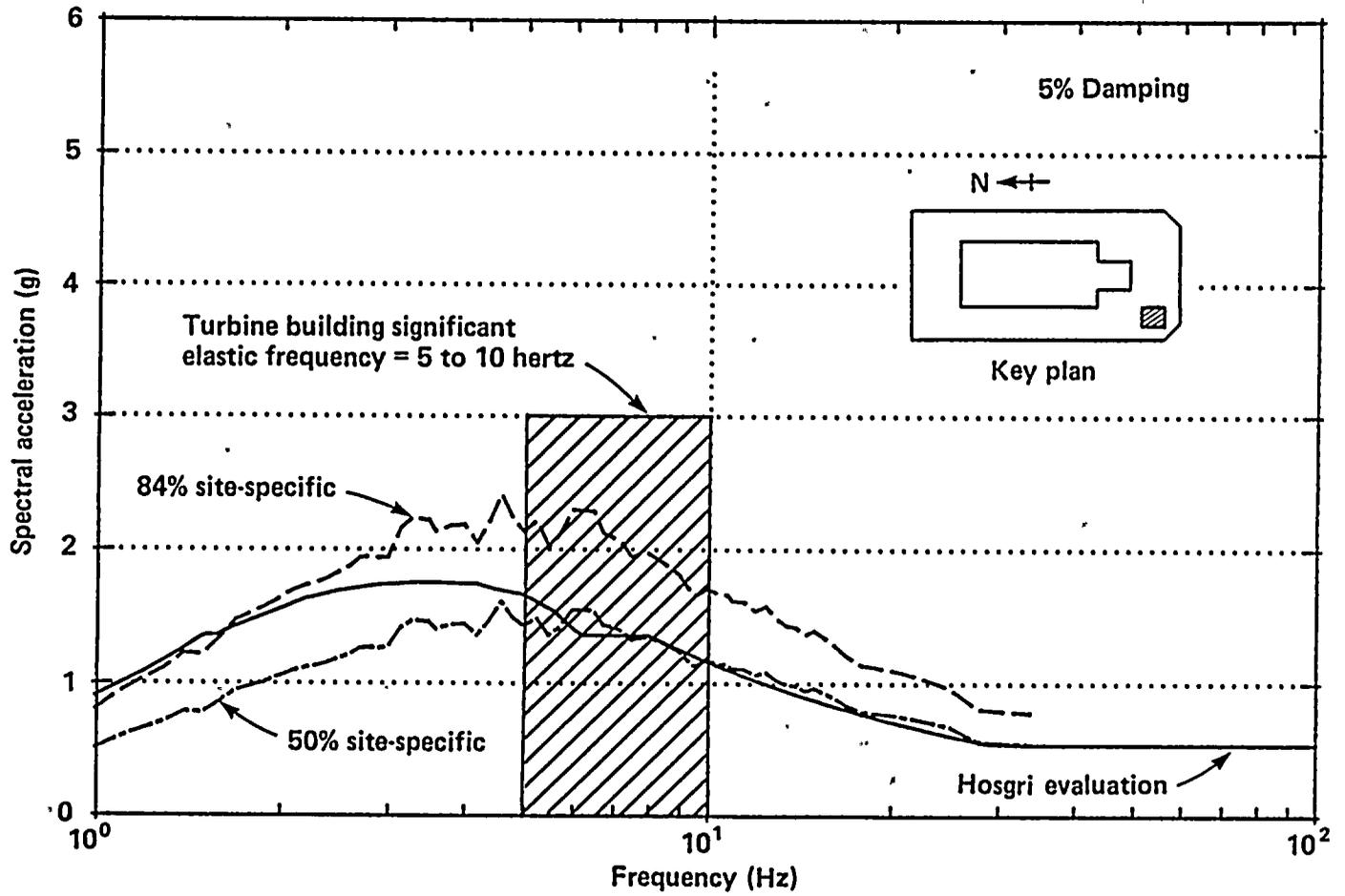


Figure 7-29

Comparison of spectra for motion at top of basemat, turbine building, diesel generator area, east/west response.

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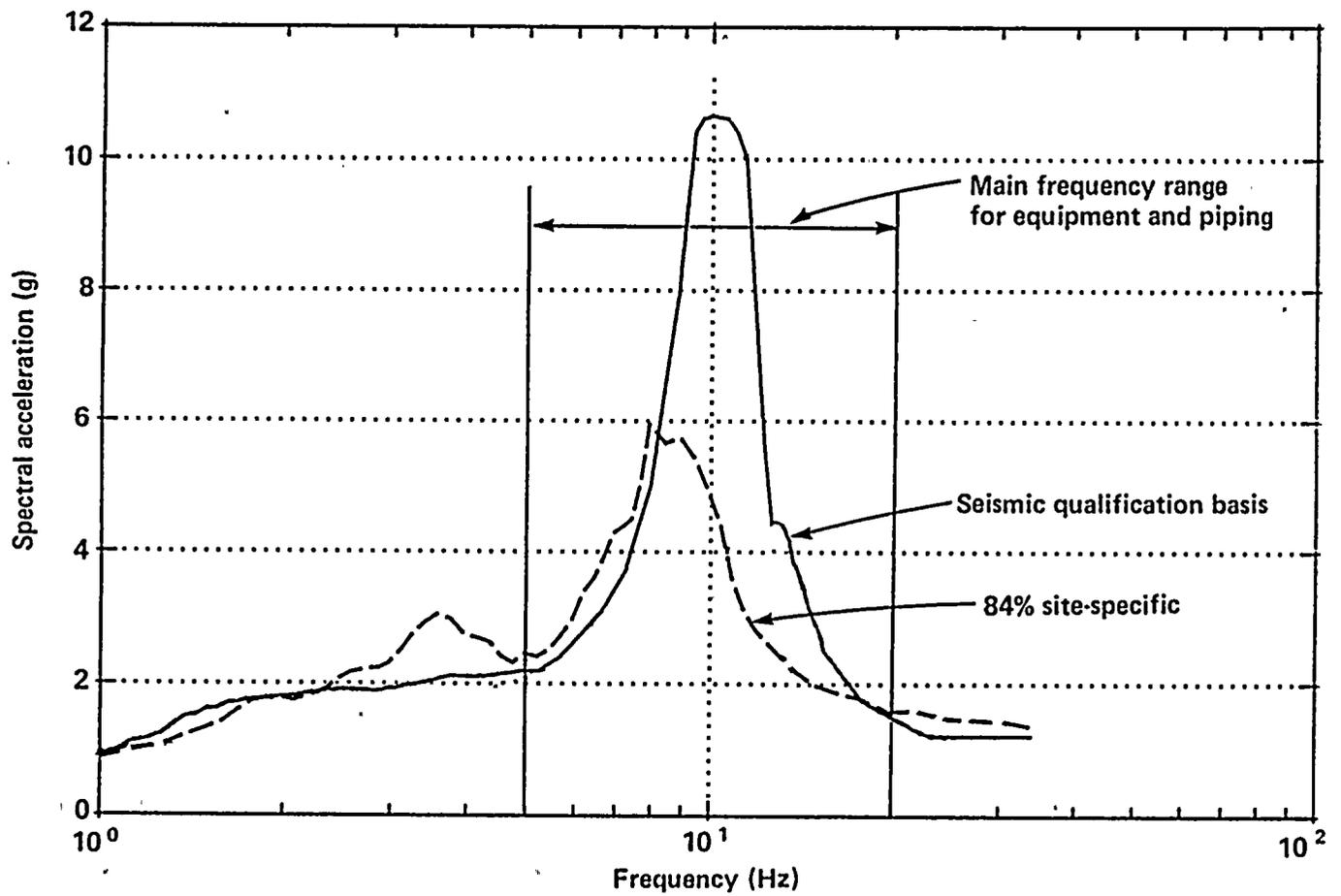


Figure 7-30

Comparison of floor response spectra for equipment qualification for the containment building, interior structure, El 140 feet, north/south response.

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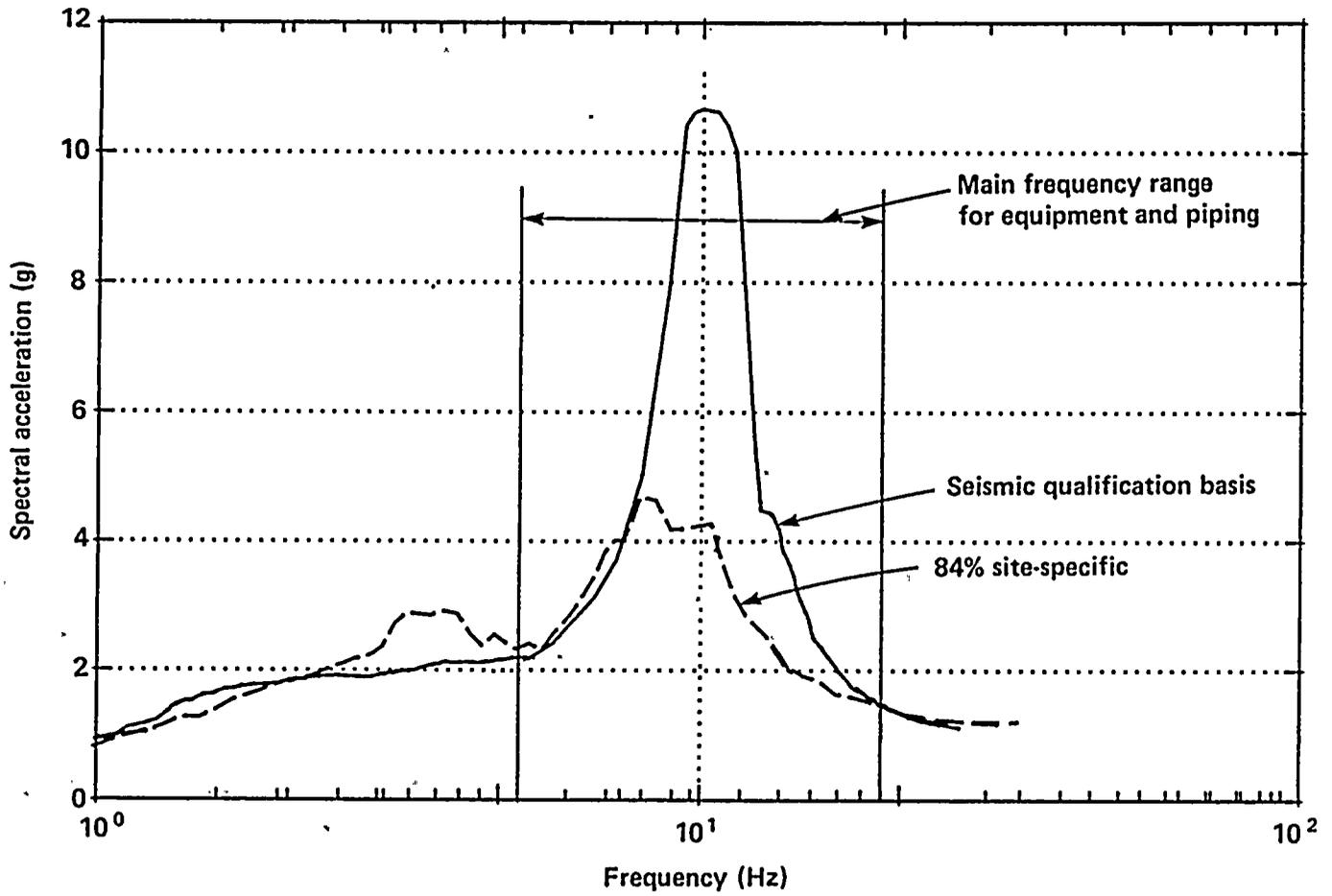


Figure 7-31

Comparison of floor response spectra for equipment qualification for the containment building, interior structure, El 140 feet, east/west response.

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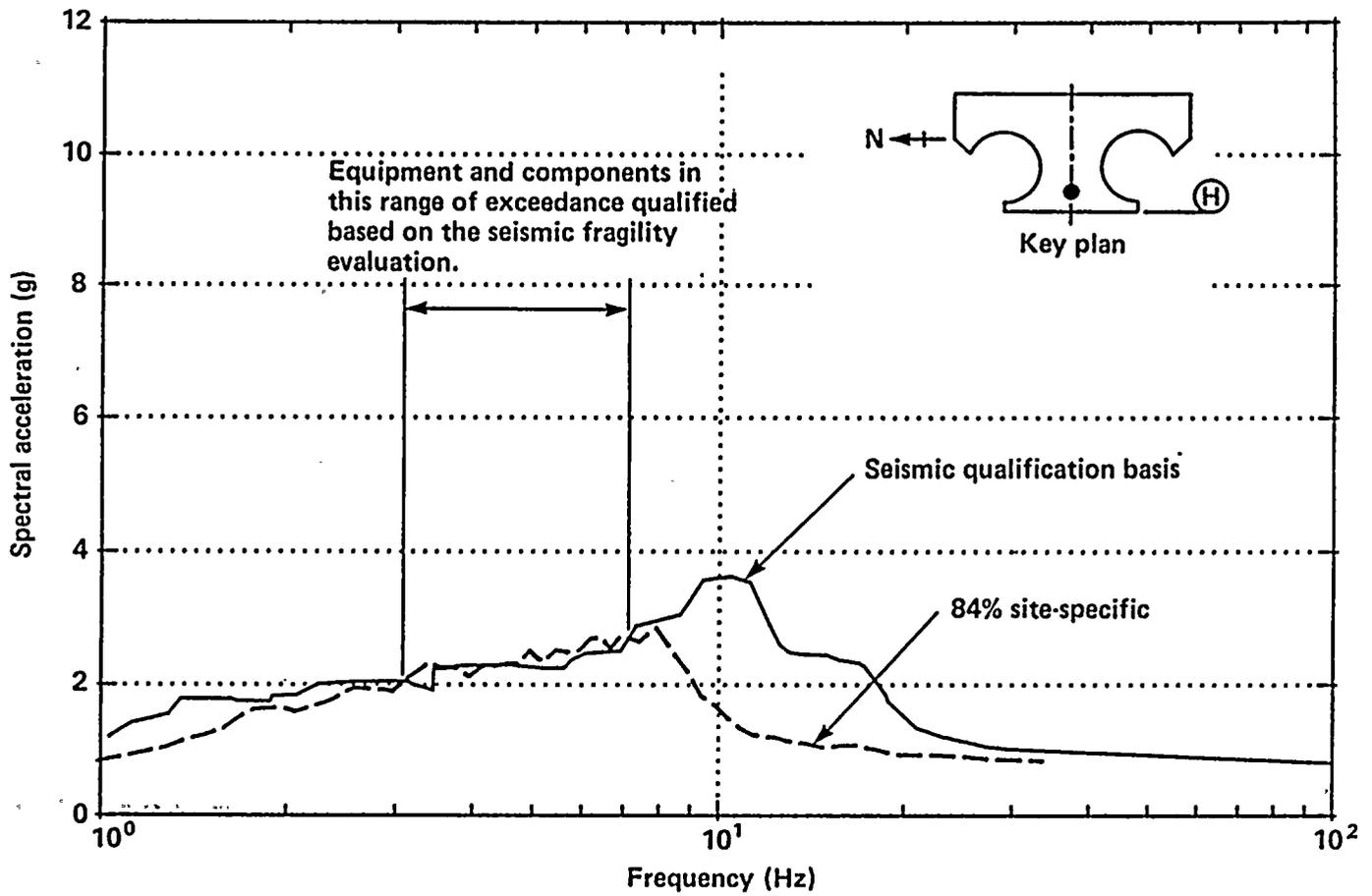


Figure 7-32

Comparison of floor response spectra for equipment qualification for the auxiliary building, El 105 feet, north/south response.

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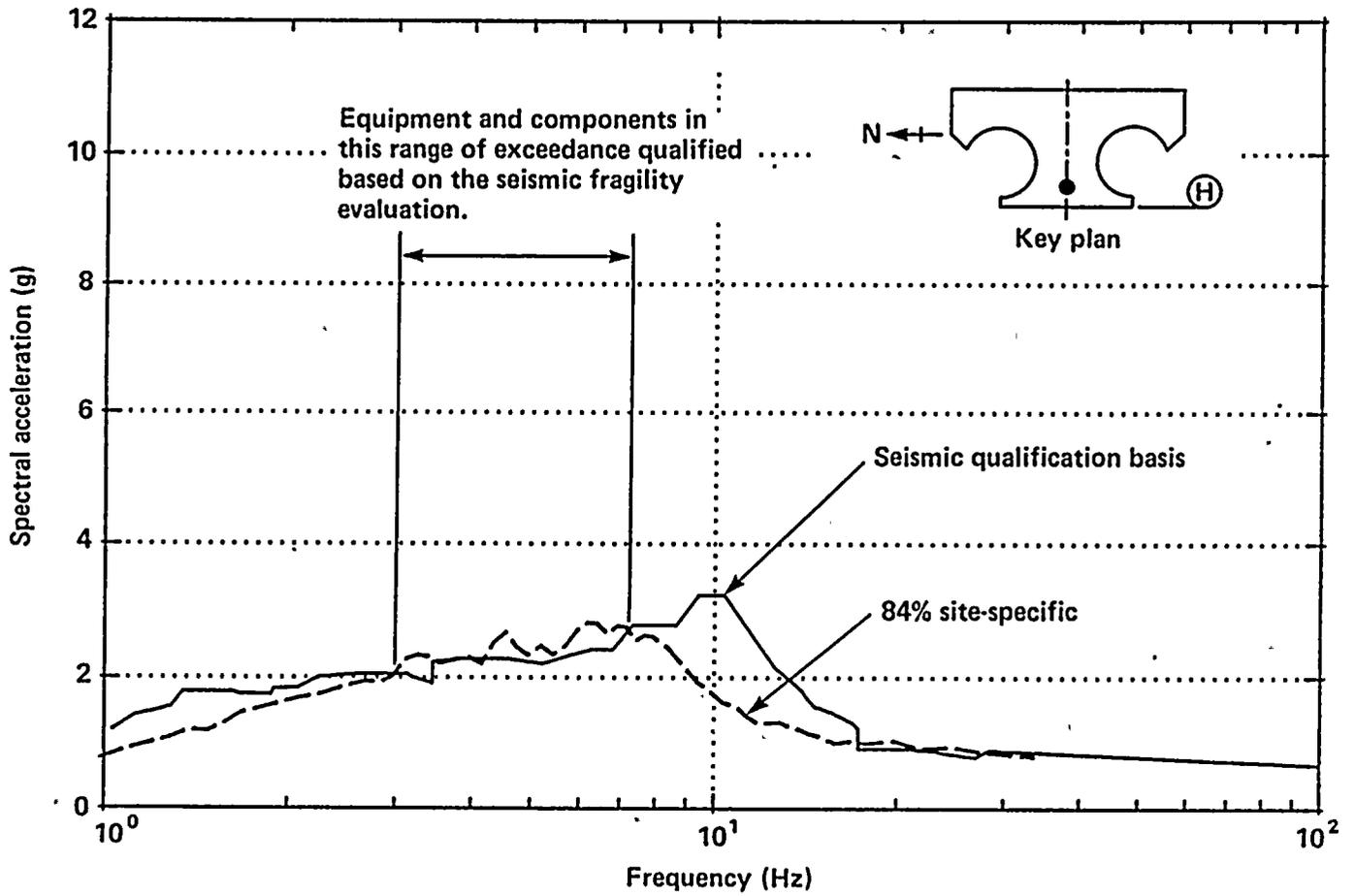


Figure 7-33

Comparison of floor response spectra for equipment qualification for the auxiliary building, El 105 feet, east/west response.

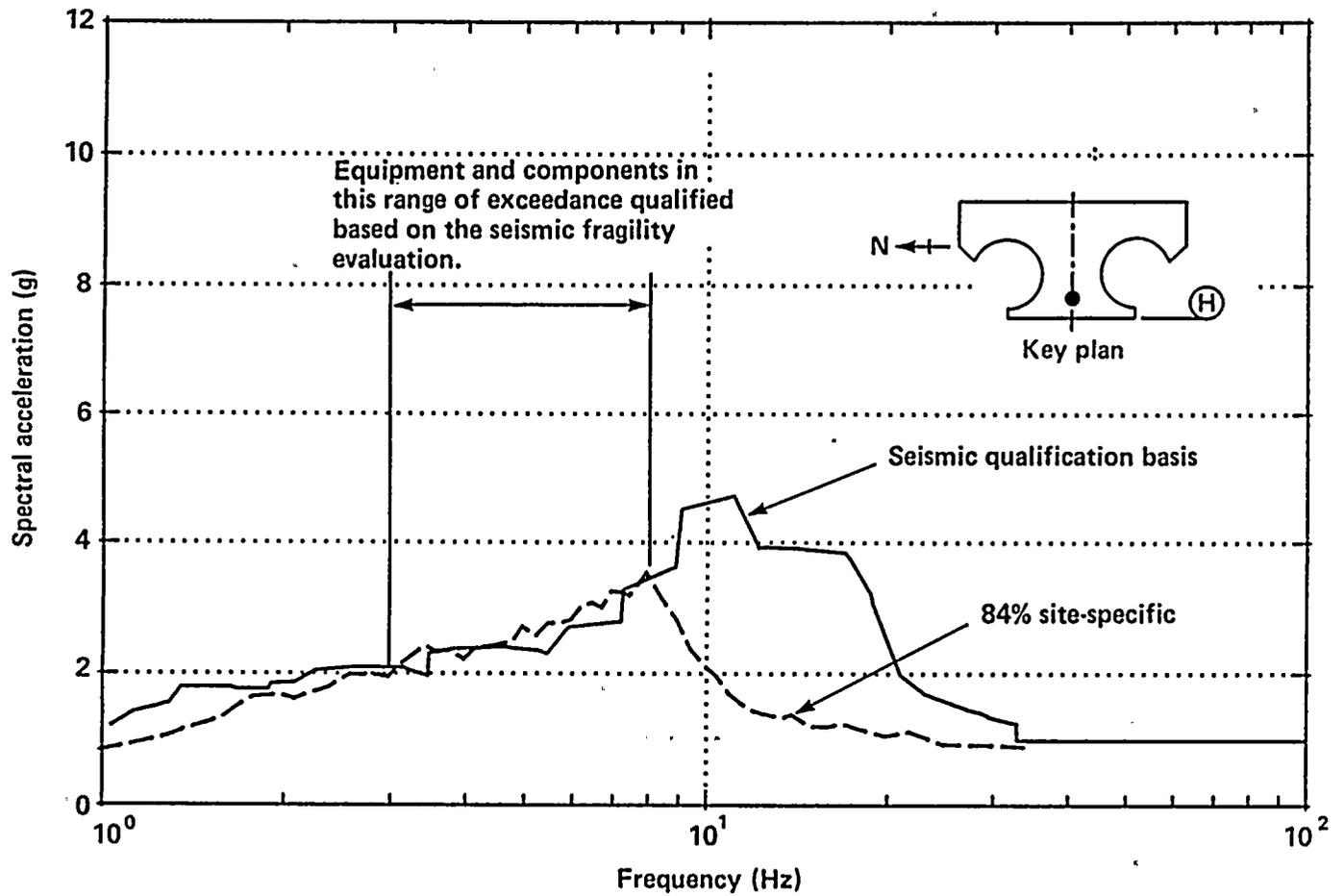


Figure 7-34

Comparison of floor response spectra for equipment qualification for the auxiliary building, El 115 feet, north/south response.

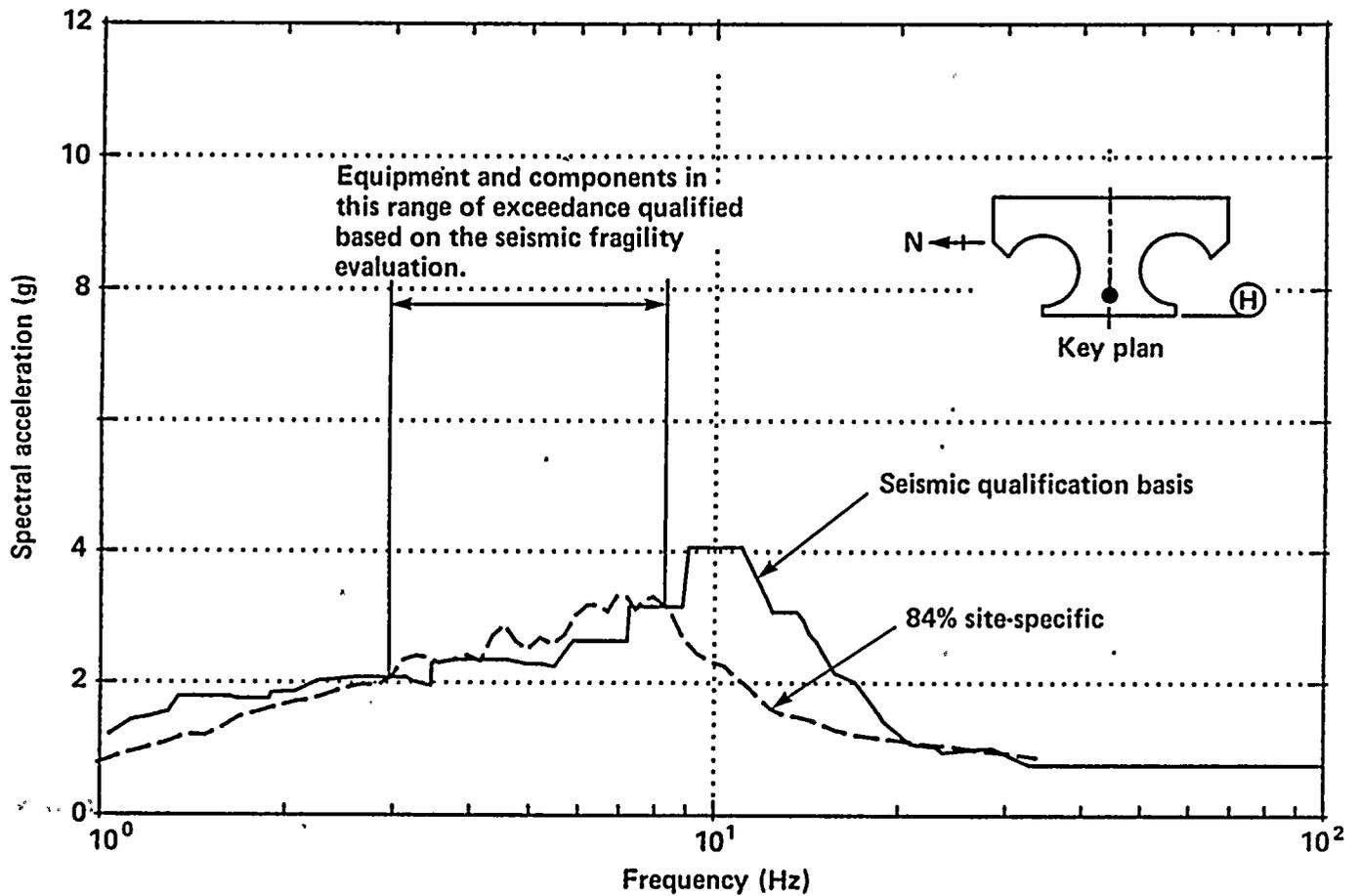


Figure 7-35

Comparison of floor response spectra for equipment qualification for the auxiliary building, El 115 feet, east/west response.

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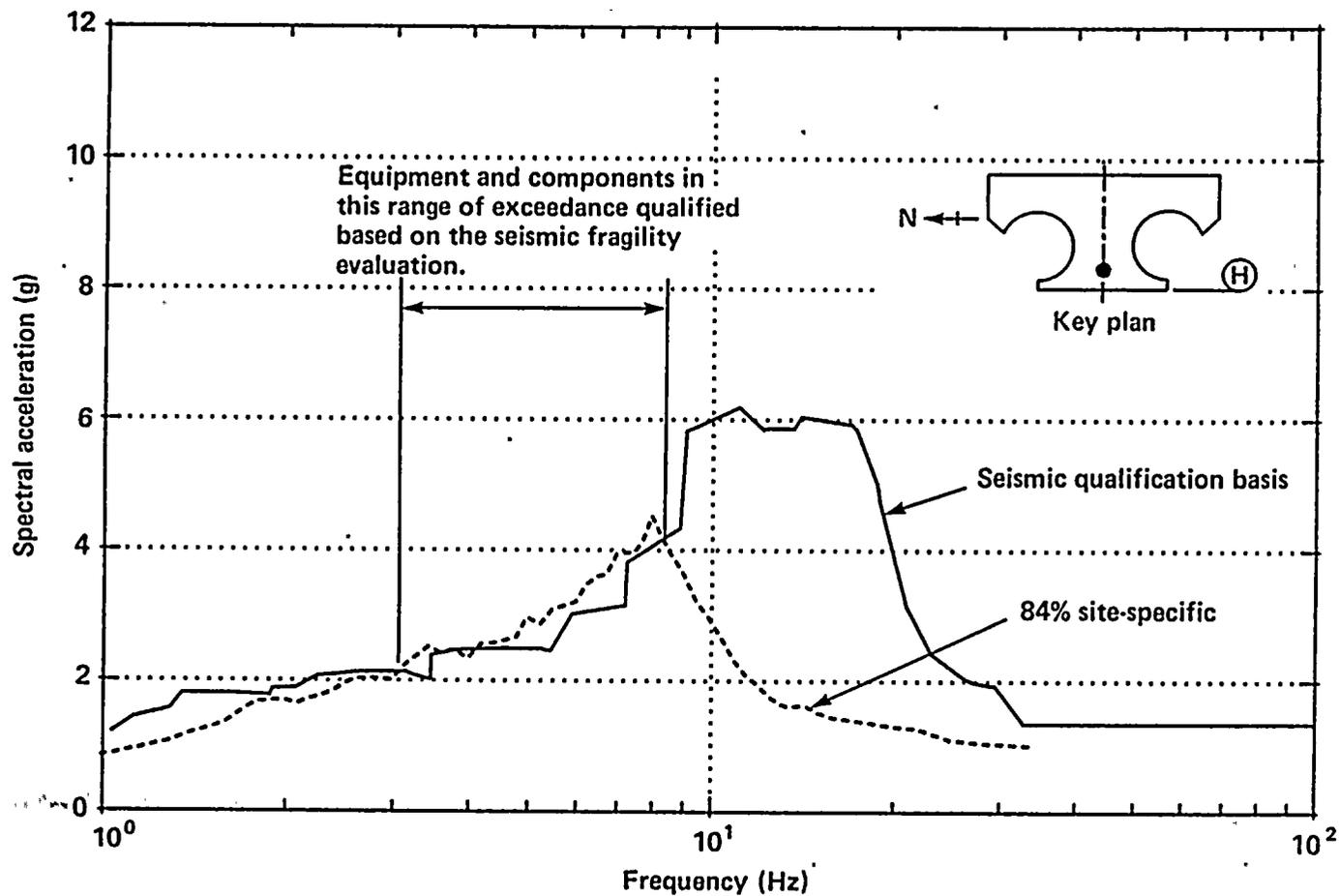


Figure 7-36

Comparison of floor response spectra for equipment qualification for the auxiliary building, El 140 feet, north/south response.

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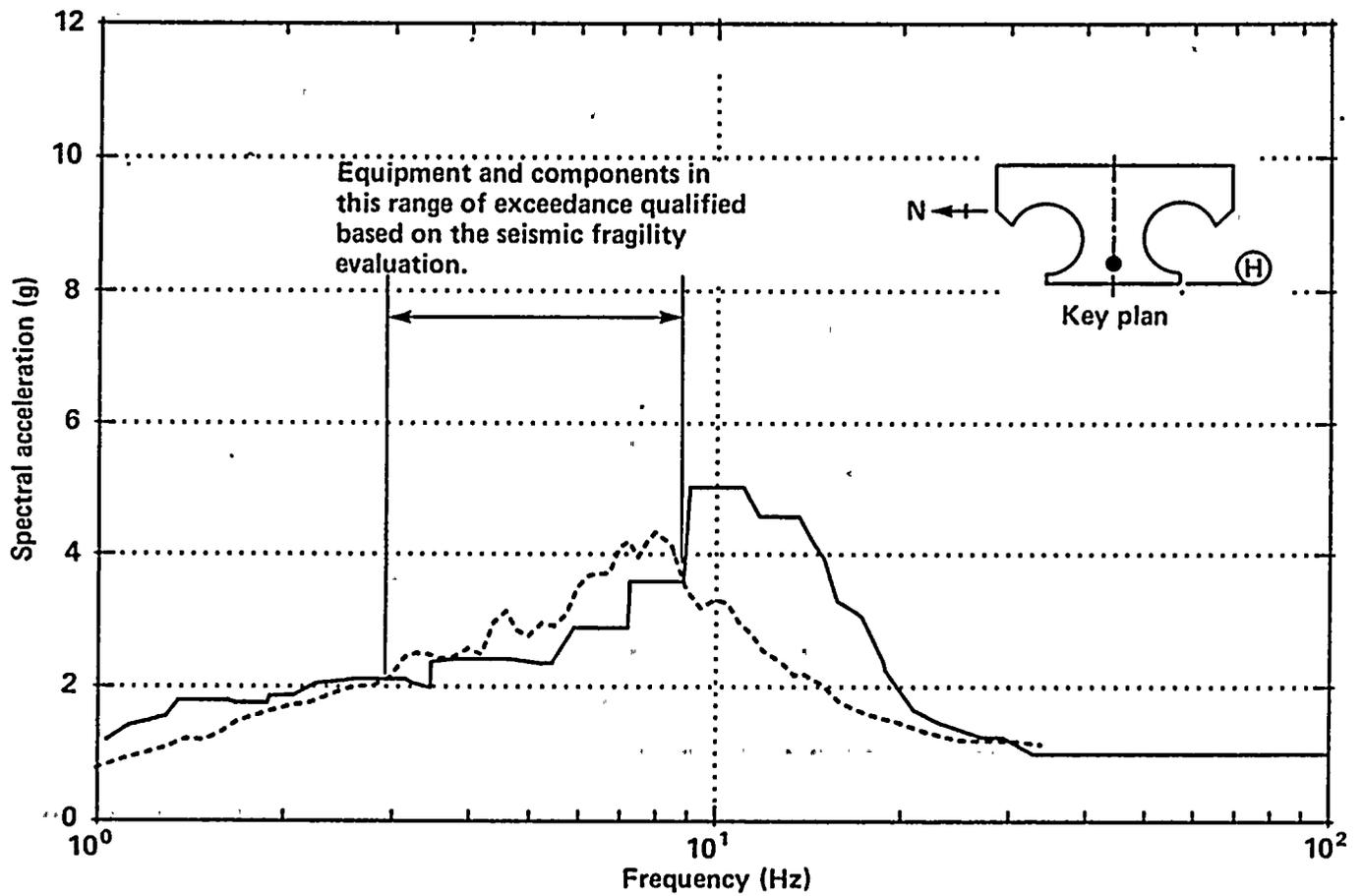


Figure 7-37

Comparison of floor response spectra for equipment qualification for the auxiliary building, El 140 feet, east/west response.

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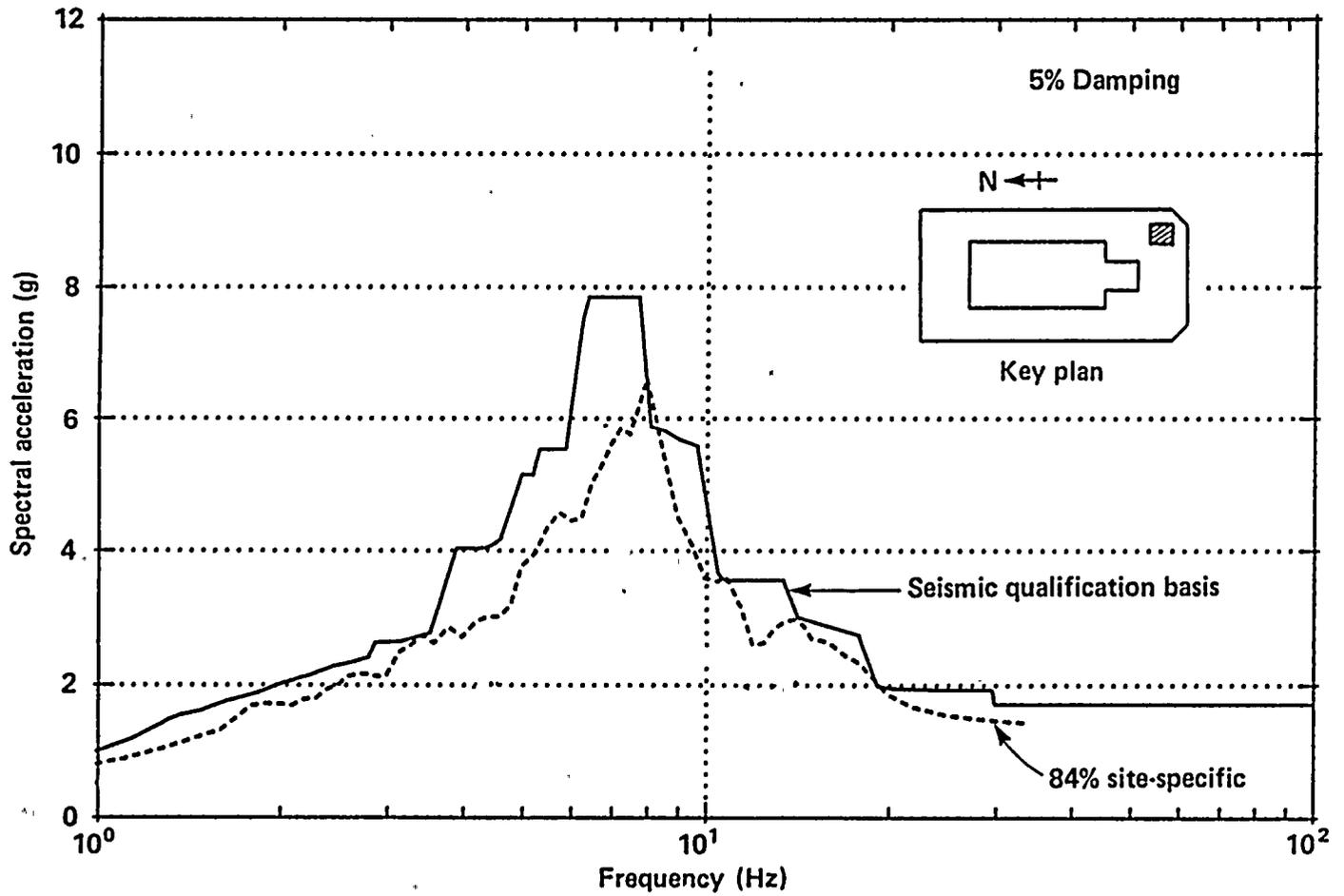
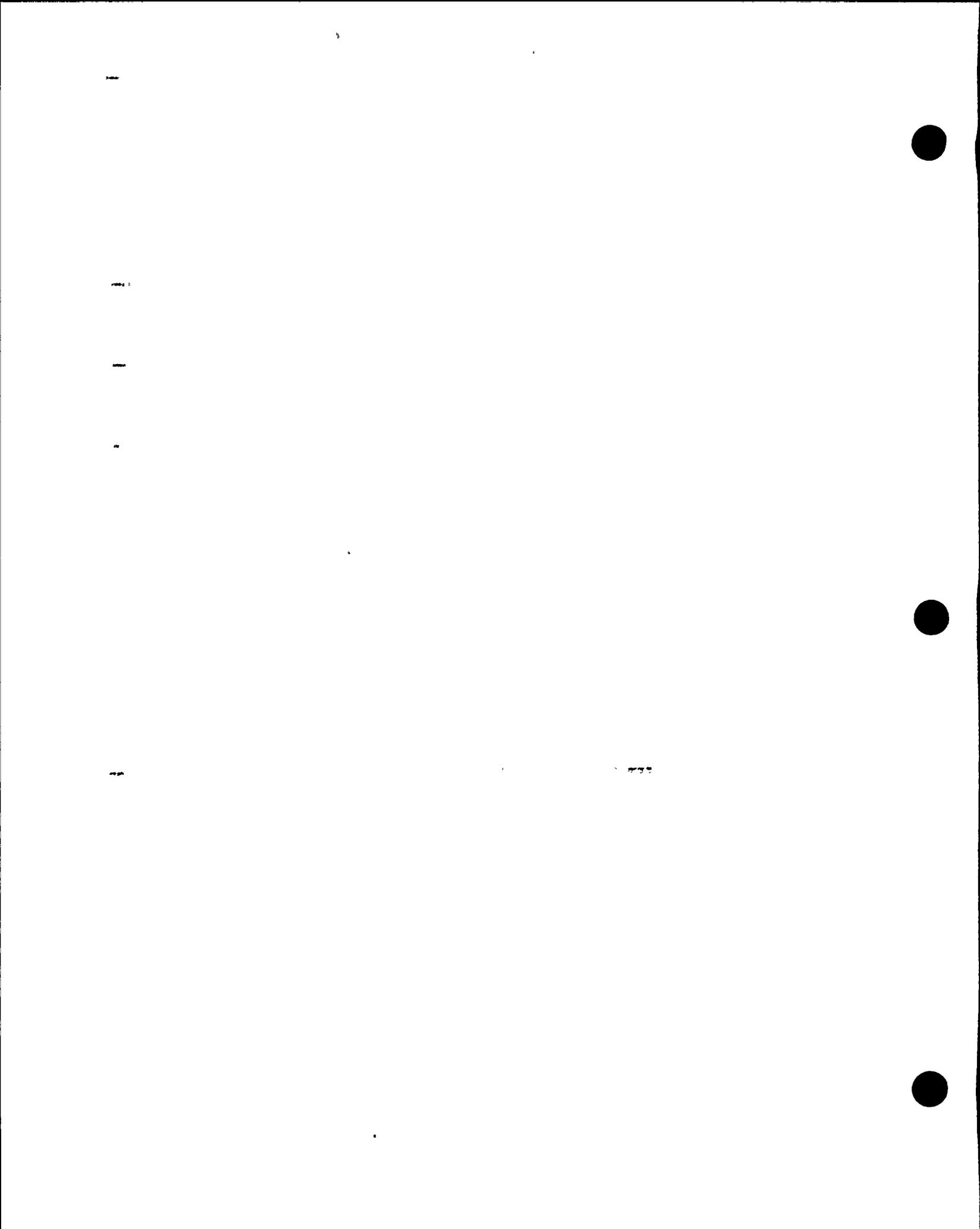


Figure 7-38

Comparison of floor response spectra for equipment qualification for the turbine building, El 119 feet, switchgear area, north/south response.



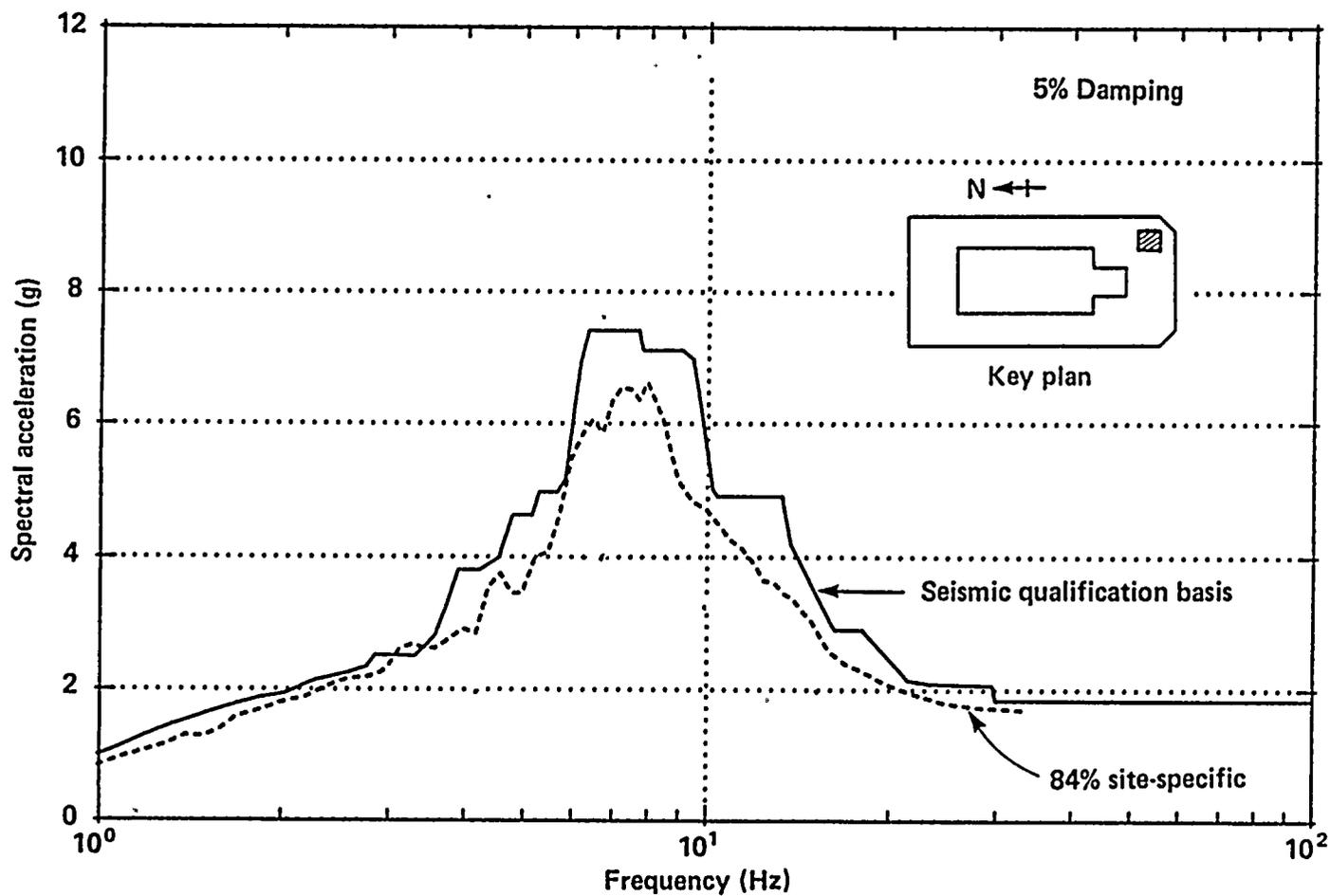


Figure 7-39

Comparison of floor response spectra for equipment qualification for the turbine building, El 119 feet, switchgear area, east/west response.

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- For the auxiliary building (Figures 7-32 to 7-37), the seismic qualification basis spectra exceed the site-specific ground-motion in-structure spectra at all frequencies above about 8 hertz (by amounts up to 100 percent) and at frequencies between 3 and 8 hertz, they fall below the site-specific ground-motion in-structure spectra by an average of about 5 percent. However, equipment in the latter range is qualified on the basis of the seismic fragility evaluations as discussed later.
- For the turbine building (El 119 feet) (Figures 7-38 and 7-39), the site-specific ground-motion in-structure spectra, in general, are enveloped by the seismic qualification basis spectra. Any exceptions are insignificant and they can be accommodated in the design margin.
- For the majority of items of equipment that are essential to Plant seismic safety (therefore, included in the Plant system model used for the probabilistic risk assessment studies), the existing seismic qualification is unaffected, because the in-structure spectra are enveloped by the corresponding seismic qualification basis spectra.
- For those essential items of equipment whose seismic qualification basis spectra do not envelop the site-specific ground-motion in-structure spectra, seismic fragility evaluations (Chapter 6) and the seismic margin assessment described later in this chapter show that each of these items is qualified for the site-specific ground-motion spectra.

DETERMINISTIC SEISMIC MARGIN ASSESSMENT

Capacities for Structures, Systems, and Components

The Expert Panel on Quantification of Seismic Margins organized and funded by the Nuclear Regulatory Commission has recommended that high-confidence-of-low-probability-of-

failure (HCLPF) seismic capacity estimates be used in seismic margin evaluations of nuclear power plants (Budnitz and others, 1985). Several authors have suggested that these seismic capacities can be back-calculated from full fragility curves used in seismic probabilistic risk assessment studies (Campbell, 1987; Kennedy, 1984; Prassinis and others, 1986). This method has been endorsed by the NRC Seismic Design Margins Working Group.

The HCLPF capacities of structures, systems and components back-calculated from full fragility curves are presented in this section. As part of the probabilistic risk assessment, fragility descriptions were developed for structures and major mechanical and electrical systems required for safe shutdown. In all cases, the fragility analyses were based on Plant-specific structures or equipment seismic qualification analyses directly related to elements in place at the Diablo Canyon Plant. The structure, system, and component fragility descriptions were used as inputs to systems analysis models and HCLPF capacities were developed for each.

All fragility estimates presented in Chapter 6 and used in the seismic probabilistic risk assessment were defined in terms of a free-field ground-surface control motion response spectral shape anchored to an average 5 percent-damped spectral acceleration (\bar{S}_a), averaged over the 3.0 to 8.5 hertz frequency range. Therefore, all HCLPF capacities are also defined in terms of average spectral acceleration and this same spectral shape. Because the spectral shape used for fragility estimates is nearly identical to the site-specific ground-motion 84 percent probability of nonexceedance spectral shape when both are anchored to the same 5 percent damped average spectral acceleration (Figure 7-3), the appropriate HCLPF capacities in terms of average spectral acceleration can be compared directly to the average spectral acceleration for the site-specific ground-motion spectra:

Site-Specific Ground-Motion Spectra:

50 percent probability of nonexceedance $\bar{S}_a = 1.30$ g

84 percent probability of nonexceedance $\bar{S}_a = 1.94$ g

It should be noted that the HCLPF capacities represent a conservative estimate of seismic capacity and that direct comparisons of appropriate HCLPF capacities with the site-specific ground motion \bar{S}_a provide a very conservative estimate of the seismic margin of the plant. In this regard the Expert Panel on Quantification of Seismic Margins (Page 5-2 of Budnitz and others, 1985) has stated:

The measure of margin adopted by the Panel is a high-confidence-of-low-probability-of-failure (HCLPF) capacity. This is a conservative representation of capacity and in simple terms corresponds to the earthquake level at which, with considerable confidence, it is extremely unlikely that failure of the component will occur. From the mathematical perspective of a probability distribution on capacity developed in seismic PRA calculations, the HCLPF capacity values are approximately equal to a 95 percent probability of not exceeding about a five percent probability of failure.

There is a margin above the conservative capacity values selected by the Panel. The median capacity, which corresponds to the 50 percent probability of exceedance, is generally at least a factor of 2 greater than the HCLPF capacity. Thus, there is no proverbial "cliff" or sudden failure which is expected to occur immediately beyond the HCLPF capacity. From another perspective, the conservative capacities are close to the lower-bound cutoff values below which there is no significant likelihood of failure.

These points should also be considered in evaluating the comparisons made in the following sections of this report.

DEVELOPMENT OF COMPONENT HIGH-CONFIDENCE-OF-LOW-PROBABILITY-OF-FAILURE CAPACITIES

High-confidence-of-low-probability-of-failure capacity estimates may be directly computed from the fragility estimates (Chapter 6) by (Budnitz and others, 1985; Kennedy, 1984):

$$\text{HCLPF } \bar{S}_a = \bar{S}_a^v e^{-1.65(\beta_R + \beta_U)}$$

where \bar{S}_a^v = median spectral acceleration capacity
 β_R = logarithmic standard deviation for randomness
 β_U = logarithmic standard deviation for uncertainty

However, the fragility estimates provided in Chapter 6 include consideration of both peak-and-valley variability and directional variability of spectral response at any given frequency for any given response direction, and assume a 50 percent probability that these sources of variability will increase the response of any component above its median response estimate. Inclusion of both peak-and-valley and directional variabilities in the fragility analysis method results in a reduction in the estimated HCLPF capacity. The fragility analysis method is primarily intended for use in seismic probabilistic risk assessment studies, and defining the site-specific ground-motion spectrum at the 50 percent probability of nonexceedance level is consistent with this usage.

Such HCLPF capacity estimates may be directly compared to the 50 percent probability of nonexceedance site-specific ground-motion average spectral acceleration. Both the HCLPF capacity estimate and the site-specific ground-motion spectrum assume that at any frequency, the spectral acceleration is equally likely either to exceed or to fall below the smoothed spectrum shape.

On the other hand, direct comparison of HCLPF capacities from the fragility analysis method with an 84 percent probability of nonexceedance site-specific ground-motion average spectral acceleration results in unintentional double-counting of the effects of peak-and-valley and directional variabilities, because these variabilities are considered both in reducing the HCLPF capacity and in increasing the 84 percent probability of nonexceedance site-specific ground-motion level. To avoid this double-counting of the effects of peak-and-valley and directional variabilities, the fragility median and resultant HCLPF capacities must be modified

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before being compared to an 84 percent probability of nonexceedance site-specific ground-motion average spectral acceleration. This point has been recognized and the appropriate modifications have been made in past seismic margin reviews.

The 84 percent probability of nonexceedance site-specific spectrum defined in Chapter 4 is for the average of the two horizontal components. As such, it does not include directional variability. Therefore, for comparison with this spectrum, the HCLPF capacities from the fragility analysis method only needs to be corrected for peak-and-valley variability effects, and not for directional variability effects.

When median and HCLPF capacities from the fragility analysis method are to be directly compared with a desired 84 percent probability of nonexceedance site-specific ground-motion level, these median and HCLPF capacities must first be redefined so that they are appropriate for the control motion response spectrum being defined at the 84 percent level instead of the 50 percent level. Redefined $HCLPF_{84}$ and $MEDIAN_{84}$ capacities appropriate for an 84 percent probability of nonexceedance site-specific ground-motion level are given by:

$$\begin{aligned} HCLPF_{84} &= (R_{84/50}) \cdot HCLPF \\ MEDIAN_{84} &= (R_{84/50}) \cdot MEDIAN \end{aligned} \quad (7-1)$$

where $(R_{84/50})$ represents the ratio of the 84 percent probability of nonexceedance response spectral acceleration for the average of the two horizontal response components at a given frequency to the 50 percent probability of nonexceedance response spectral acceleration for the average of the two horizontal components considering only the peak-and-valley variabilities that have been included in the fragility evaluations.

The peak-and-valley variabilities included in the fragility evaluations for Diablo Canyon were based

upon a study of these sources of variability using 38 pairs of ground-motion records for two horizontal components considered appropriate for the spectral accelerations at the Diablo Canyon site. All 38 pairs of two horizontal components were first scaled linearly over all frequencies to produce the same average spectral acceleration over the frequency range of 4.8 to 14.7 hertz for the average of the two horizontal components. The ratio $(R_{84/50})$, to account for peak-and-valley variabilities, was then obtained at many different frequencies from these 38 pairs of two horizontal components. For frequencies of 3.5 hertz and greater, the ratio $(R_{84/50})$ associated with peak-and-valley variability is reasonably constant and averages 1.20. At frequencies below 3.5 hertz, this ratio rapidly increases to about 1.55 near 3 hertz. Thus:

$$R_{84/50} = 1.20 \quad (7-2)$$

The ratios defined by equation (7-2) were included in the current fragility evaluations, which are conditional on definition of the site-specific ground motions at the 50 percent probability of nonexceedance level.

When the fragility evaluation HCLPF capacities are compared to a desired 84 percent probability of nonexceedance level, they should first be scaled by equation 7-2 to obtain $HCLPF_{84}$ seismic capacities that are conditional on 84 percent probability of nonexceedance ground motions.

Tables 7-1 and 7-2 present HCLPF capacities for each structure and equipment items included in the seismic probabilistic risk assessment. Capacities appropriate for comparison with both the 50 and 84 percent probability of nonexceedance ground motions are presented. In accordance with past practice, the comparison at the 84 percent probability of nonexceedance level will be emphasized. These HCLPF capacities are reported in terms of the 5 percent damped average spectral acceleration in the 3 to 8.5 hertz frequency range.

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Table 7-1
STRUCTURE HCLPF CAPACITIES

Structure	HCLPF Spectral Acceleration Capacity (g) ¹	
	50% ²	84% ³
Containment Building	3.34	4.01
Concrete Internal Structure	2.98	3.58
Intake Structure	3.23	3.88
Auxiliary Building	2.66	3.19
Turbine Building	1.84	2.21
Refueling Water Storage Tank	3.40	4.08
Condensate Storage Tank	>5	>5
Diesel Generator Fuel-Oil Storage Tank	>5	>5
Auxiliary Saltwater Piping	4.85	5.82

NOTES:

¹Values quoted are referenced to average spectral acceleration between 3 and 8.5 hertz for free-field motions.

²Values quoted from fragility evaluation in Table 6-23, Chapter 6.

³Values determined from $HCLPF_{50}$ multiplied by 1.20 (see text for explanation). These values are to be compared with site-specific ground-motion demand $[\bar{S}_a]_{3-8.5 \text{ hertz}} = 1.94 \text{ g}$.

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Table 7-2
EQUIPMENT HCLPF CAPACITIES

System and Component	Location	HCLPF Spectral Acceleration Capacity (g) ¹	
		50% ²	84% ³
Nuclear Steam Supply			
Reactor Pressure Vessel	Containment — (107 feet)	3.34	4.01
Reactor Internals	Containment — (107 feet)	3.55	4.26
Steam Generators	Containment — (140 feet)	2.55	3.06
Pressurizer	Containment — (140 feet)	3.33	4.00
Pressurizer Safety Valves	Containment — (169 feet)	>3	>3
Power Operated Relief Valves	Containment — (169 feet)	2.32	2.78
Reactor Coolant Pumps	Containment — (114 feet)	2.83	3.40
Control Rod Drives	Containment — (140 feet)	3.40	4.08
MSSS Piping	Containment — (140 feet)	>3	>3
Residual Heat Removal			
RHR Pumps	Auxiliary (58 feet)	3.35	4.02
RHR Heat Exchangers	Auxiliary (100 feet)	3.48	4.18
Safety Injection			
SI Accumulators	Containment (91 feet)	4.53	5.44
SI Pumps	Auxiliary (85 feet)	4.64	5.57
Boron Injection Tank	Auxiliary (73 feet)	3.96	4.75
Component Cooling Water			
CCW Pumps	Auxiliary (73 feet)	3.74	4.49
CCW Heat Exchangers	Turbine (85 feet)	2.55	3.06
CCW Surge Tank	Auxiliary (163 feet)	2.91	3.49
Chemical and Volume Control			
Charging Pumps (Centrifugal)	Auxiliary (73 feet)	4.45	5.34
Charging Pumps (Reciprocal)	Auxiliary (73 feet)	>3	>3
Auxiliary Saltwater			
Auxiliary Saltwater Pumps	Intake (2 feet - 2 inches)	>3	>3
Containment Spray			
CS Pumps	Auxiliary (73 feet)	3.85	4.62
Spray Additive Tank	Auxiliary (73 feet)	3.07	3.68
Main Steam			
MS Isolation Valves	Outside Containment (127 feet)	>3	>3
MS Safety Valves	Auxiliary (140 feet)	>3	>3
MS PORV's	Auxiliary (140 feet)	3.51	4.21
Auxiliary Feedwater			
AFW Pumps (Motor Driven)	Auxiliary (100 feet)	>3	>3
AFW Pumps (Turbine Driven)	Auxiliary (100 feet)	3.38	4.06

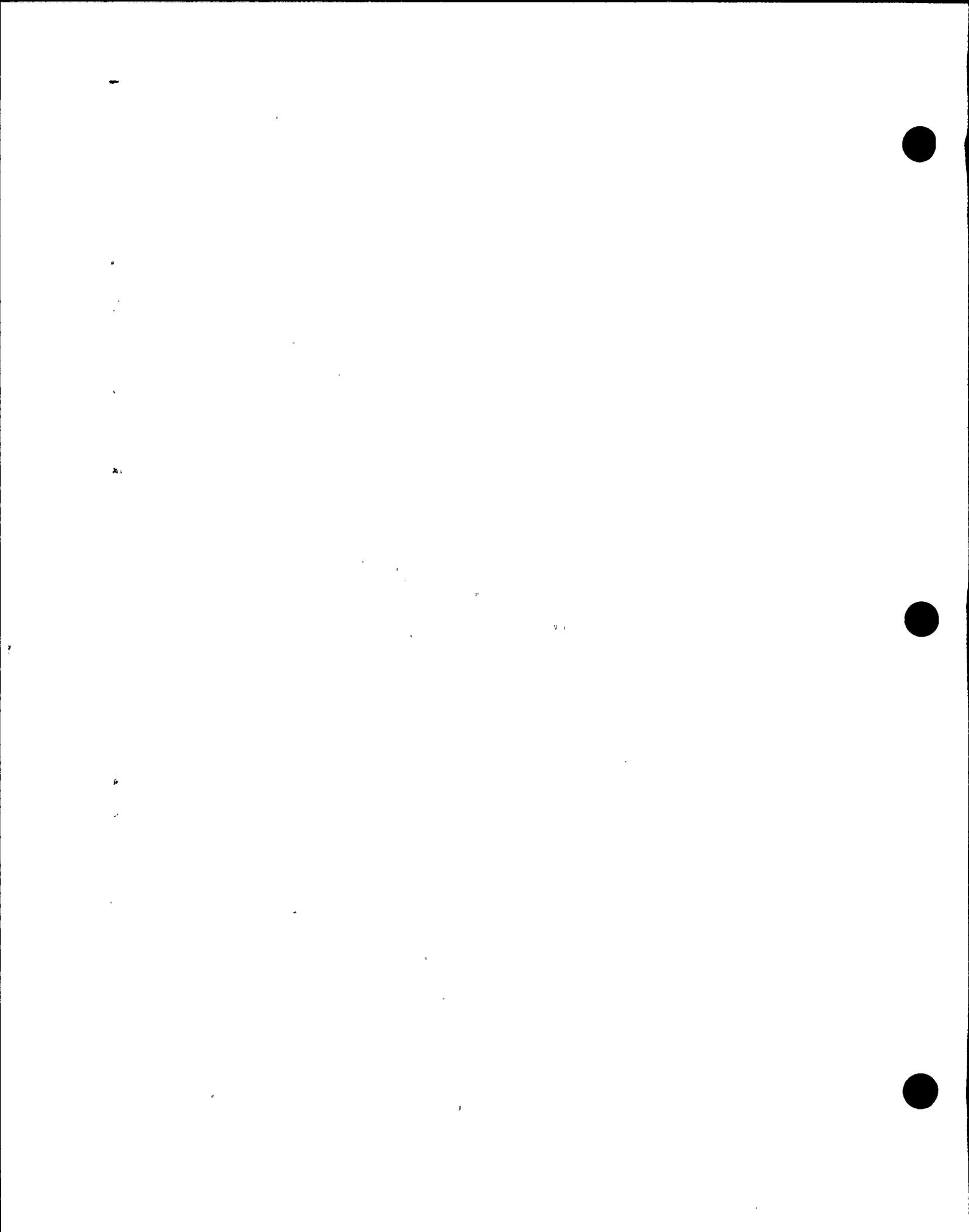


Table 7-2 (Continued)
EQUIPMENT HCLPF CAPACITIES

System and Component	Location	HCLPF Spectral Acceleration Capacity (g) ¹	
		50% ²	84% ³
Diesel Generator			
DG Fuel Oil Day Tank	Turbine (85 feet)	>3	>3
DG Fuel Oil Pumps/Filters	Underground Vault (77 feet)	3.65	4.38
DG Fuel Oil Shutoff Valve	Underground Vault (77 feet)	>3	>3
DG Air Start Compressor	Turbine (85 feet)	>3	>3
DG Air Start Receiver	Turbine (85 feet)	>3	>3
Diesel Generators	Turbine (85 feet)	3.64	4.37
DG Radiator/Water Pump	Turbine (85 feet)	3.66	4.39
DG Inlet Silencer/Air Filter	Turbine (104 feet)	>3	>3
DG Excitation Cubical	Turbine (85 feet)	2.57	3.08
DG Control Panel	Turbine (85 feet)	4.08	4.90
	Chatter Structural	2.24	2.69
DG Main Lead Terminal/Box	Turbine (85 feet)		
Containment Building Ventilation			
Containment Fan Cooler	Containment (140 feet)	2.82	3.38
Control Room Ventilation			
Supply Fans	Auxiliary (154 feet - 6 inches)	3.82	4.58
AC Units/Compressor	Auxiliary (154 feet - 6 inches)	>3	>3
Control Cabinets	Auxiliary (157 feet)	>3	>3
480V Switchgear/Inverter/DC Switchgear/Spreading Room Ventilation			
Supply/Return Fans	Auxiliary (163 feet)	3.95	4.74
Backdraft and Shutoff Dampers	Auxiliary (163 feet)	>3	>3
4160V (Vital) Electric Power			
Switchgear	Turbine (119 feet)	Chatter Structural	1.31
			2.95
Potential Transformers (Bus F)	Turbine (119 feet)	3.47	4.16
(Bus G & H)	Turbine (119 feet)	>3	>3
Safeguard Relay Panel	Turbine (119 feet)	3.39	4.07
125V DC Electric Power			
Batteries	Auxiliary (115 feet)	2.74	3.29
Battery Racks	Auxiliary (115 feet)	5.40	6.48
Battery Chargers	Auxiliary (115 feet)	2.93	3.52
Switchgear/Breaker Panels	Auxiliary (115 feet)	2.36	2.83
120V AC Electric Power			
Instrument Breaker Panels	Auxiliary (115 feet)	>3	>3
Inverters	Auxiliary (115 feet)	2.75	3.30
480V (Vital) Electric Power			
460V/480V Transformers	Auxiliary (100 feet)	2.42	2.90
Breaker Cabinets (Load Centers)	Auxiliary (100 feet)	>3	>3
Auxiliary Relay Panel	Auxiliary (100 feet)	3.57	4.28

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Table 7-2 (Continued)
EQUIPMENT HCLPF CAPACITIES

System and Component	Location	HCLPF Spectral Acceleration Capacity (g) ¹	
		50% ²	84% ³
Control Room			
Main Control Boards	Auxiliary (140 feet)	>3	>3
Hot Shutdown Panel	Auxiliary (100 feet)	2.98	3.58
Auxiliary Safeguards Cabinet	Auxiliary (128 feet)	3.22	3.86
		3.52	4.22
		>3	>3
MSSS Control			
Process Control and Protection System	Auxiliary (128 feet)	3.57	4.28
Solid State Protection System	Auxiliary (140 feet)	4.32	5.18
Reactor Trip Switchgear	Auxiliary (115 feet)	3.14	3.77
Resistance and Temperature Detectors	Auxiliary (140 feet)	>3	>3
Pressure and ΔP Transmitters	Containment (117 feet)	4.11	4.93
Miscellaneous Components			
Auxiliary Relay Rack	Auxiliary (128 feet)	>3	>3
Local Starter Boards	Various	>3	>3
Molded Case Circuit Breakers	Auxiliary (115 feet)	>3	>3
Valve Limit Switches	Auxiliary (Various)	>3	>3
Impulse Lines	Containment (Various)	2.63	3.16
Containment Purge Valves	Containment (132 feet)	>3	>3
Generic Components			
Penetrations/Penetration Boxes	Containment (135 feet)	2.83	3.40
80P Piping and Supports	Various	3.00	3.60
Hand, Relief, Solenoid, and Check Valves	Various	>3	>3
Air and Motor Operated Valves	Various	3.57	4.28
Cable Trays and Supports	Various	>3	>3
HVAC Ducting and Supports	Various	2.49	2.99

NOTES:

¹Values quoted are referenced to average spectral acceleration between 3 and 8.5 hertz for free-field motions.

²Values quoted from fragility evaluation in Table 6-24, Chapter 6.

³Values determined from $HCLPF_{50}$ multiplied by 1.20 (see text for explanation). These values are to be compared with site-specific ground-motion demand $[\bar{S}_a]_{3-8.5 \text{ hertz}} = 1.94 \text{ g}$.

Margin Assessment

When compared to the average 5 percent damped spectral acceleration in the 3 to 8.5 hertz frequency range for the site-specific ground-motion spectra ($\bar{S}_a = 1.30$ g and 1.94 g for the 50 percent and 84 percent probability of nonexceedance site-specific ground-motion spectra, respectively), it may be seen from Tables 7-1 and 7-2 that all structures and equipment items are found to have capacities greater than the earthquake review level, except for the 4-kV switchgear. As discussed above, this comparison may be made for either the 50 percent or 84 percent probability of nonexceedance level capacities. Figure 7-42 illustrates schematically the relationship of the structure and equipment items HCLPF capacities in reference to the site-specific ground-motion spectrum for the 84 percent probability of nonexceedance level, and the procedure for evaluating seismic margins.

The 4-kV switchgear relay chatter mode has the lowest HCLPF₈₄ capacity, 1.57 g, or 81 percent of the 84 percent probability of nonexceedance site-specific 5 percent damped average spectral acceleration of 1.94 g. However, the relay chatter function mode has a median capacity about 2.7 times its HCLPF capacity, 2.2 times as great at the 84 percent probability of nonexceedance site-specific average spectral acceleration. Thus, at this earthquake level, relay chatter of the 4-kV switchgear is highly unlikely. Furthermore, the consequences of 4-kV switchgear relay chatter are easily recoverable by operator action, as discussed in Chapter 6. Even though the 4-kV switchgear relay chatter fragility estimate was included in the seismic probabilistic risk assessment, it did not turn out to be a significant contributor to seismic risk because operators can reset any tripped circuits. Therefore, the 4-kV switchgear relay chatter HCLPF₈₄ capacity is not an appropriate descriptor of the plant seismic margin.

The second lowest HCLPF₈₄ capacity, 2.21 g, is for the overall turbine building structure. The

reported HCLPF₈₄ capacity is a factor of 1.14 times greater than the 84 percent probability of nonexceedance site-specific average spectral acceleration, so that a 14 percent margin exists before this HCLPF₈₄ capacity is reached. Even if the demand were to reach this level, failure is unlikely, because the median capacity is estimated to be a factor of 2.65 greater than the HCLPF capacity. Furthermore, as will be discussed in the following section, there are several sources of conservatism in the estimation of the turbine building HCLPF₈₄ capacity, so the actual HCLPF₈₄ capacity margin over the 84 percent probability of nonexceedance site-specific ground-motion average spectral acceleration is likely to be more than 40 percent, rather than 14 percent.

The diesel generator control panel has the third lowest HCLPF₈₄ capacity, 2.69 g, which is a factor of 1.39 greater than the 84 percent probability of nonexceedance site-specific average spectral acceleration. The only other components having reported HCLPF₈₄ capacities less than 3.0 g are the power-operated relief valves on the primary system (2.78 g), and the 125-volt DC electric power switchgear/breaker panel (2.83 g), both of which exceed the site-specific ground-motion average spectral acceleration by a factor greater than 1.43.

Thus, except for the turbine building, all components whose failure could lead to seismic risk to the Plant have at least a 40 percent margin between the HCLPF₈₄ capacity and the 84 percent probability of nonexceedance site-specific ground motion. Conservatisms in the turbine building capacity evaluation are discussed below.

CONSERVATISMS IN TURBINE BUILDING STRUCTURE CAPACITY EVALUATION (FRAGILITY ESTIMATES)

Because the Plant fragility is governed by that for the turbine building, a further evaluation of the conservatism used in the turbine building analysis has been made (Kennedy and others, 1988). The results of this evaluation are summarized here.

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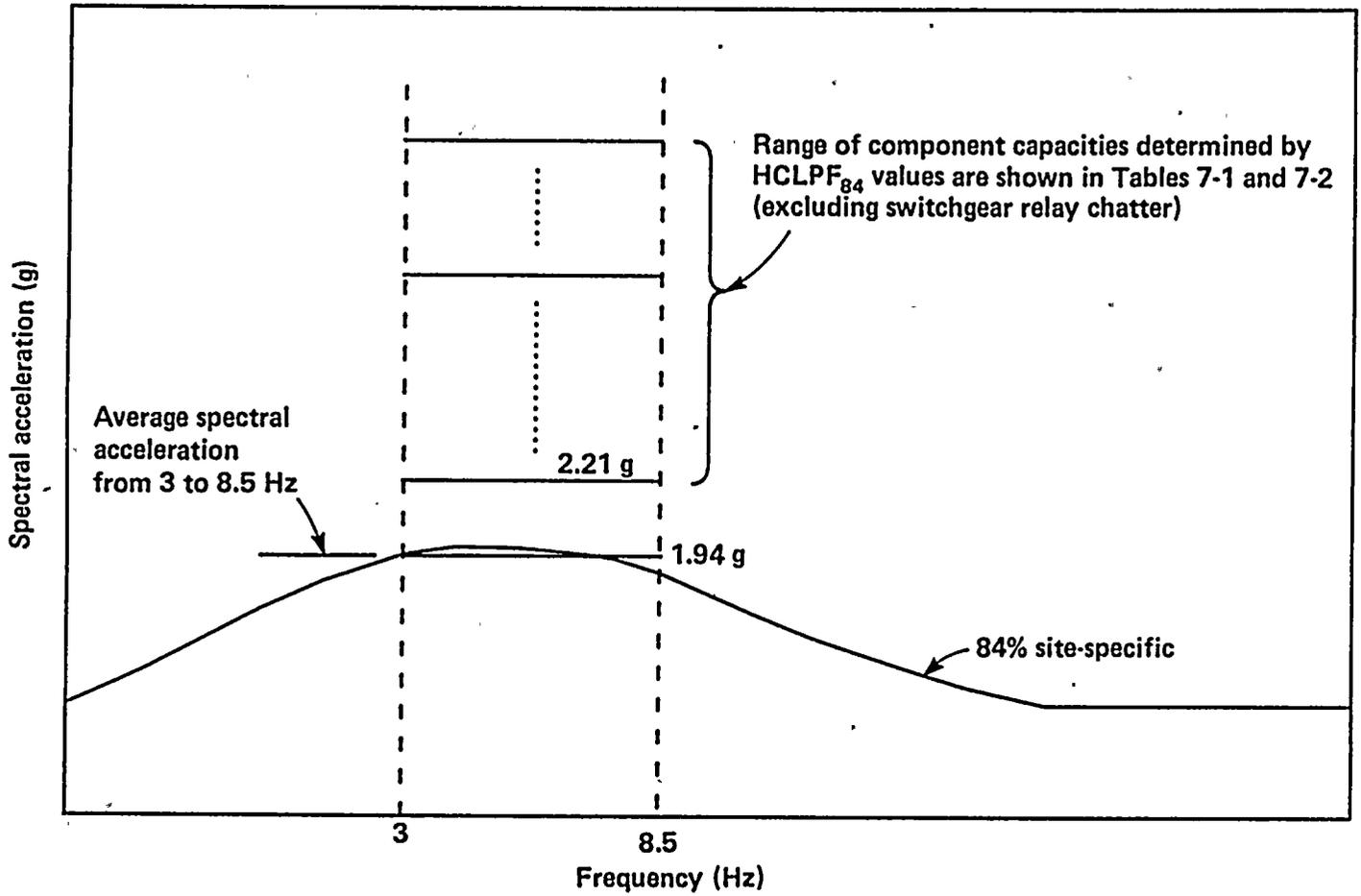


Figure 7-40
Schematic illustration for determining seismic margins.

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A number of possible failure modes that could lead to overall severe distress of the turbine building were investigated using the standard fragility evaluation method for the seismic probabilistic risk assessment. It was concluded that the most probable cause of overall severe distress of the turbine building was substantial inelastic drift and strength degradation of the two major east/west load-carrying shear walls spanning from foundation level (El 85 feet) to the operating floor (El 140 feet). An extensive study was then performed to define the fragility estimate for the major east/west load-carrying shear walls. This study is summarized in Chapter 6. In this study, 200 nonlinear time-history analyses, using 25 different ground-motion time history inputs, were performed to define the fragility estimate.

The turbine building fragility estimate specifically applies to the onset of severe structural distress (significant strength degradation) to the major east/west shear walls. Structural distress generally does not correspond to partial collapse, depending on the power of the ground-motion record that remains after this state of distress is reached. Furthermore, partial collapse is likely to be well short of total collapse, even if partial collapse occurs. Even so, in the seismic probabilistic risk assessment study, and in this margin evaluation, the onset of structural distress of these shear walls has been conservatively used as a surrogate for a structure-induced failure of all safety equipment housed in the turbine building. This substitution introduces an indeterminate, but probably substantial conservatism.

Fragility statements on the onset of shear wall distress were anchored to the average 5 percent damped spectral acceleration in the 3 to 8.5 hertz frequency range for use in the seismic probabilistic risk assessment. Therefore, all 25 ground-motion records that were used in the nonlinear analyses were scaled upward so that each had the same average spectral accelerations \bar{S}_a . A total of 75 nonlinear analyses were performed at $\bar{S}_a = 3.0$ g and 6.0 g, and 50 nonlinear analyses were performed at $\bar{S}_a = 4.0$ g, with each ground-motion recording being used an equal number of times.

It was found that considerable differences existed in the computed shear wall drifts (measure of damage) for different ground-motion records when each was scaled to the same average spectral acceleration level. In fact, the records such as Tabas, Pacoima Dam, and Karakyr Point (Gazli) which actually had the highest average spectral acceleration and thus had to be scaled and modified the least to achieve a reference \bar{S}_a such as 3.0 g, consistently produced lesser drifts (damage) than did the records that had greater scaling and modification. The records such as Tremblor (Parkfield), Coyote Lake Dam (Morgan Hill, 1984), Pleasant Valley Pump Station (Coalinga), and Dayhook (Tabas) which had to be scaled upward and modified the most to produce a reference $\bar{S}_a = 3.0$ g consistently produced the largest drifts (damage) after being scaled upward to that level. Results using each ground-motion record were equally weighted; this decision produced a much lower HCLPF \bar{S}_a capacity estimate than would have resulted if only the highest ground-motion records had been used. Basically, average spectral acceleration is one of the best single ground-motion parameters; it does not serve as a highly accurate descriptor of the capability of ground motions to damage the turbine building shear walls. Because of the large scatter of computed drifts for the same average spectral acceleration, the fragility variability factors β_R and β_U were significantly increased. This resulted in significant reduction of the HCLPF \bar{S}_a capacity. When compared to a specific ground-response spectrum, such as the 84 percent probability of nonexceedance site-specific ground-motion spectrum, the single-parameter fragility method HCLPF₈₄ \bar{S}_a capacity is conservatively biased, because it must also cover ground motions having differing spectral shapes.

The 75 deterministic time history analyses performed for the 25 ground-motion records each scaled to $\bar{S}_a = 3.0$ g provide a more precise multiple parameter description of the seismic margin of the turbine building shear walls than could be incorporated into the single parameter average spectral acceleration used in the seismic probabilistic risk assessment. It was found that large shear wall drifts (and thus, damage) only resulted when the ground motions produced high

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spectral accelerations, both at high frequency (8.6 to 9.5 hertz) associated with the elastic frequency of the shear walls, and at low frequency (1.7 to 2.8 hertz). Substantial spectral accelerations were needed at high frequency to drive the shear walls into the inelastic regime. Substantial low-frequency spectral acceleration was then needed to produce damaging levels of shear wall drift as the shear wall frequencies shifted due to inelastic behavior. In other words, very broad frequency content (1.7 to 9.5 hertz) was necessary within the ground-motion record to produce severe damage at $\bar{S}_a = 3.0$ g. The required breadth of frequency content was not adequately captured by a single ground-motion parameter. An improved deterministic seismic margin HCLPF capacity statement is obtained by requiring both the following high frequency and either of the two low frequency limits to be exceeded:

HCLPF Limits

High Frequency Limit

$$\text{Maximum } S_{a5\%} \geq 1.6 \text{ g (within 8.6 to 9.5 hertz)}$$

and

Low Frequency Limit

$$\text{Maximum } S_{a5\%} \geq 2.8 \text{ g (within 2.4 to 2.8 hertz)}$$

or

$$\text{Maximum } S_{a5\%} \geq 2.25 \text{ g (within 1.7 to 2.0 hertz)}$$

The 84 percent probability of nonexceedance site-specific ground motion 5 percent damped response spectrum gives spectral accelerations of 1.79 g, 1.83 g, and 1.55 g at 8.6 hertz, 2.8 hertz and 2.0 hertz, respectively. Thus, the high frequency HCLPF limit of the turbine building shear wall is exceeded and nonlinear drift is possible. However, the low-frequency HCLPF limits are well above the 84 percent probability of nonexceedance site-specific ground-motion response spectrum, so nonlinear drifts cannot become large. The ratio at 2.8 hertz is $2.8/1.83 = 1.53$, and at 2.0 hertz, is $2.25/1.55 = 1.45$. Thus,

there is a 45 percent margin between the 84 percent site-specific ground-motion response spectrum and the deterministically defined turbine building shear wall HCLPF capacity.

Multiple nonlinear time-history analyses were not performed for other failure modes of the turbine building. These failure modes have HCLPF₈₄ \bar{S}_a capacities back-calculated from fragility estimates that are greater than the 2.21 g obtained for the turbine building east/west shear walls. It is our judgment that these other failure modes would have multiple parameter deterministic HCLPF capacities also greater than those for the turbine building east/west shear walls.

Defining seismic margin as the difference between the appropriate HCLPF capacity and the 84 percent probability of nonexceedance site-specific ground-motion average spectral acceleration, the following conclusions can be reached:

- The seismic margin for the turbine building is at least 14 percent, and most likely in excess of 40 percent.
- The HCLPF capacity does not represent a "cliff" beyond which failure immediately occurs. Instead, it is close to a lower-bound, below which there is no significant likelihood of failure. The median capacity for the turbine building is more than 2.5 times its HCLPF capacity, and the probability of failure would only gradually increase if the ground motion were to exceed the HCLPF capacity.
- Other than the turbine building, all structures and equipment items whose failure could lead to seismic risk to the Plant have at least a 40-percent margin between the HCLPF capacity and the 84 percent probability of nonexceedance site-specific ground motion.

Conclusions of Margin Assessment

The deterministic evaluation discussed in this chapter demonstrates that the Diablo Canyon Plant has adequate margin to accommodate the site-specific ground motions for the maximum

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earthquake on the Hosgri fault, as evidenced by the following:

- The containment building has a seismic margin of at least 100 percent and the auxiliary building has a seismic margin of at least 70 percent. The most critical structure was identified as the turbine building, which has a seismic margin at least 14 percent, and most likely in excess of 40 percent.
- Among the plant components, relay chatter of the 4-kV switchgear may occur. However, the switchgear structure has ample margin to accommodate demands due to the site-specific ground motions. Therefore, no structural failure will occur. Also, the ease of recovery and specific plant procedures essentially eliminate any concern due to relay chatter.
- For all components, except the 4-kV switchgear, the minimum seismic margin is shown to be in excess of 40 percent.

REFERENCES

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- Prassinis, P. G., Ravindra, M. K., and Savy, J. B., 1986, Recommendations to the Nuclear Regulatory Commission on trial guidelines for seismic margin reviews: NUREG/CR4482 (draft).
- Prassinis, P. G., Murray, R. C., and Cummings, G. E., 1987, Seismic margin review of Maine Yankee Atomic Power Station: NUREG/CR4826.
- U.S. Nuclear Regulatory Commission, 1976, Supplement No. 5 to the safety evaluation report of the Diablo Canyon Nuclear Power Station Units 1 and 2.



Chapter 8

ASSESSMENT OF THE ADEQUACY OF SEISMIC MARGINS

To Address

Element 4 of the License Condition

ELEMENT 4 OF THE LICENSE CONDITION

PG&E shall assess the significance of conclusions drawn from the seismic reevaluation studies in Elements 1, 2, and 3, utilizing a probabilistic risk analysis and deterministic studies, as necessary, to assure adequacy of seismic margins.

OBJECTIVES

The objective of this chapter is to address Element 4 of the license condition and to summarize the conclusions drawn in Chapter 6 regarding the seismic probabilistic risk assessment, and in Chapter 7 regarding the deterministic evaluation, to assure the adequacy of the seismic margins at the Diablo Canyon Power Plant.

As required in Element 4 of the license condition, the probabilistic risk assessment and deterministic evaluations were based on the conclusions and findings from the studies performed to meet the first three elements of the license condition described in Chapters 2 through 5. The probabilistic risk analysis has assessed the probabilistic seismic risk of the Plant by convolving the results of seismic hazard and fragility analyses. The seismic hazard and fragility analyses, in turn, are based on data generated during geology/seismology/geophysics, ground-motion, and soil/structure interaction studies. Similarly, the deterministic evaluations also were performed using the data and information from these Program elements.

ADEQUACY OF SEISMIC MARGINS-

Probabilistic Risk Assessment

From a risk standpoint, earthquakes have little impact on the total risk curve. When the mean values of the core-damage curves are compared, seismic risk is approximately 18 percent of the total core-damage frequency. However, the seismic risk is somewhat overstated using this characterization, because the uncertainty associated with the seismic results is large compared with that of the nonseismic initiators.

Looking at seismic risk in isolation, most of the mean seismic core-damage frequency of 3.7×10^{-5} comes from 5 percent damped average spectral accelerations (averaged over the frequency range from 3 to 8.5 hertz) of 2 to 3 g.

The majority of seismic risk is due to a very small group of components. Of these, the turbine building contribution is 1.1×10^{-5} (mean). This is a small contribution to the total risk of 2.0×10^{-4} . Except for offsite power, equipment has minor impact on the results. Offsite power is potentially a large contributor, but only when coupled with other component failures. Furthermore, loss of offsite power is mitigated by the ability to take timely recovery actions.

When the total risk at Diablo Canyon is compared to that of other Westinghouse plants for which probabilistic risk assessments have been made, Diablo Canyon compares favorably, as shown on Figure 8-1.

in the determination of values below which there is no significant likelihood of failure.

In the determination of values below which there is no significant likelihood of failure, the conservative HCLP₂₅ capacities have been compared to an 84 percent probability of nonexceedance site-specific ground-motion spectrum defined for a maximum magnitude earthquake. This spectrum has an average spectral acceleration of 0.15 g and a peak frequency range of 0.1 to 0.5 g. The HCLP₂₅ capacities listed in Tables 2-1 and 2-2 to Table 2-3 are conservative compared with the HCLP₂₅ capacities listed in Table 2-1 and 2-2 to Table 2-3. However, it should be noted that the 84 percent probability of nonexceedance site-specific spectrum used in this comparison is also very conservative. The ratio of the 84 to 50 percent spectra is approximately 1.2. Thus, even when the HCLP₂₅ capacity spectrum calculation was made using a spectrum calculated for the 84 percent site-specific spectrum, the median capacity will be roughly a factor of 1.2 to 1.5 above the 50 percent site-specific spectrum. The 84 percent spectrum is a very conservative estimate of the true capacity of the structure.

Keeping these things in mind, the HCLP₂₅ capacity spectrum used in the comparison has the lowest HCLP₂₅ capacity which is only 1.5 g or a factor of 1.5 to 2.0 above the 50 percent spectrum. The 84 percent spectrum used in the comparison is also very conservative. The ratio of the 84 to 50 percent spectra is approximately 1.2. Thus, even when the HCLP₂₅ capacity spectrum calculation was made using a spectrum calculated for the 84 percent site-specific spectrum, the median capacity will be roughly a factor of 1.2 to 1.5 above the 50 percent site-specific spectrum. The 84 percent spectrum is a very conservative estimate of the true capacity of the structure.

Stochastic Evaluation

The stochastic evaluation compares the results of the HCLP₂₅ capacity spectrum calculation with the results of the stochastic evaluation. The stochastic evaluation is a probabilistic method for determining the probability of failure of a structure under seismic loading. The stochastic evaluation is based on the assumption that the ground motion is a stationary, Gaussian process with a power spectrum defined by the maximum magnitude earthquake spectrum. The stochastic evaluation is based on the assumption that the ground motion is a stationary, Gaussian process with a power spectrum defined by the maximum magnitude earthquake spectrum. The stochastic evaluation is based on the assumption that the ground motion is a stationary, Gaussian process with a power spectrum defined by the maximum magnitude earthquake spectrum.

It is noted that the HCLP₂₅ capacity spectrum calculation is a conservative estimate of the true capacity of the structure. The stochastic evaluation is a probabilistic method for determining the probability of failure of a structure under seismic loading. The stochastic evaluation is based on the assumption that the ground motion is a stationary, Gaussian process with a power spectrum defined by the maximum magnitude earthquake spectrum.

The stochastic evaluation is a probabilistic method for determining the probability of failure of a structure under seismic loading. The stochastic evaluation is based on the assumption that the ground motion is a stationary, Gaussian process with a power spectrum defined by the maximum magnitude earthquake spectrum. The stochastic evaluation is based on the assumption that the ground motion is a stationary, Gaussian process with a power spectrum defined by the maximum magnitude earthquake spectrum. The stochastic evaluation is based on the assumption that the ground motion is a stationary, Gaussian process with a power spectrum defined by the maximum magnitude earthquake spectrum.

The stochastic evaluation is a probabilistic method for determining the probability of failure of a structure under seismic loading. The stochastic evaluation is based on the assumption that the ground motion is a stationary, Gaussian process with a power spectrum defined by the maximum magnitude earthquake spectrum. The stochastic evaluation is based on the assumption that the ground motion is a stationary, Gaussian process with a power spectrum defined by the maximum magnitude earthquake spectrum. The stochastic evaluation is based on the assumption that the ground motion is a stationary, Gaussian process with a power spectrum defined by the maximum magnitude earthquake spectrum.

Deterministic Evaluations

In the deterministic evaluations, component capacities were defined in terms of their high-confidence-of-low-probability-of-failure capacity levels appropriate for comparison with an 84 percent probability of nonexceedance ground response spectrum (that is, HCLPF₈₄). The HCLPF₈₄ capacities have been defined in terms of the 5 percent damped average spectral acceleration within the 3 to 8.5 hertz range. Tables 7-1 and 7-2 respectively present HCLPF₈₄ capacities for the controlling failure modes for structures and for elements of the major mechanical and electrical reactor systems that are important to evaluating the probability of core damage.

When interpreting these HCLPF₈₄ capacities, the following statements of the Expert Panel on Quantification of Seismic Margins (Budnitz, 1985) should be noted:

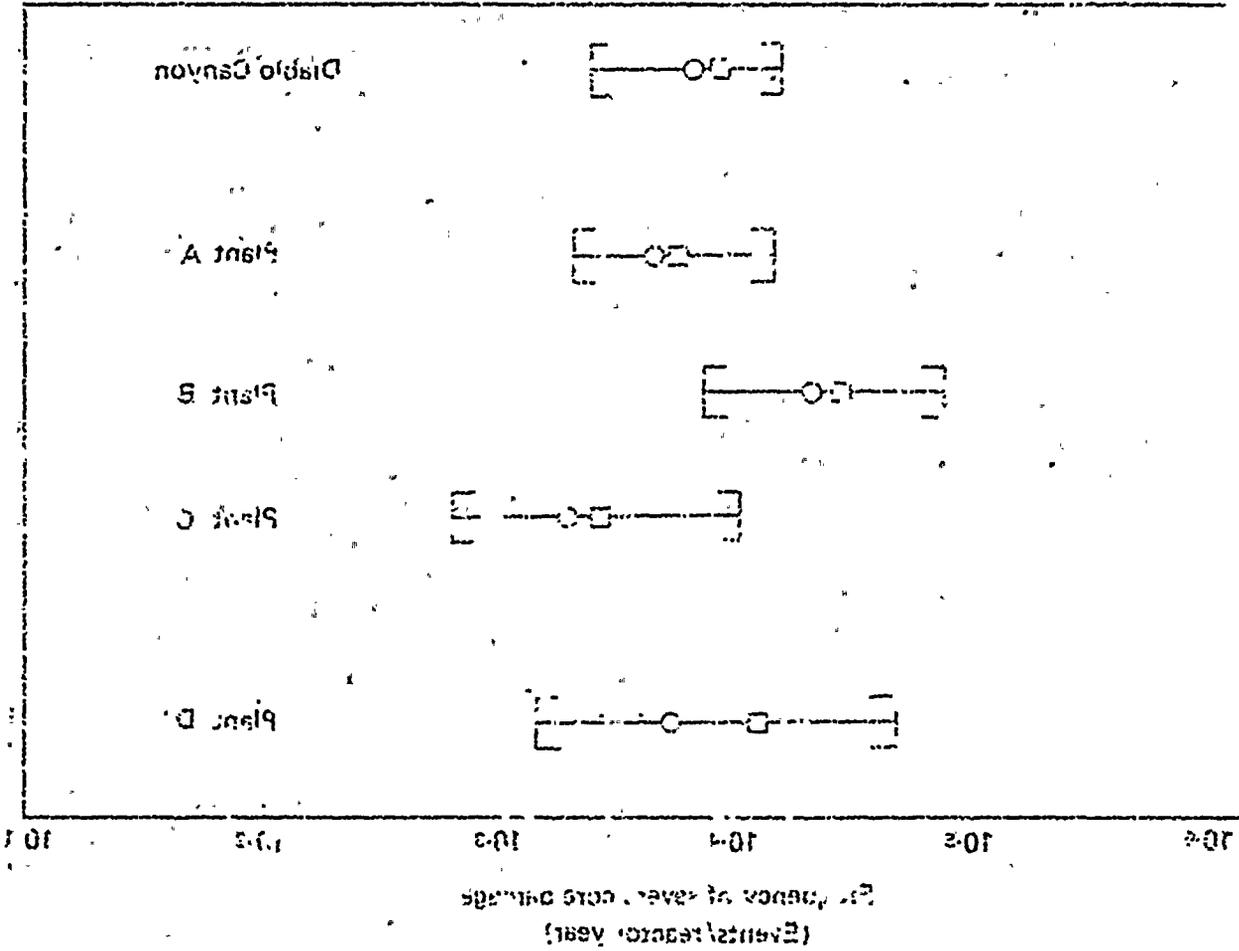
The measure of margin adopted by the Panel is a high-confidence-of-low-probability-of-failure (HCLPF) capacity. This is a conservative representation of capacity and in simple terms corresponds to the earthquake level at which, with considerable confidence, it is extremely unlikely that failure of the component will occur. From the mathematical perspective of a probability distribution on capacity developed in seismic PRA calculations, the HCLPF capacity values are approximately equal to a 95 percent probability of not exceeding about a five percent probability of failure.

There is a margin above the conservative capacity values selected by the Panel. The median capacity, which corresponds to the 50 percent probability of exceedance, is generally at least a factor of 2 greater than the HCLPF capacity. Thus, there is no proverbial "cliff" or sudden failure which is expected to occur immediately beyond the HCLPF capacity. From another perspective, the conservative capacities are close to the

lower-bound cutoff values below which there is no significant likelihood of failure.

In the deterministic evaluations, these very conservative HCLPF₈₄ capacities have been compared to an 84 percent probability of nonexceedance site-specific ground-motion spectrum defined for a maximum magnitude earthquake. This spectrum has an average spectral acceleration in the 3 to 8.5 hertz frequency range of 1.94 g, which may be directly compared with the HCLPF₈₄ capacities listed in Tables 7-1 and 7-2 to define a very conservative deterministic seismic margin. However, it should be noted that the 84 percent probability of nonexceedance site-specific spectrum used in this comparison is also very conservative. The ratio of the 84 to 50 percent spectra is approximately 1.5. Thus, even when the HCLPF₈₄ average spectral acceleration equals the average spectral acceleration for the 84 percent site-specific spectrum (that is, 0 percent margin), the median capacity will still be roughly a factor of 3 (2.0 x 1.5) above the 50 percent site-specific spectrum. Thus, a 0 percent deterministic margin obtained in this manner corresponds to a very remote possibility of failure.

Keeping these thoughts in mind, the 4-kV switchgear relay chatter mode has the lowest HCLPF₈₄ capacity, which is only 1.57 g, or a negative margin of 19 percent when compared to the 84 percent probability of nonexceedance site-specific ground-motion average spectral acceleration of 1.94 g. However, the relay chatter function mode has a median capacity about 2.7 times its HCLPF capacity, or 2.2 times as great as the site-specific ground-motion. Thus, at this earthquake level, relay chatter of the 4-kV switchgear is highly unlikely. Furthermore, the consequences of 4-kV switchgear relay chatter are easily recoverable by operator action, as discussed in Chapter 6. The 4-kV switchgear relay chatter fragility estimate was included in the seismic probabilistic risk assessment, and it was shown to be an insignificant contributor to seismic risk because operators can reset tripped circuits.



EXPLANATION

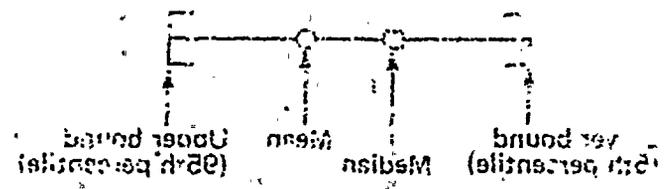
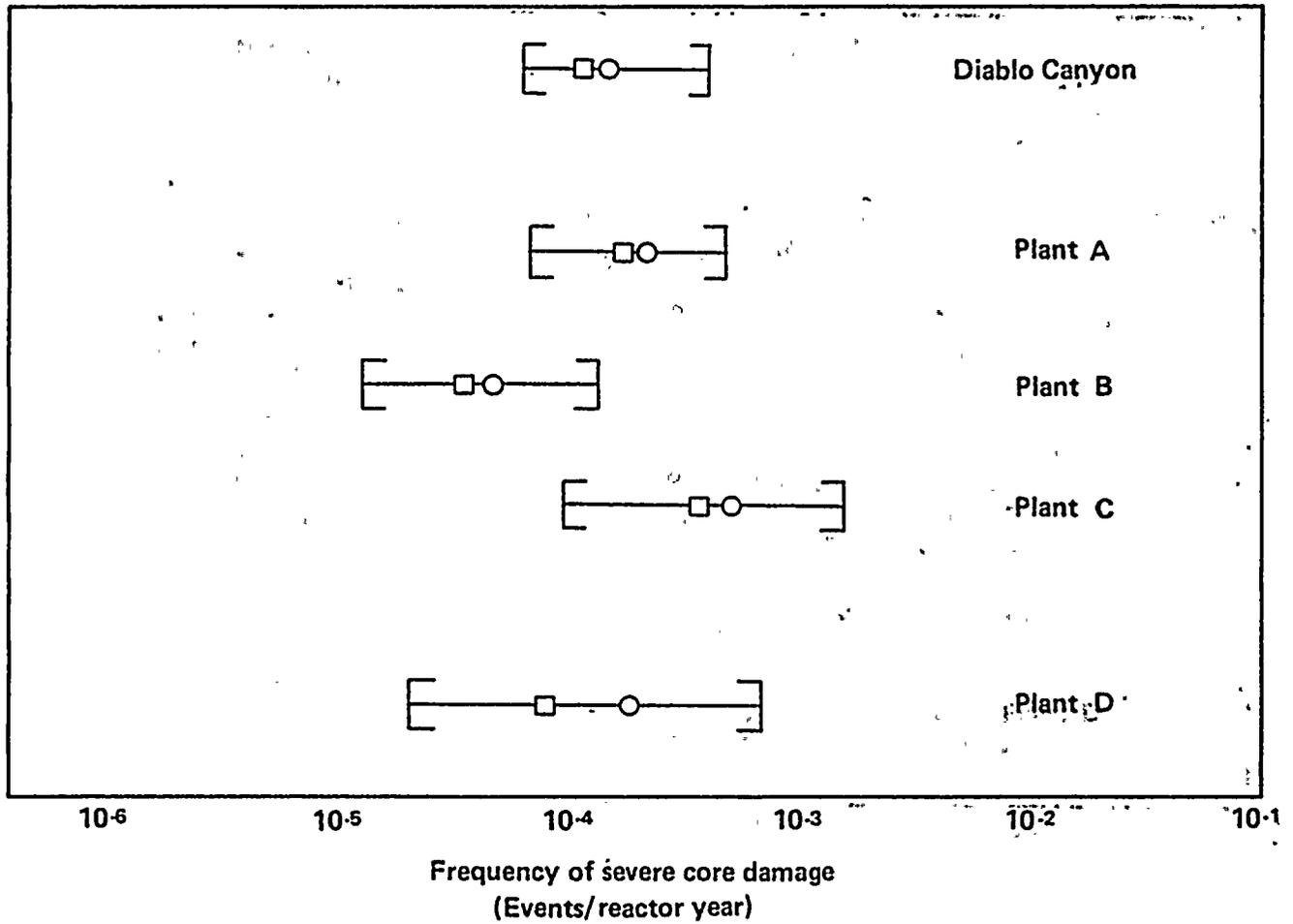


Figure 8-1 Comparison of total core damage for four different plants



EXPLANATION

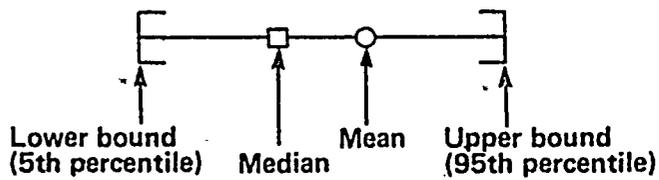


Figure 8-1
Comparison of total seismic risk for Westinghouse nuclear power plants.

controlling, were not restricted but are also likely to have greater than a 40 percent margin.

In summary, defining seismic margin as the difference between the appropriate HCLPF capacity and the 24 percent probability of nonexceedance site-specific ground-motion response spectrum, the seismic margin evaluation leads to the following conclusions:

The seismic margin for the turbine building is at least 14 percent, as identified in Table 1. Evaluations, and most likely in excess of 40 percent, as demonstrated by deterministic evaluations.

Other than the turbine building, all structures and components whose failure could lead to electric risk to the plant have a seismic margin of at least 40 percent.

The HCLPF capacity does not represent a "margin" beyond which failure would occur. Instead, it is close to a lower-bound failure. The median capacity for the turbine building is more than 1.2 times its HCLPF capacity and the probability of failure would only gradually increase if ground motions were to exceed the HCLPF capacity.

CONCLUSION

It is concluded that the Diablo Canyon Power Plant has adequate seismic margins.

REFERENCES

Knobloch, R. L., Westley, D. A., and Tong, W. H., "Probabilistic Evaluation of the Capacity of the Turbine Building Seismic Design," Report No. 1075, June 1982.

Knobloch, R. L., Westley, D. A., and Tong, W. H., "Probabilistic Evaluation of the Capacity of the Turbine Building Seismic Design," Report No. 1075, June 1982.

Knobloch, R. L., Westley, D. A., and Tong, W. H., "Probabilistic Evaluation of the Capacity of the Turbine Building Seismic Design," Report No. 1075, June 1982.

The second lowest HCLPF capacity, 2.21, is for the overall turbine building structure. The HCLPF capacity is a factor of 1.14 greater than the 24 percent probability of nonexceedance site-specific 2 percent damped average spectra variation, so a 14 percent margin exists before the HCLPF capacity is reached. Even if the margin were to reach this level, failure is unlikely because the median capacity is estimated to be a factor of 2.62 greater than the HCLPF capacity.

Diablo Canyon generator control panel has third lowest HCLPF capacity, 1.29, which is a factor of 1.29 greater than the 24 percent probability of nonexceedance site-specific 2 percent damped average spectra variation, so a 29 percent margin exists before the HCLPF capacity is reached. Even if the margin were to reach this level, failure is unlikely because the median capacity is estimated to be a factor of 2.07 greater than the HCLPF capacity.

Other than the turbine building, all structures and components whose failure could lead to electric risk to the plant have a seismic margin of at least 40 percent.

The turbine building dominates the plant seismic margin. The controlling failure mode is the failure of the turbine building structure. The failure of the turbine building structure is the most critical failure mode. The failure of the turbine building structure is the most critical failure mode. The failure of the turbine building structure is the most critical failure mode.

The second lowest HCLPF₈₄ capacity, 2.21 g, is for the overall turbine building structure. The HCLPF₈₄ capacity is a factor of 1.14 greater than the 84 percent probability of nonexceedance site-specific 5 percent damped average spectral acceleration, so a 14 percent margin exists before the HCLPF₈₄ capacity is reached. Even if the demand were to reach this level, failure is unlikely, because the median capacity is estimated to be a factor of 2.65 greater than the HCLPF capacity.

The diesel generator control panel has the third lowest HCLPF₈₄, 2.69 g, which is a factor of 1.39 greater than the 84 percent probability of nonexceedance site-specific 5 percent damped average spectral acceleration. The only other components having HCLPF₈₄ capacities less than 3.0 g are the power-operated relief valves on the primary system (2.78 g) and the 125-volt DC electric power switchgear/breaker panel (2.83 g), both of which exceed the site-specific ground-motion spectral acceleration by a factor greater than 1.43.

Thus, other than for the turbine building, all components whose failure could lead to seismic risk to the Plant have at least a 40 percent margin between the HCLPF₈₄ capacity and the 84 percent probability of nonexceedance site-specific ground motion.

Because the turbine building dominates the Plant seismic margin, the controlling failure mode defined by the fragility evaluation of this building (that is, severe distress of the east/west shear walls) was studied in greater detail by performing a total of 200 nonlinear time-history analyses (Kennedy, 1988) of this building. As discussed in Chapter 7, based on these analyses, the deterministic seismic margin obtained by comparing the resulting deterministic HCLPF capacity with the 84 percent probability of nonexceedance site-specific response spectrum was actually 45 percent for this failure mode. Other failure modes of the turbine building, which were not identified in the fragility evaluation as

controlling, were not restudied but are also likely to have greater than a 40 percent margin.

In summary, defining seismic margin as the difference between the appropriate HCLPF capacity and the 84 percent probability of nonexceedance site-specific ground-motion response spectrum, the seismic margins evaluation leads to the following conclusions:

- The seismic margin for the turbine building is at least 14 percent, as identified by fragility evaluations, and most likely is in excess of 40 percent, as demonstrated by deterministic evaluations.
- Other than the turbine building, all structures and components whose failure could lead to seismic risk to the Plant have a seismic margin of at least 40 percent.
- The HCLPF capacity does not represent a "cliff" beyond which failure immediately lies. Instead, it is close to a lower-bound, below which there is no significant likelihood of failure. The median capacity for the turbine building is more than 2.5 times its HCLPF capacity, and the probability of failure would only gradually increase if ground motions were to exceed the HCLPF capacity.

CONCLUSION

It is concluded that the Diablo Canyon Power Plant has adequate seismic margins.

REFERENCES

- Budnitz, R. J., Amico, P. J., Cornell, C. A., Hall, W. J., Kennedy, R. P., Reed, J. W., and Shinozuka, M., 1985, An approach to quantification of seismic margins in nuclear power plants: NUREG/CR4334, August.
- Kennedy, R. P., Wesley, D. A., and Tong, W. H., 1988, Probabilistic evaluation of the Diablo Canyon turbine building seismic capacity using nonlinear time history analyses: NTS Engineering Report No. 1643.01, June.

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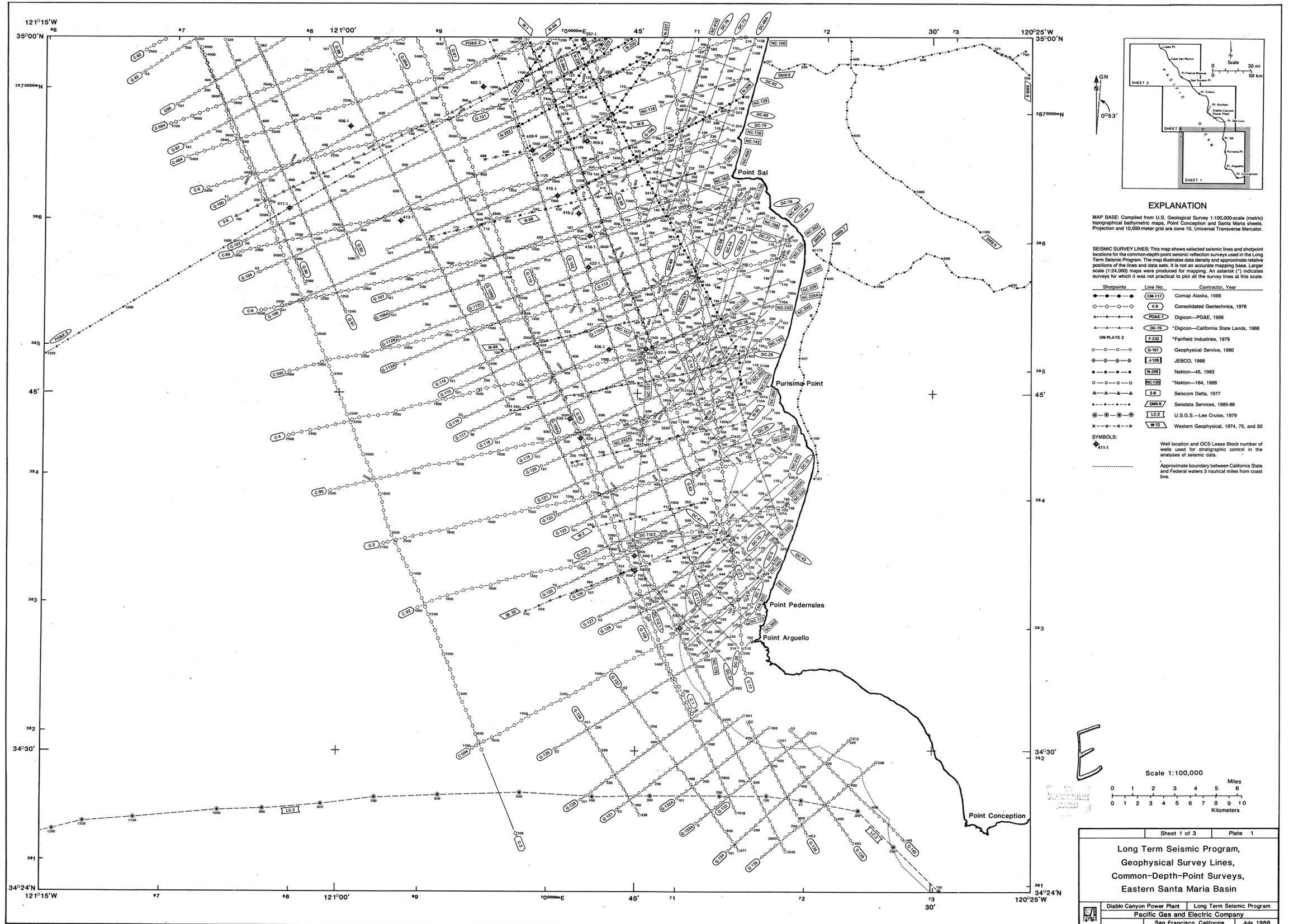
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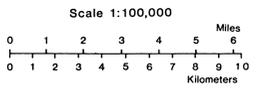
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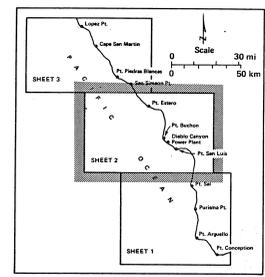
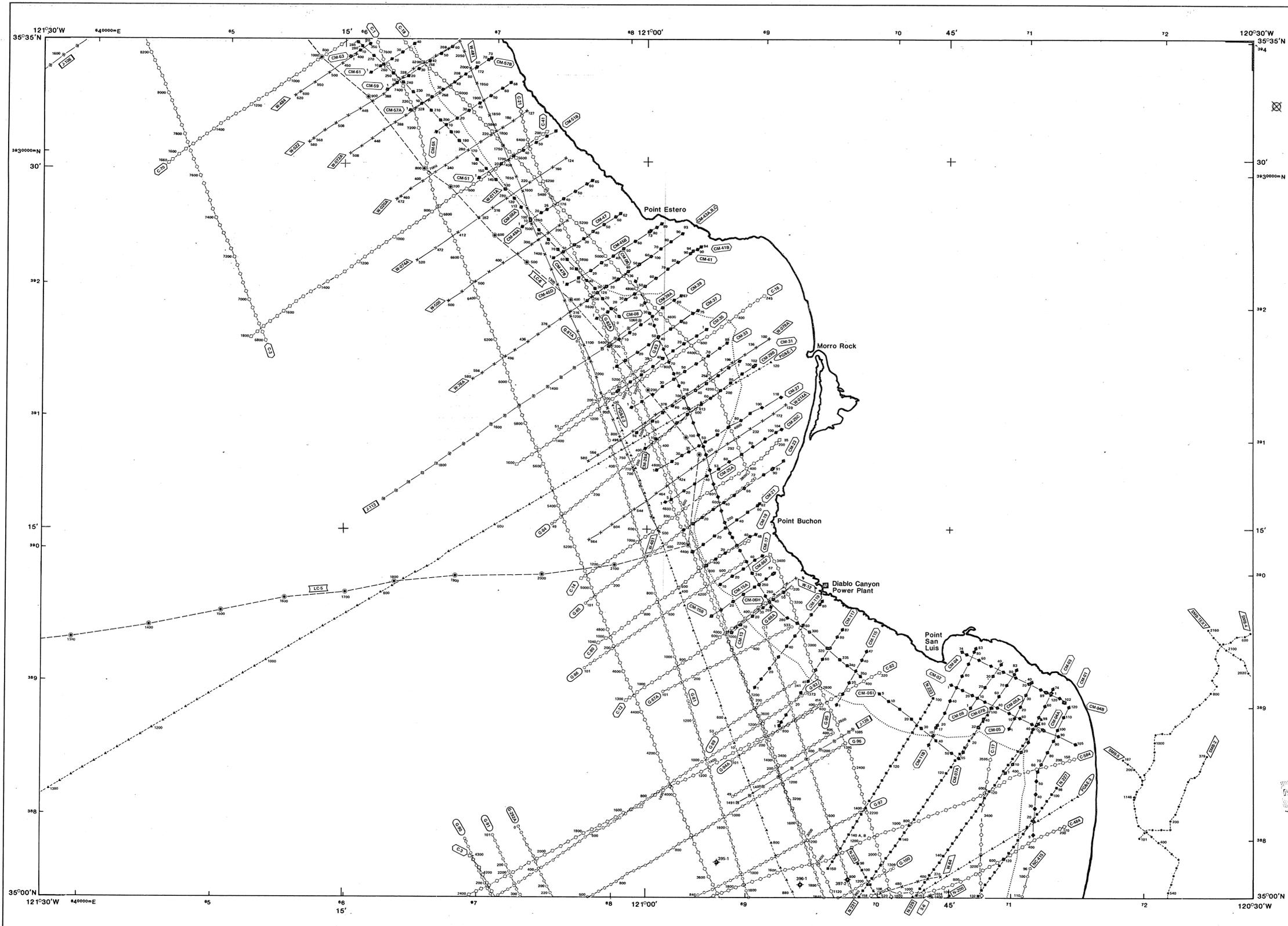


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Sheet 1 of 3	Plate 1
Long Term Seismic Program, Geophysical Survey Lines, Common-Depth-Point Surveys, Eastern Santa Maria Basin	
Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California July 1988	

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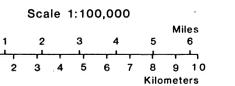
EXPLANATION

MAP BASE: Compiled from U.S. Geological Survey 1:100,000-scale (metric) topographical bathymetric maps, Point Conception and Santa Maria sheets. Projection and 10,000-meter grid are zone 10, Universal Transverse Mercator.

SEISMIC SURVEY LINES: This map shows selected seismic lines and shotpoint locations for the common-depth-point seismic reflection surveys used in the Long Term Seismic Program. The map illustrates data density and approximate relative positions of the lines and data sets. It is not an accurate mapping base. Larger scale (1:24,000) maps were produced for mapping. An asterisk (*) indicates surveys for which it was not practical to plot all the survey lines at this scale.

Shotpoints	Line No.	Contractor, Year
◆—◆—◆—◆	CM-117	Comap Alaska, 1986
○—○—○—○	CS	Consolidated Geotechnics, 1978
▲—▲—▲—▲	PGAE-1	Digicon—PGAE, 1986
△—△—△—△	DC-15	*Digicon—California State Lands, 1986
ON PLATE 2	F-222	*Fairfield Industries, 1979
○—○—○—○	G-101	Geophysical Service, 1980
◆—◆—◆—◆	J-128	JEBCO, 1988
■—■—■—■	N-209	Nekton—45, 1983
□—□—□—□	NC-139	*Nekton—164, 1986
▲—▲—▲—▲	S-4	Seiscom Delta, 1977
◆—◆—◆—◆	SM-6	Seisdata Services, 1985-86
○—○—○—○	LC-2	U.S.G.S.—Lee Cruise, 1979
x—x—x—x	W-12	Western Geophysical, 1974, 75, and 82

SYMBOLS:
 ◆11-1 Well location and OCS Lease Block number of wells used for stratigraphic control in the analyses of seismic data.
 Approximate boundary between California State and Federal waters 3 nautical miles from coast line.

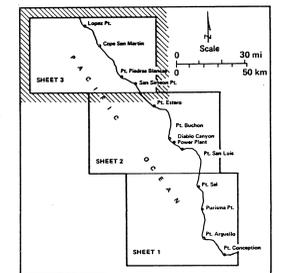
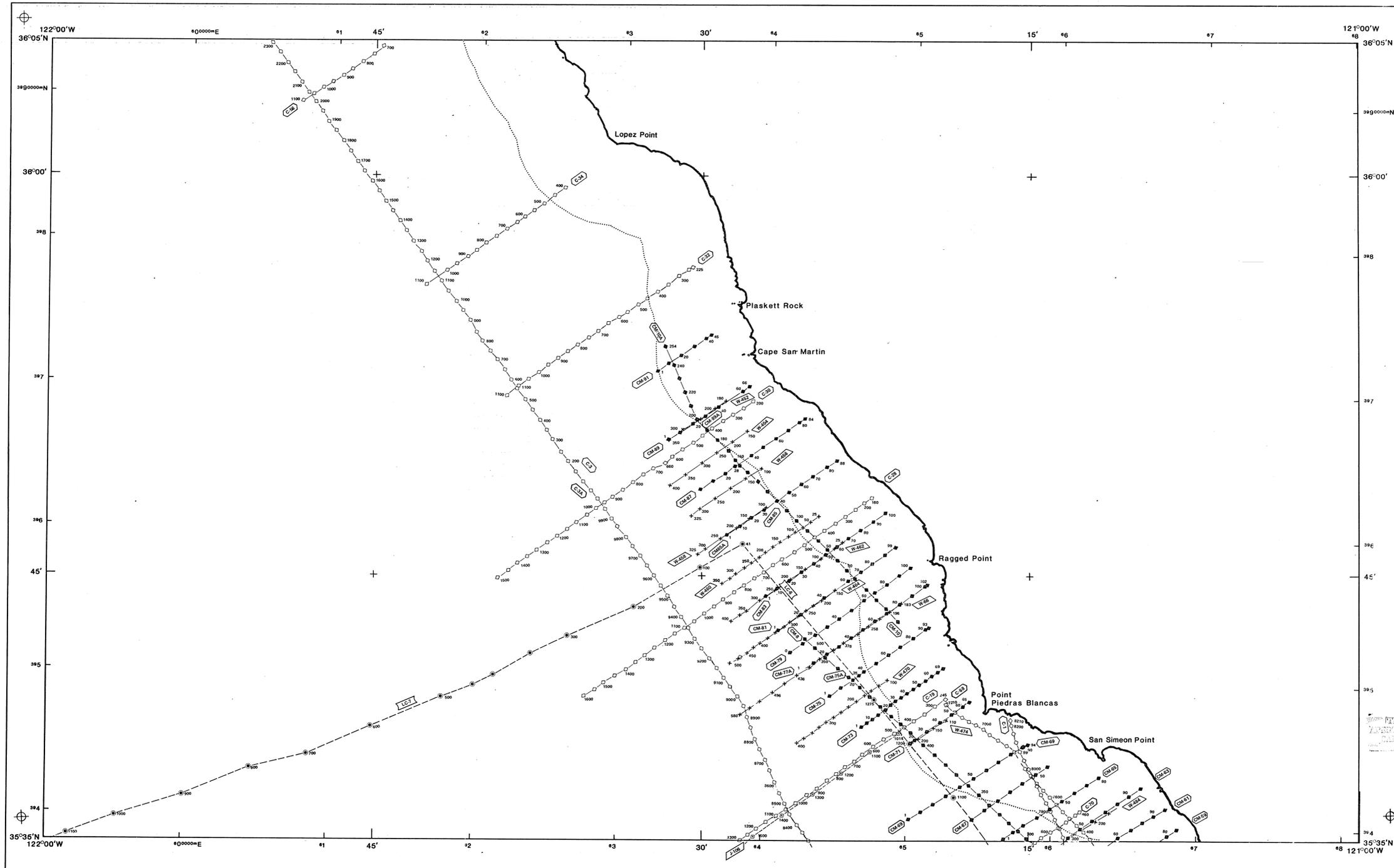


Sheet 2 of 3 Plate 1

**Long Term Seismic Program,
 Geophysical Survey Lines,
 Common-Depth-Point Surveys,
 Eastern Santa Maria Basin**

Diablo Canyon Power Plant Long Term Seismic Program
 Pacific Gas and Electric Company
 San Francisco, California July 1988

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EXPLANATION

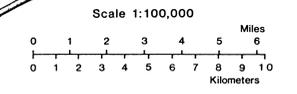
MAP BASE: Compiled from U.S. Geological Survey 1:100,000-scale (metric) topographical bathymetric maps, Point Conception and Santa Maria sheets. Projection and 10,000-meter grid are zone 10, Universal Transverse Mercator.

SEISMIC SURVEY LINES: This map shows selected seismic lines and shotpoint locations for the common-depth-point seismic reflection surveys used in the Long Term Seismic Program. The map illustrates data density and approximate relative positions of the lines and data sets. It is not an accurate mapping base. Larger scale (1:24,000) maps were produced for mapping. An asterisk (*) indicates surveys for which it was not practical to plot all the survey lines at this scale.

Shotpoints	Line No.	Contractor, Year
◆	CM-117	Comap Alaska, 1986
◇	C-5	Consolidated Geotechnics, 1978
▲	PGME-1	Digicon-PG&E, 1986
△	DC-19	*Digicon-California State Lands, 1986
○	F-332	*Fairfield Industries, 1979
○	G-101	Geophysical Service, 1980
○	J-126	JEBCO, 1988
■	N-208	Nekton-45, 1983
□	WC-130	*Nekton-164, 1986
▲	S-8	Seiscom Delta, 1977
◆	SMB-6	Seisdata Services, 1985-86
⊙	LC2	U.S.G.S.-Lee Cruise, 1979
×	W-12	Western Geophysical, 1974, 75, and 82

SYMBOLS:
 ◆ 411-1 Well location and OCS Lease Block number of wells used for stratigraphic control in the analysis of seismic data.
 Approximate boundary between California State and Federal waters 3 nautical miles from coast line.

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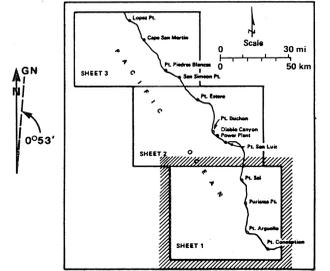
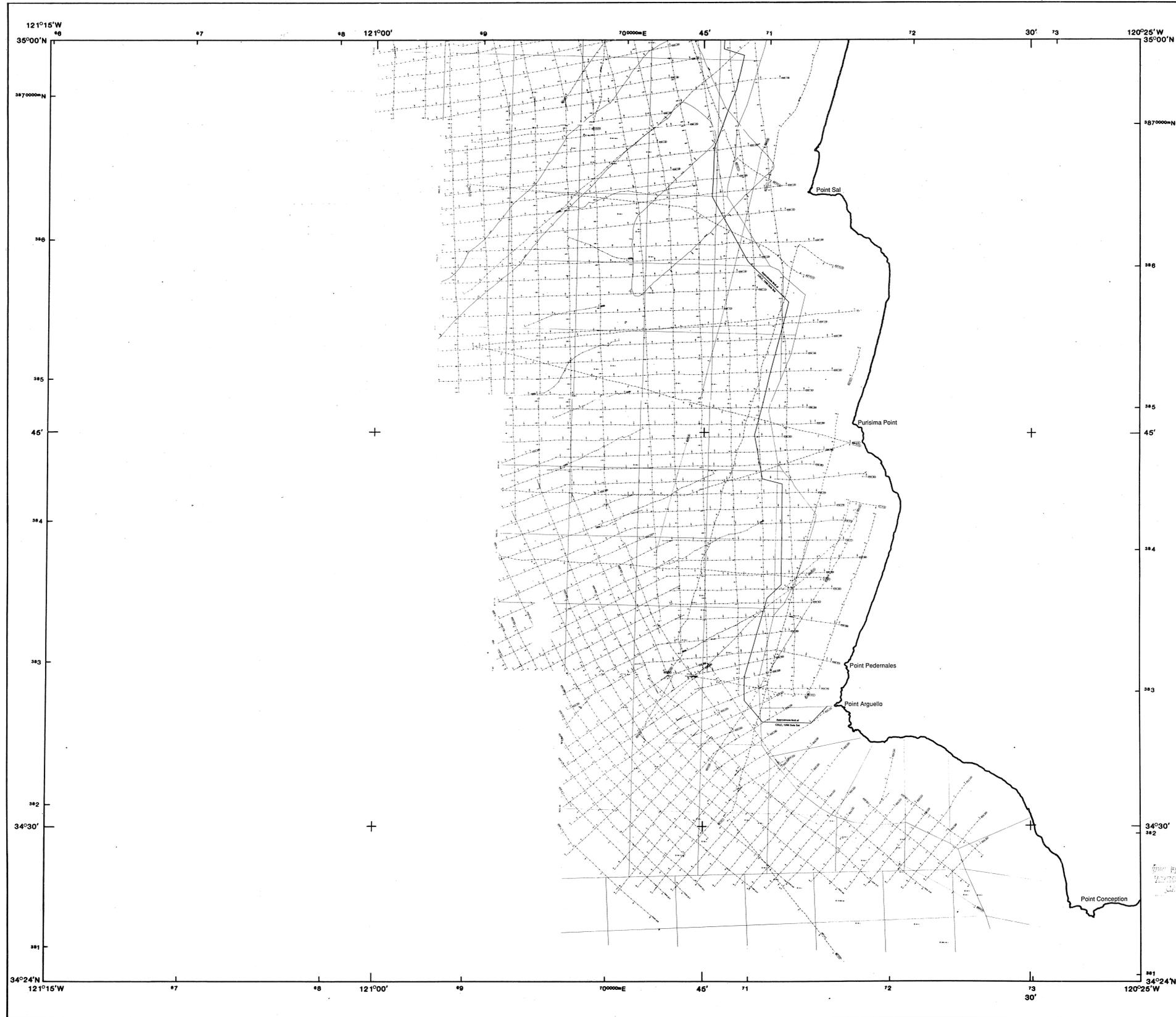


Sheet 3 of 3 Plate 1

**Long Term Seismic Program,
 Geophysical Survey Lines,
 Common-Depth-Point Surveys,
 Eastern Santa Maria Basin**

Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California July 1988	

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EXPLANATION

MAP BASE: Compiled from U.S. Geological Survey 1:100,000 (main) topographical bathymetric maps, Point Conception and Santa Maria sheets. Projection and 10,000-meter grid are zone 10, Universal Transverse Mercator. Dotted line represents approximate boundary between California State and Federal waters.

DATA BASE: This map shows data sets used in the development of the high resolution interpretation (0.5 sec two-way travel time) (Plate 1). Common-depth-point data were used for reference during interpretation. The shottracks from the common-depth-point surveys are shown on Plate 1. Table 2-3 provides additional information regarding individual surveys.

SURVEY LINES AND SHOTPOINT LOCATIONS SHOWN ON MAP:

- AQUATRONICS, 1974
- BOB, BERANAK AND NEWMAN, 1973
- COMPAG ALASKA, 1966
- FAIRFIELD INDUSTRIES, 1979
- FUGO, 1976
- KATZ, 1973
- LEW, 1975
- SCAMMON, 1980

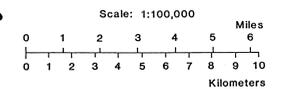
SURVEY OUTLINES SHOWN ON MAP:

- Nelson-California State Lands (CSL), 1966
- Standard Oil Company of California (SOC), 1973
- U.S. Coast and Geodetic Survey (U.S.C.G.S.), 1934

SURVEYS NOT SHOWN (POSITIONING UNCERTAIN):

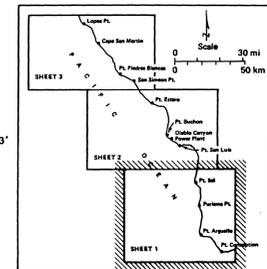
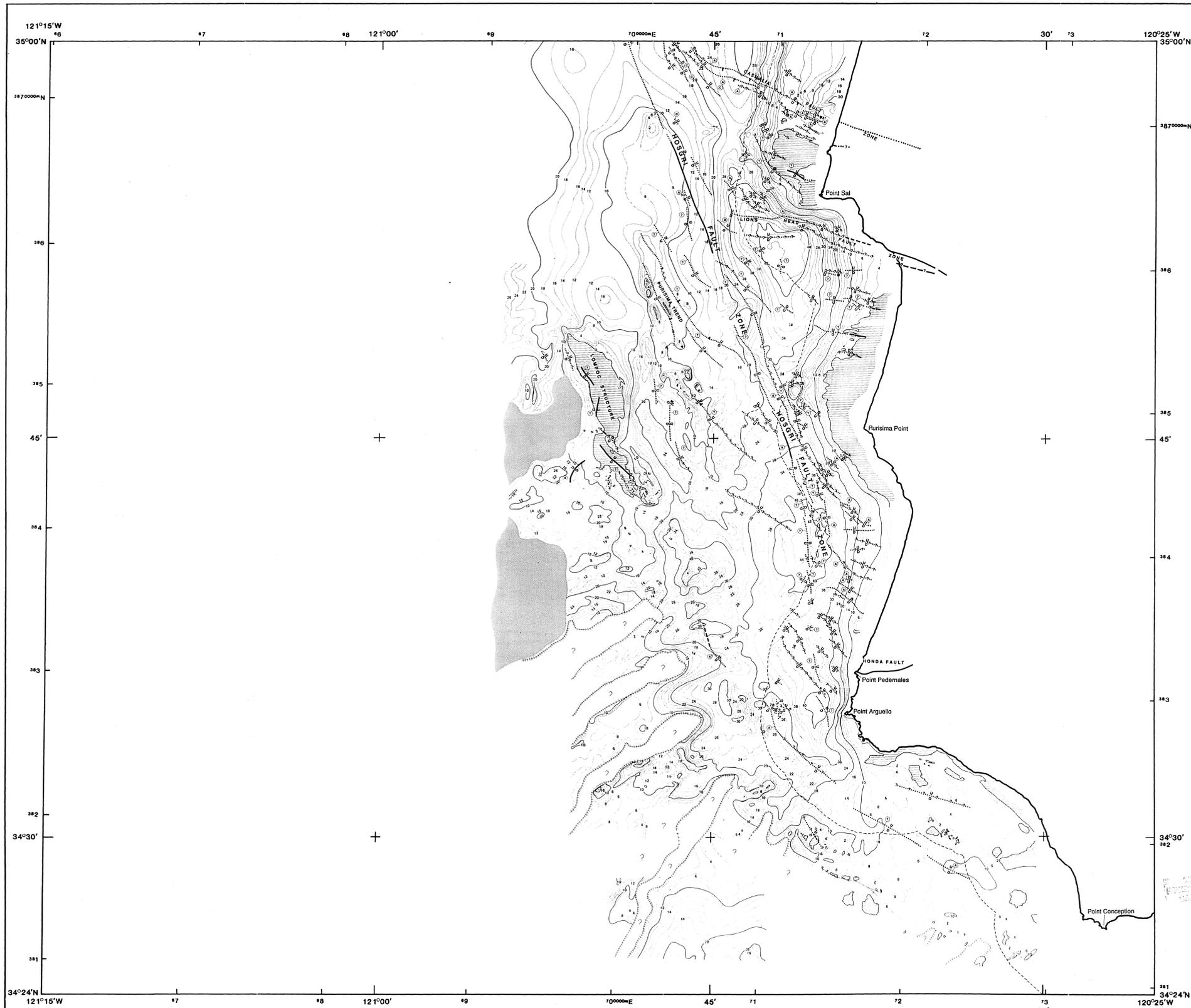
- Bartlett, 1972
- Polars, 1972

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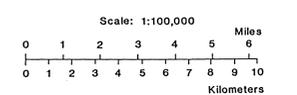
Sheet 1 of 3	Plate 2
Long Term Seismic Program, Geophysical Survey Lines, High-Resolution Surveys, Eastern Santa Maria Basin	
Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California July 1988	

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EXPLANATION

- Geologic Structures**
- - - Fault at seafloor, dashed where location inferred; arrows or U/D indicate relative sense of displacement where known; bar indicates dip of fault plane, where known.
 - - - Structural feature that could be a fault at the seafloor.
 - - - Limits of discrete sublinear zone of structural complexity within which individual faults cannot be distinguished.
 - - - Fault buried beneath post-late Wisconsinan sediment, dashed where location inferred.
 - - - Structural feature that could be a fault buried beneath post-late Wisconsinan sediment.
- Estimated Age of Most Recent Displacement**
- ⊙ Evidence of displacement during or since late Wisconsinan (18,000 years ago).
 - ⊗ Displaces 120,000-year-old marine oxygen isotope stage 5 terrace; post-late Wisconsinan beds not recognized.
 - ⊕ Pliocene horizon is cut; late Wisconsinan unconformity is present but not cut.
 - ⊙ Top Miocene horizon is cut; Pliocene horizon is present but not cut.
 - ⊙ Unknown; age control is lacking.
- Isopach Information**
- - - Contours showing thickness in meters of post-late Wisconsinan sediment; dashed where location uncertain.
 - ⊗ Area where late Wisconsinan unconformity is poorly imaged on high-resolution geophysical data.
 - ⊙ Area of seafloor outcrop.
 - ⊙ Area of probable gas-charged sediment that prevents determination of post-late Wisconsinan sediment thickness.
- Geomorphic Features**
- - - Seafloor scarp; rectangles indicate down-slope direction.
 - - - Headwall of submarine slump; paired lines indicate down-slope direction.
 - - - Margin of submarine canyon.
 - - - Axis of submarine canyon where canyon margins are poorly defined; arrows point down channel.
- Notes**
- 1) This map illustrates the trends, continuity and relationship to post-late Wisconsinan sediments of near-surface faults and structural features that could be faults.
 - 2) Selected onshore structures are shown in the coastal zone to identify potential correlation with offshore structures.
 - 3) All structure symbols extend 100 meters beyond the last geophysical or geological control point. Continuity of structures is inferred wherever data points are separated by more than 1.5 kilometers. No continuity is inferred if data points are more than 5 kilometers apart.
 - 4) Map base is compiled from U.S. Geological Survey 1:100,000-scale (metric) topographical bathymetric maps, Point Conception and Santa Maria sheets, Projection and 10,000-meter grid are Universal Transverse Mercator, zone 10. Fine dashed line paralleling coast represents approximate boundary between California State and Federal waters.

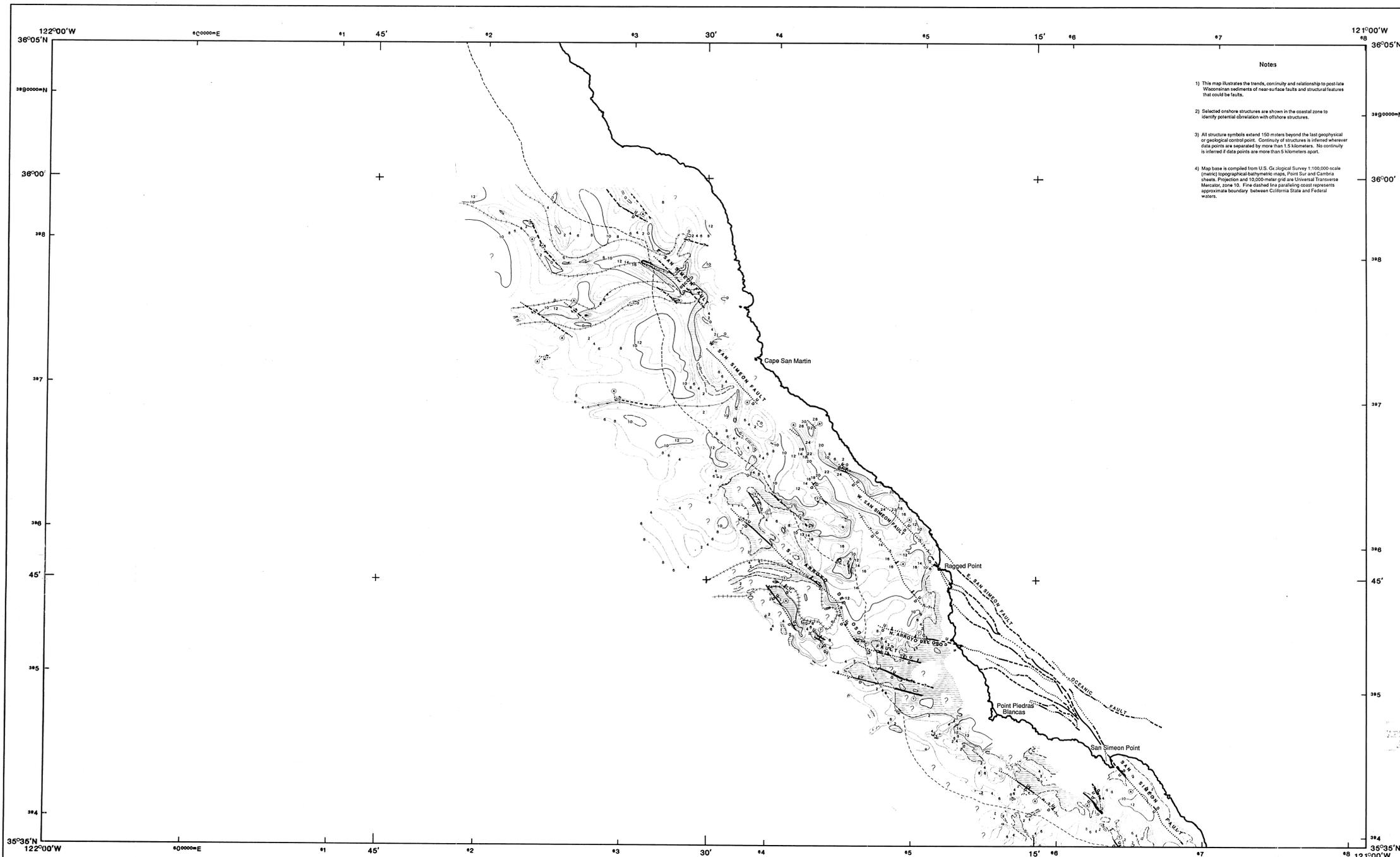


Sheet 1 of 3 Plate 4

Near-surface Faults, Thickness of Post-late Wisconsinan Sediments and Seafloor Geomorphic Features of the Eastern Offshore Santa Maria Basin, California

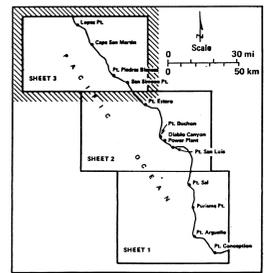
Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California July 1988	

8808050336-08



Notes

- 1) This map illustrates the trends, continuity and relationship to post-late Wisconsinan sediments of near-surface faults and structural features that could be faults.
- 2) Selected onshore structures are shown in the coastal zone to identify potential correlation with offshore structures.
- 3) All structure symbols extend 100 meters beyond the last geophysical or geological control point. Continuity of structures is inferred wherever data points are separated by more than 1.5 kilometers. No continuity is inferred if data points are more than 5 kilometers apart.
- 4) Map base is compiled from U.S. Geological Survey 1:100,000-scale (metric) topographical bathymetric maps, Point Sur and Cambria sheets. Projection and 10,000-meter grid are Universal Transverse Mercator, zone 10. Fine dashed line paralleling coast represents approximate boundary between California State and Federal waters.

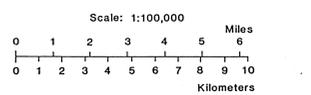


EXPLANATION

- Geologic Structures**
- Fault at seafloor, dashed where location inferred; arrows or U/D indicate relative sense of displacement where known; bar indicates dip of fault plane, where known.
 - Structural feature that could be a fault at the seafloor.
 - Limits of discrete sublinear zone of structural complexity within which individual faults cannot be distinguished.
 - Fault buried beneath post-late Wisconsinan sediment, dashed where location inferred.
 - Structural feature that could be a fault buried beneath post-late Wisconsinan sediment.
- Estimated Age of Most Recent Displacement**
- Evidence of displacement during or since late Wisconsinan (18,000 years ago).
 - Displaces 120,000-year-old marine oxygen isotope stage 5 terrace; post-late Wisconsinan beds not recognized.
 - Plio-Pleistocene horizon is cut; late Wisconsinan unconformity is present but not cut.
 - Top Miocene horizon is cut; Plio-Pleistocene horizon is present but not cut.
 - Unknown; age control is lacking.
- Isopach Information**
- Contours showing thickness in meters of post-late Wisconsinan sediment; dashed where location uncertain.
 - Area where late Wisconsinan unconformity is poorly imaged on high-resolution geophysical data.
 - Area of seafloor outcrop.
 - Area of probable gas-charged sediment that prevents determination of post-late Wisconsinan sediment thickness.
- Geomorphologic Features**
- Seafloor scarp; rectangles indicate down-slope direction.
 - Headwall of submarine slump; paired lines indicate down-slope direction.
 - Margin of submarine canyon.
 - Axis of submarine canyon where canyon margins are poorly defined; arrows point down channel.

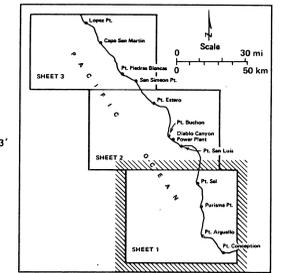
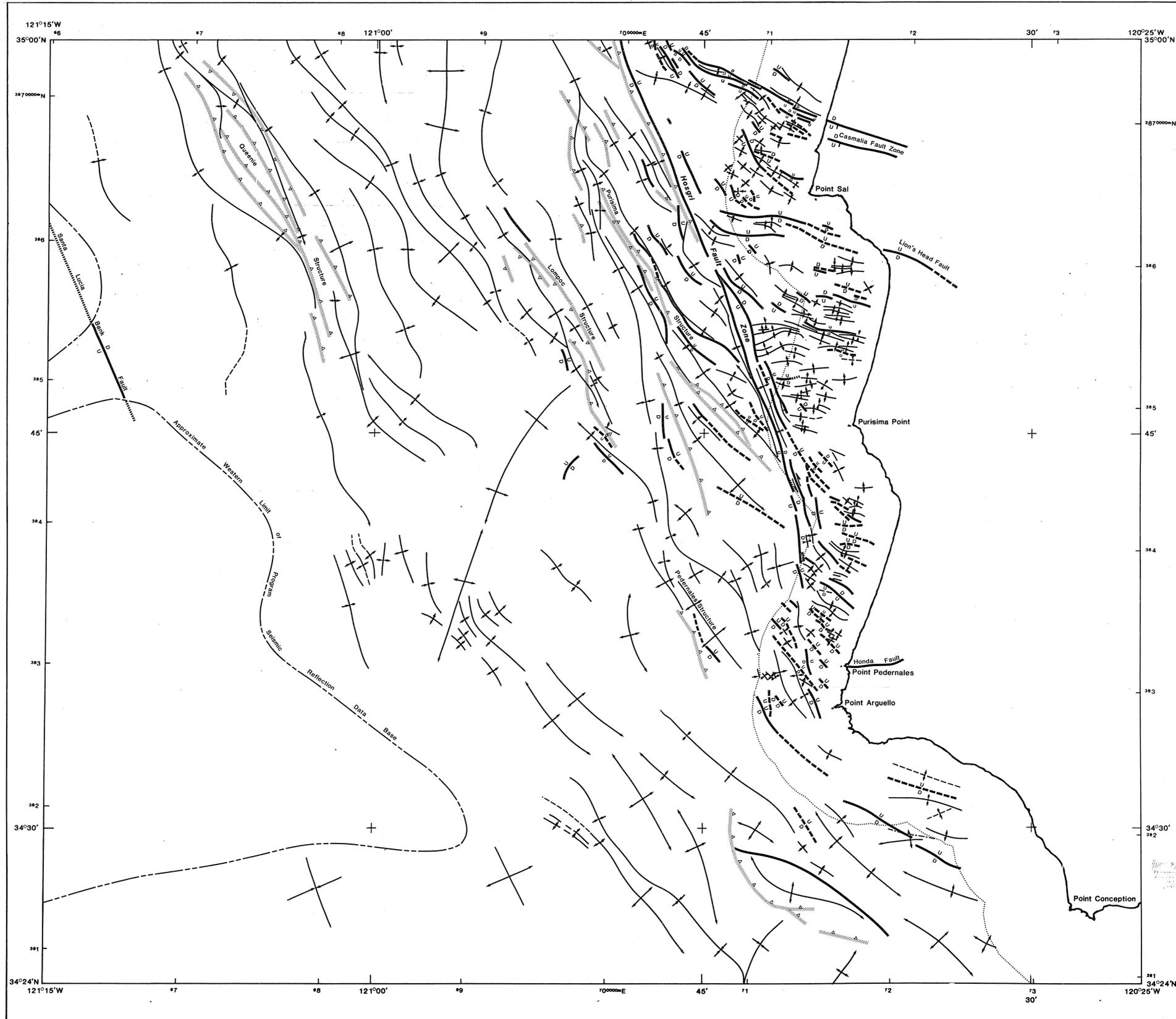
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TEMPERATURE CARD



Sheet 3 of 3		Plate 4
Near-surface Faults, Thickness of Post-late Wisconsinan Sediments and Seafloor Geomorphologic Features of the Eastern Offshore Santa Maria Basin, California		
Diablo Canyon Power Plant	Long Term Seismic Program	
Pacific Gas and Electric Company		
San Francisco, California		July 1988

8808050336-10



EXPLANATION

MAP BASE: Compiled from U.S. Geological Survey 1:100,000-scale (metric) topographical bathymetric maps, Point Conception and Santa Maria sheets. Projection and 10,000-meter grid are zone 10, Universal Transverse Mercator.

DATA BASE: This map was taken from the interpretation of common-depth-point and high-resolution seismic reflection records. The shiptracks from the common-depth-point surveys are shown on the corresponding sheets of Plate 1. The shiptracks from the high-resolution surveys are shown on the sheets of Plate 2.

STRUCTURAL TREND MAP: This map is intended to illustrate the locations, trends, continuity, and plan-view spatial relationships of geologic structures within the sedimentary rocks of the offshore Santa Maria Basin. It does not contain information about the depth of the structures nor the age of deformation.

Fault: U/D (up/down) and arrows indicate relative sense of displacement, where known. Bar indicates dip of fault plane, where known.

Inferred Fault: Structural feature observed on geophysical records that is inferred to be a fault based on continuity with known faults or other information. The location of the feature is well established, but the exact nature or sense of displacement are not well defined by the data.

Inferred Low-Angle Fault: An inferred buried or blind low-angle fault. The mapped trace represents the vertical projection of the fault tip. Continuity of traces has been inferred where apparent sudden changes in dip angle along strike prevent direct correlations of fault planes.

Fault, Approximate Location: The location or continuity of the fault is inferred. It was not observed on the geophysical records.

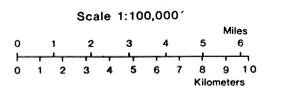
Anticline Axis: The arrow on the axis indicates direction of the plunge. Length of cross arrows indicates relative breadth of the structure. Dashes indicate inferred extension of the axis.

Syncline Axis: The arrow on the axis indicates direction of plunge. Length of cross arrows indicates relative breadth of the structure. Dashes indicate inferred extension of the axis.

Approximate boundary between California State and Federal waters 3 nautical miles from coast line.

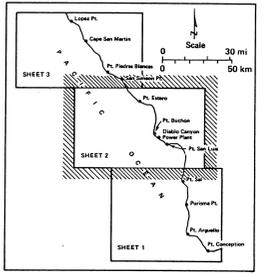
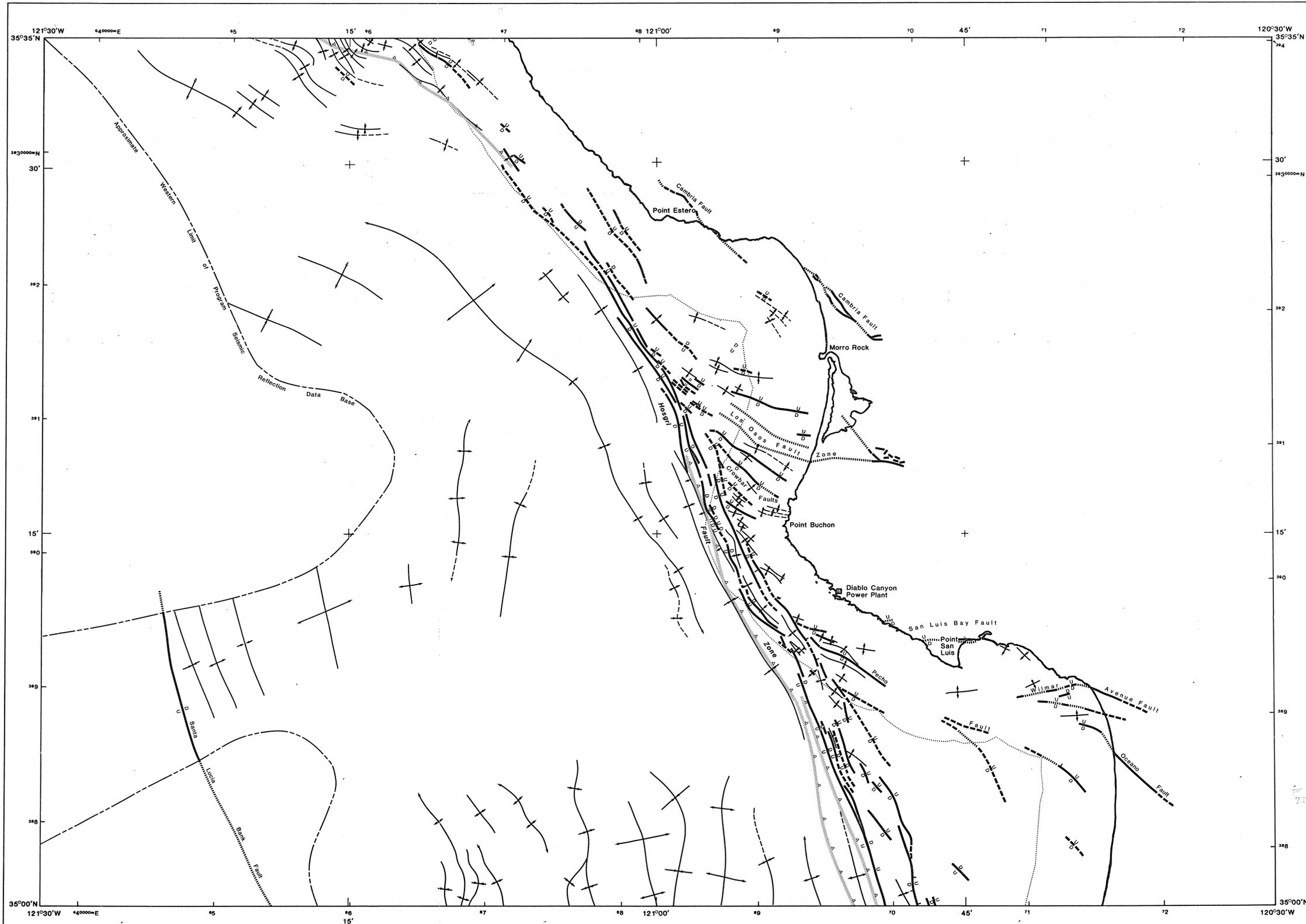
Approximate western limit of Long Term Seismic Program offshore seismic reflection data base.

E



Sheet 1 of 3	Plate 5
Structural Trend Map, Offshore Santa Maria Basin, Southern Area	
Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California July 1988	

8808050336-11



EXPLANATION

MAP BASE: Compiled from U.S. Geological Survey 1:100,000-scale (metric) topographic bathymetric maps, Point Conception and Santa Maria sheets. Projection and 10,000-meter grid are zone 10, Universal Transverse Mercator.

DATA BASE: This map was taken from the interpretation of common-depth-point and high-resolution seismic reflection records. The shiptracks from the common-depth-point surveys are shown on the corresponding sheets of Plate 1. The shiptracks from the high-resolution surveys are shown on the sheets of Plate 2.

STRUCTURAL TREND MAP: This map is intended to illustrate the locations, trends, continuity, and plan-view spatial relationships of geologic structures within the sedimentary rocks of the offshore Santa Maria Basin. It does not contain information about the depth of the structures nor the age of deformation.

Fault: U/D (up/down) and arrows indicate relative sense of displacement, where known. Bar indicates dip of fault plane, where known.

Inferred Fault: Structural feature observed on geophysical records that is inferred to be a fault based on continuity with known faults or other information. The location of the feature is well established, but the exact nature or sense of displacement are not well defined by the data.

Inferred Low-Angle Fault: An inferred buried or blind low-angle fault. The mapped trace represents the vertical projection of the fault tip. Continuity of traces has been inferred where apparent sudden changes in dip angle along strike prevent direct correlations of fault planes.

Fault, Approximate Location: The location or continuity of the fault is inferred. It was not observed on the geophysical records.

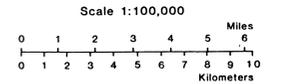
Anticline Axis: The arrow on the axis indicates direction of plunge. Length of cross arrows indicates relative breadth of the structure. Dashes indicate inferred extension of the axis.

Syncline Axis: The arrow on the axis indicates direction of plunge. Length of cross arrows indicates relative breadth of the structure. Dashes indicate inferred extension of the axis.

Approximate boundary between California State and Federal waters 3 nautical miles from coast line.

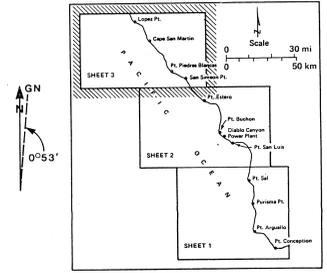
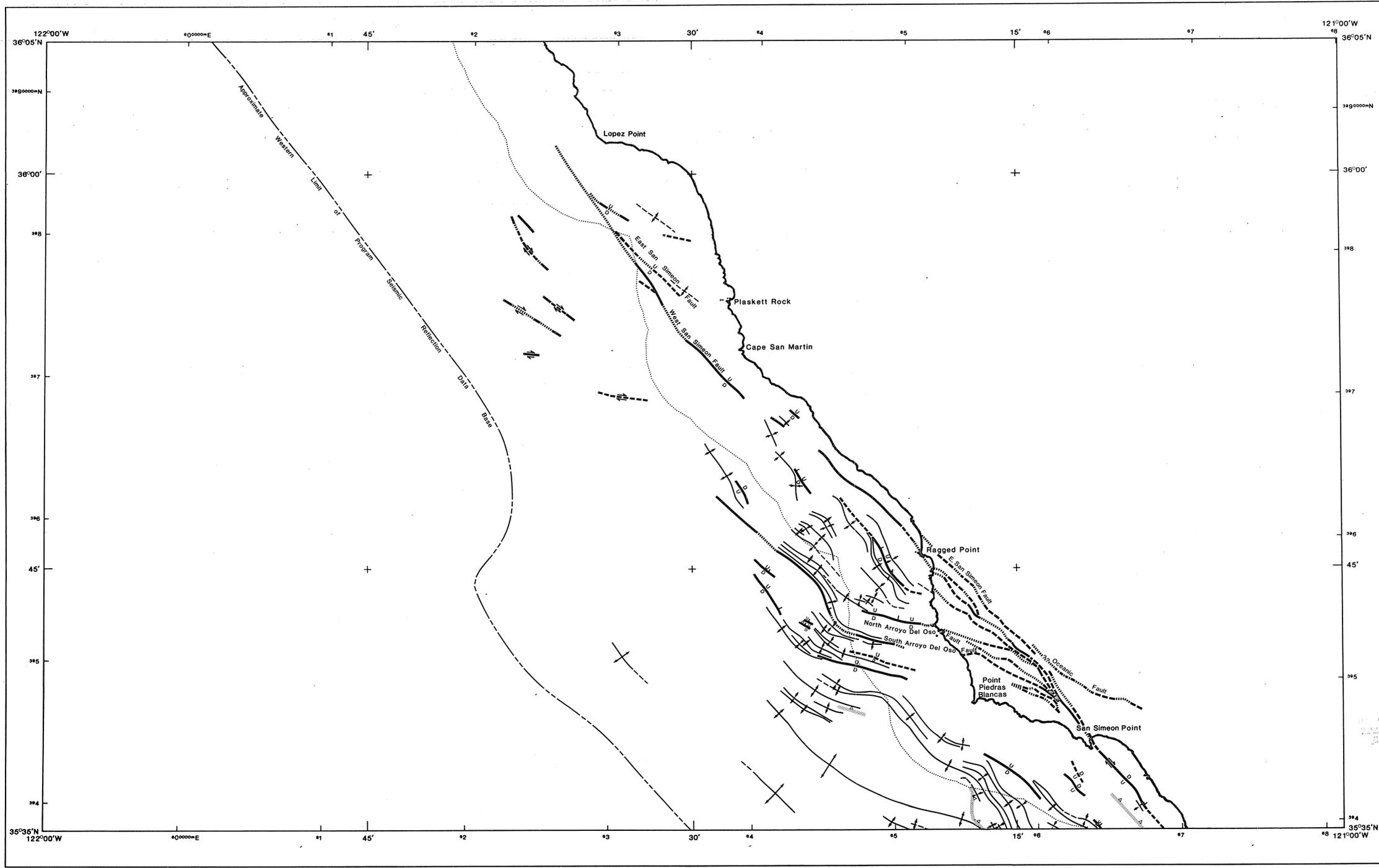
Approximate western limit of Long Term Seismic Program offshore seismic reflection data base.

E



Sheet 2 of 3		Plate 5
Structural Trend Map, Offshore Santa Maria Basin, Central Area		
Diablo Canyon Power Plant	Long Term Seismic Program	
Pacific Gas and Electric Company		
San Francisco, California		July 1988

8808050336-12



EXPLANATION

MAP BASE: Compiled from U.S. Geological Survey 1:100,000-scale (metric) topographical bathymetric maps, Point Conception and Santa Maria sheets. Projection and 10,000-meter grid are zone 10, Universal Transverse Mercator.

DATA BASE: This map was taken from the interpretation of common-depth-point and high-resolution seismic reflection records. The shiptracks from the common-depth-point surveys are shown on the corresponding sheets of Plate 1. The shiptracks from the high-resolution surveys are shown on the sheets of Plate 2.

STRUCTURAL TREND MAP: This map is intended to illustrate the locations, trends, continuity, and plan-view spatial relationships of geologic structures within the sedimentary rocks of the offshore Santa Maria Basin. It does not contain information about the depth of the structures nor the age of deformation.

Fault: U/D (up/down) and arrows indicate relative sense of displacement, where known. Bar indicates dip of fault plane, where known.

Inferred Fault: Structural feature observed on geophysical records that is inferred to be a fault based on continuity with known faults or other information. The location of the feature is well established, but the exact nature or sense of displacement are not well defined by the data.

Inferred Low-Angle Fault: An inferred buried or blind low-angle fault. The mapped trace represents the vertical projection of the fault tip. Continuity of traces has been inferred where apparent sudden changes in dip angle along strike prevent direct correlations of fault planes.

Fault, Approximate Location: The location or continuity of the fault is inferred. It was not observed on the geophysical records.

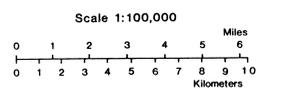
Anticline Axis: The arrow on the axis indicates direction of the plunge. Length of cross arrows indicates relative breadth of the structure. Dashes indicate inferred extension of the axis.

Syncline Axis: The arrow on the axis indicates direction of plunge. Length of cross arrows indicates relative breadth of the structure. Dashes indicate inferred extension of the axis.

Approximate boundary between California State and Federal waters 3 nautical miles from coast line.

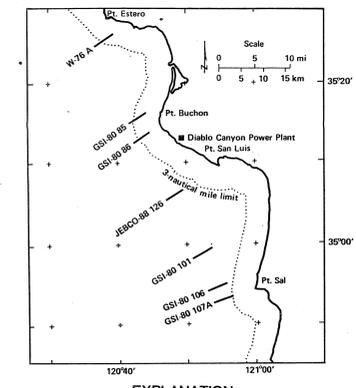
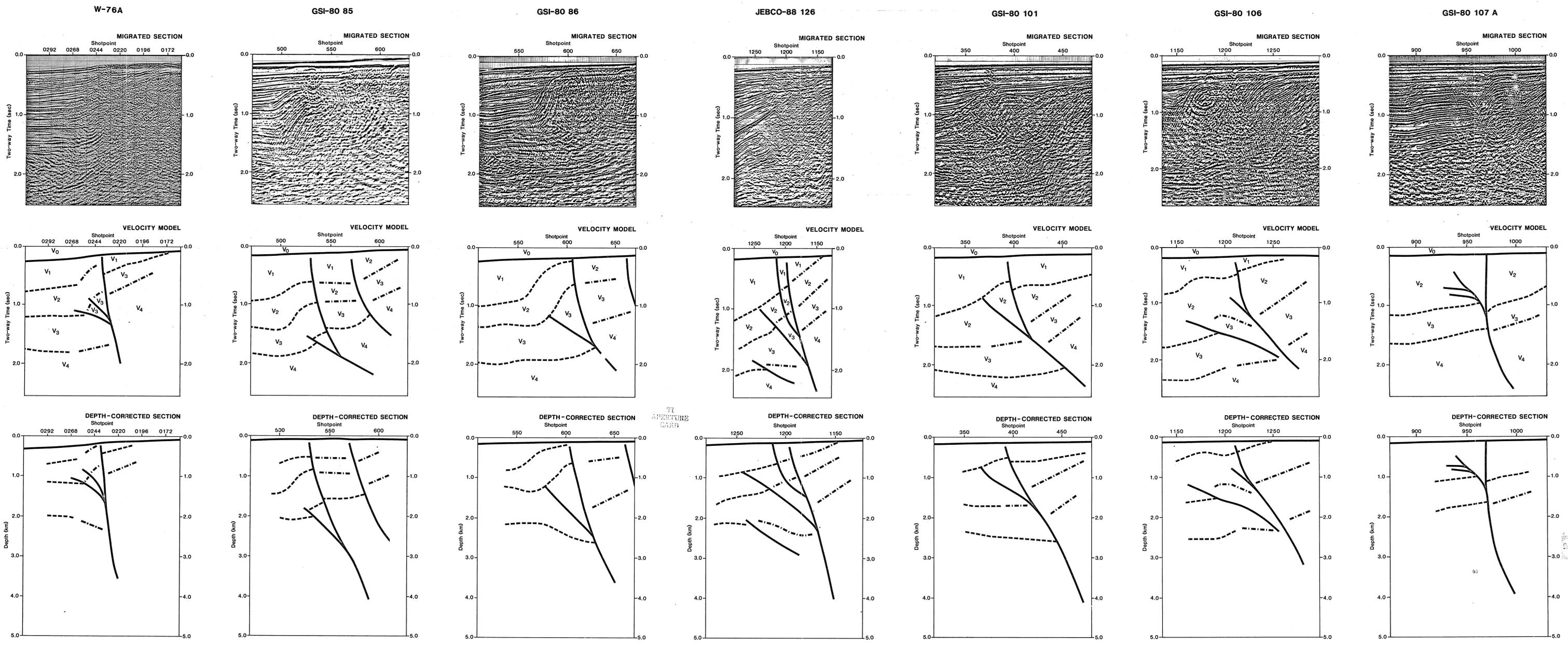
Approximate western limit of Long Term Seismic Program offshore seismic reflection data base.

E



Sheet 3 of 3		Plate 5
Structural Trend Map, Offshore Santa Maria Basin, Northern Area		
Diablo Canyon Power Plant	Long Term Seismic Program	
Pacific Gas and Electric Company		
San Francisco, California		July 1988

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EXPLANATION

MIGRATED SECTIONS: These are reproductions of migrated common-depth-point seismic records across the Hosgri fault zone. The locations of the seismic lines are shown on the index map above and with the shotpoints on Plate 1. The horizontal scale is the same on all records except for JEBCO line 126, which was produced at a different trace density.

VELOCITY MODELS: The velocity models are based on the analysis of data collected by Digicon Geophysical Corporation during PG&E's deep crustal seismic reflection studies. A 4.5-kilometer source-receiver spread was used during data acquisition, thus allowing for a more accurate velocity determination than possible from other available common-depth-point surveys. Velocity model values were further evaluated using well data, published models, and the processing velocities determined by Seisdata Services Incorporated during the 1987 reprocessing of the GSI-80 data set.

V₀ = 1,500 meters per second (sea water velocity)
V₁ = 1,770 meters per second (approximately correlative with Pliocene and younger rock units)
V₂ = 2,230 meters per second (approximately correlative with late Miocene rock units)
V₃ = 2,910 meters per second (approximately correlative with Miocene and older rocks exclusive of Franciscan basement)
V₄ = 4,500 meters per second (correlative with Franciscan assemblage rocks)

DEPTH-CORRECTED SECTIONS: These sections were derived by converting the two-way travel times in the velocity models to depths using the velocities above. They are illustrated at a vertical/horizontal ratio of 1:1.

— Cross-sectional trace of fault planes within the Hosgri fault zone
- - - - - Velocity interface: location closely approximates uniformity or formation boundary
- - - - - Velocity interface: location established on regional stratigraphic considerations, position may not coincide with local geologic boundaries

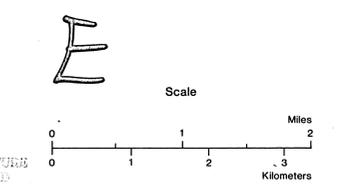


Plate 6

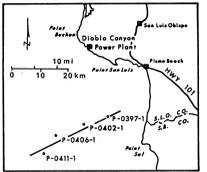
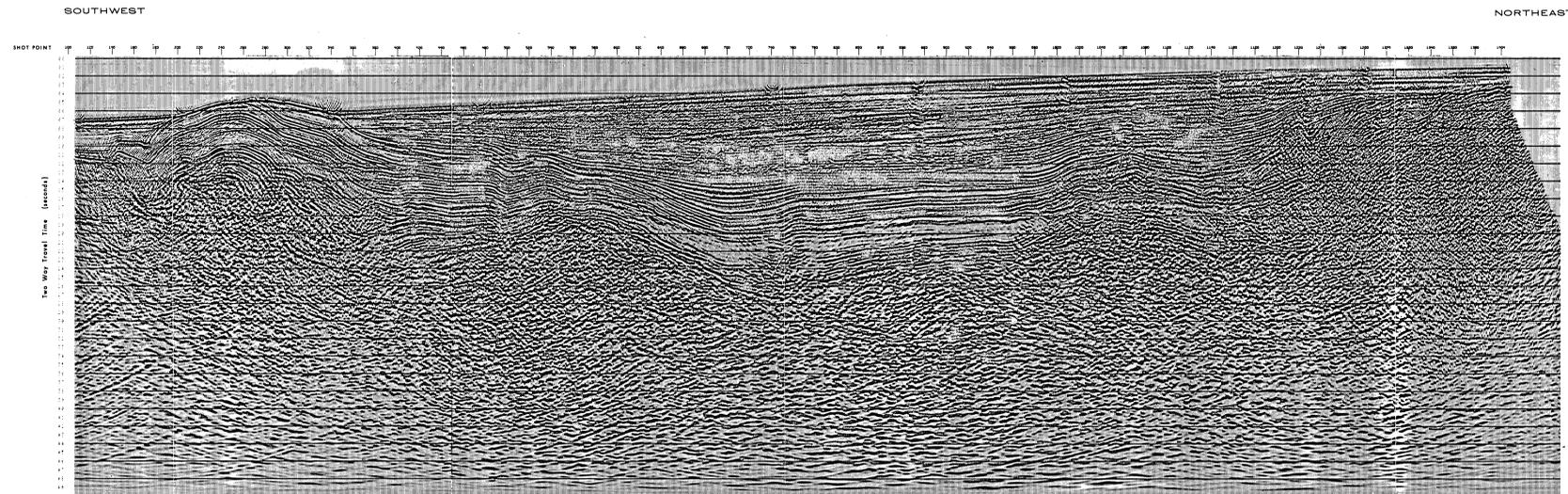
Depth-Converted Velocity Models Across the Hosgri Fault Zone, Point Estero to Point Sal

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Pacific Gas and Electric Company
San Francisco, California | July 1988

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Seiscom Delta-1977 Seismic Line 6
Wave Equation Migration



EXPLANATION

GEOLOGIC INTERPRETATION: The geologic interpretation is based on correlation between the seismic reflection network and petroleum exploration wells shown on Plate 1. Wells in the vicinity of this line are shown on the index map above and on the section.

SEISMIC REFLECTION DATA:
 Data Collected By: Seiscom Delta in 1977
 Energy Source: Air guns
 Line Length: 33 kilometers
 Record Length: 5 seconds
 Sample Rate: 4 milliseconds
 Common-Depth-Point Stack: 4.800%
 Processing: Wave equation migration

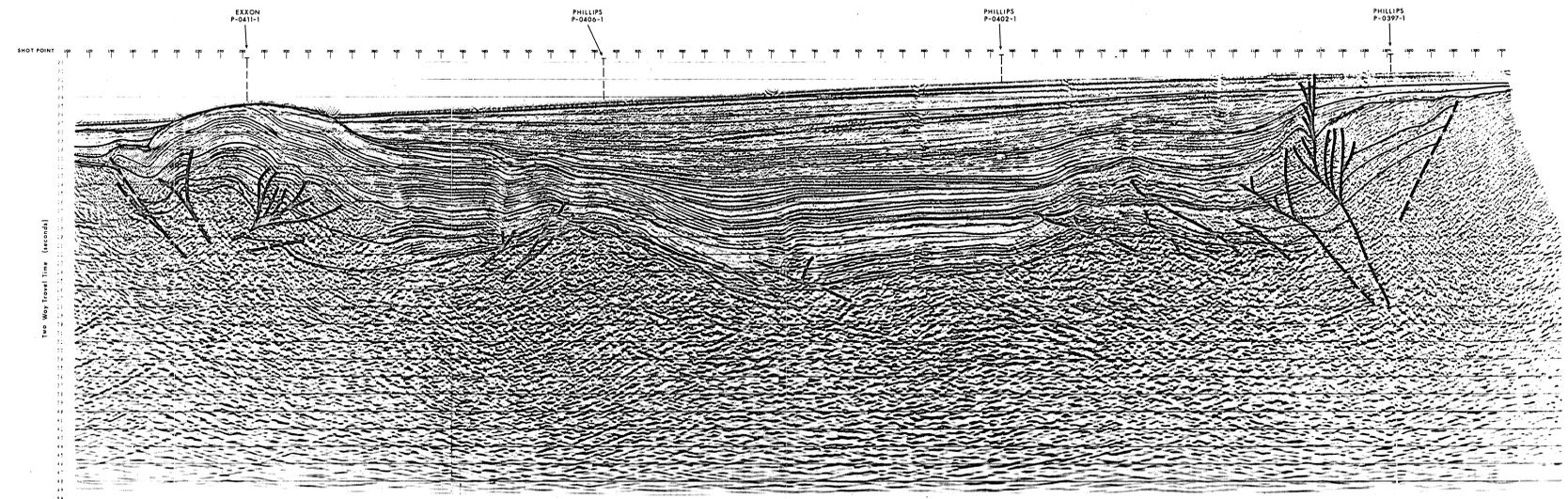
WELL INFORMATION:
 Phillips OCS P-0397-1, drilled in 1983
 Total depth 1,116 meters, water depth 97 meters
 Phillips OCS P-0402-1, drilled in 1983
 Total depth 2,648 meters, water depth 198 meters
 Projected 650 meters southeast into line of section
 Phillips OCS P-0406-1, drilled in 1984
 Total depth 1,754 meters, water depth 413 meters
 Projected 2,215 meters southeast into line of section
 Exxon OCS P-0411-1, drilled in 1982
 Total depth 1,615 meters, water depth 365 meters
 Projected 1,500 meters northwest into line of section

AGE INFORMATION:

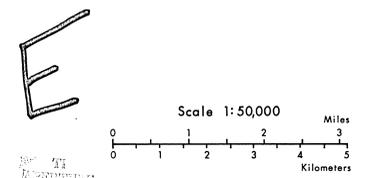
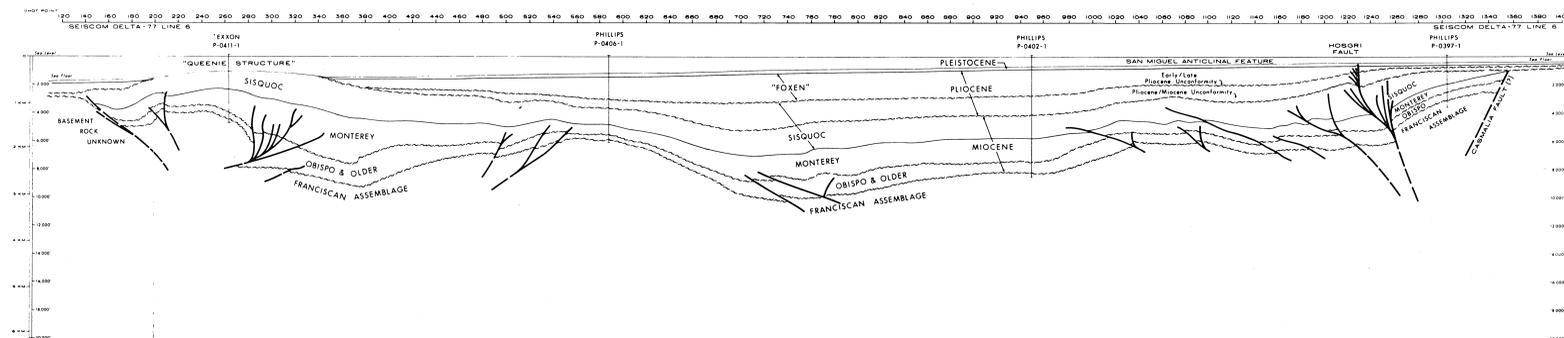
Horizon Name	Geologic Age	Million Years
Base "Foxen" Unconformity	Early/Late Pliocene	2.8-3.0
Sisquoc Unconformity	Miocene/Pliocene	5.2
Top of Monterey Formation	Late Miocene	6.5-7.0
Top of Obispo Formation	Early Miocene	16.0-17.5
Top Franciscan Assemblage	Cretaceous and Jurassic	110-140

- SYMBOLS:**
- Contact
 - - - Unconformity
 - Fault
 - - - Fault, location inferred
 - ⊙ Shot point location

Seiscom Delta-1977 Seismic Line 6
Geologic Horizons Annotated



Geologic Cross Section along SD-77 Line 6
Horizontal and Vertical Scale 1:50,000
1cm=500m (1"=4166.66')

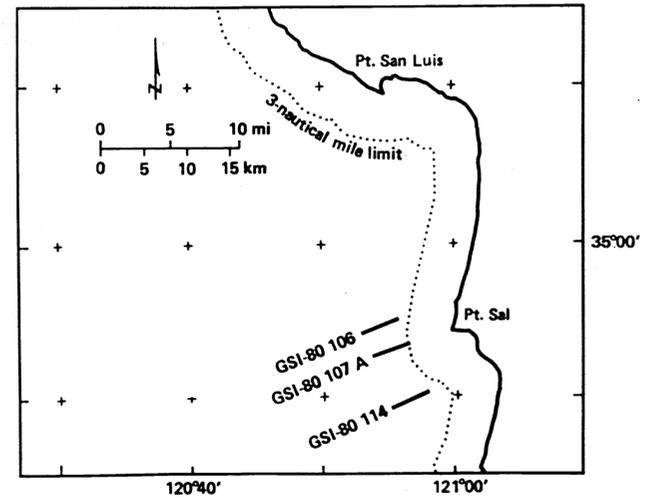
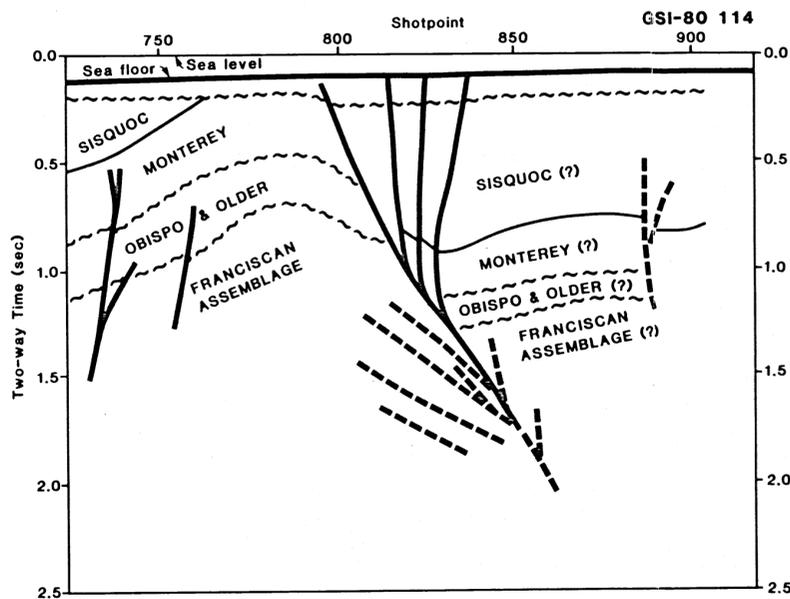
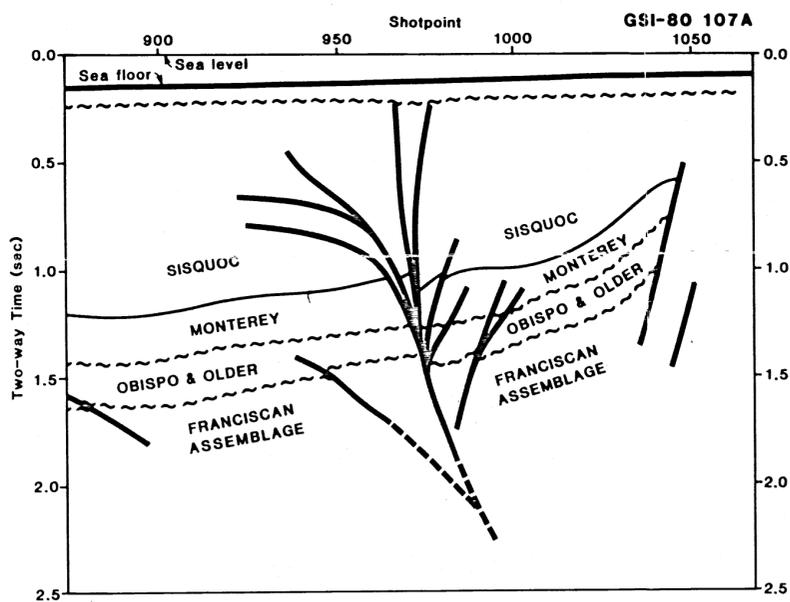
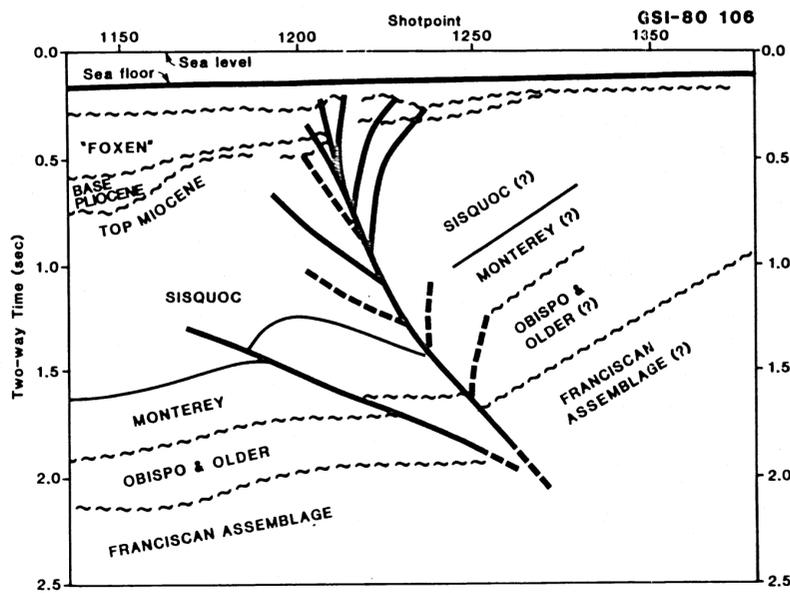


Sheet 2 of 3 Plate 7

Geologic Interpretation of Seismic Sections,
Central Santa Maria Basin,
Seiscom Delta 1977,
Line 6

Diablo Canyon Power Plant Long Term Seismic Program
Pacific Gas and Electric Company
San Francisco, California July 1988

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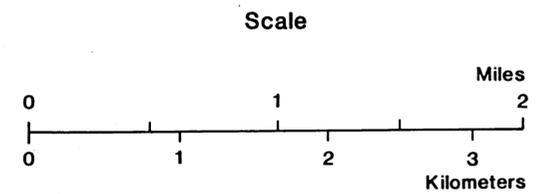
EXPLANATION

GEOLOGICAL INTERPRETATIONS: The identification and mapping of geologic units and unconformities are based on ties between the seismic line network and the petroleum exploration wells shown on Plate 1. Migrated sections and velocity models for lines GSI-80 106 and 107 A are in Plate 6. Age data for the formations and horizons are in Sheet 1, Plate 7.

- Cross-sectional trace of fault planes within the Hosgri fault zone
- Minor splay fault
- Cross-sectional fault trace with inferred or approximately located upward or downward extension
- Formation boundary
- ~~~~~ Unconformity

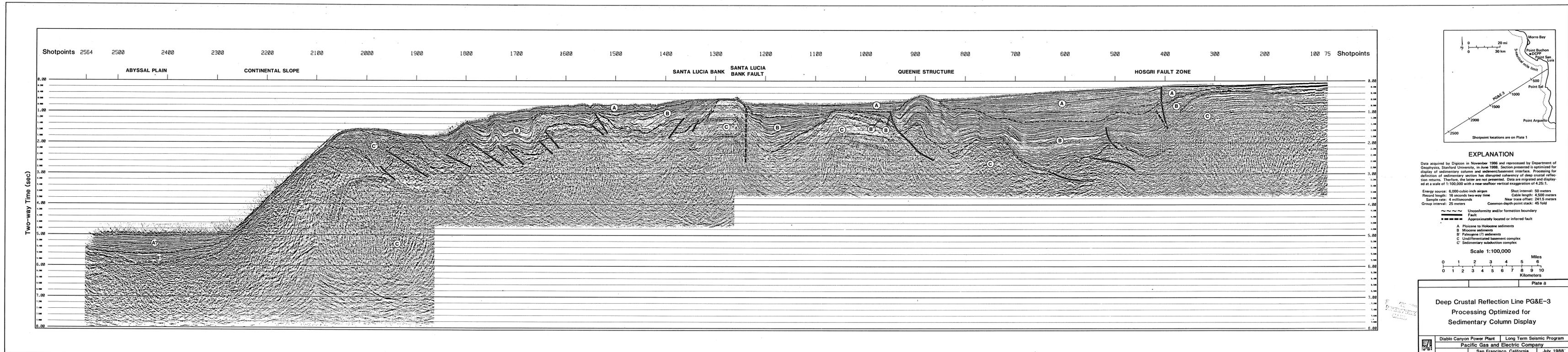
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APERTURE
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Sheet 3 of 3		Plate 7	
Geologic Interpretation of Seismic Sections Illustrating Changes in Basement Offset Across Hosgri Fault Zone, Offshore Point Sal / Lion's Head Area			
Diablo Canyon Power Plant		Long Term Seismic Program	
Pacific Gas and Electric Company			
San Francisco, California		July 1988	

8808050336-17



EXPLANATION

Data acquired by Dipson in November 1986 and reprocessed by Department of Geophysics, Stanford University, in June 1988. Section presented is optimized for display of sedimentary columns and sediment/basement interface. Processing for definition of sedimentary section has disrupted coherency of deep crustal reflection returns. Therefore, the latter are not presented. Data are migrated and displayed at a scale of 1:100,000 with a near-seafloor vertical exaggeration of 4.25:1.

Energy source: 6,000 cubic inch airgun Shot interval: 50 meters
 Record length: 16 seconds two-way time Cable length: 4,500 meters
 Sample rate: 4 milliseconds Near trace offset: 241.5 meters
 Group interval: 25 meters Common-depth point stack: 45 fold

Unconsolidated boundary
 Fault
 Approximately located or inferred fault

A. Pliocene to Holocene sediments
 B. Miocene sediments
 C. Paleogene (?) sediments
 Undifferentiated basement complex
 Sedimentary subduction complex

Scale 1:100,000

0 1 2 3 4 5 6 Miles
 0 1 2 3 4 5 6 7 8 9 10 Kilometers

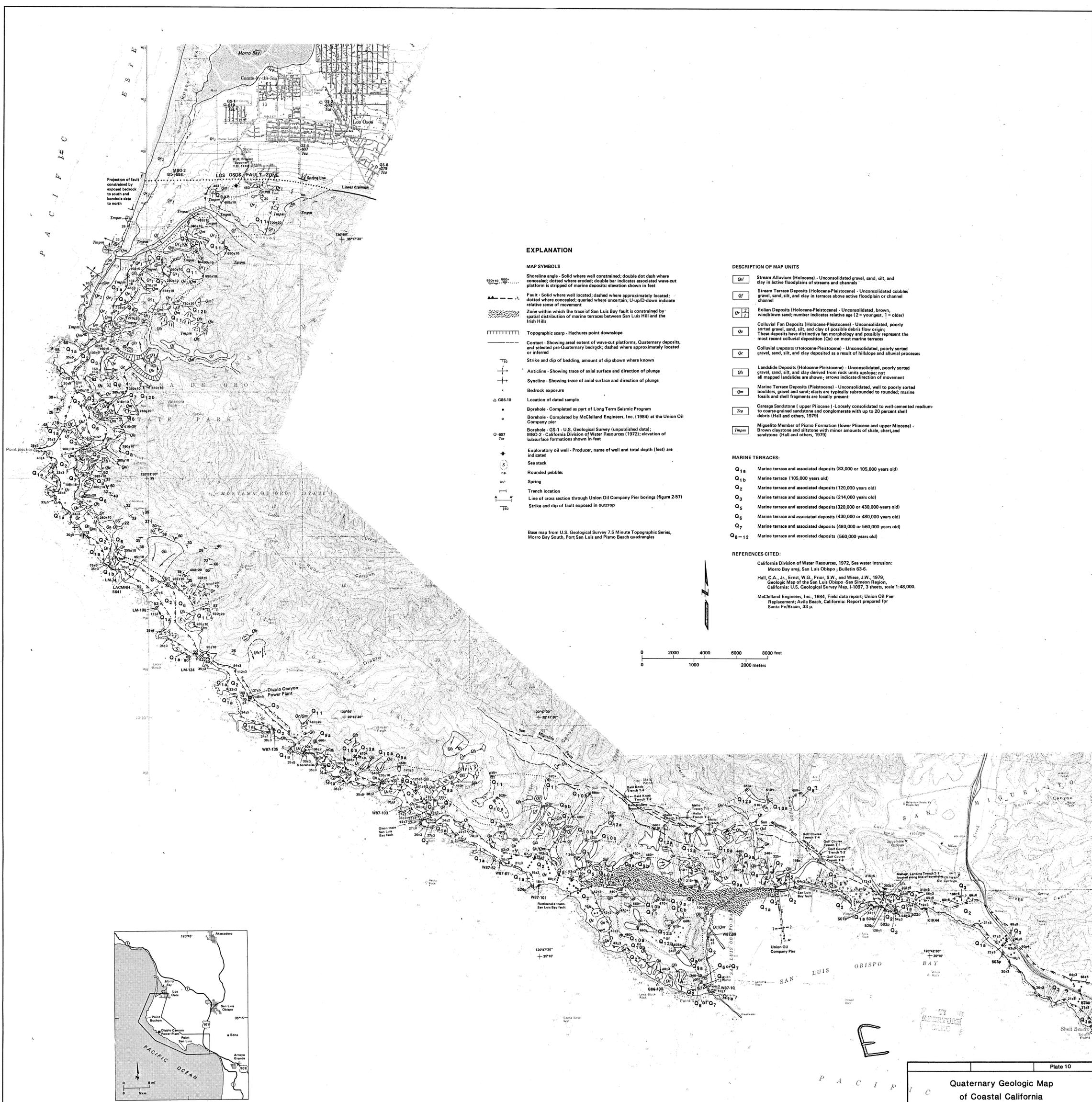
Plate 3

Deep Crustal Reflection Line PG&E-3
 Processing Optimized for
 Sedimentary Column Display

Diablo Canyon Power Plant Long Term Seismic Program
 Pacific Gas and Electric Company
 San Francisco, California July 1988

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EXPLANATION

MAP SYMBOLS

- Shoreline angle - Solid where well constrained; double dot dash where concealed; dotted where eroded; double bar indicates associated wave-cut platform is stripped of marine deposits; elevation shown in feet
- Fault - Solid where well located; dashed where approximately located; dotted where concealed; queried where uncertain; U=up/D=down indicate relative sense of movement
- Zone within which the trace of San Luis Bay fault is constrained by spatial distribution of marine terraces between San Luis Hill and the Irish Hills
- Topographic scarp - Hachures point downslope
- Contact - Showing areal extent of wave-cut platforms, Quaternary deposits, and selected pre-Quaternary bedrock; dashed where approximately located or inferred
- Strike and dip of bedding, amount of dip shown where known
- Anticline - Showing trace of axial surface and direction of plunge
- Syncline - Showing trace of axial surface and direction of plunge
- Bedrock exposure
- Location of dated sample
- Borehole - Completed as part of Long Term Seismic Program
- Borehole - Completed by McClelland Engineers, Inc. (1984) at the Union Oil Company pier
- Borehole - GS-1 - U.S. Geological Survey (unpublished data); MBO-2 - California Division of Water Resources (1972); elevation of subsurface formations shown in feet
- Exploratory oil well - Producer, name of well and total depth (feet) are indicated
- Sea stack
- Rounded pebbles
- Spring
- Trench location
- Line of cross section through Union Oil Company Pier borings (figure 2-57)
- Strike and dip of fault exposed in outcrop

DESCRIPTION OF MAP UNITS

- Qal** Stream Alluvium (Holocene) - Unconsolidated gravel, sand, silt, and clay in active floodplains of streams and channels
- Qt** Stream Terrace Deposits (Holocene-Pleistocene) - Unconsolidated cobbles, gravel, sand, silt, and clay in terraces above active floodplain or channel channel
- Qe1-7** Estuarine Deposits (Holocene-Pleistocene) - Unconsolidated, brown, windblown sand; number indicates relative age (2 = youngest, 1 = oldest)
- Qc** Colluvial Fan Deposits (Holocene-Pleistocene) - Unconsolidated, poorly sorted gravel, sand, silt, and clay of possible debris flow origin; these deposits have distinctive fan morphology and possibly represent the most recent colluvial deposition (Qc) on most marine terraces
- Qd** Colluvial Lapports (Holocene-Pleistocene) - Unconsolidated, poorly sorted gravel, sand, silt, and clay deposited as a result of hillslope and alluvial processes
- Ql** Landslide Deposits (Holocene-Pleistocene) - Unconsolidated, poorly sorted boulders, gravel and sand; clay derived from rock units uplope; not all mapped landslides are shown; arrows indicate direction of movement
- Qm** Marine Terrace Deposits (Pleistocene) - Unconsolidated, well to poorly sorted gravels, sand, silt, and clay; clasts are typically subrounded to rounded; marine fossils and shell fragments are locally present
- Qca** Caracapa Sandstone (upper Pliocene) - Loosely consolidated to well-cemented medium- to coarse-grained sandstone and conglomerate with up to 20 percent shell debris (Hall and others, 1979)
- Qp** Miguelito Member of Pismo Formation (lower Pliocene and upper Miocene) - Brown claystone and siltstone with minor amounts of shale, chert, and sandstone (Hall and others, 1979)

MARINE TERRACES:

- Q1a** Marine terrace and associated deposits (83,000 or 105,000 years old)
- Q1b** Marine terrace (105,000 years old)
- Q2** Marine terrace and associated deposits (120,000 years old)
- Q3** Marine terrace and associated deposits (214,000 years old)
- Q5** Marine terrace and associated deposits (320,000 or 430,000 years old)
- Q6** Marine terrace and associated deposits (430,000 or 480,000 years old)
- Q7** Marine terrace and associated deposits (480,000 or 560,000 years old)
- Q8-12** Marine terrace and associated deposits (560,000 years old)

REFERENCES CITED:

- California Division of Water Resources, 1972, Sea water intrusion: Morro Bay area, San Luis Obispo; Bulletin 63-6.
- Hall, C.A., Jr., Ernst, W.G., Prior, S.W., and Wise, J.W., 1979, Geologic Map of the San Luis Obispo - San Simeon Region, California: U.S. Geological Survey Map, I-1097, 3 sheets, scale 1:48,000.
- McClelland Engineers, Inc., 1984, Field data report; Union Oil Pier Replacement; Avila Beach, California: Report prepared for Santa Fe/Graun, 33 p.

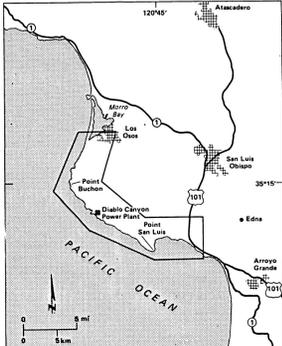
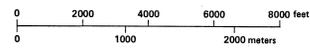
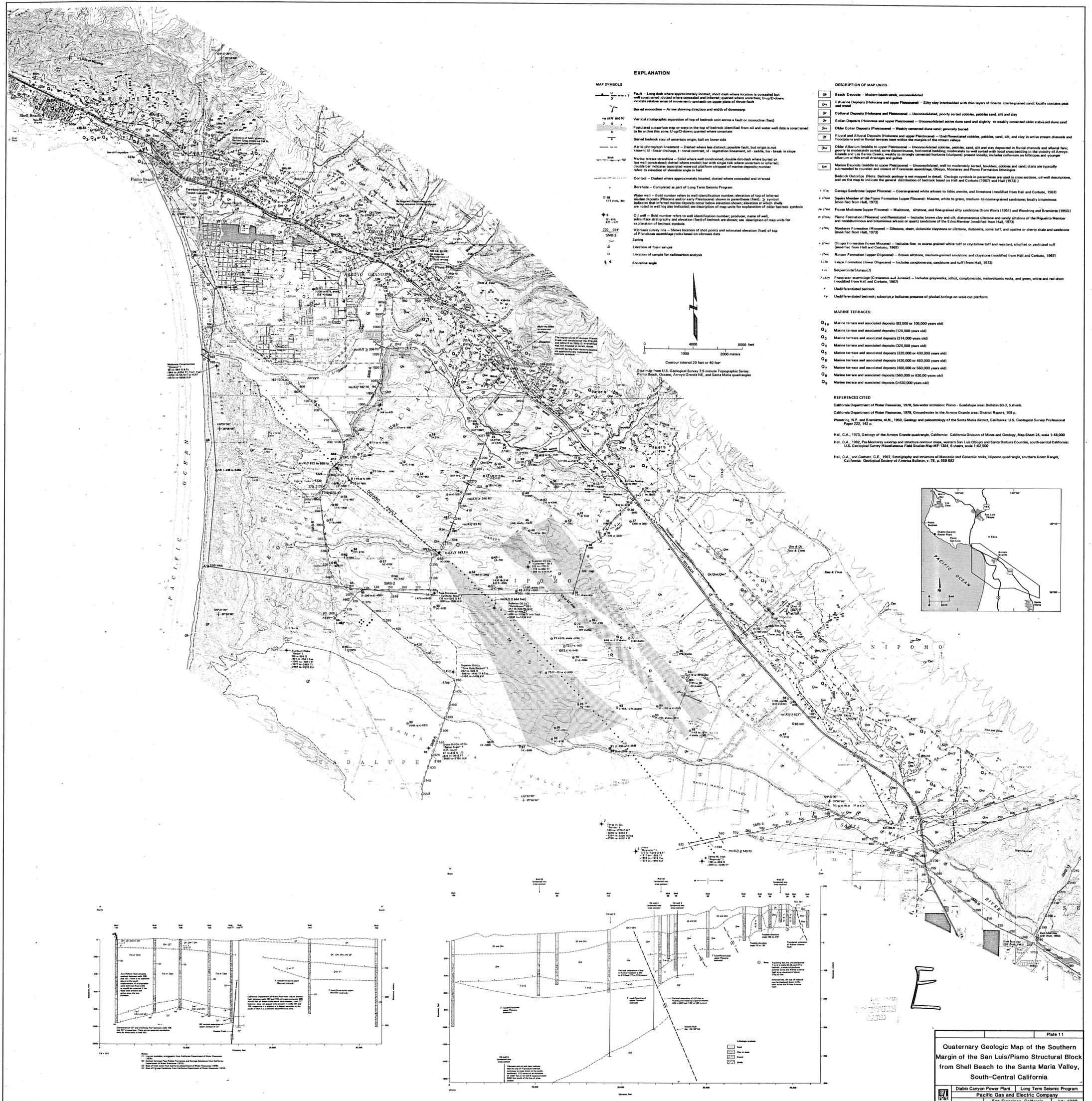


Plate 10

**Quaternary Geologic Map
of Coastal California
from Morro Bay to Shell Beach,
South-Central California**

Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California July 1988	

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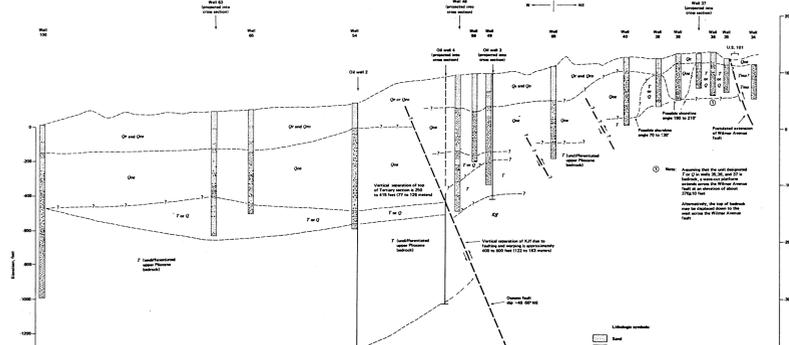
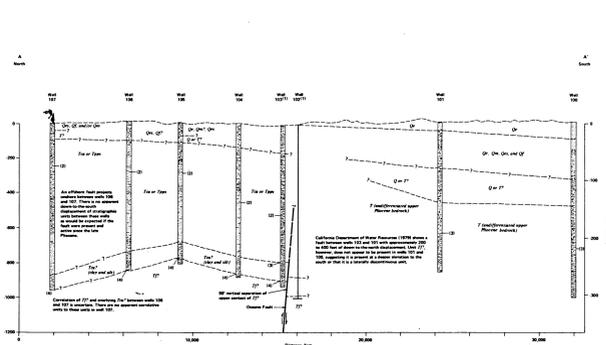
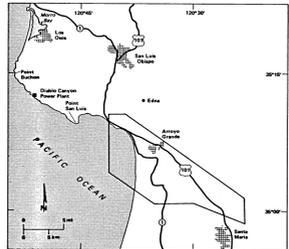
EXPLANATION

- MAP SYMBOLS**
- Fault — Long dash where approximately located; short dash where location is concealed but well located; dotted where concealed and inferred; curved where uncertain; U up/D down indicates relative sense of movement; slash on upper plate of thrust fault
 - Burial monocline — Arrow showing direction and width of downstep
 - Vertical stratigraphic separation of top of bedrock unit across a fault or monocline (feet)
 - Postulated subsurface step or warp in the top of bedrock identified from oil and water well data is constrained to lie within this zone; U up/D down; queried where uncertain
 - Burial bedrock step of uncertain origin; ball on lower side
 - Aerial photograph lineament — Dashed where less distinct; possible fault, but origin is not known; S linear drainage; 1' local contrast; v' vegetation lineament; d' saddle; bar break in slope
 - Marine terrace stratifide — Solid where well constrained; double dot-dash where buried or less well constrained; dotted where eroded; bar with single tick where uncertain or inferred; double bar indicates associated water-cut platform strip of marine deposits; number refers to elevation of shoreline angle in feet
 - Contact — Dashed where approximately located; dotted where concealed and inferred
 - Borehole — Completed as part of Long Term Seismic Program
 - Water well — Bold number refers to well identification number; elevation of top of inferred marine deposits (Pliocene and/or early Pleistocene) shown in parentheses (feet); 2' symbol indicates that inferred marine deposits occur below elevation shown; elevation at which alluvial are noted in well log also indicated; see description of map units for explanation of older bedrock symbols
 - Oil well — Bold number refers to well identification number; producer; name of well, subsurface stratigraphy and elevation (feet) of bedrock are shown; see description of map units for explanation of bedrock symbols
 - Virovona survey line — Shows location of shot points and estimated elevation (feet) of top of Franciscan assemblage rocks based on virovona data
 - Spring
 - Location of fossil sample
 - Location of sample for radiocarbon analysis
 - Shoreline angle

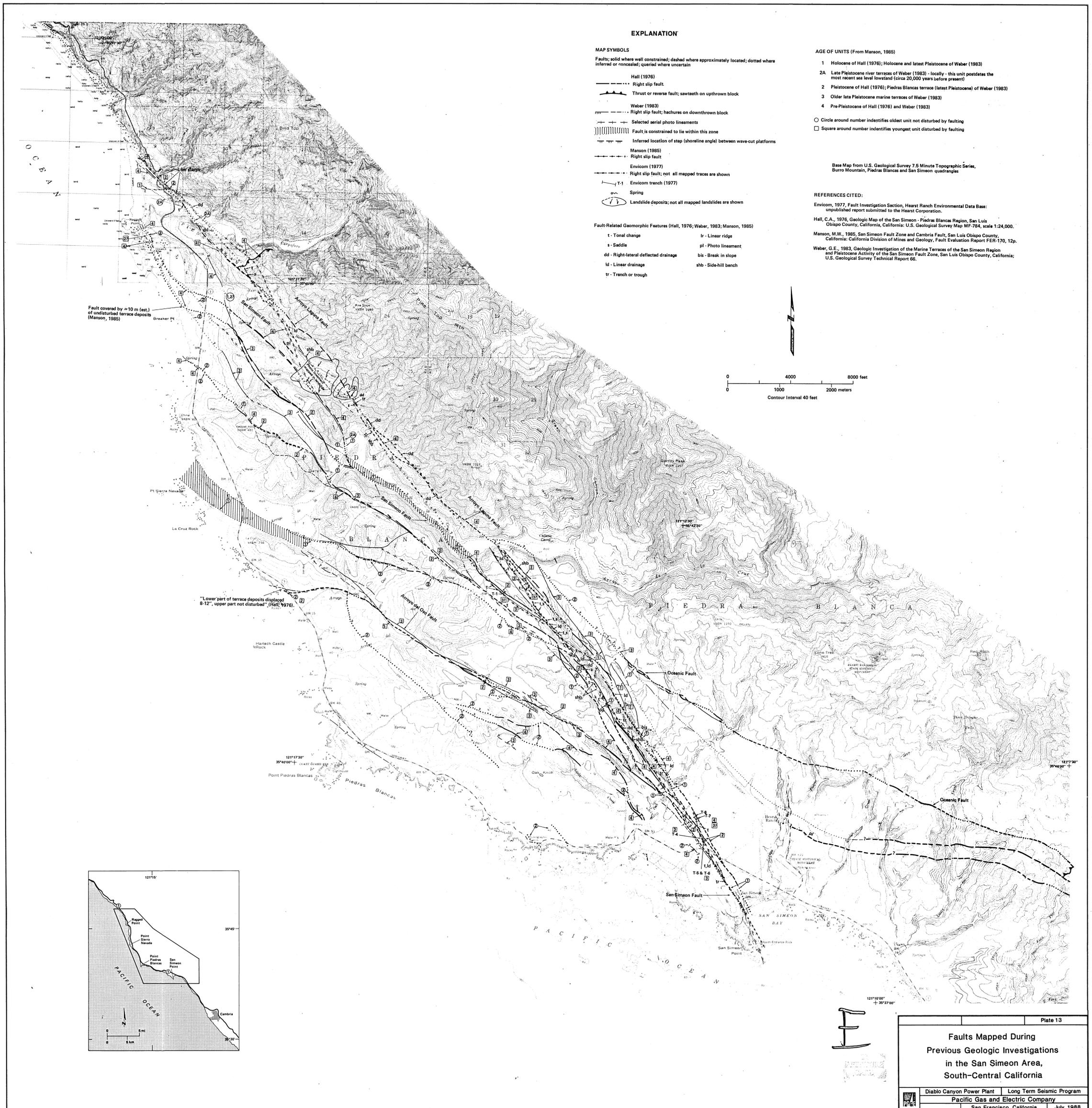
- DESCRIPTION OF MAP UNITS**
- Q₁ Beach Deposits — Modern beach sands, unconsolidated
 - Q₂ Estuarine Deposits (Holocene and upper Pleistocene) — Silty clay interbedded with thin layers of fine to coarse-grained sand; locally contains peat and wood
 - Q₃ Cultural Deposits (Holocene and Pleistocene) — Unconsolidated, poorly sorted cobbles, pebbles, sand, silt and clay
 - Q₄ Eolian Deposits (Holocene and upper Pleistocene) — Unconsolidated active dune sand and slightly to weakly cemented older stabilized dune sand
 - Q₅ Older Eolian Deposits (Pleistocene) — Weakly cemented dune sand; generally buried
 - Q₆ Fluvial and Alluvial Deposits (Holocene and upper Pleistocene) — Unconsolidated cobbles, pebbles, sand, silt, and clay in active stream channels and floodplains and in fluvial terraces inset within the margins of the stream valleys
 - Q₇ Older Alluvium (middle to upper Pleistocene) — Unconsolidated cobbles, pebbles, sand, silt and clay deposited in fluvial channels and alluvial fans; poorly to moderately sorted; some discontinuous, horizontal bedding; moderately to well sorted with local cross bedding in the vicinity of Arroyo Grande and Los Barrios Creeks; weakly to strongly cemented horizons (duripans) present locally; includes colluvium on hillslopes and younger alluvium within small channels and gullies
 - Q₈ Marine Deposits (middle to upper Pleistocene) — Unconsolidated, well to moderately sorted, boulders, cobbles and sand; clasts are typically subrounded to rounded and consist of Franciscan assemblage, Obispo, Monterey and Pismo Formations lithologies
 - Bedrock Outcrop (Note: Bedrock outcrop is not mapped in detail. Geologic symbols in parentheses are used in cross sections, all well descriptions, and on the map to indicate the general distribution of bedrock based on Hall and Corbato (1967) and Hall (1973):
 - 1 (Tm) Carajaz Sandstone (upper Pliocene) — Coarse-grained white arkosic to lithic arkosic and limestone (modified from Hall and Corbato, 1967)
 - 1 (Tm) Saurin Member of the Pismo Formation (upper Pliocene) — Massive, white to green, medium- to coarse-grained sandstone; locally bituminous (modified from Hall, 1973)
 - 1 (Tm) Fossiliferous Middle Pliocene — Massive, silty, and fine-grained silty sandstone (from Worts (1951) and Woodring and Brannietta (1950))
 - 1 (Tm) Pismo Formation (Pliocene) undifferentiated — Includes lower clay and silt, discontinuous silty and sandy siltstone of the Miguelito Member and nonbituminous and bituminous arkosic and quartz sandstone of the Edna Member (modified from Hall, 1973)
 - 1 (Tm) Monterey Formation (Miocene) — Siltstone, chert, dolomitic claystone or siltstone, diatomite, some tuff, and opaline or cherty shale and sandstone (modified from Hall, 1973)
 - 1 (Tm) Obispo Formation (lower Miocene) — Includes fine- to coarse-grained white tuff or crystalline tuff and resistant, silty and/or calcareous tuff (modified from Hall and Corbato, 1967)
 - 1 (Tm) Rincon Formation (upper Oligocene) — Brown siltstone, medium-grained sandstone and claystone (modified from Hall and Corbato, 1967)
 - 1 (Tm) Louisa Formation (lower Oligocene) — Includes conglomerate, sandstone and tuff (from Hall, 1973)
 - 1 (S) Serpentinized Laramide?
 - 1 (K) Franciscan assemblage (Cretaceous and Jurassic) — Includes gneisses, schists, conglomerates, metavolcanic rocks, and green, white and red chert (modified from Hall and Corbato, 1967)
 - 1 Undifferentiated bedrock
 - 1 Undifferentiated bedrock; subscript p indicates presence of phthalic borings on wave-cut platform

- MARINE TERRACES:**
- Q₁ Marine terrace and associated deposits (83,000 or 105,000 years old)
 - Q₂ Marine terrace and associated deposits (120,000 years old)
 - Q₃ Marine terrace and associated deposits (214,000 years old)
 - Q₄ Marine terrace and associated deposits (320,000 years old)
 - Q₅ Marine terrace and associated deposits (320,000 or 430,000 years old)
 - Q₆ Marine terrace and associated deposits (430,000 or 480,000 years old)
 - Q₇ Marine terrace and associated deposits (480,000 or 560,000 years old)
 - Q₈ Marine terrace and associated deposits (560,000 or 630,000 years old)
 - Q₉ Marine terrace and associated deposits (630,000 years old)

- REFERENCES CITED**
- California Department of Water Resources, 1970, Sea water intrusion: Pismo - Guadalupe area: Bulletin 63-3, 5 sheets
 - California Department of Water Resources, 1979, Groundwater in the Arroyo Grande area: District Report, 108 p.
 - Woodring, W.P., and Brannietta, M.N., 1950, Geology and paleontology of the Santa Maria district, California: U.S. Geological Survey Professional Paper 252, 162 p.
 - Hall, C.A., 1973, Geology of the Arroyo Grande quadrangle, California: California Division of Mines and Geology, Map Sheet 24, scale 1:48,000
 - Hall, C.A., 1982, Paleogeographic settings and structure contour maps, western San Luis Obispo and Santa Barbara Counties, south-central California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1354, 6 sheets, scale 1:62,500
 - Hall, C.A., and Corbato, C.E., 1967, Stratigraphy and structure of Mesozoic and Cenozoic rocks, Nipomo quadrangle, southern Coast Range, California: Geological Society of America Bulletin, v. 78, p. 559-582



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EXPLANATION

MAP SYMBOLS

- Faults; solid where well constrained; dashed where approximately located; dotted where inferred or concealed; queried where uncertain
- Hall (1976)
 - Right slip fault
 - Thrust or reverse fault; sawtooth on upthrown block
 - Weber (1983)
 - Right slip fault; hachures on downthrown block
 - Selected aerial photo lineaments
 - Fault is constrained to lie within this zone
 - Inferred location of step (shoreline angle) between wave-cut platforms
 - Manson (1985)
 - Right slip fault
 - Envicom (1977)
 - Right slip fault; not all mapped traces are shown
 - Envicom trench (1977)
 - Spring
 - Landslide deposits; not all mapped landslides are shown

Fault-Related Geomorphic Features (Hall, 1976; Weber, 1983; Manson, 1985)

- t - Tonal change
- lr - Linear ridge
- s - Saddle
- pl - Photo lineament
- dd - Right-lateral deflected drainage
- ld - Linear drainage
- tr - Trench or trough
- bb - Break in slope
- shb - Side-hill bench

AGE OF UNITS (From Manson, 1985)

- 1 Holocene of Hall (1976); Holocene and latest Pleistocene of Weber (1983)
- 2A Late Pleistocene river terraces of Weber (1983) - locally - this unit postdates the most recent sea level lowstand (circa 20,000 years before present)
- 2 Pleistocene of Hall (1976); Piedras Blancas terrace (latest Pleistocene) of Weber (1983)
- 3 Older late Pleistocene marine terraces of Weber (1983)
- 4 Pre-Pleistocene of Hall (1976) and Weber (1983)

- Circle around number identifies oldest unit not disturbed by faulting
- Square around number identifies youngest unit disturbed by faulting

Base Map from U.S. Geological Survey 7.5 Minute Topographic Series, Burro Mountain, Piedras Blancas and San Simeon quadrangles

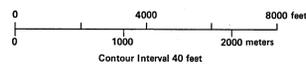
REFERENCES CITED:

Envicom, 1977, Fault Investigation Section, Hearst Ranch Environmental Data Base: unpublished report submitted to the Hearst Corporation.

Hall, C.A., 1976, Geologic Map of the San Simeon - Piedras Blancas Region, San Luis Obispo County, California: U.S. Geological Survey Map MF-784, scale 1:24,000.

Manson, M.W., 1985, San Simeon Fault Zone and Cambria Fault, San Luis Obispo County, California: California Division of Mines and Geology, Fault Evaluation Report FER-170, 12p.

Weber, G.E., 1983, Geologic Investigation of the Marine Terraces of the San Simeon Region and Pleistocene Activity of the San Simeon Fault Zone, San Luis Obispo County, California: U.S. Geological Survey Technical Report 66.



Fault covered by ~10 m (est.) of undisturbed terrace deposits (Manson, 1985)

"Lower part of terrace deposits displaced 8-12", upper part not disturbed" (Hall, 1976)

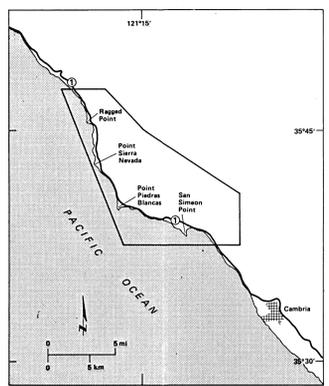


Plate 13

**Faults Mapped During
Previous Geologic Investigations
in the San Simeon Area,
South-Central California**

Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California	July 1988

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EXPLANATION

MAP SYMBOLS

- Fault — Long dash where approximately located; short dash where concealed but location is well constrained; dotted where eroded; U-shaped lines and arrows indicate relative sense of movement
- Aerial Photo Lineament — Dashed where line distinct; probable fault, to: total contact, of vegetation lineament, of linear drainage, of break in slope, of side hill bench, of change in topographic character of a slope
- Strike zone in bedrock
- Strike and dip of fault plane exposed in outcrop
- Strike and dip of bedding
- Marine Terrace Stratigraphy — Solid where well constrained; double dot-dash where buried or less well constrained; dotted where eroded; dashed where uncertain; elevation or structural angle in feet
- Contact — Dashed where approximately located; dotted where buried and inferred
- Seismic Refraction Survey line
- Trench
- Soil Pit
- Exploration Pit
- Borehole — Completed as part of Long Term Seismic Program
- Subsurface stratigraphy and elevation (feet) of the top of bedrock. See description of map units for explanation of Quaternary and bedrock symbols
- Landslide, arrow indicates direction of movement
- Spring
- Relief sea stack
- Location of dated fossil sample
- Location of radiocarbon sample
- Location of sample for thermoluminescence analysis

DESCRIPTION OF MAP UNITS

- Beach Deposits — Modern beach sands, unconsolidated
- Eolian Deposits (Holocene and upper Pleistocene) — Includes unconsolidated active sand dunes, and slightly to weakly consolidated inactive dunes sand on elevated marine terraces that has been stabilized by vegetation and soil development
- Colluvium (Holocene and Pleistocene) — Unconsolidated, poorly sorted sand, gravel, silt, and clay deposited as a result of hillside processes
- Fluvial and Alluvial Deposits (Holocene and Pleistocene) undifferentiated — Unconsolidated silt, sand, gravel, silt, and clay
- Stream Terrace Deposits (Holocene and upper Pleistocene) undifferentiated
- Old Kneel Creek
- Q₁ active 2.5 to 3.5 ka
- Q₂ historical 5.5 to 7.9 ka
- Q₃ 2.25 to 0.75 ka
- Q₄ 2.25 to 0.75 ka
- Q₅ Late Pleistocene to early Holocene
- Estuarine Deposit (Pleistocene) — Silty clay interbedded with thin layers of fine to coarse-grained sand; dark gray; contains abundant charcoal, wood, and disseminated organic material
- Older Alluvium (middle to upper Pleistocene) — Unconsolidated, weakly to moderately stratified, moderately to poorly sorted gravel, sand, silt and clay deposited in fluvial channels and alluvial fans overlying marine terrace cut platforms; presently undergoing dissection
- Marine Deposits (middle to upper Pleistocene) — Unconsolidated boulders, cobbles and sand, well to moderately sorted; clasts are typically subrounded to rounded and consist of Jurassic ophiolite, Franciscan assemblage, and Monterey lithologies

Bedrock Outcrop (Note: Bedrock geology is not mapped in detail)

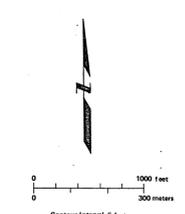
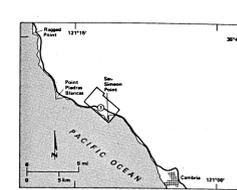
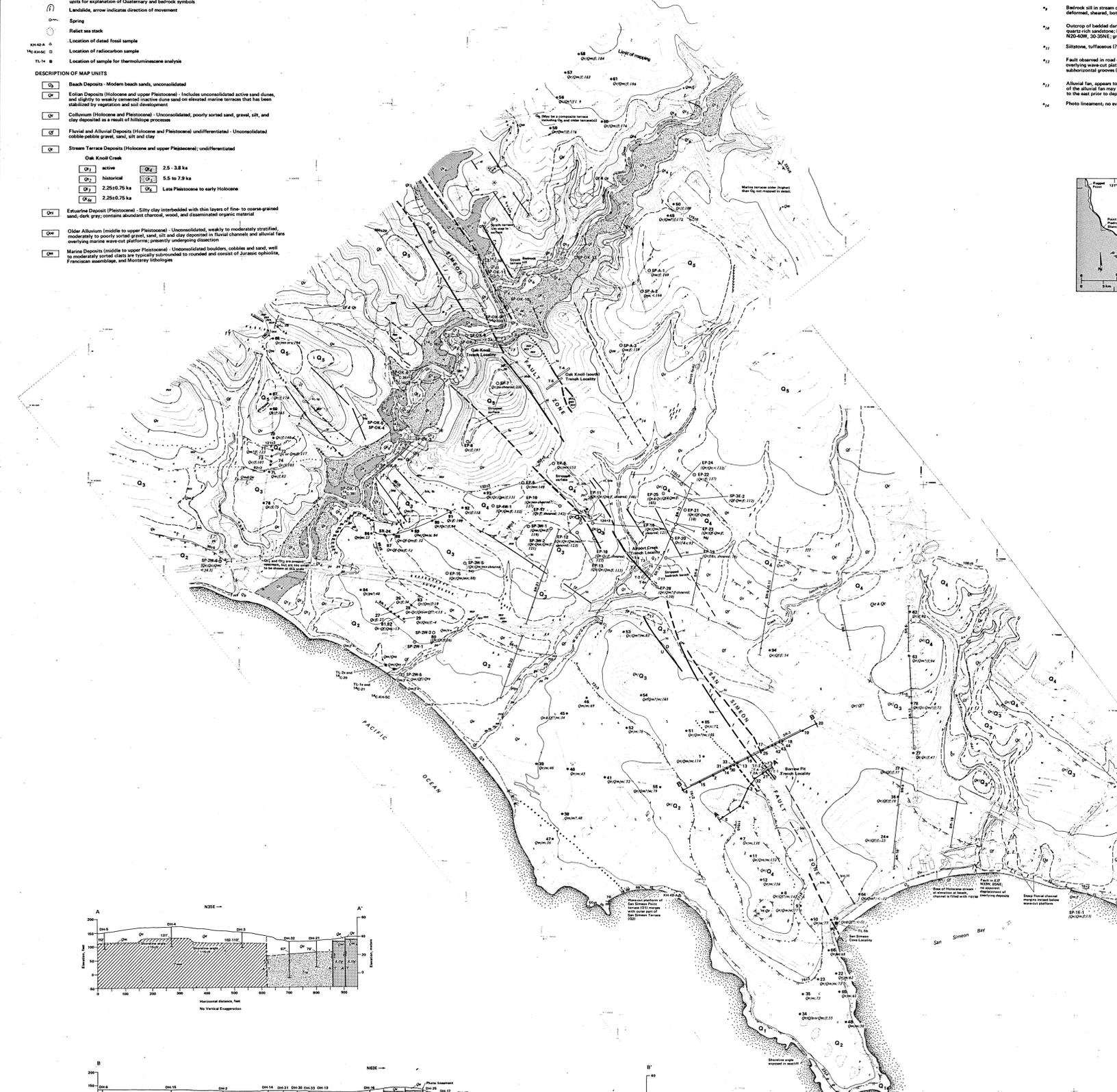
- Casapá Sandstone (Pliocene and Pleistocene ?) — Loosely consolidated to well-sorted, poorly bedded, medium to coarse-grained sandstone and conglomerate; shell debris as much as 20 percent of rock (modified from Hall and others, 1979)
- Monterey Formation (middle and upper Miocene) — Disconformable shale, porphyroscopic shale, siltstone, silty sandstone and siltstone and cherty shale (modified from Hall and others, 1979)
- Point Sal Formation (middle Miocene) — Light green siltstone, disconformable siltstone and siltstone (modified from Hall and others, 1979)
- Lopez Formation (Oligocene) — Includes green and red conglomerate, sandstone and silty claystone (modified from Hall and others, 1979)
- Tuff (age uncertain)
- Franciscan assemblage (Cretaceous or Jurassic) — includes:
 - Greywacke, shale, chert, and melange
 - Metasedimentary rocks
 - Bluechert
 - Serpentine (Jurassic?)
 - Undifferentiated bedrock
- Subscript *a* indicates presence of pholad borings on wave-cut platform

MARINE TERRACES — Informal stratigraphic names (from Water, 1983) have been assigned to each of the terraces mapped in detail:

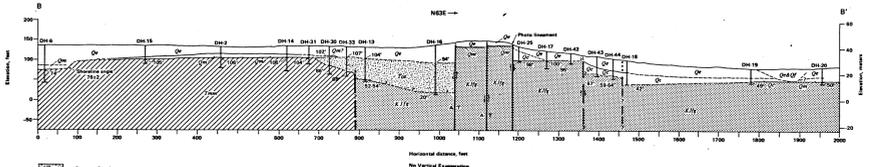
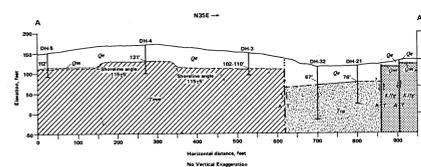
- Q₁ San Simon Point terrace (60,000 or 83,000 years old)
- Q₂ San Simon terrace (83,000 or 105,000 years old)
- Q₃ Tripod terrace (120,000 years old)
- Q₄ One terrace (214,000 years old)
- Q₅ La Cruz terrace (320,000 years old)

NOTES:

- 1. An additional fluvial terrace (Q₆), which is too small to be mapped at this scale, is observed within the zone defined by the most recently active fault trace. The localized occurrence of this terrace suggests that late Holocene uplift may have been greater in this zone.
- 2. Chert, quartz blocks (T outcrop); sheared surface common.
- 3. Erratic blocks (T in situ) of limy calcareous rock, quartz grains of varying size in siltaceous (T) matrix.
- 4. Ravine incised into buff-colored fine-grained arkose, sheared shale disconformity. Sandstone bedding N67W, 28NE.
- 5. Major shear zone: N50W to N75W, northeast dipping foliation of groups. Includes blocks of arkose. Localized remnants of stream terrace deposits and bary melange or groups downstream to the southwest.
- 6. Sharp, planar contact of stream deposits against sheared Franciscan pillow basalt of granitic, fault contact (T) — N50W, 28NE. Massive slope factors, opposite bank (south side) at sharp bend in channel.
- 7. Melange exposed in creek bottom, subparallel to drainage.
- 8. Buff-colored arkose (non-Franciscan), fine-grained, massive, uniform, closely fractured, low to moderate hardness and strength; local shear planes. Black chert pebbles conglomerate underlies the arkose outcrop, partly above depositional contact, partly along shear contact (old bedrock shear).
- 9. Bedrock sill in stream channel; very fine-grained arkose outcrop, well bedded locally; colorless, sheared, both parallel to and oblique to bedding — N50W, steep SW.
- 10. Outcrop of bedded dark gray-black chert, tan siltstone shale, and very fine-grained quartz-rich sandstone; locally sheared, crushed, brecciated blocks present. Bedding N20-40W, 10-20NE; groove 20N, 20W.
- 11. Siltstone, tuffaceous (T), weathered, flesh-colored; bedding N50W, 20NE.
- 12. Fault observed to trend out N20W, vertical; chert exposed over marine terrace deposits overlying wave-cut platform. The platform is displaced ~1 meter down to the northeast; subhorizontal groove (T) along clay lined fractures in sand overlying marine gravel lag.
- 13. Alluvial fan, appears to have originally graded to a surface higher than Q₁. Uplift of the alluvial fan may have occurred in response to faulting on a fault trace lying to the east prior to deposition of Q₁.
- 14. Photo instrument; no evidence for faulting, may be in part, an old cattle trail.



REFERENCES CITED:
 Hall, C.A., Jr., Ernst, W.G., Prior, S.W., and Wines, J.W., 1979. Geologic map of the San Luis Obispo-San Simon region, California: U.S. Geological Survey Map, 1:100,000.
 Water, G.E., 1983. Geologic investigation of the marine terraces of the San Simon region and Pleistocene activity of the San Simon fault zone, San Luis Obispo County, California: U.S. Geological Survey Technical Report 66.



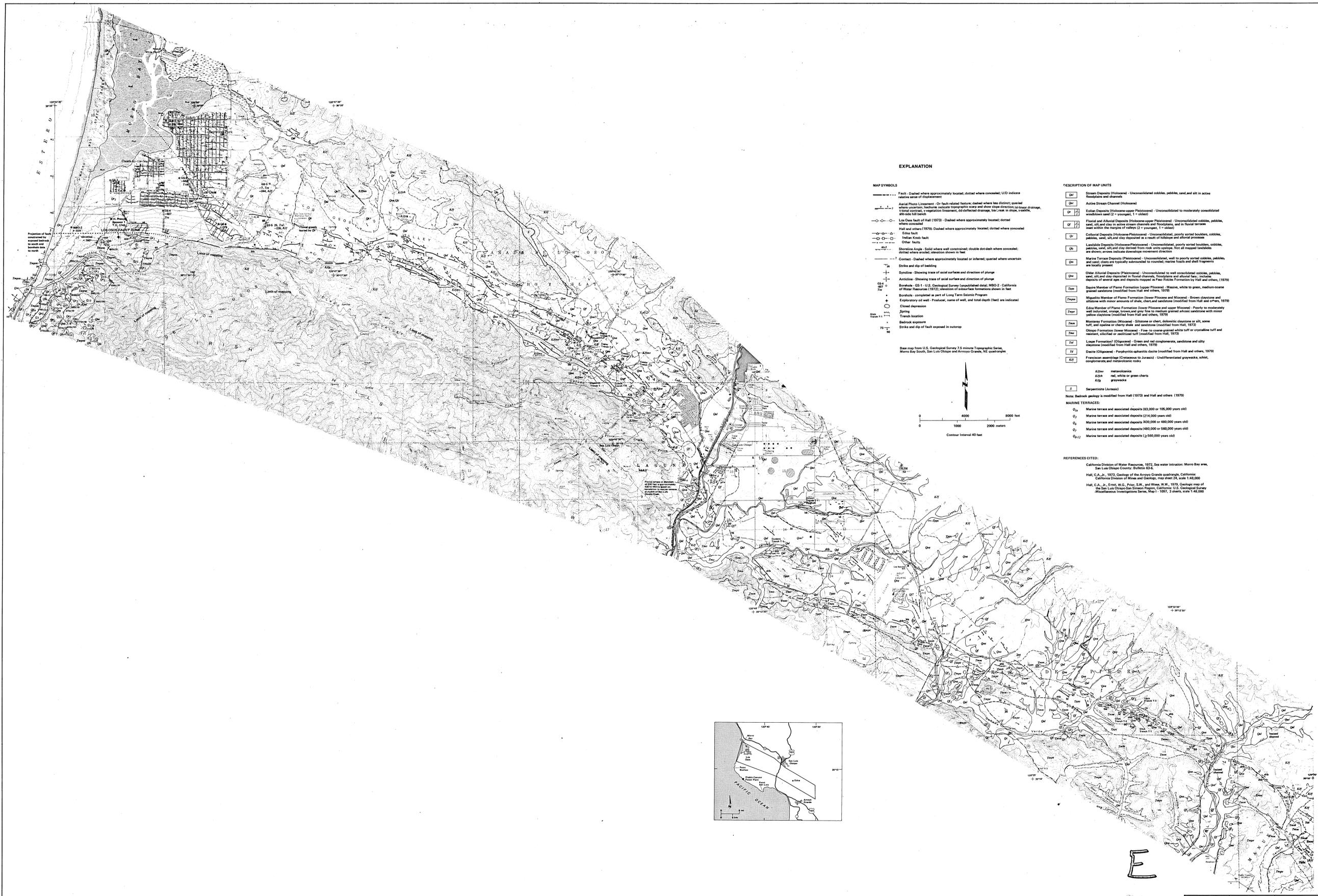
- Casapá Sandstone
- Monterey Formation
- Franciscan assemblage - greywacke

Plate 14

Quaternary Geologic Map
 of the Southern Onshore Reach
 of the San Simeon Fault Zone,
 South-Central California

Diablo Canyon Power Plant Long Term Seismic Program
 Pacific Gas and Electric Company
 San Francisco, California July 1988

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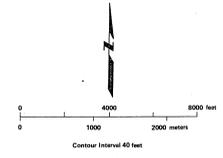


EXPLANATION

MAP SYMBOLS

- Fault: Dashed where approximately located; dotted where concealed; U/O indicate relative sense of displacement
- Aerial Photo Lineament: Or fault-related feature; dashed where less distinct; dashed where uncertain; includes topographic scarps and shows slope direction; (a) linear drainage, (b) road, (c) vegetation lineament, (d) deflected drainage, (e) break in slope, (f) satellite, (g) ridge-top hill (arrow)
- Los Osos fault of Hall (1973): Dashed where approximately located; dotted where concealed
- Hall and others (1979): Dashed where approximately located; dotted where concealed
- Strike fault
- Indian Knob fault
- Other faults
- Shaded area: Solid where well constrained; double-dashed where concealed; dotted where broken; elevation shown in feet
- Contact: Dashed where approximately located or inferred; queried where uncertain
- Strike and dip of bedding
- Syncline: Showing trace of axial surface and direction of plunge
- Anticline: Showing trace of axial surface and direction of plunge
- Strike-slip: U.S. Geological Survey (unpublished data); M80-2: California of Water Resources (1972); elevation of surface shown in feet
- Borehole: completed as part of Long Term Seismic Program
- Exploratory oil well - Producer, name of well, and total depth (feet) are indicated
- Oil depression
- Spring
- Trench location
- Radiocesium exposure
- Strike and dip of fault exposed in outcrop

Base map from U.S. Geological Survey 7.5-minute Topographic Series, Morro Bay South, San Luis Obispo and Morro, Santa Cruz, 10' quadrangle.

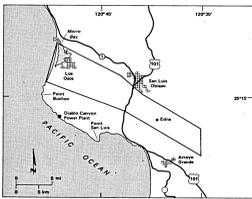


DESCRIPTION OF MAP UNITS

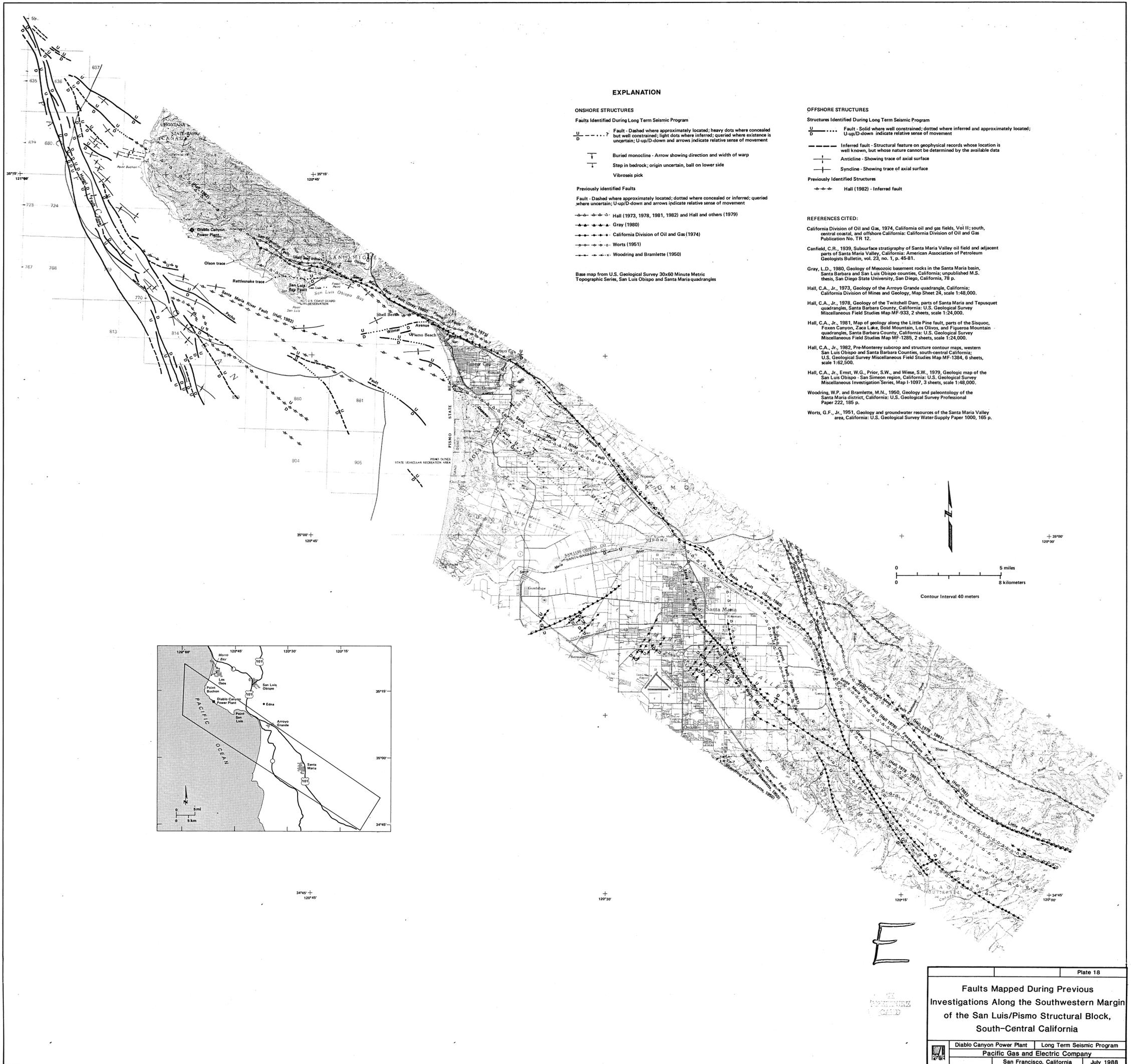
- Qw Stream Deposits (Holocene) - Unconsolidated cobbles, pebbles, sand and silt in active floodplains and channels
- Qa Active Stream Channel (Holocene)
- Qm Marine Deposits (Holocene upper Pleistocene) - Unconsolidated to moderately consolidated sand (2 = youngest, 1 = oldest)
- Qf Fluid and Alluvial Deposits (Holocene upper Pleistocene) - Unconsolidated cobbles, pebbles, sand, silt and clay in active stream channels and floodplains, and in fluvial terraces near margins of valleys (2 = youngest, 1 = oldest)
- Qc Coastal Deposits (Holocene-Pleistocene) - Unconsolidated, poorly sorted boulders, cobbles, pebbles, sand, silt and clay deposited in a variety of fluvial and alluvial processes
- Ql Landfill Deposits (Holocene-Pleistocene) - Unconsolidated, poorly sorted boulders, cobbles, pebbles, sand, silt and clay derived from rock units upland; list of mapped landfills are shown; arrows indicate down-slope movement direction
- Qm Marine Terrace Deposits (Pleistocene) - Unconsolidated, well to poorly sorted cobbles, pebbles, and sand; clays are typically subhorizontal to rounded; marine fossils and shell fragments are locally present
- Qm Older Alluvial Deposits (Pleistocene) - Unconsolidated to well consolidated cobbles, pebbles, sand, silt and clay deposited in fluvial channels, floodplains and alluvial fans; includes deposits of recent age and deposits mapped as Pale Pleistocene by Hall and others (1979)
- Qm Saurus Member of Pano Formation (upper Pliocene) - Massive, white to green, medium coarse grained sandstone (modified from Hall and others, 1979)
- Qm Miocene Member of Pano Formation (lower Pliocene and Miocene) - Brown claystone and siltstone with minor amounts of shale, chert and sandstone (modified from Hall and others, 1979)
- Qm Egan Member of Pano Formation (lower Pliocene and upper Miocene) - Poorly to moderately well indurated, orange, brown and gray clay to medium grained argillaceous sandstone with minor thin chert layers (modified from Hall and others, 1979)
- Qm Miocene Formation (Miocene) - Siltstone or shaly siltstone with some chert, and argillaceous or cherty shale and sandstone (modified from Hall, 1973)
- Qm Chico Formation (lower Miocene) - Fine to coarse grained white soft or crystalline tuff and resistant, siliceous or argillaceous tuff (modified from Hall, 1973)
- Qm Lugo Formation (Oligocene) - Green and red siltstone, sandstone and silty claystone (modified from Hall and others, 1979)
- Qm Ducta (Oligocene) - Porphyritic-aphanitic diorite (modified from Hall and others, 1979)
- Qm Franciscan assemblage (Cretaceous to Jurassic) - Undifferentiated graywacke, schist, conglomerate and metabasite rocks

Color metamorphic: red, white or green cherts; graywacke.
 Sarcopite (Jurassic)
 Note: Beachrock geology is modified from Hall (1973) and Hall and others (1979)
MARINE TERRACES:
 Q₁ Marine terrace and associated deposits (83,000 or 106,000 years old)
 Q₂ Marine terrace and associated deposits (214,000 years old)
 Q₃ Marine terrace and associated deposits (430,000 or 480,000 years old)
 Q₄ Marine terrace and associated deposits (680,000 or 580,000 years old)
 Q_{5,2} Marine terrace and associated deposits (2,660,000 years old)

REFERENCES CITED:
 California Division of Water Resources, 1972. Sea water intrusion: Morro Bay area, San Luis Obispo County. Bulletin 52-8.
 Hall, C.A.J., 1973. Geology of the Arroyo Grande quadrangle, California. California Division of Mines and Geology, map sheet 24, scale 1:62,500.
 Hall, C.A.J., Egan, G.C., Fier, S.W., and Hines, W.H., 1975. Geologic map of the San Luis Obispo-San Simeon Region, California. U.S. Geological Survey Miscellaneous Investigations Series, Map 1-1097, 3 sheets, scale 1:48,000.



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EXPLANATION

- ONSHORE STRUCTURES**
- Faults Identified During Long Term Seismic Program**
- U Fault - Dashed where approximately located; heavy dots where concealed but well constrained; light dots where inferred; queried where existence is uncertain; U-up/D-down and arrows indicate relative sense of movement
 - D Fault - Dashed where approximately located; dotted where concealed or inferred; queried where uncertain; U-up/D-down and arrows indicate relative sense of movement
 - +— Buried monocline - Arrow showing direction and width of warp
 - + Step in bedrock; origin uncertain, ball on lower side
 - + Vibroseis pick
- Previously Identified Faults**
- +— Hall (1973, 1978, 1981, 1982) and Hall and others (1979)
 - +— Gray (1980)
 - +— California Division of Oil and Gas (1974)
 - +— Worts (1951)
 - +— Woodring and Bramlette (1950)
- Base map from U.S. Geological Survey 30x60 Minute Metric Topographic Series, San Luis Obispo and Santa Maria quadrangles

- OFFSHORE STRUCTURES**
- Structures Identified During Long Term Seismic Program**
- U Fault - Solid where well constrained; dotted where inferred and approximately located; U-up/D-down indicate relative sense of movement
 - +— Inferred fault - Structural feature on geophysical records whose location is well known, but whose nature cannot be determined by the available data
 - +— Anticline - Showing trace of axial surface
 - +— Syncline - Showing trace of axial surface
- Previously Identified Structures**
- +— Hall (1982) - Inferred fault

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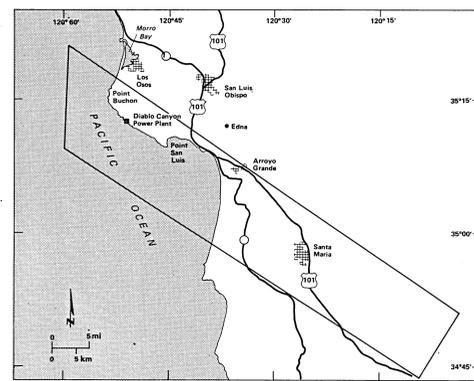
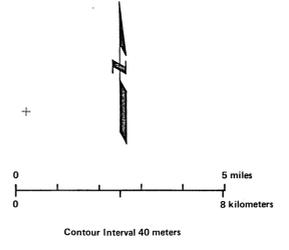
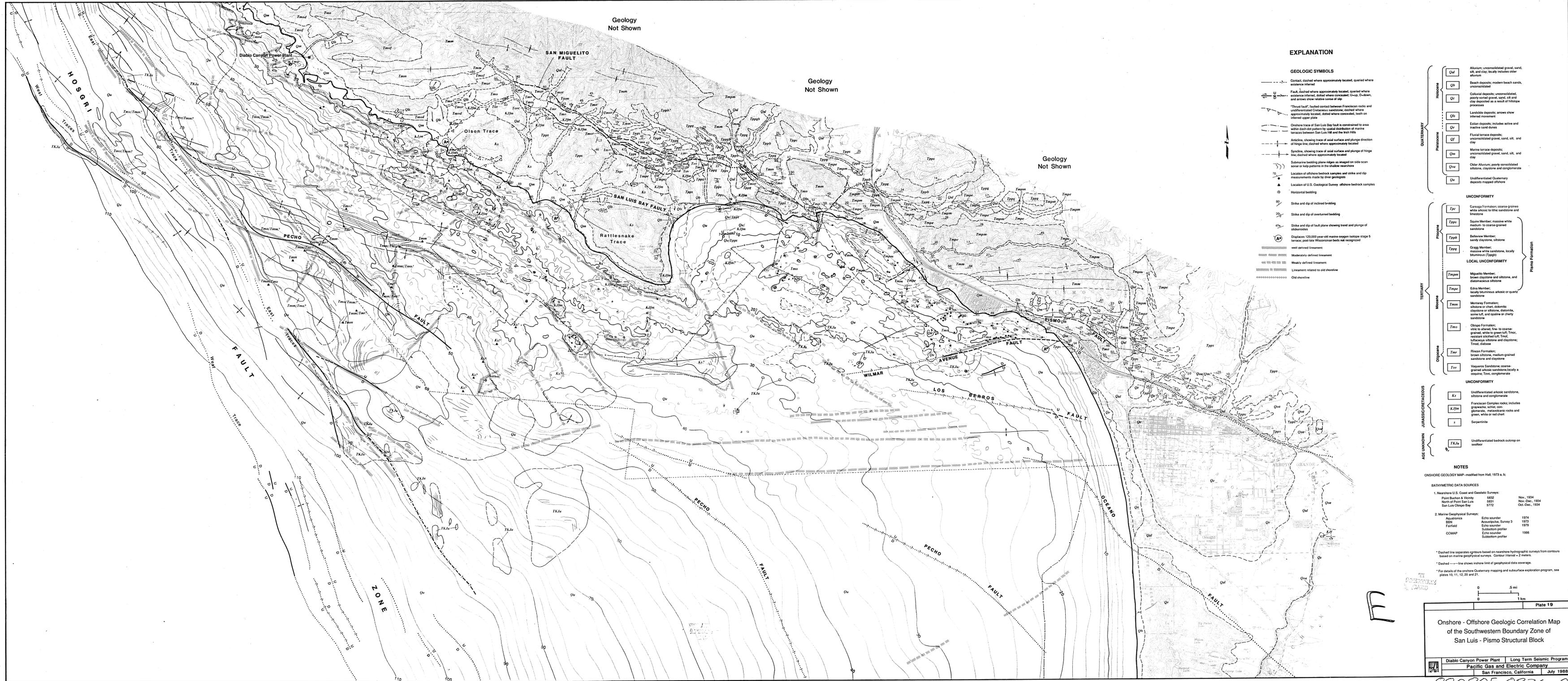


Plate 18	
Faults Mapped During Previous Investigations Along the Southwestern Margin of the San Luis/Pismo Structural Block, South-Central California	
	Long Term Seismic Program Pacific Gas and Electric Company
San Francisco, California July 1988	

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EXPLANATION

GEOLOGIC SYMBOLS

- Contact, dashed where approximately located, queried where existence inferred
- - - Fault, dashed where approximately located, queried where existence inferred, dotted where concealed; Up, Down, and arrows show relative sense of dip
- "Thrust Fault" faulted contact between Franciscan rocks and undifferentiated Cretaceous sandstone; dashed where approximately located, dotted where concealed, teeth on inferred upper plate
- Onshore trace of San Luis Bay fault is constrained to area within dash-dot pattern by spatial distribution of marine terraces between San Luis Hill and the fish hills
- Anticline, showing trace of axial surface and plunge direction of hinge line; dashed where approximately located
- Syncline, showing trace of axial surface and plunge of hinge line; dashed where approximately located
- Submarine bedding plane ridges as imaged on side-scan sonar or kelp patterns in the shallow nearshore
- Location of offshore bedrock samples and strike and dip measurements made by other geologists
- Location of U.S. Geological Survey offshore bedrock samples
- ▲ Horizontal bedding
- 80 Strike and dip of inclined bedding
- 55 Strike and dip of overturned bedding
- 45 Strike and dip of fault plane showing trend and plunge of slickensides
- (A) Displaces 120,000 year-old marine margin terrace stage 5 terraces; post late Wisconsinan beds not recognized
- Moderately defined lineament
- Weakly defined lineament
- Lineament related to old shoreline
- Old shoreline

- QUATERNARY**
- Qu Alluvium; unconsolidated gravel, sand, silt, and clay; locally includes older alluvium
 - Qb Beach deposits; modern beach sands, unconsolidated
 - Qc Colluvial deposits; unconsolidated, poorly-sorted gravel, sand, silt, and clay deposited as a result of hillside processes
 - Qd Landslide deposits; arrows show inferred movement
 - Qe Eolian deposits; includes active and inactive sand dunes
 - Qf Fluvial terrace deposits; unconsolidated gravel, sand, silt, and clay
 - Qm Marine terrace deposits; unconsolidated gravel, sand, silt, and clay
 - Qne Older Alluvium; poorly consolidated silts, clays, and conglomerates
 - Qu Undifferentiated Quaternary deposits mapped otherwise

- UNCONFORMITY**
- Tpc Caraga's Formation; coarse grained white siltstone to fine sandstone and limestone
 - Tps Squire Member; massive white medium to coarse-grained sandstone
 - Tpb Belvedere Member; sandstone and siltstone
 - Tpg Grogg Member; massive white sandstone, locally brownish (Tpgb)

- LOCAL UNCONFORMITY**
- Tmpn Maguillo Member; brown claystone and siltstone, and conglomeratic siltstone
 - Tmpe Edna Member; locally bluish-gray siltstone or quartz sandstone
 - Tmm Monterey Formation; siltstone or chert, dolomitic claystone or siltstone, dolomite, some silt, and opaline or cherty sandstone
 - Tmo Clipse Formation; vitric to silty, fine to coarse-grained, white to gray silt, trace resistant silted silt; Tmo, talusaceous siltstone and claystone; Tmod, diabase
 - Tmr Rincon Formation; brown siltstone, medium-grained sandstone and claystone
 - Tva Vaqueros Sandstone; coarse-grained silty sandstone, locally a coarse, fine, conglomeratic

- UNCONFORMITY**
- Ks Undifferentiated alkali sandstone, siltstone and conglomerate
 - KJfm Franciscan Complex rocks; includes gneiss, schist, and quartzite, metamorphic rocks and green, white or red chert
 - S Serpentina
 - TKJu Undifferentiated bedrock outcrop on seafloor

NOTES

ONSHORE GEOLOGIC MAP, modified from Hal, 1973 & 1:

BATHYMETRIC DATA SOURCES

- 1. Nearshore U.S. Coast and Geodetic Survey:
 - Point Barlow & vicinity 5828 Nov. 1934
 - North of Point San Luis 5831 Nov.-Dec. 1934
 - San Luis Obispo Bay 5772 Oct.-Dec. 1934
- 2. Marine Geophysical Surveys:
 - Acousticon Echo sounder 1974
 - BBN Acousticon, Survey 3 1973
 - Field Field 1978
 - Subbottom profiler Subbottom profiler 1986
 - COMAP Echo sounder Subbottom profiler

* Dashed line separates contours based on nearshore hydrographic surveys from contours based on marine geophysical surveys. Contour interval = 2 meters.

* Dashed --- line shows inshore limit of geophysical data coverage.

* For details of the onshore Quaternary mapping and subsurface exploration program, see plates 10, 11, 12, 20 and 21.

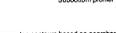


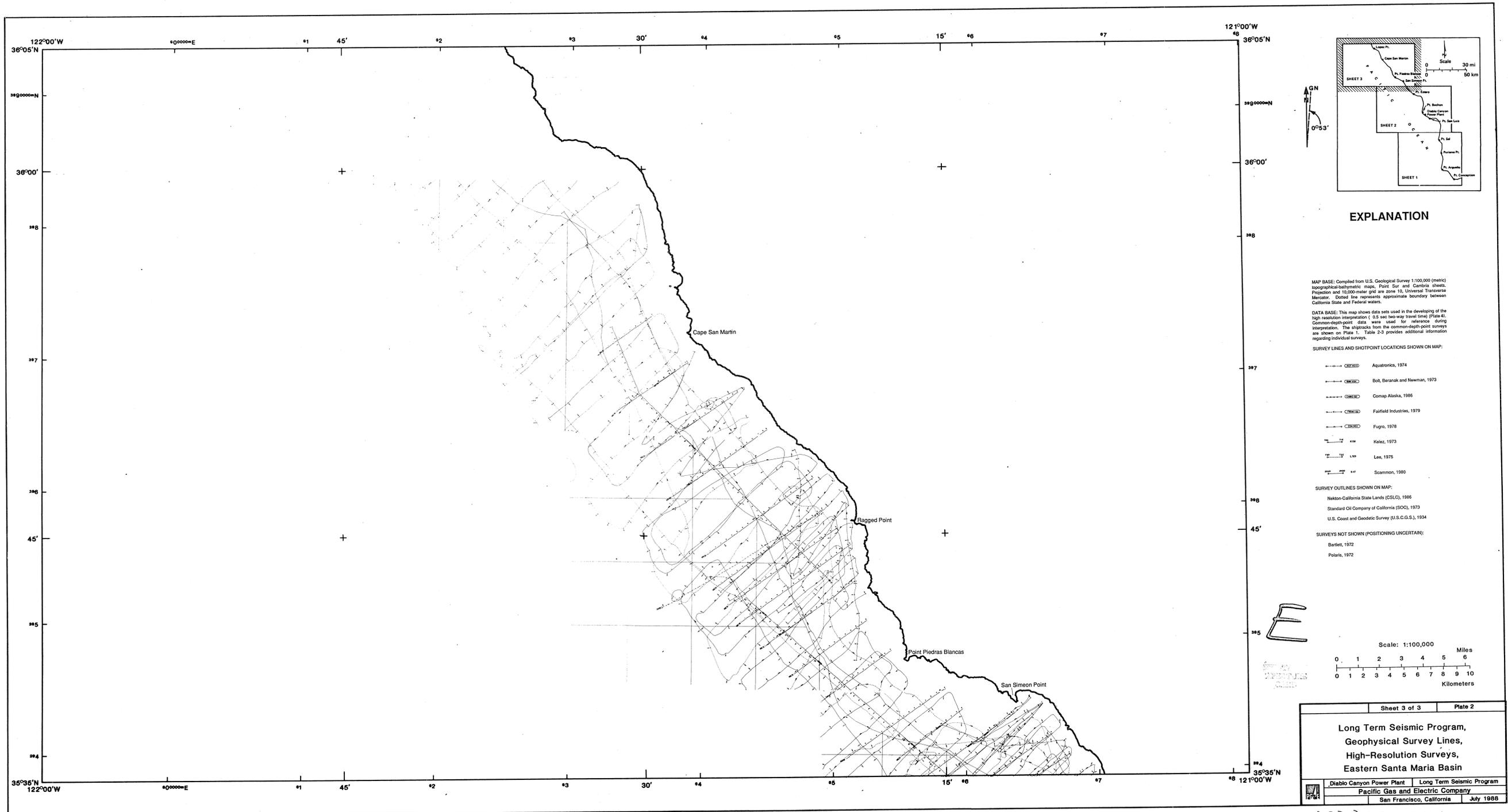
Plate 19

Onshore - Offshore Geologic Correlation Map of the Southwestern Boundary Zone of San Luis - Pismo Structural Block

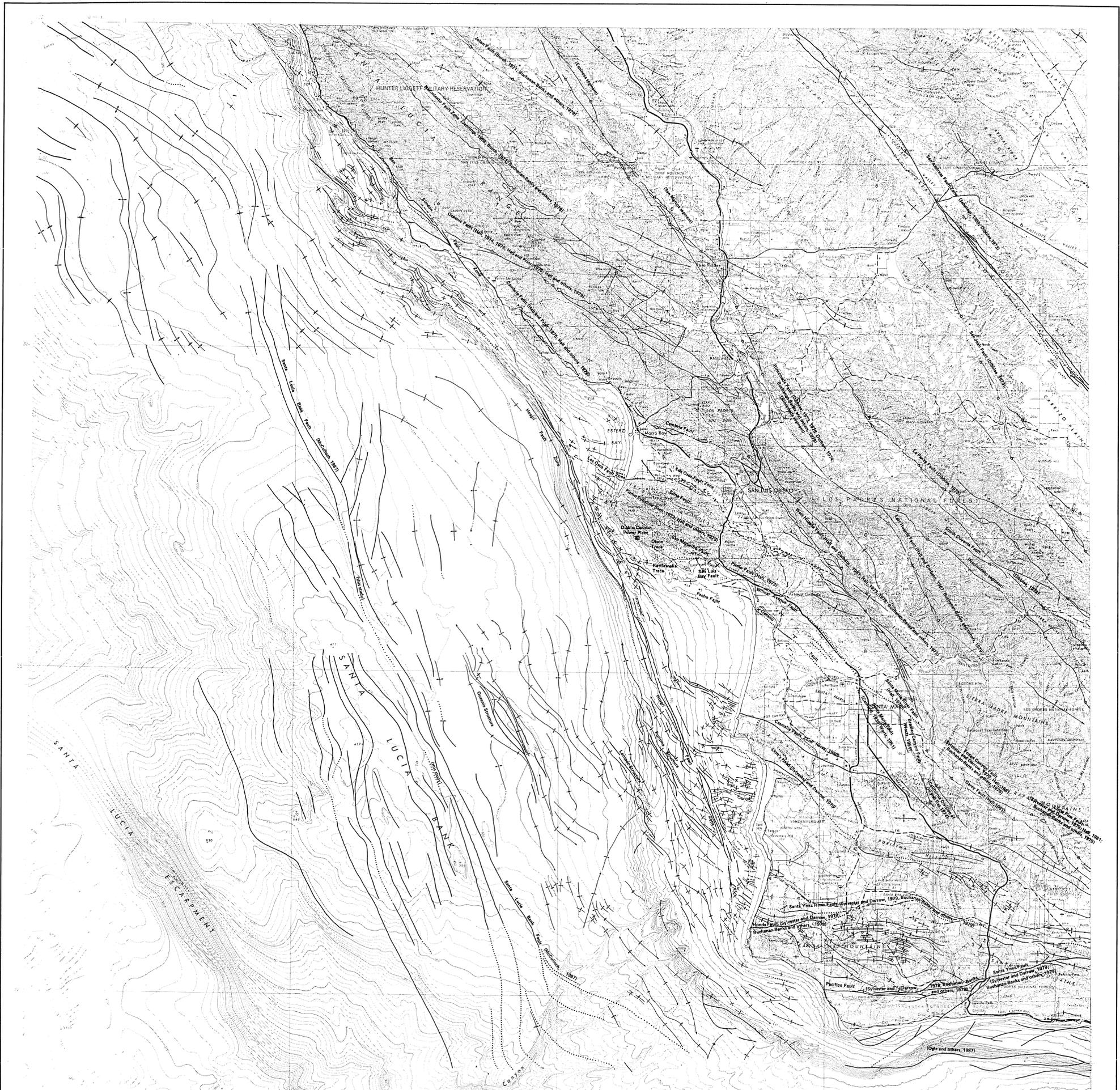
Diablo Canyon Power Plant Long Term Seismic Program
Pacific Gas and Electric Company
San Francisco, California July 1988

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EXPLANATION

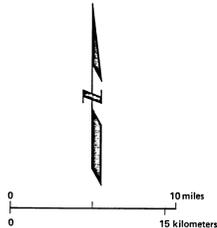
- Capable fault ; dotted where inferred
- - - - - Potentially capable fault ; dotted where inferred
- - - - - Inactive fault ; dotted where inferred
- - - - - Anticline ; showing trace of axial surface and direction of plunge ; dotted where inferred
- - - - - Syncline ; showing trace of axial surface and direction of plunge ; dotted where inferred
- - - - - Monocline

Note: Onshore folds south of 35° N latitude are from Dibblee (1950, 1966). Folds north of this latitude are from Jennings (1977).

Base map from U.S. Department of Commerce, National Oceanic and Atmospheric Administration Bathymetric Series, Cape San Martin to Point Conception (Nos 130N-20) and U.S. Geological Survey 1" x 2" Topographic Series, San Luis Obispo and Santa Maria quadrangles

Bathymetric contour intervals: 10 meters to the 200 meters depth, then 50 meters to maximum depth. Datum MLLW

Topographic contour interval: 200 feet with supplementary contours at 100 feet intervals



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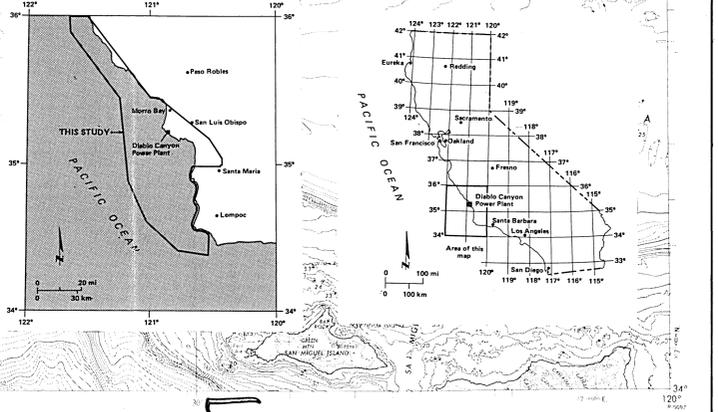
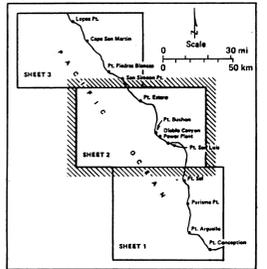
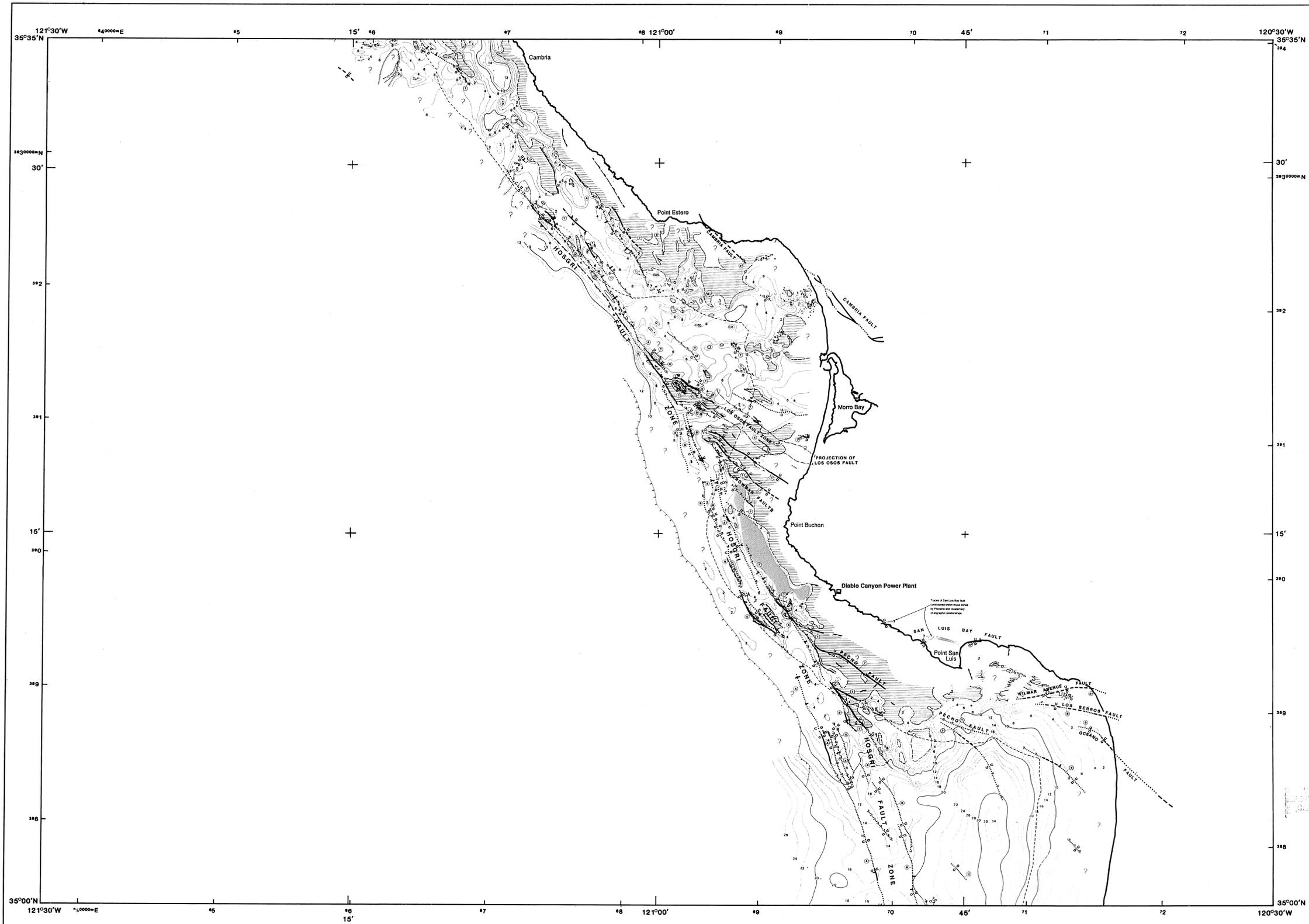


Plate 3

**Map of Faults and Folds
Identified During Previous Investigations
and During the Long Term Seismic Program,
South-Central California**

Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California July 1988	

8808050336-07



EXPLANATION

Geologic Structures

- Fault at seafloor, dashed where location inferred; arrows or U/D indicate relative sense of displacement where known; bar indicates dip of fault plane, where known.
- - - Structural feature that could be a fault at the seafloor.
- - - Limits of discrete submarine zone of structural complexity within which individual faults cannot be distinguished.
- Fault buried beneath post-late Wisconsinan sediment, dashed where location inferred.
- - - Structural feature that could be a fault buried beneath post-late Wisconsinan sediment.

Estimated Age of Most Recent Displacement

- ⊙ Evidence of displacement during or since late Wisconsinan (15,000 years ago).
- ⊙ Displaces 120,000 year-old marine oxygen isotope stage 5 terrace, post-late Wisconsinan beds not recognized.
- ⊙ Plio-Pleistocene horizon is cut; late Wisconsinan unconformity is present but not cut.
- ⊙ Top Miocene horizon is cut; Plio-Pleistocene horizon is present but not cut.
- ⊙ Unknown; age control is lacking.

Isopach Information

- - - Contours showing thickness in meters of post-late Wisconsinan sediment; dashed where location uncertain.
- ⊙ Area where late Wisconsinan unconformity is poorly imaged on high-resolution geophysical data.
- ⊙ Area of seafloor outcrop.
- ⊙ Area of probable gas-charged sediment that prevents determination of post-late Wisconsinan sediment thickness.

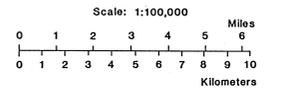
Geomorphic Features

- - - Seafloor scarp; rectangles indicate down-slope direction.
- - - Headwall of submarine slump; paired lines indicate down-slope direction.
- - - Margin of submarine canyon.
- - - Axis of submarine canyon where canyon margins are poorly defined; arrows point down channel.

Notes

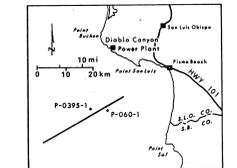
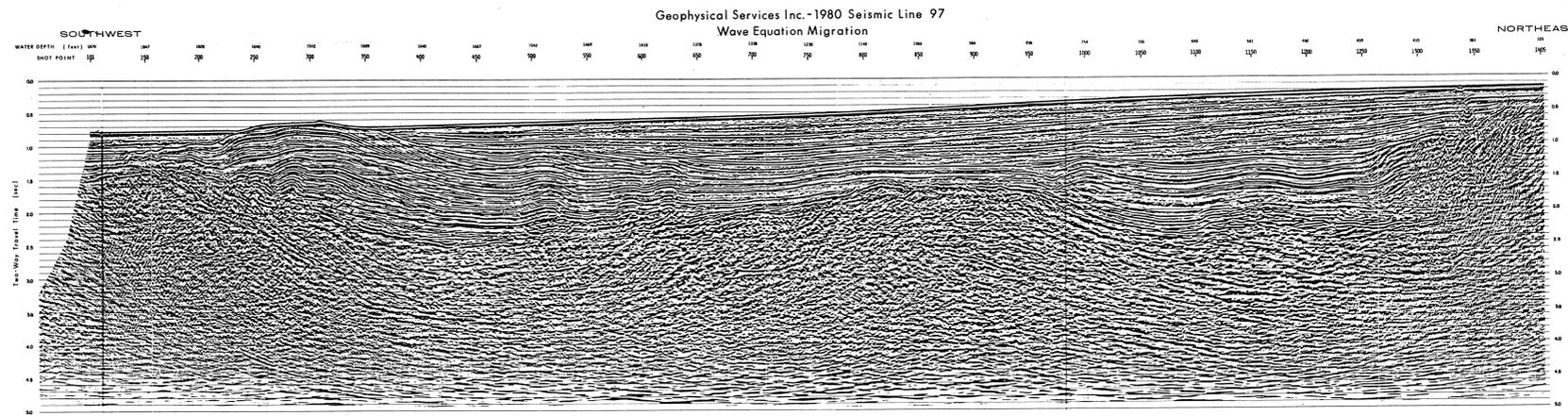
- 1) This map illustrates the trends, continuity and relationship to post-late Wisconsinan sediments of near-surface faults and structural features that could be faults.
- 2) Selected onshore structures are shown in the coastal zone to identify potential correlation with offshore structures.
- 3) All structure symbols extend 150 meters beyond the last geophysical or geological control point. Continuity of structures is inferred wherever data points are separated by more than 1.5 kilometers. No continuity is inferred if data points are more than 5 kilometers apart.
- 4) Map base is compiled from U.S. Geological Survey 1:100,000-scale (metric) topographic-bathymetric maps, San Luis Obispo and Cambria sheets. Projection and 10,000-meter grid are Universal Transverse Mercator, zone 10. Fine dashed line paralleling coast represents approximate boundary between California State and Federal waters.

E



Sheet 2 of 3	Plate 4
Near-surface Faults, Thickness of Post-late Wisconsinan Sediments and Seafloor Geomorphic Features of the Eastern Offshore Santa Maria Basin, California	
Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California	July 1988

8808050336-09



EXPLANATION

GEOLOGIC INTERPRETATION: The geologic interpretation is based on correlation between the seismic reflection network and petroleum exploration wells shown on Plate 1. Wells in the vicinity of this line are shown on the index map above and on the section.

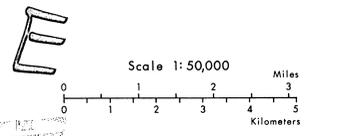
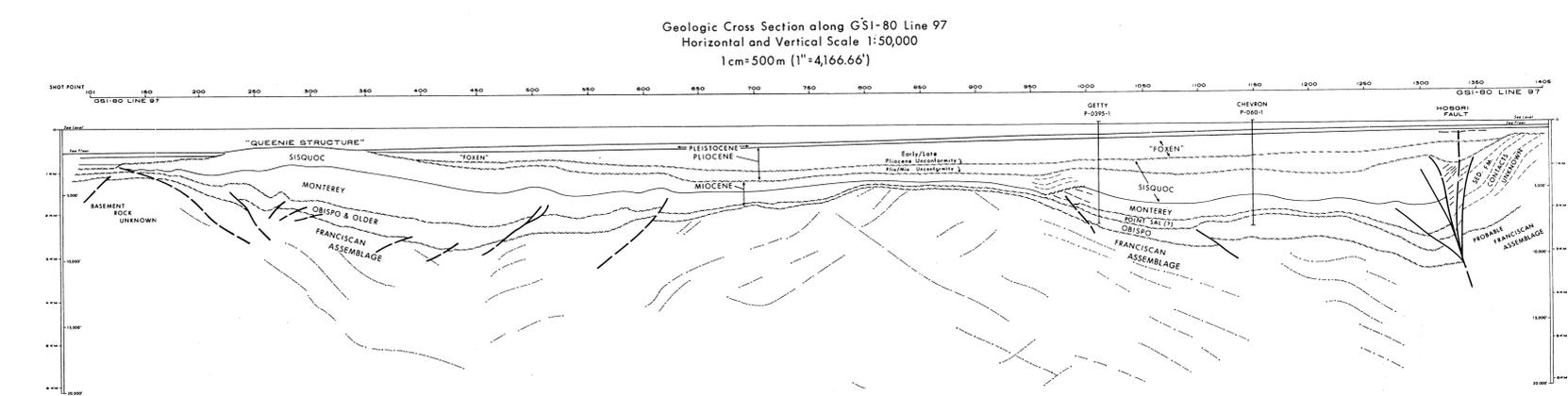
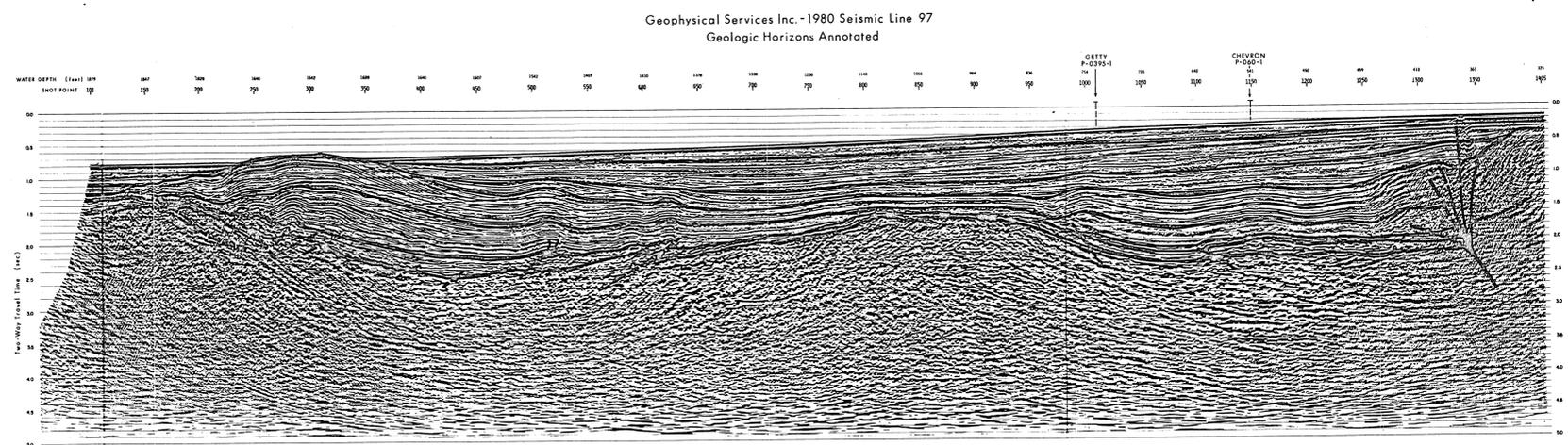
SEISMIC REFLECTION DATA:
 Data Collected By: Geophysical Service Incorporated in 1980
 Energy Source: Air guns
 Line Length: 33 kilometers
 Record Length: 5 seconds
 Sample Rate: 4 milliseconds
 Common-Depth-Point Stack: 4,800%
 Processing: Wave equation migration

WELL INFORMATION:
 Chevron OCS P-060-1, drilled in 1964
 Total depth 2,445 meters, water depth 168 meters
 Projected 1,483 meters northwest into line of section
 Getty OCS P-0395-1, drilled in 1983
 Total depth 2,377 meters, water depth 236 meters
 Projected 610 meters southeast into line of section

AGE INFORMATION:

Horizon Name	Geologic Age	Million Years
Base "Foxen" Unconformity	Early/Late Pliocene	2.8-3.0
Sisquoc Unconformity	Miocene/Pliocene	5.2
Top of Monterey Formation	Late Miocene	6.5-7.0
Top of Point Sal Formation	Early Miocene	~16.0
Top of Obispo Formation	Pliocene Stage	~17.5
Top of Franciscan Assemblage	Cretaceous and Jurassic	110-140

- SYMBOLS:**
- Contact
 - - - Stratification within formations
 - - - Unconformity
 - Fault
 - - - Fault, location inferred
 - - - Strata or fault in Franciscan assemblage or other basement rocks based on discontinuous seismic reflections
 - 700 Shot point location

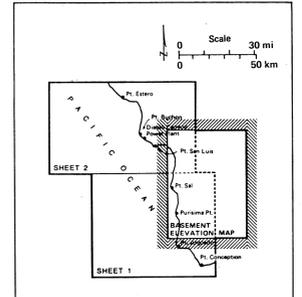
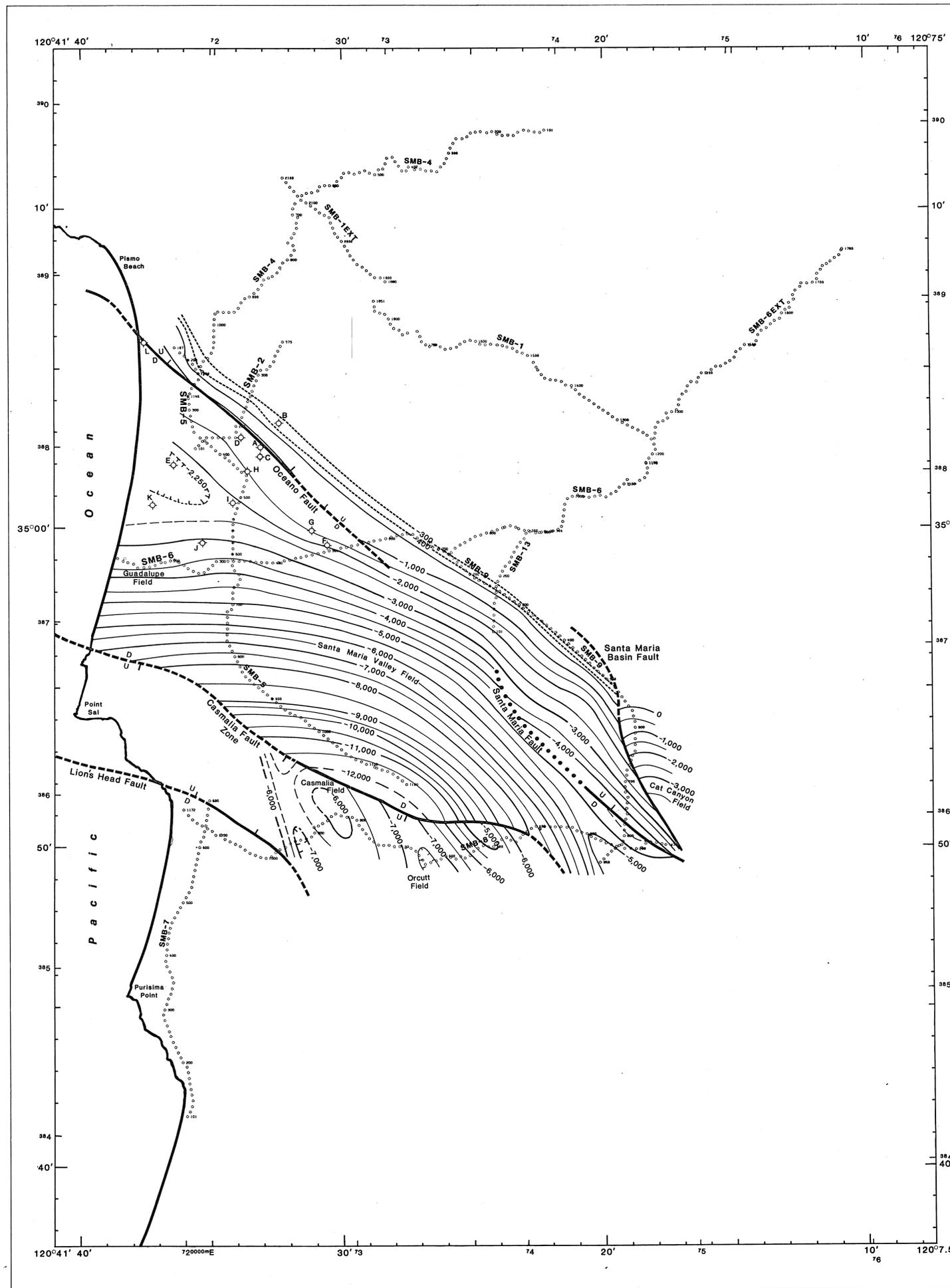


Sheet 1 of 3 Plate 7

**Geologic Interpretation of Seismic Sections,
Central Santa Maria Basin,
Geophysical Service Incorporated 1980,
Line 97**

Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California July 1988	

8808050336-15



EXPLANATION

MAP BASE: Compiled from U.S. Geological Survey 1:100,000 topographical-bathymetric maps, Santa Maria and San Luis Obispo sheets. Projection and 10,000-meter grid are zone 10, Universal Transverse Mercator.

SMB-1 Seisdata Services Incorporated
Santa Maria Valley Vibroseis Survey Line

—3,000— Contour showing basement in feet below mean sea level (MSL). Contour interval=500 feet. Heavier contours at 1,000-foot intervals.

- - - - - Approximately located contour

----- Intermediate contour

U D Fault; dashed where approximately located, dotted where inferred. Location control is from this seismic survey and Grey (1980). U-up/D-down and arrows indicate inferred sense of movement. Bar indicates direction of dip on reverse faults and sawtooth marks are on the upper plate of reported thrust faults.

Basement elevations are based on depth determinations to a prominent seismic reflector variously reported as either Franciscan assemblage or Knoxville Formation in wells. Additional depth control is from the wells indicated below, outcrop and water-well data, and Grey (1980).

WELL DESIGNATIONS	BASEMENT ELEVATION IN FEET BELOW MSL
A. Superior Hutchinson 63-1	-1030
B. Superior Callender 36-1	-336
C. Aviation Brintnall -1	-1615
D. Page Callender Mesa -1	-1283
E. Stanbury Webb Bosse -1	-2461
F. Union Bognuda -1	-1973
G. Texas Bolton -1	-1399
H. Superior Beckett -1	-1493
I. Union Sugar CH-1	-2015
J. Union Sugar Thornbury 1-75	-3100
K. Mobil La Veaga 3	-2036
L. Madonna Oceano -1	-5570

Additional control came from wells in the Guadalupe, Santa Maria Valley, Casmalia, Orcutt, and Cat Canyon oil fields.

E

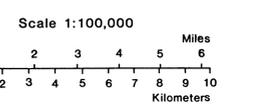
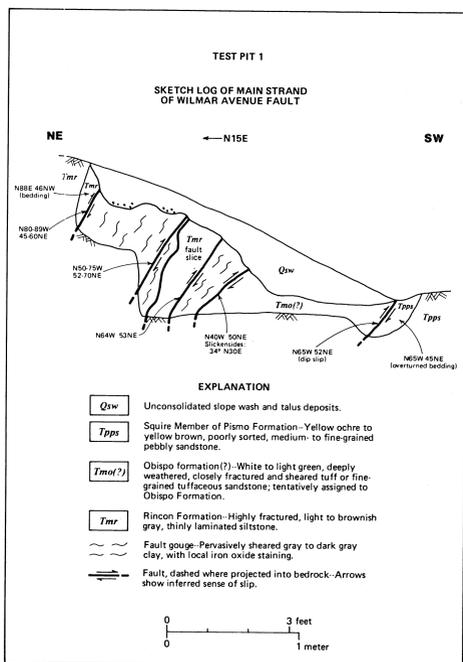
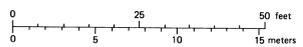
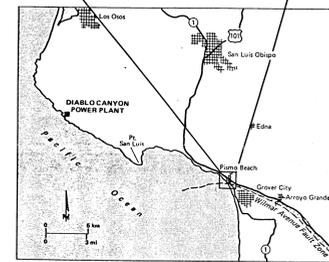
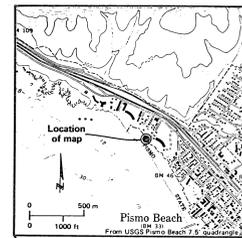
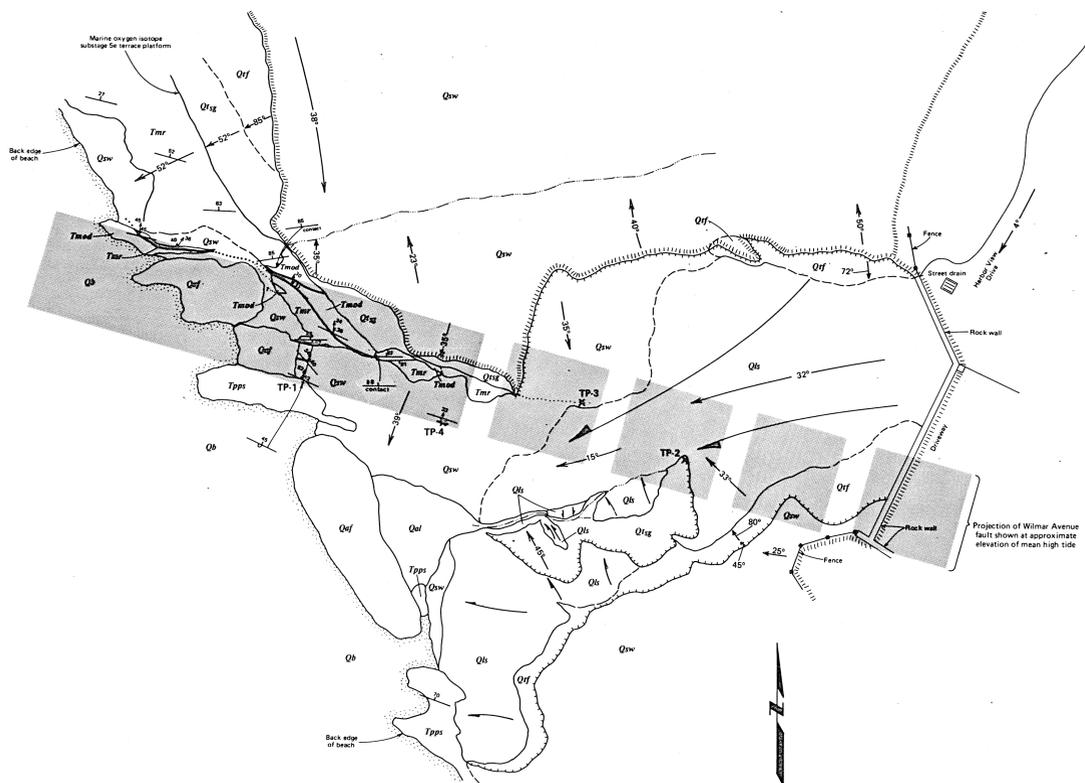


Plate 9

Generalized Basement Elevation Contours and Faulting in the Santa Maria Valley

Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California	July 1988

8808050336-19



TEST PIT DESCRIPTIONS

TP-1: Shear zone of clay gouge separates Tmr and Tpps. See geologic log.

TP-2: 2 meters of slope wash covering 0.5 meter of fine to medium sand which overlies sandy clay with gravel.

TP-3: Qt over Tmod.

TP-4: Tmr thrust over Q_{af}; pervasively sheared greenish gray to orange or reddish gray clay gouge zone 5-13 centimeters thick overlies pebbles, cobbles, and sand terrace deposits. Shear zone is oriented approximately N75W, 33NE, locally as steep as 45° NE; bedding in Tmr is oriented N81W, 33NE.

SYMBOLS

- Contact, dashed where approximate, dotted where concealed.
- Fault, dotted where concealed.
- ↗ Strike and dip of bedding. "contact" indicates attitude of contact surface.
- ↖ Strike and dip of overturned bedding.
- ↗↖ Strike and dip of fault, showing trend and plunge of striations/slickensides.
- ⊖ Landslide deposit, hachures show headwall scarp of slide, arrows show direction of movement.
- Gully or bottom of drainage
- x TP-2 Test pit location
- ↘ 23° Dip of slope in degrees
- Top of cliff
- ■ ■ Indicates approximate extent of fault zone.

MAP UNITS

Surficial Deposits

- Qaf** Artificial fill—Surficial spoil related to human activity.
- Qal** Alluvium—Fine-grained sand and other debris deposited at end of culvert.
- Qb** Beach sand—Fine-grained, well-sorted sand.
- Qls** Landslide deposit—Currently active, composed of gravel, sand, silt, and clay plus artificial debris (i.e. concrete blocks, metal objects, etc.). Slides are generally bounded by open ground cracks and low, unvegetated scarps.
- Qsw** Slope wash—Deposits of gravel, sand, silt, and clay mantling slope; highly variable thickness, derived from weathering, soil creep, sloughing, and other slope degradation processes.

Marine Terrace Deposits

- Qmf** Alluvium/colluvium, undifferentiated—Gray, gray-brown to gray-black, sandy silty clay with locally abundant angular rock fragments which impart a crude stratification to the deposits; fluvial/colluvial origin.
- Qmg** Interbedded sand and gravel—Size varies from fine-grained sand to boulders. Basal marine lag deposit on wave-cut platform contains blocks of Tmod; marine origin.

Bedrock Units

- Tpps** Squire Member of Pismo Formation (Pliocene)—Gray to yellowish green, poorly consolidated, pebbly to cobbly, poorly sorted fine to coarse-grained sandstone; massive to medium bedded.
- Tmod** Diabase Member of Obispo Formation (Miocene)—Dark gray green, medium-grained, close fracture spacing.
- Tmr** Rincon Formation (Miocene)—Dark to light gray to buff, interbedded silt and claystone; well bedded; highly fractured with gypsum veinlets and jarosite common.

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Plate 21

**Detailed Geology of the
Wilmar Avenue Fault
Sea Cliff Exposure,
Pismo Beach, California**

Diablo Canyon Power Plant	Long Term Seismic Program
Pacific Gas and Electric Company	
San Francisco, California	
July 1988	

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