BECHTEL SAIC COMPANY LLC

QA: NA

June 2004

Technical Basis Document No. 14: Low Probability Seismic Events

Revision 1

Prepared for:

U.S. Department of Energy

Office of Civilian Radioactive Waste Management
Office of Repository Development
1551 Hillshire Drive
Las Vegas, Nevada 89134-6321

Prepared by:
Bechtel SAIC Company, LLC
1180 Town Center Drive
Las Vegas, Nevada 89144

Under Contract Number

DE-AC28-01RW12101

ENCLOSURE 1

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ACRONYMS

AIN	additional information need
CLST	Container Life and Source Term
DBFD	design basis fault displacement
DBGM	design basis ground motion
DOE	U.S. Department of Energy
EBS	engineered barrier system
ECRB	Enhanced Characterization of the Repository Block
ESF	Exploratory Studies Facility
FEP	feature, event, or process
KTI	Key Technical Issue
LA	license application
NRC	U.S. Nuclear Regulatory Commission
PSHA	probabilistic seismic hazard analysis
RDTME	Repository Design and Thermal-Mechanical Effects
SDS	Structural Deformation and Seismicity
TSPA	total system performance assessment
TSPAI	Total System Performance Assessment and Integration

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1. INTRODUCTION

1.1 OVERVIEW

This technical basis document provides a summary of the conceptual understanding of low-probability seismic events. Low-probability seismic events are unlikely but possible earthquake fault displacements and vibratory ground motions that could affect the Yucca Mountain site. This document and the associated references form an outline of the ongoing development of the postclosure safety analysis that will be included in the license application (LA). The conceptual understanding summarized here also provides a framework for addressing open Key Technical Issue (KTI) agreements between the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) that are related to low-probability seismic events and postclosure repository performance. Because the characteristics of low-probability seismic events are also an input to preclosure safety analyses, the conceptual framework presented in this report additionally supports the resolution of KTIs related to preclosure seismic design.

This technical basis document is one in a series that is being prepared for each component of the repository system that is relevant to postclosure performance. This document focuses on the prediction of postclosure seismic hazards and the potential effects of these hazards on performance of the emplacement drifts and the engineered barrier system (EBS). The postclosure seismic hazards are vibratory ground motion and fault displacement. The major elements of the EBS are the waste package, drip shield, emplacement pallet, and the fuel rod cladding.

Seismic hazards are also a consideration in demonstrating preclosure performance. While a complete discussion of the seismic aspects of preclosure performance is beyond the scope of this report, the development of seismic inputs for preclosure analyses is largely identical to the development of seismic inputs for postclosure analyses. Thus, this report describes the development of seismic inputs for both time frames. It does not, however, describe how the preclosure seismic inputs are used in demonstrating compliant preclosure performance.

The relationship of low-probability seismic events to the other components of postclosure repository performance is illustrated in Figure 1-1. As higher levels of ground motion are considered, their annual probabilities of exceedance become lower. At some point, seismic loads could contribute to mechanical degradation of the waste-emplacement drifts and generate rockfall that impinges on drip shields. The residual tensile stresses induced in drip shields by rockfall could lead to accelerated drip shield corrosion, if those stresses exceed a particular threshold. Low-probability vibratory ground motion could cause impacts between adjacent waste packages, between the waste package and its emplacement pallet, between the waste package and the drip shield, between the drip shield and emplacement pallet, and between the drip shield and invert. Residual tensile stresses induced by such impacts could lead to accelerated drip shield and waste package stress corrosion cracking if those stresses exceed material-specific thresholds. Seismically induced impacts also could damage the cladding of the spent nuclear fuel waste form inside the waste packages and degrade the cladding's performance as a barrier to radionuclide migration. Seismically induced rockfall would change the shape of waste-emplacement drifts, which could affect the seepage rate of water into the drifts. The presence of seismically induced rockfall also would change thermal properties within the drifts. Volcanic events are commonly preceded and accompanied by numerous earthquakes that indicate progressive rock failure as magma rises to the ground surface, and such volcanic-related earthquakes are considered in the evaluation of seismic hazard. Seismic effects on the other natural systems and processes illustrated in Figure 1-1 also have been considered, but no other potentially significant seismic effects have been identified.

1.2 PURPOSE AND SCOPE

This document provides an overview of the current understanding of low-probability seismic events and their possible effects on the components of the repository that are potentially important to long-term (postclosure) repository performance. The focus is on the potential damage to EBS components from severe, low-probability events because less severe but more likely seismic events do not have the potential to disrupt the drip shield, the waste package, the emplacement pallet, and the cladding.

This document also discusses less severe, higher probability (i.e., more frequent) ground motion that is considered in preclosure seismic design and safety analyses. The document does not, however, describe preclosure seismic strategy or preclosure seismic design analyses. These aspects of preclosure application are described in other Yucca Mountain Project documents, such as *Preclosure Seismic Design Methodology for a Geological Repository at Yucca Mountain* (BSC 2004a) and *Preliminary Seismic Analysis for Preclosure Safety Analysis* (BSC 2003a). They are beyond the scope of this report. Similarly, hydrologic changes caused by seismic activity are detailed in *Technical Basis Document No. 3: Water Seeping into Drifts.*

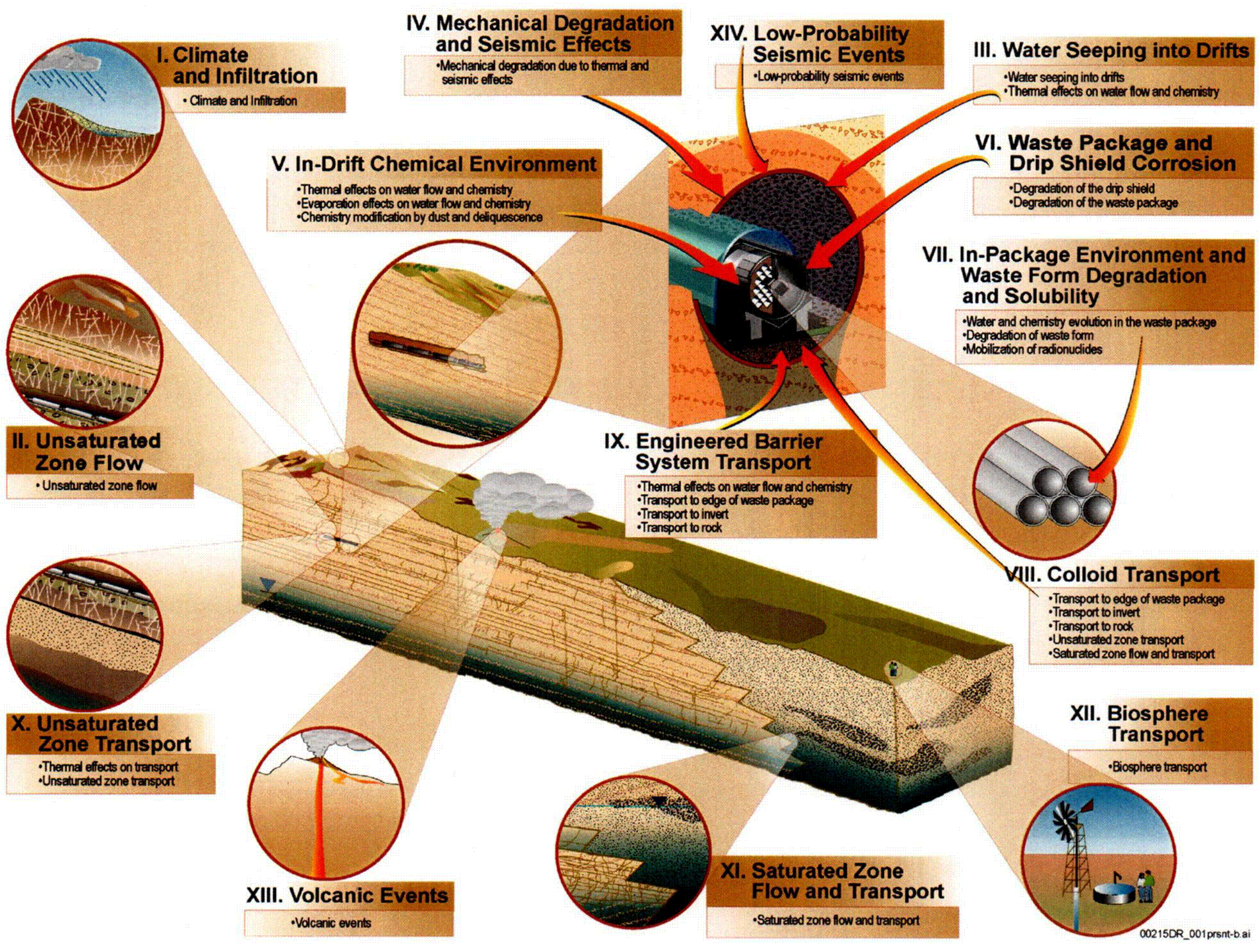

Figure 1-1. Components of the Postclosure Technical Basis for the License Application

The body of this report documents the conceptual framework for responses to open KTI agreements between the DOE and the NRC that are related to low-probability seismic events and repository postclosure performance. Detailed responses to these KTI agreements are provided in Appendices A through D, as shown in Table 1-1.

Table 1-1. Key Technical Issue Agreements Related to Low-Probability Seismic Events Addressed in This Report

KTI Agreement/AIN	Appendix	Short Description
CLST 3.10, TSPAI 3.06	A	Rockfall and vibratory loading effects on the mechanical failure of cladding, and methodology used to implement the effects of seismic effects on cladding
RDTME 2.01, RDTME 2.02, RDTME 3.03, and SDS 2.02	B	Documentation of preclosure seismic design inputs, preclosure seismic design methodology, and features, events, and processes related to potentially disruptive igneous or seismic activity
SDS 2.01 AIN-1	C	Documentation of expert elicitation process
SDS 2.04 AIN-1	D	Documentation of seismic fragility curves and seismic risk analysis

For the postclosure period, 10 CFR 63.114 requires that DOE conduct a performance assessment that consider only events that have at least 1 chance in 10,000 of occurring over 10,000 years.

Seismic events that have this probability of occurrence have been analyzed and are discussed in this technical basis document. In addition, 10 CFR 63.102(j) provides that, for the postclosure period, the event classes analyzed in the performance assessment should consist of all possible specific initiating events that are caused by a common natural process (e.g., the event class for seismicity includes the range of credible earthquakes for the Yucca Mountain site). Additional studies are currently being conducted to ascertain constraints on credible maximum ground motion, and results of those studies are not discussed in this document. The additional studies do not affect the technical bases or conclusions described in this document. The results of those studies will be included in the license application, as appropriate.

1.3 SCREENING OF SEISMIC-RELATED FEATURES, EVENTS, AND PROCESSES

The identification of seismic effects that could be significant to repository postclosure performance was accomplished as part of a comprehensive effort to identify and address the features, events, and processes (FEPs) that could affect repository performance. Each identified FEP is screened in or out of the total system performance assessment (TSPA), depending on the consequences and probability that have been assessed for that FEP. As documented in *Features, Events, and Processes: Disruptive Events* (BSC 2004b), the seismic-related FEPs are:

- Tectonic activity—large scale
- Fault displacement damages EBS components
- Seismic ground motion damages EBS components
- Seismic-induced rockfall damages EBS components
- Seismic-induced drift collapse damages EBS components
- Seismic-induced drift collapse alters in-drift thermal-hydrology
- Seismicity associated with igneous activity
- Hydrologic response to seismic activity
- Seismic activity changes porosity and permeability of rock
- Seismic activity changes porosity and permeability of faults
- Seismic activity changes porosity and permeability of fractures
- Seismic activity alters perched water zones.

Each of these seismic-related FEPs and its screening status are discussed briefly. More detailed discussion and supporting references are provided in *Features, Events, and Processes: Disruptive Events* (BSC 2004b).

Tectonic Activity—Large Scale–Large-scale tectonic activity includes regional uplift, subsidence, folding, mountain building, and other processes related to plate tectonics. These tectonic processes could alter the physical and thermal-hydrologic properties of the earth's crust in the Yucca Mountain region. These changes, in turn, would have the potential to alter the groundwater flux through the repository and the amount of water contacting EBS components and, thereby, alter the performance characteristics of the repository and its engineered components. Yucca Mountain lies within the Walker Lane domain, an area of ongoing tectonic deformation (see Section 2.1.1). However, the rate of tectonic deformation since at least the beginning of the Quaternary Period, 1.8 million years ago, is too slow to significantly affect Yucca Mountain during the regulatory compliance period of 10,000 years. Therefore, this FEP has been screened out on the basis of low consequence (BSC 2004b, Section 6.2.1.1) and is not further addressed in this report.

Fault Displacement Damages EBS Components–This FEP describes a geologic fault that intersects waste-emplacement drifts within the repository and that undergoes movement during an earthquake. The EBS components experience related movement or displacement such that performance is degraded by component shearing due to vertical fault displacement or by drip shield separation due to tilting of components. This FEP has been screened in (BSC 2004b, Section 6.2.1.2) and is addressed in Section 5.5.

Seismic Ground Motion Damages EBS Components–In this FEP, earthquake vibratory ground motion shakes the EBS components (drip shield, waste package, pallet, and invert). The vibration could directly damage the drip shields, waste packages, and waste package internals or cause impacts between EBS components that could lead to damage. Such damage could degrade the performance of the EBS components as barriers to radionuclide migration. This FEP has been screened in (BSC 2004b, Section 6.2.1.3) and is addressed in Section 5.4.

Seismic-Induced Rockfall Damages EBS Components–Seismic ground motion has the potential, because of the additional imposed stresses, to cause blocks of rock to be shaken loose from the walls of emplacement drifts. The mechanical impact of rockfall could damage the drip shields. Drip shield damage, in turn, could lead to more seepage water contacting the waste packages. The waste packages would not be directly impacted by rockfall because of the protection afforded by the drip shields. This FEP has been screened in (BSC 2004b, Section 6.2.1.4) and is addressed in Section 5.3.

Seismic-Induced Drift Collapse Damages EBS Components–In this FEP, stresses induced in the walls of the emplacement drifts by seismic ground motion lead to collapse of all or part of the drift. The resulting rubble rests partially upon the drip shields and imposes a static load. However, engineering calculations summarized in Section 5.3.2 of this report indicate that the resulting static loads would be insufficient to cause structural failure of the drip shields. The waste packages are not directly affected by drift collapse because of the protection afforded by the drip shields. The consequences of the dead weight of rockfall on drip shield corrosion will be discussed in *Technical Basis Document No. 6: Waste Package and Drip Shield Corrosion.* This FEP is screened out of TSPA on the basis of low consequences (BSC 2004b, Section 6.2.1.5).

Seismic-Induced Drift Collapse Alters In-Drift Thermal-Hydrology–Downwardly percolating groundwater encountering a waste-emplacement drift will be partly diverted around the drift opening because of the capillary barrier effect, which refers to the tendency of water to be held in the pores of unsaturated rock rather than drip into a large opening. As a result, the water seepage flux is expected to be smaller than the local percolation flux. This barrier effect is an attribute of the unsaturated zone at Yucca Mountain. Seismic activity could lead to drift collapse and resulting rockfall rubble throughout part or all of an emplacement drift. The change in drift profile and presence of rubble would reduce the effectiveness of the capillary barrier and lead to increased water seepage. This FEP has been screened in (BSC 2004b, Section 6.2.1.6) and is addressed in Section 4.7 of *Technical Basis Document No. 3: Water Seeping into Drifts.* Analyses supporting that technical basis document indicate an approximately 2% to 5% increase in seepage for worst-case changes to the drift profile. The presence of rubble also would affect thermal properties within the EBS. The presence of rubble around the drip shield will also cause changes in the temperature and relative humidity of EBS components. The magnitude of these changes has been estimated with thermal-hydraulic calculations using the multiscale model (BSC 2004c). These calculations predict changes in temperature and relative humidity for eight different waste package emplacement configurations, using bounding (high or low) values for the thermal conductivity of the rubble surrounding the drip shield. The results from these calculations (DTN: LL040310323122.044) are included in the appropriate models for TSPA.

Seismicity Associated with Igneous Activity–Volcanic eruptions are commonly preceded and accompanied by numerous earthquakes that indicate progressive rock failure as magma rises to the earth's surface. Seismic events associated with igneous activity, like seismic events associated with tectonic activity, have the potential to disrupt the integrity of components of the EBS and thereby affect repository performance. This FEP has been screened in (BSC 2004b, Section 6.2.1.7) and is addressed in the probabilistic seismic hazard analysis (PSHA) described in this report (Section 3.2.1).

Hydrologic Response to Seismic Activity–Seismic activity associated with fault movement could create new or enhanced flow pathways or connections between rock units, or it may change the rock stress and, therefore, fluid pressure within the rock. These effects have the potential to change hydrologic system attributes, such as the surface water and groundwater flow directions and water level. The effects on groundwater flow and radionuclide transport by seismic-induced changes to fracture systems have been investigated in sensitivity studies. The results indicate that changes in fracture aperture confined to fault zones have minimal effect on transport behavior in the unsaturated zone. Increased fracture aperture applied over the entire unsaturated zone domain results in effects that are no more significant than other uncertainties related to infiltration (in particular, uncertainties related to the range of future climatic conditions). A number of other studies on the effect of seismic activity on the water table level indicate that changes caused by seismic activity would be, at most, a few tens of meters and would not reach the repository level. These changes would be transient and would not significantly affect groundwater flow or radionuclide transport. Because hydrologic response to seismic activity does not provide a mechanism to significantly affect performance, this FEP has been screened out on the basis of low consequence (BSC 2004b, Section 6.2.1.8) and is not further addressed in this report.

Seismic Activity Changes Porosity and Permeability of Rock–Earthquake fault displacement and vibratory ground motion have the potential to change rock stresses and create strains that affect flow properties. Specifically, seismic activity could cause strains that alter the permeability in the rock matrix. The net effects of rock matrix permeability changes are a temporary rise or decline of the water table level and changes in groundwater flow and radionuclide transport in the unsaturated zone. However, as discussed for the preceding FEP, these effects are not significant to repository performance and, therefore, this FEP has been screened out of TSPA on the basis of low consequence (BSC 2004b, Section 6.2.1.9). It is not further addressed in this report.

Seismic Activity Changes Porosity and Permeability of Faults–Earthquake fault displacement and vibratory ground motion could cause movement along rock fractures and change stresses and strains that alter the permeability along faults. The redistribution of strain could reactivate preexisting faults or generate new faults. These effects could alter or short-circuit the flow paths and flow distributions close to the repository and create new pathways through the repository, leading to decreased radionuclide transport times. However, the effects of changes to fracture systems due to geologic effects have been investigated in sensitivity studies. The results indicate that changes in fracture aperture confined to fault zones show virtually no effect on transport behavior in the unsaturated zone. In addition, an early, corroborative analysis of the effect of a fault on flow in the saturated zone suggests that there would be negligible impact on performance, even for fault hydraulic conductivities varying over five orders of magnitude. This FEP has been screened out on the basis of low consequence (BSC 2004b, Section 6.2.1.10) and is not further addressed in this report.

Seismic Activity Changes Porosity and Permeability of Fractures–This FEP is similar to the preceding FEP, but it involves fractures rather than faults. Fractures are breaks in rock that, unlike faults, show little or no displacement parallel to the fracture surface. Earthquake fault displacement or vibratory ground motion could change stresses and strains that alter the permeability along fractures. Seismic activity could reactivate existing fractures or generate new fractures. Generation of new fractures and reactivation of existing fractures could change groundwater flow and radionuclide transport paths, alter or short-circuit the flow paths and flow distributions close to the repository, and create new pathways through the repository. These effects could decrease radionuclide transport times. The rock at Yucca Mountain is highly fractured, and existing fractures are likely to accommodate seismically induced stresses. Therefore, generation of new fractures as a result of seismic activity is likely to be negligible. And, as already noted, the effect on groundwater flow and radionuclide transport of changes to fracture systems due to geologic effects, such as fault displacement and seismic ground motion, have been investigated in sensitivity studies. The results indicate that increased fracture aperture applied over the entire unsaturated zone domain results in effects that are no more significant than other uncertainties related to infiltration. Therefore, this FEP is screened out on the basis of low consequence (BSC 2004b, Section 6.2.1.11) and is not further addressed in this report.

Seismic Activity Alters Perched Water Zones–Strain caused by stress changes from seismic events could lower rock permeabilities, effectively sealing a volume of rock against groundwater flow and leading to the formation and persistence of perched-water zones (volumes of water-saturated rock above the general water table). The generation of a perched-water zone above the repository could potentially affect the flow of water to waste-emplacement drifts. This potential effect is addressed indirectly in the model for water seepage into drifts, which shows that rock heterogeneity will lead to focusing of water flow (see *Technical Basis Document No. 3: Water Seeping into Drifts*, Section 2.2). Below the repository, the potential to release perched water because of stress changes and fracture openings has the potential to result in a pulse of radionuclides, if the perched water contains radionuclides and is allowed to drain. However, considering the amount of water in the fracture domain below the repository and the radionuclides that could be contained in this water, such a pulse would cause a minimal change in the radionuclide mass flux at the water table. Therefore, this FEP has been screened out on the basis of low consequences (BSC 2004b, Section 6.2.1.12) and is not further addressed in this report.

1.4 ORGANIZATION AND APPROACH

This report describes the information that supports the assessment of repository system performance, considering seismic disruption, as illustrated in Figure 1-2.

Section 2 summarizes the data supporting the Yucca Mountain seismic hazard analysis. This information base includes:

- Regional and local tectonic interpretations
- Regional and local seismicity compilations (location, frequency, and magnitude of earthquakes) coming primarily from earthquake catalogs that document earthquakes recorded by seismic monitoring networks and records of earthquake felt effects
- Regional and local geologic maps of earthquake faults
- Paleoseismic reconstructions of the timing and magnitude of earthquakes on individual faults
- Geodetic measurements of crustal strain rates in the Yucca Mountain region
- Studies of how seismic waves propagate through the earth's crust and attenuate with distance, based on the analysis of ground motion recordings.

Section 3 summarizes the PSHA that was conducted for the Yucca Mountain site. The PSHA provides a structured framework for documenting the range of current scientific thinking about the factors that control seismic hazard and the associated uncertainties. In the Yucca Mountain PSHA study, seven seismologists and earthquake engineers who are experts in ground motion estimation evaluated available worldwide and regional strong ground motion recordings and other relevant data about seismic wave propagation in the Yucca Mountain region. Through an expert-elicitation process, these experts provided interpretations of ground motion levels and uncertainties for a range of magnitude, distance, and faulting style combinations. Their interpretations consisted of median values and associated standard deviations (variability due to the inherent randomness of earthquake processes). In developing their interpretations, the experts considered alternative ground motion models that are consistent with the available information. In evaluating those models, the experts gave more weight to those that they determined were closer to physical reality for Yucca Mountain. For both the median and standard deviation, the experts also provided assessments of uncertainty resulting from the inability of the available data to discriminate among the possible models.

A similar process was followed in the PSHA study for the identification of seismic sources. Seismic sources are defined as areas or volumes of the earth's crust that can be characterized by a specified relationship between earthquake recurrence rates and earthquake magnitude and by a probability distribution for maximum earthquake magnitude. In this case, six expert teams, rather than individual experts, provided the interpretations. Each expert team consisted of three earth scientists who collectively had sufficient expertise in seismology, geology, geophysics, and tectonics to be able to interpret seismic source zones based on the available information.

Following an expert elicitation process, each team developed alternative seismic-source interpretations and weights for those interpretations. Uncertainty in current scientific understanding of seismic sources is expressed by the range of interpretations and the assigned weights. Variability in earthquake location, timing, and magnitude due to the random nature of earthquake occurrences is expressed by random variables that are specified in each interpretation.

The six expert teams also developed interpretations of earthquake fault displacement. The teams settled on two basic, alternative approaches. The first, called the "earthquake approach," parallels the PSHA formulation for ground shaking hazard and relates the occurrence of displacement on a geologic feature to the magnitude and distance of earthquakes in the site region. The feature in question may be a fault, a minor shear, a fracture, or unbroken ground. The second, called the "displacement approach," utilizes the geologic history of fault displacement observed at the site of interest to quantify the hazard, without invoking a specific mechanism for its cause.

The final ground motion products of the PSHA study are plots of the annual rate of exceeding a particular measure of vibratory ground motion (e.g., peak acceleration) versus ground motion level. These probability distributions are referred to as "hazard curves." There is one hazard curve for every combination of alternative seismic-source interpretations (from each expert team) and every alternative ground motion interpretation (from each ground motion expert). The weight assigned to each hazard curve is the combined weights of the associated source interpretation and ground motion interpretation. The hazard curves express the variability in ground motion due to the inherent randomness of earthquake processes, and the range of hazard curves expresses scientific uncertainty due to limits on available information. The variability and uncertainty are both carried forward into the TSPA and into the development and sampling of multiple ground motion time histories for postclosure rockfall and structural response calculations. Variability and uncertainty are also incorporated into the development of time histories for use in preclosure seismic design and safety analysis. For any annual rate of exceedance, the mean hazard curve can be deaggregated to identify the magnitudes and distances of those earthquakes contributing to the hazard.

The final fault-displacement products of the PSHA study are plots of the annual rate of exceeding particular fault-displacement levels. The fault-displacement hazard curves are defined for 17 different Yucca Mountain site locations and conditions. The site locations include locations on the known major faults, and the conditions specify a range of generic conditions (e.g., a small fault with a 2-m offset located somewhere between the Solitario Canyon Fault and Ghost Dance Fault). The range of locations and conditions is intended to cover the locations of potential interest at the Yucca Mountain site.

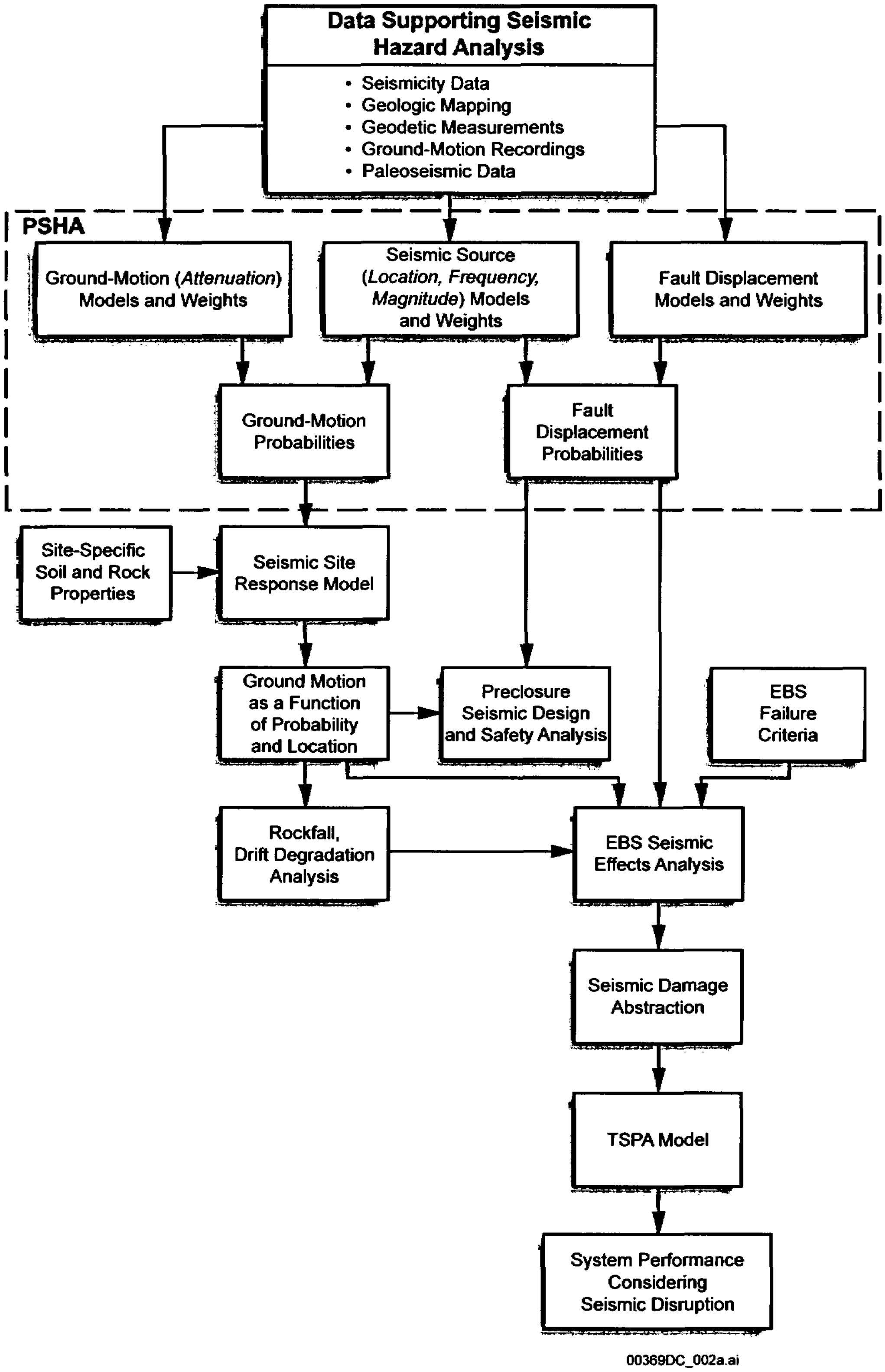

Figure 1-2. Components of the Assessment of Seismic System Performance

Section 4 describes the site-specific ground motion model and results. The ground motion hazard curves that resulted from the PSHA study apply to a hypothetical rock outcrop that has the same seismic-wave propagation properties as the rock at the repository horizon inside Yucca Mountain. The hazard curves at this reference rock location have to be modified to reflect site-specific rock properties for application to the actual locations of subsurface and surface facilities. The seismic site response model accounts for the effects of the approximately 300 m of rock overburden for the waste emplacement drifts and the effects of near-surface rock and soil at surface locations. The seismic response model also accounts for uncertainties in measurements of the site-specific soil and rock properties.

The site response model generates measures or descriptors of the level of vibratory ground motion for different annual exceedance rates at specified locations. For example, one product of the site response model is the peak ground velocity that has an annual exceedance rate of 1.0×10^{-6} at the repository horizon. The locus of values for different exceedance rates defines the peak ground velocity hazard curve at the specified location. For engineering analyses for which ground motion time histories are required, the site response model is used to generate suites of ground motion time histories representative of ground motion that would be expected from earthquakes in the contributing magnitude and distance ranges for a specified annual exceedance rate. Suites of time histories with considerable variability between the time histories are provided to model the natural variability in earthquake ground motion that results from the inherent randomness of earthquake processes.

The PSHA ground motion and fault-displacement hazard curves and the outputs of the site response model are equally applicable to the preclosure period of repository operations (approximately 100 years) and to the postclosure regulatory compliance period (10,000 years). This report focuses on their use in assessments of postclosure seismic system performance. For descriptions of their use in preclosure seismic design and safety analyses, see *Development of Earthquake Ground Motion Input for Preclosure Seismic Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain, NV* (BSC 2004d), *Preclosure Seismic Design Methodology for a Geological Repository at Yucca Mountain* (BSC 2004a), and *Preliminary Seismic Analysis for Preclosure Safety Analysis* (BSC 2003a).

Section 5 summarizes the calculated effects of seismic loading on the waste emplacement drifts and other EBS components. As noted in the discussion of seismic-related FEPs (Section 1.3), seismically induced stresses in the walls of the emplacement drifts can cause blocks of rock to be shaken loose and lead to accelerated drift degradation and rockfall. The mechanical impact of rockfall on the drip shields is not expected to cause immediate mechanical rupture but, rather, to leave residual stresses in the titanium plates of the drip shields. Similarly, vibratory ground motion is not expected to lead to immediate tensile failure but could, at very low probability levels, cause significant separation between adjacent drip shields. Severe, low-probability ground motion also could cause impacts between adjacent waste packages, between the waste package and its emplacement pallet, and between the waste package and the drip shield. These impacts are not calculated to cause an immediate puncture or tear in the barrier but would impose residual stresses in the Alloy 22 (UNS N06022) outer shell of the waste package. Given calculated residual stress levels in the drip shields and waste packages and a set of failure criteria that specify the residual tensile stress levels at which accelerated corrosion is expected to occur, the EBS seismic effects analysis then calculates the percent of the surface areas of the drip shields and waste packages that fail due to accelerated corrosion. In TSPA, immediate drip shield and waste package failure is assumed once their residual stress thresholds are exceeded, resulting in a network of through-wall stress corrosion cracks in the failed areas that exceed the stress threshold. On the drip shield, this network of cracks is expected to plug from evaporation-induced precipitation of calcite and other minerals in the groundwater, thereby preventing advective flow through the cracks. On the waste package, the crack network is assumed to always allow diffusive transport of radionuclides through the effective area of the network. The capacity of the crack network to support advective flow through the waste package is currently under investigation. Analogous to the consequence analysis for seismic loading from vibratory ground motion, the EBS seismic effects analysis also calculates failed waste package surface areas from extremely low probability fault-displacement events.

The EBS seismic effects analysis input to the TSPA is in the form of seismic damage abstractions. Based on the results of the EBS seismic effects analysis, the abstractions provide probability distributions for waste package and drip shield failed surface areas as functions of peak ground velocity. As described in Section 6, in each run or realization of the TSPA a peak ground velocity value is sampled randomly from the probability distribution defined by the peak ground velocity hazard curve for the repository horizon. This hazard curve is determined from the PSHA results and the ground motion site-response modeling. Also, in each realization, a distribution on upper-bound peak ground velocity is sampled. This distribution represents uncertainty in physical constraints on the levels of peak ground velocity that can be attained at Yucca Mountain. In each realization, if the sampled peak ground velocity exceeds the sampled upper-bound peak ground velocity, its value is reset to the value of the upper bound. Given this peak ground velocity, the TSPA then samples from the corresponding probability distributions for waste package and drip shield failed surface areas. These sampled seismic damage states, along with sampled values from probability distributions for other model inputs, are then used by the TSPA to calculate a dose to the reasonably maximally exposed individual, as defined by NRC regulations at 10 CFR 63.312. The TSPA is rerun many times to generate a statistically valid estimate of the mean annual dose. The mean annual dose is compared to the individual dose standard at 10 CFR 63.311 and is the primary measure of the effect of seismic events on postclosure performance of the repository. Additional measures of performance are projected radiation levels from specific radionuclides in a representative volume of groundwater, as defined by 10 CFR 63.332, which must meet groundwater protection standards at 10 CFR 63.331.

Section 7 provides conclusions regarding low-probability seismic events, and references are listed in Section 8.

1.5 SUMMARY OF CONCLUSIONS

This report documents the case for the following six key conclusions about low-probability seismic events:

1. Much is known about seismic hazards at Yucca Mountain. The geology and seismology of the site have been studied intensively for more than 20 years.

2. Potentially significant seismic effects on repository performance have been considered and addressed, as appropriate.

3. The seismic hazard analysis that has been carried out for Yucca Mountain accounts for both the variability in vibratory ground motion and fault displacement due to the inherent randomness of earthquake processes and the uncertainty due to limitations in scientific knowledge.

4. Large ground motion predicted by the PSHA at annual exceedance probabilities of 1.0×10^{-6} and below overestimates the severity of low-probability ground motion at Yucca Mountain. This overestimation of ground motion is being addressed through determination of constraints on maximum ground motion imposed by the stress-release characteristics of seismic sources and by limits on strain that can be propagated by seismic waves through rocks at Yucca Mountain. The constraint on maximum ground motion will be incorporated in the abstraction of seismic consequences that feeds TSPA.

5. Seismic and tectonic effects on the natural systems at Yucca Mountain will not significantly affect repository performance.

6. The EBS components are robust under seismic loads and will provide substantial protection of the waste form from seepage water, even under severe seismic loading.

1.6 NOTE REGARDING THE STATUS OF SUPPORTING TECHNICAL INFORMATION

This document was prepared using the most current information available at the time of its development. This document and its appendices providing KTI agreement responses were prepared using preliminary or draft information and reflect the status of the Yucca Mountain Project's scientific and design bases at the time of submittal. In some cases, this involved the use of draft analysis and model reports and other draft references whose contents may change with time. Information that evolves through subsequent revisions of the analysis and model reports and other references will be reflected in the LA as the approved analyses of record at the time of LA submittal. Consequently, the Yucca Mountain Project will not routinely update either this technical basis document or its KTI agreement appendices to reflect changes in the supporting references prior to submittal of the LA.

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2. DATA SUPPORTING SEISMIC HAZARD ANALYSIS

The assessment of seismic hazards at Yucca Mountain focuses on characterizing the potential vibratory ground motion and fault displacement that will be associated with future earthquake activity near the site. The PSHA was conducted based on the evaluation of a large set of data pertaining to earthquake sources, fault displacement, and ground motion propagation in the Yucca Mountain region (see Section 3). Tectonic models that have been proposed for the Yucca Mountain area and information from analog sites in the Basin and Range Province provide the basis to characterize the patterns and amounts of fault displacement. The data set also contains information providing the history of prehistoric earthquakes on nearby Quaternary faults (faults active during the last 1.8 million years). The historical earthquake record and information on the attenuation of ground motion are also important components of this data set.

This section summarizes the data sets and interpretations that support the PSHA for Yucca Mountain. The section begins by describing the seismotectonic framework of the Yucca Mountain region, followed by descriptions of historical seismicity and prehistoric earthquakes, followed by a discussion of data and analyses carried out to understand seismic ground motion and its attenuation in the region surrounding Yucca Mountain. The discussion is intended to summarize conclusions regarding these topics. A more detailed description is provided in the *Yucca Mountain Site Description* (Simmons 2004) and reference is made therein to associated documentation.

Site characterization activities that have resulted in data for understanding vibratory ground motion and fault displacement hazards at Yucca Mountain have included:

- Compilation of a historical catalog of earthquakes to support analyses of earthquake recurrence rate and magnitude distribution
- Establishment of a network of seismometers and strong-motion instruments to monitor and characterize contemporary seismicity
- Reconnaissance geologic surveys of known and suspected Quaternary faults within 100 km of the site to characterize their extent and rates of activity
- Geophysical surveys to identify and characterize the orientation of subsurface faults
- Geologic mapping of faults and geologic units in the local Yucca Mountain area
- Paleoseismic studies of known and suspected Quaternary faults in the immediate vicinity of Yucca Mountain to provide information on past earthquakes, including their number, size, extent, and timing
- Geodetic monitoring to understand rates of regional deformation

- Analysis of ground motion data from local earthquakes to evaluate the local attenuation of seismic waves

- Analysis of ground motion data from extensional tectonic regimes to provide information on the regional rate of attenuation.

The data sets that have been developed as a result of these site characterization activities over the past 20 years provide a strong basis for the PSHA interpretations (Section 3).

2.1 SEISMOTECTONIC FRAMEWORK

The assessment of earthquake hazards is a function of the seismotectonic framework of the region and vicinity of Yucca Mountain. The seismotectonic framework is characterized by the geologic history and structures that are present in the region, such as faults; the nature of tectonic processes and stresses that are currently operating; the seismicity that has been observed during the historical period of observation; and the location and rate of activity on regional and local faults. Understanding these processes and their rates of occurrence provides a fundamental basis for assessing seismic hazards. This section summarizes the understanding of the seismotectonic framework and the associated geologic and seismologic data sets that have been developed to improve that understanding. This information is given in the discussions of seismotectonic framework and characterization of faulting by Whitney (1996) and in the *Yucca Mountain Site Description* (Simmons 2004, Sections 3 and 4).

A complex history of faulting and volcanism has occurred at Yucca Mountain over the past several million years. Because the regional tectonic setting of Yucca Mountain (i.e., the Great Basin) presently is undergoing deformation, faulting can be expected to continue to occur near Yucca Mountain during the present tectonic regime. Tectonic models can represent the geologic structure of a portion of the earth's crust and illustrate how the structures have evolved through time. A tectonic model incorporates the geometry of and the spatial relations among structures, such as faults, and the mechanisms by which structures interact and respond to regional stress. When tectonic models seek to demonstrate the relations among processes of deformation and to include the pattern of historical earthquakes, they can provide insights into the seismotectonics of a region.

A number of alternative tectonic models for Yucca Mountain have been proposed to explain observed geologic structures and geophysical data in light of the history of volcanism and fault movement, uplift and subsidence, and lateral extension (Simmons 2004, Section 4.1.2). These models vary from detachment fault models involving extension to lateral-shear pull-apart models. The focus of the assessment of seismic hazards, as expressed in a "seismotectonic framework," is the assemblage of contemporary geologic structures and crustal stresses that will give rise to future seismicity. Resolving which tectonic model is "correct" is not necessary for conducting a seismic hazard analysis. The models are based on the data and observations regarding the location of structures, the orientation of tectonic stresses, rates of deformation, and observed seismicity. The assessment of seismic sources for the PSHA began first with a careful consideration of these data sets and the various tectonic models that have been derived from them (see Section 3). These data and observations are summarized below.

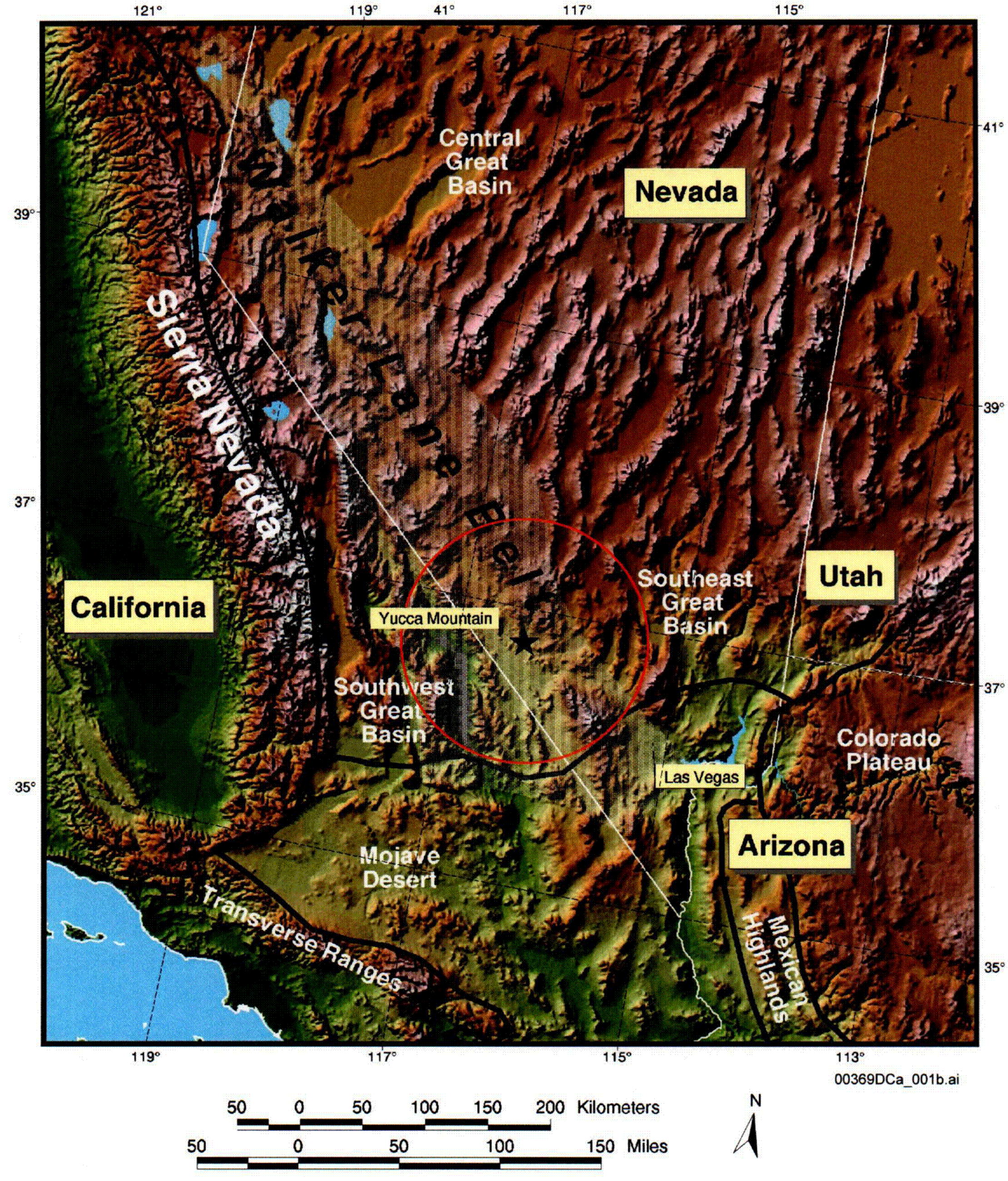
2.1.1 Regional Tectonic Setting

"Tectonic setting" refers to the geological architecture or structural configuration of the different rock masses in the area. The overall tectonic setting, the Great Basin, generally consists of fault-bounded basins and mountain ranges (including Yucca Mountain) complicated by volcanic activity that has occurred within the past 15 million years. Typically, faults in this setting include normal (extensional displacement perpendicular to the fault trace) and strike-slip (lateral displacement parallel to the fault trace) faults that reflect the extensional deformation caused by plate tectonic interactions at the western margin of the North American continent during the middle and late Cenozoic Era (65 Ma to present). The Great Basin is segmented into tectonic domains, structurally bounded blocks of the earth's crust characterized by deformations that distinguish them from adjacent domains. Three regional tectonic domains characterize Yucca Mountain and its surrounding environs: the Walker Lane domain, which includes the site; the Basin and Range domain to the northeast; and the Inyo-Mono domain to the southwest (Figures 2-1 and 2-2).

Yucca Mountain lies within the Walker Lane domain, an approximately 100-km-wide structural belt along the western side of the Basin and Range domain (Figure 2-2). The domain extends northwestward from the vicinity of Las Vegas, subparallel to the Nevada-California border, into northern California. The domain is characterized as an assemblage of crustal blocks separated by discontinuous northwest-striking right-lateral faults (with rock movement to the right) and northeast-striking left-lateral faults (Stewart 1988, p. 686; Carr 1990, p. 284). Because of its structural heterogeneity, the Walker Lane is recognized as a tectonic terrane distinct from the Basin and Range at a regional scale.

The geologic setting of Yucca Mountain is characterized structurally by two distinctly different tectonic deformation styles: an earlier compressional orogenic, or mountain-building, style of regional folding and overthrust faulting and a later extensional "basin forming" style of regional normal and strike-slip faulting. The compressional style records orogenic events that occurred primarily during Paleozoic (544 to 248 Ma) deposition, followed by a peak event that occurred in the Mesozoic (248 to 66 Ma) and terminated marine deposition. Studies of the extensional tectonics in the central Basin and Range (Snow and Wernicke 2000, p. 659) conclude that from 250 to 300 km of extension have occurred by a west-northwest motion of the Sierra Nevada block away from the Colorado Plateau, at rates initially as great as 2 cm/yr and at 1.5 to 1 cm/yr during the last 5 Ma. Research suggests that most of the current extension, as indicated by strain measurements and seismicity, is concentrated along the eastern and western margins of the Basin and Range (Thatcher et al. 1999, Figure 1; Martinez et al. 1998, p. 569).

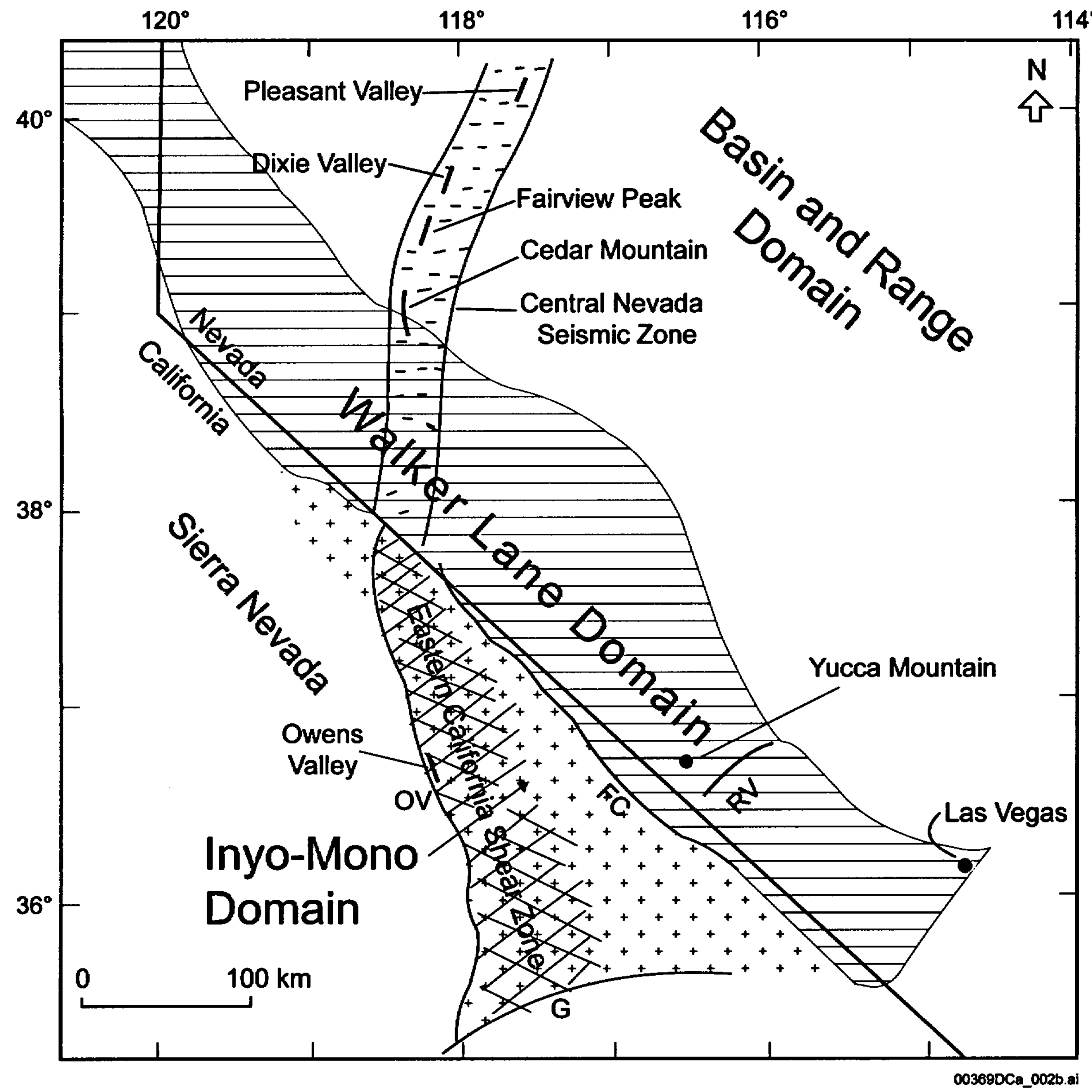
The main extensional features within the tectonic setting of Yucca Mountain were established by about 15 Ma, namely a basin and range structural pattern defined chiefly by north-south-oriented basins or troughs and fault zones associated with the Walker Lane, including the Rock Valley fault zone. The culminating tectonic event in the geologic evolution of the region and, coincidentally, the initiating event for the structural formation of Yucca Mountain was the creation of the southwestern Nevada volcanic field. This field was produced by a succession of at least five voluminous and numerous smaller eruptions that occurred over 7.5 Ma, from about 15 to 7.5 Ma. The greatest of these eruptions created the volcanic sequence (the Paintbrush and Timber Mountain groups) of which Yucca Mountain is a part. From about 11 to 7 Ma, the style of tectonic deformation in the Yucca Mountain region became more clearly one of narrow basin subsidence, possibly accompanied by adjacent range uplift.



Source: Simmons 2004, Figure 2-1.

Figure 2-1. Approximate Locations of the Physiographic Subdivisions of the West-Central Southern Great Basin

C02



Source: Simmons 2004, Figure 2-3.

NOTE: FC = Furnace Creek Fault, G = Garlock Fault, OV = Owens Valley Fault, RV = Rock Valley Fault.

Figure 2-2. Regional Tectonic Domains for Yucca Mountain and Surrounding Environs, plus Zones of Historical Seismic Activity

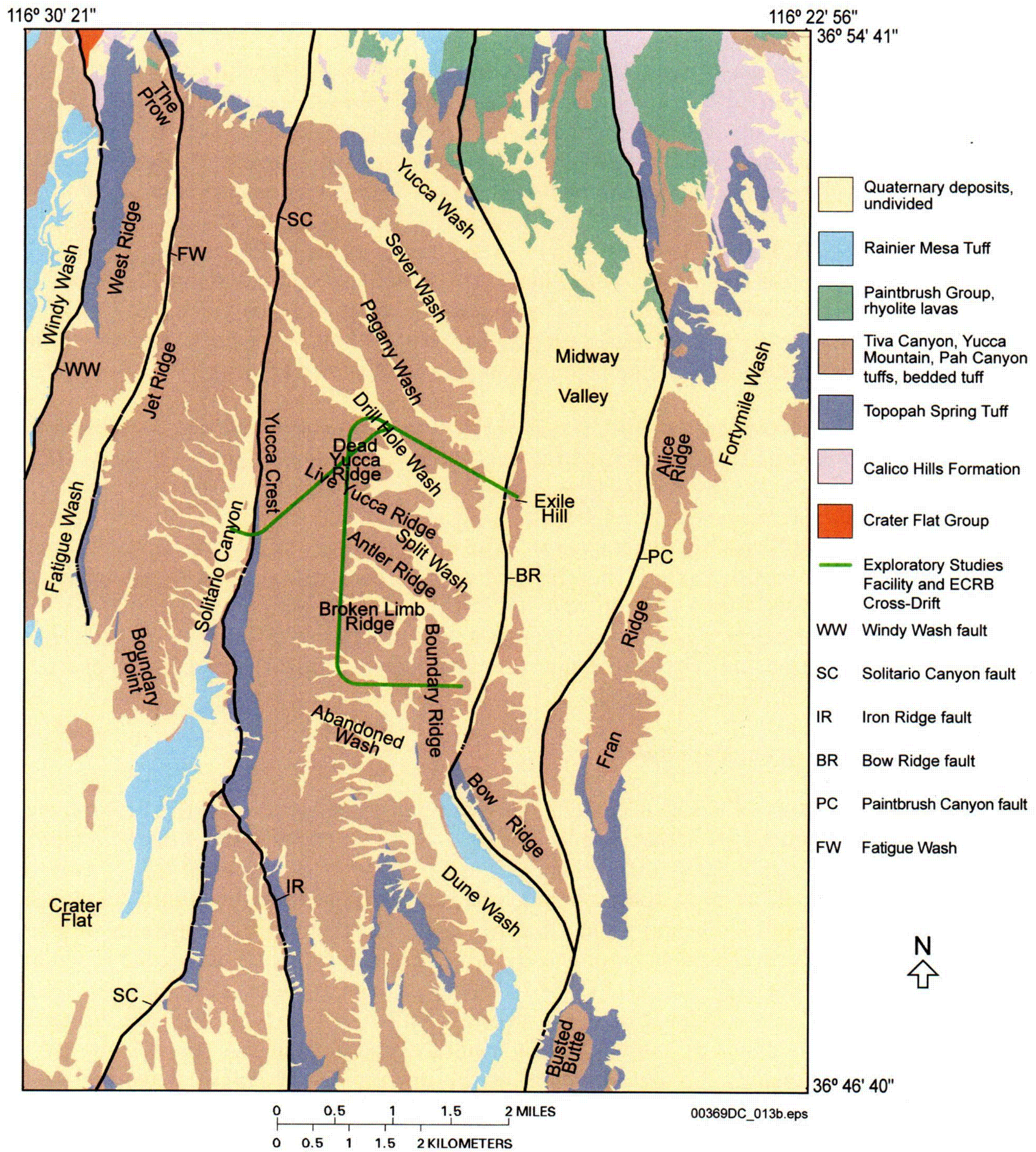
2.1.2 Site Geology

Volcanic rocks called tuffs dominate the exposed bedrock formations in the Yucca Mountain site area (Figure 2-3). The deposits consist mostly of pyroclastic flows (high-density mixture of hot, dry rock fragments and hot gases) and fallout tephra (fragments that traveled through the air), with minor lava flows (molten rock). The volcanic rocks were deposited mainly between 11 and 14 million years ago, during the Miocene Epoch of the Tertiary Period. The stratigraphy of these rocks forms the basic framework for the modeling and analyses of rock properties, mineral distributions, faulting and fracturing, hydrologic flow, and radionuclide transport. Descriptions of the stratigraphic units are given in the *Yucca Mountain Site Description* (Simmons 2004, Section 3.3.4, Table 3-1).

For seismic hazard analysis, the knowledge of the site geologic units and their physical properties is important principally in characterizing the site conditions for ground motion (see Section 4) and for consideration of rockfall during seismic shaking (BSC 2003b). The dynamic response of the rock in the emplacement drifts during seismic shaking is expected to vary according to whether the drift lies within the lithophysal or nonlithophysal members of the volcanic rock (see Section 5). Lithophysae are spherical-to-oblate cavities in the volcanic rock formed during their deposition. Presence or absence of lithophysae is one mechanism for subdividing formations and members of formations at Yucca Mountain. This is particularly true within the Topopah Spring Tuff, where the repository emplacement drifts will lie, and the overlying Tiva Canyon Tuff. As discussed in *Drift Degradation Analysis* (BSC 2003b), the mechanical response of the drifts and associated rockfall varies with whether the drift lies within lithophysal or nonlithophysal units. Likewise, the effects on the EBS from seismically induced rockfall will vary as a function of this location (see Section 5.3).

2.1.3 Contemporary Deformation

Large earthquakes on range-front faults during the past 100 years, such as the Dixie Valley and Fairview Peak earthquakes, indicate that Basin and Range extension is still underway. Epicenter distribution patterns and geodetic strain data indicate that strain presently is concentrated primarily north of Yucca Mountain, in a zone along latitude 37°N, in the eastern California shear zone, and in the central Nevada seismic zone (Bennett, Davis et al. 1999, p. 373, Figure 1) (Figure 2-2). High geodetic extension rates characterize these active areas (Bennett, Wernicke, et al. 1998, p. 566; Savage et al. 1995, p. 20266). Northwest motion of the Sierra Nevada block is accomplished by a combination of east–west extension on north-striking normal faults and by right-lateral motion on northwest-striking strike-slip faults of the Walker Lane and eastern California shear zone (Dixon et al. 1995, p. 762).



Source: Potter et al. 2002.

NOTE: Faults are shown with solid lines, although large segments of some are concealed or inferred beneath Quaternary deposits. ECRB = Enhanced Characterization of the Repository Block.

Figure 2-3. Map of Yucca Mountain Site Area Showing Distribution of Principal Stratigraphic Units, Major Faults, and Locations of Geographic Features

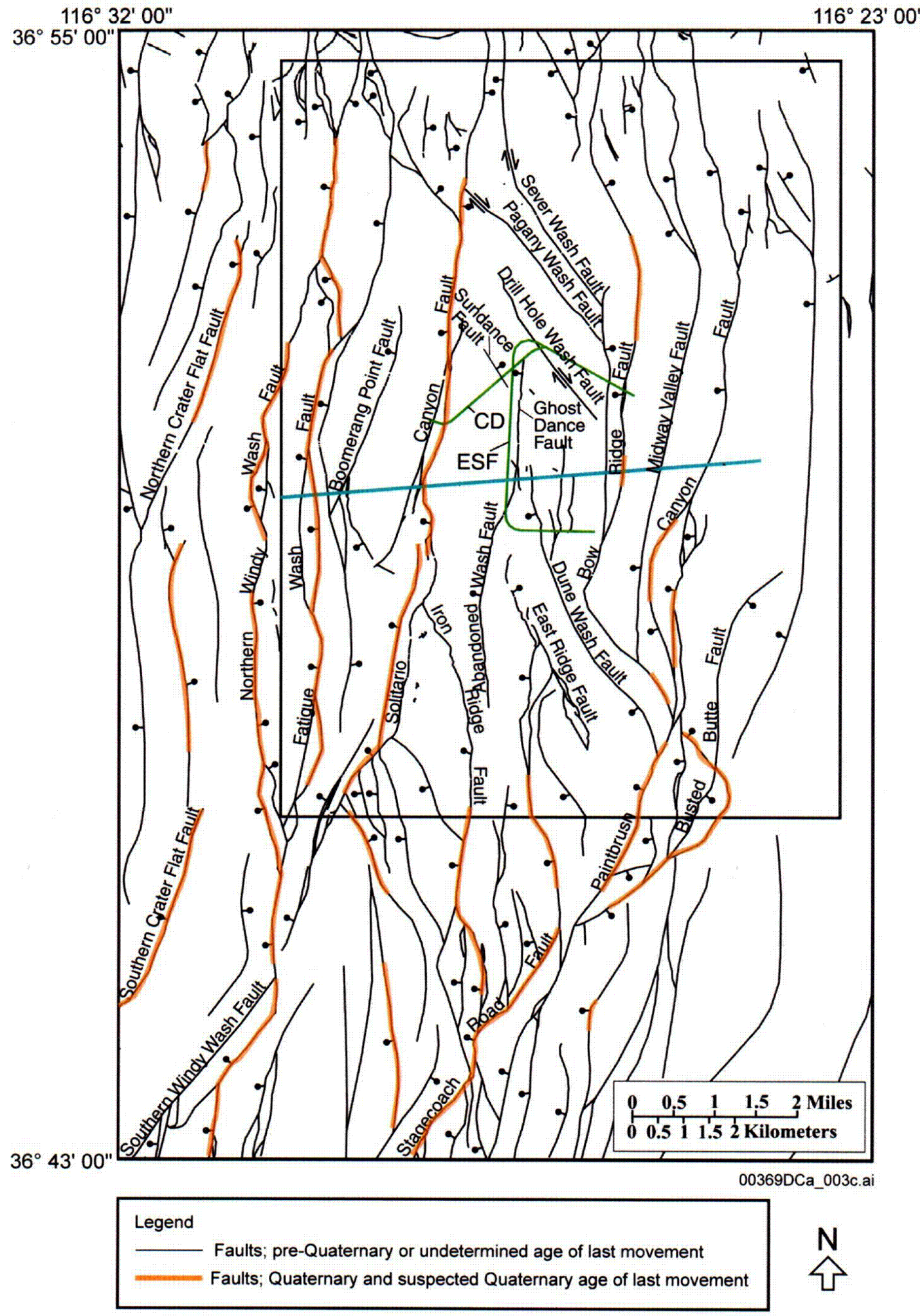
C03

Strain surveys show that the direction of extension in the Great Basin is toward the northwest, the direction of the least compressive stress. The northern Basin and Range appears to be moving at 4.9 ± 1.3 mm/yr west-southwest with respect to the continental interior and the southern Great Basin by means of crustal extension (Savage et al. 1995, p. 20265). The relatively high strain rate of the northern Basin and Range is at least partly accommodated by the central Nevada seismic zone (Figure 2-2). Trilateration (measuring changes in distances between three or more points) data show that at least 2.7 mm/yr of extension is taken up by this zone (Savage et al. 1995, p. 20265). The southern Basin and Range has an extension rate of 3 mm/yr or less (Sauber 1989, p. 123). The zone of seismicity along latitude 37°N accommodates the differential extension between the northern and southern Basin and Range provinces; the slip rate in this zone is estimated at about 3.2 mm/yr (Savage et al. 1995, p. 20267). The high strain rate zones, such as the central Nevada seismic zone, may represent concentrations of active deformation among relatively stable crustal blocks.

The kinematic boundary condition for Basin and Range deformation (the relative motions of the Pacific and North American plates) has been nearly constant for at least the past 3.4 Ma (Harbert and Cox 1989, p. 3061). During this time, tectonic activity has gradually shifted westward, from the Death Valley–Furnace Creek Fault to the Owens Valley Fault. The Walker Lane likely accommodates significant right-lateral shear. The central Nevada seismic zone trends obliquely across the older Walker Lane. Therefore, it would seem that the westward migration of tectonism in the Inyo-Mono domain and the historical surface-rupturing earthquake activity along the central Nevada seismic zone represent a concentration of crustal strain of regional extent and significant longevity. This strain zone appears to be shifting westward and perhaps northward away from Yucca Mountain.

2.1.4 Regional and Local Faults

The structural geology of Yucca Mountain and vicinity is dominated by a series of north-striking normal faults (Figure 2-4) along which Tertiary volcanic rocks were tilted eastward and displaced hundreds of meters. Movement occurred primarily during a period of extensional deformation in middle to late Miocene time but has continued at a low level into the Quaternary Period (the last 1.8 million years). These through-going faults divided the site area into several blocks, each of which is further deformed by minor faults. Block-bounding faults within the Yucca Mountain site area are spaced 1 to 6 km apart, and include, from east to west, the Paintbrush Canyon, Bow Ridge, Solitario Canyon–Iron Ridge, Fatigue Wash, and Windy Wash faults (Figures 2-4 and 2-5). Fault scarps commonly dip from 50° to 80° to the west. Displacements are mainly dip-slip (direction of slip down the fault plane), down to –the west, with subordinate strike-slip or oblique-slip components of movement exhibited along some faults. Numerous intrablock faults occur within the individual structural blocks, representing local adjustments in response to stress created, for the most part, by the large displacements that took place along block boundaries (Simmons 2004, Section 3.5).



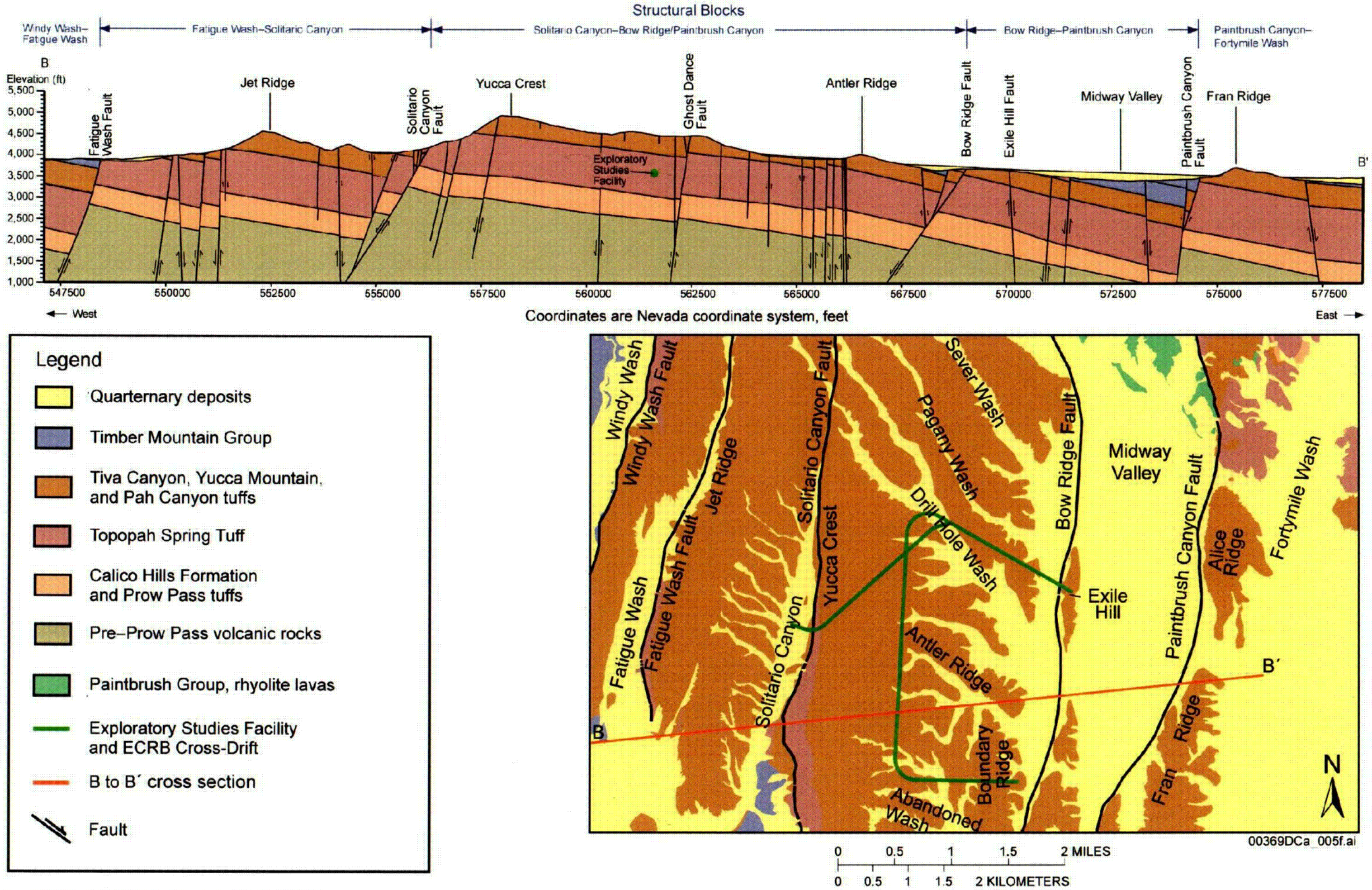
Source: Potter et al. 2002.

NOTE: All faults are shown with solid lines, although many segments are concealed or inferred. Symbols and abbreviations: bar and bell, downthrown side of fault; arrows, relative direction of strike-slip movement; ESF = Exploratory Studies Facility; CD = ECRB Cross-Drift.

Site area defined by black border. Blue line is the approximate line of cross section given in Figure 2-5.

Figure 2-4. Distribution of Faults in the Yucca Mountain Site Area and Adjacent Areas to the South and West

C04



Source: Day et al. 1998, cross section B-B'.

NOTE: Approximate line of section is also shown on Figure 2-4.

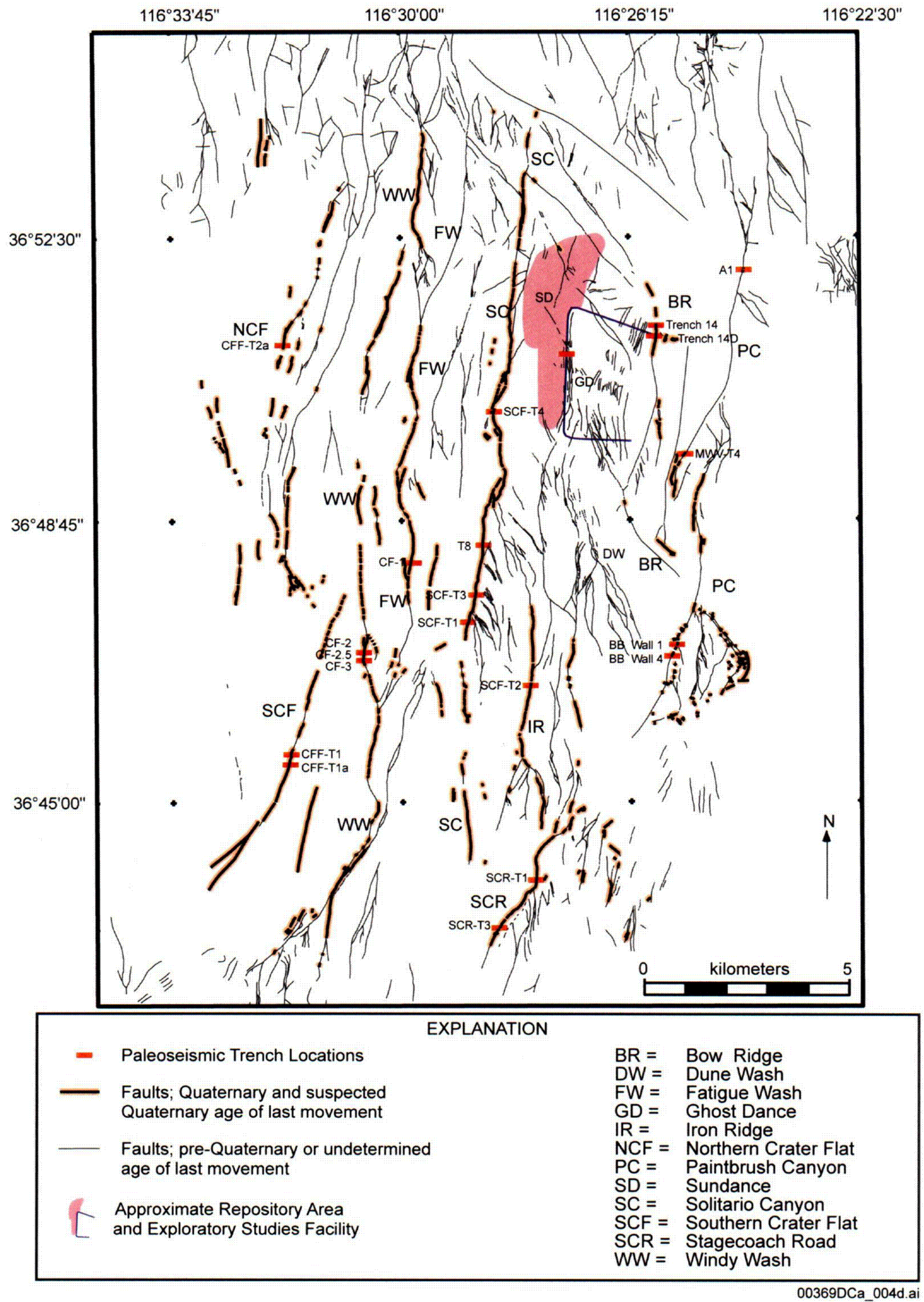
Figure 2-5. East–West Structure Section across Yucca Mountain Site Area

C05

From the standpoint of seismic hazard analysis, Quaternary faults are important potential sources of earthquakes. The assessment of the age of faults is made using a combination of geomorphic analysis, mapping of Quaternary deposits, local mapping of faulting in existing exposures, and exploratory trenching to examine the relationships between faulting and Quaternary deposits. Figure 2-6 shows the faults near Yucca Mountain that are assessed to have been active during the Quaternary Period.

Several of the block-bounding faults at Yucca Mountain show evidence of Quaternary displacements that influenced depositional patterns of surficial materials on hillslopes and on adjacent valley or basin floors and in places produced visible scarps in surficial deposits along some fault traces. However, low rates of offset and long recurrence intervals between successive faulting events on faults in the site area during Quaternary time have resulted in subtle landforms.

Information on the stratigraphic relations among surficial deposits was augmented considerably by the large-scale mapping and detailed descriptions of vertical sequences that were freshly exposed in trenches excavated, or enhanced stream or roadcut exposures, across those faults suspected of being active during Quaternary time (Whitney and Taylor 1996). Although studies concluded that there is no evidence of Quaternary displacement, trenches were also excavated across the Ghost Dance Fault because of its location relative to the area of waste emplacement. Within the site area, 52 trenches were emplaced across such faults to determine the extent of Quaternary tectonic activity with respect to (1) the number, amount of displacement, and age of individual surface-rupturing events causing earthquakes; (2) fault slip rates; and (3) recurrence intervals between successive events on a given fault. Figure 2-6 shows the locations of those trenches in the site area that exhibited evidence of Quaternary age displacement or, in the case of the Ghost Dance Fault, fractures with no displacement that might be associated with Quaternary activity. Trenches were also excavated across the Bare Mountain Fault and Rock Valley Fault to determine activity on the more significant regional faults. These assessments, which combine the mapping of Quaternary deposits at the surface with the characteristics of faulting observed in subsurface trenches, are called paleoseismic investigations. The number of trenches and the level of detailed investigation of faults in the local Yucca Mountain area provide a database for interpretations of the paleoseismic behavior of the local faults. Paleoseismic investigations and associated data are described in the *Yucca Mountain Site Description* (Simmons 2004, Section 4.3.2) and in more detail by Whitney and Taylor (1996). These paleoseismic data serve as a fundamental resource for the seismic source characterization activity in the PSHA (see Section 3.2). An example log of a mapped enhanced exposure cut across the Paintbrush Canyon Fault is shown in Figure 2-7.

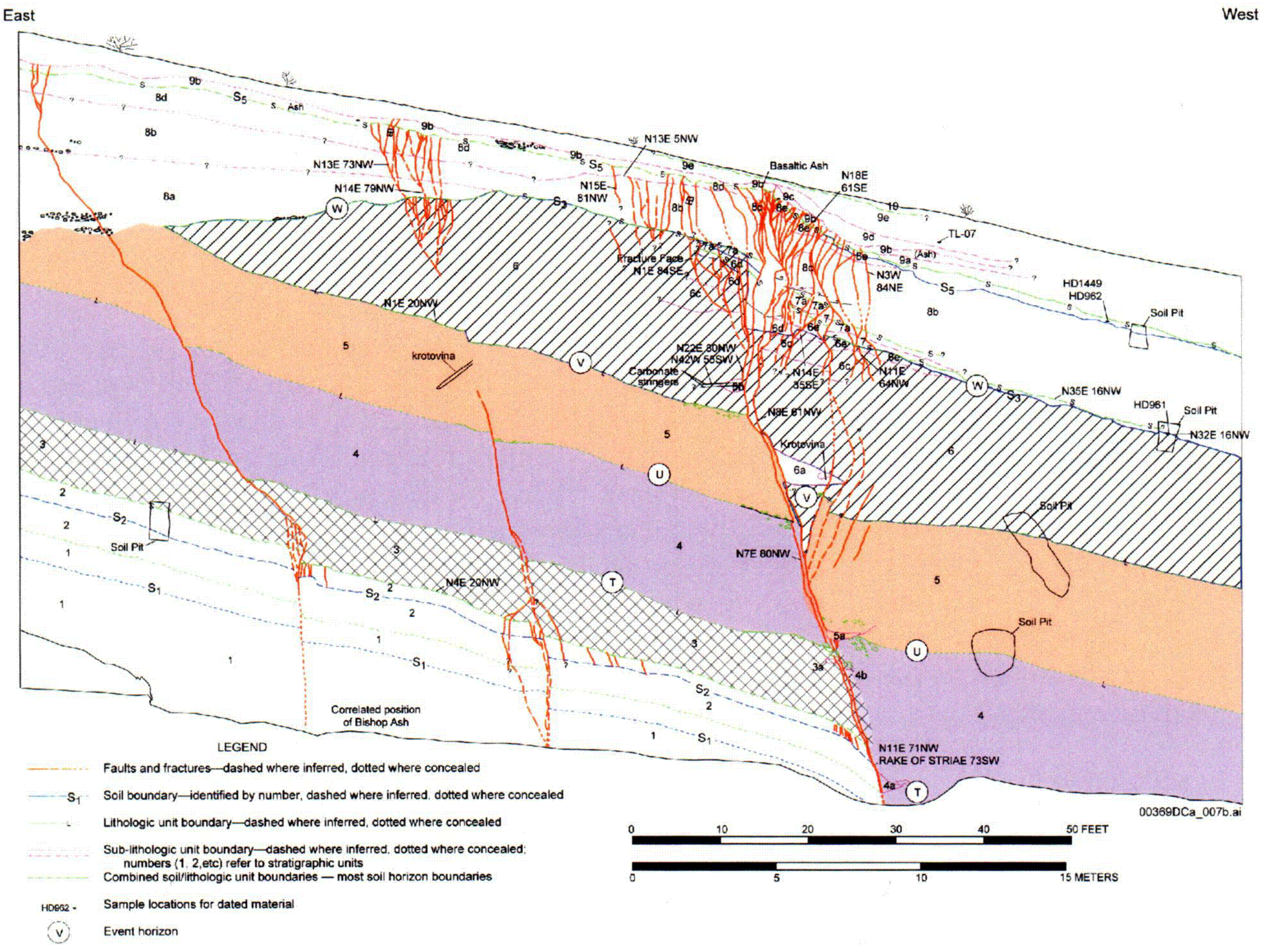


Source: Fault map is from Simonds et al. 1995; Pezzopane, Whitney et al. 1996.

NOTE: Only trenches that exhibited evidence of Quaternary age displacements are shown. In addition, trenches across the Ghost Dance Fault that exhibited fractures in the Quaternary deposits, but not displacement, are shown.

Figure 2-6. Local Faults and Paleoseismic Study Sites at Yucca Mountain

C06



Source: Menges and Whitney 1996, Figure 4.4-1.

Figure 2-7. Example Log from Paleoseismic Studies of Late Quaternary Faults near Yucca Mountain: Paintbrush Canyon Fault at Busted Butte

Geophysical surveys have also contributed to the understanding of local and regional faults in the Yucca Mountain vicinity (Oliver et al. 1995; Majer et al. 1996). Geophysical techniques employed at Yucca Mountain include seismic reflection (e.g., Brocher et al. 1998) and gravity and magnetics (e.g., Ponce and Langenheim 1994; Ponce 1996). These investigations provided information on the subsurface geometry of faults and on the location of buried faults with no surface expression.

2.2 HISTORICAL SEISMICITY OF THE YUCCA MOUNTAIN REGION

Seismic hazard evaluations rely on a description of the temporal and spatial distribution of earthquakes, their magnitudes, and how they relate to the seismotectonic processes of the region. The temporal and spatial occurrence of earthquakes for a given region is evaluated from two sources: historical (instrumental records and reported effects) and prehistoric (paleoseismic data).

Seismic monitoring of the southern Great Basin began in the early 1900s with isolated stations installed and operated by the University of California, Berkeley, and the University of Nevada,

C07

Reno. The history of seismic monitoring in the Southern Great Basin is found in the *Yucca Mountain Site Description* (Simmons 2004, Section 4.3.1.1) and *Seismicity in the Vicinity of Yucca Mountain, Nevada, for the Period October 1, 1995, to September 30, 1996* (von Seggern and Smith 1997). In the late 1950s and early 1960s, a global network (the Worldwide Standardized Seismograph Network) came into existence, thereby providing the capability to record earthquakes larger than about magnitude 4 in the southern Great Basin. Later, networks of stations were installed to monitor and study specific areas such as the Nevada Test Site and portions of the western United States.

Seismic monitoring specifically to characterize the Yucca Mountain region began when a 47-station network was installed in 1978 and 1979. The network extended to a distance of 160 km (99 mi) from the site (Figure 2-8a) and employed the analog technology of the day. In 1981, six seismograph stations in the immediate vicinity of Yucca Mountain were added to the network. In 1995, seismic monitoring near Yucca Mountain was reconfigured with the establishment of a network of three-component seismograph systems with digitally recorded and telemetered data. The Southern Great Basin Digital Seismic Network, which is operated by the University of Nevada, Reno, spans a radius of 50 km (31 mi) from Yucca Mountain and, in 2001, consisted of 30 stations (Figure 2-8b). The higher quality data obtained from the digital network of three-component seismograph systems have enabled the detection of smaller magnitude earthquakes and have resulted in improved accuracy of earthquake locations.

In addition to the seismograph network, 27 strong motion stations consisting of three-component accelerometers also monitor Yucca Mountain. These stations are designed to record larger ground motion from nearby moderate to large earthquakes. Seventeen of the three-component strong-motion stations are located at the surface, one is sited in Alcove 5 of the Exploratory Studies Facility (ESF), and nine are located in three boreholes in the surface facilities area near the North Portal of the ESF. For the boreholes, in each borehole one station is located at the surface, one at mid-depth, and one at the bottom.

2.2.1 Historical Seismicity Catalog for the Yucca Mountain Region

In preparation for the PSHA, a catalog of earthquakes was compiled for the region within 300 km of Yucca Mountain using both historical and instrumental records (CRWMS M&O 1998, Appendix G). The resulting combined catalog contains 271,223 earthquakes occurring from 1868 to 1996. Earthquakes with magnitudes down to approximately M 1 were recorded in the more recent periods as the sensitivity of local and regional seismic networks was substantially increased. Figure 2-9 shows events in the catalog with magnitude greater than moment magnitude (M_w) 3.5. The accuracy of information in the historical catalog is affected by several variables (e.g., accuracy of historical accounts, detection capability, and instrumental precision), especially the variability in seismic network coverage as a function of time. The spatial distribution of seismicity in the 300 km catalog depends both on the density of inhabitants and the density of seismographic network coverage in a particular region over time and is somewhat an artifact of the more thoroughly represented aftershock sequences of the modern period. For example, a significant portion of the catalog in terms of number of events is derived from a recent series of moderate-sized earthquakes, aftershock sequences, and volcanic swarm activity in the Mammoth Lakes, California, area. Although these events figure prominently in terms of the number of earthquakes in the catalog, they represent an insignificant portion of the total seismic energy release along the western Basin and Range Province in the past two decades.

Since the Yucca Mountain catalog was compiled from several source catalogs, each using a variety of different magnitude scales that also changed with time, a uniform magnitude scale was required to compute the earthquake recurrence for the region. In addition, it was necessary to assign magnitudes to historical earthquakes that occurred prior to calibrated seismographic instrumentation. Nevada Test Site explosions and their induced earthquake aftershocks and reservoir-induced seismicity events at Lake Mead were identified in the earthquake catalog. Nuclear explosions and related aftershocks, which appear as the prominent clusters of epicenters to the north and east of Yucca Mountain, were excluded from the catalog for purposes of calculating seismicity recurrence rates for the seismic hazard analysis.

The larger earthquakes documented in the historical catalog occurred within the Central Nevada Seismic Zone and the Eastern California Shear Zone, 100 to 300 km to the northwest, west, southwest, and south of Yucca Mountain (Figures 2-2 and 2-9). These zones of activity include the 1872 Owens Valley, California, earthquake (M_w 7.8), the 1932 Cedar Mountain, Nevada, earthquake (M_w 7.1), the 1954 Fairview Peak and Dixie Valley, Nevada, earthquakes (M_w 7.1 and M_w 6.8), and the 1992 Landers, California, earthquake (M_w 7.3). The 1999 Hector Mine, California, earthquake (M_w 7.1) also occurred in the Eastern California Shear Zone, but occurred in 1999, after the time period shown on Figure 2-9.

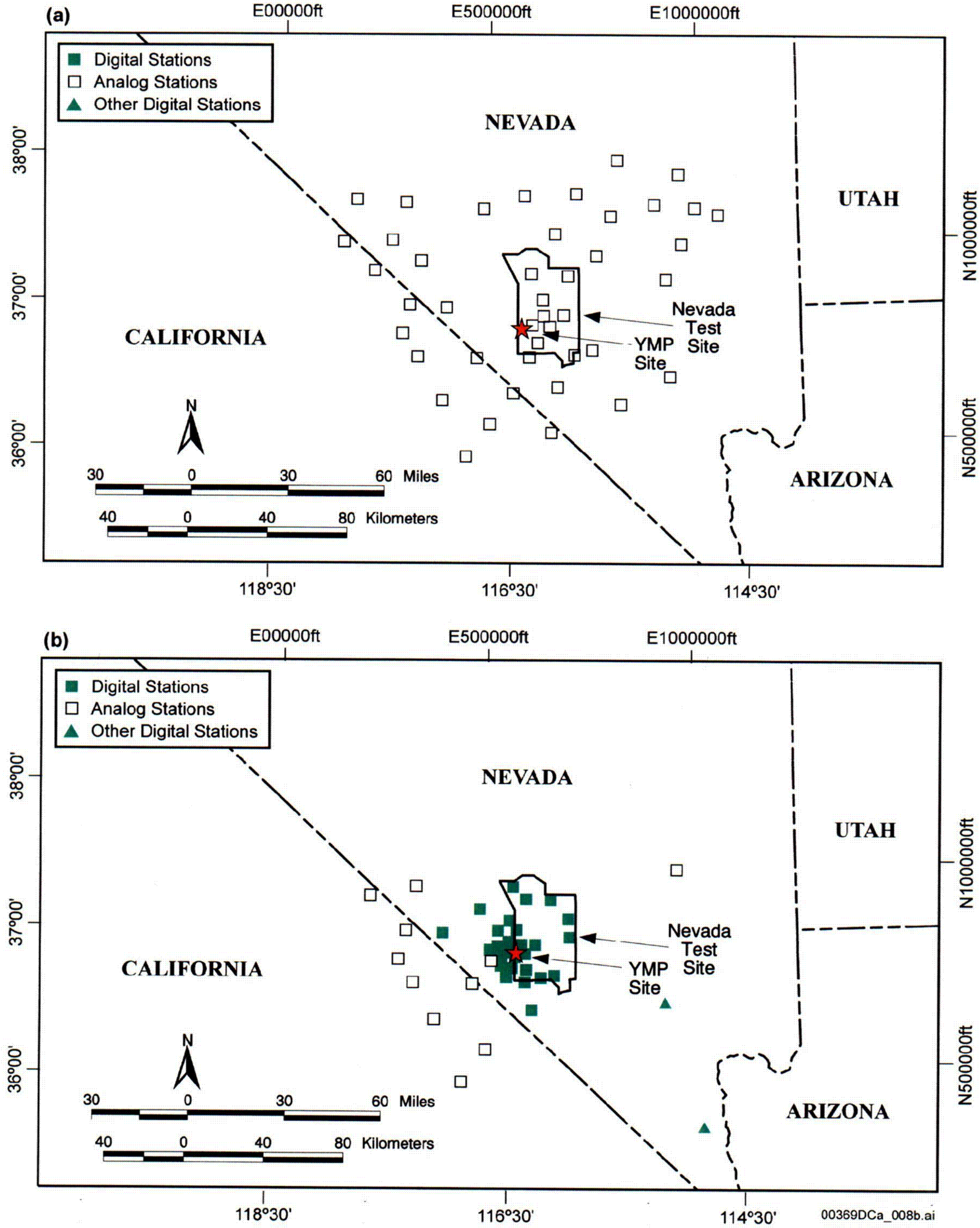
Three events during the historical period of greater than M_W 5.5 are located within 100 km of Yucca Mountain (Figure 2-10). The largest event is the 1916 M_W 6.1 earthquake that occurred in Death Valley. These events also include the 1992 M_W 5.6 earthquake that occurred near Little Skull Mountain, about 15 km southeast of Yucca Mountain, and a M_W 5.7 event in 1910 about 85 km to the northwest (Figure 2-10).

Various analyses have shown that earthquakes in the southern Great Basin occur predominantly between depths of about 2 and 15 km (e.g., Rogers et al. 1987, pp. 55 to 56; Harmsen and Bufe 1992, pp. 42 to 43). Focal mechanisms (analyses to determine the orientation and direction of faulting) of recent earthquakes within the southern Great Basin indicate that right-lateral slip on north-trending faults is the predominant mode of stress release near the site (Pezzopane, Bufe et al. 1996, p. 7-3). Normal and oblique-slip faulting is also observed. Focal mechanisms for the period 1971 through 1992 indicate roughly equal proportions of strike-slip and normal faulting (Pezzopane, Bufe et al. 1996, p. 7-38, Table 7-3).

2.2.2 Seismicity in the Vicinity of Yucca Mountain

While the southern portion of the Nevada Test Site, southeast of Yucca Mountain, is one of the more seismically active regions in the southern Great Basin, the area immediately around Yucca Mountain (within 10 km) itself is rather aseismic (Figure 2-10). Studies, including an experiment in high-resolution monitoring of seismicity at the site, have shown that the Yucca Mountain zone of quiescence is a real feature of the contemporary seismicity and not an artifact of network design or detection capability (Gomberg 1991a, pp. 16411 to 16412; Gomberg 1991b, pp. 16397 to 16398; Brune et al. 1992, p. 164). Modeling of the strain field in southern

Nevada suggests that this area is not accumulating significant strain and that Yucca Mountain is an isolated block within the structural framework of the southern Great Basin.

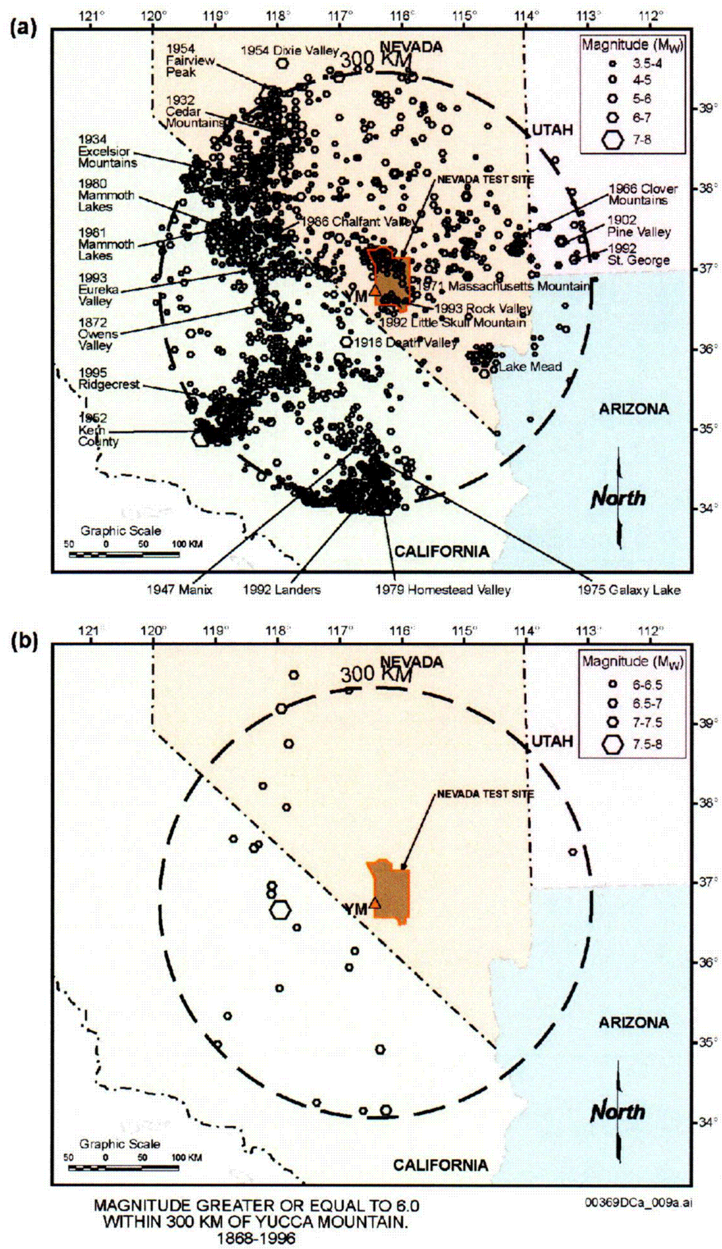


Source: Simmons 2004, Figure 4-17.

NOTE: YMP = Yucca Mountain Project.

Figure 2-8. Seismograph Stations Operating in the Southern Great Basin in 1980 (a) and 2001 (b)

C08

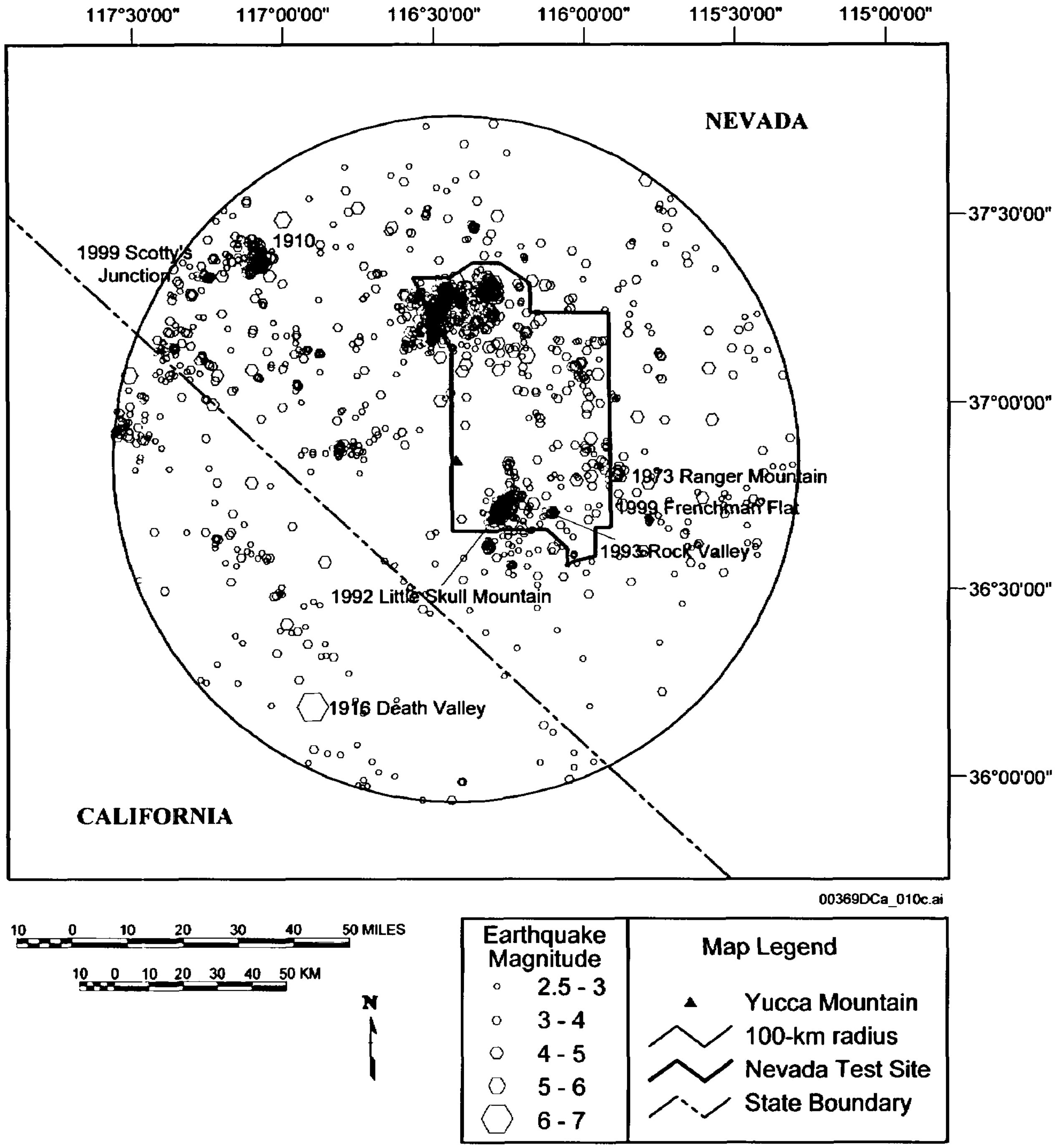


Source: DOE 2002, Figure 4-162.

NOTE: Shown are earthquakes from 1868 to 1996. Part (a) shows earthquakes with magnitude greater than or equal to 3.5; part (b) shows the subset of earthquakes with magnitude greater than or equal to 6. This seismicity catalog was compiled from a variety of sources. Coverage of older seismicity is sparse because of the absence or limited availability of seismographic coverage in the late 1800s and early 1900s. The cluster of earthquakes near the southern boundary of the Nevada Test Site represents the 1992 Little Skull Mountain earthquake and its numerous aftershocks. Many of the events in the northern part of the Nevada Test Site occurred in response to underground nuclear weapons tests. Significant earthquakes are labeled with year of occurrence.

Figure 2-9. Historical Earthquake Epicenters within 300 km of Yucca Mountain

C09



Source: Simmons 2004, Figure 4-19.

NOTE: Shown are earthquakes from 1904 to 1998. Earthquakes associated with the 1999 Scotty's Junction and 1999 Frenchman Flat sequences are also shown. Significant earthquakes or earthquake sequences are shown with years of occurrence.

Figure 2-10. Historical Earthquake Epicenters within 100 km of Yucca Mountain

From the initiation of Southern Great Basin Digital Seismic Network operation in October 1995 through September 2002, microearthquakes that have occurred in the immediate vicinity (within 10 km) of Yucca Mountain are shown in Figure 2-11. The events ranged in magnitude from about −1 to 1 M_L[1]. These microearthquakes occurred throughout the Yucca Mountain block and had focal depths between about 3 and 13 km. Focal mechanisms were determined for some of the events and are consistent with normal to normal-oblique slip on faults with northwestern to northeastern orientations.

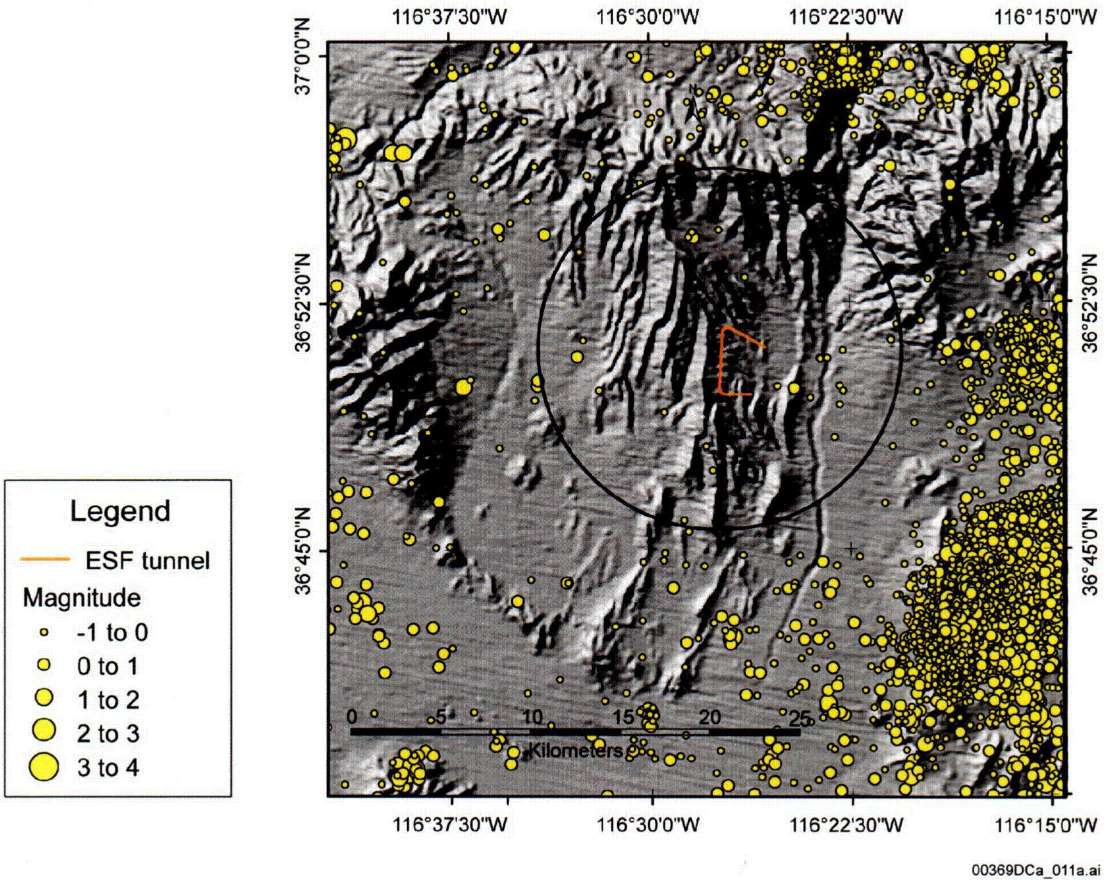
While the immediate Yucca Mountain area has been quiescent during the historical period, paleoseismic evidence indicates active Quaternary faults exist near the site. Paleoseismic events exhibit very long times between events, thus little or no microseismicity may occur on the faults during the historical period of observation. Many faults in the Great Basin with paleoseismic evidence for prehistoric surface-rupture earthquakes have little or no associated historical seismicity.

Seismicity to the east and southeast of Yucca Mountain is spatially associated with the Rock Valley, Mine Mountain, and Cane Springs fault zones (RV, MM, and CS, respectively, on Figure 2-12). This activity forms a wide, northeast-trending zone that includes the 1973 Ranger Mountain sequence, the 1992 Little Skull Mountain sequence, the 1993 Rock Valley sequence, the 1999 Frenchman Flat sequence, and other earthquake clusters (Figure 2-10). The main shocks from the Little Skull Mountain and Frenchman Flat sequences, near the ends of the seismicity zone, exhibited normal faulting on northeasterly striking planes. The Rock Valley sequence in the middle of the zone exhibited strike-slip faulting. Some seismicity in the Yucca Mountain area is also spatially associated with the southern boundary of the Timber Mountain caldera.

The larger earthquakes or earthquake sequences recorded by the Southern Great Basin Digital Seismic Network (or its predecessor, the Southern Great Basin Seismic Network) are the following (Figure 2-10):

- 1992 Little Skull Mountain sequence, including the June 29, 1992, mainshock with M_W 5.6
- 1993 earthquakes in the Rock Valley fault zone. Following the Little Skull Mountain earthquake in 1992, several earthquakes of up to M_W 3.7 occurred.
- 1999 Frenchman Flat earthquake sequence on January 27, 1999 (M_W 4.7), preceded by an extended foreshock sequence that included a M_L 4.2 earthquake.
- 1999 Scotty's Junction earthquake sequence on August 1, 1999 (M_L 5.7, with two aftershocks M_L 4.8 and 4.9).

[1] Historically, earthquake magnitude has been determined using a variety of techniques, resulting in a number of different earthquake magnitude scales. The various magnitude scales mentioned in this report, and the symbols used to indicate them, are as follows: M_L = local magnitude, M_W = moment magnitude.



Source: Simmons 2004, Figure 4-22.

Figure 2-11. Seismicity at Yucca Mountain from October 1, 1995, to September 30, 2002

2.3 PREHISTORIC EARTHQUAKES

2.3.1 Paleoseismic Studies

The identification and documentation of earthquakes occurring prior to historical times, termed paleoseismology, is possible by studying the geologic record of past events. Larger events that rupture to the surface often leave geological evidence in the form of offset strata and characteristic earthquake-related deposits. A program of geologic fault studies at Yucca Mountain reveals that the recurrence times of large-magnitude earthquakes are on the order of tens of thousands of years, much longer than the approximately 130-year historical earthquake record of the Yucca Mountain region. Thus, the prehistoric earthquake history of the Yucca Mountain site spans at least the past several hundred thousand years and is particularly important for the PSHA because it extends the record for larger magnitude events.

Paleoseismic studies are the basis for identifying the occurrence of large-magnitude surface-rupturing earthquakes and evaluating their size, age, and occurrence rate. Regional investigations were conducted to identify faults in the Yucca Mountain area that have evidence of Quaternary displacements within 100 km of the site (Figure 2-12).

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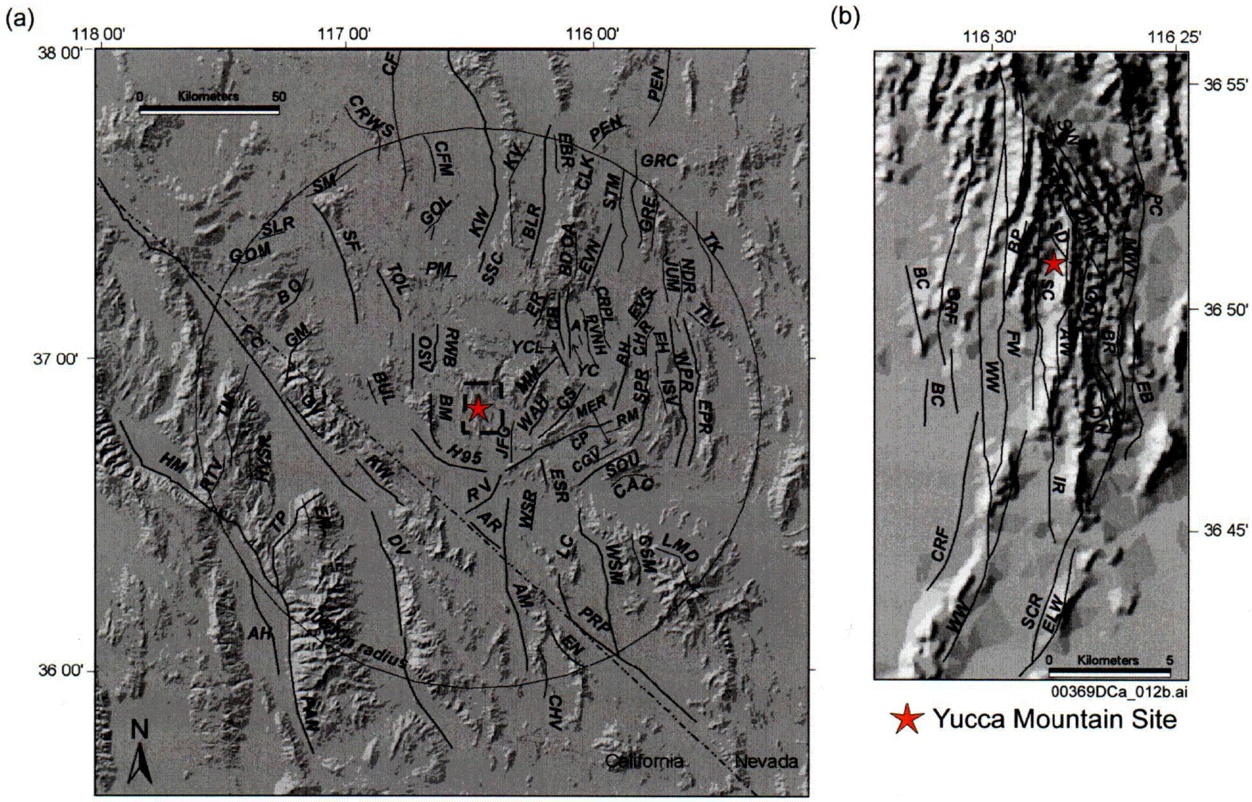
Displaced or deformed sedimentary deposits record late Quaternary faulting along local faults in the Yucca Mountain area. These faults include, from west to east, the Northern Crater Flat, Southern Crater Flat, Windy Wash, Fatigue Wash, Solitario Canyon, Iron Ridge, Stagecoach Road, Bow Ridge, and Paintbrush Canyon faults (Figures 2-6 and 2-12). Paleoseismic data for these faults provide the basis for interpretations made as part of the PSHA. These data and interpretations are summarized in the next section.



Source: DOE 2002, Figure 4-164.

NOTE: (a) Faults within 100 km of Yucca Mountain. (b) Detail of (a), showing faults near Yucca Mountain; these faults are the Abandoned Wash (AW), Black Cone (BC), Boomerang Point (BP), Crater Flat (CRF), Drill Hole Wash (DHW), Dune Wash (DW), East Busted Butte (EB), East Lathrop Wells (ELW) Fatigue Wash (FW), Ghost Dance (GD), Iron Ridge (IR), Midway Valley (MWV), Pagany Wash (PW), Paintbrush Canyon (PC), Sever Wash (SW), Solitario Canyon (SC), Stagecoach Road (SCR), Sundance (SD), and Windy Wash (WW) faults. For detailed identification of each fault labeled with initials in (a) but not identified in this note, see the *Yucca Mountain Site Description* (Simmons 2004, Figure 4-23).

Figure 2-12. Known or Suspected Quaternary Faults and Other Notable Faults in the Yucca Mountain Region

2.3.2 Paleoseismic Interpretations

Geologic studies of the local faults in the Yucca Mountain area resulted in data and interpretations of key paleoseismic characteristics that define the size and rate of occurrence of prehistoric earthquakes on these faults. These characteristics include fault slip rate, displacements associated with individual paleoseismic events, lengths of rupture, and recurrence intervals between individual paleoseismic events. Paleoseismic investigations of these faults are

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described in the *Yucca Mountain Site Description* (Simmons 2004, Section 4.3.2) and in more detail by Whitney and Taylor (1996).

Fault Slip Rate–Fault slip rate is the time-averaged rate of displacement on a fault in millimeters per year. Slip rate is an important paleoseismic parameter; it is a standardized measure of activity on the fault, which can be used for comparing the activity of many different faults. It can also provide direct input to calculations of earthquake recurrence rate for seismic hazard analyses. Fault slip rates are calculated by dividing the amount of cumulative observed net slip by the age of a specific faulted deposit or horizon. Uncertainties in the age of the unit and in the amount of offset are incorporated into uncertainty estimates of the slip rate.

Estimates of slip rates for faults at Yucca Mountain vary from 0.001 to 0.07 mm/yr. These rates are low when compared to those for other faults in the Basin and Range Province. For example, in dePolo's scheme to classify the activity of Basin and Range Province faults (dePolo 1994, p. 49), the Yucca Mountain faults fall into the moderately-low-to-low activity class. Also, slip rates for faults at Yucca Mountain are equal to or lower than values in a compilation of slip rates developed by McCalpin (1995, Table 2) for the Basin and Range Province.

Per-Event Displacement–Per-event displacements are an important paleoseismic parameter for estimating the maximum magnitude of prehistoric earthquakes. The most precise per-event displacements were estimated directly from trench log data. Multiple measurements of per-event displacement are available for local faults at Yucca Mountain. Fewer data on per-event displacements are available for regional faults, and they are based primarily on the projected measurement of geomorphic surfaces across topographic scarps or the surface trace of the faults.

Estimated per-event displacements vary from near 0 to 257 cm. For example, the range of estimates is 0 to 130 cm for the Solitario Canyon Fault, 1 to 80 cm for the Bow Ridge Fault, and 0 to 257 cm for the Paintbrush Canyon Fault. Fracture events with no detectable offsets are sometimes identified. Displacements per event are larger (80 to less than 362 cm) for the Rock Valley Fault and Bare Mountain Fault relative to the block-bounding faults at Yucca Mountain. Available estimates of single-event displacements for regional faults are in the general range of those for site faults, with the exception of displacements of 240 to 470 cm on the Death Valley–Furnace Creek fault system.

Surface-Rupture Length–Coseismic surface-rupture length is an important parameter used to define the maximum magnitudes of prehistoric earthquakes. Determination of rupture lengths for prehistoric earthquakes is estimated using surficial mapping data, the locations of trenches, and displacement-event timing data. The length of a rupture is determined by the lateral extent a given event can be identified along one or more faults. In some cases, this identification is accomplished via event correlations between sites using similarities in ages and other supportive geologic criteria. Surface-rupture lengths may be equivalent to the total fault length or may be restricted to a specific portion, or segment, of the fault.

Rupture lengths of individual site faults and regional faults in the Yucca Mountain area range from 1 to about 25 km. Fault lengths in the region surrounding the site range from several kilometers to more than 300 km for the Death Valley–Furnace Creek–Fish Lake fault system. Except for very long, likely segmented faults, the total measured length of a fault represents its maximum rupture potential. This interpretation is considered reasonable, especially for the relatively short faults at Yucca Mountain. For consideration in the PSHA, a number of rupture scenarios have been developed. These scenarios include permissible combinations of faults and fault segments that could, based on the available paleoseismic data, rupture synchronously during individual earthquakes.

Recurrence Interval–"Recurrence interval" is defined as the time interval between successive surface-rupture earthquakes. It is an important temporal measure of fault behavior in seismic hazard analysis. Recurrence intervals are calculated for individual faults at relevant sites using paleoseismic data of the number and timing of coseismic surface-rupture events. Individual recurrence intervals are estimated in cases for which there is adequate age control to isolate the timing between specific pairs of events. Uncertainties in both the dating of units and the number of possible events are incorporated into the reported ranges of recurrence intervals.

At least one and commonly two or more recurrence interval estimates are made along individual faults at Yucca Mountain. Average recurrence intervals of individual faults range from 5 to 270 ka. The long recurrence intervals reflect relatively small numbers of observed displacements in middle Pleistocene deposits and are consistent with the estimated low fault slip rates.

2.4 VIBRATORY GROUND MOTION INFORMATION

In a seismic hazard analysis, assessments are made of the size and recurrence rate of earthquakes that seismic sources might generate, as well as the propagation of earthquake energy from the source to the Yucca Mountain site. The level of ground motion that will be experienced at the site for any given earthquake location and magnitude must be assessed and is described by attenuation relations. To the extent possible, the vibratory ground motion adopted for the seismic design of the repository and analysis of its postclosure performance should incorporate the effects of the seismic sources, propagation path, and local site geology specific to the Yucca Mountain region and site. Ideally, recorded ground motion from large earthquakes in the Yucca Mountain region would be used directly to develop attenuation relations for application at Yucca Mountain. However, because large earthquakes occur infrequently in the region, such data are few and are insufficient to constrain empirical models. This situation exists even when the entire Basin and Range Province, extending from southern Oregon and Idaho to northern Mexico and western Texas, is considered. The few data recorded from larger earthquakes and the geophysical and seismological properties derived for the region, nevertheless, provide some information for estimating ground motion at the repository site. This information forms part of the basis for the expert interpretations and assessments of uncertainty that were part of the PSHA for Yucca Mountain.

Characterizing ground motion at Yucca Mountain using existing attenuation relations involves resolving whether (and to what extent) those relations for the western United States are applicable to the Basin and Range Province, in general, and to Yucca Mountain, in particular. The seismological questions include whether differences in the factors that influence ground motion in the Yucca Mountain region and in the western United States would lead to significant differences in ground motion estimates for the two regions. These factors include seismic source properties, regional crustal properties, and shallow geologic site properties at the repository.

Generally, comparisons must be made between Yucca Mountain factors and average factors inherent in the strong-motion database for the western United States.

To address these issues, six ground motion studies were carried out as part of site characterization activities and are discussed in the following sections. The first study was an empirical analysis of worldwide ground motion data from extensional regimes. The second study comprised numerical modeling of selected scenario earthquakes near Yucca Mountain in which ground motions were estimated using seismological models of the source, path, and site effects. The numerical modeling allowed the region-specific crustal structure and site-specific rock properties to be incorporated in the ground motion estimates. The third study used weak motion recordings to characterize the near-surface seismic wave attenuation at Yucca Mountain. The fourth study examined earthquake stress drops in extensional regimes to compare them to those for earthquakes used to develop western United States ground motion attenuation relations. Stress drop is a factor in determining the level of high-frequency ground motion. The fifth study investigated the possible constraint that precariously balanced rocks can provide on the levels of ground motion that have occurred in the past. The sixth study is the ground motion characterization performed as part of the PSHA project and is the most comprehensive of the six. This study was a formal elicitation of a panel of ground motion experts, which incorporated results from the other five studies and resulted in ground motion attenuation relations specific to Yucca Mountain. The ground motion characterization performed as part of the PSHA is discussed in Section 3.3.

2.4.1 Attenuation of Strong Motion in Extensional Regimes

The Basin and Range Province in which Yucca Mountain is situated is an extensional tectonic regime. At the time that the PSHA for Yucca Mountain was getting underway, a ground motion attenuation relation had not been developed specifically for extensional regimes. Thus, to develop a ground motion attenuation relation appropriate for the site region, data from extensional regimes were compiled and analyzed (Spudich, Fletcher et al. 1996). Because the number of events in the Basin and Range Province is limited, the database includes ground motions recorded in extensional regimes worldwide.

Several representative attenuation relations based on western United States data were compared to the extensional data by Spudich, Fletcher et al. (1996). The mean residual, or bias, was computed for each attenuation relation and indicates whether that relation systematically underpredicts or overpredicts the extensional strong-motion data. In general, the computed residuals indicate that the standard western United States attenuation relations overpredict ground motion from extensional regimes by about 15% to 35% on average (Spudich, Fletcher et al. 1996, Table 9; Abrahamson and Becker 1996, Figure 10.5-3).

Spudich, Fletcher et al. (1997) developed an attenuation relation (SEA96) to estimate ground motion in extensional regimes. Comparisons of median predictions from this relation with those from several western United States attenuation relations illustrate their differences. In general, at short to moderate periods, the predictions of the SEA96 relation are less than or lie at the lower limit of the values predicted by other western United States relations. At long periods, the SEA96 relation is similar to the western United States relations. Notably, however, the SEA96 relation has a much larger standard deviation at long periods than is usual for the western United States relations.

Spudich, Joyner et al. (1999) updated the attenuation relation for extensional tectonic regimes using a larger data set and corrected minor errors in the data set used for the earlier analysis. At short distances (5 to 30 km), ground motion predicted by the new relation (SEA99) are up to 20% higher than those predicted by the SEA96 relation, while at longer periods (1.0 to 2.0 s) and larger distances (40 to 100 km), they are about 20% lower (Spudich, Joyner et al. 1999, p. 1156). When compared to ground motion determined from the relation of Boore et al. (1994), results average about 20% lower, except for short distances at periods around 1.0 s. For this combination, the ground motion from SEA99 exceed those determined from the Boore et al. (1994) relation by up to 10%. The standard deviation of SEA99 is considerably lower than that of SEA96, probably because of correction of errors in the data set used for the regression.

2.4.2 Ground Motion from Yucca Mountain Scenario Earthquakes

Due to the lack of near-fault strong-motion data from earthquakes in the Basin and Range Province (including the Yucca Mountain region), a study was carried out to estimate vibratory ground motion for several earthquake scenarios potentially affecting Yucca Mountain (Schneider et al. 1996). The six participants in the study used established numerical modeling methods to simulate ground motion that was appropriate to the specific conditions at Yucca Mountain. As part of the modeling exercise, both median ground motion and its variability were estimated for each earthquake scenario.

Six earthquake scenarios were evaluated based on two criteria: (1) the postulated sources are likely to have generated significant earthquakes in the past, and (2) they are considered likely to produce ground motion that would impact seismic hazard estimates at Yucca Mountain. The six scenarios include four normal faulting events (M_w 6.3 to 6.6) at source-to-site distances of 1 to 15.5 km and two strike-slip faulting events (M_w 6.7 and 7.0) at source-to-site distances of 25 and 50 km, respectively.

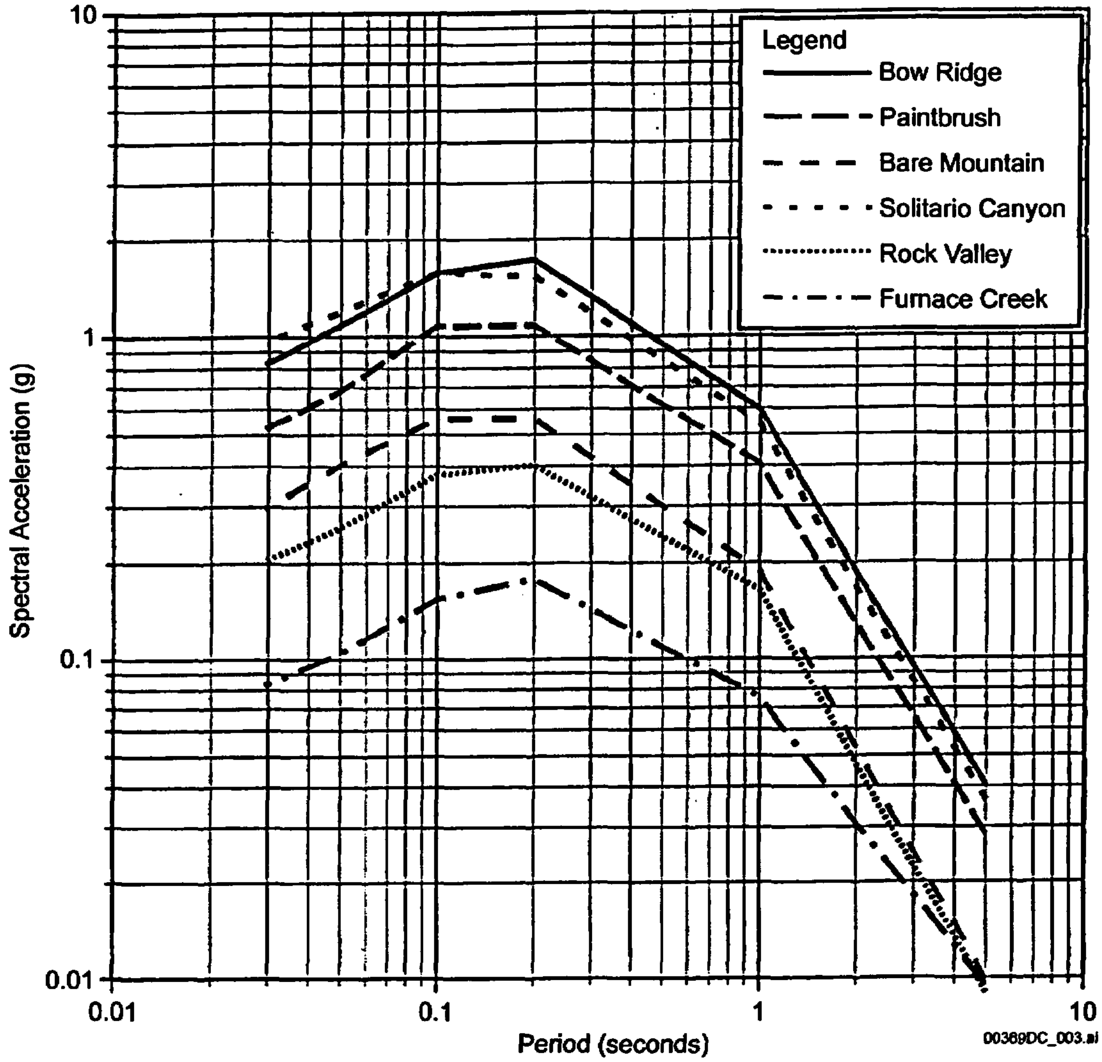
Six modeling approaches were included in the study. The methods vary significantly in their treatment of wave propagation, site response, and overall level of complexity, but all the methods accommodate the essential aspects of seismic energy being generated from a finite source and propagated along a path to a site at the earth's surface. Differences in resulting predictions capture an important component of the uncertainty in ground motion in these scenario earthquakes that can be applied to the variability of other simulations.

The study included a validation phase in which the models were calibrated using ground motion recordings from the nearby Little Skull Mountain earthquake (M_W 5.6). The six participants incorporated various Yucca Mountain source, path, and site parameters into their models to fit observed ground motion from five sites that recorded the Little Skull Mountain earthquake. Most of the six methods had also been previously calibrated against recordings from other earthquakes.

The models produced ground motion estimates that were comparatively unbiased for periods of less than 1 s (Abrahamson and Becker 1996, Figure 10.7-5), indicating that they are applicable to estimating ground motion in the Basin and Range Province. However, the bias for periods greater than 1 s indicates that the numerical simulation models do not work well for the 1992 Little Skull Mountain earthquake at long periods.

Using the Little Skull Mountain–calibrated models, the six teams computed motions for the six faulting scenarios. Five of the teams whose models were numerical simulations (i.e., all except an empirical underground nuclear explosion model) ran multiple realizations of the source process and computed a mean spectrum for each scenario. The computed median spectral accelerations for the scenario events based on the team's models are shown on Figure 2-13. Ground motion computed for the normal faulting scenario events at close distances (Bow Ridge, Solitario Canyon, and Paintbrush Canyon faults) are large (Schneider et al. 1996, Figure 10-10): 34 Hz spectral accelerations range from 0.5 to 1.0 g at distances of 1 to 3 km.

The model simulations were compared with several western United States empirical attenuation relations (Sadigh et al. 1993; Boore et al. 1994). The simulated median ground motion for the four normal faulting scenario events exceed the western United States predictions by about 60% at distances less than 5 km (3 mi) and by about 20% at 15 km (9 mi) (Abrahamson and Becker 1996, p. 10-39). The differences are largest at high frequencies, attributable primarily to low site attenuation in the shallow rock at Yucca Mountain and to larger crustal amplification for the Basin and Range Province. At long periods, the difference is attributed to the larger crustal amplification and directivity effects (stronger ground motion in the direction of rupture propagation than in other directions from the earthquake source).



Source: Abrahamson and Becker 1996, Figure 10.8-15.

Figure 2-13. Median Spectral Acceleration of Scenario Earthquakes in the Yucca Mountain Region

For the more distant strike-slip faulting earthquake scenarios, the simulated median ground motion results are greater than the western United States attenuation predictions by about 30% at a distance of 25 km at high frequencies (Abrahamson and Becker 1996, p. 10-40). This increase is similarly attributed to low site attenuation and larger crustal amplification. At 50 km, the simulated longer period ground motion results are consistent with western United States empirical attenuation predictions because the effect of local site attenuation is not as significant.

The simulated higher ground motion at high frequencies is consistent with records from the 1992 Little Skull Mountain earthquake. The high-frequency ground motion from this event is significantly larger than those predicted by western United States empirical attenuation relations.

The variability of the simulated motions is also greater than that computed for western United States empirical attenuation relations. The standard error is about 0.15 natural log units larger than that found for empirical attenuation relations.

2.4.3 Site Attenuation

Recordings of regional earthquakes at Yucca Mountain were used by Su et al. (1996) to evaluate the near-surface attenuation. Results indicated that site attenuation at Yucca Mountain is lower than for typical California soft rock. Therefore, at low levels of shaking, damping from the tuff is less than that for California soft-rock conditions. This leads to larger high-frequency ground motion on the tuff as compared to that on California soft rock, assuming that all other parameters are the same. The results of Su et al. (1996) were used to provide a site attenuation value for the Yucca Mountain PSHA.

2.4.4 Earthquake Stress Drop

Stress drop is the difference in stress across the fault before and after an earthquake. Stress drop affects high-frequency ground motion. If stress drops in the Yucca Mountain region are greater than the typical value for western United States earthquakes, then larger high-frequency motions would be expected at Yucca Mountain relative to motions determined from western United States empirical attenuation relations. To provide data to assess this potential effect, an evaluation of stress drops for earthquakes in extensional regimes was performed in support of the ground motion characterization effort in the PSHA project (CRWMS M&O 1998, p. 5-11).

The analysis used a data set composed of earthquake records from extensional tectonic regimes (Spudich, Fletcher et al. 1997), including both normal and strike-slip events. These data were supplemented with data from the 1995 Dinar, Turkey, earthquake, which were not available to Spudich, Fletcher et al. (1997). The final data set comprised 210 horizontal components from 140 sites in 24 earthquakes, a magnitude range of M_w 5.1 to 6.9, and distances from 0 to 102 km. The data were fit to a standard earthquake source model. A two-step inversion process was adopted to decouple the inversions for site attenuation and for stress drop. Stress drops computed for each earthquake were weighted to yield a median value for each mechanism.

The median stress drop for normal-faulting earthquakes was about 4.5 MPa, and the value for strike-slip earthquakes (in extensional regimes) was about 5.5 MPa. In comparison, stress drops for western United States earthquakes are about 7 to 10 MPa (e.g., Atkinson 1995, p. 1341). These differences in stress drop contribute to lower high-frequency motions in extensional regimes compared to transpressional regimes, such as coastal California. This information was considered in the ground motion characterization component of the PSHA for Yucca Mountain.

2.4.5 Implications for Vibratory Ground Motion from Studies of Precarious Rocks at Yucca Mountain

The existence of precariously balanced rocks in the Yucca Mountain region may place some constraints on the level of vibratory ground motion experienced at the site over the past several tens of thousands of years. Precariously balanced rocks provide evidence that past levels of strong vibratory ground motion have been insufficient to topple them. In areas where strong ground motion is known to have occurred historically, precarious rocks are not observed. For example, based on reconnaissance field surveys in southern California, Brune (1996, p. 43) concluded that no precarious rocks are found within 15 km of zones of high-energy release of historical large earthquakes. Laboratory physical modeling, numerical modeling, and field tests provide confidence that rough estimates of the accelerations required to topple precarious rocks can be made without extensive controlled testing (Brune 2000, p. 1107; Anooshehpoor and Brune 2000, pp. 2 to 4). Brune and Whitney (2000, p. 18) noted that numerous precarious rocks exist along Solitario Canyon and argued that accelerations at Yucca Mountain have not exceeded about 0.3 g at the surface during the past 75,000 to 80,000 years. Vibratory ground motion at the depth of waste emplacement would be less than those at the earth's surface.

Precarious rocks have also been used to test ground motion attenuation relations. Brune (2000, p. 1107) notes that, in contrast to observations near strike-slip faults, precarious and semiprecarious rocks are found nearly to the fault trace on the footwall side of normal faults in Nevada and California. Comparison of estimated toppling accelerations with accelerations predicted by a ground motion attenuation relation based largely on data for strike-slip earthquakes suggests that the attenuation relation may be conservative. The attenuation relation overestimates accelerations on the footwall of normal faults at near distances (Brune 2000, Figure 2). This result is consistent with results from dynamic foam rubber models of strike-slip and normal faulting earthquakes (Brune and Anooshehpoor 1999). That is, the models indicate that ground motion near the fault trace is less for normal faulting earthquakes than for strike-slip earthquakes. The implication of this observation is that seismic hazard estimates using ground motion attenuation curves based largely on data from strike-slip earthquakes may result in conservative values of hazard for sites such as Yucca Mountain, where normal faulting dominates.

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3. PROBABILISTIC SEISMIC HAZARD ANALYSIS

To assess the seismic hazards of vibratory ground motion and fault displacement at Yucca Mountain, a PSHA was performed. The PSHA provides quantitative hazard results to support an assessment of the repository's long-term performance and to form the basis for developing seismic design criteria for the LA. The PSHA methodology that the DOE has used for Yucca Mountain is consistent with that documented in *Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain* (YMP 1997). This methodology also is consistent with state-of-the-practice guidance provided by the Senior Seismic Hazard Analysis Committee (Budnitz et al. 1997). Key attributes of the PSHA methodology for Yucca Mountain are (1) utilization of a geologic and seismologic database developed over a 20-year period in the Yucca Mountain region; (2) explicit consideration and quantification of uncertainties regarding alternative seismic-source, ground motion, and fault-displacement interpretations; and (3) use of a formal, structured expert elicitation process to capture the informed scientific community's views of key inputs to the PSHA.

The PSHA methodology for vibratory ground motion has become standard practice for deriving vibratory ground motion hazards for design purposes. Less commonly, probabilistic fault displacement analyses are conducted to provide quantitative assessments of the location and amount of differential ground displacement that might occur. Both analyses provide hazard curves, which express the probability of exceeding various amounts of ground motion (or fault displacement). The probability is usually expressed as a frequency of exceedance per year. The resulting seismic hazard curves represent the integration over all identified earthquake sources and magnitudes of the probability of future earthquake occurrence and, given an occurrence, its effect at a site of interest.

The basic elements of a PSHA for vibratory ground motion are:

a) Identification of seismic sources that contribute to the vibratory ground motion hazard at Yucca Mountain and characterization of their geometry. This establishes the distribution of source-to-site distances for each source.

b) Characterization of seismic sources by the recurrence rate of earthquakes of various magnitudes and the maximum magnitude. This establishes the distribution of magnitudes and their rate of occurrence for each source.

c) Ground motion attenuation relations that provide for the estimation of a specified ground motion parameter as a function of magnitude, source-to-site distance, local site conditions, and, in some cases, seismic source characteristics. This establishes the distribution of ground motion that will be experienced at the site when a given magnitude earthquake occurs on a given source.

d) Integration of the seismic source characterization and ground motion attenuation evaluations, including associated uncertainties, into a seismic hazard curve and associated uncertainty distribution.

Probabilistic fault displacement hazard analysis follows a similar path:

a) Identification of fault sources of fault displacement (principal faults)

b) Characterization of the frequency, size, and locations of displacements on principal faults

c) Characterization of the amounts and locations of subsidiary displacements as a function of distance from principal faults and magnitudes

d) Integration of source characterization and distance distribution, including associated uncertainties, into a fault displacement hazard curve and associated uncertainty distribution.

PSHAs incorporate both randomness and uncertainty. For discrete variables, the randomness, also termed aleatory variability, is parameterized by the probability of each possible value. For continuous variables, the randomness is parameterized by the probability density function. An example of randomness is the amplitude of ground motion that would occur at a particular location from repeated earthquakes having exactly the same magnitude at exactly the same distance (say, magnitude 6 at 25 km distance). Variations in ground motion amplitude are expected due to unknowable complexities in earthquake-to-earthquake source properties and in the propagation path.

Uncertainty, also termed epistemic uncertainty, is the scientific uncertainty in the model of the process. The uncertainty is due to limited data and knowledge and is characterized by alternative models. For discrete random variables, the uncertainty is modeled by alternative probability distributions. For continuous random variables, the uncertainty is modeled by alternative probability density functions. Examples of uncertainty are alternative ground motion attenuation relations that express the amplitude of ground motion at a particular site as a function of distance to the source and earthquake magnitude. Unlike randomness, uncertainty is potentially reducible with additional knowledge and data.

Given the input evaluations, the hazard calculation method integrates over all values of the variables and estimates the mean probability of exceedance of any ground-shaking amplitude at the site. A plot of these results is the seismic hazard curve. The hazard curve quantifies the variability of the earthquake occurrence and ground-shaking attenuation. In addition to the variability of the seismic hazard, however, is uncertainty about the seismotectonic environment of a site. Significant advances in development of methodology to quantify uncertainty in seismic hazard have been made in the past 20 years (EPRI 1986, Volume 1; Budnitz et al. 1997). These advances involve the development of alternative interpretations of the seismotectonic environment of a site by multiple experts and the structured characterization of uncertainty. Evaluations by multiple experts are made within a structured expert elicitation process designed to minimize uncertainty due to uneven or incomplete knowledge and understanding (Budnitz et al. 1997). The weighted alternative interpretations are expressed by use of logic trees. Each pathway through the logic tree represents a weighted interpretation of the seismotectonic environment of the site for which a seismic hazard curve is computed. The result of computing the hazard for all pathways is a distribution of hazard curves representing the full variability and uncertainty in the hazard at a site.

3.1 PROBABILISTIC SEISMIC HAZARD ANALYSIS PROCESS

By necessity, evaluations of seismic source characteristics, earthquake ground motion, and fault displacement involve interpretations of data. These interpretations have associated uncertainties related to the ability of data to fully resolve various hypotheses and models. In the PSHA, a formal expert elicitation process was used to develop inputs that specifically included estimates of variability and uncertainty in interpretations (CRWMS M&O 1998). The expert elicitation process followed was generally consistent with the *Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program* (Kotra et al. 1996) and the *Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on the Uncertainty and Use of Experts* (Budnitz et al. 1997).

Six teams of three earth science experts characterized seismic sources in the Yucca Mountain site region (within a distance of about 100 km) and fault displacement potential at nine demonstration points. Seven ground motion experts characterized ground motion attenuation in the site region. Interpretations for hazard assessment were coordinated and facilitated through a series of workshops. Each workshop was designed to accomplish a specific step in the elicitation process and to ensure that the relevant data were being appropriately considered and integrated. An important goal in the elicitation process was to reduce variability in interpretations due to a lack of common understanding of the available data and probabilistic models used in the analysis. The final PSHA results were presented as mean, median, and fractile hazard curves representing the total variability and uncertainty in input interpretations.

The essential elements of the seismic source characterization, ground motion attenuation evaluation, fault displacement characterization, and PSHA results are summarized in Sections 3.2, 3.3, 3.4 and 3.5, respectively.

3.2 SEISMIC SOURCE CHARACTERIZATION

Seismic sources were interpreted by the PSHA expert teams. For each source zone, the expert teams characterized the zone's geometry, maximum magnitude, rate of earthquake occurrence, and the magnitude distribution of those earthquakes. Summaries of the source-zone characterization performed by the six expert teams can be found in *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* (CRWMS M&O 2000, Table 5); more complete descriptions are found in *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada* (CRWMS M&O 1998, Appendix E).

3.2.1 Source Geometries

As used in PSHA, a seismic source is defined as a region of the earth's crust that has relatively uniform seismicity characteristics, is distinct from those of neighboring sources, and can be used in approximating the locations of future earthquakes. Two main types of seismic sources were characterized by the seismic source expert teams: fault sources and areal source zones. Fault sources are used to represent the occurrence of earthquakes along a known or suspected fault. Uncertainty in the definition of fault sources is expressed by considering alternative rupture lengths, alternative fault dips, and possible linkages with other faults. In addition, an evaluation is made of the probability that a particular fault is active and capable of generating moderate-to-large earthquakes.

Areal source zones represent regions of distributed seismicity that are not associated with specific known faults. The events are considered to be occurring on unidentified faults or structures whose areal extents are best characterized by zones. Uncertainty in defining areal zones typically was expressed by considering alternative zonations of the region surrounding the Yucca Mountain site. For each source zone, the expert teams characterized the zone's maximum magnitude, its rate of earthquake occurrence, and the magnitude distribution of those earthquakes. Uncertainties in all of these parameters are also quantified.

Two types of fault sources were considered in the PSHA: regional faults and local faults. Regional faults were defined by most teams as Quaternary faults within 100 km of Yucca Mountain, but outside the local vicinity of the site, that were judged to be capable of generating earthquakes of M_W 5 and larger. Local faults were defined as being located within about 15 km of Yucca Mountain. The specific faults that required detailed characterization were determined based on factors including fault length and location relative to Yucca Mountain, displacement of Quaternary deposits, direct relation with seismicity, structural relation to other Quaternary faults, orientation within the contemporary tectonic stress regime, and considerations of alternative tectonic models.

The number of regional faults considered by the expert teams ranged from 11 to as many as 36. This reflected, in part, the judgments of the teams regarding the activity of various faults, as well as the decision by some teams to also include potentially active faults. For the characterization of local faults, varying behavioral and structural models were employed by the expert teams to represent the range of possible rupture patterns and fault interactions. Interpretations regarding the potential simultaneous rupture of multiple faults were included in all of the expert assessments.

Areal source zones were defined by all teams to account for background earthquakes that occur on buried faults or other faults not explicitly included in their characterizations. Seismicity related to volcanic processes (specifically to basaltic volcanoes and dike injection) was considered by all six expert teams but explicitly characterized as distinct source zones by only two expert teams. Volcanic-related earthquakes were not interpreted as separate seismic sources by the other four teams because the low magnitude and frequency of volcanic-related seismicity was accounted for by earthquakes in the areal zones.

3.2.2 Maximum Earthquake Magnitude

Maximum earthquake moment magnitude (M_{max}) was determined for each source by each expert team to represent the largest earthquake that the source is capable of generating. Two basic approaches were used to assess maximum magnitude. The primary approach, which was used for faults, was based on estimates of the maximum dimensions of fault rupture. Multiple sources of uncertainty were considered in estimating physical dimensions of maximum rupture on faults, including uncertainty in rupture length, rupture area, and displacement per event. The second approach considered historical data on the seismicity of the region. This approach was used primarily for areal source zones. For each of the sources included in the PSHA, the uncertainty in M_{max} is expressed as a probability distribution.

3.2.3 Earthquake Recurrence

Earthquake recurrence relations express the rate or annual frequency of different magnitude earthquakes occurring on a seismic source. Methods for developing these relations are usually different for fault sources than for areal sources. For fault sources, the expert teams used approaches based on estimates of fault slip rates and the average slip per event and on seismic moment rates. For areal sources, earthquake recurrence relationships were determined from the catalog of historical and instrumental earthquakes within 300 km of Yucca Mountain.

3.2.4 Example of Seismic Source Characterization Assessments

The six expert teams considered a variety of alternative models and parameters in their characterization of seismic sources. This section identifies the assessments that were made to illustrate the range of interpretations, as well as the uncertainties that were quantified. Logic trees provided a mechanism for describing and quantifying the uncertainties. Key assessments for the PSHA are given as nodes of the logic tree and alternative models or parameter values are given on the branches at each node. Weights are assigned to the alternative branches based on expert judgment regarding the relative credibility of the alternative models and parameters.

Key elements of the seismic source characterization by the expert teams were the following:

- Alternative tectonic models
  - Planar fault models
  - Shear models (buried strike-slip faults or fault systems)
  - Detachment models
  - Synchronous volcanic-tectonic events
- Thickness of earthquake-generating crust
- Areal seismic source zones
  - Source geometry
  - Recurrence model
  - Seismicity catalog for recurrence calculation
  - Spatial smoothing model and parameters
  - Maximum magnitude
- Regional fault sources
  - Probability of activity, slip type, and geometry
  - Maximum magnitude
  - Recurrence approach and parameters

- Local fault sources
  - Probability of activity
  - Synchroneity of ruptures
  - Coalescence of faults at depth
  - Downdip geometries
  - Rupture dimensions (length, per-event displacement, area)
  - Maximum magnitude
  - Recurrence approach and parameters

- Other potential sources
  - Buried regional right-lateral shear zone
  - Earthquake-generating detachment
  - Volcanic source zone
  - Fault interpreted from gravity anomalies
  - Cross-basin fault
  - Highway 95 or Carrara Fault.

For illustration, Table 3-1 presents ranges of key parameter values assessed by the experts for the PSHA (CRWMS M&O 1998). The table summarizes the probability that the fault is active and the range of maximum magnitudes, slip rates, and recurrence intervals assessed by the experts.

3.3 GROUND MOTION CHARACTERIZATION

The goal of the ground motion evaluation for the Yucca Mountain PSHA was to formulate attenuation interpretations describing vibratory ground motion at the repository. Seven experts evaluated various proponent models. The experts provided point estimates of ground motion for a suite of prescribed faulting cases, and these point estimates were subsequently regressed to attenuation equations. The ground motion constituted response spectral values (horizontal and vertical components) for specified spectral periods. The point estimates constituted an estimate of the median ground motion, its randomness (aleatory variability), and the uncertainty in each (epistemic uncertainty). Each faulting case corresponded to a particular magnitude earthquake, fault geometry, and source-site distance. The cases were designed to sample the magnitude-distance-faulting space at Yucca Mountain in sufficient detail to provide a robust regression.

The ground motion estimates and, thus, the resulting attenuation relations were developed for a reference rock outcrop (Figure 3-1). This reference rock outcrop was defined to have geotechnical conditions identical to those at the depth of the repository. The reference rock outcrop was used because site-specific data on the velocities and dynamic properties of the upper 300 m of rock and soil were limited at the time of the PSHA. For design analyses and analyses supporting performance assessment, the effect on ground motion of the material between the waste emplacement level and the earth's surface (site response) will be taken into account (see Section 4).

Table 3-1. Summary of Fault Parameters from Probabilistic Seismic Hazard Analysis Seismic Source Characterization

Fault	Probability Fault Is Active	Maximum Magnitude	Slip Rate (mm/yr)	Recurrence Interval (ka)
Bare Mountain	1.0	5.8 to 7.5	0.005 to 0.25	20 to 200
Black Cone	0.8	5.0 to 7.0	0.001 to 0.005	-
Bow Ridge	0.4 to 1.0	5.2 to 7.0	0.002 to 0.007	40 to 350
Crater Flat Fault system	1.0	5.3 to 7.0	0.001 to 0.003	-
Central Crater Flat	0.6	5.3 to 7.0	0.001 to 0.005	-
Southern Crater Flat	1.0	5.4 to 7.0	0.002 to 0.02	40 to 180
Northern Crater Flat	1.0	5.5 to 7.0	0.001 to 0.005	120 to 160
Dune Wash	0.1	4.9 to 7.2	0.0001 to 0.001	-
East Busted Butte	0.4	4.5 to 7.2	0.0005 to 0.003	-
East Lathrop Wells Cone	1.0	4.6 to 6.9	0.005 to 0.003	-
Fatigue Wash	1.0	5.5 to 7.3	0.002 to 0.02	50 to 250
Fatigue Wash–Windy Wash	1.0	5.6 to 7.2	0.005 to 0.024	-
Ghost Dance Fault zone	0.05 to 0.1	4.5 to 7.0	0.0001 to 0.002	-
Iron Ridge	0.1 to 1.0	5.1 to 7.0	0.001 to 0.005	-
Iron Ridge–Solitario Canyon	1.0	5.5 to 7.2	0.005 to 0.024	-
Midway Valley	0.1	4.9 to 7.1	0.0001 to 0.001	-
Paintbrush Canyon	1.0	5.9 to 7.4	0.002 to 0.03	20 to 270
Paintbrush Canyon–Stagecoach Road	1.0	5.6 to 7.3	0.009 to 0.05	15 to 120
Paintbrush–Stagecoach–Bow Ridge	1.0	5.5 to 7.6	0.005 to 0.02	10 to 75
Solitario Canyon	1.0	5.6 to 7.4	0.002 to 0.04	35 to 180
Stagecoach Road	1.0	5.3 to 7.1	0.01 to 0.07	5 to 75
Windy Wash	1.0	6.6 to 7.5	0.01 to 0.027	35 to 100
South Windy Wash	1.0	5.7 to 7.1	0.01 to 0.04	20 to 60
North Windy Wash	1.0	5.6 to 7.2	0.001 to 0.005	-

Source: CRWMS M&O 1998.

NOTE: Parameter ranges developed from all teams reporting (i.e., one to six teams); all parameter ranges were provided as probability distributions.

Proponent Models–The experts computed their ground motion point estimates by considering existing proponent models. The proponent models fell into several classes: empirical attenuation relations, hybrid-empirical, point source numerical simulations, finite-fault numerical simulations, and empirical blast models (CRWMS M&O 2000, Table 8).

Because no empirical attenuation models exist for the Yucca Mountain region or the Basin and Range Province, the empirical models used in this study resulted from regression analyses of strong-motion records primarily from California earthquakes. These empirical relations required adjustments so they would better fit conditions in the Yucca Mountain region. The hybrid empirical model is derived from these relations and implicitly includes conversion factors that must be separately applied to the empirical relations. The empirical relation for extensional regimes developed by Spudich et al. (1997) (Section 2.4.1) was one of the relations considered by the experts.

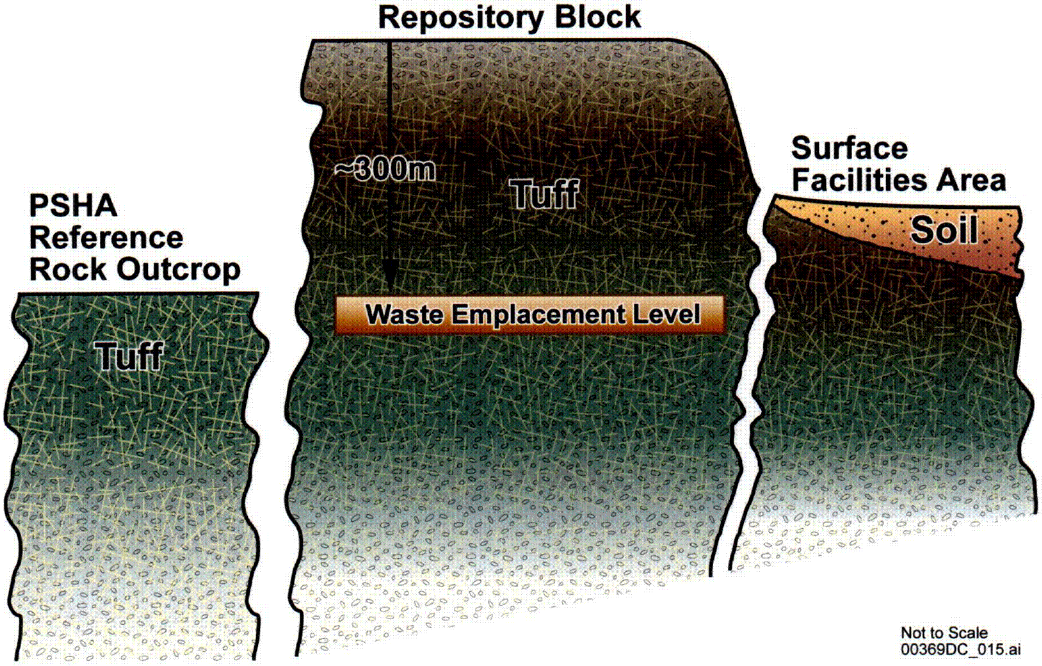

Figure 3-1. Relation of Reference Rock Outcrop to Sites for which Seismic Inputs Are Developed

The blast models are based on empirical records from underground nuclear explosions at the Nevada Test Site (Schneider et al. 1996, pp. 3-15 to 3-17). Three blast models were assessed, each with a different approach to account for differences in earthquake sources and explosion sources.

The numerical simulations were tailored to Yucca Mountain conditions and required no adjustments. The point source models are the simplest numerical models and also the best understood. The finite-fault numerical simulations were derived from the six models evaluated in the scenario earthquake modeling study previously described (Section 2.4.2). The experts chose three model approaches for their analyses:

- Stochastic method with ω^2 subevents
- Composite fractal source method
- Broadband Green's function method.

Conversion Factors–Depending on the nature of the data sets upon which they were based, the empirical relations typically represented source, path, and site conditions different from those encountered at Yucca Mountain. Suites of conversion factors were consequently computed as part of the study. They were developed using the results of numerical finite-fault simulations, stochastic point source simulations, and empirical attenuation relations. Summaries of the conversion factors are presented in *Probabilistic Seismic Hazard Analyses for Fault*

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Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada (CRWMS M&O 1998, Section 5). The factors included corrections for the following:

- **Source**–Western United States compressional and strike-slip seismic sources to Yucca Mountain extensional seismic sources
- **Crust**–Western United States crust to Yucca Mountain crust
- **Site**–Yucca Mountain surface conditions to reference rock outcrop.

Additionally, many of the proponent models did not include the full range of ground motion parameters required. For example, not all the empirical models included vertical ground motion. Thus, a variety of scaling factors was also developed and applied in the same manner as the conversion models to develop the required parameters.

Attenuation Relations–Each expert developed a set of point estimates for the defined cases covering different faulting styles, event magnitudes, source geometries, and source-site distances. The estimates comprised median ground motion, its variability, and the uncertainty in both. The estimates were determined directly from the models, the conversion factors, the adjustment factors described above, and other judgments by the experts. These estimates were then parameterized in the form of attenuation relations.

The seven sets of attenuation relations predict median ground motion that differs by less than a factor of 1.5. The experts' horizontal aleatory (randomness) estimates, the epistemic uncertainties in their median estimates (with one exception), and the epistemic uncertainties in their aleatory estimates all vary by less than about 0.1 natural log unit (CRWMS M&O 1998, p. 6-4).

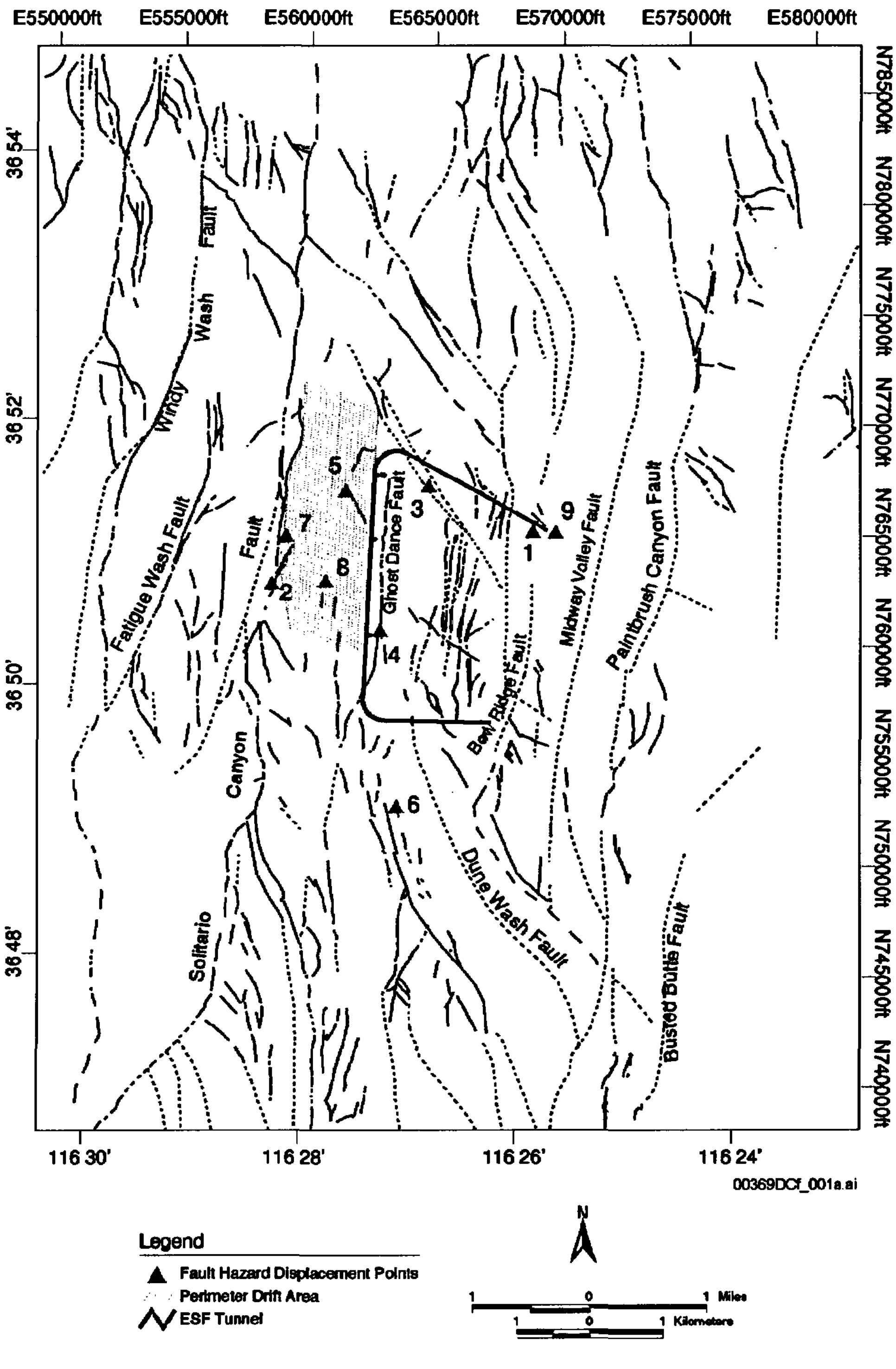
3.4 FAULT DISPLACEMENT CHARACTERIZATION

Several approaches to characterize the fault displacement potential were developed by the seismic source characterization expert teams. These approaches were based primarily on empirical observations of the pattern of faulting from historical ruptures throughout the Basin and Range and at the site.

The potential for fault displacement was categorized as either principal or distributed faulting. Principal faulting is the faulting along the main plane (or planes) of crustal weakness responsible for the primary release of seismic energy during the earthquake. Where the principal fault rupture extends to the surface, it may be represented by displacement along a single narrow trace or over a zone that is a few to many meters wide. Distributed faulting is rupture that occurs on other faults near the principal rupture in response to the principal displacement. It is expected that distributed faulting will be discontinuous in nature and occur over a zone that may extend outward several tens of meters to many kilometers from the principal rupture. A fault that can produce principal rupture may also undergo distributed faulting in response to principal rupture on other faults.

Both principal and distributed faulting are important to the assessment of the fault displacement hazard at the Yucca Mountain site. Nine locations at or near Yucca Mountain, with multiple assumed conditions at some locations, were identified to demonstrate the fault displacement methodology (Figure 3-2). These locations were chosen to represent the range of potential faulting conditions throughout the Yucca Mountain site. Some of these locations lie on faults that may experience both principal faulting and distributed faulting. The other points are sites of only potential distributed faulting.

The approaches developed by the seismic source expert teams for characterizing the frequency of displacement events can be divided into two categories: the displacement approach and the earthquake approach. The displacement approach provides an estimate of the frequency of displacement events directly from the geologic history of displacement, as interpreted from observed feature-specific or point-specific data. The earthquake approach involves relating the frequency of slip events to the frequency of earthquakes on the various seismic sources defined by the seismic source characterization interpretations for the ground motion assessment. Both approaches are used for assessing the fault displacement hazard for principal faulting and distributed faulting.



Source: CRWMS M&O 1998, Figure 4-9.

NOTE: See Table 3-2 for descriptions of demonstration points.

Figure 3-2. Location of Nine Points for Demonstration of Fault Displacement Hazard Assessment

Table 3-2. Mean Displacement Hazard at Nine Demonstration Sites

Site	Location	Mean Displacement (cm) Annual Exceedance Probability 10^{-4}	5×10^{-5}	10^{-5}	10^{-6}	10^{-7}	10^{-8}
1	Bow Ridge Fault	<0.1	<0.1	7.8	73	220	590
2	Solitario Canyon Fault	<0.1	<0.1	32	180	490	1300
3	Drill Hole Wash Fault	<0.1	<0.1	<0.1	15	75	240
4	Ghost Dance Fault	<0.1	<0.1	<0.1	13	56	170
5	Sundance Fault	<0.1	<0.1	<0.1	5.5	39	140
6	Unnamed fault west of Dune Wash	<0.1	<0.1	<0.1	13	71	210
7	About 100 m east of the Solitario Canyon Fault with the condition:						
7a	Small fault with 2 m cumulative displacement	<0.1	<0.1	<0.1	2.1	18	73
7b	Shear with 0.10 m cumulative displacement	<0.1	<0.1	<0.1	1.0	5.6	9.0
7c	Fracture	<0.1	<0.1	<0.1	0.11	0.53	0.63
7d	Intact rock	<0.1	<0.1	<0.1	–	–	–
8	Between Solitario Canyon and Ghost Dance Fault with the condition:						
8a	Small fault with 2 m cumulative displacement	<0.1	<0.1	<0.1	2.0	18	78
8b	Shear with 0.10 m cumulative displacement	<0.1	<0.1	<0.1	0.89	5.5	8.8
8c	Fracture	<0.1	<0.1	<0.1	0.10	0.52	0.63
8d	Intact rock	<0.1	<0.1	<0.1	–	–	–
9	Midway Valley	<0.1	<0.1	0.11	11	67	210

Source: CRWMS M&O 1998, Table 8-1; DTN: MO0401MWDRPSHA.000.

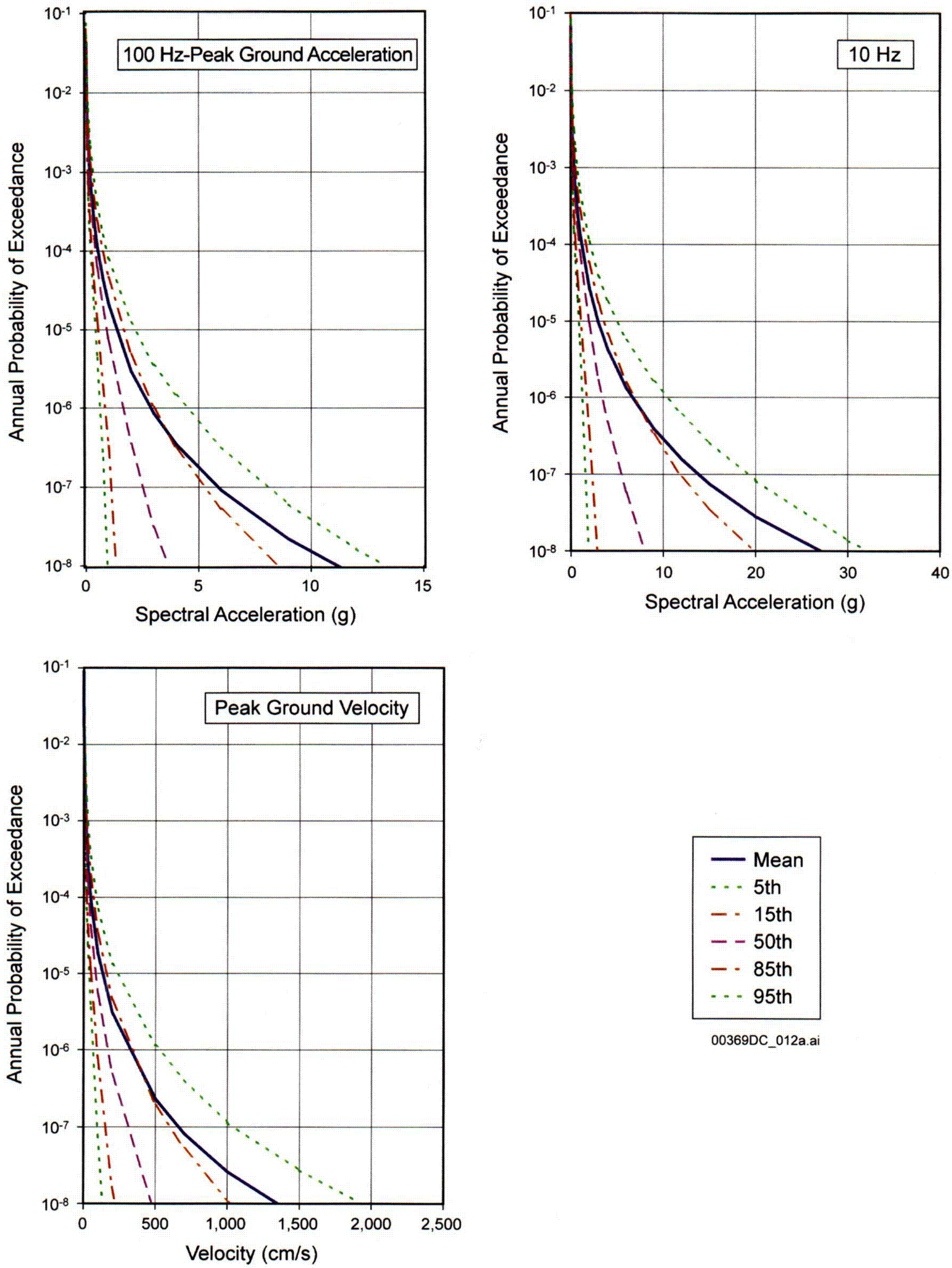
3.5 SEISMIC HAZARD RESULTS

3.5.1 Vibratory Ground Motion Hazard

Vibratory ground motion hazard was computed at a defined reference rock outcrop having the properties of tuff at a waste emplacement depth of about 300 m below the ground surface at Yucca Mountain (Figure 3-1). Ground motion computed at this reference location serves as the basis for a control motion for later site-response modeling. The site-response model incorporates the effects of the site-specific material properties at Yucca Mountain to determine seismic inputs at the surface and subsurface for use in analyses supporting design and performance assessment (see Section 4). Based on equally weighted inputs from the six seismic source expert teams and the seven ground motion experts, the probabilistic hazard for vibratory ground motion was calculated for the defined reference rock outcrop. Ground motion hazard (annual probability of being exceeded) was determined for horizontal and vertical components of peak acceleration (defined at 100 Hz), spectral accelerations at frequencies of 0.3, 0.5, 1, 2, 5, 10, and 20 Hz, and peak velocity, and is expressed in terms of hazard curves (e.g., Figure 3-3). Peak ground acceleration, 0.3-, 1.0-, and 10-Hz spectral values, and peak ground velocity are summarized in Table 3-3 for the annual exceedance frequencies of 10^{-3}, 5×10^{-4}, 10^{-4}, 10^{-5}, 10^{-6}, and 10^{-7}.

Understanding of the contributions to seismic hazard at a particular annual probability of exceedance and for a given ground motion measure can be obtained by deaggregating the hazard. This process shows what magnitude and distance combinations characterize the earthquakes contributing to the hazard. The process also highlights how ground motion uncertainty contributes to the hazard in terms of epsilon (ε) (the difference between the logarithm of ground motion and the mean logarithm of ground motion for that magnitude and distance, measured in units of standard deviation). Deaggregation of the mean hazard for an annual exceedance frequency of 10^{-4} shows that at high structural frequencies (5 to 10 Hz), ground motion is dominated by earthquakes of smaller than M_w 7.0 occurring at distances less than 15 km from Yucca Mountain (Figure 3-4a). For the same annual exceedance frequency, dominant events for ground motion at low structural frequencies (1 to 2 Hz) display a bimodal distribution that includes large nearby events and M_w 7 and larger earthquakes beyond distances of 50 km (Figure 3-4b). The latter contribution is due mainly to the relatively higher activity rates for the Death Valley and Furnace Creek faults. Results for other annual exceedance frequencies are similar, although the contribution from more distant earthquakes to hazard for the low structural frequency range decreases in relative amplitude.

The major contributor to epistemic uncertainty in the ground motion hazard is the within-expert epistemic uncertainty in attenuation relations. Additional contributions to epistemic uncertainty arise from moderate differences between the seismic source expert teams and between the ground motion experts, as well as from the uncertainties expressed by the seismic source logic trees.



Source: DTN: MO03061E9PSHA1.000.

NOTE: PGA = peak ground acceleration; PGV = peak ground velocity. The mean and various percentile hazard curves are shown.

Figure 3-3. Summary Horizontal Ground Motion Hazard Curves for Yucca Mountain

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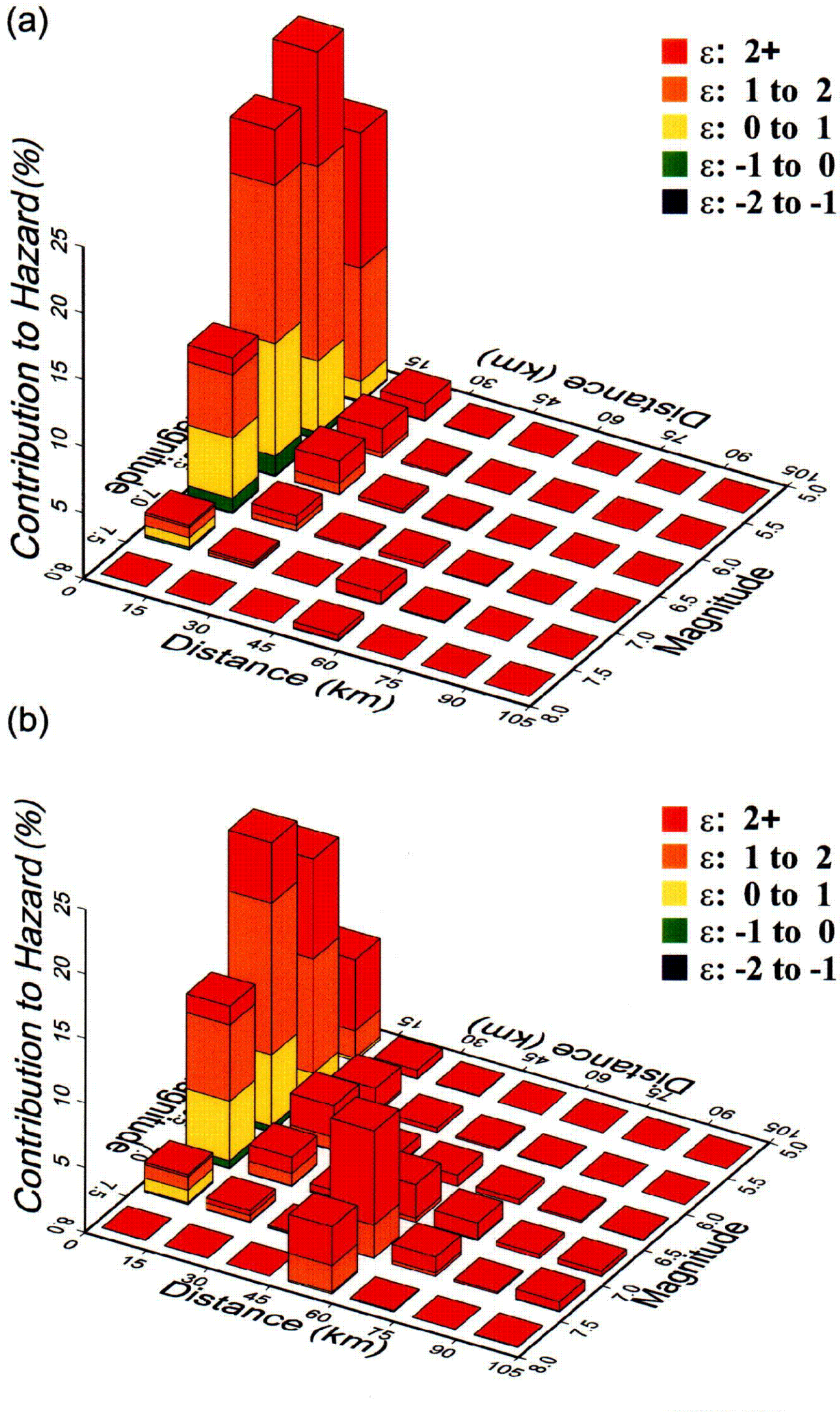

Source: CRWMS M&O 1998, Figures 7-15 and 7-16.

NOTE: Graph (a) is for 5 to 10 Hz horizontal spectral acceleration; graph (b) is for 1 to 2 Hz horizontal spectral acceleration.

Figure 3-4. Deaggregation of Mean Seismic Hazard for Horizontal Spectral Acceleration at 10^{-4} Annual Exceedance Probability

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Table 3-3. Summary of Mean Horizontal Ground Motion Hazard at Yucca Mountain

Annual Exceedance Probability	Spectral Response Frequency (Hz)				Peak Ground Velocity
	100 (Peak Ground Acceleration)	10	1	0.3	
10^{-3}	0.17 g	0.35 g	0.16 g	0.051 g	0.15 m/s
5×10^{-4}	0.25 g	0.53 g	0.23 g	0.076 g	0.22 m/s
10^{-4}	0.53 g	1.2 g	0.47 g	0.17 g	0.48 m/s
10^{-5}	1.3 g	3.0 g	1.2 g	0.44 g	1.3 m/s
10^{-6}	2.9 g	4.4 g	2.6 g	1.1 g	3.0 m/s
10^{-7}	5.8 g	11 g	5.5 g	2.3 g	6.5 m/s

Source: DTN: MO0401MWDRPSHA.000.

NOTE: Ground motion values are for the hypothetical reference rock outcrop defined for the PSHA.

3.5.2 Fault Displacement Hazard

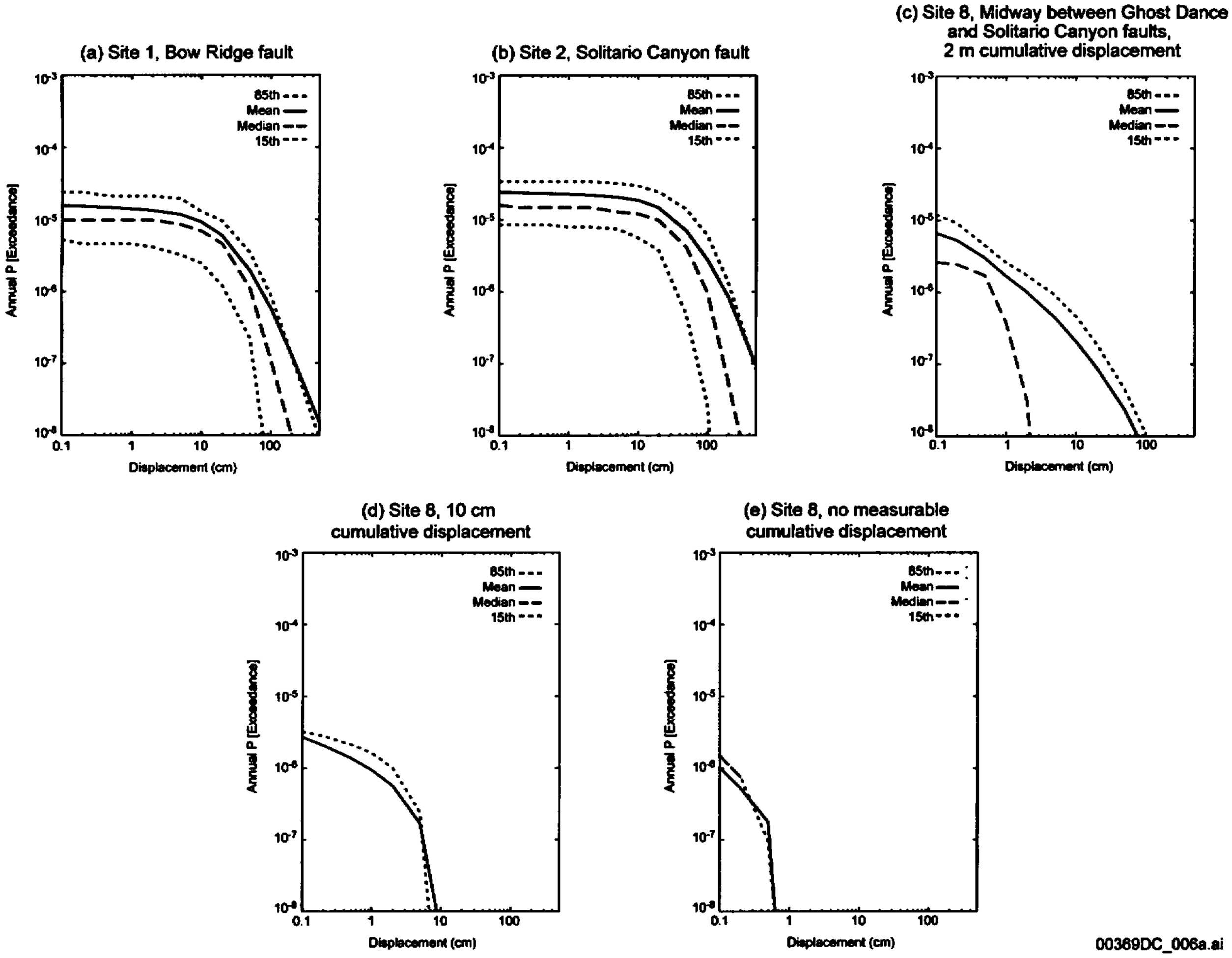
The probabilistic fault displacement hazard was calculated for nine demonstration sites located at or near Yucca Mountain (Figure 3-2) (CRWMS M&O 1998, Section 8). Two of the sites have four hypothetical conditions representative of the features encountered within the ESF. The integrated results provide a representation of fault displacement hazard and its uncertainty at the nine sites, based on the interpretations and parameters developed by the six seismic source expert teams. Separate results were obtained for each site in the form of summary hazard curves (e.g., Figure 3-5). Table 3-2 summarizes the mean displacement hazard results for annual exceedance frequencies of 10^{-4}, 5×10^{-5}, 10^{-5}, 10^{-6}, 10^{-7}, and 10^{-8} at the nine demonstration sites.

For annual exceedance probabilities corresponding to preclosure design basis fault displacement (DBFD) levels DBFD-1 and DBFD-2 (10^{-4} and 5×10^{-5}), mean displacements are less than 0.1 cm (Table 3-2). Thus, fault displacement is not a preclosure design issue.

Potential fault displacement for lower annual probabilities of exceedance (e.g., 10^{-5}, 10^{-6}, 10^{-7}, 10^{-8}), which must be considered as part of the assessment of postclosure repository performance, are not negligible for all the demonstration points examined (Table 3-2). At very low annual exceedance probabilities, mean displacement on block-bounding faults exceeds several meters. The subsurface layout, however, avoids waste emplacement across or near these faults. Assessed displacements on minor faults within the waste emplacement area range from a few centimeters up to about 250 cm. The effects of such displacements are addressed in the seismic scenario of the total system performance assessment (see Section 5).

The fault displacement hazard results display significant uncertainty. This uncertainty is indicative of the state of practice in PSHA for fault displacement, which is less mature than probabilistic analysis for ground motion. Nonetheless, the results obtained here are considered robust by virtue of the large amount of empirical data for the site, the expert elicitation and feedback process that was used, as well as the methodological developments that were undertaken as part of this study. Sites with the highest fault displacement hazard show uncertainties comparable to those obtained in ground motion PSHA. Sites with low hazard show much higher uncertainties (e.g., large spread between 15th and 85th percentile of the hazard distribution).

Also, an expected correlation exists between the amount of geologic data available at a site and the uncertainty in the calculated hazard at that site. For sites with significant geologic data, the team-to-team uncertainty in mean hazard is less than 1 order of magnitude. For sites with little or no data, the individual team curves for mean hazard span about 3 orders of magnitude. The larger uncertainty at these sites is considered to be due to data uncertainty.



Source: CRWMS M&O 1998, Figures 8-2, 8-3, 8-11, 8-12, and 8-13.

Figure 3-5. Example Summary Fault Displacement Hazard Curves for Yucca Mountain

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4. SITE-SPECIFIC GROUND MOTION

Site-specific ground motion is needed for analyses supporting preclosure design and postclosure performance assessment. Ground motion results from the PSHA are for a hypothetical reference rock outcrop and do not reflect site-specific soil and rock properties at the locations for which the ground motion is needed (e.g., the emplacement area level, the surface facilities site). The PSHA was conducted in this fashion because the site-specific rock and soil properties were not characterized at the time of the PSHA. Thus, further analyses are carried out to modify the PSHA results to reflect the appropriate site-specific conditions for each site of interest. This section describes the approach to developing site-specific ground motion for Yucca Mountain, including a ground motion site-response model, and presents results of modeling and analyses.

Locations for site-specific ground motion are determined by the needs of preclosure design and postclosure performance assessment. For preclosure design analyses, depending on what structures, systems, and components are determined to be important to safety, site-specific ground motion may be needed for the waste emplacement level and the surface facilities site (Figure 3-1). Ground motion at the depth of the waste emplacement area may be used for preclosure design of ground support and EBS components. At the site of surface facilities where waste will be handled, design basis ground motion will be used to design important to safety structures, systems, and components. At the surface facilities site, varying depths of soil overlie the bedrock. Thus, site-specific ground motion is analyzed for three soil depths spanning the range of depths at that site. Depending on the results and how they will be used, the different soil depth cases may be combined or used individually. For analyses supporting postclosure performance assessment, site-specific ground motion is developed only for the waste emplacement level.

For each location, preclosure design criteria and postclosure performance assessment requirements determine the annual exceedance probabilities for which site-specific ground motion is needed. As discussed in the report *Preclosure Seismic Design Methodology for a Geological Repository at Yucca Mountain* (BSC 2004a), for preclosure design, design basis ground motion (DBGM) levels DBGM-1 and DBGM-2 correspond to annual exceedance probabilities of 10^{-3} and 5×10^{-4}, respectively. In addition, site-specific ground motion is provided for an annual exceedance probability of 10^{-4} to support "beyond-design-basis" analyses.

To support postclosure performance assessment, selection of annual exceedance probabilities is motivated by the requirement to "consider only events that have at least one chance in 10,000 of occurring over 10,000 years" (10 CFR 63.114(d)). To address this requirement, seismic inputs based on PSHA ground motion hazard results are combined with geologic and physical constraints to bound the level of low-probability ground motions at Yucca Mountain. PSHA ground motion hazard curves are computed without imposing a bound on the random variability of ground motion. At low annual exceedance probabilities, this leads to computed ground motions that are likely to be physically unrealizable. That is, the computed ground motions produce strains that would cause damage to the rock at the site (which is not observed), thus limiting the level of ground motion that could be propagated. Also, the combinations of seismic source parameter values required to produce such ground motions may be unachievable. Because of these constraints on low-probability ground motions, seismic inputs for postclosure analyses are developed from the PSHA results only for annual exceedance probabilities of 10^{-5}, 10^{-6}, and 10^{-7}. Seismic inputs based on PSHA results with an annual exceedance probability of 10^{-8} are not developed because of the physical limitations on ground motions at Yucca Mountain. Analyses using the developed seismic inputs, in combination with constraints on low-probability ground motion at Yucca Mountain, form the basis for evaluating repository performance for seismic events with annual probabilities as low as 10^{-8}.

The format of the site-specific ground motion also depends on its use. For preclosure design, ground motion results are presented as response spectra (the response to input ground motion of a series of single degree of freedom oscillators with varying natural frequencies) and as three-component time histories that are matched to the response spectra. In addition, to support soil-structure-interaction analyses of surface facilities, soil properties consistent with the level of strain produced in the soil by the ground motion are provided. For postclosure analyses, for each annual exceedance probability of interest, a set of 17 three-component time histories is developed. The time histories are scaled to the peak ground velocity determined for the waste emplacement level. Thus, the approach to developing time histories varies depending on their use in preclosure design or postclosure performance assessment.

Section 4.1 describes the site-response model and the overall approach to developing site-specific ground motion. Results of implementing the approach are presented in Section 4.2.

4.1 SITE-RESPONSE MODEL AND APPROACH

This section describes the site-response model used at Yucca Mountain and how that model fits into the overall approach to determine site-specific ground motion.

4.1.1 Site-Response Model

Ground motion results from the PSHA for Yucca Mountain do not include effects of the upper approximately 300 m of rock and soil. In an elastic system, seismic wave amplitudes generally increase near the surface in response to a decrease in material velocity. However, this effect can be compensated by material damping in the layers. Resonance can also occur in soil and rock layers and between the surface and the soil/bedrock interface and is strongly affected by material damping. To develop site-specific ground motion that includes these effects, a site-response model is employed.

Worldwide observations of seismic ground motion show evidence of nonlinear behavior for the horizontal component of motion (e.g., EPRI 1993, Appendix 6B). Vertical ground motion, however, generally shows linear behavior (Silva 1997, p. 13). In modeling site response at Yucca Mountain, nonlinear effects are included for horizontal motion, but vertical motion is modeled in a linear fashion.

A site-response model for Yucca Mountain needs to treat seismic wave propagation through the site materials and take into account dynamic behavior of those materials. Inputs to the model consist of ground motion derived from the PSHA results and material dynamic properties developed from site-specific geotechnical data, technical information, and scientific judgment. The computational method that is used incorporates nonlinear behavior using an equivalent-linear formulation. The equivalent-linear formulation approximates a second-order nonlinear equation, over a limited range of its variables, by a linear equation. Based on the effective strains computed for the ground motion using a linear analysis, the material dynamic properties are adjusted to be consistent with the effective strains. This process is iterated until changes in the parameters are below an established tolerance level. Implementation of the approach for Yucca Mountain uses random vibration theory to determine the peak effective strains for each iteration. Thus, the model is referred to as the random-vibration-theory-based equivalent-linear site-response model.

In the site-response model, site materials are represented as a one-dimensional layered system for the purpose of site-response computation. A series of horizontal layers, each of which is characterized by a uniform velocity, density, and set of dynamic material properties, approximate the site materials. For the equivalent-linear formulation, dynamic material properties consist of curves describing how the shear modulus and material damping vary as a function of shearing strain level. As nonlinear material behavior occurs with increasing shearing strain, the shear modulus decreases (the material becomes less rigid), and material damping increases.

Because a one-dimensional model site-response model is used for Yucca Mountain it does not explicitly incorporate two- and three-dimensional wave propagation effects (e.g., effects of topography, dipping layers). However, probabilistic ground motion results for Yucca Mountain, from which input motions are derived, already include two- and three-dimensional wave propagation effects because these effects are included in the ground motion database used to assess random variability in ground motion as part of the PSHA. While it is known that two- and three-dimensional wave propagation effects are present at all sites to some extent, validations have demonstrated that simple one-dimensional models accommodate the significant and stable features of site response (Silva et al. 1996; Silva et al. 1990). Also, although lithostratigraphic units at Yucca Mountain generally dip to the east, velocity data gathered to date do not show a strong and systematic correlation with the dipping strata.

One-dimensional site response analysis, using an equivalent-linear formulation, has proven successful when applied elsewhere. In a validation study (EPRI 1993, Appendix 6B), the random-vibration-theory-based equivalent-linear model was compared to three nonlinear models for three test cases. For each test case, ground motion was recorded at a soil site and a nearby rock site. The recorded rock motions were taken as the input to the site-response models, and the computed results were compared to the recorded soil site motions. Each of the sites was reasonably well characterized in terms of its velocities and dynamic material properties. Results of this validation study show little difference between equivalent-linear and fully nonlinear formulations for the ground motion levels examined (peak ground accelerations between about 0.05 to 0.5 g). Both equivalent-linear and nonlinear formulations also compared favorably to the recorded motions. While this validation does not directly address the specific site materials and the entire range of ground motion input levels for Yucca Mountain, it provides an acceptable degree of confidence that the modeling approach adequately captures nonlinear dynamic behavior.

4.1.2 Approach to Develop Site-Specific Ground Motion

The approach to develop site-specific ground motion for Yucca Mountain consists of steps to transform the ground motion results of the PSHA to reflect the effects of the site-specific soil and rock properties at Yucca Mountain (the site response). As described in Section 3, the PSHA ground motion results are appropriate for a hypothetical reference rock outcrop characterized by a specific shear-wave velocity and site attenuation. These parameter values were specified in the PSHA to correspond nominally to the tuff properties at the waste emplacement level beneath Yucca Mountain. The PSHA results, therefore, do not include effects of the uppermost approximately 300 m of rock and soil at Yucca Mountain. Depending on the velocities and dynamic properties of this material and the location of interest, the PSHA ground motion results can be amplified or reduced, as a function of frequency, reflecting the effects of seismic wave propagation through the overlying material. Thus the site-response approach uses the PSHA results as input and provides site-specific ground motion at locations of interest as output.

One goal of any approach to address site response is to maintain the annual probability of exceedance corresponding to the input ground motion (i.e., hazard-consistency). Meeting this goal ensures that uncertainties about basic ground motion processes and models that are explicitly incorporated in the PSHA are appropriately linked to the seismic inputs for design and analyses. Approaches range from a separate PSHA using site-specific ground motion attenuation relations for each location of interest to simple scaling of the input ground motion without accounting for variability in the material properties at the site (McGuire et al. 2001, Section 6). For Yucca Mountain, an approach is used that addresses variability in material properties of the rock and soil at each location and also takes into account the range of magnitudes contributing to the ground motion hazard at a particular annual probability of being exceeded. In the terminology of McGuire et al. (2001, Section 6) this approach is referred to as 2B.

Mean PSHA results form part of the input to the site-response approach. As described in Section 3, these results incorporate assessments of alternative interpretations and the random variability of earthquake processes. Random variability in ground motion was treated as unbounded, resulting in calculated ground motions that are larger than may be physically possible. As lower annual probabilities of exceedance are considered, the mean results correspond to higher percentiles of the overall results. For annual exceedance probabilities between about 10^{-6} and 10^{-8}, the mean ground motion hazard results lie between the 80th and 95th percentiles. At these annual exceedance probabilities, the ground motion is very high and may be physically unrealizable. The rocks at Yucca Mountain may not be able to sustain the strains that would be produced by such high ground motion without physical damage that would tend to limit the amplitude of motion. In addition, the combinations of seismic source parameters needed to generate such high ground motion may not be reasonable.

Studies to examine limits to the upper range of ground motion at Yucca Mountain are underway. Three approaches are being explored to determine at what level the amplitude of ground motion may saturate. One approach looks at what level of ground motion would be required to physically damage the rock at Yucca Mountain. The strength of the rock will be compared to the levels of strain that would be induced in the rock by very high ground motion. Preservation of crystalline material lining some lithophysae and lack of observed shattered rock in underground excavations suggest ground motion high enough to damage the rock has not occurred at Yucca Mountain since the rocks were deposited approximately 12 million years ago. A second approach examines how nonlinear effects below the PSHA reference rock outcrop might limit ground motion as the motion reaches very high levels. The third approach employs numerical modeling to assess what combinations of seismic source parameters are required to produce very high ground motion at Yucca Mountain. The parameter combinations will be assessed to determine if they are realistic and reasonable.

While these studies of ground motion saturation have been initiated, results are not yet available. Unbounded ground motion reported in the following sections is used in analyses supporting postclosure performance assessment with the expectation that the calculated amount of damage caused is higher than may potentially occur for a given annual exceedance probability. For the TSPA seismic scenario, a hazard curve for peak horizontal ground velocity at the emplacement level, which incorporates available information on ground motion saturation, will be determined and form part of the seismic consequences abstraction.

For each annual probability of exceedance and location of interest, the site-response approach consists of the following steps (Figure 4-1):

1. On the basis of the PSHA for Yucca Mountain, the response spectrum with a uniform likelihood of being exceeded at any frequency (a uniform hazard spectrum) is determined.

2. The earthquakes (magnitude and distance) that contribute most to the seismic hazard at high (5 to 10 Hz) and low (1 to 2 Hz) structural response frequency ranges are determined by deaggregating the seismic hazard. Response spectra for the identified earthquakes are scaled to the uniform hazard spectrum in the appropriate structural response frequency range. These earthquakes are referred to as "reference earthquakes"; spectral amplification functions representing the site response are applied to the reference earthquakes to determine the final site-specific response spectra.

3. Also for high and low structural response frequency ranges, three earthquakes representing the range of magnitudes contributing to the hazard are identified. This step is taken because the site-response model is sensitive to the spectral content of the ground motion, which varies as a function of magnitude. As for the reference earthquakes, the response spectra for these "deaggregation earthquakes" are scaled to the uniform hazard spectrum in the appropriate structural response frequency range. The deaggregation earthquakes form the ground motion input to the response model.

4. Site-specific soil and rock property information is also characterized and forms an input to the site response model. Uncertainties in the average soil and rock properties, as well as random variation in those properties across the site, are determined and incorporated into the site response modeling for each deaggregation earthquake.

5. The site response model is run for appropriate combinations of soil and rock properties, seismic wave type, response structural frequency range, and deaggregation earthquake, depending on the location and ground motion component being analyzed. A mean "spectral amplification function" (or peak-ground-velocity scaling factor) representing the ratio of the model output response spectrum (or peak ground velocity) to the input deaggregation earthquake response spectrum (or peak ground velocity) is determined for each combination.

6. The site response effects for the deaggregation earthquakes are combined in a weighted average.
7. For each combination of soil and rock properties and seismic wave type, the weighted average spectral amplification functions (or peak-ground-velocity scaling factors) for the high and low structural response frequency ranges are enveloped.
8. For each combination of soil and rock properties and seismic wave type, the enveloped spectral amplification function (or peak-ground-velocity scaling factor) is applied to the envelope of the reference earthquake response spectra (or reference rock outcrop peak ground velocities).
9. A final envelope is taken over the modified reference earthquake spectra (or peak ground velocities) for the combinations of soil and rock properties and wave type.
10. Seismic time histories are developed that are consistent with the site-specific response spectra or peak ground velocity.

These steps are described in more detail in the following sections.

4.1.2.1 Development of Control Motion

The ground motion that serves as input to the site-response analysis is referred to as the "control motion." For Yucca Mountain, the control motion is derived from the PSHA results. The first three steps above refer to development of uniform hazard spectra and reference and deaggregation earthquakes that represent the uniform hazard spectra at various stages in the site-response modeling process. The deaggregation earthquakes form part of the input to the site-response analysis. The results of the site-response analysis are spectral amplification (or transfer) functions that characterize the effects of the site on the input ground motion as a function of response structural frequency. The spectral amplification functions are then applied to the envelop of the low and high frequency reference earthquake response spectra to derive the final site-specific input response spectra for preclosure seismic design (BSC 2004d, Section 6.3.1). For postclosure performance analyses, a similar process is followed to develop peak ground velocity transfer functions and final site-specific values of peak ground velocity.

Uniform Hazard Spectra–Uniform hazard spectra represent response spectral acceleration values for a suite of structural frequencies that have a uniform annual probability of being exceeded. During the PSHA, seismic hazard was determined for response spectral structural frequencies ranging from 0.3 to 100 Hz. (In addition, ground motion hazard was determined for peak ground velocity.) As discussed in Section 3.5, for each structural frequency the PSHA results consist of hazard curves that indicate the annual probability of exceedance for various levels of ground motion. For a given annual probability of being exceeded, a mean uniform hazard spectrum can be constructed by taking the mean PSHA spectral acceleration value at each structural frequency that was analyzed (Figure 4-2) (BSC 2004d, Section 6.2.2.3). Given the nature of a PSHA, the uniform hazard spectrum does not represent the response spectrum of a single earthquake, but rather the integrated contributions of the range of earthquakes that contribute to hazard at the Yucca Mountain site as expressed in the PSHA seismic source interpretations. The uniform hazard spectrum is thus a broadband representation of the ground motion for a given annual probability of being exceeded.

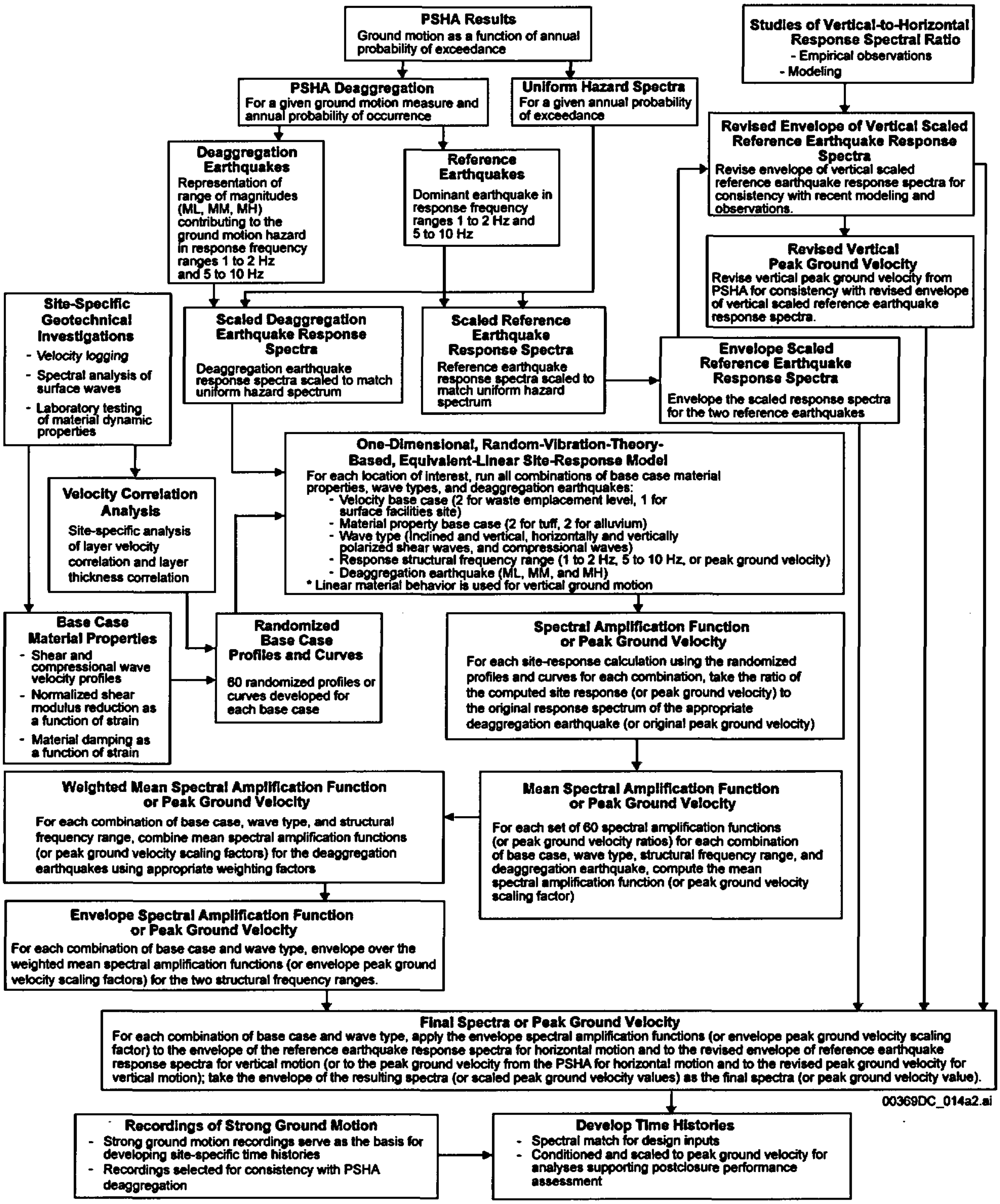
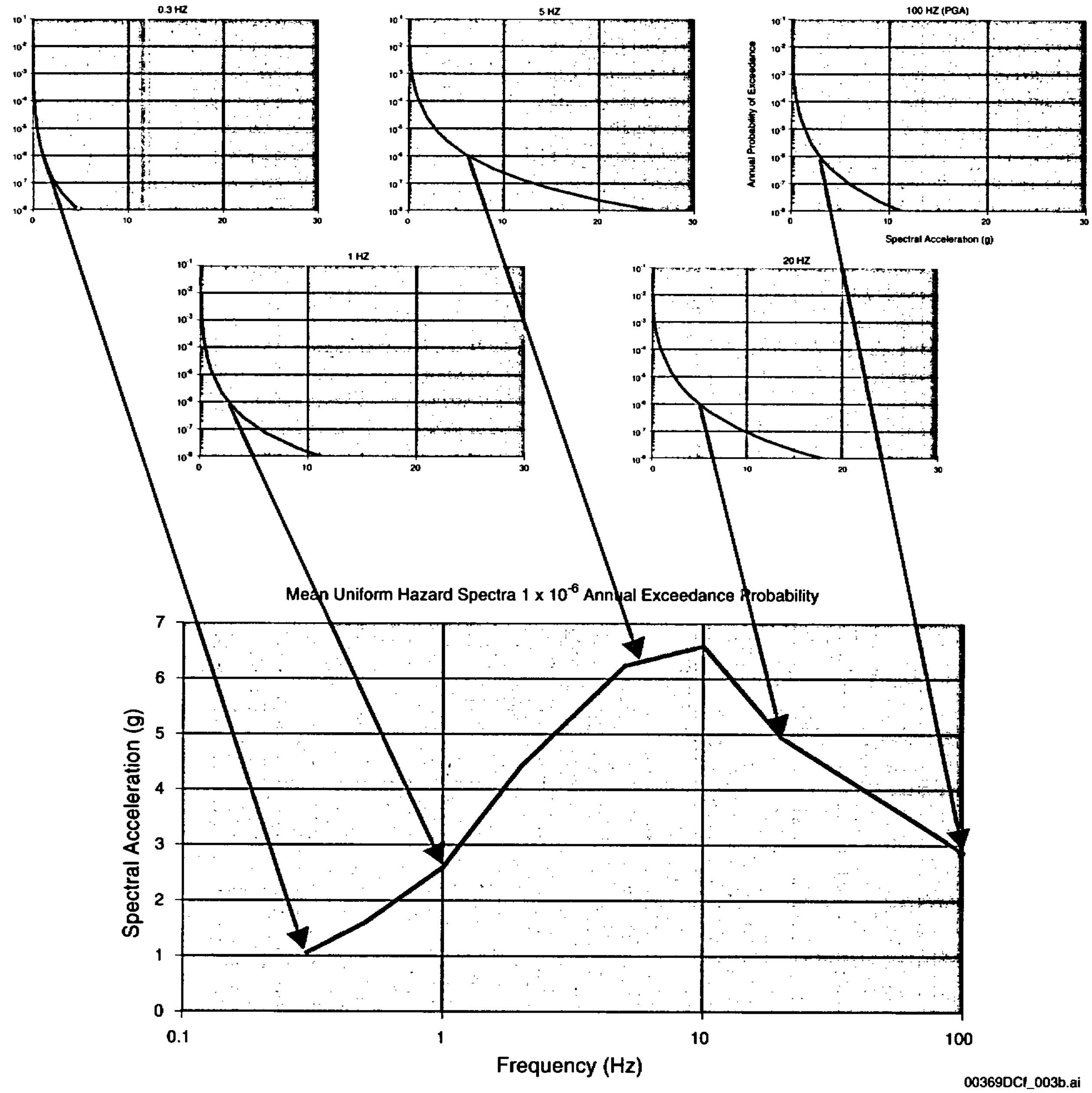


Figure 4-1. Development of Site-Specific Ground Motion



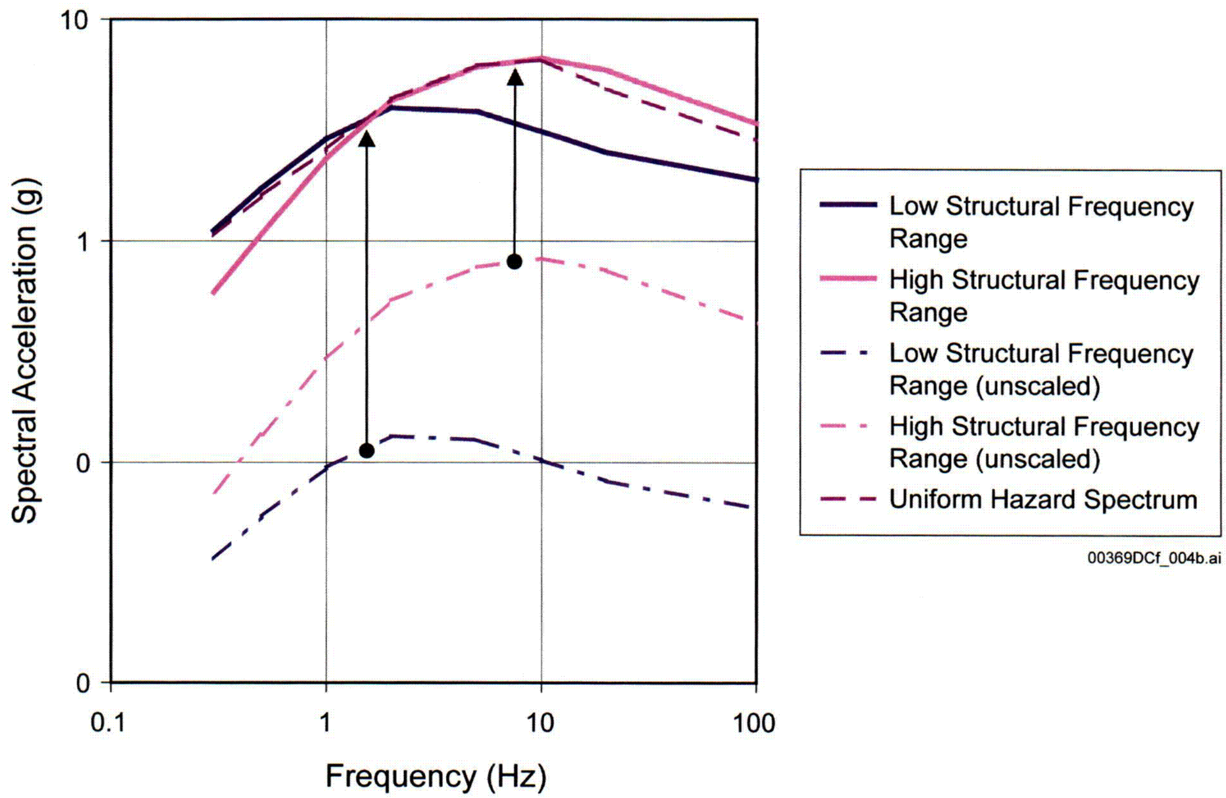
Source: DTN: MO03061E9PSHA1.000.

NOTE: For a given annual exceedance probability (10^{-6} is shown), the spectral acceleration value is taken from the seismic hazard curves for various ground motion measures (e.g., 0.3, 1, 5, 20, and 100 Hz response spectral acceleration) to construct a uniform hazard spectrum. PGA = peak ground acceleration.

Figure 4-2. Development of a Uniform Hazard Spectrum at 10^{-6} Mean Annual Exceedance Probability from Probabilistic Seismic Hazard Analysis Results

The use of such a broadband motion, which reflects contributions from earthquakes of varying magnitudes and distances, would be inappropriate for site-response analysis. When the amplitudes of control motions cause significant nonlinear response of the site materials, broadband spectra can induce higher strains than any single earthquake scaled to the same peak acceleration level and thus perturb the calculated site response. Accordingly, "reference earthquakes" and "deaggregation earthquakes" were developed to represent the uniform hazard spectrum in the site response analysis.

Reference Earthquakes–Reference earthquakes representing the uniform hazard spectrum are developed by analyzing the PSHA results to identify which earthquakes (i.e., magnitude and distance combination) contribute most to a given annual probability of being exceeded. This analysis, termed "deaggregation," is carried out for both a high (5 to 10 Hz) and low (1 to 2 Hz) structural frequency range for specific annual probabilities of exceedance. Based on the results, a reference earthquake is identified for each structural frequency range by taking the modal magnitude and distance (BSC 2004d, Section 6.2.2.4). The response spectral shape for these earthquakes, determined from the ground motion relations that were input to the Yucca Mountain from the PSHA, are then scaled to match the uniform hazard spectrum for the low and high structural frequency range (Figure 4-3). This scaling retains hazard consistency with the site uniform hazard spectrum. The scaled reference earthquake response spectra are then compared to the uniform hazard spectrum to ensure that, considered together, they adequately represent it (Figure 4-3). Reference earthquakes are identified for both the horizontal and vertical component of ground motion. For consistency, reference earthquakes for vertical motions were taken to be the same as those for horizontal motion. Once the site-specific response transfer function (spectral amplification as a function of frequency) is determined for a location of interest, it is applied to the envelope of the scaled response spectra for the reference earthquakes to obtain the input motion for that site.



Source: DTN: MO0206UNHAZ106.001.

Figure 4-3. Comparison of Reference Earthquake Response Spectra to the Corresponding Uniform Hazard Spectrum

Deaggregation Earthquakes–Nonlinear behavior of site materials, which contributes to the ground motion site response, depends on earthquake magnitude as well as ground motion amplitude. As magnitude increases, the response spectral shape of the ground motion changes and the duration and amplitude of strong ground shaking typically increases. To obtain site-specific ground motion that is consistent in probability with the control location hazard, these effects are captured in the site-response analysis through the use of deaggregation earthquakes (BSC 2004d, Section 6.2.2.5).

The deaggregation earthquakes are developed for the purpose of computing site-response transfer functions by deaggregating the ground motion hazard for a given annual exceedance probability and structural frequency range (5 to 10 Hz or 1 to 2 Hz). To represent the range of magnitudes contributing to the hazard for a given annual exceedance probability, three earthquakes are identified corresponding nominally to the mean (medium magnitude deaggregation earthquake), the 5th (low magnitude deaggregation earthquake), and the 95th (high magnitude deaggregation earthquake) percentile of the magnitude distribution. In some cases, different percentiles were used to appropriately capture the magnitude distribution resulting from the deaggregation. As for the reference earthquakes, response spectra for the deaggregation earthquakes, determined using the PSHA ground motion relations, are scaled to the uniform hazard spectrum in the appropriate structural frequency range (Figure 4-4). The

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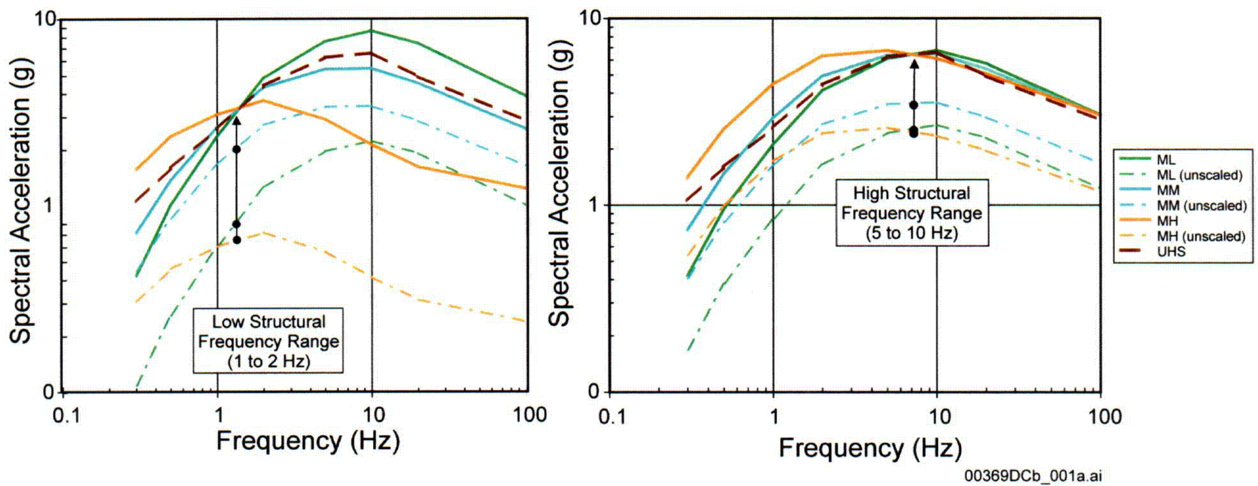
deaggregation earthquakes form the control motion for the site response analysis. With three deaggregation earthquakes for each of two response structural frequency ranges (5 to 10 Hz, 1 to 2 Hz) and two components of ground motion (horizontal and vertical), a total of 12 different control motions are involved in determining the ground motion site-response transfer function.



Source: DTN: MO0206UNHAZ106.001.

NOTE: ML = low magnitude deaggregation earthquake; MM = medium magnitude deaggregation earthquake; MH = high magnitude deaggregation earthquake; UHS = uniform hazard spectrum.

Figure 4-4. Comparison of Deaggregation Earthquake Response Spectra to the Corresponding Uniform Hazard Spectrum

4.1.2.2 Characterization of Site-Specific Velocity Profile and Dynamic Material Properties

The fourth step in the approach to developing site-specific ground motion involves characterization of the velocity and dynamic material properties of the site materials. These properties form part of the input to the site response model. Key properties are:

- Seismic velocity as a function of depth
- Shear modulus, normalized to its small-strain value, as a function of shearing strain
- Material damping, as a function of shearing strain.

Shear modulus reduction and variation in material damping as a function of shear strain are parameters that characterize the response of site materials to dynamic strains caused by seismic wave propagation through them.

Geotechnical investigations have been carried out to characterize these inputs. Results of the investigations are used to determine median values and to assess uncertainties. In addition, the properties vary randomly about their median values when the spatial extent of a location of interest is considered. To determine site-specific ground motion that is consistent with the control location hazard, these uncertainties and random variability must be incorporated into the

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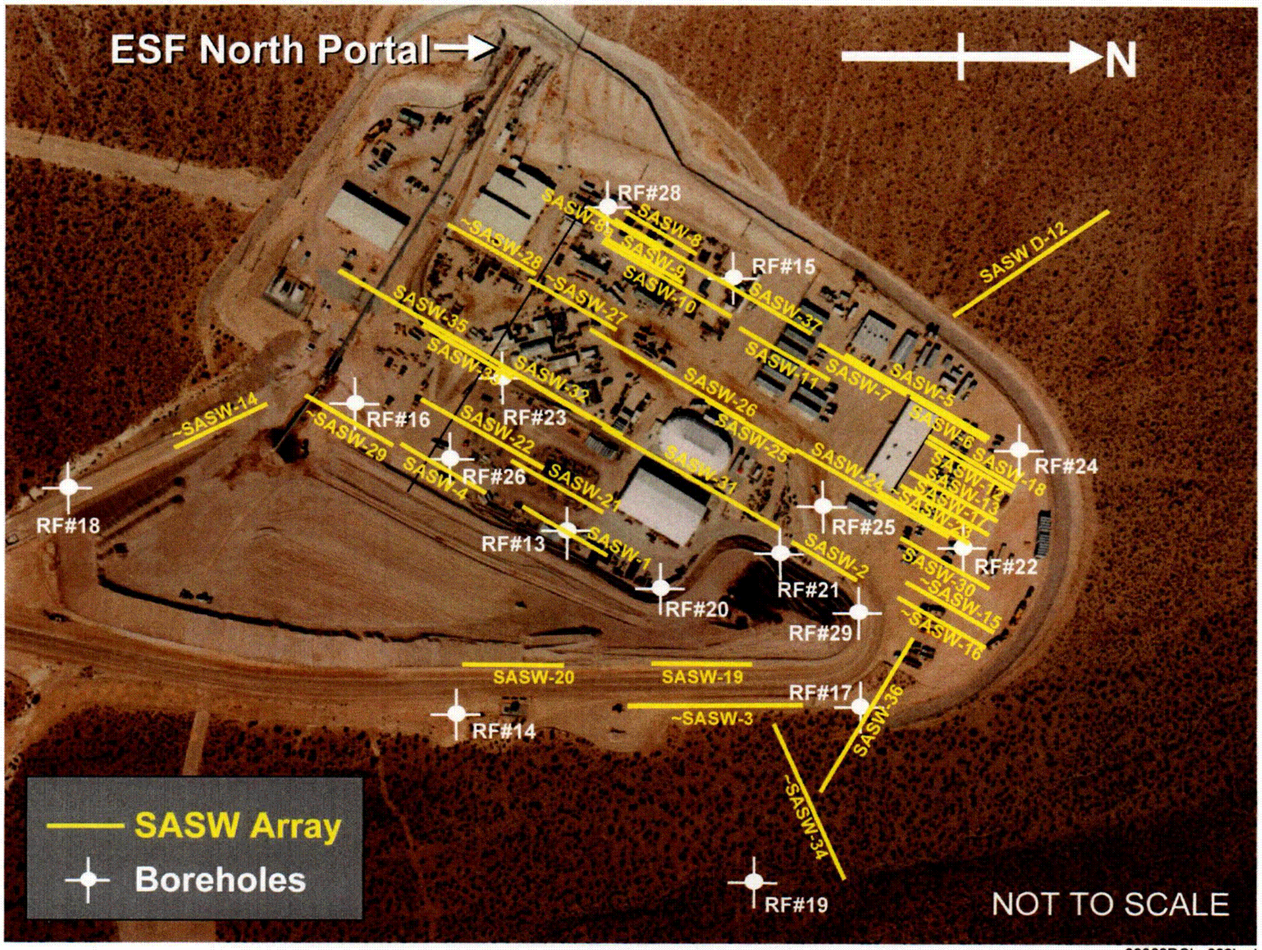
site response analysis, just as uncertainties and random variability were explicitly incorporated in the PSHA.

Geotechnical Investigations–Geotechnical investigations have been carried out to collect information on the material properties of the site (BSC 2002; BSC 2004d, Sections 6.2.3 and 6.2.4). The studies focused on the two primary sites of interest: the surface facilities area and the area above the planned waste emplacement footprint. The surface facilities area is of interest for preclosure design; the area above the waste emplacement area is characterized to allow determination of subsurface ground motion for analyses supporting both preclosure design and postclosure performance assessment. Studies consisted of drilling and logging boreholes, velocity surveys, and laboratory testing of rock and soil samples to determine the dynamic response properties of the materials (i.e., the shear modulus and damping behavior as a function of imposed dynamic strain level).

For the surface facilities area, 16 boreholes were drilled ranging in depth from 99.8 to 667.8 ft (Figure 4-5). Interpretation of geologic logs of the boreholes, along with previous information, provided adequate understanding of the geologic strata underlying the site. A soil layer overlies volcanic deposits that are faulted and dip to the east (Figure 4-6). The thickness of the soil layer ranges from 0 ft at the edge of Exile Hill to more than 100 ft at the eastern edge of the characterized area.

To characterize the velocity of the soil and rock underlying the surface facilities site, velocity measurements were collected in the boreholes. Two techniques were employed: downhole and suspension logging. In downhole logging, a receiver was located at various depths within a borehole and recorded seismic energy from a source at the surface. For suspension logging, both the source and receiver were located in the borehole. These two techniques measure both compressional-wave and shear-wave velocity. In addition, a surface-based method of characterizing velocity—spectral analysis of surface waves—was also applied. This technique measures surface wave dispersion and employs forward modeling using information about rock properties to estimate shear-wave velocity as a function of depth. While the borehole velocity measurements provide information as a function of depth at a point, the spectral analysis of surface waves technique provides information along its survey line, filling in data between the boreholes. The depth to which the spectral analysis of surface waves technique provides results are dependent on the survey length and the strength of the source. For the surface facilities area, results were obtained to depths ranging from less than 100 ft to about 500 ft. Figure 4-7 summarizes shear-wave velocity data from these studies.

For the repository block (i.e., the block of rock containing the waste emplacement area at a depth of about 300 m below the ground surface), velocity data were obtained from existing boreholes and spectral analysis of surface waves surveys (Figure 4-8). In part because of logistical considerations and the locations of existing boreholes, coverage of the repository block is limited. Some data from boreholes near but not within the repository block therefore are used in assessing its velocity. As described below, development of velocity profiles and their use in site-response modeling take into account uncertainties resulting from the limited coverage. Data from these boreholes extend to depths ranging from about 1,000 to almost 2,600 ft (Figure 4-8, vertical seismic profiling boreholes). Boreholes within the repository block are shallow, and data surveys reached depths ranging from about 25 to 180 ft. Results from spectral analysis of surface waves surveys range from near surface to 750 ft.



00369DCb_002b.ai

Source: BSC 2004d, Figure 6.2-69.

NOTE: SASW = spectral analysis of surface waves.

Figure 4-5. Boreholes and Seismic Survey Locations for the Surface Facilities Area

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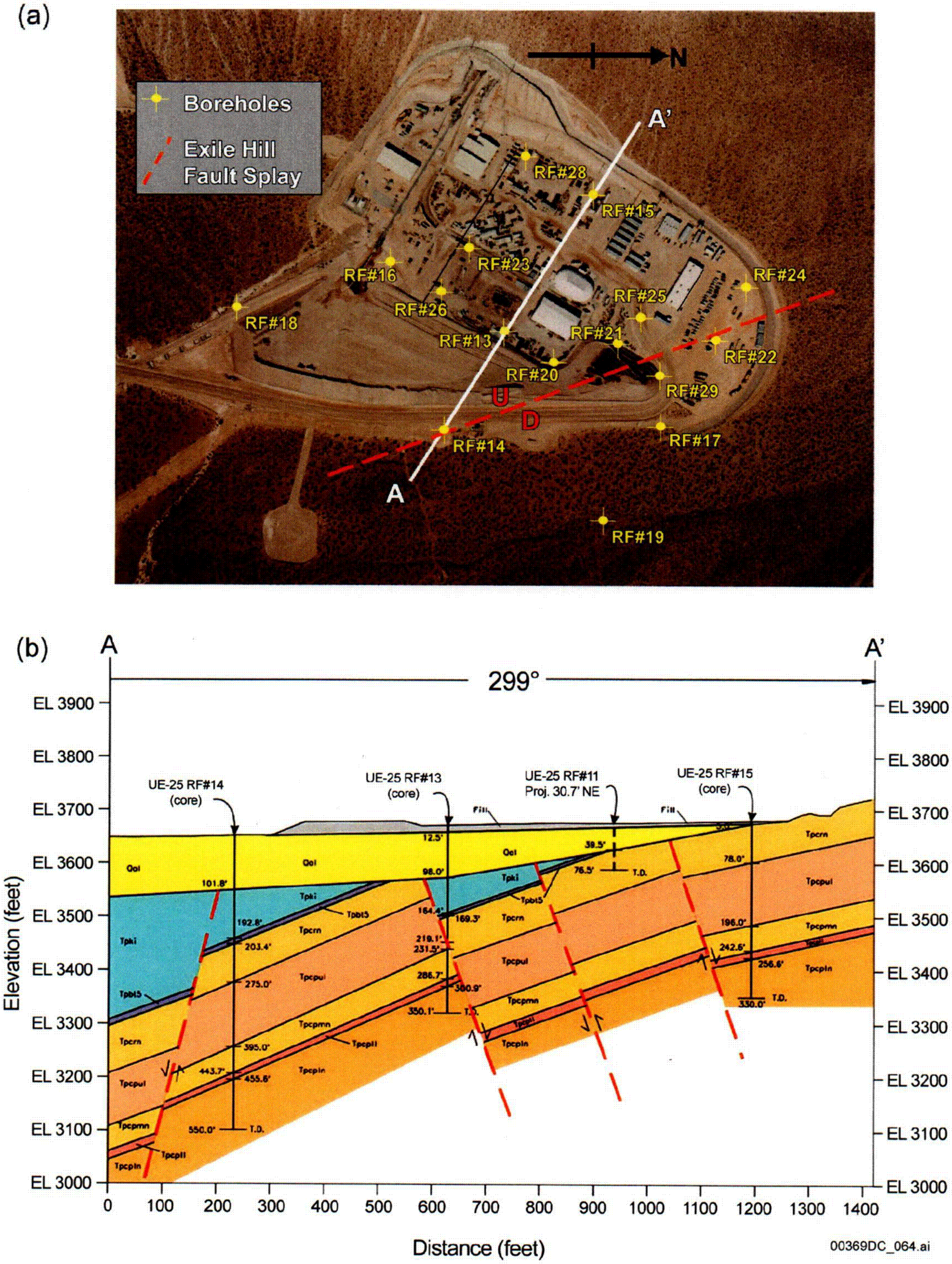

Source: BSC 2003c, Figures 6.2-55 and 6.2-56.

NOTE: (a) Shown are locations of boreholes providing data for geologic interpretation. Also shown are the locations of cross section A-A' and the interpreted trace of the Exile Hill splay fault. (b) Cross section along A-A'.

Figure 4-6. West-Northwest–East-Southeast Cross Section for the Surface Facilities Area

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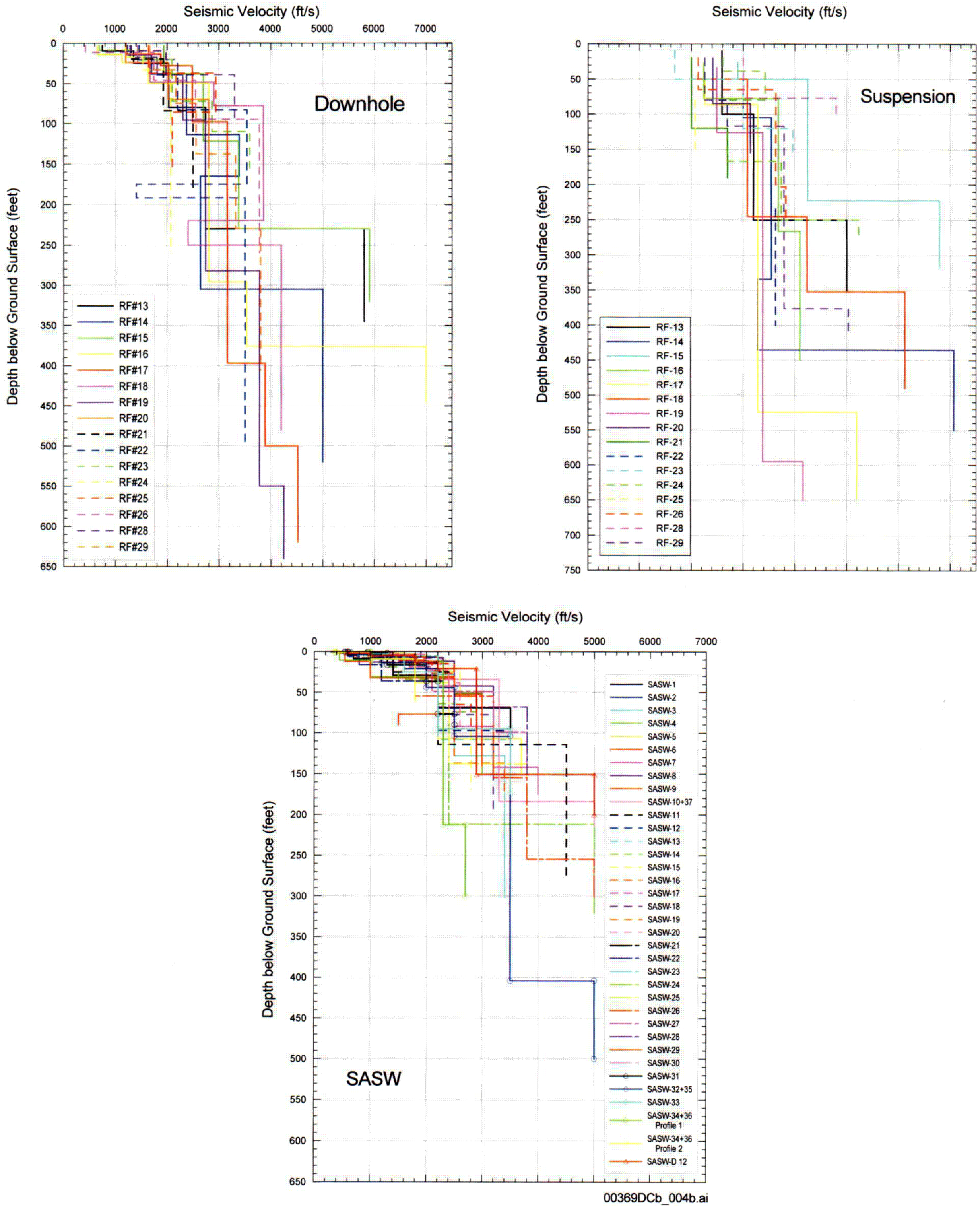
In addition to the spectral analysis of surface waves surveys carried out at the surface of the repository block, the spectral analysis of surface waves technique was applied within the main drift of the ESF. These measurements provide information on the velocity of the repository block at depths (980 to 1,150 ft) greater than those sampled using the spectral analysis of surface waves technique at the surface. Figure 4-9 summarizes velocity data from studies of the repository block.

To characterize the normalized shear modulus reduction and damping properties of the site materials, laboratory testing was carried out on rock and soil samples (BSC 2002, Sections 6.2.10 and 6.3.3). Resonant column and torsional shear tests were performed to examine the nonlinear behavior of the materials as a function of shearing strain. Tested samples were from the Tiva Canyon Tuff and soil obtained from the surface facilities area. Testing was limited to small samples that may not fully represent in situ properties. Due to the nature of the materials, intact soil samples could not be obtained and, thus, the samples had to be reconstituted in the laboratory prior to testing. As discussed below, these uncertainties are considered in developing dynamic material property inputs for the site response analysis and result in the development of multiple base-case curves (BSC 2004d, Section 6.2). Figures 4-10 and 4-11 summarize the testing results. For tuff, systematic differences in nonlinear properties as a function of lithostratigraphic unit, degree of welding, and dry unit weight were not observed. Also, for tuff, only limited nonlinear behavior was observed at the strains obtained during testing (up to about 0.1% or less) (Figure 4-10).



Source: BSC 2004d, Figures 6.2-58, 6.2-65, and 6.2-70.

NOTE: SASW = spectral analysis of surface waves.

Figure 4-7. Shear-Wave Velocity Data as a Function of Depth for the Surface Facilities Area

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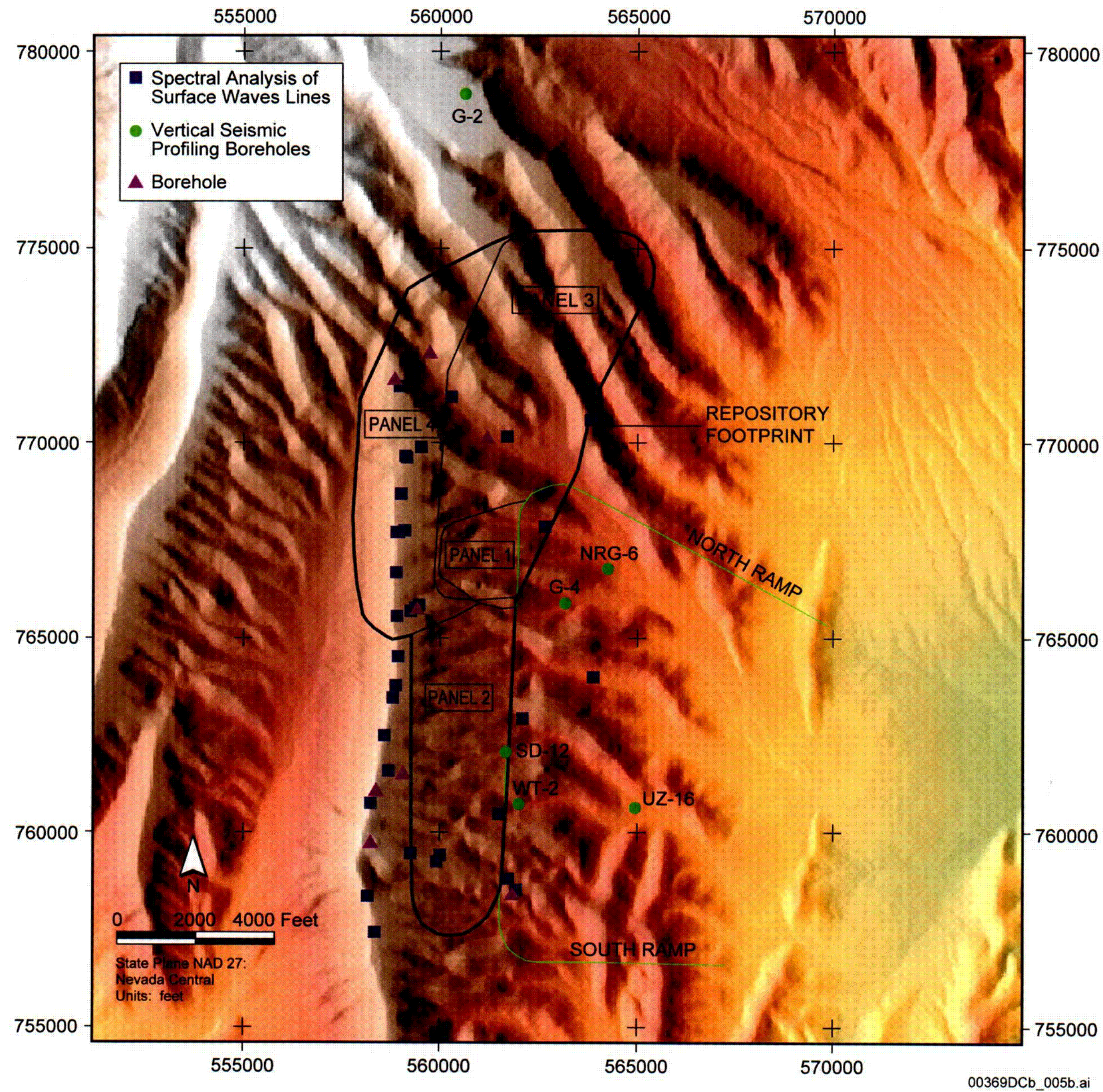

Source: BSC 2004d, Figure 6.2-62.

Figure 4-8. Boreholes and Seismic Survey Locations for the Repository Block above the Waste Emplacement Area

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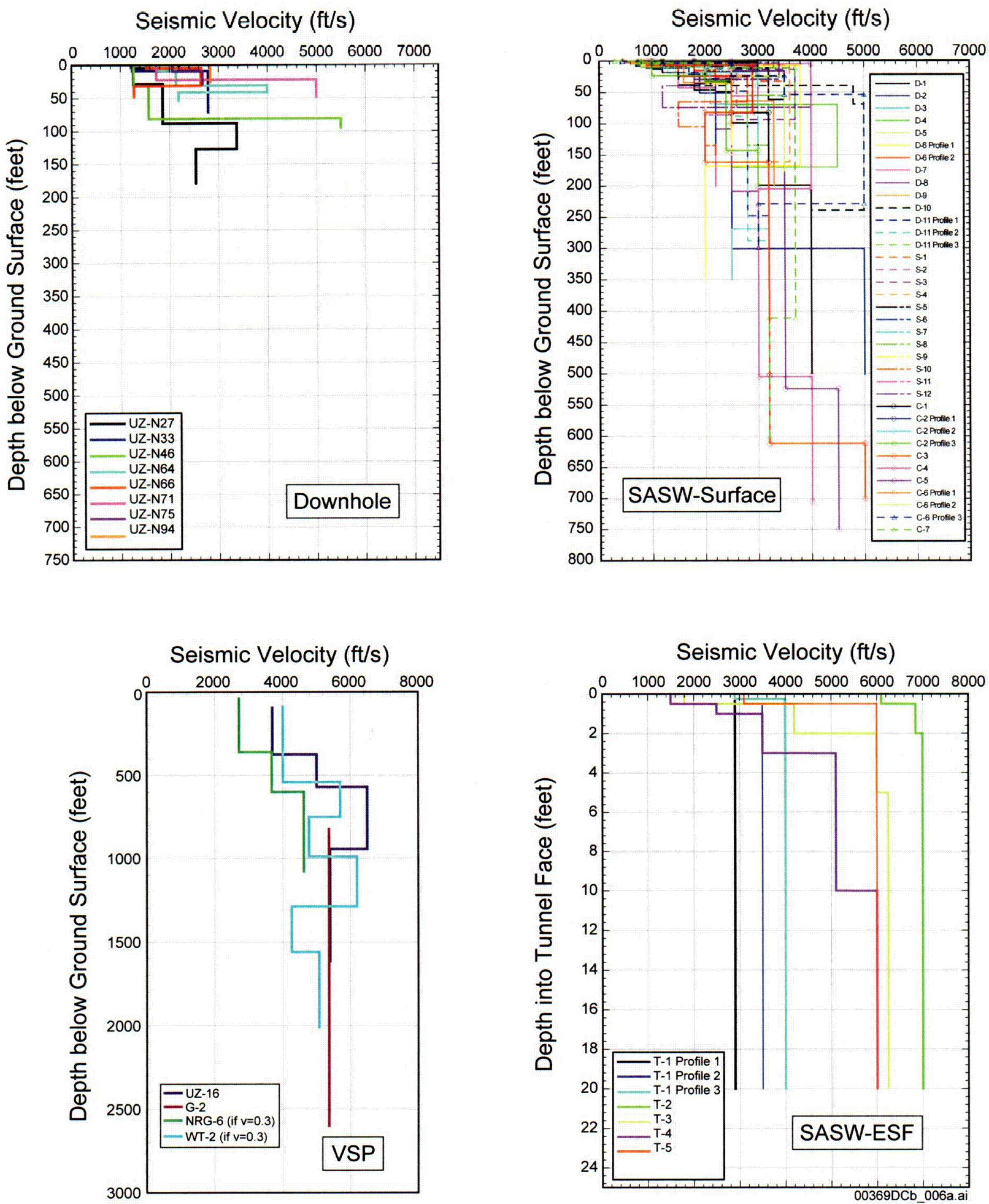

Source: BSC 2004d, Figures 6.2-63, 6.2-73, 6.2-76, and 6.2-79.

NOTE: SASW = spectral analysis of surface waves; VSP = vertical seismic profiling.

Figure 4-9. Shear-Wave Velocity Data as a Function of Depth for the Repository Block

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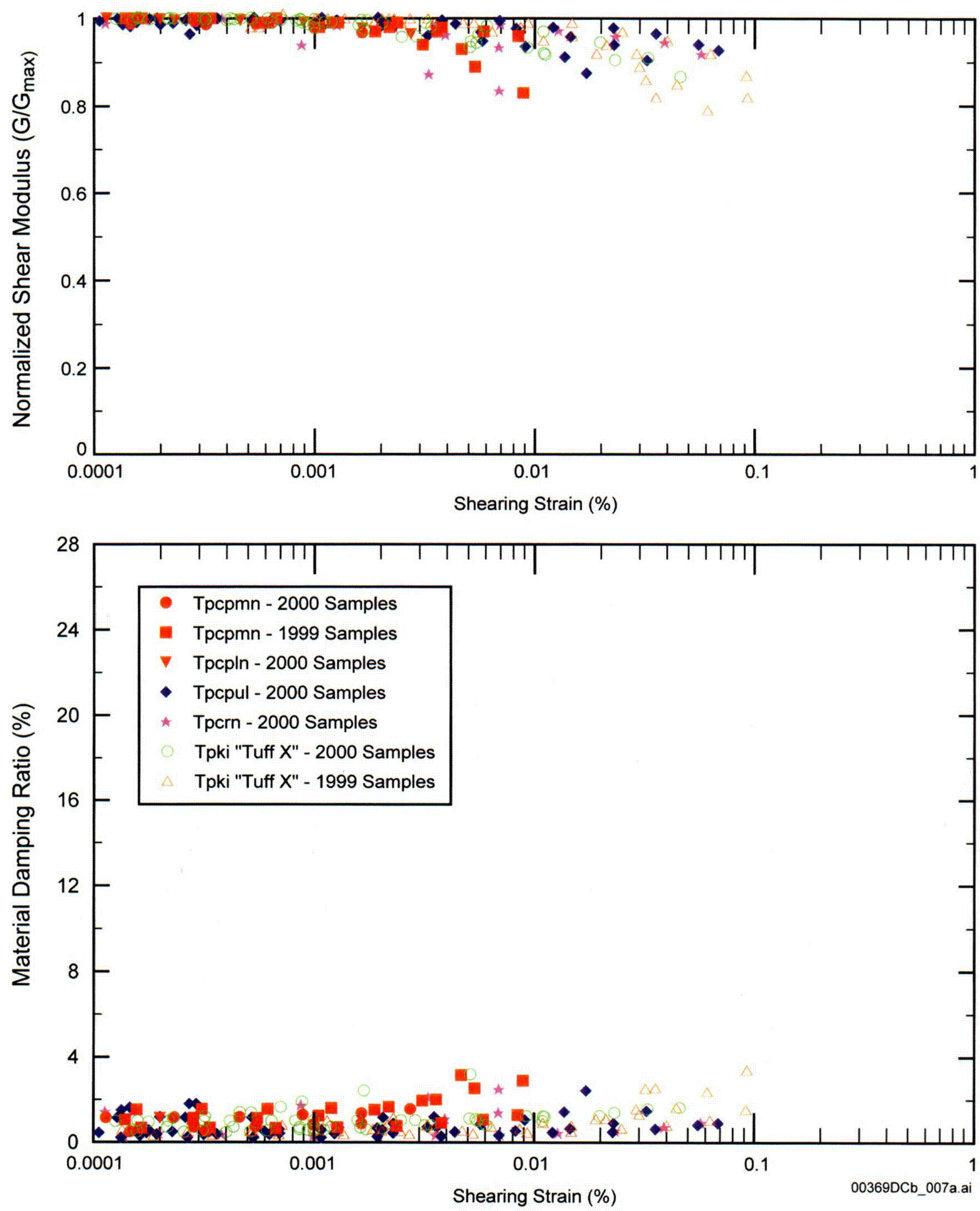

Source: BSC 2004d, Figure 6.2-95.

NOTE: Tpcpmn = Tiva Canyon Tuff, crystal-poor member, middle nonlithophysal zone; Tpcpln = Tiva Canyon Tuff, crystal-poor member, lower nonlithophysal zone; Tpcpul = Tiva Canyon Tuff, crystal-poor member, upper lithophysal zone; Tpki = tuff unit X.

Figure 4-10. Dynamic Property Testing Results for Tuff at Yucca Mountain

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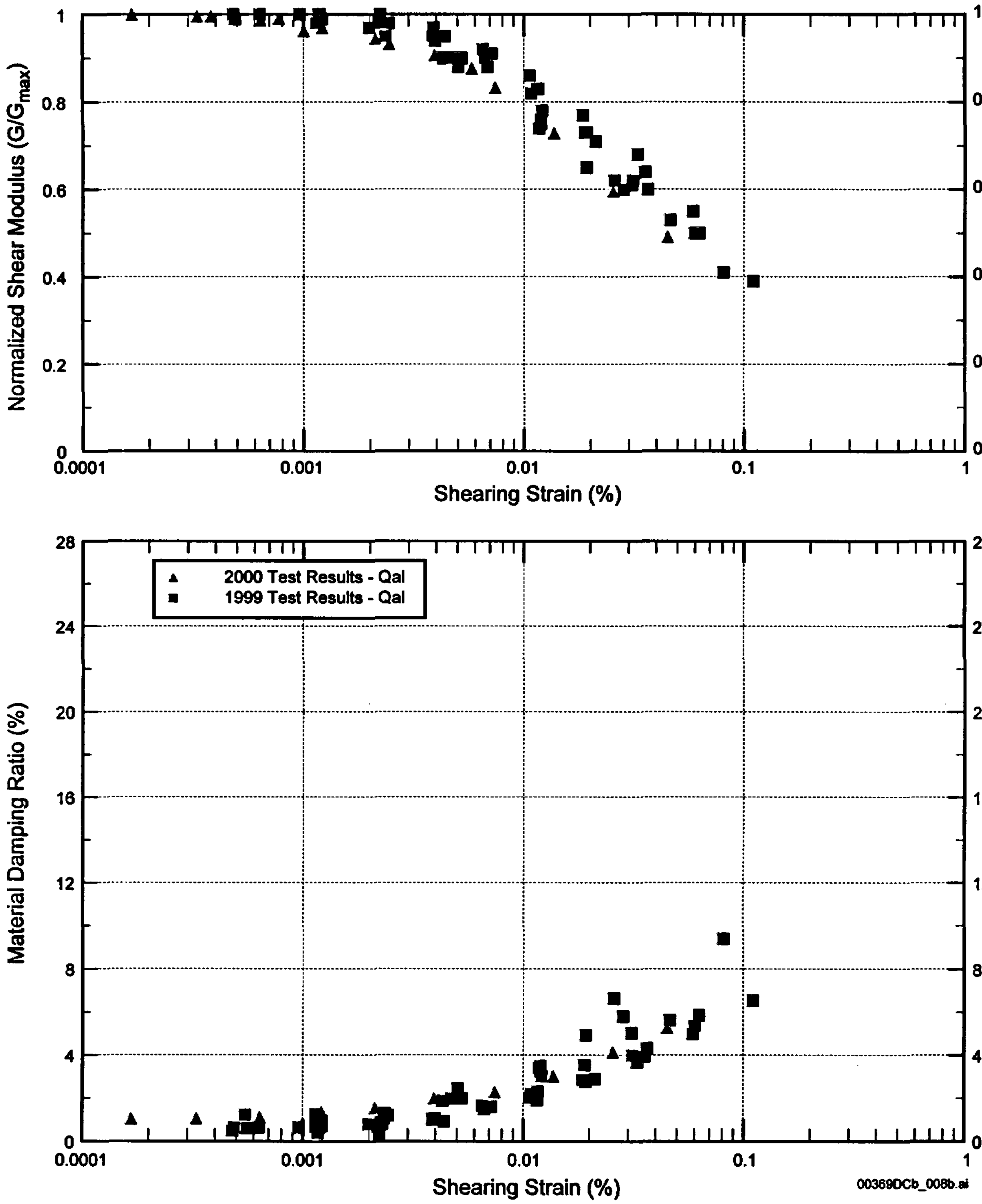


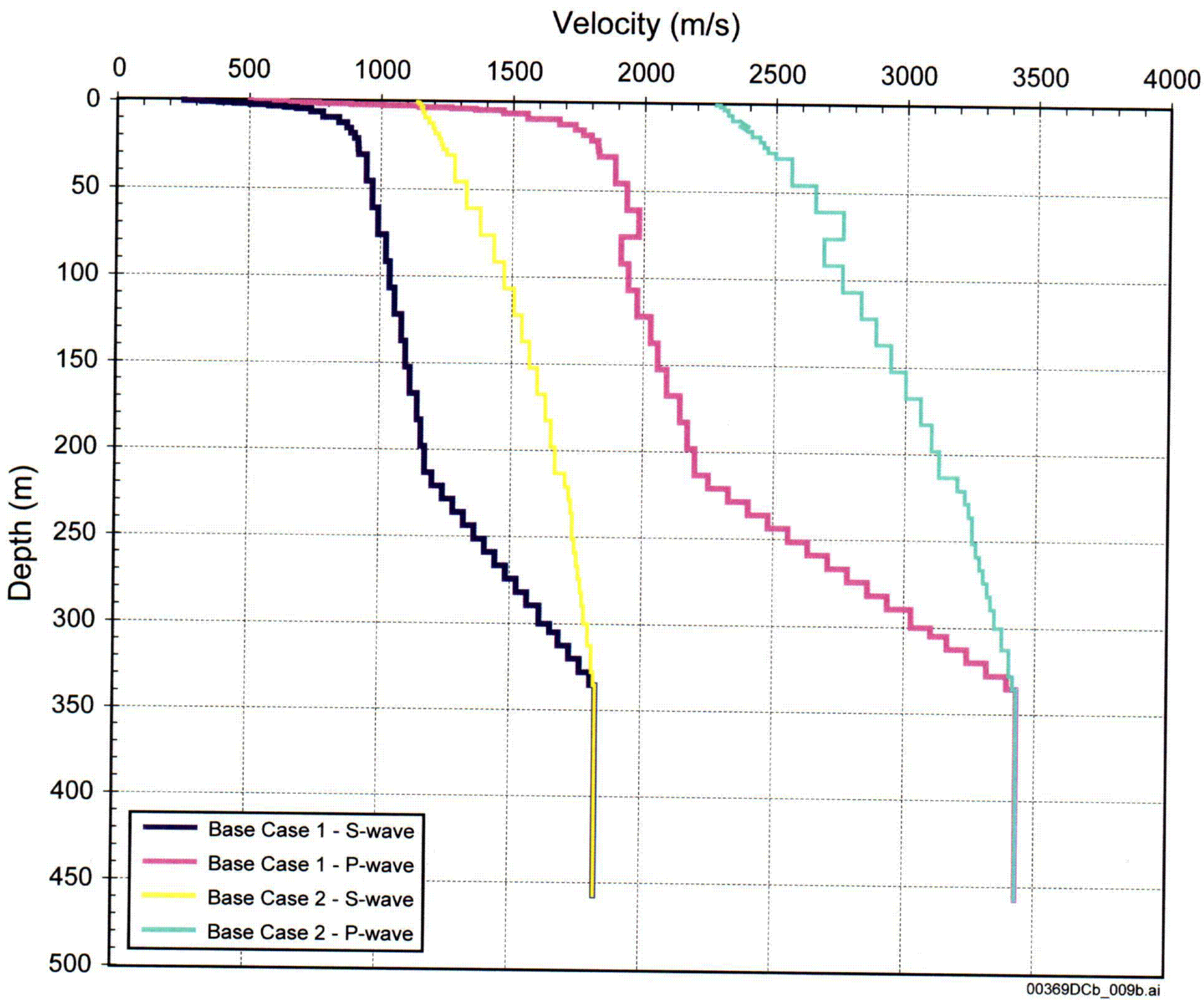
Source: BSC 2004d, Figure 6.2-110.

NOTE: Qal = Quaternary alluvium.

Figure 4-11. Dynamic Property Testing Results for Soil at Yucca Mountain

Velocity–Results of the geotechnical investigations form the basis for developing base case velocity profiles (compressional-wave and shear-wave) for the repository block and the surface facilities area (BSC 2004d, Section 6.2.3). For the repository block, results of velocity surveys in deeper boreholes located near but outside the waste emplacement area, results from shallower boreholes, and results from spectral analysis of surface waves surveys indicate considerable uncertainty in the base case velocity profile. In addition, some portions of the block containing the waste emplacement area have not been well sampled. To represent this uncertainty, two base case profiles are developed (Figure 4-12) and carried through the site response analysis. Spectral analysis of surface waves results from the ESF provide the basis for the repository block velocity at a depth of about 300 m.

For the surface facilities area, in addition to a base case profile for tuff, a base case profile for soil is developed. For each material, available data support development of a single base case profile at this location (Figure 4-13). These profiles apply to the area to the southeast of the Exile Hill splay fault, which is a north–northwest-trending, east–northeast-dipping normal fault that cuts across the surface facilities area near boreholes RF#14 and RF#29. Because of offset along this fault, the soil and rock column differs across the fault. For the area to the northeast of the Exile Hill splay fault, the applicability of seismic ground motion inputs developed using velocity profiles for the area southeast of the fault are being evaluated.



Source: BSC 2004d, Figures 6.2-80 and 6.2-82.

Figure 4-12. Repository Block Base Case Velocity Profiles for Tuff

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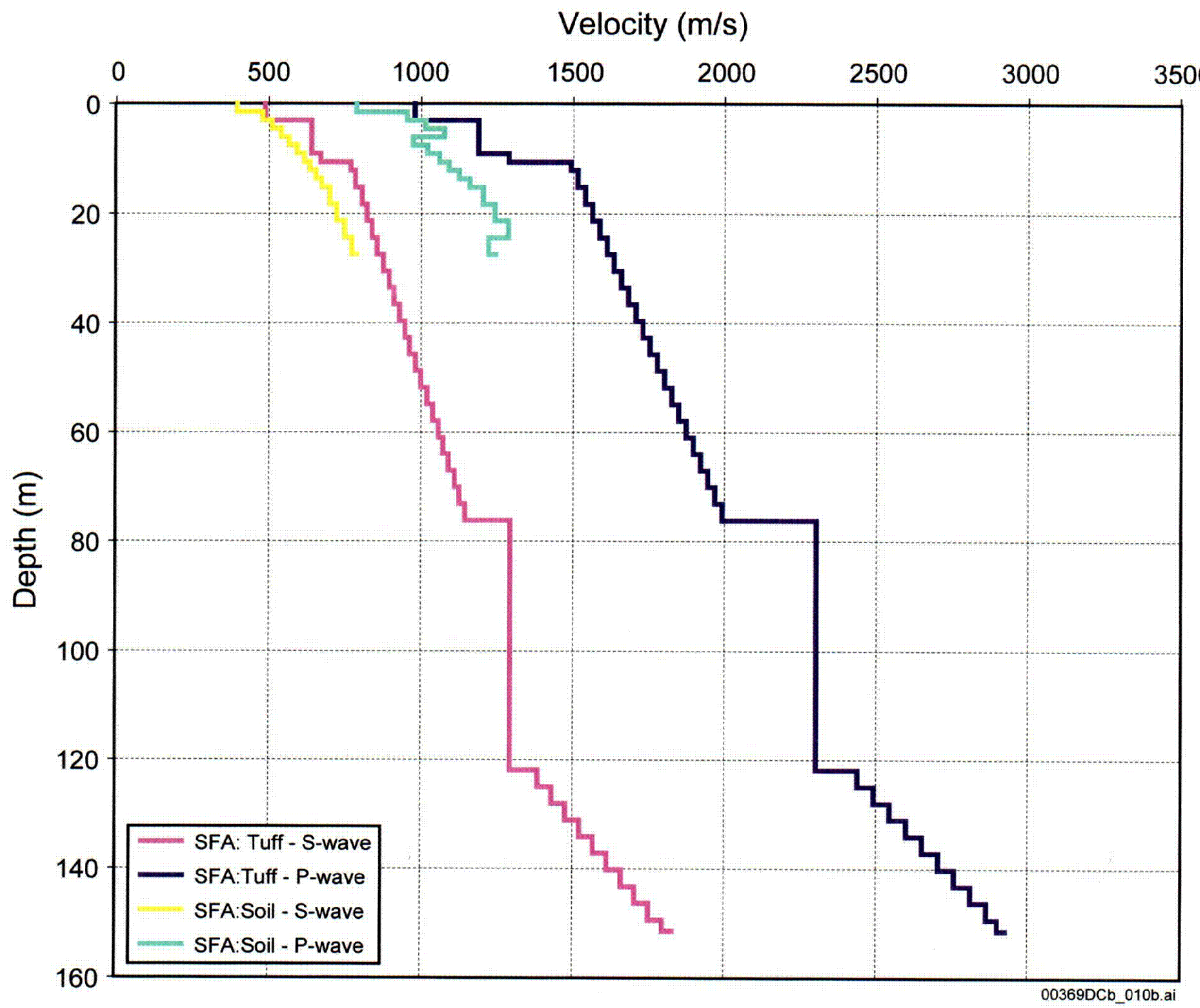

Source: BSC 2004d, Figures 6.2-83 to 6.2-86.

NOTE: SFA = surface facilities area.

Figure 4-13. Surface Facilities Area Base Case Velocity Profiles for Tuff and Soil

In addition to uncertainty in the base case velocity profile, which is addressed by developing two profiles for repository block tuff, there is also random variability in velocities across the site that needs to be accommodated in the site response analysis. To accomplish this, each base case profile is used as the basis to randomly generate a suite of 60 profiles that serve as input to the site response model (Figure 4-14). Correlation between layer velocities and thicknesses is based on an analysis of the available velocity data and thus is site-specific (BSC 2004d, Section 6.2.3.6). For each of the randomly generated profiles, the depth of the profile is also varied using a uniform distribution from about 200 to 450 m for the repository block and about 120 to 180 m for the surface facilities site. This variation accounts for the range in overburden thickness above the waste emplacement area and in the depth at which the velocity reaches the value for the hypothetical reference rock outcrop from the PSHA.

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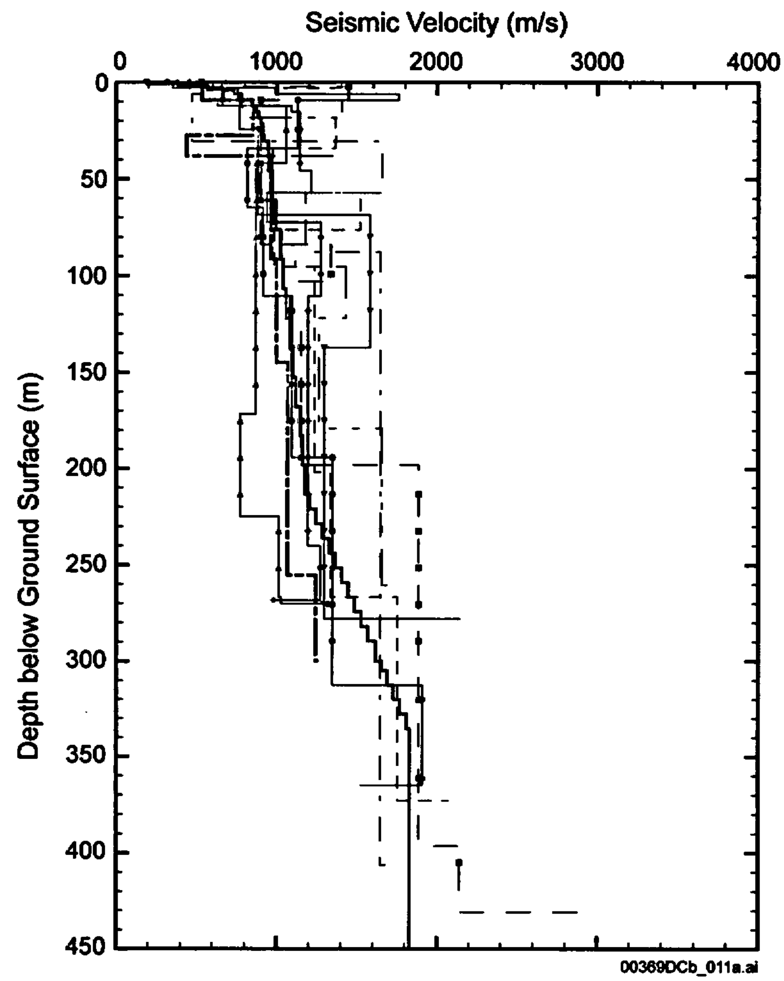


Source: BSC 2004d, Figure 6.3-1b.

Figure 4-14. Example of Random Velocity Profiles Based on Base Case Profile 1 for the Repository Block

Shear-Modulus Reduction and Material Damping–As ground motion increases and produces larger shear strains in the site materials, nonlinear behavior can take place. In the site response computations, this nonlinear behavior is accounted for through changes in shear modulus and material damping. Laboratory testing provides significant information on such behavior for Yucca Mountain site materials, but because of the scale of samples tested, there is uncertainty in how these results relate to in situ properties. For tuff, the small samples tested may not reflect the effects of fractures and voids in the in situ rock and thus the tested samples may behave more linearly than the in situ rock. On the other hand, the process of collecting the samples may disturb them and cause them to behave more nonlinearly than in situ unfractured rock. For soil, the samples were disturbed and were reconstituted for testing. Thus, soil cementation that exists in situ is not reflected in the test results. Also, the size of the soil samples precludes inclusion of some of the larger soil components (e.g., gravel, cobbles, boulders). Thus, there is considerable uncertainty in how the soil testing results relate to in situ properties.

To accommodate uncertainty in mean normalized shear modulus reduction and material damping curves for tuff, two sets of base case curves were developed (Figure 4-15) (BSC 2004d, Section 6.2.4.2). One set of curves represents the case in which in situ conditions consist of unfractured rock. The second set was developed to represent in situ conditions that reflect fracturing and heterogeneity, the effects of which are not captured in laboratory testing. For soil, two sets of curves are also developed to represent the uncertainty in mean dynamic properties (Figure 4-16) (BSC 2004d, Section 6.2.4.3). One set of curves (base case 1) accommodates the possibility of little to no cementation in the field, as well as the lack of experience with this type of material in the geotechnical literature. The second set of curves (base case 2) represents the case in which in situ cementation breaks under ground motion producing strains. The site response model is run for each of these base case sets of dynamic property curves. For the surface facilities area, four cases are run reflecting the four combinations of tuff and soil base case curves.

In addition to uncertainty in the mean dynamic property curves, random variability about the mean curves is also accommodated in the site response analysis. As for the velocity profiles, the variability is taken into account by randomly generating 60 sets of dynamic property curves for each base case set and using those randomly generated curves in the analysis. During the randomization process, the curves are allowed to vary between lower and upper bounds at −2 and +2 standard deviations, assuming a normal distribution.

4.1.2.3 Transfer Functions

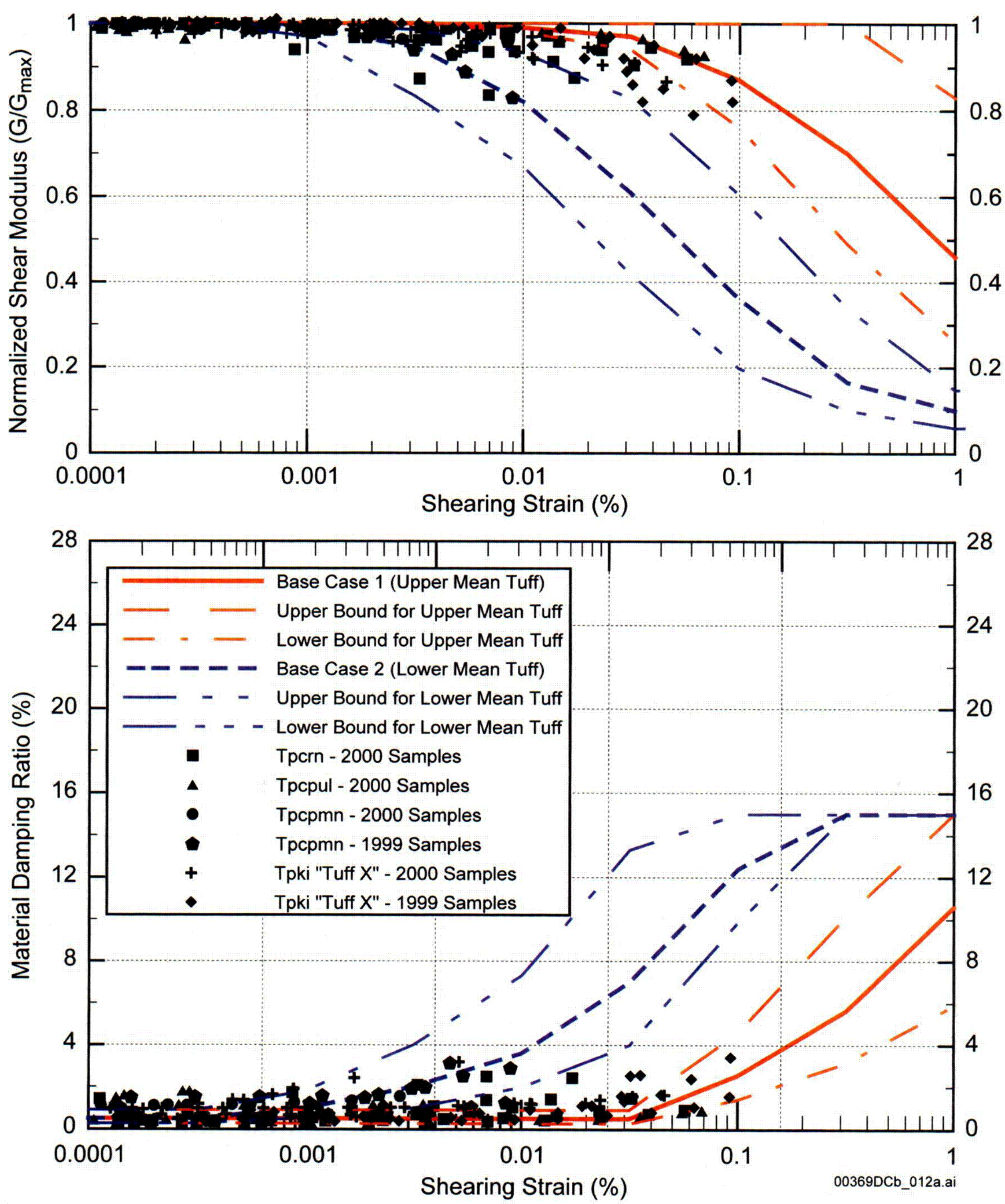
Steps 5 through 9 in the approach to developing site-specific ground motion involve calculation and application of site-response transfer functions. Site response can be thought of as a transfer function that transposes ground motion from the PSHA reference rock outcrop (the control location) to ground motion at a specific location for which seismic inputs are needed for design or performance assessment. For earthquake response spectra, the transfer function describes the amplification or reduction of the control motion response spectrum as a function of frequency and is referred to as a "spectral amplification function." For peak ground velocity, the transfer function consists of a single scaling value. The following discussion describes the approach for determining response spectra and peak ground velocity transfer functions for Yucca Mountain that result in location-specific ground motion that is consistent with the seismic hazard results for the control location (BSC 2004d, Section 6.3.1.1.2).

To determine the response spectrum transfer function, the six control motion earthquakes for horizontal and vertical component motion—three deaggregation earthquakes (low, mean, and high magnitude) for two structural frequency ranges (5 to 10 Hz and 1 to 2 Hz) are used for the site-response calculation (Figure 4-17a). For each deaggregation earthquake (control motion), the site-response calculation is carried out for 60 randomized velocity profiles and dynamic property curves (Figure 4-17b). For locations where multiple base case profiles or curves were developed to represent uncertainty, the process is carried out for each base case. In addition, the process is carried out for the different seismic wave types that are considered. For horizontal motion, these consist of inclined and vertically incident horizontally polarized shear waves and vertically polarized shear waves. For vertical motion, the wave types are inclined and vertically incident compression waves and inclined shear waves.

The result of each calculation is a response spectrum that reflects how the input motion response spectrum is modified by the site materials (Figure 4-17c). For each deaggregation earthquake and combination of base case velocity profile, dynamic material property curves, and wave type, the mean of the resulting response spectra for the 60 randomized profiles and curves is taken. This mean computed spectrum for each deaggregation earthquake is then divided by the corresponding input deaggregation earthquake spectrum to produce a spectral amplification function (Figure 4-17d). The spectral amplification function shows how the control motion response spectrum was modified by the site response as a function of structural frequency. It includes the effects of random variability in site material properties.

Then, for each combination of base case velocity profile, dynamic material property curves, and wave type, a weighted mean is computed of the spectral amplification functions for the three deaggregation earthquakes. Most weight is given to the mean deaggregation earthquake with lower weight given to the low and high magnitude deaggregation earthquakes, which nominally correspond to the 5th and 95th percentiles of the deaggregation magnitude distribution. The result of this step is a set of transfer functions, for each of the two structural frequency ranges and ground motion components, corresponding to each combination of base case velocity profile, dynamic property curves, and wave types. These weighted mean transfer functions include any earthquake magnitude- and amplitude-dependent effects on the dynamic response of site materials.

Next, for each combination of ground motion component, velocity profile, dynamic material property curves, and wave type, the weighted mean transfer functions for the high and low structural frequency range are enveloped. For horizontal ground motion, the resulting transfer functions are applied to the envelope of the response spectra for the high and low structural frequency reference earthquakes. Alternatively, the transfer functions could be applied to the horizontal uniform hazard spectrum. By applying them to the envelope of the reference earthquake response spectra, the resulting ground motion is somewhat larger. This step results in a suite of response spectra that reflect the associated site response for each combination of base case velocity profile, dynamic material property curves, and wave type. The final site response spectrum for each component of ground motion is then obtained by enveloping over all the combinations of base case velocity profile, dynamic material property curves, and wave type (Figure 4-17e). The final location-specific response spectra thus reflect uncertainty in the base case velocity profile and dynamic material properties at the site.



Source: BSC 2004d, Figure 6.2-103.

Figure 4-15. Base Case Curves for Normalized Shear Modulus Reduction and Material Damping as a Function of Shearing Strain for Tuff

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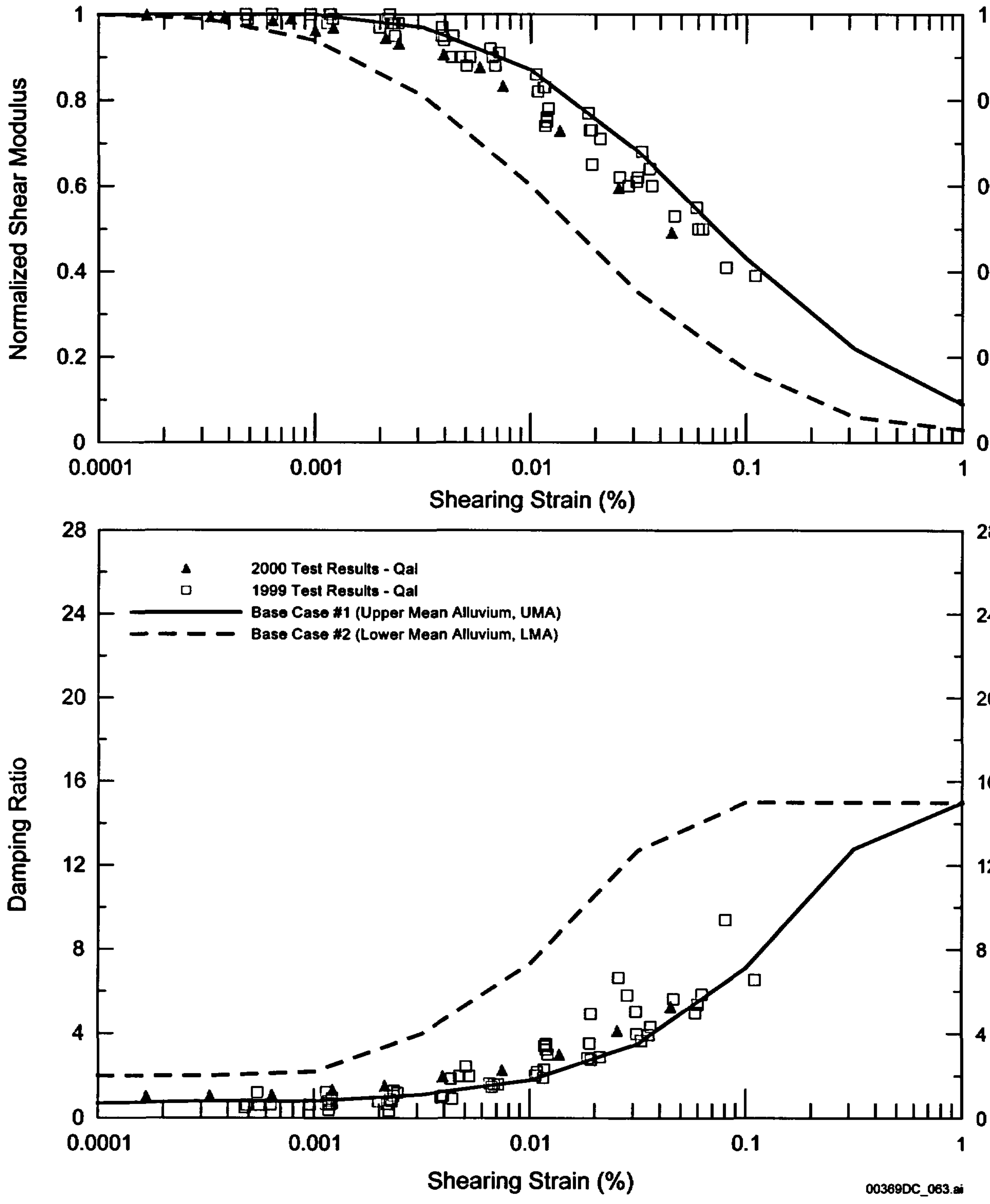
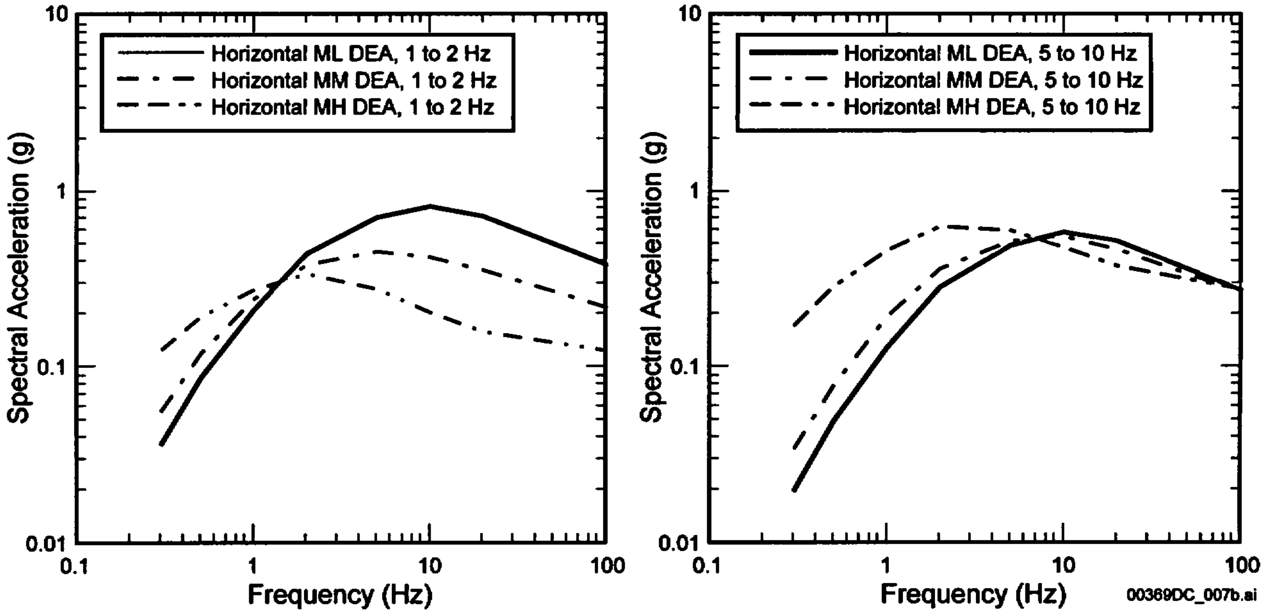


Source: BSC 2004d; Wong and Silva 2003, p. 87.

NOTE: Qal = Quaternary alluvium.

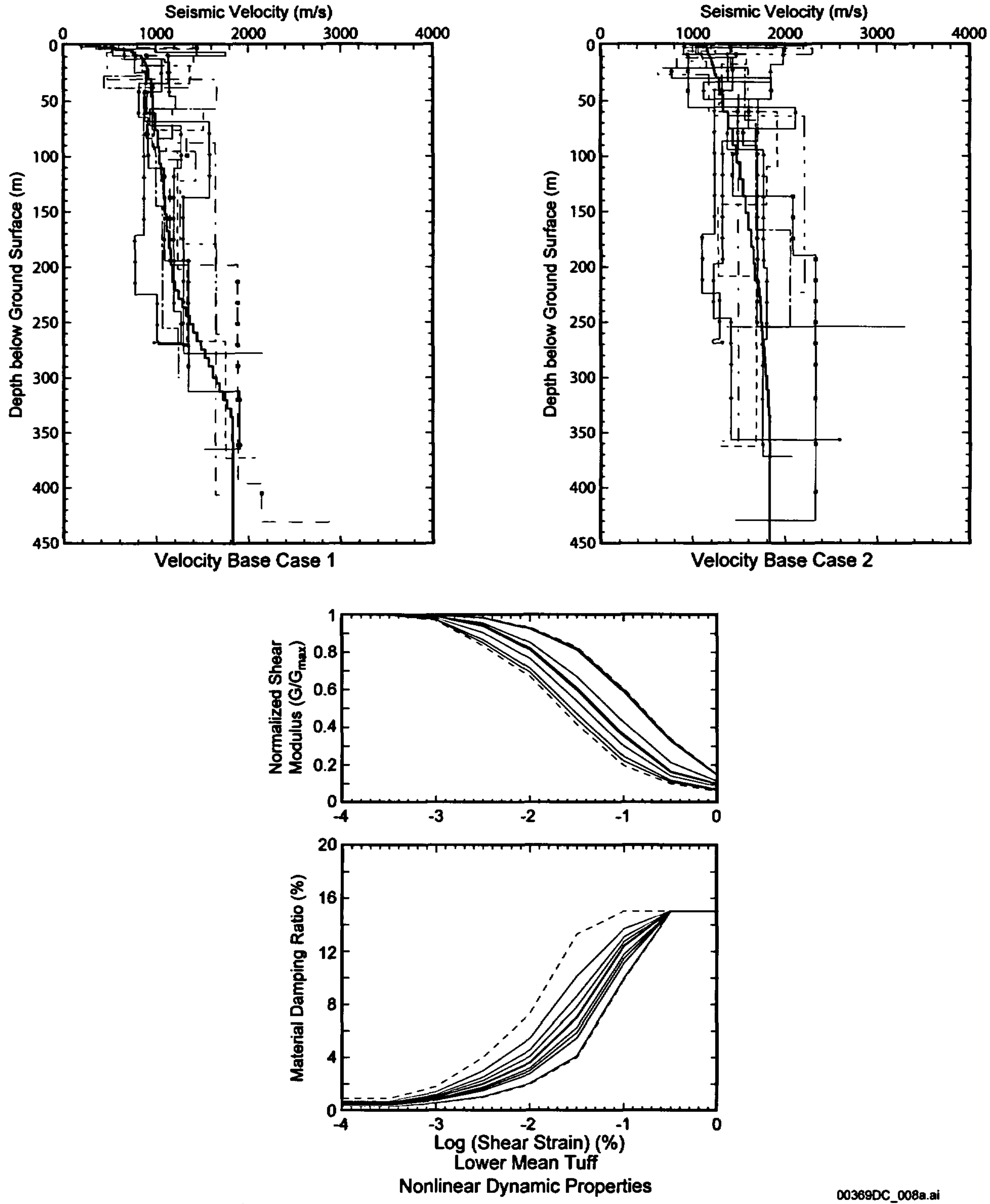
Figure 4-16. Base Case Curves for Normalized Shear Modulus Reduction and Material Damping as a Function of Shearing Strain for Soil



Source: BSC 2004d, Figure 6.3-1a.

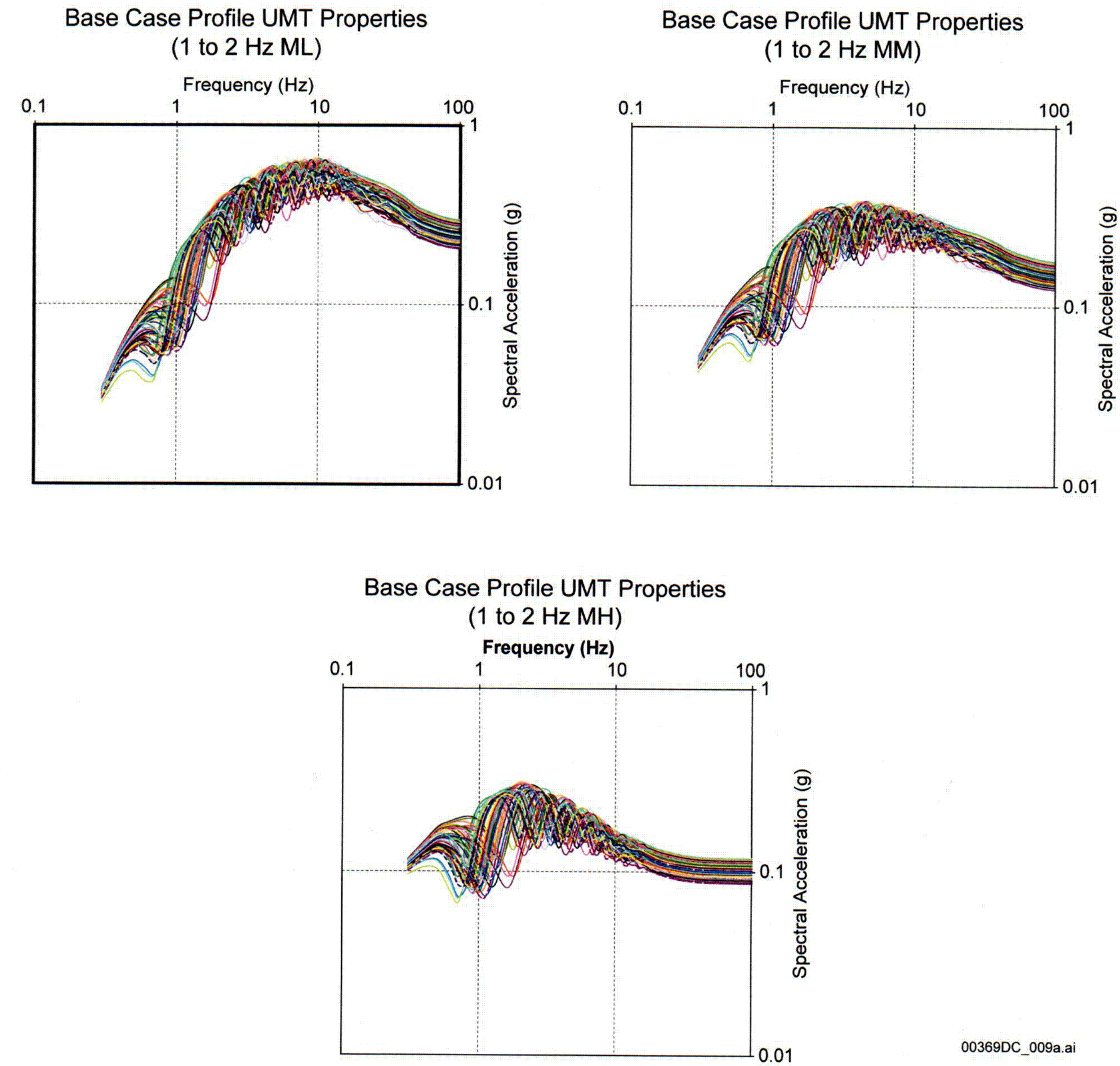
NOTE: Control motions are developed for each level of annual exceedance probability. This figure illustrates the set of deaggregation earthquakes (horizontal component) at 5×10^{-4} annual exceedance probability. ML = low magnitude; MM = medium magnitude; MH = high magnitude; DEA = deaggregation earthquake.

Figure 4-17a. Site Response Methodology: Control Motions



Source: BSC 2004d, Figure 6.3-1b.

Figure 4-17b. Site Response Methodology: Examples of Repository Block V_S Profile and Nonlinear Dynamic Material Properties Randomizations



Source: BSC 2004d, Figure 6.3-1c.

NOTE: Site response is determined for the six control motions (1 to 2 Hz and 5 to 10 Hz response structural frequency ranges; low, medium, and high magnitude deaggregation earthquakes) for combinations of 60 randomized profiles about each base-case velocity profile and 60 randomized curves for each base-case dynamic material property set. This figure illustrates the response of the randomized profiles for repository block base-case 1 and dynamic material property base-case 1 (UMT = upper mean tuff) for the 1 to 2 Hz response structural frequency range and the three deaggregation earthquakes (ML, MM, MH) for horizontal component motion. ML = low magnitude; MM = medium magnitude; MH = high magnitude.

Figure 4-17c. Site Response Methodology: Response of Simulated Profiles to Deaggregation Earthquakes Control Motion

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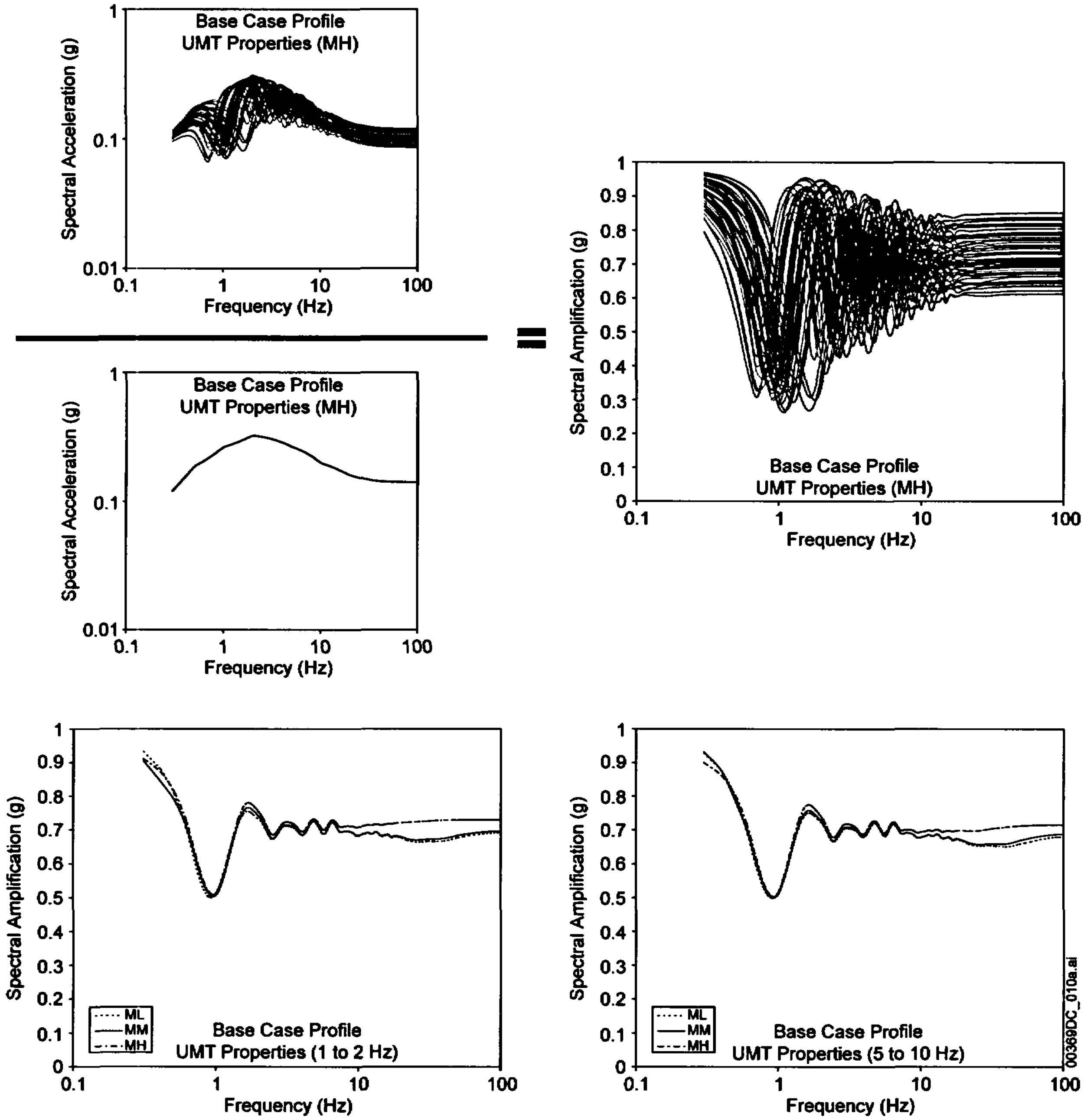
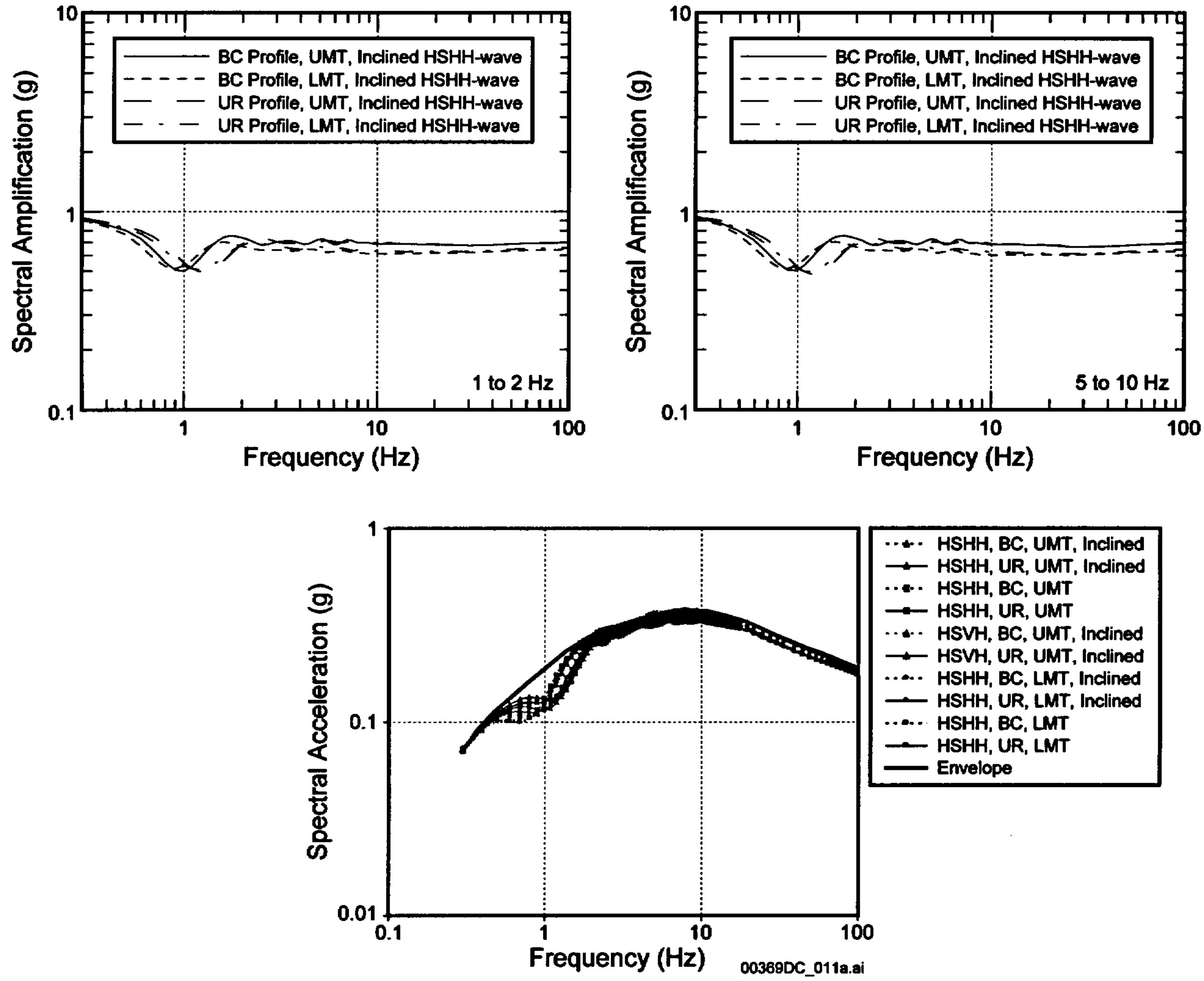


Source: BSC 2004d, Figure 6.3-1d.

NOTE: Upper graph: Spectral amplification functions are computed by dividing the modeled response for each randomized velocity profile (numerator) by the scaled response spectrum of the input deaggregation earthquake (denominator). Lower graphs: For each set of 60 computed spectral amplification functions, a mean spectral amplification function is determined. This step is carried out for each combination of wave type, base-case velocity profile, base-case material property curves, response structural frequency range, and deaggregation earthquake. Example mean spectral amplification functions are shown in the two lower plots. Magnitude dependency of the nonlinear site response is reflected in the differences between spectral amplification functions for low, medium, and high magnitude deaggregation earthquake control motions. ML = low magnitude; MM = medium magnitude; MH = high magnitude; UMT = upper mean tuff.

Figure 4-17d. Site Response Methodology: Computation of Mean Spectral Amplification Functions



Source: BSC 2004d, Figure 6.3-1e.

NOTE: Upper graph: For combinations of wave type, base-case velocity profile, base-case material property curves, and response structural frequency range, results for the three deaggregation earthquakes are combined using a weighted average. Example weighted-average mean spectral amplification functions are shown for 1 to 2 Hz (left) and 5 to 10 Hz (right) response structural frequency ranges. For the example shown, the results for the two structural frequency ranges are nearly identical. Lower graph: For each combination of wave type, base-case velocity profile, base-case material property curves, an envelope is taken over the weighted average mean spectral amplification functions for the two response structural frequency ranges and these envelope spectral amplification functions are applied to the envelope of the reference earthquake response spectra (not shown). Finally, an envelope is taken over response spectra for the various combinations of wave type, base-case velocity profile, and base-case material property curves. An example of this final step is shown in the lower graph. UMT = upper mean tuff material property base-case 1; LMT = lower mean tuff material property base-case 2; BC = base-case velocity profile 1; UR = base-case velocity profile 2; HSHH = horizontal motion of horizontally polarized shear waves; HSVH = horizontal motion of vertically polarized shear waves.

Figure 4-17e. Site Response Methodology: Magnitude-Weighted Mean Spectral Amplification Functions, Modified Reference Earthquake Spectra, and Final Spectrum (Envelope)

In computing the site response for vertical ground motion, the spectral transfer resulting from enveloping over the high and low structural frequency range for each combination of base case velocity profile, dynamic material property curves, and wave type is applied to a revised vertical spectrum. The revised vertical spectrum is obtained by scaling vertical response spectra for the reference earthquakes to a revised vertical uniform hazard spectrum and then taking their envelope. The vertical uniform hazard spectrum from the PSHA is revised such that the relation between the horizontal and vertical uniform hazard spectra accords with current understanding of vertical-to-horizontal ratios for response spectra based on observations and ground motion numerical modeling. Observations from earthquakes with magnitudes and distances comparable to those dominating the ground motion hazard at Yucca Mountain at low annual probabilities of exceedance indicate that vertical component motion exceeds horizontal component motion at frequencies greater than about 10 Hz. Observations and numerical modeling also indicate that vertical response spectra for these earthquakes peak at higher frequencies than the corresponding horizontal response spectra. The relation between the horizontal and vertical uniform hazard spectra from the PSHA does not exhibit these features. Thus, a revised vertical uniform hazard spectrum is developed. First, a vertical-to-horizontal response spectral ratio is determined for Yucca Mountain site conditions based on earthquake observations and results of numerical modeling (McGuire et al. 2001, Section 4.7). This site-specific ratio is then applied to the horizontal uniform hazard spectrum from the PSHA for given hazard levels to obtain the revised vertical uniform hazard spectrum. Finally, the response spectra for the reference earthquakes are scaled to the revised vertical uniform hazard spectrum and enveloped. The location-specific site-response transfer function is applied to this envelope to obtain the final location-specific vertical spectrum (BSC 2004d, Section 6.2.2.6).

In addition to transfer functions for response spectra, transfer functions reflecting site response are also determined for peak ground velocity. The approach used is the same and thus includes uncertainty and random variability in site material properties, as well as magnitude dependence on nonlinear material behavior. Spectral amplification functions are replaced by peak-ground-velocity scaling factors. Enveloping becomes simply taking the largest value of peak ground velocity. For vertical-component peak ground velocity, the peak ground velocity for the reference rock outcrop from the PSHA is revised to be consistent with the revised vertical uniform hazard spectrum before the velocity scaling factor is applied.

4.1.2.4 Seismic Time Histories

The final step in producing location-specific ground motion is the development of seismic time histories based on the location-specific seismic input spectra. Different approaches are used for developing time histories depending on how they will be used (e.g., in design or in evaluating postclosure repository performance). For Yucca Mountain, three approaches have been used to develop time histories: spectral matching, scaling to peak ground velocity, and scaling to peak ground velocity preceded by spectral conditioning. The spectral-matching approach is used primarily to develop time histories that will be used in design analyses. The peak-ground-velocity scaling approaches are used to develop time histories for postclosure analyses. Peak ground velocity was selected as a scaling parameter because damage to underground structures has been correlated with peak ground velocity (McGarr 1984).

Each set of time histories consists of two horizontal component records and one vertical component record. Acceleration, velocity, and displacement records are produced. For a given annual exceedance probability and location of interest, one or more sets of time histories may be developed.

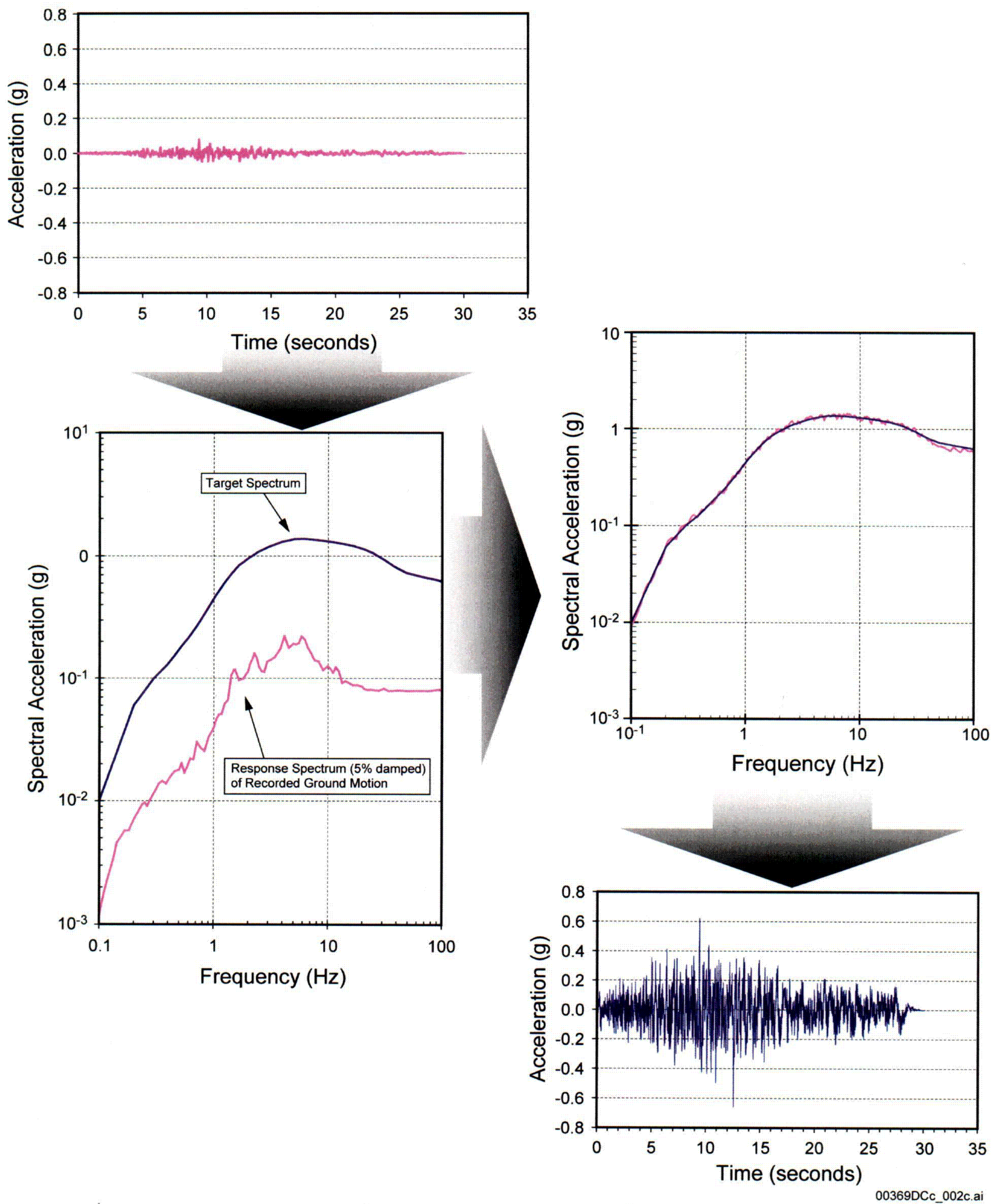
For all approaches, the time histories are based on actual recordings of strong ground motion from earthquakes in the western United States and around the world (McGuire et al. 2001, Appendix B). The original recordings are modified to reflect the results of the site-response analyses for a location of interest. Recordings for use are selected to represent those earthquakes (magnitudes and distances) that dominate the seismic hazard at a given annual probability of exceedance. By basing the time histories on actual earthquake recordings and choosing records consistent with the seismic hazard, the resulting time histories will exhibit realistic phase characteristics and durations.

The spectral-matching approach involves developing time histories whose response spectra closely match target response spectra determined through site-response analyses (Figure 4-18). Matching can be done either for individual records or, if multiple sets of time histories are involved, done such that the mean response spectra match the target spectra, but individual spectra do not. Matching is carried out in general accordance with the recommendations of McGuire et al. (2001, Section 5). However, recommendations to compare time domain characteristics (e.g., duration, the ratio of peak ground velocity to peak ground acceleration) of developed time histories to observed cataloged values for western United States conditions are inappropriate for Yucca Mountain because the Yucca Mountain site conditions differ from those for the cataloged events. Also, for the waste emplacement level, the motions are not expected to be similar to the free-field motions documented in McGuire et al. (2001). The spectral-matching approach is used to develop time histories for use in design analyses.

In the peak-ground-velocity scaling approach, the earthquake recordings are scaled such that their peak ground velocity matches the peak ground velocity determined in the site-response analysis for a location of interest. The records may be scaled such that both horizontal components match the target horizontal peak ground velocity and the vertical component matches the target vertical peak ground velocity. Alternatively, one horizontal component may be scaled to the target horizontal peak ground velocity and the scaling of the other components done in a manner to maintain the intercomponent variability of the original recordings. Both of these methods have been used at Yucca Mountain.

The peak-ground-velocity scaling approach is used to develop time histories for analyses supporting postclosure performance assessment. For these analyses, the goal is not to ensure that design acceptance criteria are met, but rather to determine how the designed structures, systems, and components that will remain after the repository is closed perform under earthquake loads that are significantly beyond their design basis. In addition to determining the consequences of the low-probability ground motion, another goal is to evaluate the variability in the consequences. Because much of the variability in consequences will be driven by random variability in the ground motion, the time histories for postclosure analyses are developed to capture and represent that random variability. For each annual exceedance probability of interest, 17 sets of time histories are developed. The recordings used as a basis for the time histories are selected to have a range of magnitudes and distances that corresponds to the magnitudes and distances of earthquakes contributing to the seismic hazard at the given annual exceedance probability. This ensures the ensuing analyses will take into account an appropriate range of response spectral shapes and durations. In analyses supporting evaluation of postclosure performance, typically 15 time histories are used from the 17 available.

A variation of the peak-ground-velocity scaling approach involves spectrally conditioning the original strong ground motion records before using them to develop time histories. Spectral conditioning modifies the original strong motion records such that their response spectra reflect to a greater degree the site conditions at Yucca Mountain. Conditioning can be done with respect to the PSHA reference rock outcrop conditions or to the waste emplacement level conditions that reflect the site response. Conditioning can be thought of as a weak spectral match. A strong spectral match is not desired in this case because it would tend to reduce the random variability of the original recordings.



Source: BSC 2004d, Figure 6.3-25.

NOTE: A recorded strong ground motion record is modified so that its 5% damped response spectrum matches the target response spectrum determined from the site response modeling.

Figure 4-18. Spectral-Matching Approach to Develop Time Histories

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4.2 SITE-SPECIFIC GROUND MOTION RESULTS

This section presents results of implementing the overall approach to site-specific ground motion, including use of the random-vibration-theory-based equivalent-linear site-response model. The results include uncertainty and random variability in the reference (control) location ground motion hazard results, as well as in the site response. Results are presented as a function of site location and annual exceedance probability.

Waste Emplacement Level–Site-specific response spectra for the waste emplacement level were determined for annual exceedance probabilities of 5×10^{-4}, 10^{-5}, 10^{-6}, and 10^{-7} (Figure 4-19). Results for an annual exceedance probability of 5×10^{-4} are used for preclosure design analyses. Results for all four annual exceedance probabilities support development of time histories for postclosure analyses.

For annual exceedance probabilities of 10^{-5}, 10^{-6}, and 10^{-7}, in addition to site-specific response spectra, site-specific values of peak ground velocity were determined (Table 4-1). These values are used to scale time histories and to develop a ground motion hazard curve for the waste emplacement level.

Table 4-1. Site-Specific Peak Ground Velocity for the Waste Emplacement Level

Annual Probability of Being Exceeded	Horizontal Peak Ground Velocity (m/s)	Vertical Peak Ground Velocity (m/s)
10^{-5}	1.05	1.37
10^{-6}	2.44	2.36
10^{-7}	5.35	6.25

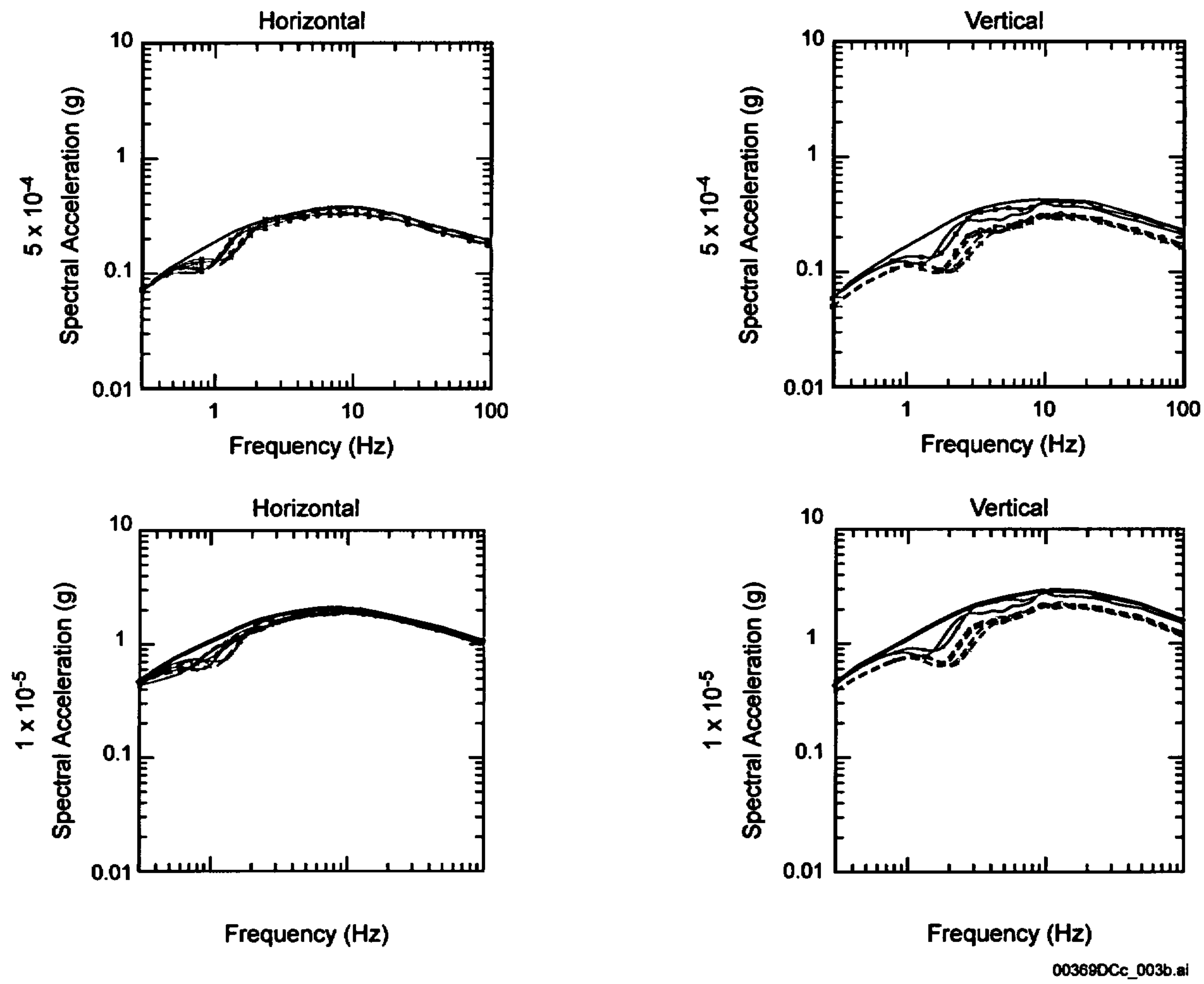
Time histories for the waste emplacement level, with an annual probability of exceedance of 5×10^{-4}, were developed using the spectral-matching approach. One three-component set of time histories was developed. An example of the match between the time history and the site-specific design spectrum is shown in Figure 4-20 for one of the horizontal components.

For annual exceedance probabilities of 10^{-5}, 10^{-6}, and 10^{-7}, the peak-ground-velocity scaling approach was used to generate time histories. A total of five suites of 17 sets of time histories each were developed for these annual exceedance probabilities. The 17 sets of recorded strong ground motion that form part of the basis for the time histories were selected to represent the range of magnitudes and distances consistent with the range indicated by the PSHA.

The first suite (Figure 4-21), for an annual exceedance probability of 10^{-5}, was developed by first spectrally conditioning the recorded strong ground motion data to weakly match the location-specific response spectra for the emplacement level at Yucca Mountain. Specifically, the ratios between response spectra for average western U.S. conditions and response spectra for the emplacement level at Yucca Mountain were determined. The western U.S. response spectra are considered typical of the strong motion records forming the basis for Yucca Mountain time histories. These ratios, or transfer functions, were then applied to the response spectrum for each of the strong ground motion records to be used in generating time histories. Finally, the modified response spectra formed targets for weak spectral matches of the original records.

Following this conditioning, the records were scaled to the site-specific peak ground velocity. In this case, one horizontal component was scaled to the peak ground velocity and the other components were scaled to preserve the intercomponent variability of the original records. This suite of time histories was used to evaluate rockfall and EBS postclosure performance.

The second suite (Figure 4-22), for an annual exceedance probability of 10^{-6}, consists of time histories for which both horizontal components were scaled to the site-specific horizontal peak ground velocity and the vertical component was scaled to the site-specific vertical peak ground velocity. For this suite, observed intercomponent variability was not maintained. Also, the records used to generate the time histories were not spectrally conditioned prior to scaling. This suite of time histories was used to evaluate rockfall and EBS postclosure performance.



Source: BSC 2004d, Figures 6.3-5, 6.3-6, 6.3-16, 6.3-17, 6.3-21, and 6.3-22.

NOTE: Site response spectra for various combinations of wave type, base-case velocity profile, and base-case material property curves. If needed, final target spectra for design (preclosure) or spectral conditioning of time histories (postclosure) are obtained by enveloping the spectra for the various combinations.

Figure 4-19. Site-Specific Response Spectra for the Waste Emplacement Area Level with an Annual Exceedance Probability of 5×10^{-4}, 10^{-5}, 10^{-6}, and 10^{-7}

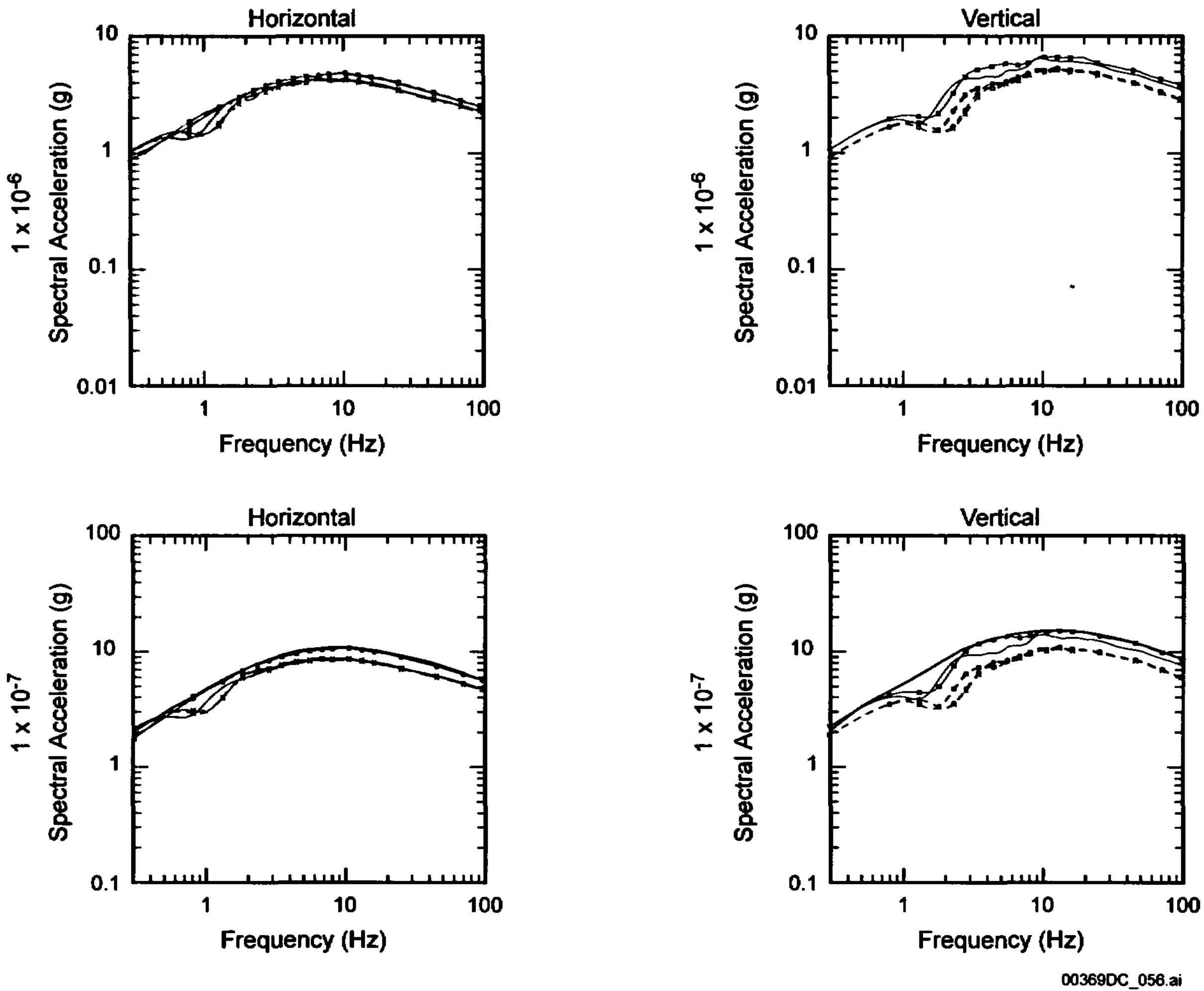
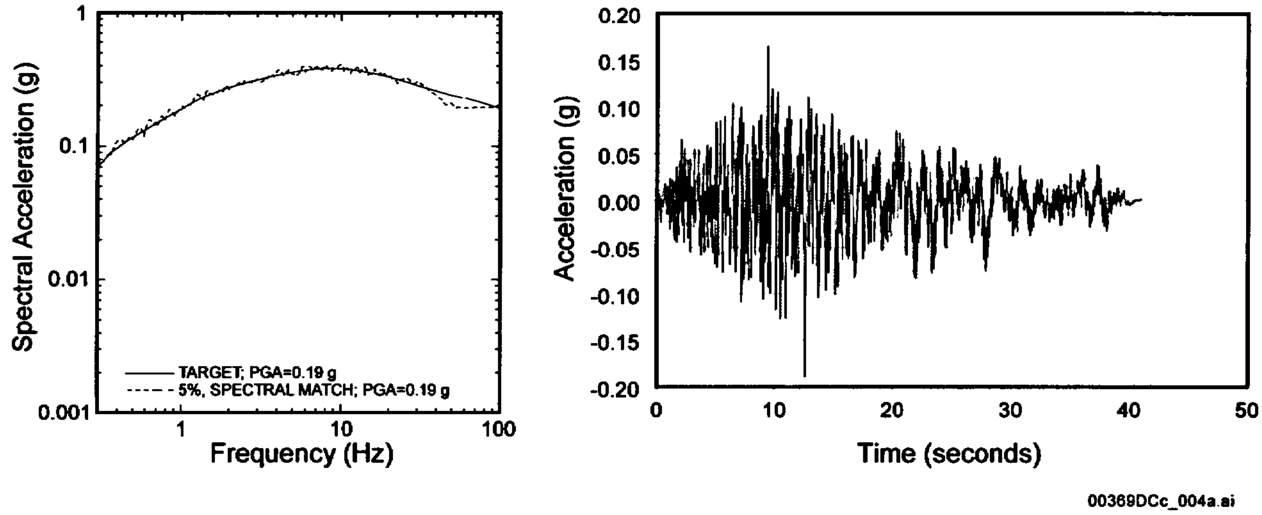


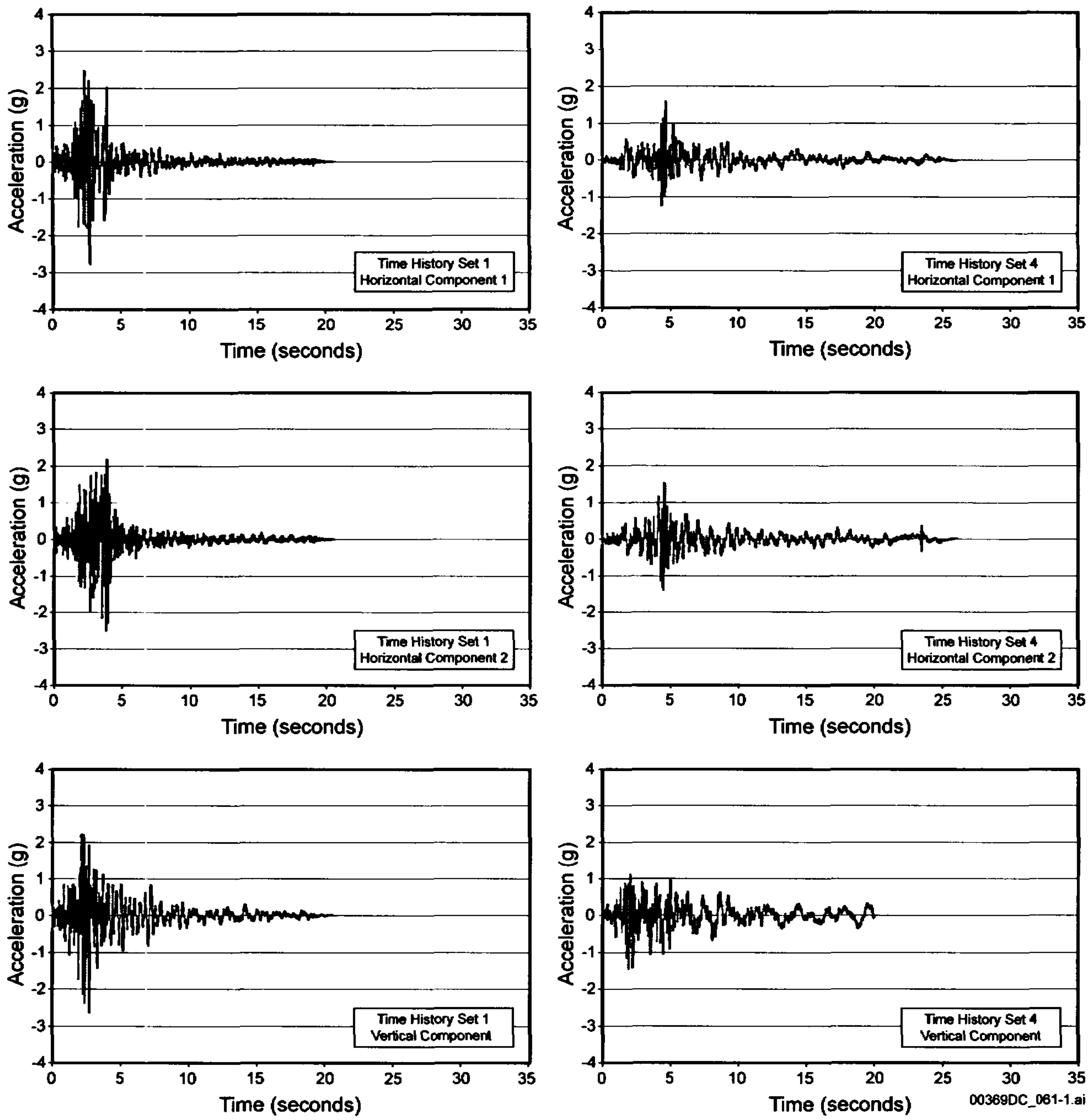
Figure 4-19. Site-Specific Response Spectra for the Waste Emplacement Area Level with an Annual Exceedance Probability of 5×10^{-4}, 10^{-5}, 10^{-6}, and 10^{-7} (continued)



Source: BSC 2004d, Figure 6.3-27.

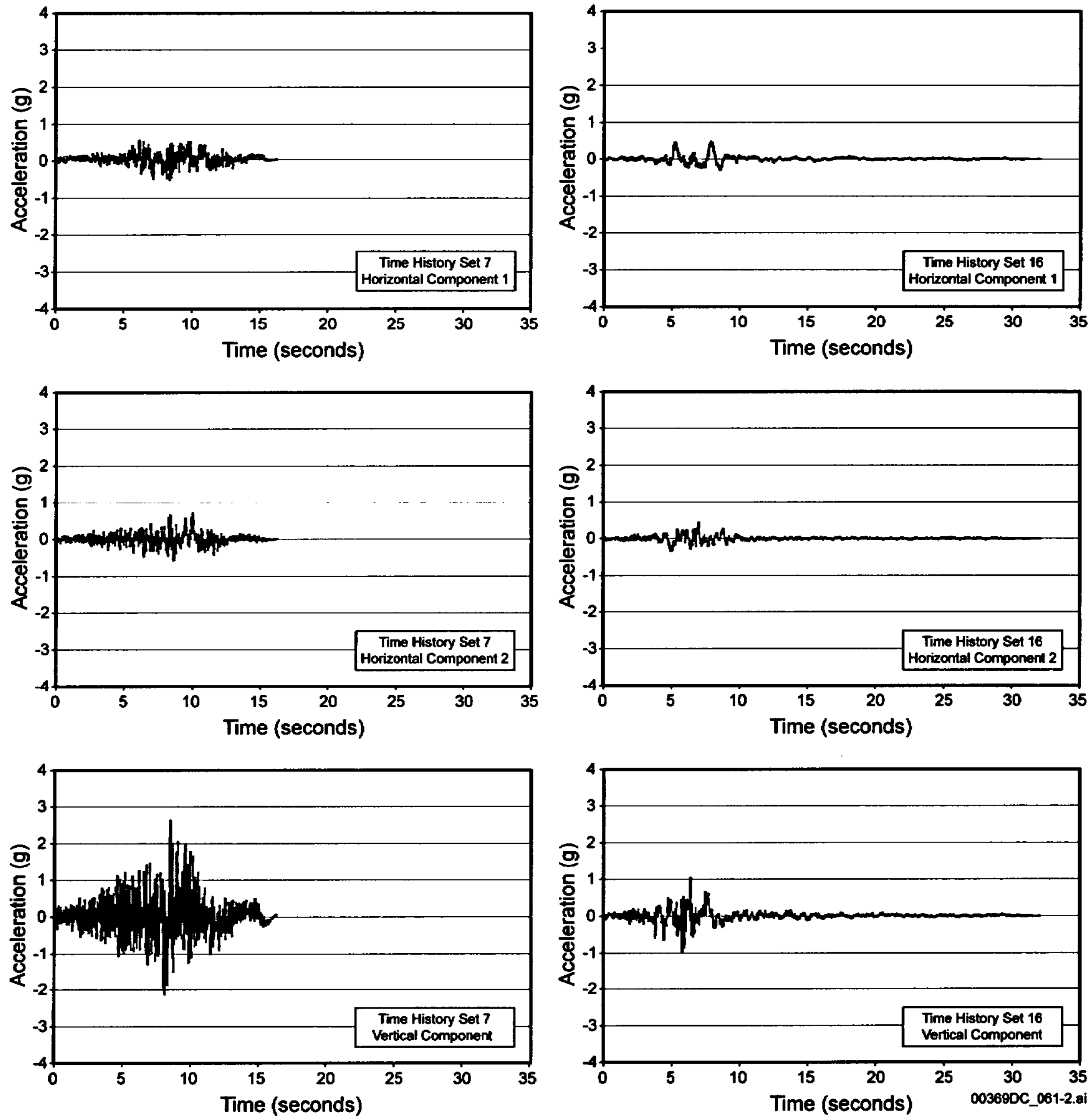
NOTE: On the left, the response spectrum of the example time history is plotted, along with the target spectrum showing a successful match.

Figure 4-20. Example Time History (Horizontal Component) and Response Spectrum for an Annual Exceedance Probability of 5×10^{-4} for the Waste Emplacement Area



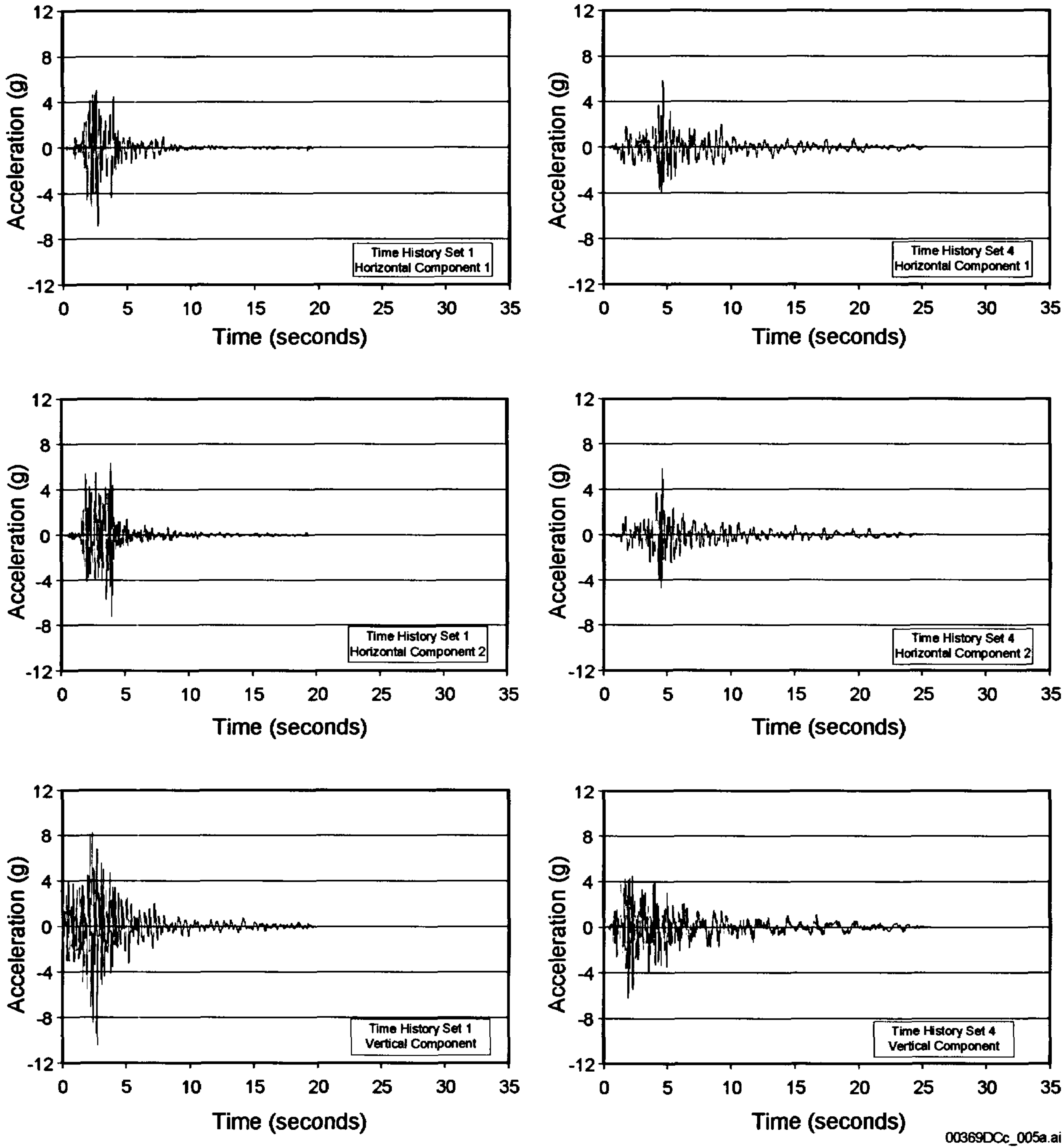
Source: DTN: MO0402AVDTM105.001.

Figure 4-21a. Example Time Histories with an Annual Exceedance Probability of 10^{-5} for the Waste Emplacement Level: Spectrally Conditioned to the Waste Emplacement Level and Scaled to Peak Ground Velocity



Source: DTN: MO0402AVDTM105.001.

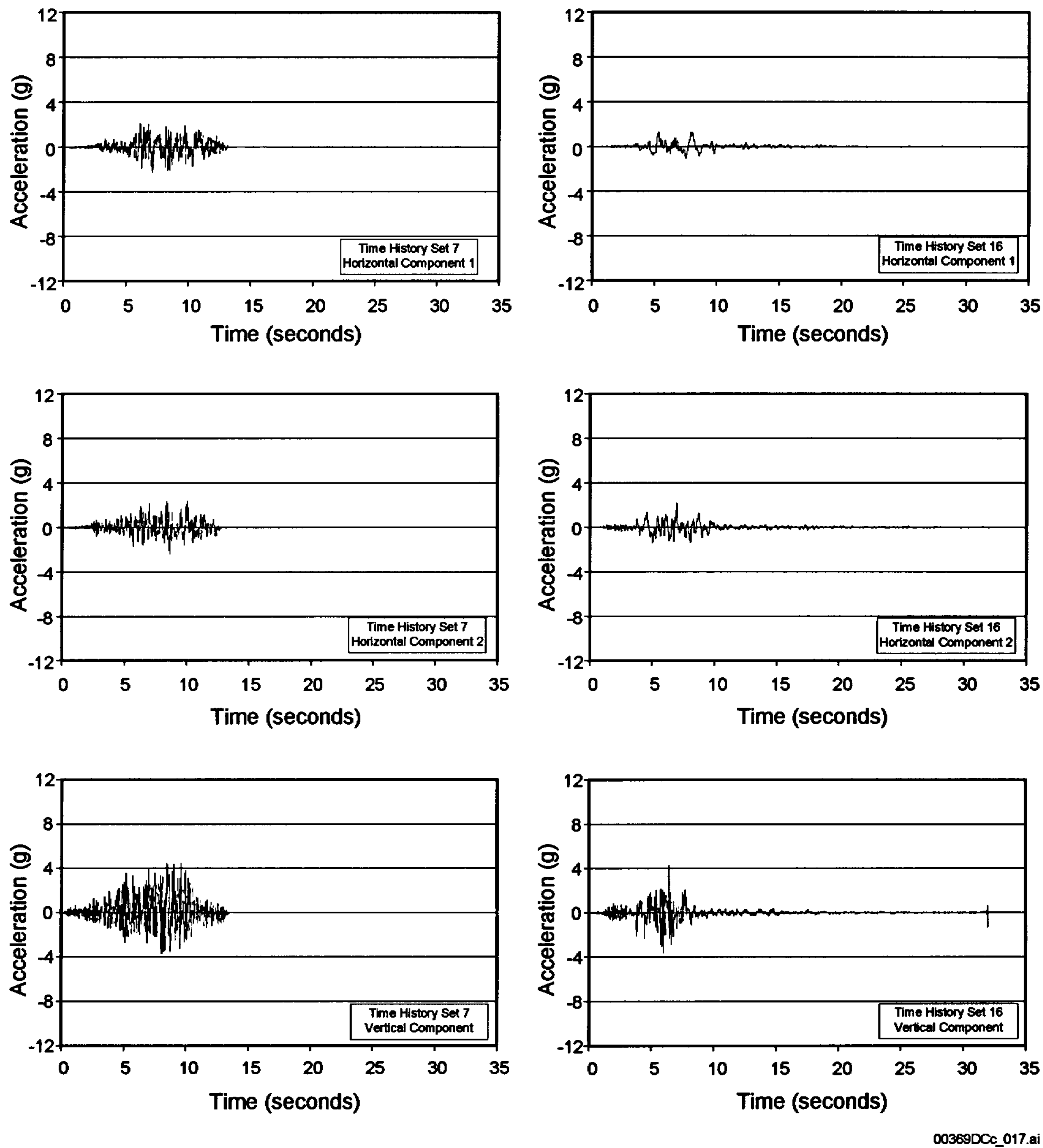
Figure 4-21b. Example Time Histories with an Annual Exceedance Probability of 10^{-5} for the Waste Emplacement Level: Spectrally Conditioned to the Waste Emplacement Level and Scaled to Peak Ground Velocity



Source: DTN: MO0301TMHIS106.001.

NOTE: Time histories are developed by scaling each component independently to the target peak ground velocity.

Figure 4-22a. Example Time Histories with an Annual Exceedance Probability of 10^{-6} for the Waste Emplacement Level: Scaled to Peak Ground Velocity



Source: DTN: MO0301TMHIS106.001.

NOTE: Time histories are developed by scaling each component independently to the target peak ground velocity.

Figure 4-22b. Example Time Histories with an Annual Exceedance Probability of 10^{-6} for the Waste Emplacement Level: Scaled to Peak Ground Velocity

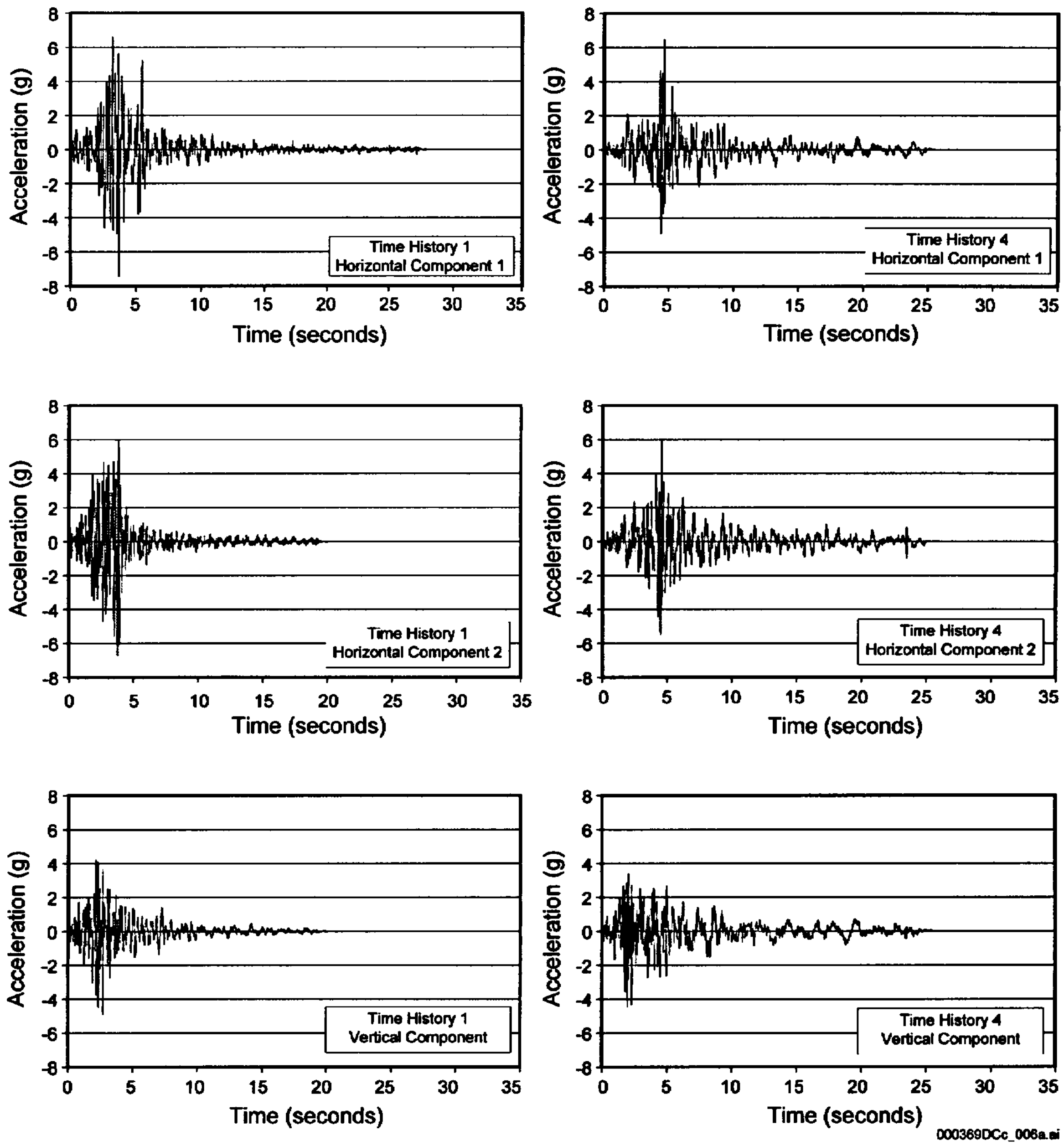
A third suite of time histories (Figure 4-23), also for an annual probability of exceedance of 10^{-6}, was developed by first spectrally conditioning the records to weakly match Yucca Mountain site conditions based on the response spectra for the PSHA reference rock outcrop. The same process was followed as for the suite of time histories developed for an annual probability of exceedance of 10^{-5}, except the PSHA reference rock outcrop response spectra were used instead of the emplacement level spectra. Following this conditioning, the records were scaled to the site-specific peak ground velocity. In this case, only one horizontal component was scaled to the peak ground velocity and the other components were scaled to preserve the intercomponent variability of the original records, as was done for the time histories with an annual exceedance probability of 10^{-5}.

Two suites of 17 sets of time histories were also developed for an annual exceedance probability of 10^{-7}. For both of these suites, the records forming the basis for the time histories were spectrally conditioned prior to scaling. In one case (Figure 4-24), they were spectrally conditioned to weakly match the response spectra for the PSHA reference rock outcrop, as described above for the spectrally conditioned and scaled time histories for 10^{-6} annual exceedance probability. In the second case, they were conditioned to the site-specific response spectra for the waste emplacement area. For the second case, two approaches to spectral conditioning were investigated. In the first approach, the process was identical to what was done for the suite of time histories for an annual exceedance probability of 10^{-5} (Figure 4-25). In the second approach to conditioning, the original strong motion records are weakly matched to the site-specific waste-emplacement-area response spectra directly rather than through a transfer function applied to the response spectrum for each record. This second approach to conditioning significantly reduces the random variability of the suites of sets of time histories (Figure 4-26). For analyses of rockfall and EBS performance, the time histories used are those that were spectrally conditioned to the PSHA-reference-rock-outcrop response spectra.

Surface Facilities Area–Site-specific response spectra for the surface facilities area were determined for an annual exceedance probability of 5×10^{-4} (Figure 4-27). Response spectra were determined for three representative thicknesses of soil (4.6, 10.7, and 33.5 m), and the results were enveloped to produce a single set of design spectra. By enveloping the results, a single design response spectrum is determined that applies to this location.

For the surface facilities area, strain-compatible soil properties were developed. Properties were developed as a function of depth reflecting effects of the strains produced by the ground motion. Properties addressed were compression-wave and shear-wave velocities, compression-wave and shear-wave damping, and Poisson's ratio. Following guidance provided in "Seismic System Analysis" (NRC 1989, Section 3.7.2), best-estimate and upper- and lower-bound soil columns were determined that are consistent with the site-response ground motion. These soil columns were determined on the basis of the multiple site-response model runs that accommodate the uncertainty and random variability in site geotechnical properties. The best-estimate soil column is taken as the mean of the results and the lower- and upper-bound columns at the plus- and minus-one standard deviation levels.

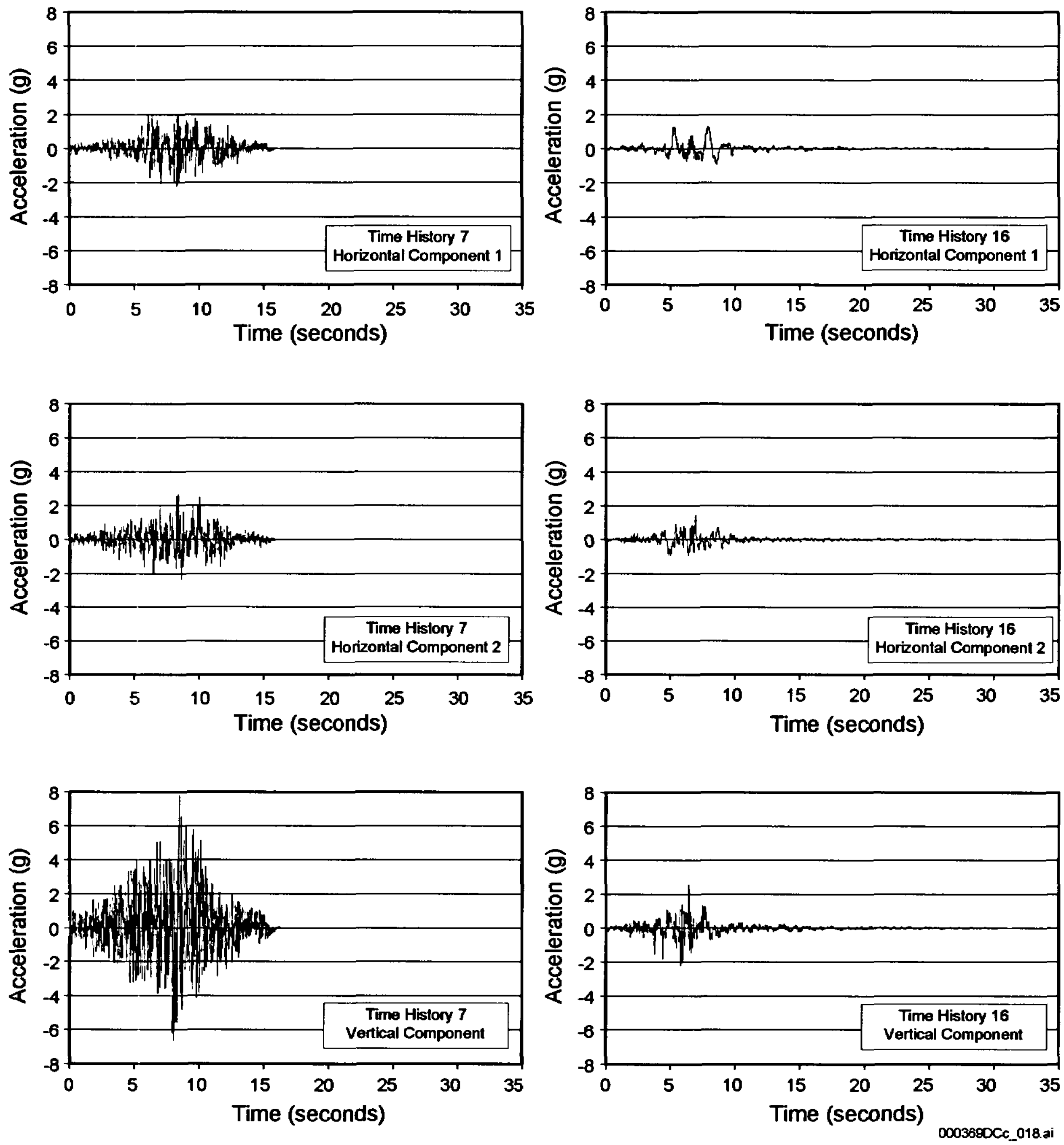
Time histories for the surface facilities area, with an annual probability of exceedance of 5×10^{-4}, were developed using the spectral-matching approach. Five three-component sets of time histories were developed. An example of the match between the time history and the site-specific design spectrum is shown in Figure 4-28 for one of the horizontal components from one of the sets.



Source: DTN: MO0403AVDSC106.001.

NOTE: Time histories are developed by first spectrally conditioning the strong motion records to weakly match the spectrum for the PSHA reference rock outcrop using a transfer function. The spectrally conditioned strong ground motion is then scaled to match the peak ground velocity for the waste emplacement level, maintaining intercomponent variability.

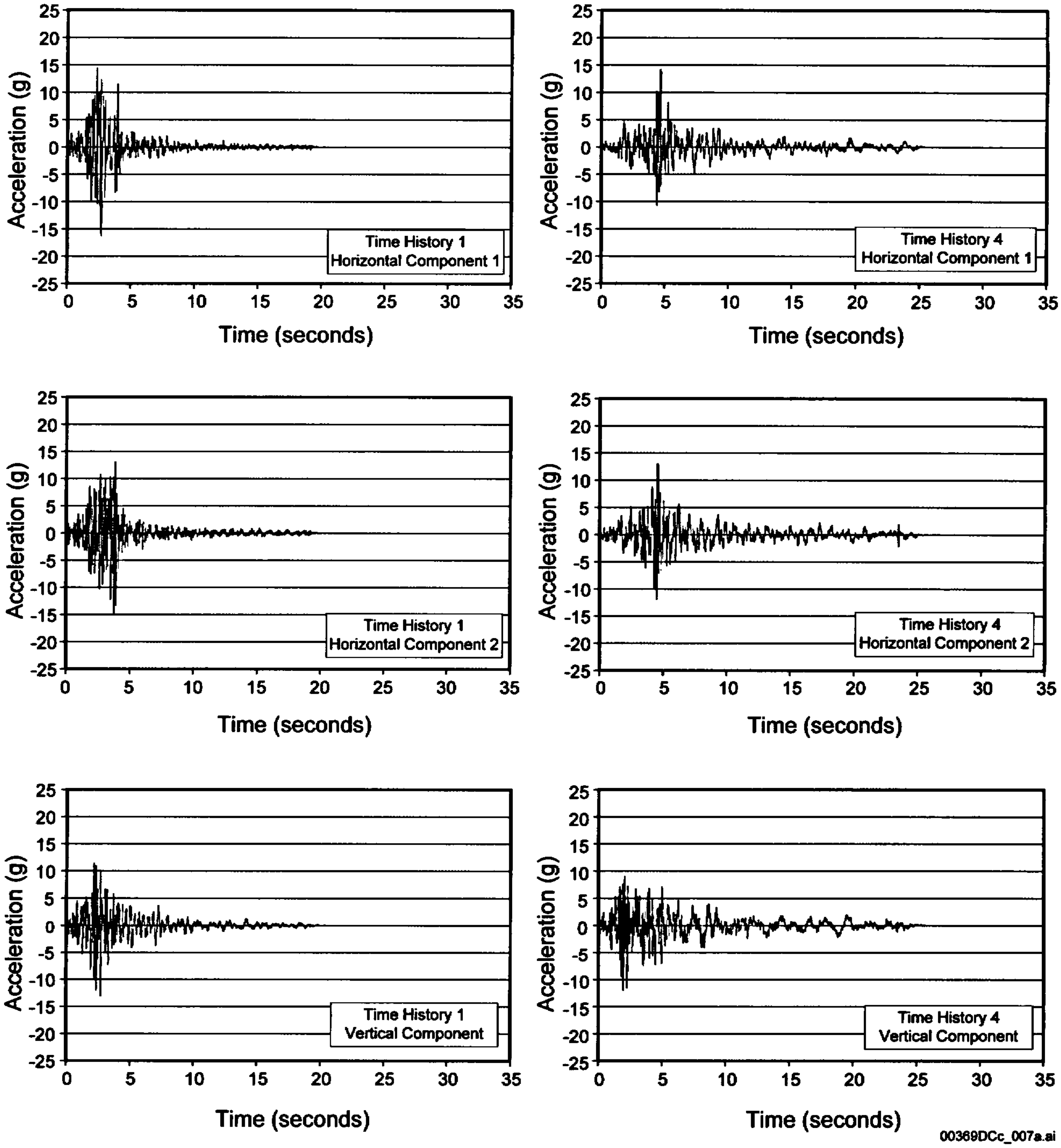
Figure 4-23a. Example Time Histories with an Annual Exceedance Probability of 10^{-6} for the Waste Emplacement Level: Spectrally Conditioned to the Probabilistic Seismic Hazards Analysis Reference Rock Outcrop and Scaled to Peak Ground Velocity



Source: DTN: MO0403AVDSC106.001.

NOTE: Time histories are developed by first spectrally conditioning the strong motion records to weakly match the spectrum for the PSHA reference rock outcrop using a transfer function. The spectrally conditioned strong ground motion is then scaled to match the peak ground velocity for the waste emplacement level, maintaining intercomponent variability.

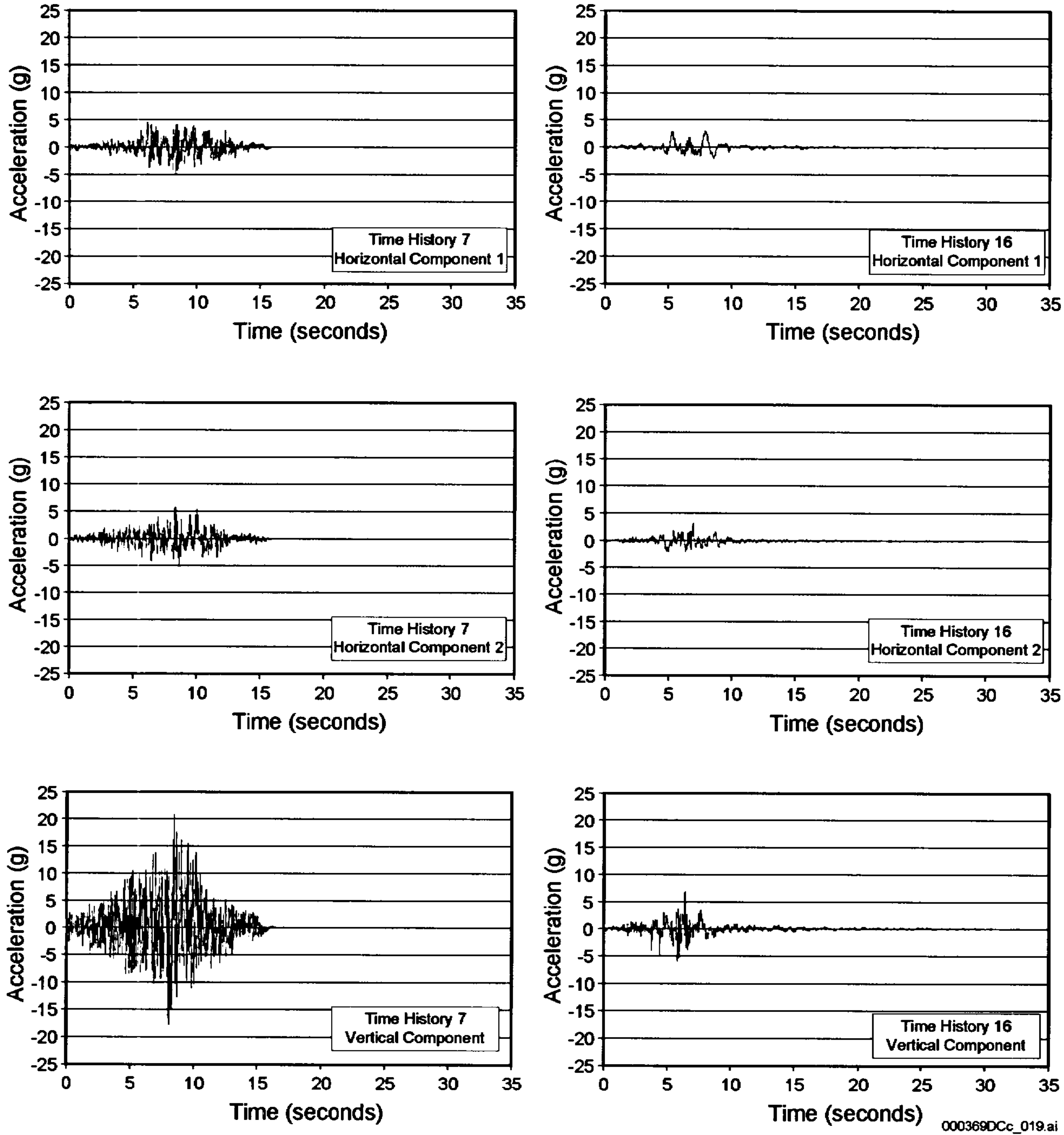
Figure 4-23b. Example Time Histories with an Annual Exceedance Probability of 10^{-6} for the Waste Emplacement Level: Spectrally Conditioned to the Probabilistic Seismic Hazards Analysis Reference Rock Outcrop and Scaled to Peak Ground Velocity



Source: DTN: MO0403AVTMH107.003.

NOTE: Time histories are developed by first spectrally conditioning the strong motion records to weakly match the spectrum for the PSHA reference rock outcrop using a transfer function. The spectrally conditioned strong ground motion is then scaled to match the peak ground velocity for the waste emplacement level, maintaining intercomponent variability.

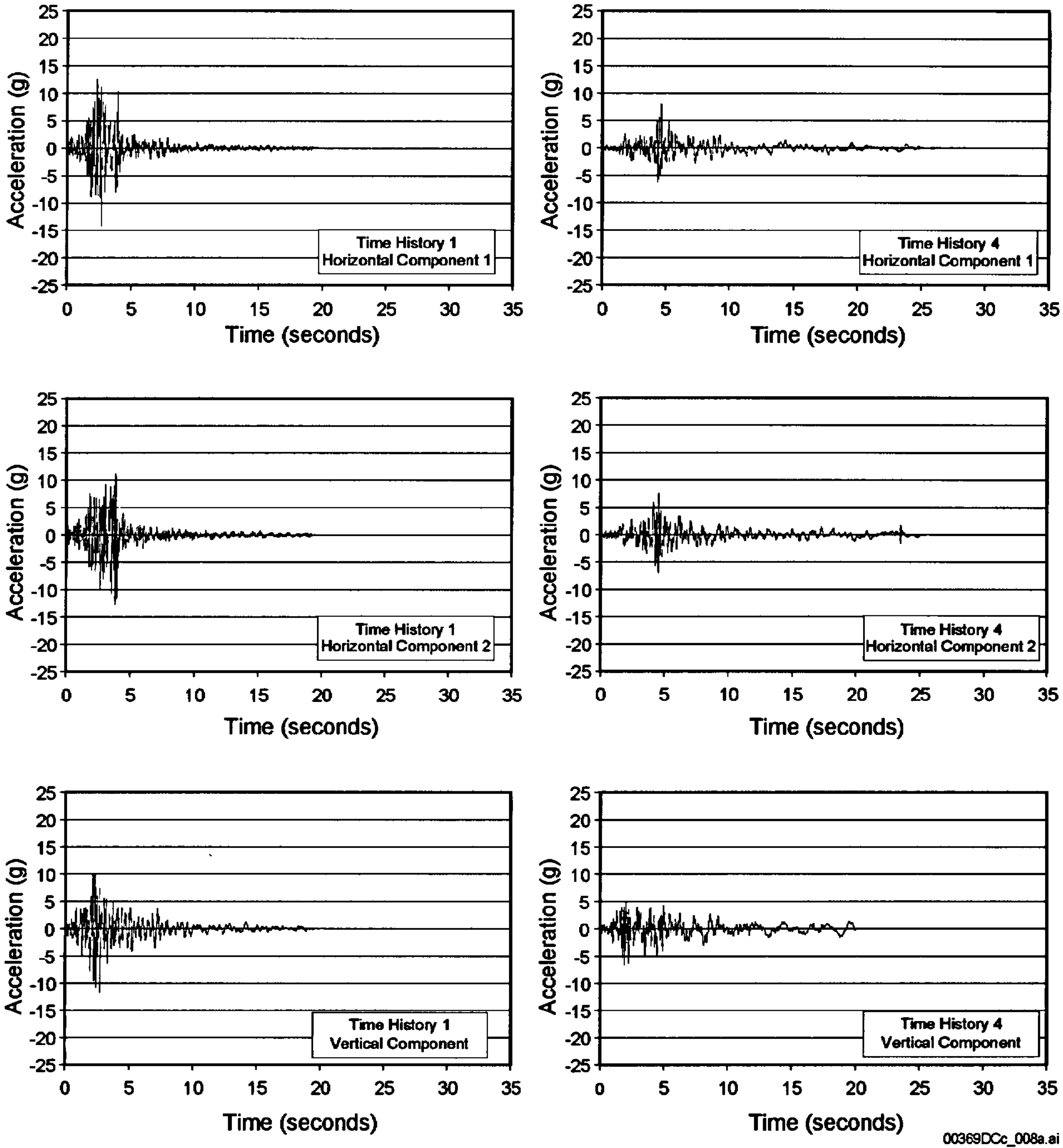
Figure 4-24a. Example Time Histories with an Annual Exceedance Probability of 10^{-7} for the Waste Emplacement Level: Spectrally Conditioned to the Probabilistic Seismic Hazards Analysis Reference Rock Outcrop and Scaled to Peak Ground Velocity



Source: DTN: MO0403AVTMH107.003.

NOTE: Time histories are developed by first spectrally conditioning the strong motion records to weakly match the spectrum for the PSHA reference rock outcrop using a transfer function. The spectrally conditioned strong ground motion is then scaled to match the peak ground velocity for the waste emplacement level, maintaining intercomponent variability.

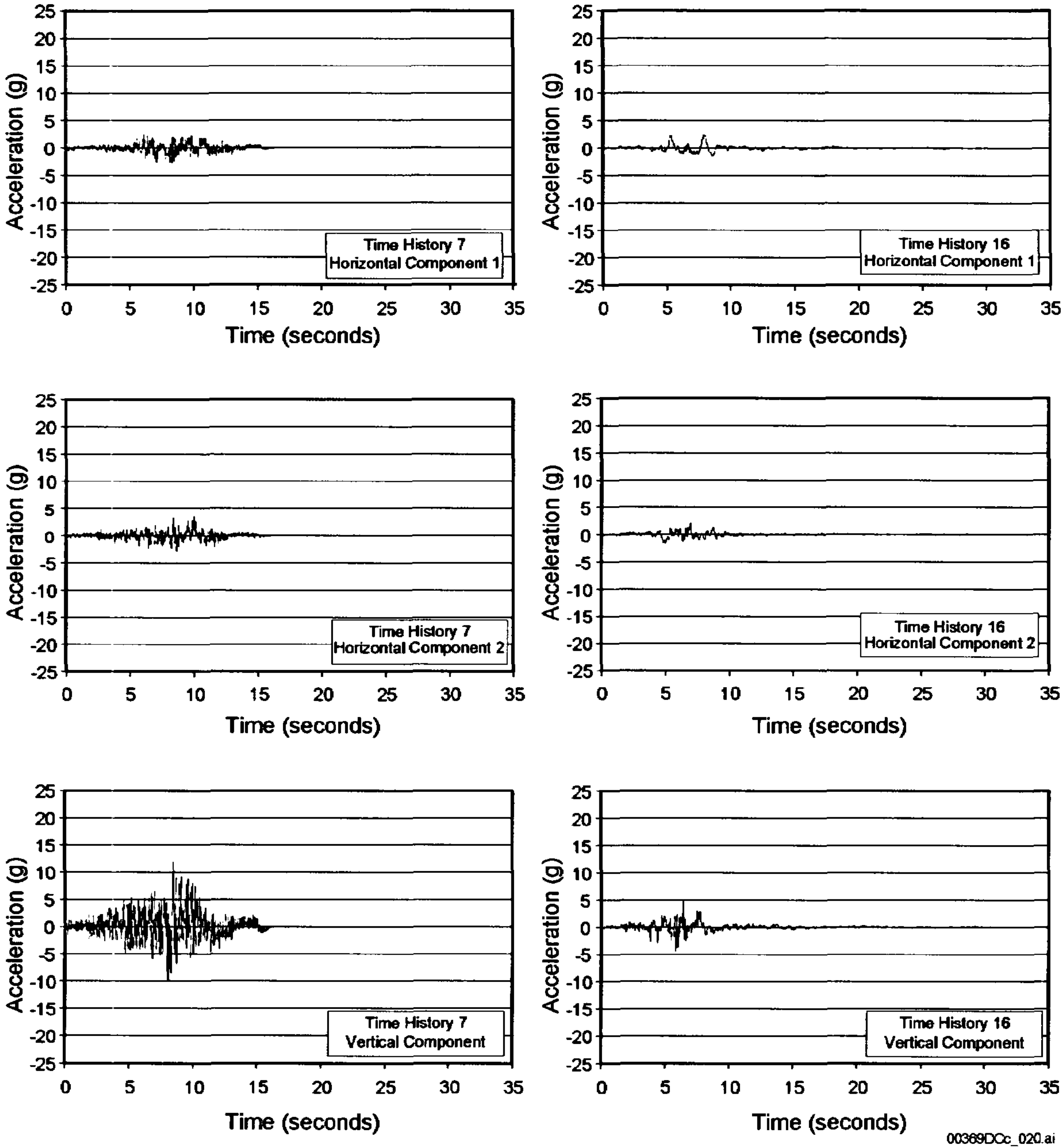
Figure 4-24b. Example Time Histories with an Annual Exceedance Probability of 10^{-7} for the Waste Emplacement Level: Spectrally Conditioned to the Probabilistic Seismic Hazards Analysis Reference Rock Outcrop and Scaled to Peak Ground Velocity



Source: DTN: MO0301TMHSB107.000.

NOTE: Time histories are developed by first spectrally conditioning the strong motion records to weakly match the final response spectrum for the waste emplacement level using a transfer function. The spectrally conditioned strong ground motion is then scaled to match the peak ground velocity for the waste emplacement level, maintaining intercomponent variability.

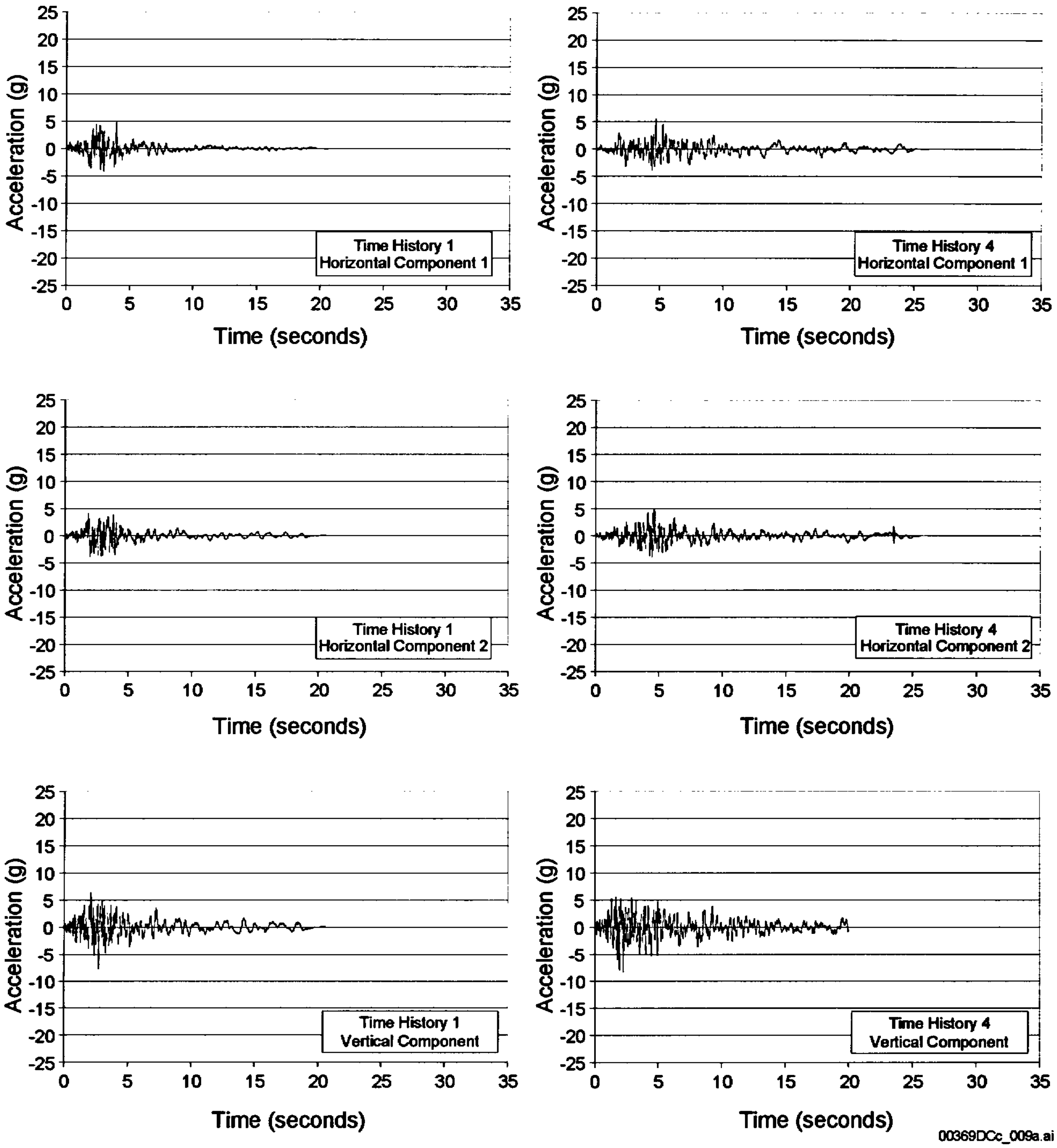
Figure 4-25a. Example Time Histories with an Annual Exceedance Probability of 10^{-7} for the Waste Emplacement Level: Spectrally Conditioned to the Waste Emplacement Level and Scaled to Peak Ground Velocity: Case 1



Source: DTN: MO0301TMHSB107.000.

NOTE: Time histories are developed by first spectrally conditioning the strong motion records to weakly match the final response spectrum for the waste emplacement level using a transfer function. The spectrally conditioned strong ground motion is then scaled to match the peak ground velocity for the waste emplacement level, maintaining intercomponent variability.

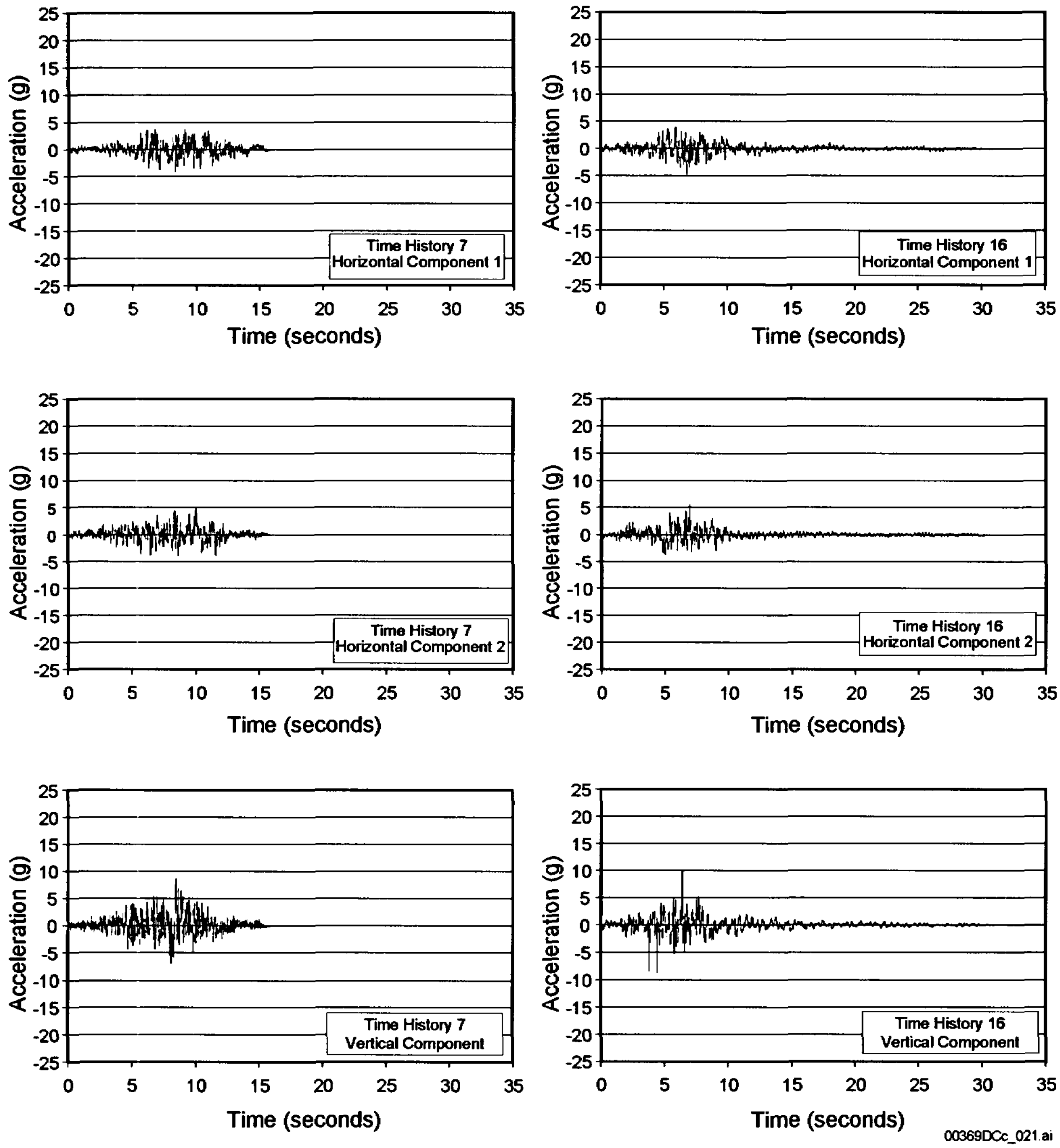
Figure 4-25b. Example Time Histories with an Annual Exceedance Probability of 10^{-7} for the Waste Emplacement Level: Spectrally Conditioned to the Waste Emplacement Level and Scaled to Peak Ground Velocity: Case 1



Source: DTN: MO0301TMHSB107.000.

NOTE: Time histories are developed by first spectrally conditioning the strong motion records to weakly match the envelope of the final response spectrum for the waste emplacement level using a direct match. The spectrally conditioned strong ground motion is then scaled to match the peak ground velocity for the waste emplacement level, maintaining intercomponent variability.

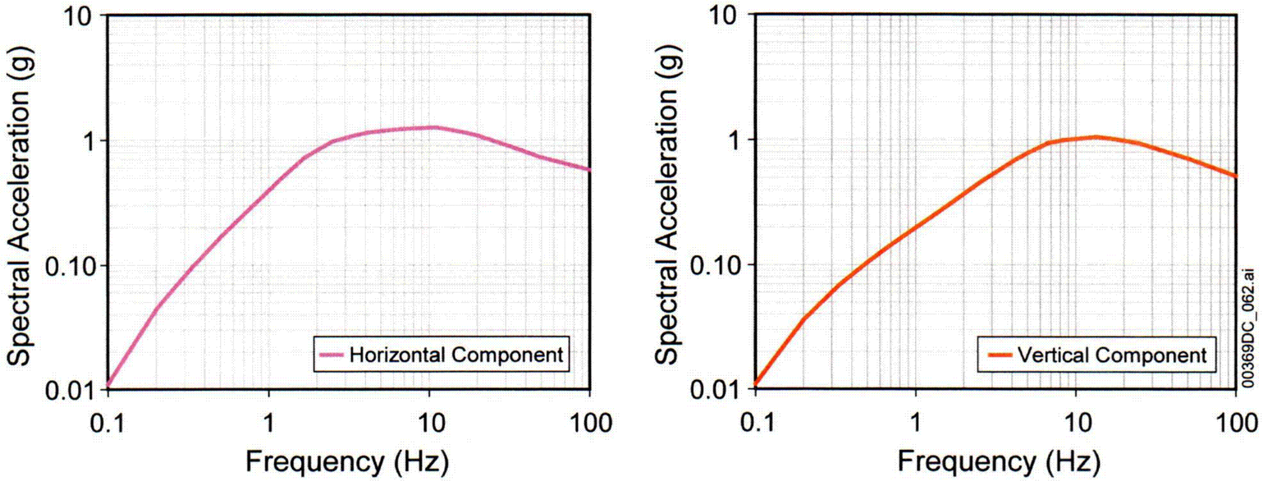
Figure 4-26a. Example Time Histories with an Annual Exceedance Probability of 10^{-7} for the Waste Emplacement Level: Spectrally Conditioned to the Waste Emplacement Level and Scaled to Peak Ground Velocity: Case 2



Source: DTN: MO0301TMHSB107.000.

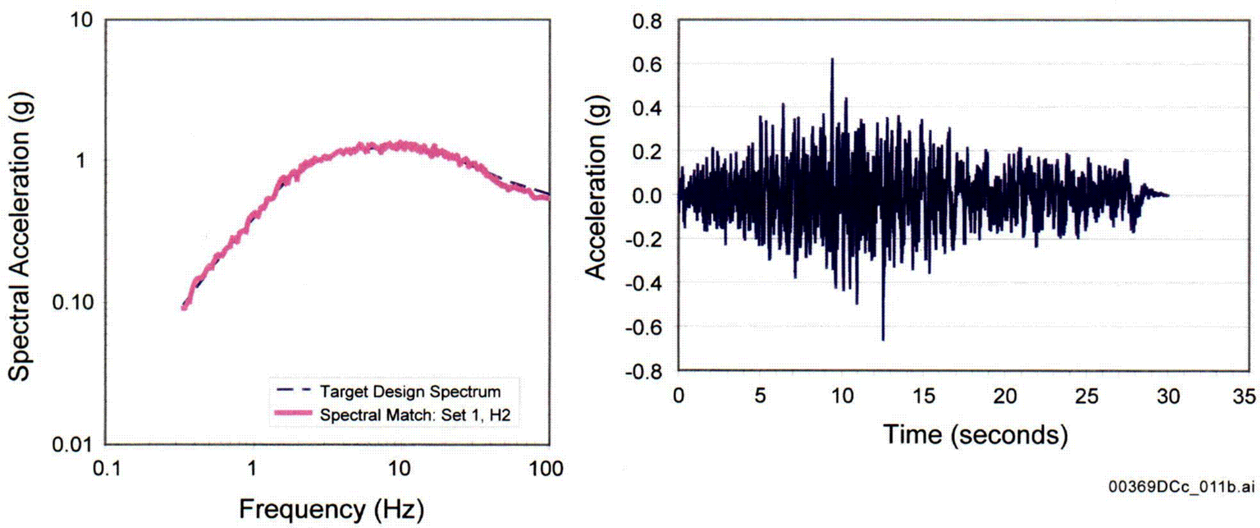
NOTE: Time histories are developed by first spectrally conditioning the strong motion records to weakly match the envelope of the final response spectrum for the waste emplacement level using a direct match. The spectrally conditioned strong ground motion is then scaled to match the peak ground velocity for the waste emplacement level, maintaining intercomponent variability.

Figure 4-26b. Example Time Histories with an Annual Exceedance Probability of 10^{-7} for the Waste Emplacement Level: Spectrally Conditioned to the Waste Emplacement Level and Scaled to Peak Ground Velocity: Case 2



Source: BSC 2004d; DTN: MO0402SDSTMHIS.004.

Figure 4-27. Site-Specific Response Spectra for the Surface Facilities Area with an Annual Exceedance Probability of 5×10^{-4}



Source: BSC 2004d; DTN: MO0402SDSTMHIS.004.

NOTE: On the left, the response spectrum of the example time history is plotted along with the target spectrum showing a successful match.

Figure 4-28. Example Time History (Horizontal Component) and Response Spectrum for an Annual Exceedance Probability of 5×10^{-4} for the Surface Facilities Area

C28

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