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GEOLOGY OF THE HUMBOLDT BAY REGION

WITH SPECIAL REFERENCE TO THE GEOLOGY OF THE HUMBOLDT BAY POWER PLANT SITE AND VICINITY

Prepared for
THE PACIFIC GAS AND ELECTRIC COMPANY

77 BEALE STREET
SAN FRANCISCO, CALIFORNIA 94106

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By

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Geology of the Humboldt Bay Region With Special Reference to the Geology of the Humboldt Bay Power Plant Site and Vicinity

I. Introduction

This report presents the results of an investigation of certain aspects of the geology in the Humboldt Bay region considered relevant to an evaluation of the seismic design of the Humboldt Bay Nuclear Power Plant. The investigation was chiefly concerned with providing additional evidence regarding the pattern and current state of tectonic activity in the structural province encompassed within the southern Eel River basin and its bordering structural zones.

A. Scope

The scope of the investigation was determined by the nature and extent of work necessary to respond to requests by the Atomic Energy Commission (AEC) for additional data, as indicated in discussions between AEC staff and the Pacific Gas and Electric Company. Specific areas to be covered during the investigation were described in a letter from Pacific Gas and Electric Company to the AEC dated September 27, 1973. This scope had been determined following discussions between representatives of the Pacific Gas and Electric Company Engineering and Siting Departments and their consultants, D. H. Hamilton of Earth Sciences Associates, Inc., Dr. G. H. Curtis of the University of California at Berkeley, and Dr. B. A. Ogle. The scope encompassed extensive programs of data acquisition by marine geophysical, drilling, geological mapping, and other means, and integration of those data into a comprehensive report on the geology of the region.

B. Performance

This investigation was carried out by Earth Sciences Associates, Inc. Dr. B. A. Ogle and Dr. G. H. Curtis provided consultation, guidance, and review during all phases of the project. The work was closely coordinated with representatives of the Pacific Gas and Electric Company Siting and Engineering Departments. The firm of Anderson, Wilcoxon, and Associates provided essential consultation in making micropaleontological determinations. The Geo-Marine division of Bolt Beranek and Newman, Inc. performed the sparker and Acoustipulse seismic reflection survey in and adjacent to Humboldt Bay. Additionally, personnel at Humboldt State University, especially Dr. J. C. Young and R. F. Kohl, provided helpful discussions and ideas based on their research in the area.

The project was directed for Earth Sciences Associates, Inc. by D. H. Hamilton, Principal Geologist. P. A. Frame, Project Geologist, was responsible for field mapping, supervision of drilling and related operations, and much of the data preparation.

C. Previous Work

The geology of various parts of the region around Humboldt Bay has been studied and described by MacGinitie (1943), Manning and Ogle (1950), Ogle (1953), Evenson (1959), Irwin (1960), Nason (1968), Silver (1971), and Hoskins and Griffiths (1971). The region encompassed by these studies extends to the continental slope offshore from Point Delgada on the south, to Big Lagoon on the north. These studies resulted in the delineation of the major structural and stratigraphic features of the region, and the elucidation of many of the details of these features. Concurrently, studies of the seismicity of the region were being made by researchers at the Berkeley Seismographic Laboratory and elsewhere. Contributions in this field were published by Byerly (1937), Bolt, Lomnitz, and McEvilly (1968), Seeber, Barazangi, and Nowroozi (1969), and Bolt and Miller (1971).

In the last few years, additional features of the geology and seismicity of the region have been the subject of papers by Griscom (1973), Simila, Peppin, and McEvilly (1973), Rich and Steele (1974), and Kohl (1974). Investigations relating specifically to the geology and seismicity of the Humboldt Bay Nuclear Power Plant were made by Byerly and Quaide (1958), Byerly (1969), Curtis (1969), and most recently, by Curtis and Hamilton (1972). The report by Curtis and Hamilton served as a point of departure for the present investigation.

D. Description of Investigation

Planning of this investigation was started in the latter part of 1973. The general outline of the program of investigation was developed after discussions between Pacific Gas and Electric Company Siting and Engineering Departments, Earth Sciences Associates, Inc., Dr. G. H. Curtis, and Dr. B. A. Ogle. The major features of the program thus developed were:

1. A marine geophysical survey, using acoustic reflection techniques, of Humboldt Bay and the adjacent offshore area.

2. Additional on-land geophysical surveys, chiefly using gravity and seismic refraction techniques, for the purpose of improving definition of the location of the buried Little Salmon and Bay Entrance faults.

3. An extensive drilling program, to provide specific data regarding the location, geometry, and relationship of these faults.

4. A program of geologic mapping in the Van Duzen River - Yager Creek area and lower Mad River area, in order to obtain more data about fault relationships in those areas.

5. A program of mapping and other study of terraces in the region.

6. Study of the stratigraphy and age of the Carlotta and Hookton Formations, and the terrace deposits in the area.

This program was initiated in January 1974 with the marine geophysical survey. This was followed by on-land gravity and seismic refraction surveys in the Buhne Point - Elk River - Humboldt Hill area. Geologic mapping and study of newly available, small (1:130,000) scale false color infrared and intermediate (1:24,000) scale black and white aerial photographs proceeded concurrently. Drilling was started in the Buhne Point area in June 1974, and it continued there and in the Elk River Valley on Humboldt Hill, and at Fields Landing, through March 1975. During this time, twenty-four bore holes were drilled ranging from 139 to 1601 feet in depth and aggregating 13,415 feet. Drilling was done with a Failing 1500 rotary wash boring rig, and core samples were obtained using a Pitcher Barrel sampler. Most of the holes were logged electrically and radiometrically using the Earth Sciences Associates' Widco well logging instrument. The micropaleontology of selected samples was studied by the firm of Anderson, Wilcoxon and Associates. Other samples, obtained during field mapping, were also analyzed by that firm. Two samples of fine grained Hookton Formation material were analyzed for paleomagnetism by Dr. J. C. Liddicoat of the University of California, Santa Cruz. Studying terraces and measuring sections of Hookton Formation and terrace deposits was done concurrently with the drilling work.

Conferences regarding the progress and findings of the investigation were held at intervals with R. L. Blum of Pacific Gas and Electric Company, Dr. Curtis, and Dr. Ogle.

Preparation of this report and supporting data was undertaken following completion of field work in March 1975. The report includes one table and twenty-two figures that present the geologic and geophysical data, and illustrate the geologic relationships determined during this investigation.

II. Conclusions

The major conclusions derived from this investigation are as follows:

1. Regarding the activity of faults in the ground near the Humboldt Bay Power Plant site, the following conclusions are indicated:

a. The Little Salmon - Yager fault is not active or seismically capable. The latest movement along this fault antedated the deposition of the early Pleistocene Upper Carlotta Formation.

b. The Bay Entrance fault and other small faults within a few miles of the plant site, including the Table Bluff, North Spit, and Ryan Creek faults, are probably inactive and not seismically capable.

c. The Freshwater fault is not active. The latest movement along this fault antedated deposition of strata of the Pliocene or late Miocene undifferentiated Wildcat Formation.

2. Faults in the vicinity of the Mad River, especially the Falor and Korbel faults, show evidence of being seismically capable. One of these faults is probably the source of the M 6.5 earthquake of December 21, 1954. Faults in the Mad River zone represent the closest source of relatively large earthquakes that could affect the plant site.

3. Faults in the Cape Mendocino - False Cape region are seismically capable. This region, and the southerly part of a seismically active zone in the offshore region, referred to as the continental slope zone, represent the most likely source areas of large earthquakes that could affect the plant site.

4. The Humboldt Bay Power Plant site is underlain by unfaulted Upper Carlotta Formation strata of early Pleistocene or Plio-Pleistocene age. The nearest

fault to the site, the Bay Entrance fault, is about 2000 feet distant from the plant at its closest point of approach.

5. Some of the results of this investigation have necessitated the modification of conclusions reached earlier on the basis of less complete data. The principal differences between conclusions presented in this report and ones given by Curtis and Hamilton (1972) are as follows:

a. The strata previously mapped as the "Carlotta Formation" at Buhne Point, Humboldt Hill, and Eureka (Ogle, 1953; Curtis and Hamilton, 1972) belong to a younger unit, described herein as the "Upper Carlotta" Formation. This formation, though of early Pleistocene or Plio-Pleistocene age, is younger than the Carlotta originally mapped by Ogle in the Eel River Valley. It post-dates the time of latest movement of the Little Salmon fault.

b. The Little Salmon fault is buried beneath unbroken Upper Carlotta strata, as well as Hookton Formation, under Humboldt Hill. It does not join with the North Spit fault, but instead continues northward under the City of Eureka.

c. The Bay Entrance fault dies out at its northerly end in the vicinity of the entrance to Humboldt Bay rather than extending offshore, and it curves to a southerly trend south of Buhne Point, probably dying out to the south under the Humboldt South Bay. It is younger than the Little Salmon fault.

d. The Freshwater fault was not the source of the 1954 "Freshwater" earthquake, and is not active.

III. Regional Tectonics

A. General Features

The Humboldt Bay region lies in the northerly part of the Coast Ranges along the easterly margin of a large embayment of late Cenozoic age referred to as the Eel River basin. The Coast Ranges and adjacent offshore shelf area here occupy a narrow belt of ground along the continental borderland between the deep-sea Gorda Basin and the Klamath Mountains.

Mapped faults and shear zones, photo lineaments, and major structural trends within this region are shown on Figure 2. Geologic maps of much of the region are presented in Figures 3, 4, and 5. The pattern of Bouguer gravity anomalies in the Humboldt

Bay area is given in Figure 6. Figure 7 shows geologic sections and gravity profiles across the Humboldt Bay - Lower Eel River area. Sparker seismic reflection profiles in Humboldt Bay and in the adjacent offshore area are presented in Figure 8.

The dominant bedrock structural features in this region are the east-west trending Mendocino fracture zone on the south and a series of northwest-trending dip-slip and strike-slip faults along the northeasterly boundary of the Coast Ranges province. The broad downwarp of the Eel River basin exists in the triangular region bordered by these fault zones and by the offshore continental slope. The present-day basin is a remnant of a formerly more extensive basin that once covered much of the region as far east as the border of the Klamath Mountains province.

The major structural patterns of this region can be readily discerned in geological, geophysical, and remote-sensing lineament maps. Three general periods of tectonic activity are represented in these records: 1) mid-Tertiary and earlier faulting and folding, present in the bedrock structure; 2) a Plio-Pleistocene basin-disruption episode of folding and thrust faulting; and 3) the current tectonic regime of west-northwest to east-west aligned shear deformation in the Cape Mendocino area and northwest aligned faulting along the northeast margin of the region. As surface features, the northwesterly lineaments along the Mad River are most prominent, but seismic activity clearly is concentrated along the Mendocino fracture zone and inland along its trend near Cape Mendocino (CDMG, 1972b).

The feature known as the Mattole River fault has been interpreted as the main onshore expression of the Mendocino fracture zone (Jennings, 1973). This fault is mapped from its point of intersection with the coastline south of Cape Mendocino, along a trace that curves to the southeast, as far south as the latitude of Point Delgada. Other similarly trending major shear zones extend through the basement rock terrane north and east of the Mattole River structure as far north as the limit of basement rock exposure south of the Eel River. The most northerly of these shear zones have been described by Ogle (1953) as the False Cape shear zone and the Russ fault. It seems conceivable that more such shear zones may exist in the basement rock buried under the Eel River Valley and, as discussed later in this section, the evidence from recent microearthquake studies in this region seems to suggest this as a likely possibility.

Numerous earthquakes in the magnitude range of 4.5 to 6.0 have been recorded in the Cape Mendocino region (Byerly, 1969; CDMG, 1972b; Smith, 1975). The Magnitude 7.2 earthquake of 1923 is the largest recorded there. The epicenter of that shock is given as $40\frac{1}{2}^{\circ}$N latitude, $124\frac{1}{2}^{\circ}$W longitude, which plots 6 miles west of False Cape on the Continental Slope zone. The relatively modest intensities (VII) reported at Petrolia and Ferndale, located only 15 and 20 miles from this point, however, suggest that the shock may well have occurred farther out to sea, perhaps on the Mendocino fracture zone.

A question that has received attention from several investigators in recent years is the relationship of the San Andreas fault to the continental borderland north of Cape Mendocino. Studies by Nason (1968), Bolt and others (1968), Silver (1971), Hoskins and Griffiths (1971), and Griscom (1973) have special pertinence to this problem.

Nason did reconnaissance mapping in the area between Shelter Cove and the Eel River. He traced several prominent shear zones with curving northwesterly to nearly east-west trends, but he showed, on the basis of continuity of stratigraphic units across its trend, that "The San Andreas fault was not found inland north of Shelter Cove".

Hoskins and Griffiths (1971) mapped the offshore part of the Eel River basin, using seismic reflection and drill hole information. Their map extended offshore to the top of the continental slope, and it showed there to be no intra-basin faulting such as would have to exist if a major break like the San Andreas traversed the mapped area.

Silver (1971) prepared a structure map of a region that extended offshore to the base of the continental slope. His map likewise shows no faults north of the Mendocino fracture zone that could be either the main trace or a major continuous branch of the San Andreas.

Griscom (1973) studied the pattern of magnetic and gravity anomalies in the region around Cape Mendocino. He concluded, in the abstract of his paper entitled "Tectonics at the junction of the San Andreas fault and Mendocino fracture zone from gravity and magnetic data", that ".....an east-west magnetic anomaly associated with the Mendocino Fracture Zone extends from the deep ocean inland at Punta Gorda a distance of 20 km. During the time this anomaly has existed, the San Andreas fault cannot have extended north of Cape Mendocino, and lateral movement between the oceanic and continental plates cannot have taken place near Cape Mendocino....."

From the foregoing, it seems appropriate to conclude that there is no major through-going branch joining the San Andreas as it is known south of Cape Mendocino with any faults in the Eel River basin.

A major structural zone lies along the northeast side of the present-day remnant of the Eel River basin. This northwest-trending zone, referred to herein as the Mad River zone, is featured by several mapped faults and remote-sensing linears, present in an 8 to 12 mile wide belt. The belt extends from the upper Eel River region, northwest to the Trinidad - Patricks Point coastal area. The Falor and Korbel faults are recognized structural features that form important elements of this zone. Recently identified parallel features along the southwesterly margin of the zone include the Fickle Hill fault and the Jacoby Creek lineament.

The Falor fault of the Mad River zone has been mapped south to about the latitude of Cape Mendocino (Ogle, 1953). However, Rich and Steele (1974) have mapped "well defined ERTS linear features" extending an additional 45 miles to the south along the same trend. These define one of a series of en-echelon trends of faults and linear features that extends throughout the Coast Ranges north of the San Francisco Bay region.

Beyond the coastline near and north of Trinidad Head, both Silver (1971) and Hoskins and Griffiths (1971) map faults in the offshore region that lie along this trend. The faults of the Mad River zone often show relative uplift on the northeast side. Several of these faults, including the Fickle Hill fault, are known or inferred to exhibit steeply northeast-dipping reverse movement. Two factors, however, suggest that a significant component of lateral slip may also be involved. The first is the relatively straight trend of some of the more prominent faults and the ERTS and infrared aerial photo linears. The second is the first motion focal plane solution determined by Smith (1974) for a M 3.4 shock that occurred in the vicinity of this belt, which shows northwest-aligned right-lateral shear as the dominant mode. A shock off Trinidad Head reported by Bolt and others (1968) also originated through right-lateral shear.

Some evidence suggests Quaternary movement or deformation in the Mad River zone. A small fault exposed in a road cut between Indianola and Bayside, east of Arcata Bay, and referred to as the Bayside Cutoff fault, seems to displace Quaternary Hookton Formation against Franciscan rock. This fault was previously interpreted as being associated with the Freshwater fault (Curtis and Hamilton, 1972), but detailed mapping during the present investigation has shown that the Freshwater is nearly 2 miles to the southwest. The Bayside Cutoff fault instead is interpreted as being a part of the northwesterly trending Mad River zone.

At College Cove near Trinidad, and within this zone, a small north-trending fault in Franciscan rock also cuts overlying Quaternary Hookton deposits.

The existence of several relatively well defined linear trends within the Mad River zone also could be indicative of Quaternary movements, but no actual surface fault breaks or even terrace breaks have yet been identified. However, as was noted earlier, there is good evidence for associating the December 21, 1954 M 6.5 earthquake with the Falor-Korbel fault system (ESA, 1975).

B. <u>The Eel River Basin</u>

The Eel River basin, as mapped in reconnaissance by Hoskins and Griffiths (1971) extends from the vicinity of the Mattole River, near Cape Mendocino, north into Oregon to about the latitude of Cape Sebastion, for a north-to-south length of approximately 140 miles. It is bordered on the west by the upper edge of the continental slope and on the northeast by a series of faults that extends northwesterly from the Eel River Valley. Remnants of the former Eel River basin are found a few miles east and south of the present basin as fault-bounded slivers of late Tertiary strata. The basin now contains as much as 15,000 feet of late Miocene and younger sediments. In the on-land part of the basin, a maximum of about 10,000 feet of late Tertiary and Quaternary deposits is present in the Eel River syncline. The basin section thins to the northeast, so that it is only about 6000 feet thick near Humboldt Hill (under the Little Salmon fault). Farther north, near Eureka and on the upper plate of the Little Salmon thrust, the Tertiary section is represented by no more than about 1000 feet of Miocene, Pliocene, and Plio-Pleistocene strata.

Structurally, the Eel River basin is a broad synclinorium. The main axial trend of the synclinorium gradually swings from west-northwest at the south to north-south at about the latitude of the Klamath River. Subsidiary folds within the synclinorial structure approximately parallel the main trend. Among the folds that have been recognized in the southerly on-land and near-shore parts of the basin are the Eel River syncline, the Table

Bluff - Tompkins Hill trend of anticlines, and the folds offshore from Humboldt Bay.

The main part of the on-land Eel River basin terminates on the south along the Cape Mendocino structural high. The termination is partly along the Russ fault, but it is chiefly a simple upwarp. This relationship is clearly evident along the north flank of Bear River Ridge, where the entire basin section is exposed in cuesta ridges which rise successively to the basement rock outcrops near the top of the ridge. Farther south, isolated remnants of the Cenozoic basin are preserved in Bear River valley, Mattole River valley, northeast of Weott, and near Garberville.

The northeasterly margin of the basin has been disrupted by faulting and partly overridden by the upper plate of the Little Salmon - Yager fault. This fault originates at depth in the Franciscan bedrock under the northeasterly margin of the basin, and it thrusts a slab of Franciscan and Yager Formation rocks with a capping of Wildcat Group strata, southwesterly over the section in the south-central part of the basin. The thrust dips northeast in the range of 25 to 45 degrees, and it represents as much as two to three miles of net dip slip movement in its central reach. The Yager branch of the Little Salmon seems to offset the trace of the Freshwater fault by about 1½ miles. The near surface part of the Freshwater therefore probably lies within the thrust plate and is detached from its former extension at depth.

East and northeast of the thin wedge of Wildcat strata on the upper plate of the Little Salmon thrust, remnants of the Cenozoic basin section exist only in northwest-aligned slivers along major faults. The most prominent of these are located along the Falor and Korbel faults, but one also exists along the easterly extension of the Yager fault. The slivers represent remnants of the northeasterly margin of the Eel River basin deposits that have been preserved through downfaulting in an area where most of the Cenozoic rocks were removed through uplift and erosion.

C. Seismicity of the Region

There are three principal lines of evidence regarding the seismicity of the region around Humboldt Bay: 1) Historical reports, as in Townley and Allen (1939) and in succeeding bulletins of the Seismological Society of America, and as compiled and summarized by Byerly (1969). Information regarding intensity and distribution of ground shaking is included in this category. 2) Instrumental recording of earthquakes by the world-wide network of seismographic stations, with records for the Humboldt Bay region starting around 1910 (Byerly, 1937; Curtis and Hamilton, 1972; CDMG, 1972b). The accuracy with which events in the region could be located has been improved in steps, beginning with the establishment of the seismograph network in northern California, including the Ferndale Station, in 1933 and 1934. Further improvements came with the installation of seismographs at Arcata in 1948 and Fickle Hill in 1968, as well as with the continuing additions to the USC&GS/NOAA and other networks through the years. 3) Studies of microseismicity in the area by means of local microearthquake recording networks. Two su h studies have been carried out during the last few years (Seeber and others, 1969, S mila and others, 1973); and a third, more extensive and longer term one is now being conducted by Dr. Stewart W. Smith.

The seismicity data yield a reasonably consistent picture, although some confusion has resulted from the rather imprecise instrumental locations of events during past years. In some instances, notably that of the 1954 "Freshwater" earthquake, this has been resolved by careful restudy of the instrumental and historical records.

The pattern of seismicity that now can be discerned is clearly dominated in both frequency and size of events by the belt of activity along the Mendocino fracture zone. This belt is chiefly concentrated near the main trace of the fracture zone, but the recent microearthquake studies clearly show that a diffuse outer zone of microseismicity exists in a band in the deep crust that parallels the fracture zone along its northerly side, and which extends under the bordering False Cape shear zone and Eel River Valley areas. Focal plane solutions of microearthquakes in this band show a predominance of steeply dipping, west-northwest aligned right lateral shearing as the source mechanism (Smith, 1975). This can be interpreted as showing that strain associated with movement along the Mendocino fracture zone or the northerly end of the San Andreas fault is distributed through the bordering deep crustal section to a distance of several miles away from the main fracture zone.

The most recent sizable earthquake to occur in this region was the one of June 7, 1975. The epicenter of this shock was located about $3\frac{1}{2}$ miles southwest of Ferndale, along the Bear River Ridge and near the mapped trace of the Russ fault. Both the main shock and the aftershock sequence were recorded by Smith's local microseismic network, so that very precise information about the event is available. Preliminary determinations available as of July 1975 (Smith,1975) indicate a magnitude of about 5.7, a hypocentral depth of 23.5 km and a left lateral first motion on a plane striking N75E and dipping 72 degrees southeast. Aftershocks continued for about two days, during which time more than thirty were recorded. Three aftershocks had magnitudes between 3.1 and 3.5. The most pronounced concentration of aftershocks was in a 13 mile long zone extending east-northeast and west-southwest from the epicenter of the main shock. The strike of this band corresponds generally to that of the plane indicated by the first motion solution for the main shock. Other aftershocks were apparently randomly distributed in all directions from the main shock, at distances of as much as 20 miles. The aftershocks all had hypocentral depths of between about 20 and 30 km. The earthquake was moderately damaging in parts of the Eel River Valley and Bear River Ridge, and it was felt or slightly damaging at scattered points in the Humboldt South Bay area and in Eureka. No detectable surface movement occurred along the Russ fault, within the False Cape shear zone, or along the Little Salmon fault (ESA, 1975b).

The northeasterly orientation and left lateral first motion of the earthquake source seem anomalous for the region, but they may represent conjugate faulting within a generally west-northwest oriented shear system. The depth of the shocks is consistent with that of the observed deep seismic zone in the region.

A second, northwesterly aligned belt of seismic activity lies along the offshore continental slope. Focal mechanisms of shocks in this belt are characterized by right lateral shear, as determined by Bolt and others (1968) and Seeber and others (1969). No single continuous fault has been identified in this region, and Silver (1971) has proposed that the faults along the continental slope may have originated through deformation of a plate above a subduction zone.

The third zone of seismic activity is much less clearly defined than either of the two zones just described. This zone is associated with the Mad River zone of northwest trending faults along the northeasterly margin of the Coast Ranges province north of the latitude of Cape Mendocino. Seismic activity in this zone is less frequent and seems to involve generally smaller events than in the Mendocino fracture and continental slope zones. However, the Magnitude 6.5 earthquake of December 21, 1954 occurred in the

Mad River zone, and numerous other felt shocks also have originated there. Contrary to earlier views that the 1954 earthquake probably occurred on the Freshwater fault (e.g., Byerly, 1969; Curtis and Hamilton, 1972), it has now been determined that this earthquake occurred on the Falor/Korbel fault system (Cloud, 1975; ESA, 1975a). Focal plane solutions for small earthquakes originating along this zone indicate steep, northwest aligned right lateral shearing as the source mechanism (Bolt and others, 1969; Smith, 1974). This is consistent with the structural trend of mapped faults within the zone.

On the basis of consideration of the tectonic framework of the region around Humboldt Bay and the historical and instrumental records of earthquakes in the region, the following parameters for distances and magnitudes of earthquakes which may be expected to affect the Humboldt Bay Power Plant site may be proposed:

1. 35 miles distance; earthquakes up to 8+ magnitude, occurring on the San Andreas fault south of Cape Mendocino.

2. 20 miles distance; earthquakes up to about 7.5 magnitude, occurring on the Mendocino fracture zone or the continental slope zone.

3. 15 miles distance; earthquakes up to nearly 7.0 magnitude, occurring on the Mad River zone, especially the Falor or Korbel faults.

4. 5 miles distance, 12 miles depth; earthquakes up to about 5.0 magnitude occurring on any of several deep zones of shearing, in the basement rocks underlying the Eel River Valley and adjacent offshore area.

There is no basis for expecting a great earthquake of 8+ magnitude any closer than the San Andreas fault, which is about 35 miles distant.

Geologic evidence, described in detail later in this report, shows the Little Salmon - Yager, and Freshwater faults to be inactive and not capable. No earthquakes need be expected from these faults.

The Bay Entrance fault is probably inactive and not capable, though evidence to demonstrate this according to all three criteria given in Appendix A to 10CFR Part 100 is not available. Nonetheless, the fault has no associated seismicity, geomorphic expression or late Pleistocene offsets, or relationship to a capable fault. In our opinion, it may be considered seismically not capable.

Other small faults in the vicinity, principally the Table Bluff, North Spit, and Ryan Creek faults, are also probably not seismically capable, though specific geologic data to substantiate this opinion are lacking.

A minor fault exposed on the north side of the Table Bluff headland creates about 6 inches of displacement within the capping Hookton Formation. This fault might be classified as capable on the basis of the criteria in Appendix A to 10CFR Part 100. Since it is an obviously minor structural feature, we consider that even if it was seismically capable, it could not generate an earthquake that would give rise to effects as severe as those expected from shocks on more distant, but much larger source structures.

These findings are summarized on Table A.

Table A

Fault	Description	Time of Latest Movement	Relationship to Other Faults	Seismicity	"Capability"	Minimum Distance from Plant
Russ fault-False Cape shear zone/Cape Mendocino shear zone	Northwest to west-trending zones of broken rock to 25 mi. in length	Not known, no documented historic breaks, but could be Holocene or Pleistocene	Onshore continuation of Mendocino fault zone	Source of June 7, 1975 M 5.4 earthquake; 1923 M 7.2 shock on trend offshore, high level of microseismic activity	Capable	16.5 mi (26.4 km)
Little Salmon-Yager	Northwest to north-trending, northeast to east-dipping thrust fault at least 34 mi. long; as much as 10,000 ft. vertical displacement.	Early Pleistocene or Plio-Pleistocene	Apparently offsets the Freshwater fault, is offset locally by the Bay Entrance fault	No historic earthquake, no microseismic activity	Not capable	0.6 mi (1 km)
Table Bluff	Northwest-trending, northeast-dipping, steep reverse fault 8-15 mi. long; about 900 ft. vertical displacement.	Probably early Pleistocene or Plio-Pleistocene	Possible intersection with Little Salmon-Yager	No historic earthquakes; a few microearthquakes at 5-10 km and 18 km depth in the vicinity of the fault (1974-75)	Probably not capable	4.5 mi (7.2 km)
Bay Entrance	North-trending, near vertical reverse fault 4-6 mi. long; about 700 ft. vertical displacement.	Post early Pleistocene, pre-Holocene	Offsets part of Little Salmon-Yager	No historic earthquakes; two microearthquakes at 5-10 km depth in the vicinity of the fault (1974-75)	Indeterminate, but probably not capable.	0.3 mi (0.5 km)
North Spit	North-northwest-trending, near-vertical fault about 6 mi. long; probably small displacement.	Post-Pliocene, indeterminate, but probably at least pre-Holocene	None	No historic earthquakes, no microseismicity	Indeterminate, but probably not capable	4.0 mi (6.4 km)
Falor-Korbel	Northwest-trending normal faults 35-40 mi. long; possibly 1000 ft. of vertical displacement.	Post-Pliocene, probably Pleistocene. Possible local late Pleistocene or Holocene.	Part of system of northwest-trending faults, possibly extending into offshore area near Trinidad Head and Big Lagoon.	Probable source of Dec. 21, 1954 M 6.5 earthquake and five aftershocks, on basis of isoseismals pattern and aftershock distribution; probable source of other earthquakes felt in Eureka; scattered microearthquakes mostly at 20-30 km depth in the vicinity of the faults (1974-75).	Seismically capable	13.8 mi (22.1 km)
Freshwater		Middle Miocene (capped by early Pliocene)	Offset by the Little Salmon-Yager	Several earthquakes of about M 4.5 instrumentally located near the Freshwater; scattered microearthquakes at 20-30 km depth in the vicinity of the fault (1974-75); (1954 Freshwater earthquake probably not on the Freshwater fault; see Falor fault.)	Not capable	8.2 mi (13.1 km)

IV. Stratigraphy

A. General Features

The Humboldt Bay area is underlain by clastic sedimentary rocks of Upper Miocene to Plio-Pleistocene age belonging to the Wildcat Group. These strata overlie Mesozoic sedimentary rocks of the Yager Formation and metamorphic rocks of the Franciscan Formation. Although the late Cenozoic formations are referred to as "bedrock", they mostly consist of compact but generally uncemented gravel, sand, silt, and clay. Only the Mesozoic rocks that crop out around the margins of the Eel River basin are thoroughly lithified. In some areas, however, in the southerly and easterly parts of the basin, sandstone and conglomerate units of the upper Wildcat Group are sufficiently coherent and resistant to erosion to form bold outcrops.

Several Quaternary units, notably the fluvial and marginal marine Hookton Formation, form thin, unconformable blankets on the older bedrock surface. Patchy remnants of stream terrace deposits are present along most rivers in the area and become extensive in the lower Eel River and Mad River Valleys. Marine terrace deposits cover much of the coastal area north of Humboldt Bay. Alluvial deposits are present along most streams, and the bottom and margins of Humboldt Bay are blanketed with fine grained and organic estuarine deposits interfingered with alluvial sand and gravel. Landslide deposits are common throughout the Eel River basin owing to the generally low strength and susceptibility to weathering of virtually all of the fine grained units of the Wildcat Group and younger formations.

B. Pre-Tertiary Rocks

1. Kerr Ranch Schist. The Kerr Ranch schist of Manning and Ogle (1950) is one of several northern California Coast Range metamorphic formations collectively referred to as the South Fork Mountain schist (Irwin, 1960). They are Mesozoic, and probably pre-Franciscan age. The Kerr Ranch schist crops out along northwest-trending belts in the mountainous area north and east of Humboldt Bay where it is faulted against Franciscan rocks. The quartz-mica schists, greenschists, and semischists of this formation were formed through low grade regional metamorphism of clastic sediments, volcanic rocks, and basic and ultrabasic intrusive rocks.

2. Franciscan Formation. Rocks of the Jurassic and Cretaceous

Franciscan Formation are exposed in the mountainous area north and east of Humboldt Bay and form the coastal headlands north of the Mad River. They doubtless extend at depth beneath Humboldt Bay, forming the basement rock of the region (under the Cretaceous Yager Formation). Coastal belt, melange, and metamorphic Franciscan units exist in the area, with coastal belt metagraywackes and metashales being common in the north and melange dominating in the Van Duzen River area, northeast of the Freshwater fault. Exposures are often deeply weathered, with outcrops of relatively fresh rocks limited to canyon bottoms and road cuts.

3. Yager Formation. The Cretaceous Yager Formation crops out mainly in the mountainous area west of the Freshwater fault. The formation has been overlapped unconformably by Cenozoic rocks in the Eel River basin, with the Yager Formation cropping out only in some canyon bottoms and being encountered in wells and exploratory borings on Humboldt Hill, Table Bluff, and Tompkins Hill. The Yager Formation is composed of clastic marine sediments, including conglomerate, sandstone, and shale. The sediments are well indurated and form rocks physically similar to coastal belt Franciscan; in the Van Duzen River area, feldspar age dates of these two formations are also similar (Kelsey, 1975). The Yager Formation is in fault contact with the Franciscan and rests unconformably on it (Ogle, 1953). Although the Franciscan is the true basement under the Eel River basin, the Yager, owing to its hardness and density, serves as the effective geophysical basement. Thus, large contrasts in seismic reflections and in Bouguer gravity and magnetic field values tend to reflect notable discontinuities in the buried surface that forms the interface between the Yager Formation and the overlying Wildcat Group.

C. Wildcat Group

The sequence of clastic sedimentary rocks of upper Miocene through lower Pleistocene age that crops out in the Eel River basin area is referred to as the Wildcat Group by Ogle (1953). He divided the group into five formations in the area southwest of the Little Salmon - Yager fault. Northeast of this fault, he mapped in less detail and differentiated only the uppermost unit, the Carlotta Formation, from the Wildcat Group. He also showed that this undivided Wildcat section thins considerably and represents only part of the section found in the Eel River area. The four lower formations of the Wildcat Group are described briefly, as follows:

1. Pullen Formation. The basal formation of the Wildcat Group is the middle Miocene to lower Pliocene Pullen Formation. Where it crops out on the southern edge of the Eel River basin, the Pullen is a diatomaceous mudstone with glauconitic sandstone and ash interbeds and scattered limestone nodules. A relatively thick basal sandstone is present locally. The Pullen Formation does not have a distinct lithology in the upper plate of the Little Salmon fault and is identified only through micropaleontological age dating. In the vicinity of Humboldt Hill, the formation is encountered only at depth. Core samples characteristically are a dark greenish gray pyritic clayey siltstone containing abundant radiolaria and scattered glauconite, mica, and fine grained sand. The Pullen Formation was deposited in the middle bathyal environment (Anderson, 1975).

2. Eel River Formation. Ogle (1953) named the section of lower Pliocene dark gray-black mudstone, siltstone, and sandstone exposed along the southern flank of the Eel River basin the Eel River Formation. Most of the sandstone and some of the siltstone is glauconitic. A thin but extensive conglomerate forms the base of the formation. To the northeast, in the upper plate of the Little Salmon fault, the Eel River Formation is finer grained and can be distinguished only by micropaleontological age dating. In the vicinity of Humboldt Hill, exploratory borings penetrated middle bathyal to abyssal, dark greenish gray, pyritic, clayey siltstone and claystone, sometimes containing glauconite, mica, or scattered fine grained sand (Anderson, 1975), and with numerous carbonate-cemented concretions. Farther east, similar Eel River Formation rocks crop out in the west fork of Ryan Creek.

3. Rio Dell Formation. Ogle (1953) states that the middle to upper Pliocene Rio Dell Formation is the thickest unit of the Wildcat Group, and has the greatest areal extent. Massive mudstone, alternating thin sandstone and mudstone, phantom-banded mudstone, and very fine grained sandstone are the principal lithologies. The formation in general thins to the north, east, and southeast from the maximum thickness (4720 feet) exposed in the Eel River basin. In the Humboldt Hill area, the Rio Dell is encountered in bore holes beneath the Little Salmon fault and in outcrops in the upper plate near Fields Landing. The formation also crops out farther east in the Ryan Creek area. Identification of the Rio Dell Formation is here based on micropaleontological

study. It is an upper bathyal to abyssal, light gray to medium greenish gray claystone and clayey siltstone containing rare shell fragments and fish debris and common pyrite, glauconite, mica, and fine grained sand layers (Anderson, 1975).

4. Scotia Bluffs Sandstone. Ogle (1953) named the predominantly fine grained sandstone unit exposed in the Eel River basin the Scotia Bluffs Sandstone. The base of this late Pliocene formation is the lowest massive, buff-weathering, fine grained sandstone, and the top is the sandstone immediately below the lowest pebble to cobble conglomerate of the Carlotta Formation. It was named for the bold, steep cliffs on the Eel River near Scotia. The lower part of the formation contains well preserved marine megafossils. Only the Brauner Well has penetrated the Scotia Bluffs sandstone in the Buhne Point vicinity. Here it is a possibly non-marine to brackish water, gray-white, fine grained, massive sandstone with limestone beds of pelecypods.

D. Falor Formation

Rocks of the Falor Formation are exposed in a northwest-trending graben in the Mad River area northeast of Humboldt Bay. These near-shore and continental sediments were named by Manning and Ogle (1950), and are composed of sandstones, clays, and conglomerates. These were deposited on a Franciscan basement and are locally capped by the Hookton Formation. The Falor thins northward from a maximum thickness of about 2500 feet. The shallow marine sediments which generally crop out south of the Mad River contain an abundant fauna and some plant remains. Coal was once mined from a thin layer in these sediments. The formation probably correlates with the Scotia Bluffs sandstone of the Eel River basin. It is early to middle Pliocene in age (Manning and Ogle, 1950). Continental sediments composed of Franciscan and Kerr Ranch schist detritus form the uppermost 200 feet of the formation and are best exposed north of the Mad River. These soft clays, pebbly conglomerates, and silts may correlate with the Carlotta Formation of the Eel River Valley. If so, the minimum age of the Falor Formation may extend into the late Pliocene or early Pleistocene.

Mapping during this investigation has extended the Falor Formation northwest into the Little River area. There the base of the Falor is a 100 foot thick section of dark gray silty clay and clayey silt containing some carbonized plant remains but no foraminifera or shell material. Above this is a 10 to 30 foot thick light brown, coarse grained, pebbly sand, locally grading to conglomerate which is in turn overlain by about 200 feet of fine to medium grained sand with numerous lenses and thin layers of cross-bedded pebbly sand.

E. Carlotta Formation

The predominantly non-marine conglomerate, sandstone, and claystone in the Eel River Valley was named the Carlotta Formation by Ogle (1953). This formation is characterized by a lower 700 to 800 foot thick interval made up largely of massive dirty conglomerate, pebbly sandstone, and friable sandstone. Ogle (1953) observed thin interbeds of volcanic ash at two localities. This interval is overlain by pebble to cobble conglomerate and pebbly sandstone alternating with blue-gray claystones locally containing abundant wood and plant fragments. This claystone-sandstone-conglomerate interval is 950 to 1500 feet thick in the Eel River basin, and it could be overlain by as much as 1000 feet of sandstone and conglomerate.

Dr. G. H. Curtis determined a Potassium-Argon radiometric age date of 2.1 ± 0.25 million years B. P. for a sample of Carlotta Formation vitric ash. The sample was collected by Ogle from an outcrop located southeast of Loleta, along the south flank of Table Bluff. Because of the possibility of some loss of argon from the fine grained ash, this date represents a minimum age for the formation. The 2.1 million years date indicates an early Pleistocene or latest Pliocene age, according to the time scale of Berggren and Van Couvering (1974).

F. Upper Carlotta Formation

Ogle (1953) observed that "all available data indicate that the Carlotta has more shallow marine clay and less conglomerate in the northern part of the area". The northern Carlotta is flat lying to gently dipping, and it caps the Little Salmon - Yager fault, while the type Carlotta of the Eel River Valley is locally steeply dipping or overturned and is overridden by the Little Salmon - Yager fault. Field mapping, geophysical exploration, and test drilling indicate that strata characterized by these differences in lithology and occurrence are widespread in the area surrounding Humboldt Bay. Consequently, in accordance with a proposal made by Ogle (1974), a separate designation of Upper or (Upper) Carlotta Formation has been adopted for this unit.

The Upper Carlotta Formation is exposed at Buhne Point and underlies much of the surrounding area. It crops out in stream valleys that cut through the overlying Hookton Formation as far east as the Freshwater Creek valley. Typically the unit is gently dipping and deposited on an erosional surface of low relief cut across Pullen, Eel River, and Rio Dell sediments. The Upper Carlotta has not been identified overlying Scotia Bluffs Sandstone, although this situation would be difficult to recognize due to similar lithologies in the two units. Maximum thickness of the Upper Carlotta is probably about 2000 feet. The maximum stratigraphic thickness penetrated by drill holes in the Buhne Point area is 1670 feet. From there the formation wedges out to the east and south.

Figure 9 shows the stratigraphy of the Upper Carlotta Formation in the Buhne Point vicinity. There the formation is made up of two units -- an upper interbedded clay and sand unit greater than 730 feet thick, and a lower sand and gravel unit greater than 940 feet thick. The contact between the two units is at the base of the lowermost, thick, gray clay bed. This bed has proven to be relatively extensive and can be followed in test borings, water wells, and outcrops for over 3 miles. Its thickness ranges between 20 and 110 feet, usually being about 40 feet. Other clay beds of the upper unit are less extensive and generally pinch out over short distances. Approximately half of the upper unit is gray, generally silty clay, the remainder being gray to brown silt and fine grained sand. The lower unit, on the other hand, is composed mainly of gray to brown silty and gravelly sand with some gravel lenses and rare thin clay and silt lenses. Lithologies of beds in this unit change markedly over short distances, but some layers can be followed in a general way over distances up to 1 mile. The sands of the lower unit are totally unlithified and create difficult drilling conditions due to caving, bridging, and artesian water pressure.

The Upper Carlotta contains many plant and animal remains. Black, partly carbonized wood chips and small branches are commonly found in both the clays and sands of this formation as are well preserved clam, oyster, and other small shells. This clayey silt and silty clay of the upper unit contains abundant foraminifera as well as diatoms and radiolarians. The foraminifera indicate this unit was deposited during late Pliocene to early Pleistocene time in a shallow marine (neritic to inner neritic) environment (Anderson, 1974-75). Among the Wildcat Group samples analyzed from the Buhne Point area, the following foraminifera were found to be unique to the Upper Carlotta Formation.

Ammonia beccarii var.

Buccella depressa

Buccella frigida

Buccella tenerrima

Bulimina cf. marginata

Buliminella curta

Buliminella cf subfusiformis

Buliminella aff. tenuate

Cassidulina cf. crassa

Discorbis sp.

Elphidiella hannai

Elphidium sp.

Hopkinsina magnifica

Nodogenerina aff. lepidula

Nonionella cf. basispinata

Valvulineria aff. araucana

G. Hookton Formation

The middle or late Pleistocene deposits of yellow-orange to yellow-brown sand, pebbly sand, and silty sand that make up the Hookton Formation cap widespread areas from Big Lagoon south to Centerville beach. The Hookton overlies the lower part of an erosion surface cut across the folded and locally faulted strata of the Wildcat Group and the Yager and Franciscan Formations. Probably the highest exposure of Hookton sediments is in the Ridgewood Heights and Fickle Hill areas at a present elevation of 1200 feet. Hookton deposits are most extensive north of Table Bluff owing to the relative increase of topographically low land surfaces in that area. North of the Eel River Valley, no more than 100 feet of Hookton sediments crop out in an exposure, although Ogle (1953) describes a 420 foot section at Centerville beach.

Hookton beds are usually flat to gently dipping and tend to parallel the attitude of the surface they were deposited on. This could result either from depositional characteristics of the beds or from gentle folding along earlier established structural trends. The Hookton was probably deposited in a flood plain, fan, or marginal marine environment.

Hookton sand layers are generally discontinuous and thin, ranging from 1 to 5 feet thick. The gravelly sands are usually cross bedded. Because of lithologic similarities, the Hookton and the lower unit of the Upper Carlotta Formation are easily confused and usually must be viewed on a scale greater than outcrop level to distinguish the two.

Only at Table Bluff and in a road cut along Broadway Street in Eureka were clay lenses found in the Hookton Formation. These silty and sandy clays were found to be barren of foraminifera, in contrast to the clay in the Upper Carlotta Formation, but they did contain diatoms and radiolarians (Anderson, 1974). Both clays record normal geomagnetic field directions, and they probably are less than 700,000 years old (Liddicoat, 1974).

At Crannell Junction near the mouth of Little River, typical Hookton sediments conformably overlie gray, fossiliferous clayey sands. Kohl (1974) determined these sands to be Late Pleistocene (Rancholabrean) age. Because of their youthful age and conformable contact with typical Hookton sediments, the gray sands are likely to be a marine facies of the Hookton Formation.

H. Terrace Deposits

Both alluvial and marine terrace deposits exist in the Humboldt Bay area. The two are usually easy to distinguish, based on location (alluvial terraces border streams and marine terraces are developed at coastal margins) and composition. The criteria become uncertain at the mouths of large streams where flood plain material interfingers with shore line deposits.

Alluvial terrace deposits are composed of generally light gray silt to boulder-size material often in vague, irregularly stratified layers. The deposits reflect the lithology upstream. The occurrence of soft, Wildcat Group boulders to 1 foot in diameter suggests that these sediments were not transported far before deposition. Alluvial terrace deposits are most extensive in the lower Eel River drainage.

Marine terrace deposits form isolated patches of flat-lying yellow to orange-brown, thinly bedded sand and gravelly sand. The deposits are similar in age, lithology, and occurrence to parts of the Hookton Formation, and they are probably largely reworked from it.

I. Bay Fill Deposits

Bay fill is deposited in much of the low area (less than about 10 feet elevation) surrounding and under Humboldt Bay. The thickest section of these late Pleistocene or Holocene deposits explored by drilling is about 100 feet. The deposits are composed of irregular, commonly discontinuous beds of clay, silt, and sand which generally interfinger with alluvial sand and gravel near the old bay margins. The sediments are gray, normally consolidated, and often have a sulfurous odor. Shell fragments and plant materials are common. A few diatoms and radiolaria and rare foraminifera are present, but none are age diagnostic (Anderson, 1974).

V. Structure

A. General Features

As described previously, the Humboldt Bay area lies near the southeasterly end of the Eel River basin synclinorium. The principal structural features within this part of the basin are the Eel River syncline and the lesser folds that border it on the north, and the Little Salmon - Yager system of thrust faults. The major structural features in the basement rock terranes adjacent to the Eel River basin are the Cape Mendocino shear zone in the ground south of the Eel River Valley, and the Mad River system of faults in the ground lying north and east of the basin (Figure 1).

B. Folds

The Eel River basin is characterized generally by relatively broad, open folds. In some places, however, steep and even overturned asymmetric folds are superimposed on the broader regional folds. Hoskins and Griffiths (1971, p. 275), speaking of the basin in general, mention that "Locally there is some suggestion of shale flowage and diapirism". Previously Ogle (1953, Plate II) presented sections showing the strata in the ground between and adjacent to the Yager and Little Salmon faults folded into an overturned isoclinal syncline. Additionally, the sparker seismic reflection surveying done in connection with the present investigation has shown the North Spit anticline to be a relatively sharp asymmetric fold that is locally breached by faulting (Figure 8). Most fold structures in both the offshore and onshore areas, however, are broad and open. This is seen in the low amplitude synclines that lie opposite Humboldt South Bay and Arcata Bay, flanking the North Spit anticline, and in the offshore Table Bluff anticline (all shown in Figure 8), and in the prevailing shallow dips measured inland.

All of the larger folds that exist in the southeasterly end of the Eel River basin have east-west to west-northwesterly trends. Going north from the Eel River Valley to Trinidad Head, the basin contains the following folds: Eel River syncline, Table Bluff anticline, South Bay syncline, North Spit anticline, Arcata Bay syncline, and Trinidad anticline. The smaller Bay Entrance anticline, Buhne Point syncline, and Humboldt Hill anticline lie in the zone of inflection between the South Bay syncline and the North Spit anticline, in the ground just west of and partly including the Little Salmon fault. These features are shown on Figures 3, 5, and 14.

C. Faults

Faults mapped between the Eel River Valley and the Mad River include the Little Salmon - Yager, Table Bluff, Bay Entrance, North Spit, Freshwater, Fickle Hill, Falor, and Korbel faults. Smaller faults have been identified south of Fields Landing, on the north side of Table Bluff, on the Bayside cutoff road north of Eureka, along Ryan Creek east of Eureka, and at College Cove north of Trinidad. Prominent lineaments that may be associated with faulting also exist along Jacoby Creek and on the Falor-Korbel trend. The faults are described as follows:

1. Little Salmon - Yager Fault System

The Little Salmon and Yager faults are parts of a northeast to east-dipping thrust that can be traced from the vicinity of Bridgeville on the Van Duzen River to the Elk River south of Eureka. The fault probably continues north at least to Arcata Bay. Other names used to identify this fault system include the Yager (for the entire system) and the Van Duzen; however, the name "Little Salmon" is published (Ogle, 1953) and is preferred here. As originally mapped by Ogle, the fault system bifurcated going southeast from the vicinity of Wolverton Creek, southeast of Fortuna, with the more northerly branch continuing as the Yager fault. Recently, however, Ogle (1975) has suggested that the Yager and Little Salmon are probably a single fault with the southerly branch being a separate reverse fault. The trace of the Little Salmon - Yager fault system is shown on Figures 3 and 4.

The Little Salmon thrust has been described by Ogle (1953) and Curtis and Hamilton (1972). Work done in connection with the present investigation was directed toward resolving several questions regarding the Little Salmon, especially the following:

1. Time of latest movement.
2. Position under Humboldt Hill and near Buhne Point.
3. Location of extension north of Humboldt Hill.
4. Relationship to the Freshwater fault.
5. Relationship to the Bay Entrance fault.
6. Relationship to the Table Bluff fault.

The information necessary to establish these relationships was obtained by extensive programs of field mapping, offshore seismic reflection surveying, and drilling, supplemented by gravity surveying, seismic refraction surveying, micropaleontological study, and electrical and radiometric bore hole logging.

In the Van Duzen River area, the Yager fault juxtaposes Cretaceous Yager Formation against Pliocene Wildcat Group rocks as far east as the Redwood House Road (Section 34 T.1N., R.2E.). Southeast of this point, the existence of the fault is inferred from the apparent offset of the Freshwater fault along the projected trend of the Yager and, still farther southeast, from the presence of isolated, fault-bounded slivers of Wildcat-type rocks in the Franciscan terrane.

The fault branch mapped by Ogle as the Little Salmon, extending southeast from Wolverton Creek, apparently rejoins the Yager at a point 8 miles farther to the southeast.

In the area between the Cooper Mill Creek fork of Yager Creek and Tompkins Hill, Scotia Bluffs sandstone is thrust over Carlotta Formation conglomerate along the Little Salmon fault. A new logging road cut located just northeast of Newberg, on Strong's Creek, exposes the fault plane. There it is represented by a 2 foot thick zone of clay gouge separating the two formations. The fault strike N11W and dips 30 degrees northeast at this point.

No good exposures of the Little Salmon fault have been located north of the one just described. The fault trace can be followed across Tompkins Hill ridge and into Little Salmon Creek by mapping the juxtaposition of undifferentiated Wildcat against Carlotta. Several gas wells in the Tompkins Hill field penetrate the fault and produce from the part of the Tompkins Hill anticline that has been overridden by its upper plate. Projections between the mapped surface trace and the well intercepts show that the fault dips from about 30 to 45 degrees northeast in this area. It is reported that the fault has not caused any casing problems or well deformation in the forty years that this field has been operated.

North of Little Salmon Creek, the Little Salmon fault has been mapped as extending along the westerly base of Humboldt Hill, although its exact location was never determined. Drilling information from the vicinity of Humboldt Hill obtained by Standard Oil Company of California and also during the present investigation confirms the location of the fault there. This information further shows that the fault curves to the northeast under the northerly end of the Humboldt Hill ridge, approximately as shown by Curtis and Hamilton (1972). Twenty-four exploratory borings were made during the 1974-75 investigation; of these, ten bottomed in or above the upper plate, of the fault, thirteen were in or over the lower plate, and one, RD-19, passed from the upper plate, through the fault, and bottomed in the lower plate. All stratigraphic identifications from the borings were confirmed by micropaleontological dating of bore hole samples. The details of geologic relationships in the Humboldt Hill - Fields Landing - Buhne Point area are described in Section VII Part C of this report.

The bore hole information from Humboldt Hill demonstrates that the Little Salmon fault line is there capped by unbroken strata of the early Pleistocene or Plio-Pleistocene Upper Carlotta Formation (described in Section IV of this report). Apparently the fault line between Little Salmon Creek and Humboldt Hill is also capped by Upper Carlotta deposits. Also, the part of the fault under the leading edge of the thrust plate is offset by the younger Bay Entrance fault near Fields Landing. This indicates an early Pleistocene or Plio-Pleistocene time of last movement of the Little Salmon fault. North of Humboldt Hill, a seismic refraction survey indicates that the Little Salmon fault line is buried beneath more than 1000 feet of Hookton and Upper Carlotta deposits. Its position is constrained to lie between undifferentiated Wildcat of the upper plate, which crops out in Ryan Creek and can be followed farther west in water wells in the City of Eureka, and the channel between Humboldt Bay and Arcata Bay, where the stratigraphic section and structural features of the lower plate offshore basin are present. The interpretation that the Little Salmon fault might curve northwestward to join the North Spit fault, presented by Curtis and Hamilton in 1972, has been shown to be invalid by the results of offshore seismic reflection surveys. The reflection data show, instead, that the basin section continues in the offshore as far north as the basement outcrop at Trinidad Head, and that nothing corresponding to either the fault or the upper plate structure is present near the North Spit faulted anticline. The Bouguer gravity pattern east of Arcata Bay (Figure 6) suggests that the offshore Arcata syncline extends under the bay, nearly to the Franciscan rock outcrop north of Indianola. This in turn suggests that the fault, if it persists this far north, must lie beneath the easterly margin of Arcata Bay.

2. Table Bluff Fault

The Table Bluff fault is mapped solely on the basis of repeated Wildcat sections in deep wells on Table Bluff, and deep seismic reflection data. Ogle (1975) has compiled data that show the fault to dip about 80 degrees north, and to cause about 900 feet of vertical stratigraphic separation on a horizon at about 2000 feet depth. Hoskins and Griffiths (1971) show the fault as extending about 9 miles west of the shore line on their "Base Miocene" map. Their mapped datum is about 5000 feet deep in the vicinity of the fault. The Table Bluff fault does not offset the Hookton or Carlotta strata that underlie the surface of Table Bluff. Offshore BBN sparker seismic reflection line 26 (Figure 8) does not definitely show a fault in the area of its near surface projection. Although this record is not clear enough to preclude the presence of at least a small fault, it does show that there is no gross offset or disturbance of the anticlinal structure in the uppermost thousand feet.

The southeasterly projection of the buried Table Bluff fault trends toward the trace of the Little Salmon fault near Little Salmon Creek (Figure 3). Both faults dip north or northeast, although the Little Salmon is a shallow thrust, dipping about 30 degrees, while the Table Bluff is a steep reverse fault dipping about 80 degrees (Figure 7). Both faults cut the Pliocene, but not the Plio-Pleistocene section. Their geometric relationship suggests that the Table Bluff fault, if it extends as far east as Little Salmon Creek, is overridden by the Little Salmon fault, rather than branching from it.

3. Bay Entrance Fault

The Bay Entrance fault was identified by Curtis and Hamilton (1972) on the basis of a stratigraphic anomaly between bore holes and on sparker seismic reflection, magnetic, and gravity anomalies. The fault was interpreted as extending from the offshore area, under the Bay Entrance and Buhne Point, and into the ground under Humboldt

Hill and thence under the Little Salmon fault.

Data from extensive sparker seismic reflection surveying in and offshore from Humboldt Bay, and numerous drill holes in the Buhne Point, Fields Landing, and Humboldt Hill areas, now accurately locate this fault. These data show that the Bay Entrance fault was correctly mapped under Buhne Point and the adjacent part of Humboldt Bay. To the west, however, the fault dies out under the central part of the Bay Entrance channel. It does not extend into the offshore area, as confirmed by its absence in five sparker lines across its projected trend.

Drill hole data now show that the Bay Entrance fault curves to the south under Buhne Point, and extends under Fields Landing and into the ground under Humboldt South Bay. It cannot be followed far south of Fields Landing, and it has not been recognized in the subsurface under Tompkins Hill, toward which it trends. It seems probable that it dies out in the South Bay vicinity.

From its northern termination at the Bay Entrance to its probable southern termination under the South Bay, the Bay Entrance fault is 4 to 6 miles long. Correlation of the lower marker claystone bed in the Upper Carlotta Formation across the fault indicates about 700 feet of northeast-side-up vertical separation at Buhne Point (between Borings RD-12 and RD-22) and at Fields Landing (between the freeway road cut and the Vita-Sea water well). The fault is associated with an anticlinal fold, and is vertical or dips steeply north or nc ast, where seen in sparker seismic reflection profiles (Figure 8). The steep dip is further confirmed by its absence in relatively deep bore holes drilled on its hanging wall side.

The Bay Entrance fault is interpreted as offsetting part of the leading edge of the Little Salmon thrust plate, near Fields Landing, as shown in Section J-K, Figure 19. The relationship of the Bay Entrance fault to the Little Salmon is that of a younger, high angle, reverse fault that chiefly exists in the Little Salmon footwall ground. Geometrical relationships preclude the Bay Entrance from having a branching relationship to the Little Salmon; the Little Salmon dips east-northeast at about 30 degrees, while the Bay Entrance is vertical or dips steeply north and east in the ground west of the Little Salmon fault line. It therefore diverges from the Little Salmon with increasing depth.

The Bay Entrance fault offsets the early Pleistocene or Plio-Pleistocene Upper

Carlotta, but it apparently does not disturb the basal contact of the surficial bay fill deposits of late Pleistocene or Holocene age. It does not exhibit any characteristics suggestive of an active fault, but it is not situated so as to permit determination of its age relative to Hookton Formation or terrace deposits.

4. North Spit Fault

The North Spit fault and anticline was first shown on a map published by Silver (1971). Subsequently Curtis and Hamilton (1972) interpreted this fault as probably representing the northerly continuation of the Little Salmon fault. The extensive sparker seismic reflection survey data obtained during the present investigation, however, conclusively show the North Spit anticline and fault to be an isolated structure, which is definitely not connected to the Little Salmon fault.

The North Spit fault anticline is located under and offshore from the Humboldt Bay north spit (or Samoa Peninsula), west of the City of Eureka. The structure strikes about N25W, and extends 7 miles along strike beyond the shore line (Figure 3). The fault dies out about 1 mile from shore, but the anticlinal fold curves to a more easterly trend, and continues at least as far east as the City of Eureka water front. This structure may well be the target of a proposed petroleum exploration well to be drilled by Standard of California on the North Spit (Munger Oilogram, 1975).

As seen in sparker seismic reflection profile (Figure 8), the North Spit fault dips steeply or vertically, and breaches the north flank of the associated anticline. The amount of displacement is not known but probably is not large since 1) similar-appearing sections exist both north and south of the fold at comparable depths; 2) the fault has a total length of only about 6 miles; and 3) no fault is shown on the Hoskins and Griffiths (1971) "Base Miocene" structure map. The latter point may indicate that the fault dies out at a depth of less than 5000 feet, as well as along strike.

The North Spit fault is in Pliocene rocks that underlie the sea floor, so it can be dated only as post-Pliocene in age. It has no direct structural relationship to any other fault, and no associated historical seismicity or microseismicity.

5. Freshwater Fault

The Freshwater fault has been mapped from an area near the Eel River at about the latitude of Punta Gorda, northwest for 38 miles to the upper reach of Freshwater

Creek, southeast of Eureka (Ogle, 1953) (Figures 3 and 4). Throughout this distance, the fault forms the boundary between the Yager Formation on the southwest, and the Franciscan on the northeast. Although Ogle mapped the Freshwater as being buried beneath undifferentiated Wildcat strata, Curtis and Hamilton (1972) concluded that it was probably active. The principal bases for this conclusion were 1) Byerly's (1969) opinion that the Freshwater was the likely source of the December 21, 1954 earthquake; and 2) the interpretation that the Bayside Cutoff fault exposure, which shows evidence of Quaternary displacement, was part of the Freshwater. Evidence gathered during the present investigation and review of data with Ogle, however, shows that Ogle's original interpretation was correct and the fault has been inactive since Pliocene or earlier time.

Evidence regarding the tectonic status of the Freshwater fault is as follows:

1) The trace of the Freshwater appears to be displaced about 1.5 to 2 miles left laterally by the Yager fault, near the Van Duzen River. The latest movement along the Little Salmon - Yager system was during Plio-Pleistocene time.

2) Ogle (1975) has made a detailed review of his field mapping data, and has commented on the significance of his (1953, p 39-40) description of the accumulation of Franciscan boulders in the undifferentiated Wildcat sediment on the Doe Creek tributary of the north fork of the Elk River. He points out that the boulders may well have been derived from a fault line scarp along or northeast of the Freshwater fault, in late Miocene or early Pliocene time, but that the fault itself is definitely overlain by unfaulted Wildcat strata.

3) Mapping in the Freshwater Creek area shows that all "basement" rock exposed there is Franciscan; hence, the Freshwater fault must be concealed under alluvium and Wildcat Formation southwest of the Franciscan exposures.

4) The rock along the south side of the Bayside Cutoff fault is Franciscan, so this fault is northeast of the Freshwater fault, and is probably related to the Jacoby Creek lineament or other northwest-trending faults lying farther to the northeast.

5) Sparker seismic reflection lines in the offshore area cross the projected trend of the Freshwater, but show an unbroken section of Wildcat strata (Figure 8).

6) Relocation of the epicenter, as well as the distribution of aftershocks and isoseismals of the December 21, 1954 earthquake, indicates that the earthquake probably

originated along the Falor-Korbel fault system rather than on the Freshwater fault.

From the foregoing, it is evident that the Freshwater fault is an old structural feature in the bedrock, which has not moved since prior to the beginning of sedimentation in the Eel River basin, during late Miocene or early Pliocene time.

6. Fickle Hill Fault

The Fickle Hill fault was first mapped by Young (1972) and shown on maps prepared by Curtis and Hamilton (1972). It is a northwest-trending north-dipping reverse fault that juxtaposes Franciscan against undifferentiated Wildcat along the southwest slope of Fickle Hill (Figure 3). The fault has been traced 4 miles. It is covered by Hookton Formation at its northerly end.

7. Falor-Korbel Fault System

The Falor-Korbel fault system is a series of northwest-trending normal faults offset by secondary northeast-trending cross faults. This system extends 40 to 50 miles from the Van Duzen River area in the southeast to the Trinidad area in the northwest (Figures 4 and 5). It may continue beyond as much as 30 miles offshore if it joins with faults mapped in the offshore by Silver (1971) and Hoskins and Griffiths (1971). Manning and Ogle (1950) first identified the faults of this system where they cross the southwest quarter of the Blue Lake quadrangle. There the Korbel, Crawford, Blue Lake, and Falor, and numerous cross faults, border downdropped blocks of the Tertiary Falor Formation. Subsequent mapping by Ogle (1975) traced the Falor fault southeast 18 miles beyond the Blue Lake quadrangle to the Van Duzen River area. Field and air photo mapping during the present investigation has shown that the Korbel fault extends northwest of the Blue Lake quadrangle through the Fieldbrook valley to Little River. There it seems to connect with a fault shown in the Franciscan Formation by Strand (1964). Other secondary faults between Falor and Franciscan rocks were also mapped in this area.

Normal faulting of the Falor-Korbel system began at the end of the Pliocene (Manning and Ogle, 1950) and probably has continued through middle or late Pleistocene time. The amount of dip-slip movement on these normal faults is unknown, but may possibly be on the order of 1000 feet. The cross faults, which offset the normal faults with as much as 2000 feet of strike-slip movement in the Blue Lake quadrangle, are probably of Pleistocene age (Manning and Ogle, 1950). One probable cross fault located northwest of

Trinidad at the south end of College Cove exhibits about 1 foot of vertical offset of the middle or late Pleistocene Hookton Formation.

VI. Landforms

A. General Features

The general features of landforms in the Humboldt Bay - Eel River Valley region are the bay and associated bars, channels and flats, the drowned lower valley floors and coastal plain, the various higher terrace erosion surfaces, the dissected uplands, and the surrounding highlands. These features have been described by Ogle (1953) and more recently by Curtis and Hamilton (1972). Studies of landforms carried out in connection with the present investigation have focused on three types of features: 1) lineaments that could be associated with faults; 2) terrace surfaces, especially terraces of marine origin; and 3) large scale landslide features.

Information regarding photo lineaments is presented in Figure 2, Fault and Lineament Map. Lineaments interpreted to have possible significance with regard to fault activity were observed only as long northwest-trending features, and as conjugate sets of shorter lineaments thought to possibly represent related cross faults within the Mad River zone of northwest-trending faults. The large scale landslides were identified along the southwest flank of Humboldt Hill. They are discussed in Section VII, part D. Terrace surfaces are discussed as follows:

B. Terrace Surfaces

Terrace surfaces and terrace-like landforms have been mapped in the region between Big Lagoon, north of Trinidad, and False Cape, south of the Eel River. Within this region there are four clearly defined marine terrace surfaces which are best preserved in the coastal area between the Mad River and Big Lagoon, and numerous levels of stream-cut terraces. Significant expanses of terrace-like surfaces are also present at Eureka, Humboldt Hill, Table Bluff, and near Fortuna. These features are delineated on the Terrace Map, Figure 10, and topographic profiles are shown on Figures 11, 12, and 13.

The marine terrace surfaces in the Mad River - Big Lagoon area are considered to represent the standard against which other surfaces in the region may be compared. The four main surfaces there have approximate shoreline angle elevations of 140, 280, 400 to 480, and 600 to 800 feet. Each of these surfaces is cut across Franciscan and Hookton Formation with Franciscan bedrock cropping out locally as ancient sea stacks and forming the lower part of the backscarp slopes. The surfaces are locally thinly mantled with terrace deposits composed chiefly of reworked Hookton material. These terrace deposits are non-distinctive, and cannot be used for correlation between terraces. As shown on the longitudinal section, Figure 11, the upper three surfaces are broadly warped into an arch with a maximum amplitude of about 200 feet in a distance of $3\frac{1}{2}$ miles.

Although the successive terraces present a definitely stepped aspect in some places, elsewhere they seem to merge, especially where the interterrace slope is underlain mostly by Hookton, and has been altered by erosion and deposition.

No means of positively dating any of these surfaces has been found; however, the basal marine facies of the Hookton Formation, into which the 280 foot terrace is cut, has been determined as Rancholabrean in age (up to about 600,000 years) by Kohl (1974). By comparison with terraces of similar elevation farther south that have been dated (e.g., Lajoie and others, 1975), the Trinidad terrace sequence might be expected to range in age from about 100,000 years for the lowest, to about 500,000 years, for the highest.

The terrace-like surface at Eureka ranges from about 30 feet to more than 500 feet in elevation and is eroded across deposits of the Hookton Formation. No distinctive terrace deposits have been identified on this surface. The most extensive part of the surface underlies the main part of the city, below an elevation of about 160 feet. The higher part of the surface, ranging from 200 to over 500 feet in elevation, mostly lies south of the valley of Martin Slough. There is no well defined break in slope between the areas of the two surfaces, although there is a suggestion of a steeper interterrace slope at about 160 to 200 feet elevation, near Cutten in the SE$\frac{1}{4}$ of Section 35 T5N, R1W. Above about 500 feet elevation, erosion has progressed to the point where the canyon sidewalls meet at the crests of intervening ridges, and no flat ridge-line remnants of upland surfaces are left. The terrain of dissected ridges and canyons that remains defines a basin-like area east of Eureka that is bordered by higher mountain areas south and east of the Elk River drainage and northeast of Freshwater Creek.

South of the Elk River, on the north end of Humboldt Hill, remnants of terrace-like surfaces are present up to about 160 feet elevation and from about 300 to 600 feet elevation. These surfaces likewise are developed on Hookton Formation.

On the Table Bluff - Tompkins Hill ridge, a broad upland surface rises gradually from about 150 feet elevation at the coast to over 600 feet elevation at Tompkins Hill. This surface continues to the southeast, along the north side of the Eel River Valley, as partly dissected uplands lying north and east of Fortuna, and north of Hydesville. These uplands were described as the Hookton terrace by Ogle (1953, p. 71). This surface is mostly underlain by Hookton Formation, though it is possible that the section of friable sand present at the west end of Table Bluff may represent a younger terrace deposit.

None of the surfaces of the Eureka, Humboldt Hill, Table Bluff, or Fortuna-Hydesville areas have notably similar morphology, and none has the clearly stepped aspect of the Trinidad terrace sequence. On the other hand, the surfaces of all five areas occupy about the same range of elevations, and all are at least partly underlain by Hookton Formation. The Trinidad terraces are partly underlain by resistant Franciscan bedrock, while the other surfaces are all in a terrane of soft sedimentary rocks of the Wildcat Group and contain well developed internal stream drainage systems.

The parts of the surface at Table Bluff, Tompkins Hill and points south have clearly been deformed by broad folding, as described by Ogle (1953, p. 71). Evidence of folding is not as readily apparent in the Humboldt Hill and Eureka areas. Continued warping along older fold axes in that area is suggested by the correspondence between the location of upland and lowland areas with anticlines and synclines, respectively, as observed in the offshore sparker seismic reflection records. These indicate that the Eureka upland area lies along the trend of the North Spit anticline, while the flanking Elk River Valley and Arcata bay lowlands correspond to the Buhne Point and Arcata bay synclines. Gentle folding of the Eureka erosion surface may have guided the major drainage courses along the axes of downwarps in the Humboldt Bay area at about the same time the Van Duzen and Yager drainages were being deflected by warping in the Eel River Valley.

In light of the foregoing, and in accordance with discussions with Doctors G. H. Curtis and B. A. Ogle, the interpretation is proposed that the Eureka, Humboldt Hill, Table Bluff, and Fortuna-Hydesville surfaces each represent erosion-modified and locally warped correlatives of the Trinidad terrace sequence. The distinct interterrace steps of the Trinidad sequence either have been erosionally degraded beyond recognition because of the relatively poor competence of the underlying Upper Carlotta or Wildcat strata, or they were not well developed originally because of the same reason or because the Trinidad headland was an area of wave energy convergence while the Eel River basin was an area of wave energy dispersion. The higher terrace elevation has been essentially obliterated through erosional dissection in the area east of Eureka, with only a terrain of ridges and canyons remaining.

This interpretation was adopted after review of alternative hypotheses, including the following:

1) Terraces like those at Trinidad were formed, but were later subsequently submerged and partially buried; the Eureka and other surfaces may be equivalent to the highest surface at Trinidad.

2) Terraces like those at Trinidad were formed, but were subsequently uplifted and mostly destroyed by erosion.

3) No terraces were formed; the Eureka and other surfaces are the original depositional surface of the Hookton Formation, preserved locally.

4) The Eureka surface is a terrace, but less well defined surfaces on Humboldt Hill and Table Bluff are not; the absence of terrace surfaces in these areas is due to tectonic lowering.

Major points leading to the rejection of these hypotheses included:

1) No submerged or buried terraces exist in the area, as shown by both sparker seismic reflection profiling and bore hole information.

2) No remnants of terrace surfaces exist at higher elevations.

3) The Eureka surface seems to definitely be an erosional surface.

4) Relatively less well defined surfaces on Humboldt Hill, Table Bluff, and along the north side of the Eel River Valley seem to also represent terraces that have been partly degraded by erosion.

5) There are no appropriate structural features along which differential vertical movements (other than by broad warping or folding) could have occurred separating the Eureka area from the other three areas.

6) Small remnants of marine terrace surfaces exist at elevations of 400 and 900 feet, near False Cape, south of the Eel River Valley.

Numerous levels of stream terraces exist throughout the region. The largest terrace areas are present at several levels within the Eel River Valley. These surfaces have been described and discussed by Ogle (1953).

C. Implications Regarding Quaternary Tectonic Deformation

Under some conditions, marine terraces can be useful gauges of post-terrace age deformation. In theory, each terrace level should be characterized by one unique elevation along its shoreline angle (original strandline, between the wave-eroded bench and the sea cliff). Thus, any warping, tilting, or displacement of post-terrace age that intersects this level linear feature should be reflected by a corresponding alteration of its geometry. In practice, however, application of this technique is often complicated by difficulties in locating, positively identifying, and tracing the shoreline angle of an old terrace and by possible confusion between marine and stream terraces in river-mouth areas. Also, where terraces were developed on materials that can be highly erodible or unstable, such as the Hookton and Upper Carlotta Formations, as well as much of the Wildcat clayey siltstone, the shoreline angle and sea cliff backscarp may rapidly degrade, and finally blend with the general slope.

In the Humboldt Bay region, only the terraces in the Mad River - Big Lagoon area have well defined backscarps and approximately defined shoreline angle traces. The pattern indicated by the projected longitudinal profiles of these traces (Figure 11), is one of broad arching of the three higher, older surfaces, designated Qtw_2, Qtw_3, and Qtw_4, with the arching increasing in amplitude for the terraces of successively increasing elevation (and age). Arching may be an expression of deformation associated with the Falor-Korbel fault system of the Mad River - Big Lagoon terraces.

Some apparent offsets of elevation appear in the profiles, but these are not well defined or consistent. Some of the apparent offset results from the oblique projection of a sloping discontinuous line to a common plane of section. The apparent offsets probably do not result from actual fault displacement of the shoreline angle. The shoreline angle of the lowest terrace surface (Qtw_1) is essentially level.

South of the Mad River, terraces are restricted to small ridges and upland areas between stream and river valleys; also, they are mostly developed on materials of relatively poor competence, and so are poorly preserved. Terrace surfaces in the Humboldt Bay area occur within the same range of elevations as those in the Mad River - Big Lagoon area, and are almost certainly correlative with them. As was noted earlier, these surfaces apparently have been deformed by gentle folding. Owing to their poorly defined form, however, it was found not to be feasible to achieve the detailed correlations necessary to evaluate the amount and exact distribution of post-terrace deformation in the area.

VII. Geology of the Humboldt Bay Power Plant Site and Vicinity

A. Geologic, Geophysical, and Geochronologic Investigation of the Site and Vicinity

The investigation of the Humboldt Bay Power Plant site was concentrated in the vicinity of Buhne Point (where the site is located), Humboldt Hill, the lower valley of the Elk River, Fields Landing, and the adjacent parts of Humboldt Bay. The objectives of this investigation were as follows:

1) To further define and obtain specific field evidence of the location and geometry of the Little Salmon fault near the site.

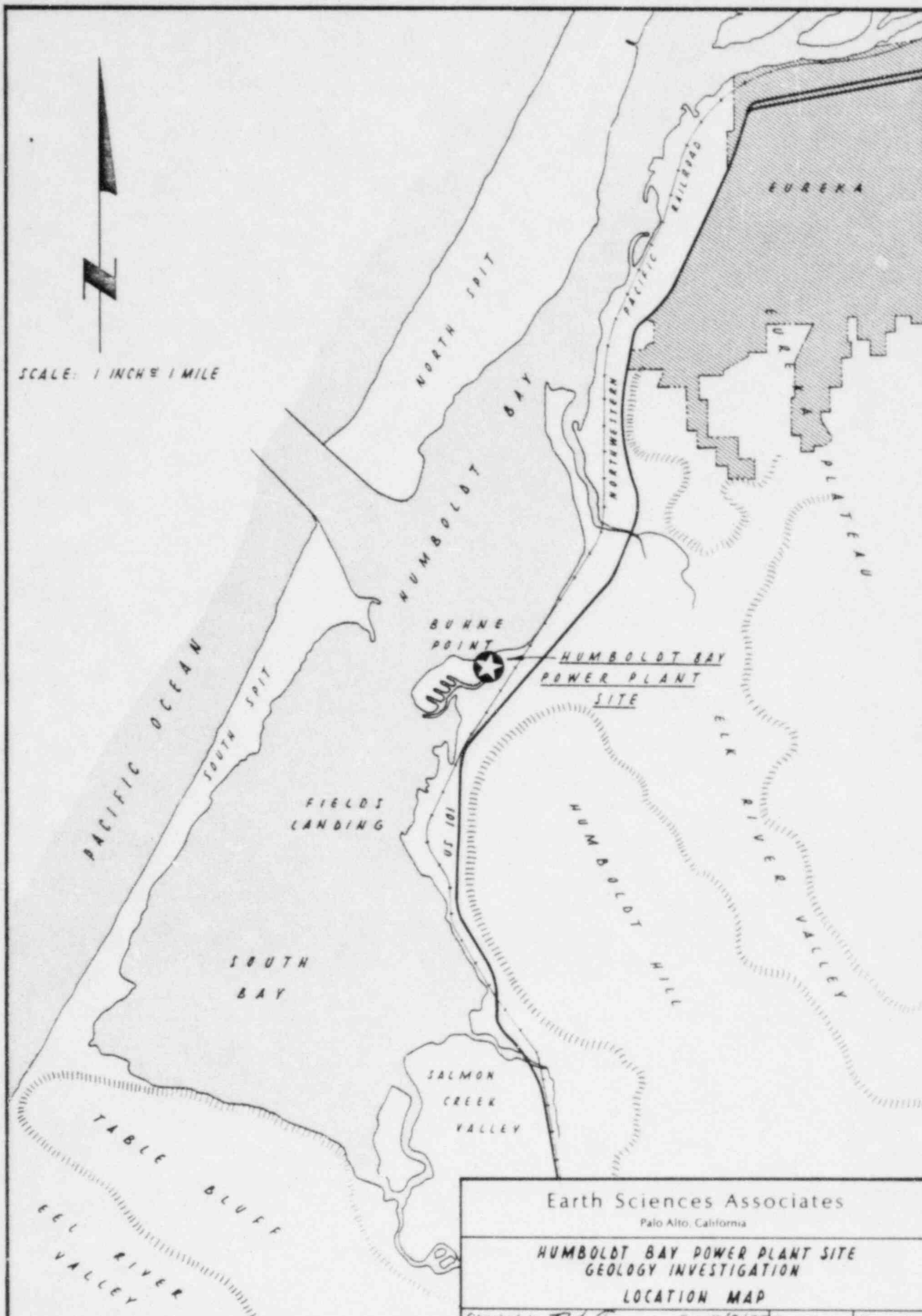
2) To determine the time of latest movement of the Little Salmon fault, as an indication of its capability for generating earthquakes and for surface displacement.

3) To further define the location, geometry, and time of latest movement of the Bay Entrance fault.

4) To determine the relationship of these two faults.

5) To obtain data permitting precise stratigraphic correlation (and dating) of marker beds within the Carlotta Formation section underlying the site in order to strengthen the evidence that the site is underlain by unfaulted ground.

Information obtained during the 1972 investigation of Curtis and Hamilton was interpreted as showing that the plant site was on unfaulted Carlotta Formation but that a newly identified fault, referred to as the possible Bay Entrance fault, passed within 1100 feet of the plant. The Little Salmon fault was interpreted as passing beneath the north end of Humboldt Hill. This fault was thought to cut and override the Carlotta Formation but to be overlain by Hookton Formation. It was therefore thought that the buried fault line was bracketed by Borings H-10 and H-11, on the north slope of Humboldt Hill. The fault was judged to be inactive.



Earth Sciences Associates
Palo Alto, California

HUMBOLDT BAY POWER PLANT SITE
GEOLOGY INVESTIGATION

LOCATION MAP

Checked by P.A. Frame Date 7/8/75		Project No	Figure No
Approved by D.H. Hamilton Date 7/15/75		1430	1

The program designed to achieve the objectives listed above progressed through three phases. Initially, extensive sparker seismic reflection and Acoustipulse (high frequency, high resolution, shallow penetration) profiling surveys were made in and offshore from Humboldt Bay. These served to delineate the location, northerly extent, and geometry of the Bay Entrance fault, and to show that the Little Salmon fault did not extend across the bay or into the offshore area.

The marine geophysical survey was followed by additional on-land seismic refraction and gravity surveys designed to provide improved information about the location of the buried traces of the Little Salmon and Bay Entrance faults. This work yielded only ambiguous results, for reasons that became evident subsequently during the investigation. These reasons were, chiefly, that the Little Salmon fault is buried at greater depth than the penetration of the refraction survey, and that it juxtaposed materials of very similar physical properties. Also, the Bay Entrance fault turns south, away from the areas covered by the surveys.

Following completion of the geophysical work, a program of drilling and sampling was undertaken. This constituted the greater part of the investigation and involved drilling, sampling, and logging twenty-four borings, totaling 13,415 feet of drill hole. The borings were all made using a truck-mounted Failing 1500 model rotary wash-boring rig, and were advanced using either roller or drag bits or by a Pitcher-barrel core-sampling device. A geologist monitored drilling conditions and cuttings return as the boring was advanced, and samples were taken when different materials were encountered, or at selected depths, nearly always including the bottom of the hole. After completion of drilling, the hole was immediately logged electrically and radiometrically. Selected samples were then prepared for micropaleontological analysis. The results of these analyses permitted positive identification and correlation of all important stratigraphic units, and thereby, determination of structural relationships in the site area.

B. Stratigraphy

The Humboldt Bay Power Plant is constructed on a section of Upper Carlotta Formation at least 1000 feet thick. Beneath this formation are rocks of the upper Wildcat Group, probably Scotia Bluffs Sandstone or the Rio Dell Formation. Nearby and overlying the Upper Carlotta sediments are thin, surficial deposits of bay fill in the lowlands and Hookton Formation on the surrounding hills.

Gently dipping beds of the Upper Carlotta Formation are exposed in the bluff that forms Buhne Point immediately west of the plant site. The stratigraphically lowest unit exposed here is a dark gray silty clay, the base of which is covered by recent shoreline deposits and riprap. The silty clay is overlain by fine grained brown to gray sand containing discontinuous, irregular layers of gray silty clay and scattered thin lenses of pebble to cobble-size gravel. The uppermost bed exposed in these bluffs is a gray sandy silt.

Through extensive drilling in the Upper Carlotta Formation (a total of 10,299 feet was drilled in this formation), the basal clay at Buhne Point was shown to be the basal clay of the upper unit of the Upper Carlotta. This clay bed can be followed in the subsurface throughout much of the surrounding area. As described in Section IV, Stratigraphy, the upper unit is composed of interbedded sands and clays. A typical section penetrated in the Buhne Point area has 50 feet of basal, medium dark gray, silty clay. Overlying this is about 65 feet of moderate brown to medium dark gray, subangular to subrounded, well sorted sand containing as much as 40 percent of scattered, fine, Franciscan-type gravel. Typically the sand is about 50 percent quartz, 40 percent feldspar and 10 percent heavy minerals and rock fragments. Above this is at least 600 feet of interbedded and interlensed sands and clays like those lower in the unit. Medium gray, clayey and sandy silt is sometimes interbedded in this section also. The proportion of clay tends to increase with height in the section. All of these sediments commonly contain shallow-water marine fossils and carbonized plant fragments and the clays and clayey silts often contain abundant microfossils.

This clay-rich upper unit is underlain by a lower unit of interbedded silty and gravelly sands. These sands and gravels are compositionally and texturally similar to the sands and gravels of the upper unit, but tend to be slightly coarser grained. The lower unit is medium gray where cored beneath sea level but becomes stained light yellowish brown by iron-rich percolating water above this level. Clay is sometimes present as lenses, usually less than 1 foot thick, or as an interstitial component of sand or silt. The lower unit contains some shell layers.

The Upper Carlotta Formation in the Buhne Point area was probably mostly deposited in a marine environment. The lower unit seems to represent a near-shore depositional environment, while the upper unit, with its thick clay layers and plant material, was deposited in more enclosed waters of an estuary or bay.

The bay fill deposits, which blanket much of the area surrounding the power plant site, fill an ancient channel system, as shown on Figures 15, 16, and 17. These sediments are unfolded and unfaulted. The grain size of these recent deposits generally increases with depth. A poorly sorted gravelly sand is present at the base of the section. This is overlain by a relatively extensive, poorly sorted, medium dark gray, silty sand with scattered clay lenses. The uppermost bay fill layer, which forms the top of all bay fill deposits, is a medium dark gray silty clay often containing plant fibers and shell fragments and occasionally fine grained sand lenses.

C. Structure

General features of the geologic structure in the vicinity of the Humboldt Bay Power Plant site are indicated on the map showing geology and exploration features of the Humboldt South Bay and vicinity, Figure 14. Details of structural features are shown on the large scale cross sections presented in Figures 15 through 19. Correlations between electric and radiometric logs of bore holes are shown on Figure 20. Contour maps of important structural horizons in the ground at and near the site are given on Figure 21. Finally, a three dimensional view of the structural relationships there is shown in the fence diagram, Figure 22.

The continuity and structure of marker beds in the section underlying the site were established by drilling two lines or fences of holes. The fences were laid out so as to extend information from beneath the plant site to nearby outcrops at Buhne Point and along the road cut north of Fields Landing, and away in other directions to the limits set by the bay shoreline and by the extent of the clay marker bed in the Upper Carlotta Formation. Data from the two main fence lines, referred to as the Buhne Point to Humboldt Hill line (Cross Section A-B) and the Humboldt Bay Power Plant to Fields Landing line (Cross Section C-D) are shown on Figures 15 and 16, respectively. The correlations indicated on these sections were verified by the drill hole logs, by paleontological study of samples from the lower clay marker bed, and by comparison of electric and radiometric logs of the borings. Ages of stratigraphic units, based on paleontological dating of foraminifera from bore hole samples, are given in Table B. The electric and radiometric logs are shown on Figure 20. Data from the bore holes along lines A-B and C-D, and at other points in the vicinity, were used to develop the contours on the base of the clay

FORAMINIFERAL AGES*

Corehole Samples

Sample No.	Age	Formation	Environment
RD-1, B-1	Probable Late Pliocene to Pleistocene	Carlotta	Inner Neritic
RD-2, B-1	Probable Late Pliocene to Pleistocene	Carlotta	Inner Neritic
RD-3, B-2	Probable Late Pliocene to Pleistocene	Carlotta	Inner Neritic
RD-7, B-1	Probable Late Miocene	Pullen	Middle Bathyal
RD-7, B-9	Probable Late Miocene	Pullen	Middle Bathyal
RD-8, B-1	Possible Pliocene	Carlotta	Probable Marine
RD-8, B-2	Probable Pliocene	Eel River	Middle Bathyal
RD-9, B-2	Possible Pliocene to Pleistocene	Carlotta	Probable Inner Neritic
RD-10, B-1	Probable Pliocene to Pleistocene	Carlotta	Neritic
RD-10, B-4	Probable Pliocene to Pleistocene	Carlotta	Inner Neritic
RD-11, B-1	Probable Late Pliocene to Pleistocene	Carlotta	Inner Neritic
RD-11, B-3	Probable Late Pliocene to Pleistocene	Carlotta	Inner Neritic
RD-12, B-2	Probable Pliocene to Pleistocene	Carlotta	Inner Neritic
RD-13, B-2	Possible Late Miocene to Pliocene	Eel River	Open Marine
RD-13, B-12	Early to Middle Pliocene	Eel River	Middle Bathyal
RD-14, B-2	Probable Pliocene	Carlotta	Middle Bathyal
RD-17, B-1	Pliocene to Pleistocene	Carlotta	Neritic
RD-18, B-3	Probable Late Miocene	Pullen	Upper to Middle Bathyal
RD-18, B-4	Middle Miocene	Pullen	Middle Bathyal
RD-18, B-5	Middle Miocene	Pullen	Middle Bathyal
RD-19, B-1	Probable Late Miocene	Reworked Pullen in Carlotta	Middle to Lower Bathyal
RD-19, B-3	Late Miocene to Early Pliocene	Eel River/ Pullen	Middle Bathyal to Abyssal
RD-19, B-4	Early Pliocene	Eel River	Middle Bathyal to Abyssal
RD-19, B-5	Probable Middle to Late Pliocene	Rio Dell	Middle to Upper Bathyal
RD-19, B-6	Probable Middle to Late Pliocene	Rio Dell	Middle to Upper Bathyal
RD-19, B-7	Probable Middle to Late Pliocene	Rio Dell	Middle Bathyal to Abyssal
RD-21, B-1	Pliocene to Pleistocene	Carlotta	Inner Neritic

Outcrop Samples

Sample No.	Age	Formation	Environment
3-74-1	Probable Pleistocene	Carlotta	Neritic
3-74-16	Late to Middle Pliocene	Rio Dell	Upper to Middle Bathyal
3-74-21	Lower Pliocene	Eel River	Lower Bathyal to Abyssal

(*) As determined by Anderson, Wilcoxon and Associates, Inc., consulting micropaleontologists.

Table B

marker bed, shown in Figure 21A. The contour map shows that the plant site is situated over the west flank of a gently folded shallow structural basin developed in the Upper Carlotta. The basin is superimposed on a larger northwest-plunging shallow syncline, the axis of which lies under the Elk River Valley. The west flank of the overall structure warps up to an anticiine, which is breached by the Bay Entrance fault, through the King Salmon peninsula and Fields Landing. A cross section extending across the entire structure including both the Bay Entrance anticline and fault, and the adjacent syncline, can be seen in sparker seismic reflection profile 17N-S, shown on Figure 8.

The Bay Entrance fault is bracketed on Buhne Point between borings H-9 on the east, and RD-12 on the west. The 700 foot projected stratigraphic discontinuity between these borings aligns with the trend of the fault indicated by sparker lines 7, 8, and 17 N-S in the bay to the northwest. Although this fault was interpreted by Curtis and Hamilton (1972) to continue on a southeasterly trend and extend under Humboldt Hill, the Power Plant to Fields Landing fence of borings showed that the clay marker bed was unbroken across this trend. Instead, the fault was found to curve to a southerly trend, and to extend between the road cut north of Fields Landing and boring RD-11 at Fields Landing. It was further bracketed by borings RD-19 and RD-10. These relationships are illustrated on Sections G-H and J-K, Figures 18 and 19. The indicated stratigraphic separation across this fault near Fields Landing is 700 feet, about the same as at Buhne Point.

Regarding the position and geologic relationships of the Little Salmon fault under Humboldt Hill, Curtis and Hamilton (1972) concluded that the fault cut and overrode the Carlotta Formation and that the Carlotta therefore was in the footwall of the fault. The fault was thought to be overlain by Hookton Formation and to be bracketed by boring H-10, in Carlotta, and H-11, which was interpreted to pass through a 400 foot thick section of Hookton, and then to bottom in sandstone, possibly of the Yager Formation, but clearly of the upper plate or hanging wall of the fault. This interpretation was tested during the present investigation by drilling a deep hole, RD-18, half way between H-10 and H-11. It was then determined that although H-10 and RD-18 started in Upper Carlotta correlative with the Upper Carlotta at Buhne Point, RD-18 encountered uppe. plate

Eel River or Pullen Formation under the Upper Carlotta and was still in this unit at its maximum depth of 1601 feet. Data from borings RD-14, 20, and 21 and Water Well 2 confirmed the continuity of the clay marker bed between Humboldt Hill and Buhne Point (Figures 15, 20, and 21A). Contours on the erosion surface underlying the Upper Carlotta and, locally, the Hookton, are shown on Figure 21B.

Boring RD-19, at Fields Landing, was started in Upper Carlotta and then passed through upper plate Eel River or Pullen siltstone into younger, lower plate Rio Dell siltstone. This demonstrated that the fault was capped by the Upper Carlotta and that the westerly, leading edge of the upper plate was no deeper than 812 feet, as shown on Cross Section G-H, Figure 18. This confirmed that borings in Fields Landing and on Buhne Point that extended to lower elevations than this, but remained in Upper Carlotta, were in fact in the footwall side of the Little Salmon fault. The geometrical relationship established by fault intercepts in the Brauner Well and in boring RD-19 that demonstrate this point are illustrated on Sections E-F and G-H, Figures 17 and 18.

Data points necessary to define the position and limits of the Little Salmon fault were provided by the Dinwiddie Well, which showed the fault to be no deeper than 1700 feet (Elevation -1450) and boring RD-18, which showed it to be no less than 1601 feet (Elevation -1356) under the northerly slope of Humboldt Hill, as shown on Section E-F, Figure 17. Correlation of the stratigraphy of the lower unit of the Upper Carlotta from Buhne Point to Humboldt Hill also showed that boring H-11 was actually in this unit (except below 430 feet, where it entered cemented Eel River Formation sandstone), rather than in Hookton as originally interpreted. This in turn indicated that much of the gravelly sand present on Humboldt Hill belongs to the lower part of the Upper Carlotta, so that the Hookton Formation is only a relatively thin capping.

The form of the Little Salmon fault surface that is indicated by available data points and constraints is contoured in Figure 21C. As indicated in Section J-K, Figure 19, part of the leading edge of the Little Salmon upper plate evidently is offset by the Bay Entrance fault. This is required by the geometrical relationship of the two faults; it was not tested by drilling.

The overall relationships between the Little Salmon fault, Bay Entrance fault, and the Upper Carlotta Formation are illustrated by the Fence Diagram given in Figure 22.

D. Ground Stability

For the purpose of evaluating ground stability, the site vicinity is characterized by three class of ground: 1) bay margin and river valley lowland, underlain by alluvial and bay fill surficial deposits, locally with a veneer of artificial fill; 2) lowland areas underlain by relatively dense Hookton and Upper Carlotta Formation; and 3) the slopes of Humboldt Hill underlain by Wildcat and Hookton deposits. The ground stability aspects of each of these areas is discussed as follows:

1. Lowland Areas

Most lowland areas in the vicinity of Buhne Point, Fields Landing, and the Elk River Valley are underlain by a few tens to nearly 100 feet of alluvial and bay fill surficial deposits, with local accumulations of organic matter. These deposits tend to be water saturated and of relatively low strength. They are compressible under loading, and they could be subject to lurching, liquefaction-induced ground failure, or other effects in the event of strong earthquake shaking. Earthquake-induced ground failure effects of this sort have been reported at numerous places in the Humboldt Bay region (Lawson, 1908; CDMG, 1972a).

In contrast to the lowland areas just described, certain areas, notably the Power Plant site near Buhne Point, much of the part of Fields Landing lying east of the Freeway, and the area at Spruce Point, are all underlain directly by Hookton or Upper Carlotta Formation. Only at the Plant site has the ground stability been investigated in detail. There, the stability has been examined via two separate approaches.

One approach has involved ascertaining the geologic stability of the site through mapping of the underlying strata. As described previously, this was done through correlation of marker beds between bore holes, with the conclusion being that the site was underlain by undisturbed strata.

A second approach has involved obtaining undisturbed samples of materials from the site subsurface and subjecting these samples to dynamic strength tests. The results of this program, performed by the consulting firm of Dames and Moore (1974) have also indicated that the in-place Upper Carlotta Formation underlying the site should be stable under expectable earthquake-shaking conditions.

2. Landslides Along the Slopes of Humboldt Hill

Work done in connection with the present investigation has resulted in the recognition of a series of very large block slump failures along the southwest slope of Humboldt Hill. These features were identified and mapped on the basis of geomorphic analysis, chiefly done through study of stereo pairs of aerial photographs. The slide blocks are recognizable only by the anomalous landforms they create along the upper southwest surface of the hill. These landforms include subdued scarps rising behind dropped, back-rotated slopes, and several closed depressions. The overall dimensions of some of the blocks are as much as 3000 feet in width by 4000 feet in length, and they may be 500 or more feet in height. Downward translational movement appears to be between 20 feet and as much as 100 feet. The slide planes must extend through the Hookton and basal Upper Carlotta section that caps Humboldt Hill and into the underlying Wildcat Group clayey siltstone.

The slide block masses are stable under prevailing conditions, but they can move slightly when subjected to relatively strong earthquake shaking. Evidence for this was obtained from Mr. Carl Herron, of Fields Landing, who reported having personally traced a west-northwest-aligned crack, formed at the time of the M 6.4 1932 earthquake. The crack extended from the lowland near the center of Fields Landing, across Highway 101, and up the slope of Humboldt Hill behind Mr. Herron's home. The crack was partially reopened again during the M 6.5 1954 earthquake. It may correspond to the crack reported to have opened at Fields Landing at the time of the 1906 earthquake (Lawson, 1908, p. 167). The trace of the crack coincides with the trace of the failure plane of one of the landslide blocks, and it must open when the block is shifted slightly during strong earthquakes.

The Power Plant site is 4500 feet from the nearest large Humboldt Hill landslide and 6000 feet from the 1932 and 1954 earth crack. It is therefore not endangered by any potential movement of these slides.

VIII. Late Cenozoic Structural History and Tectonism

The geologic and geomorphic history of the Eel River Valley area has been discussed in detail by Ogle (1953) and was later reviewed by Curtis and Hamilton (1972). The following is a summary of the major events in the late Cenozoic structural history of the region around Humboldt Bay. This is based on a synthesis of the previous work done by Ogle and others with the results of the present investigation.

A. Structural History

The structural history presented here begins with the main phase of Eel River basin sedimentation, involving accumulation of the Pullen, Eel River, and Rio Dell deposits during middle Miocene through late Pliocene time.

Toward the end of the Pliocene, general uplift, as well as local folding, uplift, and probably faulting began in the southerly part of the basin. This disturbance of the basin was reflected by the change in sedimentation from deep water marine to shallow marine of the Scotia Bluffs and then to estuarine and even fresh water deposition of the Carlotta Formation. Movement of the Little Salmon fault probably was initiated at this time, resulting in uplift of the northeasterly margin of the basin concurrently with deposition of the Carlotta Formation. As this deformation progressed and intensified, the basin was partly disrupted by overthrusting from the northeast along the Little Salmon and Yager faults. This was also the time of major development of subsidiary folds within the basin, such as the Tompkins Hill and Table Bluff anticlines, and of intra-fold faults such as the Table Bluff fault. The ground along the southerly margin of the basin was progressively uplifted and faulted, thus disrupting the southernmost part of the basin and exposing the south flank of the newly formed Eel River syncline. Locally the basin was tightly folded adjacent to the Little Salmon fault, as in the overturned synclines near the town of Carlotta, though at other points, deformation was slight, even in ground that was overridden by the thrust plate. Farther to the northeast, parts of the basin section were downdropped along the Falor and Korbel faults.

At the close of this episode of folding, thrust faulting, and uplift, the upper plate of the Little Salmon formed an upland northeast of the remaining southerly part of the basin, and the Cape Mendocino upland bordered it on the south. These uplands were then subjected to erosion, while deposition probably continued in the basin.

Deposits laid down at this time gradually lapped up onto the partly degraded Little Salmon upper plate in the vicinity of Eureka and Humboldt Hill, as the Upper Carlotta Formation.

Following, or perhaps even concurrently with deposition of the Upper Carlotta during early Pleistocene or Plio-Pleistocene time, the ground in the Humboldt Bay area was gently folded and was offset by movement along the Bay Entrance fault. It was then subjected to moderate uplift and erosion.

At some later time, during the mid Pleistocene Rancholabrean age, the Hookton Formation was deposited in a marginal marine flood plain, grading to shallow marine environment.

Following this, the mid to late Pleistocene stage of general uplift, with episodes of erosion and deposition associated with alternating high and low stands of sea level, was initiated. During the earlier part of this stage of development there were one or more episodes of gentle arching and folding that affected the three older terrace surfaces near Trinidad, and the Hookton and older Formations near Humboldt Bay and the Eel River. This deformation was accompanied by minor faulting at some points, including at the Table Bluff headland, the Bayside Cutoff road site, and the College Cove site. Uplift and faulting continued in the Cape Mendocino region, and there may have been other local faulting within the Mad River zone.

The lowest emergent terrace in the region was probably eroded during the late Pleistocene Sangamon Interglacial age. Older, higher terrace remnants continued to be degraded by erosion and locally obscured by deposition, especially in areas of weak Wildcat Group and Hookton outcrops. Streams and rivers in the area cut their channels down to the base level established by the Wisconsinan low stand of sea level. Most recently, with the return of sea level to its present elevation, lower valleys of the major drainage courses were drowned and backfilled, and surf zone erosion of the existing wave-cut bench along the shoreline was initiated.

B. Tectonism

The history and pattern of tectonic deformation in the Humboldt Bay region clearly indicates that different stress fields of varying orientation and intensity have existed in the area at different times.

During the late Pliocene basin-disruption (Little Salmon) stage, the present-day Humboldt Bay and lower Eel River area was evidently subjected to northeast-southwest oriented compressive stresses which caused overthrust faulting from the northeast, uplift along the southerly margin of the basin, and early development of northwest to east-west trending folds.

Following the Little Salmon tectonic episode, the orientation of compressive stresses apparently rotated somewhat, through a north-northeast to south-southwest alignment to a nearly north-south alignment. This gave rise to local northwest-southeast to north-south high angle dip-slip faulting on the Bay Entrance fault, and to northwest-southeast dip-slip and probably also strike-slip faulting, and northeast-southwest cross faulting in the Mad River zone.

Evidence of some later deformation associated with this stress field is given by the broad arching of terraces across the Mad River zone north of Trinidad and by gentle folding of the Hookton Formation and possibly also of older terrace surfaces in the Humboldt Bay and Eel River Valley area.

Unlike the continental plate margin stress conditions that exist north of the Eel River Valley, the stress field in the Cape Mendocino region seems to be governed largely by relative movement between the Pacific and American crustal plates, which is concentrated along the San Andreas fault south of the Cape. This stress is relieved through a wide band of shearing which is exposed in the uplifted basement rock terrane south of the Eel River, and which apparently also exists at depth in the basement rocks under the Eel River Valley, as shown by microearthquake studies. Although seismic events large enough to be felt are generated within the outer, northerly part of this band of shearing, larger earthquakes occur only in the main part of the zone, adjacent to and along the Mendocino fracture zone and San Andreas fault.

Another, less well known zone of shear deformation extends offshore from Cape Mendocino northwestward along the continental slope and into the deep ocean Gorda Basin. This zone also exhibits active right lateral shearing, as indicated by scattered earthquakes.

The area between the Cape Mendocino and the Mad River tectonic zones is evidently characterized by low tectonic stress. This is indicated by the absence of active faults, the small amount of deformation there since overthrusting by the Little Salmon fault, and by the low level of seismic activity, especially in comparison with the seismicity level in surrounding regions.

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