Form 9-014

TEI-837

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WASHINGTON 25, D. C.

GEOLOGIC AND SEISMIC INVESTIGATIONS OF A PROPOSED NUCLEAR POWER PLANT SITE ON BODEGA HEAD, SONOMA COUNTY, CALIFORNIA

PART I--GEOLOGIC INVESTIGATIONS

by

Julius Schlocker, Manuel G. Bonilla, and Alfred Clebsch, Jr.

PART II--SEISMIC HAZARDS EVALUATIONS

by

Jerry P. Eaton

September 1963

☆ U.S. GOVERNMENT PRINTING OFFICE : 1962—O-632210

TEI-837

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGIC AND SEISMIC INVESTIGATIONS OF A PROPOSED NUCLEAR POWER PLANT SITE ON BODEGA HEAD, SONOMA COUNTY, CALIFORNIA

PART I--GEOLOGIC INVESTIGATIONS

by

Julius Schlocker, Manuel G. Bonilla, and Alfred Clebsch, Jr.

PART II--SEISMIC HAZARDS EVALUATIONS

by

Jerry P. Eaton

September 1963

Report TEI-837

CONTENTS

ILLUSTRATIONS

(All illustrations are at end of report)

TABLE

Geologic and seismic investigations of a proposed nuclear power plant site on Bodega Head, Sonoma County, California

INTRODUCTION

The Pacific Gas and Electric Company (PG&E) has applied to the U. S. Atomic Energy Commission for permission to construct a nuclear-powered electric generating plant on a site adjacent to Campbell Cove on Bodega Head, Sonoma County, California. Questions have been raised as to the suitability of the site for such a plant because of: 1) its position relative to the San Andreas fault zone; 2) the possibility that minor faults, related to the San Andreas fault, might actually pass through the site; and 3) the seismic hazards posed by the nearby San Andreas fault zone.

The Geological Survey is conducting a study of the site in an effort to resolve these points, and this report presents the results of approximately 8 days of field work at and near the site between May 10 and June 6, 1963, plus a review of published geologic and seismic reports on the general area and unpublished reports on the site itself. The unpublished reports are part of the Facility License Application, as amended, AEC Docket No. 50-205 and are thus available to the reader. About two-thirds of the field work was spent in a detailed examination of the excavation for the plant and of exposures in the adjoining Campbell Cove area. About a third of the effort was devoted to the study of the geology of other parts of Bodega Head, principally around Horseshoe Cove and on the west-central, southern, and northeastern margins of the Head. Results of geologic and geophysical studies of this part of the San Andreas fault zone are included in part I.

Questions relating to the frequency and intensity of earthquakes that might be expected at the site and the kinds and degree of earth motion to be expected are important in assessing site suitability and setting design criteria for the plant, and are presented in part II.

The term "site" as used in this report, unless otherwise specified, will refer to the main plant site adjoining Campbell Cove which includes the reactor, turbine-generator, administration building, etc. Figure 1 shows the location of the first of four proposed reactors at the site. Figures 2 and 3 show the stage of excavation reached on the north and west faces on May 16, 1963.

Acknowledgments

The cooperation of officials and employees of Pacific Gas and Electric Company greatly facilitated the work. They made copies of reports, maps, and other data available and further facilitated the field work by providing on occasion surveying services and improving exposures in the site excavation by scraping with heavy equipment and by washing loose soil and fill so that the faces could be observed in detail.

Gravity measurements were made by Donald L. Peterson and Victor W. McAllister of the U.S. Geological Survey under the supervision of Don Mabey, U.S. Geological Survey. The section in this report on geophysical investigations was written by Mabey and Peterson.

Previous Investigations

The geology and seismology of Bodega Head were studied by Don Tocher and William Quaide on behalf of PG&E and are reported in PG&E's "Preliminary Hazards Summary Report, Bodega Bay Atomic Park - Unit Number 1" as Appendix IV "Report on earthquake hazards at the Bodega Bay Power Plant Site, Pacific Gas and Electric Company." Details of subsurface geology at the site as interpreted from boreholes are contained in reports prepared for PG&E by the engineering firm of Dames and Moore (1960, 1962). Some of the information from these reports has been checked independently in the field but because of lack of time, it has not been possible to field-check all such information that we have utilized. More general discussions of the geology of the area are included in reports by Johnson (1943), Travis (1952) and Higgins (1961). The geology of

Point Reyes Peninsula, which is part of the same geologic province as Bodega Head, has been mapped and described by Weaver (1949) and Galloway (1961, 1962). The age of the quartz diorite on Point Reyes has been estimated by Curtis, Evernden, and Lipson (1958). The effects of the 1906 earthquake in that area are described in a report compiled and edited by Lawson (1908).

PART I--GEOLOGIC INVESTIGATIONS

by Julius Schlocker, M. G. Bonilla and Alfred Clebsch, Jr.

Geologic setting

Topography

The site is on the eastern half of a saddle between the two southernmost hills of Bodega Head (Figure 1). Bodega Head is bounded on the north by Horseshoe Cove and makes up the southern two-thirds of a wedge-shaped bedrock peninsula that extends from Mussel Point southeastward for 2.2 miles.

Bodega Head consists mostly of three broad, low-crested, gently-rounded hills that, beginning with the northernmost, are 266, 238, and 200 feet above mean sea level. The Head is 2,000 to 2,800 feet wide and is bounded on the western or Pacific Ocean side by cliffs 100 to 200 feet high and on the eastern or Bodega Bay side by cliffs about 75 feet high. Detached low sea stacks and small, low, rocky islands are abundant beyond the western and southern shores of the peninsula.

The northern third of the peninsula reaches a height of 108 feet above sea level in a hill of gently rounded slopes about 1,250 feet south of Mussel Point. The peninsula is about 1,000 feet wide in this area.

The bedrock peninsula is tied to the mainland on its northern half by a strip of dune and beach sands 2,700 to 6,000 feet wide that makes up the northern and western border of Bodega Harbor. Salmon Creek Beach is the Pacific Ocean shore of this strip. The prevailing winds, blowing S. 50° E., have an unobstructed sweep from the beach and have created a series of sand dunes 120 to 152 feet high that are parallel to the beach and extend 2,300 feet to the southeastward. Southeast of this crest, and in the lee of the hill at Mussel Point, the dunes are generally aligned with the prevailing wind direction.

Doran Beach, a low sand bar probably created by currents that moved sand generally northwestward in a counterclockwise direction, forms the southern border of Bodega Harbor. It is about 7,500 feet long and in 1942 came within about 450 feet of Bodega Head at a point about 1,700 feet north of the straight southern shore of Campbell Cove. Since 1942, its shore has been modified by dredging and man-made fill so that it is now 800 feet east of the Head at a point about 1,000 feet north of the southern shore of Campbell Cove.

Geology

The bedrock of the Mussel Point-Bodega Head peninsula is a granitic rock that is predominantly quartz diorite in composition. Rock of similar composition, believed to be of the same origin and approximately the same age, forms the bedrock of Point Reyes Peninsula, 5 miles southeastward of Bodega Head. A sample of the Point Reyes rock was reported by Curtis and others (1958, p. 9), to be 83.9 million years old by the potassium-argon method of age determination.

The granitic rocks of Bodega Head are now partly covered by flat-lying and gently dipping uncemented to weakly-cemented deposits, probably of Pleistocene age and by younger Recent deposits. The Pleistocene deposits are mostly sand and silty and clayey sand; the overlying Recent deposits are mostly uncemented to weakly-cemented silty sand soils and clay, sand, silt, and pebbly colluvium. The term colluvium is applied here to weathered slope debris that has moved downslope mostly by gravity. The Pleistocene deposits appear to be nearshore marine and nonmarine deposits, such as beach and adjoining sea floor deposits, tidal marsh or fresh-water lake deposits, interstratified marine and nonmarine terrace deposits of alluvium and colluvium derived locally from steep shores, and minor windblown sand.

The general distribution of the Pleistocene deposits is shown on the geologic map by William Quaide that accompanied the report by Tocher and Quaide (1960).[1]

---

[1] This map was field-checked by us in critical areas. In such areas the contact between quartz diorite and terrace deposits was found to be depicted on the map within reasonable limits of accuracy. We found a few small patches of terrace deposits lying on quartz diorite, mostly near the western and southern shore of Bodega Head, that are not shown on the map; some of the area shown on the map as quartz diorite is covered irregularly by organic, silty, windblown sand soil and by slope debris. Surface exposures of quartz diorite are spotty in the latter areas.

The San Andreas fault zone and seismicity of the Bodega Harbor area

Bedrock in the area east of Bodega Harbor is the Franciscan Formation, considered to be of Jurassic and Cretaceous age, and is composed mostly of pervasively-fractured marine sandstone. The Franciscan Formation is separated from the granitic rocks of Bodega Head by the San Andreas fault zone which traverses Doran Beach, Bodega Harbor, and the neck of dune and beach sand that connects the Head to the mainland.

In other places, where the San Andreas fault zone is better exposed and has been studied in detail, it is found to be a belt within which bedrock is generally thoroughly sheared and broken and the older surficial deposits greatly disturbed. Relatively intact, little-sheared or broken blocks, several hundred feet in size, are present. Such conditions are believed to exist in the fault zone in the Bodega Bay area because they are common elsewhere in the fault zone.

Because the Franciscan Formation which lies east of the San Andreas fault zone is not intruded by the younger granitic rocks which lie west of the fault zone, and also because of inferences on the time-rate of offsetting of certain geologic features, many geologists believe that the total horizontal movement on the fault by repeated rupturing during the past 25 million years has been at least 160 miles (Crowell, 1962, p. 49; Curtis and others, 1958, p. 14).

There is some evidence to indicate that an individual rupture tends to occur along the same line, or in the same part of the zone as the one preceding. For example, in the valley 20 to 30 miles southeast of Bodega Head, between Tomales Bay and Bolinas Lagoon, and elsewhere along the fault zone, traces of older ruptures are located close to the 1906 rupture.

The strongest earthquake of record at Bodega Head was that of April 18, 1906. The intensity of shaking and its effect in the Head area are not recorded, though the intensity was probably strong. The trace of the surface rupture within the San Andreas fault zone is shown by Lawson and others (1908, atlas map 4) as striking N. 35° W. and lying 6,600 feet northeast of the westernmost shore of Campbell Cove. Observations along this rupture showed that the movement was mostly horizontal; the west side moved northward relative to the east side. The amount of horizontal displacement of the 1906 rupture in the Bodega Harbor area was not recorded. Horizontal displacement on the rupture 21 miles southeastward in the Point Reyes Station area was about 20 feet. An 18-inch vertical displacement, up on the west side, was recorded at the rupture near the town of Bodega Bay (Lawson and others, 1908, p. 65). It is not known if this was true vertical displacement or horizontal displacement of a small mound, which could have produced an apparent vertical displacement; however, a study of the distribution of living and dead barnacles and mussels along the east shore of Bodega Head 6 months after the 1906 earthquake indicated that no uplift of Bodega Head had occurred (W. E. Ritter in Lawson and others, 1908, p. 88).

Other aspects of the seismic history of the Bodega Bay area are discussed in detail in the report by Tocher and Quaide (1960, p. 2-4, 9-10, table 1).

WESTERN LIMIT OF THE SAN ANDREAS FAULT ZONE

Definition of the limits of the San Andreas fault zone near Bodega Harbor is more difficult than elsewhere because most of the geologic and topographic criteria used to define the fault zone are absent or concealed. In other places the zone is commonly marked by a well-defined trench that may contain straight valleys and ridges, disrupted drainage, undrained depressions, gouge, breccia, and a mixture of rock types. If these features are present near Bodega Harbor, they are concealed by water or by dune and beach sand.

Inasmuch as direct criteria for the width of the fault zone are absent near Bodega Harbor, indirect criteria from adjacent portions of the zone must be used. The general position of the zone can, of course, be established by the 1906 trace and by projecting the attitude of the fault zone from exposures northwest and southeast of Bodega Harbor. The 1906 trace was not everywhere in the middle of the fault zone and in relatively short distances the trace crossed from one side of the zone to the other (Higgins, 1961, fig. 2). The fault zone is well defined southeast of Bodega Bay by the trough extending from Tomales Bay to Bolinas Lagoon. This trough is 1 to 1½ miles wide, but the most active zone is narrower than the trough. Galloway (1962, p. 395) speaking of an area about 3½ miles north of Bolinas Lagoon says "...the whole faulted zone is about half a mile wide." Northwest of Bodega Harbor the fault passes out to sea and re-enters the land near Fort Ross. For about 10 miles northwest of this point the fault is not in a well-defined valley but northwest of that reach, it is in a well-defined trough for more than 25 miles. This trough, which is occupied by the Gualala and Garcia Rivers, is also 1 to 1½ miles wide but the most active zone is probably narrower than the valley. Thus based on the width of this trough, the fault zone in reaches southeast and northwest of Bodega Harbor is probably no more than 1½ miles wide. The eastern limit of the zone is probably east of the east shore of Bodega Harbor, based on the intensity of shearing of sandstone of the Franciscan Formation and on topographic evidence. The distance from the east shore of Bodega Harbor to the western limit of the fault zone as shown by Tocher and Quaide (1960) is about 1½ miles and is thus of a reasonable width when compared to adjacent portions of the zone.

Over most of its length in northern California the San Andreas fault zone occurs between granitic basement rocks on the west and Franciscan basement rocks on the east. This relation is true in the Point Reyes Peninsula, which is immediately south of Bodega Harbor; granitic rocks do not crop out north of Bodega Head. By this general rule then the fault should lie eastward of the granitic rocks of Bodega Head. However, along some parts of the San Andreas fault zone bodies of granitic rock as large as Bodega Head are included within the San Andreas fault zone (Santa Cruz Sheet, 1959, and San Luis Obispo Sheet, 1959, Geologic Map of California). Nevertheless, the granitic rock of Bodega Head to be within the San Andreas fault zone would require a considerably greater width of the fault zone than exists in nearby areas to the north and south, and furthermore there is no compelling geologic data for postulating a greater width near Bodega Head. Tocher and Quaide (1960) drew the western limit of the San Andreas fault zone about 1,000 feet east of the center of the proposed reactor, using, among other criteria, the easternmost line of exposures of the granitic rock. It is believed that the granitic rock in the subsurface extends east of the surface exposures and therefore the western limit of the San Andreas zone is at or east of the line shown by Tocher and Quaide.

GEOPHYSICAL INVESTIGATIONS

by Don R. Mabey and Donald L. Peterson

Gravity observations have been made at 57 stations along two profiles approximately normal to the San Andreas fault in the vicinity of Bodega Head (fig. 1). The stations are about 500 feet apart except at the entrance to Bodega Harbor, where there is a break in the southern profile. Position control for the gravity stations was obtained by PG&E personnel. The relative elevations are known to within one foot and the horizontal position to within 10 feet. Gravity observations were made with a Worden gravity meter having a dial constant of 0.4907 milligals per division. Reoccupation of five stations repeated the original observations within 0.15 milligals.

The gravity data were reduced to the simple Bouguer anomaly using the standard density of 2.67 g per cm^3 for the material above sea level. Near the center of profile A-A' (fig. 4) minor irregularities are produced by deviations of surface material from this assumed density. Profile B-B' would not be substantially changed by corrections for changes in surface density.

The Bouguer gravity anomaly relative to an arbitrary datum is shown in figure 4. A total gravity relief of about 13 milligals is present on both profiles. The dominant features are a gravity low centered over Bodega Harbor superimposed on a moderate westward increasing regional trend. The regional trend indicated by the difference in the gravity values on or near bedrock at Bodega Head and on the mainland east of Bodega Harbor is probably a combined effect of differing densities of near-surface rocks on opposite sides of the San Andreas fault and deeper mass anomalies. The local gravity low is probably directly or indirectly related to the fault zone.

The character of the gravity variations along the two profiles are similar. The flattening at the ends of both gravity profiles suggests that the profile extends beyond the range of effect of the low-density mass causing the local gravity low. A line connecting the lowest anomaly values on both profiles is parallel to the fault zone. Both profiles show steep gravity gradients of limited extent which must be produced by near-surface mass anomalies. For interpretative purposes, profile B-B' was selected. It is more nearly a straight line, and there is less local surface relief in the vicinity of the local gravity low.

Two causes are suggested for the gravity low: 1) low density sediments deposited in a depression along the fault zone, and 2) low density rocks within the fault zone. The average density of the undisturbed rocks adjacent to the fault zone and water saturated sedimentary deposits along the zone are estimated to be, respectively, about 2.7 and 1.8 g per cm^3. If a linear regional gradient is removed from profile B-B' the residual gravity low of 9 milligals could be produced by a thickness of about 1,000 feet of sediments 0.9 g per cm^3 lower in density than the enclosing rocks. If the sediments are assumed to be 400 feet thick under the center of the profile then a 5-milligal gravity low remains to be explained by rock in the fault zone. The density of sheared rock may be as low as 2.2 g per cm^3. A thickness of less than 2,000 feet of this material could produce the 5-milligal anomaly.

Although an analysis of the gravity data alone will not yield a unique solution for the negative mass anomaly producing the low along profile B-B', two inferences are justified. First, the limited extent of the gravity anomaly requires that the low density material be within a few thousand feet of the surface. Second, the steep gravity gradient measured 4,500 feet east of B indicates a steeply dipping density interface. This could be either an increase in the slope of the base of the sediment or the western margin of low density rock in the fault zone. A similar break occurs about 3,000 feet west of B'. A preferred interpretation of the gravity data, but not the only one, is that the unconsolidated sediments thicken eastward from Bodega Head to a point about 4,500 feet east of B. East of this point the sediments either thicken abruptly or are underlain by sheared rocks in the fault zone. If the sheared rocks are the cause of part of the anomaly they must increase in density with depth so that most of the density contrast across the fault zone has disappeared at a depth of 5,000 feet. East of a point about 3,000 feet west of B', the sediments either thin abruptly or the sheared zone terminates.

The total magnetic intensity was measured along one profile across the fault zone near Bodega Head (fig. 5) in conjunction with an aeroradioactivity survey flown in 1959. The flight level was 500 feet above the ground surface. A magnetic high of about 12 gammas was observed across the fault zone. With only one profile available it cannot be determined if this small anomaly is elongated parallel to the fault zone. The eastern edge of the magnetic high correlates with the eastern edge of the gravity low suggesting that the two anomalies may have a single source. No significant change in the magnetic profile is apparent on the west side of the fault zone.

FAULTS WEST OF THE SAN ANDREAS FAULT ZONE

The report on the 1906 earthquake (Lawson and others, 1908) mentions that breaks in the bedrock appeared outside the zone of marked fault topography. Most of these were incipient landslides but some apparently were not. G. K. Gilbert, on page 75 of this report, describes features near Mount Wittenberg, which is 1¼ miles west of the 1906 trace and about 25 miles southeast of Bodega Head:

"On Mount Whittenberg there are two bedrock cracks. One of these crosses the northeastern spur of the peak near its junction with the main crest. Its trend is approximately northwest and southeast and at one point it margins a fault-sag. As it assumes in one place the ridge phase of the fault-crop, I infer that it has horizontal displacement. On the opposite side of the main crest is a crack which was traced for about 1,000 feet. Its general course is northwest-southeast, but it is not straight and exhibits a vertical throw of 1 or 2 feet to the southwest. At one point it touches a fault-sag. Between these two long cracks a group of short cracks occurred, with a similar trend, on a knob constituting a portion of the main divide.

"About 6 miles farther south, at the head of Pine Gulch Creek, another road crosses the range, and in following this a group of cracks was seen. A short distance west of the divide, and about a mile in a direct line from the fault-trace, is a fault-sag trending northwest-southeast. On each side of it a crack was seen, the eastern crack being the wider and showing a small throw to the southwest. This crack was traced for about 0.75 mile and found to curve through an arc of nearly 90° from southeast to southwest. At its southwest end, or at least the southwestern limit of tracing, it is on a ridge, and it there expands into, or else is replaced by a group of cracks diverging fan-wise. On each member of the group faulting took place, the downthrow being toward the northwest except in the case of two apparently short cracks with downthrow to the southeast. On four of these cracks the throw was greater than 1 foot, and at one place it was about 5 feet. Each crack was associated with a pre-existent bluff or scarp, indicating that earlier movements have occurred at the same place. The field in which the principal phenomena occur is cultivated with the exception of the steeper scarps, whose faces retain a bushy growth."

Roderic Crandall (in Lawson and others, 1908, p. 253) describes cracks on Sawyer Ridge, which is on the San Francisco Peninsula:

"...there were cracks several hundred feet long almost at the top of the ridge. These were parallel to the line of the main fault, which is a mile to the east, and there was a marked downthrow of from 2 to 3 inches on the southwest side, which in this case was the uphill side. If the downthrow were on the downhill side, then it could be possible that these were landslide cracks."

The descriptions quoted above suggest that active faulting can occur outside the generally accepted limits of the San Andreas fault zone. Although the reactor site is outside the fault zone, examination of the excavations at the site has failed to reveal conclusive evidence of faulting in the sedimentary deposits overlying the granitic rock. As stated elsewhere in this report, the sediments overlying the granite are generally intact and the few breaks in them can be explained by causes other than faulting. In the vicinity of Horseshoe Cove, some linear features trending southeastward can be seen on the ground and on aerial photographs taken in 1954. One depression, less than 1 foot deep and about 4 feet wide, extends southeastward from the Cove for about 100 feet. Southeast and east of the Cove are very low and poorly defined linear ridges which also trend southeastward. Terrace deposits are well exposed on the east and south sides of the Cove and examination of them along projections of the linear features failed to show any faults in the sediments. Although the exposure is not entirely continuous, there is little doubt that the beds that crop out on the east continue around the south end of the Cove, where they overlie the quartz-diorite. The linear depression and ridges trend S. 52° E., which is also the trend of the longitudinal sand dunes east and south of the Cove. The linear features near Horseshoe Cove are probably related to wind action, possibly modified by cattle making their way to the spring at the south end of the Cove.

The possibility should be considered that a branch of the San Andreas fault might lie west of Bodega Head and that it either parallels the San Andreas or curves southeastward and joins the San Andreas at the mouth of Tomales Bay. A parallel fault would cross the Point Reyes Peninsula, and the Fault Map of California published by the Seismological Society of America in 1922 shows two faults on the peninsula nearly parallel to the San Andreas. However, the map explanation indicates these as probable faults of uncertain character and location, and the existence of the faults has not been substantiated by subsequent geologic mapping (Weaver, 1949; Galloway, 1962). We find no evidence to support the hypothesis of a fault curving southeastward to join the San Andreas at the mouth of Tomales Bay.

The Fault Mapped by F. A. Johnson near the Southwest Shore of Bodega Head

A geologic map accompanying a paper by F. A. Johnson (1943, p. 624) on the geology of a portion of Sonoma and Marin Counties shows a fault having a strike of N. 47° W. (more or less parallel to the San Andreas fault zone) cutting both the quartz diorite and the terrace deposits on the southwest part of Bodega Head and emerging along the south and west shore. We examined the shore at and for several hundred feet on either side of the fault location shown by Johnson. (Traverses are shown on figure 1.) No faults were seen in sediments that discontinuously overlie quartz diorite along the shore, however, numerous faults were seen in quartz diorite and related rocks along these stretches of shore. The faults show a great range in orientation and magnitude of movement. To illustrate this, the faults observed along the south shore (traverse D-D', fig. 1) are recorded in table 1. An earlier traverse (C-C', fig. 1) failed to show a fault in the location along the western shore as shown by Johnson.

Several faults listed in table 1 and one fault seen on traverse C-C', figure 1, have approximately the same orientation as the fault mapped by Johnson, and a zone of closely jointed rock was observed on the south shore near the point where Johnson mapped the fault. Table 1 and figure 13, however, show numerous other faults having drastically different orientations, and we found no compelling geologic evidence for mapping a fault in the location and with the attitude as mapped by Johnson in preference to numerous other locations and attitudes.

Table 1.--Fault zones observed in quartz diorite on traverse east of southernmost point of Bodega Head

Approximate distance in feet from Point D on figure 1 as measured along shore	Strike	Dip	Remarks
130	N. 80° W.	60° S.	1-inch clay gouge.
160	N. 10° E.	80° W.	1-inch clay gouge.
190	N. 75° E.	90°	3-inch, 1/2- to 1-inch, and 1/4 inch clay gouge in 14-inch mylonite zone.
220	N. 30° W.	70° E.	1- to 1/2-inch clay gouge.
320	N. 65° W.	70° - 85° W.	Numerous 1- to 3-inch shears, joints, and clay gouge zones stained brownish gray across a total zone width of 8 feet. Rock between shears, etc., is fresh and unbroken.
556	N. 70° W.	70° E.	A zone about 10 feet wide consisting of several 2- to 3-foot-wide zones of mylonite and breccia and intact rock. Slickenside striation on main shear surfaces oriented in many directions from horizontal to vertical.
640	N. 45° W.	90° - 80° E.W.	Hard mylonite, minor clay gouge in 18-inch-wide zone.
655	N. 50° W.	90°	Clay gouge and mylonite in zone 1 to 3 inches wide. Vertical slickenside striations.
685	N. - S. (?)	40° E. (?)	Mylonite zone 3 to 5 inches wide.
705	N. 50° W.	90°	Clay gouge and mylonite zone 1 to 6 inches wide. Displaced 18-inch pegmatite dike about 3 inches.

Table 1.--Fault zones observed in quartz diorite on traverse east of southernmost point of Bodega Head--Continued

Approximate distance in feet from Point D on figure 1 as measured along shore	Strike	Dip	Remarks
755	N. 50° W.	15° E.	Mylonite 1 to 2 inches wide; no clay gouge. Upper plate moved to west. Average fracture spacing of upper plate 1 to 3 inches; lower plate 1 to 2 feet.
805 (due south of hill 200)	N. 50° W.	75° W. (?)	Zone of close fracturing and rock slide 30 feet wide. Contains a few braided 1- to 2-inch-wide zones of clay gouge. Fracturing in rock is almost random and pieces are 2 to 3 inches in size compared to 0.6 foot to 4 feet in adjoining rock. Pieces of fresh-appearing rock are easily broken with geologic pick.
810	N.-S.	45° - 60° E.	Mylonite zone 1 to 4 inches wide.
860	N. 45° E.	75° W.	1-inch clay gouge; cuts two pegmatite dikes that are 1 to 2 feet thick. Displacement 6 feet either by upper plate moving up or by right lateral movement.
1,030	N. 25° W.	70° W.	Clay gouge and mylonite, 1/2 inch to 3 inches wide. Offsets 14-inch-wide pegmatite near beach level. Displaced dike not seen.
1,060	N. 70° E.	85° E.	Braided gouge and mylonite zones, 1/4 inch to 3 inches wide in zone 2-1/2 feet wide. Parallel to prominent joint set, foliation of small fine-grained dark inclusions and several 6- to 8-inch pegmatite dikes.
1,160	N. 70° E.	40° W.	Mylonite and clay gouge 1/2 to 1 inch wide. Can be seen for 250 feet on headland.
1,175	E.-W.	70° N.	Clay gouge and mylonite 2-1/2 foot wide zone near end of headland.

QUARTZ DIORITE AND RELATED ROCKS

The granitic rock of Bodega Head is mostly a coarse-grained biotite-hornblende quartz diorite. Part of it is slightly foliated, as is shown by the more or less planar arrangement of the dark minerals and feldspar, and part of it is unfoliated. Elongated dark inclusions of fine-grained rock, generally 1/4 to 1 foot long and 1 to 4 inches wide, are common in the quartz diorite and are generally alined with the foliation of the matrix rock. Nearly black, coarse-grained inclusions of irregular shape and from 2 to 10 feet in diameter were seen in two places in the quartz diorite on the shore west and south of the site. Pegmatite dikes are common. They range in width from an inch or two to about 3 feet. Osmont (1905, p. 43) saw one 7 feet wide on the southeast shore of the Head. Pegmatite dikes in foliated quartz diorite are not foliated. This indicates that the foliation developed before the pegmatite material filled the joints in which they lie.

Specimens of granitic bedrock from five localities at and near the site were studied microscopically by means of thin sections and by embedding grains in refractive index oils, and megascopically by use of feldspar staining on sawed pieces. Most of the granitic rock seen at the Head is a biotite-hornblende quartz diorite consisting mostly of plagioclase feldspar, lesser amounts of quartz, biotite, and hornblende and minor amounts (1 to 3 percent) of small orthoclase feldspar crystals. Specimens collected on the west shore about due west of the site contain about 25 percent coarse-grained orthoclase crystals; their mineral composition indicates that they are quartz monzonite or adamellite but the abundance and distribution of these rocks on the Head are not known. Spotts (1962, p. 1223) sampled the granitic rock at four places in the area between Mussel Point and the south shore of the Head. He found them all to be quartz diorite. Texturally the granitic rocks are coarse grained and hypidiomorphic granular in which only part of the minerals are bounded by crystal faces. Quartz shows wavy extinction and also mosaic breccia texture. Feldspars show a slight alteration, but not more than that shown in typical fresh granitic rock.

The small dark inclusions contain the same minerals as the enclosing quartz diorite matrix, but they are finer grained and contain more biotite and hornblende. No feldspar is present in the large dark irregular inclusions. They consist of biotite, hornblende, and quartz and minor apatite, garnet, and zircon.

The pegmatite dikes are generally zoned and consist of margins of graphic granite or quartz and plagioclase and a core of large pink potassium feldspar crystals and minor biotite.

The granitic rock exposed at high tide on the western and southern shore of Bodega Head generally shows little or no signs of chemical alteration. The rock above, about 20 feet above high tide, shows signs of alteration due to weathering which is progressively more advanced toward the top of the sea cliff. Near the top, the texture of the quartz diorite has disappeared, and the rock has been weathered to a sand-silt-clay soil. On the south shore of Campbell Cove near sea level the quartz diorite is covered by Pleistocene gravels.

Joints and faults are common in the granitic rock of Bodega Head, although they vary greatly in abundance from place to place. Most of the rock is broken by joints into blocks 3 to 5 inches wide; however, rock with joints 1 to 2 feet apart is not uncommon, and rarely a mass of rock has a joint spacing as much as 4 feet. Closely jointed rock is cut by four or more sets of joints and also by irregularly branching joints. In less jointed rock only one or two prominent sets of joints is the rule. Orientation of prominent joints varies greatly between closely spaced localities. Along the Pacific Ocean shore, west of the site, prominent north-south joints at one place are replaced by prominent east-west joints 500 feet away. Figure 6 shows strong, steeply dipping joints oriented about N. 70° E. in the headland south of hill 200.

Spacing, type, and orientation of faults is highly variable from place to place. Most abundant are sharp breaks with offsets of 2 to 12 inches. Spacing is about 1 foot apart where they are abundant, but is greater in most rock. Many of the small faults are clean, or have a 1/4 to 2-inch zone of breccia (coarsely broken rock), mylonite (pulverized but firm rock), or gouge (clayey material of pulverized and chemically decomposed rock). In some places a zone as much as 10 feet in width consists of closely spaced breccia, braided and interwoven thin mylonite and gouge zones, and blocks of relatively unbroken rock bounded by slickensided surfaces. Such disturbed zones are 30 to more than 100 feet apart. Breccia zones, 1 to 3 feet wide, of granitic rock cemented in a granitic rock matrix are found in only one of two places. Movement of these took place before complete solidification of the granitic body. Table 1 gives spacing and descriptions of prominent fault zones seen on shore near sea level between the southernmost point of Bodega Head and the headland south of hill 200.

The magnitude of movement of faults can be measured directly by noting offsetting of pegmatite dikes or dark inclusions. Although most faults show only a few inches of offset, some show 4 to 8 feet. On a few faults the dike or inclusion is offset beyond observation at the shore; the total movement for some of these was greater than 20 feet. Faults bounding foliated and unfoliated rock or closely fractured and relatively unfractured rock also indicate considerable movement of unknown magnitude, but probably greater than 10 to 20 feet.

No persistent orientation of faults was seen in the granitic rock of Bodega Head, though locally, over a distance of 50 to 200 feet, some but not all of the faults are more or less parallel. Neither is there a systematic pattern of fault displacement as shown by slickenside striations even within a 4- to 8-foot-wide zone of faults.

GEOLOGY OF THE SITE AND VICINITY

The site is located on a buried valley cut in quartz diorite and filled with Pleistocene and Recent deposits. Borehole investigations by Dames and Moore (1962, plate 2) show that through the central part of the Head the valley trends easterly; near the southwest corner of the excavation boundary of the site, it trends northeasterly. The deepest part of the valley penetrated by the borings is near the east end of the south face of the excavation where 178 feet of Pleistocene and Recent deposits were penetrated. These deposits become thinner up the slopes of the bedrock valley and cover quartz diorite to an elevation of approximately 135 feet on hills 238 and 200.

In the east half of the north face of the site excavation a spur of quartz diorite has been exposed whose axis (the line connecting high points) plunges southeastward (fig. 3, 7, 8). The highest part of the exposure is at an elevation of approximately 65 feet above mean sea level at a point about 110 feet east of the northern target marking the centerline of the reactor; the exposure is 189 feet wide at an elevation approximately 37 feet above mean sea level. The surface of the quartz diorite is generally irregular. Near the top of the spur the local relief is about 5 feet.

The bottom of the buried valley near Campbell Cove is approximately 60 feet below sea level. The valley was probably eroded to that depth during a continental glaciation when sea level was several hundred feet lower than it is at present. The glaciation was probably older than the last one, the Wisconsin, which reached its maximum about 20,000 years ago, for fossil wood that accumulated above the valley floor is older than 38,000 years.

Exposure of Pleistocene and Recent deposits in the site excavation afford a fine opportunity to investigate faulting later than the deposition of these deposits. This is particularly true of the north face of the excavation, at the contact between the quartz diorite and the sediments. If faulting occurred through the site parallel to the trend of the San Andreas fault zone, displacement of beds should be observable in the north face; if faulting occurred at large angles to the San Andreas, displacement should be observable in the west face of the cut. Faults dipping at low angles and transecting the sediments below about 30 feet above sea level would not have been evident in any face of the excavation.

Quartz diorite at the site

In May and early June 1963 the quartz diorite was exposed only on the north face of the site excavation, where its surface reaches an elevation of about 65 feet above mean sea level. Though the quartz diorite texture is preserved, rock in the face is decomposed, mostly by weathering, to a weakly to moderately well indurated material. The deeper rock tends to be less altered and more coherent, though pegmatitic rock is relatively little altered even at the highest exposures of the granitic rock.

Figures 7 and 8 show the location of the more prominent faults in the quartz diorite exposed in the north face. Details of texture and structure such as joints and faults were clearly revealed by washing the face with water. This was done June 5-6, 1963, after figures 7 and 8 were photographed. Most of the faults are oriented between N. 30° W. to N. 83° W. and dip 65° to 80° eastward, and most have 1/2- to 3-inch-wide gouge zones. The zone near the right hand edge of figure 7 consists of several braided and branching 1- to 3-inch gouge zones within a zone 4 to 7 feet wide of hydrothermally altered quartz diorite, which is somewhat more friable than that adjoining. Except for the faults noted in figures 7 and 8 the quartz diorite in the north face of the excavation, though decomposed, is not jointed and faulted more than the average rock seen near sea level on the western and southern shore of the Head. Directions of fault movement as shown by striations on slickensided fault surfaces are mostly parallel to the dip, though some are more or less parallel to the strike.

Quartz diorite in the proposed reactor excavation

Plates 3 and 4 of the April 30, 1962 report by Dames and Moore show granitic rock in the bottom 26 to 42 feet of the proposed reactor excavation. Their conclusions are based on a borehole investigation and appear to be a reasonable interpretation of their observations.

On May 23, 1963 we examined core obtained by Dames and Moore in borehole 16, located at the center and extending to about a foot above the bottom of the proposed reactor excavation, and from borehole 14, located at the south edge and extending to about two feet above the bottom of the proposed reactor excavation. NX-size core pieces (2-1/8 inches in diameter) obtained 1.5 to 6 feet above the bottom of the proposed reactor excavation (borehole 16) were between 1 and 2 feet long. The rock is slightly foliated, coarse-grained biotite-hornblende quartz diorite. Although sound, the rock is not quite as fresh-appearing as rock exposed at sea level on the western and southern shore of the Head in that the plagioclase feldspar appears more chalky white in the core. This was confirmed by microscopic examination of thin sections of a core piece from depth 155.5 feet (1.5 feet above bottom of proposed reactor excavation) given to us through the courtesy of J. Dean Worthington, Chief Civil Engineer, Pacific Gas and Electric Co. Thin sections show the feldspar, biotite, and horneblende to be slightly more weathered than that of the rock collected from outcrops on the shore.

The bottom 39 feet of borehole 16 (elevation - 27 to - 66) was cored. Rock from core 6 to 9 feet above the bottom of the proposed reactor excavation is broken into 2- to 3-inch blocks by joints or shear zones both parallel to and at 45° from the vertical core axis. Core rock from 9.5 to 22 feet above the bottom of the reactor excavation is not quite as fresh as rock below. Core lengths broken by joints or shears, mostly lined with chlorite, have an average length of 4 to 6 inches and a maximum length of 1 foot. Rock from core 22 to 39 feet above the bottom of the proposed reactor excavation is somewhat more weathered and considerably more fractured than deeper rock. Average length of pieces in the top 10 feet is about 2 to 3 inches; 14 feet from the top of the core, it is 5 to 7 inches. The rock is cut by numerous clay- and chlorite-lined fractures of various orientations. Their orientation is nearly vertical about 5 feet below the top of the core. A clayey zone of unknown thickness, from which 3 inches was recovered was penetrated about 11 feet from the top of the core.

Granitic rock from cores recovered from borehole 14 is fairly sound, but core pieces are broken into 3-inch lengths by clay- and chlorite-lined joints. The rock is generally more sheared than rock penetrated by the bottom 22 feet of borehole 16.

Rocks such as quartz diorite of Bodega Head typically extend to depths of thousands of feet beneath the earth's surface. The physical integrity of the rock generally improves with depth; that is, effect of weathering is less pronounced, jointing is less intense, and the physical strength increases. No geologic evidence has been found to indicate that the quartz diorite is not typical in this respect.

Pleistocene and Recent deposits at the site

Prior to excavation of the plant site, Pleistocene and Recent deposits were reported by Dames and Moore to cover the quartz diorite to a maximum thickness of about 180 feet. In the north and west faces of the site about 60 feet of sediments are revealed, mostly beds of clayey sand, silty sand, sand and lesser amounts of sandy silt, sandy clay, and organic sandy clay. The top layer is 5 to 8 feet thick and consists of dark-gray to grayish-brown, friable to loose, gravelly, silty sand. The sand grains are well rounded, fairly well sorted, and have frosted surfaces coated with a thin layer of carbonaceous material. Root holes and scattered pebbles of quartz diorite are common. The layer is thought to represent a mixture of windblown sand and soil developed on the underlying material and on windblown sand. It grades downward to a dark yellowish-orange, fine- to coarse-grained, clayey, friable sand, of variable thickness, up to 40 feet, and variable clay content, permeability, and bedding.

Tentatively the Pleistocene-Recent boundary is placed at a horizon at or near the base of the top layer, mostly of wind-blown sand which here overlies sediments that are mostly water-deposited. Samples of wood from the water-laid material are now being analyzed for carbon-14 content in order to determine the age of the deposits. Results may necessitate modifications of this conclusion. Most of the underlying

Pleistocene deposits are believed to be marine terrace deposits or beach deposits. Detailed stratigraphy has not been obtained.

Immediately overlying the quartz diorite in many places is a greenish gray, poorly sorted, gravelly, clayey sand of irregular thickness as great as 40 feet. It is generally without bedding, but in some places it grades laterally and vertically into slightly better sorted material with moderately well developed beds 1/8 to 2 inches thick. The sand and gravel grains are obviously derived from quartz diorite and the deposit undoubtedly represents soil that developed on quartz diorite and was transported short distances largely by gravity or by water currents. In some places, where the soil formed by weathering remained in place, the quartz diorite grades into this material and it is difficult to find the rock surface.

On the south shore of Campbell Cove the quartz diorite is covered, a few feet above sea level, by a sandy gravel bed about 4 feet thick made up of well-rounded pieces having an average diameter of 2 inches, maximum diameter 8 inches, in a sandy matrix.

In exposures near sea level on the western and southern shore, old marine terrace materials are found deposited against former sea stacks of quartz diorite.

In some places the greenish gray clayey and sandy material has been eroded from the quartz diorite surface and younger sediment has been deposited on it. This condition is shown on the righthand half of figure 7. The large wedge-shaped deposit labeled (1) is a yellowish brown, poorly cemented, highly permeable, well-bedded, medium-to coarse-grained sand. It lies partly on quartz diorite and to the left (west) on extensively gullied clayey sand. The dark patch labeled (2) is a remnant of the massive greenish-gray, clayey sand that was protected from erosion before the deposition of the overlying sand because it lies in a depression in the quartz diorite surface.

The extensively gullied deposits on figure 7 west of the sand wedge labeled (1) are mostly light-brown to yellowish-brown, clayey, gravelly, coarse-grained sands. The clay content ranges from about 3 to 20 percent. Part of the deposits are well bedded and part are massive, poorly sorted, and contain angular quartz diorite debris as large as 1 inch in diameter. Detailed views of it are shown in figures 9 and 10; their location on the excavated face is shown on figure 7. As is seen in figures 9 and 10, the bedding is irregular and part of the deposit is cross-bedded. It is thought to have been derived from erosion of debris lying on the quartz diorite slope immediately north of the site.

Figure 9 and 10 show details of the bedding of Pleistocene deposits at the site and suggest the relative ease with which the sediments could be examined for evidence of disruption by faulting.

A 3 1/2-foot thick black organic layer consisting of tree fragments in a matrix of peaty clay and sandy clay was encountered in a low temporary face about 150 feet south of the north face (fig. 11). Elevation of the top of the layer at the stadia rod on the left (east) side of figure 11 is 46.1 feet above mean lower low water (MLLW). The deposit evidently did not reach the area of the north face. Stratigraphically equivalent beds in that face probably lie between 60 and 70 feet above MLLW.

The layer contains remnants of what are believed to be tree roots in place, though the tree limbs, which reach a diameter of 1 foot, now lie parallel to the bed. Although this bed could not be followed continuously because it was concealed by vegetation and soil, it may extend 550 feet southeastward to the sharp bend of Campbell Cove, where it may be represented by a 1-foot-thick black organic layer adjacent to a layer containing two tree trunks, each about 2 feet in diameter and at least 6 feet in length lying parallel to the bedding.

The organic layer is believed to represent either a forested tidal marsh deposit, possibly where trees were inundated by rising sea level, or a fresh water lake in a forested area. In either situation the original bedding must have been virtually horizontal. The deposit now dips from 5° to 8° to the southeast. Dips of 4° to 5° were measured from this bed to the tree-bearing layer in Campbell Cove. Except locally, most beds exposed in the north face show a general dip between 2° to 10° to the south and east. Some of the dip of these beds is the original depositional dip because the materials were transported and accumulated on the southeast slope of hill 238. Nevertheless, the dip shown by the organic layer is proof that all the beds have been tilted southeastward since they were deposited.

Age of the deposits

Fossil wood from the black peaty organic layer at elevation 49.2 feet above MLLW (sample no. 1279) was analyzed for its radiocarbon age (fig. 12). Results received from Meyer Rubin of the U. S. Geological Survey's Washington, D. C. laboratories, indicate an age in excess of 38,000 years. Isolated tree limbs are also found scattered at several horizons in the sediments of the north face. The highest and, presumably, the youngest one was found at an elevation of 75 feet MLLW. It and another piece of wood from elevation 55 feet MLLW have been submitted for radiocarbon dating with the hope that an estimate will be derived from them on the rate of accumulation of the terrace deposits. Bone fragments as yet unidentified were found on the quartz diorite surface in the north face.

Structures in the Pleistocene deposits at the site

Pleistocene beds in the north and west faces and temporary faces 150 to 300 feet south of the north face were examined for possible disruption of bedding due to faulting. No faulting was found, though some disturbance of bedding from other causes was seen. If faulting took place in the area of the north and west faces during the last 38,000 years, the sediments in these faces should show disruption by such faulting. Lack of disruption by faulting strongly suggests that none took place at these faces during the last 38,000 years. The walls of the largest gully, a few feet above quartz diorite, seen on figure 8 reveals joints in friable beds 1/4 to 1 inch thick of medium to coarse sand and sparse 1/4- to 1-inch-thick layers of 1/4-inch size quartz diorite debris. About six joints were seen in the sediments of this gully. Most are 4 to 6 inches from each other, although three 1 foot apart were seen. They are about 2 mm wide and are filled with fine-grained sand. Most of them dip southward from 15° to 80°. Their strike orientation is difficult to measure, although one was exposed and had a strike of N. 80° W. and a dip 70° to 80° S. One that could be followed for 5 feet varied in dip from 15° to 40° southward. Beds are not disrupted across them.

Along one clean break that had an approximate strike of due west, dip 50° S., beds were displaced about 1 inch vertically through an interval of about 1 foot. One foot above the offset beds, however, the beds were not disturbed and therefore this displacement is believed to be caused by compaction of sediments.

Joints with no offsetting of beds are present in the bedded sediments that are about 5 feet above the quartz diorite surface and appear dark gray in figure 8 from 20 to 30 feet west of the largest gully.

Faults in the quartz diorite and details of the quartz-diorite surface in the north face were revealed by washing down with water. The faults were traced to the top surface of the quartz diorite, but none of them showed fault offsets in the overlying sediments. In many places the surface of the quartz diorite was found to be very irregular. In about four places the top of the quartz diorite was a stripped fault surface. The righthand side of the area labeled "2" in figure 7 is an example. It is clear that in all of these places some quartz diorite adjoining a fault surface was detached and removed, possibly by wave action at the shore, before sediments were deposited above the fault. In one place, where about 2 feet of quartz diorite was removed from one side of a fault before sediments were deposited, a bed 6 inches above the quartz diorite was offset by about 3/4 inch, although the beds about 3 inches stratigraphically higher and above were not disrupted. The offset here is interpreted as due to differential consolidation of sediments, for sediments on the down-dropped side of the slight break are about 2 feet thicker than those deposited on the other side of the fault-line scarp in the quartz diorite.

The possibility that fault movement of 1 or 2 inches in quartz diorite can be accomodated by and disappear in a few inches of unconsolidated sediment cannot be precisely evaluated, but it is believed to be highly unlikely.

Nearly vertical portions of the quartz diorite - sediment contact in the north face are similar to contacts of sediment against former sea stacks seen along the western and southern shore. Furthermore, similar relationships are being created today as modern sediments are deposited offshore against vertical or even overhanging cliffs of quartz diorite.

POSSIBLE FAULT CONTROL OF THE SOUTH SHORE OF CAMPBELL COVE

The nearly straight south shore of Campbell Cove and the nearly coincident alignment of the buried valley cut in quartz diorite at the site suggest possible control by a fault. No evidence for such a fault was seen in the quartz diorite and overlying sediments along the south shore of Campbell Cove, although the exposures are poor and it would be difficult to see such evidence there. Neither was evidence found in quartz diorite exposed on the western shore of Bodega Head on a line extended westward from the south shore of Campbell Cove. No faults were seen in the sediment covering the quartz diorite at the south end of the west face of the site excavation, where such a fault would be expected to pass.

ROCK-CUT TERRACE

A terrace cut in granitic rock was observed at several places along the west and south shore of Bodega Head. It appears to be absent along the eastern shore, though it may be at or below sea level there. It slopes seaward from an elevation of 10 to 20 feet above MLLW at the base of the sea cliff to about 5 feet above MLLW about 50 to 100 feet from the sea cliff. Where it is highest and closest to the base of the sea cliff, it is generally overlain by sand and gravel beds several feet in thickness. Inasmuch as the terrace was cut at or near sea level, its presence indicates an uplift of Bodega Head since it was cut; however, no data were obtained on the age of the cutting. David Hopkins, geologist, U. S. Geological Survey, suggested to us that the terrace was probably cut at a high stand of the sea during the Sangamon Interglaciation, about 100,000 years ago, and that the sediments that lie on it may have been deposited during the following Glaciation, the Wisconsin. It may have been uplifted when the sediments at the site were tilted, but no data on the age of the tilting were obtained. Tilting may also account for the absence of a wave-cut terrace on the east side of Bodega Head, although it may be absent there because wave attack on the east side of the Head was weak.

Uplift of the rock-cut terrace and tilt of the deposits lying on quartz diorite at the site, both of which may have been caused by the same crustal movement, are believed to have been gradual over the entire site.

FAULTING THROUGH THE SITE DURING FUTURE EARTHQUAKES

Although the portions of the San Andreas fault zone that were active in 1906 are more than a mile from the site according to published reports (Lawson and others, 1908), it is not possible to say that future faulting will take place only in the zones of recently active faulting. The entire fault zone must be considered highly susceptible to active faulting. The fault zone has been a zone of weakness for a long period of time, perhaps as long as 80 million years. Presently existing or future differential tectonic stresses on the two principal blocks of rock on either side of the fault are most likely to be relieved by rupturing somewhere in the fault zone, rather than by rupturing of the rock on either side of the fault zone.

Although it can be argued that the fault has, over the period of its active life, gradually grown from a single fracture of infinitesimal width to a zone of crushed and broken rock a mile or more in width and must, therefore, have incorporated blocks of sound rock during some episodes of faulting, it is nevertheless extremely improbable, now that the fault zone is well established, that future major faulting would pass through the rock of Bodega Head in preference to the weak crushed material of the fault zone itself. On the other hand, if the fault scarps reported at the time of the 1906 earthquake south of Mount Wittenberg (discussed earlier in this report) actually cut the quartz diorite, it opens up the possibility that such a phenomenon could occur on Bodega Head at the time of same future earthquake.

CONCLUSIONS

On the basis of field investigation, a review and appraisal of reports on the site and published scientific literature on the area, and an examination of core samples from boreholes at the center and near the south side of the proposed reactor excavation, the following conclusions are drawn:

1. The sediments overlying quartz-diorite bedrock at the site, the oldest of which were deposited more than 38,000 years ago, have not been displaced by faulting where they are exposed in the north face of the site excavation between 30 feet above sea level and 115 feet above sea level. Thus no faults active in the past 38,000 years and roughly parallel to the San Andreas fault zone pass through the parts of the site excavated as of June 6, 1963.
2. Quartz diorite bedrock beneath the proposed excavation for the reactor is virtually the same as that exposed on the western and southern shores of Bodega Head. The rock is jointed and faulted, and in places it probably would be necessary to remove some crushed and weathered rock from tabular zones in the quartz diorite and replace it with concrete or other suitable filling, but the rock in general is structurally sound.
3. The site is west of the San Andreas fault zone. Compelling geologic evidence is lacking for any major faults through both the granitic rocks and the overlying unconsolidated deposits of

the Head such as the fault mapped by Johnson (1943).

4. On the basis of information available on June 6, 1963, the western margin of the San Andreas fault zone is at least 1,000 feet from the center of the proposed reactor. Gravity measurements suggest that the western margin of the most intensely disturbed and crushed rock of the San Andreas fault zone is about 3,000 feet east of the proposed center of the reactor.

RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

Recently active, low-angle faults that do not show up in the faces of the site excavation could transect the proposed reactor excavation, or high-angle faults that die out between the reactor excavation and the faces of the site excavation could be present. It is therefore recommended that the excavation for the reactor be studied down to the contact between the sediments and the quartz-diorite bedrock. A careful study of this type could prove or disprove the existence of recently active faults through the proposed reactor and adjacent structures.

Investigations of the fault cracks reported by Gilbert (see p. 14 of this report) on Point Reyes Peninsula should be made to determine whether the cracks extend into the quartz diorite or are landslide or other surface features. A study of the structural relations of these features might indicate the probability of faulting through the site during some future earthquake.

REFERENCES CITED

Crowell, J. C., 1962, Displacement along the San Andreas fault, California: Geol. Soc. America Spec. Paper 71, 61 p.

Curtis, G. H., Evernden, J. F., and Lipson, J. I., 1958, Age determination of some granitic rocks in California by the potassium-argon method: California Div. Mines Spec. Rept. 54, 16 p.

Dames and Moore, consultants in applied earth science, 1960, Preliminary soils investigation and Seismic survey, proposed nuclear power plant, Bodega Bay, California: Unpublished report for Pacific Gas and Electric Company, December 2, 1960, 4 p., 17 plates.

_____1962, Foundation investigation, Bodega Bay Atomic Park, Unit No. 1, Bodega Bay, California: Unpublished report for Pacific Gas and Electric Company, April 30, 1962, 25 p., 26 plates, appendix A, 7 p.; appendix B, 2 p.

Galloway, A. J., 1961, Geology of the Point Reyes Peninsula: p. 30-34 in Land use survey, proposed Point Reyes National Seashore, National Park Service, 57 p.

_____1962, Field trip 3--Point Reyes Peninsula and San Andreas fault zone: California Div. Mines and Geology Bull. 181, p. 391-398.

Higgins, C. G., 1961, San Andreas fault north of San Francisco, California: Geol. Soc. America Bull., v. 72, no. 1, p. 51-68.

Johnson, F. A., 1943, Petaluma region, California: California Div. Mines and Geology Bull. 118, p. 622-627.

Lawson, A. C., and others, 1908, The California earthquake of April 18, 1906. Report of the State Earthquake Investigation Commission: Carnegie Inst. Washington Pub. 87, v. 1, pt. 1, 254 p.; pt. 2, p. 255-451; atlas, 25 maps and seismograms.

Osmont, V. C., 1905, A geological section of the Coast Ranges north of The Bay of San Francisco: California Univ., Dept. Geology Bull., v. 4, no. 3, p. 39-87.

Spotts, J. H., 1962, Zircon and other accessory minerals, Coast Range batholith, California: Geol. Soc. America Bull., v. 73, no. 10, p. 1221-1240.

Tocher, Don, and Quaide, William, 1960, Report on earthquake hazards at the Bodega Bay power plant site: Appendix 4 of report issued by Pacific Gas and Electric Company titled, Preliminary hazards summary report Bodega Bay Atomic Park Unit No. 1, 13 p., 2 tables, 3 photographs, 1 geologic map.

Travis, R. B., 1952, Geology of the Sebastopol quadrangle, California: California Div. Mines and Geology Bull. 162, 33 p.

Weaver, C. E., 1949, Geology of the Coast Ranges immediately north of the San Francisco Bay region, California: Geol. Soc. America Mem. 35, 242 p.

PART II--SEISMIC HAZARDS EVALUATION

by Jerry P. Eaton

The planned construction by the Pacific Gas and Electric Company of a nuclear electric power plant at Campbell Cove, Bodega Head, California, has precipitated considerable controversy over the seismic hazard posed by the nearby San Andreas fault zone to the proposed plant. Several seismologists, geologists, and engineers have prepared reports dealing with various aspects of the problem, some as consultants to P. G. and E. and some in other capacities. The present report reviews pertinent data and judgments provided by these earlier writers and offers a reevaluation of the seismic hazard to the proposed plant.

It is hoped that this review will illustrate the tenuous nature of some of the scientific judgments that must be made, these judgments then serving as the body of "fact" on which the engineering design of the plant will be based. The primary difficulty is that the seismologist is called upon to make judgments that require large extrapolations beyond his personal professional experiences and even beyond those of the science he serves. When such seismological judgments are shorn of qualifications and condensed to a convenient statement for engineering guidance, they take on an unwarranted ring of certainty that belies their shaky foundations. The thread of responsibility is broken at this step, the seismologist believing that he has handed it to the engineer, who reasonably feels that it remains with the seismologist.

There is general agreement that about once per century the San Andreas fault can be expected to shift in the vicinity of Bodega Head and to generate an earthquake comparable to that of April 18, 1906, which had an estimated magnitude of 8.2. The hazard posed by such an event to a power plant at Bodega Head has been estimated very differently by Tocher and Quaide (1960) and by Saint-Amand (1963). Two sources of danger must be considered: (1) the intense shaking of the ground at the power plant site caused by seismic waves propagating outward from the fault and, perhaps, from the actual permanent displacement (fling) along the fault of the site itself, and (2) possible dislocations within the site due to rupture by the main fault, a branch of the main fault, a minor auxiliary fault, or to landslides precipitated by shaking, etc.

Tocher and Quaide estimate that such an earthquake would produce a maximum Modified Mercali Intensity of about VIII on the quartz diorite bedrock at the site and an intensity as high as MMX in the fault zone itself. They conclude that the power plant structures should be designed to resist an earthquake of MMVIII, or to provide a margin of safety, MMIX.

Saint-Amand estimates a minimum intensity of MMIX on Bodega Head for an earthquake comparable to that of 1906. If important landslides were to occur during the main earthquake he would anticipate an intensity of MMX, and if major faulting on the Head were to occur during the main earthquake, MMXI. In support of these estimates he cites Richter's (1958) average expected maximum MM intensities for average ground conditions in metropolitan centers of California: MM VII to VIII for magnitude 6, MM IX to X for magnitude 7, and MMXI for magnitude 8.

Because recorded maximum intensities of the 1906 quake near Bodega Bay appear to have been somewhat smaller than Richter's averages would suggest and because the plant would presumably rest on the quartz diorite bedrock, MMIX appears to be a reasonable estimate of the 1906 intensity at the site. With the normal variation in intensity along the fault resulting from variations in local conditions, amplitude of slip, etc., intensities as large as MMX at the site from earthquakes no larger than magnitude 8.2 cannot be ruled out.

Peak ground accelerations that should accompany the foregoing intensities can be estimated from Gutenberg and Richter's (1942) semi-empirical relationship $\log a = 1/3 - 1/2$. MM VIII, IX, and X yield accelerations of .15 g, .32 g, and .69 g, respectively.

Housner (1961) approached the question of maximum expectable acceleration more directly. Estimating the probable length of fault break on the San Andreas required to produce earthquakes of magnitudes of 7.0 and 8.2, and assuming the same depth of break in both cases, he deduced that the intensity of shaking at the center of a magnitude 8.2 earthquake fault break should not be appreciably greater than that at the center of a magnitude 7.0 earthquake fault break. This argument assumes that the energy liberated per unit area of fault surface is the same in both cases and notes that the extra faulting required for the magnitude 8.2 earthquake lies more than twenty-five miles from the center of the break.

Saint-Amand pointed out that the foregoing result conflicts with the common observation that larger intensities are indeed observed for larger earthquakes. I suggest that the very definition of magnitude and the seismologist's ability to compute magnitudes from relatively short period body waves indicate that the amplitude of waves radiated from relatively small areas of the fault surface increases approximately ten times between magnitude 7 and magnitude 8.

An accelerogram of the magnitude 7.0 El Centro earthquake of 1940 was obtained about five miles from the end of the fault break at a station on deep alluvium. Housner estimated that if the fault had broken another fifty miles beyond the point of measurement the measured accelerations would have been forty per cent greater. He also estimated that ground motion on a granite outcrop would have been about one half as great as that measured on the alluvium. From these considerations Housner concluded that the El Centro accelerogram, with a maximum acceleration of 0.3 g, was a reasonable match for one that might be recorded at the Bodega Head site during a magnitude 8.2 earthquake originating on the nearby San Andreas fault. It appears that Housner's probable underestimate of the increase in maximum intensity between earthquakes of magnitude 7.0 and 8.2 is largely compensated by the underestimate of ground motion amplification in the sediments beneath El Centro.

Thus, we see that estimates of expectable earthquake accelerations at the Bodega Head site range from less than 0.2g (Tocher and Quaide) to 1g (Saint-Amand). It appears to me that an earthquake similar to that of 1906 would produce peak accelerations between 0.3 and 0.7g, and values approaching 1g are not impossible.

The second aspect of seismic hazard to the site, possible dislocations in the site or adjacent parts of Bodega Head during a major earthquake, is even more difficult to evaluate, and widely different opinions have been expressed. In the more common approach to this problem (Tocher and Quaide, Schlocker and others) it is assumed that the site is "safe", despite its immediate proximity to the San Andreas fault zone, if no positive geologic evidence for recent faulting on Bodega Head can be found.

It is generally agreed that the quartz diorite bedrock of the Head is intensively fractured, sheared, and offset along minor faults. Saint-Amand argues on the basis of aerial photographs and a brief field trip to the area, that several faults large enough to exert visible control over topographic features traverse Bodega Head. He considers these faults to be a real hazard to the proposed power plant. In possible vertical offsets of a recently elevated wave platform and possible horizontal offsets of some subtle linear soil features (elevated shorelines?) observed on aerial photographs, he sees evidence for recent movements along the faults.

From somewhat more detailed fieldwork, first Tocher and Quaide, then Schlocker and others, found no compelling evidence for major faults traversing Bodega Head. They made detailed examinations of the quartz diorite in sea cliffs where the proposed major faults should appear and found the rock there to be no more pervasively faulted than at other localities. Field evidence suggests that most, if not all, of the fracturing, shearing, and faulting in the quartz diorite is very ancient. Fault offsets followed up through the quartz diorite have not been found to offset pleistocene marine terrace deposits that appear to be several tens of thousands of years old. Deep weathering of the top of the quartz diorite severely restricts ones ability to follow small offsets up to the base of the pleistocene cover in many places, however.

More intensive geologic studies have been made in an excavation at the site itself. Careful examination of the quartz diorite—terrace deposit contact around the periphery of the excavation failed to reveal faulting that extended upward into the terrace deposits. Detailed mapping of minor contacts and bedding features within the pleistocene deposits being exposed in the excavation for the reactor pit is now underway. Results of this study should be followed very closely.

I believe that absence of demonstrably recent faulting in those parts of the site and Bodega Head where field relationships are reasonably clear is not an adequate criterion for extablishing the safety of the site. Though necessary, it is not sufficient. In the maze of old faults and fractures cutting the quartz diorite, minor recent offsets could be easily overlooked. On portions of the Head where the quartz diorite-pleistocene contact is badly weathered or otherwise obscured small recent offsets probably could not be traced from bedrock into the sedimentary cover. The site excavation itself samples only a fraction of the region in which faulting might prove disastrous to the plant.

The common occurrence during large earthquakes of offsets on a number of minor faults in sympathy with a large displacement on the causative fault cannot be disregarded (Fig. 1). Displacements in bedrock west of the San Andreas fault on the Point Reyes Peninsula at the time of the 1906 earthquake (Gilbert, in Lawson and others, 1908) indicate that faulting does occur outside the San Andreas fault zone in sympathy with large displacements within the zone. The occurrence of such offsets on Bodega Head during future earthquakes is a definte possiblility.

Because reliability limits on any estimate of seismic hazard to the proposed plant are so broad, the statement of tolerable risk must be very general. The magnitude of possible human damage that would result fro from the destruction of the plant by an earthquake suggests that it should be built only if there is no reasonable doubt that it would survive [illegible] earthquake likely to occur on the nearby San Andreas fault. It appears to me that the site does not meet this test and that it is not an adequately safe location for a nuclear power plant.

Few places on the earth are exposed to more certain earthquake risk than are those along the San Andreas Fault in northern and central California. The case arguing the safety of the Bodega Head site rests largely on the confidence that "granite" is a good foundation material and that it minimizes groud shaking due to earthquakes and on the judgment, supported but not proved by geologic investigations of Bodega Head, that no faulting has occurred there during the past several thousand years. The case against the site stresses seismology's lack of detailed information on events and conditions in the epicentral tract of a major earthquake. Because we cannot prove that the worst situation will not prevail at the site, we must recognize that it might.

Acceptance of Bodega Head as a safe reactor site will establish a precedent that will make it exceedingly difficult to reject any proposed future site on the grounds of extreme earthquake risk.

Additional References

Housner, George W. (1961), Earthquake Hazards and Earthquake Resistant Design, Bodega Bay Power Plant Site, Pacific Gas and Electric Company, Typewritten Manuscript.

Gutenberg, B., and C.F. Richter (1942), "Earthquake magnitude, intensity, energy, and acceleration", BSSA, vol. 32, 1942, pp. 163-191.

Richter, C. F., (1958), Elementary Seismology, W. H. Freeman Company, San Francisco, pp. 768

Saint-Amand, Pierre, "Geologic and Seismologic Study of Bodega Head, Typewritten Manuscript

Schlocker, J., M. G. Bonilla, and A. Clebsch, Jr., "Geologic investigations of a proposed nuclear power plant site on Bodega Head, Sonoma County, California," U.S. Geological Survey report TEI--837, July, 1963

U. S. Atomic Energy Commission

Washington, D. C.

Photographs available on request to the Director, Division of Licensing and Regulation, U. S. Atomic Energy Commission.

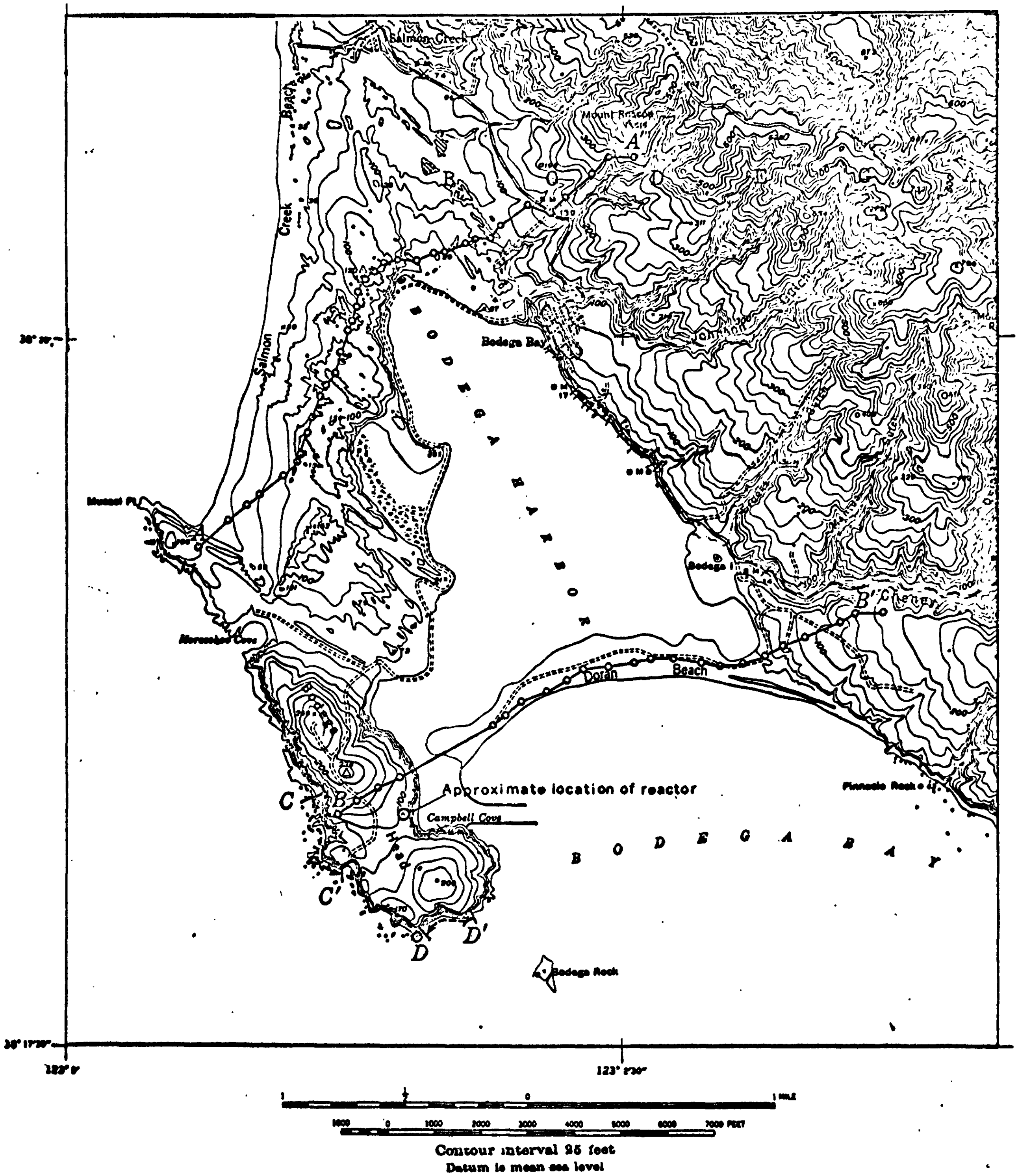


Figure 1. Map of Bodega Head area, Sonoma County, California, showing reactor site; geologic traverses C-C', D-D' along the shore; and gravity traverses A-A', B-B'

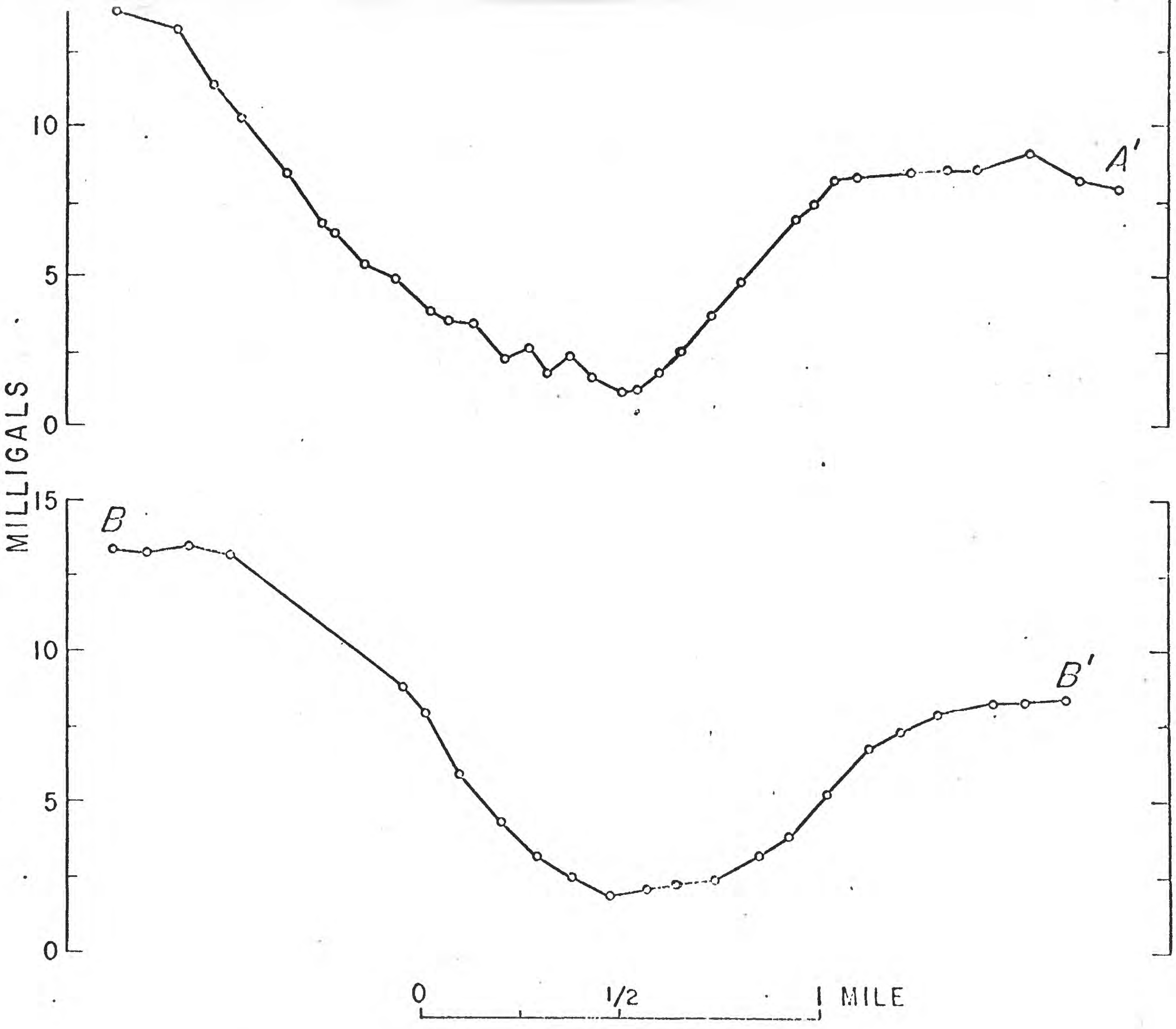
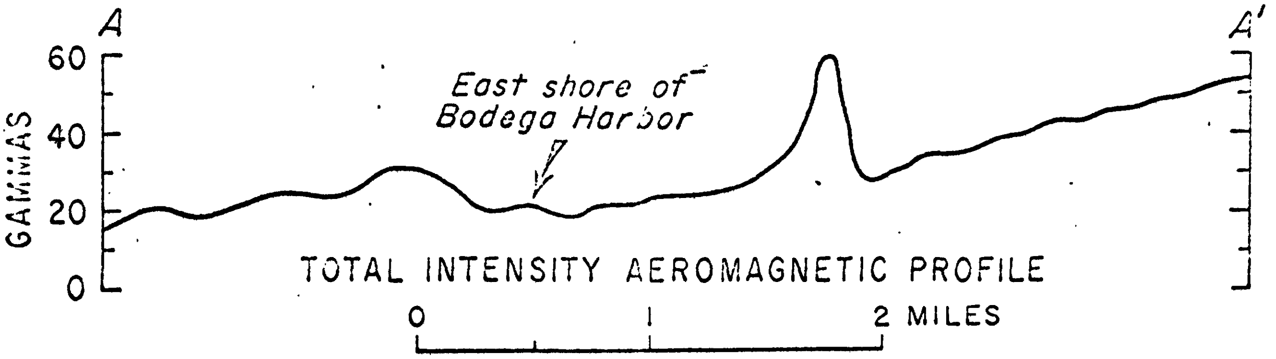


Figure 4. Bouguer gravity profiles, Bodega Head, Sonoma County, California (Location shown on figure 1.)



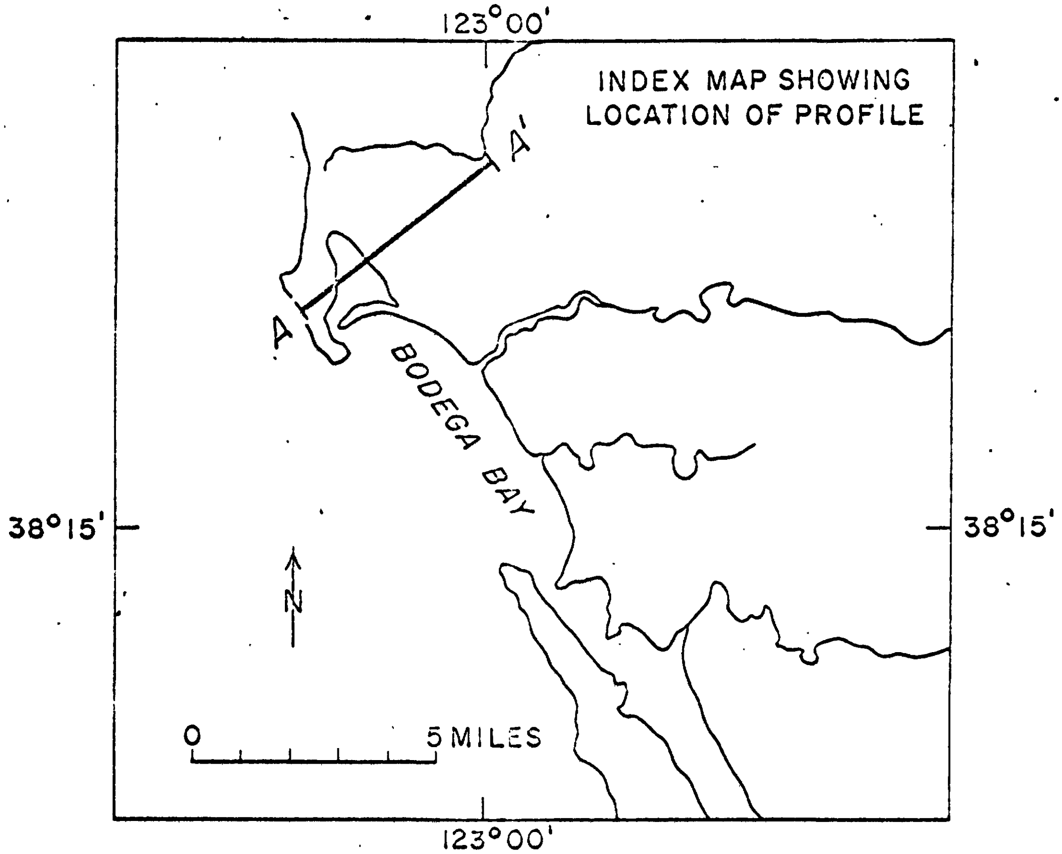


Figure 5. Total intensity aeromagnetic profile, Bodega Head, Sonoma County, California

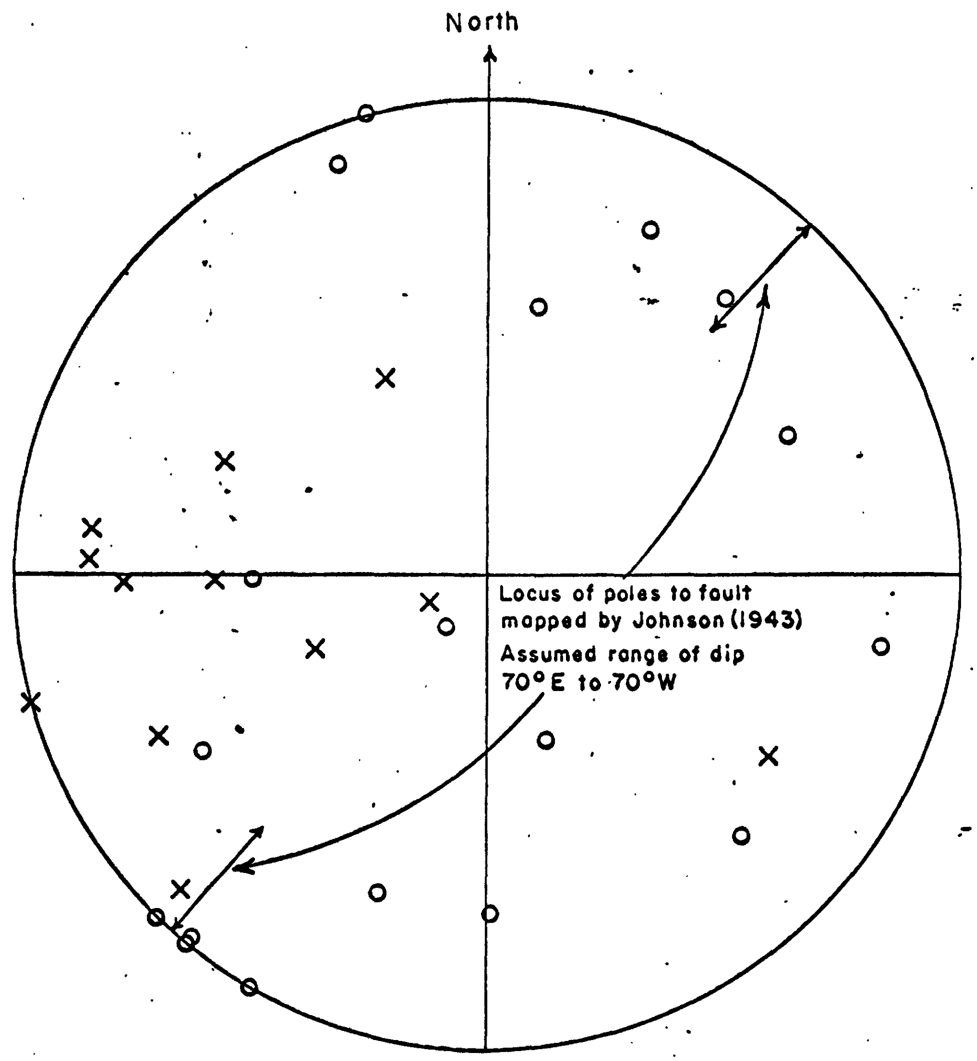
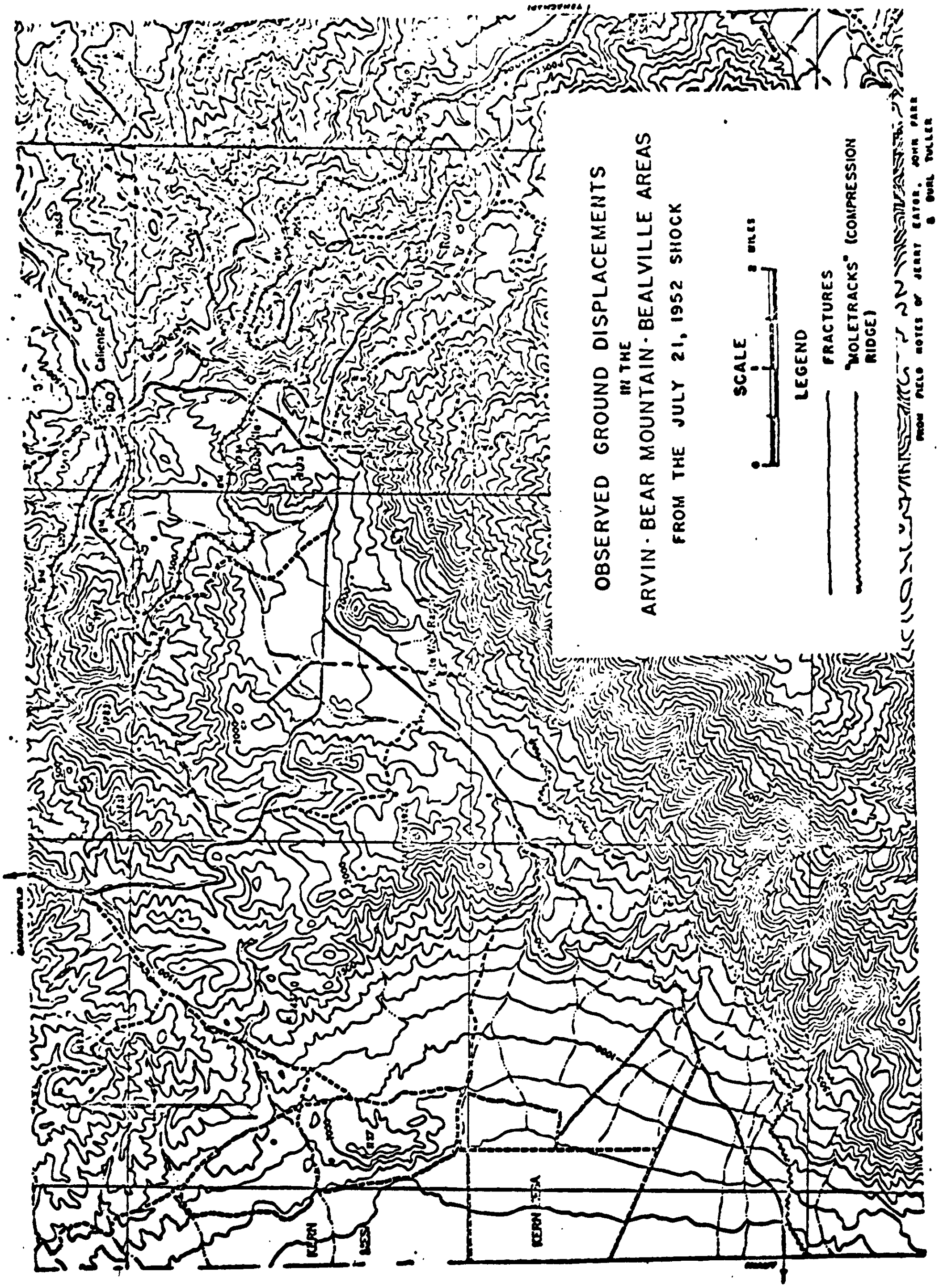


Figure 13. Poles of prominent faults in quartz diorite recorded on traverses C-C', D-D', figure 1, Bodega Head, Sonoma County, California. Plotted on lower hemisphere of meridional stereographic projection (Wulff net). O = poles of faults on traverse D-D'; X = poles of faults on traverse C-C'.



~~Figure 154.~~ Fig. 14

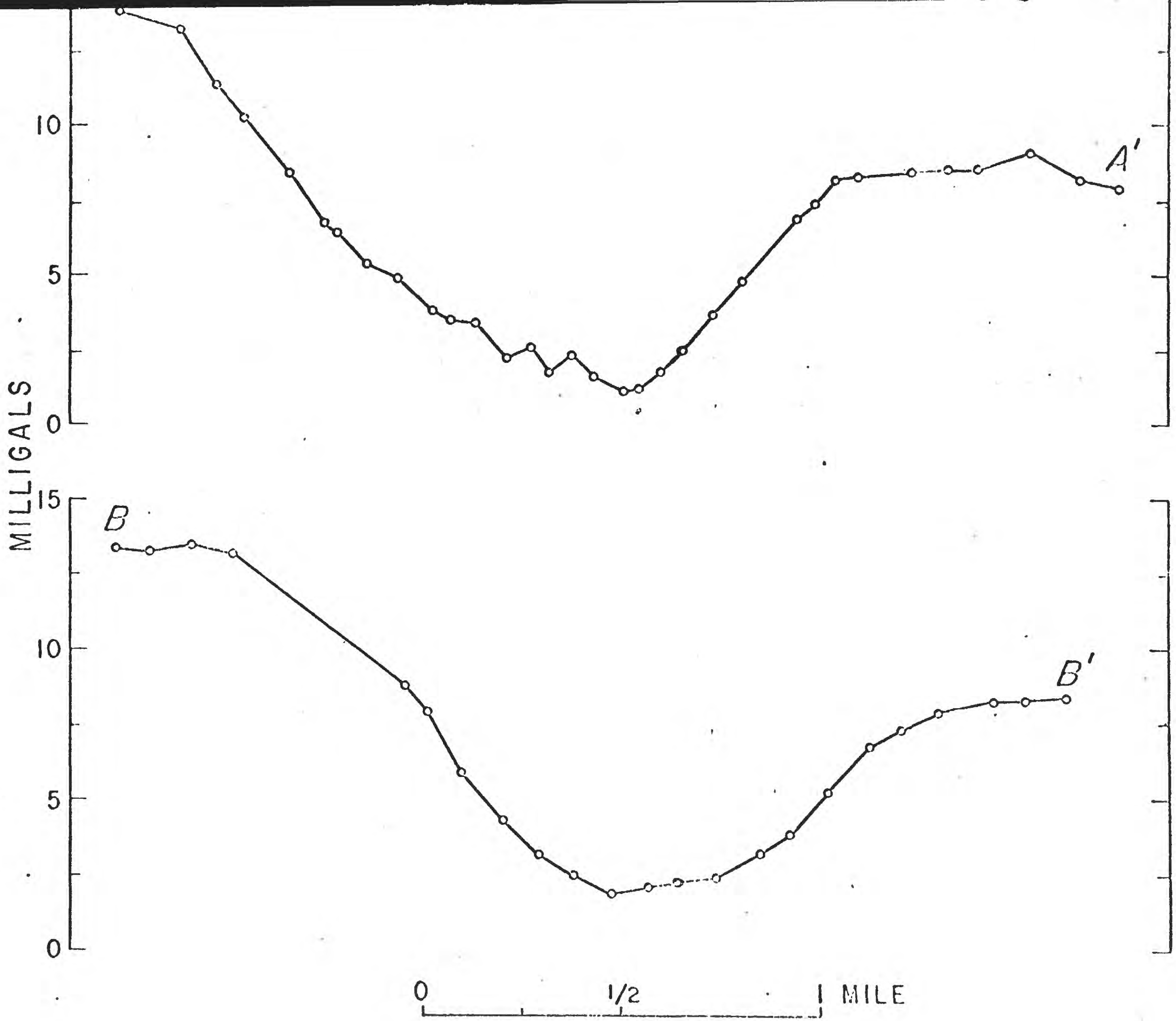


Figure 4. Bouguer gravity profiles, Bodega Head, Sonoma County, California (Location shown on figure 1.)

3