Engineering Geology of the Proposed Nuclear Power Plant on Bodega Head, Sonoma County, California

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SUMMARY STATEMENT

This report summarizes and interprets the geologic data presented in previous reports by the Geological Survey. These data bear on the possible effect of large magnitude earthquakes on the foundation of the proposed nuclear power plant on Bodega Head, California.

The crucial geologic problem at the proposed plant site is to predict the probability of a sudden permanent displacement, by rupturing, of the foundation rock of the reactor during an earthquake. Any such prediction must be based to a great extent on experience in earthquake-affected regions particularly near the San Andreas and related fault zones. The degree of confidence assigned to such predictions is necessarily low because geologic knowledge of the phenomena being evaluated is incomplete.

An upper limit on the probability of faulting at the site is set by the probability of occurrence of severe earthquakes (Richter magnitude 8.0 and above) along the San Andreas fault near the Bodega Head site. Several highly qualified seismologists have estimated that the Bodega Head site will experience a severe earthquake in the next 50 years, the assumed lifetime of the plant.

The principal hazards to the proposed plant from such a seismic event are twofold: (1) shaking of the ground due to seismic wave propagation, and (2) possible permanent displacement of the foundation rock due to faulting. The hazard due to shaking is being investigated by others, including the Seismology Division, U.S. Coast and Geodetic Survey. Prediction of possible permanent displacement must be based largely on the distribution and characteristics of the surface faulting produced by the 1906 earthquake and to a lesser extent on the distribution of faults in the excavation for the reactor and in the entire Bodega Head area. The evidence is not adequate to suggest more than a general statement of probabilities.

The site is approximately 1,000 feet west of the west edge of the active San Andreas fault zone, which is approximately 1½ miles wide here. The main surface rupture in this vicinity during the 1906 earthquake took place on the east side of the zone and had a horizontal displacement of 10 to 20 feet. Throughout Bodega Head, tectonic faults and joints are common in the granitic rocks; the most prominent ones trend northwest, northeast, and east. At the site, a principal structure is the Shaft fault, named from its exposures in the shaft excavated for the reactor. This fault, one of many tectonic faults in the granitic rocks, is the only one that has been traced downward from the surface through Pleistocene sediments into the underlying granitic rocks. It strikes N. 40° E. and has been traced on the surface a total of about 230 feet.

The Shaft fault in the bedrock is a zone that ranges from 2 to 10 feet in width and has a measured displacement in the granitic rocks of 24 feet horizontally and in the sediments of 14 inches vertically. The fault zone consists of many intersecting faults; this suggests that movement on the fault occurred several times, though the amount of vertical or horizontal movement during any one period of movement cannot be determined. The fault displaces Pleistocene sediments dated from geologic evidence as younger than 400,000 years and from radioactive carbon as older than 42,000 years. It may also have affected sediments younger than 42,000 years that are not detectably displaced, for in the soft sediments of this type displacement may be taken up by plastic deformation rather than by rupture.

Surface ruptures created during the 1906 earthquake have been described at many localities outside of the San Andreas fault zone (Lawson and others, 1908). The record of these events provides important clues for predicting future earthquake phenomena on Bodega Head. Some of the observed faults parallel the San Andreas, others lie at acute angles to it, and still others are nearly normal to it.

The principal observations of ruptures outside the San Andreas fault zone after the 1906 earthquake were made at the Point Reyes Peninsula, the San Francisco Peninsula, and the Santa Cruz Mountains; faulting may have occurred in large areas elsewhere which were not studied. No investigation was made at Bodega Head. Nevertheless, the data, particularly that from the Point Reyes Peninsula, can be used as a very general guide to the expectancy of fault displacements at various distances from the main fault zone during some future earthquake.

The 1906 bedrock ruptures on Point Reyes Peninsula were reported by G.K. Gilbert in general to increase in abundance and amount of displacement toward the San Andreas fault zone. They occurred as far as 10 miles west of the zone, but the ones farthest away were barely discernible. At distances of a mile, horizontal displacement of 2 to 6 inches was observed. At Inverness, about 2,000 feet from the zone, the reported horizontal displacement was 2 ½ feet.

The geologic setting of Bodega Head is similar to that of Point Reyes Peninsula. The granitic rocks of both areas bound the western edge of the San Andreas zone and both bedrock masses are pervasively fractured and faulted. The two areas would be expected to react similarly to the stresses culminating in major earthquakes.

In the Santa Cruz Mountains, 100 miles southeast of Bodega Head, a surface rupture approximately 1,900 feet from the main rupture in the San Andreas fault zone showed a lateral displacement of four feet.

The probabilities of displacements on Bodega Head estimated in the following tabulation are qualitative and perhaps somewhat subjective but available knowledge does not permit greater refinement. It is assumed that a severe earthquake, say of Richter magnitude 8.5, has its epicenter in the San Andreas fault zone in Bodega Harbor.

Displacement	Probability
2 inches or less	Moderate to high
Approximately 1 foot	Low
Approximately 3 feet	Low, lower than above, but still a possibility
Approximately 5 feet	Remote

From general observations, it is clear that the likelihood of occurrence and the magnitude of sympathetic faulting outside of a major earthquake fault zone decreases with distance from the fault zone. From observations of sympathetic faulting in bedrock which accompanied the 1906 earthquake, the probability of displacements of as much as one foot appear to be remote at distances of more than about 3 miles from the San Andreas fault zone.

INTRODUCTION

This report summarizes and interprets the geologic data presented in the Geological Survey's reports TEI-837 (Schlocker, Bonilla, and Clebsch, 1963, Part I; Eaton, 1963, Part II) and TEI-844 (Schlocker and Bonilla, 1963), prepared for the U.S. Atomic Energy Commission in connection with an application by the Pacific Gas and Electric Company for a license to build and operate a nuclear power plant on Bodega Head, a peninsular promontory on the Pacific coastline about 45 miles northwest of San Francisco, California. The location and geology of the shaft for the reactor foundation is shown on plates 1 to 4 of TEI-844.

Geologic data obtained during field investigation in May and June, 1963 are given in TEI-837. Results of field investigations mostly in connection with the excavation of the shaft for the reactor foundation, between July and November, 1963 are given in TEI-844. The shaft is approximately 140 feet in diameter and 75 feet deep (TEI-844, pls. 3 and 4). During September and October when the excavation of the shaft proceeded on a 24-hour a day basis the writers were able to study and map exposures of critical areas. Additional geologic data were obtained in the shaft on March 18, 1964.

The crucial geologic problem at the proposed site, which is approximately 1,000 feet west of the west edge of the active San Andreas fault zone, involves an estimate of the probability of sudden permanent displacement by rupturing of the foundation rock of the reactor during an earthquake. Additional hazards that must be considered in evaluating the suitability of the site are related to shaking during the earthquake.

The brief historical record and theoretical consideration (Benioff, 1964, p. 1,400) indicate at least one strong earthquake may occur on the San Andreas fault zone near the Bodega Head site during the assumed 50-year lifetime of the plant. The plant should, therefore, be designed to withstand damage from faulting and seismic vibrations.

The accelerations, amplitudes, and frequencies of seismic waves likely to be encountered at the site are being estimated by experts in engineering seismology, including the Seismology Division of the Coast and Geodetic Survey.

The granitic rock foundation on the floor of the present reactor foundation shaft is generally capable of supporting heavy loads. Laboratory tests show that the ultimate, unconfined compressive strength of granitic rocks in the shaft ranges from 1,037 to 16,800 pounds per square inch. Most of the rock on the present floor of the shaft probably has strength properties in the upper two-thirds of this range. Nevertheless, it is recommended that the foundation preparation include removal of the soft and plastic rock along faults to depth prescribed by standard engineering practices.

GEOLOGIC SETTING

The proposed reactor site is on Bodega Head, a peninsula consisting of a body of granitic rocks partly covered by Recent and Pleistocene sediments. Bodega Head lies along the west border of the San Andreas fault zone which is about 1½ miles wide here. At the site the shaft for the reactor is approximately 1,000 feet west of the west edge of the zone and 6,800 feet west of the main surface rupture which formed during the 1906 earthquake by right lateral displacement of 10 to 20 feet. The Recent and Pleistocene unconsolidated sediments consist of interbedded nearshore marine, beach, dune, marsh, stream, and slope debris deposits and are as much as 180 feet thick.

The site is on a buried valley system that was eroded in the granitic rocks by a surface stream and its tributaries when sea level was relatively lower (TEI-844, pl. 2). The valleys were subsequently filled with marine and continental deposits. The main buried valley crosses Bodega Head in a more or less east-west direction. At its deepest point, on the east shore of the Head at Campbell Cove, it is more than 80 feet below sea level (TEI-844, pl. 2).

Granitic rocks of Bodega Head

The granitic rocks of Bodega Head are mostly a foliated coarse-grained biotite-hornblende quartz diorite and minor coarse-grained hornblende-biotite quartz monzonite. Pegmatite and aplite dikes as much as 7 feet in thickness and dark granitic rock inclusions are common. A leucodiorite dike with a maximum width of a foot cuts the granitic rocks of the shaft.

Joints and faults

The granitic rocks of Bodega Head are generally severely jointed and faulted. Most of the rocks are cut into 3- to 5-inch blocks, but some rock is cut into 1- to 2-foot blocks, and rarely a mass of rock has a joint spacing as great as four feet. The blocks are commonly bounded by prominent sets of parallel joints and also by irregular, curving, and branching joints. Prominent joint trends are northwest, northeast, and east.

Faults are abundant in the granitic rocks of Bodega Head. The widest and best developed faults are zones of sheared rock about three to ten feet wide and are found about 100 to 300 feet apart. Between the wide shear zones the rock contains a great abundance of narrow fault zones, which generally are spaced only one to two feet apart.

Fault characteristics in the granitic rocks vary. The numerous, closely- spaced, narrow faults are sharp, clean breaks, or consist of ¼- to 2-inch wide zones of plastic gouge (clayey material of pulverized and chemically altered rock), breccia (coarsely broken rock), or mylonite (pulverized, but firm rock). The wider stronger faults consist of complexly interrelated zones of gouge, breccia, and mylonite. Each zone is as much as two feet wide. Much of the brecciated and mylonitized rock is also altered chemically to a clayey rock that can be easily broken by hand. The granitic rocks from widely-separated localities on Bodega Head are highly sheared on a microscopic scale as seen in thin sections of rock specimens.

The dominant fault trends are northwest, northeast, and east parallel to the prominent joints. The dip[1] of most of them is greater than 45° though a small percentage dip at an angle less than 20°. Hundreds of strike and dip measurements were made on faults exposed in the granitic rocks during excavation of the shaft. These data show that the

[1] Dip is measured downward from a horizontal plane.

trends of the faults vary widely, with one-third of them trending N. 70° W. to S. 80° W. The range of the most common dip is 50° to 75° S. (TEI-844, figs. 1 and 2). Faults commonly intersect and generally show offsetting, but the relation between age and orientation of faults was not studied in sufficient detail to determine relative age of faults.

Many faults are persistent in length. Where exposures are good some were followed continuously along the strike for 200 to 800 feet; many of the faults are believed to be much longer.

The magnitude of movement is difficult to measure on many faults because of the generally massive, homogeneous nature of the granitic rocks. Nevertheless, where dikes and dark inclusions serving as markers are broken by faults, the broken segments are separated an inch to more than 20 feet. Along many narrow faults the offsets are generally an inch or two, though on some the measured offsets are 4 feet to more than 20 feet. Offset observed across wide fault zones generally exceeded 10 feet.

Direction of movement on the faults is revealed by offset of dikes and dark inclusions and by slickensides on fault surfaces. A detailed study of direction of fault movement and its relationship with fault orientation was not made. The writers, however, have the general impression from a preliminary study of the offset of markers that reverse faulting is more common than normal faulting. The trend of slickensides on fault surfaces ranges from vertical to horizontal. On different fault surfaces within a single fault zone, they are diversely oriented.

The great abundance of faults in the granitic rocks of the reactor shaft is believed to be typical of the granitic rocks of all of Bodega Head. The distribution and orientation of faults seen between elevations -66 to -73 feet on the perimeter of the shaft (fig. 1) are also believed to be typical of those in the granitic rocks exposed at higher elevations during excavation of the shaft. After rock debris was removed from the final floor of the shaft, many of the faults, exposed previously only on the walls, were traced along the strike for many feet.

To judge from reconnaissance field observations the granitic rocks of Point Reyes Peninsula appear to be as pervasively fractured and sheared as those of Bodega Head.

Weathering

The granitic rock generally is mantled by 5 to 30 feet of weathered rock and soil. The soil is a mixture of sand, clay, silt, and gravel.

Pleistocene and Recent deposits

Recent and Pleistocene deposits lie on the granitic rocks in the general vicinity of the site. They are thickest, more than 180 feet, over the main buried valley south of the shaft but wedge out on the flanks of the hills of granitic rocks to the north and south of the site at elevation of about 135 feet above sea level.

In the shaft area a gray, massive (unbedded), gravelly, sandy clay, as much as 30 feet in thickness, commonly lies directly on the granitic rocks. Locally it contains many granitic rock fragments in the lower part and appears to have a gradational contact with the underlying granitic rocks (TEI-844, pl. 4). In the south part of the shaft the sandy clay is interbedded with 0.1 to 1 foot thick beds of sand and clay, probably of marine origin.

All these sediments Are covered by a gray or yellowish orange beach or near-shore marine sand deposit that thickens southward toward the main buried valley where it is more than 40 feet. North of the shaft these sediments, containing varying amounts of granitic rock gravel, are exposed in the north face of the site excavation to elevations of about 85 feet above sea level (TEI-837, figs. 2, 3, 7-10).

The Pleistocene beds generally dip southeastward up to 8°. Cross-bedding and other original sedimentary features locally dip at angles of 0° to 15° in various directions.

Fossils and age

The topmost 5 to 10 feet of sediments, mostly soil and windblown sand, are believed to have accumulated within the last 10,000 years and are designated as Recent. Fossil wood is abundant in the underlying sediments. Radiocarbon content of wood collected from these sediments near the shaft at elevations 77, 55, and 49 feet above sea level indicates the sediments are older than 42,000 years. The fossil flora in the sediments 5 to 25 feet above sea level is similar to the fossil flora found in the sediments exposed in the headlands on the northeast shore of Tomales Bay, 8 to 20 miles southeast of Bodega Head. This similarity indicates the sediments 5 to 25 feet above sea level on Bodega Head and those at Tomales Bay were deposited at about the same time (written communication, Jack Wolfe, Paleobotanist, U.S. Geological Survey). Based on invertebrate fossil data, the beds at Tomales Bay are considered to be younger than the folding of the rocks of the Merced Formation in the San Francisco Peninsula area; Louderback (1951, p. 86) estimates the folding occurred from 240,000 to 400,000 years ago. The radiocarbon and fossil data indicate the sediments between elevation of 77 feet and 5 feet are older than 42,000 years and probably younger than 400,000 years.

Shaft fault

The Shaft fault is one of many faults that cut the granitic rocks of the shaft area (fig. 1). It is one of the large faults in the shaft and is the only one that has been traced from the Pleistocene sediments downward into the underlying granitic rocks. The Shaft fault is a strongly developed 2 to 10 foot wide zone made up of broken and chemically altered rock (TEI-844, pl. 3, 4). Within the zone there are many faults and shear zones of varying width. Some of the shear zones are as much as one foot wide, and are made up of soft, slickensided, clay gouge whereas others are tight and paper-thin. Other faults in the granitic rocks of the shaft have similar characteristics, though most but not all are not as wide as the Shaft fault.

The direct connection between the Shaft fault in granitic rocks and in Pleistocene sediments is well established on the south wall and was observed on the temporary floors formed during excavation of the shaft. The average trend of the Shaft fault is N. 40° E. (for location see p1s. 2, 3, 4, TEI-844). In the granitic rocks it dips 65° to 80° W. and in the overlying sediments between 50° to 85° E. and 70° W. (TEI-844, pl. 4).

An en echelon branch of the Shaft fault in the sediments was followed from a point 2 feet southwest of the shaft collar at approximate elevation -5 feet to a point 170 feet southwest of the shaft at approximate elevation 21 feet. The fault was not seen in trench 3 (TEI-844) pl. 2) at elevation 51 to 52 feet, and 250 feet southwest of the shaft. The Shaft fault was not seen in the sediments exposed on the embankments, about 130 feet northeast of the shaft. In the shaft, the fault is not exposed locally in the gray, massive, gravelly sandy clay on the south wall (TEI-844) pl. 4) nor on the northeast wall, in these sediments.

Type and magnitude of movement on Shaft fault

The field evidence indicates that right lateral movement of as much as 24 feet in the granitic rocks and possibly as much as 3 feet in the Pleistocene sediments occurred on the Shaft fault. In the granitic rocks the broken segments of a leucodiorite dike, exposed on the bottom of the shaft, suggest that the cumulative horizontal component of movement was at least 24 feet in a right lateral sense, that is, the dike southeast of the fault is found 24 feet southwest of its location on the other side of the fault (fig. 1). Two faults, about 2 to 6 feet west and possibly part of the Shaft fault, offset the leucodiorite dike more than 3 feet in a right lateral sense (fig. 1). Though no evidence was found of vertical movement on the Shaft fault in the granitic rocks such movement may have occurred.

In the shaft the measured vertical separation of beds in the sediments across the Shaft fault was 14 inches. An apparent vertical separation of 19 inches was found between elevations -32 and -29 feet, but this amount is uncertain because the correlation of beds across the fault between these elevations is not clearly established.

The movement of the Shaft fault in the sediments also had a horizontal component as suggested by: (1) difference in thickness and succession of beds across the Shaft fault as seen on the south wall of the shaft, in trenches Nos. 1 and 2, and in the 20-foot embankment between the trenches; (2) random variation in magnitude of apparent vertical offset of beds across the Shaft fault; and (3) changes in dip of the fault, particularly the right-angled bends of the easternmost and highest branch shown on plate 4, TEI-844, near vertical control line 39 at elevation -14. Dip-slip (vertical) movement on faults probably would not result in the sharp edges of the angular blocks along the fault, but would tend to break them forming a smooth surface with no keyed-in interlocking projections and hollows as are found along the dip direction on the fault surface. The total horizontal displacement on the Shaft fault in the sediments cannot be measured. However, from known vertical displacement of 14 inches together with the geologic evidence for a horizontal component of movement, it is not unreasonable to postulate a total horizontal displacement of between one and three feet in the sediments[2].

Age of movement of Shaft fault in sediments

Geologic field data are used to determine the approximate age of the Shaft fault in the sediments. The age of faulting is less than that of the sediments which are faulted and greater than that of sediments deposited over faulted sediments. Thus, if age data on the faulted and overlying sediments are known it can be used to set limits on the time of the faulting. The geologic evidence indicates the Shaft fault displaced sediments that are more than 42,000, but less than 400,000 years old. Thus the last movement on the fault which can be definitely dated took place some time during the last 400,000 years. Because the possibility exists that the faulting occurred during the past few hundred

[2] In an earlier calculation 13 feet (TEI-844, p. 24) was obtained by assuming that the right lateral movement on beds dipping 5° southwestward was horizontal.

years, it is prudent to predict that faulting is a possibility at the site during the next 50 to 200 years.

The displacement across the Shaft fault in the sediments may represent only one and perhaps the last episode of faulting. If this is true we may conclude that there has been only one episode of faulting on the Shaft fault in more than 42,000 years, or possibly in as long as 400,000 years. Note that this conclusion is also valid if the faulting took place only a few years ago.

Origin of Shaft fault

Because of its bearing on recency of fault movement, the origin of the Shaft fault in the sediments is fundamentally important in the evaluation of its significance to site acceptability and plant design. Tectonic faulting is considered to be the most probable origin[3]. Other mechanisms considered, but rejected, are landsliding, subsidence from compaction of sediments, or lurching caused by seismic waves[4].

The continuity of the Shaft fault from the Pleistocene sediments into the underlying granitic rocks and the close coincidence in trend of this fault in both rock types indicate they were formed by the same geologic process. In the granitic rocks features such as great width, internal textural complexity, and straightness are evidence for a tectonic origin of the Shaft fault.

The absence of the Shaft fault in trench No. 3 (TEI-844, pl. 2), about 250 feet southwest of the shaft, can be attributed to dying out of the fault upward and/or laterally, or to deposition of younger sediments after faulting.

Tectonic faults of lateral movement such as those produced by the 1906 earthquake are characteristically discontinuous, en echelon, or branching (Richter, 1958, p. 178-181). The surface ruptures associated with the 1906 earthquake have been studied extensively and excellent descriptions are given by Lawson and others (1908, p. 70-72 for the Woodville area 27 miles southeast of the reactor site, and on p. 63-65 and map 3 in the atlas for the Fort Ross area 18 miles north of the reactor site). In some of these areas the main surface rupture zone is expressed as en echelon cracks whereas in others the surface ruptures are discontinuous, subparallel, and several hundred feet in length. They have a few feet of horizontal offset in their central portion but no offset at their ends. Lawson (1908, p. 53) describes the en echelon and branching nature of the 1906 ruptures as follows:

> "The width of the zone of surface rupturing varied usually from a few feet up to 50 feet or more. Not uncommonly there were auxiliary cracks either branching from the main fault-trace obliquely for a few hundred feet or yards; or lying subparallel to it and not, so far as disturbance of the soil indicated, directly

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[3] Tectonic faulting is used here for rupturing and movement related to crustal stresses such as those that produced the San Andreas fault zone and the 1906 earthquake, in contrast to local stresses that produce landslides.

[4] Faults other than the Shaft fault were found in sediments near the shaft and may be caused by landsliding. One fault, about 35 feet south of the south rim of the shaft, trends N. 70° W. Several interrelated faults, about 100 feet northeast of the northeast rim on the south cut of the ramp leading the shaft, trend about N. 55° W.

> connected with it. Where these auxiliary cracks were features of the fault-trace, the zone of surface disturbance which included them frequently had a width of several hundred feet. The displacements appear thus not always to have been confined to a single line of rupture, but to have been distributed over a zone of varying width."

The discontinuous, en echelon nature of the 1906 ruptures by analogy, therefore, may explain the absence of the Shaft fault in the sediments in trench No. 3., at elevation 51 to 55 feet, 250 feet southwest of the shaft; and in the sediments in the embankments, at approximate elevations 2 to 25 feet 50 to 100 feet northeast of the shaft. In these localities the Shaft fault may die out upward and laterally rather than by being covered by sediments.

Locally the apparent absence of the Shaft fault in the sediments on the shaft's south wall between elevations -23 and -26 feet, and above the granitic rocks on the northeast wall is attributed to rehealing of the massive and structureless, gravelly, sandy clay. The clay may have been sheared but the visible evidence for shearing was concealed by subsequent plastic deformation.

Shaft fault and San Andreas fault zone

The San Andreas fault zone is a more or less vertical complex of faults that trend northwestward and whose major movement has been right lateral. The Shaft fault strikes N. 40° E. and dips steeply westward. Field evidence indicates that it probably also has right-lateral movement.

Activity of the Shaft fault at least once during the last 400,000 years strongly suggests its contemporaneity and close genetic relation with the active San Andreas fault zone which is only 1000 feet to the east and along which movements have occurred for millions of years.

The presence of the Shaft fault indicates that local strain release in the vicinity of the shaft in the past favored a northeast direction though the presence of numerous other faults across the bottom of the shaft indicates that some strain release episodes also favored northwest and east-west directions.

SURFACE RUPTURES ADJACENT TO SAN ANDREAS FAULT ZONE

The characteristics of faults adjacent to the San Andreas fault zone were investigated to obtain empirical data that would aid in evaluating the probability of future surface rupturing at the proposed site on Bodega Head. Some of the most meaningful evidence was that obtained from the work of geologists who studied the fractures resulting from the 1906 earthquake. Surface rupturing of tectonic origin, formed during the 1906 earthquake, was described at many places west of the San Andreas fault zone, but principally at the Point Reyes Peninsula, the San Francisco

Peninsula, and the Santa Cruz Mountains. Faulting may have occurred elsewhere in many areas adjacent to the San Andreas fault zone, such as Bodega Head, that were not studied. Because the record of events of the 1906 earthquake is the only empirical information that affords clues to future earthquake phenomena in the Bodega Head area, the writers examined some of the localities described on nearby Point Reyes Peninsula and in the Santa Cruz Mountains southwest of Los Gatos. The Point Reyes area is especially pertinent because the granitic rocks are pervasively fractured and faulted similar to those found on nearby Bodega Head. The ruptures at some of these localities, which are farther from the San Andreas fault zone than is the proposed reactor shaft, appear to be of undoubted tectonic origin whereas for others the evidence was insufficient to determine their origin.

The State Earthquake Investigation Commission report (Lawson and others, 1908) contains numerous descriptions of rupturing outside of the San Andreas fault zone. Ruptures were abundant at some of the localities. For example, Gilbert (p. 75) reports: "Bedrock cracks occurred at many points within the Rift, usually appearing as branches from the faults. They were seen also at a number of points west of the Rift, their distribution reaching to the ocean in the vicinity of Point Reyes, 10 miles from the fault-trace. At the most remote points they were quite small, often barely discernible, and no system of arrangement was discovered. They are peculiarly prominent along the summit of the ridge constituting the southwestern rim of the main Bolinas-Tomales trough. This summit was visited on four lines of road, and at each locality, conspicuous cracks were found. On the road from Inverness to Point Reyes Post Office, about a mile in a direct line from Tomales Bay (that is, a mile west of the San Andreas fault zone) a crack was traced for more than 800 feet. Its general trend is east and west, but its course is not straight and it has a branch diverging at 45°. Along this crack there is a horizontal throw of from 2 to 6 inches..." (Underlining and parenthetical note by authors).

In the town of Inverness, Point Reyes Peninsula, the writers examined part of a surface rupture formed in 1906 and described by Gilbert (Lawson and others, 1908, p. 69) as "an outlying or branch fault-trace about half a mile long." This rupture is on Inverness Ridge at a point about 2,000 feet west of the west edge of the San Andreas fault zone (TEI-844, pl. 1). At the top of a ridge the writers observed the rupture to consist of two scarps, 3 to 4 feet high that trend about N. 18° W. and bound a small ridge 10 to 25 feet wide. The scarps expose surficial slope debris estimated to be 10 to 15 feet thick. Gilbert stated (Lawson and others., 1908, p. 69) that the horizontal displacement here was 2½ feet. The ruptures in the surficial material are believed to be tectonic in origin and were caused by a rupture in the underlying granitic bedrock, possibly an old fault.

Bedrock ruptures formed during the 1906 earthquake on the northeast spur and on the west slope of Mount Wittenberg, Point Reyes Peninsula, 4½ miles southeast of the Inverness locality previously described. The ruptures on the northeast spur trend northwest, and are one mile west of the west edge of the San Andreas fault zone. According to Gilbert (Lawson and others, 1908, p. 75) a ridge 3 to 10 feet wide and up to 1½ feet high was produced by horizontal faulting. Though the writers were unable to locate the ruptures at the locality given by Gilbert, it was observed that the spur is broad and its crest is an unlikely place for landslide movement. The bedrock rupture on the west slope of Mount Wittenberg, 1.3 miles west of the San Andreas fault zone also trends northwest, and according to Gilbert it was traced on the surface for about 1,000 feet. The writers observed that the surface of the main divide and the northeast spur consist of bedrock or bedrock covered by 1 to 5 feet of slope debris.

Gilbert's (Lawson and others, 1908, p. 76) opinion on the extent of bedrock fracturing in connection with widespread modification of flow of springs on Point Reyes Peninsula is expressed thusly:

> "The spring phenomena and the visible cracks may be grouped together as indications of bedrock fracturing, and their distribution indicates the regions in which the rocky foundation of the land was more or less shattered. That region includes the Rift and extends from it to the ocean. The phenomena diminish somewhat with distance from the Rift, but the fracturing appears to have been important and general through a belt 4 or 5 miles broad."

In l906 a 6,200-foot long railroad tunnel, 5 miles south of Los Gatos, California, about 100 miles southeast of Bodega Head, was offset five feet horizontally along a rupture that strikes N. 52° W. and dips 75° W. (Lawson and others, 1908, p. 111-113). This rupture is probably the main one formed during the 1906 earthquake in the San Andreas fault zone. The tunnel was excavated almost entirely in bedrock. For 5,150 feet in the tunnel southwest of the fault, rails were bent, timbers crushed, ties broken and heaved, and the tunnel in places caved. The original tunnel line was also generally shifted so that at a point 4,000 feet southwest of the 5-foot offset the shift was 14 inches. Zones of severely crushed timber supports in the tunnel between 1,000 and 1,800 feet southwest of the 5-foot offset are believed to conceal bedrock ruptures along which the rocks moved horizontally.

About 0.6 mile south of the 5-foot break in the tunnel, a fence was offset approximately 4 feet in a left lateral sense along a surface rupture formed during the 1906 earthquake. This rupture is approximately l,900 feet southwest of the probable location of the main 1906 surface rupture. The San Andreas fault zone in this area is probably only a few hundred feet wide. The left lateral rupture is believed to be the one shown on a map, figure 75 of the Earthquake Commission report (Lawson and others, 1908, see also pls. 64B, 65A, p. 276-277), that trends N. 30° to 60° W. for 400 feet and for an additional 225 feet as northwest trending en echelon cracks 10 to 40 feet long and 10 feet apart. These ruptures are in surficial materials. The relationship of surface ruptures to topography, as indicated by a field examination by the writers, led to the belief that the ruptures formed mostly by fault movement in the underlying bedrock rather than by landsliding.

At Black Mountain near Palo Alto, 82 to 86 miles southeast of Bodega Head, cracks were exceedingly abundant for as far as 1.8 miles east of the San Andreas fault zone in a wedge-shaped area between the zone and two west-dipping thrust faults that trend about N. 70° W. The cracks trended "in every direction"; some of the larger ones were several hundred feet long (Lawson and others, 1908, p. 107-108).

In addition to ruptures created by the 1906 faulting, undrained topographic depressions were seen by the writers at many places along the San Andreas fault zone extending about 200 miles south of Bodega Head, and as far as a mile west of the zone. These features appear to have been created by tectonic movement such as faulting possibly in the last 20,000 years. Such a feature is Mud Lake on Point Reyes Peninsula (TEI-844, pl. 1) about 3,000 feet west of the San Andreas fault zone. It lies in an elongate steep-walled depression probably formed by subsidence, estimated to be more than 40 feet, of a block bounded by faults. Similar opinions on such features have been expressed by other geologists (Richter, 1958, p. 482). Higgins (1961, p. 57) described the area between Point Arena and Fort Ross, 18 to 59 miles northwest of Bodega Head, as follows:

> "...numerous small ponds and depressions on the rolling summit of the ridge west of the 1906 fault trace could only have been caused by small dislocations along faults that are either part of, or closely related to, the San Andreas. Yet most of these depressions are at least half a mile southwest of the 1906 fault trace."

The surface ruptures formed during the 1906 earthquake in the rocks adjacent to the San Andreas fault zone vary widely in extent, amount of displacement and orientation. In general, the abundance and magnitude of displacement on these sympathetic ruptures increases toward the fault zone. Ruptures as far as 10 miles west of the zone in the Point Reyes area were "barely discernible." On Point Reyes about one mile west of the zone the horizontal displacement was 2 to 6 inches. At Inverness only about 2,000 feet from the zone the horizontal displacements were 2½ feet and near Los Gatos a 4 foot horizontal displacement was measured on a rupture about 1,900 feet southwest of the main 1906 rupture. Surface ruptures were generally along surface expressions of old faults, such as scarps and sags. Lawson (1908, p. 53-54), however, reported new scarps on slopes where no trace of a previous scarp was detected. Data on the orientation of the ruptures formed in 1906 in the rocks adjacent to the San Andreas zone indicate that the dominant trend is northwest.

FUTURE FAULTING ON BODEGA HEAD

The great abundance of faults, many of which are strong and persistent, is evidence of a long history of repeated fault displacement in the granitic bedrock of Bodega Head. The marked development and preferred orientation of many of the faults suggest recurrence of movement along certain favored planes of weakness. Movement on some of the faults took place millions of years ago, but measured displacement in the Shaft fault indicates movement continued at least into mid-Pleistocene time. Whether the last movement took place on the Shaft fault more than 42,000 years ago or more recently is not known, but there is no evidence to suggest a decrease in frequency of faulting in more recent time.

Both the time span and the magnitude of displacement on the Shaft fault are of engineering significance. The cumulative horizontal component of movement on the Shaft fault during the past, presumably millions of years, is a minimum of 24 feet. Based on field evidence, the last large movement, probably of 1 to 3 feet mostly of horizontal displacement, took place in the last 400,000 years.

Probability calculations of future ground displacements at the site during the lifetime of the plant should not be made on the above inference of one movement in the last 400,000 years, however, because we know nothing of the past and present rate, magnitude, and pattern of strain accumulation in the crust below Bodega Head that ultimately leads to fault movement and earthquakes. Indeed our lack of knowledge of the regional strain buildup anywhere along the San Andreas fault zone is reflected in our inability to predict the time, magnitude, or epicenter of future earthquakes along the zone. What is known about strain buildup and the earthquake record permits seismologists to estimate that approximately one severe earthquake per century will occur on a segment of the San Andreas fault zone (Benioff, 1964, p. 1,400). Thus the Bodega Head site is almost certain to experience one severe earthquake in the next 50 years, the assumed lifetime of the plant.

In connection with earthquake prediction, Tocher (1959, p. 48) writes:

> "The four years 1954-57 have seen four strong shocks in the San Francisco Bay region. Whether or not these are the first of a series which will continue for a number of years and culminate in a major shock remains to be seen. The historic record is too short and too uncertain in its details for such a definite statement; a major earthquake could hit San Francisco before these lines reach the printer, or there might not be such a shock in the next hundred years."

In lieu of information on local strain accumulation, prediction of possible displacement at the shaft must be based largely on the distribution and characteristics of the surface faulting produced by the 1906 earthquake and to a lesser extent, on the distribution of faults in the excavation for the reactor foundation shaft and on the entire Bodega Head area. Because some sections of the San Andreas fault zone were not examined after the 1906 earthquake and because other sections were examined hastily and only on the main roads, the evidence is not adequate to suggest more than a general statement of probabilities and it is used only as a very general guide to the expectancy of fault displacements at various distances from the main San Andreas fault zone during a future strong earthquake. Thus the probabilities based on it are believed to apply to all of Bodega Head and to a zone a similar distance east of the San Andreas fault zone.

The probabilities of displacements on Bodega Head are estimated in the following tabulation. It is assumed that a severe earthquake, say of Richter magnitude 8.5 has its epicenter in the San Andreas fault zone in Bodega Harbor. Displacement components can be horizontal and/or vertical. The conclusions are only qualitative and perhaps somewhat subjective but cannot be refined from available knowledge.

Displacement	Probability
2 inches or less	Moderate to high
Approximately 1 foot	Low
Approximately 3 feet	Low, lower than above, but still a possibility
Approximately 5 feet	Remote

The low probability assigned to displacements of approximately 1 to 3 feet is based partly on the inference that only one movement over this magnitude range took place on a fault in the shaft over a period of time when several, perhaps thousands, of 1906 magnitude episodes of fault-displacements and earthquakes took place on the San Andreas fault zone, some of them presumably close to Bodega Head. The site, however, is approximately the same distance from the San Andreas fault zone as are localities for which displacements of 2½ to 4 feet are reported for the 1906 earthquake; therefore, the possibility of a 2 to 3 foot offset at the site should not be ruled out.

From general observations, it is clear that the likelihood of occurrence and the magnitude of sympathetic faulting outside of a major earthquake fault zone decreases with distance from the fault zone. From observations of sympathetic faulting in bedrock which accompanied the 1906 earthquake, the probability of displacement of as much as one foot appears to be remote at distances of more than about 3 miles from the San Andreas fault zone.

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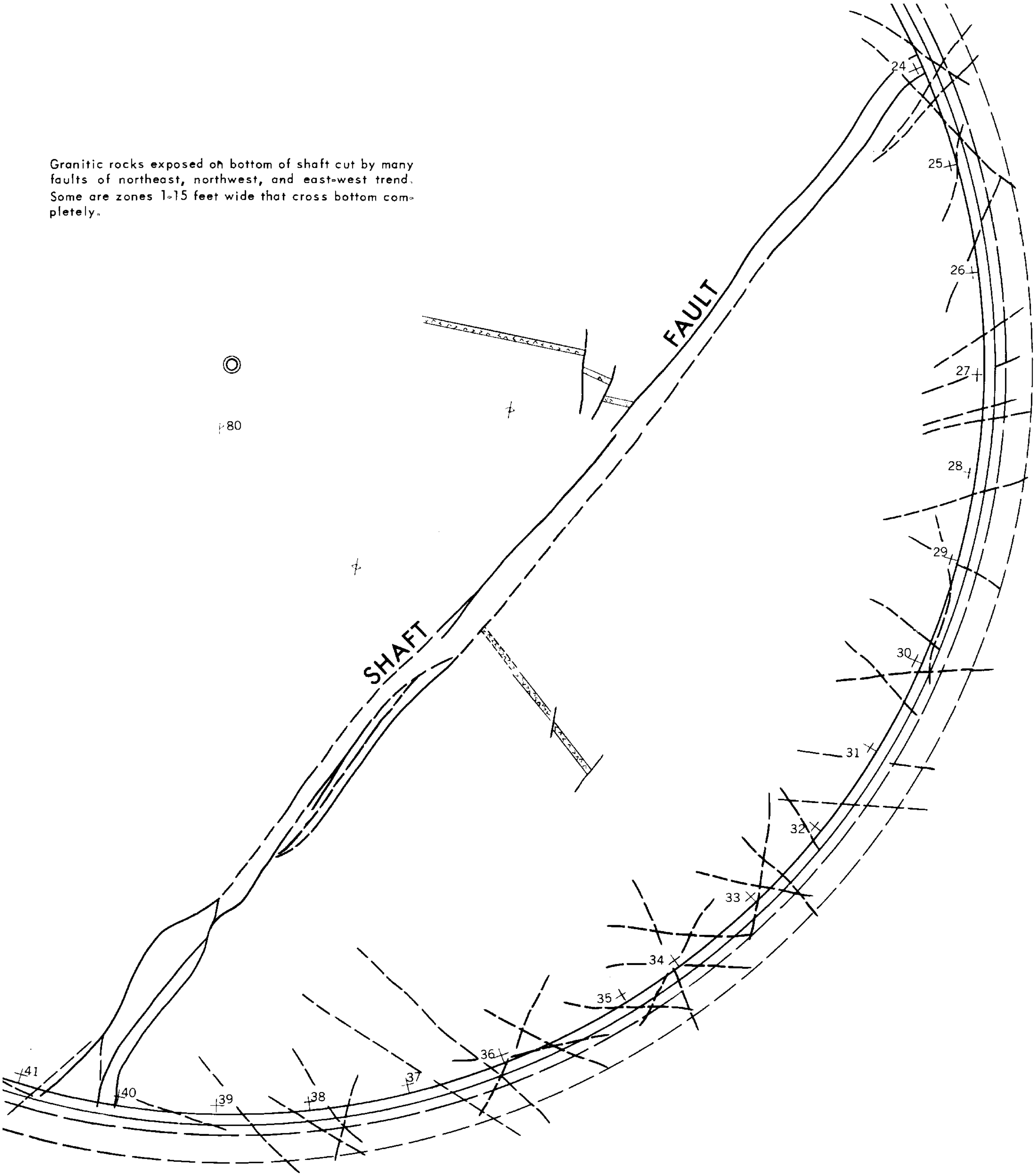

Figure l.--Bottom of shaft showing faults and probable offset on Shaft fault

[This is an abridged version of the full oversized Figure 1 showing only the area of the Shaft fault. The full Figure 1 is provided as an attachment to this report.]