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ENGINEERING GEOLOGY OF THE PROPOSED NUCLEAR POWER PLANT SITE ON BODEGA HEAD, SONOMA COUNTY, CALIFORNIA

by

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CONTENTS

ILLUSTRATIONS

(Plates and figures are at end of report)

TABLE

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ABSTRACT

This report summarizes the geology of a shaft excavated for the proposed nuclear reactor and discusses geologic features on Bodega Head and on Point Reyes peninsula that relate to geologic aspects of earthquake-resistant design.

The reactor shaft exposed Pleistocene sediments overlying granitic bedrock. The sediments are as much as 43 feet thick, dip gently southeastward, and consist of nonmarine, gray massive, gravelly sandy clay. The granitic bedrock is mostly a foliated, biotite-hornblende, quartz diorite. Faults and joints are common in the granitic rock, and one complex fault displaces the overlying sediments as well as the granitic rock. The age of the latest faulting cannot be determined.

Faults that occurred on Point Reyes peninsula in rock similar to that of Bodega Head as a result of the earthquake faulting that occurred in 1906 indicate that if some future earthquake, in which fault displacements comparable to those that occurred on the San Andreas fault zone in 1906, took place near Bodega Head, rupturing of near-surface granitic bedrock would be expected somewhere on Bodega Head.

INTRODUCTION

The Pacific Gas and Electric Company (PG&E) has applied to the U. S. Atomic Energy Commission for permission to construct and operate a nuclear-powered electricity generating plant on Bodega Head, Sonoma County, California. Questions have been raised about the potential hazards to the plant posed by its nearness to the San Andreas fault zone. The plant might be damaged by shaking from seismic waves or by rupturing due to earthquake-produced faults that might pass through the site.

Geological and seismological aspects of these problems have been investigated by the Geological Survey. Some of the results have been presented in TEI Report 837 (Part I-Schlocker, Bonilla, and Clebsch; Part II-Eaton, 1963). The present report discusses the specific points brought out in TEI-837 that could be resolved only by detailed field study at the site itself, as well as by study of the relationship between surface ruptures resulting from the 1906 earthquake and the San Andreas fault zone. To that extent the present report supplements TEI-837. It includes a detailed geologic description of a shaft excavated for the reactor foundation. The examination of the shaft was undertaken to determine whether tectonic faults cut Pleistocene and Recent sediments that overlie granitic bedrock. One of the main purposes of this report is to evaluate the probability of future surface faulting at the site. Because such faults at the reactor site would lie west of the main San Andreas fault zone, data on surface ruptures west of the San Andreas fault zone, particularly historical events, are pertinent in predicting future surface rupturing at the site. Surface rupturing that developed during the 1906 earthquake west of the San Andreas fault zone was investigated on Point Reyes Peninsula, 17 to 30 miles southeast of the site.

The report has been prepared in response to a request from Chairman Seaborg to Secretary Udall dated October 3. Close contact with the AEC regulatory staff has been maintained in order to apprise the Commission staff of work progress as it might affect studies of the site by other Government agencies and consultants to the staff.

The continued cooperation of officials and employees of Pacific Gas and Electric Company and their contractor, Peter Kiewit Sons Co., greatly facilitated this phase of the investigations. Their help is appreciated.

The location of the shaft for the reactor foundation is shown on plates 1 and 2. The term "plant north" as used in this report refers to PG&E's plant coordinate grid and is 32° 6' west of true north. The shaft is 140 feet in diameter. The bottom is at approximately -73 feet (mean lower low water datum, MLLW).

A concrete collar two feet thick, about ten feet deep, and slightly larger in diameter than the shaft proper was first constructed. The elevation of the top of the collar ranges from +0.75 to +3.88 feet. A bulldozer and a loader excavated the shaft. The granitic rock below the weathered zone was loosened by blasting. The excavated material was removed from the shaft by a clamshell bucket working from outside the collar. Horizontal ring beams, generally spaced 4 to 5 feet apart vertically, were used for wall support. Gunite placed on heavy wire mesh was used to prevent spalling and sloughing of the wall. A 48-foot sector of the wall on the south side is supported by sheet piling to about elevation -20 feet.

Geology of the wall of the reactor shaft was mapped during the actual excavation because the wall was generally covered shortly after it was exposed. In the vicinity of the plant south line, poorly consolidated wet sands had to be supported immediately after excavation; consequently structural features of the sediments were not seen in these areas.

The site is adjacent to Campbell Cove on Bodega Head (pl. 1 and 2). Details of its topographic setting and a summary of previous geologic investigations are given in TEI-837. Bodega Head is a granitic body that lies west of the San Andreas fault. The granitic rocks are partly covered by Pleistocene unconsolidated marine sediments and partly by such continental deposits as slope debris, wind-blown sand, lake deposits, and alluvium.

The power plant site is on a buried valley system that was eroded in granitic rock by a surface stream and its tributaries, when sea level was relatively lower (pl. 2). The valley was subsequently filled with marine and nonmarine deposits. The main buried valley crosses Bodega Head in a more or less east-west direction. At its deepest point on the east side of the Head at Campbell Cove (pl. 2) it is more than 80 feet below sea level (reported in TEI-837 as more than 60 feet below sea level as based on Dames and Moore map of contours on granitic rock surface).

GEOLOGY OF THE REACTOR SHAFT AND VICINITY

The center of the reactor shaft lies about 325 feet north of the northeast-trending axis of the main buried valley and on the northeast flank of a southeast-trending tributary (pl. 3). Granitic rock is exposed at the collar on the north side of the shaft at an elevation of +5 feet (MLLW), but in the southeast quadrant unconsolidated deposits extend to elevation -41 feet. In the southwest quadrant of the shaft the irregular surface on the granitic rock is at an elevation slightly deeper than -35 feet and slopes gently southwestward. Farther southwest, near the shaft wall the buried surface of the granitic rock rises on a southeastward-trending spur whose axis lies about 200 feet southwest of the center of the shaft.

Sediments in the shaft reach a maximum thickness of about 43 feet in a small buried valley cut in granitic rock on the southeastern wall (at vertical control line 32, pl. 4; also see pl. 2). Northward the sediments thin toward the granitic rock spur, but westward they lie on a slight rise in the bedrock and then thicken to about 41 feet on the southwest wall of the shaft.

Plate 4, a map of the reactor shaft wall, shows the great irregularity of the buried granitic rock surface. Note the overhang between vertical control lines 1 and 7. The nearly horizontal surface on the granitic rock at elevation of -29 feet over part of this wall area and near vertical control line 28 suggests that it is a remnant of an old wave-cut nearshore terrace. A narrow terrace at about -20 feet is also indicated by the profile.

The large rock masses resting on a clay bed above the bedrock surface between vertical control lines 23 and 25 may represent an ancient landslide.

Granitic rock

The predominant granitic rock in the shaft is a foliated, coarse-grained, biotite-hornblende quartz diorite. Dark constituents, mostly biotite, make up 10 to 30 percent of the representative quartz diorite. A few pieces of granitic rock as much as 10 inches in diameter contain both foliated dark-gray biotite-hornblende quartz diorite and a light-gray to pink, unfoliated, coarse-grained, hornblende-biotite quartz monzonite. The two types are separated by a short but unfaulted, irregular to straight, intrusive contact. A dike of unfoliated, fine- to medium-grained biotite-hornblende leucodiorite (light gray, little quartz, no potassium feldspar, An_{43} plagioclase) was exposed in several places on the final floor of the shaft (pl. 3). Where seen, it followed the south side of a 2- to 6-inch-thick zone of gouge and mylonite. Pegmatite dikes are common in the quartz diorite of the shaft. Foliation in the quartz diorite is fairly uniform in the walls and floor of the shaft and strikes N. 10° to 20° E., and has a vertical or steep eastward dip (pl. 3). Additional information on granitic rocks of Bodega Head is given in TEI-837.

Weathering

A zone at the top of the granitic rock is generally weathered to a brown color. The zone is about 8 to 18 feet thick where exposed in the shaft (pl. 4). It is thinnest on the flanks of the bedrock spur and probably is as much as 30 feet thick at the top of the spur. The bottom of the zone is generally controlled by gouge and breccia zones and may follow a steeply dipping shear zone 10 feet or more below the general bottom of the zone of brown weathering. In some places the granitic rock near its buried surface is anomalously gray in color, though the rock is highly altered.

Faults and joints

Faults and joints are abundant in the granitic rock exposed during excavation of the shaft. The number and orientation of faults and joints in the shaft between elevations -66 and -73 feet are more or less typical of the granitic rocks exposed at all levels in the wall of the shaft. Where faults and joints are closely spaced, only the preferred orientation is indicated. Most faults are marked by plastic clay gouge (pulverized and chemically altered rock) 1/8 inch to 2 inches in thickness. Some faults are marked by a plastic gouge zone nearly 1 foot in thickness. Breccia (broken rock) zones are also common along faults; the pieces in such zones are commonly streamlined slivers elongated parallel to the fault walls. Mylonite (pulverized and streaked out, but firm rock) is relatively rare.

Some of the fault zones with attendant gouge and breccia zones are more than 20 feet wide. The shape of the shaft in the northwest and north part of the wall between -37 and -51 feet was controlled only with difficulty due to excessive overbreak from blasting. Those areas occur in wide zones of crushed, sheared, and chemically altered rock.

Another way of describing the abundance of faults and joints in the granitic rocks is to give the size of blocks bounded by these fractures. The range in size of the blocks from place to place on the wall and bottom of the shaft is great, but generally the blocks are 0.1 to 1 foot across; the maximum diameter is 6 feet. Within some parts of the shear zones most of the blocks are less than 0.1 foot.

Shearing is also evident from microscope examination of thin-sections of granitic rock from the shaft. Many microscopic shears cut the quartz and feldspar crystals and are in turn filled with quartz or feldspar.

The orientation of faults and joints in the granitic rock exposed on the shaft wall is shown on plate 4 and in figures 1 and 2. Figure 1 shows the percentage of faults and joints having various strikes (bearings) grouped by 10 degree arcs. That is, all faults and joints whose strike is within the range N. 20° to 30° W. were considered as one group. One of the diagrams on figure 1 shows the distribution of 1,120 measurements made of the strike of faults and joints at all levels in the shaft. Thus if a fault or joint persists from one level to a lower level its orientation was measured at each level. Use of repeated measurements on the same feature at several levels in figures 1 and 2 tends to weight the data in the direction of persistent, continuous features. Another diagram on figure 1 shows strike-frequency of only the faults included in the 1,120 measurements used in the other diagram. Both diagrams show that the predominant strike of faults and joints is in a narrow zone 10 degrees on either side of east-west and that the least-favored strike is between north and N. 10° W. The second most-favored strike is between N. 70° W. and N. 80° W. The average dip of all the fault and joint measurements is 63 degrees.

Figure 2 shows both dip and strike of the faults in the form of a contour map of the concentration of poles to the faults. A pole is a line drawn perpendicular to a fault plane. It confirms what is shown in figure 1 and, in addition, shows that the predominant dip direction of the west-trending faults is 50° to 75° S., but the general range is 65° N. to 45° S. Many fault surfaces seen in the wall bend in open curves through large angles. Slickensides or striations caused by relative movement on fault surfaces are common and generally plunge at large angles though on some faults they plunge at low-angles or are nearly horizontal.

Strength properties

The values for the ultimate unconfined compressive strength of the granitic rock from the shaft are given in table 1. They show a range from 1,037 to 16,800 pounds per square inch. The strength values determined by the Geological Survey were made on core taken from a 10 x 10 x 14-inch piece of bedrock, typical of the fresh, unsheared rock in the shaft. It is a foliated, coarse-grained, biotite-hornblende quartz diorite that contains about 10 percent biotite and hornblende.

The granitic rock core from borehole 14 is described by Dames and Moore (1962, pl. A1C) as follows: "White and black quartz diorite (severely jointed into mod. fresh blocks up to 3") with numerous small shear zones (joints and shear zones altered to clay)". The same description is given (Dames and Moore, 1962, pl. A1D) for core from borehole 16, with the following addition in the zone in which the 2 deeper of the 3 tested cores were taken: "(grading into harder and fresh blocks up to 8") (little or no alteration in joints) (few shear zones)".

Table 1.--Strength measurements on granitic rocks from the shaft, Bodega Head reactor site, Sonoma County, California.

Sample location	Ultimate, unconfined compressive strength, pounds per square inch	Analyst and remarks
Core - bore hole 14 (pl.2):		Dames and Moore (1962, pl. A1C); NX-size (2-1/8 inch in diameter) core pieces 2.74 to 3.25 inches in length.
10 feet below bedrock surface	2,108	
31 " " " "	1,861	
34 " " " "	2,448	
Core - bore hole 16:		Dames and Moore (1962, pl. A1D); NX-size core pieces 2.5 to 3.4 inches in length.
16 feet below bedrock surface	1,037	
23 " " " "	3,673	
26 " " " "	3,953	
Rock - at wall, northeast side of shaft near vertical control line 21, elev. -31 feet. Approximately 27 feet below bedrock surface; 15 feet below brown weathering zone.		U. S. Geological Survey, Denver, Colorado Laboratory NX-size cores, 4.3 inches in length.
Perpendicular to foliation	16,800	
Parallel " "	10,000	
" " " but perpendicular to last core	12,800	

Pleistocene deposits

The predominant sedimentary material overlying the granitic rock in the shaft area is a massive gray, gravelly, sandy clay. It is thickest in the southwestern part of the shaft, reaching a maximum of 32 feet including a few thin beds of other lithologic types on the perimeter of the shaft at the plant west line (pl. 2). The gravel in the sandy clay consists of granitic rock fragments. In places the amount of granitic fragments increases in the clay forming a gradational contact with the underlying granitic rock. This evidence suggests the sediment formed in place. Rounded detrital wood fragments, however, indicate that some movement occurred prior to deposition. The gravel in the sandy clay varies in size and amount. In most places granules 2 to 4 mm in diameter make up about 5 to 10 percent of the sediment. In some places a sandy clay layer one inch to one foot thick and containing pebbles as large as 3 inches in diameter occurs within the massive sediment. The gravelly, sandy clay is mottled brown and gray in many places along the western and southwestern wall of the shaft. Mottling is especially common in the southwest sector of the shaft wall.

Southward from about the center of the shaft the nonmarine, gravelly, sandy clay is interbedded with layers of sands and clays, 0 to 1 foot in thickness, probably of marine origin. The interbedding probably resulted from north-south shoreline oscillations. Above about elevation -20 near vertical control line 34, the sediments consist of gray and yellowish-orange sand, probably of beach or near-shore marine origin.

The sand appears to thicken south of the reactor shaft toward the axis of the main buried valley. The sand lies unconformably on the older sediments.

The variations in characteristics of the sediments are well illustrated in the walls of the shaft. As would be expected in deposits such as these, details of the sedimentary sequence are complex. Before deposition of the sand at the top of the shaft, channels were cut into the nonmarine gray, gravelly, sandy-clay and later filled with clayey sand (pl. 4). The north side of the cut channel is shown between vertical control lines 27 and 29. A later channel was cut (see vertical control lines 29 and 40 pl. 2) and filled with unconsolidated, fairly clean sand. Part of this sand is gray and part is dark yellowish-orange. The two color varieties are almost everywhere separated by a black or dark brown zone of sand that is rich in oxides of iron. At places these ironstone bands follow the surface of fossil tree limbs. The fossil wood appears to occur only in the gray sand. Though fossil wood is abundant in the other sediments, it was not seen in dark yellowish-orange sediments.

Sands and clayey sands in the shaft generally contain, in addition to a large proportion of sand grains of granitic origin, rounded sand grains of red chert and greenstone presumed to have been derived from the Franciscan Formation. This formation is exposed in the Bodega Head region only on the east side of the San Andreas fault zone and sand from it was probably moved across the fault by ocean currents.

Bedding is discernible in most parts of the sedimentary section other than in the gray, gravelly, sandy clay and in parts of the thick sand deposits. Bedding in sands is marked in places by 1 to 2 mm-thick layers of black heavy minerals or by a change in average grain size. In many places, color banding in orange, brown, and gray, is parallel to bedding, though color banding in many other places lies at steep angles to the bedding. Alternating beds, 1/8 to 2 inches in thickness, are especially abundant on the south side of the shaft. Beds in the reactor shaft are generally flat lying or dip gently eastward or southward. Rarely does a thin bed or group of beds dip northward or westward.

Fossils and age

Fossil wood is abundant in the sediments. Limbs 4 to 6 inches in diameter are commonly seen. Pieces 1/4 to 2 inches long are abundant. A tree about 2 feet in diameter and more than 10 feet long was found in the northeast quadrant of the shaft at about elevation 5 feet.

Cones, fruit, seeds, and needles of the following species were found in sediments near the shaft between elevations 5 and 21 feet and identified by Jack A. Wolfe, U. S. Geological Survey (written communication, December 4, 1963).

Monterey pine (Pinus radiata)

Bishop pine (Pinus muricata)

Sitka spruce (Picea sitchensis)

Western wax myrtly (Myrica californica)

Red elderberry (Sambucus callicarpa)

Manzanita (Arctostaphylos sp.)

Bedstraw (Galium sp.)

Wolfe also states that the flora here is similar in composition to the Pleistocene flora from the northeast shores of Tomales Bay (pl. 1) and suggests that their floristic similarities indicate that the beds in which both floras are found were deposited at about the same time and under the environment of the closed-cone pine forest.

The exact age of both the beds at Tomales Bay and Bodega Head is not certain. A radiocarbon date of greater than 42,000 years was obtained from 3 fossil wood samples obtained 102 feet S. 70° W. from the center of the shaft at elevation 49 feet, 197 feet N. 32° W. of the center at elevation 55 feet, and 240 feet N. 35° W. of the center at elevation 77 feet.[1/] Thus, the sediments in and near the shaft between elevations 5 and 21 feet are considered to be Pleistocene in age.

[1/] The age of these samples was reported in TEI-837 as greater than 38,000 years. This preliminary age determination was later refined to greater than 42,000 years (Meyer Rubin, U. S. Geological Survey, written communication, August 8, 1963).

Shaft fault

The Shaft fault is the major structure in the reactor shaft area and in this report is named for the fault complex that has been traced from the Pleistocene sediments near vertical control line 39, at the approximate elevation of -12.5 feet, downward into the granitic rock near vertical control lines 40 and 41 to the bottom of the shaft (pl. 2). Southwest of the shaft the fault is exposed in exploratory trenches 1 and 2 dug in Pleistocene sediments (pl. 2).

The Shaft fault in the granitic bedrock is a well-developed conspicuous zone of faults 2 to 10 feet wide (pl. 2 and 4). Individual faults within the zone have various characteristics. Some are tight, paper-thin, clean fractures in fresh rock; others are wedges 1 to 2 feet wide, and elongated for as much as 5 feet along the dip or strike. Some of the wedges are composed of brecciated slivers of hard granitic rock whereas others are composed of soft, clay gouge zones. A zone of plastic gouge in the fault at elevation -67 feet at vertical control line 40 is nearly 1 foot in thickness (fig. 3). Individual faults branch and bend, within the zone, but most can be followed for tens of feet. The fault zone is a complex array of intersecting smaller faults, but elsewhere only a few strong subparallel ruptures can be seen and the rock between them is relatively unbroken.

The well-developed fault zone on the south wall near elevation -55 (fig. 5) consists of numerous subparallel faults. On the northeast wall, however, the fault zone is not as well developed. At the floor (elevation -73) and for about 7 feet above, the zone consists of two faults separated by about 2 feet of fairly intact rock.

At this locality each fault is a gouge and breccia zone 1 to 2 inches wide. From elevation -55 to -51 the fault zone is a foot wide and made up of gouge and breccia. Between elevation -41 to -46, the fault was traced from the south wall to the northeast wall (pl. 3 and fig. 4). At this elevation the fault is 2 to 12 inches wide and consists of several intersecting and branching faults separated locally by breccia. Near elevation -24 between vertical control lines 25 and 26 the fault splays out into several branches about 5 feet below the top of the granitic rock (pl. 4). No rupture was seen in the overlying gravelly sandy clay.

The Shaft fault strikes N. 40° E. and dips 65° to 80° W. Slickensides on individual faults of the zone range from vertical to horizontal, but most are steep, indicating a dip-slip component of movement.

Field evidence for horizontal (also called lateral, or strike-slip) movement is seen on the floor of the shaft at final grade. The evidence is conflicting with respect to direction of horizontal movement. A steeply dipping pegmatite dike that is aligned at a high angle to the Shaft fault appears to have been dragged northeastward along the Shaft fault for 11 feet (pl. 3). If the isolated pegmatite shown in plate 3 east of the fault is the same dike, it indicates left lateral movement of the Shaft fault in the granitic rock of about 37 feet. A steeply dipping leucodiorite dike is also offset by the Shaft fault proper and two west branches of it (pl. 3). Direction of offset of this dike also suggests horizontal movement of the Shaft fault, but of a right lateral nature. We believe the field evidence for right-lateral movement suggested by the offsetting of the leucodiorite dike is somewhat more reliable than that for left-lateral movement given by the pegmatite dike.

The Shaft fault intersects the granitic rock surface on the south side of the shaft at elevation -35 feet (fig. 6). At this locality the sediments-granitic rock contact appears to be offset about 1-foot downward on the west but field relations do not clearly establish this relation. At several temporary positions of the floor of the shaft (about -35 to -40 feet), as shown on plate 3, the direct connection between the Shaft fault in sediment and in granitic rock is well established. The fault is the contact between the two rock types. It dips 82° W. and was followed by hand trenching into the underlying granitic rock.

The Shaft fault in the overlying sediment is easily traced from the surface to about elevation -26 feet. It is nearly vertical about 2 feet above the granitic rock but at a point within about 8 inches of the granitic rock surface it is distributed among several thin clay gouge zones, the most prominent of which bend to the west, parallel to the rock surface and about 1 to 3 inches above it. One small gouge is vertical and appears to join a gouge zone in the rock.

The geologic map of the reactor shaft wall, plate 4, shows the dip of the Shaft fault at various levels. Above elevation -28 feet the Shaft fault complex dips steeply eastward; below this level it dips mostly westward. In the granitic rock it dips westward. From -28 feet to -26 feet the Shaft fault is 1 to 2 inches wide and is filled with gray, medium- to coarse-grained, clayey sand and with pieces of the sediment from the walls, gravelly, sandy clay (fig. 7). Between -26 and -23 it passed through in a massive, dark gray, gravelly, sandy clay of higher clay content than the underlying unit and could not be seen. When the floor of the shaft at various levels was still in similar sediments, it was impossible to trace the fault across a horizontal surface (pl. 3).

From elevation -23 to about -12.5 feet the fault cuts a well-bedded section. Near the perimeter at the south it appears either as a thin, clean break, or as a fracture about 1 to 2 mm wide, filled with sand or clay. About 15 feet to the northeast and elsewhere it forked into 2 branches that were separated about 1 foot (fig. 8). In some places the main branch ended and the other continued. In other places branches recombined to form a single break. The sediment between branches did not appear to be greatly disturbed. The line of the fault was either a sharp, clean break or a break with walls 5 to 15 mm apart and filled with sand or clay.

Beds at about elevation -16 feet appear in cross section to be folded into a monocline. The Shaft fault complex cuts this fold. Beds are 2 feet lower west of the fold and fault. The continuity of the Shaft fault from the south wall was established by cleaning off the bottom of the shaft with a strong jet of air along the fault at elevation -41 to -46 feet. The fault was followed to the northeast wall. Gunite panels were removed at higher elevations in order to examine the fault in the wall.

The amount of vertical separation of beds on the two sides of the fault varies from place to place on the south wall, though it is everywhere down on the west side, except along two minor faults near elevation -12 feet. From the granitic rock surface to about elevation -29 feet, some uncertainty in matching beds was encountered. The apparent vertical offset of the basal two feet of sediments may be about one foot. From about elevation -32 to -29 feet, the vertical separation may be as much as 19 inches. From about elevation -29 to -26 feet, it may be only about 6 inches. Vertical separation at elevation -20 feet is about one foot. Above elevation -19 feet several lines of rupture fan out. The middle line shows the greatest well-established vertical separation, 14 inches (fig. 9). The easternmost fault is marked by a one-quarter inch thick plastic clay gouge that follows beds and also breaks across beds (pl. 4). Ruptures can be followed to about elevation -12 feet. Beds here show a vertical separation of two inches across the westernmost fault. Above elevation +10 the concrete collar makes up the wall of the shaft. Conditions of observation in the collar trench in the vicinity of the Shaft fault were poor. This work was done after dark by flashlight before adequate lighting had been installed.

Exploratory trench 1 was made to intersect the Shaft fault so as to permit examination above its highest level in the shaft. Plates 2 and 3 show faults in Pleistocene sediments southwest of the shaft. Two faults were found in the trench at elevation -16 feet that are believed to be an extension of two in the shaft wall. They dip eastward and show vertical offsets of about 1/2 inch, down on the east. They could not be seen above about elevation -16 feet. Another fault was found about 9 feet to the east. It dips 70 to 85° eastward, strikes N. 35° E. to N. 42° E. and shows a vertical separation of about 1.8 inches, down on west (fig. 10). A fault believed to be this one (see plates 2 and 3) was found in an embankment to the southwest. It was traced upward to the elevation +25 feet and followed by bulldozer across this level to the asphalt drain at the base of the embankment below the elevation 55 feet bench. It was well developed where last seen near the asphalt drain 170 feet southwest of the shaft.

Exploratory trench 2 was dug in an effort to intersect the Shaft fault branch seen in the south wall of the shaft at elevation -12 feet. It could not be found. Trench 2 also crossed the Shaft fault branch found at elevation +25 feet. In the trench its strike is N. 24° E., dip 83° E. The amount and direction of movement could not be determined (fig. 11). On the +25-foot level the fault appears mostly as a black band of discoloration, 1/8 to 1 inch wide in pale brown sand (fig. 12). It splits and reconnects creating lens shaped areas a few inches wide (fig. 13).

Exploratory trench 3 was dug on the elevation 55 feet bench in an effort to follow continuation of the fault at the elevation 25 feet level. It reached to about elevation 51 feet. No faults were seen in the well-developed sand beds in the trench.

An unsuccessful search was made for a possible continuation of the Shaft fault northeast of the shaft. A bulldozer and hand scrapers were used for this purpose. Embankments northeast of the shaft were scraped clean (fig. 13).

Origin

The Shaft fault is the only structure at the proposed power plant site that transects both the younger sediments and the underlying older granitic rock. Moreover, the origin of this fault is fundamentally important in any evaluation of its significance to site acceptability and plant design. The three mechanisms that have been considered as contributing to the origin of the Shaft fault are (1) tectonic faulting, (2) landsliding, and (3) subsidence from compaction of the sediments.

Tectonic faulting is used in this report for the rupturing of rocks caused by crustal stresses of deep-seated to shallow origin such as those that produced the 1906 earthquake. The hypothesis that the Shaft fault in the granitic rocks was formed by tectonic faulting is supported by the horizontal displacement evidenced in the dike rocks. Although the field evidence is conflicting with respect to direction of horizontal movement on the Shaft fault, the zone is generally wide and consists of many intersecting faults separated locally by breccia and gouge, features that were formed during repeated movement along this zone of weakness. The strongest evidence supports a right lateral movement a minimum of $2\frac{1}{2}$ feet; the amount of vertical displacement is unknown.

The extension of the Shaft fault into the overlying Pleistocene sediments indicates that the displacements measured in the sediments along this fault are also the result of tectonic activity. In the sediments, a maximum vertical separation of 14 inches was measured across the Shaft fault. The amount of horizontal movement in the sediments was not measured in the field though the many changes in dip of the fault in the sediments as seen in the south wall of the shaft, particularly the right-angled bends of the easternmost and highest branch (see pl. 4), suggest the movement on the fault had a strong horizontal component. The differences in thickness of beds and inability to match beds across the Shaft fault, as seen in the south wall of the shaft, is evidence that strike-slip faulting has occurred. The amount of strike-slip displacement of the sediments is estimated to be about 13 feet. This value is required to produce the vertical separation of 14 inches measured across the fault that displaces through horizontal shear movement beds that dip 5°. At the site the Pleistocene beds generally dip southward and/or eastward at angles as high as 10° though the average dip is about 5° S. The horizontal displacement on the Shaft fault in the sediments is right lateral, the same relative movement as indicated by the offset on the leucodiorite dike on the floor of the shaft.

The scarcity of more or less horizontal slickensides and the abundance of those that plunge steeply along the Shaft fault both in the granitic rock and in the Pleistocene sediments, suggest that the last movement was predominantly vertical. Slickensides, however, can form by very small movements, particularly in soft gouge or soft sediments, so that the vertical slickensides may not reflect the principal direction of movement on the fault.

The absence of the Shaft fault in exploratory trench 3, about 250 feet southwest of the reactor shaft (pl. 2) can be attributed to (1) dying out of faulting upward and/or along strike, or (2) deposition of the younger sediments after faulting.

Tectonic faults of lateral movement are characteristically discontinuous, en echelon, and branching. Surface ruptures within the San Andreas fault zone produced during the 1906 earthquake illustrates these characteristics. (See description by Higgins, 1961, p. 53 of the ruptures at Fort Ross, 18 miles north of the reactor site.) It is to be expected, therefore, that the Shaft fault, a tectonic fault, cannot be traced continuously along the strike for long distances and that its absence in trench 3 is due to its dying out between trenches 2 and 3.

If the sediments were deposited after the youngest movement on the Shaft fault, then faulting of the sediments took place more than 42,000 years ago, the age of the oldest dated sediments, according to radiocarbon measurement of fossil wood. The Pleistocene beds on Bodega Head may be younger than a crustal disturbance that is estimated by Louderback (1951, p. 86) to have taken place from about 240,000 to 400,000 years ago. Thus the Shaft fault in the Pleistocene beds at the site may have originated between 42,000 and 400,000 years ago.

The Shaft fault in the sediments might represent the left flank of a landslide which moved in a southwesterly direction. The topography of the bedrock surface as depicted on plate 2, however, precludes this possibility because such a landslide would have had to move across a narrow valley and up the bedrock ridge on the opposite side of the valley. Conceivably the bedrock topography as shown in plate 2 may be incorrect in detail; even so, in order to produce a landslide that could create the Shaft fault, a southwesterly slope at least as long as the known extent of the Shaft fault would be necessary. It seems very unlikely that such a long southwesterly slope would have formed contrary to the general bayward slope of the ground surface. If the Shaft fault is the result of landsliding, deformation and disruption of sedimentary features should be greater in the sediments of the landslide mass than in the adjacent ground. This would especially be true of subaqueous landsliding. No marked differences, however, in disturbance of sediments were seen on the two sides of the Shaft fault.

An origin by compaction is favored by the location and trend of the Shaft fault along the northwestern flank of a ridge of granitic bedrock at the reactor shaft (pl. 2). The sediments are somewhat thicker west of the Shaft fault over a low place on the granitic bedrock surface and greater subsidence by compaction would be expected here. A fault caused by compaction of sediments should dip everywhere toward the area of compaction, westward for this place, and the fault movement should be of the normal type in which the down moving block lies above the fault. On the south wall of the shaft at about elevation -16 feet, theoretical displacement on the Shaft fault is down on the west about 2 feet--a condition that favors the subsidence theory. However, the Shaft fault dips both eastward and westward, but where it shows its greatest apparent vertical offset, it dips eastward, or movement was reverse to that required for compaction. Furthermore, the apparent downmoving block is below the fault. Also subsidence northwest of the fault would leave unsupported sediments above the east-dipping part of the fault. This should result in additional faults near elevation -20 between vertical control lines 38 and 39. None was seen. The undivided continuity of the Shaft fault southwest of the shaft across an area of thick sediments filling a valley cut in the bedrock surface, and onto an area of thin sediments above the adjoining ridge of bedrock, makes the origin of the Shaft fault by compaction highly unlikely.

SURFACE RUPTURES WEST OF THE SAN ANDREAS FAULT ZONE

The structural features in bedrock along the west side of the San Andreas fault were examined to determine their genetic relation to the San Andreas fault zone for comparison with similar features at the proposed reactor site on Bodega Head. The areas studied include Inverness, Mt. Wittenburg, and Mud Lake (pl. 1).

Gilbert (in Lawson and others, 1908, p. 69, and pl. 45B and 47A) describes and illustrates surface ruptures in the town of Inverness that resulted from the 1906 earthquake. Although the exact locality was not given by Gilbert, we were shown by Mr. Thomas Drew, a resident of Inverness, a feature which his father, who lived there in 1906, referred to as "the earthquake crack." This feature (locality 1, pl. 1) consists of two scarps three or four feet high bounding a small ridge 10 to 25 feet wide that strikes N. 18° W. The ridge and the bounding scarps look very much like those shown in plate 47A of the Lawson report. The topography in the immediate vicinity of the ridge also is similar to that shown on plate 47A (Lawson, 1908) and the skyline, now obscured by trees is, according to Mr. Drew, the same as in the photograph (pl. 47A). Remnants of the fence visible in the photograph were also found in the trees leaving little doubt that the locality we visited is the one pictured in the Lawson report. Gilbert states (in Lawson, 1908, p. 69) that the horizontal displacement along this crack was $2\frac{1}{2}$ feet. This undoubtedly is tectonic fault movement.

Locality 1 is at the top of a rather flat ridge and according to the Gilbert description and plate 45B (Lawson and others, 1908) the rupture extended down both sides of the ridge and across part of a flat-bottomed valley and trends at nearly right angles to the ridge and valley. At locality 1, the rupture is about 2,000 feet west of the projected edge of the San Andreas fault as shown on published geologic maps (Weaver, 1949, pl. 9; Koenig, 1963). However, Gilbert (Lawson and others, 1908, p. 194), probably influenced by the surface rupturing he saw there in 1906, considered Inverness to be within the fault zone.

Gilbert (in Lawson and others, 1908, p. 75) described cracks resulting from the 1906 earthquake that cross a spur on Mt. Wittenburg (Locality 2 on plate 1). The authors accompanied by Alan J. Galloway, a geologist who has recently mapped the geology of this area, inspected the spur in an attempt to find the cracks described by Gilbert. Although we were unable to locate the cracks, the spur is a broad ridge and landslide movement is very unlikely to have caused the cracks. We believe Gilbert was correct in ascribing them to fault movement. A subsequent study of selected aerial photographs of Mt. Wittenburg revealed a dense network of lineaments, some of which are shown on plate 1. Several of these lines extend toward the spur on Mt. Wittenburg and the fault movement described by Gilbert may have been on one of these.

The lineaments appear in various forms on the photographs. Some are prominent straight stream valleys; some consist of the alignment of short tributaries, of notches in ridges, and of trees of different height than their neighbors; and some are extremely fine dark lines. They occur in quartz diorite, shale, graywacke, and greenstone. Those shown on plate 1 are merely a sample obtained by a brief study of a few photographs and with additional study many more could be plotted.

Results of our brief study have shown that some of the lineaments are joints and faults, a few may be igneous dikes, but many of them are zones of weak rock along which erosion had been greater than elsewhere. According to A. J. Galloway (oral communication, 1963) some of the lineaments are faults having measurable offset.

The genetic relation of the lineaments to the San Andreas fault zone has not been definitely established. Some of the more prominent lineaments curve northward from the San Andreas fault and probably are branches of it (Galloway, 1961, p. 31, and oral communication, 1963). On the other hand, examination of aerial photographs of an area approximately five miles east of the San Andreas fault indicates that the lineaments are just as prominent there as they are within one mile of the fault. Even if the lineaments observed in the Mt. Wittenburg area cannot be related to the San Andreas fault genetically, they indicate that the granitic rocks have prominent zones of weakness along which fault movement has and could occur.

The distribution of many lineaments in the Mud Lake area (near locality 3) are shown on plate 1. Mud Lake is about 3,000 feet west of the San Andreas fault and it probably resulted from subsidence of a block bounded by faults. It lies in an elongate steep-walled depression whose topographic position and shape preclude origin by landsliding. It is estimated from the Double Point quadrangle topographic map that the block has subsided more than 40 feet. The rate at which this type of movement occurs is not known.

Vertical movement of as much as five feet, which Gilbert (in Lawson and others, 1908, p. 75) ascribed to faulting, occurred at locality 3 south of Mud Lake. The authors accompanied by Alan Galloway and Don Tocher, were able to positively identify locality 3 as the one that Gilbert described (op. cit., 1908, p. 75). This movement was probably caused by landsliding rather than faulting. Very large landslides are prominent just west of the locality, and study of aerial photographs reveals that an irregular scarp formed by a landslide joins the fractures described by Gilbert (1908). Moreover, the stream valley down hill from the site has been blocked by the landslide movement, causing ponding of the valley and deposition of sediments.

Additional information on the structural features resulting from the movement along the San Andreas fault during the 1906 earthquake was obtained in a railroad tunnel at Wrights Station, about 100 miles south of Bodega Head (Lawson and others, 1908, p. 111-113). The tunnel is in bedrock of sandstone and chert, and makes an angle of 80° with the San Andreas fault. As a result of the 1906 earthquake the tunnel was offset (horizontally) about five feet along a fault and damage over much of its length consisted of crushing of the timbers, breaking of ties, and caving. The tunnel was also bent out of line, the amount decreasing away from the fault. At a distance of 4,000 feet from the fault the horizontal deformation was 14 inches. The report does not state whether the fault in the tunnel was in the main San Andreas fault zone or was a secondary branch fault, but in either case, the ground was strained for a distance of at least 4,000 feet from the place where the tunnel was offset five feet.

CONCLUSIONS

On the basis of the geologic information obtained during the detailed geologic study of the proposed power plant site and the study of the faults developed by the 1906 earthquake on the west side of the San Andreas fault zone southeast of Bodega Head, the following conclusions are presented.

Significance of the Shaft fault

The Shaft fault is one of the principal faults cutting the granitic bedrock in the reactor shaft area. Its size in the granitic rock indicates that it has been the locus of stress relief at many times in the past. Drag and offset of igneous dikes by the Shaft fault indicate that its movement may be primarily horizontal like that of the San Andreas. The ruptures in the Pleistocene sediments evidently formed during the latest movement along this fault. The abrupt changes of dip with depth and the variation in offset magnitude and direction with depth also indicate that movement of the Pleistocene sediments was largely horizontal.

Whether the Shaft fault should be considered as an active or inactive fault cannot be determined. Geologic evidence bearing on the age of the latest movement of the Shaft fault is inconclusive. The field data may be interpreted to indicate that the last movement took place more than 42,000 years ago, On the other hand, it is just as reasonable to postulate that displacement in the granitic rock at some more recent time ruptured the lowest of the sedimentary deposits by shearing, whereas the sediments higher in the section absorbed the differential movement. That is, the intensity of shearing diminished upward and the unconsolidated sediments adjusted to the strain by intergranular movement, compaction, or displacements so small and diffuse that they left no visible evidence of shear.

The Shaft fault in the granitic rock of the reactor shaft is an important zone of weakness that could undergo differential movement if stressed to a degree comparable to the stresses applied to granitic rocks on Point Reyes peninsula during the 1906 earthquake. In this respect it is no different from myriad other faults in the granitic rock of Bodega Head and there is no basis for saying that it would move in preference to other faults.

Possible future faulting on Bodega Head

The commonly accepted outer limits of the San Andreas fault zone are the boundaries of the zone that has been the locus of the majority of surface ruptures. The same stress field that causes ruptures along the San Andreas fault zone is also present in the crust adjoining the zone. As was seen in Point Reyes Peninsula and at other places along the San Andreas fault zone during the 1906 earthquake, the ground surface was ruptured by sympathetic faulting at places as much as a mile from the commonly accepted border of the fault zone.

If in some future earthquake surface rupture comparable in severity to that produced in 1906 occurs on the San Andreas fault, the near-surface granitic rock of Bodega Head would be expected to rupture. The nature, direction, and amount of displacement cannot be predicted, nor can the location of such ruptures. Judging from the surface rupturing observed on Point Reyes Peninsula after the 1906 earthquake, displacement on the order of a few feet, either horizontally or vertically, should be anticipated.

An earthquake appreciably less severe than the 1906 earthquake, under the conditions stipulated, would not be expected to cause rupturing outside the San Andreas fault zone. There is no way to relate this rupturing outside the main San Andreas fault zone to earthquake severity except in the most general way; thus, it is impossible to define some "threshold severity" above which faulting outside the main fault zone would be predicted.

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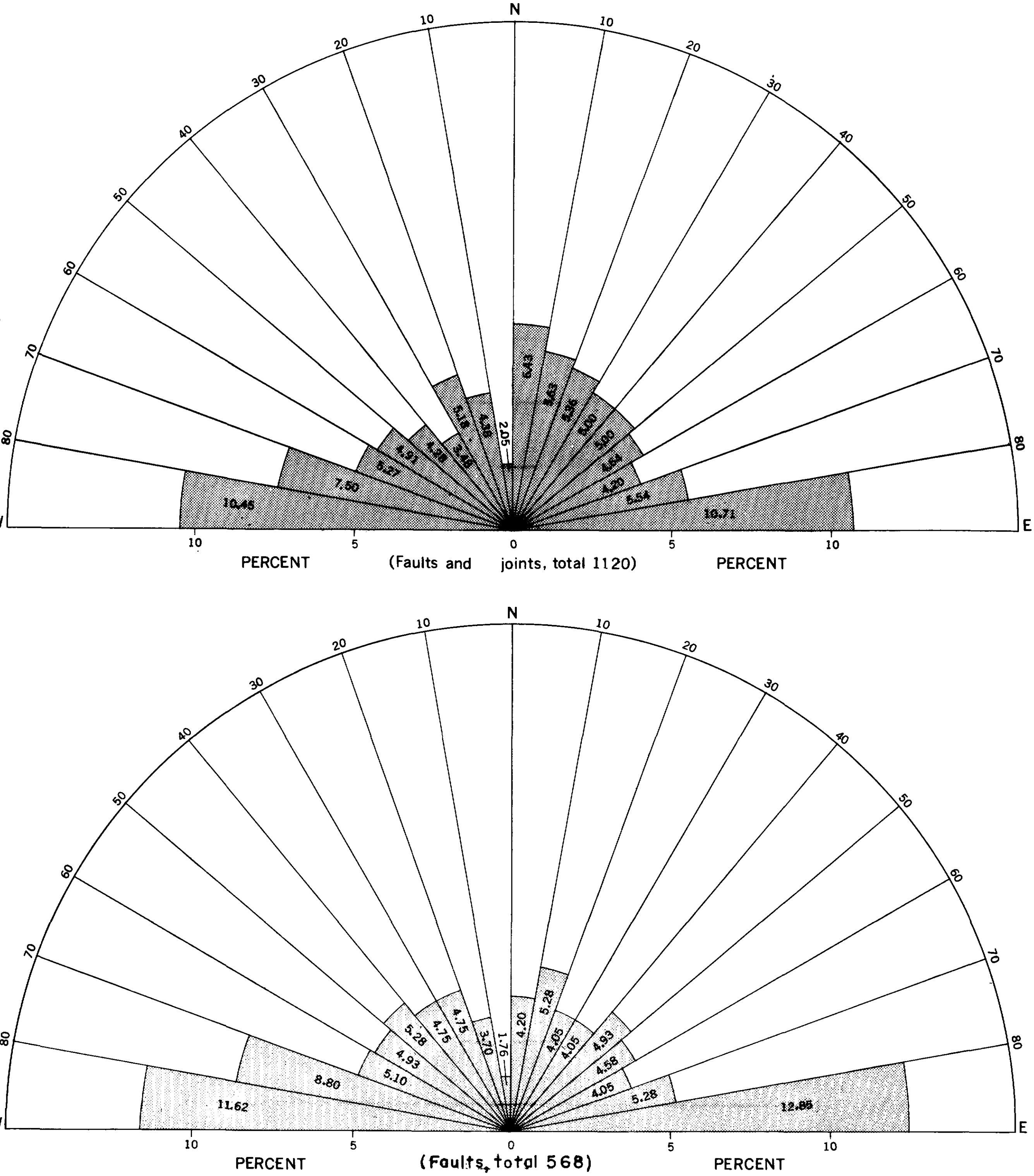

Figure 1. – Strike (bearing)-frequency diagrams of faults and joints observed in wall of reactor shaft, showing percent mapped within 10 degree intervals of strike. Includes repeated observations of faults and joints that persisted from level to level.

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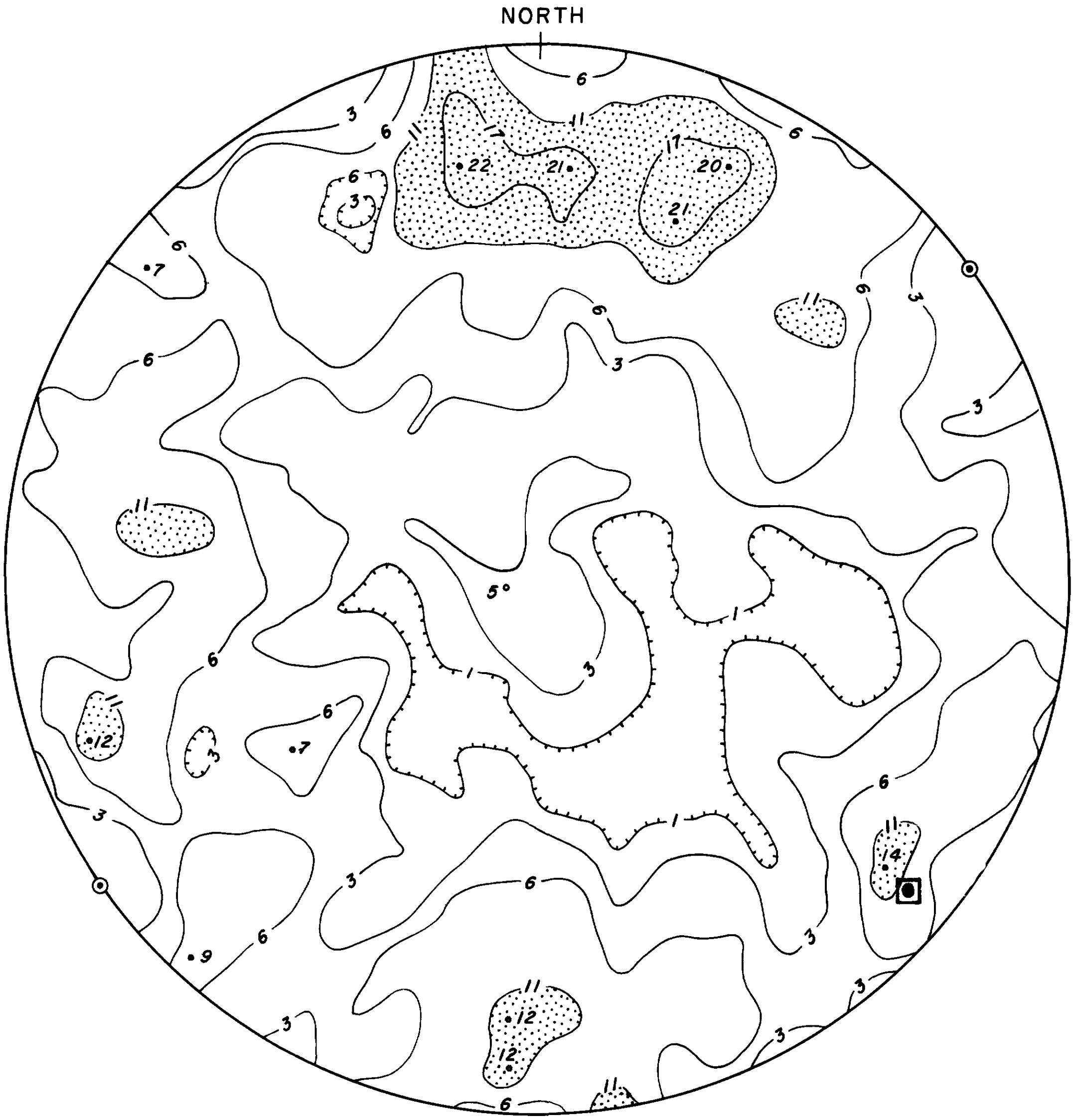

Figure 2.- DIAGRAM SHOWING ORIENTATION OF FAULTS

Contour diagram of 568 poles of faults on wall of reacter shaft. Plotted on lower hemisphere of equal-area net. Includes repeated observations on faults that persist from level to level. Contoured on 1, 3, 6, 11, and 17 pole concentration intervals; unit area for counting poles is one percent.

⊙ indicates pole to San Andreas fault zone, which for this diagram is assumed to be vertical strike N37 W. ▣ indicates pole to Shaft fault, dip 77 degrees N. W., strike N 40 E.

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Fig. 3.--Shaft fault on south wall of shaft, elevation -75 feet.

Fig. 4.--Shaft fault on floor of shaft, elevation -42 feet.

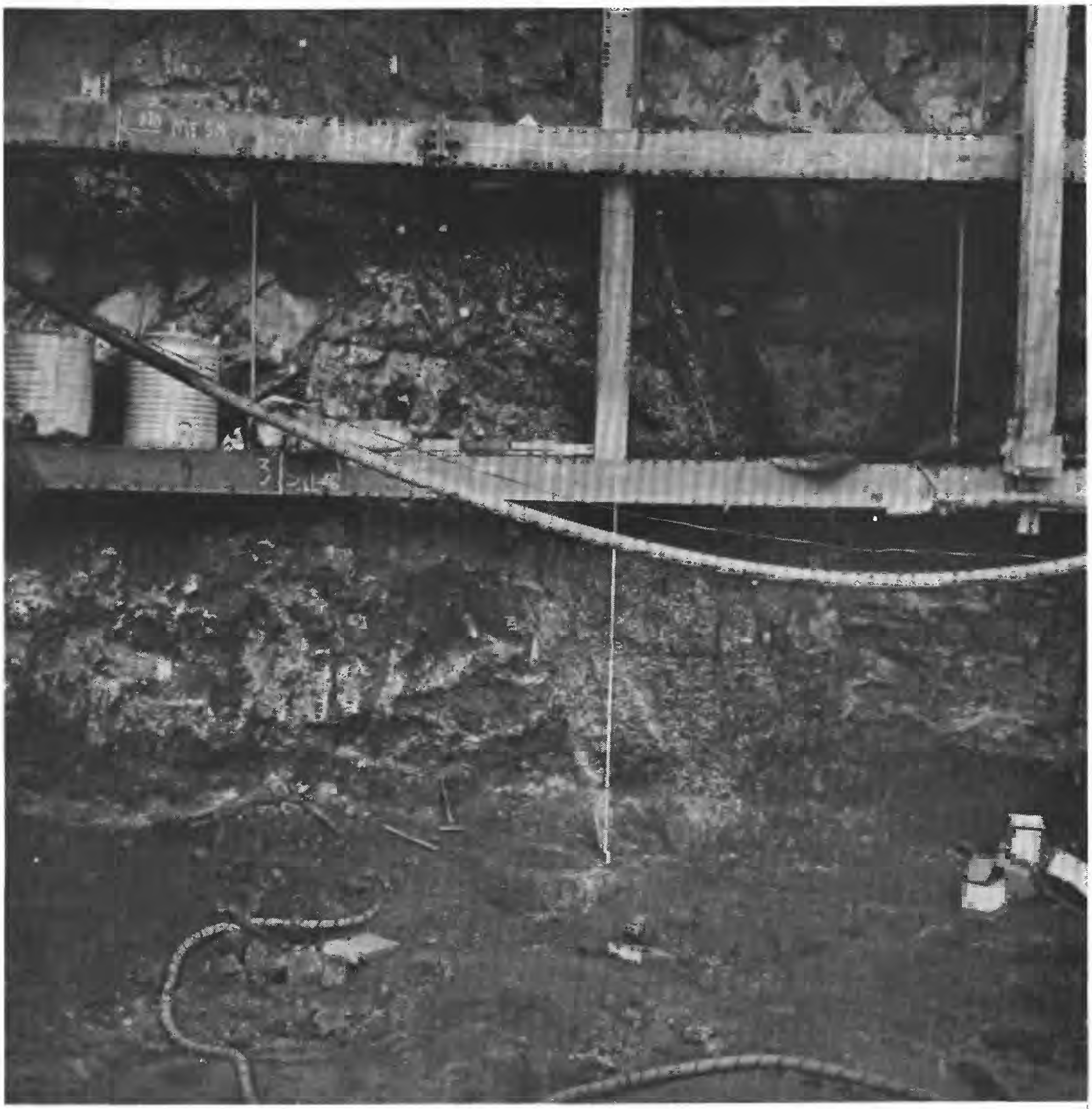

Fig. 5.--Shaft fault in granitic rock on south wall of shaft, elevation -41 to -51 feet.

Fig. 6.--Shaft fault on south wall showing sediment lying on granitic bedrock.

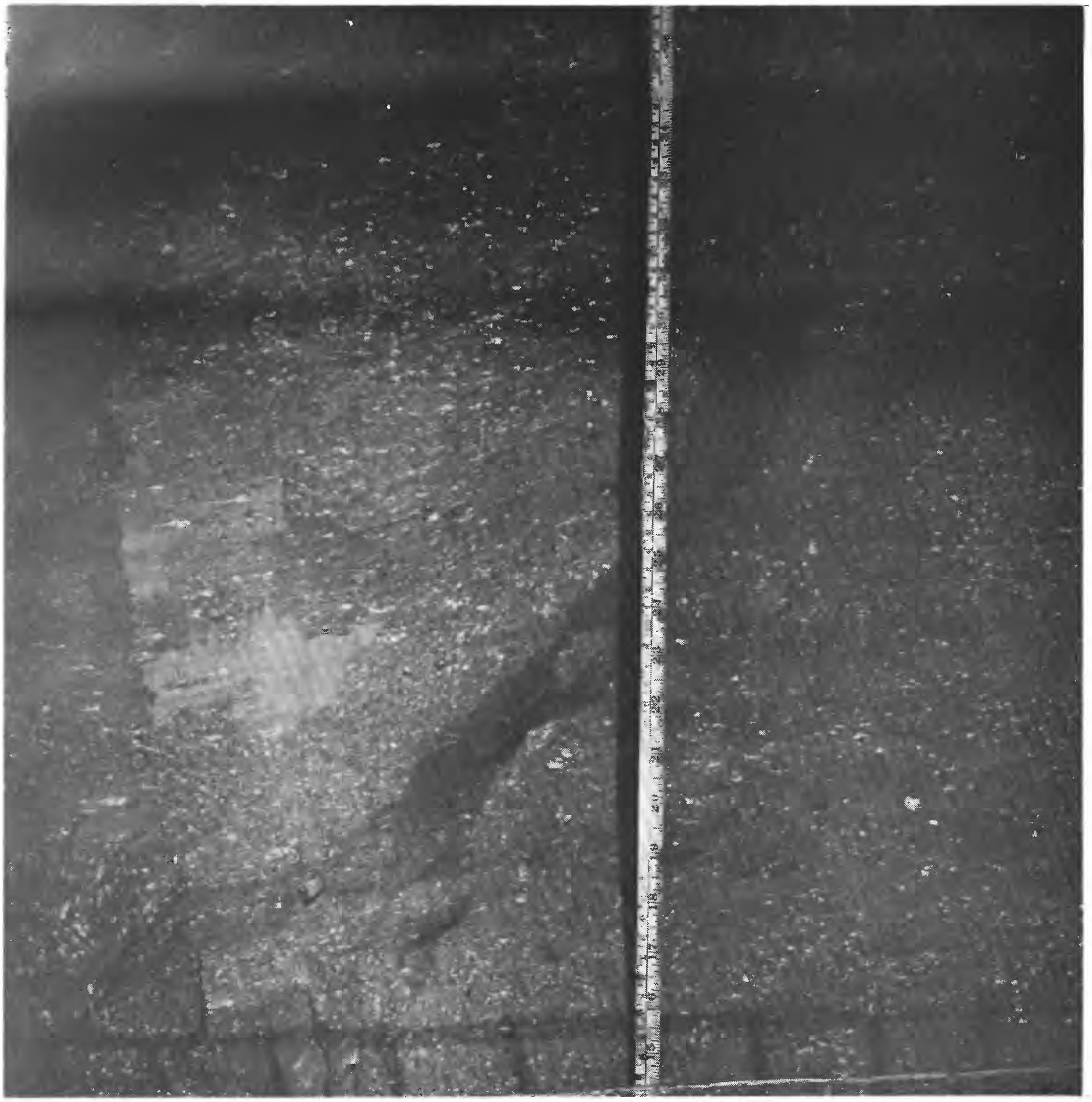

Fig. 7.--Shaft fault on south wall showing sand filling and variation in dip.

Fig. 8.--Shaft fault in floor of shaft, elevation -20 feet, showing dip and branches.

Fig. 9.--Shaft fault in sediment between elevation -13 and -20 feet showing 14-inch vertical separation.

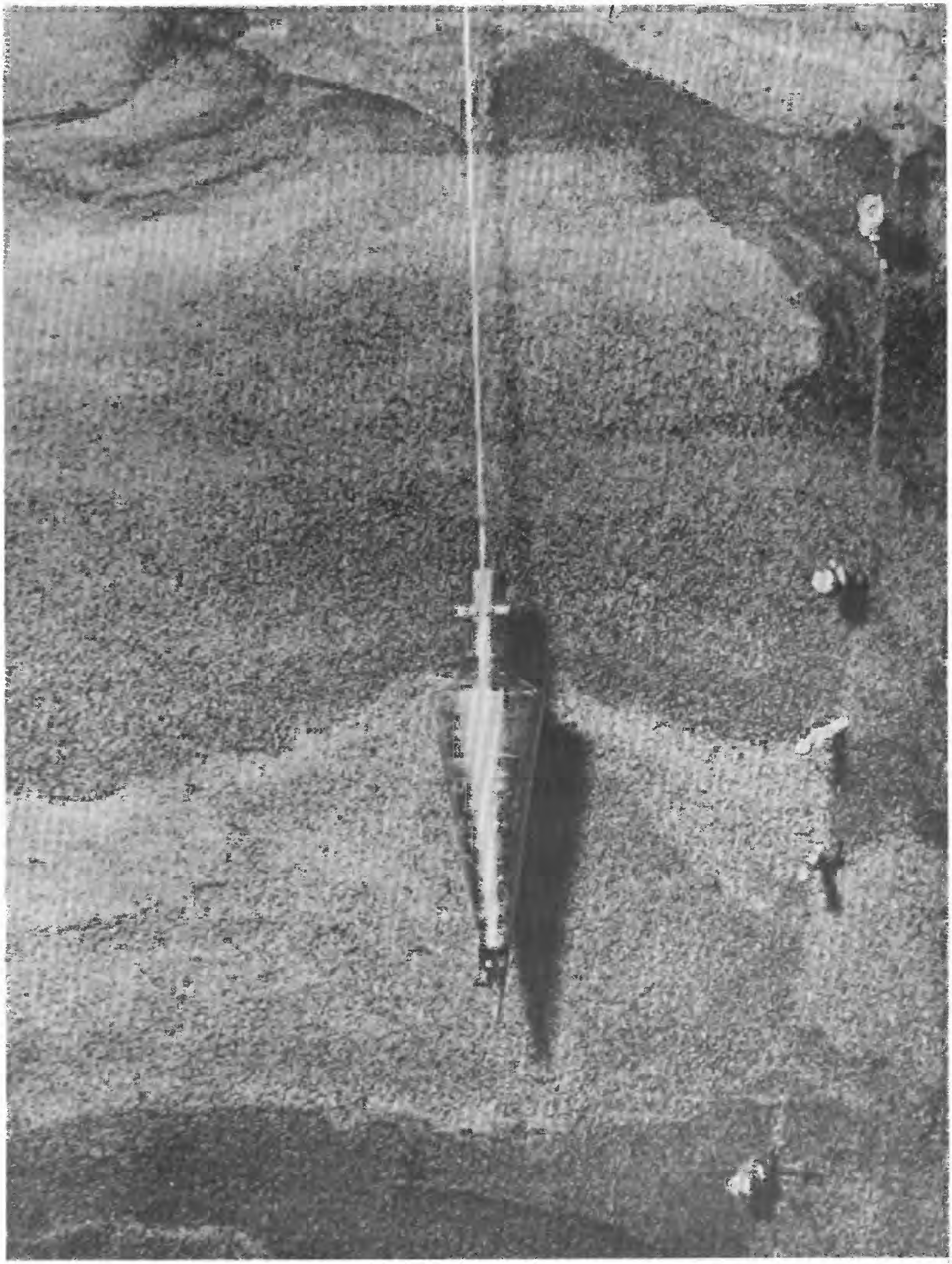

Fig. 10.--Shaft fault in exploratory trench 1, looking southwest.

Fig. 11.--Shaft fault in exploratory trench 2, looking southwest.

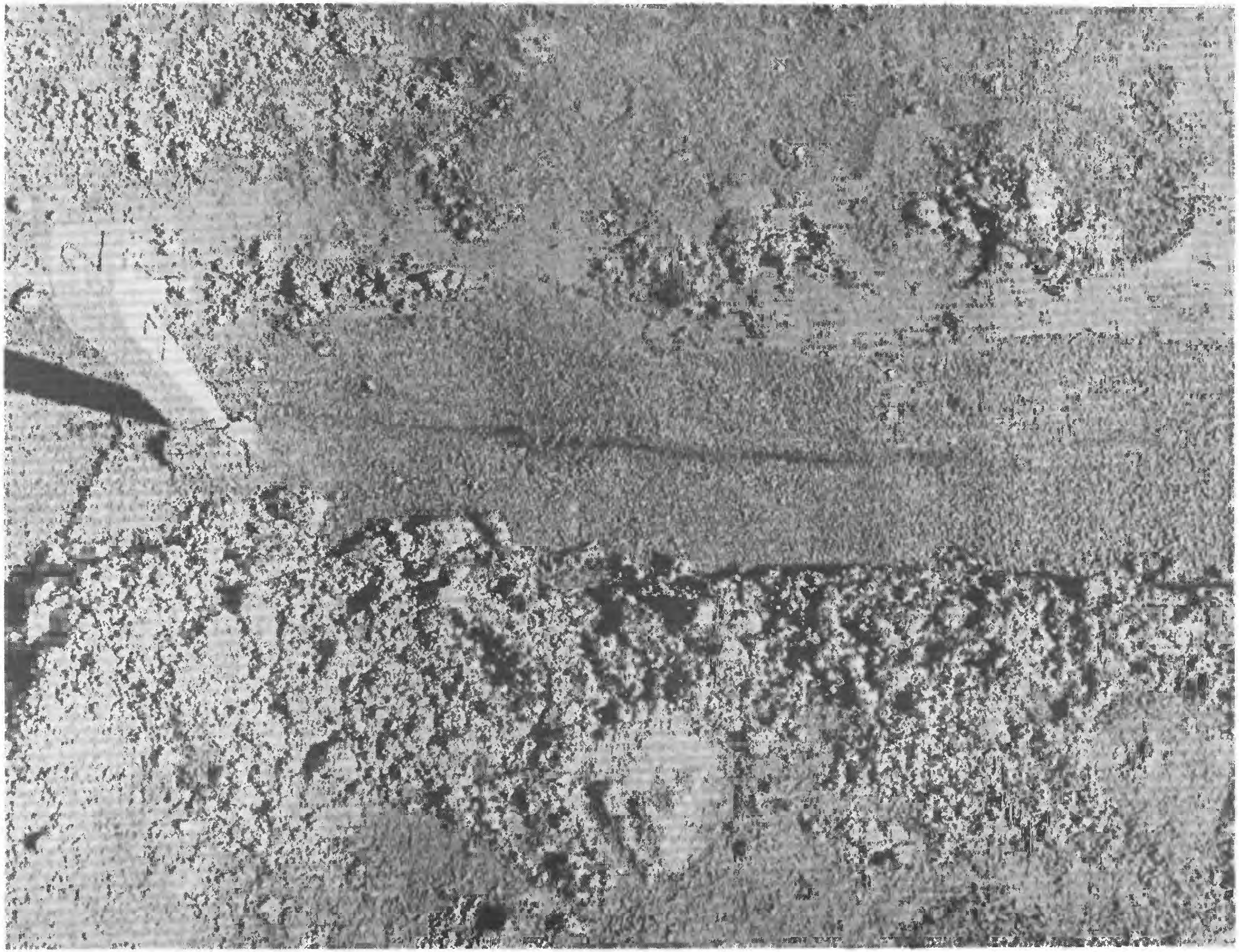

Fig. 12.--Close view of the Shaft fault on elevation 25 feet level.

Fig. 13.--Shaft fault on elevation 25 feet level.