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GROUND-WATER EXPLORATION USING THE RESISTIVITY METHOD ON THE HAWAIIAN ISLANDS OF OAHU AND HAWAII

By Adel A. R. Zohdy and Dallas B. Jackson

Denver, Colorado

Open-file report

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Work done in cooperation with the Department of Land and Natural Resources of the State of Hawaii and the Institute of Geophysics in Hawaii.

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1. Alaska Railroad Terminal Reserve, Anchorage: Soil stability study. Stability in the vicinity of boring lines 1 and 2, by D. J. Varnes. 40 p., 35 figs., 1 table. 108 Skyline Bldg., 508 2nd Ave., Anchorage, Alaska 99501.

2. Ground-water exploration using the resistivity method on the Hawaiian Islands of Oahu and Hawaii, by Adel A. R. Zohdy and Dallas B. Jackson. 38 p., 19 figs. USGS, 330 First Insurance Bldg., 110 Ward Ave., Honolulu, Hawaii 96814; USGS, P.O. Box 1660, Hilo, Hawaii 96720; Dept. of Land and Natural Resources, Division of Water and Land Development, Punchbowl and King St., Honolulu, Hawaii 96809.

3. Ultraviolet absorption and luminescence studies: Progress report for the period from April to December, 1967, by William R. Hemphill. 57 p. (incl. Appendix), 12 figs., 1 table. 601 E. Cedar St., Flagstaff, Ariz. 86001.

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The Geological Survey is also releasing in open file the following report containing supplemental data in connection with USGS Professional Paper 313-D (Biostratigraphy of the Phosphoria, Park City, and Shedhorn Formations, by Ellis L. Yochelson) and is available for consultation in the Geological Survey Library, Bldg. 25, Federal Center, Denver, Colo. 80225:

4. Charts showing distribution and abundance of fossils in the Phosphoria, Park City, and Shedhorn Formations in Wyoming, Idaho, Utah, and Montana, by Ellis L. Yochelson. 4 charts (8 sheets).

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ABSTRACT

Thirty-six resistivity soundings were made on the islands of Oahu and Hawaii to determine the applicability of galvanic resistivity methods for locating fresh-water aquifers in the State of Hawaii. Soundings were made on the northwestern part of the island of Oahu near the town of Waialua and on the island of Hawaii on the "saddle" area near Pohakuloa and the Humuula sheep station.

On Oahu, the geoelectrical study indicates that correlation among four stratigraphic units underlain by a vesicular basalt basement is possible. The electrical soundings indicate that it is feasible to determine the approximate depth to the fresh-saline water interface within the basalt. Two Schlumberger soundings with electrode spacings, $\overline{AB}/2$, reaching 6,000 feet give sounding curves of the maximum and minimum type whose terminal branches indicate that the true resistivity of basalts saturated with sea water, in the survey area on Oahu, is about 30-40 ohm-m.

On the island of Hawaii, an exploratory well drilled in basalt to a depth of 1,001 feet proved to be dry. In the area of this well, two deep soundings were made using the Schlumberger and the equatorial arrays. Although additional soundings at various orientations and larger spacings are needed, there appears to be a conductive layer below 1,600 feet which may represent basalt saturated with fresh water.

INTRODUCTION

The effectiveness of the resistivity method in solving subsurface water problems and in minimizing drilling costs has been established in many parts of the world (Breusse, 1963). On the Hawaiian Islands, the method was used by Swartz more than a quarter of a century ago (Swartz, 1937, 1939, 1940 a and b). Since then the state-of-the-art has improved considerably through the calculation of a large number of theoretical curves for a variety of earth models, as well as through the development of new scientific methods of interpretation.

During the months of December 1965 and January 1966, a feasibility study to determine the usefulness of the resistivity method in augmenting the solution of hydrogeological problems was conducted by the U. S. Geological Survey in cooperation with the Department of Land and Natural Resources of the State of Hawaii and the Institute of Geophysics in Hawaii. Electrical measurements were carried out on the northern part of the island of Oahu near Waialua, and on the island of Hawaii near Pohakuloa and Humuula. The electrical measurements consisted of intermediate and deep soundings using the Schlumberger and the equatorial electrode configurations.

Electrical Soundings

An electrical sounding consists of a series of electrical measurements conducted at the surface of the ground by which the subsurface electrical properties of rock formations may be determined. An electric current of given intensity is introduced into the ground via two electrodes that are driven into the ground 4-12 inches deep; then by measuring the resulting potential difference between another pair of electrodes, the electrical specific resistance or the resistivity of the medium may be calculated. Theoretically, the farther away from the current source the measurements of the potential difference are made, the deeper the probing would be. In regard to field procedure a variety of electrode arrangements may be used to achieve adequate depth penetration. In the present investigation, two different electrode configurations were used: The Schlumberger configuration (Kalenov, 1957) and the Bipole-Dipole Equatorial array (Berdichevskii and Petrovskii, 1956). Using the Schlumberger arrangement (figure 1a), four electrodes are placed at the surface of the ground along a straight line such that the distance between the current electrodes ($\overline{AB}$) is at least five times the distance between the potential electrodes $\overline{MN}$ i.e. $\overline{AB} > 5$ MN. In this fashion the potential gradient, rather than the potential difference, is measured to a good approximation. The formula for computing the resistivity, ρ, in this case is given by

$$\rho = \pi \frac{(AB/2)^2 - (MN/2)^2}{MN} \frac{\Delta V}{I} \qquad (1)$$

where ΔV is the potential difference in millivolts and I is the electric current in milliamperes. The electrode spacings ($\overline{AB}$, $\overline{MN}$) are measured in feet whereas the resistivity is expressed in ohm-meters through multiplication by a proper factor.

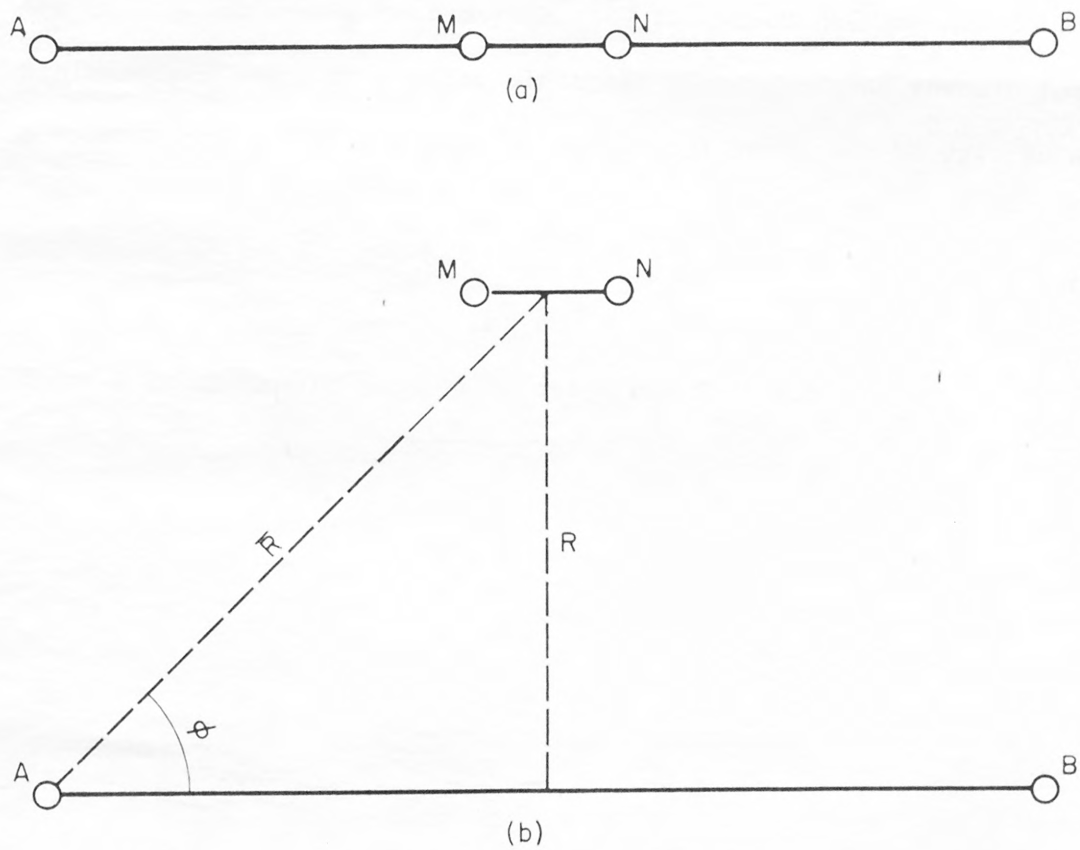

Figure 1.--Electrode configurations (plan view). Electrodes: A, B, M, N.

a. Schlumberger array.
b. Bipole-Dipole Equatorial array.

In the Bipole-Dipole Equatorial arrangement (figure 1b), the potential electrodes (M and N) are placed at right angles to the perpendicular bisector, R, of the line $\overline{AB}$. It can be shown (Berdichevskii and Petrovskii, 1956) that in the case of horizontally homogeneous and isotropic media, the exact same value of apparent resistivity would be measured as with the Schlumberger configuration. Consequently, the equatorial arrangement may be used to extend data obtained by the Schlumberger array to greater electrode spacings. The formula for computing the resistivity by the equatorial array may be written as:

$$\rho = \frac{\pi \left(\frac{\overline{AB}}{2}\right)^2}{\overline{MN}\cos^2\theta} \frac{\Delta U}{I} \qquad (2)$$

where θ is the angle between $\overline{AB}$ and $\overline{R}$ and $MN \leq \overline{R}/5$.

In order to make an electrical sounding with the Schlumberger array, the distance between the current electrodes $\overline{AB}$ is expanded, whereas with the equatorial setup the distance R is increased. The value of the resistivity is then computed using formula (1) or (2) according to the configuration used. Sounding curves are plotted on a bilogarithmic set of coordinates with the electrode spacing $\overline{AB}/2$ (or $\overline{R}$) on the abscissa and the apparent resistivity $\overline{\rho}$ on the ordinate. The field sounding curve is then interpreted by matching it to theoretically calculated sets of master curves (Compagnie Générale de Géophysique, 1963; Zohdy, 1965).

Geoelectrical Measurements on the Island of 'Oahu

A total of 32 electrical soundings were made on the northern part of the island of Oahu, near Waialua (figure 2). The maximum AB/2 spacings of the Schlumberger arrangement ranged from 600 to 6,000 feet. Interpretation of the electrical soundings suggests the following ranges for the "true" resistivities of the various rock formations:

	ohm - m
Clay saturated with brackish to saline water	<3
Clay saturated with brackish to fresh water	5 - 8
Clay, silty sand, and some gravel with fresh water	11 - 25
Sand and coral	80 - 400
Weathered basalt with fresh water	30 - 60
Fresh basalt with saline water	30 - 40
Fresh basalt with fresh water	300 - 700

There are no electric logs available to check the above given values of resistivity. Nevertheless, a number of sounding curves were sufficiently diagnostic to support the validity of the listed resistivity values.

Figure 2.--Location of electrical soundings on the island of Oahu.

In the Waialua area there are six layers of rock that are electrically distinguishable from one another. These layers may or may not all be present in the geologic section at a given locality. The six layers from top to bottom are: (1) cultivated top soil; (2) coral and sand (first coral); (3) clay; (4) coral, sand, and clay (second coral); (5) clay, silt, and sand, and (6) basalt (weathered or fresh). It was difficult to electrically distinguish the second coral reef from the underlying basalt where there was no clay bed separating the two layers. In such cases the presence of the second coral was inferred either from other soundings or from nearby wells.

The First Coral Zone:

The first sand and coral is found almost exposed at the surface near the ocean shore. Its presence was detected on the electrical soundings (E.S.) 1, 3, and 32 in the form of a high-resistivity first layer (figure 3). Its thickness varies from about 5 to 12 feet. In these soundings the soil layer is absent or less than 2 feet thick. Note that the second coral zone is clearly indicated on E.S. 32, by the maximum near AB/2 = 160 feet, whereas it is less obvious on E.S. 1, and probably absent, or at a depth of more than 150 feet, at E.S. 3. In all three soundings, however, the first coral is underlain by a very conductive clay layer. Farther from the shoreline, the soil layer is thicker and the first coral is buried under a cover of about 8 feet of soil. The presence of the first coral, however, is unmistakably clear as indicated by the maxima of E.S. 4, 5, 9, and 19 (figures 4 and 5). In all the above soundings the first coral is underlain by clay then by the second coral or basalt.

On the basis of the electrical soundings and the available wells and test holes, an isopach (equal thickness) map of the first coral was prepared and is shown in figure 6. The map indicates that the first coral diminishes in thickness and probably disappears to the south of State Highway 99.

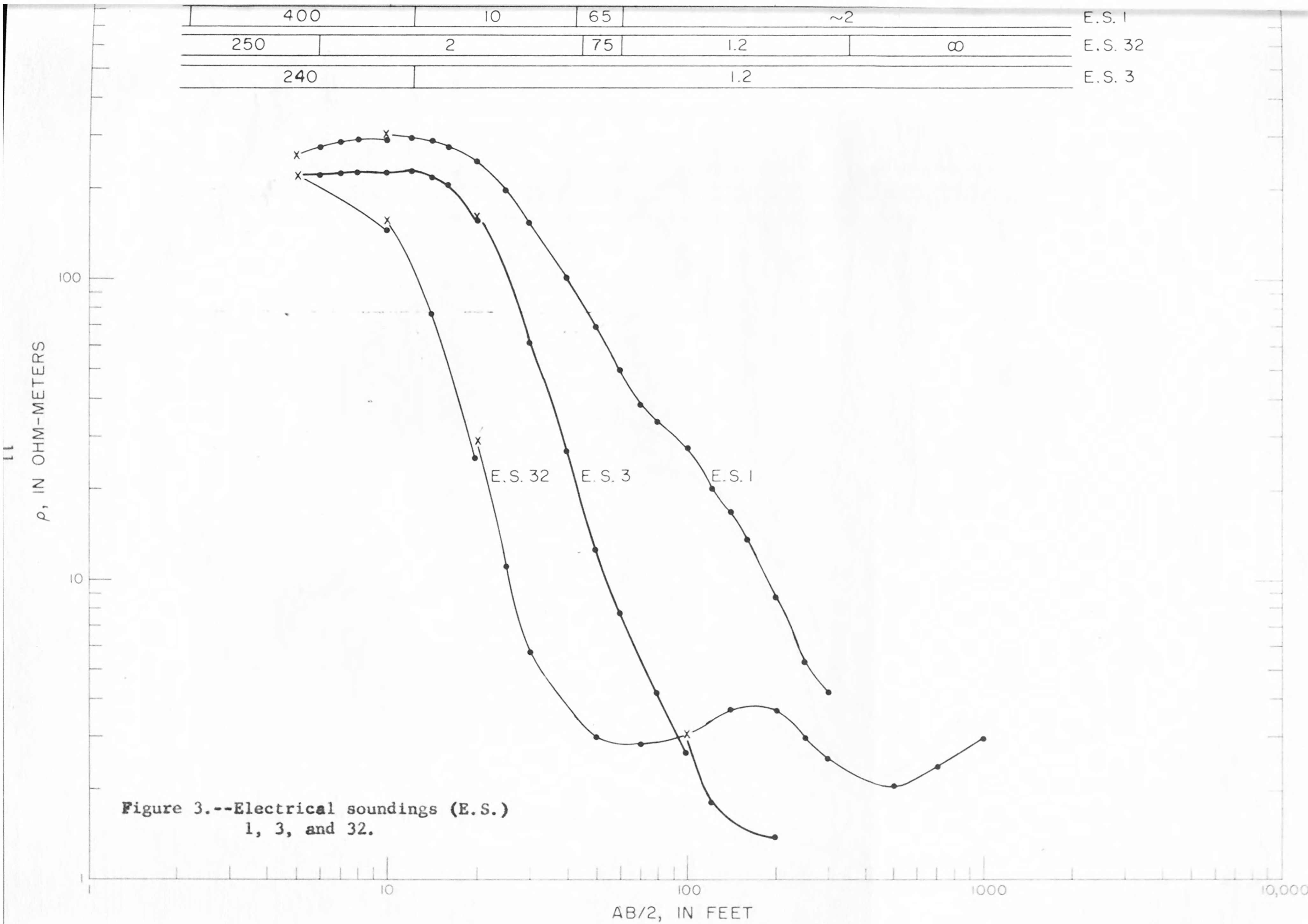

Figure 3.--Electrical soundings (E.S.) 1, 3, and 32.

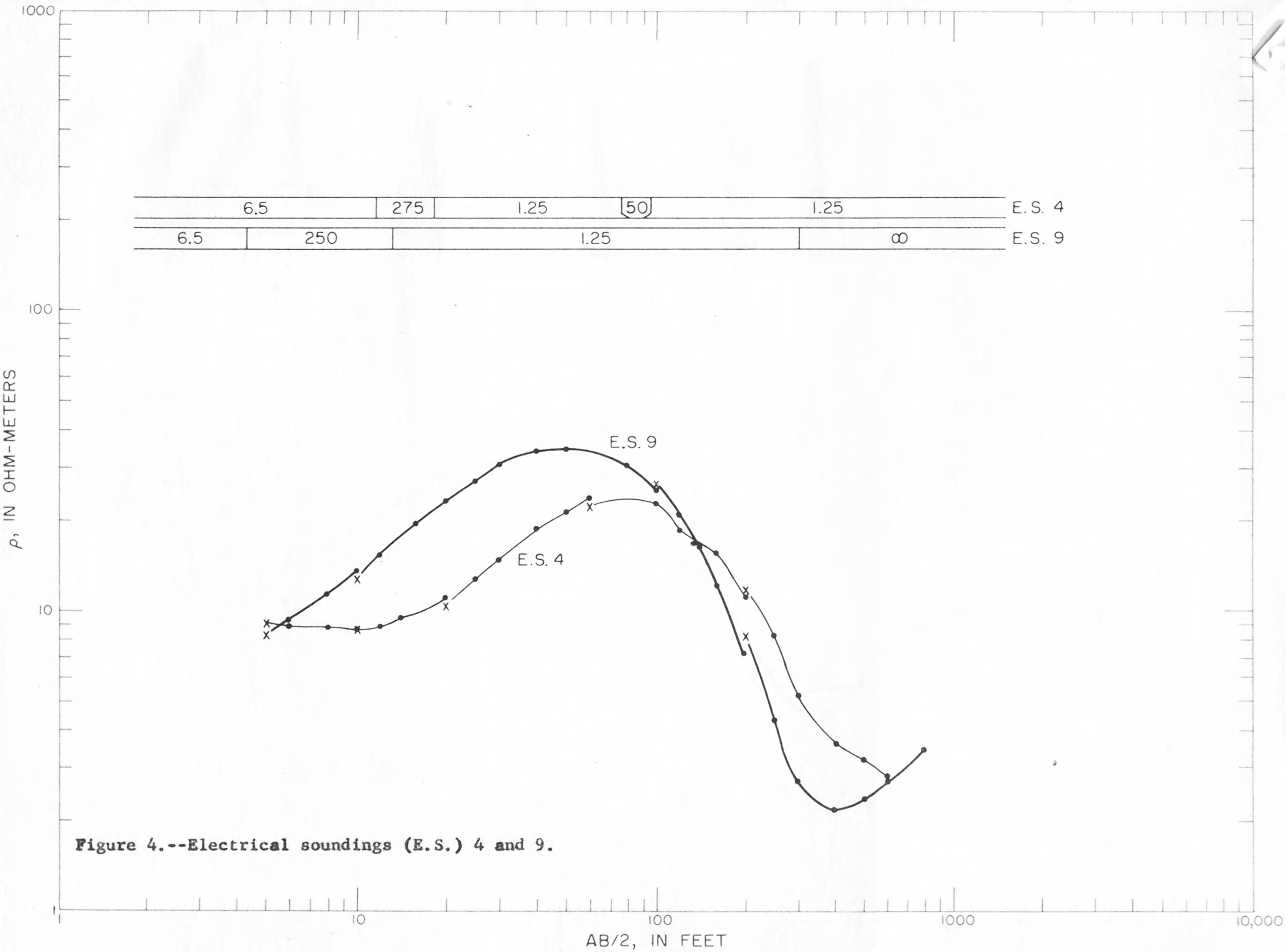

Figure 4.--Electrical soundings (E.S.) 4 and 9.

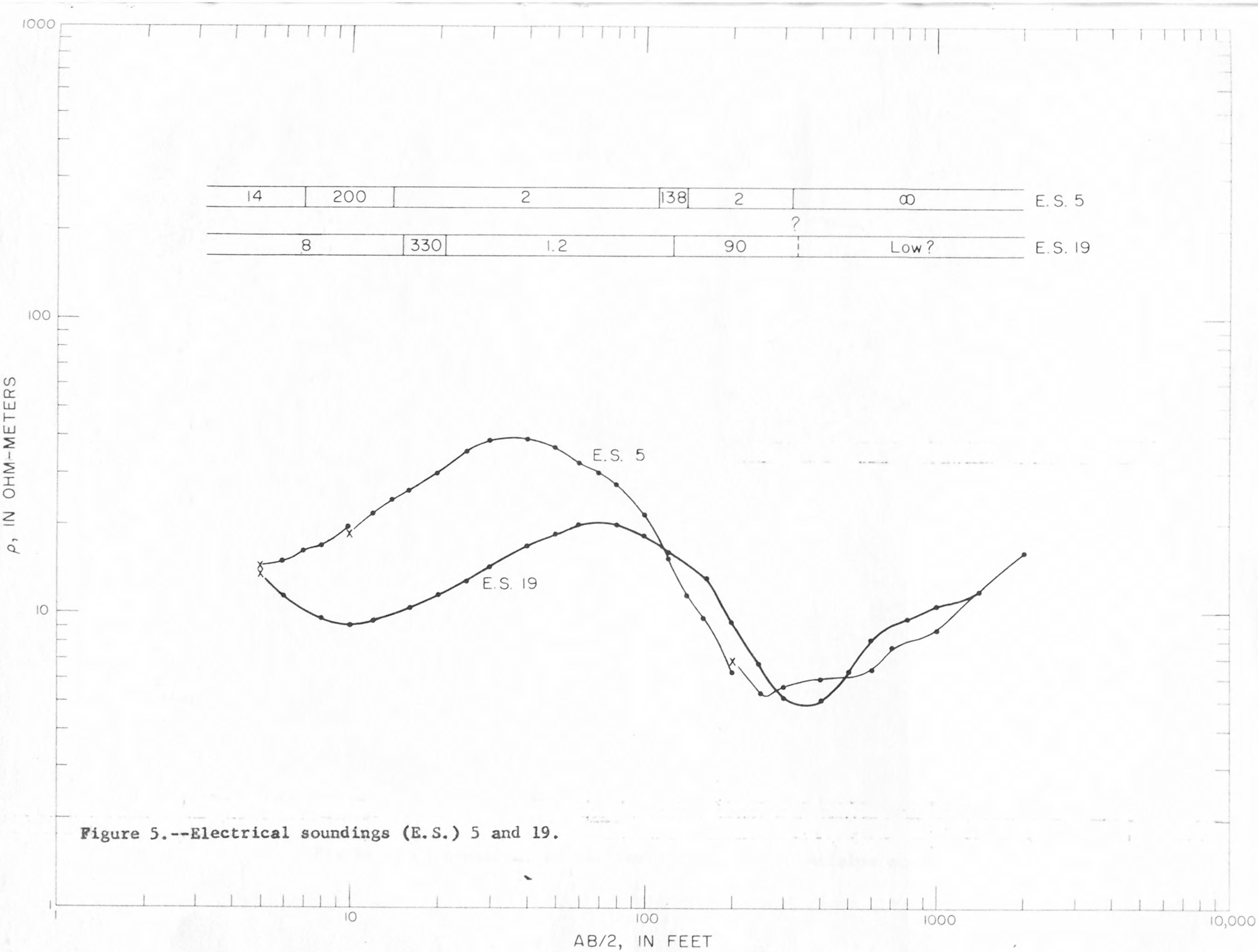

Figure 5.--Electrical soundings (E.S.) 5 and 19.

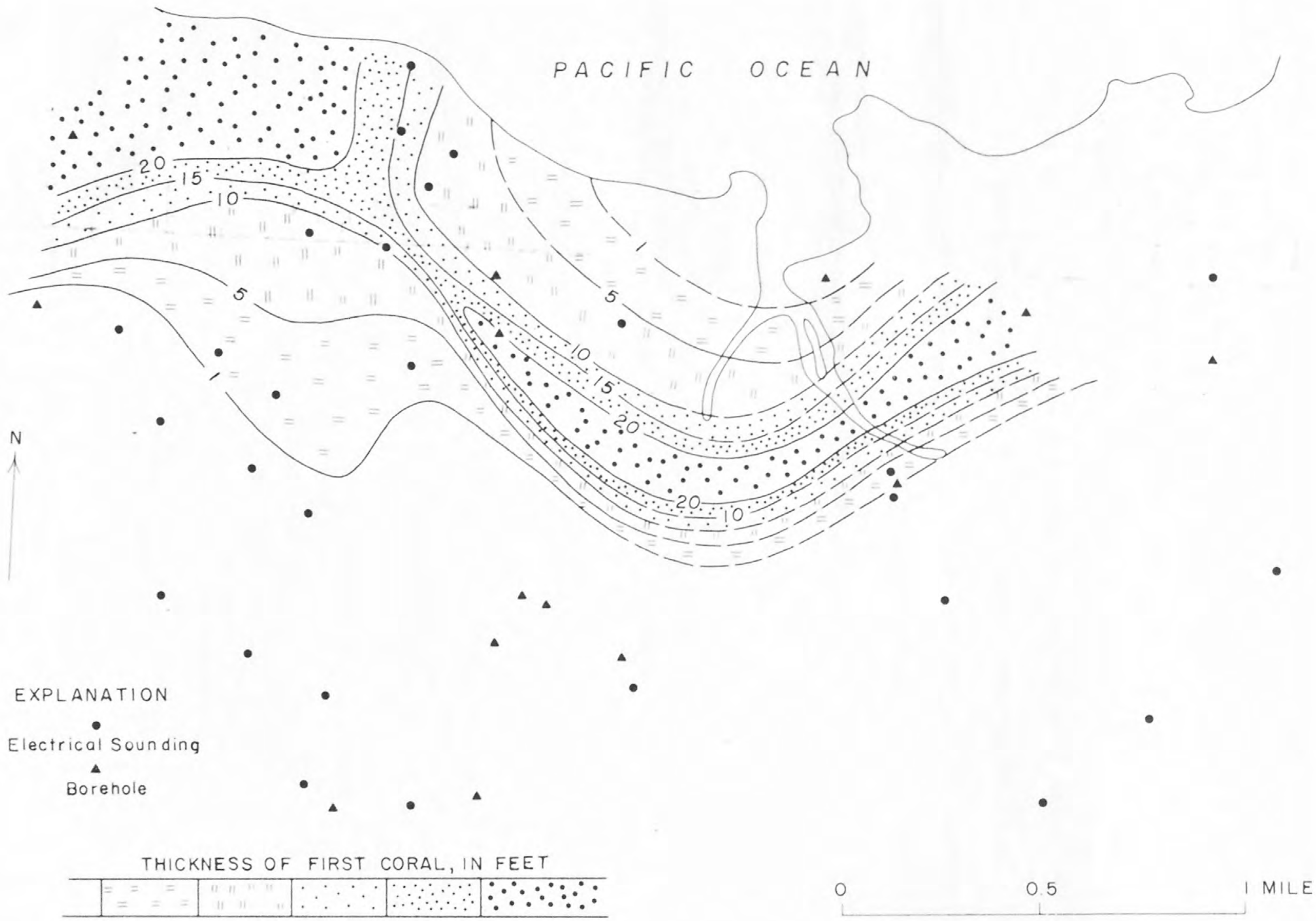

Figure 6.--Isopach map of the first coral in the Waialua area.

The Second Coral Zone:

The second coral zone is probably an important aquifer. Its detection on an electrical sounding, however, is subject to some limitations. On one hand the layer should be of sufficient thickness with respect to its depth of burial. On the other hand, it is more easily detected when it is underlain by another clay layer separating it from the underlying lava flows. A cross-section based on two wells and three electrical soundings is shown in figure 7 and indicates the presence of the second coral zone as encountered in Well 319 and as interpreted in E.S. 19 (see figure 2 for cross-section location).

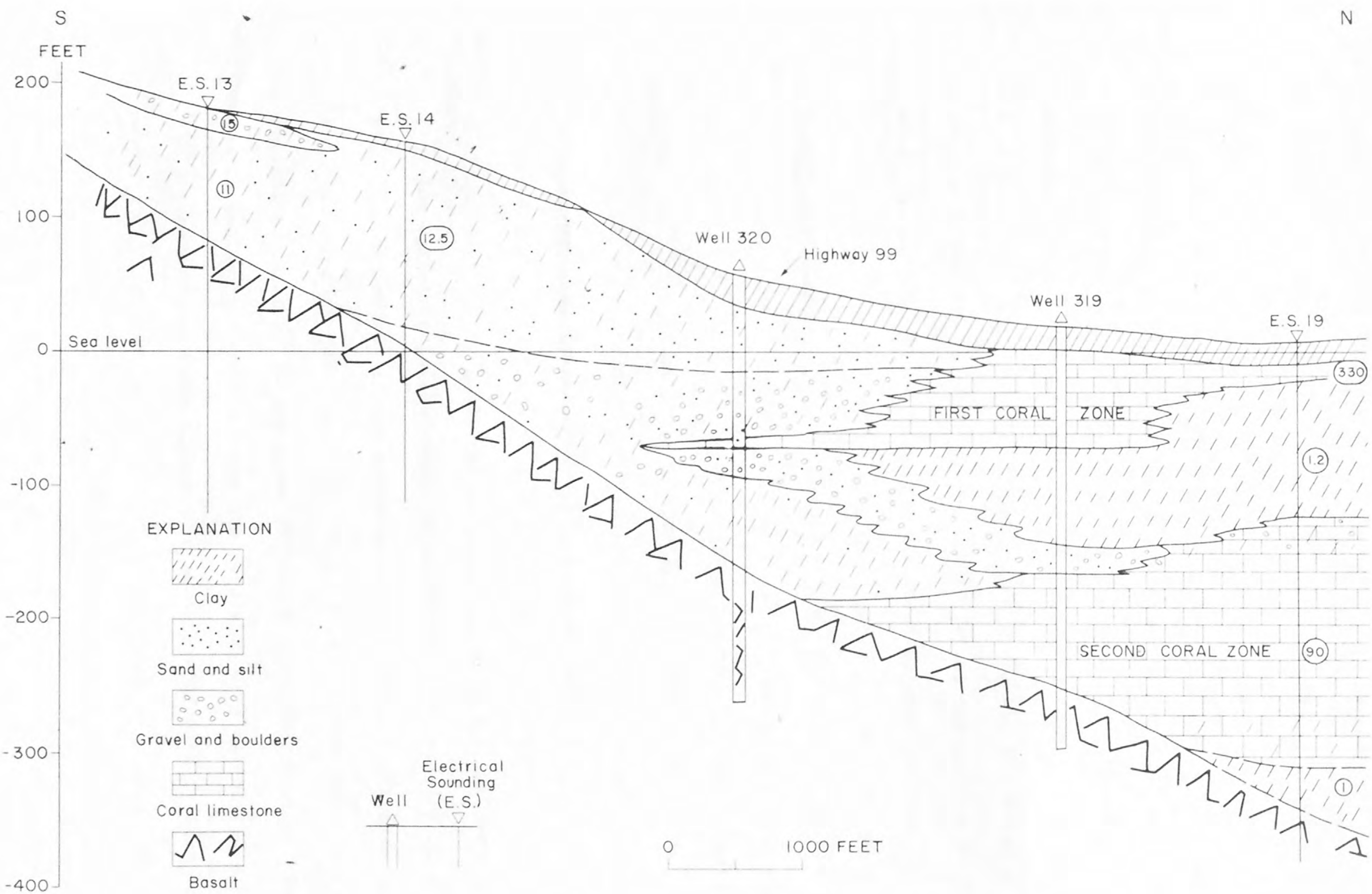

Figure 7.--A north-south section. Numbers in circles indicate values of resistivity.

The Alluvial Deposits:

South of State Highway 99, both coral reefs disappear and the sediments are composed mainly of clay with scattered thin lenses of gravel, boulders, and coral fragments. The geoelectric section, however, is fairly homogeneous and has a resistivity range of about 5 to 15 ohm-m. The electrical soundings E.S. 7, 11, 14, and 17 (figure 8) testify to the relative simplicity of the section in this area. It is interesting to note the effects of near surface heterogeneities on E.S. 14 where a small heterogeneity near one of the potential electrodes (M or N) caused the set of measurements between AB/2 of 200 and 500 with $\overline{MN}$ constant to be shifted to a higher value. Then as the $\overline{MN}$ spacing was changed at AB/2 = 500 feet the resistivity values fell back to continue the proper trend of the curve. On the other hand, a near-surface heterogeneity at one of the current electrodes (A or B) produces a disturbance in the measurements at one place only, e.g. the measurement on E.S. 7 at AB/2 = 160 feet. Such effects are generally easily recognized on sounding curves of the Schlumberger type.

The variation in the magnitude of the true resistivity of the clay (5 to 15 ohm-m) is not a random one. A definite increase in the value of the clay resistivity is observed as one moves away from the shoreline. This is in agreement with what is to be expected. The clayey sediments near the ocean are saturated with saline water whereas the inland sediments are expected to be saturated with fresher water. This is not the only factor governing the resistivity of a clay zone. An enrichment in sand and gravel content will also tend to increase the resistivity.

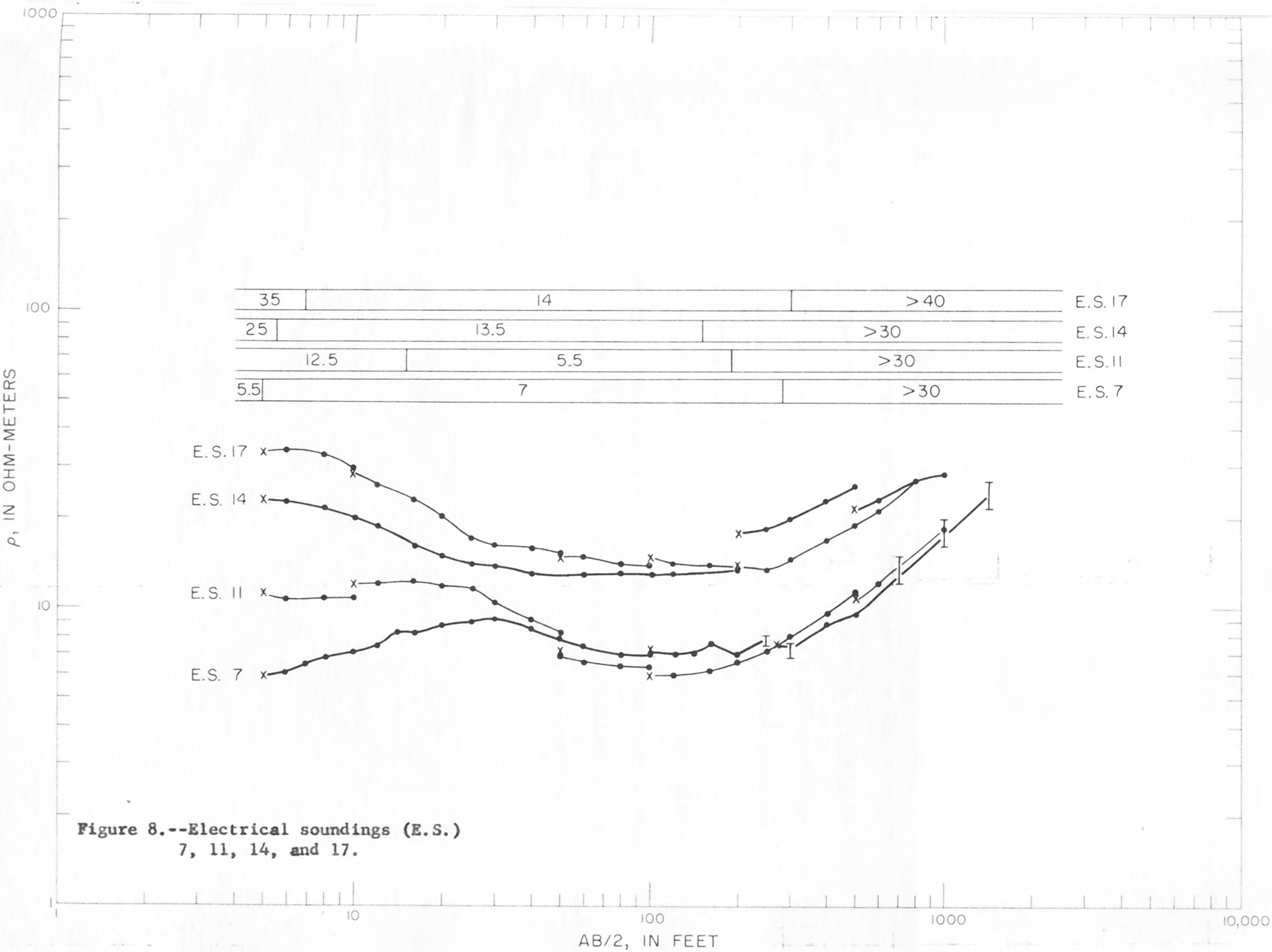

Figure 8.--Electrical soundings (E.S.) 7, 11, 14, and 17.

To illustrate the dependency of the clay resistivity on its distance from the shoreline, a plot of the estimated true resistivity of the clay as a function of the distance of the sounding from the nearest shoreline was prepared and is shown in figure 9.

<u>The Waianae and the Koolau Volcanic Series</u>:

The resistivity of the Waianae basalt seems to be exceptionally low ($\sim$ 30 to 50 ohm-m). This low resistivity value is probably due in part to the fact that the top basaltic layers are highly weathered. At greater depths where the flows may be fresher, the ground water may be saline, thus reducing the resistivity of the rocks.

A map of the estimated configuration for the top of the Waianae basalt is given in figure 10. The indicated depths are based on electrical soundings and a few wells and test holes that are sufficiently deep to penetrate the basalt. The map indicates the probable buried drainage pattern.

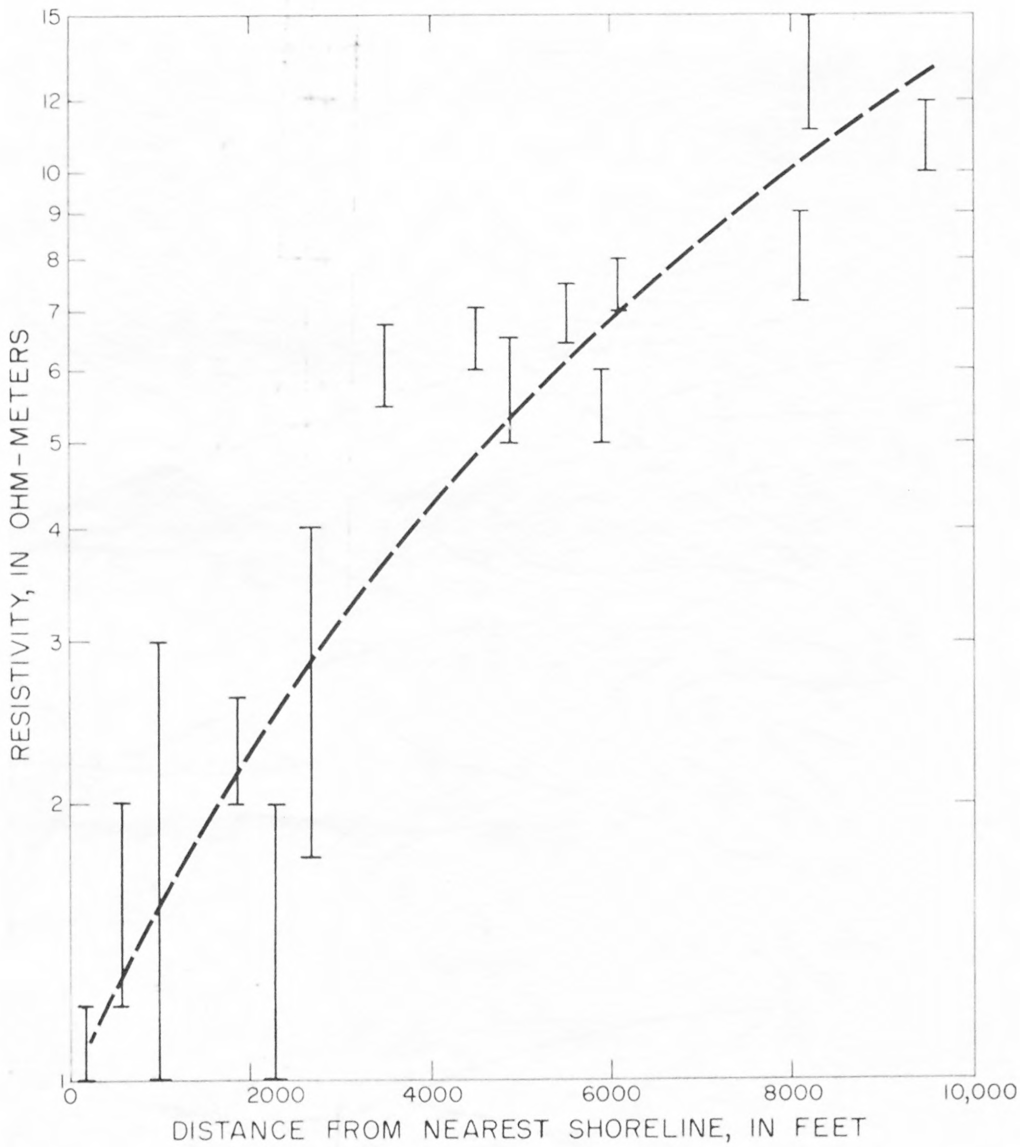

Figure 9.--Dependency of the clay resistivity on distance of an electrical sounding from the shoreline. Bars indicate possible resistivity ranges for clay.

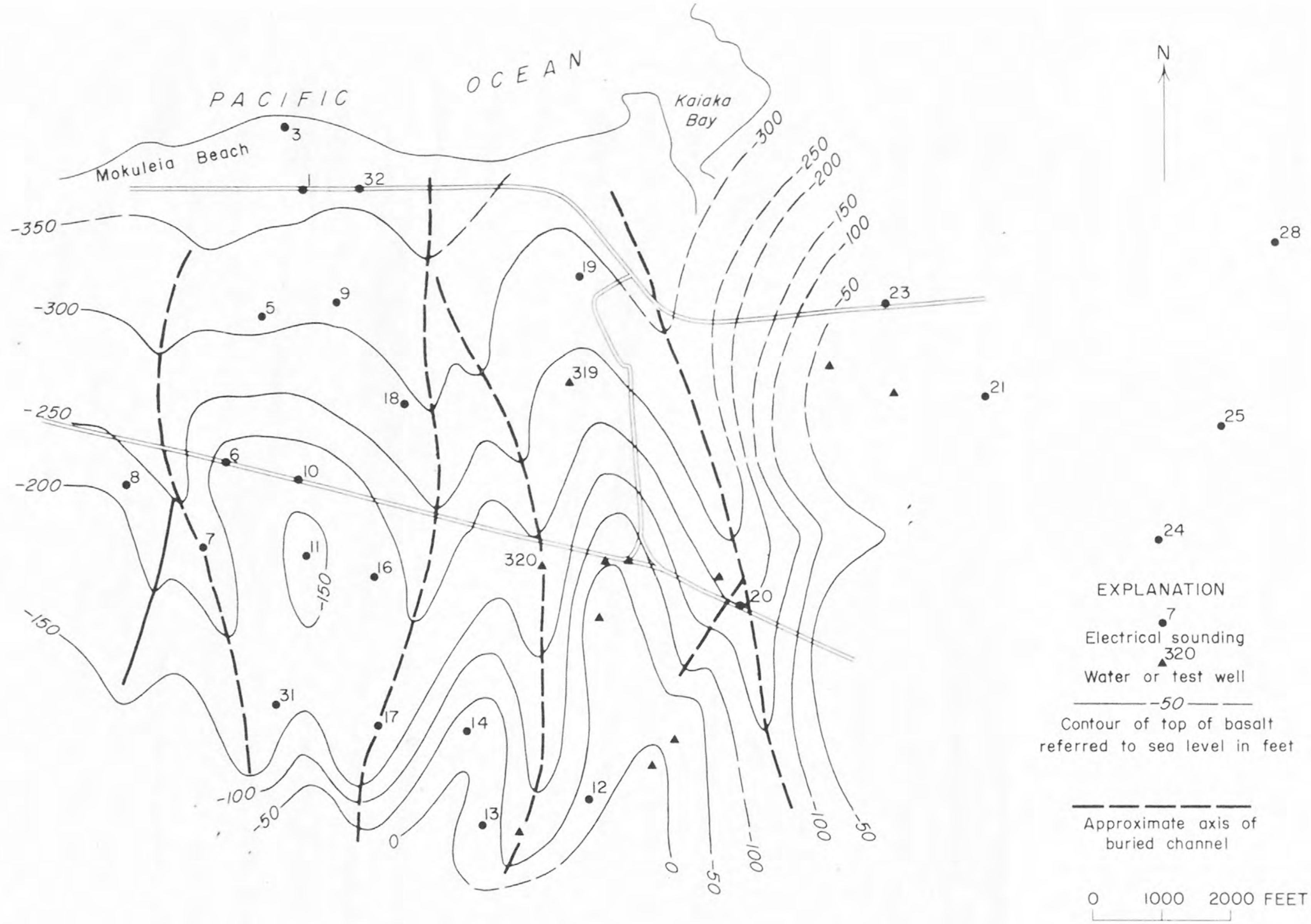

Figure 10.--Map of the top of basalt of the Waianae Volcanic Series as inferred from the resistivity data and well logs.

In contrast to basalt of the Waianae Volcanic Series we may now consider the soundings conducted on the sloping range of the Koolau Volcanic Series NW of Schofield Plateau. The soundings E.S. 21, 22, 24, 25, 26, 27, 28, 29, and 30 were carried out in that area. According to these soundings, the resistivity of the Koolau basalt is much higher than that of the Waianae basalt in the area of interest. This is primarily due to the fact that the Koolau basalt was studied at higher elevations than the Waianae basalt thus putting its upper layers beyond the reach of the low resistivity saline waters. As a result, all the sounding curves obtained over the Koolau basalt were of the maximum type ($\rho_1 < \rho_2 > \rho_3$) whereas those over the Waianae were mainly of the minimum type ($\rho_1 > \rho_2 < \rho_3$). The resistivity of the saline-water saturated basalt, of the Waianae or the Koolau type, is of the order of 30 ohm-meters. This conclusion is based on comparing the results of two deep soundings E.S. 6 (over the Waianae basalt) and E.S. 22 (over the Koolau basalt) (figure 11). With E.S. 6, $\frac{\overline{AB}}{2}$ reached 6,000 feet and with E.S. 22, $\frac{\overline{AB}}{2}$ reached 5,000 feet. Although the two soundings are basically of different shapes, their terminal branches approach the same asymtotic value of about 30 ohm-m. The question, however, does arise as to the certainty of the 30 ohm-m material representing saline-water saturated basalt. The answer is reached by considering E.S. 6. If 30 ohm-m is the resistivity of fresh-water saturated basalt, then the thickness of the fresh-water lens beneath E.S. 6 should be of the order of 5,000-6,000 feet. An interpreted thickness of 5,000-6,000 feet of fresh water would be difficult to reconcile in view of the sounding location. The center of E.S. 6 is less than 1 mile from the shoreline, its elevation less than 40 feet above sea level, and the ground water in that location of the island is not dike-impounded water. Consequently the conclusion may be reached that the 30 ohm-meters section is saline-water saturated basalt.

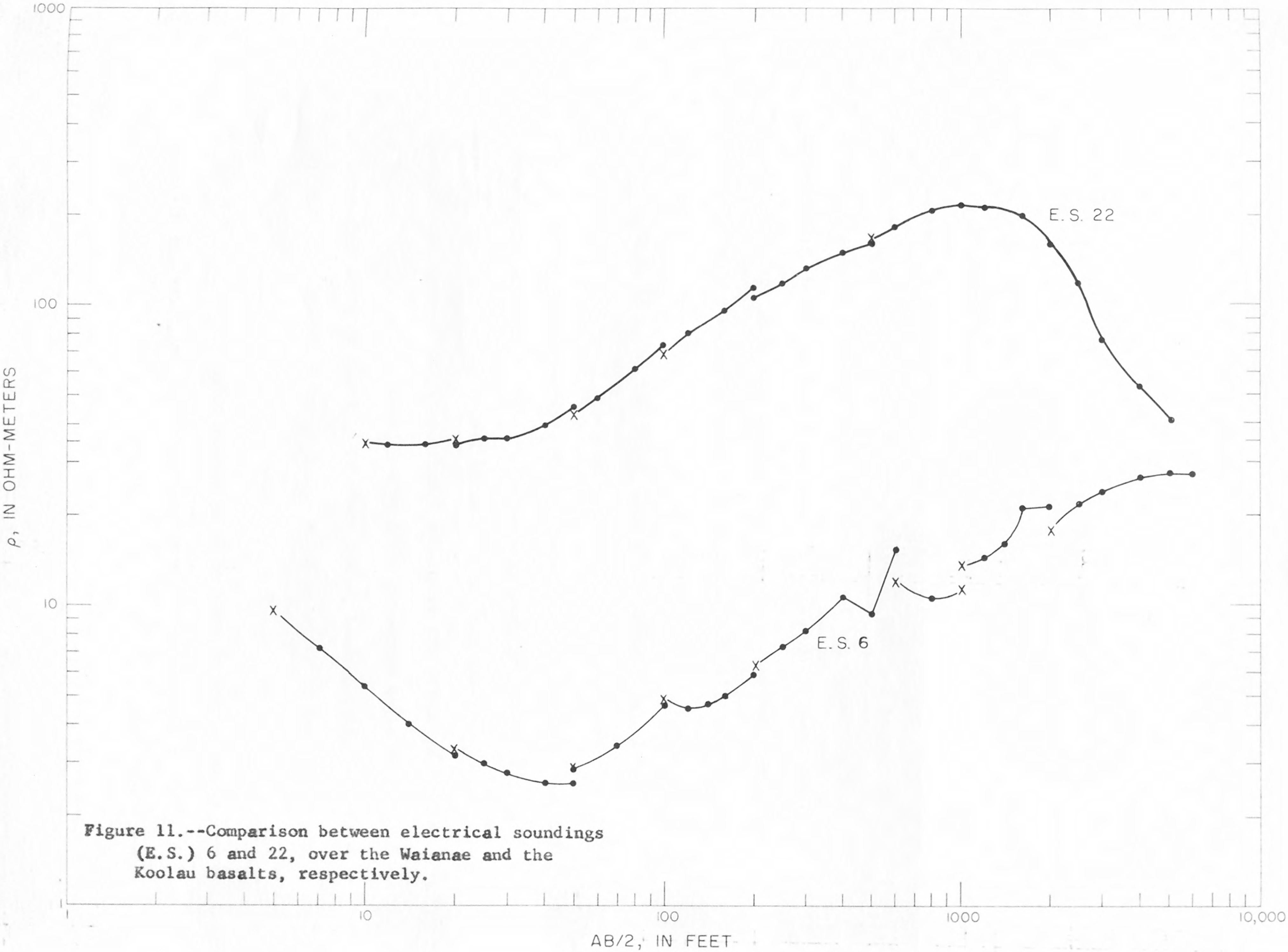

Figure 11.--Comparison between electrical soundings (E.S.) 6 and 22, over the Waianae and the Koolau basalts, respectively.

The resistivity of the basalt with fresh water (partial to complete saturation) ranges from 300 to 500 ohm-m. A lower limit of about 250 ohm-m is possible from an interpretation of sounding E.S. 25 (figure 12). There is, however, no definite upper limit on the value of the resistivity except that it is not likely to exceed 1,000 ohm-m. Considering the interpretation of E.S. 24 (figure 13), the depth to the fresh-salt water interface is estimated as 800 feet below the ground surface or 600 feet below sea level. If the Ghyben-Hertzberg relationship* holds in this area, then the fresh water level should be about 15 feet above sea level. This figure is comparable with the level of standing water in wells near sounding E.S. 24, which is about 12 to 13 feet above sea level. If one assumes the resistivity of the basalt in E.S. 25 to be 400 ohm-m, instead of the chosen value of 350, then the results of depth calculations would be closer to the actual case of observed water levels in the wells at the location of E.S. 24. However, the assumption that the Ghyben-Hertzberg relationship does hold in this area may very well be false under the existing hydrodynamic conditions. Consequently, an attempt to change the estimated depths to achieve an exact correspondence with the predicted Ghyben-Hertzberg relationship would be futile. In other words, because water well data indicate that unconfined water stands at about 12 to 13 feet above sea

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* The Ghyben-Hertzberg relationship predicts that in coastal areas underlain by salt water the fresh-salt water interface will be depressed 40 feet below sea level for every 1 foot of fresh water above sea level.

level near E.S. 24, we would expect about 500 feet of fresh water below sea level if the Ghyben-Hertzberg relationship is applied. However, because the ground water is not under static conditions, it is expected that the fresh-saline water interface will be depressed by a ratio greater than 40/1 (Todd, 1959). Therefore, the depth of 600 feet below sea level, from E.S. 24, to the salt water interface is in better agreement with what might be expected under hydrodynamic conditions.

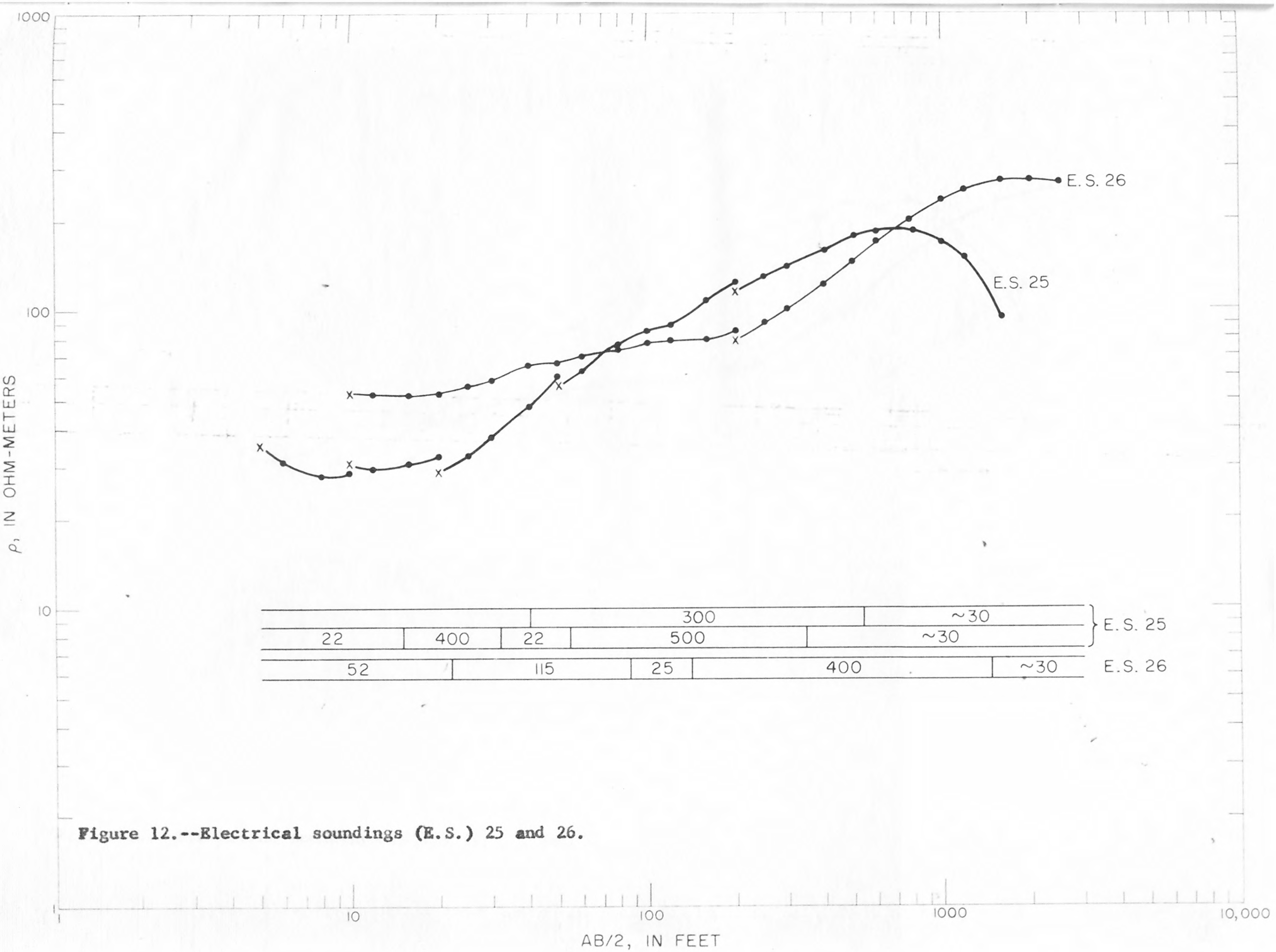

Figure 12.--Electrical soundings (E.S.) 25 and 26.

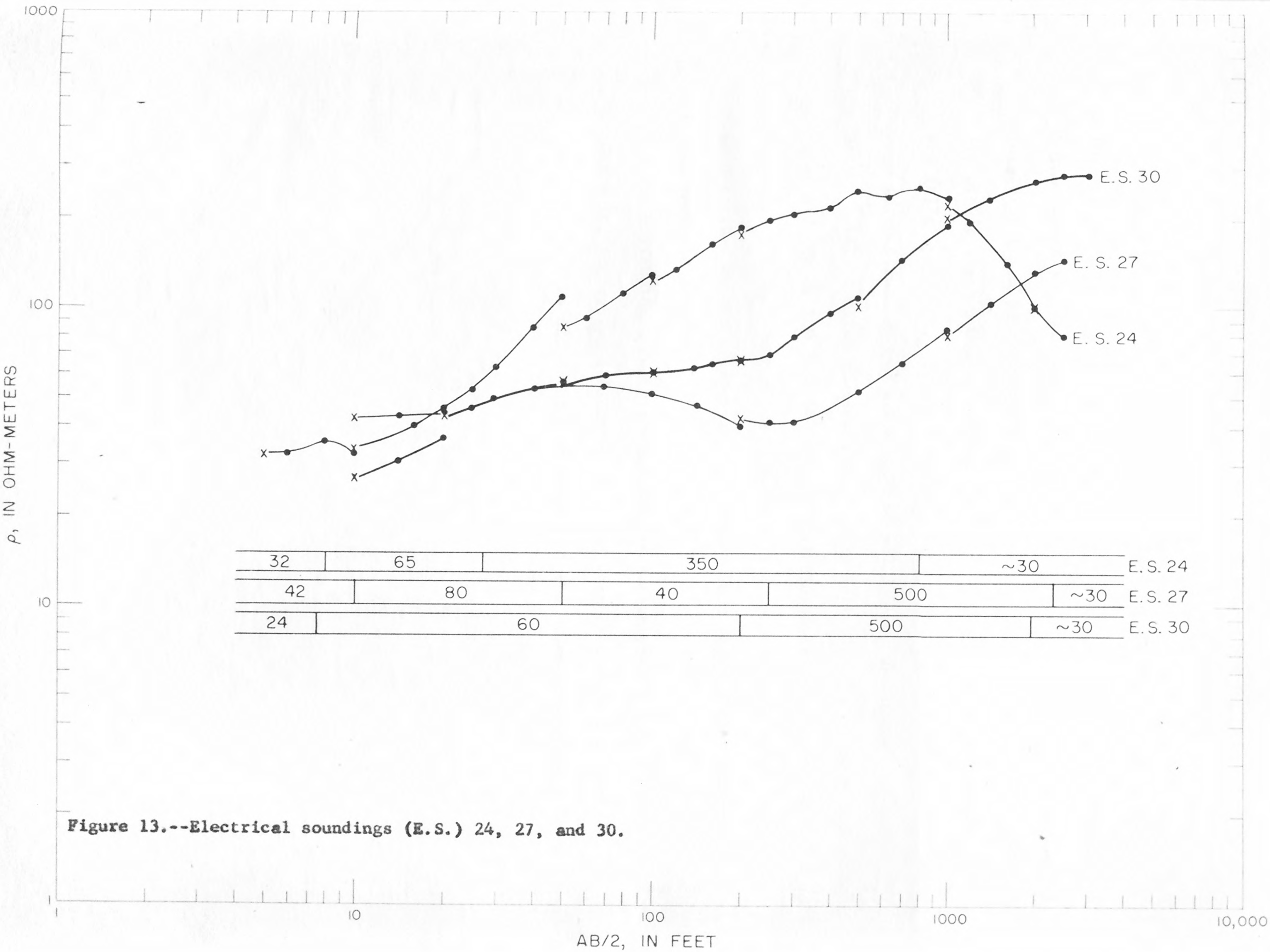

Figure 13.--Electrical soundings (E.S.) 24, 27, and 30.

Finally, according to E.S. 26, 27, 29, and 30 (figures 13 and 14), the Koolau basalt is probably weathered to depths ranging from 150-250 feet below the surface of the ground. This weathered zone seems to be primarily formed of three layers: (a) top layer of cultivated soil (25-40 ohm-m); (b) middle layer probably with boulders and gravel (about 60 ohm-m); and (c) clayey layer (20 to 40 ohm-m). The presence of a thick weathered zone is confirmed by two wells (330-1B and 330-2B) which are approximately 2 miles east of E.S. 27. In Well 330-1B a "hard blue basalt" is at a depth of 200 feet whereas in Well 330-2B it is encountered at 280 feet below the surface. The overlying material in these wells is described by the driller as "red clay", "mud rock", "clay and gravel", "mud rock and clinkers", and "boulders".

Such lithologic descriptions fit the resistivity ranges in that zone quite favorably, indicating that the weathered zone does extend over a large area and is of a thickness of the order of 200 feet.

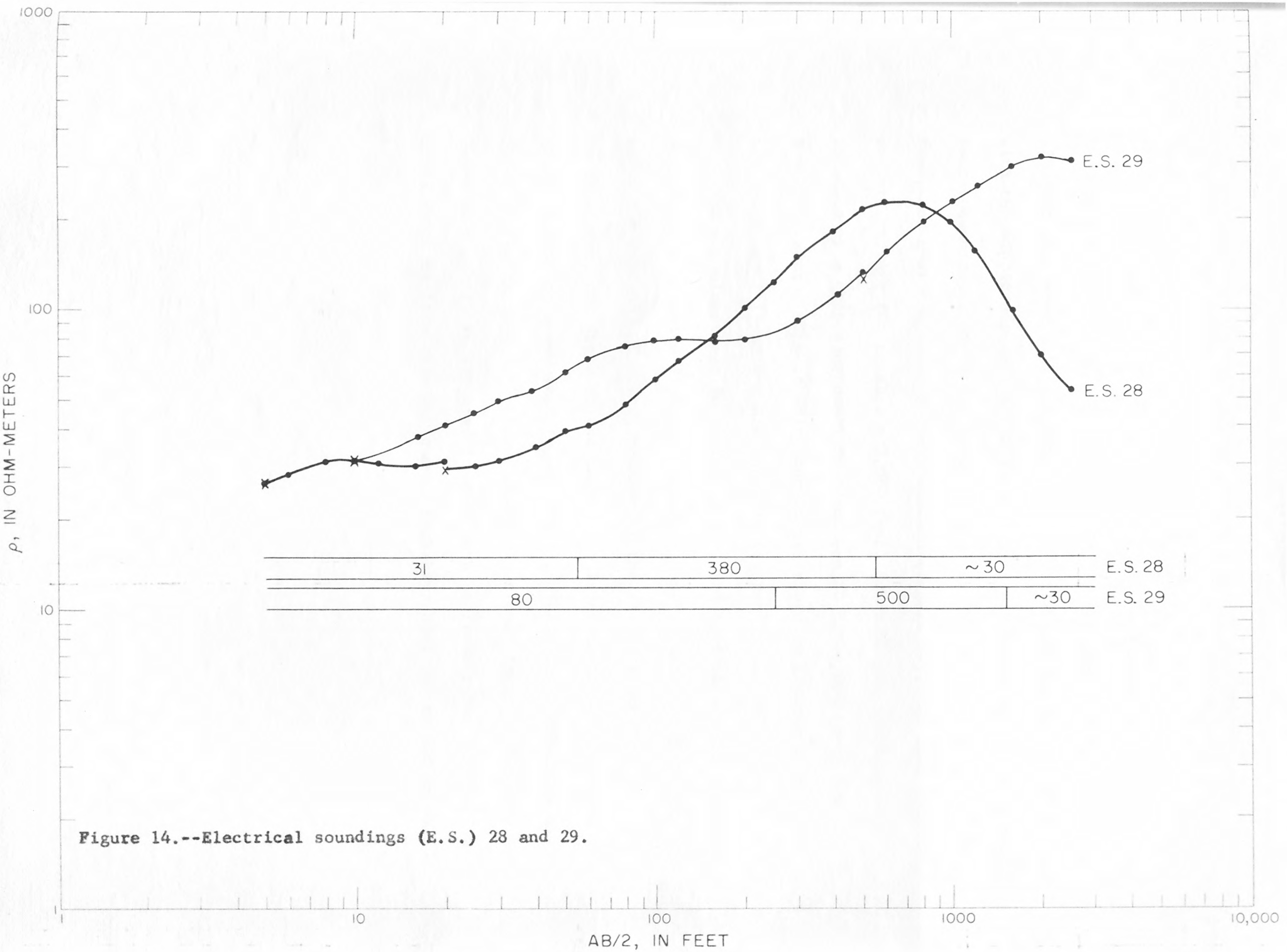

Figure 14.--Electrical soundings (E.S.) 28 and 29.

Geoelectric Measurements on the Island of Hawaii

Four electrical soundings were made on the island of Hawaii. Two of these were made with the Schlumberger configuration and the other two with the bipole-dipole equatorial arrangement. The soundings were made near Pohakuloa, where a dry well has been drilled to a depth of 1,001 feet, and near the Humuula sheep station (figure 15). At each location an intermediate (up to $\overline{AB}/2$ = 3,000 feet) Schlumberger sounding was followed by a deep equatorial sounding (up to R = 8,000 feet, i.e., $\overline{R}$ = 8,140 feet). The sounding curves are shown in figures 16 and 17 and their exact locations are shown in figures 18 and 19.

The soundings near Pohakuloa, E.S. 1 and 4, indicate the presence of a thick conductive layer at a depth of approximately 1,800 feet below the surface. However, because of the slight scatter of points on the curve, the depth to the conductive layer could be 1,600 feet (lower limit) or 2,400 feet (upper limit). These depth estimates are based on the assumption of electrically isotropic layers. The conductive layer at depth is interpreted in this case as fresh water basalt of a resistivity of less than 400 ohm-m, probably about 200 to 300 ohm-m.

Figure 15.--Location of the studied area on the island of Hawaii.

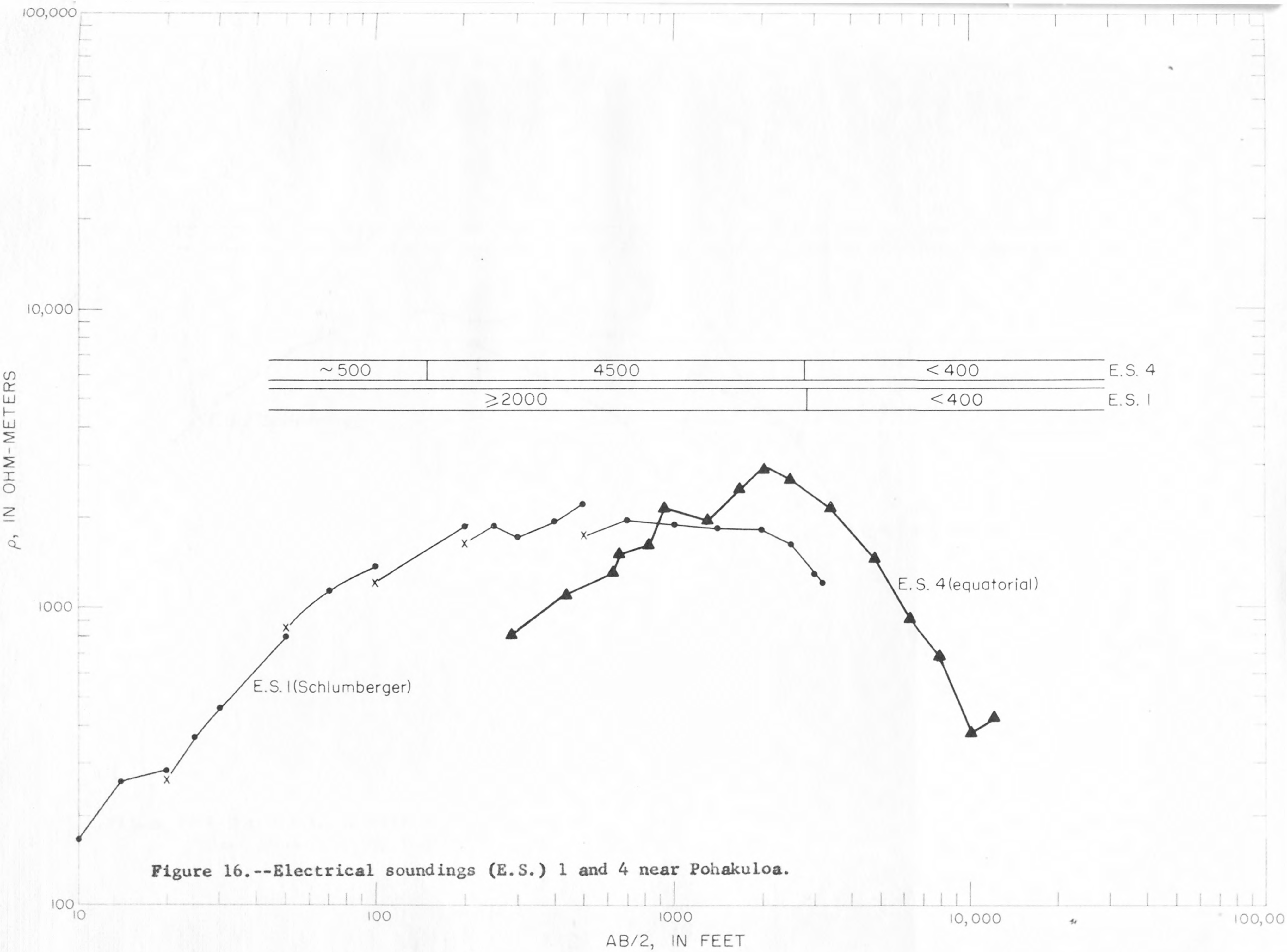

Figure 16.--Electrical soundings (E.S.) 1 and 4 near Pohakuloa.

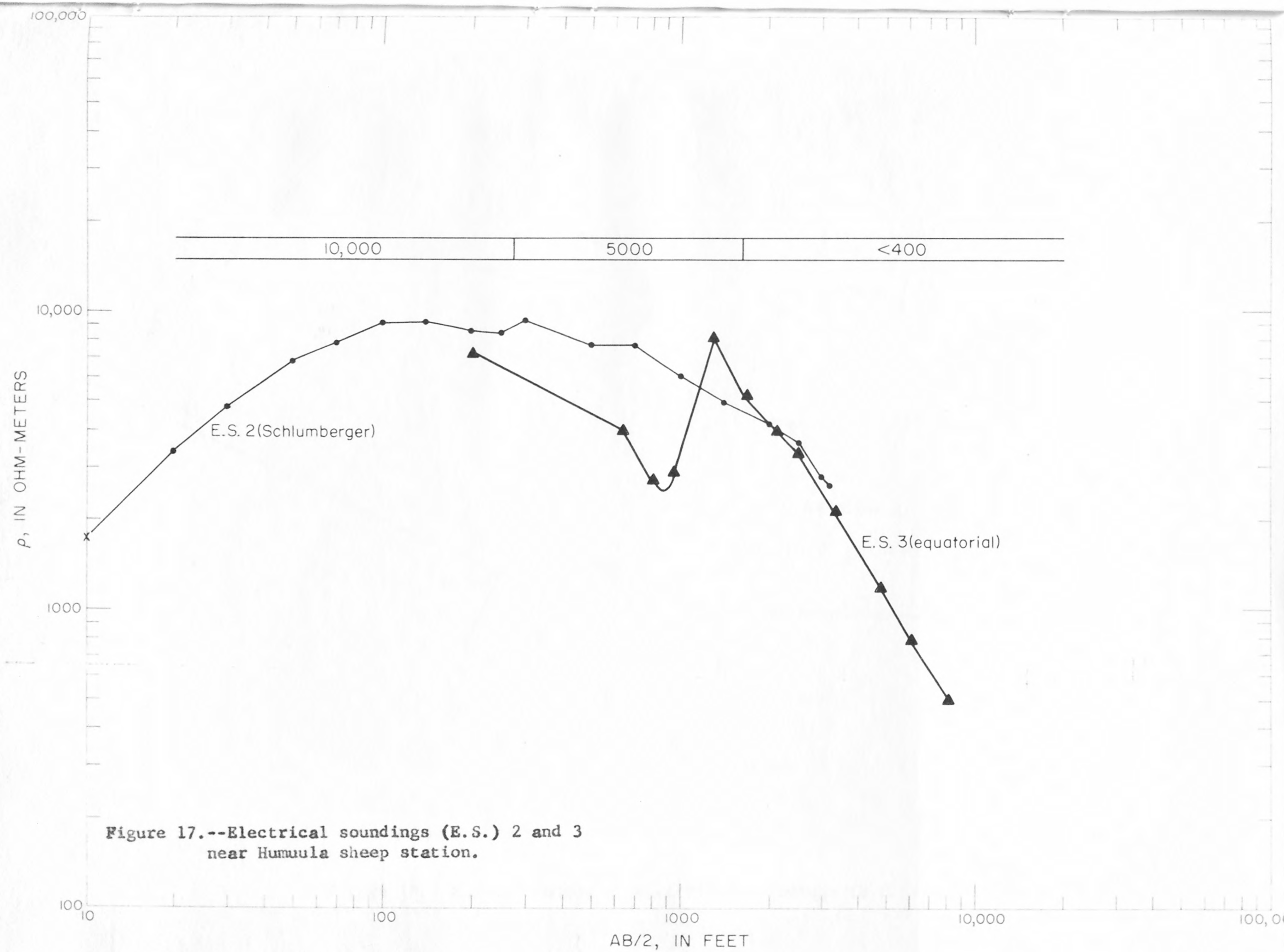

Figure 17.--Electrical soundings (E.S.) 2 and 3 near Humuula sheep station.

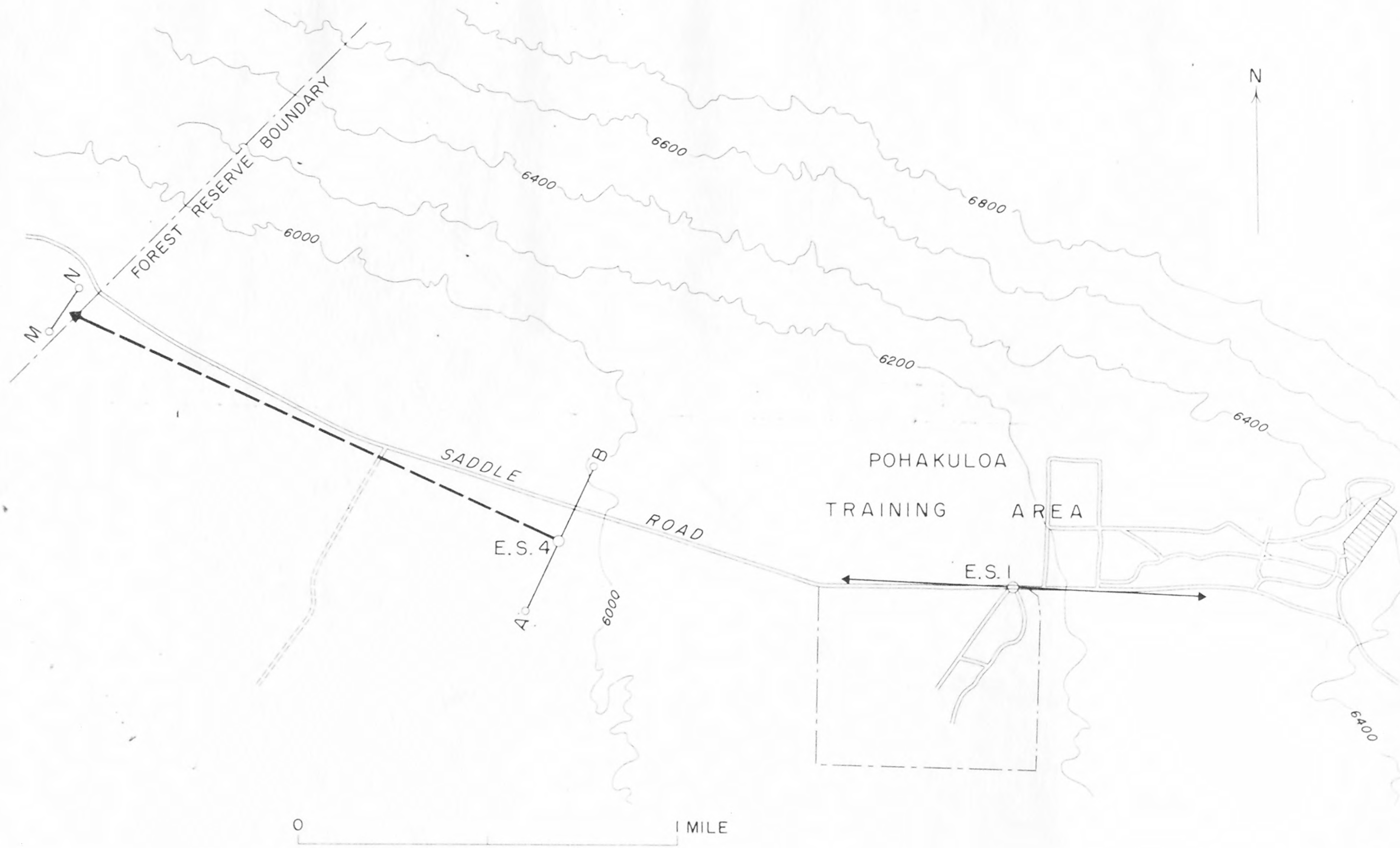

Figure 18.--Exact location of electrical soundings (E.S.) 1 and 4.

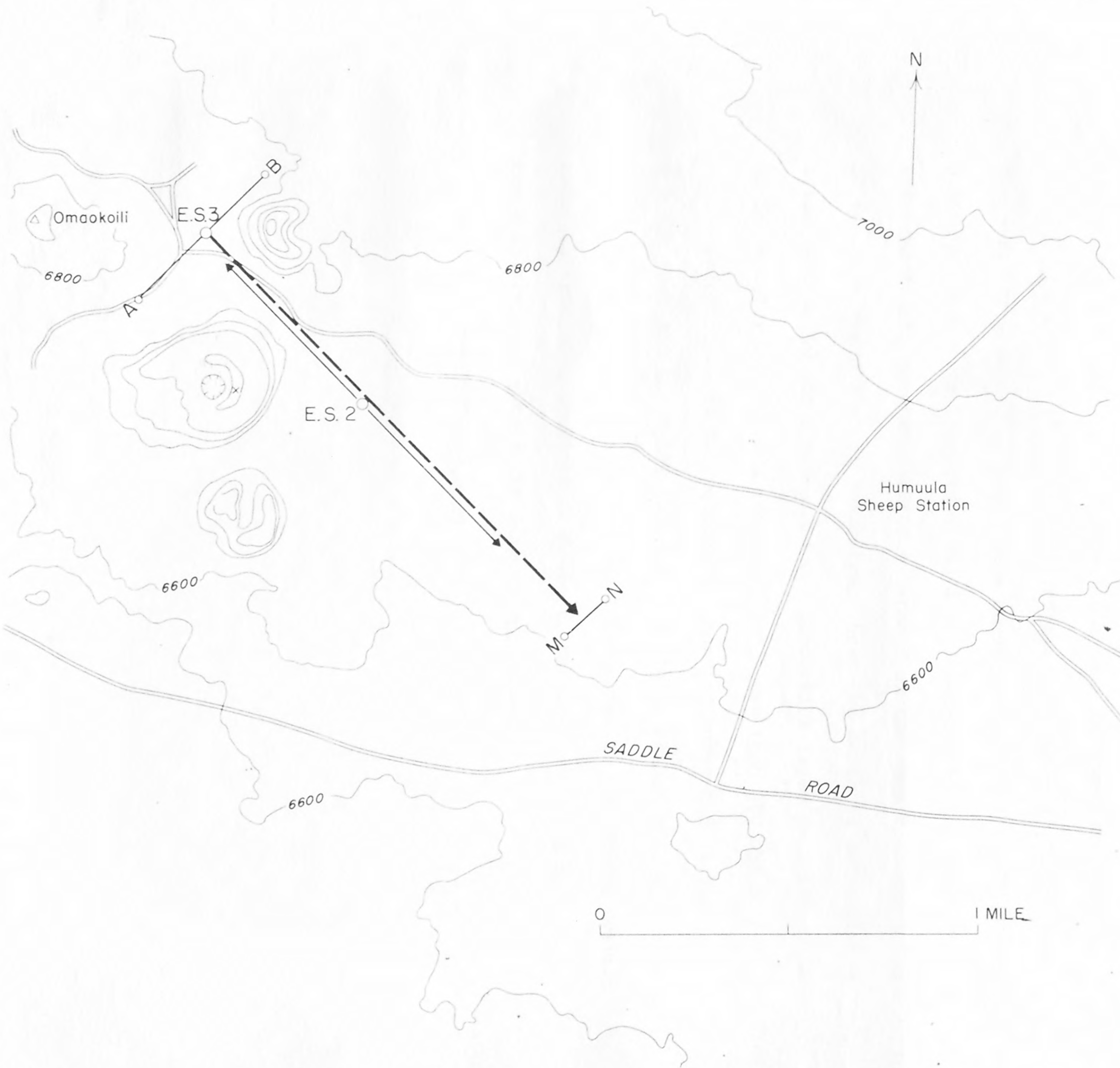

Figure 19.--Exact location of electrical soundings (E.S.) 2 and 3.

The soundings near the Humuula sheep station (figure 19) indicate the presence of near-surface lava flows that are more resistive (10,000 ohm-m) than those encountered near Pohakuloa (2,000 ohm-m). The possible presence of lava flows having a resistivity of 4,500 to 5,000 ohm-m at both localities was also indicated by the soundings. More important, however, is the existence of the same conductive layer at depth at Humuula as at Pohakuloa. Here the depth is estimated as 1,600 feet below the surface and the conductive layer is interpreted as fresh water basalt of a resistivity of less than 400 ohm-m. The strong deformation of the equatorial sounding curve E.S. 3 between $\overline{R}$ = 300 feet and $\overline{R}$ = 1,676 feet (figure 17) is caused by the proximity of the potential array ($\overline{MN}$) to two cinder cones as the saddle between them was crossed (figure 19). However, the rest of the points on the curve do serve to extend the Schlumberger curve.

Summary and Conclusions

On the island of Oahu the results of the resistivity survey seem to be in accordance with what is known of the geohydrology of that part of the island. Specifically, the survey gave valuable information on areal correlation of subsurface units, mapping of the basement surface with the delineation of possible subsurface channels and detection of the fresh-salt water interface at depth in the basalt basement. On the island of Hawaii, near Pohakuloa and Humuula, the method has indicated the presence of a thick conductive layer that may be basalt saturated with fresh water at a depth of the order of 1,600 feet below the surface.

In conclusion, the resistivity method has yielded valuable information in the survey areas that can be tied in with the known geology, and the method can be used as an effective tool to extend one's knowledge where little may be known about the geology.

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