ESTIMATION OF GROUND-WATER CONFIGURATION NEAR PAHALA, HAWAII USING ELECTRICAL RESISTIVITY TECHNIQUES

by

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GEOPHYSICAL EXPLORATION FOR HAWAIIAN GROUNDWATER, PHASE I

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ABSTRACT

In 1965 the Water Resources Research Center of the University of Hawaii began development of the necessary equipment to explore the feasibility of an extensive resistivity exploration program. Subsequent funding permitted the organization of this project with the dual purpose of developing reliable and convenient instrumentation for resistivity surveying in the Hawaiian Islands and to apply the technique toward the solution of a ground water problem in Pahala, on the island of Hawaii.

A series of 14 electrical soundings was completed at Pahala in September 1966 in an attempt to determine the extent and causes of an anomalous high water table. Four of the soundings indicated the limits of this underground reservoir to be at least 3500 feet east and 2500 feet south of a Maui-type well shaft in Pahala. The southern extent of the high head ground water suggests the northeast-southwest trending of the eruptive fissure vent about 4000 feet southeast of the well as a likely hydrologic barrier. Other soundings, indicating intermediate level water tables along the direction of the strike of the vent toward Punaluu, suggest a series of similarly trending dikes forming steps of water entrapment dropping toward the ocean.

To the north of the hypothetical sequence, a set of somewhat confused soundings indicate what may be ancient buried soil or ash surfaces serving as impermeable boundaries presenting direct normal ground-water flow from Pahala southwest above the dikes to the ocean south of Punaluu.

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INTRODUCTION

The occurrence of ground water in the Kau district, in the southern part of the island of Hawaii, has long been of particular interest. It was selected in 1919 as the first district in the Hawaiian Islands to receive comprehensive and systematic geological study (Stearns & Clark 1930, Meinzer 1930).

In 1946 high-head basal water was discovered at Pahala in the course of intended development for normal low-head basal ground water. The present survey attempted to determine the extent of this high-head water and define the nature of its occurrence, and therefore, was restricted to the area south of Pahala to the sea, and southwest between the belt highway and the ocean as far as the vicinity of Ninole. Resistivity instrument development was begun for the Water Resources Research Center in 1965, and the field work for the present project was carried out in September 1966.

GEOLOGY AND HYDROLOGY OF THE PAHALA AREA

Geology

Knowledge of the geology of the Pahala area stems originally from the work of Stearns and Clark (1930) and has been greatly expanded by Stearns and MacDonald (1946). The region lies on the southeastern flank of Mauna Loa and the southwestern rift zone of Kilauea (Fig. 1). Because these two shield volcanoes have been active through the Pleistocene and Recent, their lava flows are interfingered at depth in the boundary zone between them. The boundary is further complicated by structure. The lower flank of Mauna Loa, northeast of Pahala, is cut by a 16-mile system of normal faults lying ¼ to 2 miles northwest and nearly parallel to the surface boundary between the Kilauea and Mauna Loa lavas. The lower southeastern slopes have been dropped perhaps 100 or 200 feet in total and have formed an oversteepened part of the slope called the Kaoiki Pali. Locally there are grabens in the system. The main southwest rift zone of Kilauea also nearly parallels the present surface boundary, lying ¼ to 3 miles southwest of it.

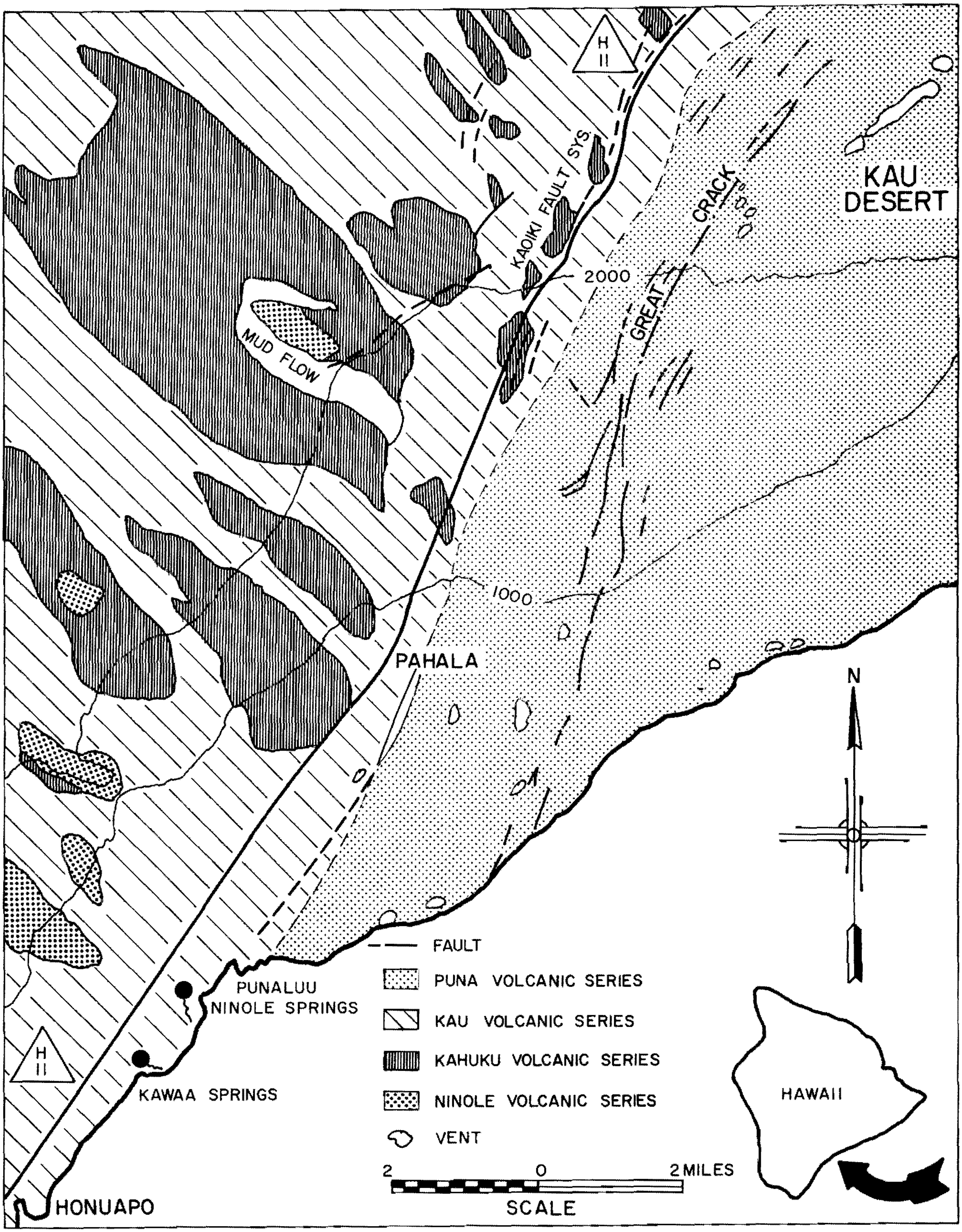

FIGURE 1. GEOLOGY IN THE SURVEY REGION AROUND PAHALA PERTINENT TO GROUND WATER STUDY. (AFTER STEARNS AND MACDONALD, 1946)

The Kaoiki fault system has not been traced closer than 4 miles from Pahala. However, less than a mile southwest of the town a fissure, which, for a length of 2 miles, served as a Kilauea eruption vent, occurs on the boundary between the Kilauea and Mauna Loa lavas. Its position suggests that it may be an extension of the Kaoiki fault system rather than the Kilauea rift zone, although, obviously, the fissure must have intersected a Kilauea rift in depth. A 6-mile long Kilauea rift, lying 3 miles southeast of Pahala, served as the eruption vent for a large lava flow in 1823. Between this vent and the fissure vent on the Kilauea-Mauna Loa border there are a few old cinder cones, indicating other fissures in depth.

The geology of the Mauna Loa slope in the vicinity of Pahala is additionally complicated by the exposure of a deeply eroded topography developed on an old series of lava flows, very probably pre-Pleistocene, called by Stearns and MacDonald (1946), the Ninole volcanic series. This series might possibly be regarded as the product of a pre-Mauna Loa volcano. The dissected and partly buried volcanic flank, which is outlined by the ridges formed by this series of lavas, appears to have been steeper than, although in the horizontal parallel to, the present Mauna Loa slope.

This old topography is nearly buried by the later Mauna Loa lava flows, which have been separated into two series on the basis of their stratigraphic relation to a very widespread ash bed, the Pahala ash. The older Kahuku series, which contain additional ash beds intercalated with the predominant lava flows, still forms about one-third of the Mauna Loa flank in the vicinity of Pahala. In the remaining two-thirds, the Kahuku series is mantled by the younger Kau volcanic series lavas. There are no historic Mauna Loa flows in the vicinity of Pahala.

Although the Pahala ash and pre-Pahala lavas are exposed in the Hilina Pali, nine miles east of Pahala, the Kilauea rocks in the vicinity of Pahala are all members of the post-Pahala-Kau volcanic series, which includes the recent 1823 lava flow already mentioned.

Hydrology

The rainfall in the Pahala area varies from a median of 30 to 45 inches per year at the coast to a maximum of about 125 inches per year in a strip at about the 3500-foot elevation. At higher elevations the rainfall decreases again, being less than 15 inches per year at the summit of Mauna Loa (Taliaferro, 1959).

In spite of this plentiful rainfall, there are no perennial streams in the Kau District. In fact, even the ephemeral streams in the rain forest flow but a few hours after a heavy rainfall, and only a very few channels in the drier areas ever carry any water during even the most severe storms. The reason for the lack of runoff is the extraordinary infiltration capacity of the surface soils and rocks.

Water appears perennially at the surface, however, at a large number of springs, mostly emerging from the Kahuku volcanic series at elevations between 2500 and 4500 feet, several miles north of the survey region. These springs were found by early geologic work (Stearns & Clark, 1930) to result nearly always from the perching of ground water on soil beds developed on ash and intercalated in the lava flows.

In 1946 an inclined shaft was started from a portal at the 774-foot altitude in Pahala with the intention of developing basal ground water near sea level for mill and domestic supplies. At an altitude of about 230 feet, a ground-water body was encountered which was at first thought to be probably perched on a soil bed. Tests indicated, however, that the water could not be drained away underground, even by two wells drilled below sea level from a chamber constructed near the bottom of the shaft at the 234-foot altitude. These wells were equipped with deep-well pumps of about 500-gpm capacity each, which have been used regularly since. Two additional horizontal centrifugal pumps were later installed in the sump formed by the bottom of the shaft, giving a total capacity of 3 mgd.

The drawdown of all of the wells was only about 1 foot. However, the water table was found to have very large fluctuations which were independent of draft. In 1952 the water-table elevations, which had to then ranged from 226 to 238 feet above sea level, were found to be reasonably well correlated with a cumulated weighted rainfall index. A possible range from 209 to 248 feet above sea level was estimated on the basis of historical rainfall record (Cox, 1952). The correlation was rechecked in 1957 and found to be essentially correct.

Experience on other Hawaiian islands suggests that a head of only 5 or 10 feet above sea level would be expectable in a normal unconfined Herzberg lens (fresh water floating on and displacing sea water) in basaltic lava flows at about 4 miles inland, similar to Pahala's location from the coast. The very high head encountered at the Pahala shaft indicates, therefore, the existence of some unusual confining structures between the vicinity of the shaft and the coast. A similar high-head basal ground-water body in the Schofield area on Oahu is believed to result from confinement by dikes (Stearns & Vaksvik, 1935), although the dikes are not exposed. Possible confining structures in the Pahala area are a dike underlying the eruptive fissure on the contact between Mauna Loa and Kilauea lavas and dikes in other fissures in the Kilauea rift zone, exposed and not exposed on the surface, and, perhaps, the weathered surface of high relief which comprise the unconformity between the Ninole series and the Kahuku series. Neither the dikes nor the unconformities could alone be wholly responsible for the confinement because neither can completely isolate the Pahala aquifer from the sea.

There are several large springs at the coast. The estimated visible flow of Ninole Spring is 20 and 25 mgd and Kawaa Spring at 10 mgd (Stearns & MacDonald,1946). Other springs with less noticeable discharge occur at Punaluu and at Honuapo. Although the actual discharges to the sea are highly localized by channels such as lava tubes, the ground-water bodies feeding them are probably ordinary Herzberg lenses whose water tables rise much less steeply inland than the lava flows through which the discharges occur at the coast.

RESISTIVITY SURVEY

Application of Electrical Resistivity Exploration in Hawaii

Prior to this effort, there have been three important resistivity efforts conducted in Hawaii. In the late 1930's, J. H. Swartz, of the U. S. Geological Survey, pioneered the technique in Hawaii (Swartz, 1937, 1939, 1940a, and 1940b).

In 1962, George V. Keller (1962), of the U. S. Geological Survey (now with the Colorado School of Mines), made 3 shallow penetration soundings using the Schlumberger configuration and four deeper soundings with a bipole spacing of over 2 miles in the vicinity of the Kilauea Caldera. All of these soundings yielded similar results, which prompted the following classification of geoelectrical zones:

(a) shallow, very recent flows having resistivities in the range of 50,000 to 100,000 ohm-meters,

(b) underlying basalt above sea level, which yielded resistivities of 800 to 1,000 ohm-meters,

(c) older rocks below sea level with resistivities of much less than 10 ohm-meters, which were interpreted as salt-water saturated rocks.

In 1965 and 1966, additional DC resistivity explorations were conducted near Waialua, Oahu and Pohakuloa, Hawaii, by Adel A. R. Zohdy of the U. S. Geological Survey. On Oahu, Zohdy (unpublished report, 1966) arrived at the following values:

clay saturated with brackish to saline water	1-3	ohm-meters
clay saturated with brackish to fresh water	5-8	ohm-meters
clay, silty sand, and some ground with fresh water	11-25	ohm-meters
sand and coral	80-400	ohm-meters
weathered basalt with fresh water	30-60	ohm-meters
fresh basalt with saline water	30-40	ohm-meters
fresh basalt with fresh water	300-700	ohm-meters

It should be noted, however, that the above values for rock containing water do not specify that they are saturated, *i.e.*, below a water table.

Instrumentation

The first resistivity apparatus used by the Water Resources Research Center was assembled and tested at the Electronics Shop of the Hawaii Institute of Geophysics in 1965 after consideration of the design by Banwell and MacDonald (1965). A Honeywell Electronik 17 single-channel chart recorder powered by 12-volt storage batteries through a

100-watt transistorized inverter was fitted with shop-designed nulling and scale-changing circuits. Power for the current electrodes was supplied by a 12-volt storage battery through a large reed-type ATR inverter to a transformer that raised the voltage to 500 volts. A powerstat then provided control of the voltage from 0 to maximum volts. With the addition of a 0 to 0.10 and 0 to 1.00 amperes full-scale ammeter and a double-pole double-throw switch, the current source proved reliable and efficient.

Point contact with the earth was made with sections of copper-coated steel lightning rods driven about 6 to 8 inches into the ground. Current to the outer stakes and potential from the inner stakes was carried by light gauge hook-up wire with nylon insulation.

During testing on Maui, a Heath EUW-20A chart recorder, with built-in 0 to 10, 0 to 25, 0 to 50, 0 to 100, and 0 to 250 mv scales as well as its own bucking circuit, was found to be more durable and convenient than the more expensive Honeywell model. A 900-watt portable gasoline engine driven alternator was also tested as an alternative to the storage battery power supply to the current electrodes. The constant speed regulator on the alternator proved unreliable and the resulting current supply was too irregular.

A sounding made near Kihei Well #3 on Maui produced a curve which, when compared with the Schlumberger theoretical curves, (CGG, 1963) gave reasonable indications of resistivity values. Interface depths, however, were not clearly defined.

Specific application to Hawaiian ground water necessitated equipment portable enough to be hand carried into very rugged areas, particularly in the volcanically active regions. It was, however, quickly realized that the large batteries and/or generator, transformer, and large reels and long lengths of cable needed for wide spreads required to delineate the basal Ghyben-Herzberg lens from higher elevations would have to be transported by a four-wheel drive vehicle. This problem was met by building two complete sets of gear: a heavy duty truck-mounted apparatus and a portable rig contained in two field telephone boxes weighing less than 15 pounds each.

Heavy duty truck-mounted apparatus. For the heavy duty instrumentation, power was again supplied to the current electrodes from a 12-volt storage battery. An ATR 250-watt inverter converted 12-volt DC to 110-volt AC regulated at this stage with a 0 to 150 VAC powerstat. The AC is in turn boosted up to 900 volts by a transformer and then rectified back to DC (see Fig. 2). A Weston 911 precision ammeter with 0 to 10, 0 to 30, 0 to 100, 0 to 300-mv and 0 to 1, 0 to 3, and 0 to 10-amps mirrored scales is used to monitor the desired current adjusted by the powerstat. A 0 to 1000-volt voltmeter was also installed so that output voltage can be checked. A double-pole double-throw telephone-type spring return switch then enables easy polarity reversal to the current electrodes through a neutral central position. All this gear plus a small resistor circuit, designed as an earth analog to take the place of the electrode array for testing of the current supply and potential recording equipment, was built into a waterproof shock-resistant box.

The current electrode wires are each 3000 feet long, allowing a total spread length of 6000 feet. The wire, a flexible and tough 14-gauge TFF produced by the International Telephone and Telegraph Company, proved strong and easy to use. The PVC insulation remained leakage-proof in wet weather even after being laid and dragged over abnormally rugged terrain, including fresh aa flows, for the duration of the survey. Each 3000-foot length was wound on a Tesco portable cable reel. Due to the weight of the wire, these lengths would have to be reduced to about 1000 feet before the reel can be truly portable for long hikes. The wires terminate in large battery clamps which can be attached directly to electrodes, normally 3/4-inch steel rods about 3 feet long, sharpened at one end. The electrodes were driven from 4 to 8 inches into the ground, as conditions permitted.

On fresh lava flows and other bare rock surfaces where driving rods into the ground was not practical, 4" x 3" x 2" sponges soaked with salt or fresh water were used as electrodes. When placed directly on the hard surface, they were less of a point source than is theoretically ideal, but were convenient and provided satisfactory results. Sounding S-3 (see Fig. 3) served as a test of this method. The sounding was run along the shoulder of the road using steel rod electrodes pounded at least eight inches into moist soil, thereby providing excellent ground contact. This sounding was repeated, about 5 feet onto the road, using saturated sponges on the asphalt. The less efficient sponges required

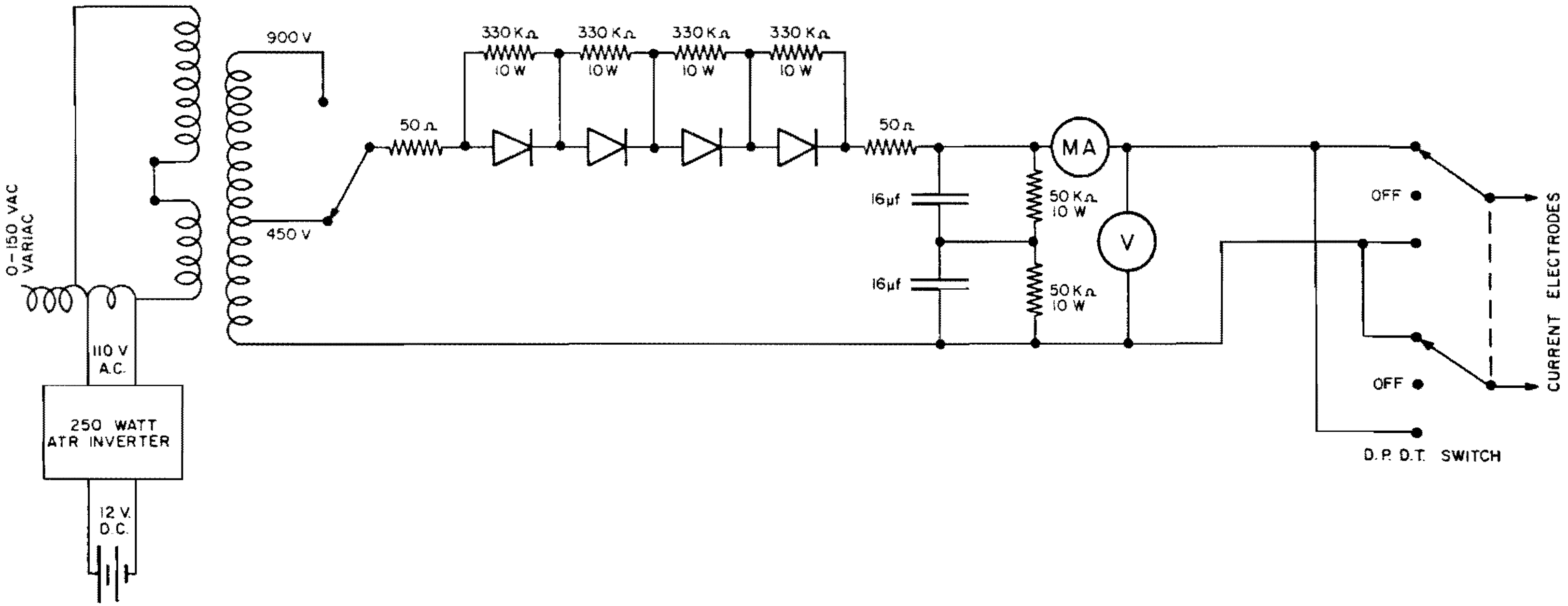

FIGURE 2. CURRENT SUPPLY SYSTEM FOR SPREADS UP TO ABOUT AB = 6000 FEET.

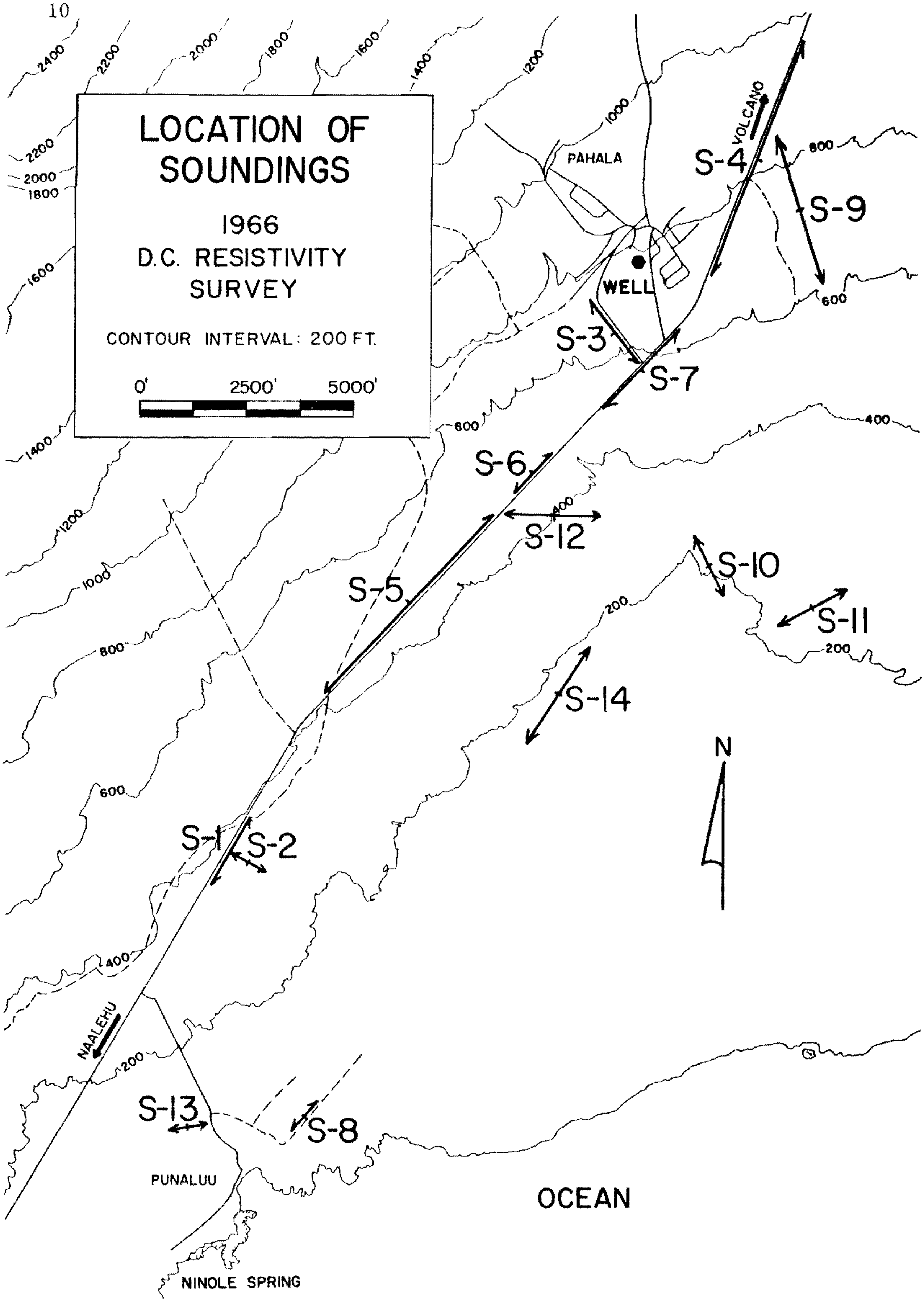

FIGURE 3. LOCATION OF DC RESISTIVITY SOUNDINGS IN THE PAHALA, HAWAII REGION FROM THE AUGUST-SEPTEMBER, 1966 SURVEY.

higher voltages than the steel rods to force necessary amounts of current into the ground. Hence, the maximum output of the current supply equipment was reached at a reduced spread length. A virtually identical resistivity curve was, however, produced to the maximum spread length.

At the potential electrodes, the higher contact resistance encountered when using sponges is a negligible factor in the very high impedance potential measuring circuit.

Although the use of salt water to improve the ground contact at the current electrodes was helpful, it was found that at the potential electrodes, salt water produced certain electrochemical effects causing extraneous voltages which greatly confused the readings. This phenomenon was also observed in ground saturated with fresh water to a smaller degree but is amenable to correction. Whenever possible the electrodes were kept dry.

Two small reels, each holding 500 feet of the previously described wire, were mounted on wooden bases for ease in deployment from the center of the spread to the potential electrodes. All the reels were insulated from the ground by rubber mats during measurements. The wires were marked in 50-foot intervals along their entire lengths for convenience while laying out the spreads.

The Heath chart-recording millivoltmeter that was tested on Maui was used for the Pahala survey. To supplement its controls, a precision voltage source was constructed to serve as a check on the meter calibration. An external bucking circuit was also added to increase the nulling power of the meter in case the anticipated large spreads produced unusually high background voltages. A simple R-C filter to be used across the meter input was built to counteract 60 cps AC interference.

Portable rig. The portable rig is analogous to the larger version. Current is drawn from Eveready No. 492 photoflash batteries. These batteries have both 180-v and 225-v terminals. In addition, 45 volts can be tapped by drawing from the two positive terminals. If the batteries are wired in series combinations, a wide range of voltages can be selected. These batteries are carried and operated from inside the power supply telephone box. A variable resistor provides a fine adjustment for the current drawn from the batteries. A 10-ma or 100-ma full scale milliammeter and a double-pole double-throw switch complete this circuit.

The electrodes, current, and potential leads for this apparatus can be the same as for the larger version. When measurements were attempted for small spreads on the rock wall face in a well shaft, however, another type of electrode used with sucess was heavy duty nails shot into the rocks with a special gun.

Potential at the inner electrodes is measured with a specially built nonrecording millivoltmeter (schematic, Fig. 4), designed by N. J. Thompson and contained in the second telephone box. It is powered by a small Burgess XX9 battery, with 9-volt and 13.5 volt taps, which also served as a source for a built-in circuit.

Field Procedure

A total of 14 DC resistivity soundings were made between Pahala and Punaluu (see Fig. 3) on the island of Hawaii, from August 21 to September 9, 1966. Two four-wheel drive vehicles were used for the survey.

The Schlumberger electrode configuration was chosen for use here because of its simplicity and greater versatility over other arrays. Since only either the potential electrodes or the current electrodes are moved after each measurement, the physical labor required in expanding the spread is reduced. Of greater benefit is the efficiency of detection and correction of small lateral anomalies that may exist around only one electrode. Furthermore, Depperman (1954) theoretically proved, and Zohdy (1964) illustrated with observed curves, that the Schlumberger configuration has better resolving power than other electrode arrays, notably the very popular Wenner-type spread.

During the course of this survey, soundings were made by groups of two, three, and four men. Maximum efficiency was attained with four men; two to operate the instruments and handle the inner electrodes, and one man at each of the current electrodes. With this arrangement two deep soundings were made each day. Contact was maintained between the outer ends of the spread and the truck at the midpoint with Halliburton CB 6 "handitalky" portable 100-ma transceivers. Communication procedure was established and rigidly followed at all times so that there could be no possibility of a misunderstanding between the instrument operator at the truck and those handling the current electrodes, which were supplied with lethal amounts of electricity at most spacings.

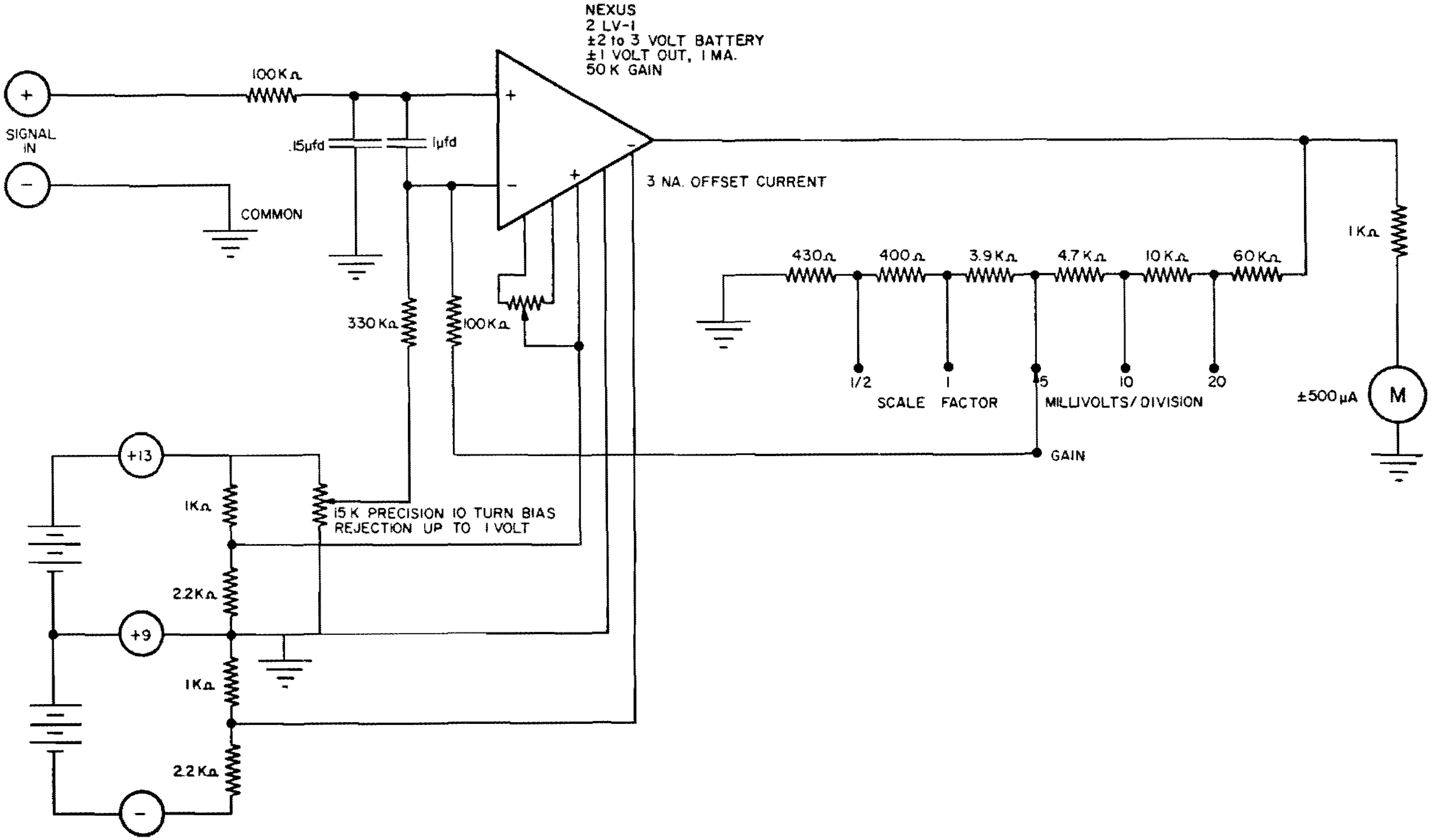

FIGURE 4. MILLIVOLTMETER FOR PORTABLE DC RESISTIVITY APPARATUS.

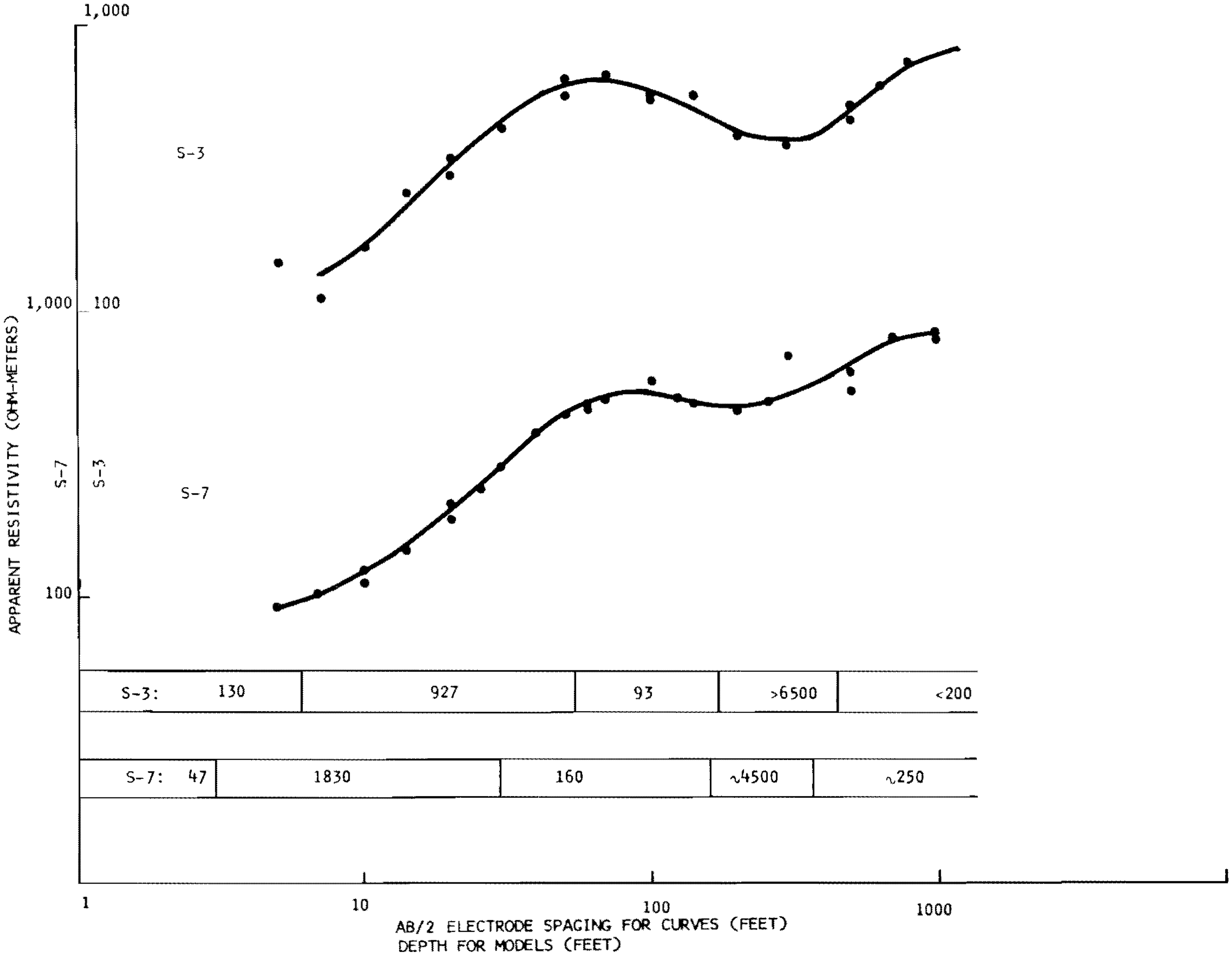

FIGURE 5. APPARENT RESISTIVITY CURVES AND INTERPRETATIONS FOR S-3 AND S-7. INTERPRETATIONS WERE MADE USING THE C.G.G. CURVE ALBUM (1963) AND THE AUXILIARY POINT METHOD. THE ABSCISSA REPRESENTS ONE-HALF THE CURRENT ELECTRODE SEPARATION FOR THE CURVE AND DEPTH FROM THE SURFACE FOR THE INTERPRETATION COLUMNS. RESISTIVITY VALUES IN THE COLUMN ARE OHM-METERS. ALL SUBSEQUENT CURVES WERE INTERPRETED IN THE SAME MANNER AND EMPLOY THE SAME NOTATION.

Good communications were also essential because of the necessity of keeping electrode contact resistance low at the current electrodes. If, on attempting to take a reading the operator found unusually high contact resistance, the equipment was disconnected and the electrode was inserted deeper into the ground. If this failed to improve contact a small amount of fresh water was poured around the electrode. On bare rock surfaces sponges soaked with salt water were used as current electrodes, and fresh water soaked sponges were used for potential electrodes.

As suggested by Adel Zohdy (personal communication), considering the most general expression for apparent resistivity as $\rho a = K\frac{\Delta V}{I}$, the current in amperes, I, supplied to a spread in the field was made numerically equal to a previously calculated geometric factor, K, for the spread spacing, so that the potential difference, ΔV, measured at the potential electrodes was numerically equal to the apparent resistivity, ρa (Table 1). The K factor was also used to correct units so that the spread configurations, which are measured in feet, yielded apparent resistivities in the conventional ohm-meter units. In actual measurements, the lowest convenient current that would produce an accurate and consistent potential drop at the inner electrodes was used.

Earth currents caused by natural telluric and self-potential effects, leakage from local power sources, etc., are cancelled out of the potential circuit with a bucking circuit. If these stray currents are not DC, they are usually of very low frequency or are 60 cps from industrial sources. The very low frequency can be treated as drift in the measurements. The 60 cps can often be eliminated simply by 60 cps R-C or toroidal inductor filters. Other problems occur when beat frequencies are generated between approximately 60 cps natural currents and the near 60 cps interference from the vibrators used to power the resistivity gear. All these effects, when recognized, can be compensated for during analysis of the field data if not eliminated during the observations.

Leakage from the lead wire to the electrodes, particularly in wet weather, can also yield erroneous measurements. Leakage is tested by placing the electrode clip at the end of the wire completely out of contact with the ground and energizing the spread. If no potential is developed, the wire insulation is secure. This test can be run on each electrode to help pinpoint leakage.

TABLE 1. GEOMETRIC FACTOR K, FOR SCHLUMBERGER ELECTRODE CONFIGURATION.
(FROM ZOHDY, PERSONAL COMMUNICATION)

($\frac{AB}{2}$, $\frac{MN}{2}$, IN FEET, RESISTIVITY IN OHM-M)

AB/2 (FT)[1]	MN/2 (FT)[2]	K (M)	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	1/10
5 (0,00,000)	1 (0,00,000)	11.48	5.74	3.826	2.870	2.296	1.913	1.639	1.435	1.275	1.148
6	1	16.75	8.37	5.583	4.188	3.350	2.791	2.392	2.094	1.861	1.675
7	1	22.97	11.48	7.656	5.742	4.594	3.828	3.280	2.871	2.552	2.297
8	1	30.14	15.07	10.05	7.535	6.028	5.021	4.304	3.767	3.349	3.014
10	1	47.37	23.68	15.79	11.84	9.474	7.892	6.764	5.921	5.263	4.737
10	2	22.97	11.48	7.656	5.743	4.594	3.827	3.280	2.871	2.552	2.297
12	2	33.49	16.74	11.16	8.372	6.698	5.579	4.782	4.186	3.721	3.349
14	2	45.94	22.97	15.31	11.48	9.188	7.654	6.560	5.742	5.104	4.594
16	2	60.29	30.14	20.09	15.07	12.06	10.04	8.609	7.536	6.699	6.029
20	2	94.74	47.37	31.58	23.68	18.95	15.78	13.53	11.84	10.53	9.474
20	4	45.94	22.97	15.31	11.48	9.188	7.654	6.560	5.742	5.104	4.594
25	4	72.85	36.42	24.28	18.21	14.57	12.14	10.40	9.106	8.094	7.285
30	4	105.75	52.88	35.25	26.44	21.15	17.62	15.10	13.22	11.75	10.575
40	4	189.49	94.74	63.16	47.37	37.90	31.57	27.06	23.69	21.05	18.949
50	4	297.1	148.6	99.03	74.28	59.42	49.50	42.42	37.14	33.01	29.71
60	4	428.7	214.4	142.9	107.2	85.74	71.42	61.22	53.59	47.63	42.87
70	4	584.6	292.3	194.9	146.2	116.9	97.39	83.48	73.07	64.95	58.46
80	4	764.1	382.1	254.7	191.0	152.8	127.3	109.1	95.51	84.90	76.41
100	4	1195.0	597.5	398.3	298.8	239.0	199.1	170.6	149.4	132.78	119.50

[1] AB/2 = ONE-HALF TOTAL CURRENT ELECTRODE SEPARATION.
[2] MN/2 = ONE-HALF TOTAL POTENTIAL ELECTRODE SEPARATION.

In all measurements, the apparent resistivity is measured several times until a consistent value is obtained. By reversing the polarity of the spread at each measurement, any spontaneous potential effects, as well as a hysteresis effect that seemed to exist in the chart recording voltmeter, are recognizable and can be corrected.

At the beginning of each spread and at frequent intervals thereafter, including every scale change, the voltmeter calibration is checked using a precision voltage supply.

During the Pahala survey all spreads were expanded to the limit of the effectiveness of the apparatus or, more often, until physically restrained by terrain.

Exploration of the Pahala Shaft

In April, 1967, the Maui-type well shaft of the Hawaii Agricultural Company at Pahala was explored. This is the only well in the area of the survey. Visual observations in the Pahala well shaft were of value, but efforts to measure resistivity failed. The shaft penetrates numerous lava flows, primarily of pahoehoe type, generally somewhat weathered, with some interbedded soil zones. The walls and backs appeared quite dry down to a depth of about 175 feet. Below this level, they were generally very wet although the rock types remained similar. The seepage caused dripping from the walls and varied considerably within the wet zone, appearing most profuse in very porous aa type flows, and often stopped in the soil zones. The soil zones ranged from a few inches to about 2 feet in thickness, while the thickness of lava flows ranged up to 20 to 30 feet. At a depth of about 400 feet, 150 feet above the water table, the seepage stopped and the rock, again mostly somewhat dense pahoehoe, was relatively dry down to the fresh-water table. The transition from wet to dry rock in the vadose zone was gradational with no apparent impermeable layers.

Resistivity Soundings

These observations shed considerable light on the interpretation of S-3 (Fig. 5) centered about one-half mile to the southwest of the well. The sounding was made over fairly moist soil (covered by thick high grass), with a surface resistivity of about 130 ohm-meters. At a depth of about 54 feet, the indicated resistivity dropped to a very low value, suggesting the top of the wet seepage zone encountered in the well at about 175 feet. The depth discrepancy might be explicable if this "wet zone" is actually the result of rain water rapidly percolating downward, since the Pahala area had experienced little rain during the month preceding the trip down the well, whereas at the time of the sounding, the area that was sounded had experienced unusually heavy rains for about two weeks lasting until three days before the measurements were made. It should, however, be noted that S-7 (Fig. 5), as well as S-4 and S-9 (Fig. 6) show similar low resistivity zones closer to the surface although observed much longer after heavy rains. It therefore seems more likely that the low resistivity is due to a permanently higher water content, resulting perhaps from a greater porosity, rather than the transient effect of the downward percolation of rain water. The difference in depth would then be explained by the approximately 0.5 mile separation of S-3 and the shaft and the difference in their ground level elevations, 640 feet and 780 feet, respectively. The actual elevations of the wet zones are comparable, 605 feet and 585 feet (Fig. 7).

The dry zone subsequently encountered about 150 feet above the water table in the shaft is likely to correspond to the higher resistivity zone indicated in S-3, as well as in S-7, S-4, and S-9 (see Fig. 7). The cause of this layer is not known, although it, too, is likely the result of a change in lava characteristics and a consequent change in porosity and water content. More careful study of the rock types, their water content and related electrical properties, in the well shaft as well as repetitive resistivity soundings to determine the permanency of the layers,should help to determine the causes of the physical and electrical interfaces.

The most remarkable correlation between the well and S-3, S-7, S-4, and S-9 is at the water table (see Fig. 7). These soundings all indicate an interface at 200 to 220 feet above sea level between the high resistivity layer and a second low resistivity layer (with resistivities in the range of 200 to 300 ohm-meters).

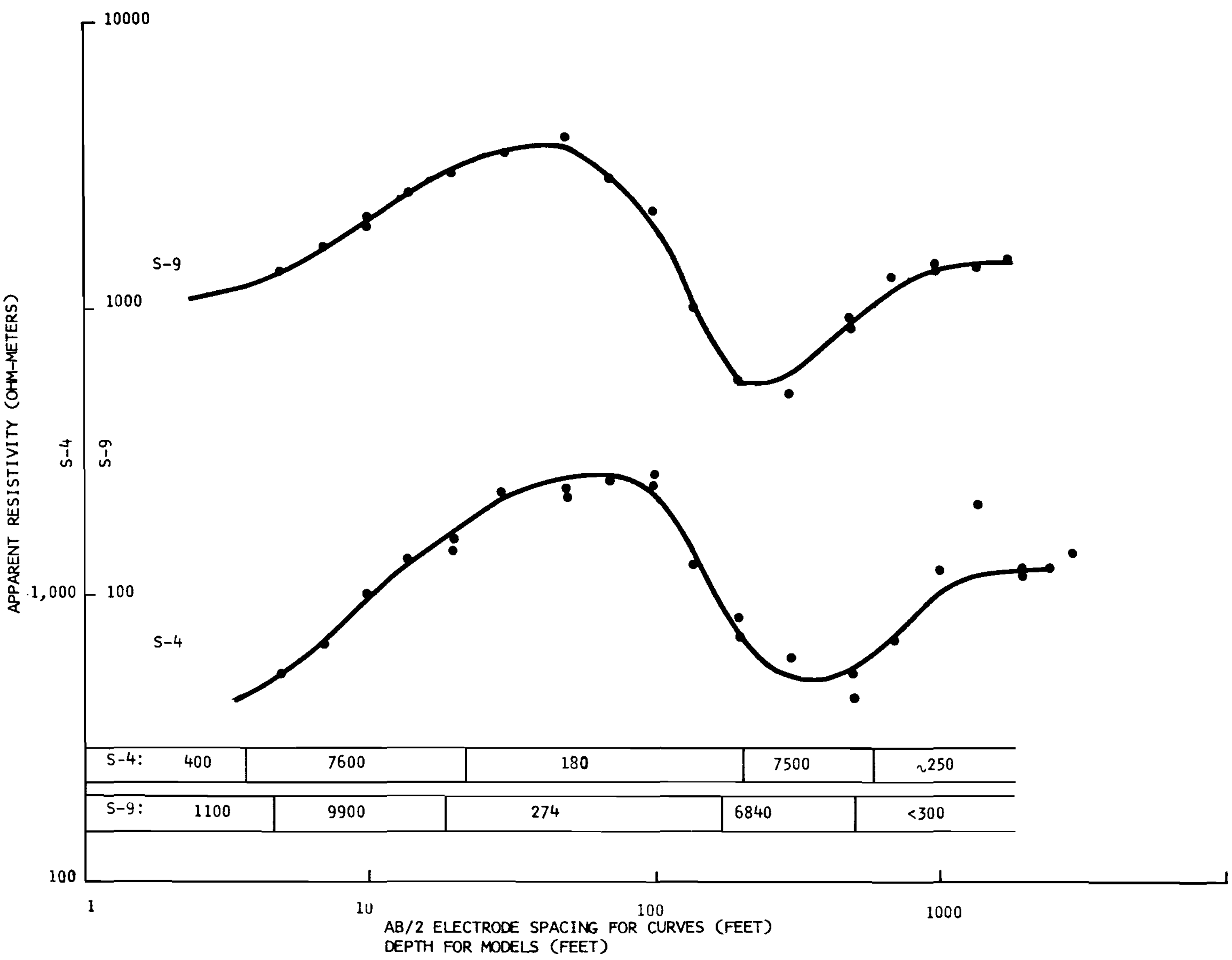

FIGURE 6. APPARENT RESISTIVITY CURVES AND INTERPRETATIONS FOR S-9 AND S-4.

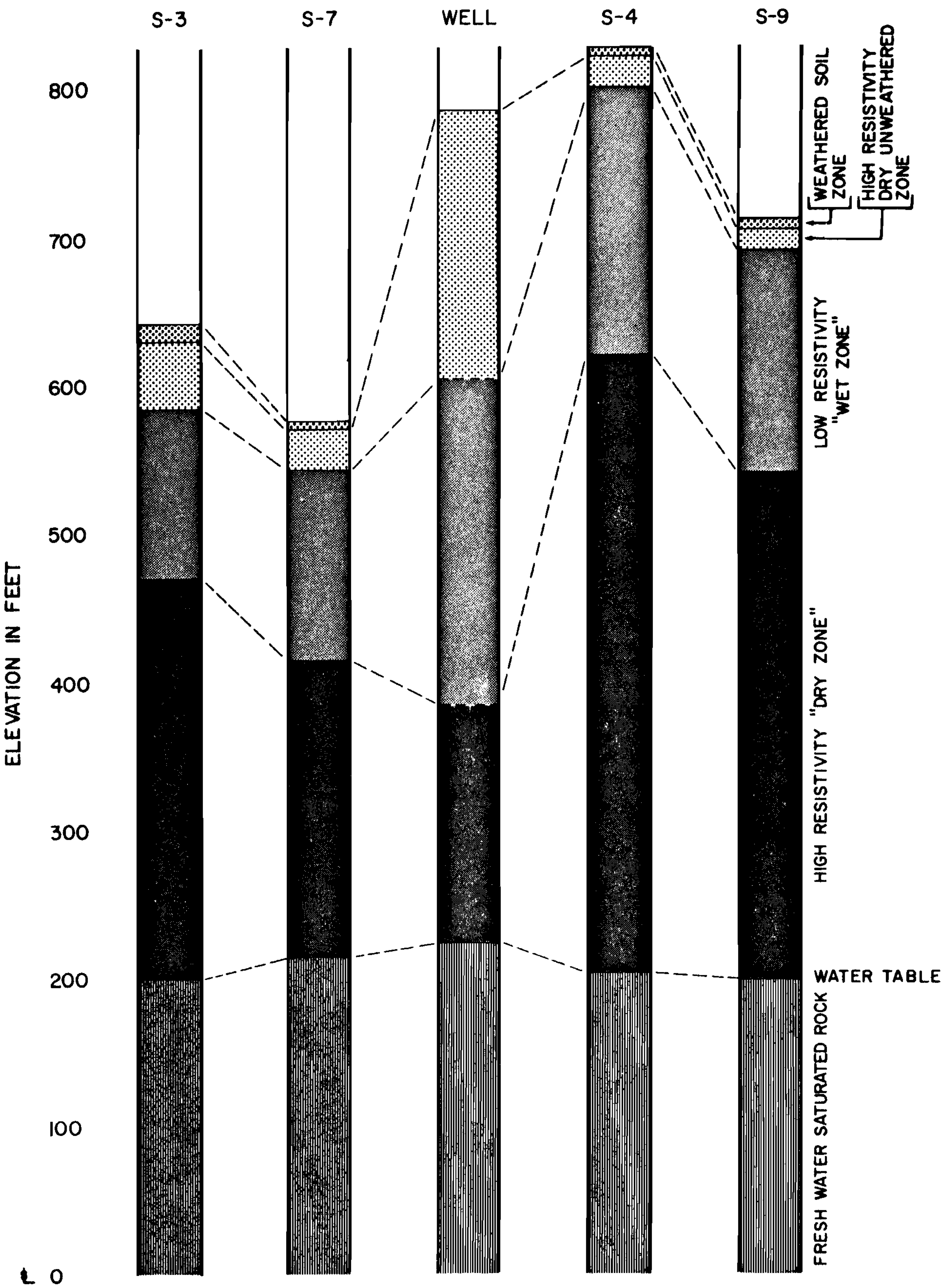

FIGURE 7. GENERALIZED GEOLOGIC COLUMNS AS INTERPRETED AT THE PAHALA WELL, AND SOUNDINGS S-3, S-7, S-4, AND S-9. NOTE THE CONSISTENCY OF THE RESISTIVITY LAYER SEQUENCE, AND THE EXCELLENT CORRELATION OF THE WATER TABLE ELEVATION.

The consistency in elevation of this interface,as indicated by the low soundings and its similarity to the elevation of the water table in the shaft,suggest strongly that the deeper low-resistivity layer is the phreatic zone and not another wet part in the vadose zone. Recognizing that an error of 15% is expectable in depth determinations from these resistivity interpretations, the correspondence of interface elevations among the soundings and between them and the shaft seems very good.

The consistently deeper sounding interpretations are also possibly the result of an oversimplified analysis since the assumption of too few layers in the model and/or the neglect of the effects of anisotropy will both result in interpretations that are too deep.

The resistivities found in the vadose "wet zone" are remarkably low, at times as low or lower than resistivities encountered below the water table. It is possible that the water-saturated phreatic rock has a much lower porosity than the wet parts of the vadose zone. If so, the very high specific surface area of the vadose wet zone may permit the retention of large quantities of water than would give electrical properties similar to the less porous saturated rock below the water table. If the intermediate high-resistivity zone is a phenomenon caused by a decrease in water content corresponding to a decrease on porosity and specific surface area, it may be that the saturation of this same layer at and below the water table would produce a resistivity comparable to the values observed.

If the ground-water body at Pahala is contained by a hydrological barrier, the fissure vent to the southeast seems a likely impermeable vertical barrier. Soundings S-10 and S-11 (Fig. 8), which are southeast of the vent, add credibility to this theory. They indicate water table elevations of 60 feet and 75 feet, respectively. The resistivity values of the upper layers in these soundings show excellent agreement. S-11 indicates an unusually high resistivity value of 485 ohm-meters for the phreatic zone. Although this value gives the best fit to the observed curve, it may be that a lower value would be appropriate, in which case its upper interface could be expected to be somewhat deeper and therefore more closely in agreement with S-10. Regardless, both soundings indicate a difference of about 150 feet in water table elevation from that in the area of the shaft, possibly the result of a barrier at the vent. However, even the

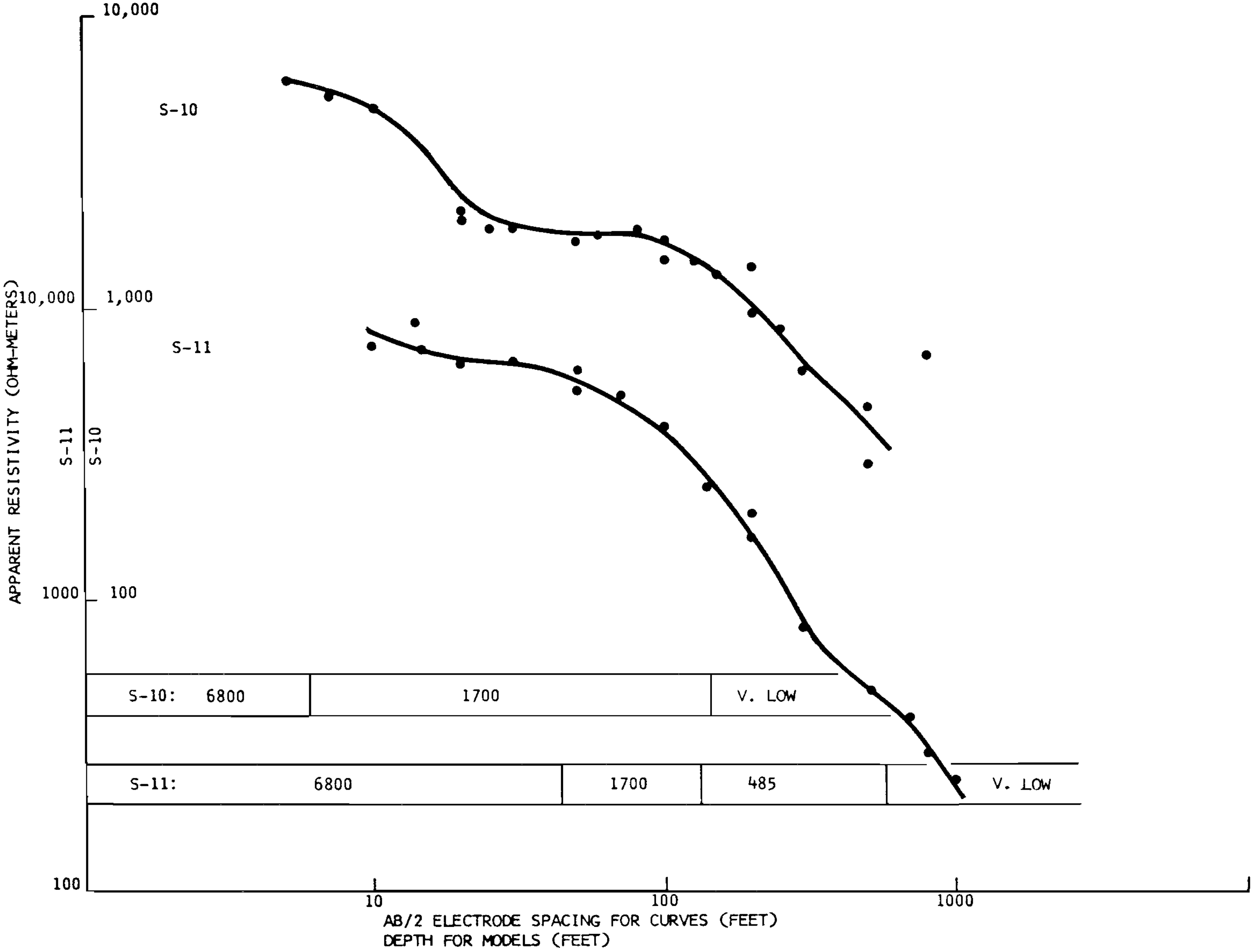

FIGURE 8. APPARENT RESISTIVITY CURVES AND INTERPRETATIONS FOR S-10 AND S-11.

reduced water table elevation at S-10 and S-11 is still too great to be the surface of a normal Ghyben-Herzberg lens in permeable Hawaiian lavas. If it is the elevation of the basal water table, additional hydrological barriers must be postulated between these soundings and the sea. Dikes in the southwest rift zone of Kilauea might be expected to provide such a barrier to the east. To the south, however, the steep hydraulic gradient implies more intersections of such dikes than would be expected considering their usual near-parallelism.

S-6, S-12, and S-5 (Figs. 9 and 10) are very difficult to interpret. All three give very confused values at electrode spacings that would correspond to current penetrations of over 100 feet. At greater spacings high resistivity values occur which could be interpreted in all cases as the electrical expression of a very high resistivity rock layer in the earth near sea level. If so, these layers, which are seen no where else in the survey area, may represent portions of a deep seated, low porosity, impermeable series of intrusives or other bodies that could contribute toward the hydrologic boundary causing the high-head entrapment under Pahala. Perhaps a geologically more reasonable hydrologic barrier in this area is the existence of a relatively impermeable Ninole soil and/or ash sequence on an ancient erosion surface representing the buried subterranean seaward extension of Ninole Valley. Although the surface resistivity expression of such a feature is not known, it could well explain the observed soundings and could certainly make an excellent barrier to the flow of the high-head ground water southwest to the sea. It is also very possible that the undulations in the resistivity curves are the result of lateral variations in resistivity, rather than vertical effects. This possibility is underscored by the fact that no surface geologic indications of any hypothetical deeper high resistivity layers could be found. These three field curves also exhibited the worst scatter of all the soundings obtained. More detailed study of this region with a fixed spread resistivity profile to determine later variations in conductivity might provide the necessary data to better evaluate S-6, S-12, and S-5.

S-14 (Fig. 10) shows a low resistivity layer beginning at an elevation of about 45 feet that is interpreted as the phreatic zone. This

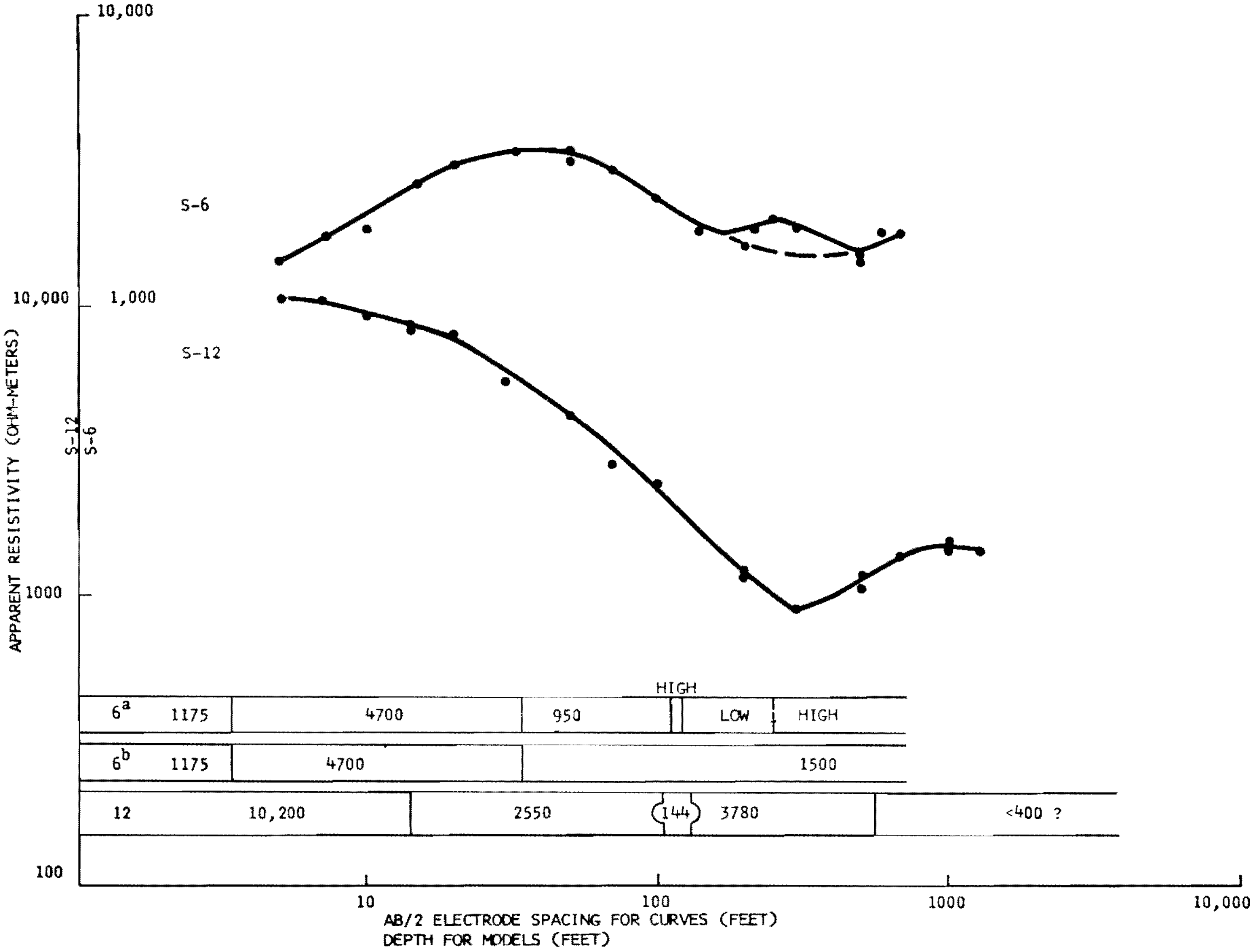

FIGURE 9. APPARENT RESISTIVITY CURVES AND INTERPRETATIONS FOR S-6 AND S-12. NOTE THAT S-6 HAS TWO INTERPRETATIONS, S-6A IF THE LAST PART OF THE CURVE FOLLOWS THE HEAVY LINE THROUGH A REASONABLE FIT IN THE POINTS, AND S-6B WHICH IS THE RESULT IF SOME OF THOSE LAST POINTS ARE CONSIDERED BAD SCATTER AND THE CURVE IS SMOOTHED ALONG THE DASHED LINE.

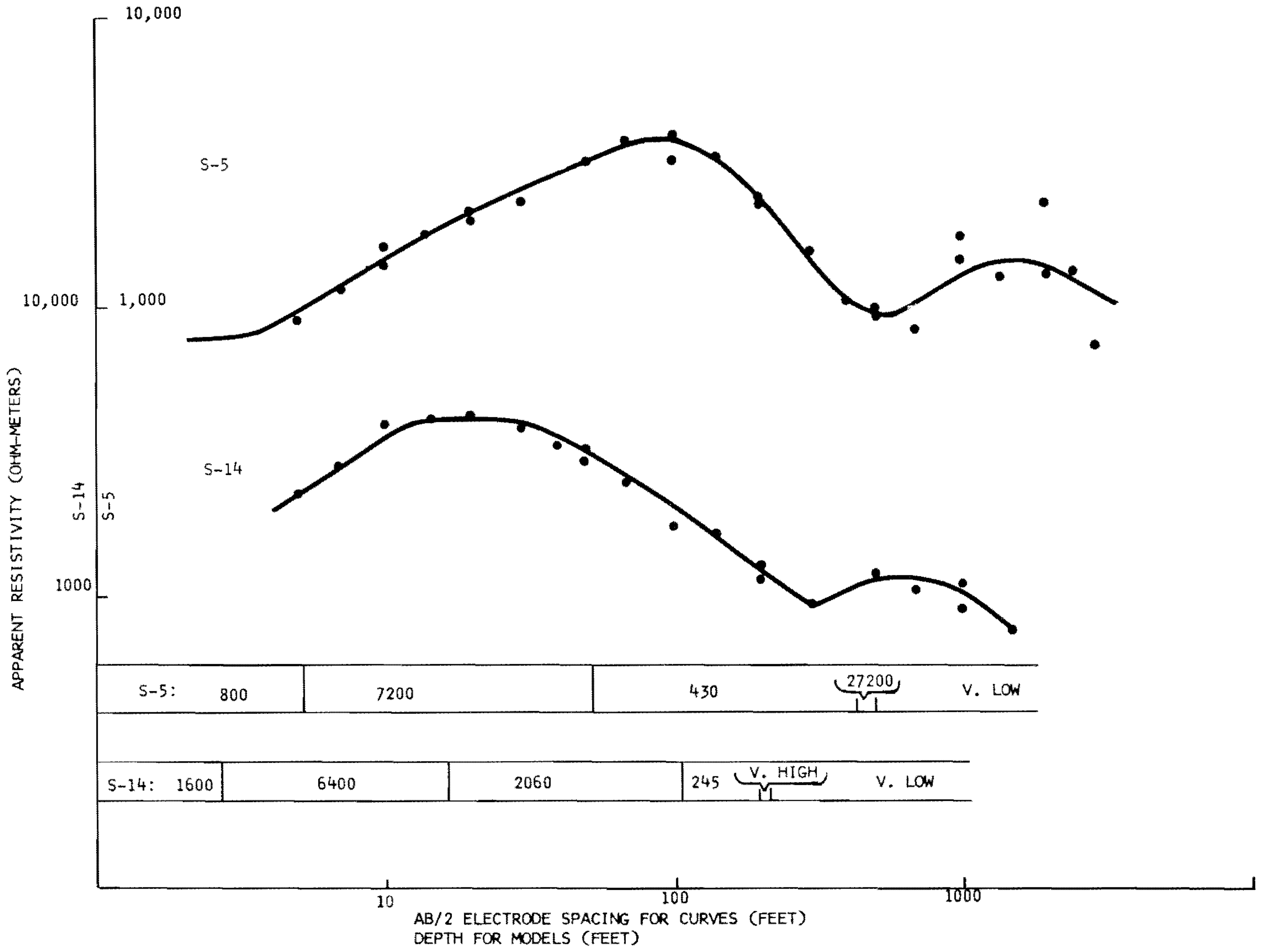

FIGURE 10. APPARENT RESISTIVITY CURVES AND INTERPRETATIONS FOR S-5 AND S-14.

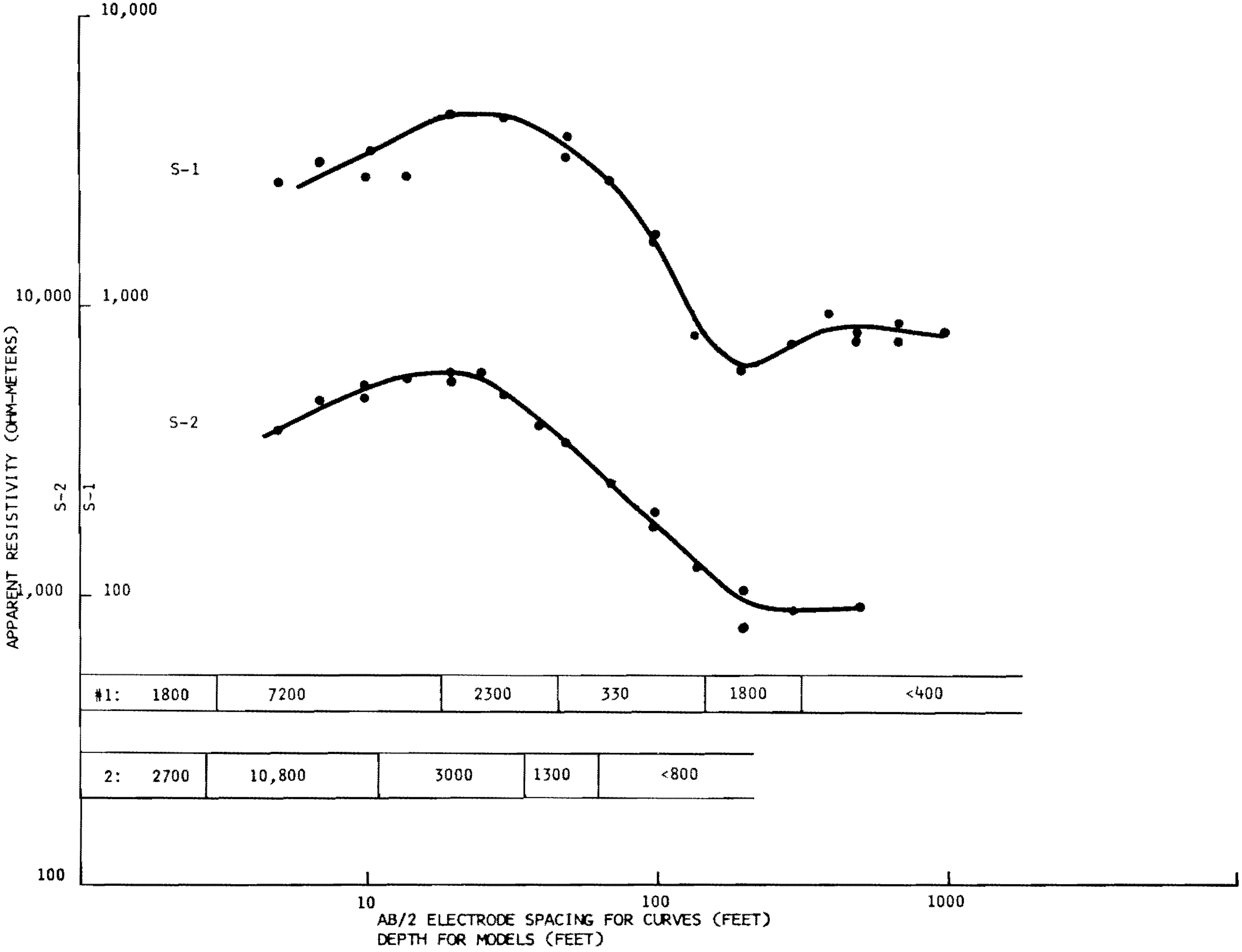

FIGURE 11. APPARENT RESISTIVITY CURVES AND INTERPRETATIONS FOR S-1 AND S-2.

sounding seems to be outside the primary Pahala entrapment, but like S-10 and S-11, the apparent water table is still higher than expected if no barriers existed toward the sea. S-14 may also still be on the fringes of the confused, possible barrier area of S-6, S-12, and S-5, owing to the very thin and high resistivity layer just below sea level which is characteristic of soundings to the north.

Close to Punaluu, S-1 (Fig. 11) indicated a section similar to that at S-14, with a low resistivity layer interpreted as the phreatic zone extending to about 50 feet above sea level. S-2 (Fig. 11) was not expanded enough to definitely indicate the water table. If the lower apparent resistivity at AB/2=200 feet were assumed correct and the curve only roughly drawn through to AB/2=300 and 500 feet, a closer match with S-1 would be obtained and an approximate depth to the apparent water table could be estimated, but it would be unreliable.

The decrease in head between the area of S-10 and S-11 and the area of S-1 and S-14 is consistent with leakage that would be expected from the S-10 and S-11 area toward the southwest along the prevailing strike of dike series with many intersecting semi-permeable and impermeable boundaries. Much of this leakage may also come from the larger reservoir under Pahala.

Although only 1000 feet from the sea and at an elevation of only about 45 feet, S-8 (Fig. 12) still exhibits an abnormally high head. An excellent break in the curve suggests that fresh water lies at a depth of only 27 feet, or about 18 feet above sea level (the depth determination is likely to be more accurate than the surface elevation). The existence of this elevation of supposedly basal water so close to the sea with absolutely no obvious boundaries is extremely difficult to justify. The proximity of the sea should have no effect on these readings, although some other lateral effect is possible. At the AB/2=500 feet point the S-8 sounding curve tends to become asymptotic to a resistivity normally too high to be salt-water saturated rock. Although based on only the very last portion of the curve, a fresh water lens with a minimum thickness of 400 feet is indicated and lends credence to the hypothesized high head of fresh water. Hydrologic barriers must therefore exist in the short distance between S-8 and the sea if the high head is correct.

S-8 is also remarkable for the extremely high resistivity of its upper layer. The electrode spread was placed on a bulldozed trail over a fresh aa lava flow of exceptionally high porosity. The rock was very dry. The 12,000 ohm-meter layer is probably the crushed and compressed aa used as fill to smooth the very rugged terrain. A depth of 6 feet is not unreasonable for this layer. The main body of the flow is composed of aa so porous that its density approaches that of pumice. It is piled in irregular chunks with large spaces between each rock. Therefore, it is not surprising that the flow has a resistivity of around 200,000 ohm-meters. This is the highest resistivity value for an extensive natural formation encountered in the field or in the literature.

The only sounding that showed what can be considered a normal basal water table was S-13 (Fig. 12) at an elevation of 80 feet. The water table indicated was about two feet above sea level. Unfortunately only one point exists at an AB/2 spacing that would be great enough to show the effect of the fresh-salt water interface, hence, only the fresh water surface is well identified. This sounding was about 1/3 mile from S-8, but it was away from the fresh aa on much older, weathered, pahoehoe flows. Although both areas were quite dry, the weathered pahoehoe was two orders of magnitude less resistive than the fresh aa.

CONCLUSIONS

Ranges of resistivity values encountered in the Pahala area are far from definitive, but may be roughly categorized as follows:

unweathered aa lava	10,000-200,000 ohm-meters
unweathered pahoehoe lava	5,000- 20,000 ohm-meters
weathered lavas	1,000- 8,000 ohm-meters
dry soil	500- 5,000 ohm-meters
wet soil	50- 500 ohm-meters
fresh water saturated lavas	50- 300 ohm-meters

As suggested by the wide ranges of resistivity values encountered, direct current resistivity has proved to be a useful tool for studying rock structure and ground-water configuration in Hawaii. It is, however, by no means the solution to all the problems encountered. The technique is greatly in need of further investigation and improvement.

A primary difficulty in the use of the technique in Hawaii arises from the complex nature of Hawaiian geology. The vast number of overlapping lava flows of variable electrical properties, in addition to the complex structure of intrusions and the presence of ground water, are far from the idealized simple models on which resistivity theory is based. Anisotropy certainly has an effect on the apparent resistivity curves and must be studied for each particular Hawaiian situation.

The repeatedly encountered difficulty arising from the electrically almost undefinable difference between wet zones above the water table and the water-saturated rocks of the phreatic zone must be further studied.

In spite of the difficulties, it is apparent that the resistivity method is useful for ground-water exploration in Hawaii. The phreatic zone has been detected and the water table elevation estimated to a depth of 600 feet below ground level in an area where correlation was possible with a well. A distinct hydraulic discontinuity has been roughly located, and with less certainty the water table was detected beyond the discontinuity.

The high head ground water encountered at the Pahala well has been found to extend at least 3500 feet northeast of the well. Perhaps more significantly, it has been traced at least one half mile south of the well shaft where the ground surface is about 200 feet lower than the shaft portal. To the south and southwest of the shaft the resistivity soundings indicate water table levels that are consistent with the hypothesis that the principal impounding structure is a northeast striking dike series below an eruptive fissure. Intersecting dikes within this area could provide the various smaller boundaries causing leaking steps of entrapment gradually descending to sea level at the coast to the southwest. The nature and exact location of the impounding structures north of the hypothetical dikes and southwest of Pahala has not been determined.

If, as is very possible, the high head water table under Pahala extends to the eruptive fissure some 5000 feet south of the shaft where the ground elevation is about 400 feet, the pumping lift for a well at this location would be less than 200 feet.

More resistivity soundings are needed between the shaft and the fissure vent area to more closely define the seaward extent of the high head reservoir and provide necessary control for possible test drilling.

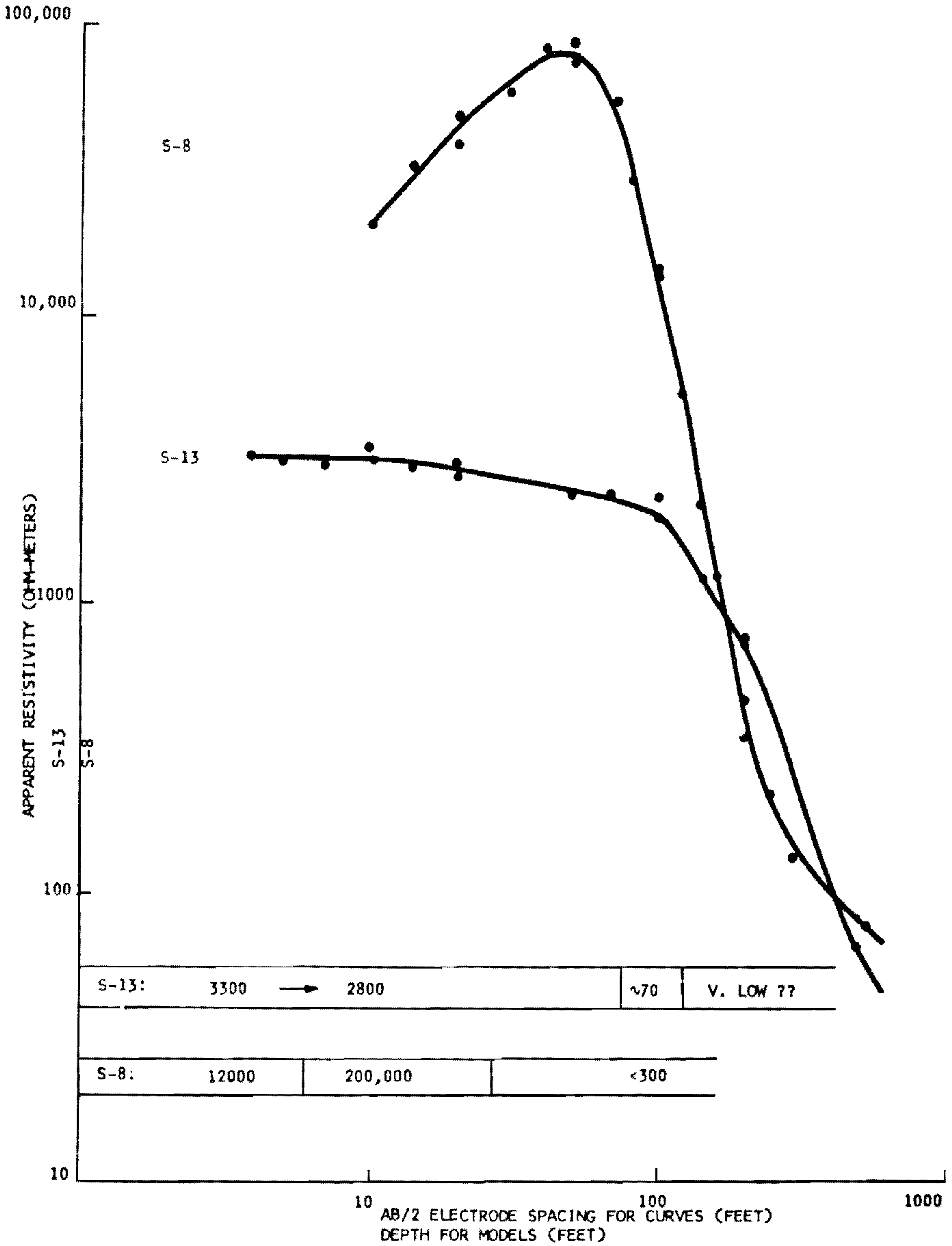

FIGURE 12. APPARENT RESISTIVITY CURVES AND INTERPRETATIONS FOR S-13 AND S-8. NOTE FOR S-13 THE POORLY DEFINED GRADATIONAL DECREASE OF APPARENT RESISTIVITY FROM 3300 OHM-METERS TO 2800 OHM-METERS. A POSSIBLE VERY LOW RESISTIVITY AT DEPTH ON S-13 MAY BE THE SALT-FRESH WATER INTERFACE.

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