GEOELECTRIC CHARACTER OF KILAUEA IKI LAVA LAKE CRUST

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ABSTRACT

Two orthogonal Schlumberger soundings were made in the Kilauea Iki pit crater on the Island of Hawaii to determine the vertical resistivity of the crust overlying a molten lava lens. The data indicate a relatively good conductor in the 6- to 12-m depth interval interposed between two high-resistivity layers. Subsequent borehole resistivity logging disclosed the existence of a second conductive section in the 29- to 34-m depth interval. The upper conductive zone results primarily from the deposition of wet salt precipitates within the vesicles and pore spaces of the basalt, whereas the lower conductive zone results from a sufficient quantity of meteoric water in the liquid phase to reduce the resistivity of the rock. A dry, highly resistive layer separates the lower conductive zone from the melt. Rock-property measurements on borehole core samples indicate that the in-place resistivity of the rock is controlled by environmental factors rather than by compositional or textural variations. Only in those samples from the 6.1- to 6.7-m depth interval are the laboratory resistivity measurements equal to the resistivities measured in the borehole. A scanning electron micrograph of minerals found within the vesicles of the rock sample from the 6.7-m depth revealed evidence of zeolite and clay development in quantities sufficient to reduce the resistivity of the rock by means of surface conduction.

INTRODUCTION

In the mid-1970's, the Sandia Corporation, under a Department of Energy grant, began a study of shallow magma reservoirs, with the ultimate objective of determining the feasibility of withdrawing heat from a molten lava body for direct conversion into a useful form of energy (Hermance and Colp, 1982). Kilauea Iki lava lake, on the Island of Hawaii, formed during the summit eruption of November–December 1959, was chosen as the site of the initial study, which consisted of first identifying and subsequently delineating an area of near-surface molten lava through the use of various geophysical methods. Staff members of the U.S. Geological Survey's Hawaiian Volcano Observatory (HVO) on Kilauea were invited to participate in the exploration phase, particularly in the application of electrical measurements to a study of the electrical character of the crust of the lava lake and to the mapping of the lateral configuration of the molten lava lens.

Kilauea Iki is a pit crater, approximately 1.6 km long and 0.8 km wide, situated immediately east of Kilauea caldera (fig. 50.1). Before the November 1959 eruption, the pit crater was 213 m deep at its lowest point and, following termination of volcanic activity, a lava lake 111.3 m deep covered the old floor of the crater (Richter and Moore, 1966). In the ensuing years, cooling and subsequent solidification, which is not as yet complete, has caused the lake surface to subside to a level perhaps as much as 10 m below the initial level.

The first geophysical mapping in Kilauea Iki occurred in April 1961, when electromagnetic profiling and sounding methods were used to identify the boundaries of the molten lava and to determine the thickness of the overlying crust. At that time the 100 °C isotherm was at a depth of less than 1 m below the lake surface, and, despite rainfall in excess of 2.5 m/yr, the meteoric water was rapidly vaporized and none remained in the rock. The resulting resistivity contrast between the dry, solidified lava, about 9 m thick at the time (Richter and Moore, 1966), and the conductive molten lava made interpretation of the field data relatively simple. In 1976, the 100 °C isotherm had descended to a depth of approximately 34 meters below the lake surface, and a perennial cycling of water in the liquid-vapor state had been established in the upper part of the lake crust. As a consequence, the added moisture has altered the upper basalt layers, adding to the complexity of an interpretation involving electromagnetic sensing of the molten lava at depth (Smith and others, 1977).

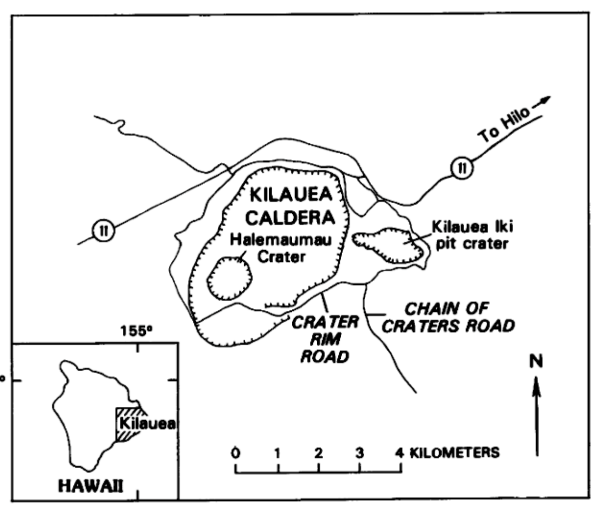

FIGURE 50.1.—Kilauea Volcano showing location of Kilauea Iki pit crater.

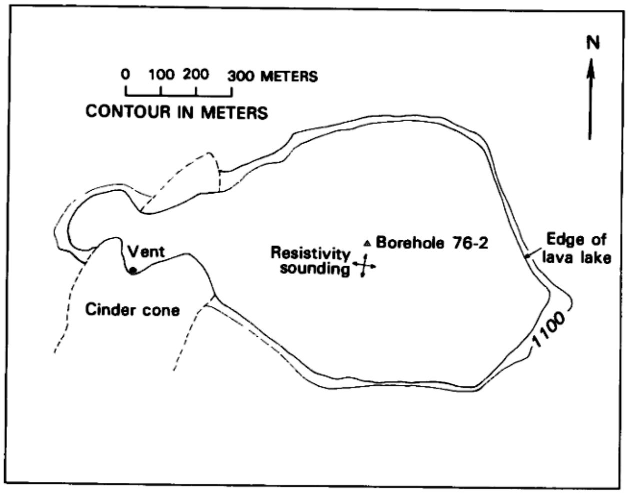

FIGURE 50.2.—Kilauea Iki lava lake showing resistivity sounding and borehole locations.

ACKNOWLEDGMENTS

I wish to express my gratitude to Neil Fishman, Jim Gude, and Richard Sheppard of the U.S. Geological Survey, Denver, for their contributions to the recognition of the unusual occurrence of zeolites within the crust of the Kilauea Iki lava lake. I am also grateful to John Forbes of the Hawaii Volcano Observatory for his help in constructing the borehole probes used in this investigation.

SCHLUMBERGER ELECTRICAL SOUNDINGS

To obtain information on the gross distribution of resistivity of the lake crust with increasing depth, two mutually perpendicular Schlumberger electrical soundings were made near the center of the lava lake in April 1976 (fig. 50.2). The sounding curves and their interpretations in the form of geoelectric sections obtained by means of a computer program developed by Zohdy (1974) of the U.S. Geological Survey are presented in figure 50.3. The east-west sounding shown in figure 50.3*A* was expanded along the major axis of the lake. The interpreted geoelectric section indicates the presence of a relative conductor within the 6- to 12-m depth interval interposed between two layers of much higher resistivity. The near-surface layer is essentially dry and hence, resistive, and as the temperature of the lower layer is increased, ground water is excluded from the rock, causing that section to become increasingly resistive with depth.

The effect of lateral variations in resistivity is evident on the sounding curve shown in figure 50.3*B*. The vertical offset in the field data observed at current electrode spacings within the 12- to 16-m depth interval, resulting from repeated measurements at two different potential electrode spacings while maintaining a fixed current electrode spacing, is an indication that the rock resistivity is higher sidewise to the center of the sounding array than at the center of the sounding itself. In Kilauea Iki, the blocklike crustal configuration has produced a network of vertical fractures, some of them visibly open, which tend to interfere with current flow. Following a procedure initiated by Zohdy and others (1973) the curve segment measured at the longest electrode spacings is held fixed in position while the other segments representing shorter electrode spacings are shifted upward or downward to form a continuous curve that can be interpreted in terms of laterally homogeneous media. As the result of an upward shift of the left-hand segment, the surface layer as interpreted from the north-south sounding is appreciably higher than that interpreted from the east-west sounding.

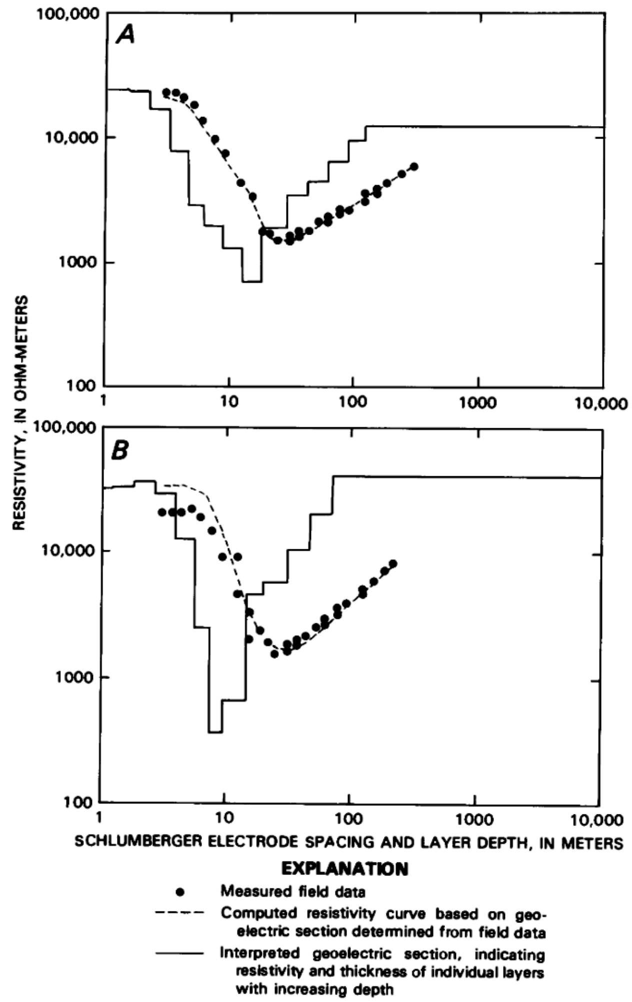

FIGURE 50.3.—Vertical electrical soundings (direct-current resistivity) made by expanding electrode array in (*A*) east-west-direction and (*B*) north-south direction.

The north-south sounding curve (fig. 50.3*B*) is similar to the east-west sounding curve in the sense that a shallow conductor is situated between two resistive layers. A fundamental difference exists in that the right-hand branch of the north-south sounding curve rises at a slope of 1, indicating that the resistivity of the lower layer increases abruptly relative to the overlying layer, whereas, the corresponding branch of the east-west curve rises at a slope of less than 1, as if sensing on a zone of gradually increasing resistivity. Neither sounding indicates the presence of an underlying conductive zone.

A problem in interpreting the soundings is to reconcile the nature of the lateral changes in resistivity that produce the slope differences between the right-hand branches of the east-west and north-south sounding curves. Efforts to develop a three-dimensional model representative of the horizontal and vertical resistivity section that may reasonably exist within the lava crust, sufficient to simulate the sounding curves, failed to produce the desired results. The resistivity variations within the lava lake and surrounding environs are highly complex and difficult to reconstruct on the basis of existing data.

BOREHOLE RESISTIVITY LOGGING

Two boreholes located 61 m north of the direct-current resistivity sounding site were drilled 41 cm apart during August 1976; they penetrated the solid-melt interface at 45.52 m (Colp and Okamura, 1978). When a borehole became available for in-hole resistivity measurements, several design schemes and materials were tested until a suitable probe was eventually assembled made of four sections of quarter-round wood moulding and wiper-type electrodes constructed of welding rod. Although the probe charred badly as the temperature increased in the lower part of the hole, its structural integrity was maintained, allowing measurements to be made until the welding rod lost its resilience and slumped to the extent that mechanical contact with the borehole wall was no longer possible. Resistivity measurements were made as with the normal array using current-potential electrode spacings of 1 and 2 m read at 0.5-m intervals.

The first successful resistivity log was obtained by early December 1976 (fig. 50.4). Resistivities are shown plotted as a function of the depth to the midpoint between the potential and current electrodes. In a general sense, each data set portrays a more complicated geoelectric section than that indicated by the vertical electrical soundings. Instead of two layers of varying resistivity overlying the hot, dry, resistive zone above the molten lava, at least four layers exist. The lowermost, relatively conductive section in the 29- to 34-m depth interval identifies the zone of highest water content where the liquid phase of a two-phase system predominates. Above the wet zone, the moisture is primarily in the vapor phase, resulting in higher resistivities. A second conductive layer exists in the 4- to 12-m depth interval; it has resistivities lower than those measured in the lower conductive zone. Obviously no standing water exists in this upper layer nor is there any reason to suspect a difference in mineralogy sufficient to cause the interval to be less resistive than the main body of solidified lava. The cause of the increased conductivity is believed to be primarily the result of wet salt precipitates forming within the vesicles and pore spaces of the rock as some condensation of the upward-moving wet steam takes place because of a subtle drop in temperature. Temperature measurements made at the time of the December logging survey (fig. 50.4) indicated values slightly less than 100 °C above the 16-m depth, thus verifying that the near-surface zone undergoes some degree of cooling as the result of intermixing with downward-moving rain water. The source of the brine is believed to be a dissolution of magmatic gases within the lower water-saturated layer, portions of which are eventually carried upward within the wet steam. Helz and others (1980) have identified the presence of thenardite—a sodium sulfate salt (Na_2SO_4)—within certain intervals of the recovered core. The high-salinity surficial waters coating the rock provide a continuous flow path for electrical current such that the bulk resistivity of the rock is greatly reduced.

In-hole resistivity measurements were repeated in April 1977 with a similar probe at the same electrode spacings as before, the only difference being that the material used for the electrodes was stainless steel rather than welding rod. The character of the resulting data profile is essentially unchanged; however, appreciable changes occurred during the 4-month time period. Among these changes is an overall decrease in the level of resistivity within the entire borehole (fig. 50.5). Apparently the borehole provides an easy escape route for steam, causing an increase in the concentration of salt and possibly the development of clay minerals in the surrounding rock owing to hydrothermal alteration, thereby reducing its bulk resistivity. Another change from the earlier log is an increase in the depth to the lower conductive zone of about 3–4 m during the elapsed 4-month time period. This change is well in excess of the 2.11-m annual solidification rate calculated by Hardee (1980). Possibly the borehole allowed an anomalous quantity of heat to escape, thereby creating a localized deepening of the 100 °C isotherm. In the December 1976 resistivity log (fig. 50.4) the hot, dry zone overlying the molten lava was highly resistive at the depth to which measurement was possible. The April 1977 log (fig. 50.5) indicates this zone to be somewhat less resistive with lower resistivities appearing at greater depth. However, the April log shows an inconsistency in the resistivity correspondence between the 1- and 2-m measurements in the 37- to 39.5-m depth interval. A breakdown in cable insulation may have occurred in the extremely high temperature environment, causing leakage that would produce erroneous resistivity values. Upon removal from the borehole, the probe was checked and found to be intact; however, the probe had cooled considerably once on the surface, so any problem with cable faults relating to thermal expansion may have gone undetected. As with the welding rod, the stainless steel electrodes lost their resilience, making continued contact with the borehole walls impossible. If the contact resistance was high because of the deteriorating condition of the potential electrodes, the measurement may have produced an anomalously low resistivity. Pockets of molten lava could conceivably exist in sufficient quantities in the near-hole environment to produce the low resistivities observed in the dry zone. If the molten lava is nonuniformly distributed, then the bulk

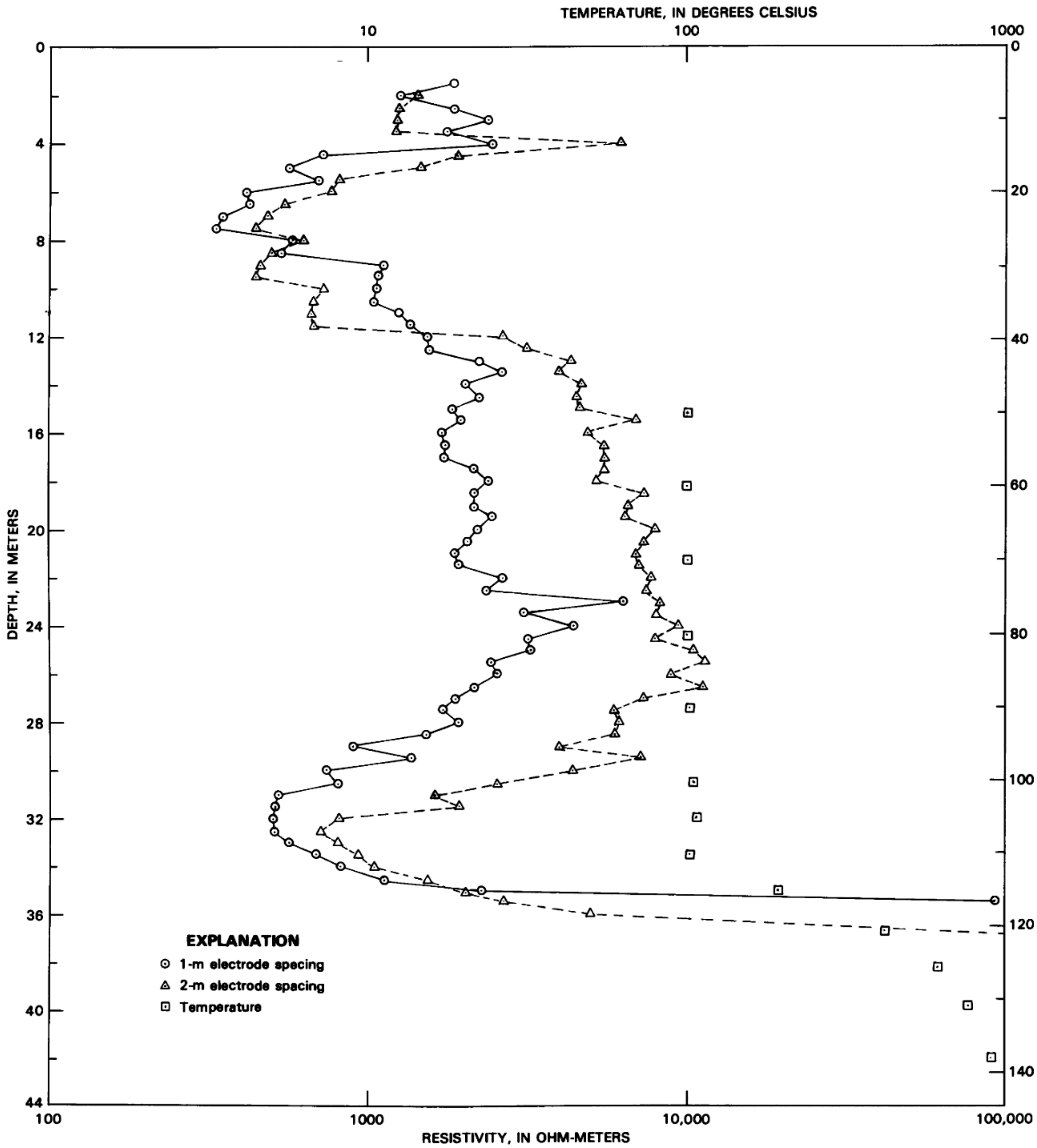

FIGURE 50.4.—Direct-current resistivity and temperature data obtained in Kilauea Iki borehole 76-2 in December 1976.

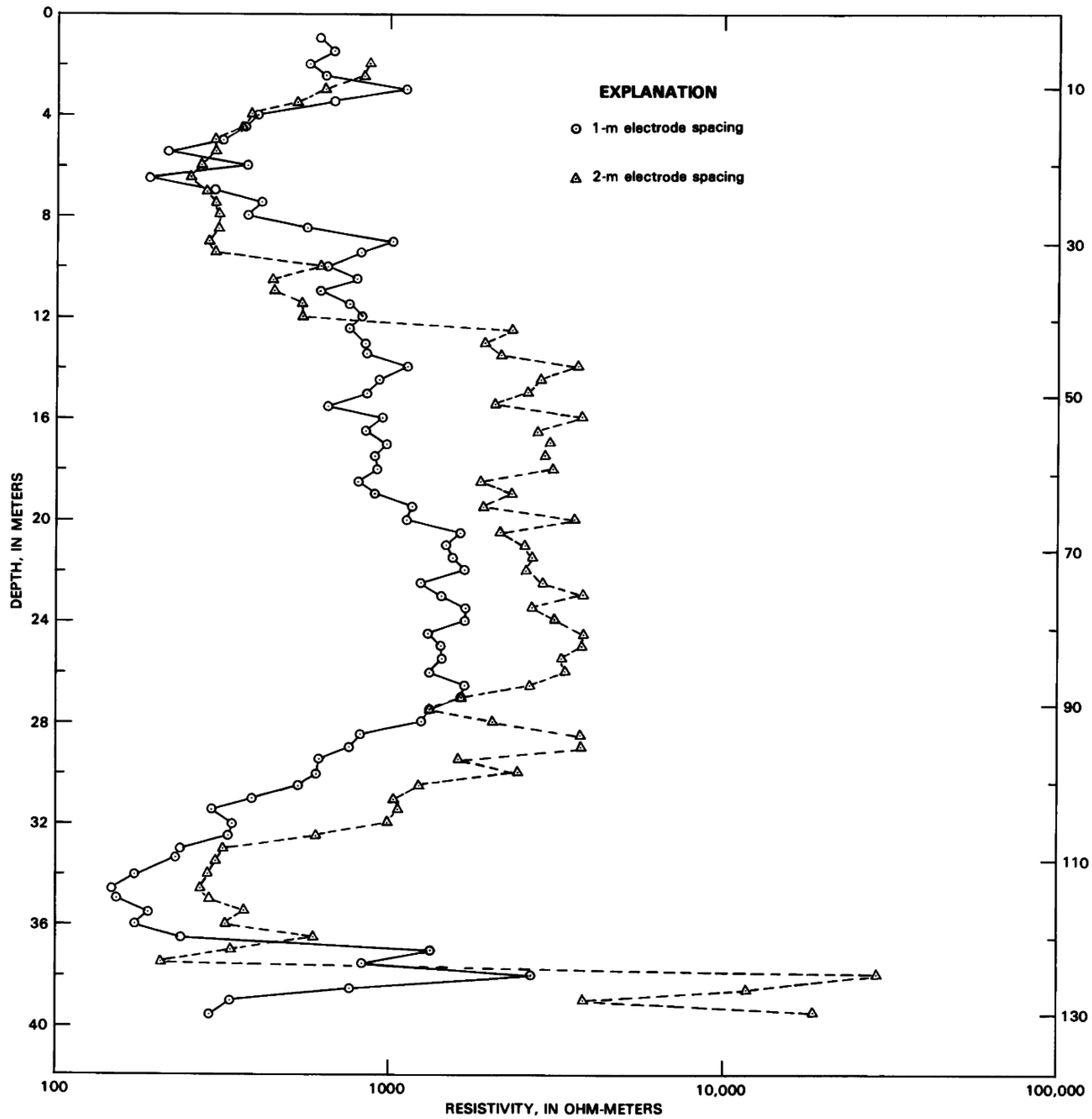

FIGURE 50.5.—Direct-current resistivity data obtained in Kilauea Iki borehole 76-2 in April 1977.

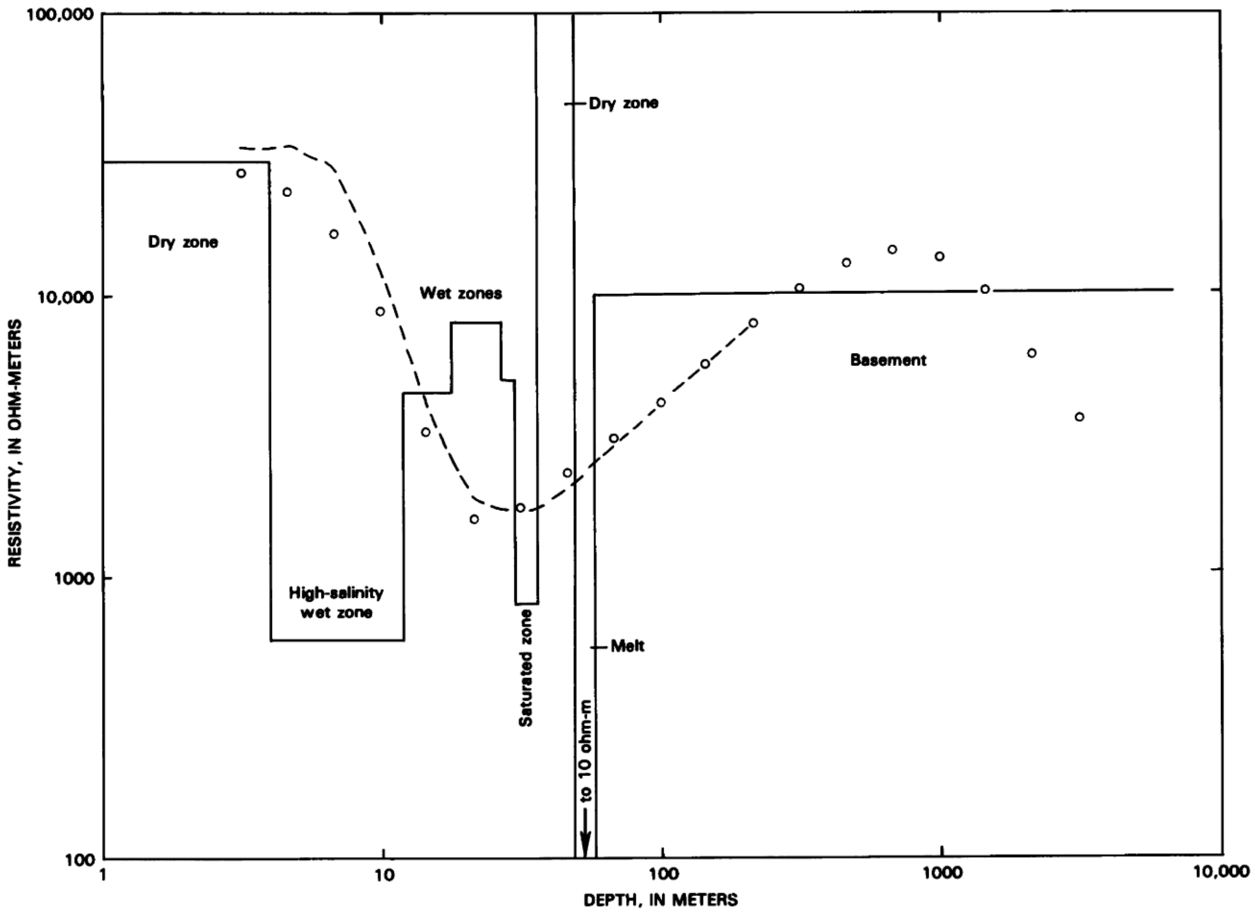

FIGURE 50.6.—Geoelectric section compiled from December 1976 borehole resistivity log obtained at 2-m spacing. Thickness of 100,000 ohm-m section and resistivity of molten lava is inferred from other data. Dashed line, adjusted field curve for north-south resistivity sounding; circles, Schlumberger resistivity values.

resistivity, which is a volume measurement, will differ as a function of electrode spacing. However, intuition suggests that the molten lava would exist in greater abundance with increasing distance from the borehole. The data do not support this notion inasmuch as the resistivities are appreciably higher at the 2-m spacing. A third explanation for the low resistivities near the bottom of the hole may be that the basalt is at a high enough temperature to become ionically conductive. If this were the case the resistivities measured at both electrode spacings would vary in a systematic and uniform manner. Despite the arguments that can be made in support of the validity of the data, the uncertainties are sufficient to judge the resistivity measurements below the 37-m depth to be questionable.

In considering the overall decrease in resistivity of the rock in near proximity to the borehole during the 4-month period between December 1976 and April 1977, it seems likely that the December log may not necessarily be typical of the resistivities of the rock at the time of drilling. As a check on how critical local alteration may have been, a theoretical Schlumberger curve was computed based on layer resistivities and thicknesses derived from the December 1976 2-m log. Because the first resistivity measurement was made at a depth of 2 m, the dry, uppermost part of the surface layer is not represented on the downhole log. Instead, a value of 30,000 ohm-m was selected for the upper 4-m layer.

The computed curve superimposed upon the north-south sounding and the columnar graph showing resistivities and thicknesses selected from the borehole data are shown in figure 50.6. Despite the generalizations made in constructing the model, the fit to the field curve is considered to be satisfactory. To a spacing of 213 m, which is the largest spacing used in the field measurement on the north-south sounding, nine resistivity layers are represented, but from the shape of the sounding curve recognizing more than three is difficult. The existence of the water-bearing conductive zone is obscured by the presence of the underlying hot, dry section arbitrarily assigned a resistivity value of 100,000 ohm-m.

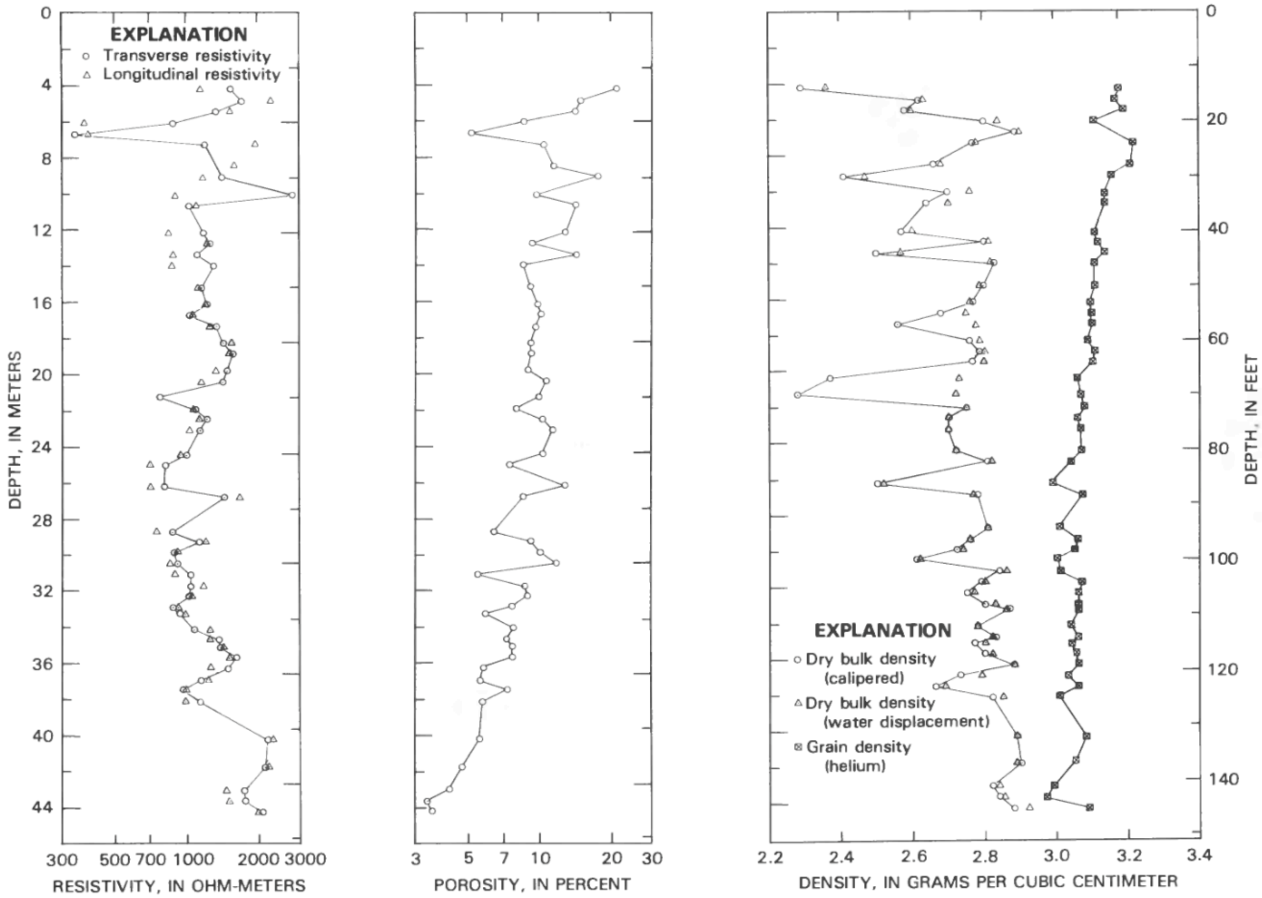

FIGURE 50.7.—Resistivity, porosity, and density values obtained on core samples from Kilauea Iki borehole 76-2.

To determine the half-spacing required to sense on the conductive magma beneath the dry zone the plot was continued by setting constraints on the thicknesses of the layers at depth. According to Hardee (1980) the hot, dry zone has, in recent years, maintained a constant thickness of 12 m. Beyond that knowledge, only estimates can be made of the parameters involving the resistivity and thickness of the molten lava. An indirect measurement of the melt resistivity was made in 1961 (Frischknecht, 1967) and, through curve matching, determined to be precisely 2.09 ohm-m. However, the molten lava was in the early stages of cooling, and subsequent degassing of the lava may have resulted in an increased resistivity requiring that a minimum resistivity of 10 ohm-m be used in order to match the north-south sounding curve. The thickness of the molten section was chosen to be 10 m, underlain by an infinitely thick section of 10,000 ohm-m resistivity. It is apparent from figure 50.6 that a Schlumberger half-spacing in excess of 400 m would be required before the effect of the molten lava becomes evident, and a half-spacing of about 1,000 m is necessary before an actual downturn in apparent resistivity is noted.

LABORATORY CORE ANALYSIS

To evaluate the causes of the resistivity variations observed in the borehole measurements, 51 core samples were obtained from the 4.27- to 44.21-m depth interval of the 76-2 borehole for laboratory rock-property analysis. Core samples were selected at spacings of 0.61 m, where available, and shaped to an approximate size of 3.33 cm diameter and 3.8 cm length. Samples oriented axially parallel (vertical) to the borehole were used for resistivity, density, and porosity measurements, whereas core samples oriented axially perpendicular (horizontal) to the borehole were only measured for resistivity. Sample resistivities were measured in a four-terminal holder (Parkhomenko, 1967) following core saturation with local tap water. Resistance measurements, made at a frequency of 100 Hz using a high-precision digital resistance meter, were converted to resistivity (in units of ohm-m) from caliper measurements of sample length and diameter.

Procedures for obtaining density and porosity data are those described by Johnson (1979a). Samples in the saturated state were weighed both in air and suspended in water and reweighed when totally dry. Rock volume was obtained using a water displacement technique discussed in Chleborad and others (1975). From the collective data, dry bulk density, saturated bulk density, and porosity were calculated. A helium pycnometer was used to determine grain density. All measured rock-property values are plotted as a function of depth in figure 50.7.

Resistivities were measured on mutually perpendicular cores cut from the same sample to examine the effect of vesicle alignment on current flow through the sample. Normally, a lava block would be expected to possess uniform electrical properties in that no distinct bedding planes are formed in the cooling process. Examination of the core samples, however, often revealed a distinct alignment of gas bubbles, particularly in the horizontal plane. Should hydrated minerals form within these vesicles their physical continuity would certainly cause an appreciably lower resistivity in one direction than in the other. In virtually all rock types, the transverse resistivity exceeds that of the longitudinal resistivity such that the anisotropy coefficient, defined as the square root of the ratio of transverse to longitudinal resistivity, is greater than 1.0 (Keller and Frischknecht, 1966). With few exceptions, the anisotropy coefficient of the Kilauea Iki basalts is very nearly equal to 1.0, and where it is slightly less than 1.0, the discrepancy may be caused by the fact that the material measured in each sample pair is not quite the same. The plot in figure 50.7 shows the transverse resistivity to be generally greater or equal to the longitudinal resistivity, although obvious exceptions do exist, particularly within the upper conductive zone as defined by the borehole resistivity log.

The environmental conditions in which the borehole and sample measurements were made are obviously so different that the character of the sample resistivity log is totally unlike that of the borehole resistivity logs. The most notable change on the sample plot is in the virtual loss of the conductive zones defined in the borehole log. Dissimilarities in measuring conditions involving factors such as temperature, pore-water levels, and water salinity are considered to be the principal cause of the resistivity differences. Samples from the 6.1- and 6.7-m depths are exceptions producing resistivities equal to those measured in the borehole.

It was anticipated that much of the contained thenardite, identified by Helz and others (1980), would be leached from the rock following the resaturation process. The sample measurements would then be expected to produce resistivities that vary as a function of porosity and mineral content. Grain densities vary only slightly, suggesting a relatively uniform mineral content. Grain densities, however, decrease with depth as a result of higher olivine and pyroxene contents in the upper part of the lava crust. According to Johnson (1979b), high density minerals having high separation temperatures are trapped in the rapidly cooling groundmass, whereas, at depth, where cooling has progressed at a much lower rate, the heavy minerals have had time to settle to the lower levels of the molten lava pool. The grain density values in figure 50.7 indicate the transition to be gradual. Large phenocrysts of olivine can be found in the near-surface lavas, but no evidence of olivine exists in the core taken from the lower lava section. The variation of the heavy mineral content of the basalt, however, would do little to alter the resistivity in the manner shown in figure 50.7.

In the absence of conductive minerals as part of the rock composition, the resistivity of a rock is controlled by porosity, the amount of water within the pore structure, and the salinity of the contained water as predicted by Archie's equation, assuming that electrical conduction is by means of the contained pore waters (Keller and Frischknecht, 1966). An attempt to statistically relate the observed resistivities of the core samples to porosity proved unsuccessful; a least-squares fit to a logarithmic model produced a correlation coefficient of -0.17, indicating that other factors also influence the resistivity of the rock.

In an experiment on a Kilauea Iki basalt sample by Olhoeft (1977), a resistivity dependence apart from volume conductance through the pore water was recognized. For resistivity enhancement to occur, alteration products, either in the form of clays or zeolites, must exist within the pore spaces of the rock. Evidence of sparse mineral content was detected within the few vesicles exposed at the surface of the 6.7-m sample. On the premise that the mineral was other than thenardite, a scanning electron micrograph (SEM) was obtained of the mineral (fig. 50.8). That figure shows the wall of the vesicle and tabular crystals of what is thought to be a zeolite. An energy-dispersive X-ray analysis, focusing on the large crystal in the upper left-hand corner of figure 50.8, indicates the mineral to be an aluminosilicate, possibly clinoptilolite or phillipsite based on comparisons of the morphology of zeolite crystals presented in Mumpton and Ormsby (1978).

Further examination of the mineral content of the vesicle revealed what is believed to be clay (montmorillonite?) coating the suspected zeolite (fig. 50.9). The quantity of vug-filling minerals

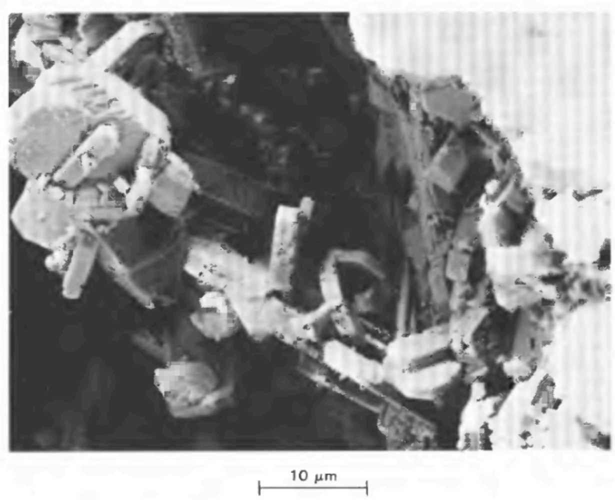

FIGURE 50.8.—Scanning electron micrograph of suspected zeolite mineral found within vesicle of basalt sample from 6.7-m depth of Kilauea Iki lava lake crust.

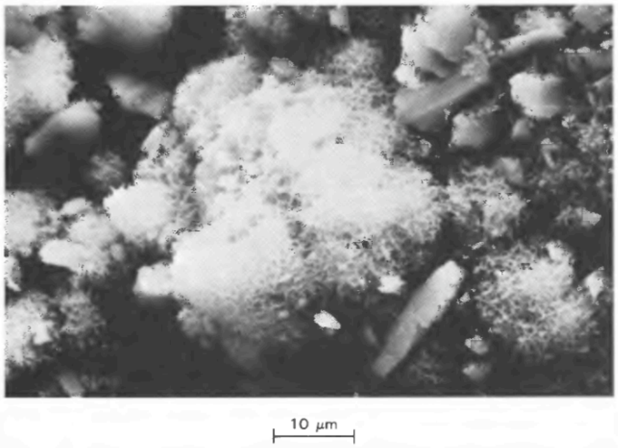

FIGURE 50.9.—Scanning electron micrograph of clay coating on suspected zeolite minerals found within vesicle of basalt sample from 6.7-m depth of Kilauea Iki lava lake crust.

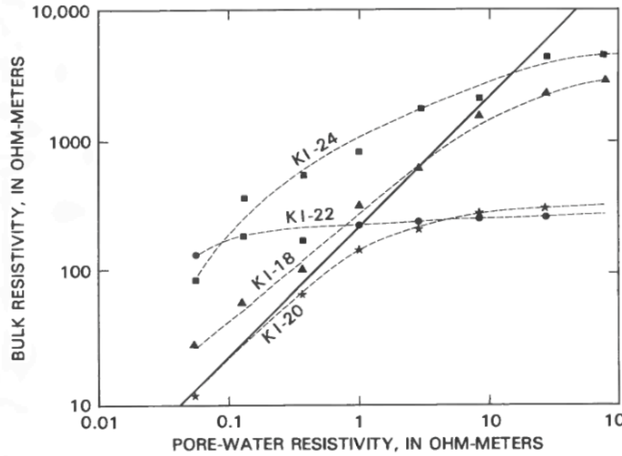

FIGURE 50.11.—Bulk resistivity variation with increasing pore-water resistivity in basalt samples KI-18, KI-20, KI-22, and KI-24, taken from Kilauea Iki lava lake crust at depths of 5.5, 6.1, 6.7, and 7.3 m, respectively. Heavy black line is plot of increasing resistivity as a function of decreasing pore-water conductivity based on Archie's equation.

was, however, insufficient to obtain a positive identification by means of X-ray diffraction.

An SEM of vug-filling minerals, found within the rock covering the surface of the lava lake, is shown in figure 50.10. Although the mineral quantity was adequate for X-ray analysis, the material proved to be an amorphorous mass containing principally silica,

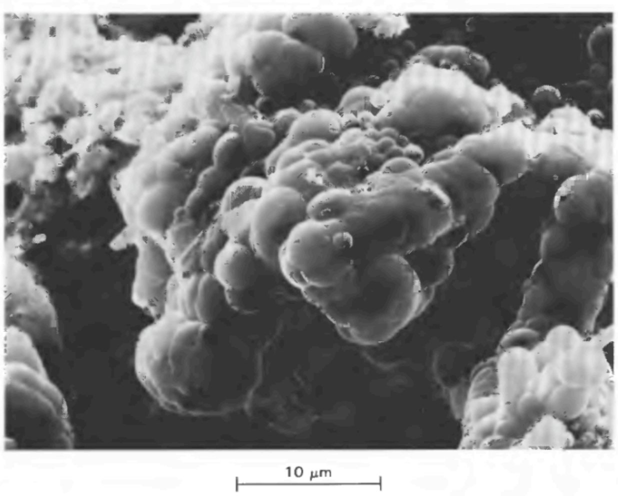

FIGURE 50.10.—Scanning electron micrograph of amorphous mass of silicon, aluminum, and potassium found within vesicles of surface sample of Kilauea Iki basalt. Lining of cavity was determined to be opal (R. Sheppard, oral commun., 1984).

aluminum, and potassium. The mineral lining the vug was determined to be opal (R. Sheppard, oral commun., 1984).

Clays, zeolites, and opal are hydrated minerals and, as such, are capable, by means of surface conduction, of altering the resistivity of the basalt if the minerals exist in sufficient quantities to provide a continuous flow path for electrical current. Surface conduction occurs in certain minerals as the result of an excess ion population within the diffuse layer located on the outer bounds of the electrolyte-solid interface (Keller and Frischknecht, 1966). A thenardite coating on the pore walls of the rock undoubtedly exerts the greatest influence on the in-place resistivity. To determine the extent to which the hydrated minerals contribute to total conduction, resistivities were measured on four samples after progressive saturation with eight KCl solutions of increasing salinity. The core samples are from the 5.49- to 7.32-m depth interval but are labeled in figure 50.11 in units of feet. Figure 50.11 shows the results plotted against increasing pore-water resistivity. Samples KI-20 and KI-22 have similar resistivities when saturated with high-resistivity pore water. As the pore-water resistivity is increased, the resultant decrease in bulk resistivity of the KI-20 sample is dramatic when compared to the relatively small change in the bulk resistivity of the KI-22 sample. The difference in the character of the two resistivity curves is believed to be the result of incomplete invasion of the sequential introduction of the increasingly saline pore water because of the much lower porosity of the KI-22 sample.

The straight line drawn asymptotic to the left hand segment of the curve labeled KI-20 on figure 50.11 is a graph of rock resistivity calculated from Archie's equation using measured values of pore-water resistivity and rock porosity (Keller and Frischknecht, 1966). The departure of the rock resistivity curve from the Archie plot indicates that current flow occurs within the structure of the hydrated minerals lining the vesicles of the rock as well as through the saturating solution. Although not shown, each sample has an equivalent Archie curve that can be drawn as straight-line projections, illustrating the relative importance of surface conduction in controlling the resistivity of each sample. Surface conduction is most apparent at the higher pore-water resistivities.

Samples KI-20 and KI-22 indicate resistivities most influenced by surface conduction as compared to the bordering samples from the 18- and 24-ft levels. Apparently the conditions for zeolite and clay development are most ideal within a very narrow horizon at the indicated depth interval of the lava crust. From the poor correlation between resistivity and porosity, however, some degree of surface conduction evidently takes place within most samples. Another reason for the lack of correlation is that the original salt content may not have been totally leached from the samples during the resaturation process, thereby causing resistivity variations as a function of differences in pore-water salinity.

SUMMARY

The geoelectric sections interpreted from Schlumberger soundings made at the center of the lava lake are basically the same, differing only in the thickness of the conductive zone and the value of the bottom-layer resistivity. The difference in the shape of the sounding curves results from lateral resistivity variations whose complexities have not been resolved. Each sounding, however, clearly indicates the presence of a conductive zone at a depth of about 7 m with a thickness of at least 3 m. No evidence of a highly conductive zone at depth representing either the water lens or the molten lava can be seen in the sounding data.

The resistivity logs obtained in the 76-2 borehole verify the existence of a conductive layer within the 4- to 12-m depth interval. In addition, an equally conductive layer was detected below the 28-m depth in a zone overlying the very hot, but dry, layer covering the molten lava at the 45.7-m depth as determined from drilling. The 28- to 35-m depth conductive zone is believed to correspond to a gas-charged hot-water lens that increases gradually in resistivity with decreasing depth as the water vapor/liquid ratios increase. In the central zone the pore spaces of the rock are thought to be filled with wet steam containing ionized molecular particles dissolved from magmatic gases mixing with meteoric waters in the lower conductive zone. Temperatures fall slightly below 100 °C in the upper zone and, coupled with possible pressure release, conditions may be ideally suited for the formation of condensation products within the cavities and pore structure of the rock. Even in substantially undersaturated rock, a wet salt coating, such as made possible by the confirmed presence of thenardite within the lake crust, is sufficient to produce an appreciable decrease in rock resistivity.

The borehole-resistivity log was repeated in April 1977. The notable changes occurring in the 4-month intervening period are the overall decrease in resistivities for the entire penetrated section and a substantial increase in the depth to the lower conductive layer identified as a zone containing hot water. According to Hardee (1980) the established rate of cooling now in progress adds 2.11 m/yr to the thickness of the crust; however, according to the resistivity log, the crust had increased almost 4 m in only a 4-month period. Possibly the two boreholes at this site allow for an anomalously high rate of heat energy release, thereby accelerating crustal development.

It is uncertain as to why the overall resistivity of the rock surrounding the borehole has decreased. The resistivity decrease, however, is believed to be related to the upward migration of the steam phase of meteoric water following a preferential path made possible by the two adjacent drillholes. Perhaps the escaping steam has produced a conductive lining on the borehole walls as a result of alteration in the form of clays and zeolites, thereby causing a decrease in the apparent bulk resistivity measured for the surrounding rock. Based on the fact that thenardite is easily recognized within the cored section, it seems more likely that concentrations of the sodium sulfate salt have been deposited within the vesicles of the basalt in near proximity of the borehole, well in excess of that which is normally formed in the rock, thereby enhancing its conductivity.

Although a borehole may alter the electrical character of the rock in the immediate vicinity of the hole, the geoelectric layering is considered to be representative of that which persists laterally within the lake crust. The fact that the December in-hole resistivity log made at the 2-m spacing could be converted to a sounding curve very similar to that measured at a site 61 m displaced from the borehole provides evidence of the continuity of the geoelectric layering. Some variation in the resistivity of the upper conductive zone may occur as rainfall increases and a certain amount of leaching takes place. However, the salt would be expected to ultimately be redeposited in the 4- to 12-m depth interval where temperature and pressure favor concentration of salts carried upward in the liquid-vapor water system.

Rock-resistivity measurements on core obtained from the 76-2 borehole produce a substantially different pattern from that observed on the in-hole resistivity logs. This difference is not surprising considering the dissimilar environments in which each set of data was taken. However, it was hoped that a sufficient quantity of salt would be retained within the samples in order to verify introduced salt as the principal cause of the anomalously low resistivity measured in the 4- to 12-m depth interval. Apparently the high porosity of most samples allowed the salt to leach out during the resaturation process. The sample from the 6.71-m depth is an exception inasmuch as its laboratory resistivity is very nearly the same as that measured in the drillhole during December 1976 at the 1-m spacing. A scanning electron micrograph of the mineral content within a single vesicle of the 6.71-m sample shows evidence of both zeolite and clay development. Resistivity measurements on samples from the 5.49-, 6.10-, 5.71-, and 7.32-m depths, made while saturated with KCl solutions of increasing salinity, show the effects of surface conduction, apparently as a result of the alteration products lining the pore spaces and vesicles of the samples. Surface conduction is most apparent in the 6.10- and 6.71-m samples, indicating that clays and zeolites are most abundant within a very narrow horizontal interval of the lava crust.

A pictorial representation of the geoelectric layering of the Kilauea Iki lava lake to a depth including the molten lava as it existed

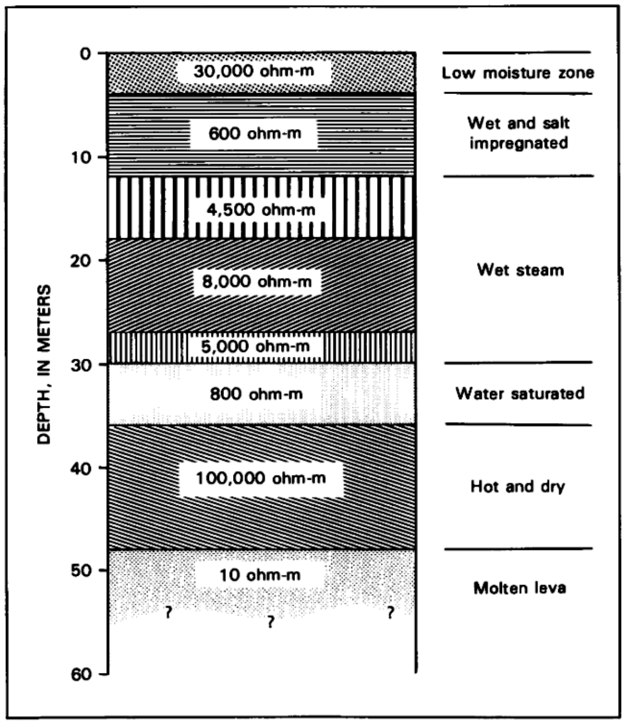

FIGURE 50.12.—Geoelectric layering of Kilauea Iki lava lake crust as determined from December 1976 borehole resistivity log made at 2-m electrode spacing.

in 1977 is shown in figure 50.12. An appreciable thickening of the crust has occurred since that time, most likely adding to the growth of the intermediate zone between the conductive crustal layers and reducing the thickness of the molten lava. From an exploration standpoint the resistivity of both conductive layers within the upper crust is sufficiently low, relative to the surrounding rock, to generate a substantial electromagnetic anomaly. However, if a 600 ohm-m resistivity value is assumed for the entire section overlying the molten lava, at very low frequencies on the order of 20 kHz, the penetrating depth of the primary signal would be more than adequate to sense on the melt. The fact that the resistivity contrast between the solidified and molten lava is at least 60:1 and typically much higher assures that the secondary fields generated by induced eddy currents stem primarily from the molten basalt layer.

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