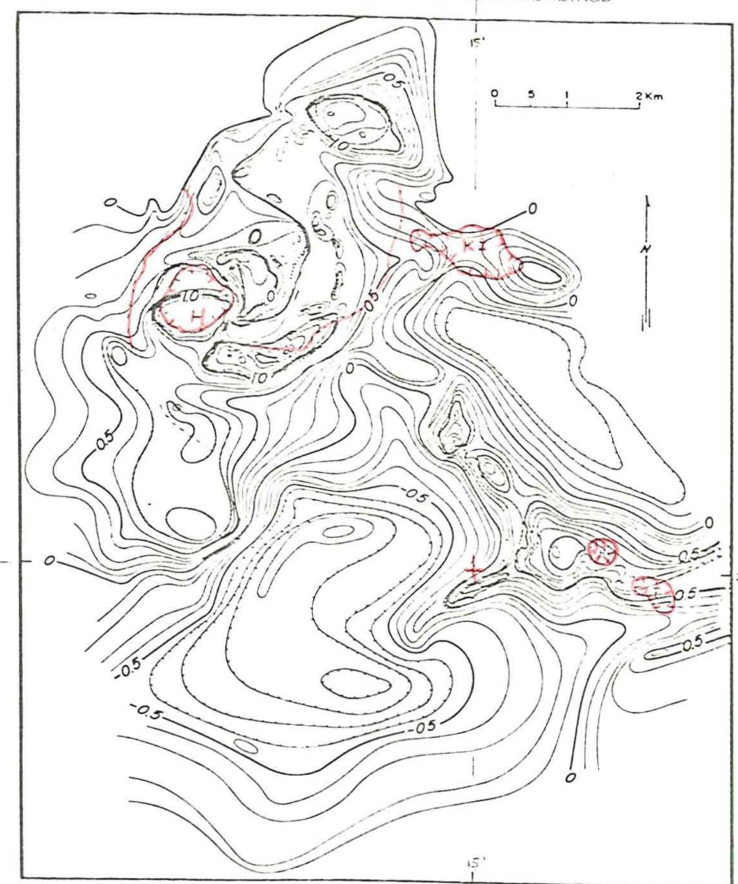

Figure 2. Contour map of the self-potential distribution over the surface of the same area shown in index map (Fig. 1). Contour interval is 0.1 V; values and polarities are arbitrarily referenced to zero contours shown, hachures indicate closed lows; shaded areas are the same as shown in Figure 1.

Previous Applications of the Method

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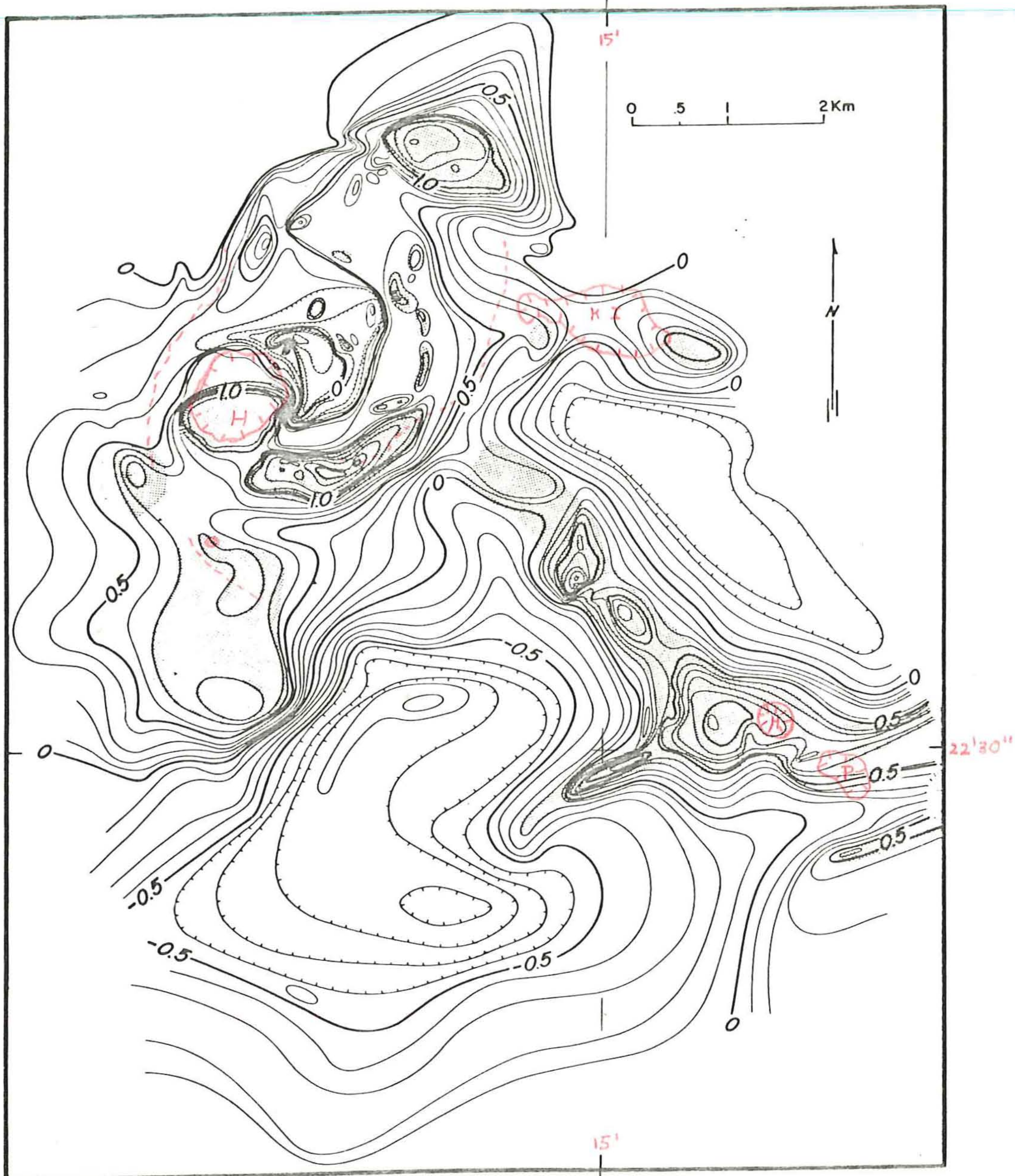

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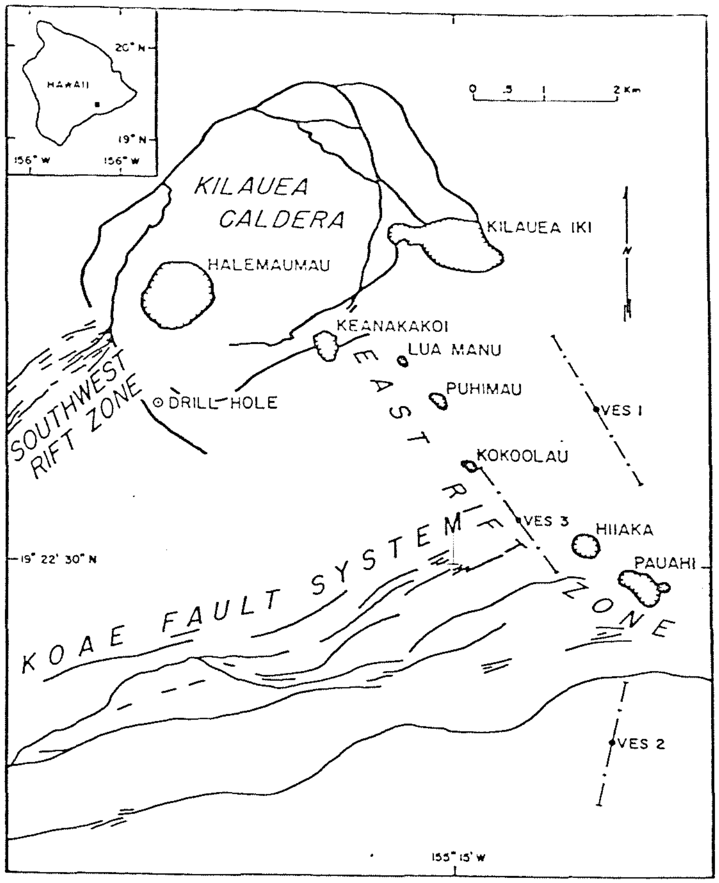


Figure 1. Index map showing the major structural features of Kilauea Volcano in the area studied. Shaded areas approximately delimit the self-potential anomalies shown in Figure 2; location and extent of three vertical electric soundings (VES) indicated by dash-dot lines; location of the 1262-m-deep drill hole (Zablocki et al., 1974) indicated by dotted circle.

Geologic Setting

Kilauea, a broad shield volcano located on the southeastern part of the island of Hawaii (Fig. 1), largely consists of a series of thin, tholeiitic basaltic flows. At its summit is a large caldera, approximately 5 km long and 3 km wide, from which rift zones extend southwestward and eastward to the ocean. Eruptions have taken place primarily in the summit area and along these rift zones, which are marked by linear fissures, pit craters, and cinder cones. Unlike the fairly straight alignment of the southwest rift zone, the upper east rift zone trends southeast from the caldera for about 5 km to intersect the east end of the Koae fault system; it then bends sharply in an east-northeast direction and can be traced offshore for about 60 km beyond the easternmost tip of the island (Moore, 1971). The Koae fault system (Duffield, 1975), is a major structural feature, whose west end merges with the southwest rift zone about 10 km southwest of the caldera.

Ground-deformation and seismic data have strongly suggested that the magma that feeds the many eruptions at the summit and its two rift zones are supplied from a shallow (3 to 4 km) reservoir complex beneath Kilauea Caldera (Eaton, 1962; Fiske and Kinoshita, 1969). This reservoir in turn is thought to be supplied by magma generated at a depth of 40 km or more in the upper mantle. Similar types of evidence further suggest that flank eruptions, particularly along the east rift in recent years, are fed from the summit reservoir via a well-established shallow lateral conduit.

Mapping Thermal Anomalies on an Active Volcano by the Self-Potential Method, Kilauea, Hawaii

CHARLES J. ZABLOCKI

U.S. Geological Survey, Hawaiian Volcano Observatory, Hawaii National Park, Hawaii 96718, USA

ABSTRACT

Surface measurement of self-potential (SP) on Kilauea Volcano appears to be the single most useful geophysical method for identifying and delineating thermal anomalies related to concealed magma reservoirs and still-hot intrusive zones. Positive potentials, as high as 1600 mV across lateral distances of a kilometer or less, are developed not only over known fumarolic areas and recent eruptive fissures but also in areas that have no surface thermal manifestations. The SP method excels because of: (1) the higher surface resolution of the causative heat sources, (2) the smooth distribution of the measured potentials (that is, insignificant short-wavelength "noise" potentials); and (3) the simplicity and relative speed of measurement.

Evidence supporting an electrokinetic origin for the large anomalies is that:

1. Top-of-source-depth determinations of the S.P. anomalies are shallow, coinciding with local water tables (<500 m), and may result from the horizontal divergence of the cooling, convective water rising above the deeper heat sources;
2. Lateral boundaries of an S.P. anomaly above a suspected magma reservoir coincide with the epicentral distribution of earthquakes at depths of 2 to 3 km and can be explained by collimation of the hydrothermal fluids by vertical gravitational forces.
3. All anomalies have a positive polarity over known or inferred hot zones, suggesting preferential adsorption of anions or other means of effecting the differential displacement of cations from anions.
4. Small negative potentials associated with some anomalies are thought to reflect the descent of cooler waters in the convective system.

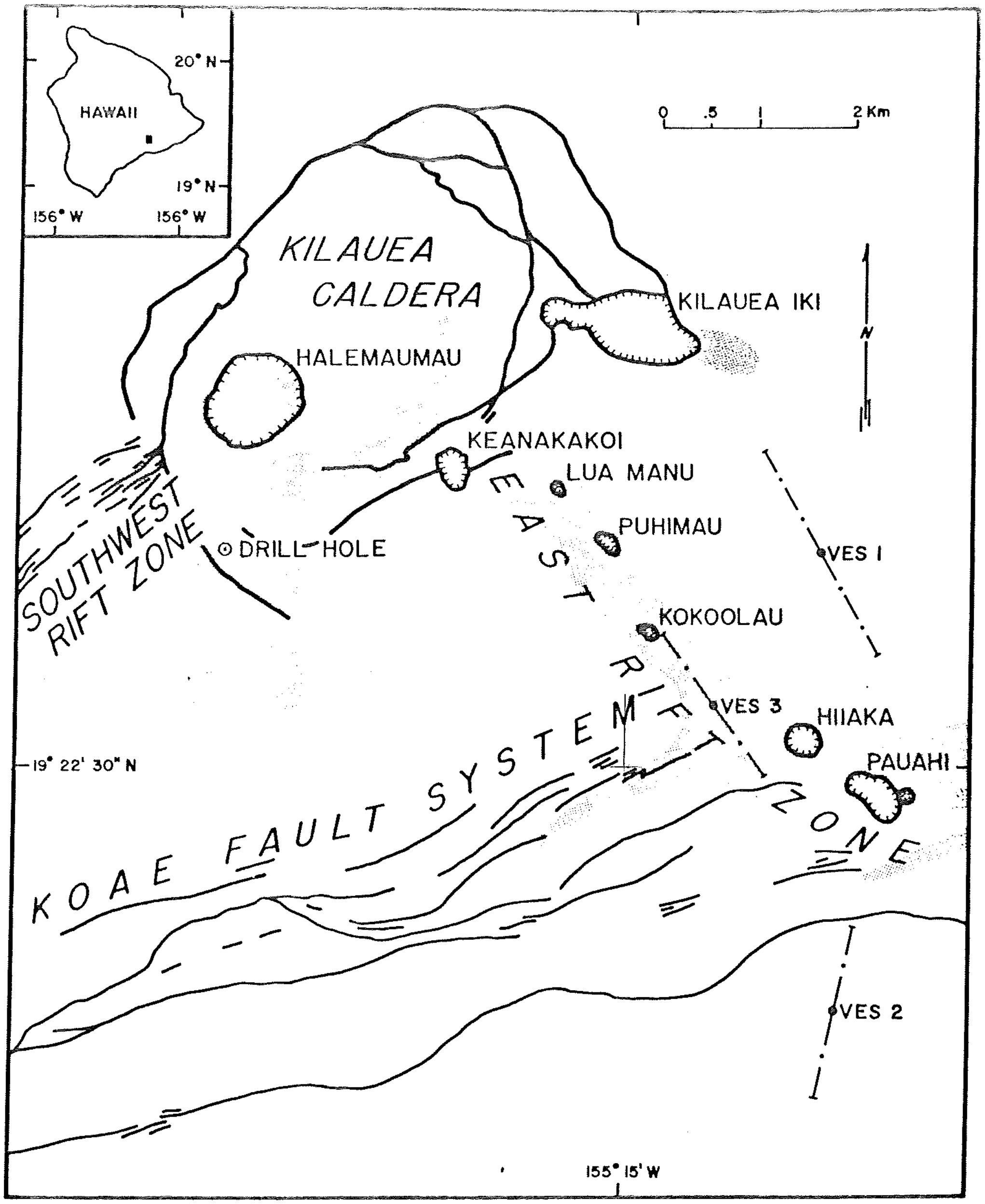
The SP technique is not only a powerful tool for mapping hot areas on an active volcano but also may provide insight into the dynamic workings of geothermal systems.

INTRODUCTION

In recent years, the U.S. Geological Survey has been developing an electrical-magnetic (E-M) geophysical program at the Hawaiian Volcano Observatory to assess the applicability of various E-M methods as effective and practical tools in studying Kilauea Volcano. The nature of Kilauea, a shield volcano, makes it particularly suited to many types of geophysical studies because: (1) it has a relatively simple geologic structure; (2) it is composed exclusively of tholeiitic basalts grossly uniform in composition; and (3) it is in a dynamic state, having erupted, for example, at six different locations from 1972 through 1974. Moreover, because Kilauean eruptions are frequent and nonviolent, many scientific studies have been carried out over the years, making Kilauea perhaps the most intensively studied volcano in the world.

Previous electrical studies of Kilauea have demonstrated the utility of electromagnetic, mutal-impedance measurements for determining the depth to, and the electrical conductivity of, ionically conductive molten magma at shallow depths in ponded lava lakes (Frischknecht, 1967, p. 18; Anderson, Jackson, and Frischknecht, 1971) and in delineating shallow active lava tubes using a VLF radio-wave technique (Anderson, Jackson, and Frischknecht, 1971). Deeper-penetrating (using large transmitter-receiver spacings) galvanic and induction methods also have been used to define the geoelectric section to depths greater than 1 km in some areas of Kilauea (for example, see Keller and Rapolla, 1974). Results from some of these studies showed that conductive zones exist at relatively shallow depths (<1 km) which are thought to be caused by the influence of hot mineralized waters above deeper hot intrusions.

These previous studies provided a firm base from which to further pursue E-M investigations. Early in the investigative program, an attempt was made to determine whether detectable differences in surface spontaneous potential (SP) coincided with known fumarolic areas. This objective was prompted by the desire to test methods that had not been previously applied and also by the observation that large steady-state potential differences existed across grounded electrodes in a telluric current monitoring study made in 1964 (Keller and Frischknecht, 1966, p. 206). It quickly became apparent that there were not only obvious correlations between self-potential anomalies and thermal areas, but also that the anomaly magnitudes were exceptionally large. These initial findings encouraged additional studies over the past two years. We now have mapped most of the summit region of Kilauea and parts of its two rift zones, a total area encompassing approximately 100 km^2. The results of these studies unequivocably demonstrate that the SP method is the single most effective geophysical method for delineating thermal areas on Kilauea Volcano and that it provides valuable insight into the dynamic eruptive aspects of this very active volcano.



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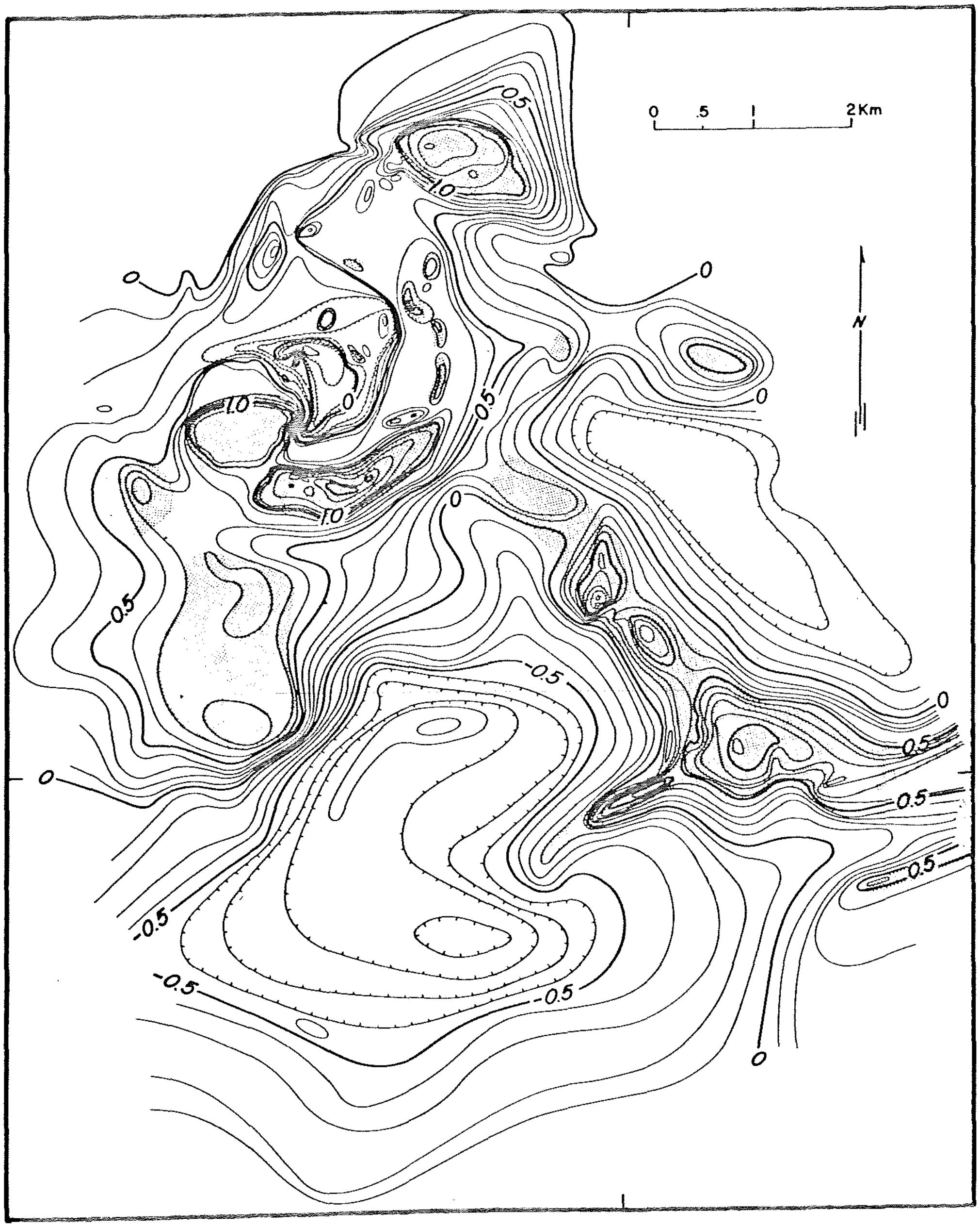

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As an exploration tool in geothermal areas, only a few results from self-potential surveys have been reported. White, Thompson, and Sandberg, (1964) measured some small-amplitude, irregular anomalies, both positive and negative in polarity, that could not be correlated with known geologic features in their studies of the Steamboat Springs thermal area of Nevada. Banwell (1970) suggested that SP studies may be useful as a survey technique in locating and delineating thermal areas on the basis of his recognition of anomalously high background potentials while making resistivity surveys in thermal areas. Similarly, Corwin (1973) recorded some self-potentials that were above background noise near Punta Banda, Mexico, that appeared to correlate with nearby hot-spring activity. Studies in the Otake geothermal area of Japan (Onodera, 1974) appear to be nondiagnostic because the resulting small-amplitude anomalies of both polarities were concluded to be caused by oxidation-reduction, electrofiltration, or topographic effects. The best correlation between SP and a known geothermal area reported to date is that determined within Yellowstone National Park by Zohdy, Anderson, and Muffler, (1973). Although only one SP profile was made, a small positive anomaly appeared to delimit the edges of the geothermal field better than resistivity and induced polarization profiles. The largest potentials observed in all these cited examples are typically less than 50 mV in amplitude. Recently, Anderson and Johnson (1973) reported a broad dipolar anomaly of about 900 mV peak-to-peak in magnitude near the area of Caso Diablo hot springs, Long Valley, California, and even larger SP gradients near the perimeter of the caldera. They attributed these anomalies to a streaming potential generated by the movement of heated ground waters and suggested that the lack of good correlation with other types of electrical surveys made in this area may have been due to a thermal zone too deep to have been detected by other methods.

MEASUREMENT EQUIPMENT AND TECHNIQUES

The basic equipment for measuring surface self-potentials consists of a pair of nonpolarizing electrodes, an insulated connecting single-conductor cable, and a high-impedance voltmeter. In our studies, we designed a voltmeter incorporating an extremely high input impedance electrometer amplifier (10^{14} ohms) whose input bias current was only 10^{-14} A. This latter specification is important in selecting an amplifier because large bias currents can cause errors in potential measurements when source impedances are large, and can also upset the electrochemical stability of the electrodes. The output of the amplifier is connected to a 3 ½ -digit bipolar digital panel meter for ease in reading the potentials. The meter, attached to the observer's belt, is compact, lightweight (<1 kg), and easy to use. Conventional copper-copper sulfate porous pots were used in most of our studies, although small, lightweight silver-silver chloride electrodes, contained in a special polymeric conductive body and attached to one end of a meter-long, insulated rod, have also proved to be very stable and rugged. Electrical contact to the ground was adequate in areas covered by tephra, where sufficient moisture is always found a few centimeters below the surface. Even on recent lava flows, reliable measurements were made by placing a moist sponge between the electrode and the ground surface. A stable reading is usually obtained in about 5 sec. We never had to apply water to the ground surface to obtain electrical contact. We believe that such a procedure could lead to errors caused by setting up undesirable diffusion potentials; moreover, the application of water prolongs the time for the potentials to stabilize.

Various schemes have been devised for making self-potential surveys. Some traverses are laid out in a closed polygon, so that any closure errors can be determined and distributed (typically less than 25 mV) when 100-m-long potential gradients are measured. Here, care is taken to occupy the exact location of the lead man's electrode as these data must be progressively added algebraically to obtain the potential distribution along the entire traverse. This procedure is rapid, and the two-man operation can cover over 3 km in an hour in nonwooded areas.

In areas where a closed traverse is not practical, or where a higher density of measurements is desired, one electrode remains fixed and the moving electrode is advanced in 100-m or smaller increments that are marked on a calibrated cable. The cabled reel is then either carried on foot or by vehicle along the traverse or remains with the fixed electrode. This technique diminishes the possibility of gross errors in measurement because the reference electrode is not moved along the traverse. When the cable has been fully extended along a traverse, the advance electrode is undisturbed and the former stationary electrode now becomes the moving electrode for the subsequent extension of the traverse. This procedure completely eliminates any errors caused by possible differences in electrode potential or by any sharp, local gradients in the vicinity of the electrodes.

RESULTS

In compiling the contour map (Fig. 2) showing the distribution of the spontaneous potential at the surface of Kilauea's summit region and the upper parts of its rift zones, the potentials measured along the various traverses were tied to a common ground reference, and the zero contour shown is the approximate background level for the area away from the summit. The traverse network was fairly dense, except for parts of the caldera where other short-wavelength anomalies may exist. These data were collected at various times during the past few years. Although the potentials in most areas have remained constant as confirmed by some remeasurements, the potentials in some areas have changed in the vicinity of recent eruptions and are discussed later in this paper. In the near future, we plan to resurvey the entire area shown over a much shorter time interval. Additional surveys have been made in other parts of Kilauea, but we will confine our discussion to some of the salient features shown in Figure 2. Before discussing the significance of these data, however, some characteristics of the map (Fig. 2) are to be noted.

1. The potential gradients are remarkably high; locally, they exceed 700 mV in 100 m. The largest potential difference shown exceeds 2300 mV over a lateral distance of about 2.5 km and is thought to represent the largest SP magnitude ever reported.
2. No low-pass filtering of the original profile data was used in constructing this map. Except for some places on the floor of Kilauea cladera, very few areas show anomalies having wavelengths on the order of the spacing used (typically 100 m) and, therefore, attest to the uniformity of the potential distribution.
3. Unlike a scalar resistivity contour map, these data are derived from a vector quantity that has a direction (polarity) as well as magnitude. Therefore, areas of inflection (for example, high-low-high) signify a real reversal in the direction of current flow in the ground.

4. The significant anomalies are all positive in polarity and are essentially monopolar (that is, they have no, or a very weak, associated negative anomaly).

DISCUSSION OF RESULTS

All the anomalies shown on the contour map can be correlated with either fumarolic areas, or areas where no surface manifestations are present, within areas where seismic and ground-deformation data with geologic inferences support the existence of magma within several kilometers of the surface. In all areas surveyed no anomalies have been delineated in which localized heat sources could not be reasonably assumed. Traverses made at some distance away from the active parts of Kilauea have shown only random variations in potential, which typically are less than 25 mV over a few hundred meters, and no long-wavelength trends have been noted. It is quite clear, then, that these large positive-potential anomalies are related uniquely to areas underlain by solidified but still-hot intrusions or by active magma reservoirs and conduits.

The following discussion presents various lines of evidence that support an electrokinetic origin for the source of these potentials. That is, the potentials are thought to result in some manner from the differential motion of certain ion species in the thermal waters which overlie deeper-seated hot zones. The many implications that these studies have furnished regarding some of the substructure and magmatic processes of Kilauea are not detailed here. Only those aspects that provide some insight into the origin of these potentials are stressed.

Steaming Flats Area

On the north rim of Kilauea caldera, a large pronounced anomaly is located over Steaming Flats, a fumarolic area overlain by prehistoric lavas. The steam area lies between the inner and outer caldera-boundary faults and is thought to be related to a hot intrusive body at shallow depth (<1 km; Macdonald and Abbott, 1970, p. 47). Although the shape of the anomaly generally conforms to the trend of the boundary faults on the northwest and south sides, the potential contours indiscriminately transect the principal faults on the north and northeast sides. This suggests that either the emplacement of the intrusion or the flow direction of the overlying thermal waters was or is not, respectively, entirely controlled by the principal faults. In detail, the SP anomaly is not centered exactly over the area where most of the steaming vents and less wooded areas are located, but easterly toward an active solfatara known as Sulphur Bank.

Closely spaced measurements in this area did not reveal any large, steep gradients in the vicinity of the steam vents, indicating that the predominant source of the potentials is not related to very near-surface phenomena. In general, most steam vents in Kilauea are not under high pressure; nor are they heated appreciably above boiling point for the altitude at which the steam issues (Macdonald, 1973). Also, except for those in a few solfataric areas, the fumarolic gases emitted from most vents consist largely of steam and air. Resistivity soundings over some steam areas show that the near-surface resistivities are very large (<1000 ohm·m). These large resistivities support the general assumption that the steam is formed at depth from the infiltration of abundant meteoric water through numerous cracks to the hotter rocks below.

Kilauea Caldera Area

An anomaly occurs over Halemaumau, the prominent pit crater and focal point for many of the eruptions of Kilauea in prehistoric and historic times. Interpolation of the contours through the crater, based on measurements obtained around its outer rim, shows that the potentials are not concentric with the outline of the crater. Indeed, many of the eruptions that have occurred within Halemaumau have developed from linear, northeasterly trending fissures rather than from a central vent.

The steep-gradient closed feature, immediately northeast of Halemaumau, is not thought to be a negative anomaly, but rather a neutral area bounded by higher positive potentials. This and the many short-wavelength features within the caldera (Fig. 2) must be related to the complex development of the present, relatively flat floor. In noting a distinctively arcuate pattern of white deposits (opal) on the surface of the caldera, Macdonald (1955) was able to correlate these occurrences with the buried margins of sunken central basins that existed in the caldera during the nineteenth century. He surmised that the buried scarps that bounded the basins, and the faults beneath them along which sinking took place, constitute the pathways that guide the mineralized steam to the surface. Some of the smaller SP anomalies have a similar arcuate pattern and correlate in a general way with some of the features mapped by Macdonald. Perhaps the restricted locations of the small anomalies and the larger "neutral" area result from extremely low permeabilities in these deeply filled basins that would drastically restrict the upward flow of the hydrothermal fluids. Despite the complexity of the potential distribution on the caldera floor, future detailed studies here may provide better insight into the principal source mechanism than in some other areas of Kilauea because of the shallow and localized nature of the anomalies.

The long, narrow feature along the southeast side of the caldera has the largest magnitude of all the anomalies at the summit. It coincides with a horst along its west end but trends onto the floor of the caldera toward its northeast side. Persistent steam emits from the bounding fault scarps of the horst which is covered by at least 10 m of ash deposits and appropriately called Sand Spit. Detailed electrical and magnetic studies made over this part of the anomaly revealed that:

1. Below the top few meters, the ash and underlying lavas are conductive (<30 ohm·m) to about 30 m, but below this depth, the rocks are very resistive (>500 ohm·m) to at least 90 m in depth.
2. The lateral boundaries of this conductive zone are very distinct, coinciding with those of the SP anomaly.
3. These boundaries are also defined by a prominent magnetic anomaly produced by the lavas immediately below the ash.

These findings lead to the following conclusions: (1) the high conductivity of the ash over the SP anomaly must be caused by hot, mineralized ground water that may be thermally perched above the hot, perhaps undersaturated lavas; and (2) because the magnetic anomaly can be attributed to the rocks immediately below the ash, the temperatures must be below the Curie temperature (<600°C), and therefore, we can dismiss the possibility that some sort of phenomenon directly related to magma is responsible for these large potentials.

Upper Southwest Rift Zone

The circular feature, about 700 m from the southwest rim of Halemaumau, is centered over part of the initial outbreak of the southwest rift zone eruption of September 1971. Copious volumes of steam still rise from many of the resulting linear eruptive and noneruptive fissures. Electromagnetic studies in this area revealed that the anomaly is underlain by a shallow, conductive zone that also is broad and circular rather than narrow and linear as might have been expected if the anomalies were caused by thin, intrusive dikes. In many other areas of Kilauea, thin fissure eruptions appear to cool fairly rapidly; and within less than a year after the eruption, little or no steam is observed from the vents. The lateral extent of this anomaly, together with the persistent steam, may be reflecting the relative massiveness of this intrusion.

Kilauea Iki Area

In the area of Kilauea Iki Crater, two SP anomalies are noted (Fig. 2)—a small one associated with the source vent of the November-December 1959 eruption on the southwest rim of this large pit crater, and a larger one centered a few hundred meters east of the crater. The larger feature has no surface thermal manifestations over its center; however, some steam occasionally is observed in a few places along the east wall of Kilauea Iki that must be related to a still-hot intrusion. No anomaly along the upper rim of this crater is associated with the partially frozen lava lake formed in this crater by the 1959 eruption; the lava lake presently has a liquid core about 30 m thick.

Magma Reservoir Area

The distinct anomaly centered about 2.5 km south of Halemaumau is interpreted to overlie an active part of Kilauea's magma reservoir complex. Detailed ground-deformation studies over the years have defined not a single deformation center but a few discrete centers that are interpreted as areas that overlie weakly interconnecting magma reservoirs or a plexus of sills and dikes a few kilometers deep (Fiske and Kinoshita, 1969; Kinoshita, Swanson, and Jackson, 1974). One such center lies immediately north of the SP feature, about 1 km south of Halemaumau. A recent analysis of deformation data obtained prior to the 1967 to 1968 summit eruption by Dieterich and Decker (1975) using a finite-element modeling technique places an inflation center virtually over the center of this SP feature.

Inflation at the summit preceding an eruption is almost always accompanied by an increase in the number of shallow microeathquakes, which generally are concentrated in the southwest part of the caldera (Koyanagi and Endo, 1971). A recent detailed seismic analysis of the earthquakes that preceded the August 1971 eruption by Koyanagi and others (1975) shows a strong correlation of the shallow earthquake epicenters with the lateral boundaries of the SP anomaly (Fig. 3). From the distribution of earthquakes, they place the central magma reservoir in the vicinity of Halemaumau below a depth of 2 to 3 km where there exists a 2 to 3 km zone conspicuously void of earthquakes, and consider the prominent zone of shallow earthquakes to the south to be a principal lateral intrusive zone. Perhaps the most compelling evidence that this area is underlain by an active part of the reservoir system is the fact that Kilauea's most recent eruption, on December 31, 1974, initially broke out over the exact center of this anomaly.

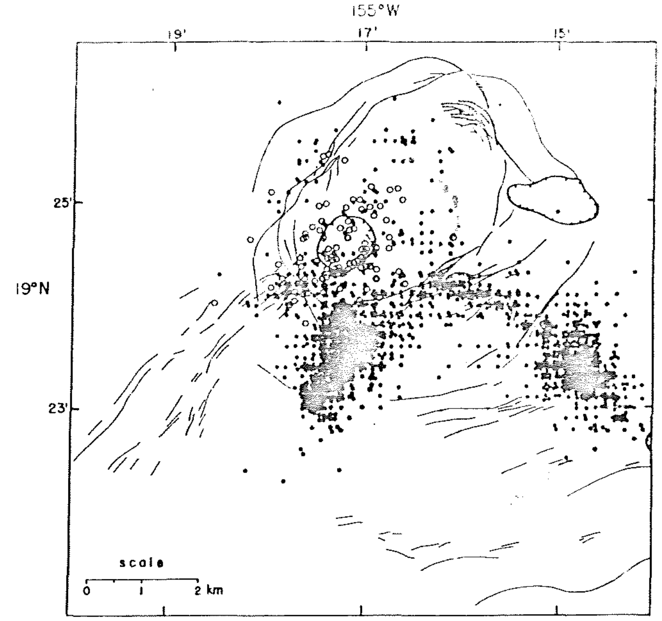

Figure 3. Plot of inflation-related earthquake epicenters for a period of several months prior to, and after, the August and September 1971 eruptions at Kilauea (modified after Koyanagi et al., 1975) showing their relation with the self-potential anomalies outlined in Figures 1 and 2 (shaded areas); shallow earthquakes 1.5 to 3 km deep (dots); deeper, long-period earthquakes, 7 to 11 km deep (circles).

It is important to note that other geophysical observations place magma at a depth of 2 to 3 km, whereas the maximum depth to the top of this SP source, as deduced from elementary potential theory, cannot exceed about 500 m at its north side and must be even shallower on the southeast side. The extreme variance in depths again suggests that these potentials cannot arise directly from very high-temperature phenomena. More likely, if the mechanism generating the SP anomalies is related to the movement of ground water by convective forces, the depth to the very hot rocks, or magma, could be appreciably deeper than the depth at which the vertically rising water cools and diverges toward the horizontal (top of SP source). Collimation of hydrothermal fluids by vertical gravitational forces could explain this clearly correlatable feature with the epicentral distribution of these inflation-related earthquakes.

Of significance are some findings from a 1262-m-deep research hole (Keller, Murray, and Towle, 1974; Zablocki, et al., 1974) recently drilled about 1 km south of Halemaumau near the north side of the SP anomaly (Fig. 1). Water table was found at a depth of 488 m, where the temperature rose from essentially ambient (20°C) to almost 80°C. Below 750 m, the temperature decreased to a minimum of 63°C and then increased monotonically to a maximum of 137°C at the hole bottom. Extrapolation of the steep thermal gradient near the hole bottom (370°C/km) would place magma about 3 km from the surface, and the observed temperature inversion may be the consequence of the hole's being located off center from a rising convective column of water (Zablocki, et al., 1974). These inferences fit a model of a highly developed hydrothermal convective cell over the main part of the anomaly. Even the broad low (negative) SP area, which borders the anomaly on the southeast side, suggests a region of descending cooler waters of a convective cell.

Upper East Rift Zone

As previously mentioned, flank eruptions along Kilauea's rift zones are probably fed from the summit's magma reservoir complex via lateral conduits. The sympathetic response of the summit's surface deformation to periodic eruptive-drainback episodes during some long-lived flank eruptions, and the low seismicity along the east rift zone between the summit and the eruptive sites suggest further that the conduit within the rift zone is fairly well established with no appreciable obstructions. The prominent positive ridge-like anomaly that extends southeast from just east of Keanakakoi Crater is interpreted to directly overlie the conduit of Kilauea's east rift zone (Figs. 1 and 2). The contour map shows, for the first time, not only the path of the main conduit, but also the extent of two intrusive zones that accompanied eruptive events at the eastern end of the Koae fault system in recent years. As in the summit area, the potentials are very large, in places exceeding 1500 mV, and none of the anomalies suggest source depths greater than a few hundred meters.

The circular positive anomalies superimposed along the axis of the ridge-like anomaly are centered on, or near, pit craters that characterize the upper part of the rift zone. These steep-walled craters, ranging in depth from a few tens to over hundreds of meters, were probably formed by collapse resulting from the withdrawal of underlying magma (Wentworth and Macdonald, 1953, p. 21). The broadest and largest SP anomaly along the ridge is located where the Koae fault system merges with the east rift zone; in this junction area, steam issues from a few cracks just west of Hiiaka Crater (Fig. 1). The spatial distribution of these features with the self-potential profile along the approximate axis of the ridge is shown in Figure 4. Superimposed on these short-wavelength anomalies is a longer-wavelength anomaly that peaks over the broadest feature, suggesting that the top to the underlying heat source may be shallower in this area. The coincidence of these local SP anomalies with the pit craters is compatible with a conceptual model in which ground water, heated by underlying magma, is guided upward along nearly vertical fractures that undoubtedly are present below these collapse features (Fig. 5). Near the top of the local water table, the cooler fluid flow diverges outward and down to form a convective cell. If the source mechanism is principally in the form of streaming potentials (Dakhnov, 1959, p. 313) developed by anion adsorption along the rock surfaces in the direction of the fluid streamlines (positive current flow in direction of fluid flow), then the resulting potentials at the surface would be those as shown in Figure 5. The reversal of the fluid flow in the convective cell might also explain the broad SP lows that flank the positive-potential ridge shown on the contour map (Fig. 2).

A vertical electrical resistivity sounding (VES-3) made over the central part of the ridge and on either side of the east rift zone (VES-1 and -2, see Fig. 1 for locations) reveals that a very low-resistivity zone lies only about 250 m below the surface along this part of the rift zone, whereas the adjacent areas have higher resistivities to at least 600 m in depth (Fig. 6). Although these findings do not unequivocably support a convective cell developed between the pit craters and the underlying conduit, they strongly suggest that hot water must exist at very shallow depths over SP anomalies. In detail, the approximate depth to the top of the SP source coincides with the depth to the top of the

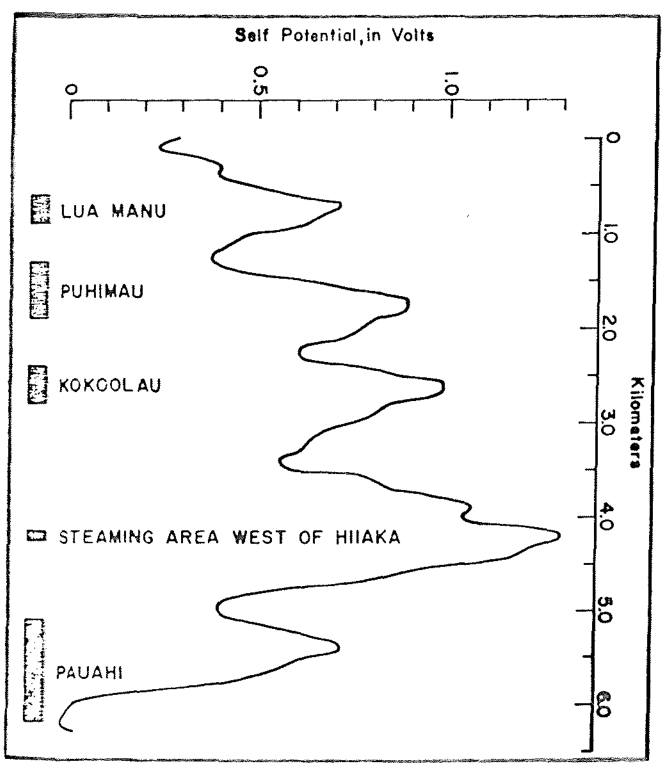

Figure 4. Self-potential profile along the approximate axis of ridge-like feature over Kilauea's upper east rift zone showing the proximity of the anomalies to the various pit craters indicated on index map (Fig. 1).

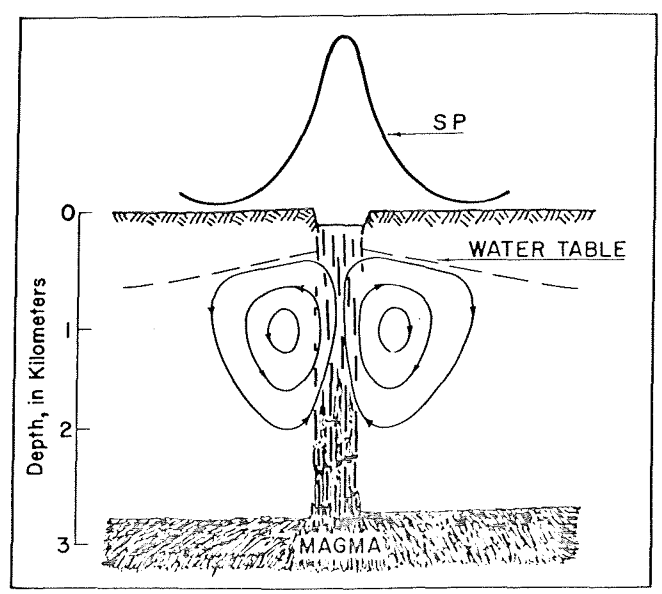

Figure 5. Conceptual model of a convecting column of water above a pit crater heated by magma in the underlying conduit and the resulting surface potential distribution; closed lines with arrows represent idealized streamlines of convecting fluid.

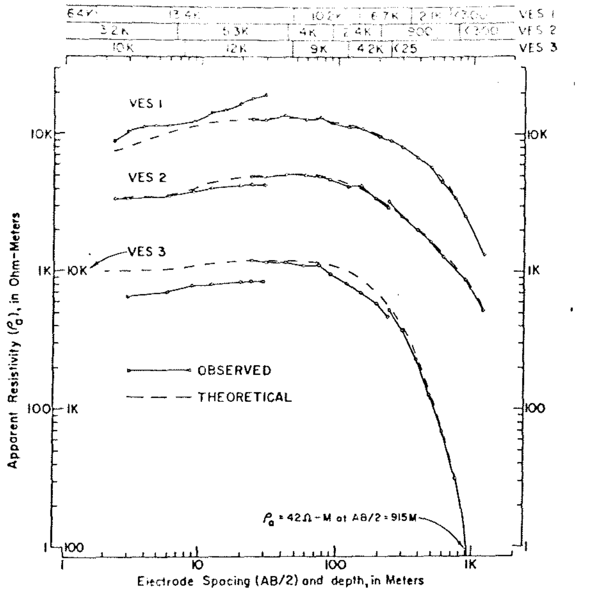

Figure 6. Vertical electric sounding curves (VES) obtained at locations shown on index map (Fig. 1); interpretation of geoelectric sections shown at top provided by D. B. Jackson, U.S.G.S. (1975, written commun.).

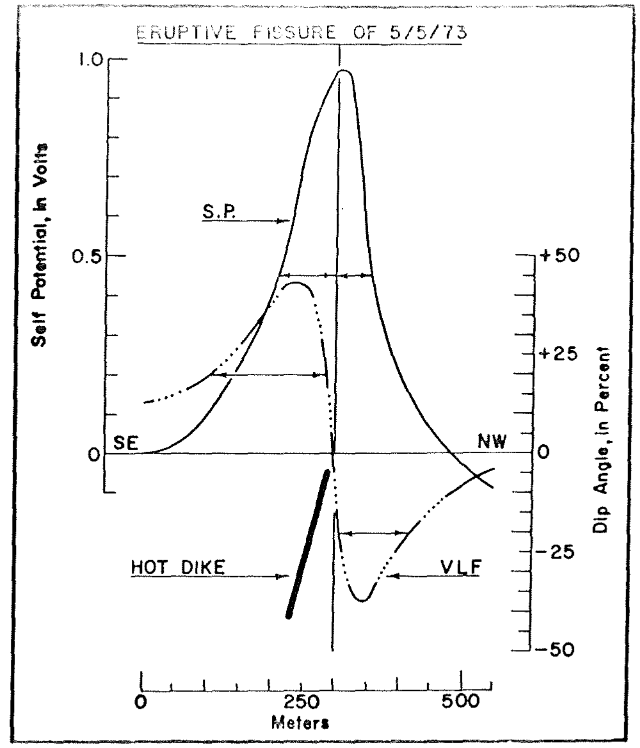

Figure 7. Self-potential and VLF (very low frequency) electromagnetic dip-angle response profiles obtained along a perpendicular traverse across the May 5, 1973, eruptive fissure; the southeast-dipping hot dike shown is inferred from asymmetry in both profiles (note differences in anomaly half-widths as indicated by arrow-tipped lines).

conductive zone (250 m). Similar to the results obtained at the summit, seismic evidence places the top of the conduit at a depth of about 2 to 3 km—again consistent with the concept of tightly collimated rising hydrothermal fluids over the magma. We also note that the distribution of the epicenters for the intrusion-related earthquakes shown in Figure 3 correlate well with the ridge-like SP anomaly.

Observations From Some Recent Eruptions

The long, narrow anomaly that projects west-southwest from the east rift zone near Hiiaka Crater into the Koae fault system (Fig. 1) is related to the eruption of May 5, 1973. Although the eruptive fissure about 1 km west of Hiiaka Crater was only about 100 m long, the anomaly continues for about 1.5 km to the west-southwest, indicating the intrusion extended further into the Koae than indicated by the surface fissure. Because of the simple sheet-like configuration of the May 5, 1973, fissure, additional electrical studies have been made across this feature to gain further insight into possible source mechanisms for large self-potentials.

Figure 7 shows the self-potential distribution and the response from a very low frequency (VLF) electromagnetic survey along a traverse perpendicular to the fissure obtained ten days after the eruption. Summarized briefly, the VLF-EM method utilizes a directional radio receiver, tuned to a transmitter in the 15 to 25 kHz band (here 18.6 kHz), that measures a dip angle, which is proportional to the vertical component of the magnetic field. Across a thin, tabular, vertical buried conductor, the theoretical response results in an antisymmetric-shaped profile (similar to a sine wave) in which the zero-crossover is positioned directly over the surface projection of the conductor (see Paterson and Ronka, 1971, for details). The potentials in Figure 7 exceed 1000 mV in about 200 m, and the maximum occurs directly over the fissure. The steep gradient and large magnitude of the VLF anomaly attest to the high conductivity of this shallow dike, and possibly, to the immediately intruded lavas. Of particular significance is the asymmetry exhibited in both profiles (note the large differences in the width of the VLF anomaly at ±20% dip angle and that of the half-widths on the SP profile). For the VLF response, the asymmetry requires a dipping conductor whose "hanging wall" side is the direction of the slower fall-off of the dip angle (the southeast side here). Similar asymmetry in the shapes of SP and VLF profiles has been obtained over eruptive fissures elsewhere at Kilauea.

In interpreting SP data, virtually all analytical methods devised previously have assumed point, line, dipolar, spherical, or sheet charge- or current-source configurations (see for example, de Witte, 1948; Meiser, 1962; Yungul, 1950; Roy, 1963). If, for example, we chose a dipping, dipolar current-sheet model to match the SP profile shown in Figure 7, the indicated direction of dip would be opposite to that determined from the VLF response. This is illustrated in Figure 8, which shows the potential profile computed for a 45 degree northwest-dipping current sheet (from Edge and Laby, 1931, p. 245). The characteristic shape of this profile is very similar to that of the measured potentials shown in Figure 7 except that the steepest gradient and the minimum potential are located on the hanging-wall side of the current sheet. This apparent contradiction can be reconciled if we assume a phenomenological model of a hot dike that dips away from the steep-gradient side; in this attitude, the streamlines of fluid flow on the footwall side would turn down with less horizontal extension than on the hanging-wall side (Fig. 8). Again, if we consider a positive current flow in the direction of the streamlines,

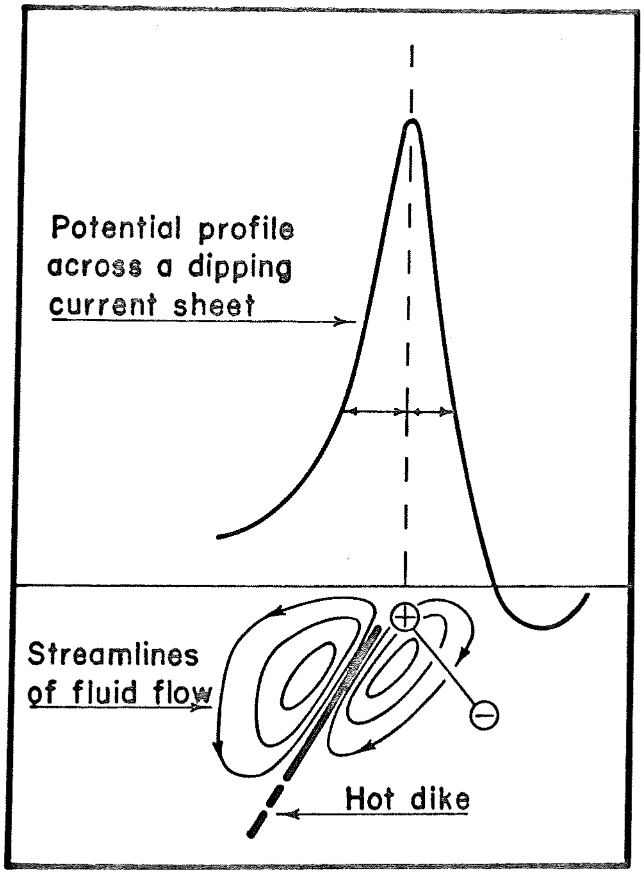

Figure 8. Theoretical potential profile over a buried dipolar current sheet dipping 45 degrees to the right; a similar profile can result from a buried hot dike dipping to the left with the pattern of idealized streamlines of fluid flow shown.

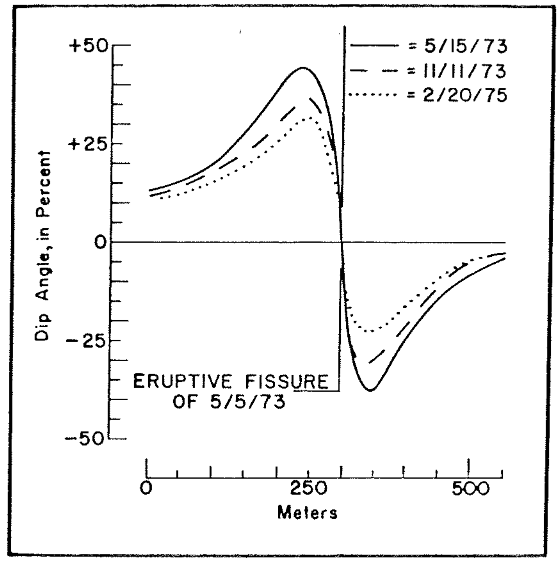

Figure 9. A comparison of three VLF dip-angle profiles along the same traverse across the eruptive fissure of May 5, 1973, showing the progressive decrease in amplitude with time.

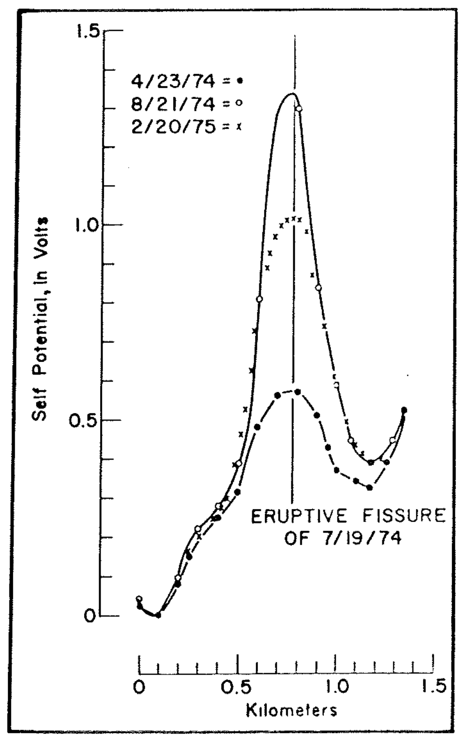

Figure 10. A comparison of three self-potential profiles along the same traverse across an eruptive fissure of July 19, 1974, showing the changes in the potential distribution with time.

the resulting surface potentials would be in the same sense as those observed.

Repeated surveys over the May 5, 1973 fissure and some other recent, thin eruptive fissures also show that some anomalies progressively decrease in amplitude with time. This might be expected as these thin dikes at shallow depths lose their heat fairly rapidly. The gradual decrease in the VLF amplitude (corresponding to a decrease in electrical conductivity) over a 21-month period for the May 5, 1973, eruptive fissure (Fig. 9) and the change in the potential distribution over the July 1974 eruptive fissure near Lua Manu Crater 3 months before, and 1 and 6 months after eruption (Fig. 10) are excellent examples. A characteristic common to both examples is that although the amplitudes diminish with time, the wavelengths of the anomalies appear to be stable; that is, the effective depths to the sources do not noticeably change. This is inconsistent with a model that would directly relate the magnitude and shape of an anomaly to the depth of the causative source. Rather, these observations suggest that hydrothermal parameters, such as height of local water table and permeability, largely control the apparent depth (anomaly wavelength) of both types of anomalies, whereas the temperature of the cooling dikes influences their magnitude.

CONCLUDING REMARKS

The results from the studies presented herein demonstrate the exceptional utility and reliability of the self-potential method for delineating zones of magma or hot rock that underlie the active volcano of Kilauea. All positive anomalies can be related unambiguously and exclusively to anomalous subsurface localizations of heat. The results obtained to date, coupled with the relative ease of measurement, have established the self-potential technique as another powerful tool to investigate the volcanologic processes at Kilauea Volcano.

The phenomenological cause of the resulting large potentials is not yet understood. Such an understanding is essential for a complete utilization of SP data in quantifying the configuration of subsurface heat sources as well as the mode of distribution of the associated hydrothermal fluids. This is particularly so at Kilauea where the geologic "noise" or background potentials are insignificant in comparison to the magnitudes of the heat-related potentials and, therefore, warrant as refined an interpretive scheme as can be developed.

The use of a simple, dipolar, current-sheet source as an equivalent model can be misleading in regard to the attitude of the causative source. Good fits of some observed data with the potentials developed from monopolar current sources of various dimensions have been obtained (not presented here). Although these models tend to place approximate depth and width limits on the region from which the potentials occur, they still do not reveal the nature of the mechanism. However, if these limits are considered within the context of other geophysical observations presented here, they collectively provide constraints on any proposed mechanism. For example, it seems reasonable that the high rock permeabilities, abundant ground water, and the shallow heat sources in Kilauea are adequate to support fluid convection. However, analytical studies of transient as well as steady-state free convection (see for example, Cheng and Lau, 1974) incorporating the appropriate boundary conditions and constraints are needed to test the plausibility of the conceptual models presented herein. Even more fundamental is the need to demonstrate the anion-adsorption efficiency of basaltic lavas, particularly with respect to water chemistry and prevailing temperatures and pressures. If such lines of study should support a streaming potential mechanism, then a new dimension in studying the dynamic aspects of geothermal systems will be attained.

Two other types of electrokinetic phenomena have been considered as possible source mechanisms for generating self-potentials. One involves a vertical differential displacement of ionic charge resulting from the low-temperature precipitation of negatively charged colloids, such as silica, thereby leaving the rising hot solutions relatively enriched in cations (D. B. Hoover, 1974, written commun.). The other possibility involves the production of hydrogen from the decomposition of meteoric, and, possibly, juvenile water at elevated temperatures. The inherent high mobility and diffusion rate of hydrogen, as well as its polarity, are very appealing. In measuring the oxygen fugacities of magmatic gases in holes drilled into a crystallizing lava lake in Kilauea, Sato and Wright (1966) proposed a mechanism to account for some anomalous zones of high oxygen fugacity as follows:

". . . a certain horizon of the lake gradually cools to the temperature range in which oxygen and water molecules can no longer diffuse through the basalt freely, while hydrogen continues to escape toward the surface because of its greater diffusion rate. . . . This preferential escape of hydrogen induces further thermal decomposition of water and locally generates high oxygen fugacities, so that oxidation of the basalt occurs in the horizon. . . . As the temperature of the horizon decreases further, even the diffusion of hydrogen becomes difficult, and the hydrogen ascending from underlying layers begins to react with, and possibly reduce, the previously oxidized basalt."

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