A Hydrogeophysical Survey Using Remote-Sensing Methods from Kawaihae to Kailua-Kona, Hawaii

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ABSTRACT

Several geophysical techniques have been specialized for applications to exploration for ground water in an insular basaltic environment. This article describes a multidisciplinary application of several such techniques to the Kona Coast of Hawaii in Hawaii. Aerial infrared scanning and low-level aeromagnetic surveys were the major reconnaissance techniques. For detailed study, modified audiomagnetotelluric and D. C. resistivity profiling methods were used. The improved knowledge of subsurface structure confirmed the expectation that no large flows, such as suitable for commercial exploration, occur in that coastal sector.

KEY WORDS

Geophysical methods; multidisciplinary studies; infrared scanning; aeromagnetic; audiomagnetotelluric; D. C. resistivity; basaltic terrain; Ghyben-Herzberg lens; and coastal environments.

INTRODUCTION

This article describes several geophysical methods which have been used to study the subsurface geology indirectly from the surface or above the surface. This work was requested and funded by the Hawaii State Department of Natural Resources in order to:

(1) Obtain a fast, economical aerial reconnaissance for assistance in evaluating ground-water resources, and

(2) To guide and provide supplemental data during the exploratory drilling phase of water resource investigations in the area.

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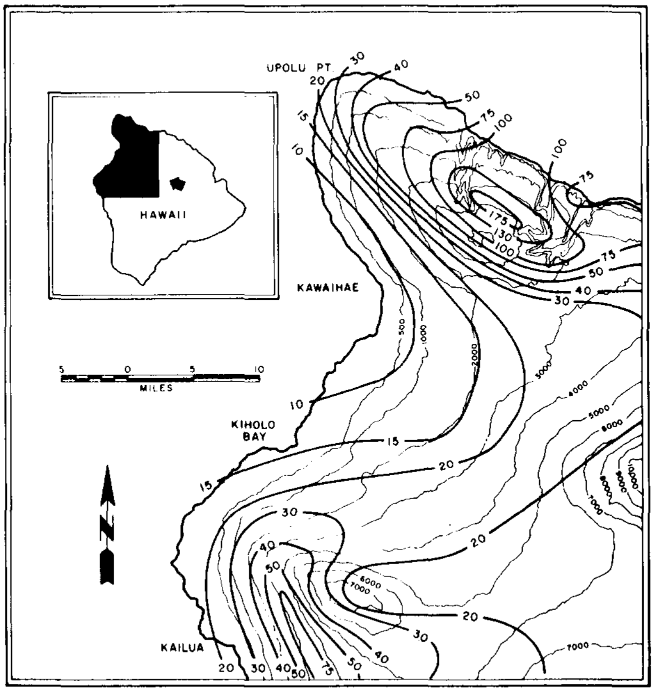

Fig. 1. Mean annual rainfall in northwest Hawaii. Contours are in units of inches per year. (After Cox, Peterson, Adams, Lao, Campbell, and Huber, 1969.)

The rainfall on the area of interest is very slight north of Hualalai and is only about ten inches per year along the shoreline; isopleths are shown in inches per year on Figure 1. As this area is within the rain shadow of Mauna Kea and Mauna Loa Mountains, little trade wind rainfall is received. More than half of the yearly rainfall occurs from May to September (Taliaferro, 1958).

The infiltration capacity of the surface is very high, and there are no perennial streams. Stream flow records for the largest streams in the area, summarized by Davis and Yamanaga (1963 and 1968), offer no promise of large dependable supplies of water. Although small amounts of ground water may be perched on ash beds, no perched ground water is definitely known and there are no perched-water springs in the area.

Dikes deep within the rift zones of Mauna Kea, Mauna Loa, and Hualalai possibly form compartments capable of impounding ground water at levels above the basal-water bodies. However, dikes probably do not control ground-water flow at or above sea level in the nearshore areas (Cox *et al.,* 1969). The line of cinder cones northwest of the summit of Hualalai and the cinder cones north of the summit suggest the existence of dikes in these areas. The nature of their influence on ground-water movement is not known, but they appear to be so oriented and of such continuity as not to constitute a major barrier to ground-water flow (Cox *et al.,* 1969). Cinder cones on the south flank of Mauna Kea and on the north flank of Mauna Loa likewise suggest the existence of dike systems that may possibly intersect in the saddle area between the two mountains. Recent resistivity soundings by Zhody (1965) suggest that high-level dike-impounded water may be found in this area.

Probably the only significant ground-water body is a Ghyben-Herzberg lens, floating on and displacing sea water in the lava flows near sea-level throughout the coastal area between Kawaihae and Kailua-Kona. In general, recharge of fresh water to the basal lens is small throughout the area except on the western slopes of Hualalai where it is moderate to large. Consequently, the water-table gradient and the thickness of fresh water are both very small. Mixing of fresh ground water and sea water by ocean tides extends inland several thousand feet to a few miles and produces brackish ground water in the nearshore areas. Small amounts of brackish water from basal aquifers discharge freely along much of the shoreline.

Observations of the basal lens can be made only at and near the shore where numerous shallow wells, water holes, and coastal springs occur. However, there are a few sites inland where deep wells provide additional information pertinent to higher elevations. Stearns and Macdonald (1946) reported the chlorinity of more than 30 dug wells, springs and water holes between Hapuna Beach and Keauhou, approximately 5 miles south of Kailua-Kona. With the exception of the old Camp Drewes Marine well at Hapuna Beach, which produced water containing 560 ppm Cl^-, all of the chloride contents reported were greater than 1,000 ppm and most were greater than 2,000 ppm. A shoreline sampling program of coastal springs, ponds, and water holes between Kawaihae and Kailua-Kona was conducted to provide ground control for the infrared study, which appears as one of the subsections of this report. In general, the chlorinites measured ranged from 1,000 to over 15,000 ppm, and most of the values were greater than 2,500 ppm.

The potential supply of fresh basal ground water in the area between Kawaihae and Kailua-Kona is not known with certainty. Cox *et al.* (1969) estimated that the recharge to the basal ground-water body north of Hualalai and extending approximately to Kawaihae is probably less than 50 million gallons per day and that the shoreline discharge averages only a few million gallons per day per mile. Davis and Yamanaga (1968) estimated that the average daily recharge in the wet zone on the west slope of Hualalai probably amounts to several tens of millions of gallons.

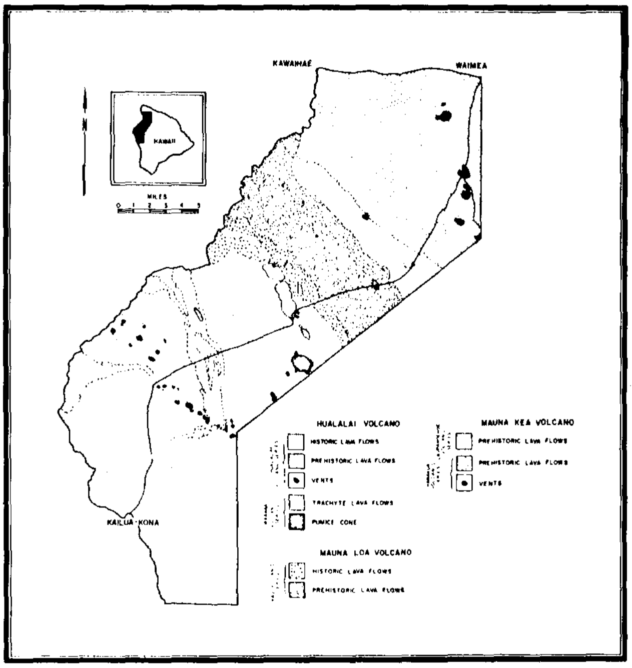

Fig. 2. Surface geology of the coastal area in the vicinity of Kawaihae to Kailua-Kona, Hawaii (after Stearns and Macdonald, 1946).

GEOLOGY

The surface geology of the coastal area between Kawaihae and Kailua is given in Figure 2.

This area is underlain by lava flows from Mauna Kea, Mauna Loa, and Hualalai Volcanoes. The lavas generally are basalt flows, partly pahoehoe, but primarily aa, although the Mauna Kea lavas of the Hamakua series in the northern part of the area are capped by Pahala ash. Subsurface lava flows date back to perhaps the late Pliocene; however, all exposed rocks are Pleistocene in age (Doell and Cox, 1961). Both Mauna Loa and Hualalai historic flows are present in the area.

The northern part of the area is underlain by Mauna Kea lava flows of the Mahakua and Laupahoehoe series. The Hamakua volcanic series consists primarily of basalt and some andesite lava flows with minor amounts of interbedded ash. The Hamakua lavas are covered by Pahala ash, which is a few feet thick near the belt highway, and are found only in scattered patches along the coast. In general, the Hamakua lavas are moderately to highly porous and permeable and yield water freely to wells. Flows of the Laupahoehoe volcanic series outcrop along a two-mile-wide strip just south of the Hamakua lavas. These rocks consist primarily of andesite flows with numerous cinder cones at the sources of the short flows. The Laupahoehoe lavas generally are less porous and less permeable than the Hamakua lavas.

South of the Mauna Kea slopes, a strip of Mauna Loa lavas approximately 3½ to 7 miles wide flowed through the saddle between Mauna Kea and Hualalai and down into the ocean. These lavas, which are all members of the Kau volcanic series, are basalt flows similar in composition and structure to the Hamakua flows. One of the Kau flows in the area, the Kaniku flow, which erupted in 1859, is historic. The Kau lavas, like the Hamakua lavas, are highly porous and permeable and are saturated near sea level.

To the southwest of the 1859 flow is the slope of Hualalai. This slope is underlain generally by basalt lava flows of the Hualalai volcanic series, similar to the Kau flows from Mauna Loa and the Hamakua flows from Mauna Kea. At the north edge of the Hualalai lavas and approximately 5 miles inland from the sea, a thick trachyte flow, which erupted from Puu Waawaa, is exposed. The flow is partly covered with later Hualalai basalt flows and its base is not exposed. The Hualalai lavas generally are highly porous and permeable.

GEOPHYSICAL SURVEYS

Four different geophysical surveys were made between Kawaihae and Kailua-Kona from June 1968 to June 1969. Infrared and aeromagnetic surveys were flown along the coastline, a surface resistivity survey was conducted a few hundred yards inland from the shore, and an audiomagnetotelluric (AMT) survey was run along the belt highway. A review of the literature on the geology and hydrology of the area and a study of the tidal-zone algae was made (Brilliande and Lepley, 1970).

The results of these surveys will be presented in the above order, as this proceeds from the most general to the most particular.

Infrared Scanning

The AGA Thermovision is a high-speed scanner which converts incident infrared energy in the 2 to 5.5 micrometer band into a visible image on the face of a cathode ray tube. A mosaic of the wide-angle infrared images mounted on an aerial photograph of Anaehoomalu Bay is given in Figure 3 with the thermal anomaly indicated by a black arrow.

Infrared images were recorded in real-time energy with AGA Thermovision instrumentation, following those procedures previously reported by Adams and Lepley (1968). The coastal sections covered for Hawaii are shown in Figure 4. Index maps of all areas surveyed and a few sample mosaics of the coastal areas having thermal anomalies have been compiled (Adams, Peterson, Mathur, Lepley, Warren and Huber, 1969).

This effort differed from a previous survey in having a pretest using a wide angle lens (11° × 11°), and having an instrument port in the aircraft. Some modifications of camera and auxiliary equipment were also made.

Fig. 3. Mosaic of 11° × 11° infrared images mounted on an aerial photograph of Anaehoomalu Bay. The thermal anomaly is indicated by black arrow.

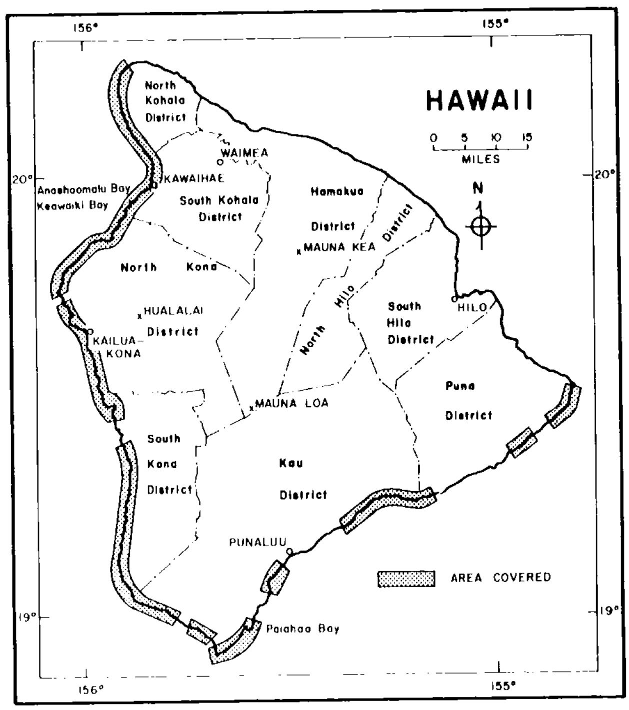

Fig. 4. Map of Hawaii showing areas covered along the west and southeast coasts.

Pretests were conducted at Portland State University, Portland, Oregon, with the assistance of Dr. Leonard Palmer of the Department of Earth Sciences.

The 11° × 11° field of view was a noteworthy improvement over the 5° × 5° field available during the effort of the previous year. The wide angle model was used at a sensitivity of 10° C although the 5° × 5° model had been utilized best at 5° C sensitivity.

The instrument port in the aircraft permitted mounting the mirror completely within the aircraft cabin. This eliminated the high noise environment which occurred when the camera unit was extended out the baggage door.

During June 1969, the eruption of the Kileaua volcano caused heavy pollution of the lower atmosphere and affected the quality of the infrared images by causing an effect similar to that of dense haze. When weather conditions were clear, most of the images were of high quality.

Although many cool zones were discovered, as previously pointed out, the image only reveals a thermal anomaly: Ground-based observations are required to ascertain water quality. Designation of the locations of notable thermal anomalies does not necessarily imply association of fresher water. Other work has emphasized that not all thermal anomalies have associated fresher water, and not all fresher water has associated thermal anomalies. An infrared survey should only be considered a reconnaissance technique to obtain an instantaneous, synoptic sample, as surf, currents, and tides preclude meaningful quantitative interpretations.

A ground-truth, offshore survey was conducted during June 1968 for comparison with both the 1968 and 1969 infrared data. Temperature and conductivity measurements were made from a boat by alternately measuring temperature and conductivity at a cell suspended in surficial water off the bow of the boat. A typical geographic distribution of the observed data is shown for the northern portion of the Kona Coast (Figure 5). Temperature above 70° F. is shown by the bar to the left and the resistivity is shown by the bar to the right. Comments on shore features are also given.

Aeromagnetics

An aerial magnetic survey was conducted to delineate subsurface rock structures which might control the flow of ground water under the basaltic terrain of South Kohala between Kawaihae and Makolea Point along the NW coast of the Island of Hawaii. Total magnetic field was measured with an ELSEC Proton Magnetometer type 592. Location of observations was obtained from a 16 mm Bell and Howell movie camera, Model 200 EE, mounted vertically to take color photographs of the ground in flight through a port in the floor of the aircraft. The camera was

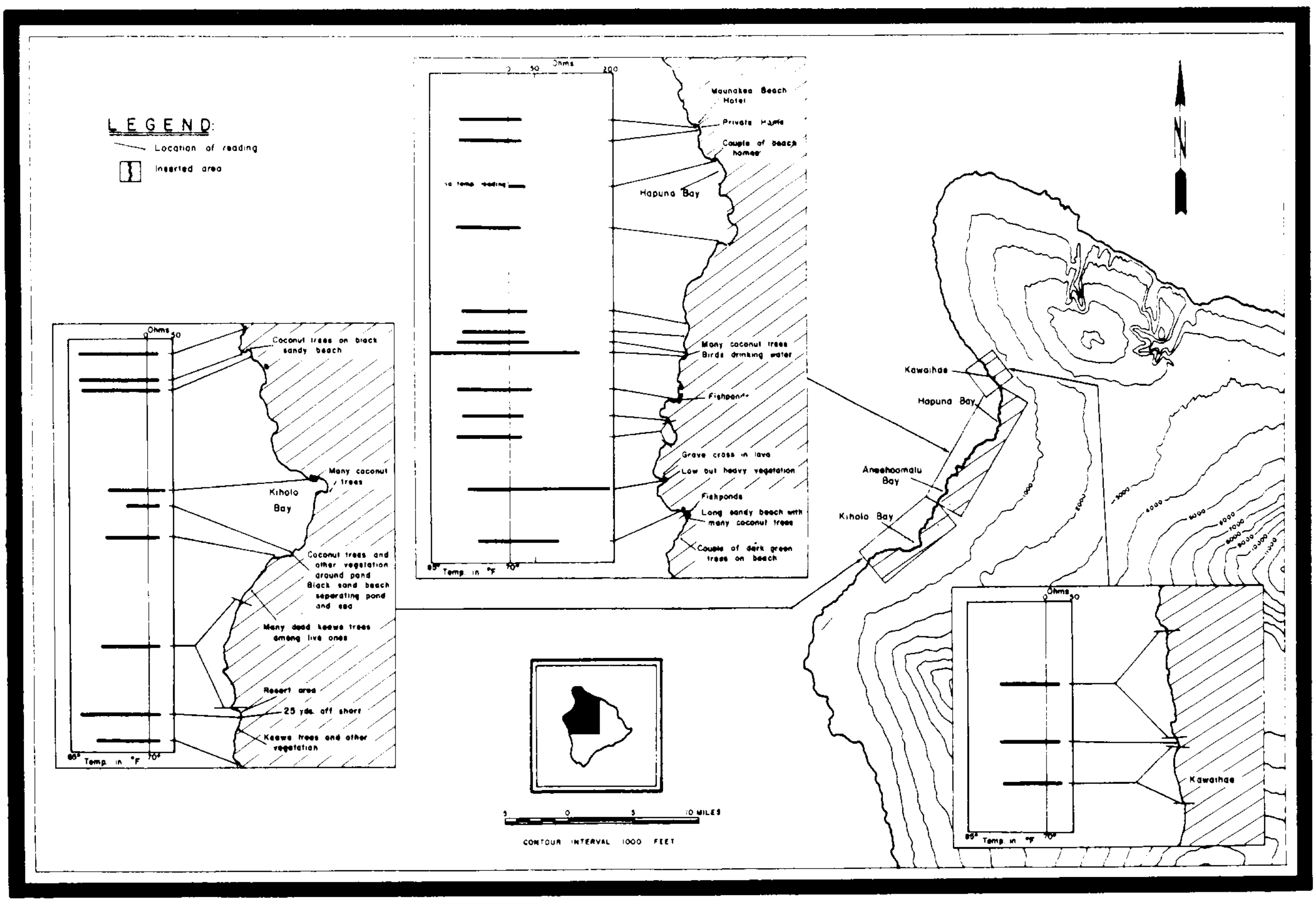

Fig. 5. The resistivity (expressed in ohms) and temperature (expressed in degrees F) data obtained by an offshore survey are plotted in horizontal bar graphs in three enlarged segments for the area between Waiakailio Bay to Kumukehu Point.

triggered electrically at a speed of 1 frame-second and a synchronous time mark placed on the chart in the recorder unit to provide correlation of the camera image and the recording chart. Additional correlation was obtained by holding a light colored filter in front of the camera lens for a few seconds and marking by hand the corresponding position on the chart. At the aircraft speed of 100 mph, the 6.4 second polarization cycle period permitted a surface sampling interval at about 800 feet. A regional magnetic field map of the island of Hawaii had been developed from observations at 10,000 feet by Malahoff and Woollard (1965). The total magnetic field as mapped at about 4,000 feet in the Kawaihae to Anaehoomalu Bay area is shown as Figure 6 and that mapped at about 3,000 feet from Makolea Point to Anaehoomalu Bay is shown as Figure 7. The two maps are not combined because the altitudes in the two cases differed by about 1,000 feet. The small area east of the Anaehoomalu Bay, overlapped by the two surveys, showed similar anomaly features in the two figures. As expected, these low level aeromagnetic surveys show a higher value of the field strength and greater details of the anomalous features than the regional map by Malahoff and Woollard (1965), although the general pattern of the field remains the same.

The main features of Figure 6 are:

(1) A magnetic high in the north-central area which is a part of the Kohala dipole field. Its southern extension (A) is rather pronounced and has a closure of about 150 gammas and is elongated in an east-westerly direction.

(2) A small plateau area (B) with two small (50 gammas) closures on the southwest flank of the high (A).

(3) Steep gradient on the southeast flank of the high (A) towards the regional low (C) of the Mauna Kea dipole field.

South of Anaehoomalu Bay the magnetic field pattern continues into Figure 7. The field steadily decreases in strength southwards and shows the following features:

(1) A second plateau area (D) east of Keawaiki Bay with a small nose-like feature (E) protruding towards the southeast.

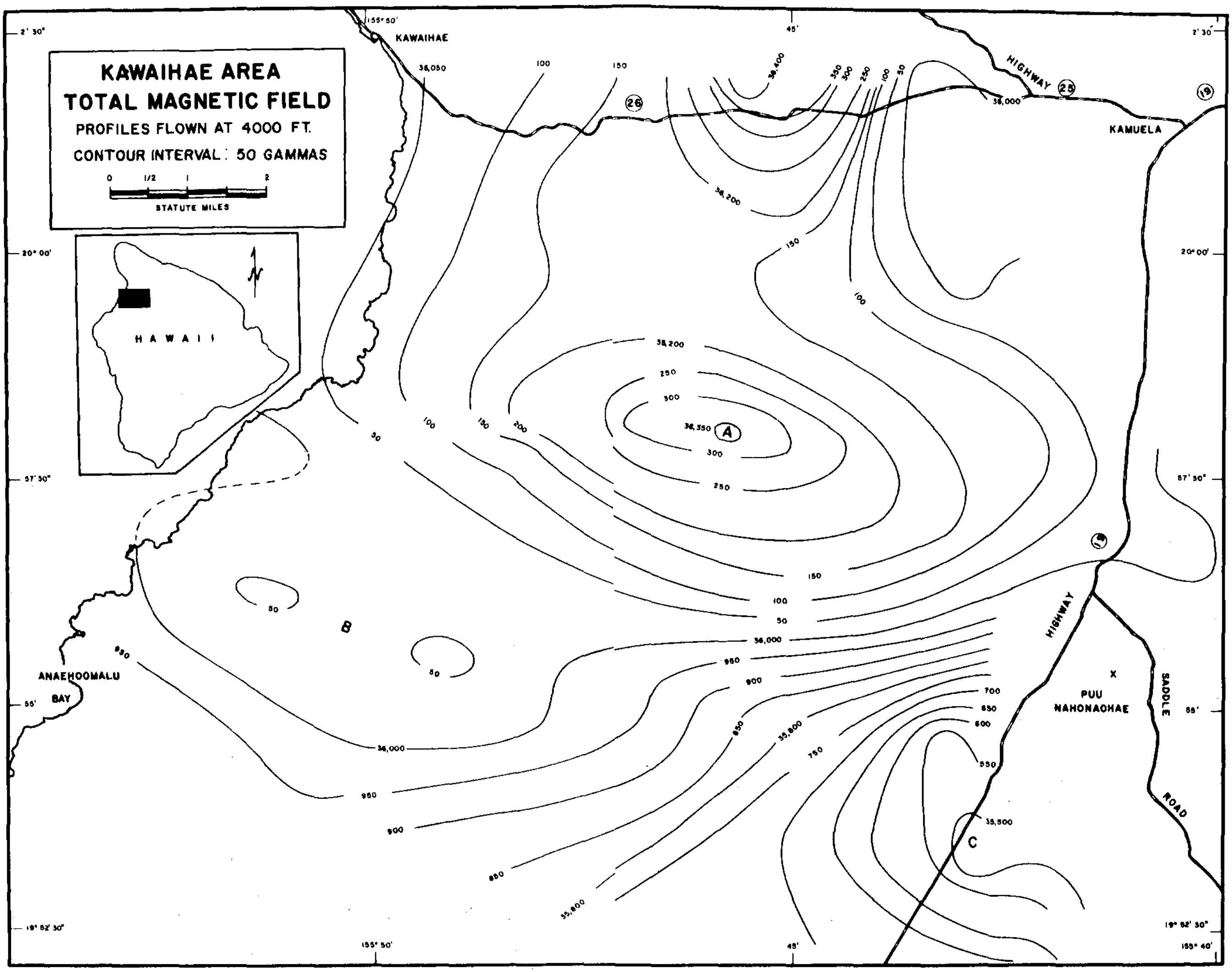

Fig. 6. Total magnetic field map of Kawaihae area.

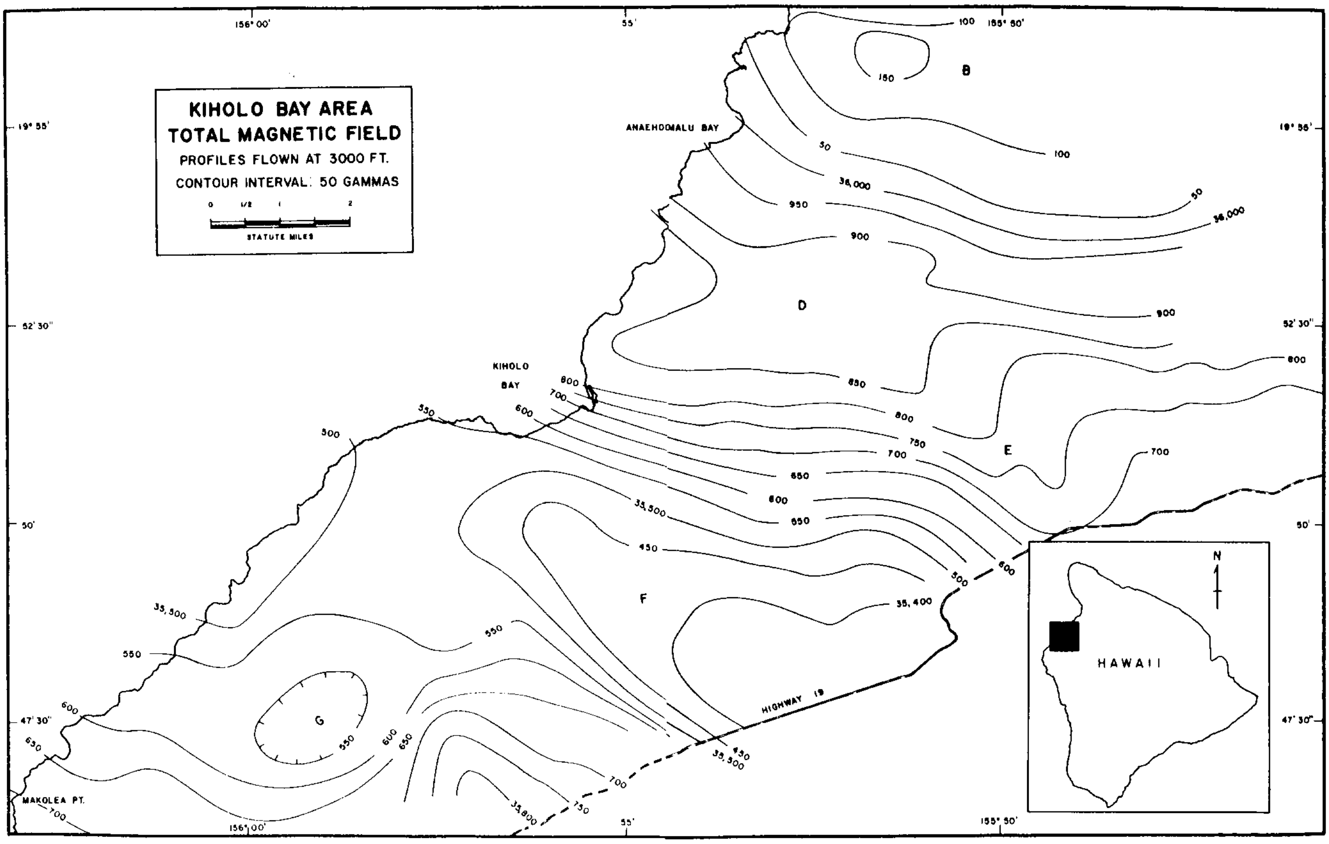

Fig. 7. Total magnetic field map of Kiholo Bay area.

(2) A pronounced NW-SE trending low valley (F), southeast of Kiholo Bay.

(3) A flat low area (G) on the southwestern flank of the valley (F).

All the above features, except the regional pattern and the effect of the Kohala and Mauna Kea dipole fields, have been delineated as a result of the low-level and closely-spaced aeromagnetic profiles.

The steep gradient in the magnetic field between the high (A) and the regional low (C) in Figure 6 could be due to an east-west dike or intrusive-filled rift zone and it corresponds to a sharp break in the apparent resistivity profile along the Waimea to Kailua-Kona Road (Lepley and Adams, 1968). The audiomagnetotelluric (AMT) survey there shows high resistivity to the northern side and low to the south. The zone of steep gradient towards the valley (F) seems to indicate a northwest extension of the Hualalai rift-zone, as proposed by Stearns and Macdonald (1946), and is picked up as a resistivity low in the AMT profile.

Audiomagnetotellurics

The magnetotelluric method for determining earth resistivity has been described by Keller and Frischknecht (1966). The method consists of determining the electrical impedance normal to the earth's surface by measuring the mutually perpendicular horizontal components of the electric and magnetic vectors of the naturally-occurring magnetotelluric field.

The electric field component is detected between metal rods driven into the ground or placed on lava rock 31 meters apart. The horizontal component of the magnetic field at right angles to the electrode line is detected with a calibrated induction coil of 30,000 turns of wire on a square frame having 1.2 m^2 of air core. The details of instrumentation are described by Lepley and Adams (1970).

Computation of the resistivity was based on the Cagniard (1953) expression

$$\rho A = \frac{1}{\omega\mu} \left(\frac{E_x}{H_y} \right)^2 \qquad \ldots\ldots\ldots\ldots \quad (1)$$

where H is the magnetic field component in amperes per meter, E is the electric field component in volts per meter, ω is the angular frequency in radians per second and μ is $4\pi \times 10^{-7}$.

Station locations were along the road from Waimea to Kailua as shown in Figure 8. The apparent resistivity is plotted in a coordinate system of station numbers versus frequency with the frequency decreasing downward and the station numbers representing mileage from the Waimea Airport. A contour map of the apparent resistivity values represents a distorted geophysical cross section of resistivity, integrated downward from the surface.

A major NNW-SSE trending vertical structure crossing the Waimea to Kailua-Kona highway at station 6 is indicated by the change in apparent resistivity as measured by the AMT method. A significant change of

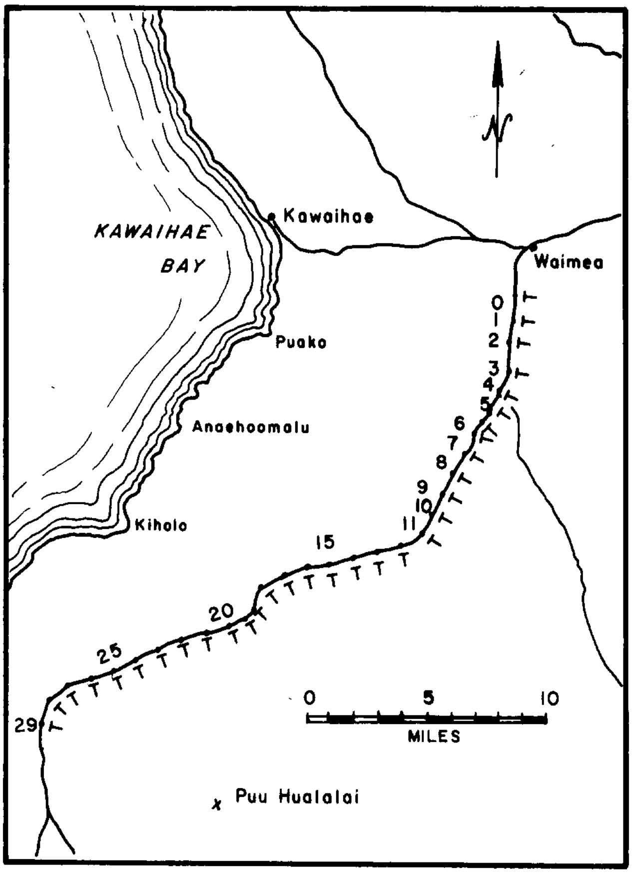

Fig. 8. Station locations on AMT profile.

the electrical character of the deep rocks was found on the two sides of the structure. The data to the north of the structure, near Waimea, indicate higher resistivity than to the south, from the Saddle Road intersection to Huehue Ranch. This contrast may be due to one or both of two causes: (1) different rock material from two different volcanic groups (Mauna Kea and Mauna Loa); (2) depression of the fresh-sea-water interface to the north and lack of such depression to the south of the structure.

D. C. Resistivity

The D. C. resistivity profiling technique, using the Wenner electrode configuration, has been applied to elevations less than 300 feet along the coast between Kawaihae and Kailua-Kona.

Previous investigation using electrical resistivity sounding and profiling techniques and reported by Adams (1968), indicated that the salt-fresh interface in the Kohala district to the north of Kawaihae generally occurred at sea level.

A fresh-water layer displacing the sea water downwards results in a higher apparent resistivity. In general, a greater thickness of fresh water than normal would result in a positive anomaly in the resistivity. Therefore an area suitable for potential fresh-water development should be characterized by a positive resistivity anomaly. A depressed fresh-salt interface is not the only cause of a high resistivity anomaly. A similar anomaly may be caused by the resistivity contrast between dry rock and wet rock. Therefore, an anomalous profile does not positively indicate fresh water but only the more probable sites of fresh-water zones.

The equipment and field procedure is a development of those previously reported by Cox *et al.* (1969) and Adams (1970). In Figure 9, the apparent resistivity and the elevation along the profile for the northern section of the coastal area of interest is shown, together with the apparent resistivity as corrected for elevation following the procedure developed by Adams (1970). The most apparent anomaly occurs north of station 150 and corresponds to the highest elevation along the profile, hence may be due to the dryer ground conditions at higher elevations. The secondary anomaly between Stations 104 and 125 is located in a trough, so any investigation along this profile should begin near or at this site. Another resistivity anomaly occurs between stations 175 and 187. A resistivity profile across the flow to Anaehoomalu Bay was reported by Cox *et al.* (1969).

Additional details on the resistivity procedures and interpretations, especially an improvement of the elevation correction procedure, is given by Huber and Adams (1970).

Note that the electrical resistivity anomalies are relative. The existence of these anomalies does not necessarily posit the existence of ground water in quantities suitable for commercial exploitation.

SUMMARY

Rainfall in the area between Kawaihae and Kailua-Kona is very low. However, the rainfall in the western part of the Mauna Kea-Mauna Loa Area Saddle may provide significant ground-water recharge. The geological controls on the seaward discharge of this ground water are poorly known. Review of the literature showed that the extent of the northeast rift of Hualalai, which might conceivably act to channel flow in the basal ground-water lens, is not well defined. Furthermore, the zone of intercalated flows from Mauna Kea and Mauna Loa, in the area of the Saddle Road and Belt Road junction, is probably further complicated by buried structures associated with the cinder cones scattered in the area.

To provide information bearing on these uncertainties, an aeromagnetic survey was made over the area and an audiomagnetotelluric (AMT) survey was run along the Belt Road. The data from these two surveys correlated well. The AMT data indicate a deep lateral change in apparent resistivity about three miles south of the Saddle-Road-Belt-Road junction. Lateral orientation of this lateral change is provided by the position of the steep gradient region on the aeromagnetic map of the total magnetic field intensity. The resulting interpretation is Line X on Figure 10. The higher apparent resistivities occurring in the province to the north of Line X are attributed to the higher resistivity of the Mauna Kea lavas or to a

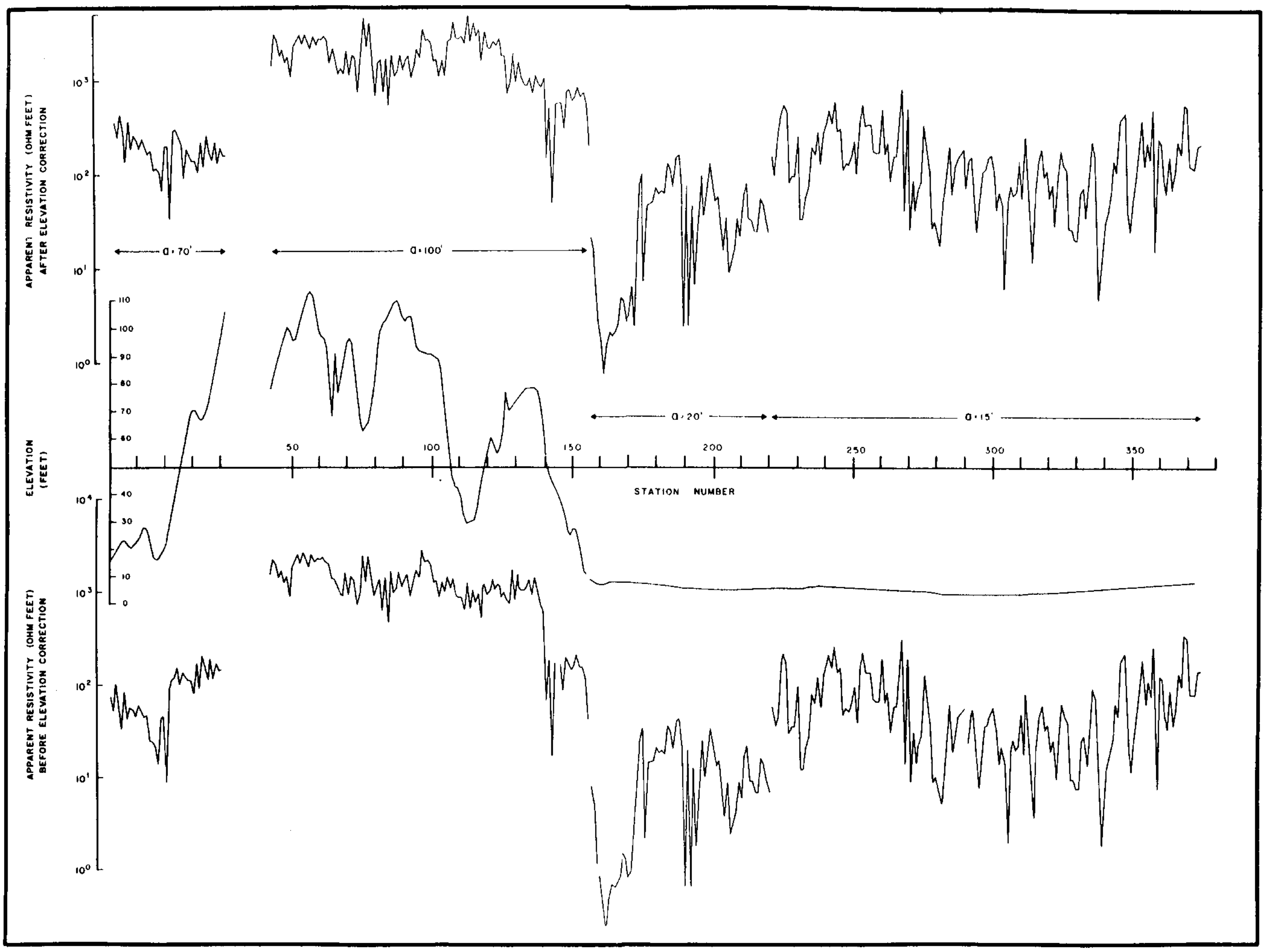

Fig. 9. Resistivity profiles, both before and after the elevation correction, and an elevation profile for north section.

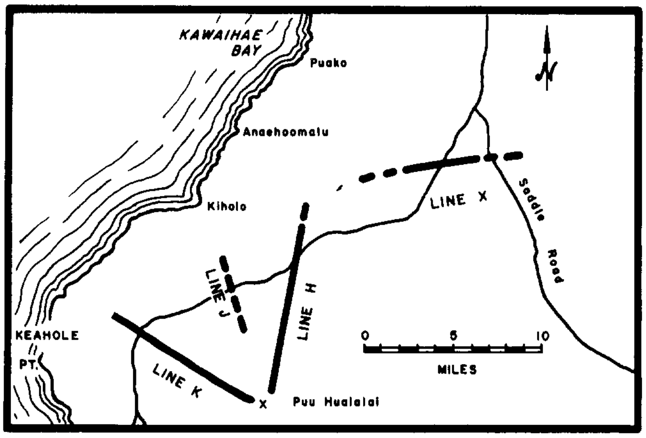

Fig. 10. Major structural features indicated by audiomagnetotelluric and aeromagnetic data.

higher water table depressing the salt-brackish interface.

The AMT data suggest that the northeast Hualalai rift zone extends from Puu Waawaa to Puu Anahulu. From the aeromagnetic total field map, the routing of the rift extension is approximated as Line H in Figure 10. This verified extension of the rift zone could control movement of basal water. At the junction of Lines X and H is a relatively optimum area for any further investigation.

The AMT and aeromagnetic data also agree well on the position of the two anomalies given as Lines J and K in Figure 10. Line K is the known northwest rift of Hualalai and Line J is without apparent surface expression. These two lines diverge from the possible recharge area of the Hualalai summit. The structural controls of basal-water movement are therefore probably not significant.

The rift zones, defined by the Lines H and X, probably have low permeability and therefore funnel the basal water into a swath between Hapuna and Anaehoomalu Bays. To further localize possible flow zones in this swath, electrical resistivity profiles were made from Puako to Anaehoomalu Bay. Only two sections showed notably anomalous apparent resistivity. Extensive fresh-water discharge is not indicated by either the infrared scanning, electrical resistivity, or the algal survey along that coastline (Brilliande and Lepley, 1970).

Electrical resistivity profiling and infrared scanning conducted between Keahole Point and Kailua-Kona showed only one small anomaly. A previously drilled hole mauka of the site adequately tested the potential of this anomaly and found it to be unproductive.

The biological indicator technique developed concomitantly with the application of this series of geophysical techniques in order to provide time-integrative information on infrared anomalies (Brilliande and Lepley, 1970) is useful in mature ecological environments, but not on the Kona coast of Hawaii.

ACKNOWLEDGEMENTS

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Mr. Edward Katahira and Kenneth Taylor conducted the off-shore ground-truth work.

The aeromagnetic survey was assisted by Charles Dorigan, Frederick Duennebier, Steve Hammond, Howard Yashita, and Roy Araki. Dr. Alexander Malahoff and Mr. Ken Culler provided guidance on operation of magnetometer and airplane, respectively.

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Electrical resistivity fieldwork was performed by P. Milner, D. Loomis, R. Nishioka, J. Cochran, A. Omori, W. Kimura, and D. Kimura. Elevation data was provided by the Department of Transportation offices of the State of Hawaii.

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