AEROMAGNETIC AND NEAR-SURFACE ELECTRICAL EXPRESSION OF THE KILAUEA AND MAUNA LOA VOLCANIC RIFT SYSTEMS

By Vincent J. Flanigan *and* Carl L. Long

ABSTRACT

Aeromagnetic and electromagnetic data from a draped (90-m terrain clearance) survey of the rift systems extending east and southwest from the summits of Kilauea and Mauna Loa Volcanoes are interpreted to reflect near-surface magnetic and electrical resistivity characteristics of the rift zones. Shallow dike complexes of more intense magnetism than their extrusive equivalents are the main source rocks for the observed magnetic anomalies along the rift zones. Conductive rocks are reflected in the electromagnetic data as apparent resistivity lows. Sharp lateral changes of conductivity are detected as VLF magnetic anomalies and are interpreted to represent relatively narrow, conductive zones over feeder dikes along active parts of the rift zones.

The spatial relations of the interpreted magnetic source rocks to observed apparent resistivity and VLF magnetic anomalies are generally consistent with geologic and structural observations. The active part of the east rift zone of Kilauea lies south of the magnetic source rocks in the upper one-third of the east rift zone, reflecting southward movement of Kilauea's south flank. Farther east, beyond Napau Crater, the active part of the east rift zone of Kilauea, as interpreted from VLF magnetic anomalies, lies in the central to northern part of the interpreted magnetic source rocks. This change of spatial relation of the geophysical anomalies is interpreted to reflect structures transverse to the rift zone that are associated with large-scale block slumping of the south flank of Kilauea. Similarly, large-scale block slumping on the west flank of Mauna Loa is reflected by magnetic anomalies east of the active part of the rift zone. A major apparent resistivity and magnetic low transverse to the southwest rift zone of Mauna Loa may reflect the southern boundary of the subaerial Alika slide, which extends 80 km offshore from Mauna Loa's west coast.

The buttressing of Mauna Loa by Mauna Kea on the north and Kilauea on the south, as recognized by geophysical data, contributes to the complexity of the Mauna Loa northeast rift zone. The VLF magnetic anomalies defining the active northeast rift zone of Mauna Loa are present only in the upper 10–12 km of the rift, thus indicating that the action of buttress forces limits recent volcanic activity farther east along the rift zone.

Two interpretations of an apparent reversely polarized magnetic dipole anomaly over Kapoho Crater are modeled. One model assumes an intrusive body in which the direction of remanent magnetism is nearly opposite to the present magnetic field of the Earth. The other model assumes a nonmagnetic body separating two magnetic dike systems—the northern system related to development of Mauna Loa's northeast rift zone and the southern one related to Kilauea's east rift zone.

INTRODUCTION

Mauna Loa and its smaller neighbor, Kilauea, have been studied, and volcanic activity extensively documented for only the relatively brief historical period extending back to the late 19th century. Accumulated evidence from observations of earth scientists has allowed a better understanding of growth, structural complexity, and volcanic activity of these two shield volcanoes. The purpose of this paper is to examine some of the more obvious aeromagnetic and electromagnetic features and show how they complement or augment observations of other earth scientists.

In early 1978 the U.S. Geological Survey (USGS) conducted several airborne surveys that covered large areas of the Island of Hawaii. An aeromagnetic survey of the entire island was flown at a mean terrain clearance of 300 m (Godson and others, 1981). In addition, a low-level (90-m mean terrain clearance) total-field magnetic and very low frequency (VLF) electromagnetic survey was flown over the rift zones extending east and southwest from the summits of Kilauea and Mauna Loa Volcanoes (fig. 39.1; Flanigan and others, 1986a, b). Data from the low-level survey form the basis of this paper.

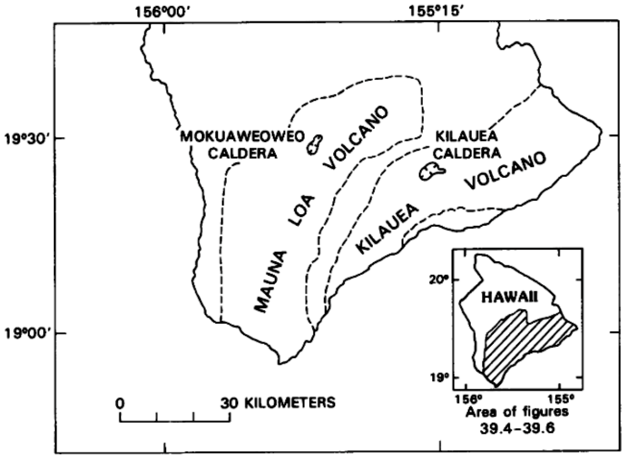

FIGURE 39.1.—Index map of Island of Hawaii, showing boundary (dashed) of airborne electromagnetic-magnetic surveys over Kilauea and Mauna Loa Volcanoes.

Extensive airborne and shipborne magnetic surveys were made over the Hawaiian Ridge in the mid-1960's by Malahoff and Wollard (1966) and Malahoff and McCoy (1967). Most of the data from these earlier magnetic surveys were used with the 1978 data to compile a composite aeromagnetic map of the Hawaiian Islands as part of a cooperative ongoing effort by the Society of Exploration Geophysicists and the USGS to produce gravity and magnetic maps of the United States (Godson and others, 1984).

The low-level airborne survey made by the USGS, primarily designed to record VLF responses, was the first and perhaps only such airborne survey on the Island of Hawaii. The airborne VLF method has proven practical in engineering and geologic applications on the contiguous continental United States and Alaska (Frischknecht, 1971; Hoekstra and others, 1975; Arcone, 1978, 1979).

Extensive ground VLF surveys, along with other electromagnetic methods, have been utilized in geophysical studies mainly in the Kilauea Volcano summit area and parts of the rift zones extending east and southwest from the summit (Zablocki, 1978).

METHODS

Problems related to aeromagnetic surveying, and in particular over magnetic Hawaiian terrain, are addressed by Malahoff and Wollard (1966). Topographic aeromagnetic anomalies are expected in those areas where the survey aircraft cannot maintain constant terrain clearance. Studies are currently being done in an effort to evaluate and remove terrain effects from aeromagnetic maps (Blakely and Grauch, 1983). Aeromagnetic surveys flown at constant altitude (barometric) or constant terrain clearance (draped) are both subject to some degree of erroneously induced magnetic anomalies due to rugged topography. In fact, terrain effects may be enhanced in magnetic terrane in drape-flown surveys over that of traditional barometric-flown magnetic surveys (Grauch and Campbell, 1984). In the low-level aeromagnetic survey described here the fixed-wing aircraft was successful in maintaining ± 30 m of the nominal survey height, except when the aircraft passed over pit craters and cinder cones.

Theoretical terrain-induced magnetic anomalies were computed for two-dimensional models approximating volcanic cones, craters, and calderas to qualitatively evaluate the observed magnetic anomalies (not shown here). Terrain anomalies, using magnetic susceptibilities of approximately 1.0×10^{-2} cgs units, were not over 400 nanoteslas (nT). The most distinguishing feature about the theoretical terrain anomalies is the short wavelength of the anomaly, usually much shorter than the wavelength of many of the observed anomalies. Thus, in an area of abrupt terrain variation, the observed anomaly is a composite magnetic response of the terrain and the magnetic geologic sources.

Hawaiian intrusive rocks, primarily in the form of dikes, have an intensity of remanent magnetization more than 10 times that of the induced magnetization (Decker, 1963; Malahoff and Strange, 1965). It is evident from aeromagnetic data and confirmed by theoretical modeling (Flanigan and others, 1986a) that about the same apparent order of magnitude difference exists between the magnetic properties of intrusive dike systems and lava flows. The reason for this apparent difference of bulk magnetic properties is not clear because the dike rocks are a composite (over time) of the same extrusive rocks comprising the lava flows. The direction of remanent magnetization of lava flows on the Island of Hawaii is essentially the same as the Earth's present field direction. However, remanent magnetization directions on samples of massive basalt flows may not be representative of the overall section. Sequences of exposed Hawaiian lavas (in fault scarps and sea cliffs) are highly porous. L.A. Anderson (oral commun., 1984) says drill core recovery from drill holes in the Kilauea area is about 20 percent, suggesting that the bulk of the section is composed of porous rocks not easily recovered during drilling. We assume that postcooling movement of the lava flows either by tumbling of blocks in breccia envelopes in flows or by postcooling compaction of pahoehoe flows has caused a jumbled assemblage of remanent magnetization directions. The net result would be an apparent lower bulk magnetization of the flow rocks than the intrusive rocks. Induced magnetization would remain unaffected.

Sources of magnetic anomalies are based upon a qualitative interpretation, consistent with the magnetic anomaly shape and approximate orientation of the body with respect to the Earth's magnetic field direction. To illustrate the relative amplitude and anomaly shape that might be expected, an assumed two-dimensional dike representing intrusive rocks of bulk magnetism 10 times greater than the extruded basalt flows was rotated in the Earth's magnetic field, and the theoretical magnetic response calculated (fig. 39.2) at several positions. The magnetic anomaly varies from a symmetrical magnetic high of about 400-nT amplitude, when the dike is oriented parallel to the direction of the Earth's magnetic field (solid line on fig. 39.2), to a dipole anomaly of over 3,000-nT amplitude for a dike oriented about normal to the direction of the Earth's magnetic field (azimuth 90° or 120° on fig. 39.2). Note: for rocks normally polarized—that is, the direction of the remanent magnetism is the same as the Earth's present field direction—the dipole magnetic high is on the south and the low is on the north. For magnetic features oriented normal to the Earth's magnetic field direction, the edges of the magnetic body lie under the apex of the dipole high and low. For magnetic sources oriented parallel to the Earth's magnetic field, the edges of the causative body lie under the point of steepest gradient of the magnetic anomaly. Of course there are any number of cases in between the two extremes mentioned above. Thus, locations for magnetic source rocks based on these qualitative considerations have greater uncertainty in those areas where the strike of the magnetic source rocks is not parallel or normal to the direction of the Earth's present magnetic field.

The theory of radio wave propagation and the measurement of electric and electromagnetic properties of the Earth's near surface has been extensively discussed elsewhere (Wait; 1962; Paal, 1965, 1968; Barringer and McNeil, 1969; Patterson and Ronka, 1971; and Frischknecht, 1973). Details of the electrical and electromagnetic parameters measured by the USGS airborne VLF equipment used to acquire data presented in this paper are given in Flanigan and others (1986b).

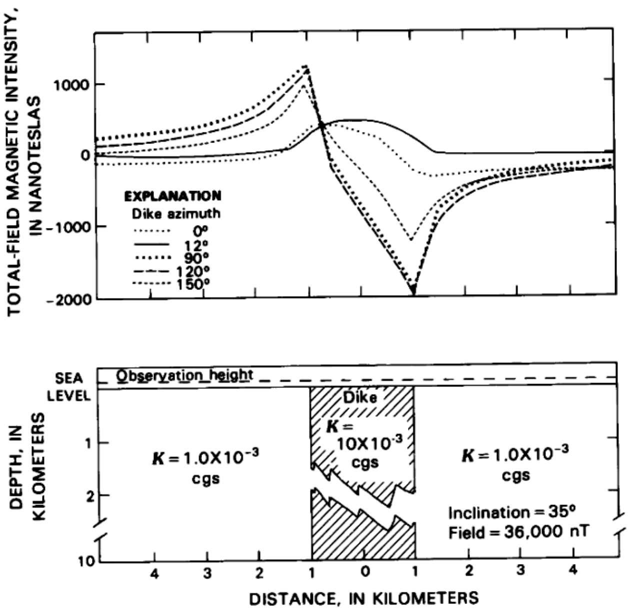

FIGURE 39.2.—Theoretical models of magnetic dike rocks rotated in Earth's magnetic field showing relative amplitude and anomaly shape. Remanent magnetism is considered to be parallel to direction of Earth's present magnetic field. Susceptibilities (K) are shown in cgs units.

Briefly, the VLF technique measures the local electric and magnetic characteristics of a vertically polarized groundwave transmitted by one of many VLF communication transmitters located worldwide. The local amplitude of the electric and magnetic fields of the transmitted radiowave is dependent on several factors, such as: transmitted power output, distance between transmitter and receiver site, propagation events in the ionosphere, local topography, and resistivity of the Earth between the transmitter and receiver.

Earth resistivity values are computed from the amplitude ratio of the horizontal electric field to the vertical electric field (wave tilt; Hoekstra and others, 1975). Inasmuch as the Earth resistivities determined by the wave tilt usually are a combined response over a layered earth composed of differing resistivities, they are called apparent resistivities. Wave-tilt apparent resistivities may vary significantly from those determined by ground VLF methods mainly because the airborne and ground methods use different magnetic and electric field components of the transmitted radiowave which are affected differently by the conductivity (inverse of resistivity) and thicknesses of the layered Earth.

The thickness of the upper surface of the Earth that influences the VLF electromagnetic responses, called the skin depth, is related to the surface apparent resistivity and the frequency of the electromagnetic field. The skin depth for rocks of 100 Ω-m apparent resistivity is about 36 m, and for 10,000 Ω-m is about 360 m.

VLF magnetic measurements discussed in this paper are the responses of the measured magnetic field to geologic sources of differing conductivities. The VLF magnetic responses are particularly sensitive to sharp lateral changes of conductivity. In addition, the vertical and horizontal VLF magnetic field components have diagnostic responses to geologic sources, particularly those of high conductivity contrast. To illustrate these diagnostic responses, the real part of the VLF magnetic responses for the horizontal and vertical field components are shown in figure 39.3 over conductive bodies of different widths. The distinctive shape of the VLF magnetic responses over narrow and wide conductive bodies is readily apparent.

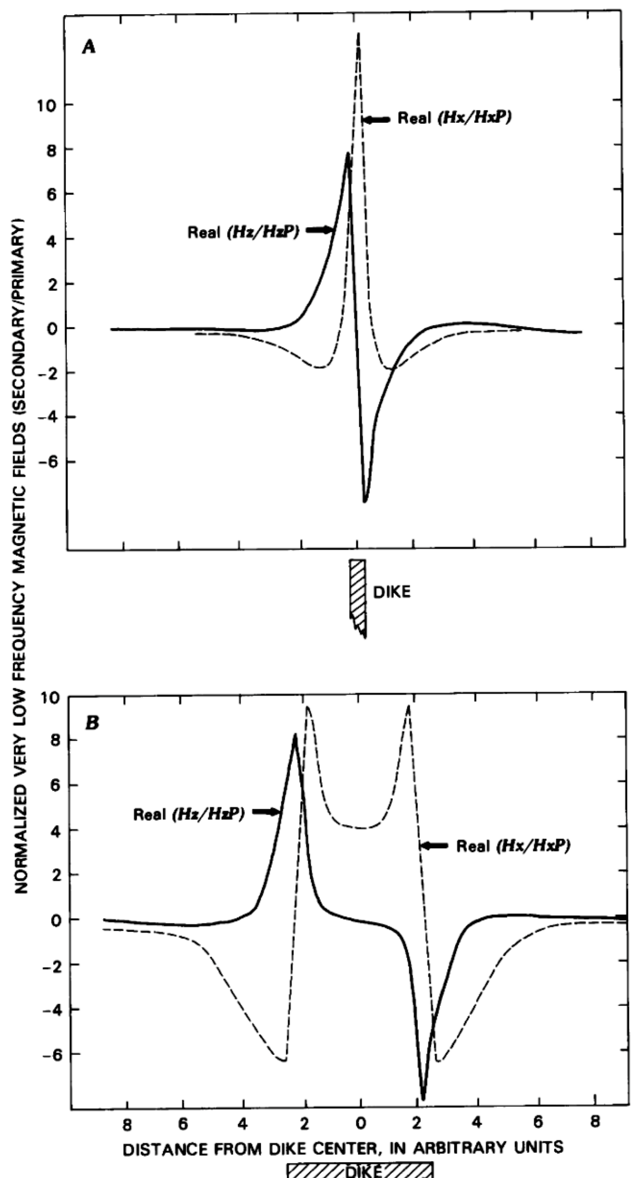

FIGURE 39.3.—VLF magnetic field component response over conductive dikes of 30-m (**A**) and 500-m (**B**) width. Conductivity contrast is 10, that is, a conductive dike of 0.01 mho/m in host of 0.001 mho/m. Horizontal (Hx) and vertical (Hz) magnetic fields have been normalized to primary (P) field components.

Factors affecting the resistivity of basalt over the rift systems of Kilauea and Mauna Loa Volcanoes are important in understanding the VLF data presented in this paper. In nonthermal areas, resistivities of basalt lava flows are $3\text{–}20 \times 10^3$ Ω-m (Keller and Rapolla, 1974; Zablocki, 1976). Zablocki (1978) suggests several possible causes for these high resistivities: (1) high permeability of the lava flows resulting in very little water in the zone of aeration above the local water table; (2) resistive pore water in the vadose zone, probably resulting from previous leaching of exchangeable ions from the rock by heavy rainfall; (3) negligible chemical alteration of the flows and surficial ash deposits, thereby maintaining to a minimum the amount of clays in the rock which can contribute to double-layer conductivity in the rock pores (Keller and Frischknecht, 1966).

In contrast to nonthermal areas, areas of recent volcanic activity along the rift systems are often associated with low resistivity (high conductivity) values. Conductive zones associated with magma injected from the summit reservoirs of Kilauea and Mauna Loa are generally relatively narrow, probably because of low thermal conductivity of the basalt, which impedes heat transfer from the injecting magma to the surrounding rocks (Zablocki, 1978). Basalt flows directly over eruptive fissures and related ground cracks become conductive by ascending hot mineralized water or vapor derived from the interaction of ground water with high-temperature magma in the injecting dikes. Large zones of conductive basalt are expected to be developed over magma reservoirs where thermal convection cells have been operative for long periods of time.

Factors other than thermal may also reduce ground resistivities. Thick soils are expected to contribute to lower apparent resistivity values than in areas where overburden is thin or absent. Such soils are widely present in the northwest and northern edges of the Kilauea survey area.

Some apparent resistivity lows along the edges of the survey areas may be an artifact of the automatic gridding program (Webring, 1981), which projects data 2 km beyond the end of real data. Thus, caution should be used when viewing automatically contoured data, particularly near the boundary of the survey area.

ACKNOWLEDGMENTS

The authors owe much to and acknowledge the contributions of many associates in the U.S. Geological Survey who were instrumental in the original concept of the airborne survey, in particular C.J. Zablocki, John Lockwood, and other scientists of the Hawaiian Volcano Observatory who conceived the project and assisted in the logistics during the actual survey. To the aircraft flight crew, Donald Rohret, electronic technician, and pilot M.G. Steward we extend thanks. To Frank Frischknecht who has led the research and development of the airborne VLF method and provided the authors with many helpful hints and suggestions during the compilation and interpretation of the data we extend a special thanks. Last but not least, we acknowledge the assistance of technicians Mark Sherrard and Pam Mohr who were extremely helpful in the actual compilation of the data. Obviously, responsibility for the validity of the interpretations presented here are the authors' alone.

MAGNETIC AND ELECTROMAGNETIC FEATURES

KILAUEA VOLCANO

Numerous magnetic features were delineated over the east and southwest rift zones of Kilauea Volcano. The most prominent magnetic feature on figure 39.4 is associated with the east rift of Kilauea Volcano and consists of linear dipole anomalies, of nearly 2,000-nT amplitude, extending eastward from the summit of Kilauea to within 7 km of the coast, where the dipole anomaly abruptly terminates as a linear feature. East of this termination point, several individual magnetic highs and lows characterize the magnetic expression of the rift zone.

An east-trending series of linear magnetic dipoles, having about one-half the amplitude of the east rift magnetic anomaly, are present 10–12 km farther north. The wavelength of this northernmost linear magnetic anomaly is 6 km, as compared to the east rift magnetic anomaly of about 2 km.

The southwest rift of Kilauea Volcano is characterized by a series of magnetic highs, generally aligned with the eruptive fissures, ground cracks, and scarps of the southwest rift zone, but mostly southeast of the surficial volcanic features.

A north- to northeast-trending belt of magnetic highs, only partially delineated by the low-level survey, is evident along the northwest to north edges of the Kilauea survey area in the more extensive aeromagnetic survey of Godson and others (1981).

The apparent resistivities of near surface (less than 100 m depth) lava flows in the central part of the Kilauea survey area range from under 100 to over 2,500 Ω-m (fig. 39.5). Steep apparent resistivity gradients along the northern edge of the Kilauea survey area are related to powerline interference (see Flanigan and others, 1986b). The steep apparent resistivity gradient along the southern part of the Kilauea survey area, where the survey aircraft flew over the ocean, is the response to the high resistivity contrast between rock and sea water. Several small (less than 1-km diameter) conductive zones are associated with Kilauea caldera and along the active parts of the east rift zone. Three conductive zones (40–250 Ω-m) trend north-northwest from near the seacoast to the east rift of Kilauea. Apparent resistivities of less than 400 Ω-m cover a large area south of Kilauea caldera.

VLF magnetic anomalies associated with zones of comparatively sharp lateral changes of conductivity are also shown on the apparent resistivity map (fig. 39.5). Where the VLF magnetic anomalies were detected by adjacent flightlines, they have been connected to indicate the general trend of the conductor axis. Trends of VLF magnetic anomalies follow volcanic features along the east and southwest rifts of Kilauea, along the southern part of Kilauea caldera, and along east-west conductors in the area south of Kilauea caldera.

Geophysical features discussed above have been combined in a single illustration for ease of discussion (fig. 39.6).

DISCUSSION OF RESULTS

The spatial relations of the magnetic source rocks to the VLF electromagnetic anomalies along the east rift of Kilauea Volcano is particularly interesting. The interpreted boundaries of the magnetic source rocks encompass most of the surficial expression of the east rift zone (cones, craters, and cracks) as shown by Stearns and Macdonald (1946). Assuming that the VLF magnetic anomalies are associated with narrow, shallow, abrupt changes of conductivity related to feeder dikes along the east rift, then the currently active zone extends south to at least Napau Crater (fig. 39.6), and generally along the southwest and south edges of the interpreted composite dike system built by earlier injections along the east rift zone (Swanson and others, 1976). East of Napau Crater, the active dike system as defined by the VLF magnetic anomalies (fig. 39.6) changes direction to the northeast and continues eastward along the central and northern part of the interpreted magnetic dike system. The reason for the shift to the central part of the interpreted composite dike system is not readily apparent.

Several indirect lines of evidence suggest a structure zone trending about normal to the east rift that may intersect the rift just east of Napau Crater. A north-northwest zone of conductive lava flows (marked R_1, fig. 39.6) intersects the east rift of Kilauea in the area just east of Napau Crater. Rocks are an order of magnitude more conductive than outside of the zone. Assuming the upper 50–60 m of basalt has been altered or contains higher amounts of conductive waters than outside of the zone, then a break in the impervious dikes constraining fluid flow on the southeast side of the rift similar to the reasoning hypothesized by Zablocki (1977, p. 9; Zablocki and Koyanagi, 1979) might be invoked.

Although no surface transverse structure is associated with this conductivity anomaly, several geologic features support this conclusion. Topographic contours within the conductive zone change in direction to the northeast. Fault scarps of the Hilina fault system have an apparent left-lateral offset in this area. Block movement to the southeast on the south flank of Kilauea Volcano, suggested by Fiske and Kinoshita (1969) and well documented by Swanson and others (1976), would allow for such transverse structures, particularly if the south flank is not being forced southward as a contiguous block.

The distribution of 1968–71 earthquakes (Koyanagi and others, 1972) in the south flank of Kilauea has a density pattern that delineates two aseismic zones parallel but offset from the shallow resistivity anomalies R_1 and R_2 (fig. 39.6). The seismicity is caused

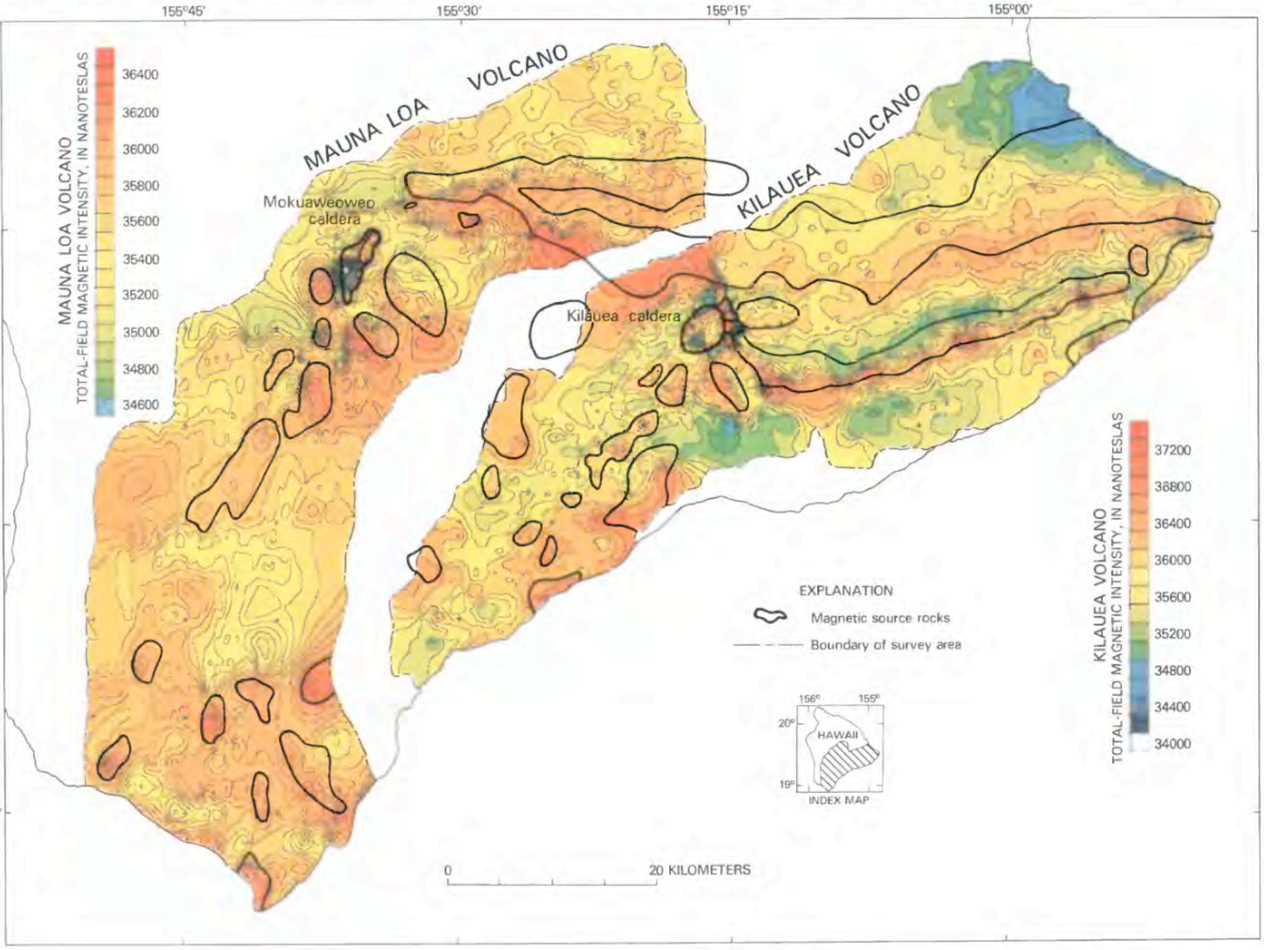

FIGURE 39.4.—Aeromagnetic map of total intensity of Earth's magnetic field over Kilauea and Mauna Loa rift systems.

by volcanic activity in the summit and the rift zones and the subsequent adjustment of the south flank to these stresses (Koyanagi, and others, 1972). If there is differential movement within the south flank, then transverse structures are likely along the edges of the blocks moving seaward from the rift zones. The Kealakakua and Kahuku faults are thought to represent the landward boundaries of sizable terrain subject to large-scale submarine block faulting on Mauna Loa's west flank (Lipman, 1980, fig. 2) analogous to movement of Kilauea's south flank.

Two other zones of conductive rocks, roughly transverse to the east rift were delineated farther east (R_2 and R_3, fig. 39.6). Conductive zone R_2 is situated at another apparent offset (left-lateral) in the currently active part of the rift zone. Here again rocks are considerably more conductive ($<160\ \Omega$-m) than the surrounding basalt flows. Though conductive zones R_1 and R_2 have not been confirmed by ground measurements, independent geophysical work generally confirms the existence of the third transverse conductive zone (Zablocki, 1977). A significant self-potential (SP) anomaly, aligned northwest, was attributed by Zablocki and Koyanagi (1979) to permeable fractures that maintain fluid continuity with a heat source. Numerous warm springs along the downslope beaches and the occurrence of hot (55 °C) brackish water in wells in the conductive area (Macdonald, 1973) support the conclusion that the zone is related to a transverse structure that has offset the rift zone in a left-lateral sense. The linear dipole magnetic anomaly also has a left-lateral offset at this point. A small (300 nT) magnetic low, correlative with a resistivity low, is centered over the Puulenna Crater area, suggesting that Zablocki and Koyanagi's (1979) heat source may still be above the Curie temperature.

An apparent reversely polarized magnetic anomaly is present over the Kapoho Crater area (figs. 39.4, 39.6). The detailed data (fig. 39.7*A*) show a dipole anomaly with a 900-nT low south of a 700-nT high. The apex of the high-low is oriented about 30° counterclockwise to the Earth's present magnetic field direction. If the direction of the remanent magnetic field were exactly opposite the Earth's present magnetic field, the alignment of the dipole anomaly would be in the same direction as the Earth's present magnetic field and the sign of the dipole anomaly would be opposite, that is, with a magnetic high north of the magnetic low. A three-dimensional magnetic anomaly was computed over a cube-shaped body 2.5 km

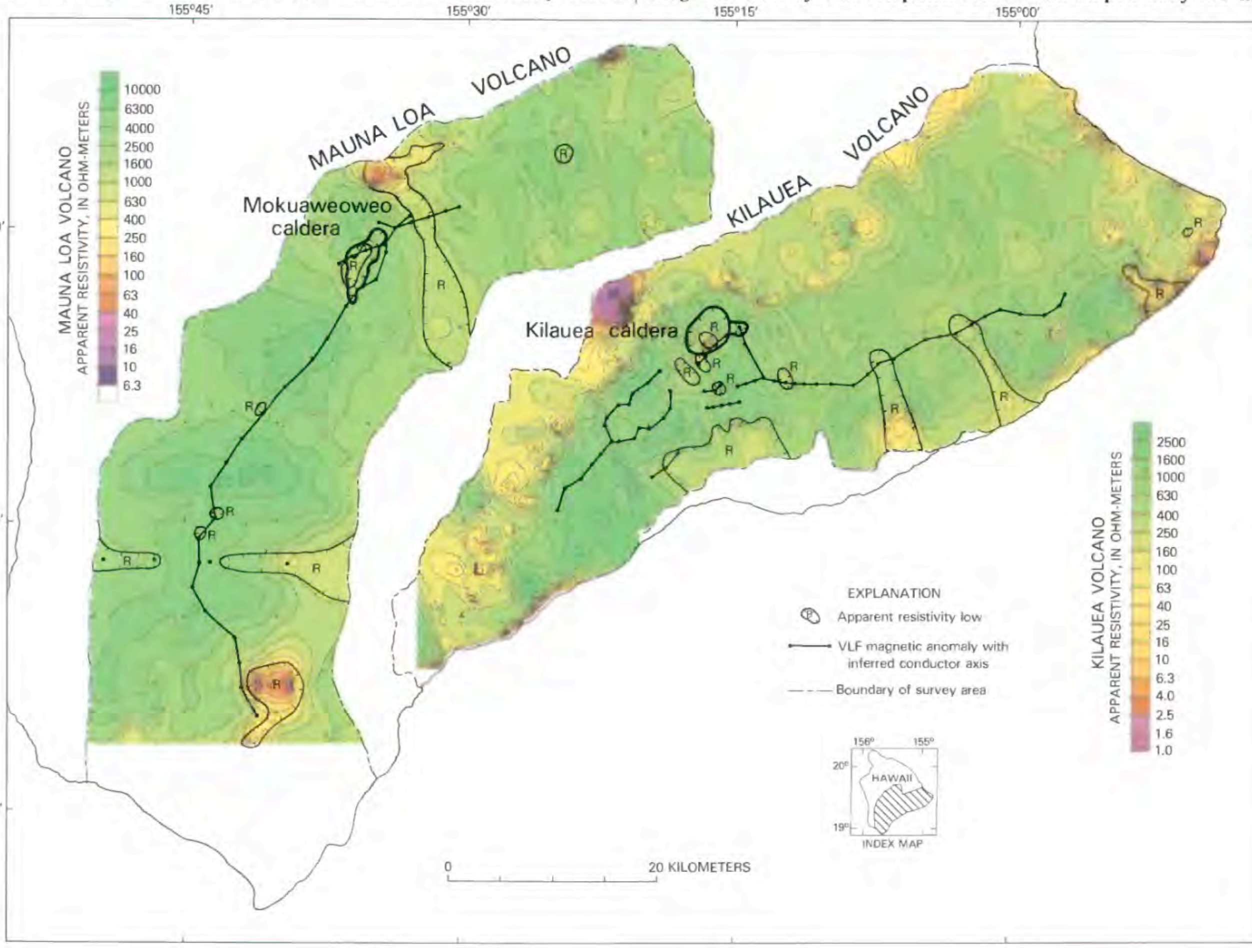

FIGURE 39.5.—Apparent resistivity map and location of VLF magnetic anomalies relative to Kilauea and Mauna Loa rift systems.

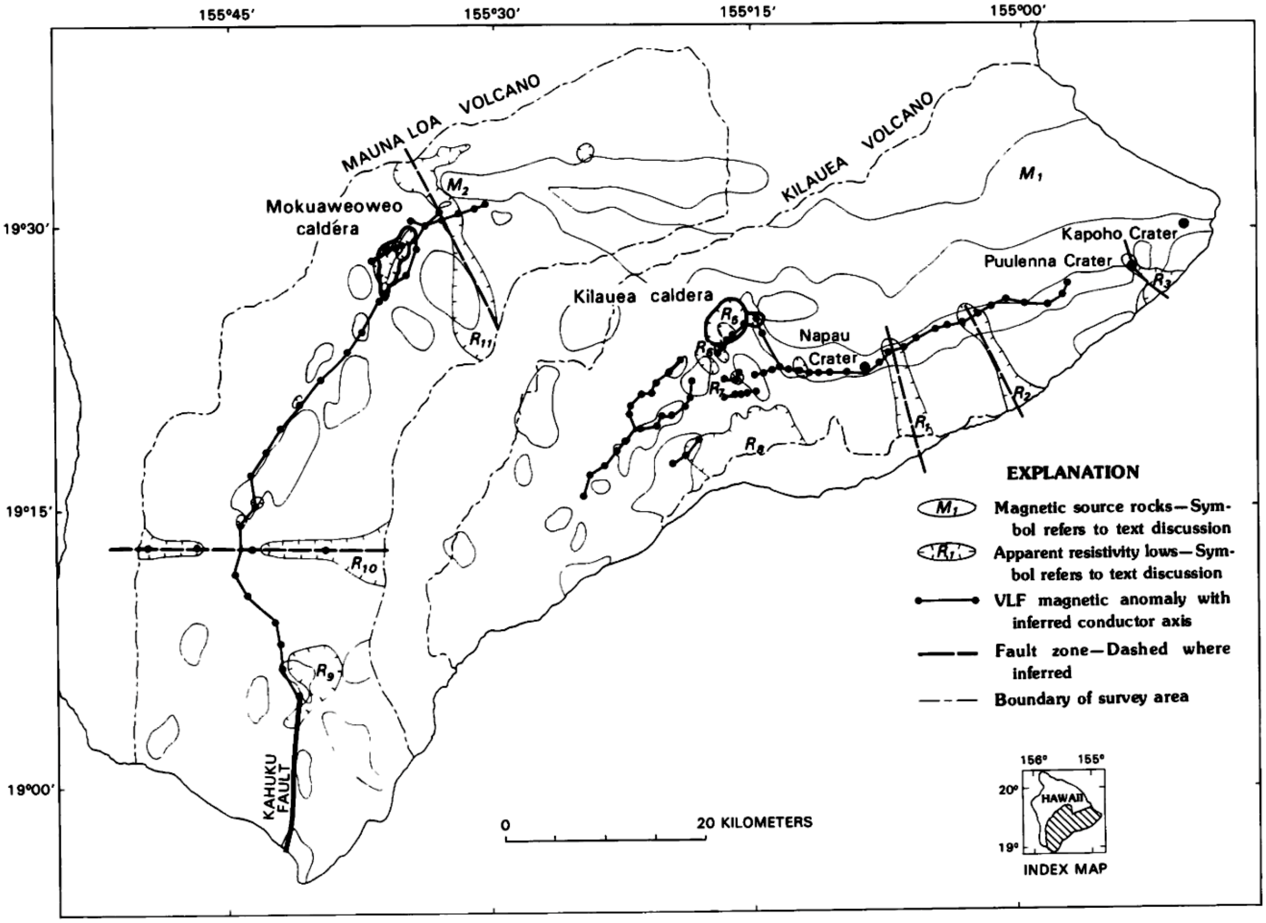

FIGURE 39.6.—Interpretive map of Kilauea and Mauna Loa rift systems, showing magnetic source rock, apparent resistivity anomalies, and VLF magnetic anomalies.

on each side (fig. 39.7*B*; from T.G. Hildenbrand, written commun., 1984). In order to produce a magnetic anomaly that matches the observed data (fig. 39.7*A*) it was necessary to rotate the remanent magnetic direction 30° counterclockwise from the exact opposite of the Earth's present field direction. Thus, one possible explanation to the Kapoho Crater apparently reversed dipole magnetic anomaly is that a body of rock of about 15.6 km^3 cooled when the Earth's magnetic field was in a period of reversal. An alternate explanation when considering the magnetic setting of the dipole anomaly is that the magnetic high is part of a broad magnetic high extending eastward from the summit of Mauna Loa (M_1, fig. 39.6) and the magnetic low is the magnetic expression of a magma chamber still above the Curie temperature and thus nonmagnetic. Norris (1976), commenting on data from a ground magnetic survey, observed a magnetic high over Kapoho Crater and suggested "that if subsequent measurements were to show a proportionate magnetic low near the south rim, then it could be concluded that there is an anomalously nonmagnetic body beneath Kapoho Crater." To test this theory, a configuration of magnetic bodies was assembled and the magnetic response calculated (M.W. Webring, written commun., 1984). Susceptibilities and vertices describing the body location were allowed to vary in order for the theoretical calculations to best-fit the observed data in a least-squares sense (fig. 39.8). Considering the oversimplification of the theoretical model the calculated data fit the observed data reasonably well. The model represents intrusive dike rocks associated with the east rifts of Mauna Loa and Kilauea separated by a magma chamber all of which have been buried by flows from Kilauea's east rift zone.

Additional geologic and geophysical evidence is necessary to determine which of the two (if either) above possible explanations for the apparent reversed dipole anomaly over Kapoho Crater is the most geologically reasonable. Reversely polarized rocks have not been reported for the Island of Hawaii where they are considered to be younger than the last period of magnetic field reversal, thus suggesting that the first model is unreasonable. We would expect low apparent resistivities caused by alteration of flow rocks lying directly

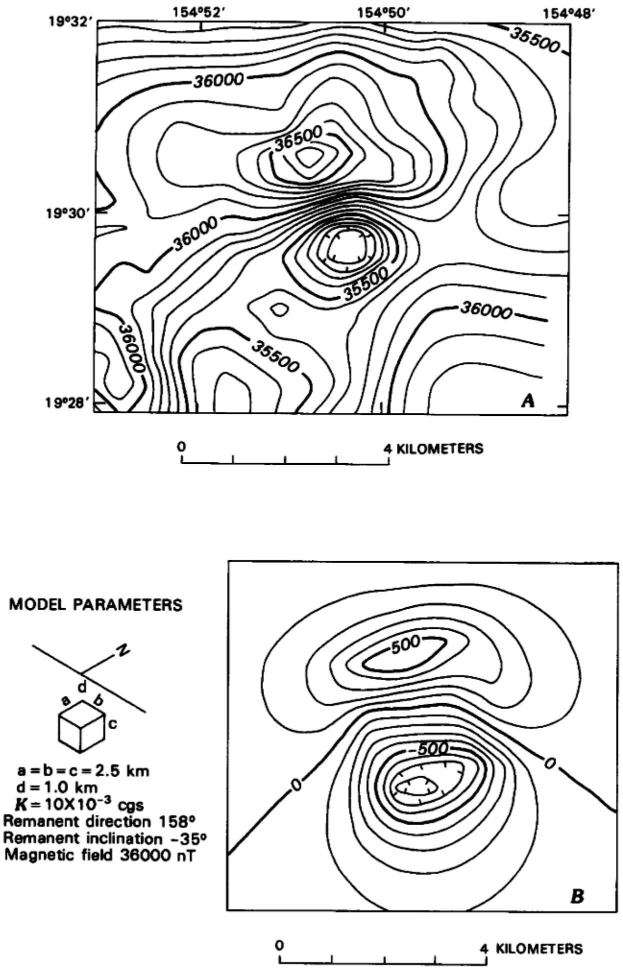

FIGURE 39.7.—Magnetic contour maps of Kapoho Crater. Contour interval is 100 nT. Hachures indicate closed low. ***A***, Observed magnetic anomaly. ***B***, Theoretical magnetic anomaly over assumed magnetic body (from T.G. Hildenbrand, written commun., 1984). Remanent magnetization direction assumed nearly reversed to direction of Earth's present magnetic field.

over the magma chamber as assumed in the second model, and apparent resistivity lows were not observed. However, recent volcanic activity in the Kapoho Crater area may have masked any near-surface apparent resistivity anomalies associated with the inferred underlying magma chamber. Dipole resistivity data presented by Skokan (1974, fig. 29b) indicates that a deep conductivity anomaly may be present in the Kapoho Crater area. This conductivity anomaly may be related to intrusion of sea water or possibly to a very conductive magma body.

Numerous aeromagnetic anomalies are present in the Kilauea Volcano summit area. Terrain-induced magnetic anomalies occur over the abrupt edges of the caldera (Decker, 1963) and are particularly noticeably over Halemaumau and Kilauea Iki Craters. Models (not shown) computed at 90 m above terrain features in the Kilauea summit area have an amplitude of about 150 nT, less than 20 percent of the observed anomalies, suggesting the observed anomaly is a combined aeromagnetic response of topography and geologic magnetic sources. Magnetic source rocks trending north-northwest intersect northeast- east-trending magnetic sources in the summit area.

A simple theoretical model over an assumed 1-km diameter, 4-km deep nonmagnetic magma chamber south of Halemaumau, as suggested by Eaton (1962), would produce an aeromagnetic anomaly of about 100 nT. It is doubtful that one could positively identify the Kilauea summit magma chamber by magnetic modeling because of the presence of magnetic source rocks of unknown configuration

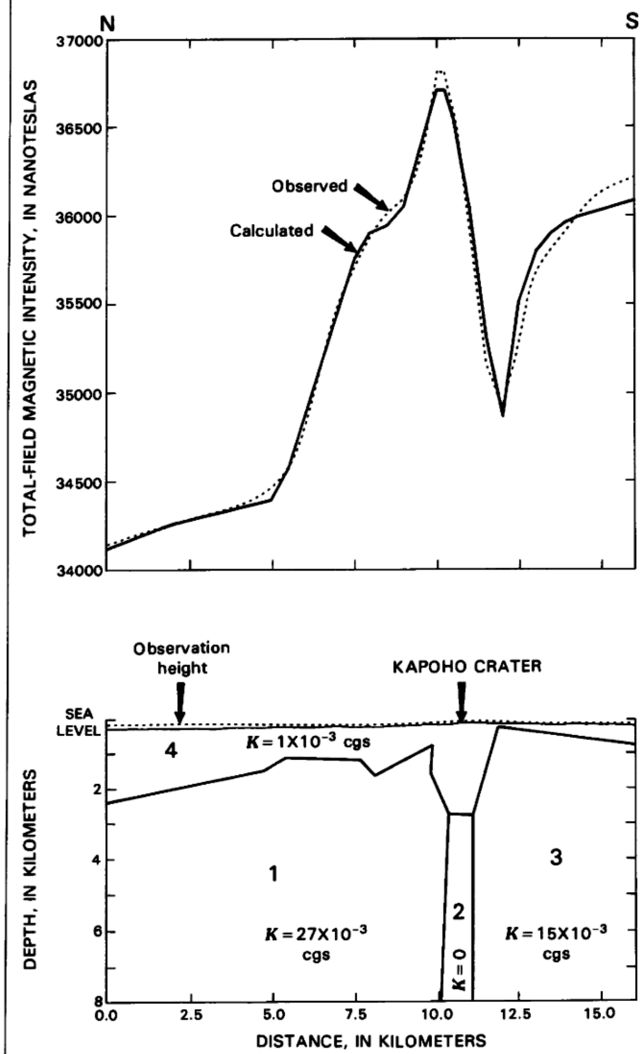

FIGURE 39.8.—Theoretical 2½-dimensional model over Kapoho Crater area assuming intrusive dike rocks to north (body 1) and south (body 3) of Kapoho Crater and nonmagnetic magma chamber (body 2) about 2 km deep beneath flow rocks (body 4). Susceptibilities (K) are shown in cgs units.

which are the apparent sources of the bulk of the observed aeromagnetic anomaly.

Apparent resistivity anomalies in the Kilauea summit area are thought to be caused by conductive rocks related to eruptive volcanic features similar to those outlined by Zablocki (1978, fig. 24) in the Sand Spit horst area. The airborne VLF data indicate an apparent resistivity low (R_5, fig. 39.6) just southeast of Halemaumau Crater. The airborne VLF magnetic-anomaly locations correspond very closely to Zablocki's VLF tilt and ellipticity measurement across Sand Spit horst. Apparent resistivity low R_5 lies north of the VLF magnetic anomaly, suggesting surface rocks are more conductive than to the south. Eaton (1962), by use of tilt measurements, indicates that the pre- and post-eruptive swelling and subsidence of Kilauea point to a magma reservoir just south of Halemaumau Crater. The VLF apparent resistivity data do not reflect directly the magma reservoir, but indirectly indicate increased alteration and (or) conductive hot circulating fluids associated with rock overlying the reservoir.

Other apparent resistivity lows have been delineated in the area southwest of Kilauea caldera (R_6, fig. 6). These conductive zones were also detected by surface VLF measurements by Zablocki (1978), who attributed them to conductive anomalies associated to cracks and hot steaming fissures. Apparent resistivity low R_7 (fig. 39.6) is thought to be associated with conductive features caused by intrusion into the Koae fault system at its junction with the east rift zone as described by Duffield (1975), and generally confirms ground geophysical observations of Jackson and Sako (1979). A broad apparent resistivity low (R_8, fig. 39.6) covers a significant area just north of the Hilina fault scarps south of Kilauea caldera. Gravity subsidence of large blocks of the unbuttressed south flank of Kilauea is largely responsible for the Hilina fault system (Swanson and others, 1976, p. 33). In places the surface of the fault blocks are nearly level or dip gently inland. These gentle slopes suggest the possibility of soils, which would contribute to low apparent resistivities. However, only a thin layer of ash is present in the near-surface rocks that could contribute to low VLF apparent resistivities (D.B. Jackson, written commun., 1985).

VLF magnetic anomalies are associated with many of the apparent resistivity anomalies in the Kilauea summit area (fig. 39.6). Most notable are VLF magnetic anomalies related to the conductive anomalies in the southern part of Kilauea caldera and to the southwest and an east-trending conductive zone parallel to the Koae fault system. Abrupt lateral changes in resistivity contrast are the causes for the VLF magnetic anomalies, and inasmuch as only one anomaly was detected at the edge of the feature they are considered to be narrow features. One would expect to see two VLF magnetic anomalies, one at each edge, of a broad conductive feature that had a sharp lateral resistivity contrast at each edge.

Several VLF magnetic anomalies extend southwest from Kilauea caldera. One of these was briefly ground-checked and thought to be related to a seismic cable extending from the Hawaiian Volcano Observatory. This anomaly was not included on figures 39.5 and 39.6. However, the other long VLF magnetic anomalies shown may have similar sources (J.P. Kauahikaua, written commun., 1984).

MAUNA LOA VOLCANO

Magnetic data (fig. 39.4) in the Mauna Loa survey area are similar to that recorded over Kilauea Volcano in several ways. The northeast rift of Mauna Loa, like the east rift of Kilauea, is characterized by linear magnetic dipoles (M_2, fig. 39.6) extending eastward from several kilometers northeast of Mokuaweoweo caldera; however, the amplitude of the magnetic dipoles is about one-half that of the Kilauea east rift. A southeast-trending linear magnetic dipole intersects the Mauna Loa east rift about 15 km east of the summit and appears to be contiguous with the east-west long-wavelength (6 km) linear magnetic dipole (M_1, fig. 39.6) crossing the northern part of the Kilauea survey area. Steep magnetic gradients outline Mokuaweoweo caldera.

The magnetic expression of the Mauna Loa southwest rift, like the Kilauea southwest rift, is composed of discontinuous linear magnetic highs of a few hundred nanoteslas extending southwest from the summit to beyond the southern tip of the island. The magnetic data accurately reflect the prominent westward bulge in the rift zone coincident with the topographic ridge of Mauna Loa's southwest rift zone (Lipman, 1979).

Two conspicuous breaks in the linear magnetic anomalies occur in the Mauna Loa magnetic data: (1) a northwest-trending magnetic low crosses the northeast rift zone at the northeast end of Mokuaweoweo caldera and (2) an east-west magnetic low crosses the southwest rift zone near the apex of the bulge.

Qualitative interpretive lines (fig. 39.4) show the approximate location of intrusive rock considered to be the source of the magnetic anomalies mentioned above.

Apparent resistivities of near-surface rocks in the Mauna Loa survey area range from 16 to over 10^4 Ω-m (fig. 39.5). Lava flows of highest apparent resistivity are present mainly in the upper one-third of the southwest rift zone. Apparent resistivity lows (<1,000 Ω-m) occur over Mokuaweoweo caldera and in the southern part of the survey area; these lows coincide with the two transverse magnetic breaks mentioned above. VLF magnetic anomalies (fig. 39.5) were detected along the entire length of the southwest rift zone except near the southern tip of the island where powerline interference and an equipment malfunction rendered the VLF data unuseable. Conductive zones produce VLF magnetic anomalies in Mokuaweoweo caldera and along its southeast edge that extends northeast for 10 km or more, beyond which no other VLF magnetic anomalies were seen. Northeast of the caldera, pairs of VLF magnetic anomalies, spaced 1 km or more apart along the flightline, were detected on several flightlines.

DISCUSSION OF RESULTS

Injection of magma into Hawaiian shield volcanoes, surface eruptions, and subsequent gravitational slumping of the flanks of the volcanoes are important mechanisms for volcano growth (Swanson and others, 1976; Lipman, 1979; Normark, 1979).

The structural complexities and growth of Mauna Loa, like Kilauea Volcano, reflect the interaction of concurrent and past volcanic activity in adjacent volcanoes (Fiske and Jackson, 1972; Lipman, 1980). For example, Mauna Kea Volcano interferes with the unrestricted growth of Mauna Loa by forming a northern buttress. The same is true of Kilauea Volcano, which is buttressed on the northwest by Mauna Loa. Lipman (1979, 1980) postulates that the buttressing effect of Mauna Kea and the growing Kilauea Volcano has affected the recent growth of Mauna Loa: (1) recent volcanic activity along the Mauna Loa northeast rift zone has been limited to the first 20 km from the summit; (2) buttressing of the south flank of Mauna Loa by the growing Kilauea Volcano has limited southeast gravitational slumping of that flank, with the net result that the active part of the Mauna Loa southwest rift zone has migrated to the west; (3) westward migration of the active part of the rift zone accompanied by block slumping to the west accounts for the west bulge in the zone.

The spatial relation of the interpreted magnetic source rocks (dike and dike swarms) and the VLF magnetic data (narrow conductive zones) add weight to Lipman's observations. For instance, VLF magnetic anomalies (fig. 39.6), probably associated with the active part of the Mauna Loa southwest rift zone, follow the fissure vents, spatter cones, and pit craters that are thought to be less than 5,000 yr old. Magnetic source rocks generally lie to the east of the VLF magnetic anomalies, suggesting westward migration of the active part of the rift zone similar to the postulated south to southeast migration of the active rift zone on the upper one-third of Kilauea's east rift zone (Swanson and others, 1976). The eastward offset of the magnetic anomalies in relation to the VLF magnetic anomalies also confirms Lipman's (1980) gravity observations, which generally indicate dense rocks are present east of the surface evidence of recent volcanic activity. The dense rocks are interpreted to be dikes and dike swarms of greater density than the adjacent rocks.

Several small, circular, apparent resistivity lows with associated VLF magnetic anomalies along the active part of the Mauna Loa southwest rift zone are thought to reflect conductive rocks associated with volcanic vents.

Another subcircular apparent resistivity low (R_9, fig. 39.6) covers a significantly larger area (30 km^2) than the small conductive zones mentioned above. The long axis of apparent resistivity low R_9 is aligned roughly north-south and lies just east of Kahuku fault (Lipman, 1980, fig. 1). Aeromagnetic anomalies southeast of apparent resistivity low R_9 are aligned northwest-southeast and appear to be a continuation of the southeast structural trend of the rift zone at the lower end of the bulge (fig. 39.6). Apparent resistivity low R_9 is thought to be related to the high conductivity of near-surface rocks at the intersection of Kahuku fault and an inferred northwest- to southeast-trending fault zone, possibly the northwest extension of Waiohinu fault (Malahoff and Wollard, 1966). The characteristics of the conductive rock in the inferred fault intersection area are unknown; however, the salinity of intrapore fluids and clay content in the zone may contribute to the low apparent resistivity of the zone. The anomaly also appears to coincide with the 1868 eruption vent. The 1868 eruption was accompanied by movement along the Waiohinu fault, all of which suggest a possible thermal anomaly as the source of the observed resistivity anomaly.

An east-west apparent resistivity low (R_{10}, fig. 39.6) cuts across the southwest rift zone a few kilometers north of the apex of the bulge in the rift zone. The east-west trend is along the aircraft flightline direction so the possibility of an equipment-base shift that would contribute to such an apparent resistivity low was considered. The anomaly is considered valid for three reasons: (1) it was detected on three successive flightlines, thus its width (north-south) is at least 3.2 km; (2) the east-west apparent resistivity anomaly is coincident with an east-west aeromagnetic low, as seen on, not only the aeromagnetic data presented here, but also the 300-m flight-height aeromagnetic survey of Godson and others (1981); (3) the high-level (12,000-ft barometric) aeromagnetic data of Malahoff and Wollard (1966) also show a similar break in the magnetic data in this area. Malahoff and Wollard (1966, p. 289) interpret the east-west to southeast magnetic feature to be related to a now-buried ancient volcanic complex lying along an east-west rift zone crossing the Hawaiian Ridge.

Assuming that a deep-seated crustal fracture zone crosses the Mauna Loa southwest rift zone at the apex of the bulge, it has affected the conductivity of the near-surface rocks. The most obvious reason is near-surface water held in by rift-related dikes flows out and downslope along the transverse structure, analogous to transverse structures on Kilauea's east rift zone. Several VLF magnetic anomalies were detected on one flightline crossing the area, indicating that in some places there are rather sharp boundaries of rock of differing resistivity. Though the Malahoff and Wollard aeromagnetic survey was better suited to detect deep magnetic sources, there is apparently some shallow geophysical expression of the same features reflected in the low-level aeromagnetic-electromagnetic data presented here.

The aeromagnetic and electromagnetic data follow an asymmetric bulge in the topographic and geologic expression of the Mauna Loa southwest rift zone, and it seems plausible that the east-west zone just discussed has played some part in the development of this asymmetry. Of course it is obvious that the buttressing effect of Kilauea on the east-southeast flank of Mauna Loa prevents growth of Mauna Loa in the southeast direction, which adequately accounts for the westward migration of the active part of the southwest rift zone, but it does not address the asymmetry seen in the geophysical data. The subaerial Alika slide, a result of oversteeping of Mauna Loa's west flank, (Normark, 1979) extends 80 km off the west coast and may have been controlled on the south by the transverse zone inferred from the geophysical data.

Another zone transverse to the northeast rift of Mauna Loa has a similar geophysical relation to that just discussed; that is, it is a northwest-trending apparent resistivity low (R_{11}, fig. 39.6) coincident with an aeromagnetic low and occurs just north of Mokuaweoweo caldera. Here, once again, the high-level aeromagnetic data of Malahoff and Wollard (1966, fig. 13) indicate a northwest-trending magnetic low that crosses Mauna Loa's northeast rift zone in the same area. Many eruptive fissures cut the north flank of Mauna Loa at high angles (Lockwood, 1979) and may be indicative of stresses active during the evolution of Mauna Loa that are also responsible for the aeromagnetic and electromagnetic features seen in the near-surface rocks. Here, once again, northeast-trending rift dikes ruptured by a transverse structure may allow near-surface water to flow downslope and are, thus, the cause of the conductive anomaly.

A VLF magnetic anomaly, thought to be associated with eruptive volcanic features, extends about 10 km northeast of Mauna Loa summit (fig. 39.6). The VLF magnetic anomaly defines a conductor axis cutting the northwest-trending apparent resistivity low and generally lies south of magnetic source rocks (M_2, fig. 39.6). These relations imply that in the first 10 km northeast from the summit the presently active part of the rift zone has moved south relative to presumably older complex dikes (the source of the aeromagnetic anomalies). Farther to the east no VLF magnetic anomalies were detected, although volcanic cones extend for 25 km or more east of the summit. Perhaps buttressing of the lower part of Mauna Loa's northeast rift zone by Mauna Kea Volcano on the north and Kilauea Volcano on the south has restricted volcanic activity. Or perhaps conductive zones associated with feeder dikes are deeper, having been covered by lava flows occurring at higher elevations, hence are at a depth greater than can be detected by the VLF method. Alternatively, the presence of VLF magnetic anomalies only along the upper (10 km) part of Mauna Loa's northeast rift zone may be more closely related to the presence of greater amounts of conductive electrolytes than occur farther east along the rift zone.

The middle to lower Mauna Loa northeast rift zone is implied to be complex by the distribution of dike swarms interpreted as the aeromagnetic source rocks in area M_1 (fig. 39.6). The aeromagnetic expression of the northeast rift zone divides about 15 km from the summit, one fork continuing east, the other, southeast—toward Kilauea Volcano. Whether this southeast fork represents a one-time interconnection between the volcanoes is not known. It is almost certainly an early evolutionary feature of Mauna Loa development because: (1) prehistoric volcanic centers, if they ever existed, are absent along this zone, having been covered by flows from the summit area and (2) the long wavelength of the magnetic anomaly suggests deeper source rocks than associated with the Kilauea east rift zone.

SUMMARY AND CONCLUSIONS

Linear magnetic dipoles reflect intrusive dikes along the rift zones of Kilauea and Mauna Loa Volcanoes. The linear magnetic anomalies, normally polarized, vary in shape and amplitude according to the orientation of the source rocks with respect to the Earth's present field direction. At least 2 km of southward displacement of Kilauea's south flank is necessary to accommodate the intrusive dike system associated with the Kilauea east rift. The linear magnetic dipole anomaly along the Kilauea east rift zone is terminated on the eastern end of the island by an interpreted structure transverse to the rift zone. The magnetic data suggest a left-lateral offset of about 1.5 km in the rift zone beyond the termination point.

VLF magnetic anomalies are interpreted to reflect zones of conductive rocks of limited horizontal extent, but having relatively sharp lateral boundaries with large conductivity contrasts, and are interpreted as defining the currently active part of the rift zones. Most of the VLF magnetic anomalies are present along eruptive and intrusive volcanic features, thus confirming earlier ground electrical geophysical surveys.

The spatial relation of interpreted magnetic source rocks to the active part of the rift zones are important indicators of the recent evolutionary development of Kilauea and Mauna Loa Volcanoes. In the upper one-third of the Kilauea east rift zone the active part of the rift zone lies along the southern edge of interpreted magnetic source rocks, correlating with independent observations that the south flank of Kilauea is being forceably moved to the south by repeated magma injection from the summit reservoir. Just east of Napau Crater the active part of the Kilauea east rift zone is over the central and northern part of the interpreted intrusive dike system, suggesting controlling factors such as transverse fault zones caused by differential movement of Kilauea's south flank. Large-scale block slumping with accompanying transverse boundary faults of Kilauea's south flank are proposed as a possible explanation for the spatial relation of the active rift zone to early magnetic dike rocks. Rupture of impervious dikes bounding the east rift zone allowing downslope movement of conductive hot-water electrolytes may produce apparent resistivity lows along the postulated transverse boundary faults.

Two explanations for an apparently reversely magnetized magnetic dipole over the Kapoho Crater area are suggested from theoretical magnetic models. One model assumes a 2.5-km cube-shaped body of rock in which the remanent magnetic direction is nearly opposite the Earth's present magnetic field direction. This model has two drawbacks: (1) reversely polarized magnetic rocks have not been reported on the Island of Hawaii; (2) in order to compute a magnetic response of this theoretical model that closely resembles the observed data, the remanent magnetic direction must be rotated about 30° counterclockwise. This rotation infers that either there has been postcooling rotation of that part of the island or that the remanent magnetic field direction was not exactly opposite to the Earth's present magnetic field direction, a condition seldom seen or recognized in magnetic data interpretation. The second model assumes magnetic dike rocks north and south of Kapoho Crater are separated by a nonmagnetic shallow magma chamber. Absence of a resistivity anomaly over the proposed shallow magma chamber may be due to covering by young resistive lava flows.

The effects of concurrent growth of Kilauea and Mauna Loa Volcanoes are reflected in the magnetic and electromagnetic data, most clearly in evidence along Mauna Loa's southwest rift zone. Interpreted source rocks for aeromagnetic anomalies along the upper part of Mauna Loa's southwest rift zone lie east of the active rift zone as defined by VLF magnetic anomalies and are consistent with gravity data and geologic observations indicative of westward migration of the rift zone. An east-west aeromagnetic and apparent resistivity low near the apex of the bulge in the Mauna Loa southwest rift zone is interpreted as offset of water-constraining dikes along the southwest rift by a transverse structure, allowing conductive ground water to flow downslope. The Alika landslide which incorporates a large part of the west flank of Mauna Loa, may have been controlled on the southern boundary by this inferred transverse structure.

A northwest-trending zone just north of Mokuaweoweo caldera, reflected as apparent resistivity and aeromagnetic lows in the airborne data, is interpreted as another transverse structure that has allowed impounded near-surface water to flow downslope.

Many of the conclusions and observations presented here have a reasonable correlation with the observations of other earth scientists, others are highly speculative and hopefully will stimulate future research in understanding the evolutionary development of these two very interesting Hawaiian volcanoes.

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