

## Magnetic Surveys Over the Hawaiian Islands and Their Geologic Implications<sup>1</sup>

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**ABSTRACT:** A geophysical and geological analysis is made of a total field magnetic survey of the major islands of Hawaii. It is established that the regional distortion of the earth's normal magnetic field due to the topographic mass of the Hawaiian Ridge rising in places to over 30,000 ft above the ocean floor seldom exceeds 150 gammas. On each island, local magnetic anomalies having the form of lenticular and circular dipoles are found. The lenticular dipole anomalies appear to be related to crustal rifts that have been invaded by magmatic material of mantle origin, and the circular dipole anomalies are associated with primary areas of volcanic eruption. Although the inferred crustal rifts have surface geologic expression in some areas, such as the Koolau Mountains on Oahu, for the most part they do not. Furthermore, offshore magnetic data indicate that these features extend beyond the islands and out into the adjacent, deep-water, oceanic area where they can be traced for 100 miles or more. The most pronounced of these features is associated with the ocean floor Molokai Fracture Zone, which magnetically extends across the Hawaiian Ridge without interruption for an unknown distance to the west. The circular dipole anomalies appear to represent the effect of intrusions in volcanic pipes or vents rising from these crustal rifts which strike essentially east-west on the islands of Hawaii, Lanai, Maui, and Molokai, and west northwest-east southeast on Oahu, Kauai, and Niihau. With two exceptions, all of the anomalies indicate normal polarization conformable with the earth's present field.

DURING THE YEAR 1964, the authors carried out the first of a series of planned magnetic surveys over the Hawaiian Ridge and adjacent oceanic area. The area covered extends from the island of Kauai on the north to the island of Hawaii on the south.

In this present paper, the magnetic results are examined on both a qualitative and a quantitative basis as to their relation to the centers of volcanism which built the Hawaiian Ridge and to the primary geologic tectonic trends having surface expression or bathymetric expression on the ocean floor. As will be shown, good correlations exist between the pattern of magnetic anomaly values and the volcanic features of the islands as well as the oceanic rifts having bathymetric expression. In order to minimize the magnetic effects of local changes in geology, soils, and the terrain associated with

mountains such as Mauna Kea (elevation 13,796 ft), the magnetic profiles were flown at least 2,000 ft above the ground surface. Although a complex pattern of magnetic anomalies is obtained because of the low magnetic latitude of Hawaii, the interpretation is straightforward. Depth and size estimations were based on the interpretive procedures of Vacquier et al. (1951) as well as on the basis of magnetic susceptibility-remnance measurements. These results were then compared with those determined from other geophysical measurements and the geologic probability of the anomalous bodies assessed. Finally, the magnetic effects of the derived geologic bodies were computed, using a two-dimensional, high-speed computer program and the derived theoretical profiles compared with those observed. All the profiles used in these comparisons were corrected for terrain. Because the regional magnetic gradient at the low magnetic latitude of Hawaii does not exceed 6 gammas per mile, it

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is not necessary to remove the regional magnetic gradient to bring out the relatively large magnetic anomalies ranging from 500 to 2,000 gammas. All anomaly maps were corrected for heading errors which, in general, did not exceed 40 gammas.

#### METHODS AND MATERIALS

##### *Aircraft and Instrumentation*

Most of the observations were obtained by using an Elsec proton magnetometer towed by an aircraft. The sea north of Maui over the buried extension of the Molokai Fracture Zone was surveyed using RV "Teritu" and the U. S. Coast and Geodetic Survey ship "Surveyor." Data for other adjacent marine areas had been surveyed earlier by the Scripps Institution of Oceanography (Arthur D. Raff, personal communication) and the U. S. Naval Oceanographic Office (1962).

The aircraft used for the program was an "E" model of the Stinson L-5 powered by a 190 horsepower Lycoming O-435-1 engine. The magnetic measurements were made with the Elsec magnetometer with a polarization time of 7 seconds. For the speed of the aircraft, flying at approximately 100 miles per hr, this polarization interval permitted a surface sampling interval of 819 ft (250 m). The proton procession signal was registered digitally on a dial readout and recorded by hand in the aircraft.

A total of 18,000 miles was flown in checking out the equipment design, operation, and actual data flights. Access doors opened the right-hand side of the aircraft fuselage, allowing stowage of all equipment needed for the project. An experimental certificate was obtained from the F. A. A. on the aircraft to permit the opening of the side door in flight in order to lower the "bird" which contained the magnetometer sensing head over the side for trailing behind the aircraft. The Elsec magnetometer with its incorporated power supply was placed to the right of the rear seat for operation by the observer. The door was closed after the 100-ft cable was fully extended. The drag induced by the trailing of the bird reduced the airspeed by approximately 5 miles per hr.

The bird was suspended from the aircraft by a braided nylon rope through which passed the

coaxial cable to the magnetometer head. The end of the nylon suspension rope was anchored to a ring welded to the fuselage structure. The bird was designed to be of sufficient size to accommodate the rotation of the sensing head. Prior to each flight, the head was oriented in an east-west direction without regard to the direction of the flight lines. The bird was constructed of a hand lay-up of woven fiberglass cloth and reinforcing mat with polyester resin. The finished laminate was  $\frac{1}{8}$  inch thick. Fins made of  $\frac{1}{4}$ -inch plywood supported the fiberglass-reinforced tail ring.

Numerous flight tests were conducted to establish the suspension point of the bird for the best flight characteristics. This point was found to be  $10\frac{1}{2}$  inches aft of the nose. A spoiler of triangular cross section was added to the top nose surface to decrease the aerodynamic lift of the bird. If the bird was suspended at the incorrect point, an ever-increasing pendulum effect was encountered. The first model of the bird proved unstable. This instability was corrected by lengthening the fins by 4 inches. It was necessary to fly during periods when air turbulence was at a low level or nonexistent in order to obtain valid data. When heavy turbulence was encountered, the bird was immediately retrieved for the safety of the bird and the aircraft. During the project, the bird was flown at speeds up to 100 miles per hr, and on only one occasion during the actual data flights did the bird demonstrate any unusual flight characteristics. This was during a short period of extreme turbulence which occurred over the island of Hawaii near Kawaihae. Severe pitching resulted before the bird could be retrieved into the aircraft.

Navigational checks and positioning were accomplished by a combination of pilotage and dead reckoning. Flight lines were marked on topographical maps of a 1/62,500 scale, with direct observations being made on surface cultural and topographical features during the flights. On over-sea flights, the track, speed, and drift rate were recorded over land and then extrapolated over the seaward portion of the flight line. Horizontal positioning of any flight line of the survey is regarded to be better than the order of 500 ft or 150 m. The over-land flight lines were spread at 1-mile intervals.

Absolute ceiling of the aircraft with all equipment aboard was 15,500 ft. Indicated cruising airspeed of the aircraft with the bird in tow at 10,000 ft was 80 miles per hr, and at 15,000 ft the indicated airspeed was 73 miles per hr. Full power and a high angle of attack were required in order to maintain that altitude. The equipment used proved adequate for all altitudes up to 15,000 ft.

### *Methods Used in the Interpretation of Magnetic Anomalies*

Nearly all the magnetic anomalies observed over the Hawaiian Islands and the neighboring oceanic area can be divided into two groups:

1. Local dipole anomalies related to centers of volcanism marked by surface caldera, volcanic peaks, or geologic evidence defining a former vent area.

2. Elongate, dipole anomalies related to dike complexes, observable, and probable, rift zones in the crust that appear to be occupied by intrusives at depth.

In the study of these anomalies, four factors were evaluated: (1) approximate size and shape of the anomalous geologic body, (2) orientation in the earth's magnetic field at the latitude of Hawaii, (3) depth to the top of the anomalous body, (4) susceptibility contrast and the natural remanent magnetization contrast between the surrounding rocks and the anomalous body.

An approximation to the above parameters can be obtained by utilizing various analytical procedures based on the shape of the anomaly profile for the magnetic latitude. The three parameters can then be further defined through theoretical computations using two- or three-dimensional techniques with machine programming. These results are then matched with those observed.

Most total force magnetic anomalies observed over the Hawaiian Ridge and the surrounding oceanic areas exhibit normally polarized magnetic dipoles which remain as dipoles even after topographic corrections have been applied. These dipoles are of such intensity and wavelength that they can only be interpreted as vertical intrusive rocks intruding into the volcanic domes along elongate rift zones.

As volcanism in the Hawaiian Islands appears in most cases to follow similar structural patterns, a scheme for estimating the horizontal cross-sectional size of the intrusive body, the depth to the top of the body from the level of observation, and the vertical length of the body would be useful for the rapid evaluation of the shapes of such intrusive bodies. The horizontal size of the body may be determined by the inspection of the relationship between theoretical anomaly contours over theoretical bodies, as those computed by Vacquier et al. (1951), and by using this relationship to derive the horizontal size of the body giving rise to the observed magnetic anomaly. Depth to the top of the anomalous body may be readily determined by using "depth indices" such as those in Vacquier et al. (1951). For dipole anomalies over the Hawaiian Islands, the  $G$  index was found to be the one giving the most consistent results and less likely to be affected by interference from superposed smaller wavelength dipole anomalies.

As is the case in the Hawaiian Islands, the susceptibility and the natural remanent magnetization contrast between the extrusive and intrusive rocks of the volcanic domes may be obtained from measurements made on rock samples in the laboratory. Theoretical susceptibility contrast may be computed by using the formula

$$K = \frac{\Delta T_m}{\Delta T_c T}$$

where  $K$  is the minimum susceptibility contrast (Vacquier et al., 1951);  $\Delta T_c$ , the total amplitude of the intensity anomaly selected from the appropriate theoretical body, as computed in Vacquier et al.;  $T$ , the intensity of the regional magnetic field at the point at which the anomaly is situated; and  $\Delta T_m$ , the observed amplitude of the actual anomaly.

Having thus determined the above factors, another set of theoretical models, computed for the latitude of the Hawaiian Islands, may be used to determine the total vertical length of the intrusive geologic body.

The amplitude of the magnetic anomaly associated with the geologic body depends on the magnetization of the body, on the length, and on the depth to the top of the body from the

level of observation. A series of theoretical geologic bodies with variable depths to the top of the body and variable length-to-width ratios may be constructed. As the depth to the top of the geologic body increases, the amplitude of the magnetic anomaly profile decreases.

Using arbitrary units for  $d$ , the depth to the top of the body, and corresponding arbitrary units for the length and width of the geologic body, a series of theoretical, two-dimensional, vertical geological bodies were constructed and their total force magnetic anomaly profiles computed. Each particular model (Fig. 34A to F) has a set of five of the profiles, computed for  $d = 0.5, 1, 2, 5, 10$ , and  $15$  in arbitrary units.

The profiles were calculated using a combined susceptibility-natural remanent magnetization of  $10.0 \times 10^{-3}$  cgs units, a common magnetization contrast, observed from specimens and computed from anomaly profiles, between the intrusive and extrusive basalt rocks of the Hawaiian Islands. The models are assumed to have an infinite horizontal length and a strike parallel to magnetic latitude. The models are magnetized in a regional total force magnetic field of 36,000 gammas, with a dip of  $35^\circ$  N. The total force magnetic profiles are assumed to strike parallel to magnetic longitude, i.e., perpendicular to the strike of the models. In practice it was found that by comparing computed total force magnetic profiles over models that had been computed using two- and three-dimensional techniques, end effect errors, in the case of two-dimensional assumptions, are likely to be less than 10% if the geologic body has in horizontal section a width of one unit and a length of four units.

The total force magnetic anomaly profiles were computed by using machine programming in integrating the effects of horizontal and vertical magnetic fields of volume elements over the cross sections of the geologic models (Heirtzler et al., 1962).

By comparing observed total force magnetic anomaly profiles with those computed in Figure 34A to F, the figures become useful as a means of rapidly determining the vertical length of the highly magnetized, vertically or near-vertically dipping intrusives intruded within the Hawaiian volcanoes of the Hawaiian Ridge, or within elongate seamounts or rift zones of the ocean

floor, in the magnetic latitude where the magnetic dip is between  $30^\circ$  and  $40^\circ$ . Similar relationships would also hold true for the above-mentioned geologic features within the Southern Hemisphere latitudes where the magnetic dip is also from  $30^\circ$  to  $40^\circ$ , though the anomaly dipoles would be reversed in sign.

The curves in the figure may also be used in aeromagnetic surveys to measure the magnetic sensitivity with elevation. For instance, if zones of magnetization 1 km in width are to be examined at an elevation of 3 km, extremely sensitive instrument techniques would have to be used in order to determine whether the zones of magnetization are 40 km in vertical length (Fig. 34E). On the other hand, too low a flight elevation will record anomalies that are great in amplitude with steep gradients—frequent crowding of anomalies—which may lead to difficulties in sorting.

For the equatorial latitudes at least, the best flight elevation with respect to the wavelength of the geologic body to be examined is that with a ratio of 1:1 (Fig. 34D). That is to say, at a flight elevation of 2 km, reasonable total amplitudes of 700 gammas peak-to-peak to 120 gammas peak-to-peak for the anomalies can be expected, depending upon the vertical length of the magnetized body. At this ratio, reasonable estimates of the vertical lengths of the magnetized bodies can also be made, because the total wavelengths of the anomalies caused by relatively short geologic bodies are readily distinguishable from those caused by relatively long geologic bodies.

This procedure for determining the lengths of intrusive magnetized bodies and for selecting appropriate aeromagnetic flight elevations may be used at any magnetic latitude, providing an appropriate selection of models is computed for that latitude range.

#### RESULTS, DISCUSSION, AND CONCLUSIONS

##### *Problems in Magnetic Surveying Over Magnetic Terrain*

The primary advantage of an aeromagnetic survey method over those of ground surveys is the greater rate and density of coverage that can be achieved. An additional advantage is that the effect of changes in surficial geology and terrain



is not only minimized, but the terrain corrections are simplified. In ground surveying methods, such as those described by Nettleton (1940), terrain corrections are not considered because only relations found in petroleum provinces are treated. In such areas, the sedimentary rocks encountered at the surface are relatively non-magnetic as compared with the buried crystalline rock complex at depth, and the terrain effect is negligible. Ground magnetic surveys in such areas, therefore, define geologic boundaries beneath the sediments in the crystalline rock complex.

Surveying over a surficial magnetic rock surface presents an entirely different problem. In such areas, a magnetic dipole is induced over each topographic rise as well as subsurface bodies having an abnormal magnetic susceptibility. Because the magnetic intensities of any two-pole magnetic body vary inversely as the square of the distance between the sensing head of the magnetometer and each of the induced poles on the geologic or topographic body creating the anomaly, near-ground magnetic surveys over highly magnetic country rock, such as basalt, reflect local terrain irregularities as well as the effect of buried geologic bodies. Which effect will be dominant depends upon the relative susceptibility contrast associated with each body, the size of the respective bodies, their geometry, orientation in the earth's field, and the distance from the magnetometer sensing head to each body. To illustrate this relationship, the apparent susceptibility contrasts between air and normal basalt is of the order of  $15.0 \times 10^{-3}$  cgs units, which is similar to the contrast between normal basalt and intrusive gabbroic dike rock. If all other factors are equal, but the distance between the sensing head and a local basaltic terrain feature (such as the wall of a caldera) is of the order of 20 ft, and the distance between the sensing head and the top of an intrusive mass in the underlying volcanic feeder pipe is of the order of thousands of feet, it is obvious that the terrain effect will be dominant. To assess the magnetic effect of basaltic terrain in Hawaii, a total force ground magnetic survey as well as an airborne survey was carried out across the crater of Kilauea Iki on the island of Hawaii.

Kilauea Iki is a small side crater merging

with Kilauea Crater along the northeastern portion of the latter. The floor of the small crater lies 650 ft below the rim. The total magnetic intensity, as observed with the polarizing head 4 ft above ground level, varied from a reading of 39,400 gammas at the rim of the caldera to a reading of 34,300 gammas at the floor of the caldera. This change would normally be interpreted as indicating a magnetic anomaly of  $-5,100$  gammas due to anomalous geology located within the confines of the Kilauea Iki crater. However, if the aeromagnetic anomaly above Kilauea Iki is examined, the maximum residual anomaly that can be assigned to an anomalous body within the crater is only 60 gammas. Also, it was noted that, if a magnetic reading is taken on basaltic terrain at 5 ft above ground level, a difference of up to 300 gammas can be obtained from the effects of local irregularities in terrain. Because of this pronounced ground-level terrain effect and the occurrence of highly ferromagnetic secondary minerals in basaltic soils, no surface magnetic surveys were attempted for the study of subsurface geologic structure. All observations were made using an airborne system.

The flight elevations over the islands varied between 15,000 ft above sea level for flights above the peaks of Mauna Loa and Mauna Kea on the island of Hawaii to 8,000–10,000 ft for the remaining islands. These elevations were chosen on the basis of theoretical studies of the magnetic effects to be expected for topography. At a flight elevation of 10,000 ft, the magnetic effect to be expected for an 8,000-ft peak built of material with a magnetic susceptibility of  $1.0 \times 10^{-3}$  cgs units and a natural remanent magnetization of  $10.0 \times 10^{-3}$  cgs units should be of the order of  $+100$  gammas. It was on the basis of both theoretical and actual profiles across the topographic features of Maui, Molokai, and Oahu that a standard flight elevation of 8,000–10,000 ft above sea level was selected for use everywhere except where this elevation would not permit clearance of the land surface by at least 2,000 ft.

#### *Comparison of Ship and Airborne Magnetic Survey Data at Sea*

The total force magnetic intensity survey results obtained with the airborne magnetometer

required only a correction for the heading error resulting from towing the polarizing head in a north-south direction 100 ft behind the plane. The average heading error varied from 30 to 40 gammas. Because the normal magnetic field gradient was low, no significant error would have been introduced if this effect had been neglected.

The total force magnetic field out to 150 miles north of Maui was surveyed by the U. S. Coast and Geodetic Survey ship "Surveyor," whereas the remainder of the offshore areas adjacent to the islands were surveyed using the University of Hawaii RV "Teritu." However, aeromagnetic profiles were also taken over the sea tracks of the "Surveyor" out to 50 miles north of Maui. Although the aircraft was flown at 8,000 ft above sea level and the ship observations were made a few feet below sea level, no significant differences in values were observed between the airborne and seaborne data. This lack of difference in values can be attributed to the great depth of the anomalous geologic bodies lying below the ocean floor which cause ocean magnetic anomalies.

#### *Possible Origin of Hawaiian Magnetic Anomalies*

Magnetic anomalies result from changes in the magnetic characteristics of rock masses which, in general, can be related to the percentage of magnetite and ilmenite present. As these two minerals are present to some extent in most igneous rocks, the natural thing to expect in the magnetic study of an oceanic archipelago of volcanic origin, such as the Hawaiian Islands, is a composite anomaly pattern. The basic component would be that portion which can be related directly to the size and geometry of the volcanic mass rising from the sea floor and the strength and inclination of the earth's magnetic field, and on this would be superimposed the effect of local variations in types of lava present and intrusions within the volcanic pile.

Even a casual inspection of the regional magnetic map (Fig. 1) shows that the island mass effect of the Hawaiian Islands is of such secondary importance as to be lost in the overriding magnetic effects originating from other geologic causes. This empirical observation is further substantiated by quantitative calculation,

which indicates that only about a 60-gamma effect is to be expected for the island mass. Similarly, local variations in the lavas present do not appear to be too significant in terms of changes in the anomaly pattern. Although there may be petrologic significance in the somewhat smaller magnitude anomalies observed on the island of Hawaii as compared with other, older islands, this could also be the result of higher temperatures at depth in this island, which is the only one now characterized by active volcanism. Probable areas of abyssal intrusion defined by either surface fracture systems or volcanic centers of eruption are associated everywhere with the magnetic anomalies which occur mostly as dipole pairs. It is significant, though, that only primary central vent areas and rift (fracture) zones that were the source of the bulk of the volcanic rocks forming the islands are marked by magnetic anomalies. Secondary centers of eruption, such as Diamond Head on Oahu, are not defined magnetically. In connection with rift zone type of anomalies, Figure 1 shows that most of the rift zone type anomalies do not terminate at the physical boundaries of the islands on which they occur. Some extend for considerable distances into the adjacent oceanic area. This suggests that the rift zone type anomalies may well be independent of the geology of the islands and are related to intrusions at depth in crustal fractures. Along these rifts, and locally at the intersections of crosscutting crustal fractures, magma penetrated to the ocean floor to initiate a series of seamounts that developed into the Hawaiian Islands. Because each locus of magmatic intrusion (whether now defined geologically by a major volcanic mountain peak, such as Mauna Kea on Hawaii, a submerged seamount, a deeply dissected vent area recognizable only through its associated dike complex and boundary faults, such as the ancient Waianae caldera and the present day Koolau range on Oahu or the Molokai Fracture Zone on the ocean floor) requires a similar theoretical contrast in magnetic susceptibility, it is probable that the controlling lithology at depth is much the same in each case and represents some differentiate of what originally was probably mantle material. This conclusion is based, in part, on depth analysis as the source of the magnetic anomalies as well as the seismic

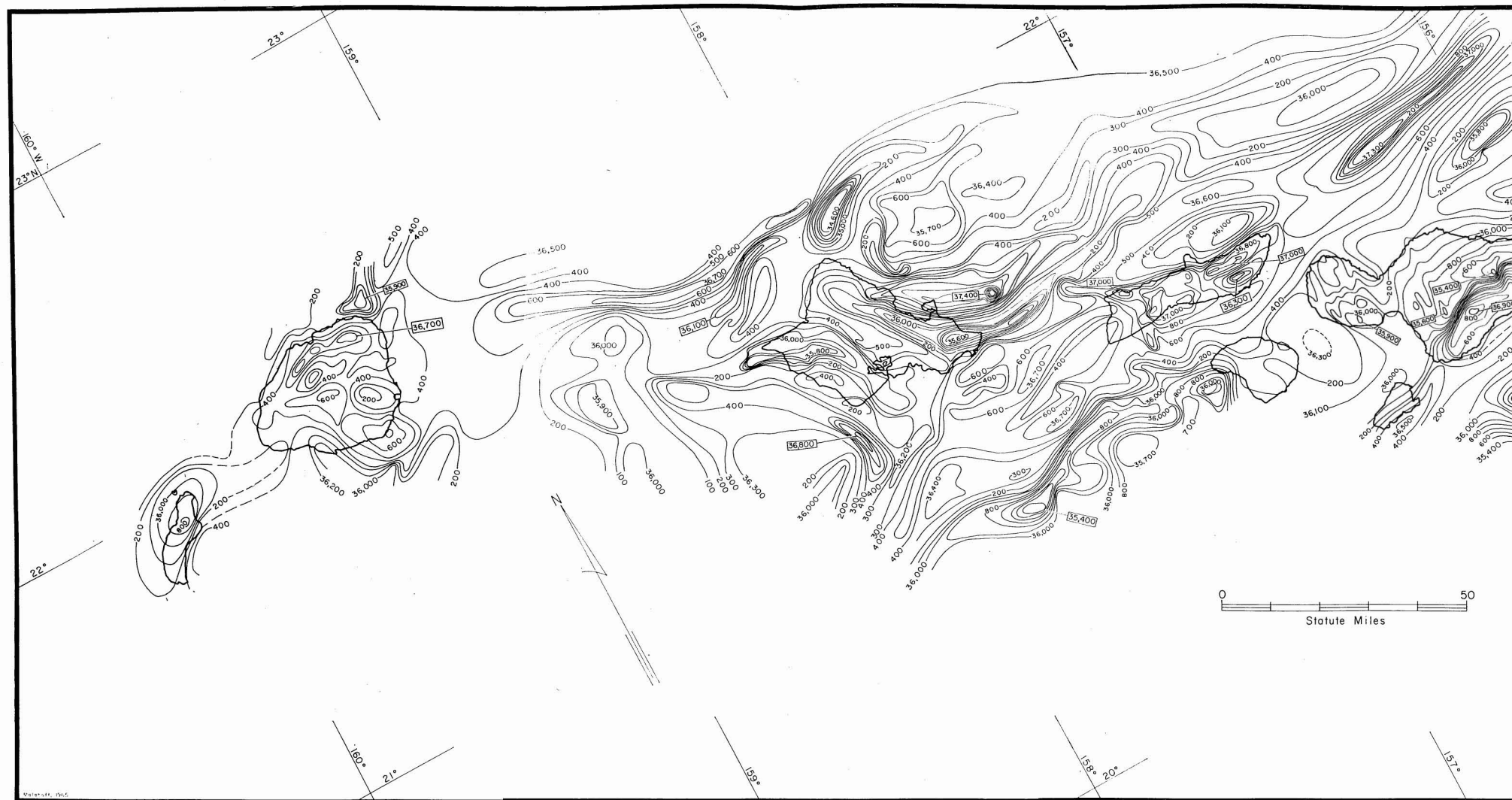
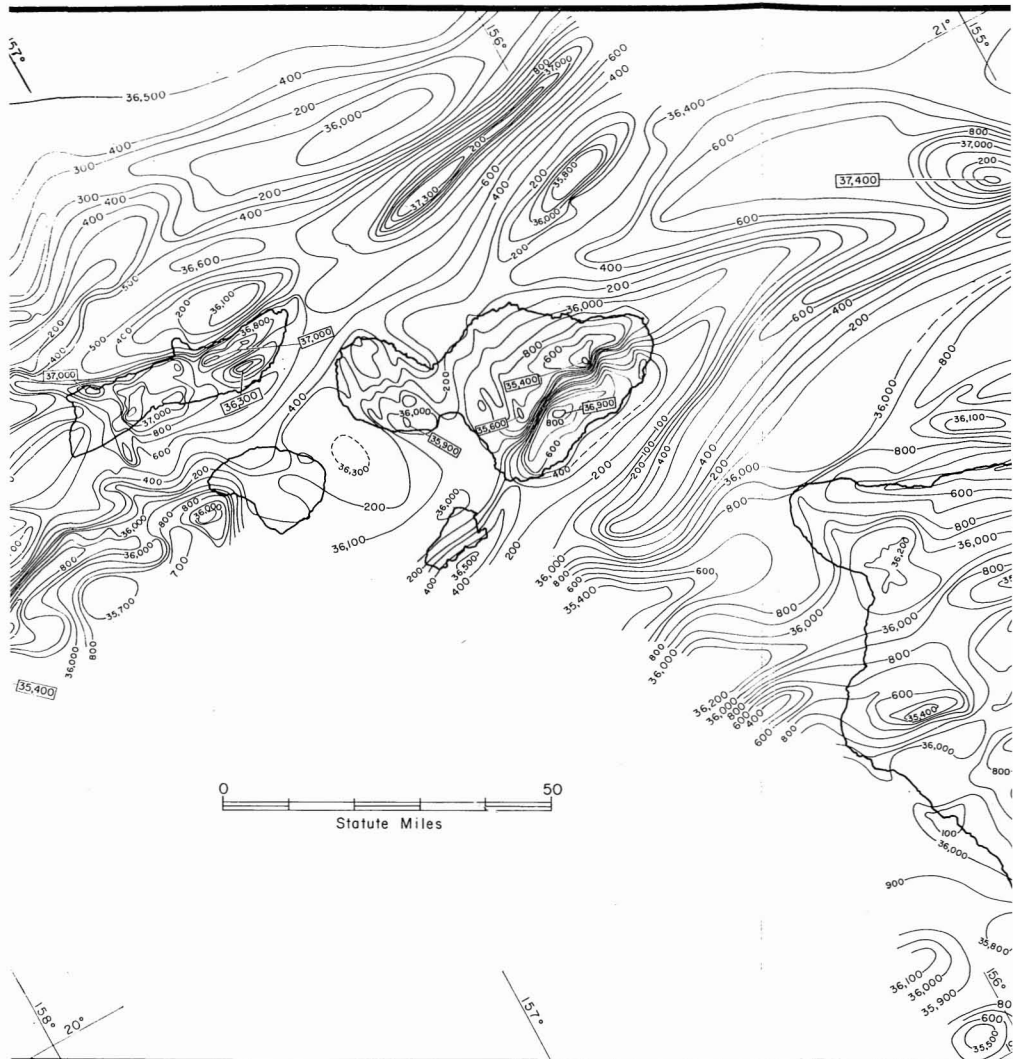


FIG. 1. Total force magnetic intensity map of the Hawaiian Swell, Hawaii to Oahu. Contour interval at 100 gammas. (After Malahoff



ii to Oahu. Contour interval at 100 gammas. (After Malahoff and Woollard, 1965.)

refraction measurements which indicate the rift zone type anomalies originate from depths ranging from 4–10 km below sea level. The failure to obtain magnetic anomalies over the late-stage centers of volcanic activity, such as Diamond Head and Koko Head on Oahu which were centers of alkalic basalt extrusion, probably lies not so much in the difference in the mineralogic constituents of the extruded lavas, but rather in the difference in susceptibility contrast between the rock at depth representing the source magma and the enclosing rock. Whereas the primary intrusions appear to have had their magma source in the mantle and were emplaced in the crust, the late-stage intrusions could well have been derived from shallow magma chambers that developed (Eaton, 1962) within the volcanic pile itself. Thus, the composition of the magma and its equivalent rock magnetic susceptibility could be essentially the same as that of the primary enclosing tholeiitic basalt, and the alkalic basalt would be the result of *in situ* differentiation through the gravity separation of early formed olivine, as suggested by Macdonald et al. (1960).

Under these conditions there would be no contrast in magnetic susceptibility either at the surface over the vent or at the depth of the magma chamber, since the bulk of the available iron would be in the form of nonmagnetic silicates rather than oxides. Although these observations do not identify the exact lithologic character of the rock material causing the observed anomalies, it does appear to be an intrusive which contains a higher percentage of magnetite and possibly ilmenite than does the enclosing crustal rock. Because the associated gravity anomalies all indicate that these intrusives must also have a density of 3.2 gm/cc, it is probably very similar to peridotite. However, until one or more anomalous areas, such as the Koolau caldera on Oahu, are drilled, no real answer can be given to this problem.

#### *Magnetic Properties of Rocks of the Hawaiian Islands Used in the Reduction of Magnetic Data*

As susceptibility and the natural remanent magnetization of rocks are essential factors in the interpretation of the total force magnetic anomalies, it might be well to review the data for the Hawaiian Islands. Studies of this nature

on the Hawaiian rocks have been carried out by Doell and Cox (1963), Decker (1963), and Tarling (1963) as well as by the senior author of this paper. The results of all these determinations are summarized in Table 1.

As the table shows, there are two groups within the extrusive basaltic rocks that appear to have greatly differing susceptibilities and intensities of natural remanent magnetization. The first group, those having low magnetic susceptibilities, are predominantly olivine-rich rocks, in which olivine makes up more than 15% of the total weight of the rock sample. Rocks in this group include those from Hualalai Volcano on the island of Hawaii, which have susceptibilities that average  $0.41 \times 10^{-3}$  cgs units and intensities of remanent magnetization that range from  $0.5$  to  $5.0 \times 10^{-3}$  cgs units, and samples of garnet peridotite from Salt Lake Crater on Oahu, which range in susceptibility from  $0.4$  to  $0.5 \times 10^{-3}$  cgs units and have an intensity of remanent magnetization which averages between  $1.0$  and  $2.0 \times 10^{-3}$  cgs units.

In the second group, those having a high magnetic susceptibility, are the olivine-poor lavas, such as those found on the island of Hawaii. These olivine-poor lavas have an average susceptibility of  $2.5 \times 10^{-3}$  cgs units and natural remanent magnetization of  $10.0 \times 10^{-3}$  cgs units.

Similarly, intrusive rocks show extensive variations in magnetic properties. One dike rock sample collected on East Maui had a susceptibility of  $6.8 \times 10^{-3}$  cgs units and a natural remanent magnetization of approximately  $100 \times 10^{-3}$  cgs units. On the other hand, fine-grained dike rocks collected near the Iao Needle, West Maui, had an average susceptibility of only  $0.12 \times 10^{-3}$  cgs units and a remanence of  $3.0 \times 10^{-3}$  cgs units. These low values of magnetic properties of West Maui intrusive rocks could account perhaps for the reversed dipole effects in the magnetic field observed over West Maui. However, most of the intrusive rocks sampled in the Hawaiian Islands have intensities of remanent magnetization that are, on the average, higher by  $5 \times 10^{-3}$  to  $10 \times 10^{-3}$  cgs units, and susceptibilities that are higher by  $2 \times 10^{-3}$  cgs units than the basaltic lavas which they intrude.

Altogether, 40 samples of basalt were col-



TABLE 1

AVERAGE VALUES<sup>1</sup> OF SUSCEPTIBILITY ( $\mu$ ) AND NATURAL REMANENT MAGNETIZATION FOR ROCKS OF THE HAWAIIAN ISLANDS

FORMATION	NRM $\mu$ (Tarling, 1963)		NRM <sup>2</sup> $\mu$ (Authors)		NRM $\mu$ (Decker, 1963)	
Hawaii (tholeiite)			11.0	3.2	10.0	1.0
Hawaii (olivine-rich basalt)			5.0	0.5		
Hana (E. Maui)	17.31	4.63	—	—		
Kula (E. Maui)	137.30	13.28	100.0	5.0		
Honomanu (E. Maui)	0.96	2.66	1.0	2.5		
Honolua intrusive rock			20.0	2.8		
Honolua (W. Maui)	14.34	2.74	15.0	2.7		
Wailuku intrusive rock			1.0	0.5		
Wailuku (W. Maui)	8.19	2.01	10.0	2.8		
Lanai	5.88	0.92				
East Molokai	19.43	2.13				
West Molokai	13.22	1.16				
Koolau dike rock (Oahu 1) <sup>3</sup>			20.0	3.2		
Koolau dike rock (Oahu 2) <sup>4</sup>			2.0	0.5		
Koolau (Oahu)	3.09	1.83	5.0	1.8		
Waianae (Oahu)	2.67	2.19	—	—		
Honolulu peridotite	—	—		0.4		
Honolulu (Oahu)	4.78	3.92	3.0	3.2		
Koloa (Kauai)	6.45	1.24	5.0	2.1		
Napali (Kauai)	4.21	1.01	5.0	2.0		
Niihau	—	—	—	—		

<sup>1</sup> Values in cgs units by  $10^{-3}$ .

<sup>2</sup> As determined with an astatic magnetometer.

<sup>3</sup> Dike rock collected along Pali Highway (Oahu 1).

<sup>4</sup> Dike rock collected from Keolu Hills quarry (Oahu 2).

lected from the island of Hawaii, representing both tholeiitic and alkalic basalts; 20 samples were collected from the island of Maui, representing both intrusive and extrusive rocks; 30 samples were collected on Oahu, and 10 on Kauai. All samples were collected from unweathered outcrops and were oriented in the field. Susceptibilities of the rock samples were measured by using cores and a susceptibility bridge. The rock cores were bored in a direction parallel to the vector of the earth's present magnetic field in Hawaii, and intensities and direction of polarization (whether normal or reversed) were measured with the aid of a simple astatic magnetometer.

Because the islands of Hawaii have been formed by the extrusions of numerous stratigraphically thin basaltic flows, whose magnetic properties appear to vary from flow to flow,

the susceptibilities used in topographic reductions and anomaly computations were averaged out for each individual volcano. The collection pattern followed, therefore, was one which would give samples representing as large a vertical section through a given volcano as possible.

The susceptibilities for rocks on the island of Hawaii for all the volcanoes except Hualalai average  $2.3 \times 10^{-3} \pm 1.0 \times 10^{-3}$  cgs units. However, 80% of the rock samples have a value of  $2.2 \times 10^{-3} \pm 0.5 \times 10^{-3}$  cgs units. The intensities of remanent magnetization average  $11 \times 10^{-3}$  cgs units. As indicated earlier, the olivine-rich basalts collected from Hualalai Volcano had low susceptibilities of the order of  $0.4 \times 10^{-3} \pm 0.2 \times 10^{-3}$  cgs units. The values adopted for all computations on Hawaii except Hualalai Volcano were  $2.2 \times 10^{-3}$  cgs

units for susceptibility and  $11 \times 10^{-3}$  cgs units for natural remanent magnetization.

For purposes of computation, the extrusive rocks on the islands of Maui and Kahoolawe were divided into two groups: those of West Maui and those of East Maui (the latter including Kahoolawe). However, no rock samples were actually collected on Kahoolawe, because it is a bombing range and a closed area. In assuming the same susceptibilities and intensities of natural remanent magnetization for East Maui and Kahoolawe, no error is likely, for, as seen from inspection of the total intensity magnetic map of Maui and Kahoolawe (Fig. 2), it appears that both Haleakala Volcano and Kahoolawe originated from extrusions from the same "primary" rift zone.

On East Maui, the bulk of the lavas is represented by the Honomanu basalts, which have an unusually low remanence value which averages  $1.0 \times 10^{-3}$  cgs units with an average susceptibility of  $2.6 \times 10^{-3}$  cgs units. Rocks of Kula series, on the other hand, which have a maximum thickness of 2,000 ft at the summit of Haleakala, have an unusually high n.r.m. (natural remanent magnetization) of  $137.3 \times 10^{-3}$  cgs units. Because the data available are too sparse to determine what is a true representative n.r.m.-susceptibility value for the bulk of the rocks forming East Maui, the writers were forced to compromise and use an average value for all the rocks sampled in East Maui. Therefore, using Tarling's values (Table 1), as well as the writers' values, a mean natural remanent magnetization of  $15.0 \times 10^{-3}$  cgs units was employed in computing the topographic effects on East Maui and Kahoolawe.

Similarly, an average value using Tarling's and the writers' values of  $12.1 \times 10^{-3}$  cgs units for the n.r.m. and  $2.7 \times 10^{-3}$  cgs units for susceptibility was employed for the topographic reduction over West Maui.

Inasmuch as the writers did not collect any samples on Molokai and Lanai, Tarling's values were used in the magnetic computations involving these islands. An n.r.m. of  $5.88 \times 10^{-3}$  cgs units and a susceptibility of  $0.92 \times 10^{-3}$  cgs units were used for the island of Lanai. An n.r.m. of  $19.43 \times 10^{-3}$  and a susceptibility of  $2.13 \times 10^{-3}$  cgs units were used for East Molokai, and an n.r.m. of  $13.22 \times 10^{-3}$  cgs

units and a susceptibility of  $1.16 \times 10^{-3}$  cgs units were used for West Molokai.

The topographic effects of the Waianae and Koolau volcanic series on the island of Oahu were reduced using the following values. An n.r.m. of  $2.67 \times 10^{-3}$  cgs units and a susceptibility of  $2.19 \times 10^{-3}$  cgs units based on Tarling's measurements were used for the topography associated with the Waianae volcanic series. An n.r.m. of  $4.47 \times 10^{-3}$  cgs units and a susceptibility of  $2.68 \times 10^{-3}$  cgs units were used for the topography associated with the Koolau volcanic series. However, intrusive rocks sampled by the writers in the Koolau caldera showed considerable variation in values. Specimens of fine-grained, dark, magnetite-rich intrusive rocks collected near the periphery of the caldera had an n.r.m. of approximately  $20.0 \times 10^{-3}$  cgs units and a susceptibility of  $3.9 \times 10^{-3}$  cgs units. On the other hand, fine-grained, dense intrusive rocks, rich in pyrite, collected near the center of the caldera had an approximate n.r.m. of  $1.0 \times 10^{-3}$  cgs units and a susceptibility of  $0.5 \times 10^{-3}$  cgs units. Because of the scarcity of suitable outcrops, it is not known which of these intrusive-rock suites is representative of the bulk of intrusive rocks at depth. However, as both of the suites of intrusive rocks sampled are normally polarized and the Koolau magnetic anomaly (Fig. 3) is inversely polarized, a possible explanation for the inverse polarized anomaly on the basis of the data available may be that the magnetic anomaly results from rocks having lower susceptibility and n.r.m. value than the surrounding basalts, present at depths within the Koolau caldera.

The magnetic properties of rocks on Kauai were averaged and only one set of values was used because there appears to be little difference in values between the Koloa basalts and the Napali basalts. For the topographic reductions on Kauai as well as on Niihau an n.r.m. value of  $5.14 \times 10^{-3}$  cgs units was used.

In order to solve many of the problems stated in this paper concerning the gross differences observed in the magnetic properties of rocks collected in the Hawaiian Islands, a thorough program of sampling both intrusive as well as extrusive rocks will be necessary. Sampling of both bathymetric and topographic features over the Hawaiian Ridge will be necessary also. Be-



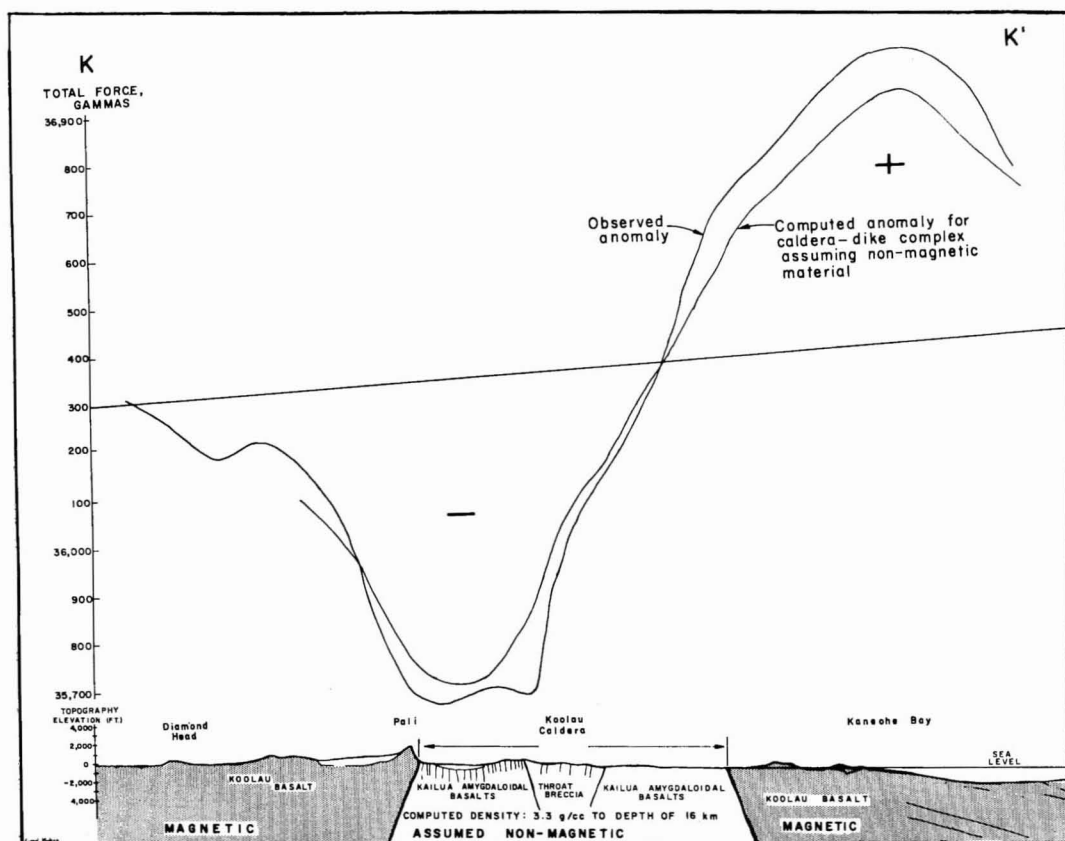


FIG. 3. Magnetic profile along line K-K' (see Fig. 29), Diamond Head-Kaneohe Bay, across the Koolau caldera, island of Oahu.

cause of the lack of suitable samples, the writers adopted an average value of n.r.m. of  $10.0 \times 10^{-3}$  cgs units and a susceptibility of  $1.0 \times 10^{-3}$  cgs units for the basaltic rocks forming bathymetric features.

Although it can be argued that, because all of the Hawaiian Islands are composed predominantly of tholeiite, average magnetic values could have been used also for all of the islands, rather than somewhat different values for each island, such a procedure cannot be justified when the data in hand indicate there are real differences in average values for each island. Even though the lithology may be identical, this does not guarantee that the n.r.m. values, which are related to the strength and direction of the earth's field at the time of eruption, will be the same, inasmuch as it is known that the earth's field is subject to secular change.

#### *The Magnetic Field Over Offshore Areas*

The Hawaiian Islands were the first portions of the Hawaiian Ridge to be surveyed in this investigation. Because of the apparent complexity of the magnetic field observed over the islands, and the lack of knowledge of the nature of the anomaly-free regional magnetic field, a companion marine magnetic survey was essential. Although both the U. S. Navy Oceanographic Office of the Scripps Institution of Oceanography as well as the U. S. Coast and Geodetic Survey had made magnetic surveys in the region, none of these covered the essential area adjacent to the islands. The first measurements related to the present study were carried out to sufficient distance north of Maui to avoid probable magnetic anomalies over the extension of the Molokai Fracture Zone, which the Scripps Institution of Oceanography measurements





(Arthur D. Raff, personal communication) had shown to be magnetically disturbed. These measurements were carried out on the "Surveyor."

The total magnetic intensity map of the area studied is shown in Figure 4. This map shows a striking convergence of anomalies and steep magnetic gradients immediately north of Maui. Farther north, beyond the nearshore anomalies which are associated with elements of the Molokai Fracture Zone, and north of latitude  $21^{\circ}41'$  the magnetic field over the Hawaiian Rise is smooth, with a uniform gradient of 6 gammas per degree of latitude. Although magnetic anomalies are observed north of  $21^{\circ}40'$  which are of the same wavelength (20 km or greater) as those observed south of this latitude, the amplitudes of these anomalies to the north do not exceed 100 gammas.

Of local significance in this survey are the two distinct dipole anomalies associated with the Molokai Fracture Zone north of Maui. One lies 20 miles north of Maui, where a 1,300-gamma peak-to-peak anomaly occurs. The other lies 20 miles northwest of Maui, where a 1,200-gamma peak-to-peak anomaly occurs.

By using depth and susceptibility contrast estimations coupled with two-dimensional model studies, the following geologic analyses were determined. The dipole anomaly centered at  $156^{\circ}15'W$  and  $21^{\circ}10'N$ , and here named the "Hawaiian Deep magnetic anomaly," appears to be caused by an intrusive body some 25 km wide and 65 km long, striking approximately east-west. The top of the anomalous body lies at a depth of about 8.5 km below sea level and it appears to extend vertically downward to a depth of 17.5 km. The rock associated with this body appears to have a susceptibility that is greater by  $18.0 \times 10^{-3}$  cgs units than that of the surrounding crustal rock. As indicated, geographically this anomaly is situated directly above the crustal downwarp and bathymetric low termed the Hawaiian Deep. It is also situated directly above a small bathymetric feature within the Hawaiian Deep that varies from 10–20 km in width and in height from 600–1,600 m (see Figs. 5 and 6). It is significant that the area of the shallow "Moho" depth of 5.8–7 km recorded by Shor and Pollard (1964) and Western Geophysical Company (unpublished)

lies on the western end of this anomaly and over the center of the disturbing body as defined by the point of inflection of the magnetic anomaly (Fig. 7). Thus, there is a reasonable argument that the anomalous Moho depth and the magnetic anomaly are related to the same cause. Considering the uncertainty in the depth analysis of magnetic anomalies, and the fact that the induced upper pole may not correspond to the actual upper surface of the body, there is also reasonable agreement with the seismic depth of 5.8–7 km and the magnetic depth determination of 8.5 km. As the anomaly is normally polarized, and the combined magnetic and seismic data show that the disturbing rock mass is not only more magnetic than the surrounding crustal rock but also extends well below normal mantle depths (12 km) and has a normal mantle velocity, it must represent an intrusion of mantle material into the crust and not represent a crustal displacement as postulated by Shor and Pollard.

Similarly, the normally polarized magnetic anomaly which is centered on  $156^{\circ}10'W$  and  $21^{\circ}05'N$  appears to be related to an intrusion that is 35 km long and 24 km wide. This anomalous region strikes southwest and abuts against the island of Maui. Its top appears to be located at about 9.0 km below sea level. The rocks causing the anomaly appear to have a greater than the surrounding rocks by about  $11.0 \times 10^{-3}$  cgs units.

As indicated earlier, no significant magnetic anomalies are observed, or are to be expected, in association with the Hawaiian Ridge itself. Similarly, the magnetic effect of bathymetric features at a depth of 13,000–18,000 ft below the plane of observation is observed to be negligible. All the observed magnetic anomalies appear to have resulted from intrusive rock sources.

#### *The Regional and Residual Magnetic Field North of Maui*

The observed regional magnetic gradient north of Maui, as deduced from Figure 4, is 6 gammas per minute of latitude; and that determined south of the Hawaiian Islands, from data taken by the U. S. Naval Oceanographic Office (1962), is 5 gammas per minute of latitude. Removal of the regional magnetic field from the total intensity magnetic field of the ocean

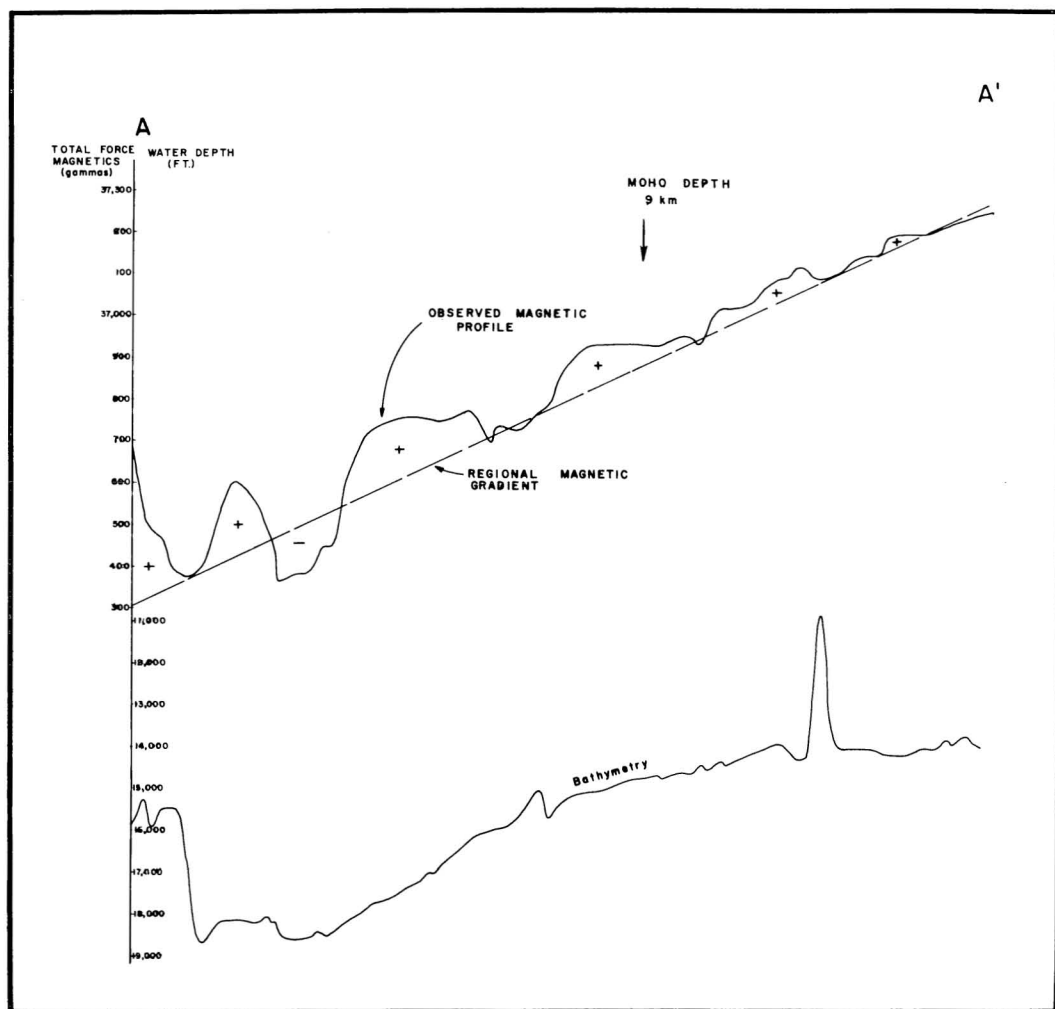


FIG. 5. Magnetic profile along line A-A' (see Fig. 4) north of the island of Maui.

area north of Maui does not change any characteristics of the major anomalies and only brings out low-amplitude, large-wavelength (10–20 km) anomalies, as shown in Figure 8.

Because the gradient of the regional magnetic field over the Hawaiian Islands is low in comparison with the large amplitude of observed magnetic anomalies, no attempt was made to remove the regional magnetic field from the other areas studied.

#### *The Molokai Fracture Zone*

Menard (1964) shows that the Molokai Fracture Zone extends from the Baja California Seamount Province to the edge of the Hawaiian

Deep, where the bathymetric expression of the fracture zone disappears. On the basis of bathymetric data alone, this marks the terminus of the Molokai Fracture Zone. However, as will be shown, magnetic data suggest that it continues across the Hawaiian Ridge for a presently undetermined distance westward.

By combining magnetic data taken by the U. S. Naval Oceanographic Office (1962), the University of Hawaii, and the Scripps Oceanographic Institute (Arthur D. Raff, unpublished), it is possible to relate magnetic anomalies to this and other prominent bathymetric features. As seen from Figure 9, the magnetic anomalies, as well as bathymetric features as-

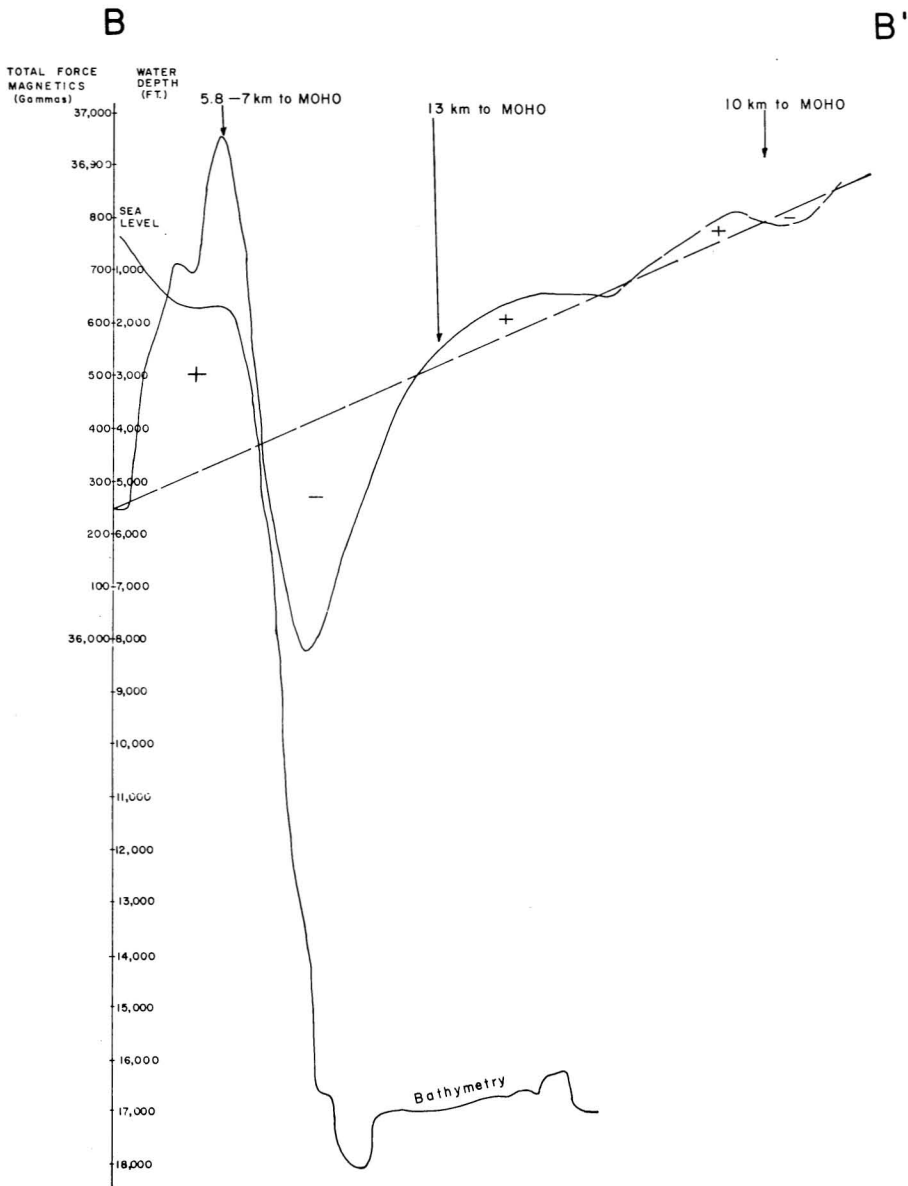


FIG. 6. Magnetic profile along line B-B' (see Fig. 4) north of the island of Maui.

sociated with the Molokai Fracture Zone, occur as elongated parallel bands. It is also noted that the magnetic anomalies observed along the bathymetric expression of the Molokai Fracture Zone have a distinctive high amplitude. Because the topographic effect of the associated bathymetry cannot alone explain the anomalies, there must be associated intrusive rocks having a high magnetic susceptibility. Although it is not

known whether these actually crop out, a depth analysis of the anomalies suggests that they do not, and that relations are similar to those defined seismically and magnetically north of Maui. In other words, it appears that the anomalies are caused by intrusions into crustal fractures developed by lateral faulting. Therefore, it is not surprising that, although the bathymetric expression of the Molokai Fracture Zone ceases

near the edge of the Hawaiian Deep, the associated magnetic anomalies continue westward without interruption along the strike of the Molokai Fracture Zone. However, it is to be noted that there are some notable changes where this trend intersects that of the Hawaiian Ridge. North of Maui, as seen from Figure 4, the "Hawaiian Deep magnetic anomaly" bifurcates into two distinct anomaly trends. One trend crosses the island of Molokai and continues to strike in an east northeast-west southwest direction for at least another 600 km without any change in strike direction. The second trend strikes to the northwest, to merge into the anomaly defining the Koolau Primary Rift Zone of Oahu (Fig. 10).

Two local high amplitude magnetic anomaly dipoles are superimposed on the Koolau Primary Rift Zone anomaly. One anomaly (1,400 gammas peak-to-peak) is located over the Koolau caldera on Oahu. The other anomaly (1,600 gammas peak-to-peak) is located in the Kaiwi Channel and has no known geologic counter-

part. Over the northwestern portion of Oahu, the Koolau Rift Zone anomaly merges with the Waianae Primary Rift Zone anomaly on the leeward side of Oahu to form a single anomaly trend striking in a direction parallel to the strike of the axis of the Hawaiian Ridge. As the southern end of the Waianae Primary Rift Zone anomaly terminates against the west southwest strike of the Molokai Fracture Zone anomaly belt, it appears to have been broken by translational movement along the latter. This is the only notable instance of direct discordance between the strike of the Hawaiian Ridge-oriented magnetic anomalies and the magnetic anomalies oriented parallel to the Molokai Fracture Zone.

If the elongate primary magnetic anomalies represent crustal fractures invaded by mantle material, Figure 10 defines the "rift" zones. These were constructed along the inflection zones of the elongate magnetic dipole anomalies as marking the geographic location of the source of the anomalies. As will be seen, primary volcanic vents are marked by intense local dipole

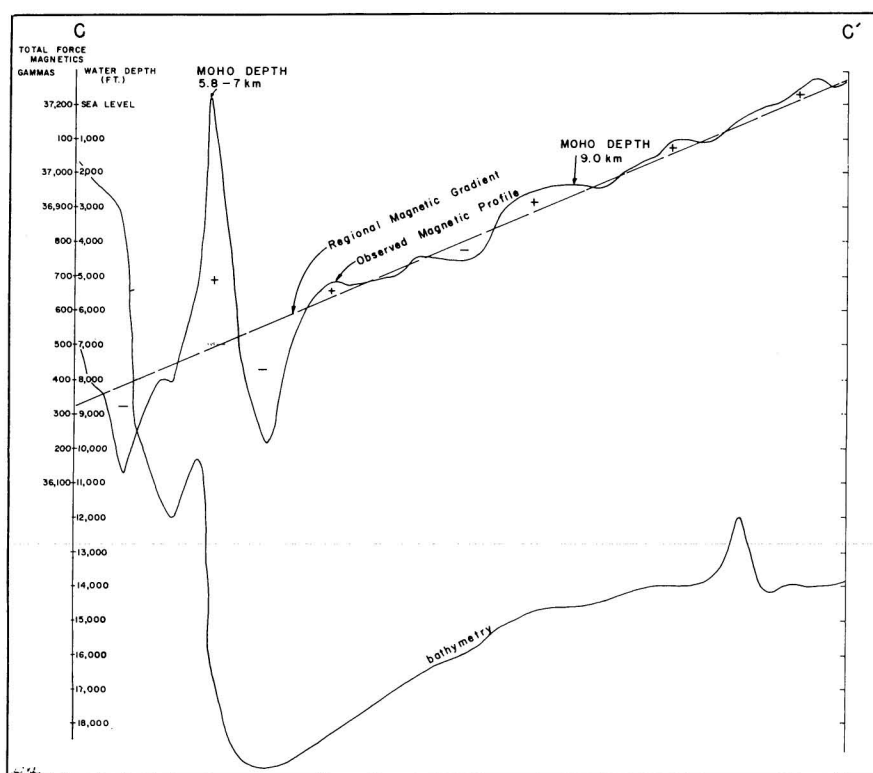


FIG. 7. Magnetic profile along line C-C' (see Fig. 4) north of the island of Maui.

Inasmuch as the majority of the primary anomaly trends and rift zones defined south of the island of Oahu appear to strike parallel to

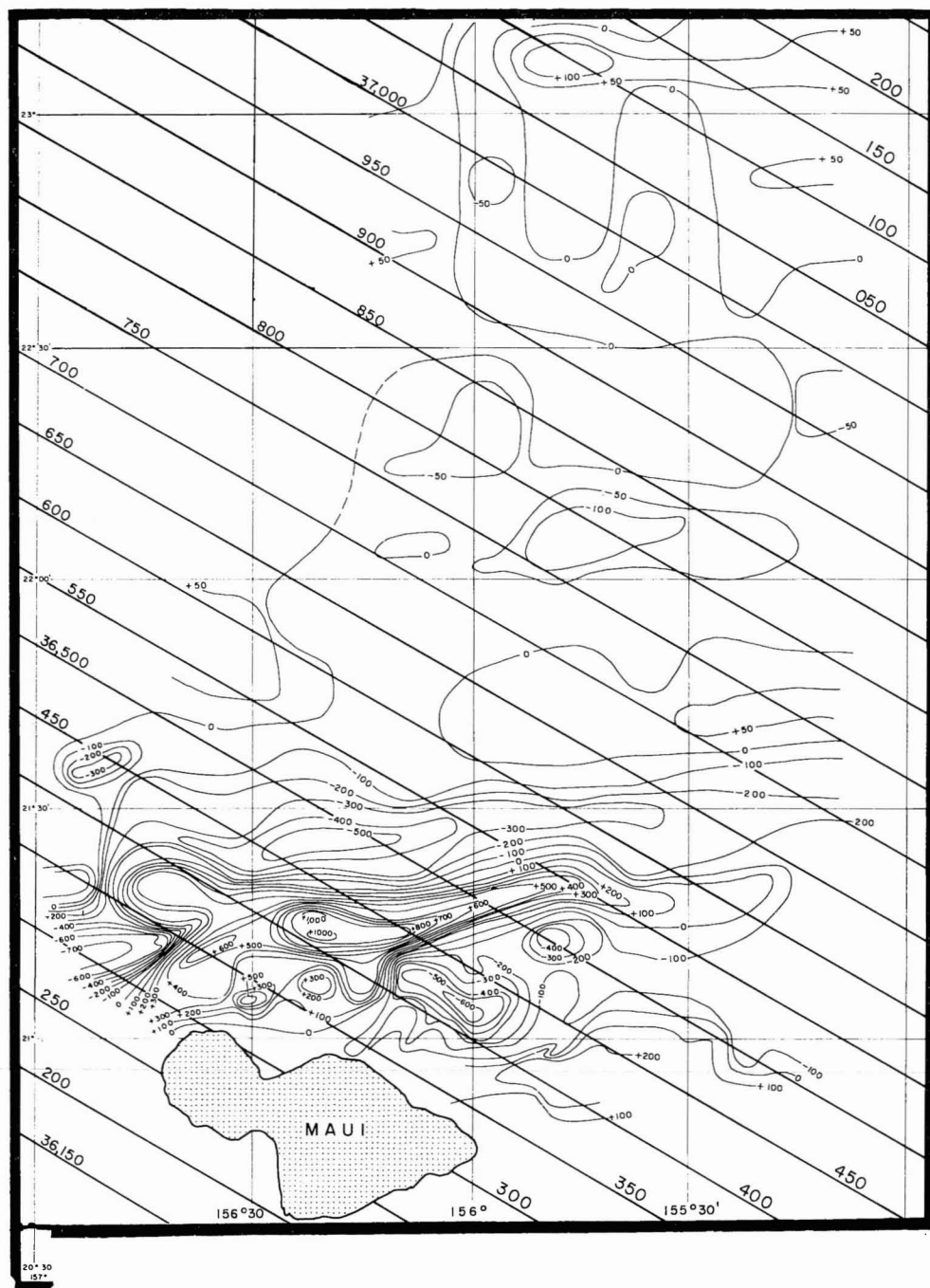


FIG. 8. Total force residual magnetic anomalies of ocean area north of Maui. Contour interval at 50 gammas. Heavy lines indicate regional total magnetic intensity.



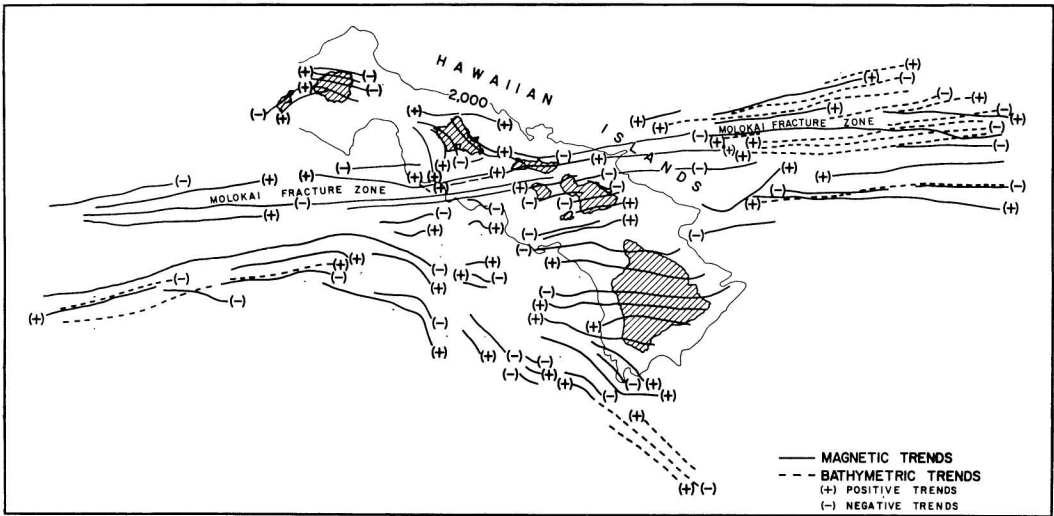
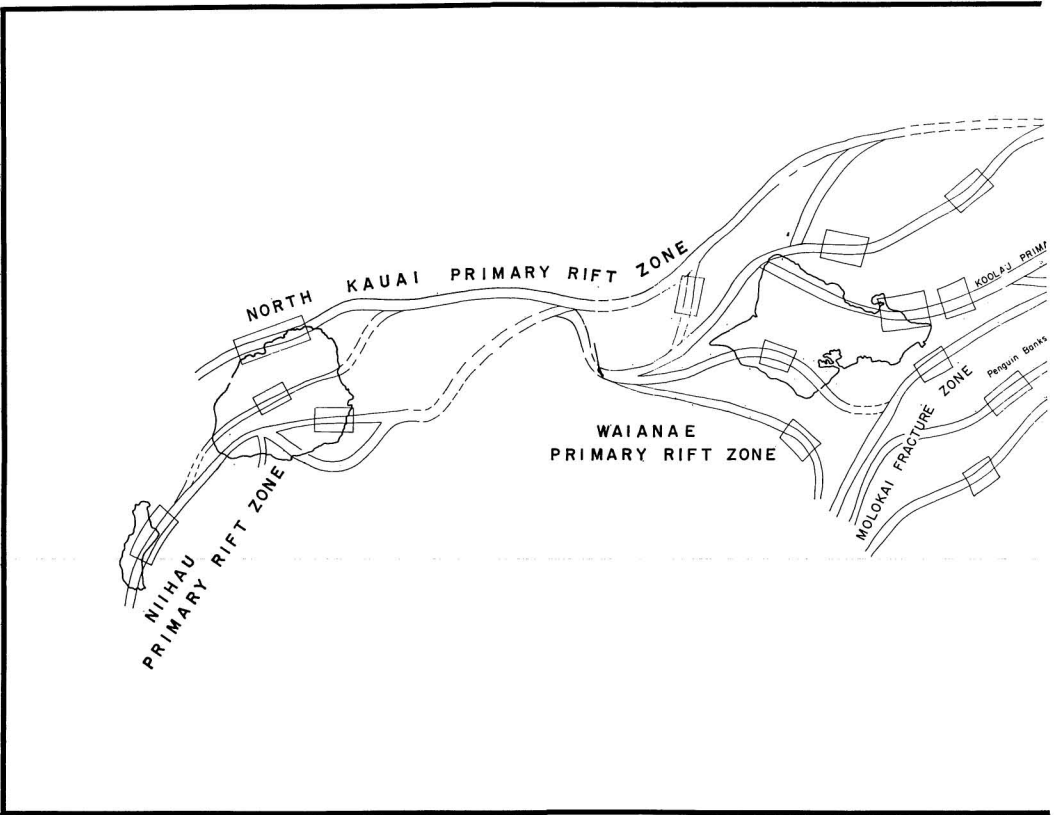


FIG. 9. Magnetic and topographic trends over the Hawaiian Rise.

FIG. 10. Sketch of primary rift zones and volcanic pipe zones, Oahu to Hawaii islands.



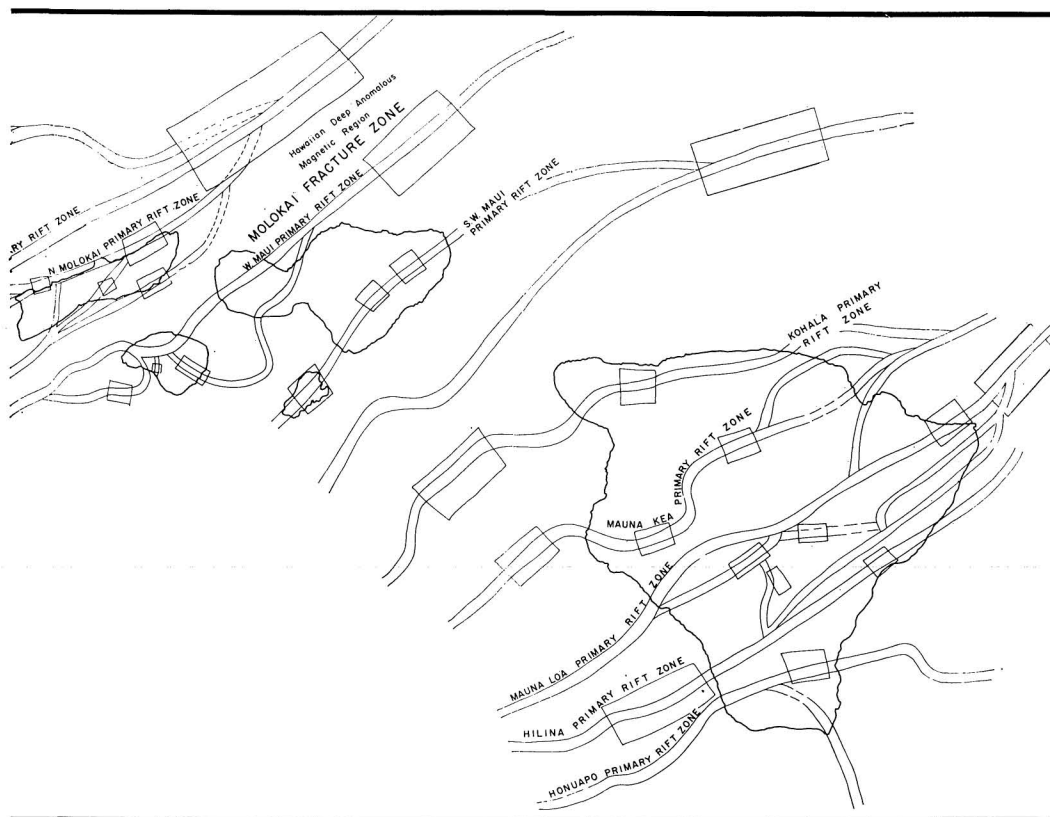
the strike of the Molokai Fracture Zone, the island of Molokai probably marks the area of intersection of two tectonic trends. Probably the older one strikes parallel to the axis of the Hawaiian Ridge, and the other strikes parallel to the Molokai Fracture Zone.

In order to assess quantitatively the nature of the magnetic anomalies and their association with geologic and tectonic features, it is best to carry out those analyses over areas of known geology. Therefore, the magnetic field has been analyzed on an individual basis for each major island of the Hawaiian Ridge.

#### *General Remarks on Geology of the Hawaiian Islands*

The Hawaiian Islands represent a series of basaltic shields that developed from the outpourings of lava from a number of primary volcanic vents. These, in turn, appear to have been located on a major crustal rift zone that is now defined by the Hawaiian Ridge extend-

ing some 2000 km from Kure Island to the island of Hawaii. Because volcanism appears to have been a progressive phenomenon, with the island of Hawaii representing the most recent addition to the Ridge, the fracture zone appears to be one that is undergoing continuous development. An alternate interpretation proposed by Wilson (1963) is that there was only one center of volcanism and that the Ridge developed by crustal migration to the northwest away from Hawaii. The continuity in strike of the Molokai and Murray fracture zones across large reaches of the Pacific Ocean and the Hawaiian Ridge, however, tends to discount this rather intriguing theory. As indicated earlier, the present magnetic study indicates that there are major anomalies associated with known fracture systems, such as the Molokai Fracture Zone, and with implied fractures in the crust and primary centers of volcanism. In each case, the intrusion of rock at depth having a high magnetic susceptibility is indicated.



Measurements of dike rocks collected in the islands have shown that, in general, the susceptibility and remanent magnetization in these intrusive rocks are higher than that in the surrounding extrusive rocks by a factor of two. These relations verify the results of theoretical analyses of the anomalies, and suggest that most of the magnetic anomalies in the Hawaiian Islands are explainable by having magnetic intrusive rocks occupy the rift zones and the primary volcanic vents responsible for the formation of the islands.

### *Island of Hawaii*

**GEOLOGY OF HAWAII:** Since the geology of the island of Hawaii has been described in detail by Stearns and Macdonald (1946), it is reviewed here only briefly. The rocks constituting this island are basalts and their differentiates, whose magnetic susceptibilities vary between  $2.6 \times 10^{-3}$  and  $0.2 \times 10^{-3}$  cgs units. Because the intensity of remanent magnetization is approximately 10 times the numerical value of the susceptibility, it has not been possible, in general, to discriminate between the magnetic effects of the individual formations. As will be seen, the principal magnetic anomalies are associated primarily with intrusive features such as centers of volcanism and dikes.

Although the island is only 93 miles long and 76 miles wide, Stearns and Macdonald identify five major volcanic centers: Kohala Mountain, Mauna Kea, Hualalai, Mauna Loa, and Kilauea. The earliest eruptions appear to have taken place in Tertiary time.

Hualalai Volcano was active from Tertiary to Recent time and has erupted basalts and trachyte along three rift zones. In 1801 an eruption produced olivine basalt with a large proportion of ultrabasic to dioritic inclusions.

Kohala Mountain is built largely of olivine basalts, tholeiitic basalts, and ash erupted along three rift zones trending across the summit of the volcano. Most of the activity was during the Middle Pleistocene. Caldera faults defining a shallow graben containing alkalic basalt now mark the summit area.

Mauna Kea, the highest of the volcanoes, is composed of tholeiitic basalt with a capping of alkalic basalt and ash, erupted along three rift zones trending away from the summit. The

volcano was active from the Pleistocene to Recent, and the summit is now marked by several large cinder cones.

Mauna Loa, the largest and second highest volcano in Hawaii, is located adjacent to Mauna Kea. It is active periodically and has erupted olivine basalt along two rift zones. A large caldera marks the summit.

Kilauea is the smallest and currently the most active of the volcanoes. It is located at the intersection of two rift zones.

Although, as seen, rift zones defined by surface fissures and chains of volcanic cones which usually intersect at the summits are associated with all the volcanoes, most of these surface fissures do not have magnetic anomalies associated with them. Thus the surface fissures appear to be superficial features. Figure 11 shows their locations and identifies the individual volcanoes with which they are associated. It is along these rifts that most of the recent flank eruptions have occurred. Their locations suggest that they have originated from the dilational forces associated with the development of the individual volcanic shields.

Similarly, there are normal faults (Fig. 12) which appear to be superficial features that have resulted from the rapid growth of the volcanic shields. These are of three types: (1) circular or concentric faults originating around pit craters (calderas), (2) faults parallel to rift zones, and (3) faults near the coast, dipping seawards. The horizontal extent of these faults, which are generally less than 10 miles in length, is small. Continuous strike directions are uncommon.

A comparison between the superficial structural patterns and deep-seated features such as the primary rifts and volcanic vents on the island of Hawaii can best be made by comparing Figures 11 and 12 with 13, which presents the total force intensity magnetic map of the island. As seen from Figure 13, the summits of all five volcanoes on the magnetic map are marked by dipole anomalies polarized normally; i.e., with the positive pole to the south and the negative pole to the north. Because at the magnetic latitude of Hawaii a dipole effect will be produced by nearly vertically sided bodies whose vertical dimensions are in excess of the minimum horizontal dimension by a factor of two or

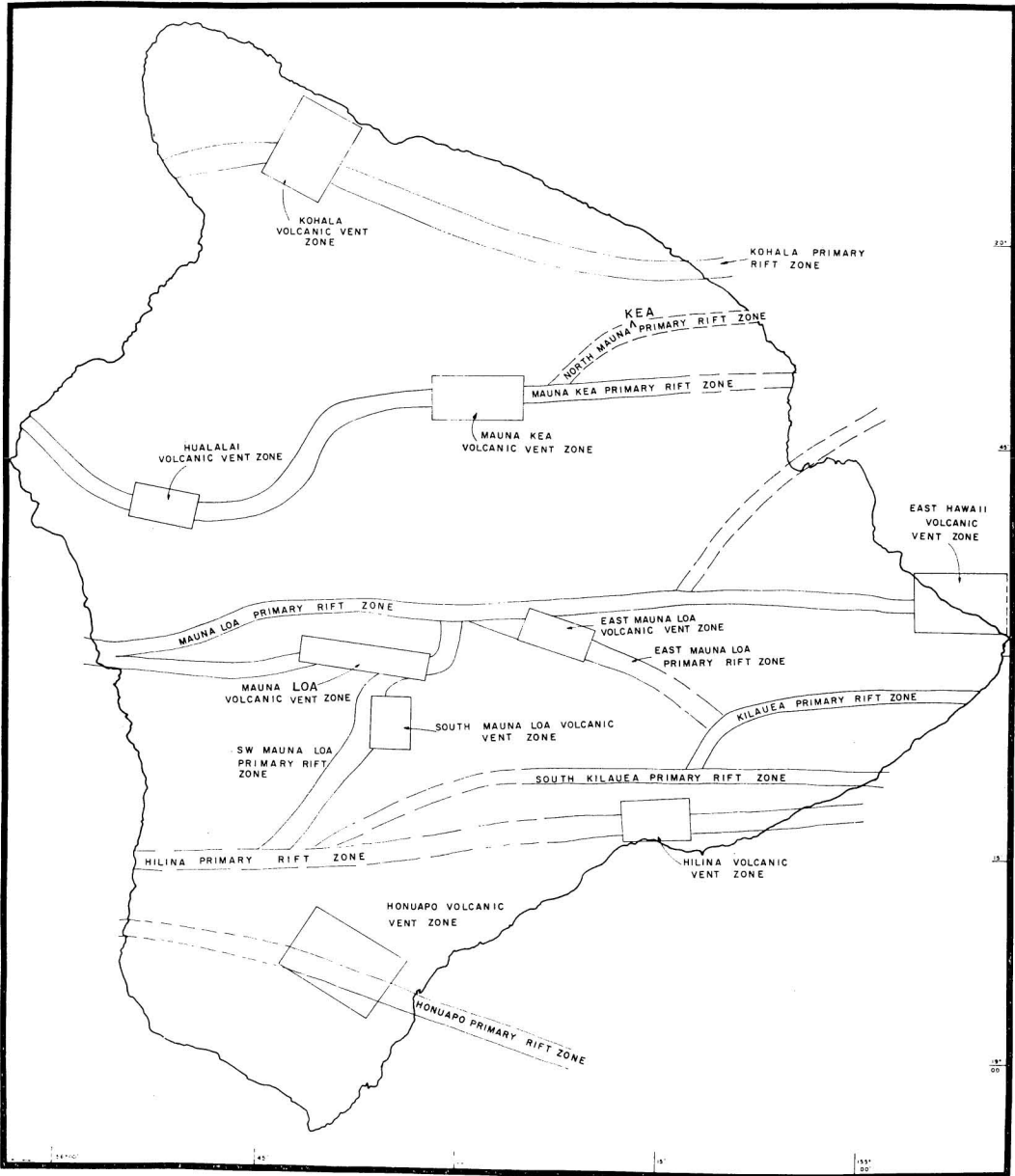


FIG. 11. Primary rift zones and volcanic pipe zones for the island of Hawaii.

greater, the points of inflection on the profiles across the dipoles mark approximately the center of the anomalous body. Lenticular magnetic gradients defining dipoles persisting for long horizontal distances, such as the one striking in an east-west direction north of Mauna Loa, are interpreted as being due to intrusive rock in

major crustal fractures. On this basis, the magnetic anomaly field of Hawaii can be subdivided as follows:

a. Dominantly east-west striking primary rift zones probably representing intrusions derived from considerable depths that are occupying primary fractures in the crust.

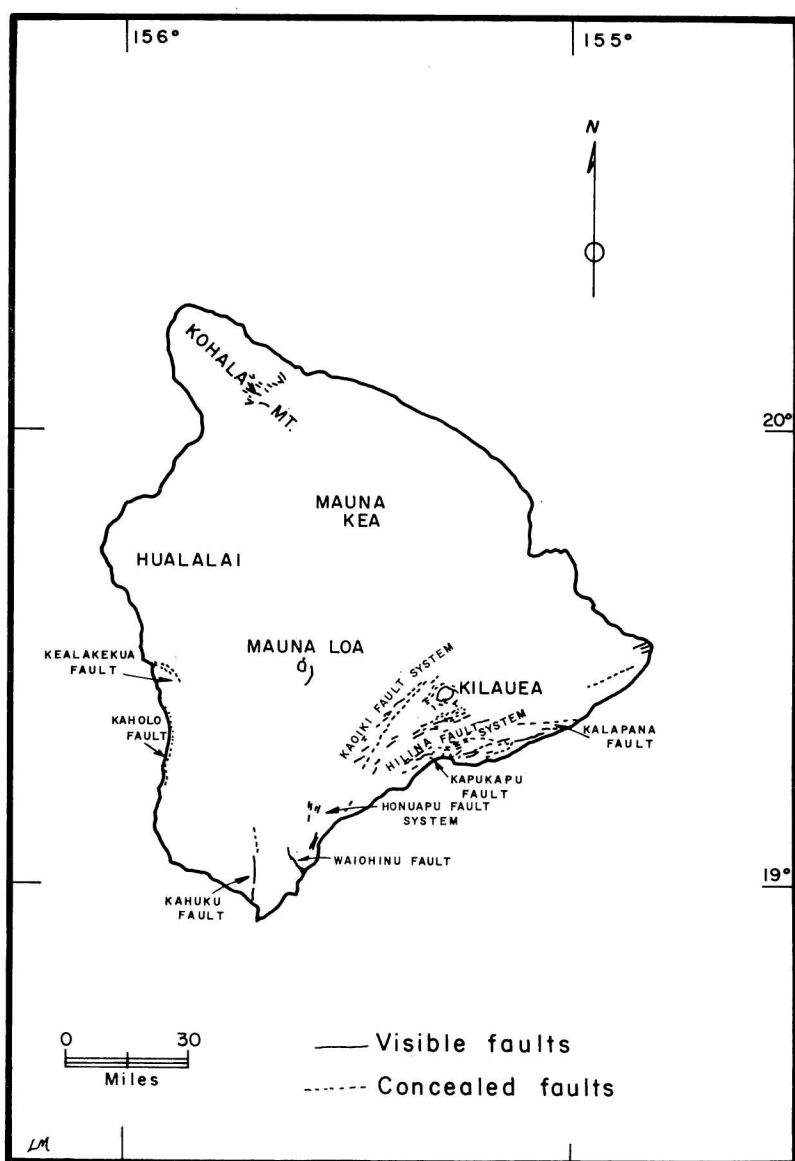


FIG. 12. Map of the island of Hawaii showing location of visible and concealed faults. (From Stearns and Macdonald, 1946.)

b. Dipole centers associated with volcanic vents. It appears significant that all these volcanic center anomalies are located on the axes of the principal longitudinal anomalies related to primary crustal rift zones, and that the latter, in general, do not coincide with secondary fracture systems.

Some superficial rift zones, such as the south-

west rift zone on Mauna Loa, do have an associated magnetic effect; however, most primary rift zone anomalies (Fig. 11), such as the east-west rift zone anomaly north of Mauna Loa and the Mauna Kea-Hualalai rift zone anomaly, do not have associated superficial features. Judging from the magnetic depth estimates and sizes of the dipole anomalies, these primary rift zone



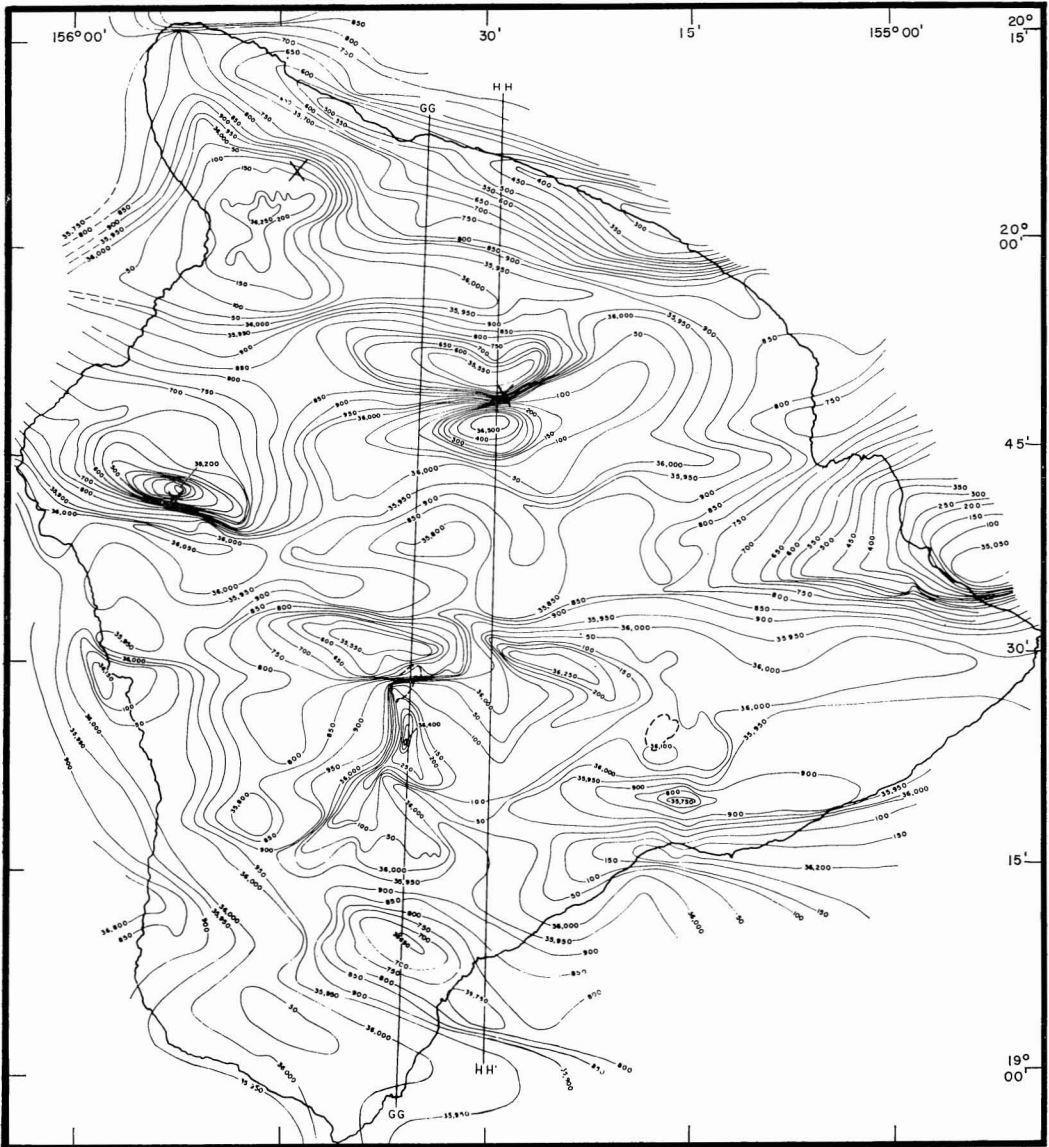


FIG. 13. Total force magnetic map of the island of Hawaii, based on aeromagnetic profiles flown at 14,000 ft over Mauna Kea and Mauna Loa, and at 12,000 ft over the rest of the island. Contour interval at 50 gammas.

anomalies originate from depths as great as 10 km below sea level. The absence of anomalies over most of the "fundamental fissures" deduced from geologic investigations can be explained only by an obvious difference in rock material from that causing the primary rift zone anomalies, and a lack of contrast in magnetic susceptibility of the intrusives filling the secondary fissures and the surrounding lavas.

Although the magnetic anomalies do not indicate that the major volcanoes are interconnected with each other except where two vents are located on the same primary rift anomaly, this possibility is not ruled out, inasmuch as a shallow connection would not have magnetic expression if the rock were above the Curie temperature.

In all cases, it is notable that the volcanic

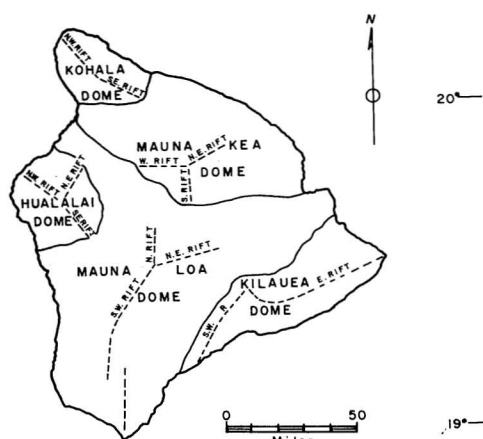


FIG. 14. Map of the island of Hawaii showing surface rift zones. (From Stearns and Macdonald, 1946.)

vents are located on the east-west primary rift anomaly zones. As discussed previously, these primary rift zones, defined by elongate dipole anomalies, are not confined to the island mass but extend into the adjacent ocean. Thus, on the island of Hawaii, moving south from Kohala Mountain, we have:

1. The "Kohala Primary Rift Zone," on which is located the volcanic center of Mt. Kohala.

2. The "Mauna Kea Primary Rift Zone," which strikes in a general east-west direction and on which are located the Mauna Kea and Hualalai vents. This primary rift zone is located some 20 miles south of the "Kohala Primary Rift Zone." The northeast rift on Mauna Kea, as shown by Stearns and Macdonald (Fig. 14), appears on the main limb of the primary rift zone, as does the west rift. However, although the south rift is reflected in the magnetic anomalies as a southward bay, it is improbable that it has any significant depth or magnetization, as the local anomaly is only  $+80$  gammas. The primary rift zone apparently enters the area of Mauna Kea along the northeast rift, and changes direction beneath the west rift of Mauna Kea. The trend then experiences a southward deflection between the mountains of Mauna Kea and Hualalai and enters beneath the summit of Hualalai Volcano, continuing to strike westward out to sea. The southeast rift of Hualalai Vol-

cano is defined by a  $+50$ -gamma anomaly, which disappears in the Mauna Loa Primary Rift Zone. However, the magnetic anomaly is too low, in view of the anomalies produced by the volcanic pipe complexes, to warrant an assumption that the Mauna Loa and Mauna Kea primary rift zones are interconnected at shallow depth along this rift. The northeast rift appears as a short low positive local magnetic anomaly of  $+50$  gammas, which persists for only 12 km northeast of the summit of Hualalai Volcano. The northwest rift is difficult to interpret in terms of local residual magnetic anomalies, because it lies directly along the negative limb of the Hualalai magnetic anomaly.

3. The "Mauna Loa Primary Rift Zone" strikes from Cape Kumukahi westward and is marked by a magnetic low of  $-950$  gammas located 2 miles north of the trend. The magnetic low may be interpreted as being caused by a flat shallow source of molten nonmagnetic magma (located at a depth of 5–10 km from the surface) with dimensions of 8 km by 2 km. However, because the contours of this anomaly do not close seaward, no definite statements on size or shape of the cause of this anomaly can be made. Some curious branches of this rift zone bifurcate so that the volcanic pipe complex of Mauna Loa Volcano is located on a southwestern extension of the rift zone. A secondary pipe complex of Mauna Loa is located 10 km south of Mauna Loa's summit, and probably accounts for the southern extension of the  $+330$  milligal Bouguer gravity anomaly on the gravity anomaly map of the island of Hawaii (Kinoshita et al., 1963). Similarly, another pipe complex is located 15 km northeast of the summit of Mauna Loa, on a branch of the Mauna Loa Primary Rift Zone.

4. The "Kilauea Primary Rift Zone" appears as an east-west striking feature 8 km south of Cape Kumukahi, curves southward and joins an indistinct east-west striking rift zone 10 km south of Kilauea caldera. It is difficult to locate the Kilauea caldera on any of the primary rift zones. Judging from the strike of these rift zones, it appears that Kilauea Volcano originated in the zone of coalition between the southeast branch of the Mauna Loa Rift Zone and the two Kilauea rift zones. Although Kilauea caldera has a distinct gravity anomaly associated with

it, the magnetic anomaly is almost nonexistent. We can deduce from this association that the vent material beneath the caldera is dense and nonmagnetic or partially magnetic, as would be the case with a partially molten vent complex.

5. The "Hilina Primary Rift Zone" has been named after the Hilina Fault System, with which it apparently has a direct association. It is surprising that such a prominent surface feature as the Kilauea Southwest Rift has no magnetic anomalies associated with it. In fact, it cuts right across the zone of strong east-west striking anomalies. It can only be concluded from this evidence that the Kilauea Southwest Rift is only a superficial feature. The Hilina trend has a distinct, normally-polarized magnetic anomaly of 450 gammas peak-to-peak associated with it. This anomaly could be the result of intrusion along the Hilina Fault System, or it could be due to an ancient volcanic complex now submerged beneath the covering lavas of the Kilauea series.

6. The "Honuapo Primary Rift Zone" crosses the shoreline of the island of Hawaii in the neighborhood of the town of Honuapo. As seen in Figure 11, this rift zone has a vent tube magnetic dipole anomaly associated with it. No doubt this broad dipole marks the center of an extinct volcanic vent now buried.

It is important to note that the primary rift zones described above are not linear and, in places, are sharply bent, suggesting that there has been intrusion along intersecting fractures. In all cases, the rift zones probably exist, but they have not been marked on Figure 11. However, the general strike of the primary rift zones is east-west and the bending is probably the result of local differential tectonic movement on cross faults. As it is unlikely that two cross-cutting sets of fractures would be open at the same time, intrusions were not necessarily contemporaneous, but could have taken place in two stages, with the short flexure offsets in the dominant east-west trends representing leakage of magma into the joining fractures as they open up with a change in regional stress pattern. Although the point cannot be proved, it is not unlikely that vents on the primary rift zones developed at points of weakness where two sets of crustal fractures intersect.

Under this concept, the volcanoes which formed the island are secondary features superimposed on primary crustal rifts. In this respect, the writers are in agreement with the theory of Betz and Hess (1942), which proposes a fissure eruption origin for the Hawaiian Islands. However, as is evident, there is no single fault zone forming fissures from which magma erupted in mass.

Inasmuch as on Oahu the primary rift zones are oriented northwest-southeast and strike parallel to the axis of the Hawaiian Ridge rather than east-west, as they do on Hawaii, Maui, and Molokai; and inasmuch as both trends are present on Kauai, it appears that not only are there two sets of primary fractures associated with the Hawaiian Islands, but also that intrusion into them must have been governed by a change in regional stress pattern whereby the northwest-southeast sets were closed after the development of Oahu. Although the primary rifts are oriented east-west, it is the continuation of the Ridge along this same general strike that constitutes the principal argument for the centers of volcanism in Hawaii being localized at points of weakness where the earlier, now-closed, northwest-southeast fractures intersect the east-west fractures that stand out so prominently in the magnetic anomaly pattern.

The lack of negative anomalies and the absence of subdued positive anomalies above the summit of Mauna Loa, which is periodically active, appear to substantiate the existence of a secondary shallow magma chamber as postulated by Eaton (1962). Similarly, the lack of any pronounced magnetic anomalies beneath the Kilauea caldera suggests the existence of such a chamber. In this respect, these two volcanoes appear to differ from the other Hawaiian volcanoes, all of which have marked dipole anomalies associated with the vents.

QUANTITATIVE INTERPRETATION OF THE MAGNETIC ANOMALIES OVER THE ISLAND OF HAWAII: Depth, size, and shape estimates of the volcanic pipe zones, together with comparable model studies, are presented in Table 2.

As indicated earlier, rocks from 30 exposures were sampled on the island of Hawaii and analyzed in the laboratory for susceptibility,

using a susceptibility bridge, and for comparative remanence, using an astatic magnetometer. The samples ranged from tholeiite, collected from the Kilauea caldera walls, to alkalic basalt, collected from the area of recent eruption in the Puna district and from the 1919 and 1929 Mauna Loa lava flows. Olivine nodule-rich lava samples were also collected from the 1801 Hualalai lava flow. The susceptibilities ranged from  $1.54 \times 10^{-3}$  cgs units for tholeiite to  $3.62 \times 10^{-3}$  cgs units for samples of recent alkaline basalt. However, it should be noted that the susceptibilities of even neighboring samples of the same lava flow may vary by as much as  $\pm 1.0 \times 10^{-3}$  cgs units, depending on the absence or presence of local concentration of ferromagnetic minerals. Samples from rock quarries of massive fine-grained basalt, such as those collected in the vicinity of Kona airport, had variations of only  $\pm 0.2$  cgs units. Olivine-rich samples of alkalic basalt from Hualalai Volcano yielded susceptibilities as low as  $0.37 \times 10^{-3}$  cgs units. This selection of surface samples, which certainly cannot be regarded as representative of the bulk of the lavas of the Hawaiian volcanoes, does give a reasonable assemblage of representative susceptibilities.

Decker (1963) obtained an excellent fit of measured and observed profiles across the walls and floor of the Kilauea caldera, using an average value of  $1 \times 10^{-3}$  cgs units for susceptibility of basalt and a natural remanent magnetization of  $10 \times 10^{-3}$  cgs units. In the present study, the measured susceptibilities do

not deviate by more than a factor of two from the averaged values of Decker. The observed remanence values are approximately the same. The value of susceptibility of  $1.5 \times 10^{-3}$  cgs units and a remanence of  $11.0 \times 10^{-3}$  cgs units have been assumed in all the magnetic reductions and computations for the volcanoes of the Hawaiian Islands.

By using depth estimation methods coupled with theoretical model studies, depth estimates and shape and size estimates were carried out for major magnetic anomalies. In order to simplify the mathematical computations, rectangular shapes for the horizontal cross section of vents were adopted.

A summary of all the analyses is shown in Table 2. The tops of the volcanic vent zones appear to lie within a zone extending from sea level to 4 km. The top surface of the postulated Ninole vent (Stearns and Macdonald, 1942), now buried beneath flows from Mauna Loa, appears to be located at a depth of 3.4 km below sea level.

Another anomaly that is not represented by a surface feature is the Hilina volcanic vent. This feature is not reflected in the gravity anomalies (Fig. 15), yet it marks the center of a 400-gamma peak-to-peak magnetic anomaly. In the geologic cross section by Stearns and Macdonald (Figs. 16 and 17), an upwarp of the Hilina volcanic series, as well as a system of faults, is shown to occur in the vicinity of the point of inflexion of the magnetic anomaly. Therefore, the Hilina magnetic anomaly (Figs.

TABLE 2  
ANALYSES OF THE TOTAL FORCE MAGNETIC ANOMALIES OVER THE ISLANDS OF HAWAII

1*	2*	3*	4*	5*	6*	7*	8*
Kahuku pipe complex	3.05	14.5 by 09.5	6.5	-3.40	$2.30 \times 10^{-3}$	400	5
Mauna Loa pipe complex	4.30	16.8 by 04.0	2.7	+1.60	$6.95 \times 10^{-3}$	800	20
Hualalai pipe complex	3.05	8.8 by 04.9	1.3	+1.75	$6.95 \times 10^{-3}$	800	15
Kohala pipe complex	3.05	8.8 by 11.2	5.7	-2.65	$14.00 \times 10^{-3}$	800	10
Hilina pipe complex	3.05	9.6 by 05.6	4.0	-0.95	$11.30 \times 10^{-3}$	400	12
Mauna Kea pipe complex	4.30	12.0 by 06.0	1.9	+2.70	$13.80 \times 10^{-3}$	1500	8

1\* Name of feature.

2\* Elevation of flight level above sea level in kilometers.

3\* Cross sectional size of anomalous body in kilometers from the total magnetic intensity map.

4\* Depth estimates to top of anomalous body in kilometers (Vacquier method).

5\* Top of anomalous body with respect to sea level in kilometers.

6\* Magnetization contrast of anomalous body with surrounding rock in cgs units (Vacquier method).

7\* Maximum amplitude of anomaly in gammas peak-to-peak.

8\* Length of anomalous body in kilometers from theoretical models.

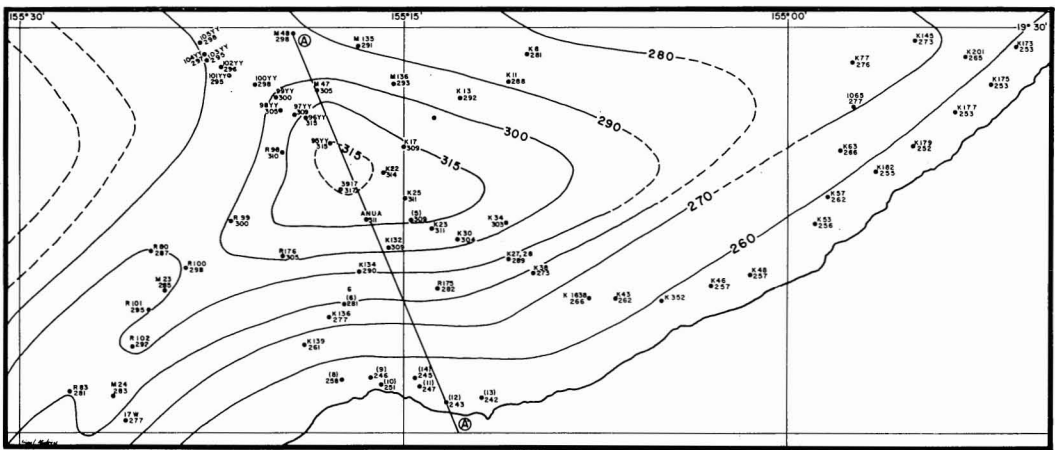


FIG. 15. Bouguer anomaly map of the Kilauea area on the island of Hawaii,  $\rho = 2.3$  gm/cc. Contour interval at 10 mgals. (After Kinoshita et al., 1963.)

17 and 18) probably marks an inactive center of volcanism containing more magnetic rocks than the surrounding basalts but having the same density as the surrounding basalts. The top of this center appears to be buried now at a depth of 0.95 km below sea level beneath the lava flows of Kilauea.

Also, the top of the Kohala volcanic vent appears to be located at a depth of 2.65 km beneath sea level.

The remaining major magnetic anomalies representing the vents for Mauna Loa, Mauna Kea, and Hualalai volcanoes occur at depths located above sea level. The Mauna Loa vent appears to originate from a depth of 1.9 km above sea level, and the Mauna Kea vent appears to originate from a depth of 2.7 km above sea level. The Hualalai vent has a depth of 1.75 km above sea level. It is difficult to judge the overall accuracy of the depth estimation

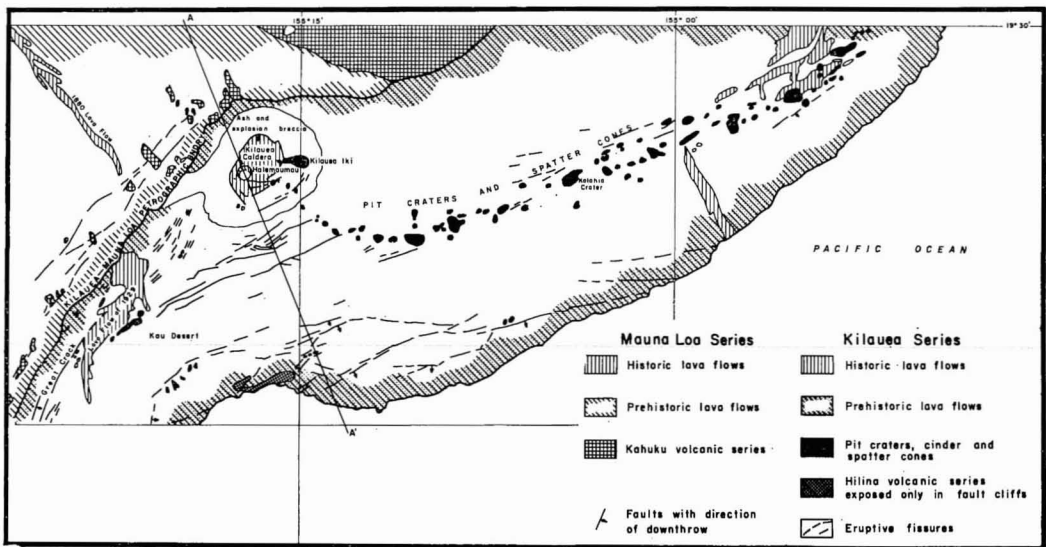


FIG. 16. Map of the geology of Kilauea Volcano, island of Hawaii.

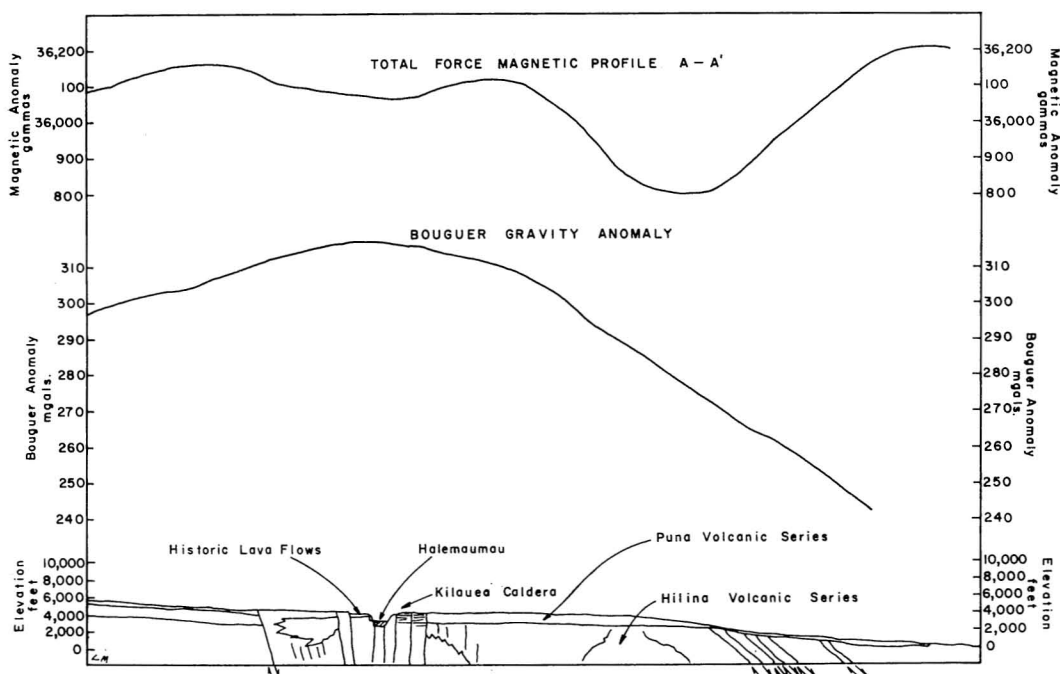


FIG. 17. Implied geological cross-section across Kilauea Volcano, island of Hawaii, with magnetic and gravity profiles along line A-A' (see Figs. 16 and 18).

methods. However, the writers believe that, because the total force magnetic dipole anomalies are distinct and can be reasonably approximated by Vacquier models, the  $G$  indices for the magnetic anomalies of Hawaii cannot be in error by more than 0.5 km.

The apparent susceptibility contrast between the rocks of the volcanic vent complexes, calculated by using Vacquier's relationships, varies between  $2.3 \times 10^{-3}$  cgs units for the Ninole vent and  $14.0 \times 10^{-3}$  cgs units for the Kohala vent.

It is obvious from a study of Figure 16 and the above data that the horizontal dimensions of all the vent complexes are in excess of their geologic expression. This difference might well reflect the presence of shallow magma chambers as postulated by Eaton (1962), or represent a spreading of the vent zone at depth, as suggested by analyses of the gravity anomalies associated with vents. Judging from the analyses of the vertical dimensions of the volcanic vent zones, the intrusive rock complex in the vents on the island of Hawaii extend upward from a

depth of 19 km below present sea level (some 4–5 km beneath the present level of the Mohorovicic discontinuity) to near the present surface. It is important to note though, that the bottom level of a 20-km-long vent zone may be varied by as much as 3 km without influencing the total anomaly profile by more than 5–20 gammas. Similarly, the bottom of the vent zone may be raised or lowered by several kilometers by altering slightly the general susceptibility contrast or natural remanent magnetization.

Inasmuch as the top of the Ninole vent complex lies at the deepest level, it could represent the oldest vent, but this is by no means certain. Certainly one would not interpret the fact that the top of the vent complex associated with Mauna Kea Volcano stands higher than that associated with Mauna Loa as indicating that it is the younger of the two.

**MAGNETIC EFFECT OF TERRAIN ON THE ISLAND OF HAWAII:** As stated previously, the flight elevations for taking the profiles in Hawaii were chosen so as to minimize the effect of terrain. All of the magnetic profiles used in



the magnetic computations were corrected for terrain at the flight level at which the magnetic readings were recorded.

The largest topographic effect was produced by the peak of Mauna Kea, where the aeromagnetic profiles, out of necessity with the light plane used, were taken at an elevation of only 300 ft above the highest point. The maximum effect of terrain above this point was +600 gammas (Fig. 19). As seen from Figure 19, the terrain correction here changed the magnetic profile to a textbook-type symmetrical dipole profile. The magnetic effect of the flank of Mauna Loa on the same profile was +190 gammas. The reason for this relatively low terrain effect on Mauna Loa lies in the greater height of the level of observation above ground surface. The terrain effect of Kohala Mountain was +100 gammas, and that of Hualalai Mountain, on the same profile, was +130 gammas. As indicated, a magnetic susceptibility of  $10.0 \times 10^{-3}$  was used in computing all of the effects of terrain. It should be noted that, because the topographic slope of the terrain was considerably less than  $35^\circ$ , the inclination of the earth's magnetic field in Hawaii, the topographic terrain correction in every case produced only a positive effect.

Because the magnetic terrain corrections did not alter the shape of the magnetic anomalies to any great extent even over Mauna Kea, it was not essential to correct the total magnetic force

anomaly map of Hawaii (Fig. 13) for topographic effects on the magnetic field.

#### *Islands of Maui and Kahoolawe*

**GEOLOGY OF MAUI:** Maui is the second largest island in the Hawaiian group and was formed by two volcanoes. East Maui contains the 10,025-ft high Haleakala Volcano and West Maui contains a deeply dissected volcano 5,788 ft high.

The flat isthmus connecting the two volcanoes was made by lavas from East Maui banking against the flows from West Maui. The oldest rocks on East Maui are the Honomanu basalts, which were extruded in the Pliocene or early Pleistocene period along three rift zones (Stearns and Macdonald, 1942) to form a shield about 8,000 ft high. Covering this dome are the Kula volcanics extruded in early or middle Pleistocene time. These consist of hawaiites, ankaramites, and related alkalic basalts. Volcanic activity was renewed in the middle to late Pleistocene and continued at least until about 1750 A.D., when the Hana lavas were deposited. During early Pleistocene time, it is probable that Maui, Kahoolawe, Lanai, and Molokai were joined as one island.

West Maui is composed of the older tholeiitic Wailuku basalts extruded in the Pliocene or early Pleistocene along two rifts and a set of radial fissures. The basalts form a shield 5,600 ft high. Iao Valley marks the center of the

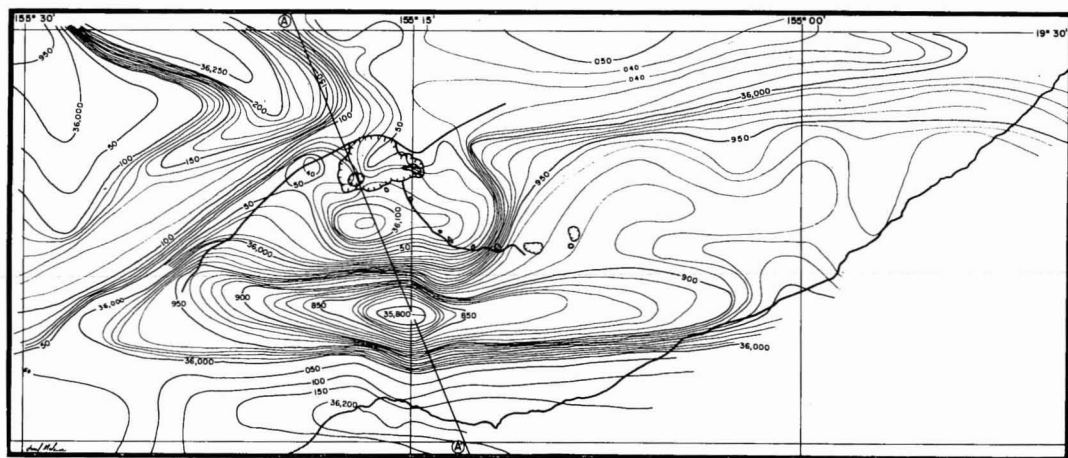


FIG. 18. Magnetic anomalies of Kilauea Volcano, island of Hawaii, flown at an elevation of 10,000 ft. Contour interval at 10 gammas.



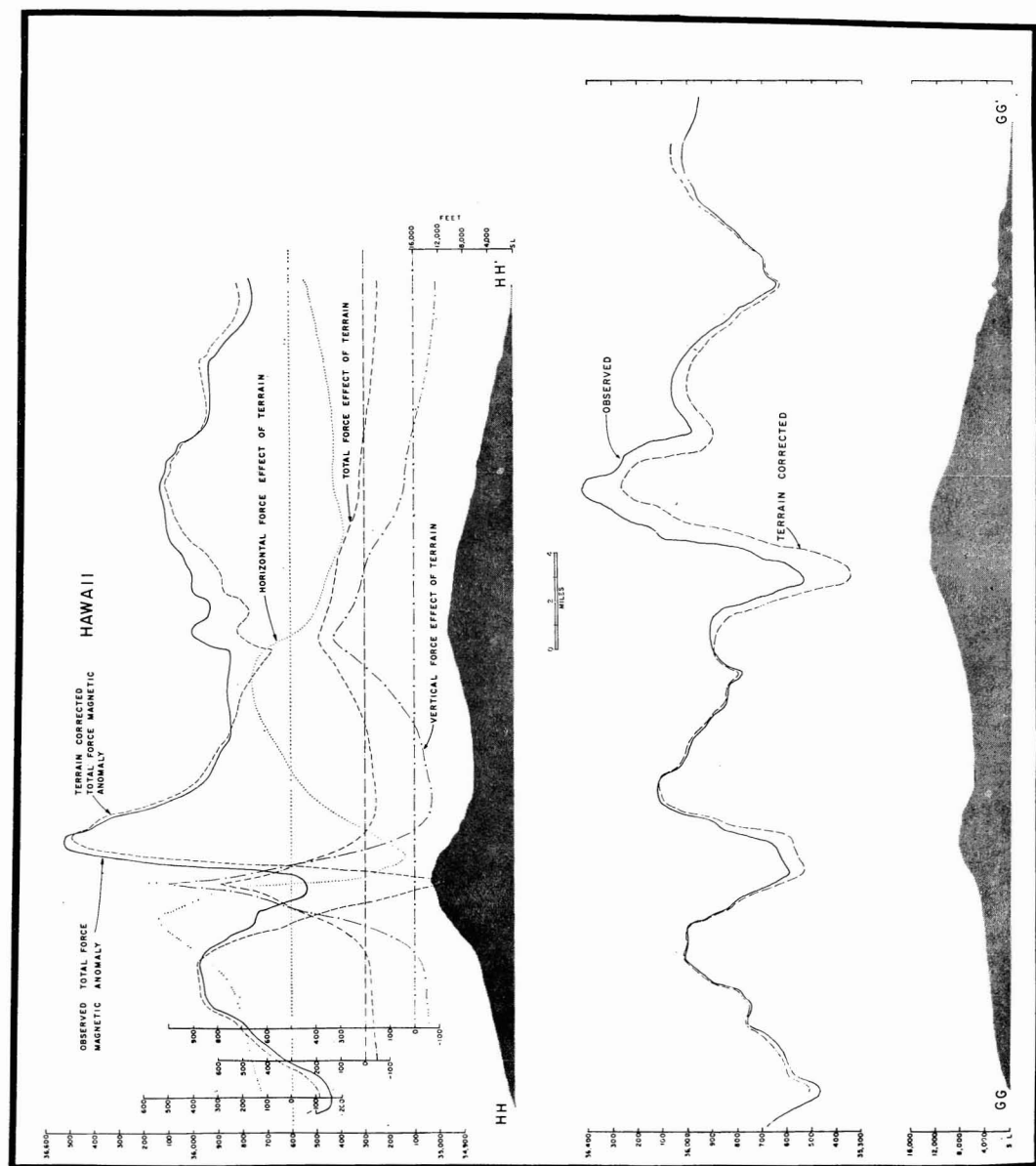


FIG. 19. Terrain-corrected magnetic profiles (above) HH-HH' and (below) GG-GG' along the island of Hawaii (see Fig. 13).

eroded caldera of this shield. Over this shield there is a thin veneer of Honolulu soda trachytes and mugearites. These were extruded in the late Pliocene (?) or early Pleistocene time.

Generally, the flows on Maui, according to Stearns and Macdonald (1942), were fed by magma that rose through fairly straight, vertical,

narrow fractures (Fig. 20). At depth, the dikes are massive and cross-jointed; and, where they underlie rift zones, they form dike swarms 1-3 miles wide. Bosses and plugs on West Maui range from 100 to 3,000 ft in diameter.

**GEOLOGY AND GEOLOGIC STRUCTURE OF KAHOLAWE:** Because it appears from the mag-

156°

21°

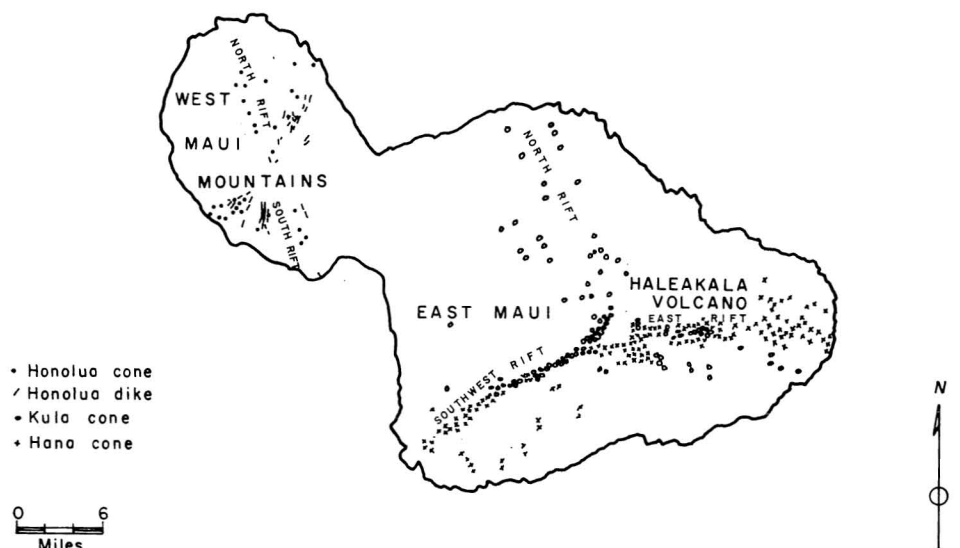


FIG. 20. Vents of the Hana, Kula, and Honolua volcanic series, and associated rift zones, island of Maui. (From Stearns and Macdonald, 1946.)

netic surveys that the island of Kahoolawe lies on the Southwest Primary Rift Zone defined on Maui, the magnetic field relations to geology on Kahoolawe are considered along with those for Maui.

Kahoolawe Island, according to Stearns (1940), is a shield-shaped, extinct volcano, 11 miles long, 6 miles wide, and 1,491 ft high, lying  $6\frac{3}{4}$  miles southwest of Maui. The island consists chiefly of tholeiite erupted from three rift zones and a vent at their intersection. The strike and position of these rift zones is defined by dike patterns in cliff faces and from the alignment of cinder cones present.

**THE MAGNETIC FIELD OVER THE ISLANDS OF MAUI AND KAHOOLOWE:** From an inspection of the total force magnetic map (Fig. 2), it appears that Maui was formed from eruptions on two east-west trending primary rift zones similar to those described on the island of Hawaii. Geologic observations in Haleakala Crater show that the southwest primary anomaly trend on Maui parallels the geologic East Rift and Southwest Rift of Stearns and Macdonald (1942). The surface manifestations of the Southwest Maui Primary Rift Zone anomaly, therefore, appear to be these two rift zones. The analysis

of this primary rift zone defines a belt of magnetic rocks two miles wide. As elsewhere, the natural remanent magnetization of dike rocks collected in Haleakala Crater by Malahoff was approximately 10 times the intensity of the surrounding lavas, although the petrographic composition of both the lavas and dike rocks was essentially the same. The direction of polarization of these dike rocks from Haleakala was normal.

Figure 21 shows that there are two principal centers of volcanism on the southwest primary rift zone anomaly, one marked as East Haleakala Volcanic Vent and the other as West Haleakala Volcanic Vent. Another volcanic vent zone is indicated on the same rift zone and has been named Kahoolawe Volcanic Vent, which is defined by a normally polarized dipole over the island of Kahoolawe (Figs. 22 and 23).

Although the West Maui Primary Rift Zone anomaly strikes in the same general direction as does the southwest primary rift zone anomaly, there is no connection between the two magnetic anomalies. It appears, therefore, that the two volcanic shields of East and West Maui originated along two separate primary rift zones. The isthmus between the two portions of Maui,

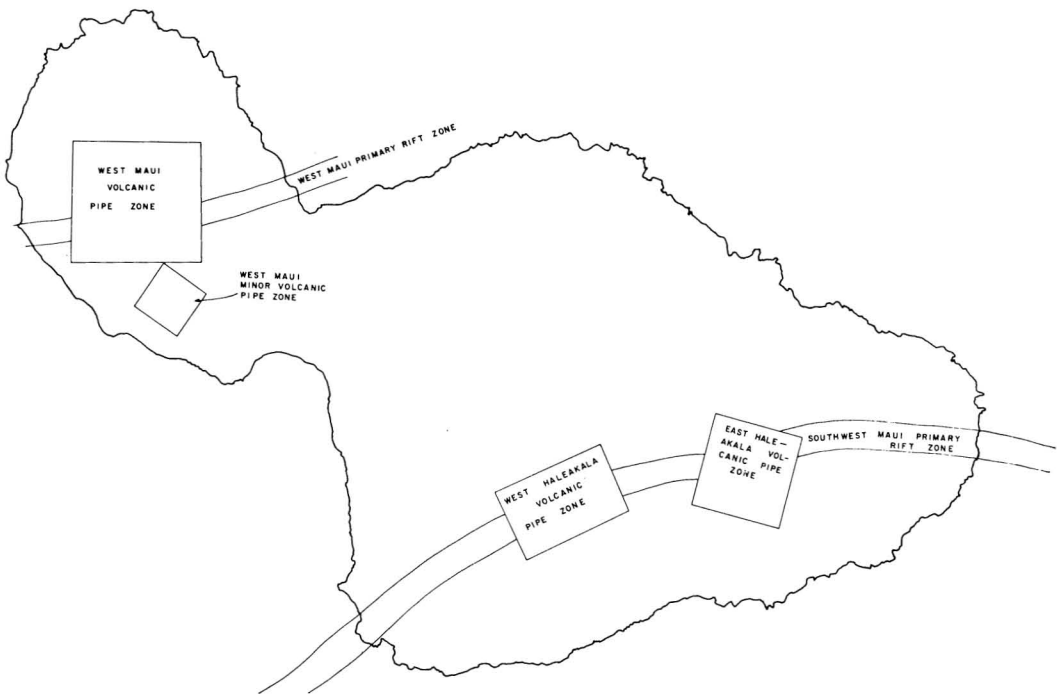


FIG. 21. Sketch of the primary rift zones and volcanic pipe zones of the island of Maui.

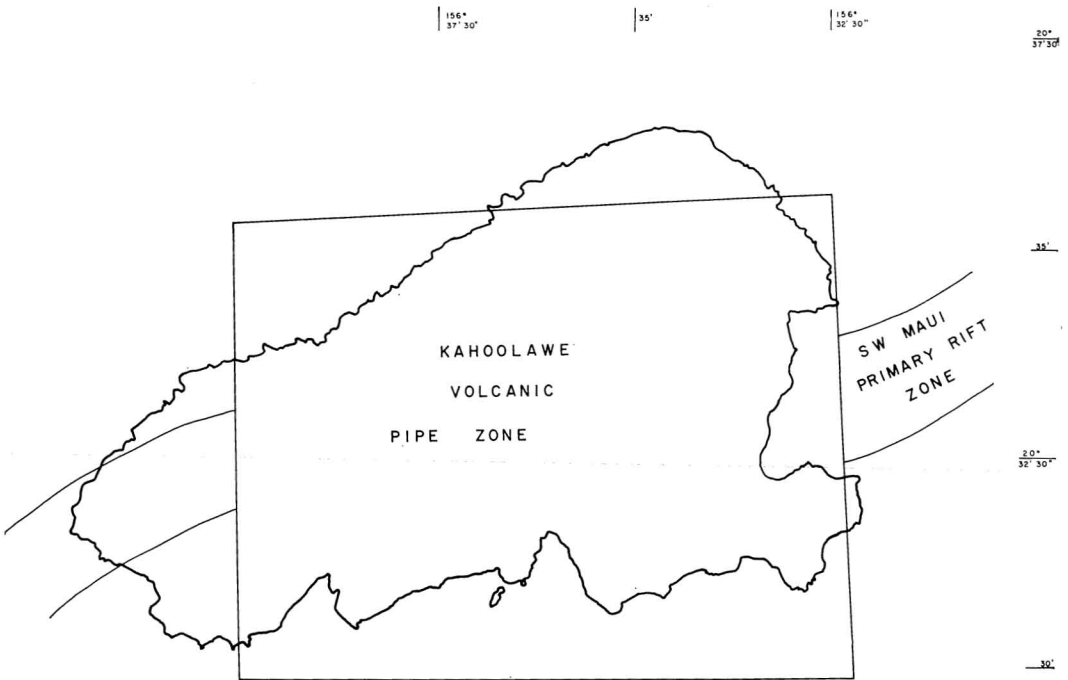


FIG. 22. Sketch of the primary rift zones and volcanic pipe zone of the island of Kahoolawe.

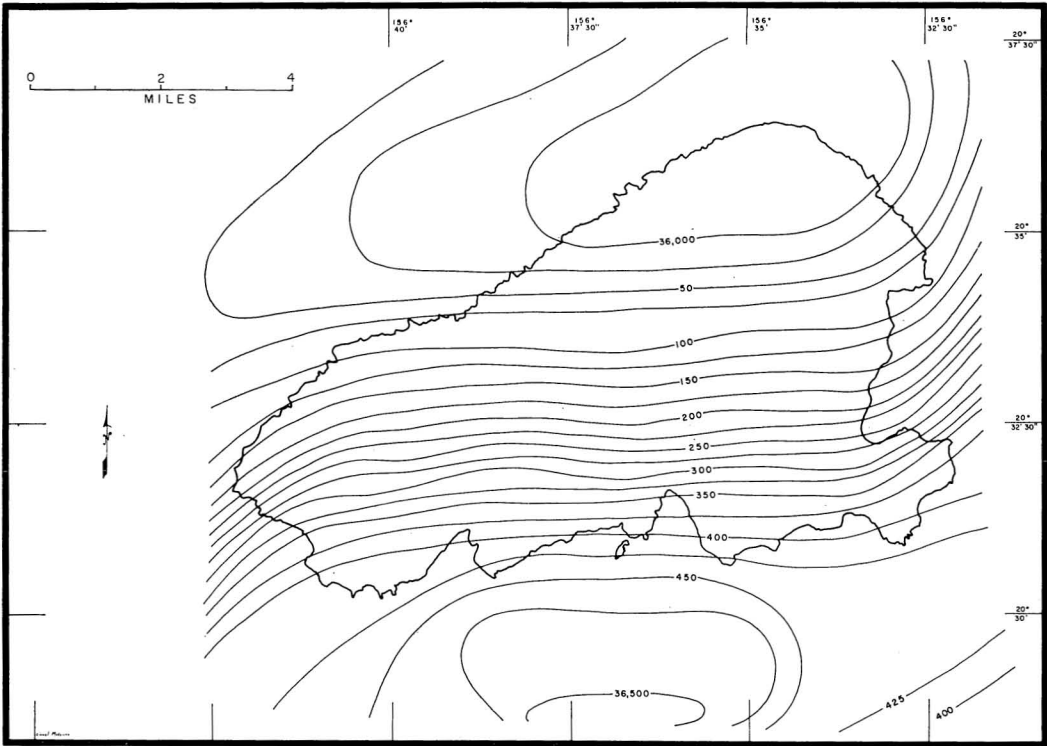


FIG. 23. Total force magnetic map of the island of Kahoolawe, based on aeromagnetic profiles flown at 8,000 ft. Contour interval at 25 gammas.

TABLE 3  
ANALYSES OF MAGNETIC ANOMALIES OVER THE ISLAND OF MAUI

1*	2*	3*	4*	5*
East Haleakala Volcanic Pipe Zone	4.0	7.3 by 07.3	15 approx.	$16.0 \times 10^{-3}$
West Haleakala Volcanic Pipe Zone	3.3	8.0 by 06.4	12	$18.0 \times 10^{-3}$
West Maui Volcanic Pipe Zone	1.6	9.5 by 08.9	9	$5.0 \times 10^{-3}$
West Maui Minor Volcanic Pipe Zone	0.5	4.0 by 04.0	3	$3.0 \times 10^{-3}$
Kahoolawe Volcanic Pipe Zone	2.4	10.0 by 12.8	2	$7.0 \times 10^{-3}$

1\* Name of feature.  
2\* Depth to top of anomalous body below ground level in kilometers.  
3\* Approximate horizontal cross section of anomalous body in kilometers.  
4\* Vertical length of anomalous body in kilometers.  
5\* Magnetization contrasts between anomalous body and surrounding rock in cgs units.

as well as the shelf area between the isthmus and the island of Kahoolawe, is devoid of any anomalies, suggesting that this area is clear of any intrusives. A negative embayment of 30–70 gammas in the contours north of the West Haleakala Volcanic Vent anomaly suggests that a shallow north-striking zone of dikes is present within the lavas of the Haleakala dome. At its southern end, the zone of dikes, as suggested by the magnetic anomalies, is offset westward by a distance of six miles from the geologically defined North Rift Zone of Stearns and Macdonald (Fig. 20). This offset is so great that it is highly unlikely that the two are related.

**QUANTITATIVE ANALYSIS OF THE MAUI AND KAHOOLOWE MAGNETIC ANOMALIES:** As on Hawaii, selected magnetic profiles were corrected for the magnetic effects of topography before quantitative analysis was attempted. Using analysis techniques, as described earlier, depth and size estimates, and magnetization contrasts were derived for the anomalies of Maui. These values are listed in Table 3.

All the magnetic anomalies, with the notable exception of the West Haleakala Volcanic Vent anomaly, are reflected also by gravity highs (Kinoshita and Okamura, 1965) which suggest that, as on the island of Hawaii, the magnetic anomalies are due to dense, highly magnetic, intrusive rocks located within the volcanic vents. The West Haleakala Volcanic Vent, as defined by a single dipole anomaly, appears to

be of shallow origin and only 2 km thick, though broad in horizontal cross section.

As on the island of Hawaii, the anomalous geologic bodies giving rise to the magnetic anomalies all appear to be vertically oriented.

The apparent reversals in the direction of magnetization observed for the two West Maui magnetic anomalies could be due to reversely polarized rocks occupying the vents or to weakly magnetized rocks occupying the vents. It may be significant that weakly magnetized rocks were collected from intrusive rocks of the Wailuku series. The surrounding basalts of the same series recorded higher remanence effects of  $9 \times 10^{-3}$  cgs units.

### *Island of Molokai*

**GEOLOGY:** The geology of this island has been described by Stearns and Macdonald (1947). The island was formed by eruptions from two principal volcanoes, West Molokai and East Molokai. West Molokai now stands 1,300 ft and East Molokai 4,900 ft above sea level. Both volcanoes were built up from the sea floor, probably during Tertiary time.

East Molokai is built of basaltic lavas with a thin cap of mugearites. Dikes cut the lower members of the volcano and trend east and northwest. On the basis of the dips of the flows the main volcanic center lies north of the present coastline. Intrusive rocks are common, and consist of stocks, plugs, and dikes which occur

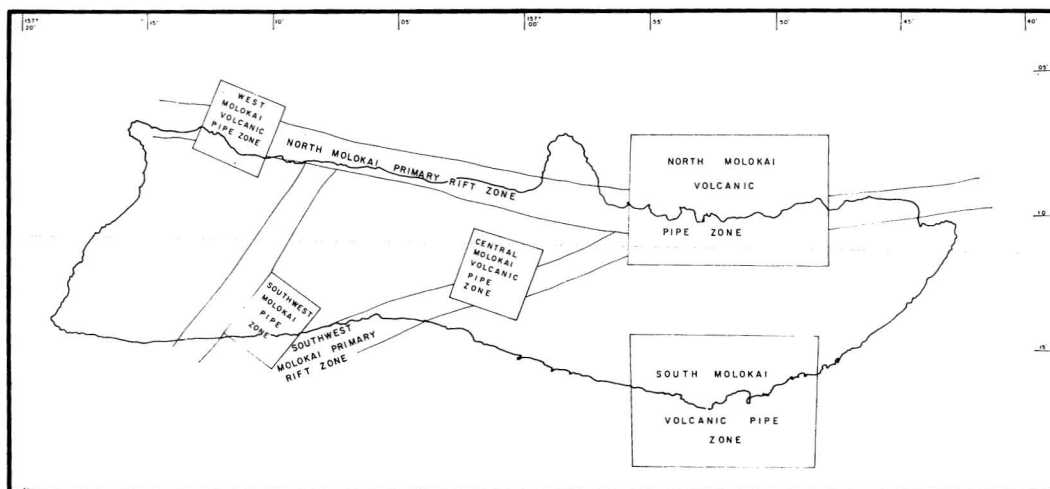


FIG. 24. Sketch of the primary rift zones and volcanic pipe zones of the island of Molokai.

TABLE 4  
ANALYSES OF TOTAL FORCE MAGNETIC ANOMALIES OVER THE ISLAND OF MOLOKAI

1*	2*	3*	4*	5*
North Molokai Volcanic Pipe Zone	0.8	14.0 by 10.0	8	$12.4 \times 10^{-3}$
South Molokai Volcanic Pipe Zone	1.0	13.0 by 09.5	10	$6.9 \times 10^{-3}$
Southwest Molokai Volcanic Pipe Zone	0.2	4.8 by 05.6	10	$7.7 \times 10^{-3}$ (reversed)
West Molokai Volcanic Pipe Zone	0.3	4.8 by 05.2	10	$13.9 \times 10^{-3}$

1\* Name of feature.  
2\* Depth to top of anomalous body below ground level in kilometers.  
3\* Approximate horizontal cross section of anomalous body in kilometers.  
4\* Vertical length of anomalous body in kilometers.  
5\* Magnetization contrasts between anomalous body and surrounding rock in cgs units.

along two rift zones, one trending east and the other northwest.

The West Molokai shield is built up of basaltic lavas of the West Molokai series, and is cut by dikes which strike southwest.

MAGNETIC RELATIONS: Figures 10 and 24 indicate that two elements of the Molokai Fracture Zone cross the island. The North Molokai Primary Rift Zone anomaly (Fig. 24) defines here a bifurcation in the strike of the Molokai Fracture Zone. Along the northern shore of East Molokai, the rift zone defined strikes slightly south of west, whereas along the

northern shore of West Molokai, it strikes north of west. The Southwest Molokai Primary Rift Zone anomaly shows no change in east-west strike and appears to intersect the North Molokai Primary Rift Zone anomaly. This intersection occurs at the location of the North Molokai volcanic vent, which is defined geologically and topographically by a caldera.

Although there are numerous minor magnetic anomalies over Molokai (Fig. 25), five major anomalies define five major centers of intrusion. Two of these appear as broad anomalies on West Molokai and three as smaller an-

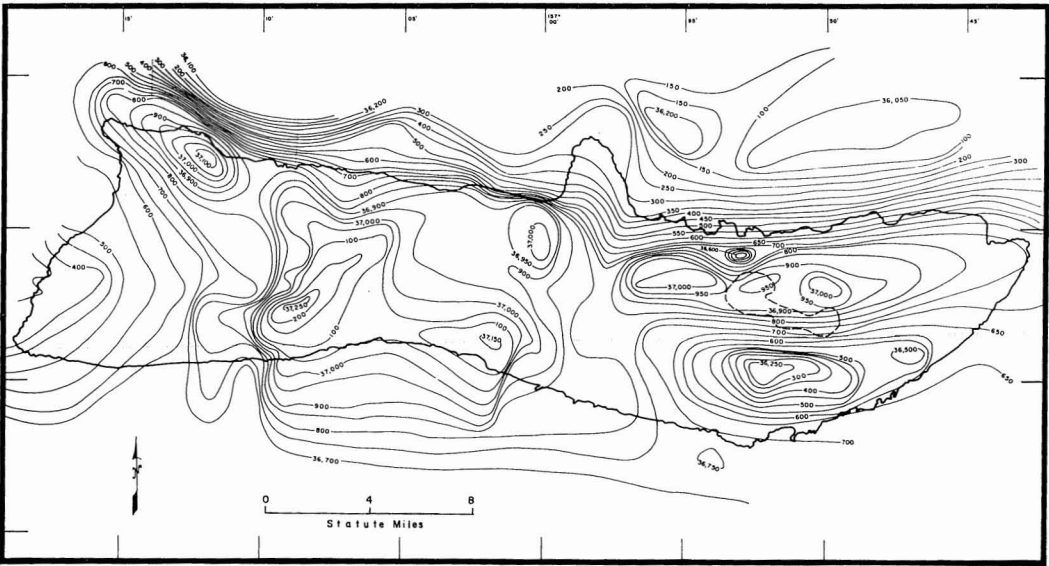


FIG. 25. Total force magnetic map of the island of Molokai, based on aeromagnetic profiles flown at 8,000 ft. Contour interval at 50 gammas.

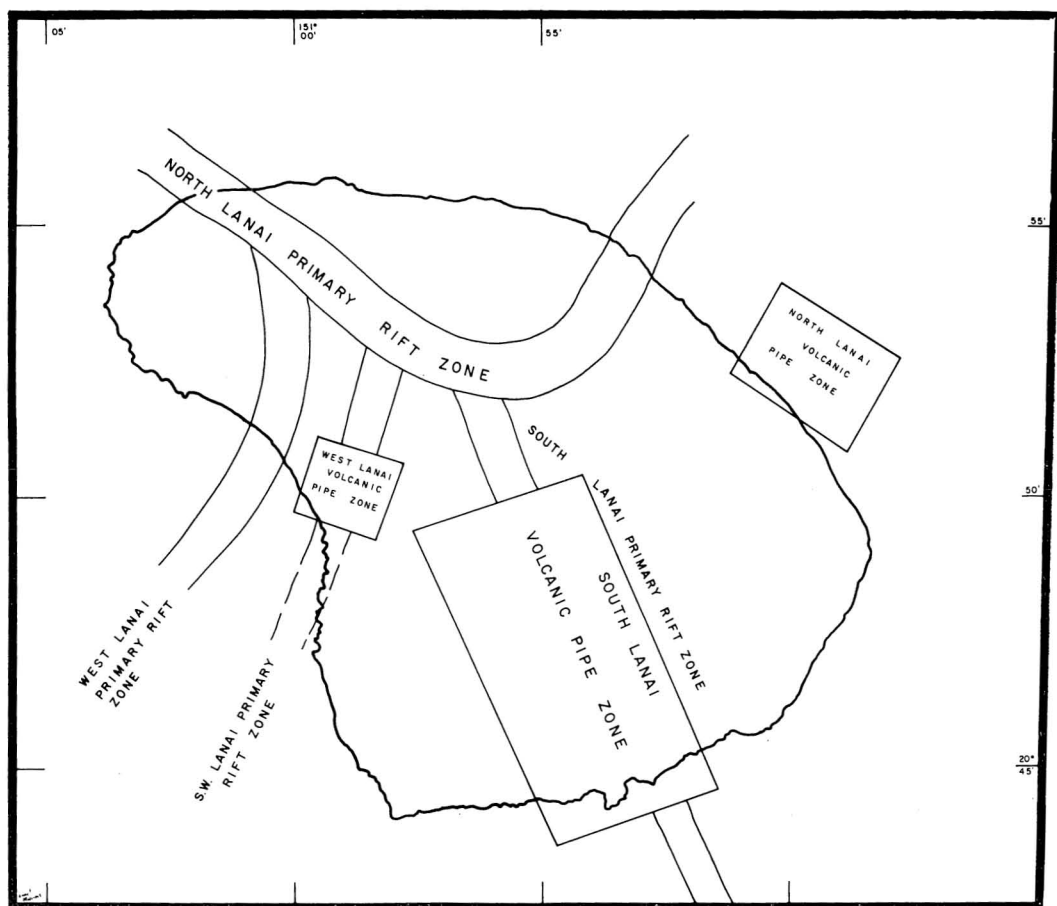


FIG. 26. Sketch of the primary rift zones and volcanic pipe zones of the island of Lanai.

omalies on East Molokai. The smaller anomalies appear to represent shallower sources which are superimposed upon the broad anomalies associated with the volcanic vent zone. These in turn are superimposed upon the primary rift trends believed to result from intrusions in crustal rifts. It appears, therefore, that East Molokai was formed by volcanic eruptions originating from at least two centers, and that West Molokai was formed by eruptions originating from at least three centers. The results for the analyses of the four principal magnetic anomalies are listed in Table 4.

In connection with the Southwest Molokai Volcanic Vent Zone, it is to be noted that the associated anomaly is inversely polarized. As explained in connection with relations on Maui, this can be explained as being due either to a reversal of the earth's magnetic field during the

period of solidification of magma within the vent, or to a filling of the vent with possibly olivine-rich rock which is less magnetic than the surrounding basalts. The computed magnetization contrast of  $7.7 \times 10^{-3}$  cgs units between the pipe zone rocks and the surrounding basalts is well within the range of possible magnetization contrast between olivine-rich basalt and tholeiitic basalt.

#### *Island of Lanai*

**GEOLOGY:** Lanai consists of a single shield-shaped volcano. According to Stearns (1940b), outpouring of lava has taken place from three sets of fissures that form three rift zones (Fig. 26), a northwest rift zone, a southwest rift zone, and a faulted south rift zone. Numerous dikes and faults occupy these rift zones. Basaltic flows erupted from these fissures and formed the



shield, and very little pyroclastic material appears to have been associated with the eruptions.

**MAGNETIC RELATIONS:** The three rift zones as described by Stearns are all reflected by magnetic anomalies (Fig. 27). Three major primary rift zone anomalies and two major volcanic vent zone anomalies are indicated. The prominent North Lanai Primary Rift Zone anomaly (Fig. 10) appears to be a member of the Molokai Fracture Zone system. The westward portion of the North Lanai Primary Rift Zone anomaly coincides with the Northwest Rift Zone of Stearns. Similarly, the South Lanai Primary Rift Zone anomaly coincides with the faulted South Rift Zone of Stearns. The West Lanai Primary Rift Zone has no apparent surface expression.

The South Lanai Volcanic Vent Zone anomaly, as elsewhere, probably reflects the intrusive rocks from which the majority of the lavas of Lanai originated. This vent zone is also marked by a pronounced gravity high. Though the geologic extent of the vent zone is broad (12 km long, 6.5 km wide) the total amplitude of the associated magnetic anomaly is low (150 gammas peak-to-peak). A depth analysis of this anomaly indicates that the top of the disturbing body lies at a depth of only about 0.8 km below the surface and appears to have a thickness of only about 2–5 km. The probable magnetization contrast with the surrounding basalts is low and of the order of  $2.0\text{--}5.0 \times 10^{-3}$  cgs units.

Similarly, the magnetic anomalies designated as the West Lanai Volcanic Vent Zone and the

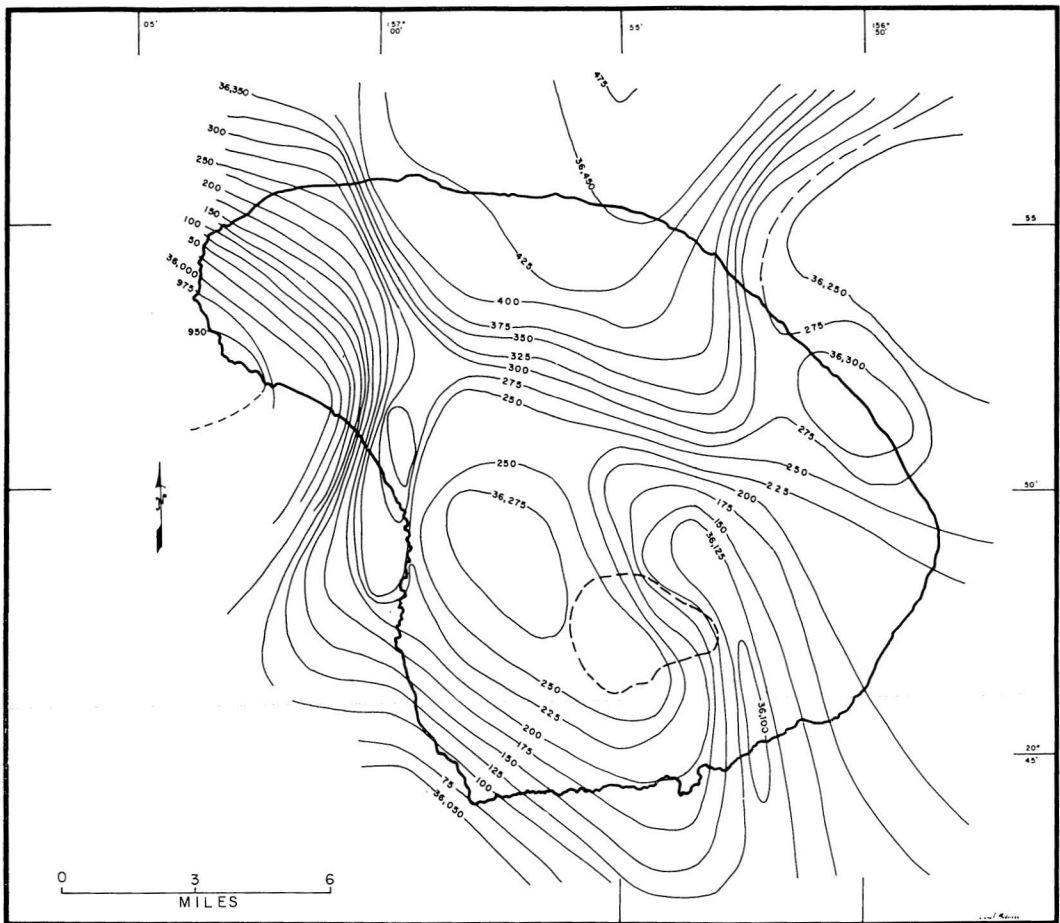


FIG. 27. Total force magnetic map of the island of Lanai, based on aeromagnetic profiles flown at 8,000 ft. Contour interval at 25 gammas.

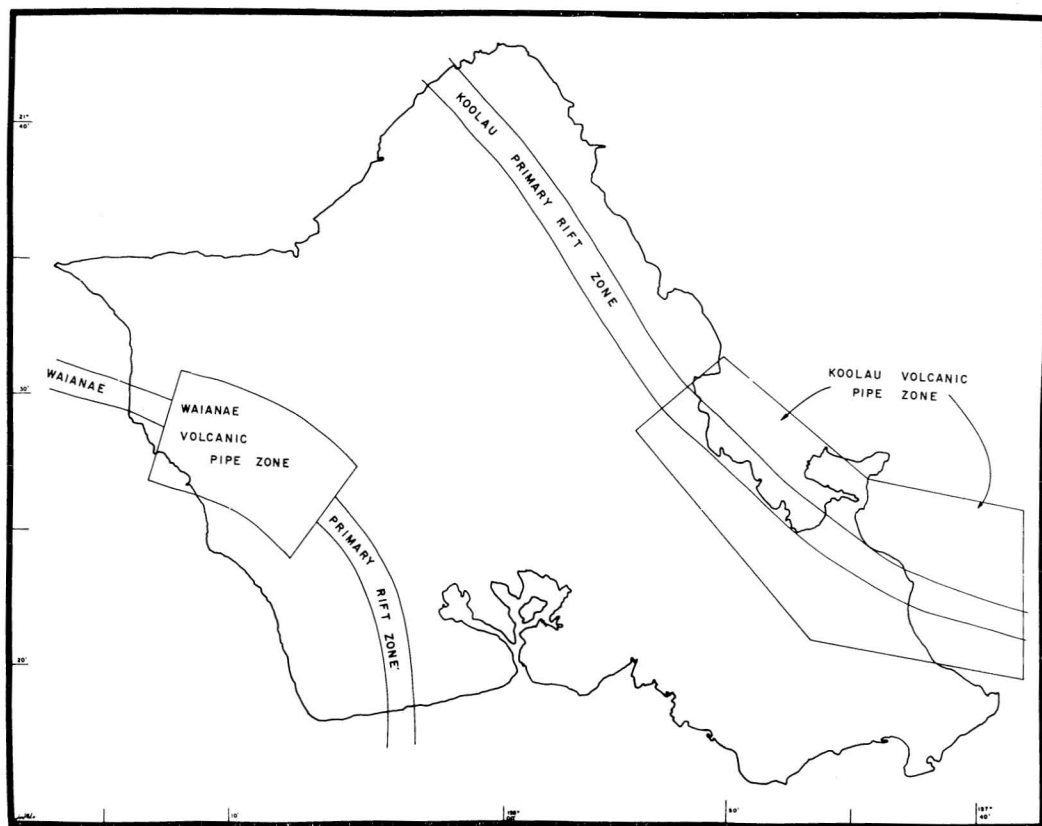


FIG. 28. Sketch of the primary rift zones and volcanic pipe zones of the island of Oahu.

North Lanai Volcanic Vent Zone are small in amplitude, 25 gammas for the former and 50 gammas for the latter. These two volcanic vent zones also probably represent shallow sources of volcanic activity. Geologically, the West Lanai Volcanic Zone is located in the area of the Southwest Rift Zone of Stearns (1940).

#### *Island of Oahu*

**GEOLOGY AND GEOLOGIC STRUCTURE:** Oahu was built by lavas erupted from two centers—the Waianae Volcano and the Koolau Volcano. Three groups of lavas form the Waianae volcanic range. The older lavas, probably of late Tertiary age, appear to be largely pahoehoe basalts, while the late stage eruptions produced large cinder cones and some alkalic basalts. The Waianae Volcano, like other Hawaiian volcanoes, produced only small amounts of ash, and the lavas were extruded both from a central vent and from fissures. Dikes and rifts are

numerous in the Waianae caldera and range in thickness from a few inches to several feet. Stearns (in Stearns and Vaksvik, 1935), after a study of the rift zones on Kilauea and Mauna Loa and in the Waianae caldera, noted that in almost all cases of rifting in the Hawaiian volcanoes the magma is confined to fissure zones that rise from the magma reservoir to the surface. Concentration of dike rocks in certain zones such as these probably could produce the elongate magnetic trends observed over such rift zones. Three dike systems have been mapped by Stearns (1939), and it will be seen that all of these rift zones lie within the boundaries of the Waianae Primary Rift Zone anomaly (Fig. 28). Furthermore, judging from the magnetic trend map of the seaward magnetic anomalies (Fig. 9), the Waianae Primary Rift Zone extends offshore west and south of Oahu.

The Koolau volcanic range is composed of the Koolau, Kailua, and Honolulu series. Both

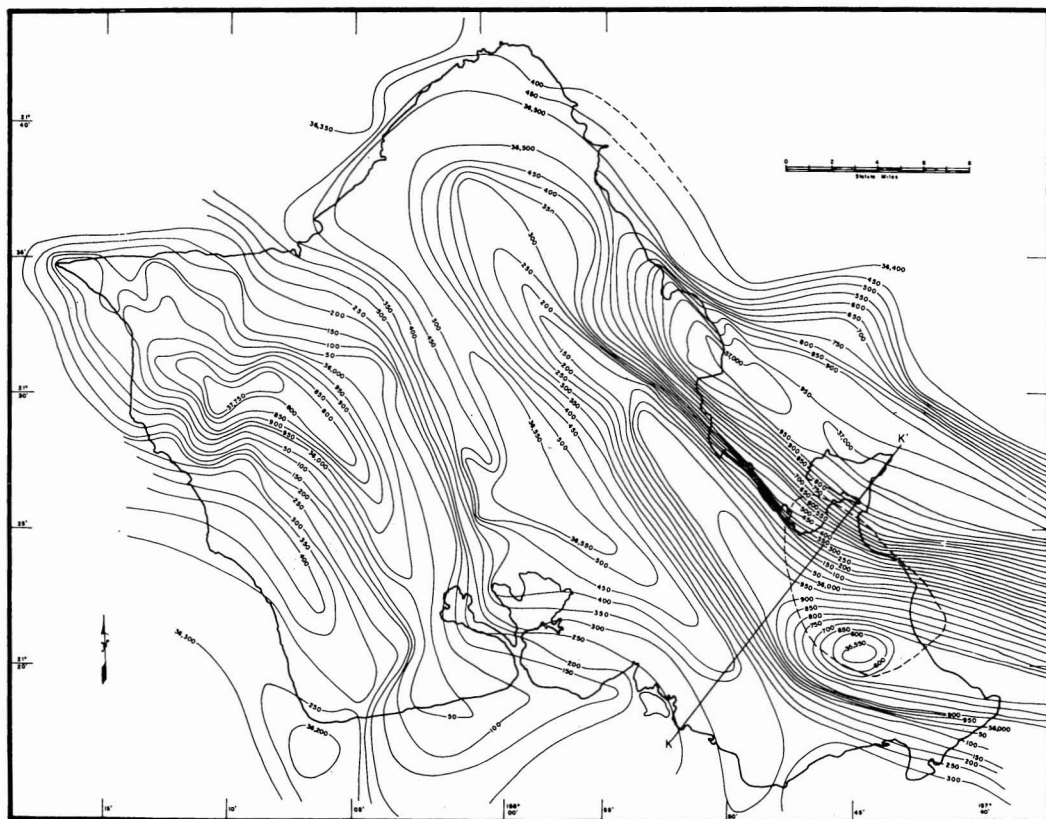


FIG. 29. Total force magnetic map of the island of Oahu, based on aeromagnetic profiles flown at 10,000 ft. Contour interval at 50 gammas.

the Koolau and Kailua series were erupted from the Koolau Volcano, and the Kailua series represents a hydrothermally altered intra-caldera group. Dikes are very common in the Kailua series, which occupies the Koolau caldera, and form a complex with younger dikes intruding into older ones. Many of the dike breccias and flows in the Koolau caldera are hydrothermally altered. It is believed that rocks of both the Kailua and Koolau volcanic series were erupted from the fissure zones of the Koolau Volcano. Fissure eruptions also characterized the building up of the Koolau volcanic shield. As in the Waianae area, the Koolau Primary Rift Zone anomaly (Fig. 28) coincides with the rift and dike zones of the Koolau Volcano, and, as with the Waianae Primary Rift Zone, is not confined by the shores of the island of Oahu.

**MAGNETIC RELATIONS:** The magnetic field of the island of Oahu (Fig. 29) is relatively sim-

ple. There are two primary rift zone anomalies, the Koolau and the Waianae, on each of which is located a large and distinct volcanic vent zone anomaly. These correlate with the Waianae and Koolau volcanic calderas. Both of these two volcanic centers are marked by distinct positive gravity anomalies (Woollard, 1951; Strange, 1964). However, the Koolau caldera, which is marked by a large amplitude 1,200-gamma peak-to-peak magnetic anomaly, is inversely polarized, whereas the Waianae caldera is marked by a 650-gamma, normally-polarized magnetic anomaly. The Koolau caldera has also been studied by seismic measurements (Adams and Furumoto, 1965; Furumoto et al., 1965), which show high velocity rock (7.5 km/sec) at a depth of only 1600 m.

Inasmuch as the Koolau caldera marks not only the site of one of the largest magnetic anomalies observed so far over the Hawaiian

Ridge, but also the only prominent magnetic anomaly which is inversely polarized, it is of special interest. This reversal in the magnetic field observed over the Koolau caldera can be explained either by the intrusion of weakly magnetized volcanic rocks within the Koolau Rift Zone or by a temporary reversal of the earth's magnetic field during the solidification of Koolau intrusive rocks. The explanation is not obvious, as studies of the extrusive rocks give conflicting data. The Honolulu series, for example, does not exhibit reversed magnetic polarization. Also, dike rocks collected within the Koolau caldera by the writers show normal directions of polarization in the laboratory. However, their intensities of remanent magnetization are lower than are those of the surrounding basalts. On the other hand, the results of polarization studies by McDougall and Talling (1963) indicate that the Koolau series of basalts are inversely polarized.

As the magnetic anomaly across the Koolau caldera (Fig. 3) shows that the point of inflection of the dipole is centered over the middle of the Koolau caldera, the inverse polarization is not a surficial effect but is one extending to depth. A gravity analysis (Strange, 1964) of the gravity high over the caldera requires a rock density of 3.2 gm/cc extending from a depth of 1 km to at least 16 km, and horizontal dimensions expanding with depth, as shown in Figure 3. This corroborates closely the seismic analysis by Adams and Furumoto (1965). The high seismic velocities and high densities suggest that the disturbing rock mass is a peridotite. However, it is not clear whether the inverse magnetic polarization is related to diamagnetism or to a past reversal in the earth's magnetic field. That the observed low susceptibilities for olivine-rich rocks could account for the anomaly is shown by the theoretical profile for a peridotite-filled caldera (Fig. 3): the computed profiles fit the observed profile within 50 gammas. A magnetization contrast of  $15 \times 10^{-3}$  cgs units would give excellent agreement between the observed and computed profiles. If this is the case, one then has to account for most other vent zones having the caldera "pipe" filled with highly magnetic rock having a susceptibility of approximately  $2 \times 10^{-3}$  cgs units. On a statistical basis, the diamagnetic explanation appears to be less reasonable than a reversal

in polarity. Only by drilling to the source rock, however, will the explanation be determined.

The geologic analysis of the Koolau Volcanic Vent Zone magnetic anomaly, on the basis that it is a ferromagnetic body inversely polarized, indicates that it is approximately 12 km wide at a depth of 1.6 km and extends to a depth of approximately 16 km. The intrusive rock having reversed polarity has a magnetic susceptibility of  $20 \times 10^{-3}$  cgs units.

The analysis of the magnetic field over the Waianae caldera shows that the Waianae Volcanic Vent Zone averages 9 km in width at a depth of 800 m and extends to a depth of 5 km. The rocks occupying the vent zone are normally polarized with a magnetization contrast of  $9.0 \times 10^{-3}$  cgs units.

### *Island of Kauai*

**GEOLOGY:** According to Macdonald et al. (1960), Kauai is one of the oldest of the Hawaiian Islands. It consists principally of a shield volcano built up from the sea floor by innumerable eruptions of thin lava flows from a central vent and rift zones (Fig. 30). Activity started in the Kauai Volcano in early or middle Pliocene times. Growth of the shield was rapid and was completed before the end of the Pliocene. Towards the end of its growth, the summit of the shield collapsed and formed a large central caldera. A smaller caldera in the southeast portion of the island may or may not have had a contemporaneous origin. Later flows filled the grabens that formed after the caldera collapsed. The flows that built up the shield volcano as well as the later flows that filled the caldera are composed predominantly of olivine basalt.

Thus, the volcanic shield is made up of a basaltic sequence, termed the Waimea Canyon series, which is divided into four formations. The eastern part of the shield is veneered by later lavas of the Koloa series, which were erupted after a long period of erosion and continued through most of the Pleistocene epoch. Dikes occur in all the formations over most of the island with a dominant east-northeast trend (Macdonald et al., 1960). However, no well-developed dike complexes, like those found on the other islands, are observed.

**MAGNETIC RELATIONS:** The total intensity magnetic map of Kauai (Fig. 31) shows that

three major primary rift zone anomalies cross the island. These are designated in this paper as the North Kauai Primary Rift Zone, the Waimea Primary Rift Zone, and the Koloa Primary Rift Zone (Fig. 30). One volcanic vent zone is indicated on each of these primary rift zones. All three vent zones are normally polarized with maximum peak-to-peak amplitudes of the magnetic anomalies ranging from 300 gammas (North Kauai Volcanic Vent Zone), to 400 gammas (Waimea Volcanic Vent Zone), to 500 gammas (Koloa Volcanic Vent Zone). All three primary rift zones strike in a general westerly direction, converging towards the western portion of the island. It is significant that the Niihau Primary Rift Zone anomaly originating over the island of Niihau

converges with the Koloa Primary Rift Zone anomaly. This association suggests a common rift zone origin for the two islands—or, more likely, that Niihau was formed as a result of southward branching of the Koloa Primary Rift Zone. It is also significant that, as in all the Hawaiian Islands, the primary rift zones originate in the ocean and cross the island without interruption.

The Waimea Volcanic Vent Zone coincides with the magma conduit which is defined geologically and is believed to be the source for the lavas which built the Kauai shield. The geologic analysis indicates that the vent zone is approximately 11 km long and 6.5 km wide, with its upper surface buried about 1.6 km beneath the peak of Mt. Waialeale and its base

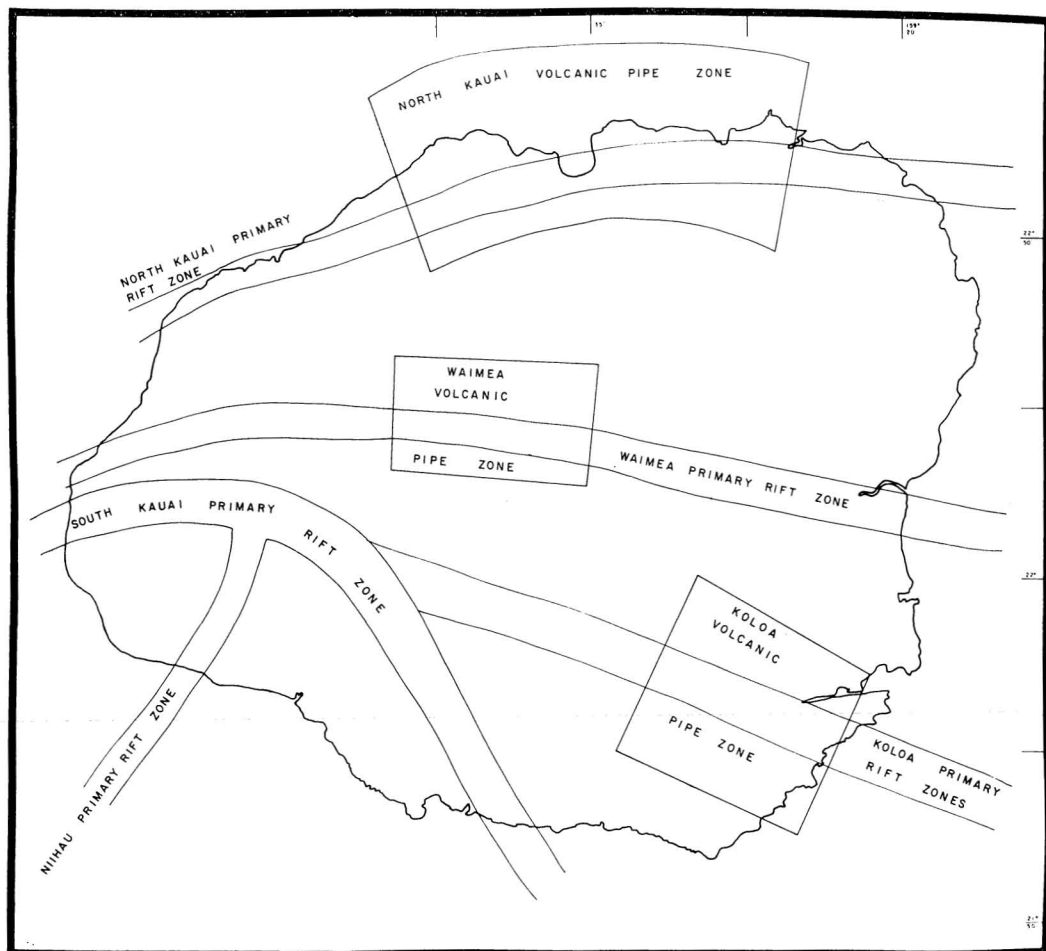


FIG. 30. Sketch of the primary rift zones and volcanic pipe zones of the island of Kauai.

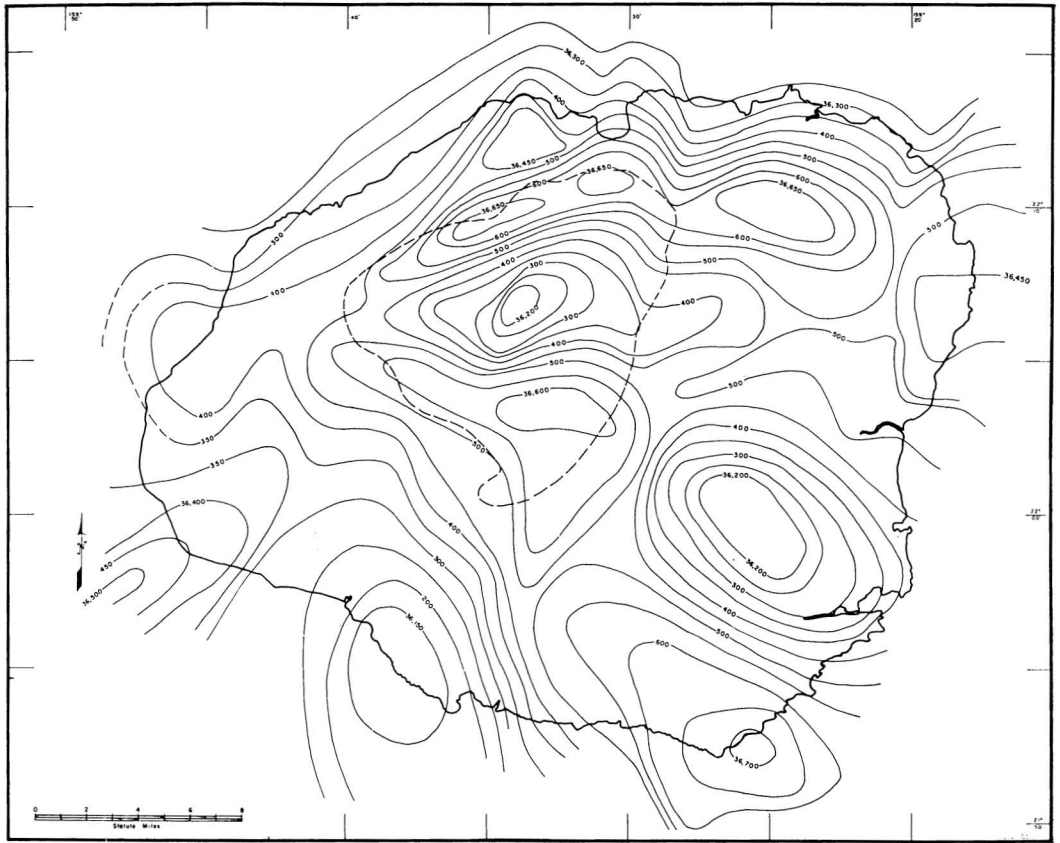


FIG. 31. Total force magnetic map of the island of Kauai, based on aeromagnetic profiles flown at 8,000 ft. Contour interval at 50 gammas.

at 5 km. Rocks within the vent zone appear to have a magnetization contrast of  $5.5 \times 10^{-3}$  cgs units with the surrounding basalts.

The Koloa Volcanic Vent Zone is approximately 11 km long and 9.5 km wide. The top of the anomalous body is buried about 2.1 km beneath the surface. Rocks within the pipe zone appear to have a magnetization contrast of  $70 \times 10^{-3}$  cgs units with the surrounding basalts.

The North Kauai Volcanic Vent Zone, though defined by a distinct magnetic anomaly, appears to be unrelated to any major center of volcanism. The vent zone is approximately 21 km long and 9.5 km wide. No quantitative analysis of this anomaly was attempted because the magnetic coverage off the north shore of the island was insufficient to define the position of the negative pole of the anomaly's dipole pair.

#### *Island of Niihau*

**GEOLOGY:** The geology of Niihau is relatively simple. According to Stearns (1947) the mass of the island is composed of a deeply weathered remnant of a basalt shield of Tertiary age, cut by a dike complex trending northeast-southwest. Stearns placed the vent two miles out to sea from the eastern shore of the island (Fig. 32).

**MAGNETIC RELATIONS:** Analysis of the total intensity magnetic map of Niihau (Fig. 33) shows that one primary rift zone anomaly strikes northeast-southwest along the island and one distinct volcanic vent zone anomaly is located on this trend in the middle of the island (Fig. 32). The magnetic map places the center of the Niihau Volcanic Vent Zone about  $\frac{1}{2}$  mile inland from the eastern coast of the island. This vent zone probably marks the central vent from which the lavas that formed

Niihau originated. The dike zones mapped by Stearns on Niihau have the same strike as the Niihau Primary Rift Zone and the largest concentration of the dikes occurs within the boundaries of the trend.

The horizontal dimensions of the vent zone are 8 km by 8 km and the top surface of the anomalous body is located 0.8 km beneath the surface and its base at 6.0 km. The dike rocks that are exposed above the vent zone probably are representative of the anomalous volcanic rocks occurring within the deeper portions of the pipe zone. This conclusion stems from the apparent association between the Niihau dike

swarms and the Niihau Volcanic Vent Zone. Rocks within the vent area appear to have a magnetization contrast of  $8.0 \times 10^{-3}$  cgs units with the surrounding basalts.

#### CONCLUDING REMARKS

The airborne magnetic study reported here has shown that the area on and adjacent to the Hawaiian Islands is characterized by two types of magnetic anomalies: those that are elongated and extend for several tens of kilometers, and those that are centered over local areas. In all cases the local type anomalies are superimposed on the axes of the elongated type anomalies.

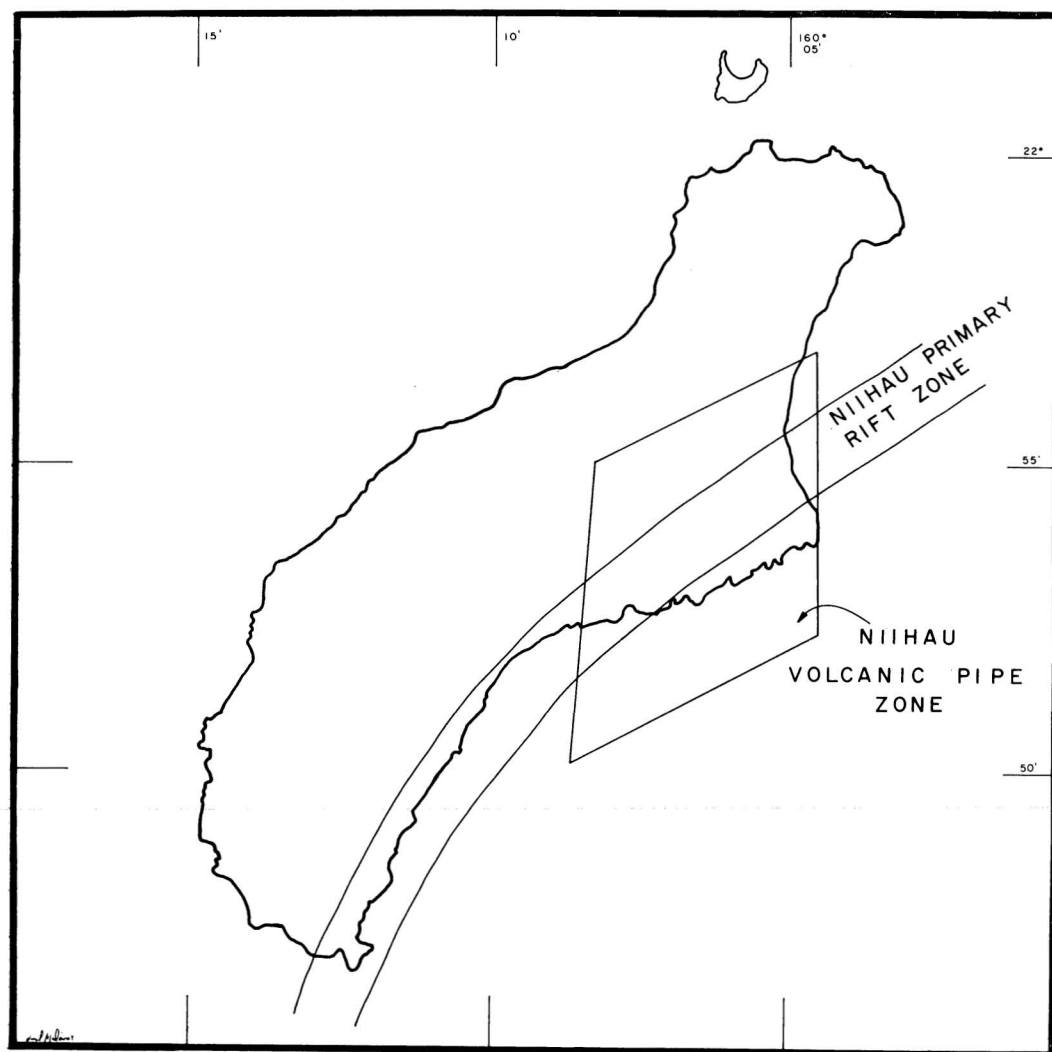


FIG. 32. Sketch of the primary rift zone and volcanic pipe zone of the island of Niihau.



Geologically, the local anomalies are associated with centers of volcanism, but most of the elongate anomalies do not have surface geologic counterparts and are believed to represent intrusions of mantle rock into rift type fractures in the upper mantle and overlying crust.

The majority of the prominent magnetic anomalies defining trends of crustal rifts strike

parallel to one of the two directions of the Hawaiian Ridge. One direction parallels the east-west strike of the Molokai Fracture Zone. The other direction parallels the west north-west-east southeast strike of the crest of the Hawaiian Ridge. Inasmuch as the trends parallel to the Hawaiian Ridge are truncated by those parallel to the Molokai Fracture Zone, the

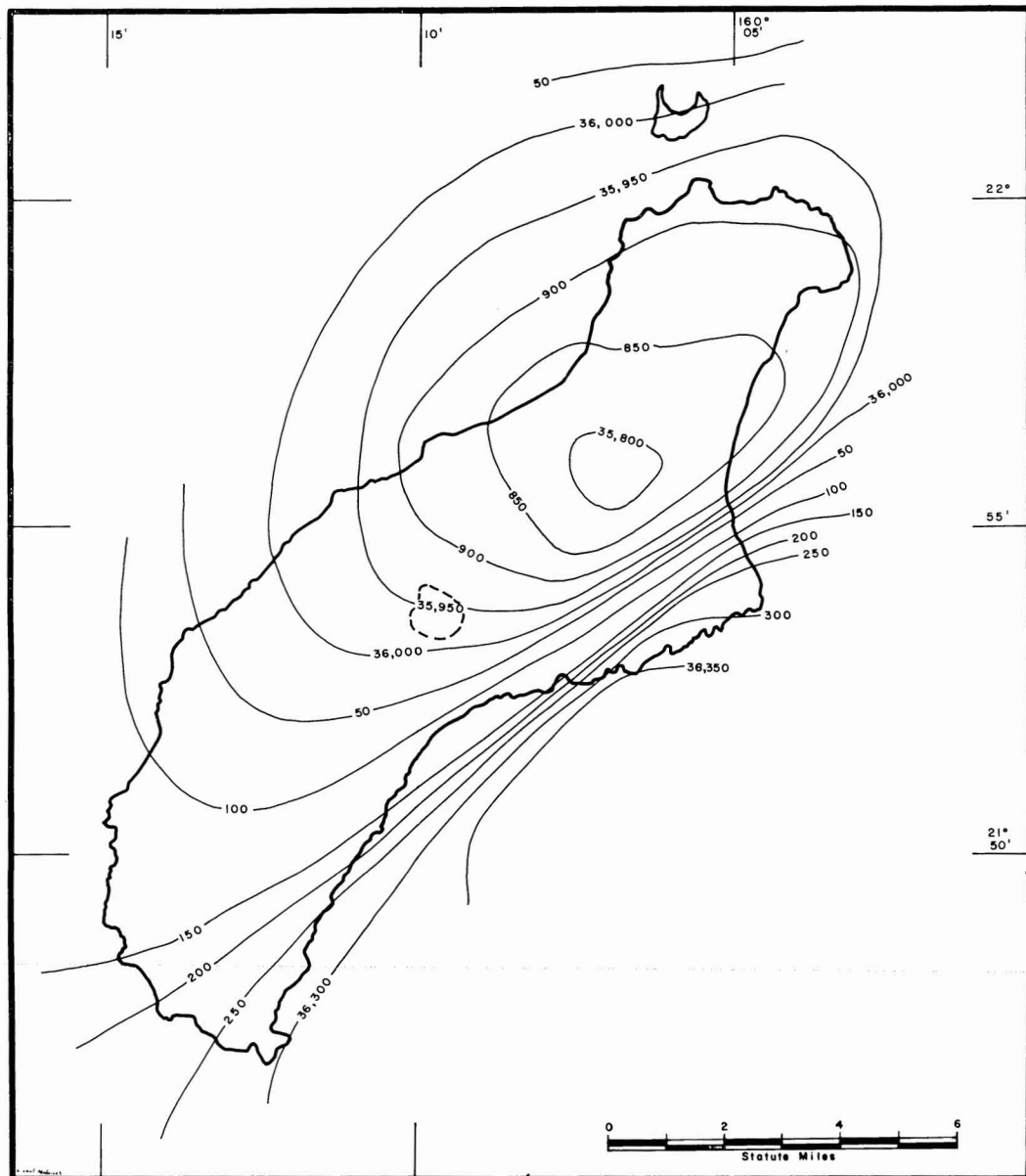


FIG. 33. Total force magnetic map of the island of Niihau, based on aeromagnetic profiles flown at 8,000 ft. Contour interval at 50 gammas.

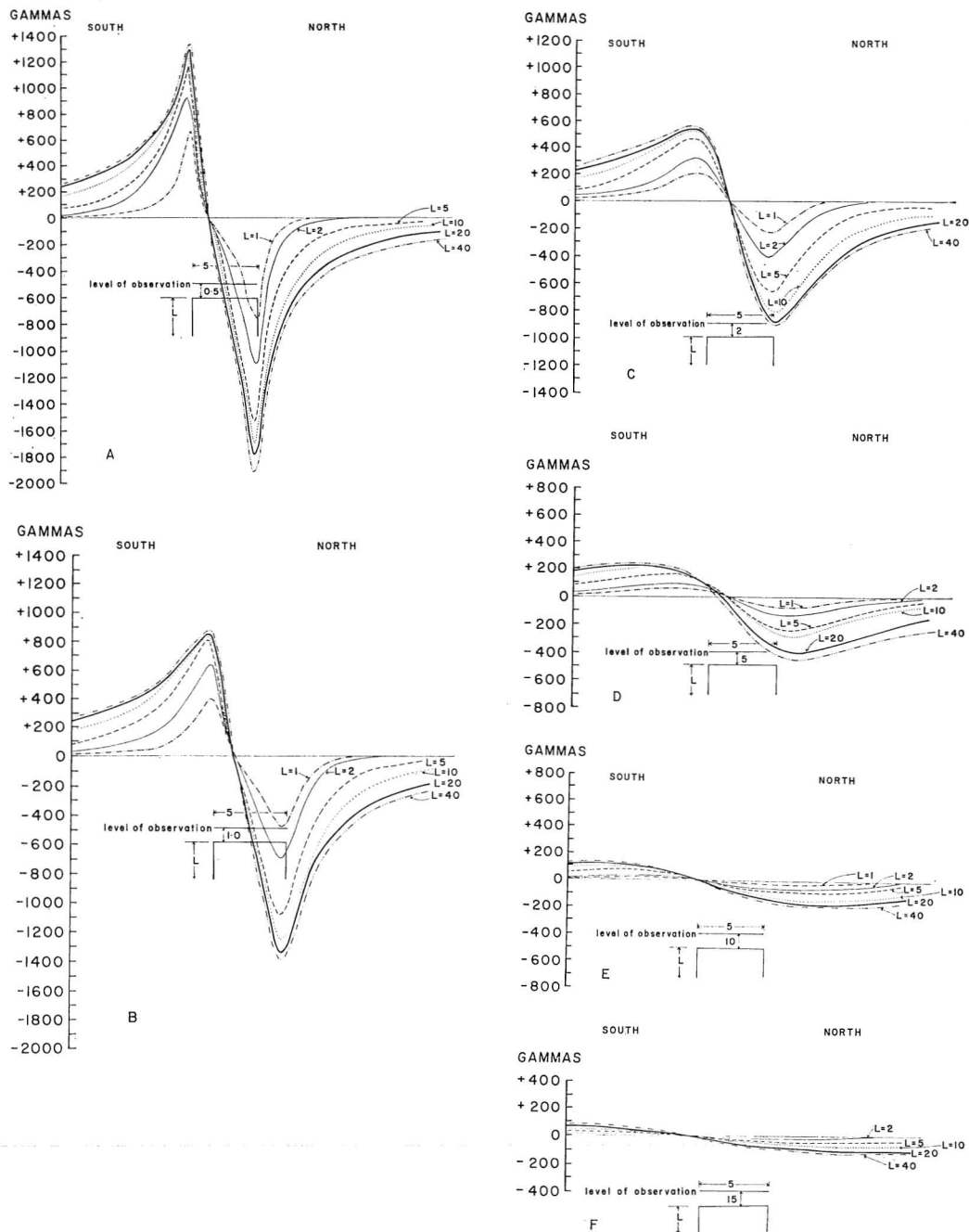


FIG. 34A-F. Magnetization of two-dimensional vertical bodies, where strike of profile = 0°; inclination of earth's magnetic field = 35°; total regional magnetic force = 36,000 gammas; susceptibility =  $10.0 \times 10^{-3}$  cgs units; and depth to top of body from level of observation = (A), 0.5 unit; (B), 1.0 unit; (C), 2.0 units; (D), 5.0 units; (E), 10.0 units; and (F), 15.0 units.

trends paralleling the Hawaiian Ridge probably are geologically older. Although data are available only for the eastern end of the Hawaiian Ridge, they support the concept of a progressive development of the Hawaiian Islands along a major fault or fracture zone. However, because the strike of east-west magnetic anomalies crosses the Hawaiian Ridge without interruption (Fig. 9), there is little question that the Molokai Fracture Zone has played an important role in the development of the islands lying east of Molokai. Certainly, some of the Hawaiian volcanoes appear to have formed where tectonic elements of the Molokai Fracture Zone have intersected with tectonic elements of the Hawaiian Ridge. All the magnetic anomalies on the islands of Hawaii, Maui, Kahoolawe, Molokai, Lanai, Oahu, Kauai, and Niihau apparently have developed from intrusions into crustal and upper mantle rift zones which are continuous for long distances.

Save for one major exception—the Koolau caldera anomaly on Oahu—most of the anomalies indicate normal polarization and the presence of intrusive rock similar to peridotite. In no case does the topographic effect bias the anomaly picture indicating that the anomaly control is from intrusives at depth.

Because of the consistency and the lack of any discordance in the magnetic anomalies, it is highly unlikely that the Hawaiian Ridge developed through any mechanism of horizontal drift of the crust from a single volcanic center, as was postulated by Wilson (1963).

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