AN ANALYSIS OF GRAVITY ANOMALIES
OVER HAWAIIAN VOLCANOES

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By

Babu Rao Vadrevu

Thesis Committee:

Alexander Malahoff, Chairman
George H. Sutton
John C. Rose

We certify that we have read this thesis and that in our opinion it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Geosciences-Solid Earth Geophysics.

Alexander Malahoff

Chairman

John C. Rose

George H. Sutton

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I. INTRODUCTION

The Hawaiian Ridge, extending some 2500 km in a northwest-southeast direction from Midway to the island of Hawaii, is one of the major island ridges of the Pacific basin. It was built up by basaltic lava outpourings from a number of central vents and fissure zones on the earth's crust. Pit craters, rift zones and surface calderas mark these centers of vulcanism on the islands of the ridge. On some parts of the islands, exposed dikes show that these centers of eruption contain intrusives. Intensive geophysical investigations conducted over the volcanic domes indicate prominent anomalies in the form of gravity highs, dipole magnetic anomalies, and high seismic velocities at shallow depths. The Koolau Volcano on the island of Oahu is characterized by a high local Bouguer gravity anomaly of the order of +110 mgal, and the gravity analysis by Strange et al. (1965) indicated a large high-density volcanic pipe complex, the dimensions of which were in close agreement with those obtained from an analysis of seismic data (Adams and Furumoto, 1965).

The present study of the dimensions of the source bodies of the volcanic pipe complexes of the southern Hawaiian islands is a continuation of the study initiated by Woollard in 1951. The aim of the study was to investigate the possible shapes and sizes of the source bodies giving rise to the high gravity anomalies over the volcanoes of the islands of Hawaii, Maui, and Molokai. The assumptions as to the dimensions, location, and densities of the models used in this study were based on the available geological, magnetic, and seismic evidence for the areas under study.

The dimensions of the volcanic pipe complexes giving rise to the observed gravity anomalies were computed by using a two-dimensional gravity graticule method. The data used were obtained from the published results of gravity surveys over the islands carried out by the U. S. Geological Survey and by the Hawaii Institute of Geophysics. These two organizations established a network of gravity stations on the islands and published terrain-corrected Bouguer gravity anomaly maps reduced for a density of 2.3 gm/cc. These maps have been used in the present study of the volcanic centers of Kohala, Mauna Kea, Mauna Loa, and Kilauea on the island of Hawaii, of Haleakala on the island of Maui, and of East Molokai Volcano on the island of Molokai.

II. GEOLOGY OF THE HAWAIIAN ISLANDS

The geology of the Hawaiian Islands has been well documented in a series of publications by Stearns and by Stearns and Macdonald (1946).

The Hawaiian Islands, located along the axis of the Hawaiian ridge, are a series of basaltic shield volcanoes, developed from the outpourings of basaltic lava from a number of central vents and fissure zones, mainly along a crustal fracture extending for about 2500 km in a northwest-southeast direction from Midway to Hawaii. The ridge is flanked by a moat and a rise, which are called the Hawaiian Deep and the Hawaiian Arch respectively, on either side of the ridge, but prominently displayed on the northern side. The ridge is intersected by large fracture zones like Murray and Molokai Fracture zones.

The Hawaiian volcanoes are characterized by fissure-type eruptions. Many workers (Malahoff and Woollard, 1965) have postulated that vulcanism occured at the intersection of major northwest-southeast fracture and cross-cutting fractures, thus developing centers of vulcanism at approximately 40 km apart. The volcanic vents are usually found to be associated with two major rift zones and a minor rift zone. Evidence shows that some rift zones are superficial while others extend down to the mantle and are filled by intrusives (Malahoff, 1965). Numerous dikes of varying widths are observed within the calderas and in the rift zones, for example in the eroded caldera of Koolau Volcano on Oahu. Further, there is evidence of circular and boundary faults along the periphery of the calderas, as well as faults paralleling rift zones and the coasts. The main volcanic mass consists of olivine basalts, with andesite, trachyte, and alkaline basalts in evidence in the later stages of vulcanism.

Island of Hawaii

The island of Hawaii, the largest of the Hawaiian islands, has been built up by five volcanoes, namely, Mauna Kea (13,784 ft elev), Mauna Loa (13,679 ft elev), Hualalai (8,251 ft elev), Kohala (5,505 ft elev), and Kilauea (4,040 ft elev).

Mauna Kea, the highest of the volcanoes, has a dome of tholeiitic basalts, with a cap of alkali basalt and ash. A caldera is located on the summit of the dome.

Mauna Loa, the second highest, has a central caldera and prominent southwest and northeast trending rift zones.

Kohala mountain appears to have developed over a set of rifts--distinct northwest and southeast trending rifts, and a poorly developed southwest trending rift. The summit caldera displays distinct graben structure. Evidence of at least 250 dikes ranging in width from a few inches to about 40 ft was found in the windward canyons of the volcano (Stearns, 1946).

III. PREVIOUS GEOPHYSICAL STUDIES OF THE HAWAIIAN ISLANDS

Various organizations have conducted geophysical work on and around the Hawaiian Islands, but only the results pertinent to the present problem will be discussed here.

Gravity Studies

A reconnaissance gravity survey by Woollard (1951) indicated that the Bouguer gravity anomaly over the island of Oahu varied from a low of about +190 mgal to a high of about +310 mgal. Local gravity highs of the order of +110 mgal were found to be associated with the Koolau and Waianae Calderas. The rift zones of the two volcanoes were found to be associated with +50 mgal local gravity highs. As the two major volcanoes and their rift zones dominate the gravity field of the island, it was evident that the high gravity anomalies are not due to the topographic effect of the island mass. It was significant to note that Salt Lake crater on Oahu with eclogite inclusions has only a +5 mgal gravity effect and other late stage volcanic centers such as Diamond Head, Koko Head, and Punchbowl craters have no gravity effects at all, implying zero density contrast between the pipe fillings and the surrounding lavas (Strange et al., 1965). Quantitative analysis of gravity data has shown that the Koolau gravity anomaly on Oahu can be analyzed in terms of a high density plug 6 km wide and a density of 2.9 to 3.2 gm/cc situated close to the surface, with increasing width towards the bottom (Fig. 1) (Strange et al., 1965).

Bouguer gravity anomalies located over the islands of Hawaii, Maui, and Molokai (Figs. 2 and 3) (Kinoshita, 1965; Kinoshita and Okamura, 1965; Strange et al., 1965) also indicated that the major volcanic centers were characterized by high positive gravity anomalies of the order of +240 to +330 mgal. The volcanic centers and their associated Bouguer gravity anomalies are summarized in Table 1.

Magnetic Studies

Airborne magnetic studies conducted by Malahoff and Woollard (1965) showed that the local magnetic anomalies are of two types: (1) lenticular dipole anomalies related to crustal rifts that have been invaded by intrusive material of mantle origin and (2) circular dipole anomalies associated with the primary volcanic centers. Quantitative studies of the magnetic anomalies suggested that the source bodies of varying lengths situated at depths of 2 to 6 km in the primary volcanic centers and in the rift zones are responsible for the observed magnetic anomalies.

Seismic Studies

Seismic refraction studies of the Koolau plug conducted by Adams and Furumoto (1965) supported the interpretations of the gravity and magnetic data that a dense plug is located beneath the Koolau Caldera. The plug contains

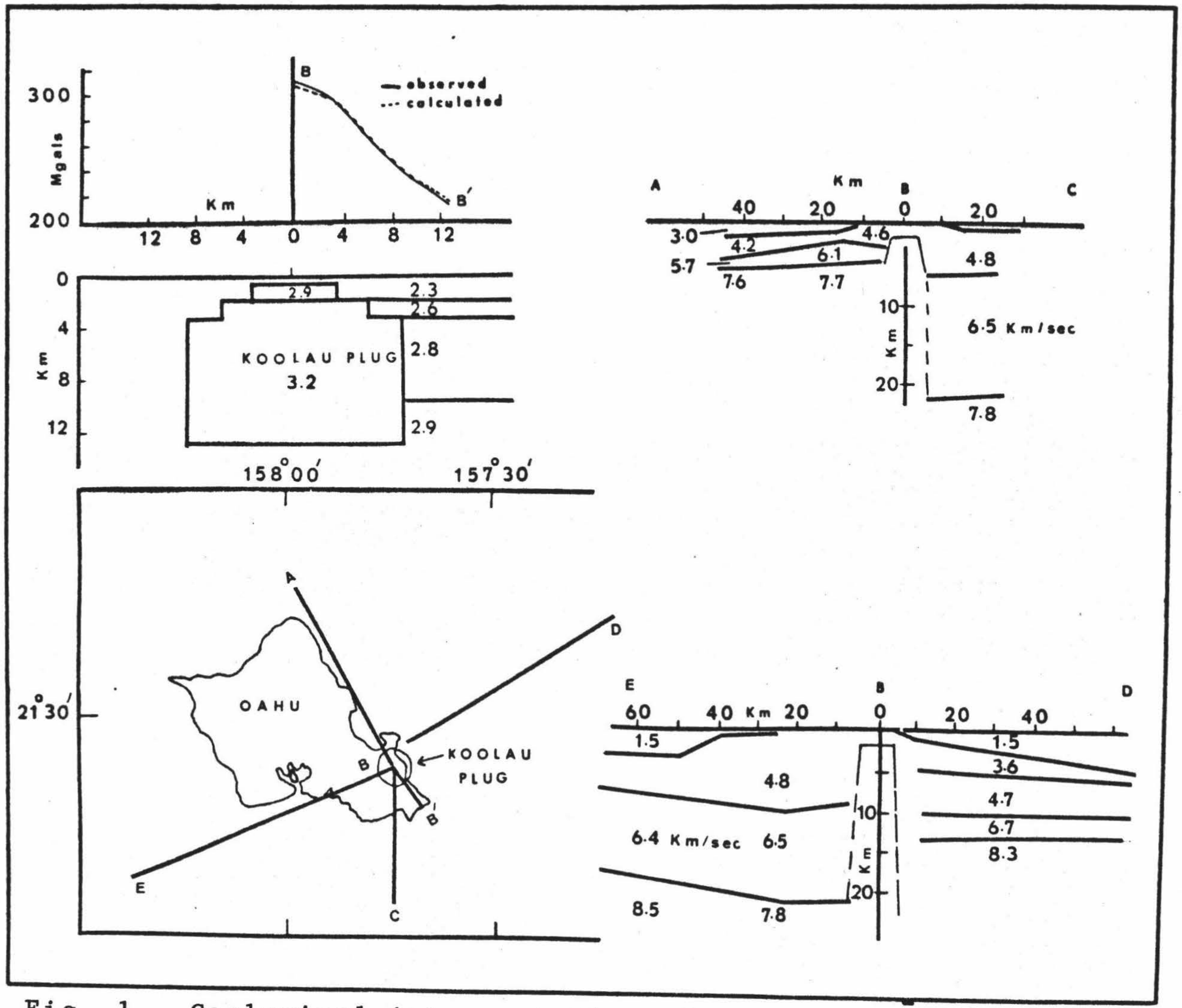


Fig. 1. Geological interpretation of gravity and seismic studies of the Koolau plug, Oahu, Hawaii. (After Strange et al., 1965; Furumoto et al., 1965)
(Density in gm/cc)

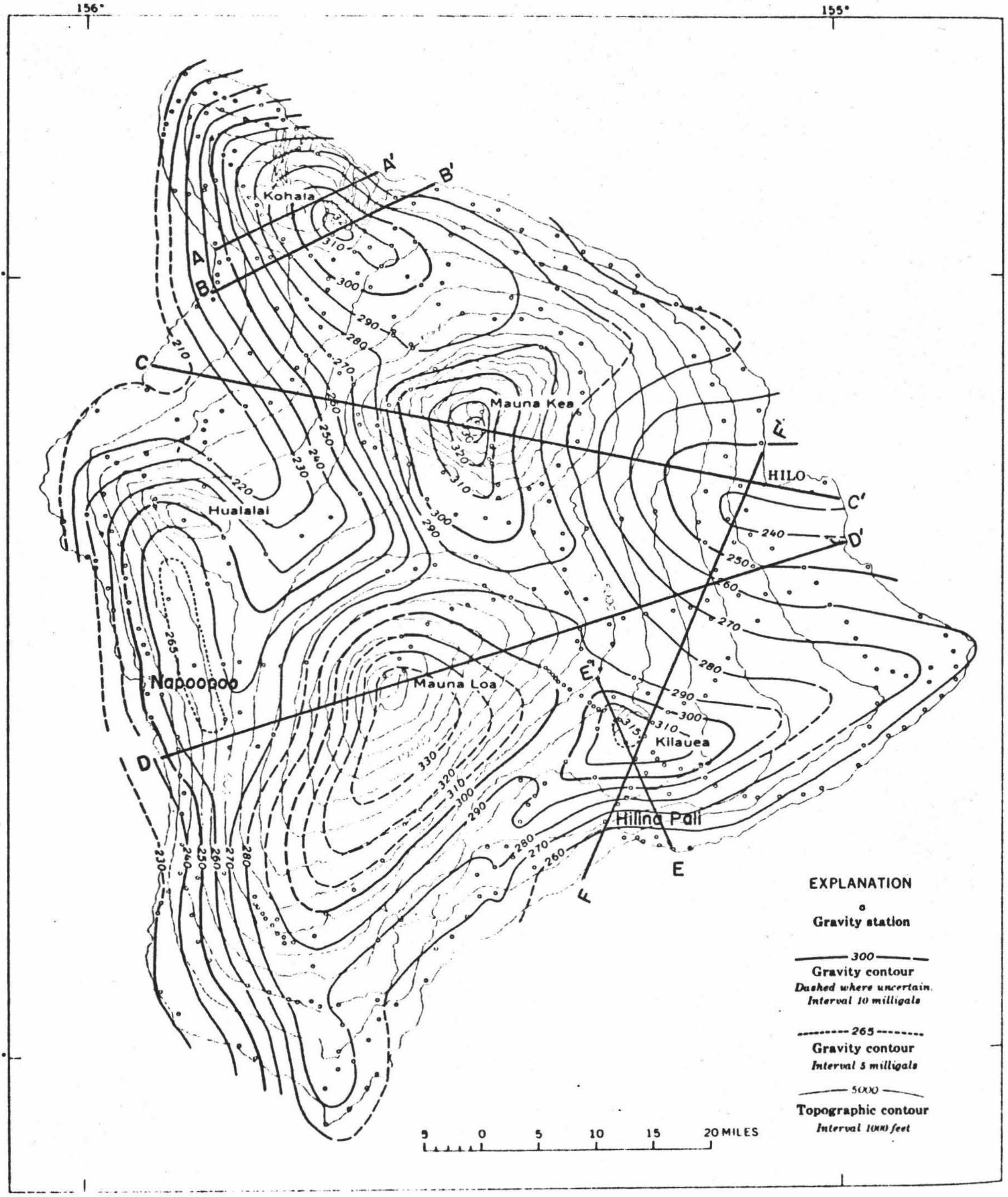


Fig. 2. Bouguer gravity anomaly map of the island of Hawaii: Based on a rock density of 2.3 gm/cc. (After Kinoshita, 1965)

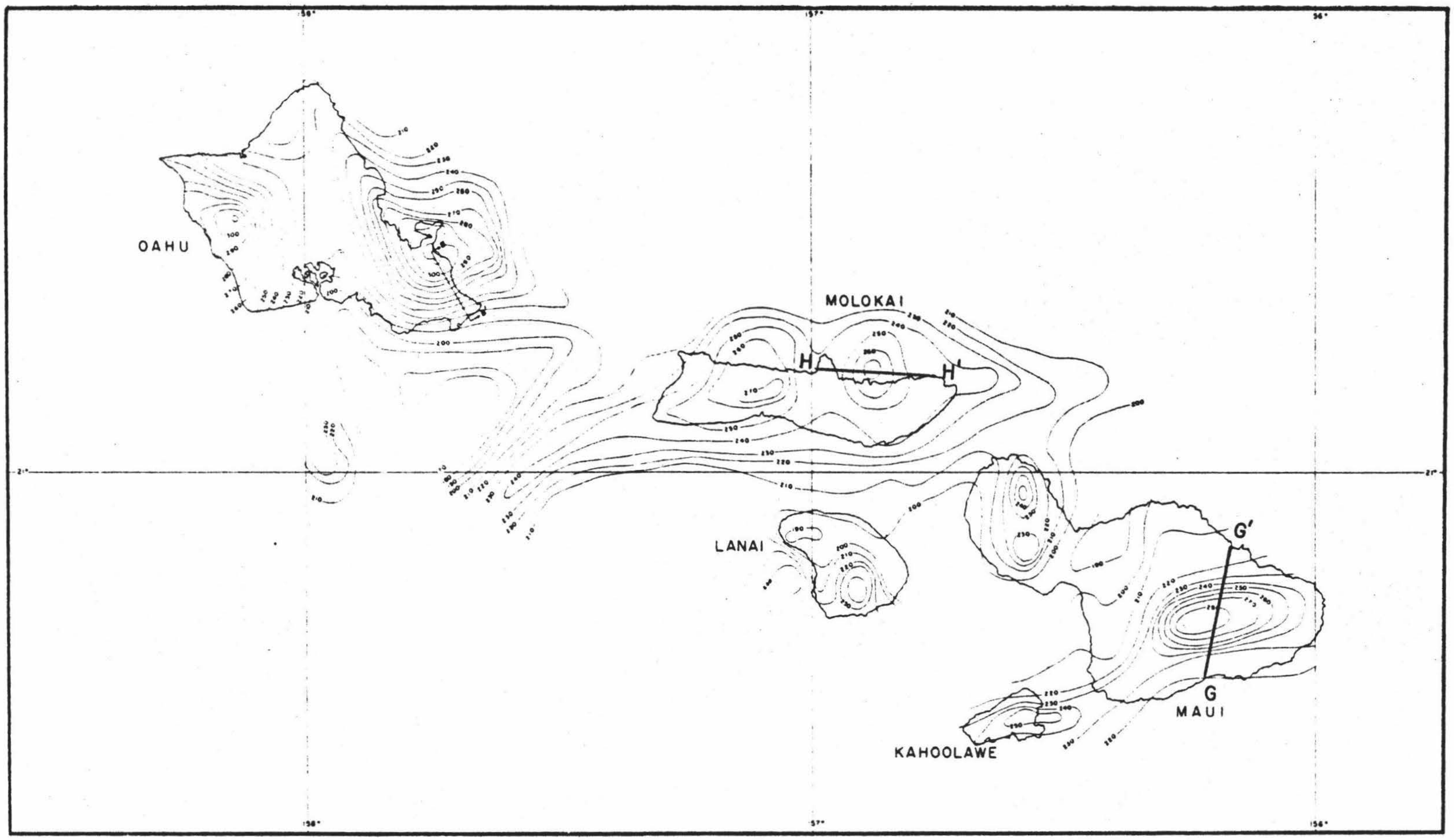


Fig. 3. Bouguer gravity anomaly map of the islands of Oahu, Molokai, and Maui: Based on a rock density of 2.3 gm/cc. (After Strange et al., 1965)

TABLE 1.

LIST OF HAWAIIAN VOLCANOES ON THE ISLANDS OF HAWAII, MAUI, MOLOKAI, AND OAHU, THEIR ELEVATIONS AND THEIR BOUGUER GRAVITY ANOMALIES

Volcano	Elevation, meters	Bouguer Anomaly (ρ=2.3 gm/cm^3), mgal	Coastal Value, mgal
Hawaii			
Kohala	1679	+328	+240 to +270
Mauna Kea	4202	+332	+210 to +240
Mauna Loa	4170	+338	+250
Hualalai	2515	+269	+210
Kilauea	1230	+317	+240
Maui			
West Maui	1765	+252	+190 to +220
Haleakala	3056	+282	+220
Molokai			
West Molokai	420	+270	+235 to +240
East Molokai	1516	+270	
Oahu			
Waianae	1228	+312	+195 to 200
Koolau	946	+313	

rocks with seismic velocities of 7.7 km/sec at a depth of 2 to 3 km, surrounded by material with a velocity of 4.63 km/sec at the top and to the southeast. The width of the plug as calculated from seismic data is 5.4 km down to 3 to 5 km below sea level, and seismic reflections from this depth suggested the existence of a much wider magma chamber below. The top of the plug is situated 1.6 km below sea level. The configuration of the dense plug as determined from the analysis of gravity data is therefore in close agreement with the configuration of the plug as determined from the seismic data.

In addition, the same study indicated a high velocity material of 7.7 km/sec at a depth of 5 to 6 km beneath the northwest rift zone of Koolau Volcano (Fig. 1). The seismic studies showed positively that high-velocity and high density material occurred at very shallow depths in the rift zones and in the central vents. According to Adams and Furumoto (1965) the value of 7.7 km/sec is close to the arbitrary value of 7.8 km/sec assigned to the mantle material, and it can be conjectured that the mantle material has risen through the plug and the rift zones to the shallow depths.

Crustal Structure

The crustal thickness beneath the axix of the Hawaiian Ridge has been found to be 15 km on the average (Hill, 1969), about 13 km beneath the Hawaiian Deep located north of the

Ridge, and about 10 km beneath the Hawaiian Arch located beyond the Deep (Shor, 1960; Shor and Pollard, 1964). Crustal thicknesses of as much as 20 to 21 km have been reported south of Oahu by Furumoto (1965), and as little as 9 km north of Maui by Shor and Pollard (1964).

From the coastal seismic refraction profiles carried out by the U. S. Geological Survey (Hill, 1969) over the island of Hawaii, the crustal structure beneath that island can be represented by the following layers: (1) a basal layer of 4 to 8 km thickness in which the P-wave velocities range from 7.0 to 7.2 km/sec; and (2) an upper layer of 4 to 8 km thickness in which the P-wave velocities increase with depth from 1.8 to 3.3 km/sec at the surface to 5.1 to 6.0 km/sec at depth. The top layer could be identified with the basaltic lava flows and the bottom layer may be either the original oceanic crust, or a dense intrusive system of dikes and sills or a stack of floored magma chambers filled with ultramafic cumulates associated with the central vent of each volcano as postulated by Jackson (1968; Hill, 1969). Recent seismic measurements in the Pacific Ocean (Maynard, 1970; Sutton et al., 1970) indicate the presence of a deep oceanic crustal layer with an average seismic velocity of 7.3 km/sec between the mantle and the normal basal crustal layer of velocity 6.8 km/sec. The implications of this result are not yet definite.

The Moho was found to be 12 km deep under the northeast and southeast coasts of Kilauea, and to vary in depth from about 18 km under the west coast of Mauna Loa to about 14 km under the northwest coast of Hualalai and Kohala. From the coastal refraction profiles of Hill (1969) Moho appears to be generally 12 to 20 km deep under the northeast coast of Kohala, but it is probably nearer to 14 to 15 km. The crustal thickness appears to increase by about 2 to 3 km towards the center of the island from the coasts, but mantle-like material may occur at depths as shallow as 10 km under Kilauea.

From the Sailor Hat experiments, the mantle was found to be at least 18 km deep under the southern coast of Maui (Woollard, 1966) and 15 km deep immediately north of Maui (Shor and Pollard, 1964).

From the gravity, magnetic, as well as seismic studies, therefore it is evident that high velocity, high density material occurs at shallow depths in the volcanic centers and in the rift zones. This material is most likely to be the intruded mantle material, in the form of dike swarms, sills, and pipe complexes, giving rise to the observed gravity highs, dipole magnetic anomalies, and high seismic velocities obtained over these centers of vulcanism, and the gravity method is well suited to investigate the dimensions of the source bodies as evidenced by the studies of the Koolau plug on Oahu.

IV. ANALYSIS OF GRAVITY DATA

Method of Analysis

Of primary consideration in the construction of gravity models are the size and shape of the anomaly and the probable density range for the gravity source body and the country rock. In the analysis carried out by the writer, crustal structure and seismic velocity information was utilized in converting the available velocity data into a density model by using the Talwani modification of the Nafe-Drake Curve (Talwani et al., 1959) (Fig. 4).

All the density models calculated for the various gravity profiles over the volcanic centers were based on the land data alone. Calculation of the water layer effect, and the effect of changes in crustal thickness in going from land to sea, on the land gravity data were also made. The combined effects of these two, however, did not exceed a 5 mgal maximum at the edges of the islands and therefore were ignored in the analysis of gravity model calculations.

As the volcanic plugs are assumed to be the principal source of the gravity anomalies, observed over the volcanic centers, the assumed crustal structure surrounding the plug was held constant, and the configuration of the plug was altered in order to obtain a fit between the observed and calculated anomaly profiles. Profiles were taken in such a way as to include the gravity effect of a single volcano. In general the assumed model consisted of an upper layer

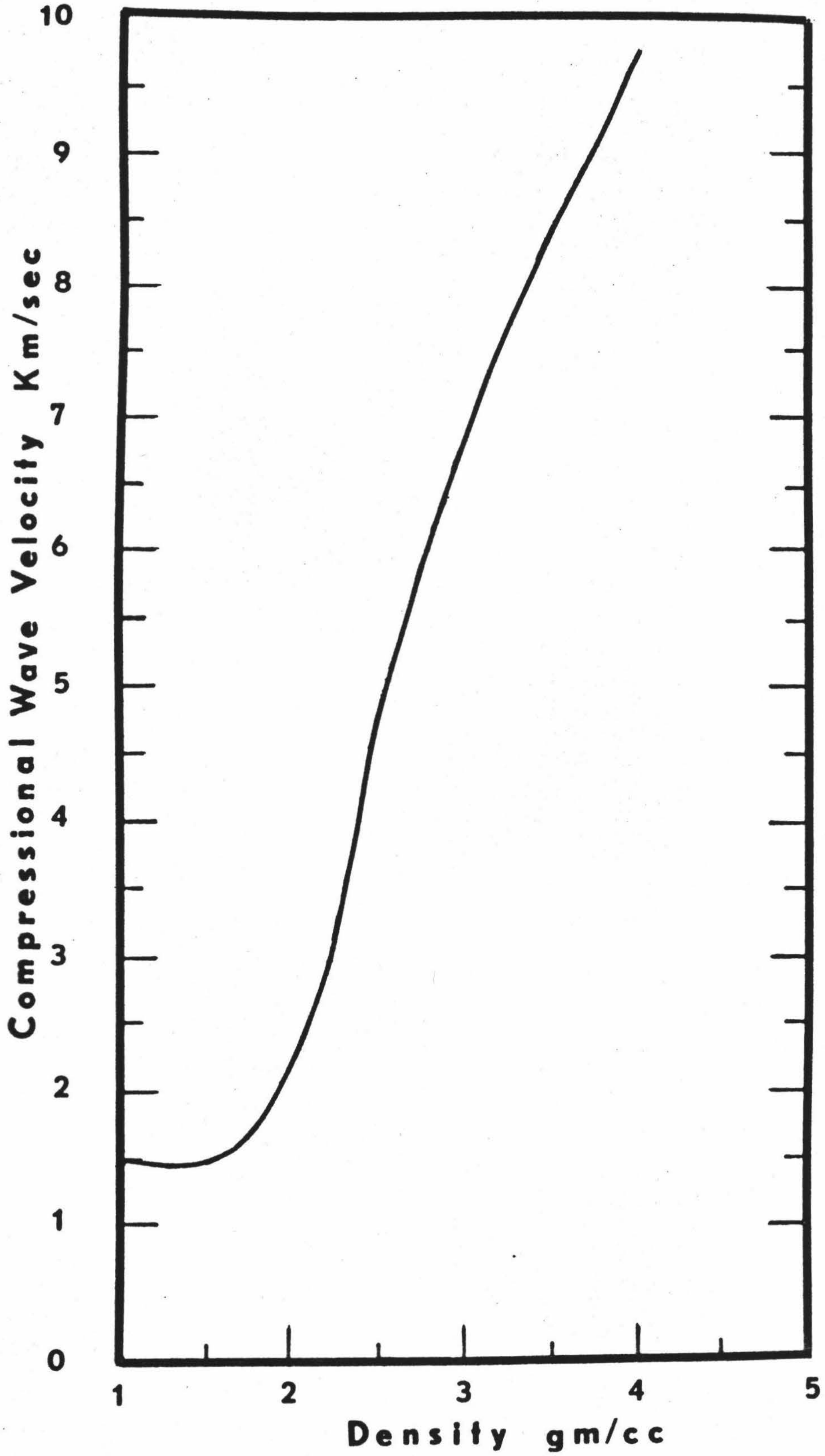


Fig. 4. Seismic wave velocity vs bulk density of rocks. (After Talwani, et al., 1959)

2 to 3 km thick with a density of 2.3 gm/cc, parallel to the topography, a second layer 5 to 8 km thick with a density of 2.6 to 2.7 gm/cc and a basal layer of density 3.0 gm/cc, corresponding to seismic P-wave velocities of 1.8 to 3.3 km/sec, 5.0 to 6.2 km/sec and 7.0 km/sec respectively. The density of the plug was assumed to be 2.8 to 2.9, 3.0, and 3.2 gm/cc at the top, middle, and bottom portions of the plug respectively. Thus the plug has a density contrast of 0.5 to 0.6 gm/cc at the top, 0.3 to 0.4 gm/cc at the middle, and 0.2 gm/cc at the bottom. The bulk density of the volcanic mass above sea level was taken to be 2.3 gm/cc (Woollard, 1965).

The gravity effect of the assumed model was calculated using a two-dimensional gravity graticule of Robertson (1953), in which the gravity effect is given by the formulae (see Appendix):

$$\Delta g = N\sigma X \times 10^{-4} \text{ mgal} \tag{1}$$

for the dots and

$$\Delta g = 0.00813\sigma X \tag{2}$$

for the semi-cylinder effect, where

Δg = calculated gravity effect in mgal
N = number of dots
σ = density contrast
and X = map scale in feet/inch.

The results of the gravity analysis are presented in Table 2, along with the quantitative estimates from magnetic studies for comparison.

Results

The Bouguer gravity anomalies of the volcanic centers of Kohala, Mauna Kea, Mauna Loa, and Kilauea on Hawaii, Haleakala on Maui, and East Molokai Volcano on Molokai, were analyzed and the results are presented below. The analyzed profiles are shown in the Bouguer gravity anomaly maps of the respective islands.

Island of Hawaii

Kohala Mountain

The Bouguer gravity anomaly map of Hawaii (Fig. 2) shows that Kohala Volcano, at the northern side of the island, is characterized by a gravity high of +320 mgal, displaced slightly to the south of the topographic high. The coastal gravity value is of the order of +240 mgal on the northwest coast and of the order of +270 mgal on the northeast coast. Two profiles AA' and BB' (Fig. 2) were analyzed.

From the coastal seismic refraction profiles (Hill, 1969) the velocity structure on the northwest coast of Kohala consists of a 3.3 km thick layer of velocity 3.7 km/sec, a 7.0 km thick layer of velocity 6.0 km/sec, underlain by a basal layer 4 km thick and of velocity 7 km/sec and the depth to the mantle being 14 km. On the northeast coast the 7.0 km/sec layer occurs at a depth of 3 to 6 km.

TABLE 2.

DIMENSIONS AND DEPTH TO THE ANOMALY SOURCE BODIES BENEATH THE HAWAIIAN VOLCANOES AS DETERMINED FROM THE INTERPRETATION OF GRAVITY AND MAGNETIC ANOMALIES

Volcano	Elevation Meters	Gravity				Magnetics*		
		Elevation To Top, From Sea Level, km	Dimensions, km			Elevation To Top, km	Dimensions, km	
			Width Top	Width Bottom	Vertical Extent		Cross Section	Vertical Extent
Kohala	1679	-2.0	6.0	14.0	12.0	-2.65	8.8x11.2	10.0
Mauna Kea	4202	0.0	10.0	18.0	18.0	+2.70	12.0x6.0	8.0
Mauna Loa	4170	-3.0	12.0	18.0	15.0	+1.60	16.8x4.0	20.0
Kilauea	1230	-1.0	6.0	14.0	11.0	none indicated	none indicated	none indicated
Haleakala	3056	0.0	6.0	14.0	16.0	+0.8 +0.8	7.3x7.3 8.0x6.4	15.0 12.0
E. Molokai	1516	-3.0	5.0	8.0	13.0	+0.8	14.0x10.0	

*After Malahoff (1965).

Accordingly, the density model constructed by the writer consists of a 3 km thick layer of density 2.3 gm/cc paralleling the topography, a 2.6 gm/cc layer up to 10 km depth, and a 3.0 gm/cc layer up to 14 km depth, with an additional slab of 3.0 gm/cc density material on the northeast coast to account for the shallow high velocity material. The assumed plug model as well as the agreement between the observed and computed anomalies for the two profiles AA' and BB' is shown in Figs. 5a and 5b respectively.

The volcanic plug responsible for the observed gravity anomaly is found to be 6 km wide at the top and 14 km at the base, with a density range of 2.9 to 3.2 gm/cc. The top of the plug is located 2 km below sea level. Calculations showed that it is necessary to assume a plug with increasing width to account for the observed gravity anomaly. The plug has a density contrast of 0.6, 0.4 and 0.2 gm/cc with the surroundings and the 2.6 gm/cc layer has a contrast of 0.3 gm/cc on the flanks of the dome.

The agreement between the observed and calculated anomalies for the two profiles is good and well within 5 mgal as shown in Figs. 5a and 5b.

Mauna Kea Volcano

Mauna Kea Volcano, located in the central region of the island of Hawaii (Fig. 2), is characterized by a gravity anomaly of +330 mgal. The coastal gravity value is of the order of +210 mgal on the west coast and +240 mgal on the

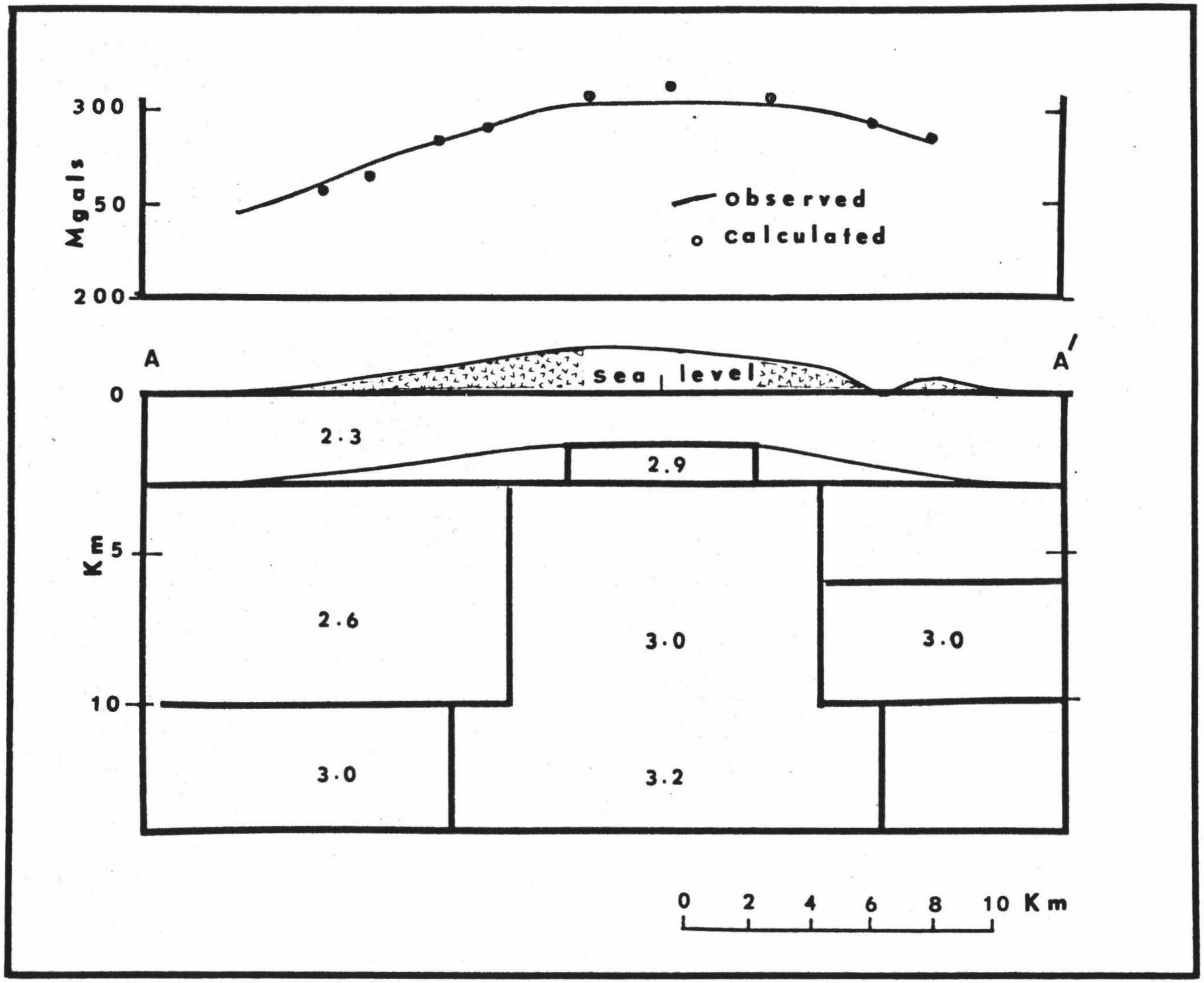


Fig. 5a. Crustal interpretation of Bouguer gravity anomalies over Kohala Mountain along profile AA'. (For location see Fig. 2.) (Density in gm/cc)

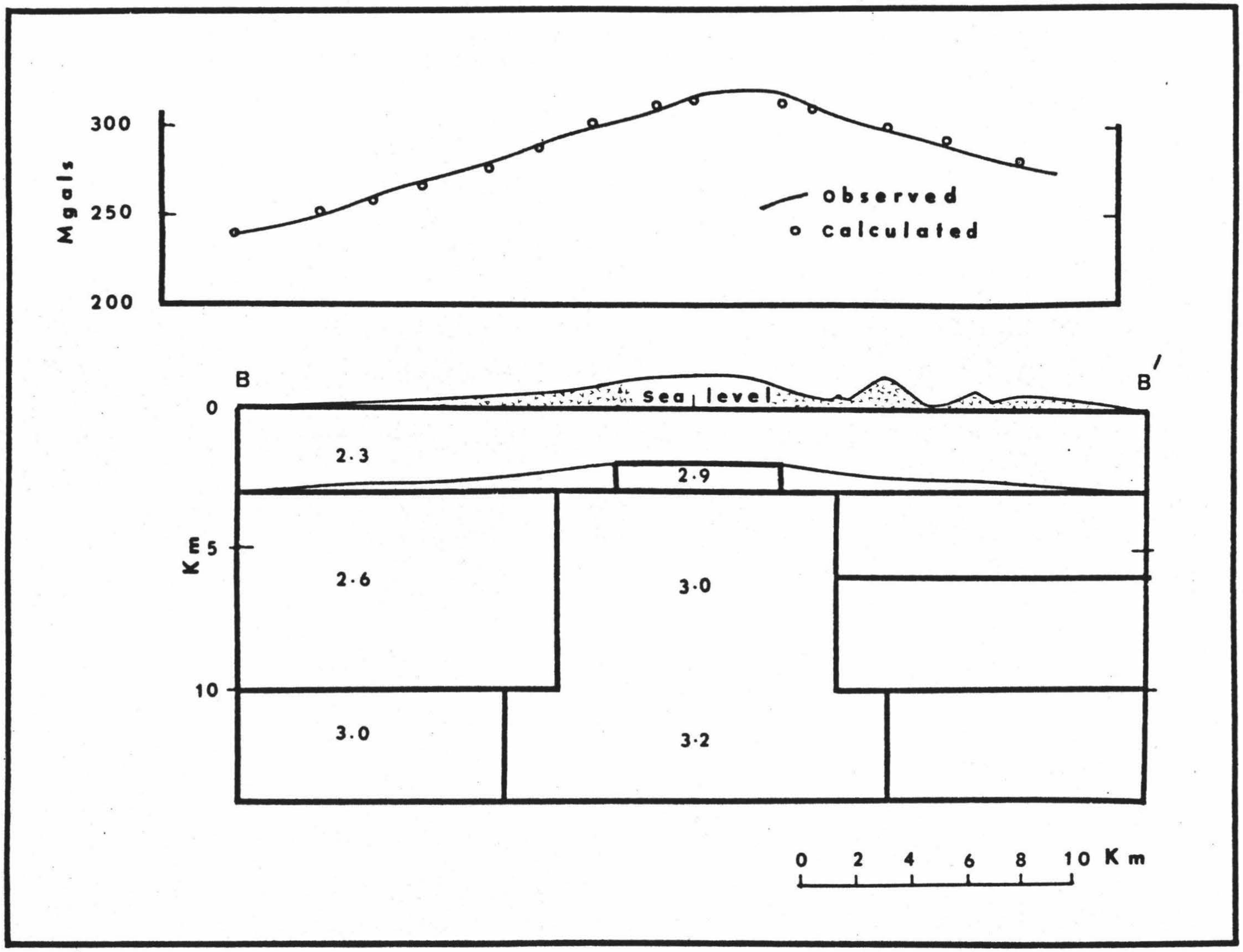


Fig. 5b. Crustal interpretation of Bouguer gravity anomalies over Kohala Mountain along profile BB'. (For location see Fig. 2.) **(Density in gm/cc)**

east coast. The profile CC' approximately running east-west from Hilo on the east coast to a point between Kawaihae and Key Hole point on the west coast was selected for analysis (Fig. 2).

The seismic velocity structure on the Hilo side of the profile consists of a 0.7 km thick layer of velocity 3.5 km/sec, a 3 km thick layer of velocity 4.7 km/sec, a 6.4 km thick layer of velocity 6.2 km/sec, and underlain by a basal layer of velocity 7.0 km/sec down to the mantle, which is at 14 km depth (Hill, 1969). The velocity structure on the western end of the profile was assumed to be the same as the one used for Kohala Volcano. As mantle depths are found to increase towards the center of the island, a 16 km deep mantle was assumed under the summit of Mauna Kea.

In accordance with the velocity structure, the assumed density structure consists of a 3 km thick first layer of density 2.3 gm/cc paralleling the surface topography, a 7 km thick layer of density 2.7 gm/cc, a 4 km thick layer of density 3.0 gm/cc, and the density of the plug range from 2.9 to 3.2 gm/cc (Fig. 6).

The gravity solution yielded a plug 10 km wide from sea level down to 6 km below sea level, 14 km wide down to 10 km and 18 km wide down to the mantle. The agreement between the observed and computed anomalies was reasonable and well within the 5 mgal limit as shown in the Figure 6.

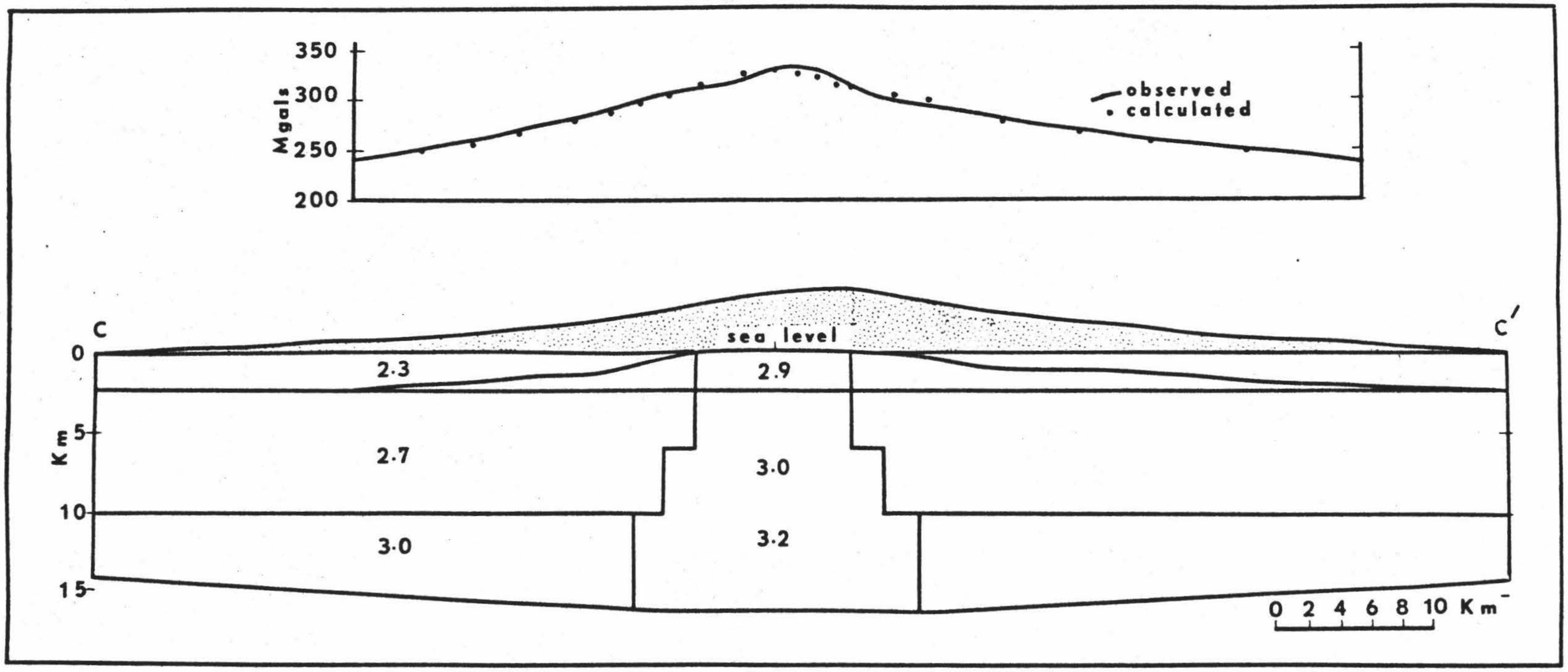


Fig. 6. Crustal interpretation of Bouguer gravity anomalies over Mauna Kea Volcano along profile CC'. (For location see Fig. 2.) **(Density in gm/cc)**

Mauna Loa Volcano

The gravity anomaly on Mauna Loa Volcano, situated south of the center of the island, is much broader than that over the other volcanic centers of the island and of the order of +330 mgal, displaced to the east of the topographic high. The anomaly associated with the prominent southwest rift zone of Mauna Loa is also displaced to the east. The coastal gravity value is of the order of +240 mgal and the west coast of Mauna Loa appears to be affected by a rift zone evident on the gravity map of the island (Fig. 2) as an elongated anomaly of the order of +265 mgal for which there is no geological evidence.

The profile DD' (Fig. 2) extending from south of Napoopoo on the west coast to Hilo on the east coast was selected for the analysis. The depth of mantle was taken to be 16 km beneath the west end of the profile, 18 km beneath the summit of Mauna Loa and 14 km beneath Hilo, the eastern end of the profile. The velocity structure on the Hilo side has already been discussed in connection with the Mauna Kea profile. The velocity structure on the western end of the profile consists of 2.5 km/sec layer, 0.7 km thick, a 4.7 km/sec layer, 3 km thick, a 6.0 km/sec layer, down to a depth of 10 km, and a 7.0 km/sec layer down to the mantle (Hill, 1969).

The assumed density model and the agreement between the observed and computed anomalies is shown in Figure 7.

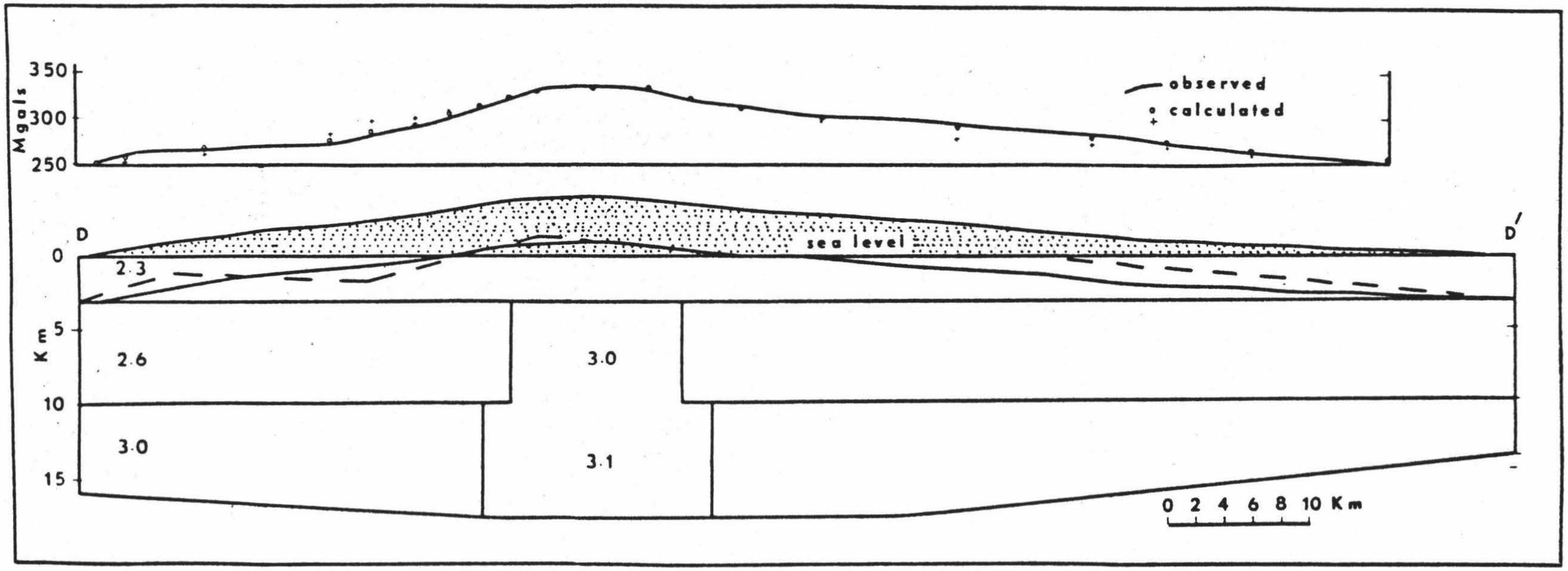


Fig. 7: Crustal interpretation of Bouguer gravity anomalies over Mauna Loa Volcano along profile DD'. (For location see Fig. 2.) **(Density in gm/cc)**

\+ calculated anomalies with the 2.3 gm/cc layer paralleling the surface topography.

0 calculated anomalies with the 2.3 gm/cc layer as shown by dashed lines.

The volcanic plug responsible for the observed gravity anomaly was taken to be 12 km wide at the top, increasing to 16 km from a depth of 10 km down to the mantle, and the top of the plug is situated 3 km below sea level.

This body differed from the others in that the density contrast at the bottom portion of the plug was taken to be 0.1 gm/cc instead of 0.2 gm/cc used for the other plugs. This was done in order to obtain a reasonable fit between the calculated and observed profiles. Further, when the first layer was taken to be parallel to the surface topography, the calculated gravity was found to be higher on the flanks of the volcanic dome, which was attributed to the near surface irregularities in density. The topography of the first layer was therefore altered as shown in Figure 7 in order to achieve a satisfactory agreement between the observed and computed anomalies over the whole width of the profile.

Kilauea Volcano

The Kilauea Volcano, located on the south coast of Hawaii, is characterized by a gravity high of +315 mgal. The anomaly pattern clearly shows the east and southwest rift zones. The coastal gravity value is of the order of +240 to +250 mgal.

Two profiles EE', extending from summit to the coast, and FF', extending from Hilanapali to Hilo as shown in Figure 2 were analyzed for the Kilauea Volcano.

The coastal seismic refraction profiles (Hill, 1969) indicated that the mantle is only 12 to 13 km deep beneath the southeast coast of Hawaii. The mantle depth was taken to be 14 km beneath the Hilo end of the profile as discussed earlier. The velocity structure on the Hilanapali end of the profiles appears to be consisting of a thin layer of velocity 1.8 km/sec overlying a 3.1 km/sec layer up to 3 km deep, underlain by a 5.1 km/sec layer, with the top of 7.0 km/sec layer 7.0 km deep under Hilanapali, whereas, it is 10 km deep under Hilo. The assumed density model, in accordance with the seismic velocities, is shown in Figures 8a and 8b for the two profiles, along with the observed and computed gravity anomaly profiles.

A suitable source body responsible for the observed gravity anomaly is found to be 6 km wide at the top, situated 1 km below sea level, with the plug widening to 10 km in the middle and to 14 km at the base (Figs. 8a and 8b).

As Kilauea is an active volcano, much observed and much studied, two other gravity model types, namely, the "vertical cylinder" model and the "inverted pyramid" model were investigated and compared with the results shown in Figures 8a and 8b.

The gravity effect due to a finite vertical cylinder of length $(Z_1 - Z_2)$ and radius R can be obtained by subtracting the effect of an infinite cylinder at depth Z_2 from that of depth Z_1. The gravity effect of an infinite

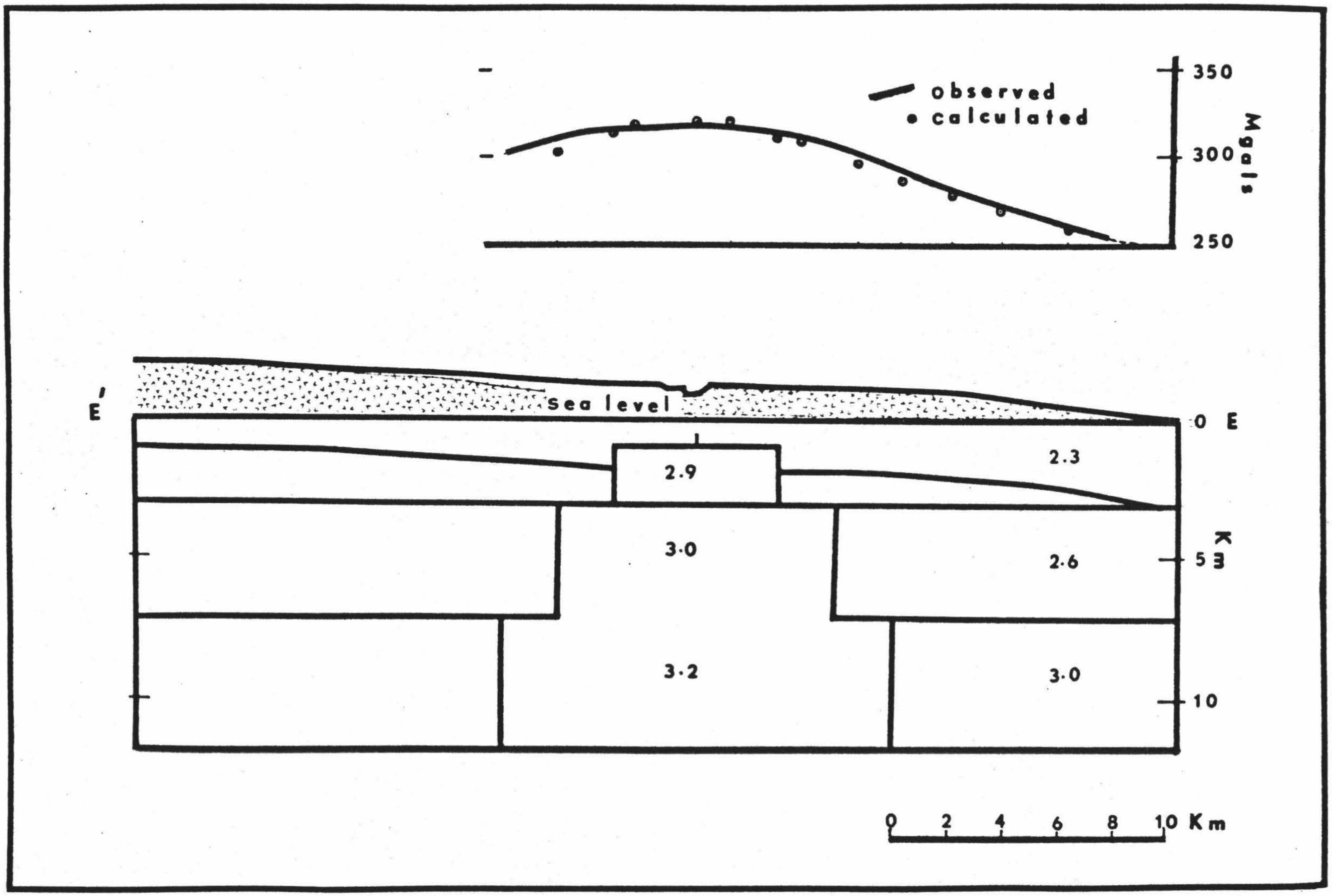


Fig. 8a. Crustal interpretation of Bouguer gravity anomalies over Kilauea Volcano along profile EE'. (For location see Fig. 2.) (Density in gm/cc)

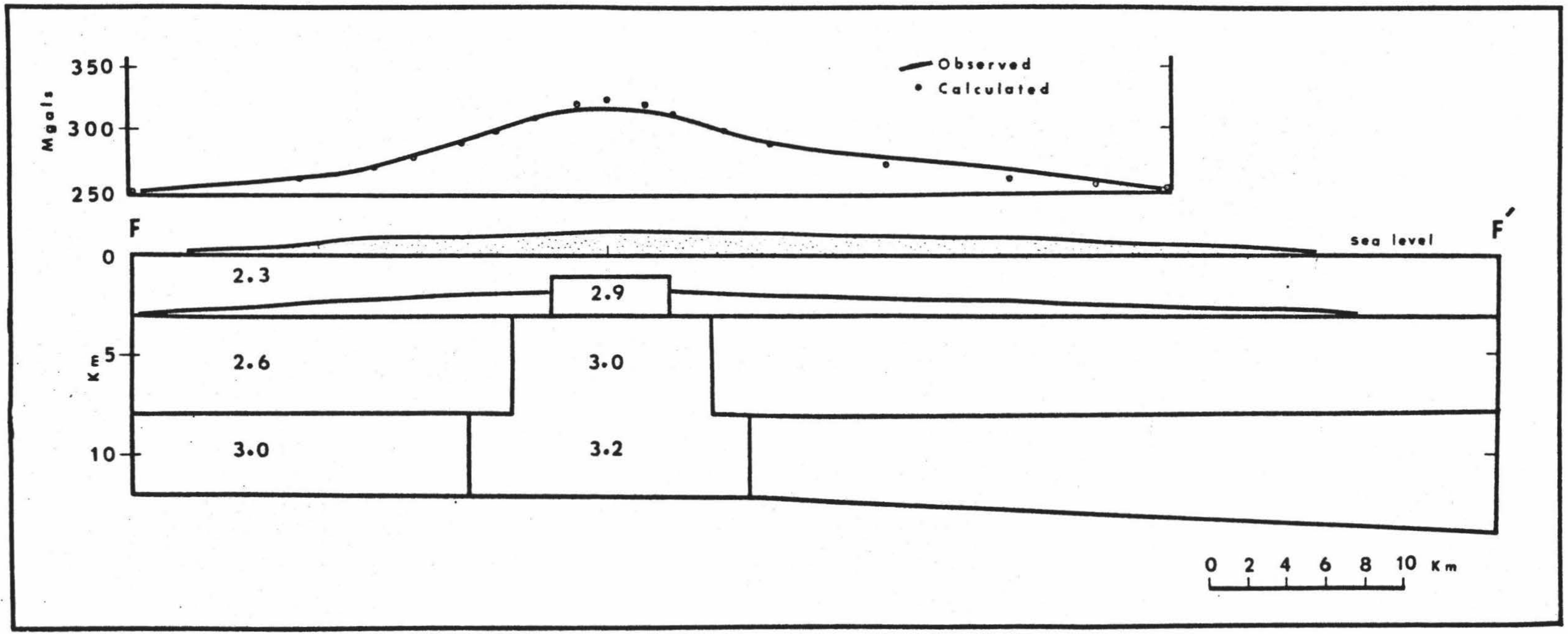


Fig. 8b. Crustal interpretation of Bouguer gravity anomalies over Kilauea Volcano along profile FF'. (For location see Fig. 2.) (Density in gm/cc)

vertical cylinder is given by

$$\Delta g = Kf(X/Z) \text{ in which}$$

$$K = \frac{G\pi R^2\sigma}{Z}$$

and $$f\left(\frac{X}{Z}\right) = \frac{1}{[1 + (X/Z)^2]^{1/2}}$$

where G = Gravitational constant (6.67×10^{-8} C.G.S. units)

R = Radius of the cylinder

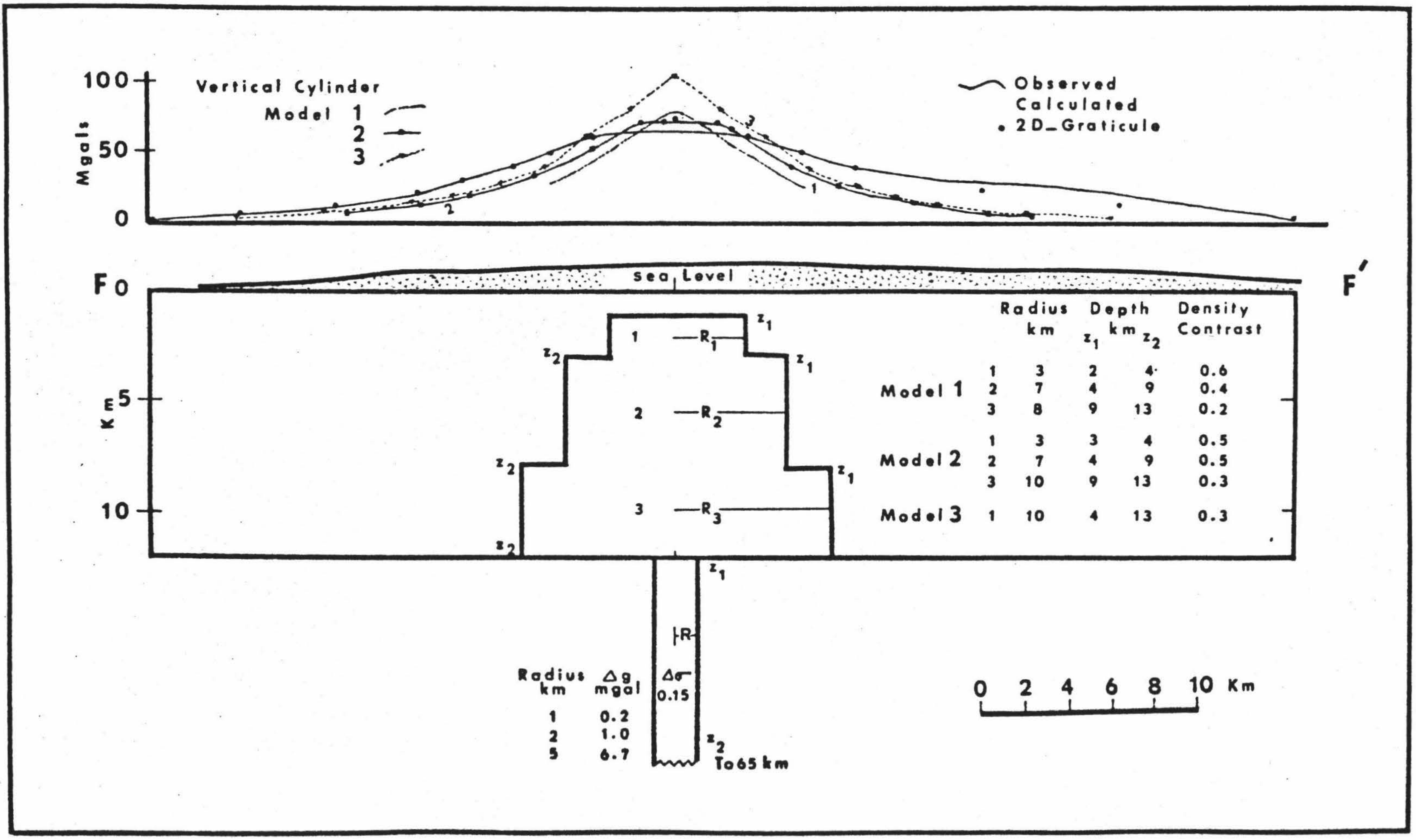
Z = Depth to the top

X = Distance from the axis of the cylinder

σ = Density contrast.

By using this formula the calculated gravity effect due to finite cylinders of different radii for different parts of the plug did not yield a good solution consistent with the observed anomaly (Fig. 9). It appears, therefore, that the volcanic pipe complexes probably are not of perfect geometric shapes, but may be elongated and irregular in cross section and hence a two-dimensional approximation appears to give a better fit of the calculated to the observed anomalies.

An "inverted pyramid" model was also attempted for the Kilauea profile FF'. This is an inversion of the model type in the previous computations. The inverted model did not give a satisfactory fit between the observed and calculated anomalies. However, the general shape of the inverted



		Radius km	Depth km z_1	Depth km z_2	Density Contrast
Model 1	1	3	2	4	0.6
	2	7	4	9	0.4
	3	8	9	13	0.2
Model 2	1	3	3	4	0.5
	2	7	4	9	0.5
	3	10	9	13	0.3
Model 3	1	10	4	13	0.3

Radius km	Δg mgal
1	0.2
2	1.0
5	6.7

Fig. 9. Vertical cylinder model for Kilauea Volcano along profile FF'. (For location see Fig. 2.) (Density in gm/cc)

model could be altered to give a reasonable fit (Fig. 10). The "inverted pyramid" model type was not favored by the writer as it does not confirm with the available seismic evidence of Koolau plug on Oahu and with general geological reasoning for the shape and structure of the Hawaiian volcanic plugs.

Island of Maui

Haleakala Volcano

From the Bouguer gravity anomaly map of Maui (Fig. 3) Haleakala Volcano on East Maui is characterized by a +280 mgal anomaly, while the coastal gravity is of the order of +210 to +220 mgal. The southwest and east rift zones are evident in the gravity map of the island. Contrasted with the Haleakala Volcano, the West Maui Volcano appears to contain two centers of eruption each with an anomaly of +240 mgal. The isthmus between East Maui and West Maui is characterized by a low of +190 mgal.

The gravity anomaly over Haleakala Volcano was analyzed along the profile GG' (Fig. 3). In the absence of any coastal seismic refraction profiles, the reported mantle depths of 15 km and 18 km (Woollard, 1966, and Shor and Pollard, 1964) were assumed applicable for the crustal structure of Maui. The assumed density model and the agreement between the observed and computed anomalies are shown in Figure 11.

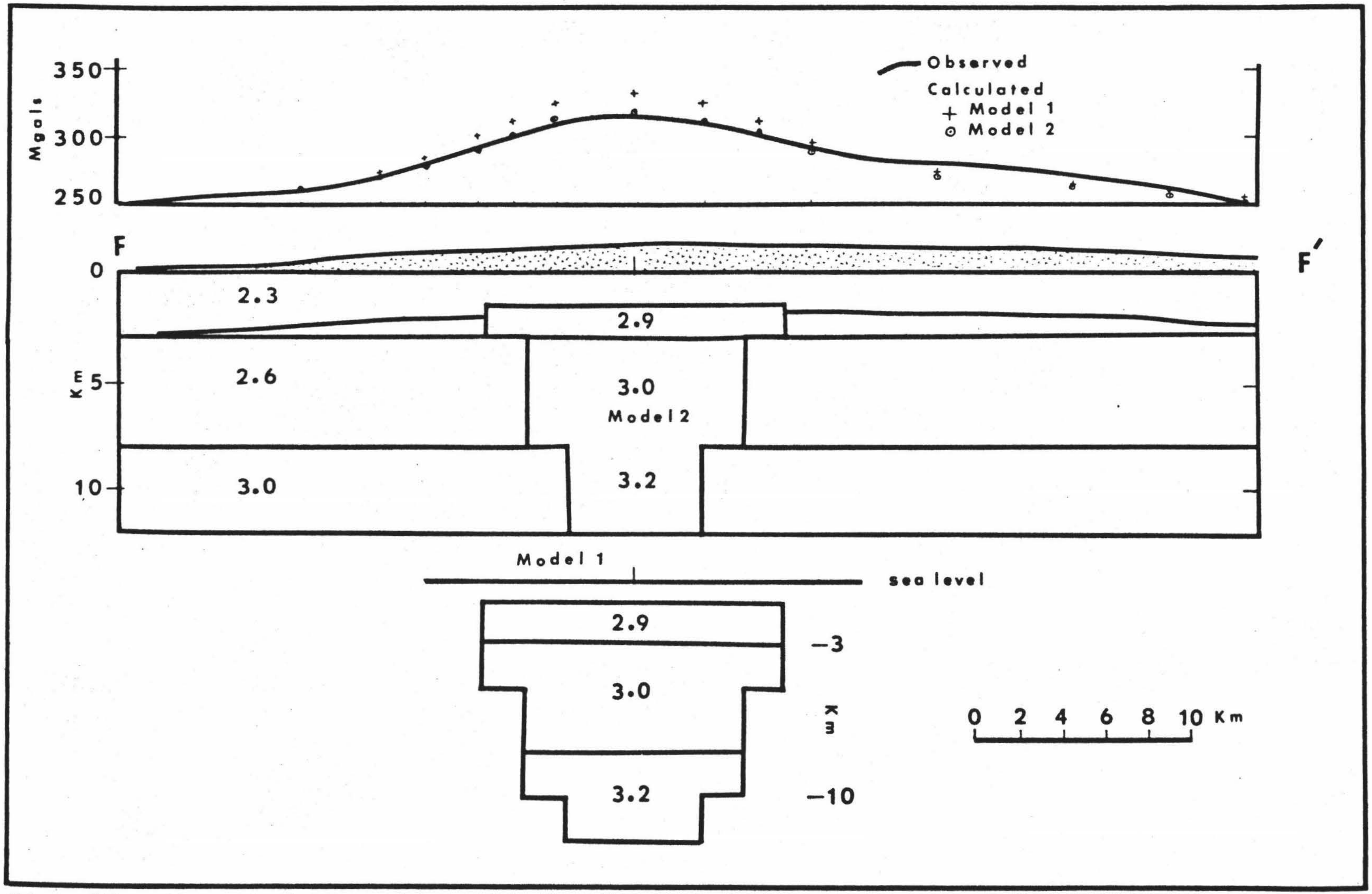


Fig. 10. Inverted pyramid model for Kilauea Volcano along profile FF'. (For location see Fig. 2.) **(Density in gm/cc)**

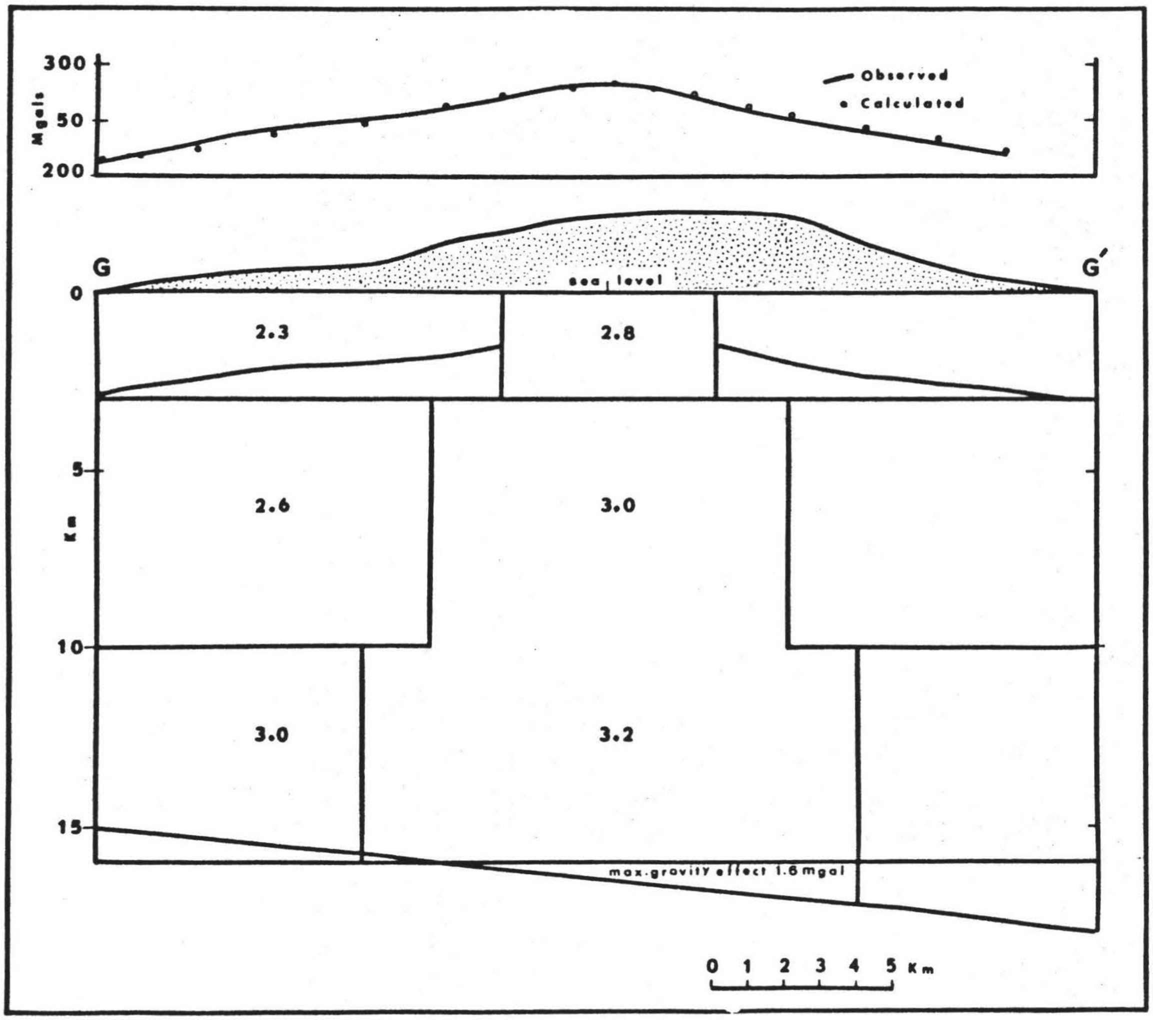


Fig. 11. Crustal interpretation of Bouguer gravity anomalies over Haleakala Volcano along profile GG'. (For location see Fig. 3.) **(Density in gm/cc)**

The volcanic plug, assumed to be the source of the gravity anomaly, is 6 km wide at the top, 9 km wide in the middle, and 12 km wide at the base, and the top of the plug is situated at sea level.

Island of Molokai

The island of Molokai was formed by eruptions from two shield volcanoes on an east trending line. The Bouguer gravity anomaly map of the island is shown in Figure 3. The West Molokai Volcano is characterized by a +270 mgal anomaly and the coastal gravity is of the order of +230 to +240 mgal. The southwest rift zone of West Molokai Volcano can be seen as a continuation of the +240 mgal gravity contour, extending to Penguin Banks, south of Oahu. The East Molokai Volcano anomaly is also of the same order of magnitude and the central vent lies offshore on the northern coast.

East Molokai Volcano

An offshore profile HH' was taken for the analysis of the East Molokai Volcano (Fig. 3). Since no seismic refraction results were available, an average mantle depth of 15 km (this being the average mantle depth value for the Hawaiian Ridge) was assumed beneath the profile.

The assumed density model and the agreement between the observed and calculated anomalies is shown in Figure 12.

As the local anomaly is of the order of only +30 to +40 mgal a smaller plug was obtained. It is 5 km wide at

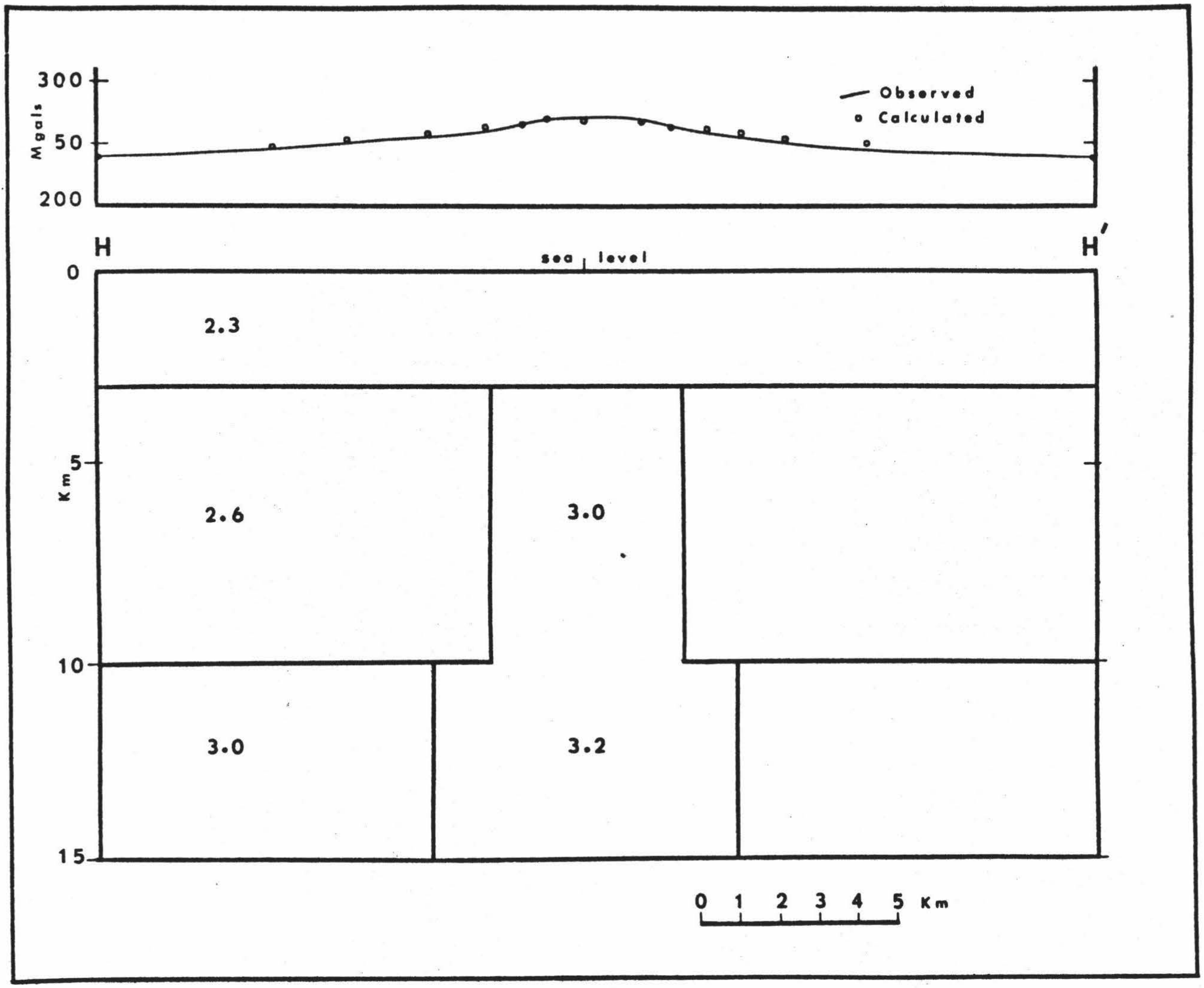


Fig. 12. Crustal interpretation of Bouguer gravity anomalies over East Molokai Volcano along profile HH'. (For location see Fig. 3.) (Density in gm/cc)

the top and 8 km wide at its base and the top is located 3 km below sea level.

West Molokai Volcano, being the same order of magnitude in anomaly, the results of East Molokai Volcano are assumed to be applicable to West Molokai Volcano also.

V. DISCUSSION

Density Considerations

Woollard (1951, 1965) has shown that the bulk density of the Hawaiian Ridge above sea level is 2.3 gm/cc because it is at this value of density that the Bouguer gravity anomalies observed over the islands show minimum correlation with the topography. Laboratory measurements of densities (Woollard, 1951; Strange et al., 1965) of various rocks on the island varied from 1.8 to 3.0 gm/cc, the average being 2.3 gm/cc. Certain dike rocks, with basic inclusions, yielded densities of the order of 2.8 to 3.1 gm/cc. Further, from the relationship between wet and dry densities of basalts, water saturated basalts were shown to exhibit higher densities of about 0.1 to 0.2 gm/cc than the dry specimens.

Based on these considerations and on the seismic velocities, the density model assumed for the Hawaiian Ridge in general consists of 2.3 gm/cc for the volcanic mass above sea level, 2.1 gm/cc for the sediments, 2.5 gm/cc for the first 1.5 km below sea level, 2.6 gm/cc for the next 1.5 km, 2.8 gm/cc for the main crustal layer and 2.9 gm/cc for the basal layer.

The density model assumed for the gravity solution of the Koolau plug (Fig. 1) consists of 2.3 gm/cc for the first 1.5 km below sea level and 2.6 gm/cc for the next 1.5 km, followed by 2.8 and 2.9 gm/cc for the crustal layers. The density of the plug was taken to range from 2.9 to 3.2 gm/cc, giving contrasts of 0.6 gm/cc at the top, 0.4 gm/cc with the 2.8 gm/cc layer, and 0.3 gm/cc with the 2.9 gm/cc layer. In terms of density contrast, the assumed density model in the present study, with density values of 2.3, 2.6 to 2.7, and 3.0 gm/cc for the top 3 km of the upper layer, the main crustal layer, and the basal layer, respectively, and with corresponding plug densities of 2.8 to 2.9, 3.0, and 3.2 gm/cc, is very similar to the Woollard model for the Koolau plug. Since gravity anomalies depend on density contrasts, absolute densities are of little significance in the analysis of local anomalies. Hence it appears that a plug with density contrasts of 0.6 to 0.5 gm/cc at the top, 0.4 to 0.3 gm/cc in the middle, and 0.2 gm/cc at the base satisfactorily explains the observed gravity anomalies over the volcanic centers on the Hawaiian Islands. In this respect, the present study therefore supports the earlier structural deductions of Strange et al. (1965) for the Koolau plug.

Assumed Model

The general assumed model for the Hawaiian volcanic plugs was made to confirm to the surface expression of the calderas. The model was constructed so that the width increased towards the base. The configuration of the model was based mainly on the seismically confirmed gravity solution for the Koolau plug on Oahu.

The present study indicates that the volcanic plugs generally are 6 to 12 km wide at the top--depending on the width and magnitude of the anomaly--and 14 to 18 km wide at the base. The plug density ranges from 2.8 to 3.2 gm/cc. The tops of the plugs are situated at varying depths ranging from sea level to 3 km below sea level. The shape and dimensions of the plug agree in general with that of Koolau plug, but they are located much deeper.

The dimensions and depths to the source bodies in the present study agree with the magnetic size estimates (Table 2) within reasonable limits. Because of the inherent differences in the nature of the parameters that give rise to gravity and magnetic anomalies, no better agreement can be expected between the gravity and magnetic solutions. Kilauea Volcano, for instance, which shows a gravity anomaly of +315 mgal, has no magnetic anomaly located over it and Koolau Volcano on Oahu, with the same order of gravity anomaly, shows the only prominent reversely magnetized anomaly observed over the Hawaiian Volcanoes.

Other Models

The assumption of a regular three-dimensional body for the volcanic plug, like a finite vertical cylinder of different radii at different depths, did not yield satisfactory agreement between the observed and the computed anomalies (Fig. 9). This observation strengthens the idea that the volcanic plugs are probably irregular and elongated and the two-dimensional approach is a better approximation for obtaining computed gravity anomalies that are consistent with the observed anomalies.

From the theory of two-dimensional gravity interpretation (Appendix), if the length of the body is greater than or equal to eight times the depth, the interpretation based on the theory of infinite length should be accurate to 5% or better. In the present study, assuming that the length-to-depth ratio is at least of the order of four or more, the results will be correct to within about 10%.

It is generally assumed that the magma that gave rise to the lavas originated at a depth of 60 to 65 km (Eaton, 1960) and reached the upper parts of the crust through a conduit. Assuming the conduit as a vertical cylinder calculations have been made to ascertain the effect of such a cylinder at the surface. The gravity effect of a cylinder extending from a depth of 65 km to the base of the crust, which is located at a depth of 12 km beneath sea level for the Kilauea profile FF' (Fig. 9) with a density contrast of 0.15 gm/cc between the magma and the surroundings would contribute little to the surface gravity anomaly. The computed gravity effect is 0.2 mgal for a cylinder of radius 1 km, 1.0 mgal for a cylinder of radius 2 km and 6.6 mgal for a cylinder of radius 5 km. Hence, little can be said about the dimensions of a magma feeding conduit located between the magma source and the base of the crust from the gravity data alone.

Existence of Magma Chambers

From the study of ground tilt measurements and harmonic tremors associated with the movement of the magma, the existence of a magma chamber was suggested at a depth of about 3 km for the Kilauea Volcano (Eaton, 1962; Hill, 1969). Earlier, seismic studies by Adams and Furumoto (1965) indicated a magma chamber at a depth of 3 to 4 km for the Koolau Volcano on Oahu. The 2 km depth to the source body from the surface, obtained in this study for Kilauea, was in agreement with these observations. The suggestion by Hill (1969) that similar magma chambers and high density cores are included within all the Hawaiian volcanoes, with partial or full recrystallization for the older volcanoes, therefore appears to be reasonable.

From the analysis of gravity data observed over the Hawaiian volcanoes, the writer is of the opinion that source magma forming at depths of 60 - 65 km reach the base of the crust through narrow conduits. The magma intrudes the crustal layers through fissures and cracks in the form of dikes and sills and may form magma chambers included within the dense high velocity cores of the volcanoes. The magma is erupted either through the central vents or through the rift zones. Thus formed volcanic pipe complexes in the central vents, peripheral dike swarms, and the intrusions along the rift zones are responsible for the high positive Bouguer gravity anomalies, magnetic dipole anomalies, and high seismic velocities at shallow depths observed over the Hawaiian volcanoes.

VI. CONCLUSIONS

(1) The high positive Bouguer gravity anomalies of the order of +50 to +110 mgal observed over the volcanic centers of the Hawaiian Islands can be attributed to the intruded high density mantle material, which may be in the form of dikes, sills or magma chambers, partly or fully recrystallized.

(2) Dimensions and depth to the top of the source bodies were obtained by using two-dimensional gravity graticule method. The tops of the bodies range from sea level to 2 to 3 km below sea level. Models with top diameter agreeing in general with the surface expression of the associated vents and increasing in diameter with depth appears to provide the best solutions.

(3) Generally, the volcanic plugs are 6 to 12 km wide at the top and increasing to 14 to 18 km at the base. The plugs extend down to the base of the crust. The length of the bodies is assumed to be at least 4 times the depth to the center of the mass so that the two-dimensional interpretation will be correct to within 10%.

(4) Models with density contrast of 0.5 to 0.6 gm/cc at the top, 0.3 to 0.4 gm/cc at the middle and 0.2 gm/cc at the base appears to provide the best fit to the observed gravity anomalies.

(5) The results obtained, generally agree with the results of the earlier gravity, magnetic, and seismic

studies carried out over the Hawaiian Islands.

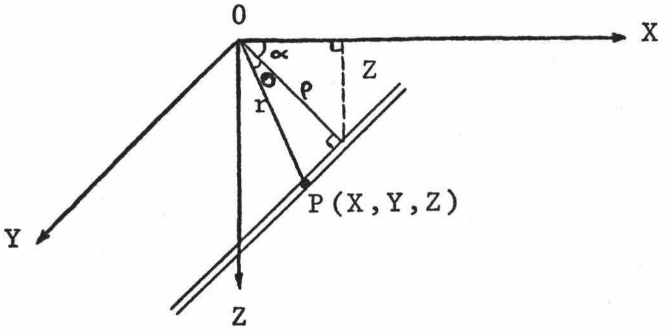
APPENDIX

TWO-DIMENSIONAL GRATICULE FOR INTERPRETATION OF GRAVITY DATA

In a technical note Robertson (1953) outlined the theory and method of construction of two-dimensional graticules in the interpretation of gravity and magnetic data. He presented the formulae for the construction of graticules for gravity, gravity gradient, curvature, and their application in the interpretation of magnetic data. But the relevant details in the construction of gravity graticule only, along with the estimates of error involved in the assumption of infinite extent of the body in the strike direction are presented below.

Any body which is infinitely long in one direction can be considered as a two-dimensional body and the gravity effect can be calculated by assuming that the body is composed of large number of rods parallel to the strike direction.

Consider the axis of the rod to be parallel to the Y axis and at a depth Z below the plane of reference XOY.



$$Y = \rho \tan \theta$$

$$dy = \rho \, Sec^2\theta d\theta$$

$$r = \rho \, Sec\theta$$

Let μ = mass per unit length

G = gravitation constant

The gravity effect at the origin due to the element of length dy at P is given by $G\mu Z \, dy/r^3$, and due to the whole rod by

$$\Delta g = G\mu Z \int_{Y_1}^{Y_2} \frac{dy}{r^2}$$

$$= \frac{G\mu Z}{\rho^2} \int_{\theta_1}^{\theta_2} \cos\theta d\theta$$

$$\Delta g = \frac{G\mu Z}{\rho 2} (Sin\theta_2 - Sin\theta_1)$$

Let the length of the rod be 2b and $\theta_2 = -\theta_1 = \Phi$

$$\Delta g = \frac{2G\mu Z}{\rho^2} Sin\Phi$$

In the case of a rod of infinite length,

$$\Delta g = \frac{2G\mu Z}{\rho^2} = \frac{2G\mu Sin\alpha}{\rho} \qquad (1)$$

Δg is a maximum when $\rho = Z$ (i.e. $X = 0$) and falls to half value when $\rho = Z\sqrt{2}$ (i.e. $X = Z$)

In the case of a rod of finite length, the error involved in assuming the rod is of infinite length is as follows.

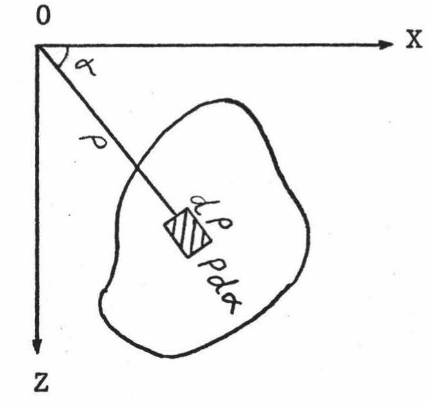
X = 0					X = Z				
b/Z	2	3	4	6	b/Z	2	3	4	6
% error	10.6	5.1	3.0	1.4	% error	18.4	9.5	5.7	2.7

Thus if the rod length >8Z the interpretation based on the theory of infinite length should be accurate to 5% or better.

The same conditions apply in the case of a body of roughly cylindrical cross section provided $\overline{Z}$ is used in place of Z where $\overline{Z}$ is the depth of the center of gravity of the cross section of the body.

Two-Dimensional Gravity Graticule

In comparing the gravity effects of assumed subsurface structure with actual observed values of gravity, graphical techniques can be used especially if the body is irregular in shape, as it is difficult to calculate the gravity effect of an irregular body by analytical means. The graphical techniques generally involve the use of transparent templates called "graticules", which are superimposed over a cross section of the structure whose gravity effect is to be computed. The graticule generally consists of a fan-shaped pattern of dots, whose point of convergence is placed over the gravity station on the section (XOZ plane), and the gravity effect of any body outlined on the section can be determined by counting the number of dots it covers on the graticule.



For a line element extending from +∞ to -∞ the gravity effect is given by equation (1)

$$\delta\Delta g = \frac{2G\mu \operatorname{Sin}\alpha}{\rho}$$

Let $\mu = \sigma\rho d\alpha d\rho$

where ρ is the density of the body. (In practice, the density contrast between the body and the surrounding rocks will be used.)

Then for any two-dimensional body of finite cross section

$$\Delta g = 2G\sigma\int \operatorname{Sin}\alpha d\alpha d\rho \qquad (2)$$

where the integration is taken over the cross section of the body.

If the XZ plane is divided into sectors by a system of concentric circles centered at "0" and a system of straight lines radiating from "0", then

$$\Delta g = 2G\sigma\sum\int_{\alpha_m}^{\alpha_{m+1}}\int_{\rho_n}^{\rho_{n+1}} \text{Sin}\,\alpha\, d\alpha\, d\rho \qquad (3)$$

where the summation is carried out for all sectors falling within the cross section of the body.

$$\therefore \quad \Delta g = 2G\sigma\sum(\rho_{n+1} - \rho_n)(\cos\alpha_m - \cos\alpha_{m+1}) \qquad (4)$$

If the system of radial lines and semi-circles are arranged so that $(\rho_{n+1} - \rho_n)(\cos\alpha_m - \cos\alpha_m - \cos\alpha_{m+1})$ is constant for all values of m and n, then, Δg can be expressed as

$$\Delta g = N\sigma W \qquad (5)$$

where N is the number of sectors falling within the cross section of the body and

$$W = 2G(\rho_{n+1} - \rho_n)(\cos\alpha_m - \cos\alpha_{m+1})$$

If the centers of the sectors are marked with a dot then it is only necessary to count the number of dots falling within the cross section of the body.

A graticule can be constructed in the above manner with equal weight to all dots or with different weights according to convenience.

In using the graticule, the graticule and the cross section of the body must be of the same scale. If the cross section of the body is drawn to a different scale, then the normal weights are to be multiplied by the ratio of map scale to the graticule scale.

Sometimes when the gravity effect of sediments overlying basement is being evaluated, it is necessary to know the effect of the infinite semi-cylinder of radius x feet (scale x feet per inch being used). This value in milligal is added to that obtained by counting the dots lying within the sedimentary cross section.

For the infinite semi-cylinder with center at the origin, we have

$$\Delta g = 2G\sigma \int_0^{\pi} \int_0^{X} \text{Sin}\alpha d\alpha d\rho \qquad (6)$$

$$= 4G\sigma X$$

$$= 0.00813\sigma X$$

where X is the distance scale used in feet/inch.

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