The Structure of Koolau Volcano from Seismic Refraction Studies[1]

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THE ISLAND OF OAHU in the Hawaiian Archipelago was formed by the coalescing of two volcanoes, Waianae Volcano on the west and Koolau Volcano on the east. Both volcanoes have been dormant for tens of thousands of years. Erosion and weathering have cut deeply into them so that present topography does not clearly indicate the former shapes and sizes of the volcanoes.

A gravity survey by Woollard (1951) showed unusually high Bouguer anomalies over the caldera sections of both volcanoes. These high anomalies have whetted the interests of geophysicists, and recently projects were planned to make a detailed survey of the Koolau Volcano, using whatever geophysical and geological methods were available. In the fall of 1963 and the winter of 1964 intensive gravity surveys (Strange, Machesky, and Woollard, p. 350 in this issue) were carried out over the volcano. An aerial magnetic survey (Malahoff and Woollard, 1965) was carried out during the spring and summer of 1964. After information and data from the gravity and magnetic surveys became available, seismic refraction profiles were planned and carried out during the fall of 1964.

The prominent features of the Koolau Volcano are the caldera area, the northwest rift zone, and the southeast rift zone. From surface geology the existence of the northwest rift zone and the caldera was known (Stearns and Vaksvik, 1935; Stearns, 1946). Gravity surveys (Strange, Woollard, and Rose, p. 381 in this issue) later confirmed the findings by surface geology for the caldera area, but showed that the northwest rift zone was farther to the east than had been indicated by geology and topography. The southeast rift zone became known only after the gravity surveys.

[1] Hawaii Institute of Geophysics Contribution No. 90.

INSTRUMENTATION

Because mobility was necessary for the planned seismic refraction program, the recording units were housed in trucks. The trucks contained recording cameras, amplifier banks, portable box-type darkrooms, communications gear, geophones, and other accessories to set up a recording station.

The geophones were Hall-Sears geophones, with a natural frequency of 4.5 cps. Most of them were vertical components, but a few horizontal components were used. A typical spread consisted of six geophones in line, with 50-ft spacings.

The amplifiers were model type T-1, manufactured by Fortune Electronics. These completely transistorized amplifiers with low power comsumption were found to be very satisfactory in field operations.

The recording cameras were manufactured by Southwest Industrial Electronics, Ltd. These cameras contained sufficient channels to record the signals from the six geophones at two different dynamic levels.

Communication between the recording trucks and the shooting party was done usually through Citizen's Band transceivers. The all-important shot instant was also transmitted by Citizen's Band transceivers by an audio tone beginning at the shot instant.

The firing of the explosives was done by a device, familiarly called the "tricky ticker," which in essence is a break-circuit chronometer operating a fixed sequence of audio tones and switches for firing. Details of the firing equipment may be found in Steinhart and Meyer (1961:158–163).

FIELD WORK AND DATA PROCESSING

The seismic refraction traverses carried out for the project are shown in Figures 1, 2, and 3. Figure 1 shows the traverses designated by code

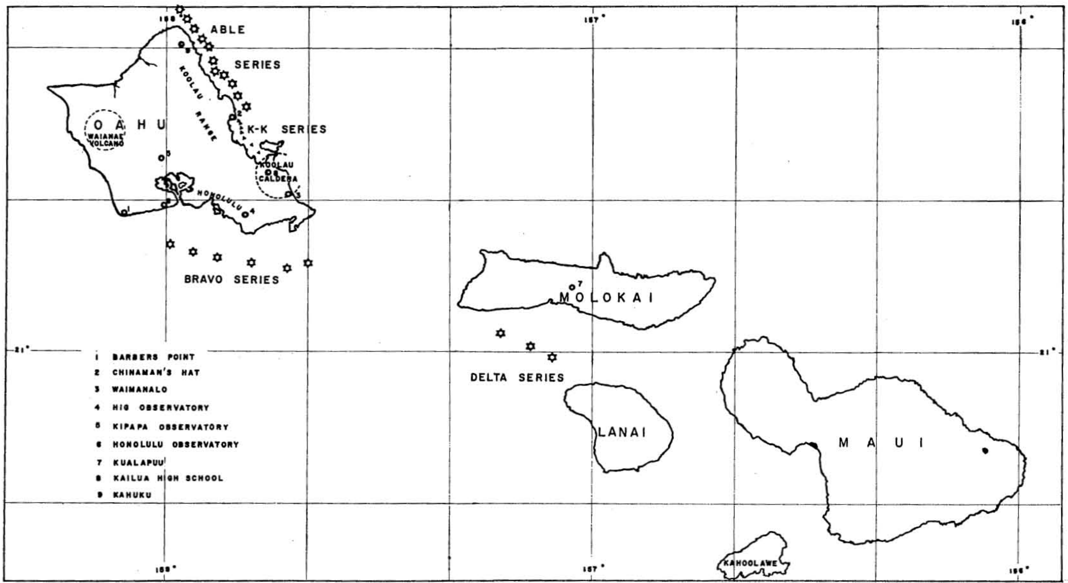

FIG. 1. Map of the Hawaiian Islands with locations of seismic refraction traverses and recording stations.

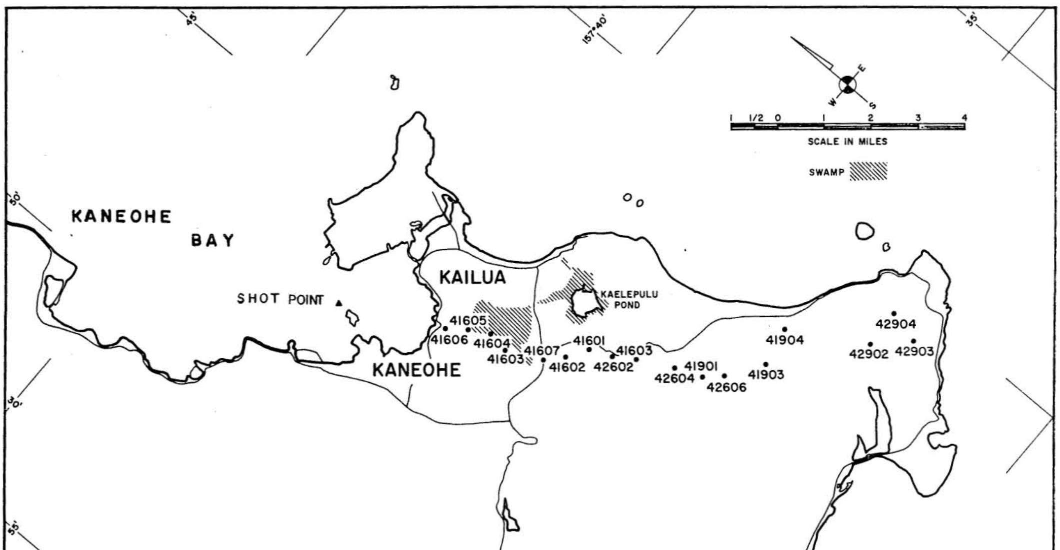

FIG. 2. Map of Koolau Caldera with shot point and recording stations for GASHOUSE series.

names ABLE, BRAVO, DELTA, and K-K; Figure 2, traverse GASHOUSE; and Figure 3, the shorter traverses in the caldera area to probe for shallow structures.

In the longer traverses of ABLE, BRAVO, DELTA, and K-K the explosives were set off under water at sea. The technique of fixed recording stations with moving shot points was used. For the K-K series the shooting crew operated from outboard motorboats because the largest charge-size amounted to 40 lb of TNT. For the ABLE, BRAVO, and DELTA series, the 85-ft R/V "Neptune I" of the University of Hawaii was used as a shooting platform because the charge-size used was large—either 200 lb or 500 lb of nitromon. For the K-K series the charges were detonated at the bottom of the bay, which on the average was 40 ft deep. For the ABLE, BRAVO, and DELTA series all shots were fired 75 ft below the water surface.

In the GASHOUSE series (Fig. 2) a fixed shot in Kaneohe Bay on the north side of Oahu was used while the recording trucks moved in a southeast direction away from the shot point.

In a number of short traverses to probe for the shallow structures of the caldera area, charges ranging from ½-lb blocks of TNT to 35 lb of nitromon were detonated in a drainage canal cutting across Kawainui Swamp which is located in the caldera area. For these short traverses the technique of fixed recording units and moving shot points was used. The shooting crew operated from shallow-draft rowboats.

Some rapid analyses of data were done in the field to judge whether data being gathered were adequate. The bulk of the data, however, was processed at the Hawaii Institute of Geophysics after the field work had been completed.

In data processing the seismograms were first examined and arrival times were picked by eye. After rough travel-time graphs were plotted

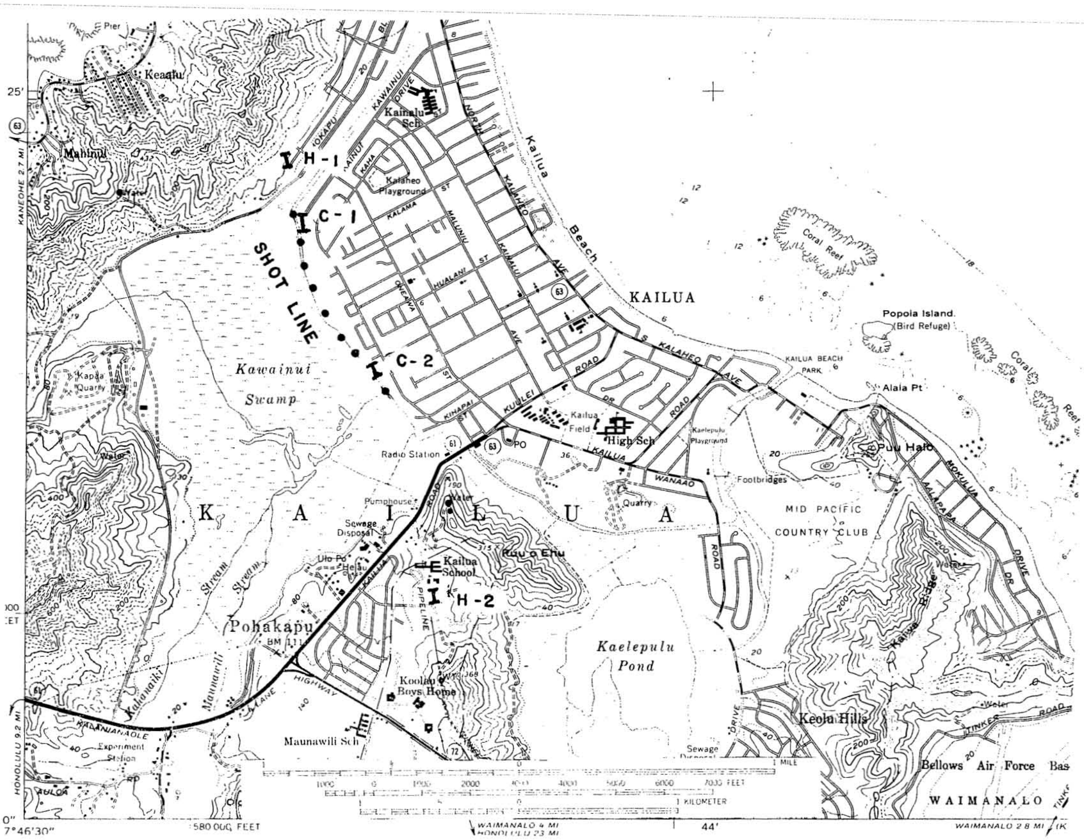

FIG. 3. Location map of refraction traverse and recording stations near Kawainui Swamp.

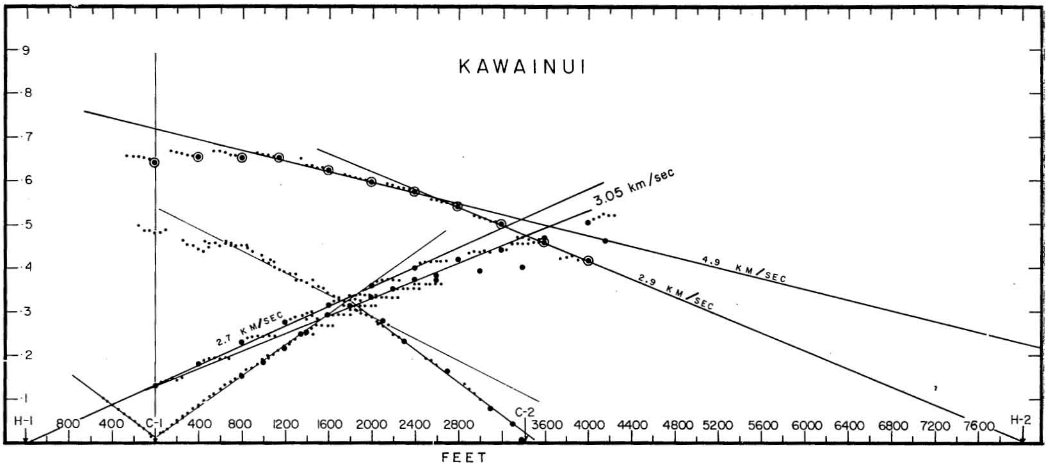

FIG. 4. Travel time plots of refraction traverses in Kawainui Swamp.

and critically examined, corrections for water depth at shot points and elevation at recording sites were made to the raw data.

The corrected data were fed into an IBM 7040 computer for processing. The computer program gave the slopes, velocities, and intercepts of the various branches of the travel-time plots and the variances of the slopes and intercepts. Calculations of depth to the top of the various layers were done by using desk calculators.

DATA AND INTERPRETATION

After reviewing the gravity and magnetic data the authors decided to run seismic refraction surveys over the caldera area, the northwest rift zone, and one of the flanks not disturbed by a rift zone. For the flank investigation the western flank was chosen first, but inclement weather forced the transfer of the operations to the southern flank, which is on the leeward side of the island. The short traverses and the GASHOUSE series were designed to outline the volcanic plug in the caldera area; the K-K and ABLE series were planned to parallel as closely as possible the northwest rift zone as outlined by the ridge of high gravity anomalies. The BRAVO series was designed to run along the strike of the south flank. The DELTA series was intended to extend the investigation to the island of Molokai, but data were inadequate to attempt any analysis.

Caldera Area

Two consecutive traverses were carried out in the drainage canal which cuts across the northern section of Kawainui Swamp located in the caldera area. For the first traverse recording units were located at C-1 and C-2 of Figure 3 and shots were detonated in the canal at 200-ft or 400-ft intervals. For the second traverse the recording units were placed farther apart at H-1 and H-2, and the shots were again detonated in the canal at 400-ft intervals. The recording units consisted of a 250-ft geophone spread with geophones spaced 50 ft apart. The spread was in line with the shot line.

The travel-time plots for both traverses are shown in Figure 4. The abscissa is given in terms of feet, but the velocities have been converted into units of km/sec for easy comparison with other plots to follow. The larger dots represent the arrival times of the first geophone in the spread. From the figure it can be seen that the apparent velocity across the spread often does not agree with the step-out velocity. This indicates complicated bedding beneath the spread.

A few unusual features are conspicuous on the travel-time plots. For both traverses the plots indicate very high velocities at the ends of the profile. Because the distances involved preclude penetration to great depths, these apparent high velocities have been interpreted in

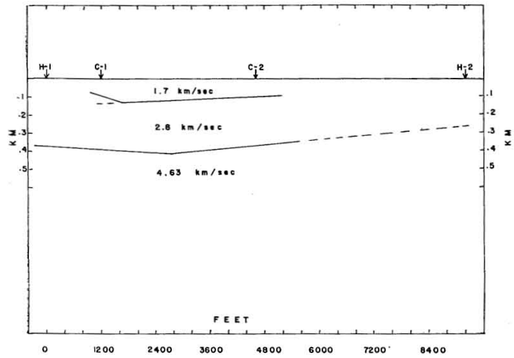

FIG. 5. Section structure under Kawainui Swamp from seismic refraction surveys.

terms of sloping beds, rather than in terms of high-velocity layers. The presence of infinite apparent velocity over the spread at point C-1 gives support to this interpretation.

An interpretation of the travel-time plots and data gave the shallow structure shown in Figure 5. The water layer in the canal (average depth, 4–6 ft) was undetected and hence is disregarded in this discussion because all explosions were set off at the canal bottom. The first layer detected had a seismic velocity of 1.7 km/sec and extended to a depth of 300–400 ft. The second layer had a velocity of 2.8 km/sec. the 2.8 km/sec layer dips 38° under site C-1 to give an apparent infinite velocity across the geophone spread. The third layer, the deepest layer detected, was assigned a velocity of 4.63 km/sec. This value was obtained from the results of GASHOUSE series. The 4.63 km/sec layer dips 8° in the midsection between C-1 and C-2.

For probing the deeper structures in the caldera the GASHOUSE series (Fig. 2) was carried out. Details of the field work, data, and interpretation of this series are given in another paper (Adams and Furumoto, p. 296 in this issue). Analysis showed that a layer of velocity 4.64 km/sec was intruded by a plug that had a velocity of 7 km/sec as a lower bound. The depth to the top of the plug from the ground surface was estimated to be 1.6 km.

Northwest Rift Zone

To investigate the northwest rift zone, series ABLE and K-K were carried out. For the K-K series recording units were placed at Chinaman's Hat Island and at Kailua High School (Fig. 1). The site at Kailua High School is identical with site H-2 described in the discussion on the caldera area. For the ABLE series recording was done at Kahuku and again at Kailua High School (Fig. 1).

The travel-time plots for K-K and ABLE series are given in Figure 6. Notice in the figure that the 5.58 km/sec line is common to the ABLE and K-K series. For the other lines, however, such a happy coincidence does not occur. It is best to consider the two series separately for analysis.

For the K-K series the 5.58 km/sec layer matches the 6.74 km/sec layer in the reversed profile. On the Chinaman's Hat recording a 5.2 km/sec layer is evident and this corresponds to the 4.9 km/sec layer in the Kailua High School recording of the series in the caldera area. However, the pairing of 5.2 and 4.9 should not be done to determine true velocity, because the value of 4.9 is the result of complicated dipping and faulting in the caldera zone. Instead, as was done for the caldera interpretation, the value of 4.64 km/sec, obtained from the GASHOUSE series, was assigned as the true velocity for this layer.

For the layer just below the water the value of 3.0 km/sec was taken from the Chinaman's Hat recording. This layer becomes 2.8 km/sec on land, as was seen in the caldera area data.

Calculations made from the travel-time data yielded the following:

Layer	*Velocity* (km/sec)	*Km to Top of Layer* Chinaman's Hat	Kailua
a	3.0	0	0
b	4.64	0.7	0
c	6.1	1.7	0.8

The ABLE series form a reversed profile and a split profile on the northern end. For the Kahuku recording the layer that should correspond to the 5.58 km/sec layer of the Kailua recording is discernible only as second arrivals. The arrivals match well with a set of second and third arrivals with an apparent velocity of 6.8 km/sec on the north side of the Kahuku station.

There is an offset in the Kailua recording of the 7.16 km/sec line. Whether this is due to faulting is not certain.

For the layer just below the water a velocity of 3.0 km/sec has been assigned. This assumption is based on the data from Chinaman's Hat.

Calculations from the travel-time data yielded the following:

Layer	*Velocity* (km/sec)	*Km to Top of Layer* Kahuku	Chinaman's Hat
a	3.0	0	0
b	4.17	1.2	0.7
c	5.71	3.8	1.7
d	7.6	5.4	(Dipping 2° to NW)

On the southern portion of the recording at Kailua High School station the velocity of 7.38 km/sec appears as second arrivals. When this value was paired with the 8.17 of the Kahuku recording, we obtained 7.7 km/sec for layer *d;* 7.7 km/sec was then assigned to layer *d* for the southern portion of the structure.

A section structure for the ABLE and K-K series is given in Figure 7. Notice the consistent lateral variation in velocities; the lower velocities are in the northern section although the layers are deeper.

The Southern Flank

For the BRAVO series to the south of the island of Oahu recording units were set up at Barbers Point on Oahu and at Kualapuu on the adjacent island of Molokai (Fig. 1). Distance between the recording units was 109 km. Because of inclement weather, the shots could be set off only in the protected lee of the island of Oahu.

The travel-time plots of the BRAVO series are given in Figure 8. The upper set of lines rep-

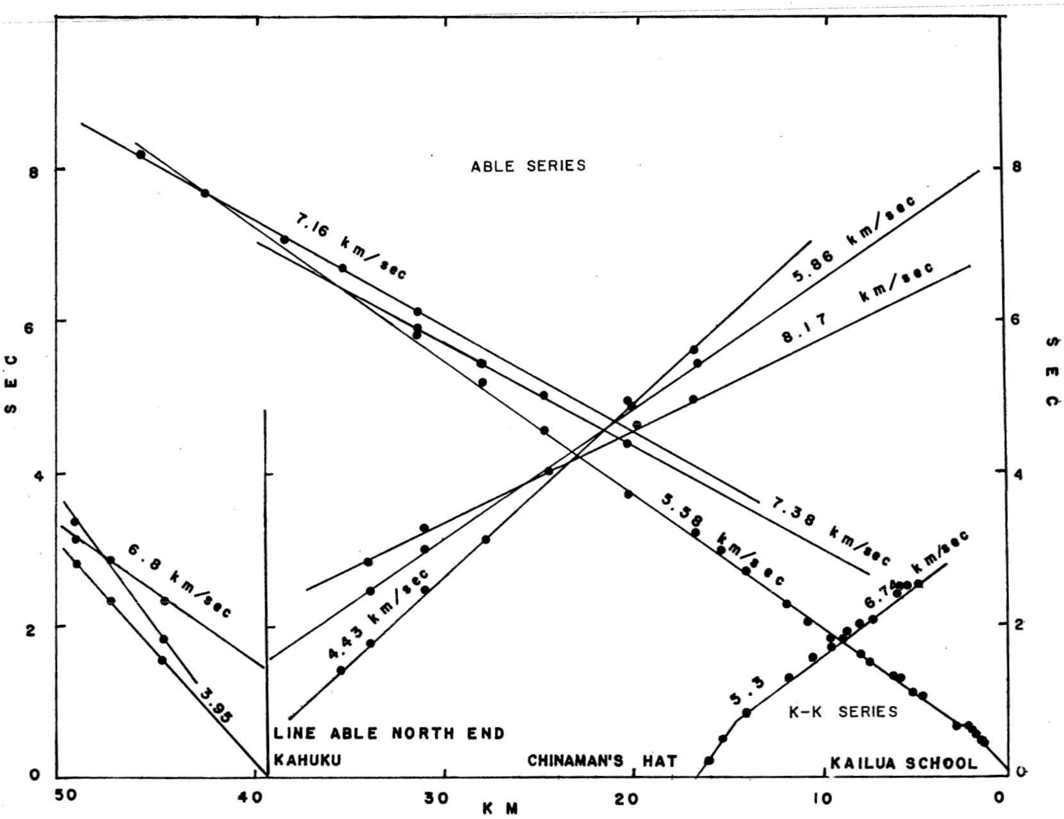

FIG. 6. Travel time plots of K-K and ABLE series.

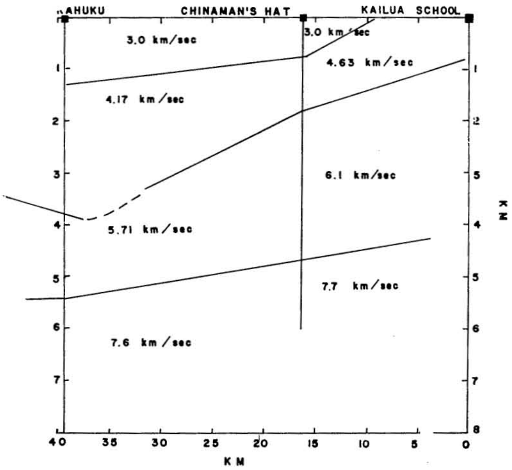

FIG. 7. Section structure under northwest rift zone.

resents the arrival times recorded at Barbers Point; the lower set, the arrival times recorded at Kualapuu.

Because of the shortness of the shot line, interpretation had to rely on second and third arrivals. For these later arrivals correlation from one seismogram to the next was sought by looking for similarity in wave forms as well as linear relations on the travel-time curve.

Interpretation began by assuming that the first layer below the water layer had a velocity of 3.0 km/sec. Then the 4.96 km/sec line of the Kualapuu recording was paired with the 4.97 km/sec line of Barbers Point. The 6.9 km/sec line was paired with the 6.65 km/sec line. The 8.88 km/sec line was considered to be arrivals from the Mohorovicic discontinuity; no comparable line on the Barbers Point recording could be found to match this. The 17.16 km/sec line is probably a reflection from one of the layers.

Inasmuch as the layers with velocities of 4.97 km/sec and 6.8 km/sec showed no dip or very little dip, it was assumed that at least under line BRAVO the Mohorovicic discontinuity was horizontal. This assumption is justified even from gravity data, which showed that the BRAVO series had run along the strike of the flank of the volcano. This assumption results in a velocity of 8.8 km/sec for the mantle.

Calculations from the travel-time data yielded the following:

Layer	*Velocity* (km/sec)	*Km to Top of Layer*	*Dip*
Water	1.5	0	0°
a	3.0	.45 (average)	
b	4.97	2.6	0°
c	6.8	10	1.1°
d	8.8	21	0°

The section structure deduced from the travel-time curves from the BRAVO series is given in Figure 9.

THE STRUCTURE OF KOOLAU VOLCANO FROM COMPOSITE DATA

When the section structures of the caldera, northwest rift zone, and southern flank were fitted together, the over-all structure of Koolau Volcano shown in Figure 10 was obtained.

Three layers were detected in the northwest rift zone. The unusual feature of a high velocity layer, 7.6–7.7 km/sec, at very shallow depths, should be noted.

An explanation of this phenomenon is that differentiation in the magma chamber under the rift zone separated the magma into a 5.7–6.1 km/sec layer and a 7.6–7.7 km/sec layer. Further investigation with longer refraction traverses should be carried out over the rift zone to determine whether there is another layer with higher velocity under the 7.6–7.7 km/sec layer.

From interpretations of the reflected phase of the GASHOUSE series, Adams and Furumoto (p. 296 in this issue) proposed a magma chamber at a depth between 3 and 4 km. This agrees well with the depth to the 7.6–7.7 km/sec layer which, when extended to the cal-

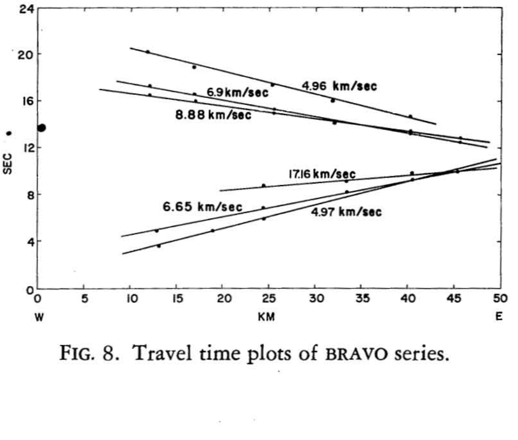

FIG. 8. Travel time plots of BRAVO series.

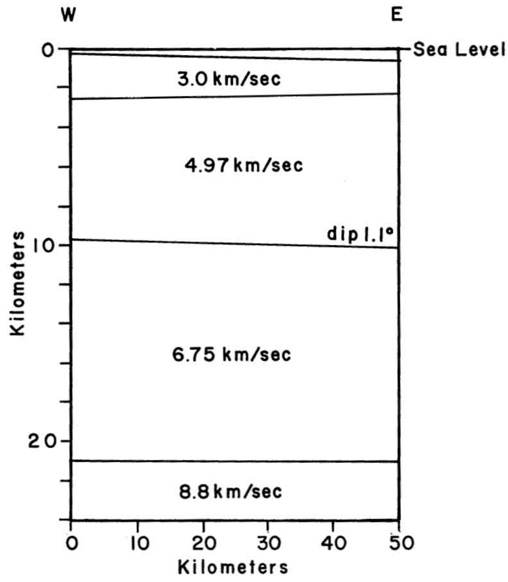

FIG. 9. Section structure on south flank.

dera area, attains a shallow depth of about 4.3 km.

The behavior of the 5.7–6.1 km/sec layer is curious, because it appears clearly in the K-K series but was undetected in the GASHOUSE series. Hence, we have the interpretation that this layer pinches out at the north end of the plug.

The section structures from BRAVO series and GASHOUSE series have been juxtaposed for the southern flank. Because of the disparate character of the two, the grounds for juxtapositioning may not be as firm as those for the rift zone and the plug; but the composite picture fits well with the gravity survey (Strange, Woollard, and Rose, p. 381 in this issue). The depth of 21 km for the Mohorovicic discontinuity for the southern flank is deeper than normal for oceanic areas, but far from startling for volcanic islands. The results of refraction surveys by the U.S. Geological Survey show that along

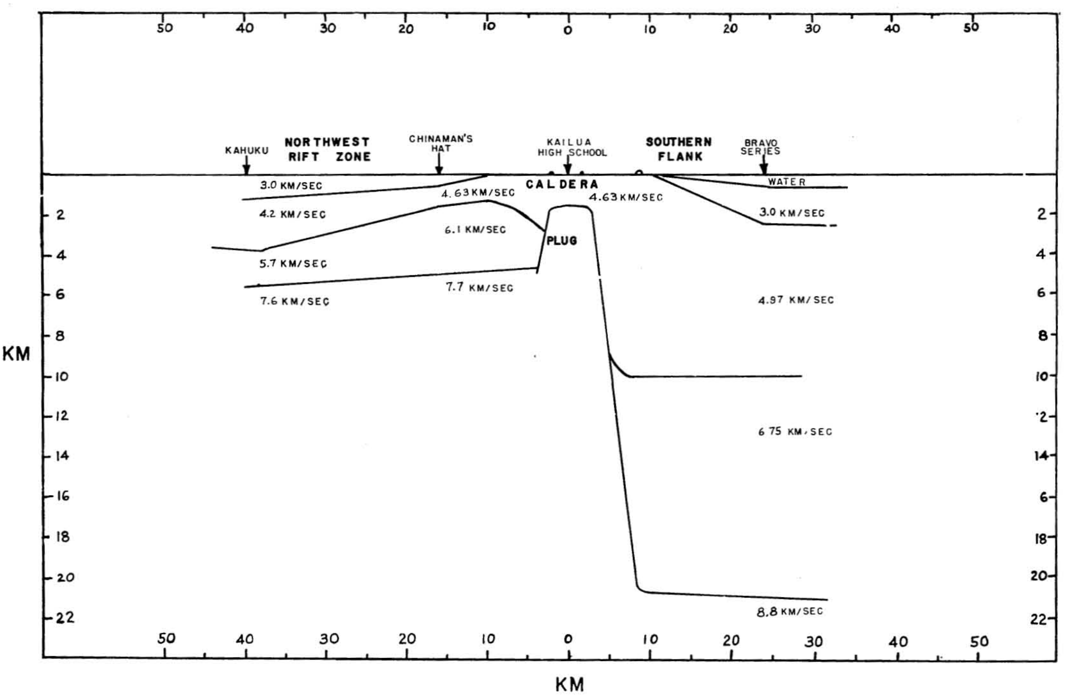

FIG. 10. Section structure of Koolau Volcano from composite seismic refraction data.

the western shore of the island of Hawaii the Mohorovicic discontinuity is at a depth of about 16 km (D. Hill, 1964, personal communication).

An interesting product of the study is the existence of high velocity materials at shallow depths in the rift zone and in the plug of the volcano. The value of 7.7 km/sec is close to the arbitrary value of 7.8 km/sec assigned to mantle material. It can be conjectured that mantle material has risen through the plug and rift zone to shallow places. It can also be postulated that differentiation in magma chambers caused denser material with higher seismic velocity to settle out. But all these are conjectures which can be resolved only by analysis of actual samples obtained by drilling in the rift zone and plug, or by drilling to depths considered to be the normal mantle.

CONCLUSIONS AND ACKNOWLEDGMENTS

The seismic refraction project carried out over the Koolau Volcano yielded an over-all picture of the subsurface structure that fits well with gravity and magnetic data. Materials of unusually high velocity at shallow depths were found in the plug and rift zone. This may very well be the first time that quantitative values for the internal structure of a volcano have ever been published.

Further investigations by seismic techniques are recommended, especially on the eastern flank and the southeast rift zone.

The authors thank the numerous staff members and graduate students of the Hawaii Institute of Geophysics who participated in carrying out the difficult field work of the project.

The study was carried out under the auspices of the National Science Foundation through Grant GP-2257.

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