Seismic Studies of Subsurface Structure in the Ewa Coastal Plain, Oahu, Hawaii[1]

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ABSTRACT: Seismic studies using well-logging, refraction, and reflection methods were carried out in 1965 in conjunction with a core-sample drilling project in the Ewa Coastal Plain, Oahu, Hawaii. The seismic well-logging technique gave a complicated velocity-depth profile, with higher velocities associated with reef limestone and lower velocities associated with mud deposits. The seismic refraction method showed a simpler velocity-depth profile with only a few distinct layers. The seismic reflection method corroborated the simpler profile obtained with the refraction method. The two profiles were reconciled, as the complicated profile can be averaged out into the simpler profile.

The averaging-out process can be applied to the whole sedimentary column so that a P-wave velocity value may represent the sedimentary layer at any given locality. However, no single value can be assigned as typical for sedimentary layers for the entire Hawaiian area. The velocity values depend upon the composition of the layer, which is made up of varying proportions of mud, reef limestone, and weathered basalt.

Layer 2 of the oceanic crust in the Hawaiian area has a rather uniform character, with seismic velocities ranging from 4.8 to 5.1 km/sec, and thicknesses from 4 to 8 km.

BECAUSE STUDIES to date of the upper crust in the Central Pacific Basin have been largely geophysical in nature, actual samples of the crust were needed to correlate published geophysical data with suggested lithologic and stratigraphic interpretations. With this objective in mind, drilling projects to recover core samples were carried out in 1965 in the Ewa Coastal Plain on the island of Oahu, Hawaii. Following the drilling, and after the stratigraphy was roughly determined, seismic well-logging and seismic refraction were conducted in the vicinity of the holes to correlate seismic parameters with the drilling data. This paper deals with the results of the seismic work.

The Ewa Plain was chosen for the drilling project because it is the widest coastal plain on any island in the Central Pacific Basin. Stearns and Chamberlain (1967) have reported preliminary results of the drilling and descriptions of core samples, and Resig (1969) has reported the paleontology of the core samples. Early results from a similar drilling project carried out on Midway Islands have been reported by Ladd, Tracey, and Gross (1967).

The seismic program was conducted in four stages: (1) acoustic logging of the well designated as Ewa I (see Fig. 1), (2) an east-west seismic refraction traverse of about 1,800 meters (about 5,900 feet) in the vicinity of Ewa I, (3) two seismic refraction traverses at sea off the Ewa Coastal Plain, and (4) seismic reflection probing at the Ewa I site.

FIELD WORK

1. *Well Logging*

The logging instrumentation for Ewa I Well was rather simple, consisting of a 12.5-Hz vertical geophone attached to a strong two-conductor cable and made water-tight. The cable, marked at 100-foot intervals, acted both as signal conductor and as support for the geophone. The geophone was lowered manually into the well at intervals of 100 feet. After each

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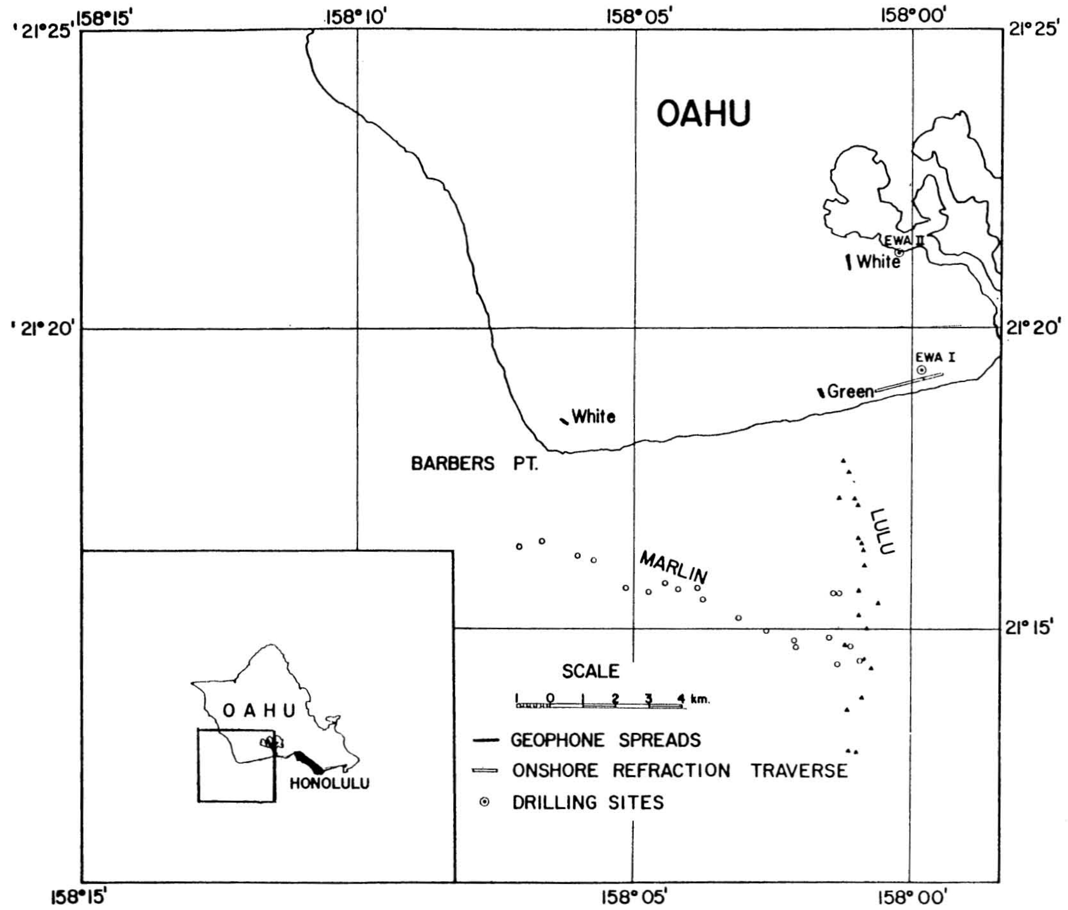

FIG. 1. The Ewa Coastal Plain, Oahu, Hawaii, and the adjacent sea. The black triangles are the shot points for refraction traverse Line LULU; the circles are shot points for Line MARLIN.

incremental lowering, time was allowed for the cable and geophone vibrations to die away before seismic recording was attempted.

The amplifiers used in the recording instrument were the conventional types commonly used in refraction or reflection work, and several recordings were made at each depth with different gain and filter settings. The recorder, a two-channel, hot-pen, visual type, was operated at its maximum speed of 100 mm/sec. This speed is not quite satisfactory for the work, but the signal arrival times were read to an accuracy of ± 2 milliseconds.

As a seismic source, the ground was pounded with a sledge hammer for recordings down to a depth of 500 feet. For greater depths, explosives were used, ranging from blasting caps and boosters to one pound of nitrocarbonitrate, the latter for recordings at 1,000 and 1,100 feet. For recording the instant of the seismic source, a 4-Hz vertical geophone was placed on the ground surface and as near as possible to the hammer impact or explosive source.

Recordings were made both while lowering the geophone and while raising it. The data from the two sets of measurements were in good agreement.

2. *Onshore Short-Range Seismic Refraction Profile*

In the second stage, a seismic refraction traverse using closely spaced geophones was attempted close to the site of Ewa I Well. The area near the well is rather heavily populated and the only location for which permission could be obtained to use explosives. A shot hole was punched through the coral bedding about 15 meters due west of the well. A split profile was attempted by laying out geophone spreads along the paved street that ran in a generally east-west direction paralleling the shore line. The traverse is shown as "onshore refraction traverse" in Figure 1. The eastern segment of the split profile was terminated at 250 meters at the boundary of a military reservation. The western segment went out to 1,600 meters where signals became too weak to be detected. The shot size had to be limited to one pound of nitrocarbonitrate in order to avoid complaints from residents of the area.

Vertical geophones of natural frequency 4 Hz were used in the spread. Conventional exploration-type seismic amplifiers were used, and recording was done on photographic oscillographs. The explosives were detonated electrically. The shot box was coupled to a transmitter, so that a 600-Hz tone was terminated at the instant the shot went off. The 600-Hz tone was recorded on the photographic oscillograph.

The distances from the shot point to the geophones were measured by surveyor's chains. Terrain correction was not necessary because the area was essentially flat. Weathering correction was unnecessary since at most there was only a foot of top soil overlying the coralline limestone.

3. *Offshore Marine Seismic Refraction*

In the third stage, two marine seismic refraction traverses up to 14 km were planned offshore from the Ewa Plain: Line LULU ran north-south, and Line MARLIN ran northwest-southeast (see Fig. 1). Stationary recording units (GREEN and WHITE in Fig. 1) were set up on land. A chartered ship (codename DOGHOUSE) equipped with recording hydrophones was stationed at the seaward end of the lines. Ship positions have not been indicated on the map, as they varied from time to time due to drifting.

The research vessel "Teritu" of the University of Hawaii was used as the shooting ship. Charges of up to 100 pounds of nitrocarbonitrate were suspended from floats by 50-foot lengths of rope and were detonated electrically. Transit parties on land located the shot points as the explosions revealed their locations by visible water spouts. The distances between the shot points and the recording vessel (DOGHOUSE) were then determined by recording the arrival time of acoustic water waves, the velocity for which was taken as 1.50 km/sec.

For the stationary spreads on land, the recording instruments were the same as those used in stage two. For the recording vessel at sea, a hydrophone was suspended at a depth of 200 feet from a surface float. Machinery noise was at a minimum because the ship was a sailing vessel, and the noise resulting from dragging the hydrophone through the water was eliminated by slackening the hydrophone cable at shot times. Recording on the vessel was done by photographic oscillographs.

4. *Seismic Reflection Measurements Near Ewa I Well*

Six months after stage three was complete, seismic reflection measurements were made near Ewa I Well as the fourth stage of the study. The objective of this stage was not to delineate further the subsurface profile, which was already known from the results of stages one to three, but to find out whether seismic reflection technique was feasible with the relatively unsophisticated recorder available to us. The recording instruments were the same as those used in the refraction work. To compensate for the lack of a tape recorder, shots were fired repeatedly at one spot, and for each firing the filter settings in the amplifiers were varied. Altogether 23 shots were fired.

The geophone spread is shown in Figure 2. There were three geophones in a cluster at each of the numbered positions. The positions were about 50 feet apart. For each channel of recording, three geophones were connected in series to cancel out ground roll; that is, one geophone from position 6, another from position 5, and another from position 3 were connected in series and funneled into one amplifier.

DATA AND INTERPRETATION

Well-Logging and Onshore Refraction

The plot of travel time versus depth from the well-logging work is given in Figure 3. As

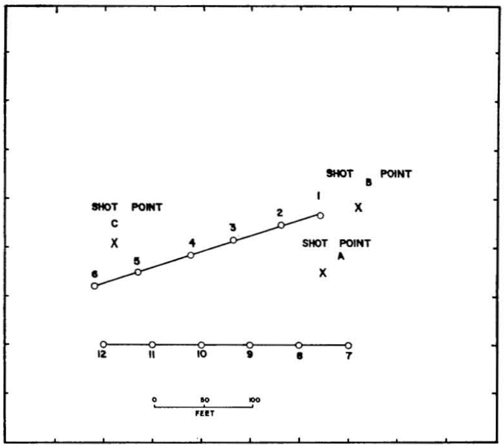

FIG. 2. Layout of geophone clusters for seismic reflection profiling.

mentioned, the data are accurate to ±2 milliseconds, and multiple recordings were made at each depth to confirm the signals.

The travel-time plot of the onshore seismic refraction traverse near the well site is given in Figure 4. The plot is rather straightforward. Unfortunately, however, the geography ruled out the possibility of a reversed profile and shortened one end of the split profile. By assuming horizontal plane layers, the velocity-depth profile was calculated from the travel-time plot.

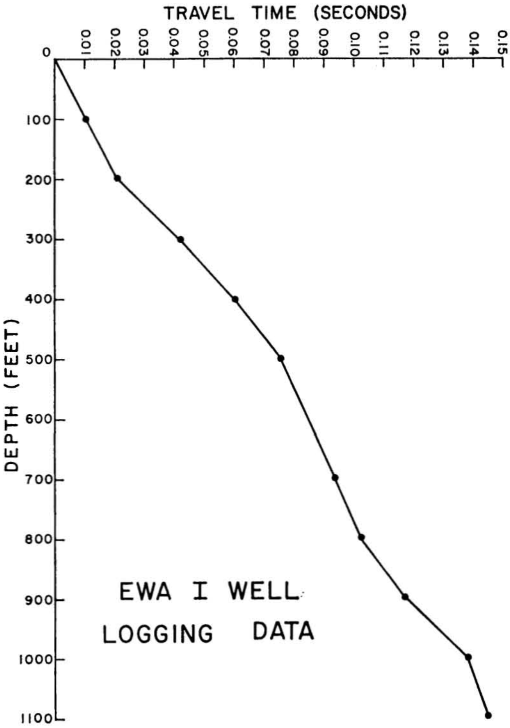

FIG. 3. Travel-time plots from well-logging data.

Given in Figure 5 are the velocity-depth profiles from the well-logging and seismic refraction work. The stratigraphy as inferred by Resig (1969) from the drilling samples has been placed alongside the profiles for comparison.

At first glance, the velocity-depth profile obtained by well logging seems to differ greatly from that by refraction. However, simple calculation shows that the average of the well-logging velocities from the surface down to the 500-foot depth is 2.3 km/sec, and that for the 500- to 1,000-foot depth is 2.8 km/sec. These average values agree well with the respective average values of 2.1 km/sec and 2.8 km/sec obtained by the refraction method. The refraction technique gives average velocities while well logging brings out smaller structure.

Comparison of the well-logging profile with stratigraphic data reveals that the higher velocities of 3.0 km/sec for the layer between 0- and 200-foot depths and of 3.6 km/sec for the layer between 500- and 700-foot depths are associated with reef limestone. In the stratigraphic column the depth interval between 270 feet and 350 feet also appears to represent limestone; but well logging indicates an average velocity of 1.7 km/sec. Stearns and Chamberlain (1967) described this section of the stratigraphic column as muddy limestone, with mud filling the interstices. We noticed that the other sections having low velocities, such as the section between 200 and 300 feet with a velocity of 1.3 km/sec and that between 900 and 1,000 feet with a velocity of 1.5 km/sec, were also described as mud by Stearns and Chamberlain. On the other hand, mud was infrequently mentioned for those sections with the higher velocities of 3.0 or 3.6 km/sec.

A qualitative correlation of seismic velocity with lithology emerges from the data. Higher velocities in the range of 3.0 to 3.6 km/sec represent reef limestone; lower velocities, approach-

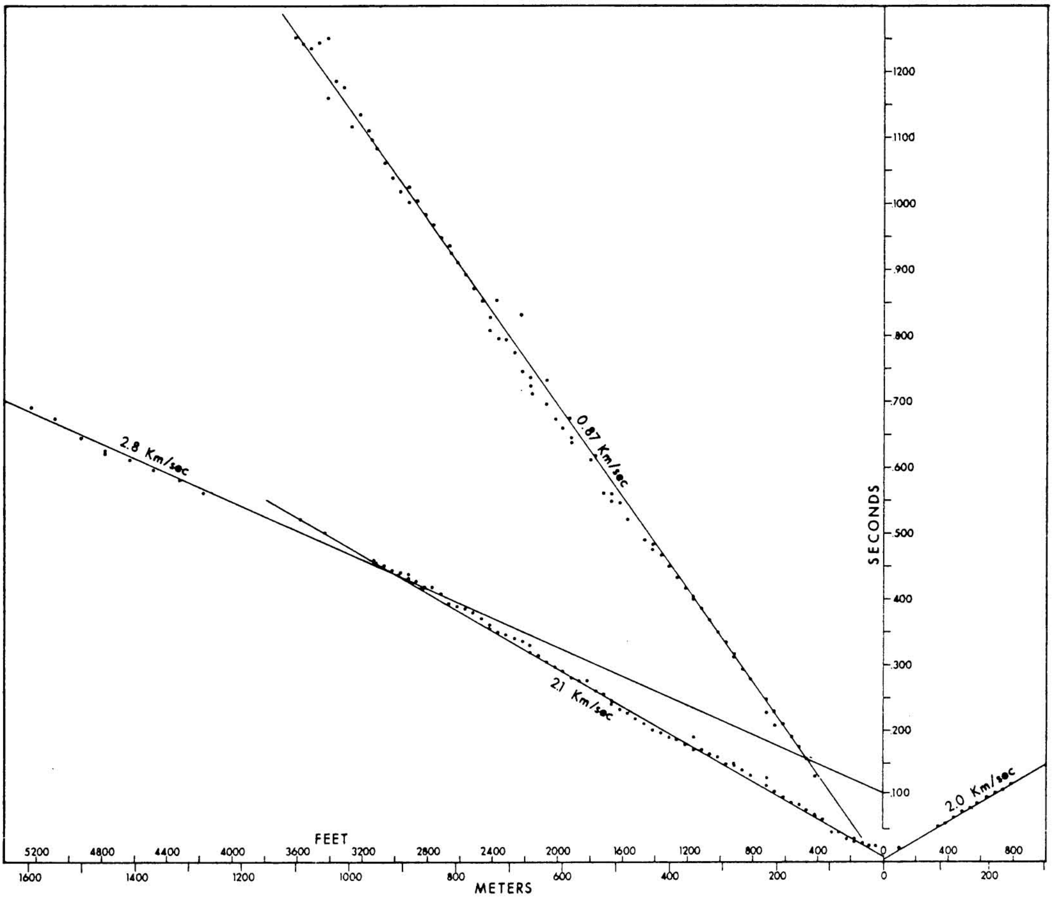

FIG. 4. Travel-time plots for onshore seismic refraction traverse alongside Ewa I Well.

ing that of seawater (1.5 km/sec), represent mud. Intermediate values represent those sections where reef limestone and mud are intermixed. The high value of 4.6 km/sec for the deep section is associated with basalt. This value agrees with refraction data as obtained in stage three of the present work.

Marine Seismic Refraction Offshore

The travel-time plots of the marine seismic refraction traverse carried out offshore from the Ewa Plain are given in Figures 6 and 7. Corrections for water depth were made by substituting for the water a layer having a seismic velocity of 2.4 km/sec, which may be considered an average of the 2.1 and 2.8 km/sec values obtained from the onshore refraction line.

The calculation of the velocity-depth profiles was rather straightforward. The results are given in Figures 8A and 8B. Line LULU shows a 2.4-km/sec layer underlain by a 4.0-km/sec layer. Line MARLIN revealed three layers; a 2.3-km/sec layer, a 4.0-km/sec layer, and a lower 5.1-km/sec layer. The interfaces between the layers generally slope downward toward the sea.

The 2.3- to 2.4-km/sec layer of both traverses can be identified with the sedimentary column as probed by Ewa I Well and as profiled by the onshore refraction line. In fact, averaging out the onshore refraction data gives a velocity value of 2.4 km/sec for the whole sedimentary layer.

The 4.0-km/sec layer and the 5.1-km/sec

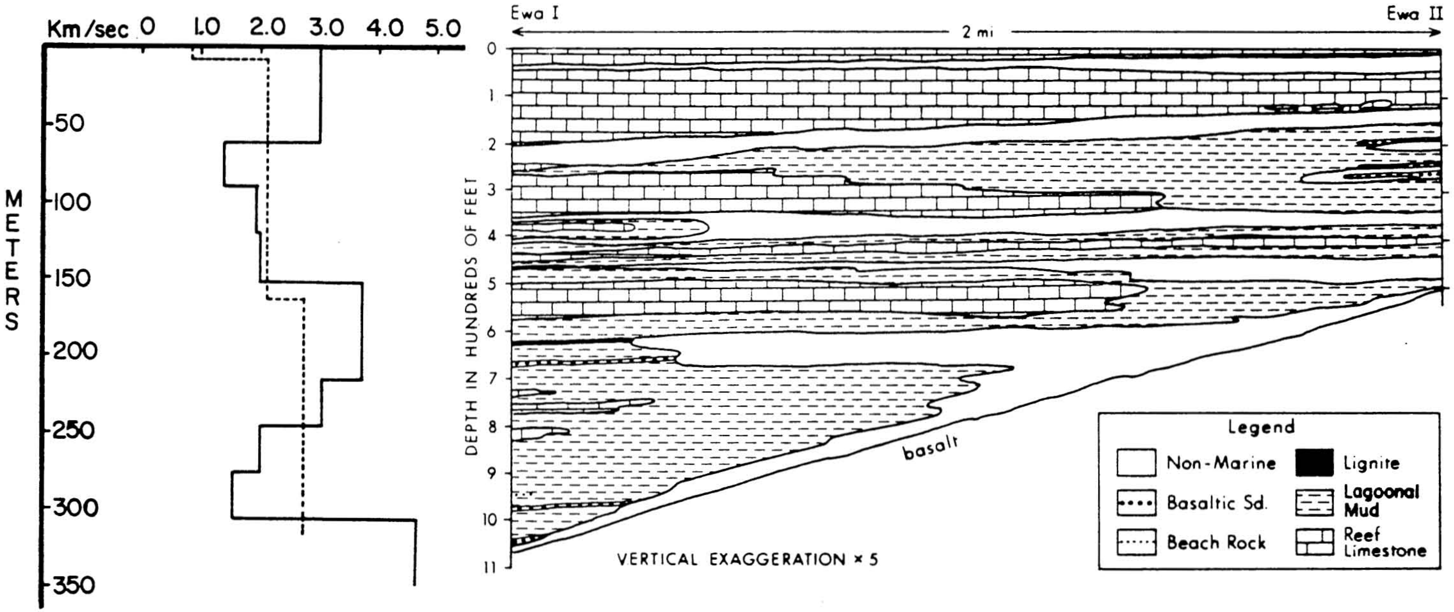

FIG. 5. Velocity-depth profiles and geological column by Resig (1969). The solid line represents velocity-depth profile by well logging; the dotted line, that by seismic refraction.

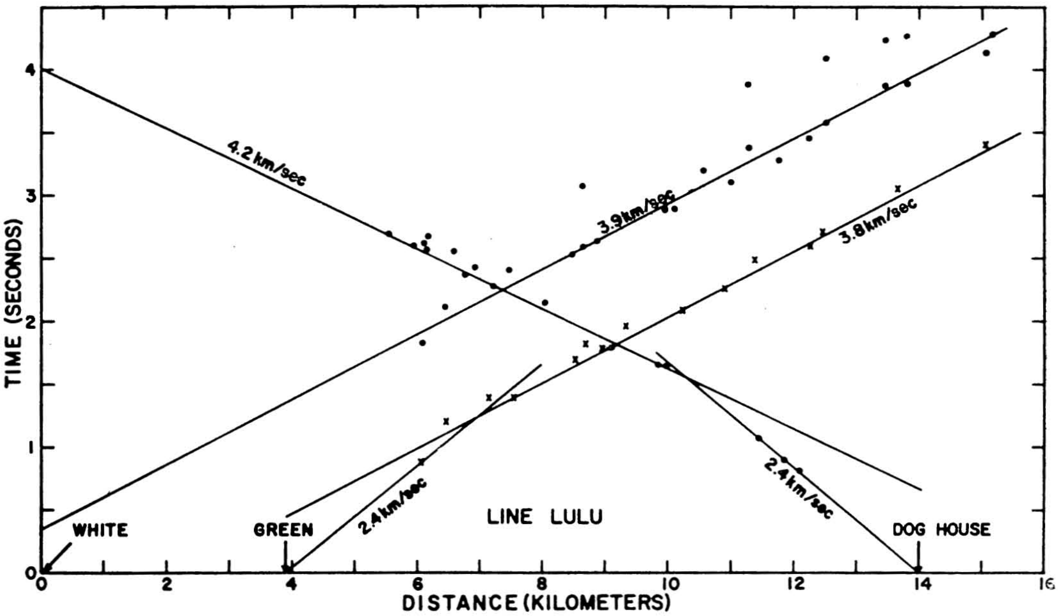

FIG. 6. Travel-time plot of Line LULU.

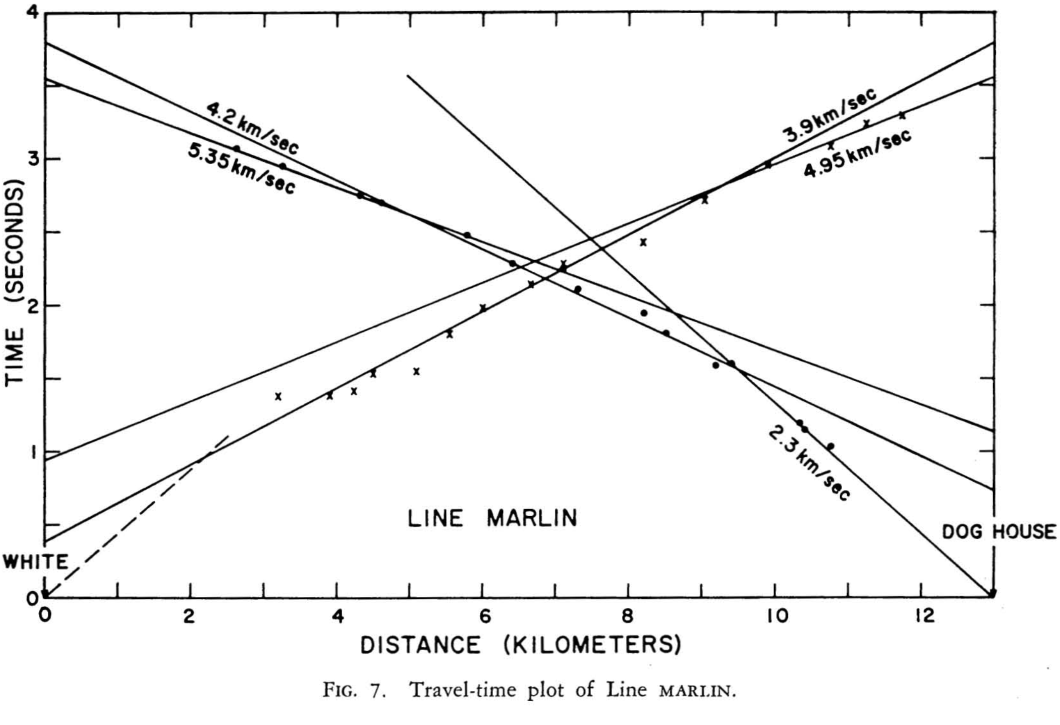

FIG. 7. Travel-time plot of Line MARLIN.

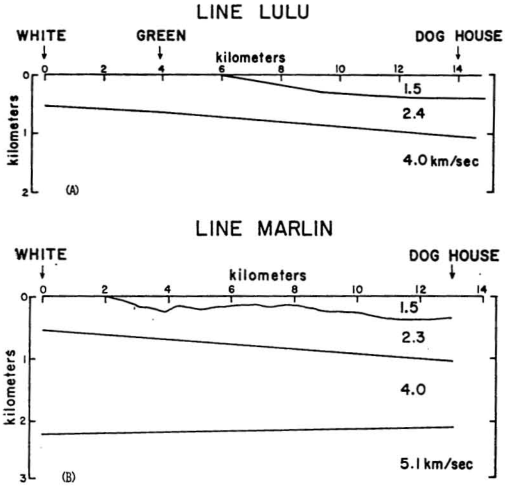

FIG. 8. The section structure offshore from Ewa Plain, as revealed by (*A*) Line LULU and (*B*) Line MARLIN.

layer will be discussed in detail later in this paper.

Reflection Measurements

The reflection seismograms from shots 3 and 23 are given in Figures 9A and 9B. These are the best ones from the series. There were five distinct signals discernible from the various seismograms. The signals varied in quality from seismogram to seismogram; however, the range in arrival times is given in Table 1.

To account for the arrivals in terms of reflected signals, travel times were calculated by using the profile structure as derived from the onshore seismic refraction data. The results of the simple calculations are illustrated in Figure 10. The seismic refraction profile had placed a discontinuity at the 560-foot depth and drilling had placed the top of the basaltic layer at the 1,077-foot depth. With the velocities obtained from refraction data, most of the arrivals in the reflection measurements can be accounted for. Arrival No. 1 is due to reflection from the basaltic layer; Arrival No. 2 cannot be accounted for; Arrival No. 3 is due to a reflection at the interface between the 560-foot depth and the basaltic layer; and Arrival No. 4 is due to double reflection from the basaltic layer. As for Arrival No. 5, if we assume that it is a single reflection from a deeper layer, the reflecting boundary will have to be placed at a depth of 1.5 km (Fig. 10). We have not been able to correlate this reflector with layers defined in the refraction profiles.

DISCUSSION

We will consider first the subsurface structure of the area in the vicinity of Ewa I Well. The onshore refraction survey showed the sedimentary column to be made up of at least three layers: (1) a superficial layer with a velocity of 0.87 km/sec; (2) an intermediate layer, of 2.1 km/sec; and (3) a lower layer, of 2.8 km/sec. The superficial layer was not detected by well-logging methods, probably because it was too thin. Because the velocity of the layer is lower than that of water, we inferred that the layer is made up of loose material above the water table. There must have been a channeling effect of the acoustic signals in the layer, for the seismic signals persisted even at great distances when arrivals from other layers were beginning to fade out. Because the superficial layer is so thin and less significant than the other two layers, it will not be discussed further.

The differences between the well-logging profile and the onshore refraction profile have been pointed out, and reconciliation of the differences by an averaging process is proposed. This explanation can be considered satisfactory as it can be justified on a quantitative basis.

The averaging-out process can also be extended to the results of the offshore refraction lines, LULU and MARLIN. The offshore work gave a value of 2.4 km/sec as the velocity of the sedimentary layer, while the onshore refraction showed the sedimentary layer to be composed of two thinner layers with values of 2.1 and 2.8 km/sec. Again, if we average out the values 2.1 and 2.8, with appropriate weights according to layer thickness, we obtain the value 2.4.

The process of averaging out velocities leads to an interesting conclusion. When a refraction survey is carried out with large-scale explosives and widely spaced shots, the resolving power (i.e., the ability to discriminate and detect the various layers) is limited and rather coarse. The result is a simple velocity-depth profile with one layer, or only a few layers at most. The

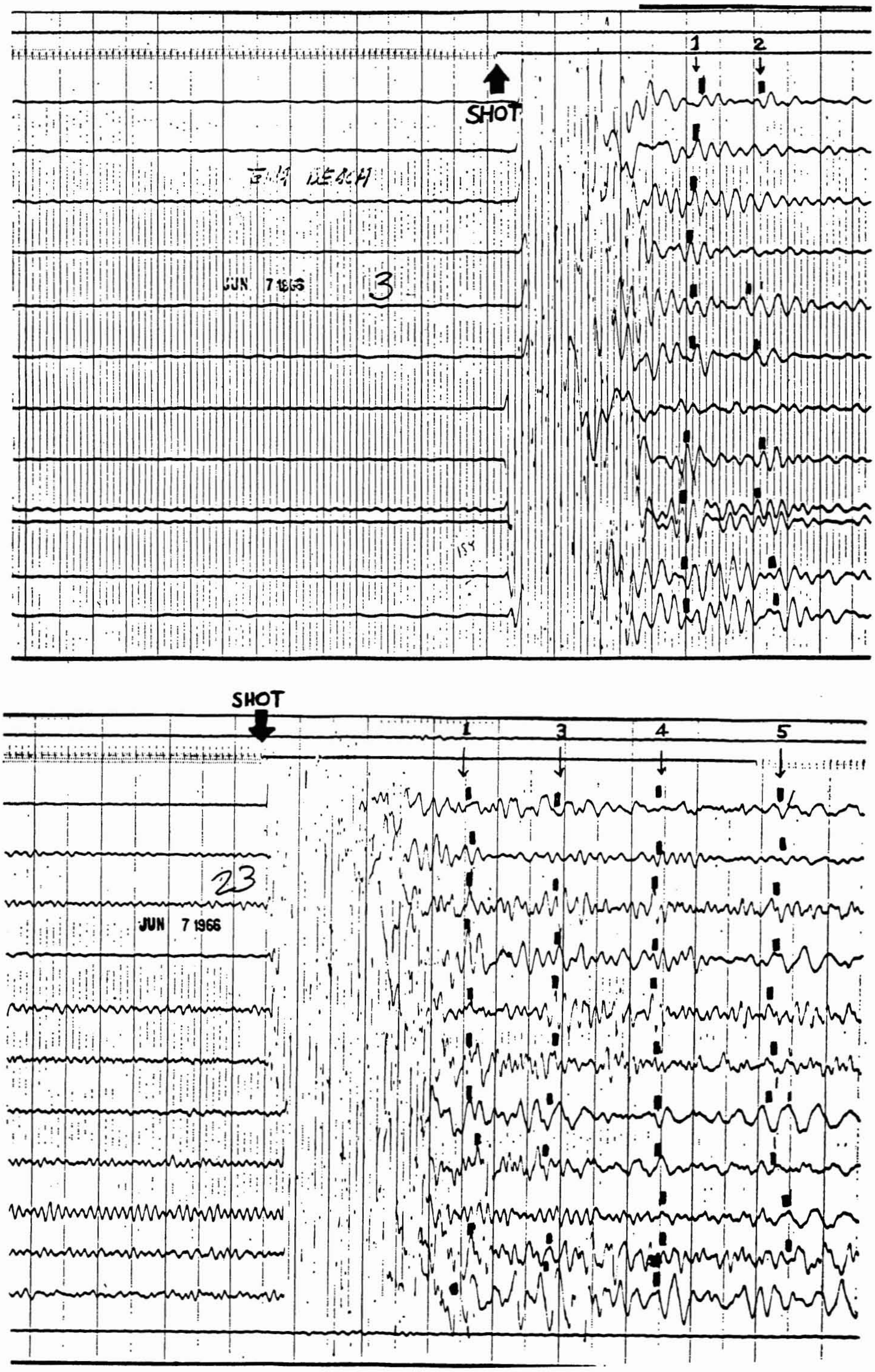

FIG. 9. Seismograms from reflection shots 3 (*upper*) and 23 (*lower*).

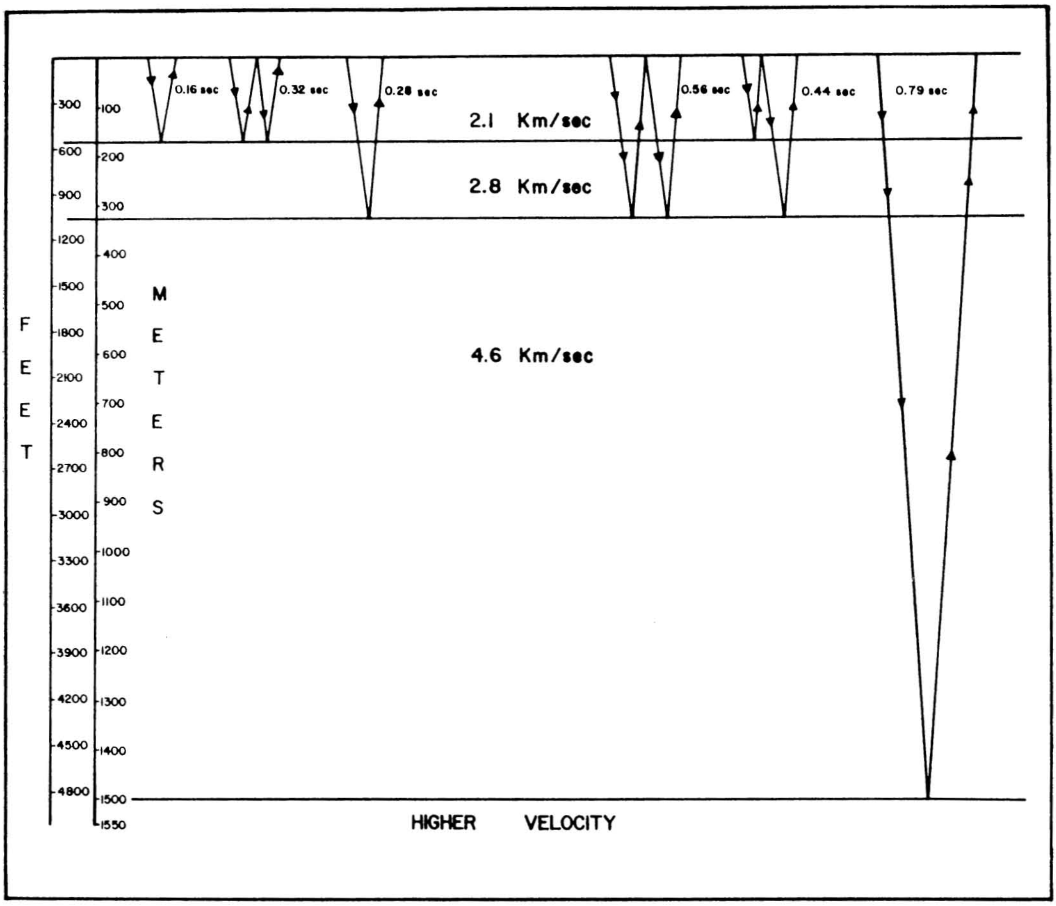

FIG. 10. Computed ray paths for various reflected signals.

resolving power can be refined by using smaller-scale explosives and by closer spacing of the shots or geophones. The resolution is further increased by resorting to well-logging techniques. As the resolving power of the seismic work is increased, a more complicated velocity-depth profile results. The complicated profile at first glance may not resemble the simple profile obtained by using coarser methods. However, when the complicated profile is averaged out with proper weights assigned to the velocities, the result will agree fairly well with the simpler profile. A sedimentary column made up of alternating layers of reef limestone, mud, and basaltic fragments, as in the case of the Ewa Plain, can be averaged out and represented by a single velocity. For the Ewa Plain, the resultant velocity works out to be 2.4 km/sec. In all probability, we can apply the averaging-out process to other areas as well, and obtain resultant velocities for the sedimentary layers there. However, the resultant velocity will have different values at different places. The value 2.4 km/sec is characteristic of the Ewa Plain, but not necessarily of the other places. This has been shown in numerous published refraction surveys carried out in the Hawaiian Islands.

TABLE 1

REFLECTION-SIGNAL ARRIVAL TIMES

ARRIVAL NUMBER	TIME (seconds)
1	0.27–0.31
2	0.38–0.40
3	0.43–0.44
4	0.59–0.62
5	0.77–0.81

In Figure 11 are shown some of the representative results of seismic refraction profiles obtained onshore and on the shelf around the major islands of Hawaii. We have not included surveys carried out in the deep water. The profiles for East Maui and West Maui were obtained by Shor and Pollard (1964), those for Hilo and Ka Lae by Ryall and Bennett (1968), and those for Hawi, Cape Kumukahi, Hilina Pali, and Napoopoo by Hill (1969). The results for Penguin Banks, Diamond Head, Barbers Point, West Lanai, Kahuku, and Makapuu are from previous HIG surveys (Furumoto, 1967; Furumoto et al., 1965, 1968).

The refraction traverses from which were derived the profiles in Figure 11 were long, and all were carried out by setting stationary recording stations at the ends of the traverses and setting off explosives in a line between the recording stations. The velocity-depth profiles represent the subsurface structure obtained for the area directly under the recording stations. The only exception is the profile off Diamond Head—it represents the section at about the center of a 60-km traverse. Hence these velocity-depth profiles are straightforward calculations by the investigators from their data, with a minimum of extrapolation and projection.

In the velocity-depth profiles of Figure 11, the values marked with asterisks have been assumed by the various investigators. If we discount assumed values and consider only observed values, we find that the highest velocity obtained for the sedimentary layer is 3.0 km/sec at Kahuku, and the lowest, the 2.1 km/sec obtained at the Ewa Plain in our present study. It is evident from such a range in values that there is no typical value for the resultant velocity of the sedimentary layer. As the sedimentary layer is made up of thinner layers with velocities ranging from 1.3 km/sec to 3.6 km/sec, the resultant velocity at any one locality will depend upon the proportion of low-velocity to high-velocity material there. As is known, the proportion is not everywhere uniform; in the Ewa Plain, reef limestone is abundant, but in other coastal areas the reef layer can be rather thin.

Although no value can be selected as the typical velocity for the sedimentary layer, one must often assume a value to process some types of refraction data. This is true in cases where the shot points are widely spaced. In a number of his traverses, Hill (1969) was forced to assume values for the sedimentary layer. In such cases, a judicious choice can be made by considering the geology of the area in question.

TABLE 2

AVERAGE OCEANIC CRUST VELOCITIES ACCORDING TO RAITT (1963)

LAYER	VELOCITY (km/sec)	THICKNESS (km)
1	—	—
2	5.07 ± 0.63	1.71 ± 0.75
3	6.69 ± 0.26	4.86 ± 1.42
4	8.13 ± 0.24	—

The layers beneath the sedimentary layer will now be discussed. But before doing so, to avoid confusion, we will establish some working definitions. It has been the custom to name oceanic crustal layers according to numbers. Raitt (1963) has assigned velocity values to these layers (see Table 2). We shall extend Raitt's convention to the Hawaiian area on the grounds that layers corresponding to Layers 2 and 3 are found in the area. However, modifications are necessary for our classification as the Hawaiian area is not strictly an oceanic area as defined by Raitt. The velocity range of the layers applicable to the Hawaiian area is given in Table 3. Raitt did not assign velocity values to Layer 1, but it is usually considered to be an unconsolidated sedimentary layer (Hill, 1957).

For the Hawaiian area we acknowledge that there are two layers above Layer 2. Layer A contains sediments, reef material, and derivatives of basalts, such as mud. Layer B is a basaltic

TABLE 3

VELOCITY RANGE OBTAINED FOR THE CRUST IN THE HAWAIIAN AREA

LAYER	VELOCITY (km/sec)
A	1.5–3.5
B	3.5–4.2
2	4.5–5.7
3	6.0–7.1
3L	6.9–7.5
4 (mantle)	7.8–8.6

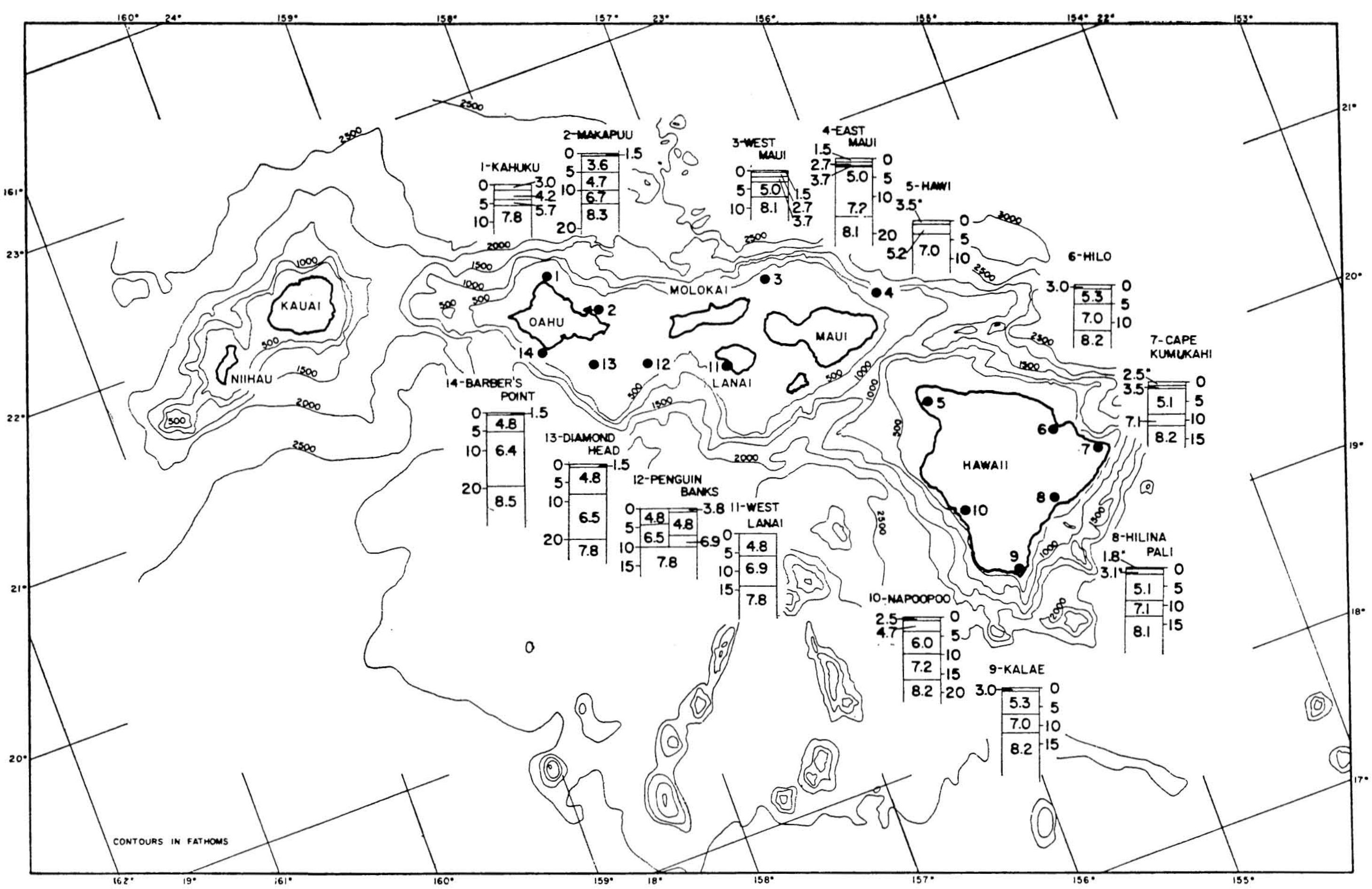

FIG. 11. Composite picture of seismic refraction results on and around the major islands of the Hawaiian Archipelago. The velocity values are in kilometers per second and depths are in kilometers. Bathymetry contours are in fathoms. Results for East and West Maui are by Shor and Pollard (1964), those for Hilo and Ka Lae by Ryall and Bennett (1968), those for Hawi, Cape Kumakahi, Hilina Pali, and Napoopoo by Hill (1969).

layer, but its velocity is definitely different from that of Layer 2. In Line MARLIN, the distinctions among Layers A, B, and 2 were quite definite.

We also make a distinction in the lower crustal layers in the Hawaiian area. We recognize that for the Hawaiian area, especially in the oceanic parts, a distinct layer with a velocity higher than that for Layer 3 has been detected below Layer 3 and above the Mohorovicic discontinuity. We shall name this high-velocity layer, Layer 3L. However, a lengthy discussion of Layer 3L is not within the scope of this paper, which is devoted to the upper layers.

In some instances the values overlap, not necessarily causing confusion; for example, when Layer A and Layer B were detected, as was the case for Lines LULU and MARLIN, the distinction was quite clear.

Consider for the moment the layer beneath the sedimentary layer, which we have named Layer B. Lines LULU and MARLIN both give a value of 4.0 km/sec; the well logging gives a value of 4.6 km/sec. From Figure 6, the stepout time between stations GREEN and WHITE in Line LULU gives a velocity of 4.3 km/sec for Layer B, which agrees with the velocity recorded by Station DOGHOUSE. The value of 4.6 km/sec from well logging may have been in error, for the geophone may have become lodged in the hole while being lowered. The value of 4.6 km/sec was obtained from the deepest lowering of the geophone. In all the other positions, recordings were made while the geophone was being lowered and while it was being raised. The arrival times agreed in both instances. But for the deepest position, this method of checking was not available, and the possibility remains that the geophone may have become obstructed part way down.

We shall take the value of 4.0 km/sec as the velocity for Layer B at Ewa. The layer is made up of basalt lava flows—as we have seen from the drilling samples at Ewa I Well and at Ewa II Well (Stearns and Chamberlain, 1967; Resig, 1969). This value may seem low for the basalt layer, but it can be easily explained. In the Hawaiian Islands, layers of solid lava flows alternate with layers of soft clinker material or weathered material (Stearns and Vaksvik, 1935). This phenomenon of alternating layers is visible even to a casual observer in many road cuts in the islands. The velocity of the solid basalt may be higher, say 4.35 km/sec and above (Manghnani and Woollard, 1968), but the softer layers between the solid flows tend to lower the resultant velocity.

Let us now consider the properties of Layer 2. In Figure 11, the velocity of Layer 2 for the Hawaiian Islands is shown to vary from 4.7 km/sec to 5.3 km/sec except at Kahuku. We consider the values at Kahuku to be anomalous, as refraction measurements were deliberately made over a zone of intrusive material known as the Koolau Rift Zone. In regard to thickness, Layer 2 varies from 4 to 8 km, except at Hawi where Hill's (1969) measurement indicates that it may be as thin as 2 km. The thickness of Layer 2 in the Hawaiian Islands is much greater than that reported by Raitt (1963) for the average oceanic crust (cf. Table 1). On the whole, Layer 2 in the Hawaiian Islands appears rather uniform—a velocity range of 4.7 to 5.3 km/sec and a thickness of 4 to 8 km, except at Hawi.

We wish to point out another feature evident in Figure 11. The velocity for Layer 3 is greater than 6.7 km/sec if the crust is thinner than 15 km, and less than 6.5 km/sec if the crust is thicker than 15 km. We have limited this paper to discussion of the shallower layers, however, and will discuss Layers 3 and 3L in a future paper, at which time we will present more data on these layers.

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