

Seismic Refraction Studies of the Crustal Structure of the Hawaiian Archipelago¹

AUGUSTINE S. FURUMOTO and GEORGE P. WOOLLARD

IN RECENT YEARS several seismic refraction studies have been made of the crustal structure in and near the Hawaiian Islands. Earlier investigators were Raitt (1956) and Shor (1960). A crustal analysis of earthquake travel time was made by Eaton (1962). Shor and Pollard (1964) made refraction studies to the north of the island of Maui in connection with Mohole site selection investigations. Results of recent refraction studies over the Koolau volcano on the island of Oahu are reported in other papers in this issue (Furumoto et al., p. 306; Adams and Furumoto, p. 296). Some unpublished results include those from the seismic refraction survey made in 1963 by Western Geophysical Company, over the area as outlined by Shor and Pollard, that showed a subnormal depth to the mantle, and from the refraction surveys conducted by the U.S. Geological Survey across the island of Hawaii during the summers of 1963 and 1964. Of these, the authors had access to the results obtained by Western Geophysical Company and, through verbal communication with D. Hill, to those of the Geological Survey.

Because seismic results can best be considered in terms of their location, they will be divided on the basis of their geomorphic associations. Three crustal and geomorphic provinces are represented: the Hawaiian Arch, the Hawaiian Deep, and the Hawaiian Ridge. The locations of the measurements relative to these three features are shown in Figure 1, along with depth to bottom and depth to mantle. The recording stations of the refraction surveys are designated by numbers or letters in Figure 1. Two numbers are listed next to the station designation; the upper number gives the depth to the ocean bottom, and the lower the depth to the Moho discontinuity.

THE HAWAIIAN ARCH

The Hawaiian Arch is a broad topographic feature lying to the north of the Hawaiian Ridge and separated from it by the north Hawaiian Deep or Trench.

Shor and Pollard (1964) found that over the Hawaiian Arch the average depth to the Moho is 10.4 km. At one location (Station 29 of Fig. 1) the depth to the Moho was as shallow as 9 km. These workers claim an accuracy of ± 0.5 km for their depth estimates. The repeat studies in the same area by Western Geophysical Company and a reanalysis of Shor and Pollard's data by the National Science Foundation confirm these results in general. The new data and the reanalysis show that the average depth to the mantle in this area is 10 km. The structure of the crust in the area is defined by four distinct layers having the following velocity values: Layer *a*, 2.15 km/sec; layer *b*, 4.20 km/sec; layer *c*, 5.56–6.41 km/sec; layer *d*, 6.82–7.01 km/sec.

The underlying mantle has a velocity of 7.97–8.68 km/sec, which appears to vary according to azimuth. East–west oriented measurements have a higher velocity than those oriented north–south. This suggestion of anisotropy is definitely established in one section where cross-oriented measurements show a velocity of 8.1 km/sec in a north–south direction, and of 8.7 km/sec in an east–west direction. As all the measurements were reversed to obtain true velocity values, anisotropy appears to be well established. On the basis of the combined studies of the Western Geophysical Company and Shor and Pollard, a site for a potential drill hole to the mantle was designated at approximately 22°22'N and 155°28'W. The site, as seen in Figure 1, lies on the southern flank of the Hawaiian Arch at a location where the depth of water is about 2380 fathoms (4350

¹Hawaii Institute of Geophysics Contribution No. 91.

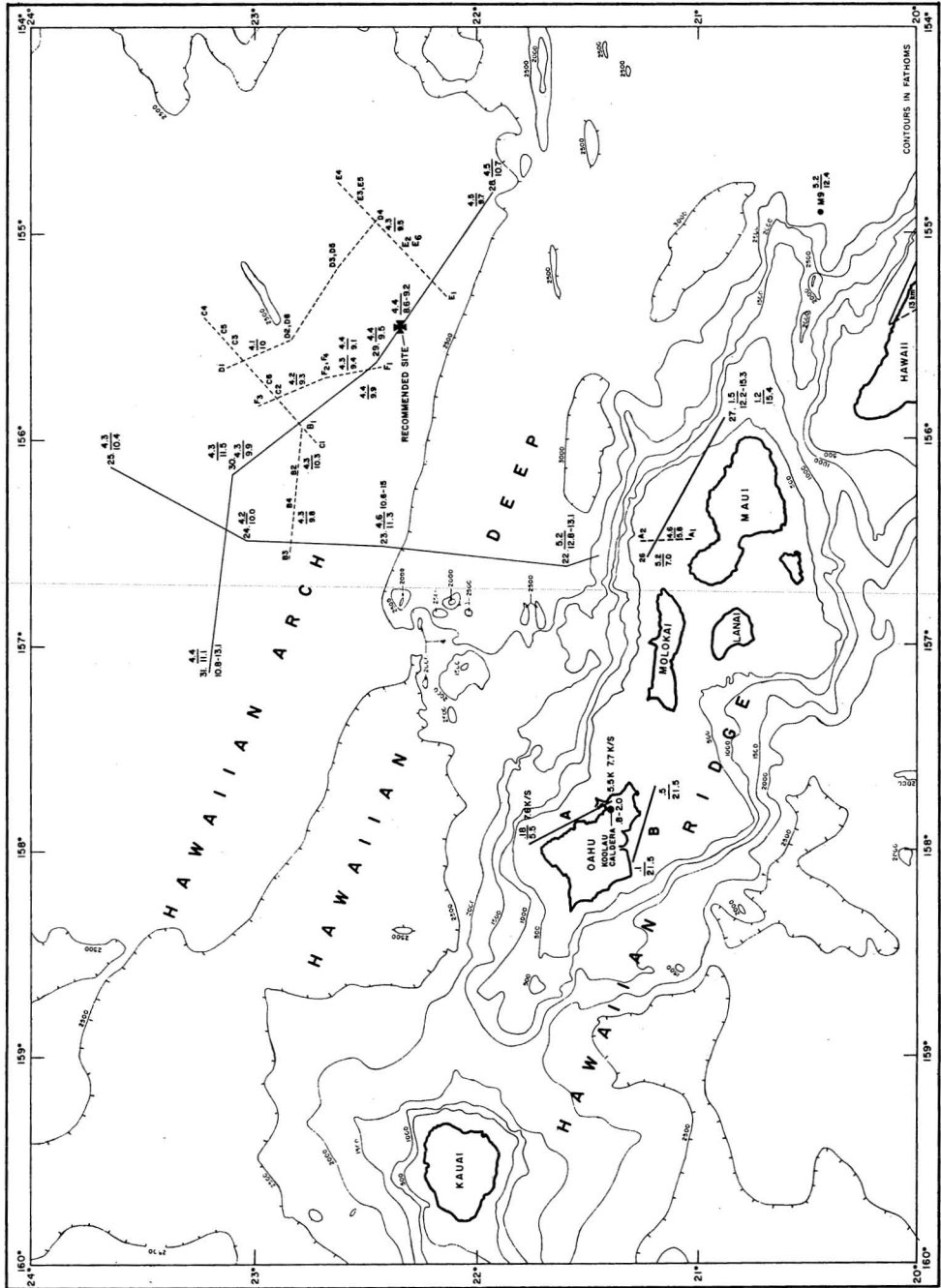


FIG. 1. Location of seismic measurements and depths to mantle.

m). The estimated depth to the mantle is 9 ± 0.4 km. This location corresponds roughly with Shor and Pollard's Station 29, where they obtained what appeared to be anomalous crustal structure. Here their measurements indicate that the basal crustal layer has a velocity of 6.97 km/sec, which is somewhat high for this layer, and that the layer's thickness is only about half its normal value. However, the reanalysis of their data by the National Science Foundation, as shown in Figure 2, indicates much less abnormality in crustal thickness and much less variation in adjacent depths to the mantle. As seen in Figure 2 the average mantle depth is 10 km.

THE HAWAIIAN DEEP

Shor and Pollard (1964) established one pro-

file over the Hawaiian Deep (Station 22, Fig. 1) and found that the mantle there was deeper than normal, 13 km. The overlying crust is composed of four layers having velocity values similar to those observed on the Arch. Although layer *c* is relatively thin, layer *d* is significantly thicker than elsewhere. An earlier measurement on the flank of the trench off the east coast of Hawaii by Raitt (1956) showed a crust composed of three layers with a depth to the mantle of 12.4 km.

THE HAWAIIAN RIDGE

Shor and Pollard (1964) established one profile (Station 26, Fig. 1) on the shallow water shelf just north of the island of Maui that is of considerable interest. The Moho discontinuity,

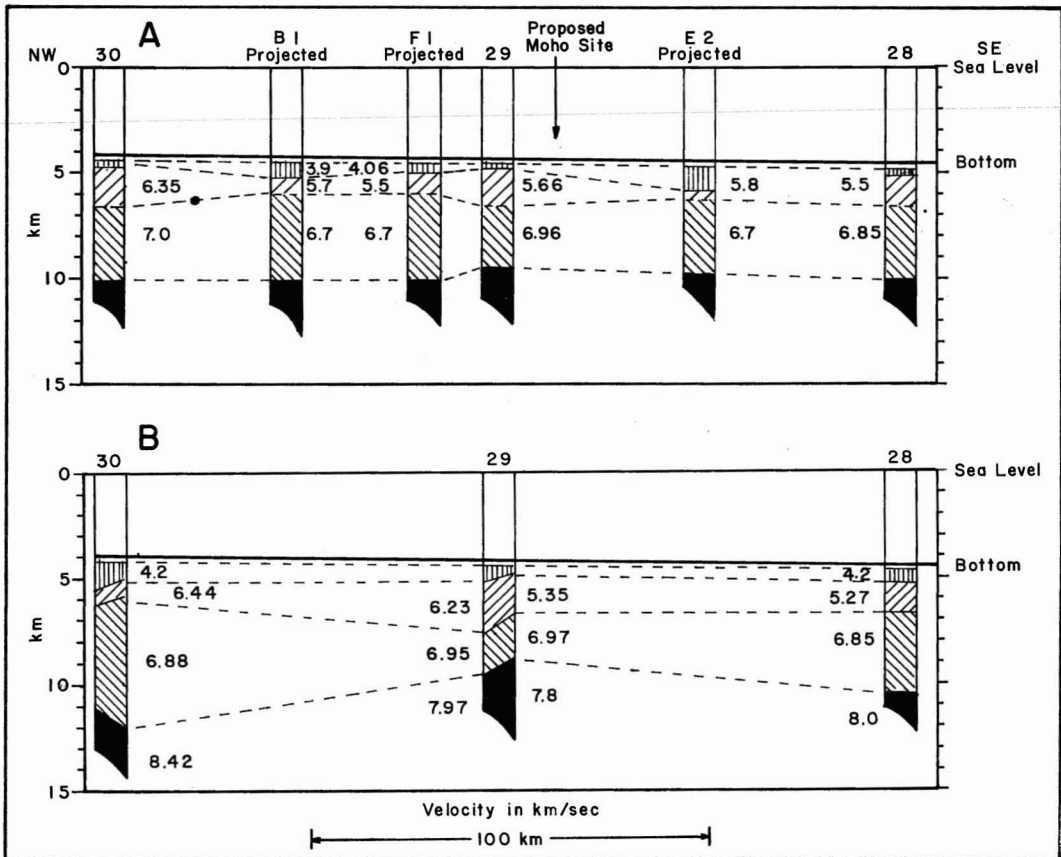


FIG. 2. A: NSF reworked crustal section across proposed mohole site. Stations 28, 29, 30 after Shor and Pollard (1964); stations B1, F1, E2 from unpublished data of Western Geophysical Co. B: Published section (after Shor and Pollard, 1964) along northwest-southeast section on flank of Hawaiian Arch.

having a velocity of 8.10 km/sec, showed irregularities in depth which they felt appeared to be best explained by faulting, the upthrown side of the fault giving an anomalous depth to the mantle of 7 km. This, however, could be related equally as well to a buried volcanic rift or pipe filled with mantle-like material. The magnetic relations (Malahoff and Woollard, in a forthcoming issue of *Pacific Science*) strongly suggest this as the true explanation. The reality of very shallow mantle material here is substantiated by the Western Geophysical Company measurements which yielded a depth of 5–8 km in the adjacent area (Station A1-A2, Fig. 1).

Another shelf section off the east end of Maui, examined by Shor and Pollard (Station 27, Fig. 1), showed a depth of 15.5 km to the mantle, with a crust having the following velocity structure: Layer *a*, 2.68 km/sec; layer *b*, 3.65 km/sec; layer *c*, 4.96 km/sec; layer *d*, 7.15 km/sec(?); Moho, 8.10 km/sec.

Layer *d* was not actually defined, but probably is present. The results obtained along the north coast of Hawaii by the U.S. Geological Survey, recording on land and shooting at sea (Eaton and Ryall, personal communication), suggest a depth to the mantle of 13.0 km in this area. This agrees with the analysis made by Eaton (1962) of earthquake travel time data on Hawaii, which suggested a depth of 13–15 km to the mantle.

The work of the Hawaii Institute of Geophysics was concentrated in and around the island of Oahu and was concerned with both crustal structure and centers of volcanic eruption. Detailed explanation and results are given elsewhere in this issue (Furumoto et al., p. 306; Adams and Furumoto, p. 296). In brief, these studies showed Moho-like velocities at very shallow depths (1–2 km) over primary volcanic pipes and at deeper depths (6 km) beneath the rift zones. The volcanic pipe measurement, showing a velocity greater than 7.0

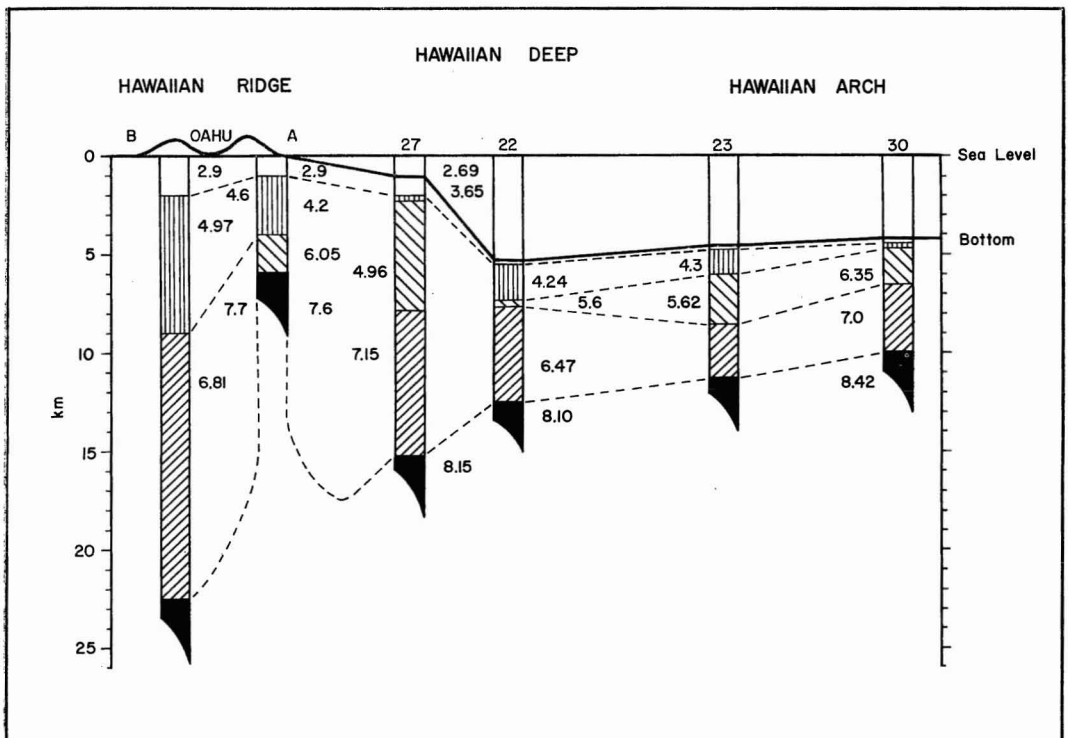


FIG. 3. Composite crustal section across the Hawaiian Archipelago. Stations A and B after Furumoto et al. (p. 306 in this issue); stations 27, 22, 23, 30 after Shor and Pollard (1964). Velocity in km/sec.

km/sec, was made over a plug in the caldera area of Koolau Volcano. The plug had intruded into a layer having a velocity of 4.63 km/sec. The rift zone measurement, showing a velocity of 7.6–7.7 km/sec, was made on a profile paralleling the northwest rift zone of the Koolau Volcano. The northwest rift zone was outlined by a local gravity anomaly high (+50 mgal) which indicates an abnormal mass distribution.

It is not clear whether the 7.6–7.7 km/sec layer which occurs at a depth of about 5.5 km under the rift zone is the true mantle or, more likely, is a differentiate of the mantle marking the magma chamber that furnished the Koolau Mountain volcanics.

To the south of Oahu a crustal traverse, although with incomplete measurements, indicated mantle depth to be close to 21 km. If the same slope associated with the basal crustal layer's upper surface applies to the crust-mantle interface, the mantle velocity is at least 8.4 km/sec.

It should be mentioned that the occurrence of intrusive bodies, such as the plug in the caldera, complicates refraction measurements on volcanic islands. The relatively small area of the islands, precluding long refraction spreads on land, imposes another complication. Therefore, it is not surprising that the present measurements, incomplete as they are, are the first to come up with values on the depth to the mantle. Previous studies of volcanic islands, such as those made by Officer et al. (1952) on Bermuda, by Raitt (1952) on Kwajalein and Bikini, and by Gaskell and Swallow (1953) on Funafuti and Nukufetau, have defined only the depth to the volcanics and, in a few cases, to the upper crustal structure. All failed to give information on crustal thickness or to define the seismic nature and boundaries of the volcanic pipes and rift zones present.

SUMMARY

On the Hawaiian Arch the depth to the mantle is about 10.0 km on the average and locally is as shallow as 9 km. On the shelf area north of Maui a velocity comparable to the velocity of the Moho is found at a depth of 5.8 km. Magnetic data suggest this shallow depth is re-

lated to an intrusive. On the island of Oahu high velocity material of 7.7 km/sec is also found at a shallow depth (5 km). This is related to a known volcanic rift zone marked by high gravity and magnetic values. South of Oahu along the axis of the Hawaiian Ridge a depth of 20–23 km is defined for the mantle. Between the Hawaiian Ridge and the Hawaiian Arch in the area of the Hawaiian Deep the depth to the mantle is about 13.0 km. The above relations are summarized by a composite section across these three features, as shown in Figure 3. This section shows clearly that the origin of the Hawaiian Deep must be related to crustal subsidence beneath the Hawaiian Ridge. This is in agreement with current theory on the origin of seamounts and atolls, and would explain the progressive change from atolls at one end of the Hawaiian Ridge (Midway I.) to the high relief (13,500 ft) associated with Hawaii on the other end of the Ridge.

REFERENCES

- EATON, J. P. 1962. Crustal structure and volcanism in Hawaii. In: *The crust of the Pacific Basin*. Am. Geoph. Union, Monogr. 6, pp. 13–29.
- GASKELL, T., and J. C. SWALLOW. 1953. Seismic experiments in two Pacific atolls. *Occasional Papers of The Challenger Soc.*, Vol. 3, 13 pp.
- OFFICER, C. B., M. EWING, and P. C. WUENSCHHEL. 1952. Seismic refraction measurements in the Atlantic Ocean, Part IV. Bermuda Rise and Nares Basin. *Bull. Geol. Soc. Am.* 63:777–808.
- RAITT, R. 1952. The 1950 seismic refraction studies of Bikini and Kwajalein Atolls and Sylvania Guyot. *Scripps Institute Report* 52–38, 35 pp.
- . 1956. Seismic refraction studies of the Pacific Basin, Part I. Crustal thickness of Central Equatorial Pacific. *Bull. Geol. Soc. Am.* 67:1623–1640.
- SHOR, G. G. 1960. Crustal structure of the Hawaiian Ridge near Gardner Pinnacles. *Bull. Seism. Soc. Am.* 50(4):563–573.
- and D. D. POLLARD. 1964. Mohole site selection studies north of Maui. *J. Geoph. Res.* 69(8):1627–1638.