

# Seismic-Refraction Studies of Eniwetok Atoll

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 260-S



# Seismic-Refraction Studies of Eniwetok Atoll

By RUSSELL W. RAITT

## Bikini and Nearby Atolls, Marshall Islands

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*A study of seismic-wave velocities  
down to the Mohorovičić discontinuity*



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## CONTENTS

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	Page
Abstract-----	685
Introduction-----	685
Acknowledgments-----	685
Operating procedure-----	686
Shore stations-----	687
Reflection studies-----	687
Lagoon survey-----	687
Deep-sea survey-----	687
Firing procedure-----	688
Receiving equipment-----	688
Theory of interpretation of seismic-refraction observations-----	688
Travel-time plots-----	690
Accuracy of travel times-----	692
Velocities-----	694
Subsurface structure-----	695
Reef structure-----	695
First and second layers-----	695
Third layer-----	696
Fourth layer-----	696
Fifth layer-----	697
Sixth layer-----	697
Bibliography-----	698

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## ILLUSTRATIONS

---

	Page
FIGURE 219. Location of shot lines and receiving stations-----	686
220. Model of subsurface structure assumed for interpretation of travel-time plots-----	689
221. Travel-time plots for section through stations A, B, C, D, E, K, and K'-----	690
222. Travel-time plots for section northwest from station A-----	690
223. Travel-time plots for section through stations F, D, G, and L-----	691
224. Travel-time plots for section through station J-----	691
225. Travel-time plot of short profile across reef northwest of island of Elugelab-----	692
226. Travel-time plots for section through stations F, B, and A-----	692
227. Travel-time plots for section through stations E and G-----	693
228. Travel-time plots for section through stations M and I-----	693
229. Travel-time plots for shots received at station H-----	694
230. Oscillograms of $\frac{1}{2}$ -pound shots at short range and 80-pound shots at long range-----	694
231. Hypothetical subsurface section through Eniwetok Atoll from north to south-----	696
232. Hypothetical subsurface section through Eniwetok Atoll from west to east-----	697

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## BIKINI AND NEARBY ATOLLS, MARSHALL ISLANDS

### SEISMIC-REFRACTION STUDIES OF ENIWETOK ATOLL

By RUSSELL W. RAITT<sup>1</sup>

#### ABSTRACT

Observed seismic velocities at Eniwetok Atoll indicate the presence of 6 layers of rock, in which the average velocities are 2.44, 3.06, 4.15, 5.59, 6.90, and 8.09 kilometers per second, respectively. Previous drilling permits the identification of the first 2 layers as calcareous deposits and the third layer (4.15 km/s) as volcanic. The calculated depth of the third layer beneath the drilling sites was about 0.3 km greater than the depths at which volcanic rock was penetrated by the drill. This may be due to the fact that, in calculations, the vertical seismic velocities in the first 2 layers were assumed to be equal to the horizontal velocities measured in those layers, whereas the vertical velocities are probably less because of the presence of unconsolidated material between the cemented layers in the first 2 zones.

The fourth layer (5.59 km/s) is thought to be a hard crystalline rock, probably basalt. The fifth layer (6.90 km/s), identified with the crustal layer extensively present in the Pacific Ocean basin, is found at a depth of 9–10 km, and the sixth layer (8.09 km/s), characteristic of the layer just below the Mohorovičić discontinuity, is reached at a depth of 16–17 km.

#### INTRODUCTION

Seismic-refraction observations at Eniwetok Atoll in October and November 1952 had as their objective the delineation of the volcanic-rock layer immediately beneath the lagoon and the determination of the seismic-wave velocity as a function of depth down to the Mohorovičić discontinuity. Primary emphasis was placed on determining the seismic velocity in the layer of calcareous sediments forming the upper surface of the atoll and the configuration of the volcanic rock immediately beneath.

In planning the survey, the previous seismic-refraction studies at Bikini and Kwajalein (Dobrin, Perkins, and Snavely, 1949; Raitt, 1954) and the drilling at Eniwetok (Ladd, Ingerson, Townsend, and others, 1953) were very helpful. The Bikini studies indicated the form of the travel-time data to be expected. The drilling at Eniwetok reached a hard formation at a depth of 4,610 ft (1.41 km) beneath the island of Elugelab and 4,170 ft (1.27 km) beneath Parry Island. At

Parry Island the hard formation was determined to be olivine basalt. This gave additional support to the identification of the 4-km/s (kilometers per second) layer at Bikini, found at an average depth of 4,300 ft (1.3 km), as volcanic rock and indicated that the structure at Eniwetok and Bikini is similar.

#### ACKNOWLEDGMENTS

This work was supported by the Office of Naval Research under Contract Nonr-233(05) and the Bureau of Ships under Contract NObsr-43356. Support from the Office of Naval Research was administered by J. W. Smith, who arranged for the delivery of the large quantities of explosives and other supplies needed in the investigation.

A seismic-refraction operation of the magnitude of the Eniwetok studies requires the cooperation of many people, whose help is gratefully acknowledged.

H. Kirk Stephenson of the Los Alamos Scientific Laboratory directed the project for that organization, and his active participation in the survey was an essential feature of its success. J. D. Isaacs was scientific leader, and Comdr. C. N. G. Hendrix was liaison officer for the Scripps Institution scientific group. Comdr. John Lofland, USN, and Comdr. Theodore Eunson, USN, arranged for the necessary shore installations, transportation, and ship facilities.

The officers and crews of U. S. S. *Lipan* (ATF 85), R/V *Horizon*, and R/V *Spencer F. Baird* were of great help. Their commanding officers were Lt. R. M. Hughson, Noel L. Ferris, and Laurence E. Davis, respectively.

Members of the firing and recording groups were Joel H. Swartz, U. S. Geological Survey; Edwin M. Hamilton and Maxwell Silverman, U. S. Navy Electronics Laboratory; Chief Gunners Mate Daniel Howlett, USN; and Willard C. North, Daniel K. Gibson, Arthur D. Raff, Richard J. Smith, Alan C. Jones, Richard P. VonHerzen, and Winter D. Horton, Jr., Scripps Institution of Oceanography.

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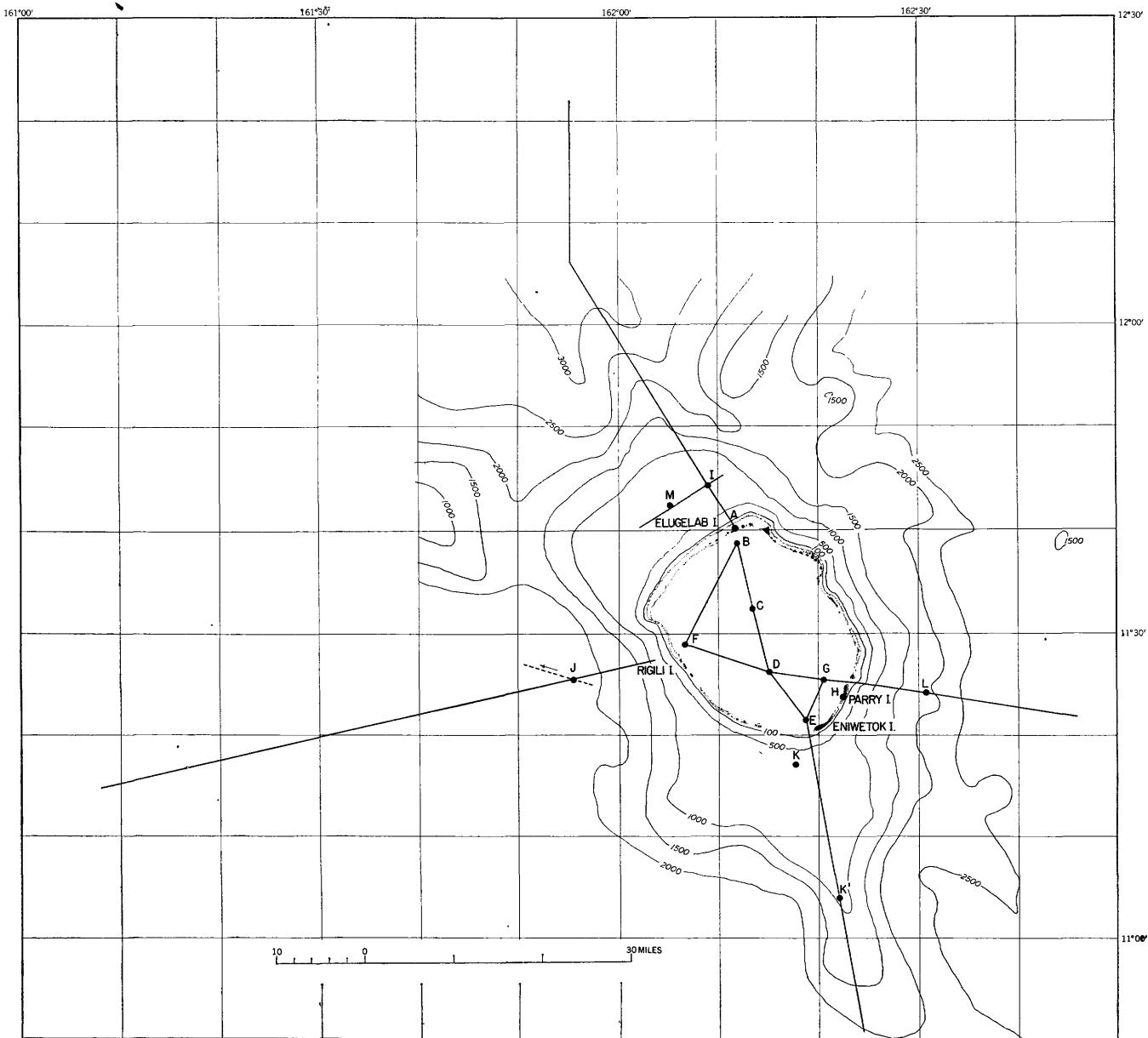


FIGURE 219.—Location of shot lines and receiving stations. Depth contours are in fathoms.

The author is indebted to Beauregard Perkins for suggestions made during his technical review of the paper.

#### OPERATING PROCEDURE

The plan of operation is shown in figure 219. The topography of the bottom surrounding the atoll was previously determined by K. O. Emery (Emery, Tracey, and Ladd, 1954). The letters represent receiving stations, and the heavy solid lines represent the lines along which shots were fired. The spacing of the stations and the directions of the lines in the lagoon were determined by the desired objective of optimum reversed control of the volcanic layer and by the necessity that the firing ship stay well clear of the coral

shoals scattered throughout the lagoon. In extending the lines into deep water, advantage was taken of the two navigable passages on the southern and eastern sides.

Taken together, the lines of shots provide 2 sections across the atoll, 1 roughly north and south, and the other west and east. The north-south line, with eight stations, was laid out not only to obtain adequate data concerning the upper layers but also to extend the lines to maximum feasible range in the hope of achieving penetration to the Mohorovičić discontinuity beneath the atoll.

Three types of stations were occupied: shore stations, A and H, where portable equipment was set up

in tents on Elugelab and on Parry Island; lagoon stations, B-G, at which the U. S. S. *Lipan* (ATF 85), at anchor, served as receiving ship, using the same type of portable equipment used ashore; deep-sea stations, I-M, at which the Scripps Institution of Oceanography's R/V *Spencer F. Baird* served as receiving ship. The *Baird* was also used at lagoon station G for the line G-L. During this operation, and also while *Baird* was at K receiving shots fired on line D-E, the portable equipment from station A and the U. S. S. *Lipan* was used at station H.

#### SHORE STATIONS

In order to tie in the survey to the points at which drilling had determined the depth to volcanic rock (Ladd, Ingerson, Townsend, and others, 1953), receiving stations were occupied at the drill holes on the island of Elugelab and Parry Island. At Elugelab (station A) tests using conventional geophones at the surface were unsatisfactory owing to a high noise level. The signal-to-noise ratio of the refracted waves was much better for a hydrophone lowered into the drill hole. Consequently all shots used at station A were received on a hydrophone lowered to a depth of 250 ft in the test hole drilled on Elugelab. Shots received at this station were fired in the lagoon along the lines from F to B, and from B through C and D to E. Shot distance for these profiles was obtained with the help of a radio sonobuoy placed in the lagoon 800 yd from station A in about 10 fathoms depth. Shots outside the atoll were fired along a line bearing approximately 330° until well out from the base of the slope, thence bearing 0°. Shot distances for this line were obtained with the aid of a radio sonobuoy placed about 100 yd beyond the reef opposite station A.

A profile from station A to the edge of the outer reef was recorded to determine the differences, if any, between reef and lagoon structure, and to complete the short-range part of the profile extending northwestward to deep water. Shots were fired from a DUKW in water of about 4-foot depth normally covering most of the outer reef opposite Elugelab. The shot instant was transmitted by radio sonobuoy and the shot position was surveyed by taking sextant angles between known points near the Elugelab drill hole.

At Parry Island the noise level in the drill hole was higher than at Elugelab; hence the seismic waves were received on a hydrophone planted on the lagoon bottom (station H) about 500 yards from shore opposite the Parry Island drill hole. In this location, the noise level was much lower than in the drill hole. The depth was about 10 fathoms. At this station shots fired along lines D-E and G-L were recorded.

#### REFLECTION STUDIES

While setting up and testing the Elugelab shore station, about 2 days were spent attempting to obtain reflections from the volcanic rock, known from drilling (Ladd, Ingerson, Townsend, and others, 1953) to be at a depth of 4,610 feet at this point. Geophones and drill-hole hydrophones were used. Shots were fired at varying distances of as much as one-half mile from station A. Records of all shots showed irregular disturbances for several seconds following the first arrival, with no outstanding reflections identifiable with the volcanic rock or other subsurface interface.

Although these tests do not preclude the possibility that good reflections might be obtainable elsewhere, it was concluded that it would be inadvisable to plan a reflection survey when reflections were unobtainable at one of the principal control points.

#### LAGOON SURVEY

In the initial plans for the survey, the *Baird* was to serve as a receiving ship for all stations except the shore stations, and it was fitted out for this purpose. However, owing to a delay of about 2 weeks in the arrival of the *Baird*, the U. S. S. *Lipan* (ATF 85) was used as a substitute. The receiving equipment, which consisted of the portable instruments from the Elugelab shore station, was more primitive than the multichannel installation on the *Baird*, but this was not a serious handicap to the lagoon survey as noise levels were generally low, and, except for the long profiles extending outside the lagoon to the south, the ranges were short.

At each receiving station, the receiving ship was carefully anchored with reference to gyrocompass bearings on the nearest island points. The receiving hydrophones were suspended at a depth of 75 ft and floated about 100 yd from the ship. Owing to the swinging of the ship at anchor, the hydrophone moved through a considerable arc, but the combined departure from the normal station positions shown in figure 219 due to this effect and to errors of position determination was probably no more than 200 yd. The firing ship similarly maintained position along the designated lines by gyrocompass bearings, and with the same probable departure. Distances between shot and hydrophone were obtained much more accurately than this by measurement of the travel time of the waterborne sounds; therefore the error in the ship's position would not affect the value of the depth calculation but would cause a maximum error of 200 yd in the location of the depth value.

#### DEEP-SEA SURVEY

Fortunately, the *Baird* arrived as the lagoon phase of the survey was completed. The deep-water survey

could not have been carried out with the use of the *Lipan* as it had no deep-water echo sounder, which is essential for calculation of the water delay in deep-sea seismic-refraction work. The final deep-sea phase of the survey was completed with the *Baird*, and the portable station on the *Lipan* was moved to the Parry Island drill hole.

At deep-water stations I, M, J, K, K', and L, anchoring was not practicable and the *Baird* either lay to or was underway slowly, attempting to maintain position. Throughout much of this phase the wind was high, frequently having a velocity of 17–21 knots, and the combined wind and current drift while lying to was between 2 and 3 knots. Attempts to maintain position by turning the screw slowly were only partially successful. Hence the positions shown are only rough estimates of the average position during the shot recordings. In most cases the *Baird* was probably within 1 nautical mile of the indicated position. An exception was the large drift during the shooting of the first part of profile J, indicated by a dashed line. During the shooting along the southwest end of this line, the *Baird* got underway and held position reasonably well. As stated above, these changes in position of the receiving ship affect only the location of the depth value. Seismic-refraction operations under these conditions, from the standpoint of noise level, firing conditions, and general operational difficulties, are marginal.

#### FIRING PROCEDURE

With the exception of a few experimental reflection shots and the short profile across the Elugelab reef (see Shore Stations), all shots were fired from the Scripps Institution of Oceanography's R/V *Horizon*, which proceeded along the courses indicated in figure 219 at speeds ranging from 6 to 11 knots. Shots were made up from tetrytol demolition blocks. The charges varied from one-half pound at distances less than 5 km from the receiving station to as much as 80 lb at the maximum range of 50–100 km. They were fired with slow-burning fuse ignited just before being dropped overside. The time of firing was recorded by picking up the direct blast on the *Horizon*'s echo sounder and transmitting it by radio to the receiving ship, where it was recorded by the oscillograph used to record the seismic waves.

#### RECEIVING EQUIPMENT

The *Baird*'s receiving equipment was very similar to that used in the Bikini survey (Raitt, 1954). Three hydrophones were suspended by their electrical cable from surface buoys to depths of 75 ft in the lagoon survey and 200 ft in the deep-sea survey. In the lagoon the very slow currents permitted the suspending cable

to hang vertically and the hydrophone depth was very close to 75 ft. In the deep sea, however, the wind and current drift caused the suspension to assume a substantial angle with the vertical, and the average depth was therefore probably close to 120 ft. A multichannel oscillograph on the *Baird* recorded the outputs of the 3 hydrophones on 3 low-frequency (3–20 cycles per second) channels, on 3 intermediate-frequency channels (20–200 cps), and on 3 high-frequency channels (500–3,000 cps). All channels recorded at 2 levels of sensitivity of 20-decibel-level difference. Except at very short range the seismic waves through the earth were received only on the low-frequency channels. The higher frequencies were used to identify the waterborne waves, whose travel times were used to determine the shot distance.

Timing on the oscillograph was obtained by timing lines flashed every 1/100 second, with 1/10 seconds accented. The timing disk was driven by a fork-stabilized synchronous motor. The accuracy of the timing was controlled by frequent comparison with a break-circuit chronometer which was calibrated daily with time signals from radio station WWV.

A two-channel pen oscillograph was used at the portable station ashore and on the U. S. S. *Lipan*. One channel recorded the low-frequency seismic waves, the other performed the double function of recording the radio-transmitted firing signal and the high-frequency waterborne sound. Some records were made with 2 hydrophones, both recording the low-frequency waves but only 1 the high-frequency waves. The low noise levels and good signals obtained in the lagoon gave little additional advantage to the use of more than one hydrophone. However, in the deep-sea work the noise levels from rough sea conditions gave a real advantage to using three hydrophones, as was done on the *Baird*.

#### THEORY OF INTERPRETATION OF SEISMIC-REFRACTION OBSERVATIONS

Knowledge of the earth's interior is yielded both by travel times of sound waves and by the intensity and spectra of the waves. However, travel times are more tractable in analysis and more easily measured. In the present study, as in most seismic interpretations, the travel times form the sole basis for the interpretation of the subsurface structure.

The specific methods used in the interpretation were the same as those used by the author in the Bikini survey (see Raitt, 1954); the formulas and diagrams are repeated here for reference.

Figure 220 illustrates a subsurface section consisting of three layers in which the seismic velocities are  $c_0$ ,  $c_1$ , and  $c_2$ . In seismic work at sea the upper layer is water. For the example illustrated, the velocities  $c_1$

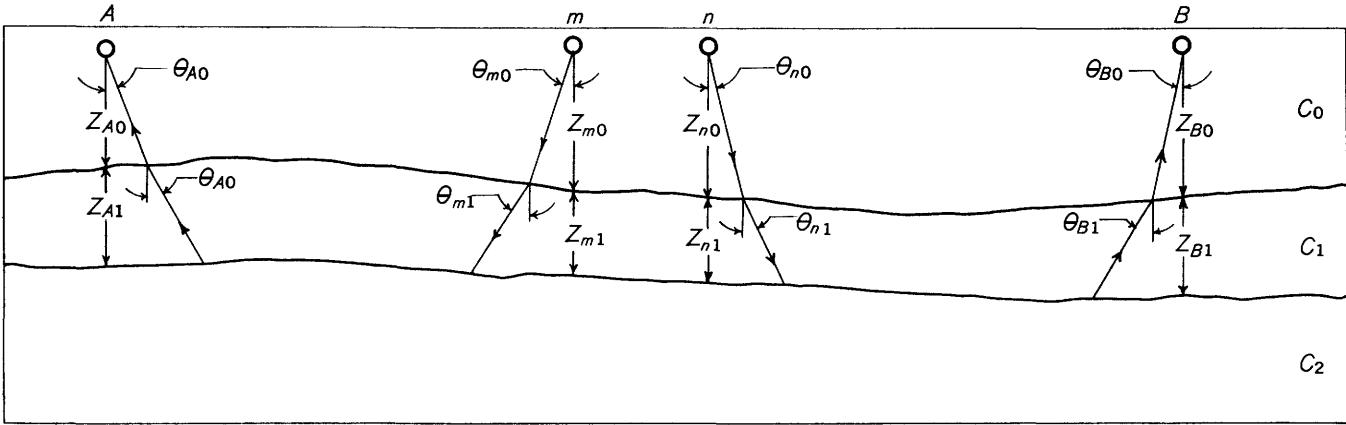


FIGURE 220.—Model of subsurface structure assumed for interpretation of travel-time plots.

and  $c_2$  are 2 and 4 times as great, respectively, as  $c_0$ , the velocity in water. Points  $A$  and  $B$  represent receiving stations and  $m$  and  $n$  represent shot points. The sound rays shown are critically refracted through the third layer. The symbols for the various angles and the thicknesses of the layers, used in the calculations, are illustrated in the figure.

The travel time,  $T_{Am}$ , for a sound pulse to travel from  $m$  to  $A$  is

$$T_{Am} = \frac{X_{Am}}{c_2} + \frac{z_{A0} \cos \theta_{A0}}{c_0} + \frac{z_{m0} \cos \theta_{m0}}{c_0} + \frac{z_{A1} \cos \theta_{A1}}{c_1} + \frac{z_{m1} \cos \theta_{m1}}{c_1} \quad (1)$$

and the travel time,  $T_{Bn}$ , for the pulse to travel from  $n$  to  $B$  is

$$T_{Bn} = \frac{X_{Bn}}{c_2} + \frac{z_{B0} \cos \theta_{B0}}{c_0} + \frac{z_{n0} \cos \theta_{n0}}{c_0} + \frac{z_{B1} \cos \theta_{B1}}{c_1} + \frac{z_{n1} \cos \theta_{n1}}{c_1}, \quad (2)$$

where  $X_{Am}$  and  $X_{Bn}$  are the horizontal distances between shots and hydrophones.

In equation 1 the term  $\left(T_{Am} - \frac{X_{Am}}{c_2}\right)$  is called the intercept time (Gardner, 1939). The four remaining terms of equation 1 are called delay times and are designated  $\tau_{A0}$ ,  $\tau_{m0}$ ,  $\tau_{A1}$ , and  $\tau_{m1}$ , respectively.

If the delay times for the water layer are subtracted from the total travel times, the corrected travel times are

$$T'_{Am} = \frac{X_{Am}}{c_2} + \tau_{A1} + \tau_{m1} \quad (3a)$$

and

$$T'_{Bn} = \frac{X_{Bn}}{c_2} + \tau_{B1} + \tau_{n1}. \quad (3b)$$

For gently sloping structures the seismic velocity in the third zone is, to a sufficient degree of approximation,

$$c_2 = \frac{2}{\frac{dT'_{Am}}{dX_{Am}} + \frac{dT'_{Bn}}{dX_{Bn}}}. \quad (4)$$

If the contact between the second and third layers is nearly horizontal and if shots  $m$  and  $n$  are fired at the same point  $m$ ,  $\tau_{m1}$  and  $\tau_{n1}$  may be considered equal to a first approximation; and if a third shot is fired at point  $A$  and the resulting pulse is critically refracted through zone  $C_2$  and recorded as a first arrival at point  $B$ , then the delay times at  $A$ ,  $m$ , and  $B$  are determined by the three measured intercept times,

$$T'_{Am} - \frac{X_{Am}}{c_2} = \tau_{A1} + \tau_{m1}, \quad (5a)$$

$$T'_{Bn} - \frac{X_{Bn}}{c_2} = \tau_{B1} + \tau_{m1}, \quad (5b)$$

$$T'_{AB} - \frac{X_{AB}}{c_2} = \tau_{A1} + \tau_{B1}. \quad (5c)$$

The values of  $\tau_{A1}$ ,  $\tau_{m1}$ , and  $\tau_{B1}$  may be derived by solving equations 5a-c simultaneously. The thicknesses of the second layer beneath points  $A$ ,  $m$ , and  $B$  to a first approximation are

$$z_{A1} = \frac{c_1 \tau_{A1}}{\sqrt{1 - \left(\frac{c_1}{c_2}\right)^2}}, \quad (6a)$$

$$z_{m1} = \frac{c_1 \tau_{m1}}{\sqrt{1 - \left(\frac{c_1}{c_2}\right)^2}}, \quad (6b)$$

and

$$z_{B1} = \frac{c_1 \tau_{B1}}{\sqrt{1 - \left(\frac{c_1}{c_2}\right)^2}}. \quad (6c)$$

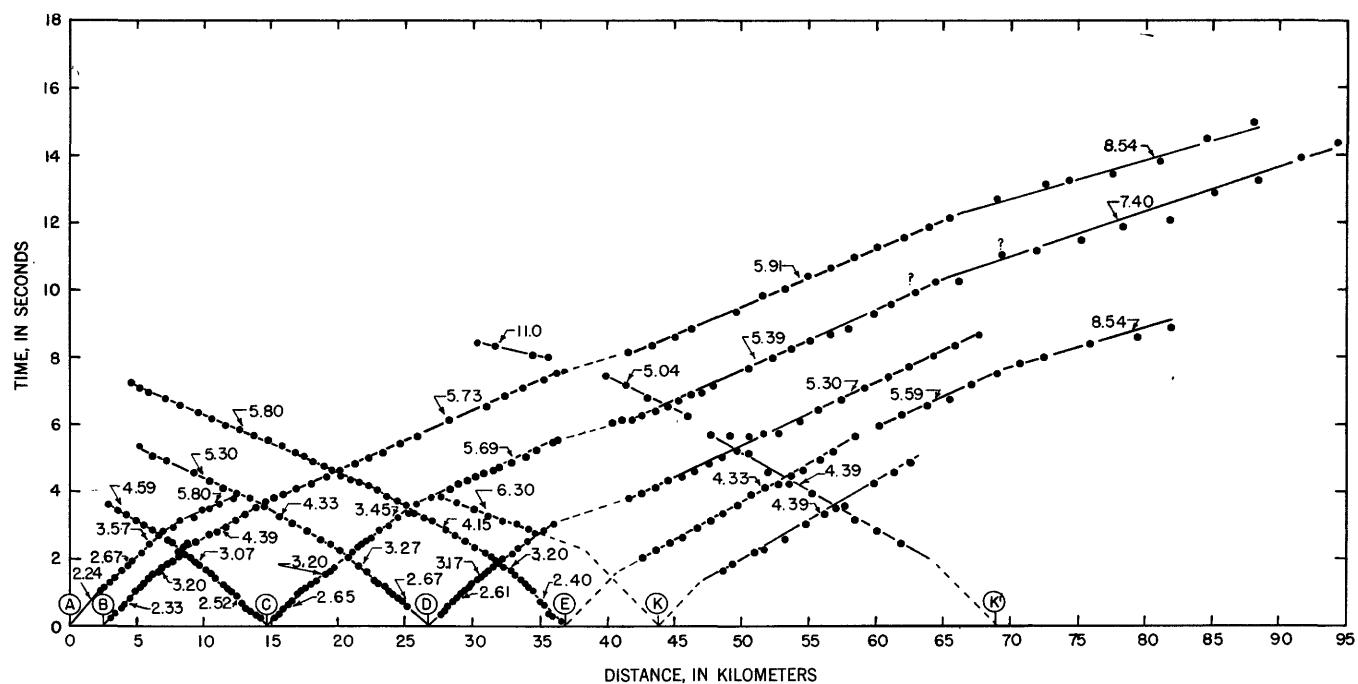


FIGURE 221.—Travel-time plots for section through stations A, B, C, D, E, K, and K'. Times are corrected for water delay; apparent velocities are in kilometers per second.

The process here outlined can, in principle, be repeated indefinitely for deeper horizons of successively higher speeds of transmission. The practical difficulties and cumulative errors become severe if the number of layers with small velocity contrasts is large.

#### TRAVEL-TIME PLOTS

The observed travel times of the bottom-refracted waves, corrected for water delay, are plotted in figures 221 to 229. In order to facilitate comparison of pro-

files, they are plotted together in related groups. For example, figure 221 contains all shots received at stations A, B, C, D, E, K, and K', fired along the lines that pass through each of these stations. For each time-distance graph the distance of each shot point from the corresponding receiving station is accurately plotted. Since the receiving station was fixed and the shot point varied for each profile, the zero point for each graph represents the true distance of the receiving station from the traverse reference station shown at zero distance (for

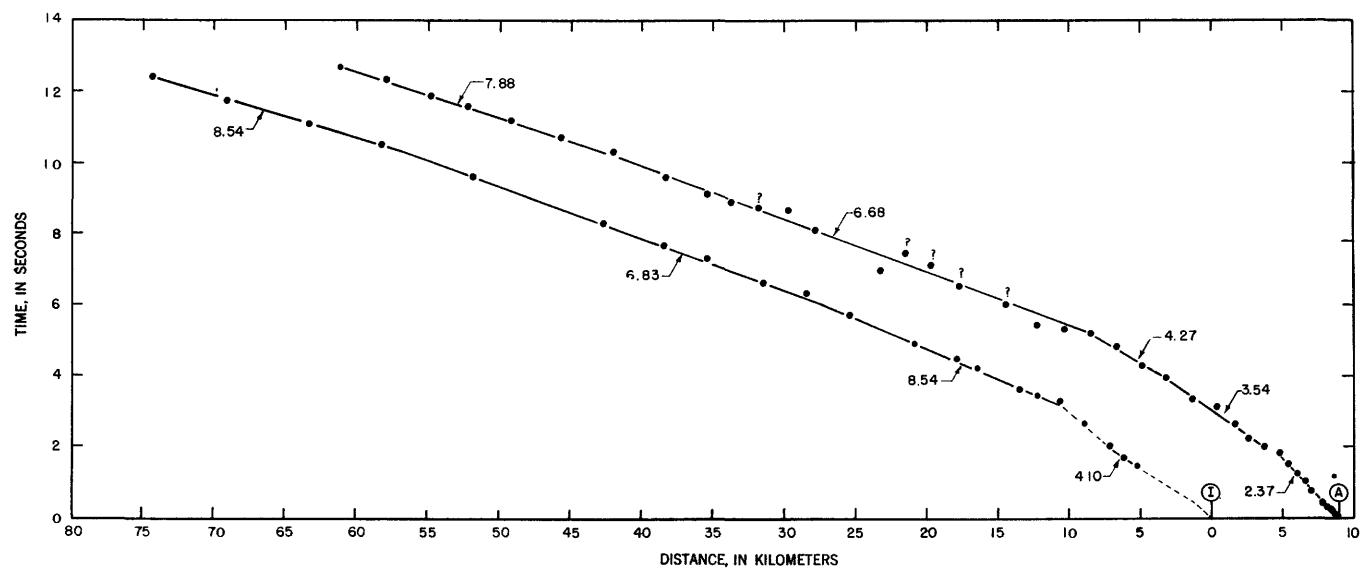


FIGURE 222.—Travel-time plots for section northwest from station A. Times are corrected for water delay; apparent velocities are in kilometers per second.

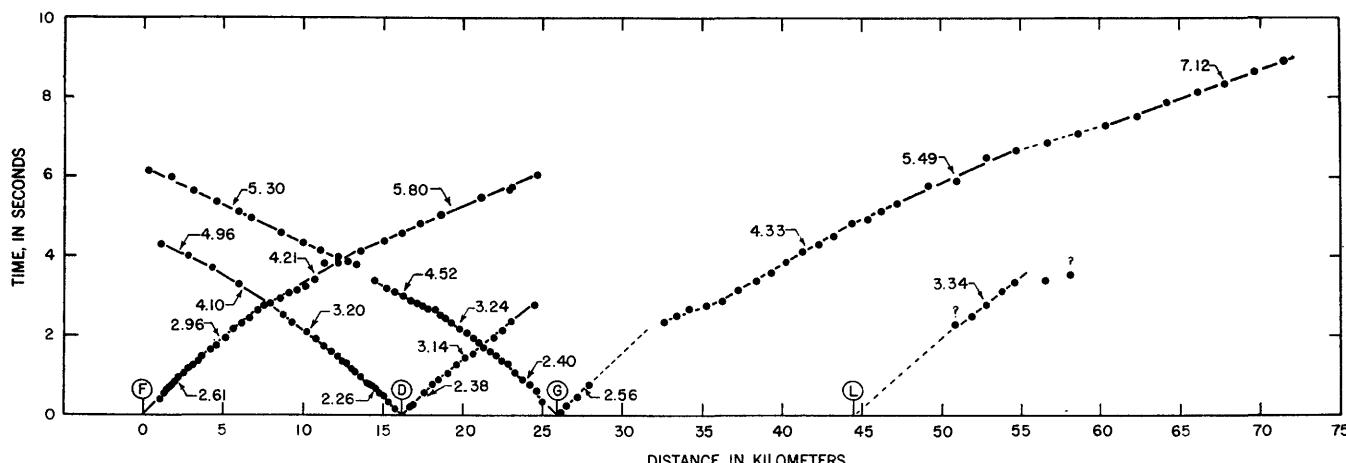


FIGURE 223.—Travel-time plots for section through stations F, D, G, and L. Times are corrected for water delay; apparent velocities are in kilometers per second.

example, from station A in figure 221). Because the receiving stations are generally not on a straight line, the distances from the shot points to stations other than the receiving station or between stations other than the reference station are only approximate in the graph.

It can be seen that most of the travel-time plots can be represented roughly by segments of straight lines. The lines drawn on the plots have been fitted by inspection, and the corresponding apparent velocity for each segment is indicated in kilometers per second (kmmps). Just as in the Bikini survey, the data require at least six velocity groups or layers to represent the range of values. These are, roughly, 2.5, 3, 4, 5.5, 7, and 8 kmmps.

One significant difference from the Bikini lagoon profiles is the greater prominence at Eniwetok of the 3-kmmps layer, which was observed on so few profiles at Bikini that its existence throughout the la-

goon was hypothetical. At Eniwetok, however, it is observed on every lagoon profile. This yields information about the structure of the calcareous deposits, but unfortunately it masks part of the important 4-kmmps segment and increases the distance between the shot and the receiver at which this velocity is first observed. Hence, the segments representing the layer believed to be the upper part of the volcanic rock are short and the degree of reversed control is considerably less than expected. In order to obtain the maximum information about this layer, and to increase the accuracy of the determination of velocities from the short segments in the first 15 km of profile, the number of shots at short range was increased significantly above that used in the Bikini survey.

Gaps in the profiles, indicated by dashed lines, resulted from two causes: in sections E-K in figure 221

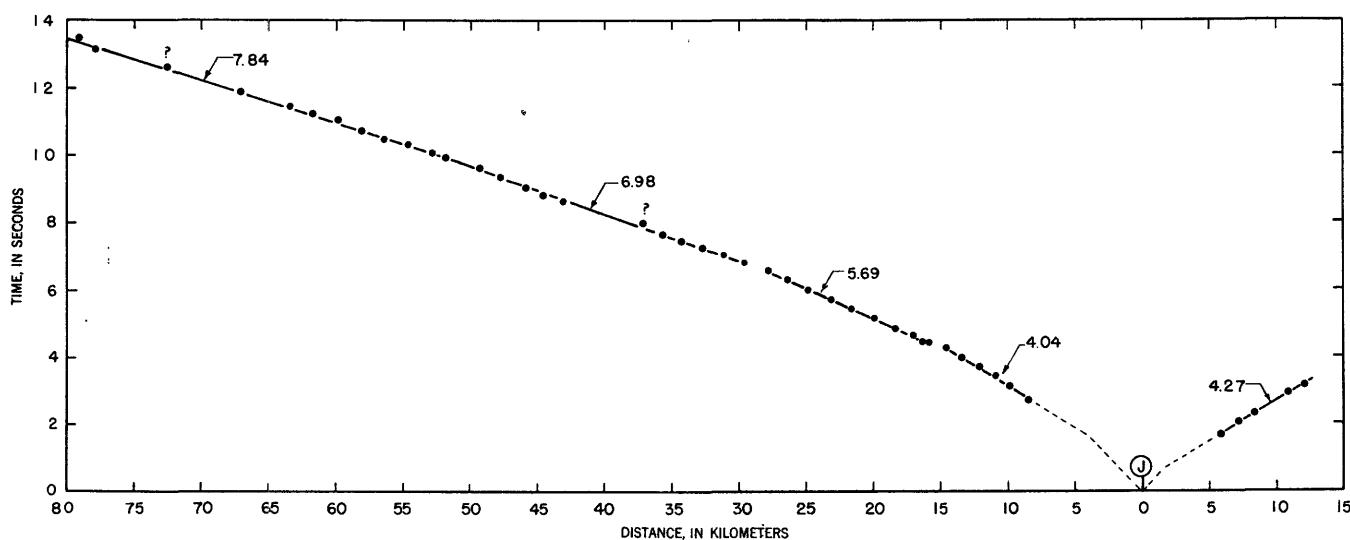


FIGURE 224.—Travel-time plots for section through station J. Times are corrected for water delay; apparent velocities are in kilometers per second.

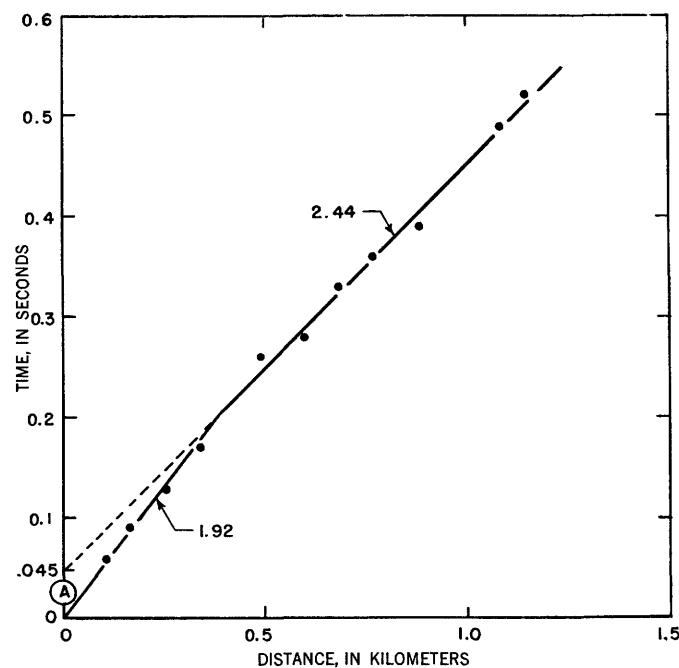


FIGURE 225.—Travel-time plot of short profile across reef northwest of Elugelab. The plotted distance is the direct distance  $\sqrt{\Delta^2 + 0.076^2}$ , where  $\Delta$  is the horizontal distance and the hydrophone depth is 0.076 km.

and G-L in figure 223 the lines crossed areas where underwater shots were prohibited because of the risk of damage to or interference with undersea installations, and the short-range first arrivals at the deep-water stations were masked by bottom echoes and direct water waves. The gaps due to the first cause were not serious, but the loss of the short-range information in the deep-water stations made it impossible to determine the velocity in sediments outside the lagoon.

#### ACCURACY OF TRAVEL TIMES

At short ranges the first-arriving elastic pulse is sharply defined and its arrival time can be measured with little difficulty to 0.01 second (see fig. 230).

At greater ranges the pulse decreases in amplitude, and the initial pressure pulse is frequently masked by the background noise. This phenomenon is illustrated by figure 230A, which shows the initial part of the pulses produced by the first four 1/2-pound shots south of station B. In the uppermost record, at the shortest range, the beginning is sharp and unquestionable. In the lowest record the beginning is barely detectable and was estimated by comparison with the preceding

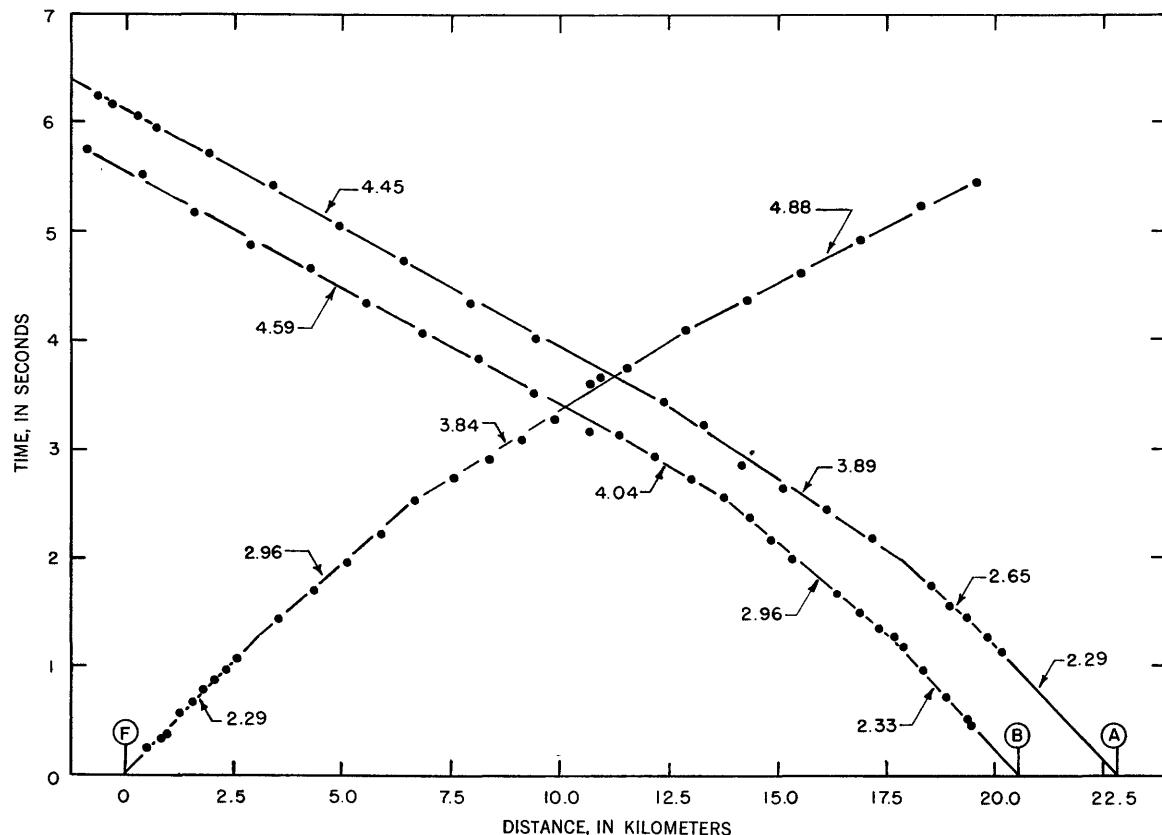


FIGURE 226.—Travel-time plots for section through stations F, B, and A. Times are corrected for water delay; apparent velocities are in kilometers per second.

records and with other comparable records to be 0.08 second ahead of the first negative swing.

This procedure of comparing records has been followed throughout the survey. The beginnings have been chosen by lining up groups of adjacent records on significant similar features and picking the beginnings with reference to the records which show the most conspicuous onsets. An example of this procedure for distant shots is shown by figure 230B, the record of three 80-pound shots at the end of the profile that extends south from station C for a distance of about 80 kilometers. Where similarity of form of the first wave is maintained for a considerable distance, this method of picking the beginning of the pulse yields an accurate slope of the travel-time curve, even though the arrival time may be questionable.

An ever-present potential source of error is the possibility that the true beginning wave group is too weak to observe and that the observed wave has taken a longer path but arrived with much greater intensity. This is particularly likely to occur in as complicated a structure as Eniwetok, where there are many possible paths for the waves to travel, and there is a good possibility that the initial ones frequently are much weaker than late arrivals. This possibility is greatest at greatest range, where even the strongest signals are weak. Hence, all of the sources of error

tend to increase with range. The error in picking the beginning of the first observed wave is roughly  $0.02\Delta^{\frac{1}{3}}$  second, where  $\Delta$  is the range in kilometers. Failure to observe a weak first arrival can be reduced by multiple profiles like section A-K' at Eniwetok, but there is no satisfactory way of estimating the expected error from this cause.

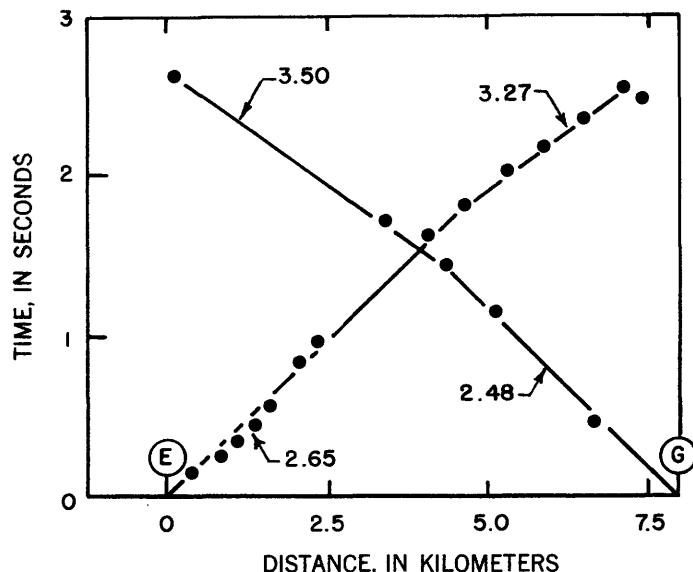


FIGURE 227.—Travel-time plots for section through stations E and G. Times are corrected for water delay; apparent velocities are in kilometers per second.

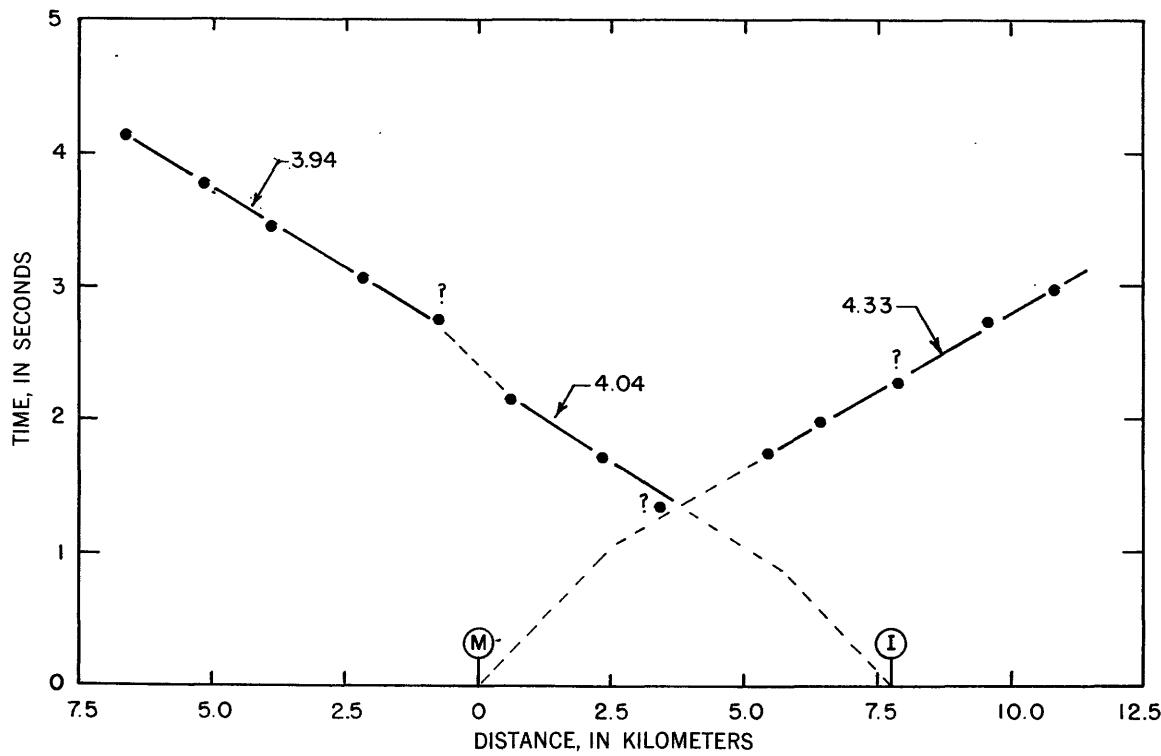


FIGURE 228.—Travel-time plots for section through stations M and I. Times are corrected for water delay; apparent velocities are in kilometers per second.

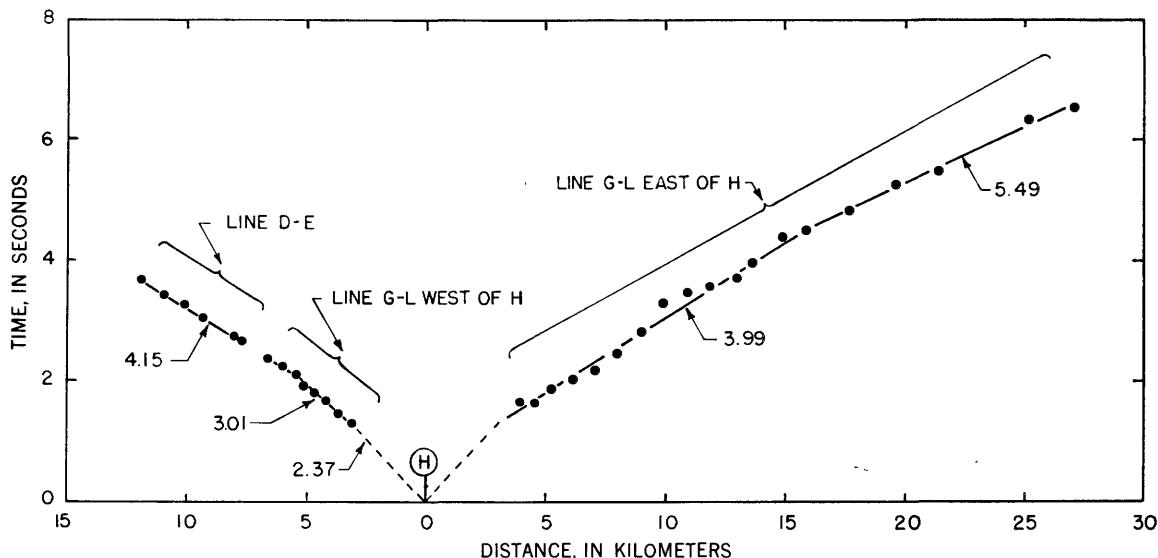


FIGURE 229.—Travel-time plots for shots received at station H. Times are corrected for water delay; apparent velocities are in kilometers per second.

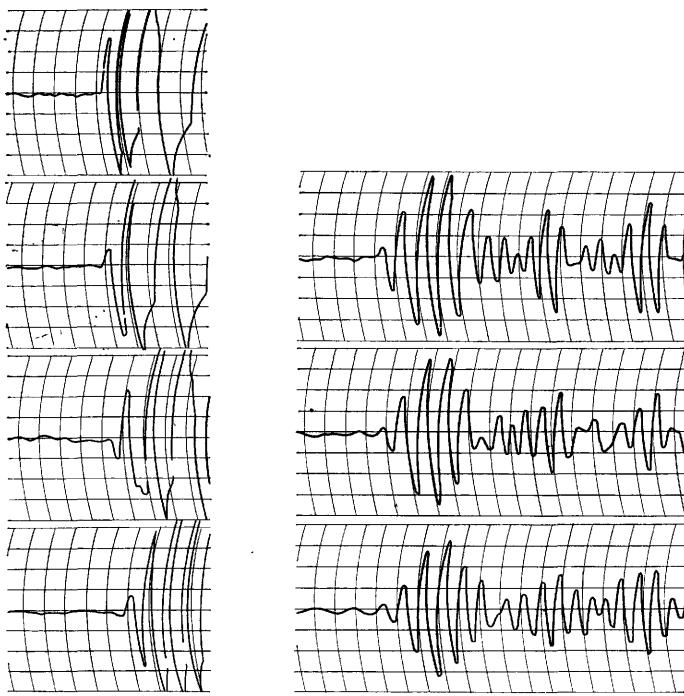


FIGURE 230.—Oscillograms of (A) the first four  $\frac{1}{2}$ -pound shots south of point B and (B) three 80-pound shots at the outer end of the profile extending 80 km south of point C.

#### VELOCITIES

Even though many parts of the shooting lines were traversed by the firing ship as much as 5 and 6 times, it is apparent that the distance over any one layer in which true reversed control was established is very small.

Consequently no attempt was made to determine true velocities for specific areas as was done at Bikini, where the reversed control of the third layer was better than at Eniwetok. Instead, velocities for each layer were averaged for the entire survey and a single velocity value, used for the entire area of the survey, was determined for each layer.

In making the averages it was assumed that the variations in apparent velocity were due primarily to irregularities in the thickness of the overburden rather than to changes in true velocity. Hence, following the procedure of equation 4, the harmonic mean of the apparent velocities is taken as the best measure of velocity in the formation. Not all of the data are equally suitable for this average. Some of the first arrivals are of poor quality, water delays may be of doubtful accuracy because of rough bottom topography, and drift of the receiving ship over a sloping bottom may give a spurious slope to the time-distance curve. The velocity segments that have been used in the averages are listed in the following table.

Station	Profile direction	Apparent velocity (kmps)	Station	Profile direction	Apparent velocity (kmps)
First Layer					
A	NW	2.37	E	NW	2.40
	SW	2.29		NE	2.65
B	S	2.24	G	SW	2.48
	SW	2.33		W	2.40
C	S	2.33		E	2.56
	N	2.52	F	NE	2.29
D	S	2.65		E	2.61
	N	2.67	Harmonic mean velocity		
	SE	2.61			
	W	2.56			
	E	2.38			2.44

Station	Profile direction	Apparent velocity (km/p)	Station	Profile direction	Apparent velocity (km/p)
Second layer					
A.....	SW	2.65	E.....	SW	3.20
B.....	S	2.67	G.....	NE	3.27
B.....	SW	2.96	F.....	W	3.24
C.....	S	3.20	H.....	NE	2.96
C.....	N	3.07		SE	2.96
D.....	S	3.20		NW	3.01
D.....	N	3.27			
	SE	3.17	Harmonic mean velocity		3.06
	W	3.20			
	E	3.14			
Third layer					
A.....	SW	3.89	F.....	SE	4.21
B.....	SW	4.04	I.....	NW	4.10
B.....	S	4.39		W	3.94
C.....	N	4.59	M.....	E	4.33
C.....	S	3.45	J.....	W	4.04
D.....	N	4.33	K.....	S	4.39
D.....	W	4.10	K'.....	N	4.39
E.....	NW	4.15	H.....	W	4.15
G.....	W	4.33			
F.....	NE	3.84	Harmonic mean velocity		4.15
Fourth layer					
B.....	S	5.73	G.....	W	5.30
C.....	SS	5.91	F.....	SE	5.80
C.....	S	5.69	J.....	W	5.69
D.....	S	5.39			
D.....	N	5.30	Harmonic mean velocity		5.39
E.....	SE	5.30			
	NW	5.80			
Fifth layer					
A.....	NW	6.68	J.....	W	6.98
G.....	E	7.12			
I.....	NW	6.83	Harmonic mean velocity		6.90
Sixth layer					
A.....	NW	7.88	J.....	W	7.84
I.....	NW	8.34			
			Harmonic mean velocity		8.09

### SUBSURFACE STRUCTURE

Following the foregoing principles of theoretical interpretation, depths to the interfaces between the 6 principal layers have been estimated for the 2 north-south and east-west sections across the atoll and plotted in figures 231 and 232.

In these figures hachured interfaces indicate that the refracted waves from shots fired above that part of the interface have been received with a velocity corresponding to the layer immediately below. The dashed interfaces are extrapolations and interpolations from the areas of direct observations. The necessity of making these assumptions in order to calculate depths to deeper layers is one of the principal sources of error, for an error in estimating these dashed interfaces will be reflected in an error in the hachured interfaces beneath them. Because of the preponderance of dashed interfaces on the flanks of the atoll and in the deeper layers, the structure in these areas is necessarily schematic and the error can be large. For the shallow

layers beneath the lagoon, the concentration of observations gives more complete control and more accurate detail.

### REEF STRUCTURE

The detailed profile (fig. 225) across the reef northwest of Elugelab indicates the presence of a thin, low-velocity layer on the reef surface in which the seismic velocity is 1.92 km/p. The thickness of this layer is calculated to be 108 m, which puts the depth of its base about 50 or 60 m below the average depth of the lagoon. It is of interest to note that this depth is of a reasonable order of magnitude for a previous glacial lowering of sea level (Daly, 1910). It is nearly the same as the depth of the volcanic basement beneath Bermuda (Officer, Ewing, and Wuenschel, 1952), at 60 to 100 m, believed to have been eroded to sea level during the Pleistocene epoch. The lower seismic velocity in the material deposited since that time may be a result of relatively rapid deposition, or it may merely indicate that the relatively cavernous structure of the outer reef results in a lower seismic velocity than in the lagoon deposits. The properties of this low-velocity layer are similar to the layer indicated in the first survey of Bikini (Dobrin, 1950) at receiving stations on the periphery of the lagoon.

### FIRST AND SECOND LAYERS

The first and second layers are considered together because drilling has shown that beneath the atoll they represent calcareous deposits formed by reef and lagoon organisms (Ladd, Ingerson, Townsend, and others, 1953). Velocities of 2.44 and 3.06 km/p, respectively, in these layers are characteristic of partly consolidated sediments.

The first layer is probably composed of material very similar to that now forming the lagoon floor. Although the short-range travel times show irregularities indicating inhomogeneity, there is no consistent tendency for the time-distance curve to have a positive intercept when projected to the time axis, which would be expected if there were a lower velocity layer above the first zone mapped. The observed irregularity in the arrival times of the pulses reduces the possibility of detecting a thin overlying layer, and it is possible that a layer of 2 km/p velocity and 50 m thickness, for example, would not be observed.

The thickness of the first layer decreases regularly from about 600 m at the edge of the atoll to about 200-300 m in the center. The discontinuity at its base is not definitely established, since the observations could also be explained by a moderately rapid increase of velocity with depth in the upper few hundred meters

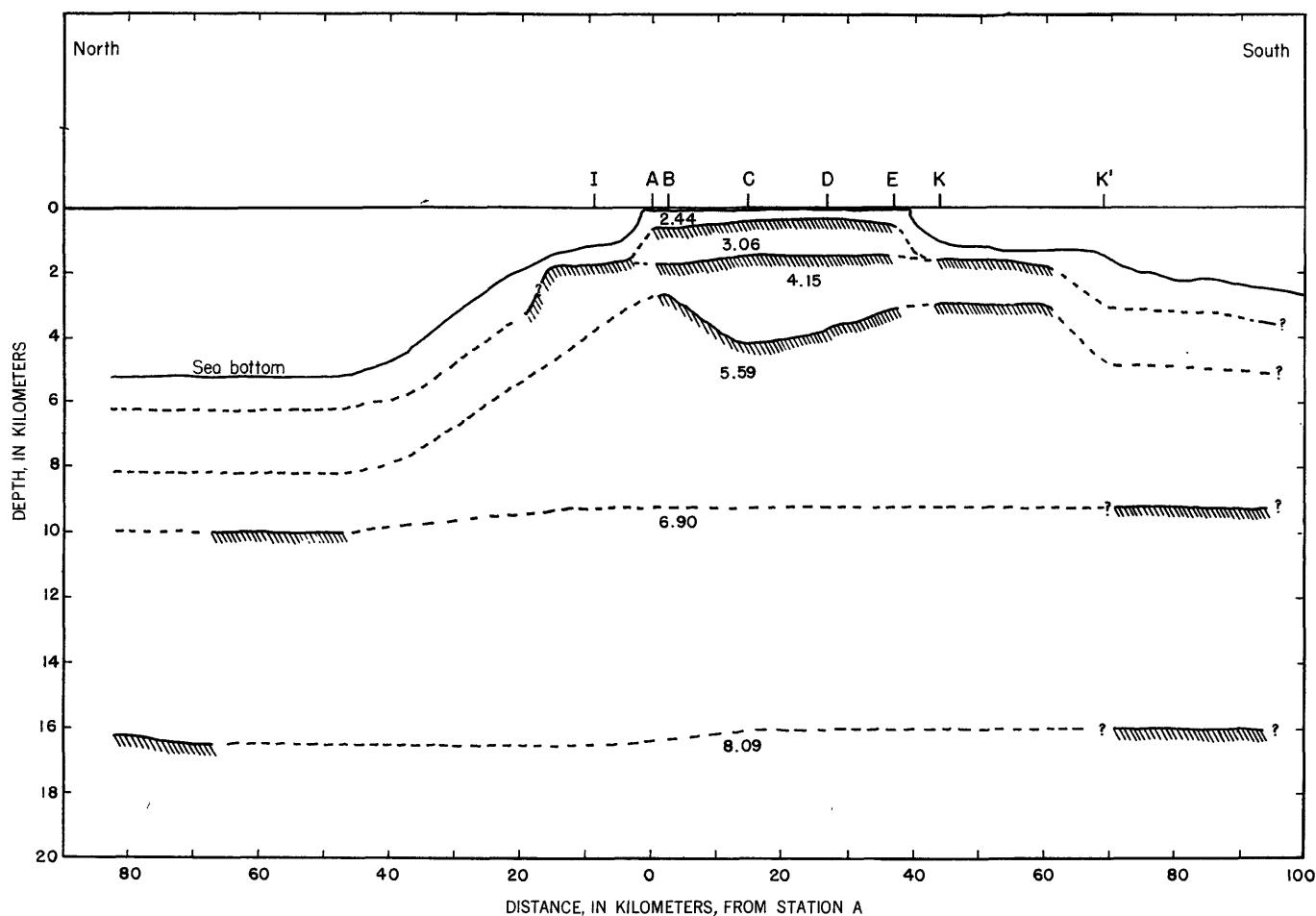


FIGURE 231.—Hypothetical subsurface section through Eniwetok Atoll from north to south. Velocities are in kilometers per second.

due to compaction caused by pressure of the overlying material.

The second layer is about 1 km thick. The irregular variation in thickness indicated by the time-distance graphs is probably no greater than the experimental error in reading arrival times and calculating the water delay. There is no systematic change of thickness toward the center of the lagoon. In calculating the structure outside the lagoon, the second layer was assumed to be absent since no direct evidence of its presence was obtainable.

#### THIRD LAYER

The third layer (4.15 kmmps) is found at all points of the seismic survey to be deeper than the points at which it was penetrated by the drilling that identified it as volcanic rock (Ladd, Ingerson, Townsend, and others, 1953). It is difficult to explain why the seismic observations show this layer to be deeper than was determined by drilling. It is possible that the horizontal velocity in the first and second layers may

be greater than the vertical velocity, owing to the presence of thin layers of consolidated material in which the velocity is higher. For example, if the second layer consists of 2 strata, an upper, thin stratum of hard rock in which the seismic velocity is 3.06 kmmps and a lower, thick stratum in which the seismic velocity is about 2.44 kmmps, the average vertical velocity would be such that the calculated depth to the third layer would be in agreement with the drilling results. Also, the upper part of the volcanic formation may be highly fractured or vesicular. Its average compressibility could be quite high, hence the velocity in it could be low even though the drilling was very hard through individual blocks. The velocity in such a formation might be little greater than the 3.06 kmmps in the second layer and would be masked by it.

#### FOURTH LAYER

A seismic velocity of 5.59 kmmps, the velocity in the fourth layer, is characteristic of a hard crystalline rock. It is in close agreement with one of the few values, 5.6 kmmps, identified with basalt in the literature (Brock-

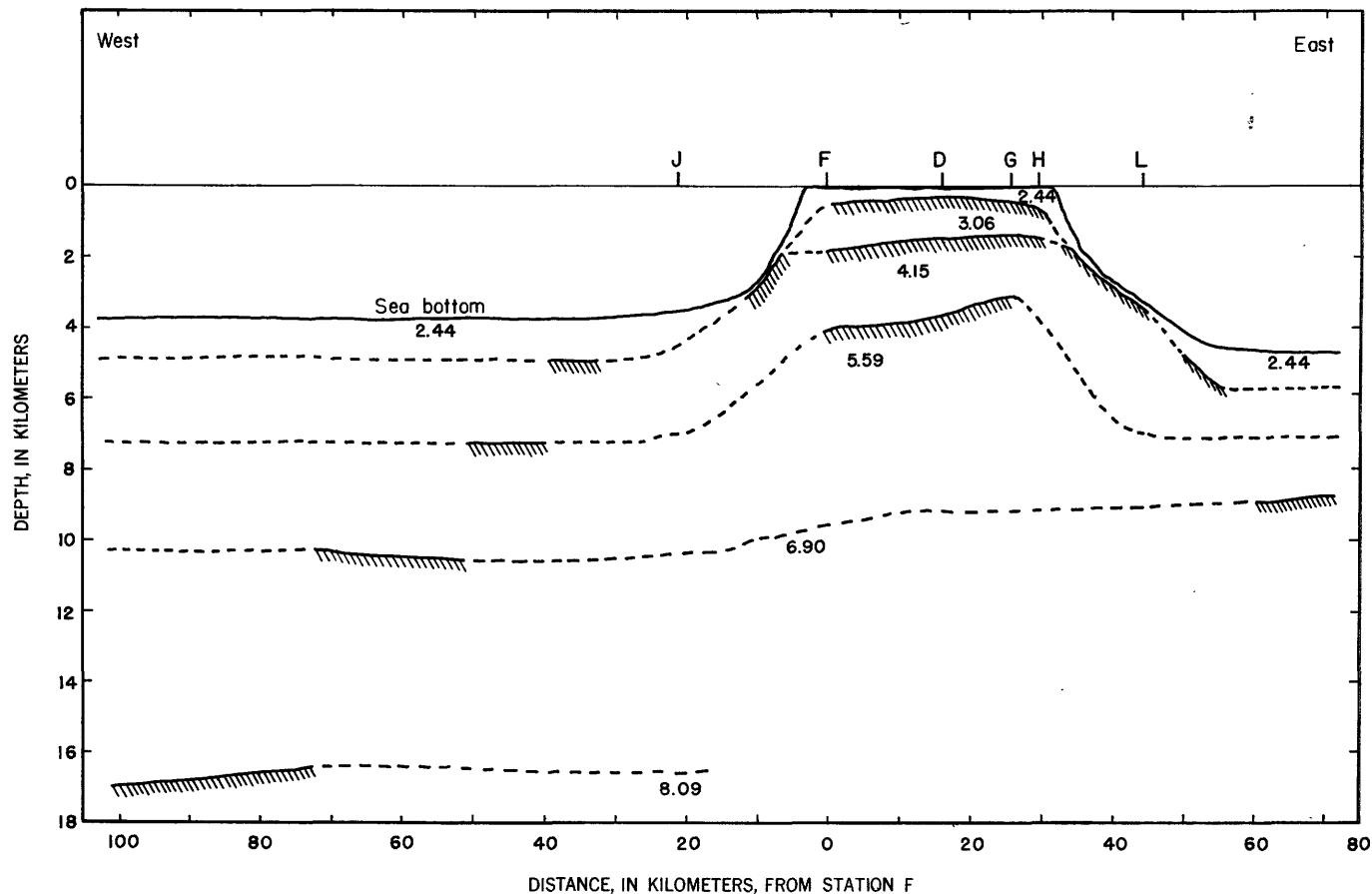


FIGURE 232.—Hypothetical subsurface section through Eniwetok Atoll from west to east. Velocities are in kilometers per second.

amp and Wölcken, 1929). The plotted interface between the third and fourth layers does not necessarily indicate a structural or lithologic discontinuity. It merely indicates the approximate depth at which a velocity of 5.59 km/s is reached. It is possible that the fourth layer is largely plutonic rock intruded from below, while the third layer is mostly extruded. On the other hand, it may all have been extruded. The higher velocity in the fourth layer could then be attributed to compaction or consolidation produced by the pressure of the rocks above.

#### FIFTH LAYER

The velocity of 6.90 km/s in the fifth layer identifies it with the crustal layer in the Pacific basin (Raitt, 1956) which has a velocity between 6.5 and 7.0 km/s. This is higher than field measurements of velocities in known rocks, and it may represent a rock type never observed at the earth's surface. Current petrologic doctrine indicates that it represents a dense basic rock, probably olivine basalt. Its depth below sea level, 9–10 km, is greater than the 7- to 9-km depth at Bikini (Raitt, 1954), and substantially greater than the 5- to

8-km depth considered to be characteristic of the Pacific basin.

Because it was observed at only a few places, its depth can only be roughly indicated, and practically nothing has been learned about the form of its surface. At the southern end of profile A-K' (see fig. 221) the great irregularity of the points, owing to subsurface anomalies of unknown character, made it uncertain as to whether the pulses received had been refracted through the 6.90 km/s or the 8.09-km/s layer. The depths are therefore questionable, although consistent with those obtained on other profiles.

#### SIXTH LAYER

The velocity of 8.09 km/s in the sixth layer is characteristic of the velocity found at the base of the earth's crust below the Mohorovičić discontinuity. Its depth, 16–17 km, is greater than at Bikini (13 km). This is due primarily to the great depth of the fifth layer, whose thickness, about 6.5 km, is not much greater than that observed at Bikini or generally throughout the Pacific basin.

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