SEISMIC REFRACTION MEASUREMENTS IN THE ATLANTIC OCEAN BASIN*

(PART ONE)

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ABSTRACT

A REVERSED seismic refraction measurement was made 120 miles northwest of Bermuda (400 miles east of Cape Hatteras) in 2,800 fathoms of water. A velocity of 24,800 feet per second (7.58 km/sec.) for the second layer was identified with the ultrabasic layer of earthquake seismology. Assuming a velocity of 5,600 feet per second (1.70 km/sec.), clearly indicated by earlier measurements, a thickness of 4,500 feet was obtained for the sedimentary layer. The granitic and intermediate layers were absent.

I. INTRODUCTION

A RECENT passage of the research vessels ATLANTIS and CARYN from Woods Hole to Bermuda gave the first opportunity to use two ships in an offshore seismic refraction profile, all previous work of this kind having been done with

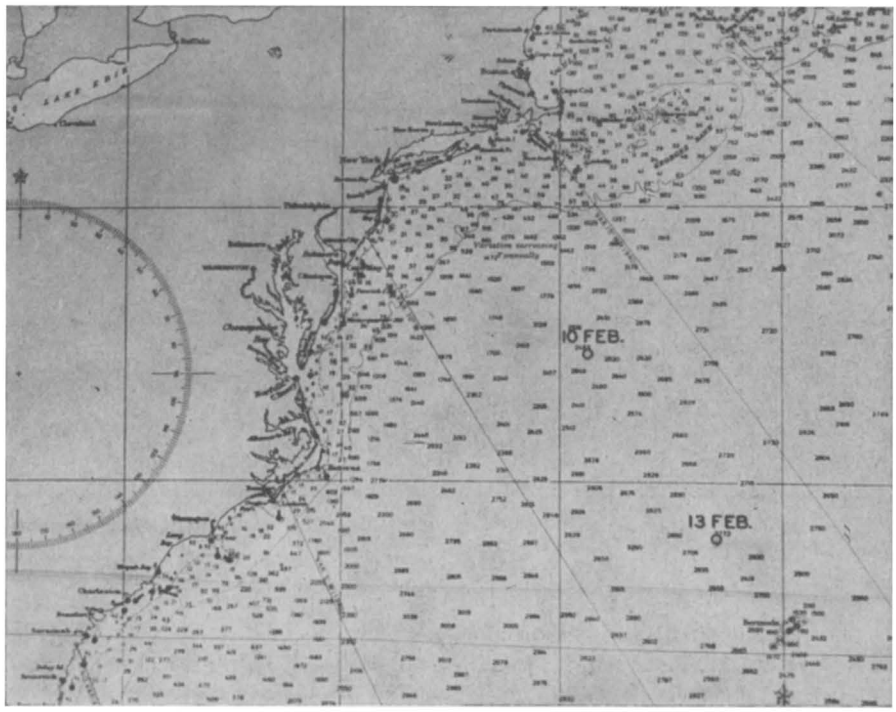

Fig. 1. Station locations.

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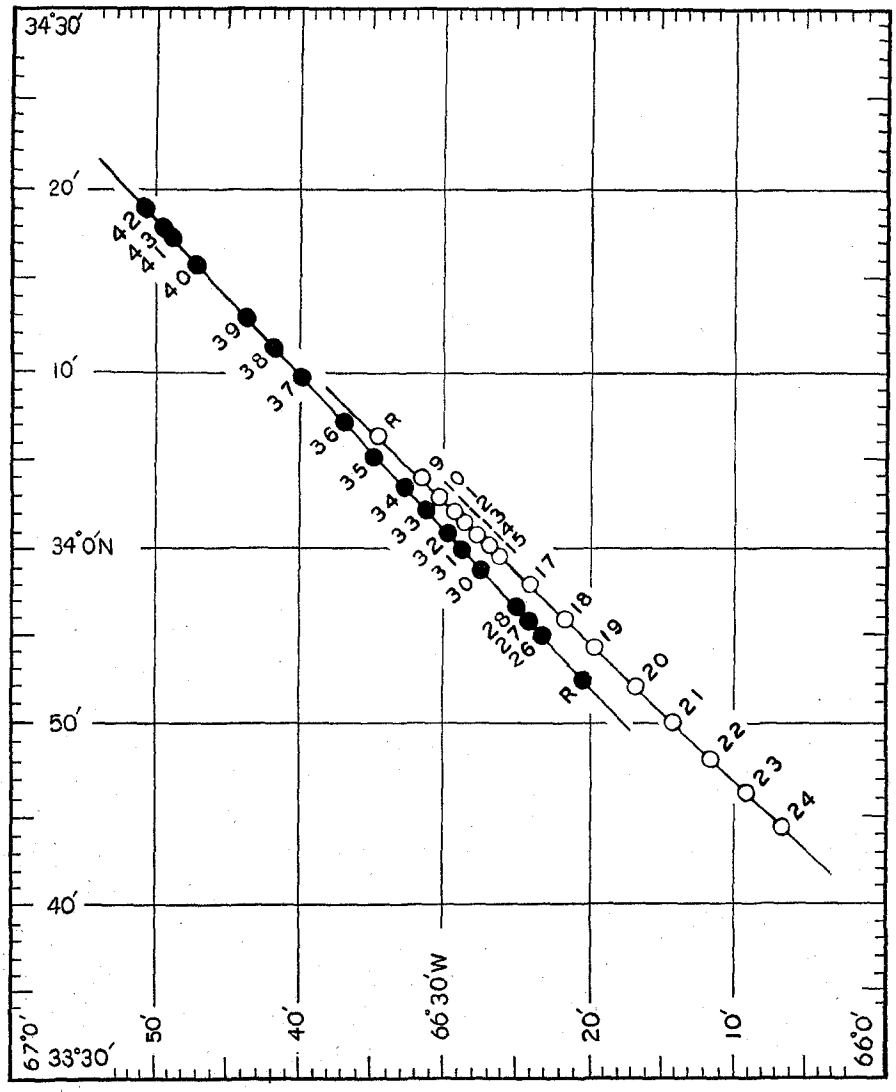

Fig. 2. Station chart, February 13, 1949. Legend: ○, Profile I; ●, Profile II; ●R, receiving vessel; ○R, receiving vessel.

a single ship and a twenty-foot whaleboat. Time was allotted for two reversed profiles, but stormy weather caused cancellation of the first one after shots up to seven miles distance had been made at latitude 37° 23′ N and longitude 69° 23′ W on February 10, 1949. On February 13, in an area about 125 miles northwest of Bermuda, in 2,800 fathoms, at latitude 34° N and longitude 66° 30′ W (fig. 1), a complete reversed refraction profile was made.

II. Acknowledgments

This work was done as part of a longer cruise during February and March, 1949, by the research vessels Atlantis and Caryn of the Woods Hole Oceanographic Institution under its contract NObs-2083 with the Navy Department, Bureau of Ships. Additional equipment, material, and personnel for this part of the cruise were supplied by the following agencies: Penrose Fund of the Geological Society of America; Office of Naval Research, contract M6-onr-271; and the Geophysical Research Directorate, Cambridge Field Station, A.M.C., U. S. Air Force, Contract W-28-099-ac-396.

III. Method of Measurement

Figure 2 shows the locations of shots 9 to 24 made by the Atlantis while running to about 35 miles on course 140° T from the first receiving position of the Caryn. This constitutes Profile I. Profile II, consisting of shots 26 to 43, was made with the Caryn about 18 miles 140° T from her first position and with the Atlantis running about 35 miles on course 310° T. The charges ranged up to 300 lbs., and were all fired under way. The operation required 11 hours, and produced the most complete refraction profile beyond the continental margins known to us.

The travel time of the seismic signals was determined by recording on the seismogram a radio signal sent from the shot point at the instant of the explosion. As a safeguard against missed radio signals, events at both vessels were related to absolute time by the aid of WWV time signals. Loran coverage was good and the positions of both vessels were checked frequently by Loran. The actual distance between vessels for each shot was determined from the travel time of the direct sound transmitted through the water.

The seismic detector was a hydrophone floated at a depth of about 50 feet about 100 feet from the Caryn. The amplifying and recording system had several channels for recording both the high-frequency water waves and the lower-frequency ground waves.

IV. Results

Figure 3 shows the seismograms for shots 11, 12, 13, 15, and 20. The ground waves are marked with G, the direct water waves by D, and the first reflection R. The numerals represent travel time in seconds. The first two traces on shot 11 are a high-frequency rectified channel, the third and fourth are dead, the fifth is an intermediate-frequency channel, and the sixth to ninth are low-frequency channels. It will be noted that the first four traces are covered, to conserve space, on all other shots, and that the paper speed was reduced by a factor of about 4 on shot 20. This series of records illustrates the many characteristic features of the phases R, G, and D, which distinguish them, and also

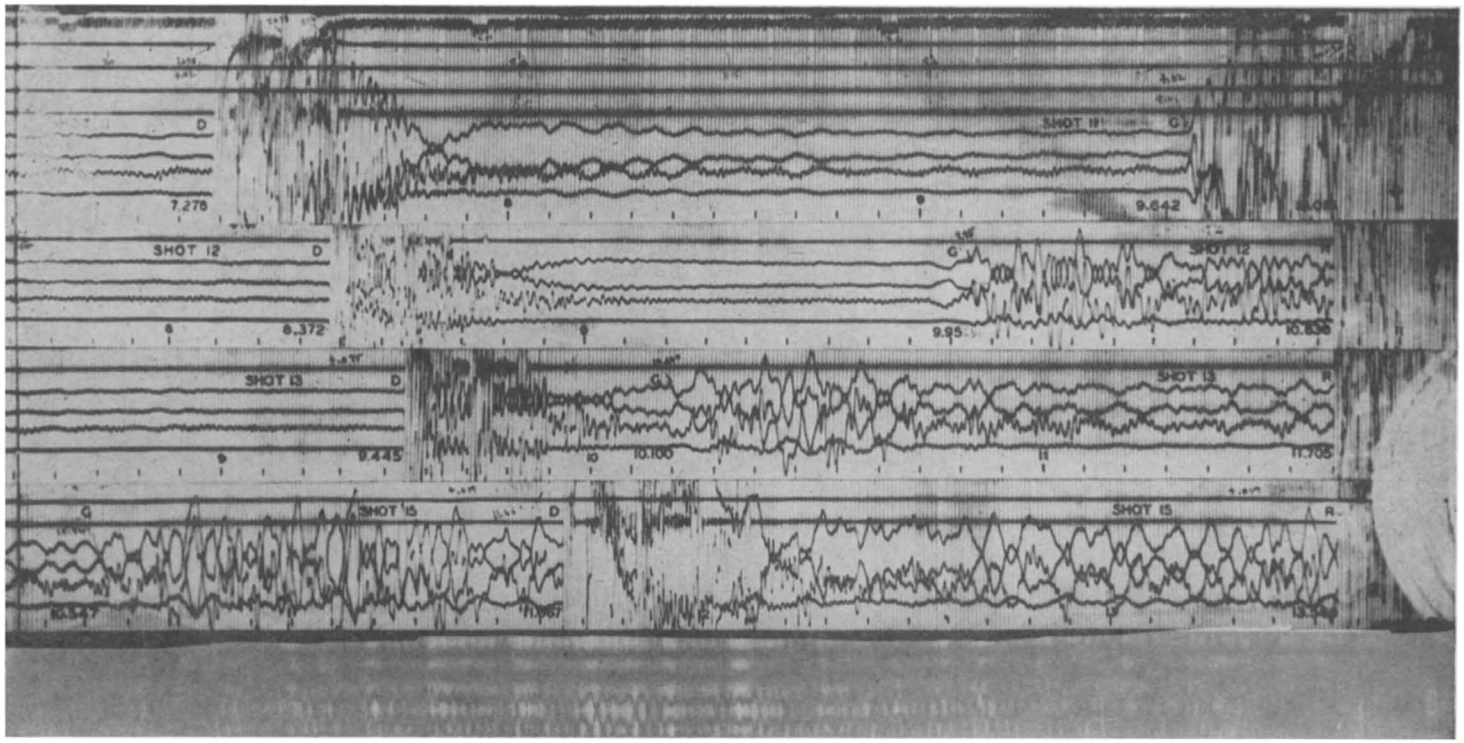

Fig. 3. Representative seismograms where G is travel time of ground wave, D is travel time of direct water transmission, and R is travel time of first bottom reflection. Travel time is given in seconds.

TABLE 1

Shot no.	Charge	Explosion instant	Water travel time	Ground wave	Bottom reflections			Ground-wave residual[a]
					R_1	R_2	R_3	
	lbs.		*sec.*	*sec.*	*sec.*	*sec.*	*sec.*	*sec.*
9	4.5	095523.56	4.16	.....	8.032	14.365	21.09	.....
10	4.5	100842.97	5.84	.....	9.028	14.966	21.48	.....
11	25	101907.53	7.28	9.642	10.018	15.560	21.960	−.069
12	25	102713.14	8.37	9.95	10.838	16.077?	22.27	+.024
13	25	103422.86	9.45	10.100	11.705	16.675	22.735	−.045
15	25	105052.95	11.67	10.547	13.569	18.002	23.667	−.026
17	55	112058.22	.....	.....	.....	.....	.....	.....
18	300	113924.27	.....	.....	.....	.....	.....	.....
19	300	115921.75	20.67	.....	21.83	24.80	29.27	+.150
20	300	121949.76	24.62	13.13	25.61	28.23	32.11	+.015
21	300	124011.96	28.06	13.82	28.93	31.27	34.90	+.030
22	300	130007.85	31.64	14.50	32.45	34.57	37.76	+.007
23	300	132002.33	35.08	15.16	35.83	37.76	40.76	−.008
24	300	134032.42	38.37	15.78	39.00	40.81	43.55	−.074
26	4.5	161937.62	4.185	.....	8.019	14.337	20.967	.....
27	4.5	162623.62	5.465	.....	8.781	14.765	21.44	.....
28	25	163346.33	6.80	.....	9.662	15.250	.....	.....
30	25	165540.30	10.27	10.090	12.38	17.10	.....	−.146
31	25	170540.50	12.14	10.580	13.970	18.308	.....	+.126
32	25	171311.88	13.59	10.760	15.253	19.340	24.77	−.002
33	55	172426.32	15.72	11.180	17.182	20.900	25.92	−.020
34	55	173548.52	17.94	11.765	19.270	22.634	27.32	+.106
35	55	175043.21	20.65[b]	12.290	.....	.....	.....	.....
36	55	180716.34	23.94	12.958	24.990	27.673	31.64	+.062
37	300	183028.30	28.17	13.80	29.06	31.40	34.93	+.031
38	300	184522.70	30.95	14.40	31.77	33.92	37.19	+.057
39	300	190030.15	33.66	14.83	34.42	36.43	.....	−.076
40	300	193050.69	38.72	15.97	39.37	41.19	43.92	+.025
41	300	194521.42	41.28	16.30	41.91	43.36	46.26	−.172
42	300	195934.60	.....	.....	.....	.....	.....	.....
43	300	201527.54	.....	.....	.....	.....	.....	.....

[a] Residuals are observed times less times calculated from $T = 8.283 + X/25{,}500$ for Profile I and from $T = 7.959 + X/24{,}200$ for Profile II.
[b] Water wave not recorded—interpolated from neighboring shots.

the advantageous fact that D is brief, permitting G to be read in the interval between D and R.

The list of data taken from each shot is shown in table 1 and the travel-time curves for both profiles are plotted from a common origin in figure 4, where the squares represent Profile I and the circles represent Profile II. The abscissas are water-wave travel times in seconds, which may be considered as the distance between the two ships in units of 5,000 feet. The ground waves lie

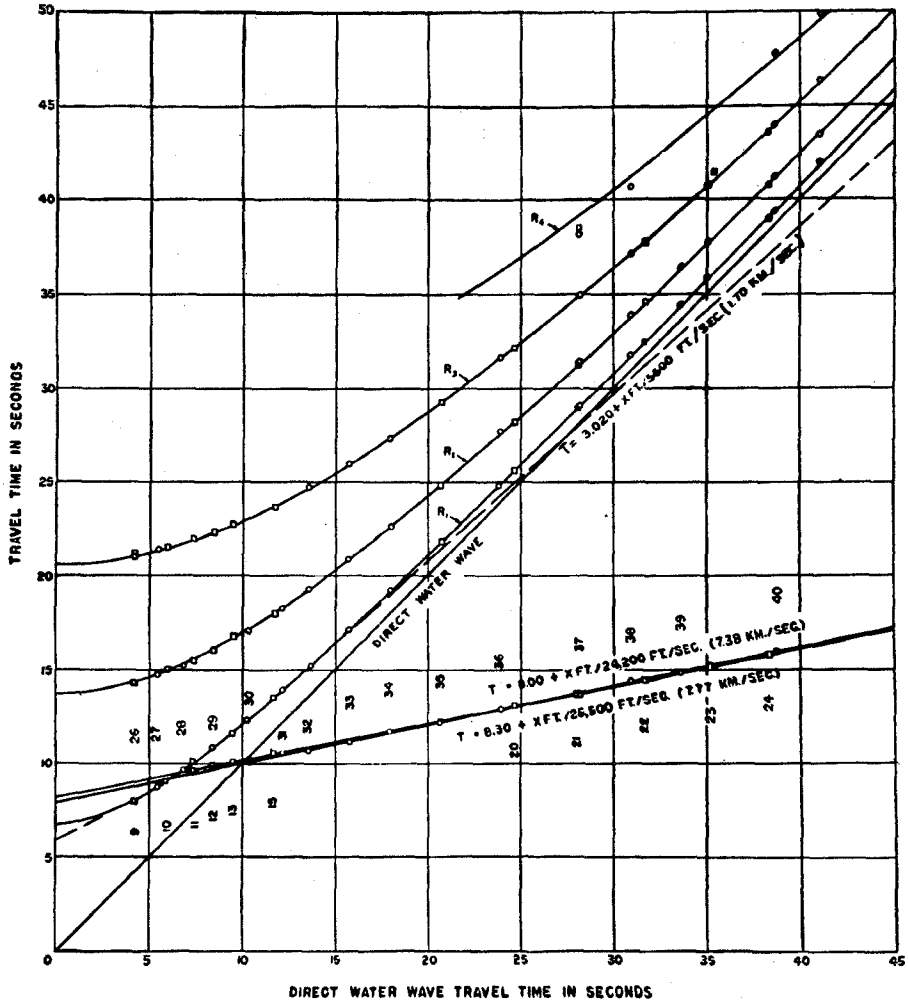

Fig. 4. Travel-time curves. Legend: ○, receiving station, 34° 06′.5 N, 66° 35′ W, shot station azimuth, 140° T; ● receiving station, 35° 52′.5 N, 66° 20′.5 W, shot station azimuth, 310° T.

on two slightly different straight lines which intersect at about 27 seconds or about 22.5 miles, which compares well with the distance of 18 miles separating the two positions of the CARYN. The close agreement of the two "apparent velocities," namely, 24,200 ft/sec. or 7.38 km/sec. and 25,500 ft/sec. or 7.77 km/sec., indicates that only a very slight slope is present in the basement surface and that the true velocity in the basement rocks is 24,800 ft/sec. or 7.58 km/sec.

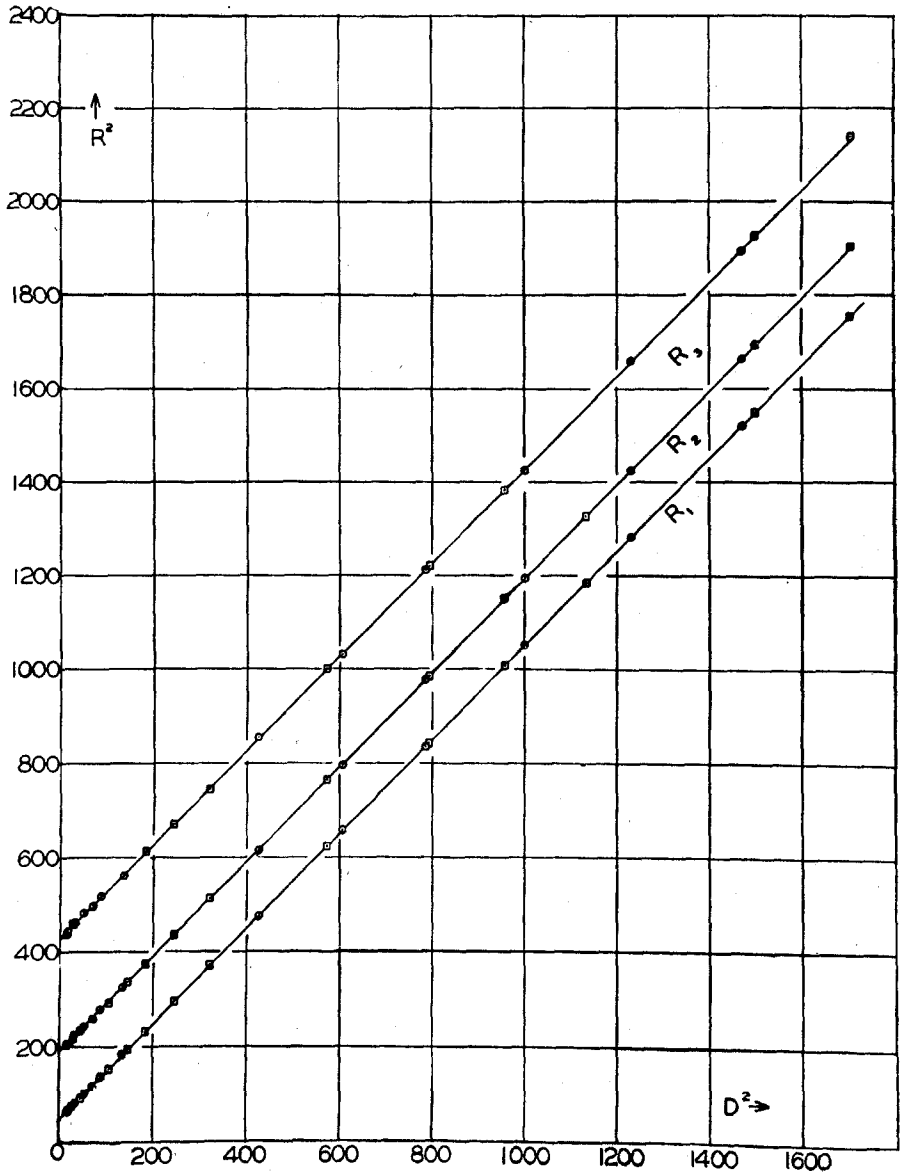

Fig. 5. Graph of R^2 vs. D^2 where R is the travel time of the first bottom reflection and D is the travel time of direct water transmission

The curves R_1, R_2, and R_3 are the reflections of various orders from the ocean floor, and squares and circles lie on common curves. The fact that the ground-wave curves cut across the reflection hyperbola R_1, instead of coming tangent to it, shows the presence of a layer of low-velocity medium (presumably unconsolidated sediment) between the ocean floor and the basement surface. In our other work, mostly unpublished, the velocity of sound in this sedimentary layer has been given as 5,600 ft/sec. or 1.70 km/sec. by a strong masked phase emerging from the R_1 hyperbola at about 14 seconds. In the present profile this phase is absent, possibly because the velocity is even less than 5,600 ft/sec. Despite this absence, we have used the velocity 5,600 ft/sec. shown by the dashed line in figure 3, in computing the thickness of the sedimentary layer, finding it to be 4,500 feet, with a slope of 20 minutes. The absence of this phase will be investigated in subsequent work. The theory that a variation in absorption coefficient is responsible is one which will be tested.

Some question might be raised about the identification of the direct water wave and some of the bottom reflections at longer distances. The validity of treating the refraction paths through the water as straight lines might also be questioned. Consequently, in figure 4, the squares of the water-wave times (distances) have been plotted as abscissas, and the squares of the reflection times R_1, R_2, R_3, etc., as ordinates. These quantities are related by the equations

$$R_1^2 = D^2 + H^2$$
$$R_2^2 = D^2 + 4H^2$$
$$R_3^2 = D^2 + 9H^2$$

where D is the direct water-wave travel time and H is the time which would be required for a vertical reflection from the ocean floor.

In figure 5 it is seen that the lines for the various orders of reflection are straight and have intercepts in the ratios 1 : 4 : 9, etc. Thus identification and treatment of the direct and bottom reflected waves is on a firm basis.

V. Discussion

The velocity 7.58 km/sec., found here under 2,800 fm. (5.13 km.) of water and 4,500 ft. (1.37 km.) of sediment, compares well with the velocity 7.78 km/sec. at a depth of 38 km. near Albany, N. Y., and 7.76 km/sec. at a depth of 25 km. near New Haven, Conn., as found by Slichter* from studies of quarry blasts. It also compares well with the value 7.747 km/sec. at a depth of 33 km. given by Jeffreys (1939) as a world average of P_n, particularly when we note that extrapolation of this velocity back to zero depth by use of the rate of increase of .003 km/sec/km. deduced from his velocity-depth table gives 7.65 km/sec. Byerly (1946) found 7.72 km/sec. at a depth of about 14

* Personal communication, in which Professor Slichter kindly made available to us his preliminary results.

km. from the Port Chicago explosion, but he has found 8.0 km/sec. for the speed of P_n in central California. He suggests that the speed of P_n may be lower in northern California. Gutenberg (1944) gave 6.91 km/sec. for the second intermediate layer at depths of 22 to 23 km.

Leet (1938 and 1941) gave for P_n 8.43 km/sec. at a depth of 36 km. in New England.

Hodgson (1947) examined a profile extending from the Canadian Shield to New England and found for P_n 8.2 km/sec. at a depth of 36 to 47.5 km. Tuve *et al.* (1948) found 7.05 km/sec. at a depth of 24 km. and 8.15 km/sec. at a depth of 42 km. in the Washington, D.C., and Maryland area. Reich *et al.* (1948) found 6.55 km/sec. at a depth of 21 km. and 8.2 km/sec. at a depth of 31 km. in the southern part of the Black Forest in Germany. Rothé *et al.* (1948) found 6.41 km/sec. at 16 km. and 8.13 km/sec. at 31 km. from the same region. The British National Committee for Geodesy and Geophysics (1948) reports 8.10 km/sec. at a depth of 26½ km. in northern Germany. Gutenberg (1946) found 7.99 km/sec. and 8.04 km/sec. for P_n in the New Mexico–Arizona–southern California area.

We had originally decided to identify our velocity 7.58 km/sec. with P_n on the basis of Jeffreys' world average, but as the result of advice generously given by Byerly and Gutenberg we have decided that there must be kept open the possibility that it is the lower part of the intermediate layer. The decision between these possibilities can be made from longer refraction profiles in the oceans, from refraction studies over the continental margins, or from a more concordant value of P_n from seismologists.

The significance of the present result will be increased if in subsequent work it is found to be typical of the entire ocean basin. A companion paper on the implications of this result for earthquake surface wave dispersion has been submitted for publication.

Summary

A reversed seismic refraction profile was made a latitude 34° N, longitude 66° 30′ W, in 2,800 fathoms of water, 400 miles east of Cape Hatteras and 120 miles northwest of Bermuda. The basement rock was found to have a velocity of 24,800 ft/sec. (7.58 km/sec.). No velocity was determined for the sedimentary cover. Using the value 5,600 ft/sec. (1.70 km.) for this layer, as indicated by earlier measurements, a thickness of 4,500 ft. (1.37 km/sec.) was obtained.

(Contribution 483 from the Woods Hole Oceanographic Institution).
Lamont Geological Observatory
(Columbia University)
(Contribution No. 10).

References

British National Committee for Geodesy and Geophysics
1948. "Report of Seismic Work on the North German Explosions, 1946–47." I.G.U. meeting, Oslo, 1948.

Byerly, Perry
1946. "The Seismic Waves from the Port Chicago Explosion," *Bull. Seism. Soc. Am.*, 36:331–348.

Gutenberg, B.
1944. "Reflected and Minor Phases in Records of Near-by Earthquakes in Southern California," *Bull. Seism. Soc. Am.*, 34:137–160; see p. 140.
1946. "Interpretations of Records Obtained from the New Mexico Atomic Bomb Test, July 16, 1945," *Bull. Seism. Soc. Am.*, 36:327–330.

Hodgson, J. H.
1947. "Analysis of Travel Times from Rockbursts at Kirkland Lake, Ontario," *Bull. Seism. Soc. Am.*, 37:5–17.

Jeffreys, Harold
1939. "A Further Study of Near Earthquakes," *Mon. Not. Roy. Astron. Soc., Geophys. Suppl.*, 4:196; also pp. 510 and 571.

Leet, L. D.
1938. "Travel Times for New England," *Bull. Seism. Soc. Am.*, 28:45–48.
1941. "Trial Travel Times for Northeastern America," *Bull. Seism. Soc. Am.*, 31: 325–334.

Reich, H., G. A. Schulze, and O. Förtsch
1948. "Das geophysikalische Ergebnis der Sprengung von Haslach im sudlichen Schwarzwald," *Geologische Rundschau*, 36:85–96.

Rothé, J. P., E. Peterschmitt, and P. Stahl
1948. "*Les Ondes séismiques des explosions.*" I.G.U. meeting, Oslo.

Tuve, M. A., *et. al.*
1948. "Studies of Deep Crustal Layers by Explosive Shots," *Trans. Am. Geophys. Union*, Vol 29, No. 6, p. 772.