SEISMIC REFRACTION MEASUREMENTS IN THE ATLANTIC OCEAN, PART VI: TYPICAL DEEP STATIONS, NORTH AMERICA BASIN*

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INTRODUCTION

IN THE spring of 1951, thirty-three deep-sea refraction stations were made by the members of Lamont Geological Observatory, Columbia University, on the research vessels ATLANTIS and CARYN of the Woods Hole Oceanographic Institution. This paper contains the results of six of these stations, three of which were made in the region to the south of Bermuda and three in the region to the northwest of Bermuda (see fig. 1). The crustal structure reported in this paper is considered to be typical of the crust of the western North Atlantic. The measurement at a single station reported in Part I of this series of papers (Ewing *et al.*, 1950*a*)[1] is recalculated, the basement rocks being subdivided into two layers in the new calculation to conform with the result which is firmly established for the six new stations. Two other groups of stations were shot in the Carribean Sea–Puerto Rico Trough area, and on the continental shelf and slope south of Cape Cod, Massachusetts. The results of a third group in the Bermuda, Bermuda Rise, and northern part of the Nares Basin areas have been included in Part IV of this series, Officer *et al.* (1952).

The equipment and the method of investigation and interpretation have been discussed in other parts of this series, Ewing *et al.* (1950*a*), Tolstoy *et al.* (1953), and Officer *et al.* (1952), and will not be repeated here.

STATIONS

Stations 16, 17, and 18 were shot in the region south of Bermuda known as the Nares Basin. This region is flat over a large area at a depth of 5.8 km. (3,200 fathoms) and extends south and southeast from the Bermuda Rise to the ridge north of the Puerto Rico Trough. Stations 16 and 17 were shot in the flat part of the Nares Basin and station 18 in the hilly topography on its northern perimeter.

Stations 27 and 28 were shot in the region northwest of Bermuda. This region is flat at a depth of 5.0 km. (2,700 fathoms). Station 29 was shot in the bordering region near the base of the Continental Rise. (The Continental Rise is the gently sloping area, about 0.5 degree, between the bottom of the Continental Slope and the deep basins.)

Three refraction horizons were measured: a sedimentary layer G_1 coincident with the bottom of the ocean and having a velocity of about 1.8 km/sec. and a thickness of 0.5 to 2.0 km., an intermediate layer G_2 having a velocity of about 6.5 km/sec. and a thickness of 2.3 to 6.0 km., and a lower layer G_3 having a velocity of about 7.9 km/sec. and thickness too great to measure by the present methods. In addition to the refraction arrivals through G_1, G_2, and G_3, the direct wave traveling from the shot to the hydrophone in the surface sound channel (D) and the first, second, third, etc., bottom reflections (R_1, R_2, R_3, · · ·) were received (see fig. 2). On all the stations a straight line was found graphically for G_1, G_2, and G_3, respectively, that best satisfied the reverse points and the observed travel times.

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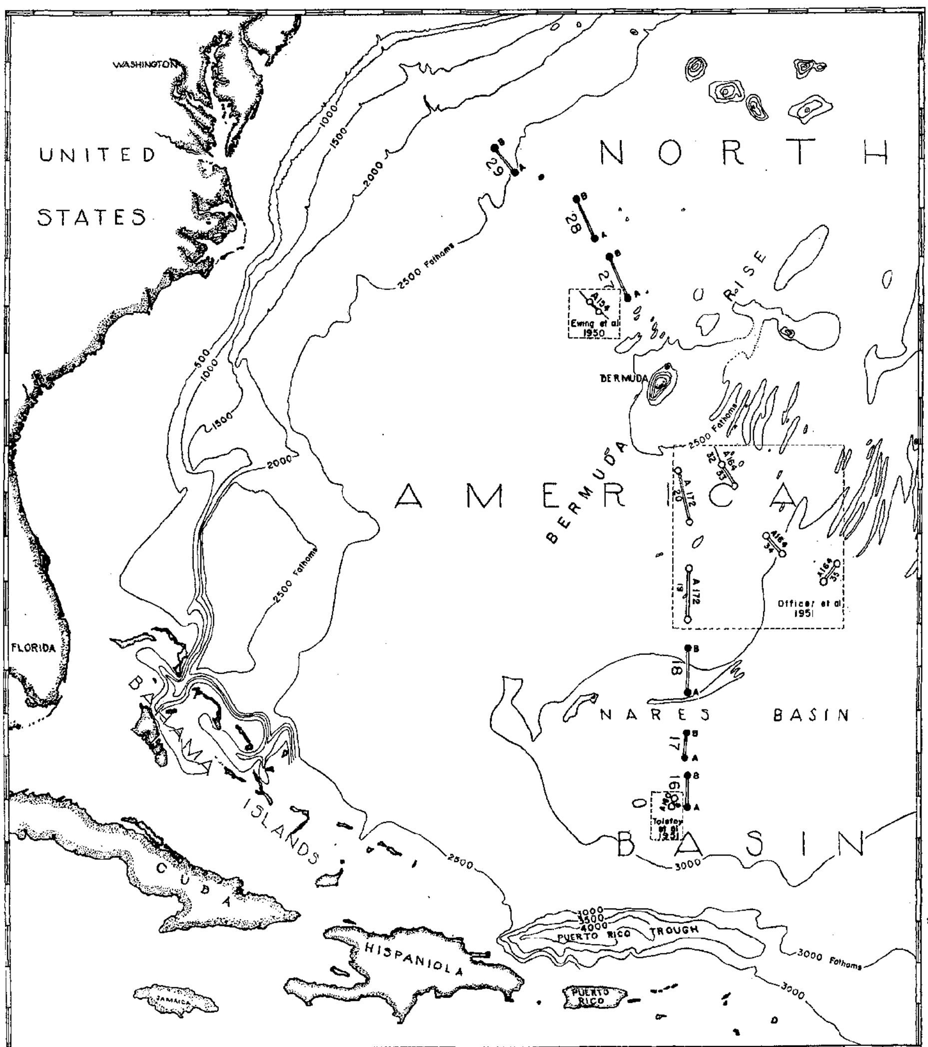
[1] For references see list at the end of this paper.



Contours after Tolstoy (1951)

Fig. 1. Geographic location of seismic profiles.

Several secondary arrivals are conspicuous on many of the seismograms. These include the doubly refracted phase G_{2a}, which we have found on several previous occasions (Ewing *et al.*, 1950*b*), and a similar phase, G_{3a}, refracted from beneath the Mohorovičić discontinuity. In addition, there is a path involving one round-trip passage fewer through the sedimentary layer (G_{2b}), giving clear phases about one second before the double refraction.[2] There are also good observations on an SV phase (G_{2s}) which is due to transformation of part of the compressional waves into vertically polarized shear waves at the contact between the sediment and the underlying rocks, with transformation back to compressional waves when the energy re-

[2] Hersey *et al.* (1952) have reported the case of one passage fewer through the sediments.

enters the sediment. The ray paths for these phases are shown in fig. 3. Figure 8 is an illustration of several of the seismograms used in this paper, showing the character of the various phases discussed above.

Station 27.—Station 27 extends to a distance of about 110 km. The travel times for G_1, G_2, G_3, and G_{2s} were all determined in the "A" direction (CARYN receiving, ATLANTIS shooting). Only G_2 and G_3 were determined in the B direction, but the determinations of these layers are of high quality. The travel-time curves are shown in figure 4, *a*, and the constants of the refraction travel-time equations are listed in table 1.

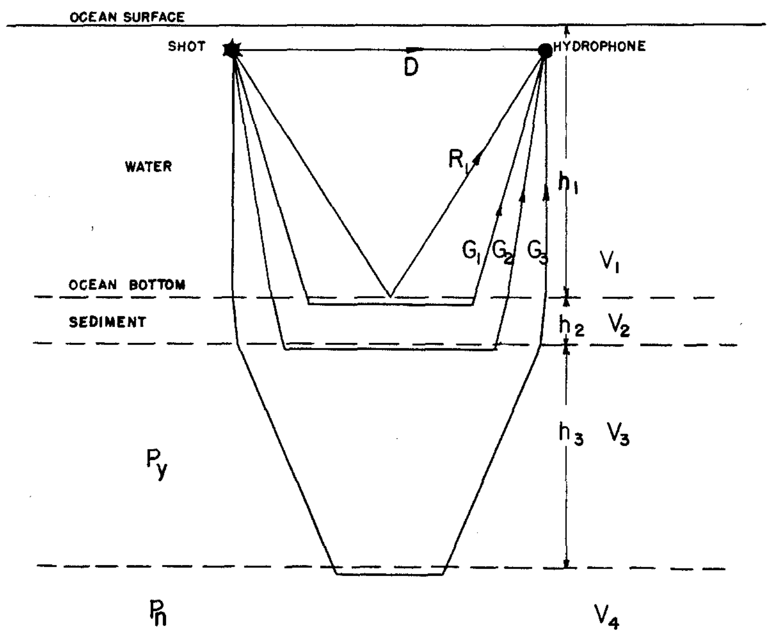


Fig. 2. Ray diagram of D, R_1, G_1, G_2, and G_3.

The reasons for identifying G_{2s} as a shear wave are given below in the section on layer identification and geophysical results.

Station 28 (fig. 4, b; table 1).—Here G_2 and G_3 are well determined in both directions, while G_1 is measured in the "A" direction only and G_{2s} in the "B" direction.

There are very strong arrivals for G_{2a}, G_{2b}, and G_{3a} at some distance for both directions of the profile. The authors consider that this unusual strength of G_{2b} is probably due to a very high reflection coefficient of the ocean floor at this station. Comparable occurrences of G_{2a}, the strength of which does not depend upon the coefficient of reflection of the ocean floor, have been observed on a number of previous stations.

The "A" direction of this station is unusual for the good second arrivals which aid greatly in the determination of G_3.

Station 29 (fig. 4, c; table 1).—Here G_2 and G_3 are determined in both directions, while G_1 and G_{2s} are observed in only one direction.

The velocity for G_3 found here is 7.43 km/sec., the lowest value yet found. The

TABLE 1

Position			Surface water velocity V_1	Travel-time equations[a]			
Sta.	Lat. N	Long. W		G_1	G_2	G_{2s}	G_3
	deg. min.	deg. min.	km/sec.				
16A	22 52	64 06	1.525		T=8.67+D/4.332		T=8.98+D/5.027
16B	23 37.5	64 02	1.525		T=8.25+D/4.175		T=8.81+D/4.861
17A	23 53.5	64 00.5	1.528		T=8.60+D/4.470		T=9.21+D/5.527
17B	24 30	64 01	1.528		T=7.43+D/3.824		T=8.73+D/5.086
18A	25 36	64 00.5	1.530		T=7.70+D/4.210	T=7.42+D/2.219	T=8.49+D/4.991
18B	26 31	64 01.5	1.530		T=8.12+D/4.333		T=8.90+D/5.188
27A	34 17.5	65 32	1.531	T=4.35+D/1.280	T=7.68+D/4.097	T=6.53+D/1.871	T=8.47+D/5.350
27B	35 51	66 05	1.531		T=7.72+D/4.107		T=8.66+D/5.426
28A	35 29	66 25	1.531	T=3.72+D/1.217	T=7.73+D/4.145		T=9.02+D/5.363
28B	36 17	66 53	1.531		T=7.89+D/4.185	T=7.74+D/2.372	T=9.20+D/5.449
29A	36 52	68 42.5	1.531	T=3.02+D/1.127	T=8.32+D/4.388	T=8.15+D/2.451	T=8.92+D/4.902
					T=8.37+D/4.503[b]		T=9.65+D/5.288[b]
29B	37 37.5	69 08	1.531		T=8.09+D/4.287		T=8.73+D/4.812
					T=8.19+D/4.418[b]		T=9.47+D/5.170[b]
A-154A	34	66 30	1.524		T=8.21+D/4.803		T=8.55+D/5.238
A-154B	34	66 30	1.524		T=7.85+D/4.462		T=8.38+D/5.000

[a] D denotes direct water-wave travel time in seconds.
[b] Alternative interpretation.

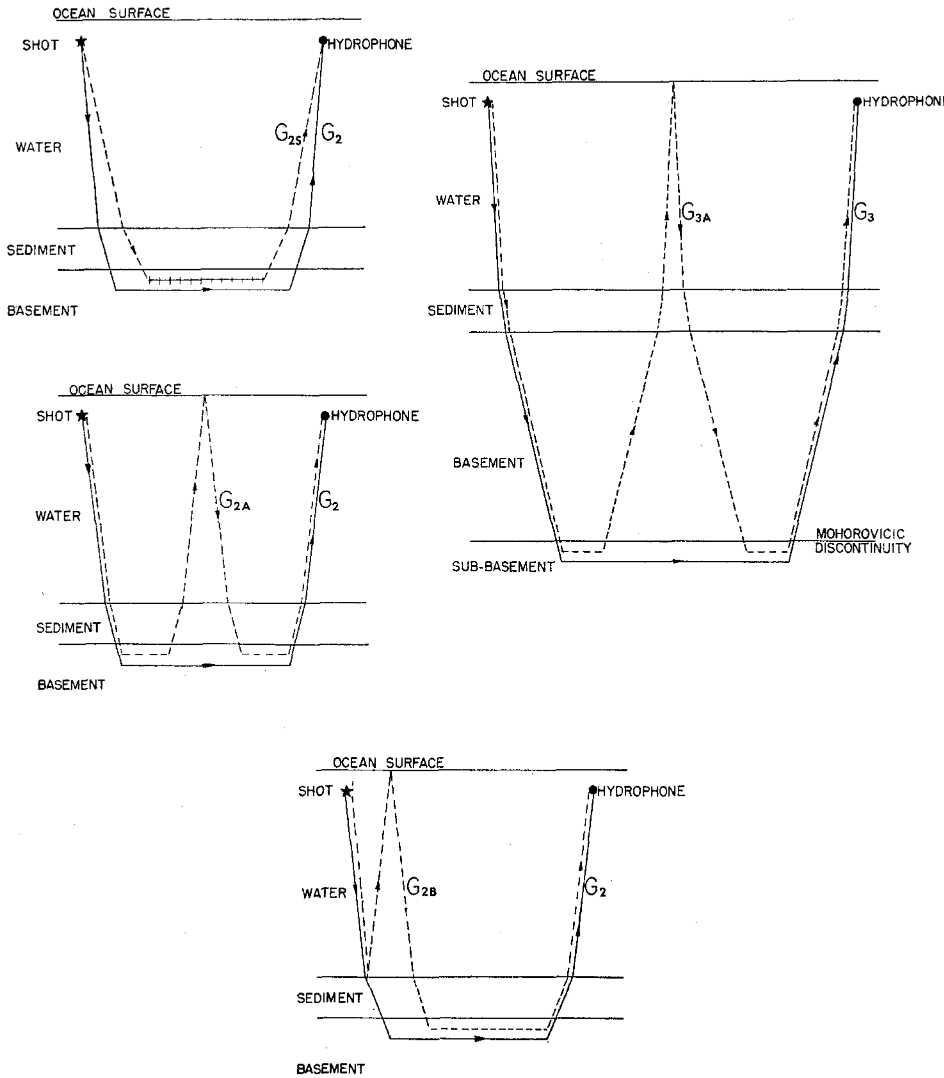


Fig. 3. Ray diagrams of G_2, G_{2S}, G_{2A}, G_{2B}, and G_{3A}.

velocity for G_2 is 6.63 km/sec., the highest value in the present group of stations. The fact should be considered that a slight ridge in the basement with its crest at about the midpoint of the station would not be detectable by the reversed profiles in this particular case, and that it would cause the observed value of G_3 to be less than the true value and that of G_2 to be greater. An alternative explanation is possible, the ambiguity being due to the spacing of shots. The interpretation involves the assumption that all G arrivals except the last one on each half of the station represent the G_2 layer, while the last travels through the G_3 layer with an assumed velocity of 8.0 km/sec. This gives the following results: $h_1 = 4.49$ km.; $h_2 = 2.2$ km., $V_2 = 1.72$ km/sec.; $h_3 = 8.0$ km., $V_3 = 6.82$ km/sec.; $V_4 =$ (8.0 km/sec. assumed). See tables 1 and 2 for comparison with first interpretation.

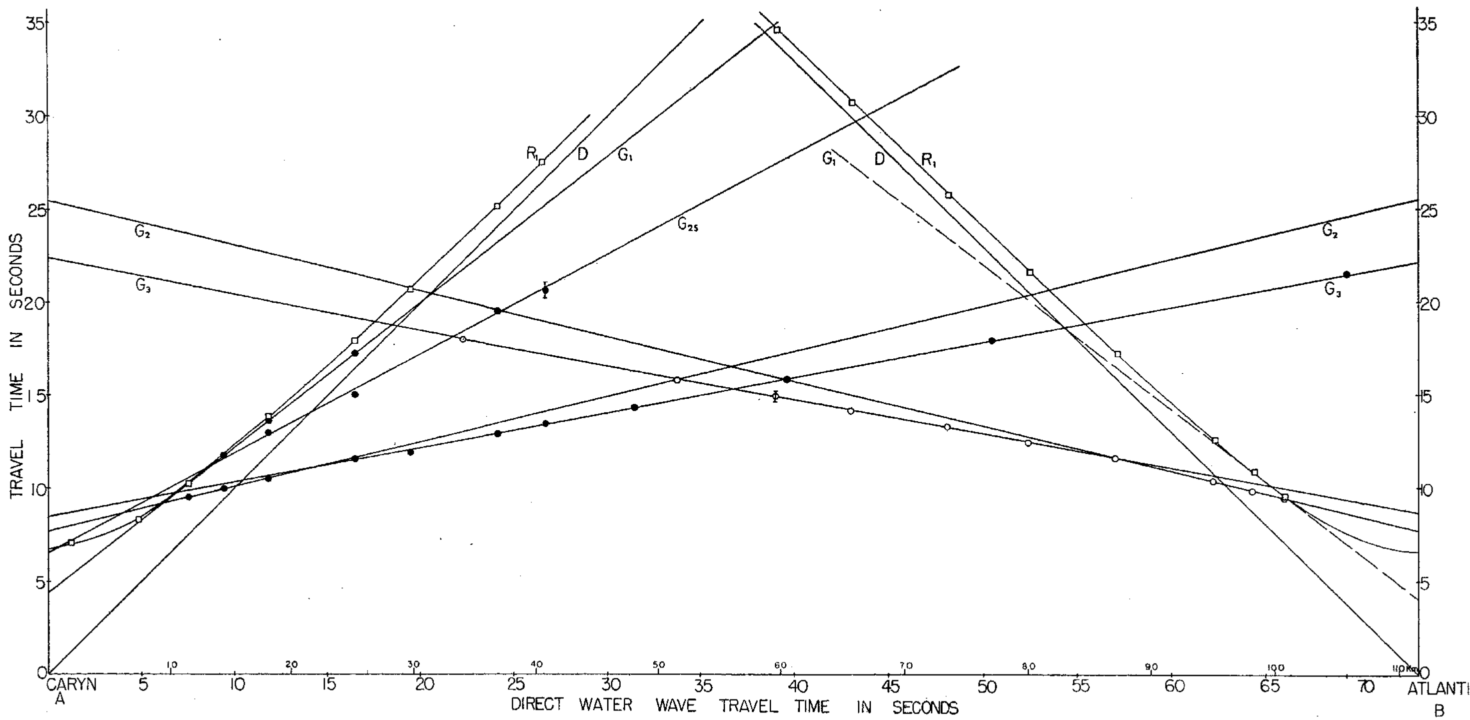


Fig. 4, *a*. Atlantis-Caryn refraction station 27. May 31, 1951.

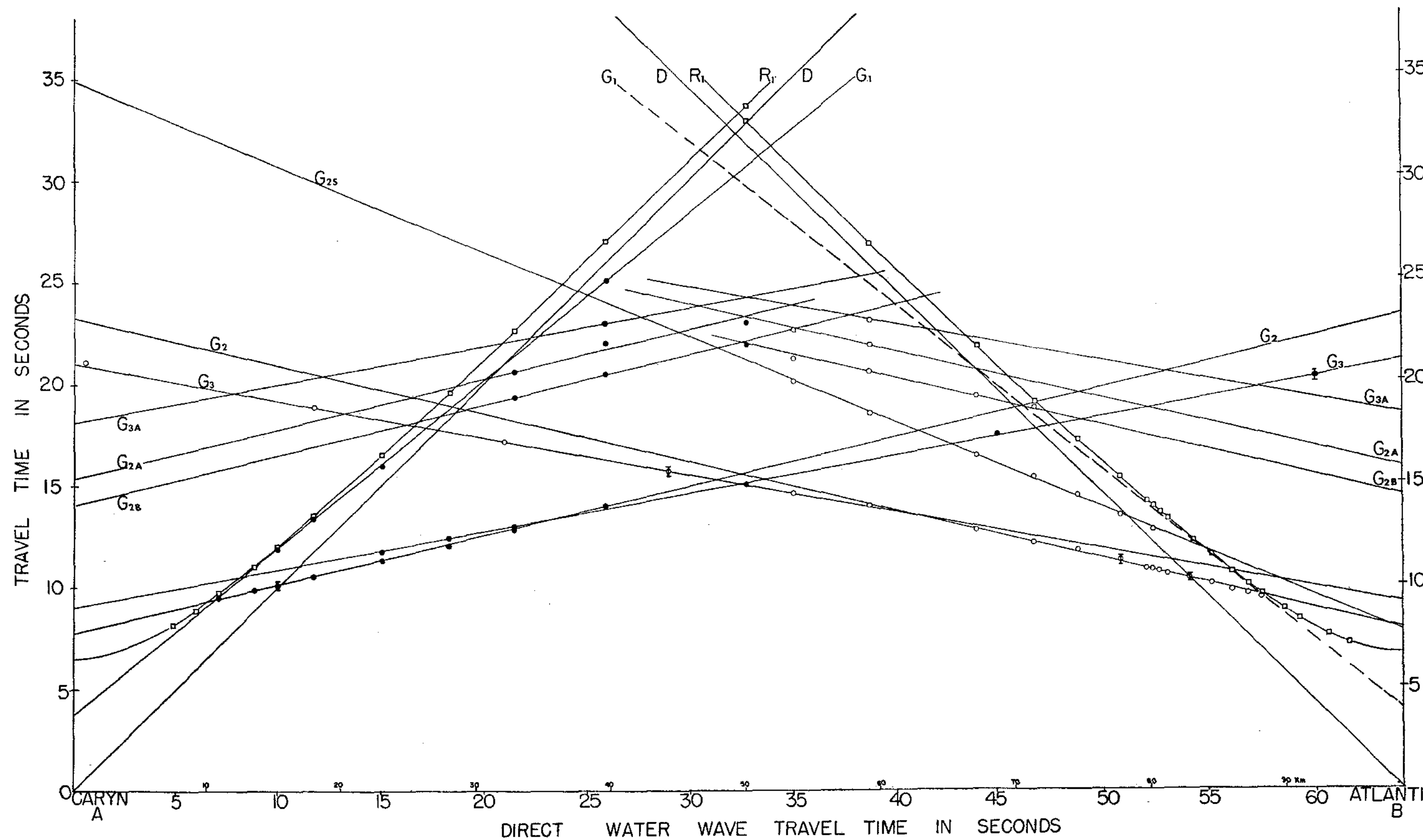


Fig. 4, *b*. Atlantis-Caryn refraction station 28. June 1, 1951.

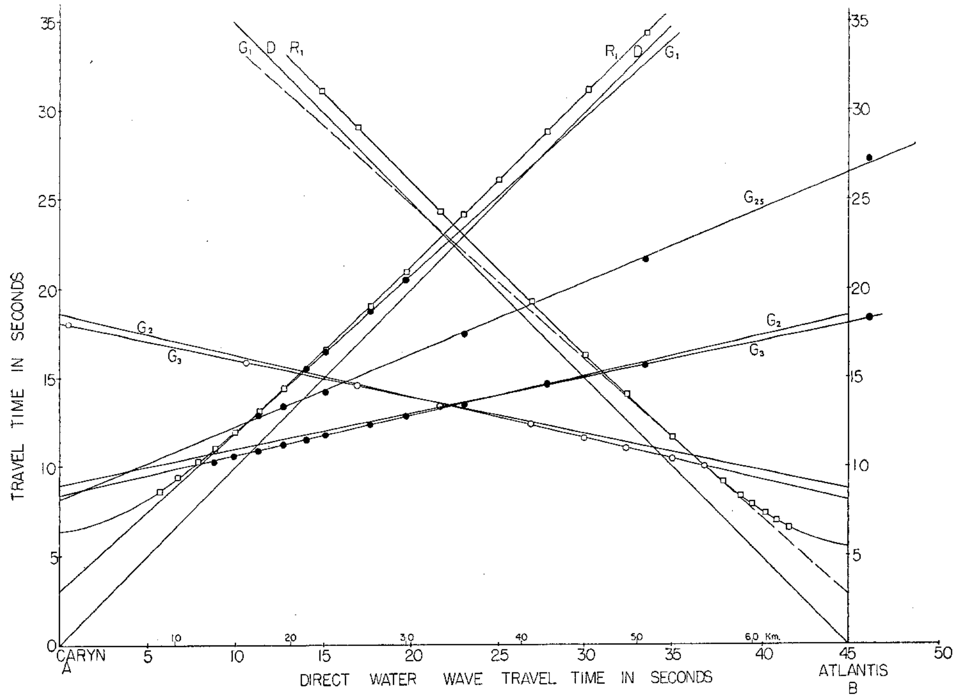


Fig. 4. *c*. Atlantis-Caryn refraction station 29. June 2, 1951.

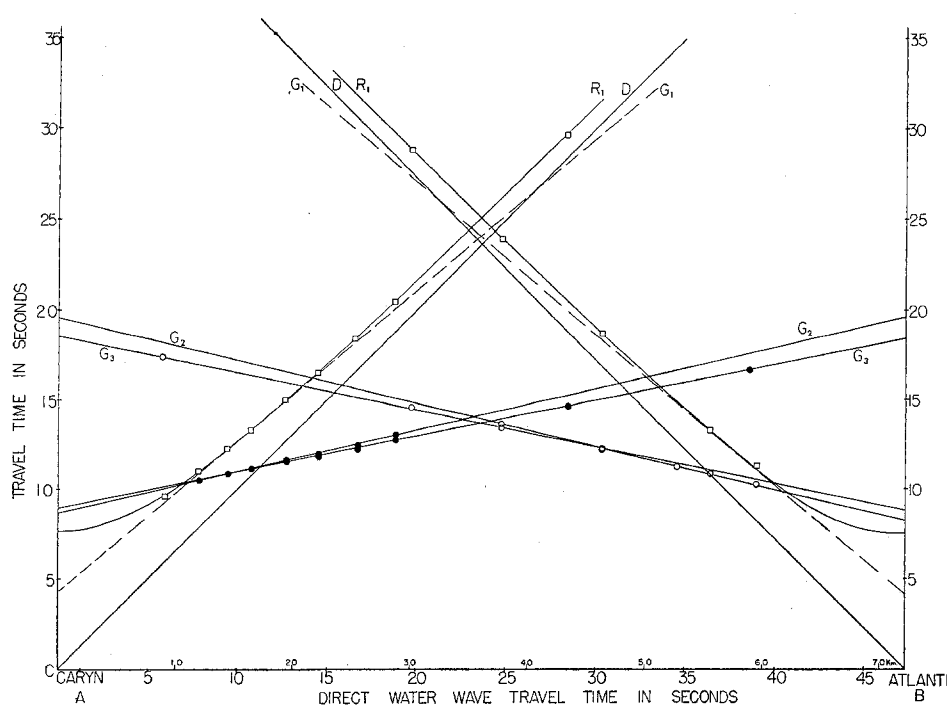


Fig. 5, *a*. Atlantis-Caryn refraction station 16. May 17, 1951.

Station 16 (fig. 5, a; table 1).—The travel-time lines for G_2 and G_3 are well determined for both directions of this station, the "A" direction being unusual in the amount of information obtained from second arrivals on G_2. G_1 was not observed in either direction, and the velocity of 1.83 km/sec. used for it in the calculation of depth was taken from the average of previous stations in this general area. The

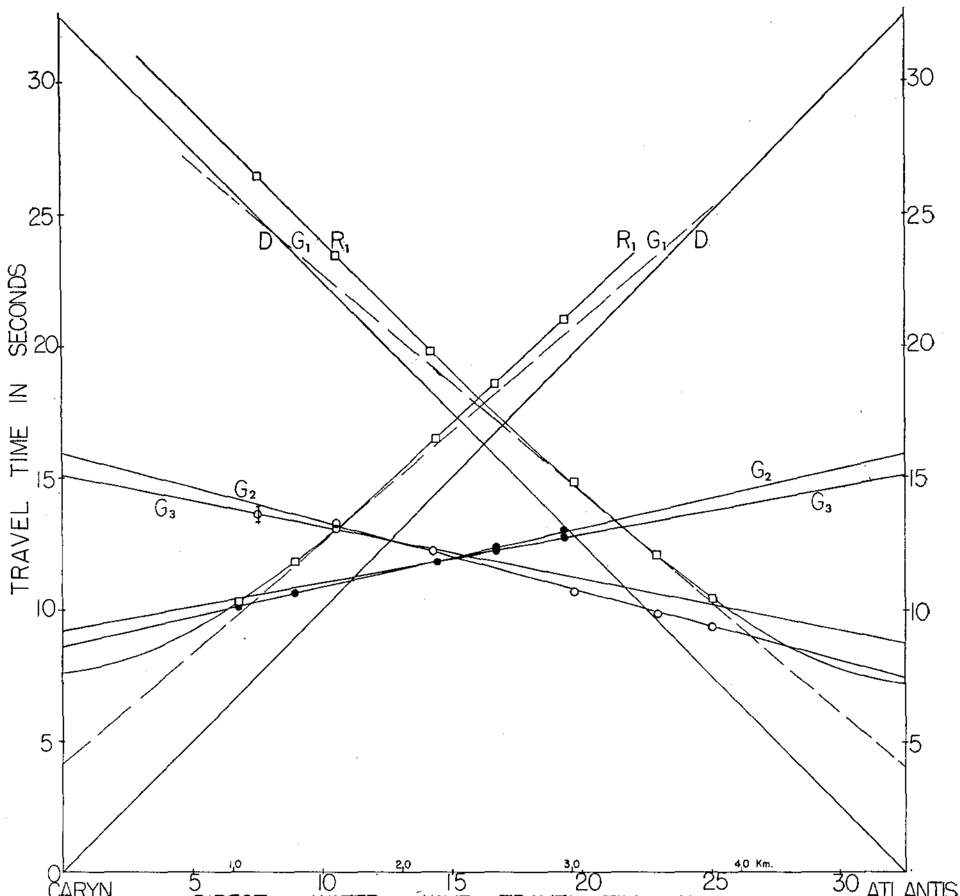


Fig. 5, *b*. Atlantis-Caryn refraction station 17. May 18, 1951.

same had to be done for G_1 at stations 17 and 18. Even if an error of 10 or 15 per cent is made in estimation of the velocity for G_1, the error in total depth will be small since the sedimentary layer is not thick.

The thinness of the G_1 layer in the region of stations 16–18 is one probable cause for the greater difficulty in measuring its velocity by the refraction method.

Station 17 (fig. 5, b; table 1).—This is the poorest measurement of the present group. Owing to a shortage of explosives and very rough sea conditions, only a rough determination of G_3 was made. G_2 is well determined, and the velocity for G_1 must be assumed from the results of earlier measurements.

Station 18 (fig. 5, c; table 1).—Station 18 gave a good determination of G_2 and G_3.

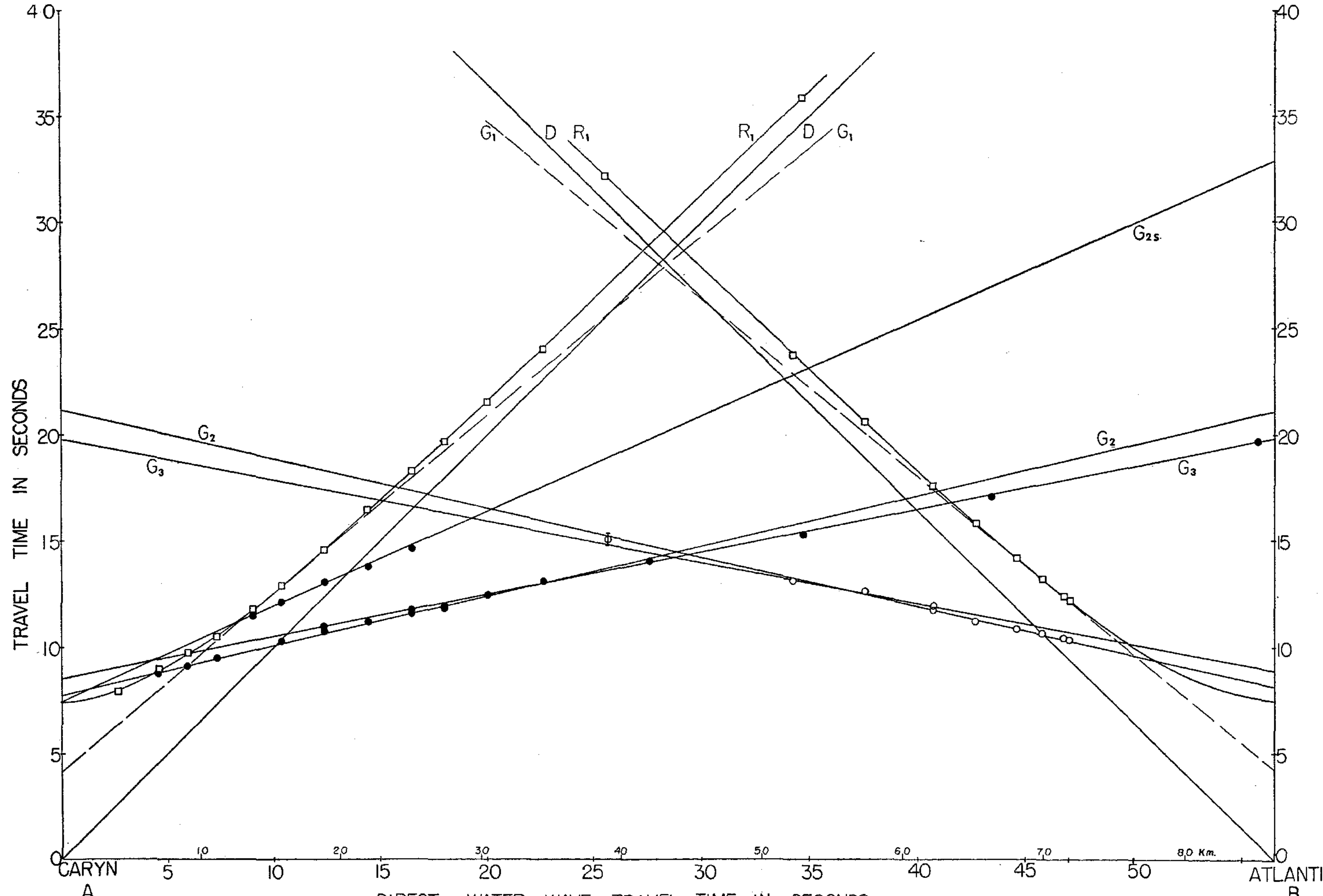


Fig. 5, *c*. Atlantis-Caryn refraction station 18. May 19, 1951.

The G_3 line on the "B" part of the profile is not well measured by its own shots, but its accuracy is increased by the good evaluation of the reverse point from the "A" end of the profile. The G_1 layer was not measured.

Table 2 is a compilation of the velocity and thickness calculations for the six stations. A summary of the values for stations 16, 17, and 18 and for stations 27, 28, and 29 is also given, with a comparison of other deep-sea refraction results. The errors quoted for V_3 and V_4 are obtained from a confidence interval of 80 per cent

TABLE 2

VELOCITIES, DEPTHS, AND THICKNESS OF SEISMIC LAYERS

Station	Velocities (km/sec.)			Depths and thicknesses (km.)				
	V_2	V_3	V_4	h_1	h_2	h_1+h_2	h_3	$h_1+h_2+h_3$
16	1.83[a]	6.51±.17	7.56±.18	5.84	0.93	6.77	2.35	9.12
17	1.83[a]	6.31±.16	8.09	5.84	0.53	6.37	4.26	10.63
18	1.83[a]	6.54±.09	7.79±.22	5.58	0.72	6.24	4.30	10.60
27	1.95	6.26±.08	8.21±.12	5.09	1.21	6.30	3.64	9.94
28	1.86	6.36±.06	8.27±.27	5.03	1.31	6.34	5.97	12.31
29	1.72	6.63±.17	7.43±.54	4.49	2.15	6.65	4.20	10.84
29[b]	1.72	6.82	8.0[a]	4.49	2.20	6.69	8.0	14.7
Average 16, 17, 18	1.83[a]	6.45	7.81	5.75	0.73	6.48	3.64	10.12
Average 27, 28, 29	1.84	6.42	7.97	4.87	1.56	6.43	4.60	11.03
Hersey *et al.* (1951)	1.71[a]	6.64	7.94	5.30	1.13	6.43	2.91	9.34
Officer *et al.* (1951)	1.70	6.63	8.03	5.45	1.56	7.01	2.93	9.94
A-154	1.83	7.05	7.80	5.12	1.35	6.47	2.81	9.28

[a] Values not experimentally determined.
[b] Alternative interpretation.

for a Student t distribution. This method gives a more reliable determination of probable error for measurements involving small samples than the more conventional least-square error calculations; see Hoel (1946). Thanks are expressed to C. Kisslinger, of Saint Louis University, for suggesting this method. The confidence interval of 80 per cent used by Kisslinger (1950) for a similar problem has been used by the authors.

LAYER IDENTIFICATION AND GEOPHYSICAL RESULTS

The G_1 layer is identified as the unconsolidated sediment at the bottom of the ocean, as in all previous papers of this series. Its coincidence with the bottom is indicated by the tangency of its refraction line with the bottom reflection curve. The G_2 layer has an average velocity of 6.43 km/sec. and is identified with the intermediate layer of continental seismology (P_y). The G_3 layer has an average velocity of 7.89 km/sec. and is identified with the material below the Mohorovičić discontinuity (P_n). (For a more detailed discussion of the identifications of P_y and P_n see Officer *et al.*, 1952.)

There is no indication of an additional seismic layer between the unconsolidated sediment and the G_2 layer. Several of the profiles have shots which carry the G_2 velocity line into the bottom reflection curve in such a way that if an additional layer is present it is too thin to be measured by the refraction method.[3] It is probable that the consolidated layer of volcanics and (or) sediments found by Officer *et al.* (1952) in the Bermuda Rise region originated in the Bermuda area and is not of regional extent.

At stations 18, 27, 28, and 29, as was mentioned in the previous section, a refraction line having seismic velocities varying from 2.85 to 3.75 km/sec. and intercepts varying from 0.1 to 1.1 sec. below the first high-velocity line was obtained which was identified as a shear refraction through the first high-velocity basement (see table 3). This is based on the following analysis (see also Hersey *et al.*, 1952): First,

TABLE 3

DATA ON SHEAR REFRACTION

Station	h_2	V_s	V_3/V_s
	km.	km/sec.	
18	0.91	3.36	1.94
27	0.97	2.85	2.19
28	1.74	3.62	1.76
29	2.58	3.75	1.77

the sediment thickness is calculated by considering these arrivals as shear refractions through the first high-velocity basement is comparable with that obtained using the compressional velocity line. Discrepancies in the thickness determinations are due in part to the greater difficulty of picking the shear arrivals which appear as second arrivals, and the absence of readable shear arrivals on the reverse side of the refraction stations in question. Second, the velocity and intercept of this line agree with what one would expect on the basis of elasticity theory for a shear refraction from the G_2 layer. At stations 28 and 29, where there is a good determination of this line, 1.77 and 1.76 are obtained for the ratios of the compressional to shear velocities, consistent with the predicted value of 1.73, assuming that Poisson's ratio is 0.25. At stations 18 and 27, where there is a poorer determination of this line, the comparison of the experimental and theoretical ratios of the two velocities is not as good. Third, the velocity line cannot be interpreted as a compressional refraction from a hypothesized layer above the G_2 layer, for in three out of four cases this hypothesis leads to a negative thickness. (Thicknesses of -0.87 km., 0.12 km., -1.03 km., and -1.43 km. were determined from stations 18, 27, 28, and 29, respectively.) Table 3 is a summary of the data on the shear refraction.

Practically all the refraction arrivals came in with a dominant period. There was no evidence of dispersion, but on some records two frequencies were present, one being about twice the other. The periods varied from record to record and from profile to profile, but were constant during a particular refraction arrival. Most of the periods observed were from 0.03 to 0.08 sec.

[3] This statement applies only to detection of the layer by first arrivals.

Interpretation of Structure

On the average the unconsolidated sediment is about twice as thick in the region northwest of Bermuda as in the Nares Basin, 1.56 km. and 0.73 km., respectively. Since the depth to basement is nearly the same in the two regions, the greater thickness of sediments is expressed as a difference in the bathymetric level of the two regions. The Nares Basin is flat at a depth of 5.8 km. (3,000 fathoms), and the region northwest of Bermuda is flat at 5.0 km. (2,600 fathoms).

Station 29, starting up the Continental Rise, shows a greater thickness of sediments, 2.15 km., than that of its neighboring stations 27 and 28, 1.21 km. and 1.31 km., respectively. From these three stations alone the statement cannot be made that the sediments are generally thicker on the Continental Rise than in the associated deeper regions. That question should be answered by the results of other profiles in similar locations.

Seismology

This set of refraction stations forms the best set of measurements to date on the seismic structure of the North America Basin. All the stations except station 17 were carried out far enough to give a good determination of P_n. Table 2 gives a comparison of this set of data with two other published sets. The general agreement of all the deep-sea refraction data is striking and rules out the possibility that any one set of data was taken in an anomalous region. The average result is characteristic of the North America Basin.

Comparison with Earlier Results

The stations presented in this paper lie near to two previously reported. From Part I of this series the station lying about 60 miles southwest of our No. 27 has been recomputed with inclusion of a small correction for depth of the bombs in water. The correction for bomb depth produced a systematic effect, since the large bombs used for all longer shots sank deeper than the smaller ones used for short distances. The application of this correction made the separation of the basement into layers G_2 and G_3 clear, in accordance with the result at the six new stations. The revised travel-time curve for station A-154 (fig. 1) is shown in figure 6, and the constants for the layers are given in tables 1 and 2. This recalculation amounts to a refinement. In the previous calculations a thin superficial basement layer differing but little from the substratum had been averaged in with the substratum. The discrepancies between the recalculated values for the station and the values obtained for the neighboring station 27 of this paper may be due in part to a local elevation in the bottom. This elevation is indicated by forerunners on R_1 coming in about 0.07 sec., before the large amplitude R_1 arrivals on records 31 through 34 (see fig. 6), but does not show on the fathometer track of the shooting vessel. This situation is made possible through drift of the receiving vessel during the refraction station.

The station A-160-4 (see fig. 1) from Part III lies very near to No. 16. The measurements at this station were made by the whaleboat technique, no long shots being obtained to give precise determinations of basement velocity G_2; and G_3 was not detected. The velocity for G_2, 6.05 $\pm$ 0.29 km/sec., has less precision than our velocity of 6.51 $\pm$ 0.17 km/sec. for station 16. The difference between the two

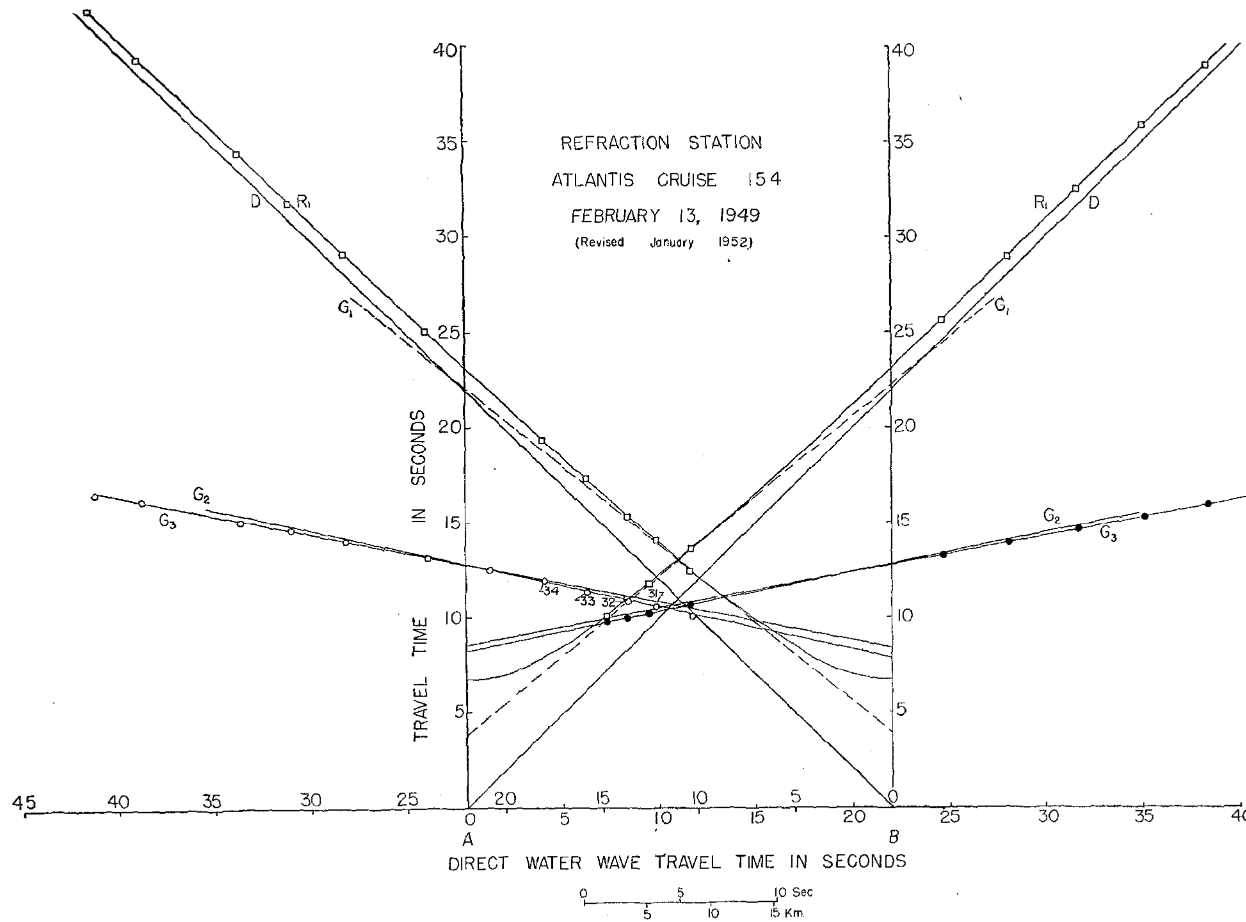


Fig. 6. Revised travel-time curve for station A-154.

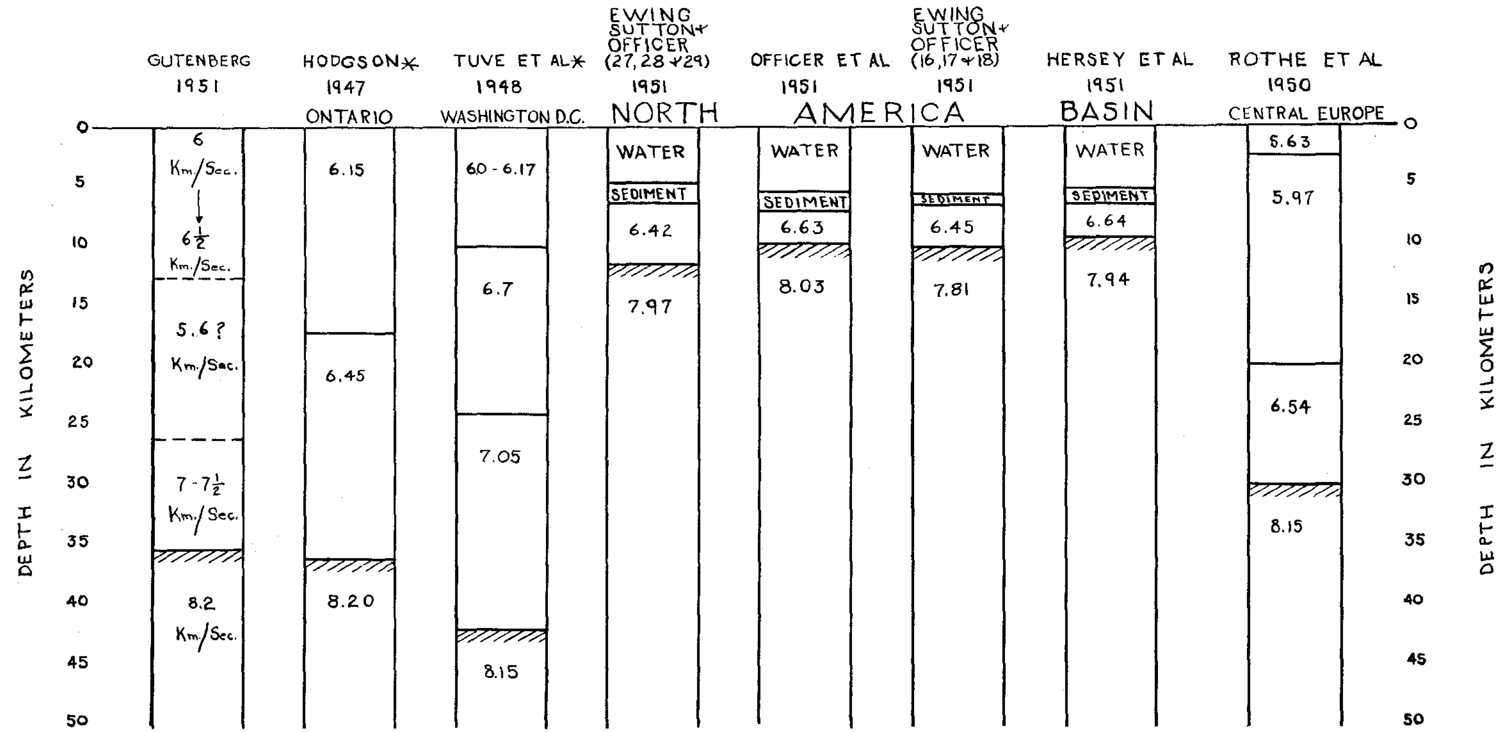


Fig. 7. Seismic sections.

* In papers presented at the International Union of Geodesy and Geophysics meetings (Brussels, 1951), Hodgson reported a single 6.25 km/sec. layer reaching a depth of between 36 and 40 km. with an 8.20 km/sec. layer below, and Tatel reported a layer varying from 6.0 km/sec. near the surface to 7.0 km/sec. at a depth of about 40 km. with an 8.0 km/sec. layer below.

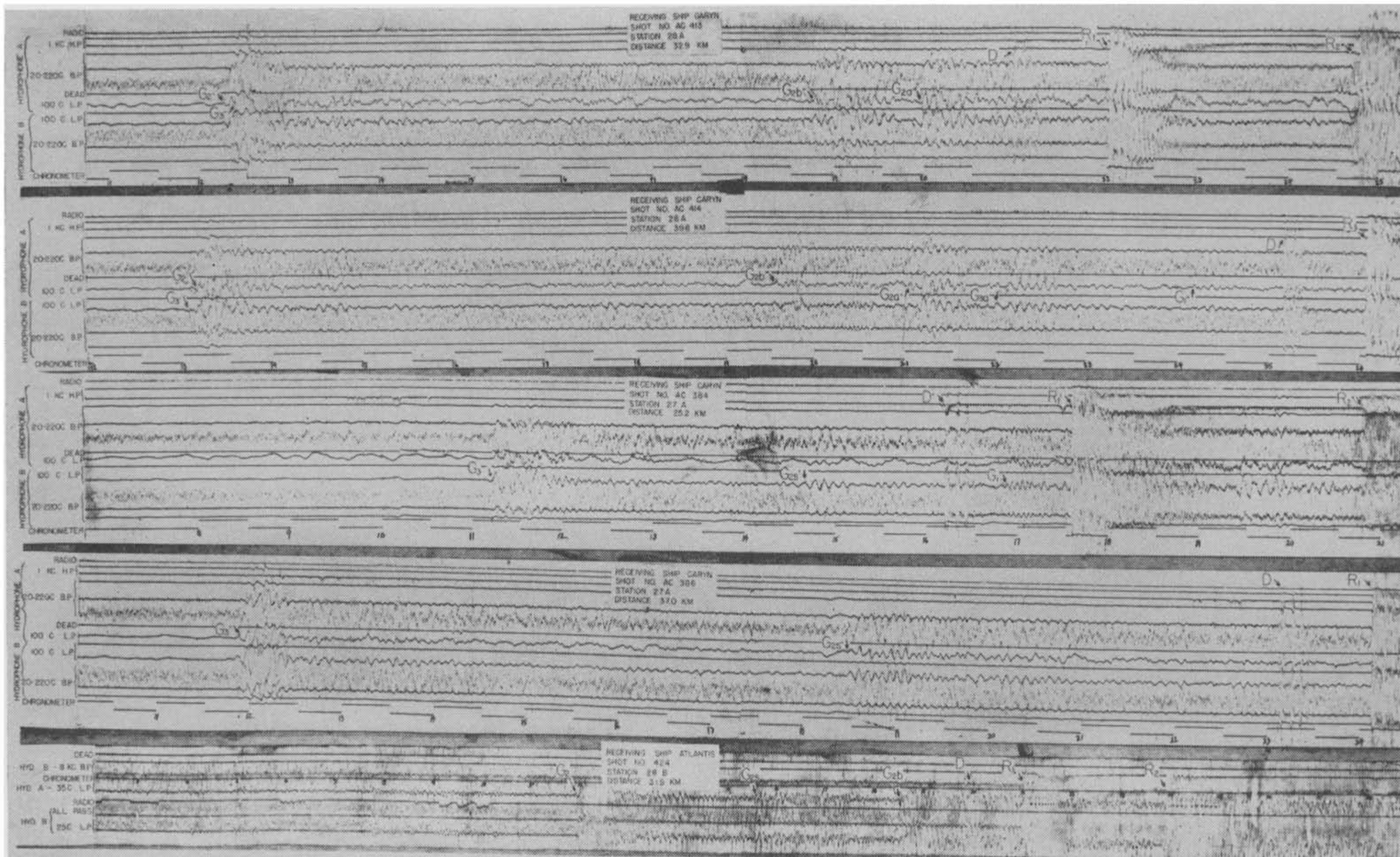


Fig. 8. Seismograms.

values for velocity is just within the limits of precision indicated. The sediment thickness 0.76 to 0.93 km. reported for station A-160-4 on the basis of an assumed sediment velocity of 1.6 km/sec. is not in conflict with the value 0.93 km. for station 16 based on a sediment velocity of 1.83 km/sec. The station A-160-5 from Part III is about 200 miles east of station A-164-35 (fig. 1), and is a typical deep station. Like A-160-4 it suffers the handicaps of a whaleboat station and is also unreversed. The result G_2 at 7.07 ± 0.68 km/sec. and a sediment thickness of 0.34 to 0.42 km. should not be considered in conflict with the present result for typical deep stations, because the possible spread of values includes our G_2 at one end and G_3 at the other.

Figure 7 is a group of sections comparing the seismic structure of the North America Basin with that of various continental sections. The depth to the Mohorovičić discontinuity has an average value of 10 km. (below sea level) under the Atlantic Ocean, in comparison with an average value of 40 km. under North America.[4] The material below the Mohorovičić has an average velocity of 7.9 km/sec., and the material above, an average velocity of 6.5 km/sec. The depth to the 6.5 km/sec. layer has an average value of 6.5 km.

Comparison with Dispersion of Earthquake Waves

Ewing and Press (1952) have shown that the characteristics of propagation of Rayleigh waves across ocean basins could be explained by the effect of a layer of water overlying ultrabasic rock having an equivalent compressional velocity of slightly under 7.90 km/sec. In this investigation the calculations were simplified by treating the water and sediment as a single liquid layer and the basement rock as a single homogeneous layer of infinite thickness. More recently it was shown (Jardetzky and Press, 1953) that a layered basement under the ocean consisting of 5 km. of basic rock (6.9 km/sec.) overlying ultrabasic rock (8.1 km/sec.) could explain the observed dispersion equally well within the limits of experimental error. Although the velocity values of the ultrabasic layer tend to be somewhat lower than that indicated by Rayleigh-wave dispersion, the agreement between the two methods is considered satisfactory since refractions give the velocity of the uppermost portion of the ultrabasic layer whereas dispersion studies tend to average the velocity over a depth of about 1 wave length (100 km.).

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[4] Raitt, in a paper presented before the Seismological Society of America on March 24, 1951, found, for some stations in the Pacific Basin between North America and Hawaii: a sedimentary layer having a maximum thickness of 1 km., an intermediate layer having a velocity of 6.7 km/sec., and an 8.25 km/sec. layer starting 5 km. beneath the ocean bottom.

The coöperation of Captain A. K. Lane and the crew of the ATLANTIS and Captain J. Pike and the crew of the CARYN were important to the success of the operation. Thanks are expressed to Dr. J. B. Hersey for the loan of the receiving equipment on the ATLANTIS.

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