

Some Seismic Profiles near the Western End of the Puerto Rico Trench

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ABSTRACT A cooperative program of seismic refraction profiling was completed in the vicinity of the Puerto Rico Trench by Hudson Laboratories, Woods Hole, Lamont, and Texas A. & M. Profiles completed near the western end of the Trench were analyzed at Hudson Laboratories. Five seismic layers are indicated below the water layer. The thickness/velocity relationships are as follows: 5.1 km of 1.5 km/sec. (water); 1 km of 1.7 km/sec. (sediment); 1.5 km of 3 km/sec. (metamorphics?); 2 km of 5.5 km/sec. (basement); and 2 km of 7.1 km/sec. (high speed basement). Below these, typical Moho velocities of 8.1 km/sec. were measured. Total depth to Moho ranges from 9 to 12 km below sea level, the greatest variation occurring in the basement layers. The least depth was measured 65 miles north of the Puerto Rico Trench.

The purpose of this study is to determine by seismic means the minimum depth to the Mohorovicic discontinuity. The material below this discontinuity is the upper part of the earth's mantle and is often simply referred to as "Moho," a designation that will be followed in this report.

A proposal to drill to Moho has been implemented by American Miscellaneous Society (Hess, 1959). Preliminary to drilling, a program of seismic exploration was undertaken by both East coast and West coast oceanographic laboratories (Raitt, 1960). The schedule in the Atlantic called for a detailed coverage north of the Puerto Rico Trench where shallow Moho depth had been reported (Talwani *et al.*, 1959).

METHOD AND DATA REDUCTION

At the beginning of a typical profile, the Gibbs¹ would commence the firing run down the line of ships (Bear,² Vema,³ Hidalgo⁴) and on past the last ship to about 40 miles. Then at the end of the profile, the Gibbs would lay to, stream hydrophones, and record shots from the other ships to complete the reverse. This method of using a fast

¹ The USNS Gibbs is a 310 ft converted Navy seaplane tender of 2800 ton displacement, capable of a speed of 18 knots. She is operated by Military Ships Transportation Service for Hudson Lab-

ship to shoot heavy charges for more than one listening ship was first used by Hersey (Hersey *et al.*, 1952) and is a modification of the offshore seismic refraction technique pioneered by Ewing (Ewing *et al.*, 1937).

TABLE I
LAYER VELOCITIES IN KILOMETERS PER SECOND

Profile	v_1^*	v_2	v_3	v_4	v_5	v_6
112N	1.51	1.75	3.02	5.73	7.06	8.27
112M	1.51	1.70	3.02	5.61	7.10	8.05
112S	1.51	1.71	2.90	5.80	7.09	8.15
111	1.51	1.69	2.81	4.99	6.31	8.13
110	1.51	1.79	3.85	5.83	7.02	8.10

* v_1 , velocity of first layer. v_2 is velocity of second layer, etc.

TABLE II
LAYER THICKNESSES IN KILOMETERS,
TOTAL DEPTH, AND SLOPE

Profile	h_1^*	h_2	h_3	h_4	h_5	T.D. †	Slope ‡
112 N North	5.20	0.05	1.55	0.98	4.64	12.42	degrees 0.91
South	5.20	0.47	1.25	1.81	2.64	11.37	
112 M North	5.20	0.34	1.49	1.59	3.08	11.70	2.59
South	5.20	0.14	1.27	1.51	1.20	9.32	
112 S North	5.21	0.34	1.77	1.05	0.65	9.02	-2.05
South	5.21	0.34	0.43	3.07	1.22	10.27	
111 West	5.15	0.49	0.63	1.55	2.78	10.59	0.72
East	5.31	0.42	0.60	1.19	3.73	11.24	
110 West	5.19	0.18	0.66	3.55	5.18	14.76	-0.63
East	5.35	0.28	2.20	2.19	4.06	14.08	

* h_1 , thickness of first layer v_1 . h_2 is thickness of second layer v_2 , etc.

† Sum of all layer thicknesses, including water layer v_1 .

‡ Angle Moho makes with the horizontal in the plane of the profile. Negative slope dips to the south or west, positive slope to the north or east.

Shots were fired on a 5 min. schedule or faster, with a small charge ($\frac{1}{2}$ or 3 pounds) for the nearest ship, 25 or 55 pounds for the intermediate ship, and 110 or 300 pounds for the distant ship. The 300 pound Mark VIII's were double primed with both a $2\frac{1}{2}$ and a $\frac{1}{2}$ pound demolition block set in the center well. Refraction profiles up to 100 sec. in travel time were completed in this manner, and detailed seismic reflection

oratories of Columbia University under contract with the Office of Naval Research. She carried a full load of 10 tons of $\frac{1}{2}$, $2\frac{1}{2}$, and 55 pound TNT blocks in the hold plus 40 Mark VIII 300 pound depth charges in deck-mounted depth charge racks.

² Woods Hole Oceanographic Institution.

³ Lamont Geological Observatory.

⁴ Texas A. & M.

records were obtained from the close-in shots for each ship as the shooting ship sailed past. Shot instants were monitored from a hull-mounted crystal headphone and recorded *versus* chronometer time (checked against National Bureau of Standards Radio Station WWV) on a Brush recorder. They were also picked up on the Edo fathometer and radioed to the three listening ships.

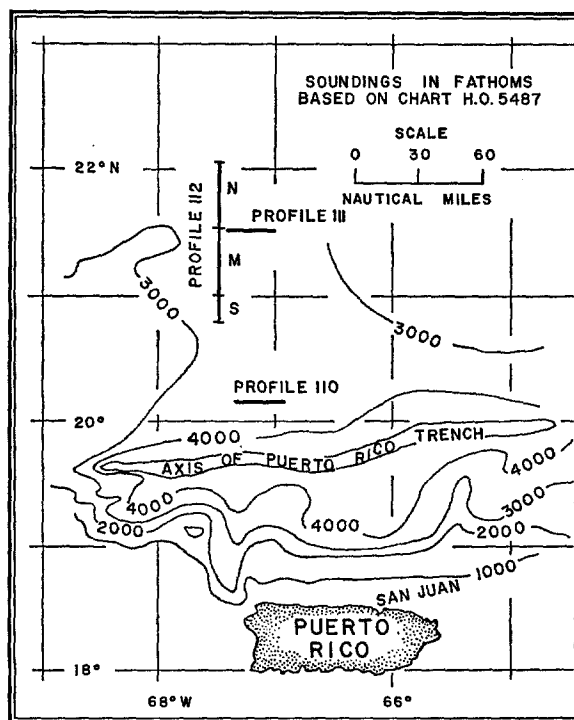


FIGURE 1. Location of profiles.

About 1500 shots were fired, ranging from $\frac{1}{2}$ to 300 pounds of TNT. All were fuse-fired. Because of her superior speed, the Gibbs was selected to complete most of the firing runs and return to Roosevelt Roads, Puerto Rico, for a second load of depth charges. Thus about three-fourths of the 18 shot runs completed were made by the Gibbs.⁵

Seismic "picks" were made back at the laboratory and read to 0.01 sec. Corrections to surface of reference were made for hydrophone depth, shot depth, and bottom topography (Officer *et al.*, 1959).

In arriving at the final travel time plot, travel time curves were drawn by eye fit and velocities and depths computed after the method of Ewing *et al.* (1937), and

⁵ In addition to the seismic program Gek (geomagnetic electrokinetograph) measurements were made on the run out and back. Fathometer records were taken continuously throughout the cruise.

Officer *et al.* (1959), assuming straight rays, parallel boundaries between layers, and refraction according to Snell's law. The resulting models were compared with those adjoining, and, if a misfit was present, a slight reinterpretation was made on both profiles. The final results reported here are thus one interpretation from many, albeit the one that seems to fit the data best. Velocities are believed good within 5 per cent and depths within 10 per cent. The sediment layer is perhaps as poorly defined as any and may not fall within these limits because the layer is generally less than 1 km thick.

RESULTS

The data are presented as a set of travel time curves with distance, expressed in terms of direct water wave travel time, on the x -axis and travel time of the ground arrival on the y -axis. In this way the velocity of the line can be computed from the inverse slope shown. Apparent velocities, in terms of surface water velocity, and intercepts are written along each line for identification. When reduced to sea level reference for geologic section, the true velocities and thicknesses are shown in kilometers per second and kilometers, respectively, on each profile. They are shown in Tables I and II together with the total depth to the Mohorovicic discontinuity and the slope of that discontinuity.⁶

In the following, the first ship receiving is discussed first, *i.e.* the "opening" of the profile, the second ship constituting the reverse until shot past, when it then becomes the opener and so on in turn for all ships' stations.

Profile 112 was shot from north to south (Fig. 1) along 67°30'W with the Gibbs being the anchor ship at the north end at 21°58'N. Hidalgo shot from the Gibbs down the line of ships past Vema to Bear and then hove to for listening. Bear then shot on south to 20°44'N making an 80 mile profile altogether. All ships shot into Bear for the reverse. The travel time curves for profile 112 are shown in Fig. 2.

All points on the Gibbs' end are good, except for the 300 pound Mark VIII's at 54, 60, and 69 sec. out, which fall below the high velocity line. The 5.7-km/sec. layer has no first arrivals on it nor does the 3.02 km/sec. layer. However, the lines reverse well, and the interpretation is consistent with the adjoining profiles. There is evidence of a possible shear arrival (Katz and Ewing, 1956) on the reverse. The Moho and high velocity basement lines are well determined.

All points on the Vema profile are good except for the distant shots, which again fall below the Moho line. There are no first arrivals for the 3.02 km/sec. and 5.61 km/sec. layers on the Vema end, but Hidalgo shows a possible first arrival on the 5.61 km/sec. layer. There is evidence of a shear arrival on both

⁶ The "total depth" is the sum of all layer thicknesses h_1, h_2, h_3, h_4, h_5 , including the water layer; the "slope" is the algebraic sum of slopes of interfaces between layers ($W_{12}, W_{23}, \dots, W_{56}$) and represents the angle that the Mohorovicic discontinuity makes with the horizontal in the plane of the profile.

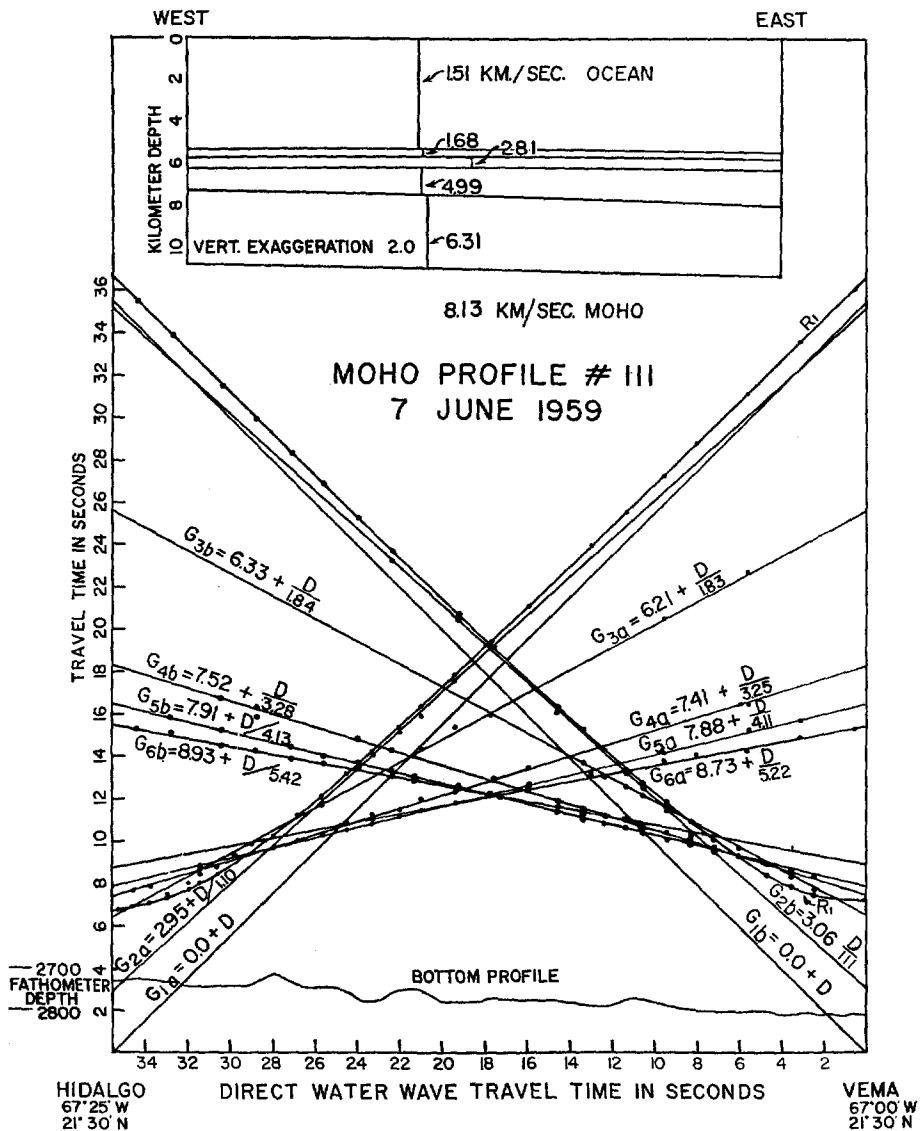


FIGURE 3. Travel time curves and geologic section of profile 111.

the opening and reverse. The Moho and high velocity basement lines are well determined.

The southern end of profile 112 is the shortest of its three sections and therefore suffers from lack of points. However, the Moho line is well determined by three long shots on the reverse, and, happily, there are four clear first arrivals on the 5.8 km/sec. layer, which strengthens the interpretation on the other profiles. The 2.9 km/sec. layer is very poorly defined with only two points on the opening end and one on the reverse. The reverse shows no points on the

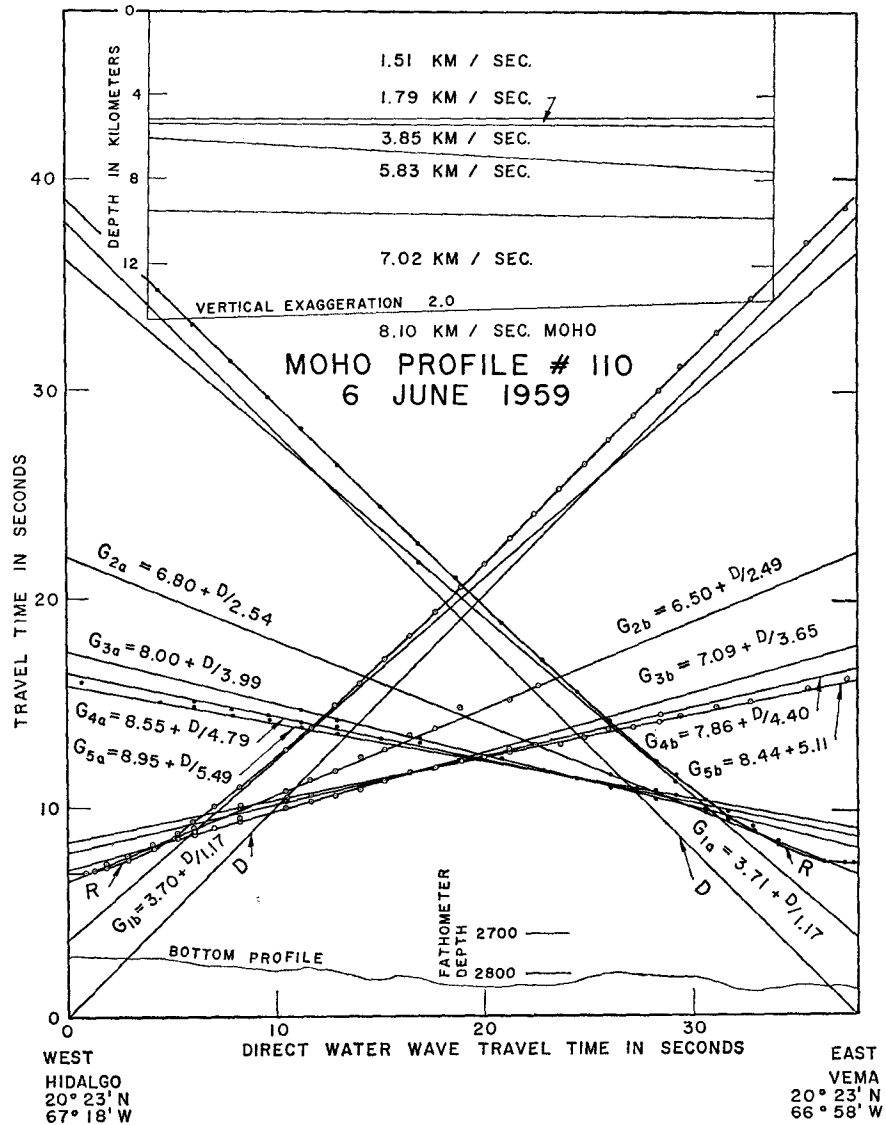


FIGURE 4. Travel time curves and geologic section of profile 110.

sediment line. The high velocity basement line has no first arrivals on it, probably because it thins appreciably from the 4.64 km measured at 112 North to 0.65 km (Table II).

Profile 111 is just east of the Vema position on profile 112 (Fig. 1). The points on this profile (Fig. 3) are all good for the opener, with Vema shooting west from Hidalgo, although there is some scatter on the Moho line for distant shots. On the reverse, the last point on the Moho line is high, due to a

noisy record. This is an unusually good profile in that, although shots up to only 55 pounds were used, the arrivals are all well above background. There are no first arrivals on the sediment line or on the 2.77 km/sec. line, and the first arrivals on the 6.23 km/sec. line are common points. The total depth at the west end of profile 111 is 10.59 km. The corresponding depth along profile 112 is 11.37 km, so that the interpretation is consistent with that of profile 112, within 10 per cent. The velocities of the layers are lower than those corresponding in profile 112, possibly due to anisotropy since the latter was shot normal to the strike of the regional structure, and the former parallel to it. Both the high velocity basement and Moho lines are well determined.

Profile 110 was shot further south than the other profiles (Fig. 1) with Hidalgo opening as she shot west from Vema. All the points (Fig. 4) are good except the last one, which has poor signal-to-noise ratio and falls late, and the point about 20 sec. out is obscured by noise. All points on the reverse are good. Both the high velocity basement (7.02 km/sec.) line and the Moho line are well defined by first arrivals. The 5.83 km/sec. layer has a couple of first arrivals on the opening end and ten on the reverse, lending increased weight to the presence of this layer in the area. It is thicker here than on the other profiles where the refracted arrivals are late making it a "masked layer." This profile also has the thickest (5.18 km) section of high velocity basement (7.02 km/sec. layer).

DISCUSSION AND CONCLUSIONS

The structure of the Outer Ridge revealed in this work is similar to that shown by Talwani *et al.* (1959). The thickening of the "crust" under profile 110 corresponds to the thickening under their profile 12. The minimum depth to Moho under profile 112 South corresponds to their minimum depth near profile 11. In both cases the minimum depth is between 9 and 10 km. All six layers are represented in both sections, the presence of the 5.5 layer in cases where it is "masked" being strengthened by the present work. There are, however, several things that are remarkable in the present study. With the deployment of four ships each equipped both to shoot and to receive, not only can very long profiles be shot, but also details within a long profile can be delineated. This then presents an unusual opportunity for aligning layers so that they match on adjoining profiles. One would, for example, put much more stock in the second arrival 3.02 km/sec. line of profile 112 Middle and its appearance on adjoining profiles than in a single determination like that of profile 110.

The benefit of very long profiles is also shown in the distant shots recorded by the Gibbs' profile 112 North and the last one recorded by Vema. These shots all fall below the Moho line, indicating either a velocity dependence

with latitude or else the presence of a deeper and faster "sub-Moho" line. In this case the latter interpretation is preferred because in both profiles 112 Middle and 111 the Moho velocity is lower rather than higher. The long shots for the reverse of 112 South provide the only points on the Moho line; without them it would have been impossible to interpret the profile short of assuming a reverse.

In the region where no Moho points are found on the reverse of 112 South, there were a number of shots. These records have been examined repeatedly by several observers, and arrivals on both the high speed and low speed basement were absent, as well as those of the Moho line. There are, however, several strong arrivals that come too late by 3 or 4 sec. yet too early for the 2.9 km/sec. layer (Fig. 2). Thus there is some local structure indicated, but this does not show up in the adjoining profile, nor does the opening end indicate any structure in the deeper layers. The area of structure, then, is between Hidalgo's position and the arrival of the first refraction, about 7 sec. out. Various alternate interpretations were tried to match this indicated structure, but none was consistent with the reverse or with the long shots on 112 Middle, which shows no break in the Moho line through this area. There are also very strong subbottom reflections on the Hidalgo end of 112 South that indicate a strong discontinuity from within the 2.9 km/sec. layer.

The shallowest depth to Moho as measured by these profiles is 9.02 km at 21°N; 67°30'W. This depth is probably not accurate to better than 10 per cent, and the velocity of layers is probably not accurate to better than 5 per cent due to the inherent averaging effect of refraction profiling.

The position of least Moho depth is on the Outer Ridge, about 150 miles north of Puerto Rico. This particular place on the Outer Ridge exhibits anomalously high velocities, indications of local structure, and strong reflectors within the 2.9 km/sec. layer. Investigation of these parameters would be worthwhile either by further shooting or, in the case of the 2.9 km/sec. layer, by preliminary drilling, such as that recently completed in the Pacific.

This work was sponsored by the Office of Naval Research. The success of the Gibbs' cruise is in no small part due to the conscientious seamanship of Captain Dwight Hutchinson and his officers and men. The scientific work on board ship was aided immeasurably by the know-how and hard work of the late John Hennion of Lamont Geological Observatory, Miss E. T. Bunce and Miss Helen Hays of Woods Hole Oceanographic Institution. Without their help the excellent quality of the records could not have been attained. Additional help was furnished by Arthur Main, Robert Bennin, Kenneth T. Morse, and James O. Lee of Hudson Laboratories, and Robert C. Brown of Dartmouth College. Additional help and advice from Dr. C. S. Clay and Maurice Blaik were instrumental in getting the equipment ready for the field. Special acknowledgment goes to Dr. Maurice Ewing and Dr. John E. Nafe of Lamont Geological Observatory who planned, organized, and directed the program, Dr. Nafe acting as group leader during the field work. Dr. Robert A. Frosch, Director of Hudson Laboratories, arranged for the senior author to use the USNS Gibbs for the experiment.

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