Seismic Investigation of Geological Structure
Bordering the Caribbean Island Arc, Part I

by

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Dr. C. B. Officer was chief scientist of the Bear and the cruise, and John Ewing was chief scientist of the Atlantis.
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INTRODUCTION

In recent years the seismic refraction technique has been used extensively to study the crustal structure of the earth beneath the great oceanic areas. These studies have led to the recognition of a characteristic oceanic crustal structure quite distinct from that characteristic of continental areas. This distinction has naturally led to investigations of the transition region between oceanic and continental structure.

As part of an extensive deep-sea refraction program in 1951 members of Lamont Geological Observatory, Columbia University, made a series of eight profiles across the eastern Caribbean, which, except for a single profile by Hersey in 1949, represent the first refraction work in the area. The interpretations of these profiles were made by G. H. Sutton and preliminary calculations reportedly indicated the typical ocean basin structure beneath the Caribbean with a definite thickening of lighter material in the Puerto Rico trench. Hersey's single profile and six of Sutton's profiles were used by Ewing and Worzel (1954)\(^1\) along with the gravity measurements of Hess (1938, see map)\(^2\) in an attempt to present a consistent picture of the structure of the West Indies. This data, however, was too sparse to allow more than a calculated guess to be made.

Interest in the Caribbean island-arc area continued with the 1955 investigation by Officer, et al., who made 47 seismic refraction profiles covering the exterior Atlantic basin,
the interior Venezuelan basin, the Puerto Rico trench, and the island arc of the Lesser Antilles and Puerto Rico. The results of this investigation indicated a Caribbean crustal structure suggestive of a slightly altered standard oceanic structure and led to the consideration of a complementary relation between the origin of an island-arc and deep-sea trench and the origin of the altered interior basin. Officer, et al. concluded from the 1955 data that the island-arcs and deep-sea trenches are the result of horizontal compression at the border between the altered Caribbean basin structure and the normal Atlantic basin structure.

In the summer of 1956 this work was continued on the Atlantis-224 and Bear-141 cruises in which the author took part. Thirty profiles, covering the same general areas as the 1955 profiles, were positioned to complete and reinforce the 1955 data. This paper is concerned only with the 1956 profiles located outside the island arc, in particular, profiles 2, 4, 6, 17, and 20. The 1956 profiles 1, 3, 5, 18, and 29, located in the same area, were computed by D. G. Harkrider, the author of Part II of this work. (See map for location of both the 1955 and the 1956 profiles in the area considered in this paper.)

Whereas previous seismic work in the area was confined to the refraction technique, provisions were made on both the '55 and '56 cruises for recording data suitable for reflection studies on the shorter range shots.
The results of all '55 and '56 profiles outside the island arc are discussed later in this paper.
TECHNIQUE AND INSTRUMENTS

Technique

The technique employed for obtaining the refraction data involves the use of two ships, one shooting and the other receiving. At the position chosen for one end of the profile the receiving ship heaves to and "goes on silent ship," i.e., all motors off. Two hydrophones are placed in the water, battery power switched on, and instruments checked. The shooting ship is then given the order to begin shooting, setting off from the receiving ship at a constant speed on the desired course. The records are developed and rough-plotted immediately, allowing the receiving ship operators to estimate for each succeeding shot the most advantageous charge size and spacing. Generally the shooting is begun with 3# charges fired at 5-minute intervals; however, to increase the resolution a 3-minute spacing of shots is sometimes used in the region where the first refraction arrival is expected to be received. As the range is increased, shot intervals and sizes are correspondingly increased, the last two to four shots being 300-pound depth charges fired at 30 to 60-minute intervals. This long spacing, of course, considerably reduces the resolution obtained, but closer spacing of such large charges would be highly impractical. Fortunately, the high velocity lines can usually be determined consistently in spite of the relatively small
number of points obtained for them.

Before each shot the shooting ship gives a one minute warning, which enables the receiving instruments to be warmed up. The shooting ship also transmits the estimated fuse burning time and the instant at which the charge is thrown overboard. With this information the camera operator can conserve photographic paper by delaying the starting of the camera paper drive motor until a few seconds before the shot is expected.

The shooting ship takes a continuous echo sounder recording of the bottom topography over which it passes. The transducer head of the echo sounder is used to pick up the sound of the shot and the first bottom reflection, \( R_1 \), both of which are transmitted to the receiving ship and recorded on one of the galvanometer traces. This "shot instant," of course, must be corrected for the time it takes the sound to travel from the shot to the receding shooting ship. The shooting ship also records the "shot instant" and \( R_1 \). This information serves a dual purpose. If the receiving ship misses the transmitted "shot instant" but records the transmitted \( R_1 \), the position of the "shot instant" on the record is easily obtained from the shooting ship's record of the \( R_1 - "shot instant" \) time interval. Also, since the reflection received by the shooting ship travels an essentially vertical path the \( R_1 - "shot instant" \) interval may be used to calculate depths in regions where the echo
sounder does not record a bottom reflection or where the depth record is questionable.

The receiving ship also takes depth recordings between shots because in regions of great relief quite large changes in water depth may result from a few hours' drifting. Also, both ships take frequent bathythermograph records to determine water temperature.

The navigation is handled by the ships' officers and use is made of Loran, celestial fixes, and, where possible, sights on islands. The absolute positions of the profiles may be in error by as much as a few miles. The range between shot and hydrophone, however, can be determined with great accuracy from the travel time of the direct water wave, or D-wave, which is trapped in the 50 to 200-foot isothermal water layer extending down from the surface. From the temperature readings the sound velocity in this layer can easily be computed to ±5 feet. As the D-time can be read to 1 millisecond, the ranges between shot and hydrophone, which may be as much as 60 miles on some of the longer profiles, can theoretically be determined to ±5 feet.

When the end of the profile is reached the shooting ship heaves to and prepares to receive. The original receiving ship then shoots up to the new receiving ship, thus reversing the profile.

As is generally the case in any seismic work, the most bothersome problem encountered is that of picking up noise
which may hide the desired arrivals. The most successful technique for combating this problem in deep-sea refraction work seems to be the one in which the hydrophones are "slacked" for each shot. Plastic floats are spaced along the hydrophone cables so as to give the cable and phone a slight negative buoyancy. About 100 feet of cable is paid out and 50 to 100 feet is coiled on the deck for "slacking." At a more or less empirically chosen time before the expected explosion the "slacker" begins slowly to pay out hydrophone cable. This procedure eases the cable tension allowing loops to form between floats and form a "shock absorber" between the ship and hydrophone.

The use of two hydrophones recording through separate amplifier channels is also very helpful in reducing the chances of confusing noise and arrivals. If one phone is noisy the other may be used, or if both phones are quiet only those events occurring on both are picked as arrivals.

The distinction between the various arrivals recorded on the photographic record is based on record-to-record correlation and recognition of the physical character, i.e., amplitude, frequency, and general shape of each. This is facilitated by making multi-channel recordings of the energy from each hydrophone. Different filter and gain settings are used for each channel. In general, the direct and reflected wave arrivals are picked on the high-pass traces while the various refracted arrivals, or ground waves, are
picked on the low-pass traces (see sample records, Figure 1).

One second chronometer ticks with a missing tick every 60 seconds are recorded on one of the galvanometer traces and serve as the fundamental timing system. In addition, the galvanometer cameras have a built-in timing system which marks one-tenth and one-hundredth divisions on the record.

**Instruments**

The instrumental setup for the *Atlantis* shooting and *Bear* receiving is illustrated in the form of a block diagram in Figure 2. The hydrophones used were Brush Development Company Type AX-58C and contain two series-connected Rochelle Salt piezoelectric crystals, the electrical output of which is matched to cable impedance through a cathodic follower preamplifier. The crystals are immersed in castor oil in a rubber boot to obtain impedance matching between crystal and water.

Each hydrophone output went to a "suitcase" amplifier, a wide band, accurately calibrated amplifier designed at WHOI. The output of each suitcase was divided into two signals.

From the first "suitcase" one output went to the magnetic tape system and the other went to a Houston Technical Laboratories recording oscillograph via a 24-channel HTL Console Seismic System (7000-B), 12 channels of which
were used for each phone. Only the signals from this first hydrophone were tape recorded to provide data for use in reflection studies.

From the second "suitcase" one output went to the camera via the HTL Console and the other went to the camera through a "Six-Channel Driver," a two-stage amplifier with interstage filtering.

The HTL system was used to record the low frequency refraction arrivals and the "Six-Channel Driver" was used to record the high frequency isothermal channel arrival.

The radio receiver output was recorded on one of the camera traces as was the output from the break-circuit chronometer.

The receiving instrument setup on the Atlantis was simpler. No magnetic tape recordings were made. The hydrophone outputs went to a three-channel amplifier and analyzer consisting of three separate units, each passing a particular range of frequencies at both high and low levels. The amplifier outputs were recorded by a Century Geophysical oscillograph.

The instrument setup for shooting was essentially the same on both ships. An Edo Corporation echo sounder recording into a WHOI helical recorder provided a continuous record of bottom topography below the shooting ship. Before the instant of detonation the echo sounder was turned off and the sounder head was used to receive the wave from the
explosion. Both the direct and bottom reflected arrivals were sent over the radio transmitter to the receiving ship. Both arrivals were also recorded on a Sanborn single channel recorder on the shooting ship.
The method for treating refraction data showing multiple sloping layers was developed by Ewing, et al., in 1939 and is repeated here merely for the sake of completeness. The following four assumptions are made:

1) The individual layers are bounded by planes and seismic wave velocity is constant within each layer.

2) Snell's Law, i.e., \( \frac{\sin \alpha_1}{\sin \alpha_2} = \frac{v_1}{v_2} \) describes the path of the seismic wave at the interface between two layers.

3) A wave traveling in any layer with velocity \( v \), and incident upon the surface of the layer at an angle \( \alpha \) with the normal, has an apparent velocity \( \frac{v}{\sin \alpha} \) along the surface.

4) Interchanging shot-point and receiving-point will not change the travel time.

An example of a travel time graph for four sloping layers with velocities \( v_1 \), \( v_2 \), \( v_3 \), and \( v_4 \) is shown in Figure 3, which represents a profile "a" shot from A to B and the reverse profile "b" shot from B to A. The heavy lines represent the first arrival times of each shot plotted against the range of the shot. The later arrivals, when observed, should fall on the continuations of the heavy lines.

The inverse slopes of the lines (distance/time) represent apparent layer velocities and are different for the two directions of shooting, that is, up dip and down dip.
The apparent velocities obtained on a profile "a" are denoted by a subscript a; the apparent velocities obtained on the reverse profile "b" are denoted by a subscript b. The fact that \( v_a = v_b \) in the sample travel time graph means that the upper boundary of the first layer is horizontal.

The circled points in the illustration are the reverse points, of which there are two for each layer, one for each direction of shooting. It is seen that each pair satisfies assumption (4), i.e., the interchangeability of shot and receiving stations. The only data taken from the travel time plots are the apparent velocities and the time intercepts, i.e., the zero-distance intercepts of the various branches.

**Calculating True Velocities from Apparent Velocities**

The possible refraction paths between two points A and B for the case of four sloping layers are shown in Figure 4, where \( \omega \) represents the dip of a given interface with respect to the one above it (positive dip is shown in Figure 4), and the angles \( \alpha, \beta, \) and \( \iota \) are defined in the figure. The perpendicular distance from A to the \( V_1V_2 \) interface is \( h_{1a} \), the perpendicular distance from the foot of \( h_{1a} \) to the \( V_2V_3 \) interface is \( h_{2a} \), and so forth. The \( h_{nb} \)'s are similarly defined at the B end of the profile.

Consider profile "a," i.e., the receiving ship is stationary at A and the shooting ship is moving to the right.
Figure 4
Reflected Wave Paths

Figure 5
Fictitious Wave Paths Associated With Zero Time Intercepts.
As noted previously, the travel time lines plotted for this direction of shooting give the apparent velocities denoted by $V_n$, where $n$ represents the layer associated with the $n$th branch of the travel time plot. Assumption (3) now gives

$$\sin (i_2 - \omega_2) = \frac{V}{V_2}$$

Similarly the reverse profile gives

$$\sin (i_2 + \omega_2) = \frac{V}{V_b}$$

In deep-sea refraction work the ocean, the velocity and bottom slope of which are easily determined, is the first layer. Therefore, $i_2$ may be determined from the above equations. It then follows from Snell's Law that for the critical angle refraction

$$\sin i_2 = \frac{V}{V_2}$$

from which $V_2$ can be determined.

Next, consider the apparent velocities $V_a$ and $V_b$. Proceeding as above, the following relations are obtained

$$\sin (\alpha_3 - \omega_2) = \frac{V}{V_3}$$

$$\sin (\alpha_3 + \omega_2) = \frac{V}{V_3}$$

from which $\alpha_3$ is determined. For the incident and refracted waves at the $V_1/V_2$ interface Snell's Law gives
\[
\frac{\nu_{13}}{\nu_2} = \frac{\sin \alpha_{13}}{\sin (\alpha_{13} - \omega_{13})} = \frac{\sin \beta_{13}}{\sin (\alpha_{13} + \omega_{13})}
\]

from which \( \alpha_{13} \) and \( \omega_{13} \) are determined. Snell's Law for critical angle refraction is used to determine \( \nu_3 \), i.e.,

\[
\sin \alpha_{13} = \frac{\nu_3}{\nu_2}
\]

Repeating this procedure for the fourth layer gives the relations

\[
\sin (\alpha_{14} - \omega_{14}) = \frac{\nu_{14}}{\nu_{4a}} \quad \sin (\beta_{14} + \omega_{14}) = \frac{\nu_{14}}{\nu_{4b}}
\]

\[
\frac{\nu_{14}}{\nu_2} = \frac{\sin \alpha_{14}}{\sin (\alpha_{14} - \omega_{14})} = \frac{\sin \beta_{14}}{\sin (\beta_{14} + \omega_{14})}
\]

\[
\frac{\nu_{14}}{\nu_3} = \frac{\sin \alpha_{14}}{\sin (\alpha_{14} - \omega_{14})} = \frac{\sin \beta_{14}}{\sin (\alpha_{14} + \omega_{14})}
\]

\[
\sin \alpha_{14} = \frac{\nu_3}{\nu_4}
\]

Succeeding layers are treated in the same manner.

**Depth Calculations from Time-Intercepts**

In Figure 4 it is evident that moving point B toward A will not change any of the angles. This is illustrated more concretely by the fact that the same apparent velocity is obtained at any distance along a given travel time branch and will also be obtained at any point on the extension of a given branch. Since the apparent velocities determine the angles, the angles associated with the fictitious wave paths
obtained by shrinking $X$ to zero must be the same as those associated with the real wave paths. Also, it is obvious from Figure 3 and the previous discussion that each wave path gives a straight line travel time plot which can be represented by an equation of the form

$$t = \frac{X}{v_a} + T_a$$

where $T_a$ is the time intercept, i.e., zero distance intercept, of the $v_a$ branch of the travel time graph. These intercepts, of course, have no physical meaning; there are no real refracted arrivals for distances less than a certain $X$ determined by the critical angle. However, in the calculation of depths to the various interfaces the time intercepts have a convenient mathematical significance.

Figure 5 has been constructed from Figure 4 by decreasing $X$ to $0$ and thus represents the fictitious wave paths associated with the time intercepts. The angles, as discussed above, are not changed by this construction.

The fictitious paths along the intercepts, i.e., CE, HJ, and OQ, represent negative distances because they, in effect, have been constructed by moving the two ends of the real paths along these interfaces toward each other. The shortest real path, of course, approaches zero, but by continuing to move the two points in the same direction the negative fictitious paths are obtained.

From this figure the following expressions are obtained
for the time-intercepts:

\[ T_{2a} = \frac{(AC + AE)}{V_1} - \frac{CE}{v} \]

\[ T_{3a} = \frac{(AF + AG)}{V_1} + \frac{(FH + GJ)}{V_2} - \frac{HJ}{V_3} \]

\[ T_{4a} = \frac{(AK + AL)}{V_1} + \frac{(KM + LN)}{V_2} + \frac{(MO + NO)}{V_3} - \frac{DQ}{v} \]

Using the geometry of Figure 5 the above expressions may be written in terms of the angles and velocities.

\[ \sin i_2 = \frac{V_1}{V_2} \]

\[ \tan i_2 = \frac{\sin i_2}{\cos i_2} = \frac{\sin i_2}{\cos i_2} \cdot \frac{\sin i_3}{V_1} = \frac{(\sin i_2)^2}{V_1 \cos i_2} \]

\[ T_{2a} = \frac{2h_1}{V_1 \cos i_2} - \frac{2h_1 \tan i_2}{V_1} \]

\[ (1) \quad T_{2a} = \left( \frac{2h_1}{V_1 \cos i_2} \right) \left( 1 - \sin^2 i_2 \right) = \frac{2h_1 \cos i_2}{V_1} \]

Similarly,

\[ T_{3a} = \frac{(AF + AG)}{V_1} + \frac{(FH + GJ)}{V_2} - \frac{HJ}{V_3} \]

From the geometry of Figure 6 it is obvious that

\[ (2) \quad \frac{(AF + AG)}{V_1} = \frac{h_1}{V_1 \cos \alpha_{13}} + \frac{h_1}{V_1 \cos \beta_{13}} \]

In Figure 6 the path FH + GJ - HJ has been shifted to the path DR + DS - RS, the travel time for which is known to be

\[ (3) \quad 2h_2 \cos i_{23}/V_2 \]
Fictitious Paths Shifted At V₁ V₂ Interface

Figure 6

Geometry Of Shot Instant Correction

Figure 7

Surface Of Reference Correction For R₁

Figure 8
from the derivation of Equation (1). The travel time for
the shifted path is larger than that of the unshifted path
by the amount $FD/V_a + DG/V_b$ where $V_a$ and $V_b$ are the ap-
parent velocities along the segments FD and DG on the inter-
face $V_1 V_2$. From assumption (3)

$$V_a = V_a' / \sin(i_{23}' - \omega_{23})$$

$$V_b = V_b' / \sin(i_{23}' + \omega_{23})$$

Applying Snell's Law gives

$$V_a = V / \sin \alpha_{13}$$

$$V_b = V / \sin \beta_{13}$$

Also, from the geometry of Figure 6

$$FD = h, \tan \alpha_{13}$$

$$DG = h, \tan \beta_{13}$$

Thus,

$$FD/V_a + DG/V_b = h, \tan \alpha_{13} / V + h, \tan \beta_{13} / V$$

Combining (2), (3), and (4) gives

$$T_{2a} = 2 h_2 \cos i_{13}' / V_1 - h_1 \tan \alpha_{13} / V_1 - h_1 \tan \beta_{13} / V_1$$

$$+ h_1 / (V_1 \cos \alpha_{13}) + h_1 / (V_1 \cos \beta_{13})$$

$$= 2 h_2 \cos i_{13}' / V_1 + h_1 (\cos \alpha_{13} + \cos \beta_{13}) / V_1$$

The expression for $T_{2a}$ is obtained in the same manner
and the resulting time intercept formulas are:

$$T_{2a} = 2 h_1 \cos i_{13}' / V_1$$
By the method of induction the derivation can be extended to include any number of layers. It must be remembered that expressions (1), (5), and (6) give the depths under the A end of the profile. The depths at B are found by shifting A to B. It has been shown that the angles do not change, thus the depths at B are given by the expressions above with \( T_{na} \) replaced by \( T_{nb} \).

The vertical depth to a given layer at A or B can be calculated from the appropriate \( h \)'s and \( \omega \)'s. However, on the profiles presented in this paper the \( \omega \)'s are generally so small as to make this calculation unnecessary and the \( h \)'s are taken as the vertical depths.
CORRECTIONS TO TRAVEL TIME VALUES

The arrival times of the various waves cannot be used directly from the records. There are several corrections which must be made for each arrival before making the travel time plots.

Shot Instant Correction

Figure 7 shows the distance relations between the shooting ship and the shot at the time of explosion. The hypotenuse of the triangle is the path taken by the direct wave to the shooting ship. The arrival of this wave is the "shot instant" which is radioed to the receiving ship. Obviously, the time represented by the hypotenuse must be added to the radioed "shot instant" to give the true shot instant. The vertical leg of the triangle is the depth of the shot and can be found from the recorded bubble pulse interval of the explosion. An underwater explosion creates a gas bubble, which oscillates about its equilibrium position, each oscillation giving a detonation. The bubble pulse interval can be plotted empirically as a function of depth and charge size, and thus with the known charge size may be used to determine the depth.

The horizontal leg of the triangle in Figure 7 is found by multiplying the ship's speed by the time elapsed between the dropping of the charge and its explosion. The ship's speed is obtained by taking the inverse slope of the
plot of D distance of each shot versus time of day of the shot, making allowances, of course, for known changes in ship's speed.

The lengths of the two legs of the triangle are converted to seconds using the water velocity computed for the isothermal channel. The calculated value of the hypotenuse, in seconds, is the shot instant correction and must be added to all arrival times read from the records.

Surface of Reference Correction

In order to compare seismic depths on different profiles it is necessary to reduce the travel time data to a surface of reference, which in the case of deep sea refraction profiles is chosen to be sea level. As both the shot and hydrophone are below sea level the travel times of the refracted and reflected waves must be corrected to bring them up to the surface of reference. Theoretically, there is also a correction for the direct wave, but this is negligible in most cases.

From Figure 8 it is evident that the $R_1$ travel time must be corrected by the time it would take the wave to travel from A to B plus the time it would take the wave to travel from C to D. If the depth of hydrophone plus depth of shot is given in seconds then the correction which must be added to $R_1$ is

$$ R_1 \text{ correction} = (\text{shot} + \text{hydrophone depth}) \times \cos \phi $$
where $\theta$ is the angle of incidence of $R_1$ on the bottom. The values of $\cos \theta$ were obtained from a graph in Officer and Wuenschel (1951)\(^6\) which gives $\cos \theta$ versus range for various depths of water.

The surface of reference correction for the refracted arrivals is made in the same manner as that for $R_2$. The angle of incidence on the bottom is given by

$$\sin \alpha = \frac{C_v}{C_h}$$

where $C_v$ is the "time average" of the sound velocity in water taken from sea level to the bottom.\(^7\) It is defined by the relation

$$C_v = \frac{H}{\int_0^H \frac{dh}{C(h)}}$$

where $C(h)$ is the instantaneous velocity at a depth $h$, and is that velocity which when multiplied by the vertical reflection time will give the true depth of water.

Officer and Wuenschel also present in their paper a graph of $\cos \alpha$ versus the ratio $C_h/C_v$. Multiplying the shot plus hydrophone depth in seconds by the proper $\cos \alpha$ factor gives the surface of reference correction which must be added to the refraction arrival.

**Topographic Correction**

As mentioned previously the usual method of reduction of refraction data is based on the assumption of plane
surfaces. The topographic correction is made to eliminate irregularities in the travel time plots arising from observed deviations of the ocean bottom from a plane surface. The deviations are taken with reference to a mean base line which best fits the observed topography. The topographic corrections reduce the travel times to this base line.

Figure 9 illustrates the method used in making the topographic corrections for \( R \). It was assumed that \( \Phi \) remains constant after reduction of the reflection point to the mean base line. The correction which must be added is

\[
R, \text{ topographic correction} = 2Ah \cos \phi
\]

where \( Ah \) is the deviation of observed topography from mean base line at the midpoint between shot and receiver. \( \cos \phi \) may again be found from the graph in Officer and Wuenschel.

The following development of topographic corrections for the refracted arrival is taken from Sutton and Bentley (1953). As discussed previously a suitable mean base line must be chosen. Also, on the basis of the type of topography and structure suspected, it is necessary to choose \( L_x \), the deepest layer in which the topography is assumed. In Figure 10:

- \( \bar{C}_v \) is the average vertical sound velocity in water;
- \( C_x \) is the velocity in \( L_x \), the deepest layer in which the topography is assumed;
- \( C_n \) is the velocity in \( L_n \), the deepest layer traversed by the arrival in question;
Figure 9 Topographic Correction For $R_1$

Figure 10 Ray Path Through Topography
$\Delta h$ is the depth to the assumed base line minus the actual depth.

From the geometry of Figure 10 the travel time for the undeformed case (dashed lines) may be written as:

\[ T_1 = \frac{x}{c_n} - \frac{2}{c_n} \left[ h_1 \tan \alpha_{15} + h_2 \tan \alpha_{25} + h_3 \tan \alpha_{35} + h_4 \tan \alpha_{45} \right] \]

\[ + 2 \left[ \frac{h_1 \sec \alpha_{15}}{C_v} + \frac{h_2 \sec \alpha_{25}}{C_2} + \frac{h_3 \sec \alpha_{35}}{C_x} + \frac{h_4 \sec \alpha_{45}}{C_4} \right] \]

The travel time for the deformed case is:

\[ T_2 = \frac{x}{c_n} - \frac{2}{c_n} \left[ h_1 \tan \alpha_{15} - \frac{\Delta h}{2} \tan \alpha_{15} + h_2 \tan \alpha_{25} \right. \]

\[ + h_3 \tan \alpha_{35} + \frac{\Delta h}{2} \tan \alpha_{35} + h_4 \tan \alpha_{45} \]

\[ + 2 \left[ \frac{h_1 \sec \alpha_{15} - \Delta h \sec \alpha_{15}}{C_v} + \frac{h_2 \sec \alpha_{25}}{C_2} + \frac{h_3 \sec \alpha_{35}}{C_x} + \frac{\Delta h \sec \alpha_{35}}{2 C_x} + \frac{h_4 \sec \alpha_{45}}{C_4} \right] \]

Subtracting the two travel times gives:

\[ \Delta T = T_1 - T_2 = \Delta h \left[ \frac{\tan \alpha_{15}}{c_n} + \frac{\tan \alpha_{25}}{C_n} + \frac{\sec \alpha_{15}}{C_v} - \frac{\sec \alpha_{35}}{C_4} \right. \]

\[ = \frac{\Delta h}{c_v} \left[ \left( \frac{\sec \alpha_{15} - c_v \tan \alpha_{15}}{C_n} \right) - \frac{c_v}{C_x} \left( \sec \alpha_{35} - \frac{C_x}{C_n} \tan \alpha_{35} \right) \right] \]
Making the substitutions

\[
\sin \alpha_{15} = \frac{c_v}{c_n} \quad \sin \alpha_{35} = \frac{c_x}{c_n}
\]

gives

\[
\Delta T = \frac{\Delta h}{c_v} \left[ \frac{1 - \frac{c_v^2}{c_n^2}}{1 - \frac{c_x^2}{c_n^2}} \right] - \frac{c_v}{c_x} \sqrt{1 - \frac{c_x^2}{c_n^2}}
\]

Thus, for a change, \( \Delta h \), in water depth \( \Delta T \) is the topographic correction which must be added to the travel time of the refracted arrival. The equation for \( \Delta T \) is unaffected by the number or thickness of layers between the water and \( L_x \) or between \( L_x \) and \( L_n \).

The \( \Delta h \) in the equation must be measured at the point where the refracted wave passes through the surface of relief. This requires the calculation of the offset distance, i.e., the horizontal distance from the point directly below the shooting ship to the point of emergence of the refracted wave on the surface of relief. The offset distance is given by the expression

\[
D = h_1 \tan \alpha_1 + h_2 \tan \alpha_2 + \ldots + h_{(x-1)} \tan \alpha_{(x-1)}
\]

Usually, the first term is large compared to the succeeding terms, which, therefore, may be neglected.

One problem in using this topographic correction is that of choosing the layer \( L_x \). In the case of large corrections a trial and error approach can be used to obtain
the best reduction in scattering, but if the corrections are small the differences obtained by varying the choice of \( \ell_x \) will be too small for reliable comparison of reduction in scattering.

Using the above expression for the topographic correction \( (\Delta T) \) Sutton and Bentley have calculated a number of curves giving \( \Delta T \) for \( \frac{\Delta h}{\ell_x} \) second as a function of \( \frac{\ell_x}{\ell} \) for various values of \( \frac{\ell_x}{\ell} \). These curves were used by the author in calculating the topographic corrections for the profiles presented in this paper.
CALCULATIONS AND ASSUMPTIONS

Estimating Sedimentary Velocity

At the distance where the critical angle of refraction is first obtained on the $\nu_2$, $\nu_3$ interface the travel times of the waves reflected and refracted from this interface are equal. The refraction line is tangent to the $R$, reflection curve at this point. On none of the profiles presented in this paper was the immediate sedimentary material measured by a refraction line. The first measured refraction was from a horizon at some depth beneath the bottom. In order to make the depth and velocity calculations a velocity had to be estimated for this first thickness of material.

The procedure used for obtaining this estimate is as follows. A line is constructed parallel to the first refraction line, $\nu_2$, of the travel time curve and tangent to the reflection curve. This is the line which would have been obtained if the $\nu_2$ horizon were at the bottom. For the purposes of this estimation the fictitious wave paths associated with the time-intercepts are assumed to be vertical. Thus, the thickness of material above the measured layer is given approximately by

$$h_{2a} = \frac{T_{3a} - T_{2a}}{2} \times \nu_2$$
where

\( \tau_{3a} \) is the \( V_{3a} \) time-intercept;

\( \tau_{1a} \) is the time-intercept of the tangent to the curve;

\( \bar{V}_2 \) is the estimated velocity in the unmeasured layer.

Lawhorns has prepared for the Caribbean area a graph of average vertical velocity versus depth below the bottom. This graph was constructed using data obtained from his reflection investigation of the upper few thousand feet of the sedimentary column. Using the approximate \( h_{2a} \) the appropriate \( \bar{V}_2 \) was obtained from Lawhorns graph. This value of \( \bar{V}_2 \) was then used in the time-intercept formulas for the exact calculations of \( h_{2a} \), \( h_{2b} \), and so forth.

**Unreversed Velocities**

On profiles with unreversed velocities it was generally assumed, for purposes of calculation, that the layer in question thinned to a thickness of from 200 to 500 feet at the end of the profile where no refraction line was obtained. The choice of these values was somewhat arbitrary and was based on the assumption that these thicknesses must be small compared to those of the underlying and overlying layers, or else a refraction line would have been measured for them.

**Masked Layers**

On two profiles the velocity normally associated with the crustal layer is missing from the travel time plot of
the first refraction arrivals. However, there is in both cases an unusually thick section of overlying material. In such cases, the thinner layer beneath the thick section is "masked," i.e., the thinner layer never appears as a first arrival on the travel time graph. For the purposes of calculation the missing travel time branches were drawn in using time-intercepts chosen to give "normal" thicknesses of the crust as measured elsewhere in the general area.
GEOPHYSICAL RESULTS

Individual Profiles

The positions given in the following discussions of the individual profiles are average positions and do not show the drift of the receiving ships during the shooting of the profiles. The position of the beginning of the profile is given first. The map showing the location of the profiles, the bottom topography plots, and the travel time graphs are presented at the end of this paper.

Before the refraction lines were drawn, all the corrections discussed in the fourth section (beginning on page 19) were applied to the arrival times. For each profile an average velocity for the unmeasured portion of the sedimentary column was estimated using the method outlined in the preceding section. The treatment of the velocities stated to be unreversed or "masked" was also as outlined in the preceding section.

The calculated velocities and thicknesses for all the 1955 and 1956 profiles in the area covered by this paper are presented in Tables I, II, and III which have been set up in the form used by Officer, et al. (1957). The divisions of the tables are as follows:

A - 1.6-2.0 km/sec., unconsolidated sediment
B - 2.2-3.0 km/sec., partially lithified to lithified sediment
C - 3.2-4.2 km/sec., sedimentary or volcanic rock
D - sedimentary, igneous, or metamorphic rock
E - crustal velocities, i.e., velocities in the
material immediately overlying the major discon-
tinuity, designated \( E_1 \) and \( E_2 \) where two are found
F - velocity beneath the major discontinuity

A pictorial representation of the calculated results for
the profiles presented in this paper is given in Figure 11.
Figure 12 is a pictorial representation of the 1956 profiles
interpreted by Harkrider in Part II of this investigation.

Refraction Profile 2 (22°-39'N, 61°-54'W) to (22°-03'N,
61°-48'W)

This profile was taken in the Atlantic basin about 400
miles northeast of Puerto Rico. The bottom topography is
relatively flat except for a 2000-foot peak at the south end
(see topography plot), which caused considerable scatter in
the travel time data. As shown in the enlarged portion of
the travel time plot the scatter was practically eliminated
by making the topographic corrections discussed in the fourth
section of this paper. The average water depth for the pro-
file is 5.8 kilometers. The base line chosen as the refer-
ence plane for the topographic corrections has a 0.10° dip
to the north. In general, the refraction lines are very well
determined for this profile.

Beginning at the top of the geologic column, the
calculations show a thin unconsolidated sedimentary layer
Figure 11. Calculated Layer Thicknesses and Depths (Profiles 2, 4, 6, 17, and 20)
Figure 12. Calculated Layer Thicknesses and Depths (profiles 1, 3, 5, 18, and 29)
with an estimated velocity of 1.8 kilometers per second. Below this is the first crustal layer, which has a velocity of 6.0 km/sec. and thins from 1.7 kilometers at the north end of the profile to 1.4 kilometers at the south end. Underlying this is a second crustal layer with a velocity of 6.9 km/sec. and a uniform thickness of 4.0 kilometers. The velocity below the major discontinuity is 8.0 km/sec., the usual value for the Atlantic basin (see Ewing, Sutton, and Officer (1954)).

Refraction Profile 4 (19°-04'N, 60°-28'W) to (18°-30'N, 60°-09'W)

The profile was taken about 120 miles northeast of Barbuda and is essentially parallel to the island-arc axis. It is located on the Atlantic side of the eastward extension of the Puerto Rico trench. On the map included with this paper the contour intervals, unfortunately, are too large to show this extension, which parallels the axis of the island-arc.

The bottom has exceptionally low relief and slopes gently to the southeast; the base line has a 0.18° dip to the southeast. The water depth increases from 5.9 kilometers at the northeast end to 6.2 kilometers at the southeast end.

The high velocity lines on both ends of the profile have one or two weak points, in particular, the last point on the Atlantis high velocity line. However, there are a sufficient number of good points to firmly establish all the refraction
lines drawn on the graph.

The estimated velocity for the sedimentary layer is 1.8 km/sec, which gives a calculated thickness for this layer of about .5 kilometer. The first crustal layer has a velocity of 5.7 km/sec and thickens toward the southeast end of the profile. The second crustal layer has a velocity of 6.9 km/sec, and thins from 6.3 kilometers at the northwest end of the profile to 4.3 kilometers at the southeast end. The total thickness of the crustal layers measured on this section is about two kilometers greater than that for the Atlantic basin section represented by profile 2. The velocity below the crust is 8.4 km/sec, which is considerably higher than the corresponding Atlantic basin velocity.

Refraction Profile 6 (17°-25'N, 60°-45'W) to (18°-25'N, 61°-20'W)

This profile was taken about 60 miles northeast of Barbuda and is parallel to the axis of the island arc. It is located between the island arc and the Puerto Rico trench. The bottom topography is irregular, varying from 1200 to -600 feet with respect to the horizontal base line chosen at 18,300 feet (5.6 kilometers).

On this profile the normal crustal velocity was not measured because of the unusually thick section of overlying material which "masked" the arrivals from the crustal layer. The dashed lines on the travel time plot represent the crustal refraction lines which were constructed according to the
procedure outlined in the fourth section. These lines were used in the calculations.

Second refraction arrivals were used to determine the first branch of the travel time plot. The interpretation of this profile was complicated by the wide spacing of shots on the Bear refraction lines and the noise on the records of both ships. Nevertheless, the measured refraction lines are well established.

On this profile a 1.2 kilometer thick sedimentary layer of velocity 2.6 km/sec. is measured. Below this is a 3.5 km/sec. layer which decreases from 4.1 kilometers at the southeast end to 2.5 kilometers at the northwest end. The third measured layer below the surface has a velocity of 4.8 km/sec. and thickens to the northwest. The assumed crustal velocity gave a calculated thickness for the crust of 4.7 kilometers at the southeast end and 6.4 kilometers at the northwest end.

The velocity below the major discontinuity is 8.4 km/sec. which agrees with profile 4. The total thickness of the material above the major discontinuity is considerably greater than that for the Atlantic basin.

Refraction Profile 17 (18°-28'N, 60°-39'W) to (18°-10'N, 61°-14'W)

Taken transverse to the island-arc axis the profile extends from the Puerto Rico trench toward the island arc. It cuts across profiles 5 and 6 of the 1956 cruise. The
bottom topography is quite irregular and the water depth increases from 6.5 kilometers at the trench end to 5.3 kilometers at the end near the island of Barbuda. The base line has a 0.93° dip toward the trench.

In general, the arrivals from the highest velocity layer were very weak on both ends of the profile. The first line plotted on the Atlantis end of the profile and determined entirely by second arrivals is not a simple refraction line and was not included in the calculations. The calculations were further complicated by the measurement of an unreversed velocity at each end of the profile. The smallest measured velocity was found only at the northeast or trench end and the next higher measured velocity was found only at the end nearer the islands. As explained in the preceding section the calculations were carried out by assuming that the measured layers thinned to a small thickness at the end where they were not measured.

On this profile, also, the velocity below the major discontinuity was determined to be 8.4 km/sec. The 7.0 km/sec. velocity calculated for the crustal layer is slightly higher than normal for the area. Also, the crust thins considerably to the southwest, i.e., toward the islands. The layer above the crust has a velocity of 5.5 km/sec. and thickens from 5.9 kilometers at the trench end to 7.4 kilometers at the end nearer the islands.

An interesting feature of this profile is the
apparently anomalous arrival received for both directions of shooting at a range of about 45 kilometers from the Bear end of the profile. This distance corresponds to a point at the base of the large peak shown by the bottom topography plot. This suggests to the author that the peak is a surface expression of some deeper topographic feature in a higher velocity layer. If the emerging wave passed up through this higher velocity material the travel time would be shortened as shown on the graph.

Refraction Profile 20 (19°-28'N, 64°-07'W) to (19°-21'N, 65°-09'W)

The profile was taken about 60 miles north of the Virgin Islands and south of the Puerto Rico trench, and is essentially parallel to the axis of the trench. The bottom topography is quite irregular. The difference in the topography recorded by the two shooting ships is the result of several hours' drifting from the time the Atlantis ceased shooting to the time the Bear began shooting. A horizontal base line was chosen at 6.0 kilometers.

There is some scattering of points on all the branches of the travel time curve except the first. As on profile 6 the crustal refractions are masked by an unusually thick section of overlying material. Following the procedure outlined in the preceding section, assumed crustal velocity lines (dashed) were constructed for use in the calculations. The refraction lines, particularly the highest velocity line,
are not well determined, but there is not much doubt as to
the over-all structure and thicknesses. The calculated
velocities have a larger probable error than for the previous
profiles.

The assumed crustal velocity was 6.8 km/sec. which gave
a crustal thickness of about 3.6 kilometers. As on profiles
4, 6, and 17 the subcrustal velocity is 8.4 km/sec. The
layer overlying the crust has a velocity of 5.6 km/sec. and
a thickness of about 10 kilometers. The uppermost layer has
a velocity of 3.7 km/sec. and a thickness of 2.5 kilometers.
The total thickness of the section measured by this profile
is over two and one-half times that for a typical Atlantic
basin section, e.g., profile 2.

Summary and Interpretation of Results

Using the results of the profiles presented in this
paper it is possible to describe a cross-section transverse
to the axis of the Puerto Rico trench and extending from the
Atlantic basin to the southwest end of profile 17.

Beginning in the Atlantic basin the subcrustal velocity
increases from 8.0 km/sec. for the basin section (profile 2)
to 8.4 km/sec. beneath the trench and its slopes, i.e., from
profile 4 to the southwest end of profile 17. The depth to
the lower boundary of the crust is 11.5 kilometers in the
ocean section and increases to a depth of 20.5 kilometers
beneath the trench axis, where it apparently remains constant
for the length of profile 17. The 5-kilometer-thick, two-layered crust of the ocean section thickens to 8 kilometers beneath the northern slope of the trench (profile 4). Beneath the southern slope of the trench the crust has thinned to a single layer which is 6.5 kilometers thick at the trench axis.

The total thickness of lower velocity material overlying the crust increases from about 0.5 kilometer in the Atlantic basin to 7.5 kilometers beneath the trench axis. This material above the crust continues to thicken toward the islands, reaching a maximum of 12.7 kilometers at the southwest end of profile 17. The layer velocities observed for this supra-crustal material range from an unconsolidated sediment velocity of 1.6 km/sec. to a 5.5 km/sec. velocity. The higher velocities, i.e., around 5.5 km/sec., would be characteristic of a wide variety of rock types, ranging from lithified sedimentary to igneous to metamorphic rocks.

Although profile 20 was taken 200 miles to the west of the area described by the above cross-section, its relative location with respect to the trench and island-arc axes approximates a position between the end points of profile 17. A comparison of profiles 20 and 17 reveals a remarkable similarity between the over-all structure revealed by each. The major discontinuity is at a depth of 22 kilometers on profile 20 compared to 20.5 kilometers on 17. The sub-crustal velocity observed on both is 8.4 km/sec. The
uniform crustal thickness on profile 20 compares favorably with the mean crustal thickness on profile 17. Both profiles are overlain by a very large thickness of 5.5 km/sec. material above which there are comparable thicknesses of 1.6 to 3.8 km/sec. material.

The above comparison may be considered as evidence for the contention that the island-arc, deep-sea trench sequence is a linear feature, i.e., it has similar transverse cross-sections at all points along its axis.
Seismic Profiles

The additional seismic refraction work considered in this section includes the 1955 profiles 42, 43, 44, 45, and 46 reported in Officer, et al. (1957) and the 1956 profiles 1, 3, 5, 18, and 29 interpreted by Harkrider (1957). The results of these profiles are presented in Tables II and III.

In the following comparisons and correlations the profiles are considered in groups which have approximately the same relative position in the island-arc sequence and, therefore, as pointed out in the previous section, might be expected to show similar structure.

Profiles 1, 2, 3, and 4 show a gradual transition in geologic structure as the trench area is approached. Profile 3 fits very nicely in the gap between profiles 2 and 4, and shows the increase in subcrustal velocity to 8.4 km/sec. which was observed on profile 4. Profile 1 does not correlate quite so well; the total crustal thickness and the crustal velocity compare favorably with the values observed on profiles 2, 3, and 4, but the 8.2 km/sec. crustal velocity would seem more appropriate for a section between profiles 2 and 3 which have subcrustal velocities of 8.0 km/sec. and 8.4 km/sec., respectively.

Although profile 5 shows crustal and subcrustal velocities which are somewhat higher than those observed on
profiles 4, 6, and 17, the 15-kilometer depth to the major discontinuity fits well with the increase of this depth from 11.5 kilometers on profile 4 to 20.5 kilometers at the southwest end of profile 17. The great thickening of supra-crustal material and the corresponding lowering of the major discontinuity which was observed at the island-arc end of profile 17 is also observed on the island-arc end of profile 18. Profile 20 shows an even greater thickness of supra-crustal material and gives the major discontinuity depth as 22 kilometers which is the same as that for the island-arc end of 18. Profile 42 which correlates with profile 20 shows an undetermined thickness of supra-crustal material having the same velocity as that of profile 20. The sub-crustal velocity was not measured on profile 42. In summary it seems that profiles 4, 5, 6, 17, 18, 20, and 42 offer conclusive proof that the depth to the major discontinuity increases as the trench area is crossed from the Atlantic basin toward the island arc.

Profile 29 was taken high up on the southern slope of the trench and shows a section which does not readily correlate with any of the other profiles. The subcrustal velocity was not measured.

Profiles 45 and 46 were taken in the western portion of the trench. The section observed on profile 45 resembles one of the ocean basin sections shifted down about 3 kilometers. The section under profile 46 compares in a general
way with the profiles to the east. The crustal velocities, however, are somewhat lower and the crustal thicknesses are greater. There is only a small amount of supra-crustal material, which compares well with the corresponding 1956 profiles 4 and 5.

Gravity Measurements

The gravity contours shown on the map at the end of this paper were taken from Hess (1938). The most outstanding feature of this gravity picture is the well-defined negative gravity strip which essentially parallels the axis of the island arc and is located between the trench and the island-arc axis. In the past there has been some difficulty in explaining why the axis of this negative gravity strip is offset from the axis of the trench. Theories advanced to explain the source of the gravity anomaly generally assumed a greater thickness of crustal material centered beneath the axis of the trench. The seismic measurements discussed in this paper, however, show that there is a great thickness of supra-crustal material along the negative anomaly axis.

An inspection of each profile in the negative gravity strip reveals almost perfect correlation between the gravity results and the seismic results. Consider profile 17, for example. The thickness of the supra-crustal material at the southwest end is almost double that at the northeast end. Correspondingly, the negative gravity anomaly is much
greater at the southwest end of the profile than it is at the northeast end.

Profiles 20 and 43 both show large thicknesses of supra-crustal material and both are in the region of relatively large negative anomaly.

The only profile which does not appear to agree fully with the gravity contours is profile 18. The southeast end of profile 18 shows a section of supra-crustal material which is both thicker and of lower velocity than the section at the corresponding end of profile 17. Yet, the negative gravity anomaly is shown in the map to be greater for the thick end of profile 17 than it is for the thick end of profile 18. This suggests that the -100 to -150 contour might be extended to include the southeast end of profile 18. Such an extension could well be the case as the control for the gravity contours on the map is not extensive.

Conclusion

It is the writer's opinion that the additional geophysical evidence presented in this section has in each instance confirmed the correctness of the interpretation of the geologic structure as it was described in the summary of the preceding section.
APPENDIX
Geographic location of seismic refraction stations bordering Caribbean Island area.
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$T =$ thickness in km. \hspace{1cm} $V =$ velocity in km/sec. Subscripts indicate directions.

Note: Bracketed velocities were assumed, velocities in parentheses were unreversed.

Table I. Summary of 1956 Results, Part I
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\(T = \text{thickness in km.} \quad V = \text{velocity in km/sec.} \quad \text{Subscripts indicate directions.}\)

\text{Note: Bracketed velocities were assumed, velocities in parentheses were unreversed.}

\text{Table II. Summary of 1956 Seismic Results, Part II}
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$T =$ thickness in km.  $V =$ velocity in km/sec. Subscripts indicate directions.

Note: Bracketed velocities were assumed, velocities in parentheses were unreversed.

Table III. Summary of 1955 Results, Puerto Rico Trench and Vicinity
REFERENCES


