THE RICE INSTITUTE

A SEISMIC STUDY
OF THE SHALLOW SUB-BOTTOM MATERIALS
OF THE EASTERN CARIBBEAN

by

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I. INTRODUCTION

A. General Purpose

Investigations were undertaken in the Caribbean-Antilles region in an attempt to describe the broad structural and compositional attributes associated with this striking geographic feature. The topographic feature of the Puerto Rico trench suggests an accumulation site for large thicknesses of sedimentary material. The terrestrial association between mountain ranges and thick stratigraphic sequences suggests at once that such a trench might at some future time become a mountain range. This and many other lines of evidence has led some geologists and geophysicists to propose a theory of geosynclinal origin for mountain ranges. If the existence of a broad crustal downwarp could be shown below the Antilles island arc - Puerto Rico trough then overwhelming evidence would be given that the association was a geosyncline and a zone of crustal weakness which, under stress, might be sheared and thrust to form the great thrust sheet-fold Alpine type mountains. The seismic refraction technique was used since it measures velocity discontinuities and allows the calculation of the depth to the discontinuity (e.g., the Mohorovičić discontinuity) and any slope it might have as well as the seismic velocity in the various materials. This method also extends these determinations to large depths. It was also desired to obtain data on the sedimentary material using the reflection technique.

Work was begun by H. Ewing, C. B. Officer et al in this area in 1951 when the ATLANTIS - 172 and the CARYN - 22 passed through the Western Venezuelan Basin. Some sound transmission studies had been carried out in the islands previously. Several cruises had been made.
before to study the structure of the Atlantic basin and Nares basin. Most of this work was done with the Lamont Geological Observatory and the Woods Hole Oceanographic Institution by C. B. Officer, J. B. Hersey, H. R. Johnson, M. Ewing, P. C. Wuenschel, G. H. Sutton, and others. T. F. Gaskell and J. C. Swallow, and I. Tolstoy have also done some work in this area. The chief intention of the 1951 cruise was to gather refraction and sound transmission data although tape recordings were made. These later proved to be of poor quality and no study was made. Research was begun in earnest in the Caribbean-Antilles area by C. B. Officer, J. Ewing, H. R. Johnson, and R. S. Edwards in the spring of 1955 aboard the ATLANTIS and CARYN of the Woods Hole Oceanographic Institution. This cruise covered the entire eastern Caribbean area in both deep and shallow water. The work was continued in the summer of 1956 to obtain better control and verification of the results obtained in 1955. This work was done on board the research vessels BEAR and ATLANTIS of the Woods Hole Oceanographic Institution with the joint cooperation of Lamont Geological Observatory and The Rice Institute. It was directed by C. B. Officer with the assistance of senior scientists J. Ewing, J. Hennion, and R. S. Edwards. The remainder of the scientific party was composed of professors, graduate, and undergraduate students from Rice, M.I.T., Harvard, Princeton, Utah, Wisconsin, and Cornell. Data taken on the cruises of 1955 and 1956 was extensive, especially that of the recent cruise. The completeness was greatly aided by improved and more versatile instruments giving the most complete data per shot obtained to the present. The data obtained is usable for refraction-crustal study.
reflection-sediment study, and sound transmission study.

Some modestly extensive gravity work has been done in this area. Vening-Meinesz (1926, 1937), Hess and Ewing (1937), and Shurbet and Worzel (1953-6) have been major contributors to this research.

This brief summary of previous work is given because the purpose of the two refraction cruises was to gather more data and correlate all the known phenomena observed from different approaches if possible into a theory for the history and future of this area.
B. Purpose of this Investigation

The purpose of the present investigation was to utilize the data taken in the Venezuelan Basin area of the Caribbean to extend the method of study of bottom sediments by seismic reflection-refraction techniques, and to describe the sediments and their variation in the Venezuelan Basin and the Grenada Trough. It was desired to extend the previous work as to technique and at the same time describe a previously unexamined area as far as possible with regard to structure, thicknesses, and properties of the sediments. This was greatly aided by the versatility of the instruments used to analyze frequencies.
C. Previous Deep-Sea Reflection Studies

No previous reflection studies have been made in the eastern Caribbean. Hersey and Ewing\textsuperscript{3} made numerous reflection stations in the North Atlantic in the area bounded at the corners by Bermuda, North Carolina, Cuba, and Puerto Rico. Weibull\textsuperscript{4} also made some reflection stations in the North Atlantic. However, neither of these investigations used a profile technique. There was only a single shot and detector per station and no control could be obtained concerning the sediment velocities and properties. Hill\textsuperscript{5} did some research in the northeast North Atlantic using a method akin to profiling. He was not interested in the close range reflections but centered his investigation on the refraction arrivals which penetrated only a slight depth of the sediments. The causes for this were concluded by him to be due to an increase in the velocity of sound in the sediments with depth. Multiples of these arrivals were observed but no multiple bottom reflections were, from which Hill concluded, incorrectly, that there were no multiple bottom reflections. The frequency range of his instruments had too low an upper limit to record the multiple reflections. Officer\textsuperscript{6} carried out research between Bermuda and the continental United States on the abyssal plain using a profile technique which, in general, is the same as used for the present investigation. He described the physical properties of the sediments in some detail and also interpreted a series of these profiles\textsuperscript{7}. J. Nafe and J. Ewing (unpublished) also did some work of this type in this same general area. Their profiles were designed to give a broad areal coverage. J. Nafe and C. Drake (unpublished) have done an empirical study on the results of all marine refraction profiles available to them.
By plotting the velocities observed versus the thickness for all sediment refractions they derived an approximate formula to express the variation of velocity in the sediments with depth.
II OPERATIONAL EQUIPMENT AND TECHNIQUES

As has been mentioned above, the purpose of the cruises of 1955 and 1956 was of a multiple nature. Much equipment was needed to make both refraction profiles and shallow sediment studies as well as accessory equipment for determining several variable environmental factors. The data was taken from both cruises although the author was present only on the latter. Only that equipment essential to the present investigation will be described in detail below with occasional reference being made to the overall equipment assemblage.

The data was taken in the following general manner. The signal from the hydrophone was amplified and recorded directly on magnetic tape without any filtering. Only seismic data was recorded. Timing and shot instants were determined in a manner to be described in the next section. The magnetic tapes were played back in the laboratory to a set of amplifiers with a wide range of filtering and recorded on a standard photographic galvanometer recording oscillograph.

The data from the 1955 cruise was taken aboard the R/V ATLANTIS while that from the 1956 cruise was taken aboard the R/V BEAR. The system used for the tape recording of the two sets of data were essentially the same on both cruises so that only one will be described in the following discussion.

Two hydrophones were used on each cruise for taking data but only the output of one was tape recorded each time. The hydrophone was a Brush Development Company type AX-58 unit consisting of two 45° X-cut Rochelle salt crystals connected in series and immersed in castor oil
for proper matching to the water. The detector was fitted with a cathode follower type preamplifier mounted in the hydrophone unit. This preamplifier provided a proper impedance match between the high impedance crystal and the low impedance hydrophone cable and amplifier input circuit and greatly increased low frequency performance.

The cable was an eight conductor, neoprene sheathed cable of marine type. The cable was floated in such a manner as to provide slightly negative buoyancy which with proper manipulation resulted in great improvement in sensitivity by reducing the background noise. The method of handling of the hydrophones will be described below.

The cable led directly into the input of a wide range amplifier designed and built for the purpose by the Woods Hole Oceanographic Institution. These amplifiers are known as "suitcase" amplifiers and have flat response from 5 to 10,000 cycles per second. They include no filtering and operate wide band with a dynamic range of 120 db maximum with calibrated attenuator settings in 2 db steps. These instruments operate on AC or DC and provide the power for the hydrophone preamplifiers.

The output from the suitcase amplifiers was fed into the input of the modulator-demodulator unit of a dual-channel Magnetocorder and thence recorded on one fourth inch magnetic tape on the Magnetocorder reel transport. Two tracks were recorded on the tape from the modulator-demodulator, one at high level and the other at a lower level. The signal being recorded was monitored independently. This monitoring
instrument allowed visual determination of overload by presenting the recording amplitude as a deflection on a cathode ray tube. The monitor was operated variously on both high and low level tracks. The Magne-recorder performance was essentially flat from 10 to 10,000 cycles, down slightly at 10,000 cycles (3 db) and dropping off rapidly below 10 cycles. Calibration strips were placed on the tape at frequent intervals during the cruises.

The above equipment was operated in conjunction with other equipment to provide direct long period photographic records which could be interpreted rapidly on location. However, the above equipment is all that was required to place the seismic data on the tape. Other equipment was necessary however, to give a complete environmental and physical description for each shot.

Continuous profiles of the bottom topography were taken throughout the cruises by echo sounders. These were Edo Corporation echo sounders modified by the Woods Hole Oceanographic Institution and connected to a special recording device built by Woods Hole Oceanographic Institution. The recorder allowed great accuracy and flexibility in determining depths, especially in very deep water. A helix wire rotated at a variable speed under a knife edge and recorded on 19 inch chemically treated paper driven at a speed proportional to the helix speed. The signal was applied between the helix and knife edge and the electric impulse darkened the paper, giving a graphic picture of the bottom contours. The drive speed could be adjusted so that the period of rotation of the helix corresponded
to a certain predetermined vertical travel time of the ping in the water. The Edo unit was timed by the helix rotation so that a ping was generated at the beginning of each helix sweep. A further control allowed certain pings to be eliminated and also allowed certain sweeps to be disregarded. In very deep water this aided the recording greatly since several pings would be in transit between the ship's pinger and the bottom and the gain necessary to record the echoes would be such that noise due to the ship and near surface reverberations would tend to obliterate the echoes. A distributor on the helix shaft timed the Edo transmitter. The burst pulses, or pings, were of a frequency of 12,000 cycles per second. The sweep speed choices were available at various intervals of depths. As an example of the operation of the sounder, let us assume the water to be 1,800 fathoms deep. The recorder could be set to record intervals of from 25 fathoms to 1,000 fathoms. At the rapid sweep, one rotation of the helix required the same time that the ping did to reach a depth of 50 fathoms, i.e. down to 25 and back. At this rapid sweep rate greater detail of relief could be obtained but at the depth of the example the bottom trace would probably be hidden in the reverberation noise. At the 1,000 fathom sweep scale, very little detail is obtainable since 19 inches corresponds to 1,000 fathoms on the paper. So at the depth of the example, one might set the recorder at a scale of 400 fathoms per sweep. In this case the recorder would transmit a ping at the beginning of a sweep and would rotate 4½ times before the echo was recorded. This allows greater detail of observation and yet retains ease of operations.
The transducer was a standard Edo Corporation transducer and was mounted in a streamlined body and towed over the side at the end of an articulated cable.

The instants of shot detonation at the shooting ship were received through the echo sounder equipment. Previous to detonation the echo sounder pinger was turned off. The detonation signal was fed into a radio transmitter and transmitted to the receiving ship. The signal was monitored by feeding the signal from the transducer into an amplifier which drove a Sanborn hot stylus recorder. This gave a strip record of the shot and the bottom reflection as received by the shooting ship. The signal transmitted was received by the listening ship over the receiver and placed on a special trace in the galvanometer camera. This allowed accurate determination of travel times.

The chronometer was used to time both the shot records and the receiving directly recorded records and is mentioned here only because these records gave certain data essential to this investigation. Second marks were recorded on both records from the break circuit chronometer. No timing was recorded on the tape.

Close check was necessary on the temperature of the near surface isothermal water layer through which the direct water wave arrival travelled. This arrival was the chief method used to determine the shot to receiver distance. Standard bathythermographs were periodically lowered to depths of from 450 to 900 feet and gave a graphic record of temperature versus depth. The temperature observed allowed the determination of the
velocity with which the surface wave travelled.

Navigation was at all times celestial but was checked by LORAN where possible.

The playback system provided a wide range of frequency analyses on one record. The tapes were played back on a Magnecorder identical to that used for recording. One channel was monitored by earphones, generally the high gain channel, while the signal was taken off either channel depending on the recorded amplitude. The chosen output of the Magnecorder was split and fed into two separate units. The Magnecorder was operated AC on playback and was isolated from the line by an isolation transformer. Some 60 cycle hum was still seen although greatly reduced.

One unit consisted of a galvanometer driver unit containing six channels of which four were used. Each driver channel had an amplifier and rectifier with an external filter. The drivers could be operated either AC for low frequencies or rectified to give the envelope of high frequency signals. In our case they were used for high frequency analysis and were operated with rectifiers. Each channel had a high and low level output plug having the same signal at different voltages. Both outputs of channel one were used and the high level signal placed directly on trace 7 and the low level signal on trace 8. The filter was set to pass high frequencies above 500 cycles. The high level output of channel two was placed on trace 9 with no filtering. Imperfect operation on this setting was obtained as is evident on the records. The high level output of channel three was placed on trace 10 with high pass filtering set to
pass frequencies above 2,000 cycles. The high level output of channel five was placed on trace 11 with a band pass filter set to pass from 300 to 500 cycles. The driver unit could be operated on batteries or on AC and was operated AC on the playback. Gain was controlled by step switches calibrated in 2 db steps with a maximum gain of about 40 db.

The second unit was a Houston Technical Laboratories model 7,000-B 24 channel seismic amplifier rack whose inputs had been especially adapted for this work. In operation, all of the odd numbered channels were in parallel as were all the even numbered ones. Only the even numbered channels were used in this investigation and were fed commonly by the Magnecorder output. In the 7,000-B, six filter channels are present, three high cut and three low cut each containing two sections so that a given pair of high and low cut filters performs the filtering for a certain four amplifier channels. In the present work, only two channels were dependent on each pair of filter settings. The filters could be set for cutoff frequency and slope. The amplifiers could be set for AGC or linear amplification as well as for range of operation and recording level. The following general data is stated by Houston Technical Laboratories for the unit. The frequency response is 3 db from 5-500 cycles per second. Harmonic distortion is less than one percent behind the input transformer (50 hy) and before filtering at an input voltage of less than 50 millivolts. Crosstalk signal to noise ratio was excellent at -70 db from adjacent channels. A damping resistor was used in the output stage to match the galvanometers.
The amplifier settings were as follows. Channels one and three were placed on traces 1 and 2 respectively with the low cut filters out and the high cut filters set at 20 cycles with a cutoff slope of 36 db/octave. Channels five and seven were placed on traces 3 and 4 respectively with the low cut filters set at 21 cycles and cutoff slope of 36 db/octave and with the high cut filters set at 47 cycles with a cutoff slope of 36 db/octave. Channels one, three, five, and seven were operated in the 'Wide band' position having a flat frequency response from 5-500 cycles.

Channels nine and eleven were placed on traces 5 and 6 respectively with the low cut filters set at 48 cycles with a cutoff slope of 36 db/octave and the high cut filters set at 75 cycles with a cutoff slope of approximately 80 db/octave. Channels thirteen and fifteen were placed on traces 12 and 13 respectively with a low cut filter setting of 70 cycles and cutoff slope of 36 db/octave and with a high cut filter setting of 120 cycles and cutoff slope of 36 db/octave. Channels nine, eleven, thirteen, and fifteen were operated in the 'medium range' position having a flat frequency response from 15-500 cycles.

Channels seventeen and nineteen were placed on traces 14 and 15 respectively with low cut filters set at 120 cycles with a cutoff slope of 36 db/octave and the high cut filters set at 215 cycles with a cutoff slope of 36 db/octave. Channels twenty-one and twenty-three were placed on traces 16 and 17 respectively with low cut filter settings of 210 cycles at a cutoff slope of 36 db/octave and high cut filter settings of 320 cycles with a cutoff slope of 36 db/octave. Channels seventeen, nine-
teen, twenty-one, and twenty-three were operated in the 'high range' position having maximum response from 45 to 500 cycles but down 3 db at the upper limit.

The recording levels of all channels were set equal and the individual gains varied to adjust for differences in the tape recorded levels. This is also true for the driver unit. The lowest numbered channel of each pair having the same filter setting was operated at a lower gain than the higher numbered channel, usually of the order of one half the gain of the higher numbered one.

The outputs of both the above described units were fed into the galvanometer block of a Houston Technical Laboratories model RS - 8U recording oscillograph. As used on the cruise of 1956 for making the refraction records 33 galvanometers were used. In the making of the tape playback records only seventeen traces were used and the remaining galvanometers displaced off the paper. The galvanometers had a natural frequency of 500 cycles per second and were damped, in the author's estimation, to about 0.7 critical. The photographic paper was 10 inches wide and was driven at approximately 13 inches per second. Timing lines were supplied internally by the camera's timing system consisting of a 100 cycle tuning fork driving a synchronous motor by means of carbon buttons proximal to its tines. The 7000-B and RS - 8U units operated from 12 volt batteries with high voltage being supplied by their own dynamotor unit.
The field procedure employed was essentially that used in previous work of this nature but will be described here for clarity. On the profiles under investigation, each ship would receive at one reverse station of each profile. The investigations of 1955 were carried out aboard the R/V ATLANTIS and the R/V CARYN of the Woods Hole Oceanographic Institution. The 1956 study was aboard the R/V ATLANTIS and the R/V BEAR of the Woods Hole Oceanographic Institution.

The technique that follows is that used for the general refraction work with special attention to the tape recording to follow. To begin a profile, one ship, assume the BEAR, would heave to and silence all engines and machinery and put the hydrophones in the water. The hydrophones' cables had floats attached along the cable to give slightly negative buoyancy which permitted a slow rate of sinking. Before each shot the cable and phone were pulled in near the ship and a loop of slack left on board. About 40 seconds before the refraction arrivals were expected the loop was thrown into the water and the cable payed out slowly by hand during the duration of the recording. The catenary caused in the sections along the cable by the floats and the gentle sinking rate prevented surface roll and ship noise from being transmitted down the cable to the hydrophone. This greatly increased overall performance by reducing the background noise in the hydrophone.

The other ship, assume the ATLANTIS, proceeded away on a predetermined course firing charges at intervals specified by the receiving ship. Usually around thirty shots were fired on each leg of a reversed
profile. The size of the charge was varied with distance of observation and ranged from ¼ to 300 pounds. Profile lengths averaged about fifty miles. All shots were fired by safety fuse. The receiving ship was notified by radio in advance of each shot to enable them to silence the ship, slack the phones, and warm up the recording instruments. After firing the last prescribed shot the ATLANTIS would stop, the BEAR would secure from listening and, after the ATLANTIS' hydrophones were in the water, begin shooting on the same course followed by the ATLANTIS. Operations were secured upon arrival of the BEAR at the ATLANTIS.

When shooting, each ship received the shot instant on the echo sounder (Edo) transducer and transmitted the signal by radio to the receiving ship. The signal transmitted was also recorded on the shooting ship for comparison with the refraction record and enabled travel time determinations when the shot instant was missed by the receiving ship. Chronometer checks were made frequently to insure determination of the absolute time of the explosion.

As was mentioned above, bathythermograph and echo sounder records were maintained on both ships.

After the radioed shot instant the receiving ship received refraction arrivals followed by the direct water wave followed by the first and higher order bottom reflections. The tape recorder was turned on a few seconds before the direct water wave and was left recording for the duration of the bottom reflections. The refraction record was stopped after the first bottom reflection.
On playback, the camera was turned on after the direct water wave arrival and before the first bottom reflection and left running for about 2 or 3 seconds after the first bottom reflection.
III ANALYSIS OF DATA

Eight profiles were made in the deeper portions of the eastern Caribbean Sea, located as shown in Figure 1. The cruise on which the individual profiles were made is indicated on the figure. Although the profiles as made at sea were reversed, only one leg of the profiles were tape recorded so that these reflection profiles are not reversed.

The times of the various arrivals observed on the records were measured with respect to the instant of high frequency bottom reflection. The bottom reflection time will be denoted by $T_{RI}$. Arrivals were not picked on a particular cycle as in oil exploration but were picked on the basis of the character of a reflection group. An attempt was made in all cases to pick the beginning of an arrival group. Generally the beginning was easiest to see on traces whose frequencies were higher than 75 cycles. Low frequency arrival components built up very slowly to maximum amplitude and the beginnings of particular arrivals were extremely difficult to pick on these traces in most cases. More will be said about this in the discussions which follow.

Several factors greatly complicated the reading of the reflection records. These factors resulted chiefly from the shooting techniques required to give the long range refraction profile. One factor which at times aided picking but in general was detrimental resulted from the fact that the charges were fired at depth in the ocean. This procedure resulted in bubble pulses caused by oscillation of the explosion gas bubble until the gas pressure reached equilibrium with the hydrostatic pressure at the depth of firing. The bubble pulse oscillation frequency varied with charge size and shot depth and therefore was not constant over each profile.
Another factor resulted from a combination of the shot depth and the hydrophone depth. The hydrophones on both cruises were at an average depth of 100 feet at the arrival instants while the shot depths varied. At these depths of the shot and receiver, each arrival was complicated by the various surface reflected arrivals following ray paths as shown in Figure 2. Naturally these surface reflected waves accompanied bubble pulse arrivals also and greatly complicated the records at times in that the train of energy from the various sources belonging to one arrival tended to mask the next arrival group or to interfere with it.

Multiples of arrivals were a constant possibility but were not observed on the profiles.

Several factors were determined exclusive of the reflection records. It was necessary to know accurately the distance between the shot and the receiver and also to know the time interval between the shot instant and reception of the bottom reflection. This data was obtained from the refraction records which included on each record the radio shot instant, the direct water wave arrival, and the first bottom reflection. The travel times could then be determined accurately from these records subject to the corrections described below.

The sound velocity structure in the ocean was determined from repeated bathythermograph lowerings for the upper portion and from previous hydrographic stations for the lower portions. The bathythermograph observations gave a good control over the variable near surface water down to between 450 and 900 feet. The deeper water sound velocity structure is considerably more stable and can be assumed to be essentially
the same as is given in the British Admiralty tables from previous hydrographic stations. The bathythermographic data allowed accurate computation of the isothermal layer sound velocity and thence the distance between shot and receiver since the direct arrival is bonded to this channel. The overall velocity structure allowed accurate depth calculations.

Two corrections were necessary to the travel time readings before the points were plotted and theoretical curves calculated to fit them.

The first correction resulted from the charge being dropped over the side of the ship while underway so that it exploded astern and below the ship. A short interval of time elapsed between the explosion and reception of the sound at the echo sounder head on the shooting ship which gave the radio shot instant. This correction was determined as follows. Experimental data was available on the bubble pulse intervals for each shot size as a function of depth. A record of fuse burning time was kept by stopwatch aboard the shooting ship as was a record of charge size. The horizontal component (range) of the distance between shot and head was computed from the ship’s speed plot and the fuse burning time. From the observed bubble pulse interval, the vertical component of the distance (depth) was obtained. The final correction was obtained by taking the square root of the sum of the squares of the components and is illustrated in Figure 3. The second correction involved computing all travel times on the basis of a reference level as is done in exploration geophysics. This reference level was chosen as sea level. The correction was derived as follows from the geometry shown in Figure 4. The correction desired is
the time required for sound to travel the distances AR and SB at the velocity of the water at this depth. This velocity was taken as 5,000 feet per second and, although the true value fluctuated about this value, it gives sufficient accuracy for the correction. This correction was calculated for $T_{R_1}$. $\theta$ will vary slightly for sub-bottom arrivals but not to any significance. Also, the fact that the ocean velocity structure resulted in arcuate ray paths in the water is negligible within the accuracy of the correction. The distances AR and SB are easily determined from the relations

$$AR = D\cos \theta \quad \text{and} \quad SB = d\cos \theta$$

The total correction is given by $(D + d)\cos \theta$. The cosine of $\theta$ was determined from existing computed graphs giving the cosine of $\theta$ plotted against range, with several isodepth lines drawn in allowing easy interpolation.

Had the bottom topographic relief been severe or at a considerable slope it would have been necessary to correct for this effect. A correction to remove the effects of bottom irregularity is helpful in allowing calculations to be based on a plane surface. The effect of the topography is to cause scatter of the observed data points (uncorrected) about the theoretical calculations based on a plane surface. However, it was fortuitous that the bottom topography was smooth on all profiles
as will be seen later. Only on profile 31 of the 1955 cruise was the topography rough and this only at a distance greater than half the range of shooting. Since the bottom reflection and (at this range) the shallow sub-bottom refraction paths were incident on the bottom at approximately the midpoint of the profile this topography had no effect on the results of this investigation. This is because the only topography exerting an effect on the arrivals is that at the points of incidence and emergence, and that between these points, for a particular arrival. It would however, have affected second or higher order multiple arrivals had they been studied.

The calculations and visual perception of the data were facilitated by plotting the time differences between the sub-bottom reflections and the bottom reflection against range rather than the total travel times of the reflections. It was mentioned above that the sub-bottom reflections were picked from the records with time relative to the bottom reflections, information which could be easily plotted and which avoided cumbersome plots.

Before beginning a discussion of the theoretical basis for the investigation it would be instructive to examine a typical record such as shown in Figure 5 and to point out some of the more distinctive features of records of a deep-sea reflection profile made in this manner. The bottom reflection is clearly seen on the high frequency traces with somewhat less excitation of those traces below 300 cycles/second in frequency range. Sub-bottom reflections are richer in low frequency energy and have little or no high frequency components. This is a general observation and
FIG. 5. TYPICAL SHORT RANGE RECORD
indicates little or no penetration by high frequencies of the bottom sediment, probably due to differential absorption. Surface reflected waves are indicated where they can be seen. The bubble pulse interval is shown on the record. It is quite noticeable on this record as it is on many records that the bubble pulse contains relatively more low frequency energy than the original explosion. This result was mentioned by Ewing and Worzel.

After plotting the observed arrival times versus range in seconds of direct water wave travel time, the range scale was converted to feet. Calculations were then based on velocities expressed in feet per second, and not on velocities expressed as seconds of travel time. The first approximation necessary to theoretical calculations was the assignment of a time average velocity to each layer. Time average velocity was used in all cases for the following reason. It is defined as the ratio of depth to vertical time and is stated by the relation

\[ c_a(z) = \frac{z}{\int_0^z \frac{d\zeta}{c(\zeta)}} \]

where \( z \) = depth, \( c_a(z) \) = average velocity as a function of depth, and \( c(z) \) = instantaneous velocity as a function of depth.

It is not correct to assume a constant velocity in the sediment for reasons which will be indicated below. If the velocity does vary with depth as will be shown, then an average velocity of the layer is needed for calculations. Such an average velocity is given by the relation above. In the initial analysis, this approximation was usually taken as a ratio with respect to the average velocity of the water column. After this initial work had been found inadequate, various time average
velocities were assigned and curves computed from them until a good fit was obtained to the observed data. In the later analyses it was necessary to know the ratio between the velocities of sound in the water just above, and the sediment just below, the bottom interface. The reasoning used in this determination is outlined in detail in section VI. The velocity of the water at the bottom was determined from curves given by Ewing, Worzel, and Pekeris.

A first interpretation of the data was attempted under the assumption that the portions of the observed arrival curves within a range of 25,000 to 30,000 feet could be approximated by computed curves based on straight line ray paths, disregarding the velocity structure of the ocean (Fig. 6) and any present in the sediment layers. In other words, constant velocities for ocean and sediment layers were assumed. Curves were computed and compared to the observed curves as illustrated by Figure 7. The geometry used to derive the range and travel time of a point on these curves is shown in Figure 8. The travel time is given by

\[ T = \frac{2h}{c_2 \cos \theta_2} - \frac{H}{c_1} \frac{\cos \theta_1 - \cos \theta_3}{\cos \theta_1 \cdot \cos \theta_3} \]  

(3)

and the range by

\[ R = 2H \tan \theta_3. \]  

(4)

The depth \( h \) is determined from the intercept of the observed arrival curve with the range = 0 line and the assumed velocity for the sediment
layer \((c_2, \text{ found as } c_2/c_1 = a, \text{ where } a \text{ is a ratio mentioned above and } c_1 \text{ is the average velocity of sound in the water}) \) according to \(2h/c_2 = \text{the intercept time.}\)

It is seen from Figure 7 that the observed arrival diverges markedly from the theoretical curve beyond a range of 40,000 feet in the example. This universal result on these profiles indicated that the sediment did not possess a constant sound velocity as was assumed. This same result was noted by Officer\(^6,7\) on reflection profiles in the Atlantic northwest of Bermuda. In the light of this result it became necessary to consider the sub-bottom materials as a variable velocity medium. Another conclusion resulting from this was that a given reflection event from the bottom of a particular layer became a refraction event within the layer at and beyond a certain angle of incidence on the layer. For theoretical calculations to be made under these conditions it was necessary to assume that the velocity as a function of depth could be approximated by some simple mathematical function. Several approximations were investigated, all of which were given by the general relation

\[
c(\xi) = c_0(1 + k\xi)^{1/n}
\]

(5)

where \(n\) is an integer greater than zero. The curve for \(n = 1\) is linear, that for \(n = 2\) is parabolic, and so forth. Various exponential functions were examined superficially but were found unsuitable. All investigations on these approximations were carried out experimentally by computing curves based on them and comparing to the same set of
observed data. The expressions for $n$ equal two, three, four, five, and six were examined with the final conclusion that the parabolic $(n = 2)$ expression best approximated the actual velocity structure in the sediment layers. Thus the entire sediment column's velocity structure could be approximated by a series of parabolic equations related to each other by assuming that the velocities at the discontinuities were continuous. Good results were obtained with this method. Officer 6 also used the parabolic approximation but did not alter his equation for each reflection interval. Figure 9 is a sketch of (5) at various values of $n$ with the time average velocity to a given depth held constant. The factor $k$ in this equation has the units of inverse feet and is the gradient factor.

The first step in computing a theoretical curve based on the parabolic equation

$$C(z) = C_0 (1 + k \alpha)^{\gamma} \quad C_0 = C_t$$

(5a)

was to plot on a large graph the observed travel time of the bottom reflection ($T_{R_1}$) versus the range ($D$) in feet. At each plotted point on this curve the slope was taken. The angle of incidence of the $R_1$ path on the bottom for a particular range of reception was derived as follows (Fig. 10). The relation

$$\frac{\sin \theta_b}{C_b} = \frac{\sin \theta_r}{C_r} \quad \text{or} \quad \sin \theta_b = \frac{C_b}{C_r} \sin \theta_r$$

(6)

may be written immediately from Snell's Law. From Figure 10, the expression
may be written, and substituting (7) in (6) gives \( \sin \theta_b = \frac{c_b}{c_n} \). But \( c_n \) is simply the inverse slope of the bottom reflection travel time versus range graph so that the resulting equation for the angle of incidence on the bottom (\( \theta_b \)) for a particular bottom reflection may be written as

\[ \sin \theta_b = c_b \text{ (slope of } T_{b1} \text{ vs. } D \text{ at } D). \]

The angle of refraction \( \theta_0 \) into the sediment may be written from Snell's Law as

\[ \sin \theta_0 = \frac{c_t}{c_b} \sin \theta_b, \]

where the ratio \( \frac{c_t}{c_b} \) is based on the assumption discussed above.

Kaufman\(^{10} \) gives a table of formulae derived for the parabolic gradient approximation which allows direct computation of the needed factors in computing the theoretical curves. The average velocity-depth function is given as

\[ \bar{c}_t = \frac{c_t}{2} \left[ (1 + k h) \sqrt{2} + 1 \right], \quad \text{where } \bar{c}_t = \text{ average velocity of the sediment layer}, \]

which, after rearranging, allows calculation of the gradient \( k \) from the expression

\[ k = \frac{4\bar{c}_t - 4\bar{c}_s c_t}{4\bar{c}_s c_t}, \quad \text{where } h = \text{ thickness of layer}. \]
Two sets of equations are given for computing the displacements and travel times along the ray paths. One set is for reflection arrivals (Fig. 11A) and the other is for refraction arrivals (Fig. 11B). An auxiliary equation gives the depth of penetration of the ray as a function of the angle of refraction into the sediment (or layer) and is used to determine when to switch calculations from one set of equations to the other. This equation is given as

\[ Z = \frac{1}{k} \cot^2 \theta_0 \]  

and the value of \( Z \) where \( Z = h \) is the value at which calculations are modified.

Kaufman states, for the reflection case \( Z > h \) (Fig. 11A), that the displacement \( x \) is given by

\[ x = \frac{1}{57.296 k \sin^2 \theta_0} \left[ (2\theta - 2\theta_0) - 57.296 \left( \sin \theta - \sin \theta_0 \right) \right] \]  

and the travel time \( t \) by

\[ t = \frac{4}{57.296 \kappa c \sin \theta_0} \left[ \theta - \theta_0 \right] . \]  

The angle \( \theta \) is the angle between the ray path and the normal at any given depth (the bottom of the layer in this application) and is easily determined from (5a) by setting \( z = h \) to give \( c_B \) and then applying Snell's Law. The final result is that
For the refraction case, $Z < h$ (Fig. 11B), the displacement $X$ is given by

$$X = \frac{1}{57.296 \, k \sin^2 \Theta_0} \left[ (180 - 2 \Theta_0) + 57.296 \, \sin 2 \Theta_0 \right]$$

(15)

and the travel time $T$ by

$$T = \frac{4}{57.296 \, k c_{\pm}} \left( \frac{90 - \Theta_0}{\sin \Theta_0} \right).$$

(16)

After computing the travel times and displacements for a particular $\Theta_0$, and thus a particular $D$ and $T_{R_1}$, the computed travel time and displacement were added to $T_{R_1}$ and $D$ respectively and plotted on the graph of $T_{R_1}$ versus $D$. Since the method used was to plot differences in bottom and sub-bottom reflection travel times the two curves were subtracted and the difference plotted on the graph containing the observed data. This gave a particular theoretical curve to compare with the observed data.

At first, all calculations based on gradients were made using the previously determined velocities and depths derived from the straight-line ray path method described above. This procedure proved unsatisfactory in that gradient curves computed on this basis generally passed beneath the observed curves and indicated that too great values
Fig. 11B Geometry for refraction calculations.

Fig. 12B Travel time graph of Fig. 12A plotted as difference from R1 vs range.

Fig. 11A Geometry for reflection calculations.

Fig. 12A Ray paths of refraction arrivals assuming no layering.
of average velocity were being used. This result demonstrated that the initial assumption was either insufficient or incorrect and that the arrivals either became refractions within their respective layers inside the range of about 40,000 feet (varies with water depth and layer thickness) or that the effects of the velocity structure was such as to decrease the travel time for a particular range of observation as compared to that indicated by curves based on straight-line ray paths. Both of these indications seem to be effective in causing the above difficulty. In the example of Figure 7, taken from profile 26, the average velocity indicated by the theoretical (Rayleigh) curve is 6,450 feet/second to a depth of 2,000 feet. It will be seen in the next section that, using the theory being described, the average velocity is actually 6,000 feet/second to a depth of 1,650 feet. From this development it was then deemed necessary to attempt to describe the data in an entirely different manner.

Beyond a range of about 50,000 feet on these profiles only one arrival was observed on each record, a strong arrival with considerable low frequency energy and little high having the character of a refraction. It was decided to attempt to fit a computed curve to these points beyond this range. These arrivals are refractions and penetrate only moderate to slight depths of the sediment, as is shown in Figure 12A. Because of the slight depth of penetration, the curve describing these arrivals yields valuable information concerning the upper part of the sediment for each profile. Using the values obtained for the gradient on these moderately distant points, the curve
was extended by extrapolating the gradient to large depths and computing the arrival curve for all angles of bottom incidence. The final curve had the general shape illustrated by Figure 12B with the apex of the cusp at the range of minimum refraction reception. Information from this curve was then used as a basis to describe the closer range reflection arrivals with the result that good descriptions could be made of all arrivals. More detail will be given concerning the results in the descriptions of the individual profiles below. It is believed that this curve fitting the mentioned distant points gives the best description of the velocity structure in the upper sediment for a particular profile. If the gradient (denoted by the term 'general' gradient) determined by this curve approximated the entire column then the lower leg below the cusp would be expected to predict approximately the first refraction arrival observed on the directly recorded records. This arrival is understood to be the first refraction arrival appearing before the bottom reflection on the records. Failure to observe this in most instances in the investigations is best explained by two considerations. The first is that the arrival as predicted by the general curve would follow a curved path and would penetrate a sizeable thickness of the column (Fig. 12A). The range of observation would be around 30,000 feet in most cases. At this range of observation the charges being fired were small and the recording level fairly low, so that this arrival following the lower leg of the cusp would be very weak. Also, at a depth of ± 4,000 feet there is an abrupt change from sedimentary material to oceanic crustal material with an associated
abrupt increase in velocity. Thus no arrival of this sort would be expected because of this velocity discontinuity. The second factor arises from this discontinuity. The first refraction arrival observed follows a critical angle refraction path along this discontinuity.

Curves were next computed to describe the close range arrivals according to equations (12) and (13). In general, good agreement was found between the general gradient and that found in describing the first layer on the various profiles. The gradient for this first layer is larger than the general gradient in a few cases and generally represents a thinner section when this occurs.

Curves describing reflections from succeeding layers were computed in the same manner as for the first layer with the difference that the computed displacements and travel times were added to those of the layer above instead of to $T_{R1}$ and $D$. The resulting points were plotted exactly as before and the curves subtracted to give the theoretical curve. The gradient values for these deeper layers will be seen in the next section to have diminished from the shallow layer gradients (and also the general gradients) in most cases.
IV. DESCRIPTION OF PROFILES

The profile locations are shown on Figure 1 with the dot indicating the recording station. Profiles 24, 25, 26, and 27 were made in 1956 and profiles 29, 31, 32, and 33 were made in 1955.

The travel time graph of profile 29 in the Grenada Trough is shown in Figure 13 along with the computed curves for each arrival. Figure 14 shows the bottom topography as observed beneath the shooting ship. The general curve was computed for arrivals beyond a range of 35,000 feet and has a gradient value of $9 \times 10^{-4}$ feet$^{-1}$. The first reflection is from a depth of approximately 390 feet (referred to the bottom) and indicates an average velocity to this depth of 5,200 feet/second. The gradient computed for this average velocity is $8.94 \times 10^{-4}$ feet$^{-1}$ which is in excellent agreement with the general gradient. In all computations the velocity in the top of the sediment ($c_t$) is taken as .97 of that in the bottom of the water. This assumption was discussed above and will be clarified in the next section. This velocity ($c_t$) is 4,812 feet/second on profile 29. This arrival is of moderate strength and has frequency components up to 300 cycles/second at close range and up to 250 cycles/second at the moderate range around 35,000 feet although there is only a small amount of energy associated with these frequencies relative to lower frequencies. It is striking from Figure 13 that the curve describing this arrival blends smoothly into the general curve. This is to be expected and furthermore, if the general curve does approximate in any case the entire observable column, the general curve will be given by the refraction portions (i.e. those parts of the curves for the arrivals where the arrivals are refractions which
Fig. 13  Travel time graph and computed curves, Profile 29
'turn around' at depths above the reflectors for which they are being calculated) of the curves computed for each reflection. This feature is well demonstrated on this profile as is seen from Figure 13. The second reflection from a depth of 850 feet indicates an average velocity to this depth of 5,700 feet/second or an interval average velocity of 6,100 feet/second between the first and second reflectors. The gradient calculated for this interval is $8.46 \times 10^{-4}$ feet$^{-1}$. Again this is in good agreement with the general gradient and the curve for this arrival blends into the general curve. The velocity at the reflector is 6,620 feet/second. This arrival is weaker than the first and has relatively less high frequency energy. It is a general observation on all arrivals in this investigation that the relative amount of energy in each frequency band (see section on playback technique) for a given arrival is a function of range of observation, with the major portion of the energy tending to be associated with lower frequencies as the range increases. The third arrival is from a depth of approximately 4,000 feet and indicates an average velocity to this depth of 8,350 feet/second or an interval average velocity of 9,080 feet/second. The gradient computed for this interval is $6.56 \times 10^{-4}$ feet$^{-1}$ and is slightly smaller than the general gradient. The velocity at the reflector is 11,540 feet/second. This arrival is invaluable to the discussion above concerning the general curves' derivation from the particular reflection-refraction curves. The computed curve for this arrival shows the cusp (shown as the secondary cusp on Fig. 13) for the true general sediment curve. (This is due to the
depth penetrated by the arrival and the velocity structure present; in general, no arrivals are present at sufficient depth to give this cusp in calculations. It is seen to occur at less range than the general curve cusp. This shift of the cusp apex towards zero range generally indicates an increase in the general gradient but this is not the case in this instance because of the use of a sequence of parabolic curves to describe the velocity structure. The individual parabolas are referred to different initial velocities and are not comparable directly. Before they may be compared, all of them must be referred to the velocity in the top of the sediment ($c_t$).

It is also seen in the figure that the curve for the second arrival blends into the upper leg of the cusp of the true general sediment curve. This is expected and furthermore, the point of divergence of the true general curve from the original general curve allows an estimate of the depth to which the original curve is a good approximation. This depth is approximately 900 feet, or roughly the depth of the second reflector. It is possible that this result is more than coincidence and indicates a factor (lithologic or structural) causing the reflection and a change in the velocity structure. It might be mentioned in passing that the lower leg of the true general curve does not predict the first refraction arrival as discussed in the preceding section. The refraction records were available to the author but no arrival could be definitely discerned above the background at the range predicted. This third arrival is fairly strong considering its depth of penetration and contains little energy associated with fre
quencies greater than 120 cycles/ second.

It is of interest to compare the results of the reflection study to those of the refraction study on this profile. A composite of the results is shown in Figure 15. The refraction arrival computed to come from a depth of 1,500 feet adds some significance to the conclusion that there is a discontinuity at 900 feet or so below the bottom. It is not impossible that these two events may correlate. The second refraction arrival from the sloping layer is not greatly different from the reflection at 4,000 feet. The velocities computed by both methods are seen to be in good agreement in both cases.

The travel time graph for profile 33 is shown in Figure 16 again with the computed curves for each arrival. This profile was shot along the axis of a small trench trending east-west. The bottom topography observed is shown in Figure 17. As in all profiles, an average depth of water was used in calculations and is shown in the figures by the straight line. This approximation is sufficient where the bottom had no great relief or slope as was the case on the profiles under consideration. The general gradient, and curve, was computed for ranges greater than 60,000 feet and gave a gradient of $7 \times 10^{-4}$ feet$^{-1}$. $c_t$ is 4,914 feet/ second. Extrapolation to closer ranges gave a fair agreement with the curves computed for the various arrivals. The first reflection is from a depth of 390 feet and indicates an average velocity to this depth of 5,200 feet/ second. The gradient for this interval is $6.32 \times 10^{-4}$ feet$^{-1}$ and is somewhat smaller than the general gradient. The velocity at the reflector is 5,490 feet/ second. On this profile
Fig. 15 Reflection and refraction sections, Profile 29.
Fig. 16 Travel time graph and computed curves, Profile 33
the calculation of the general curve was complicated by the large range at which the shallow refraction became the only observed arrival. The general curves are more sensitive to changes in the gradient value in the region of the cusp and become more insensitive to such changes at longer range. In order to compute the general curve for this profile, several points within the range of 60,000 feet were used to indicate the gradient value to assign to the general curve, although the arrivals around this range of observation are seen to differ from the general curve. This first arrival is strong and has some excitation of frequencies in the neighborhood of 250 cycles/second. The beginning of this arrival on each record was usually difficult to determine although its presence was obvious. The second reflection from a depth of 1,450 feet indicates an average velocity to this depth of 5,950 feet/second or an interval average velocity of 6,220 feet/second. The gradient for this interval is $5.65 \times 10^{-4}$ feet\(^{-1}\). This curve blends into the curve for the first layer as is seen in the figure. The velocity at the depth of the second reflector is 6,990 feet/second. This arrival is of approximately the same strength as the first and shows less high frequency energy as is expected. The third reflection from a depth of approximately 3,700 feet indicates an average velocity to this depth of 7,350 feet/second or an interval average velocity for this layer of 6,300 feet/second. The gradient computed for this interval is $4.11 \times 10^{-4}$ feet\(^{-1}\). No cusp for the true general sediment curve was obtained in calculations although the last reflection comes from considerable depth. This is due to the lower velocities. This
arrival is also strong and is composed predominantly of low frequency components. Most of the energy of the arrival is associated with frequencies below 100 cycles/second. The lower leg of the general curve computed initially accurately predicts the first observed refraction. However, the validity of placing importance on this prediction is doubtful in the light of the factors mentioned in the preceding section.

The refraction data obtained on this profile is confused by the misfortune that the reverse leg (that leg not tape recorded) was shot over a considerable topographic hill. This change in topography resulted from the drifts of the two ships caused by currents. One arrival is computed for the eastern end of the profile and is found to have come from a depth of 1,250 feet and to have travelled at a velocity of 6,700 feet/second. The second reflection arrival came from approximately this depth but indicates a slightly higher velocity. A refraction horizon at the same depth was found at the western end of the profile but differed from that at the eastern end in that it travelled at 10,000 feet/second. No indication of a lateral variation sufficient to explain this is present in the reflection data.

The next two profiles to be discussed are 25 and 26 which were made in the abyssal portion of the Venezuelan Basin. The travel time and theoretical curve graphs are shown in Figure 18 and the bottom topography in Figure 19. No general sediment curve was computed for these profiles.
Fig. 18.1 Travel time graph and computed curves, Profile 25
Fig. 18.2 Travel time graph and computed curves, Profile 26
Fig. 19.1 Bottom topography, Profile 25

Fig. 19.2 Bottom topography, Profile 26
Profile 25 was made in slightly deeper water than 26 and shows a thicker column down to the single reflector observed. On profile 25, the reflection from a depth of approximately 3,000 feet indicates an average velocity of 6,600 feet/second. The gradient given by this velocity is $6.05 \times 10^{-4}$ feet$^{-1}$. The velocity at the depth of the reflector is 8,280 feet/second. On profile 26, the single reflection is from a depth of 1,650 feet and shows an average velocity to this depth of 6,000 feet/second. The gradient computed for this interval is $6.53 \times 10^{-4}$ feet$^{-1}$. The velocity at the depth of the reflector is 7,085 feet/second. $c_t$ is 4,915 feet/second. It is noticeable that the gradients computed for both profiles are in very good agreement. The significance of this will be discussed below. The character of these arrivals is very similar and show little excitation from frequencies above 120 cycles/second.

Profiles 24 and 31 are located on the west flank of the Aves Swell and are essentially parallel. The travel time plots with the computed curves are shown in Figure 20 and the bottom topography in Figure 21. The general curve computed for profile 24 for ranges greater than 40,000 feet gives a gradient value of $3.6 \times 10^{-4}$ feet$^{-1}$. The surface sediment velocity $c_t$ is 4,949 feet/second. The first reflection from a depth of 1,000 feet shows an average velocity to this depth of 5,425 feet/second and gives a gradient for this interval of $5.32 \times 10^{-4}$ feet$^{-1}$. The velocity at the reflector is 6,000 feet/second. The second reflection from a depth of 2,000 feet indicates an average velocity to this depth of 5,920 feet/second or an interval average velocity
Fig. 20.2 Travel time graph and computed curves, Profile 24
of 6,420 feet/second. The gradient computed for this interval is $2.95 \times 10^{-4}$ feet$^{-1}$ and the velocity at the reflector is 6,840 feet/second. The first reflection is fairly strong and contains some high frequency components up to 250 cycles/second. The second reflection is somewhat stronger than the first and is composed chiefly of low frequencies (below 150 cps). The gradient shown by the first interval is noted to be somewhat larger than the general gradient which appears to be a rough average of the gradients of the two layers. This is seen to be the case in the light of the fact that at a range of 40,000 feet the arrival observed on which the general curve is based has penetrated to a depth of approximately 1,500 feet, considerably below the first reflector. The third reflection from a depth of 2,800 feet indicates an average velocity to this depth of 6,300 feet/second or an interval average velocity of 7,270 feet/second for the layer. The gradient computed for this interval is $3.43 \times 10^{-4}$ feet$^{-1}$ and the velocity at the reflector is 7,710 feet/second. This arrival is also strong and is composed of frequencies below 120 cycles/second. The increase in value of the gradient shown by the lower layer over that of the second layer is curious and will be discussed in detail below.

The general curve was calculated for profile 31 for ranges greater than 40,000 feet and gives a general gradient of $5.5 \times 10^{-4}$ feet$^{-1}$. $c_t$ is 4,837 feet/second. The first reflection from a depth of 950 feet indicates an average velocity of 5,440 feet/second. The gradient computed for this arrival is $5.93 \times 10^{-4}$ feet$^{-1}$ and the velocity at the reflector is 6,050 feet/second. The second reflection from a
depth of approximately 2,600 feet gives an average velocity to this depth of 6,430 feet/second or an interval average velocity of 7,010 feet/second. The gradient computed for this interval is $4.55 \times 10^{-4}$ feet$^{-1}$. The velocity at the reflector is 7,970 feet/second. The general gradient agrees closely with that given by the first reflector in this case and this agreement is borne out by the fact that the arrival observed at the range of 40,000 feet has penetrated to a depth of approximately 1,050 feet, only slightly below the first reflector. The first reflection is fairly strong and contains some high frequency components. The second reflection is strong and contains only lower frequencies below 150 cycles/second. There is little readily apparent agreement between these two profiles. A correlation between them is possible based upon other considerations which are outlined in detail in the next section.

Refraction data was available for profile 31 but the calculations and interpretations were severely complicated by the topography. The figure shows only the topography below the shot line which was tape recorded. The topography under the reverse leg showed less irregularity but had a marked slope between approximately the same terminal depths indicated in Figure 21. Calculations on the refraction data showed an event from a depth of 2220 feet beneath the bottom below the ATLANTIS' receiving position which is the receiving point for the reflection data. The velocity associated with this arrival was computed to be 6,100 feet/second. There is a rough correlation between the prominent second reflection and this refraction with respect
to depth but the velocity values obtained differ to a large extent. This disagreement should not be construed as a disqualification of either investigation due to the different methods of observation and calculation. The refraction study involved taking into account the bottom topography of both legs as well as the refraction data obtained by the other ship on the reverse leg. The reflection investigation of this paper is concerned only with that portion of the bottom topography, observed by the shooting ship, on which the arrivals essential to calculations were incident or beneath.

Profiles 27 and 32 were made on a topographic promontory which borders the other side (away from Puerto Rico) of the trench in which 33 was made. The travel time graphs are shown in Figure 22 and the bottom topography in Figure 23. The general curve of profile 32 was computed for ranges greater than 45,000 feet and gives a general gradient of $5 \times 10^{-4}$ feet$^{-1}$. Points in the vicinity of this range limit were used to determine this general curve due to the relative sensitivity to a change in the gradient of the computed curves at this range as compared to longer ranges. The surface sediment velocity is 4,890 feet/second. The first reflection is from approximately 390 feet and indicates an average velocity of 5,200 feet/second. The gradient computed for this interval is $6.94 \times 10^{-4}$ feet$^{-1}$. The velocity at the reflector is 5,500 feet/second. The second reflection from a depth of 1,780 feet indicates an average velocity to this depth of 5,940 feet/second or an interval velocity of 6,150 feet/second for the layer. The gradient for this interval is found to be $3.72 \times 10^{-4}$ feet$^{-1}$ and the velocity at
Fig. 22.1 Travel time graph and computed curves, Profile 32
the reflector is 6,790 feet/second. Again, the general gradient is a rough average of the gradients found for the first two layers and this observation is verified by the calculation that the arrival received at a range of 50,000 feet has penetrated to a depth of 1,000 feet, considerably below the first horizon. The third reflection for this profile is from a depth of 2,730 feet and indicates an average velocity to this depth of 6,435 feet/second or an interval average velocity of 7,360 feet/second. The gradient for this interval is \(3.88 \times 10^{-4} \text{ feet}^{-1}\) and the velocity at the reflector is 7,940 feet/second. The gradient for the third interval is noted to be slightly greater than that for the second interval but is in good agreement with it. This same phenomenon was noted on profile 24 and again suggests a need for further discussion which will be presented in the next section. The first reflection is fairly strong and has some high frequency (250 cps) components. The second reflection is strong and contains little high frequencies. The third reflection is of the same strength as the second, but occurs in the energy train of the second and is therefore difficult to discern, with respect to the beginning of the arrival, on some records.

The general curve computed for profile 27 gives a general gradient of \(6 \times 10^{-4} \text{ feet}^{-1}\). This curve was again computed for ranges greater than 40,000 feet. The surface sediment velocity is taken as 4,885 feet/second. The first reflection is from a depth of 1,780 feet and indicates an average velocity of 5,940 feet/second. The gradient computed for this interval is \(5.90 \times 10^{-4} \text{ feet}^{-1}\) and the
velocity at the reflector is 6,990 feet/second. The second reflection from a depth of approximately 3,050 feet indicates an average velocity to this depth of 6,680 feet/second or an interval average velocity of 7,710 feet/second. The gradient is \(3.49 \times 10^{-4}\) feet\(^{-1}\) and the velocity at the reflector is 8,420 feet/second. The first arrival is very strong and has the same character with regards to frequency makeup and relative intensity as the second reflection of profile 32. The second reflection of profile 27 is also very strong and resembles in detail the third reflection of 32. It is considerably more distinct and sharp than that of 32, however. No distinct event was found on profile 27 which correlated with the first reflection of 32, however. Considerable random energy is present on the records in the intervals between \(R_1\) and the first reflection and this may represent the 'missing' arrival. Some light may be thrown on this apparent discrepancy by an examination of the bottom topography figure. Although located in the same area the profiles are almost transverse to one another. The topography observed in shooting profile 27, although relatively smooth, is seen to fluctuate over a vertical range of the order of 400 feet in the first 100,000 feet away from the receiving station. The topography of 32, with the exception of the initial drop, does not fluctuate over 100 feet. The first reflection from profile 32 is from a depth of 390 feet. If the topography shown for 27 is due to submarine erosion or non-deposition of this upper layer then the variations in thickness would not present an easily observed, continuous event since the topographic relief is of the same order of magnitude as the thickness of
the layer observed on 32 when the topography showed considerably less relief. These two hypotheses compliment each other and may explain the difficulty. The excellent agreement shown by the two reflections (one on each profile) from a depth of 1,780 feet indicates that the material to this depth is fairly uniform in composition and thickness, although the observed points for this event on profile 27 do not exhibit the smooth nature of the points on profile 32 for this event. This is due to the bottom topography of profile 27. The last reflections on both profiles have the same nature but indicate different thicknesses.
V GEOLOGICAL ASPECTS

Attempts at a general geologic correlation of the results of these profiles are frustrated somewhat by the uncertainty as to the nature and origin of the Aves Swell. This prominent north-south trending feature parallels perfectly the Lesser Antilles island arc and topographically appears to be a volcanic chain similar to them.

Another complicating factor is the lack of adequate control over determination of faulting and folding in the deep-water areas. Nearly all of this has been done by inference from topography, surface geology of the islands, and seismic (earthquake) activity.

From studies of surface geology of the islands, both the Lesser and Greater Antilles, the conclusion has been drawn that as one travels from Cuba to Grenada along the island arc, the deformation and volcanism observed become progressively younger. The general sequence for a given island seems to be one of marine sedimentation followed by deformation and intrusion of quartz diorites. Erosion then removed much of this cover and Oligocene or Miocene limestones were deposited and the island uplifted or downwarped to give the present configuration. The Greater Antilles have possibly two major deformational periods in their history, one in the upper Cretaceous and the other in the middle Eocene. The Lesser Antilles show only the Eocene deformation. The quartz diorite intrusions are later Cretaceous in the Greater Antilles but are late middle Eocene in the northern, or 'Limestone', Caribbees of the Lesser Antilles. The age of the oldest dated rocks is late Cretaceous in the Virgin Islands but is Eocene or younger in the Lesser Antilles. This evidence indi-
cates the gradual spread of activity (both volcanic and tectonic) from Cuba to the Lesser Antilles.

Hess has postulated a 60 kilometer downbuckle along the strip of negative gravity anomalies observed along the general trend of the foredeep bordering the island arcs on the Atlantic side. He proposes that large scale crustal adjustment to this downbuckle would manifest itself in large faults. Such a movement is proposed to have shifted the entire Lesser Antilles to the east. Other stated evidence is that the Cretaceous sediments of southern Puerto Rico are folded with the folds striking southeast. No evidence of these folds is found on the floor of the ocean and Hess proposes that they were once aligned with the Lesser Antilles chain which he refers to as a geanticline. Little account is taken of the presence of the large Aves Swell except an observation that it resembles a chain of volcanic peaks.

Christman also suggests a Tertiary downbuckle but suggests that the center of volcanic activity has shifted from east to west as determined from dating of the oldest rocks on St. Bartholomew and St. Martin in the Limestone Caribbees.

The Lesser Antilles in general show an Eocene deformation which also affected the older Greater Antilles. Volcanism extending from late Eocene to Recent is characteristic of the volcanic Lesser Antilles. The Lesser Antilles are subdivided into two groups in the literature. Anguilla, St. Martin, St. Bartholomew, Sombrero, Barbuda, Antigua, Grand Terre de Guadeloupe, and Maria Galante are in one group characterized by Miocene limestone caps. Saba, St. Eustatia, St. Kitts,
Montserrat, Nevis, Guadeloupe, Dominica, Martinique, St. Lucia, St.
Vincent, the Grenadines, and Grenada are in the other group characterized by continuous volcanism from, at the latest, Oligocene to Recent. The former group is called the 'Limestone' Caribbees, while the second, younger group is called the 'volcanic' Caribbees.

Schuchert, basing his study on Hill, has noted the three-fingered appearance of the Lesser Antilles and the Aves Swell and, quoting Hill, suggests they may be structurally related to Venezuelan geology. Schuchert believed the Greater Antilles to represent a geosyncline and geanticline narrowing to the east and ending in the Virgin Islands. He believed much of the southeast Caribbean to belong, in the Paleozoic, to the northern part of South America and to have been downfaulted greatly during the Cretaceous. Schuchert also thought the Puerto Rico-Virgin Islands mass to be outlined by faults. St. Croix is by this theory also surrounded by large faults, the Anegada pass between the islands being presumably a graben. Hess, in mentioning the similarity of the Aves Swell to a volcanic chain, notes that if this feature is volcanic in origin the causitive volcanoes are extinct and furthermore, the swell is inactive seismically, having virtually no earthquake epicenters associated with it. This latter fact does not necessarily negate the possibility that the Aves Swell is younger than the Lesser Antilles proper since the Virgin Islands area is active seismically but inactive volcanically. The former fact indicates that the swell is probably older than the presently active (volcanically) Lesser Antil-
les, but what its relation is remains unclear. A similar relation of a chain parallel to a larger arc and lying on its concave side away from the foredeep is seen in the Mariana Island-Trench association in the Pacific Ocean. No information on this association was available to the author.

Recent seismic refraction work has confirmed the probable volcanic nature of the Aves Swell. The Grenada Trough is thought to be a sort of submarine intermontane basin probably underlain by a volcanic basement.

The above discussion is presented as a background of the theories concerning the origin of the Antillean island arcs. No direct attempt at correlation will be made but a few broad conclusions may be reached concerning the reflection findings keeping the geologic history and theories in mind.

A composite of the sections determined from the profiles under investigation is given on Figure 24. On this composite, the indicated correlations are based on either similarity in thickness, nature of the arrivals, or instantaneous velocity-depth relations or a combination of these. Figure 25 is a composite of the instantaneous velocity versus depth curves computed from (5a) for each profile. Figure 25 allows much easier comparison between the different gradients computed, especially where a section is described by two or more gradients.

A first general observation from the composite section (Fig. 24) is that the present surface topography reflects that of the base-
Fig. 24 Composite of sections.

NOTE: Round velocities to nearest 10 feet/sec.
Round gradients to nearest hundredth.
"Basement" is used here to denote the horizon implied from the deep, strong reflections observed on the profiles, and not an absolute basement implying crystalline rocks.

Another general observation from the velocity-depth composite (Fig. 25) is that the velocity in the sediment has the same general variation with depth over the entire Venezuelan Basin portion covered by this investigation. Profile 29 in the Grenada Trough is concluded from this comparison to represent an entirely different environment from that of the Venezuelan Basin.

The bulk of this section will discuss these two composites in detail.

It is observed from profiles 25 and 26 that the sediment layer described by these profiles thickens toward the south. Profile 25 is located about 70 nautical miles south of 26 and is in the bathymetrically deepest part of the Venezuelan Basin. The composite shows 25 to be in water slightly less deep than 26 but a reference to Figure 19 shows the average depth to be slightly greater on 25. A reference to Figure 25 shows the instantaneous velocity-depth curves for these two sections to be in good agreement. This implies that the sediment is of the same nature and in the same state, probably unconsolidated, at both sites. Considerable noise between R₁ and the reflection on both profiles indicates that the material is not completely homogeneous although no distinct arrivals could be followed for either. Most of this noise occurred about 0.2 seconds after R₁ and would indicate inhomogeneity at a depth of around a thousand feet. This noise may be
the evidence of layering on 25 and 26. Layering could be expected here since it is observed on the rest of the profiles. The variation in thickness observed leads to the conclusion that the sedimentary filling is thickest in the lowest (deepest) part of the basin, as might be expected. This conclusion is subject to the accuracy of the correlation of the 'basements' to represent the same horizon, and thus time. The results of this investigation do indicate that sedimentation has been relatively even over the time represented.

Profiles 24 and 31 are located about 40 nautical miles apart on the west flank of the Aves Swell. The southernmost, 24, is proximal to the large central peak of the Aves Swell chain. Profiles 27 and 32 are located in approximately the same place and, being at nearly right angles, give a more detailed description of the sediments there. On the basis of location, they should be expected to show the same general section. A discussion was presented in the preceding section giving a possible explanation for the lack of the shallow reflection on 27 as observed on 32 and will not be repeated here. From Figure 24, the thickness of the upper layer from profile 27 is seen to be exactly the same as that of the two uppermost layers of 32 combined. Figure 25 shows the velocity-depth structure to be in fairly good agreement for these intervals. It is not unlikely that, if the thin upper layer could be demonstrated for 27, the velocity structures would be identical, since both sections show the same average velocity to this depth. The lower layers from the two profiles differ somewhat in thickness, but the rate of increase of the velocity with depth is seen from Figure 25 to be
almost identical in them. Thus the results from these two profiles are in good agreement and do show the same general section as expected.

It has been mentioned previously that there was little apparent agreement between profiles 24 and 31. After an examination of Figure 25 and a comparison with profiles 27 and 32 the situation becomes somewhat clearer. The correlation between these four profiles is based on the following argument. It was noted from profiles 27 and 32 that the average velocity to a depth of 1,780 feet is the same. The presence of the arrival from the bottom of the thin upper layer of 32 gives better control over the incremental rate of variation of velocity with depth in this section. Profile 27 may be inferred to have a similar velocity structure from this result. The lower layer from 24 shows the same rate of increase of velocity with depth as does the middle layer from 32 (and, by inference, the lower part of the upper layer from 27). No section is found on 31 with a corresponding rate of increase of velocity. The upper layers vary somewhat, in this line of comparison, among these four profiles. The upper layers of 24 and 31 are in good agreement with respect to thickness and velocity structure. The complete lack of a layer from 31 with the velocity structure shown by the middle layers from 24 and 32 (and 27 by inference) is an anomaly which is difficult to explain. The arrivals on 31 were distinct and fairly sharp but random energy was present between the two arrivals. It seems most probable that no distinct arrival was observed from 31 corresponding to that observed from the bottom of the middle layer of 24.

Profile 33 is located in a slight topographic trench about 35
nautical miles south of Puerto Rico. From Figure 25 it is evident that
33 is in fairly good agreement with the velocity structure trend estab-
lished by the six profiles already discussed. A considerably thicker
section is noted from 33 than from any previous profile, however. The
upper layer from 33 agrees well with the upper layer from 32 and with
the general trend of the velocity structure from 25 and 26 in the up-
permost portions of these sections. The middle layer of profile 33
shows a rate of increase of velocity similar to that from the lower
layer of 31. There was some difficulty met in picking the first re-
flection on the records of this profile. The very slight curvature
shown by the observed points allows considerable flexibility in the
fitting of a theoretical curve to them. For this reason, the second
arrival was also treated as if the first did not exist. This gave a
theoretical check on the second layer and gave better confidence to the re-
sults. The thick lower layer from 33 agrees well with the lower layer
of 27 in general rate of increase of velocity with depth. The general
similarity of the shape of the instantaneous velocity-depth curve for
33 to the rest of the above described profiles leads to the correlation
shown on Figure 24. The thicker lower layer of profile 33 may indicate
subsidence of the trench during deposition of this layer, or may simply
indicate a filling of a topographically low area. In general, the sedi-
ments in the lower layers from the profiles tend to show an attempt to
smooth the topography of the 'basement'. The upper layers from 32 and
33 (and 27 (?)) are in good agreement as are the upper layers from 24
and 31. The correlation between all of them indicates thicker deposition
on the Aves Swell flank during the time represented.

Profile 29 in the Grenada Trough is located in a sort of submarine intermontane basin. Figure 25 shows that the section differs markedly from the sections shown by the Venezuelan Basin profiles with respect to velocity structure. The thin upper layer from 29 is in fairly good agreement with the other profiles, however. Below this the section shows a marked divergence into high velocity material. The probability that velocity structures of this nature are associated with at least partly lithified material will be discussed in the next section. It is probable that this trough has received more material of volcanic origin than has the Venezuelan Basin.

An attempt to describe the physical properties of the materials present will be left to the next section. From the generally good agreement seen for the profiles of the Venezuelan Basin from Figure 25, it is concluded that the eastern Caribbean floor is covered with generally low velocity material to an average depth of 3,000 feet. The seismic velocity, although relatively low, varies considerably with depth in this material and indicates that for the most part it is unconsolidated. The material is of the same general composition and indicates that the variation of state (i.e., diagenetic processes, etc.) with depth is fairly uniform over the area.

Further discussion of the possible geological meaning of the sections will be left to the next section.

The question occurs, in a description of this sort, as to what the effects of dipping layers on the results might be. It is well known
from terrestrial seismic exploration that a boundary dipping up from receiver to shot causes a higher apparent velocity than the true to be observed. The converse of this is that a layer dipping down from the receiver to the shot causes a lower apparent velocity to be observed. For terrestrial cases, Nettleton\(^{20}\) gives the error introduced in neglecting a slope of 5.5 degrees as less than 0.5%. This is based on straight line ray paths (no variation of velocity with depth), however. Gardner, quoted by Nettleton, has shown that a dip of greater than 10 degrees is necessary to introduce appreciable error into calculations based on a linear increase of velocity with depth. Dipping layers were not taken as an important factor in this investigation since topographic dips of greater than 1 degree are rare and when present extend only for brief ranges. The effects of dipping layers were examined by the author, however. The exact effect is extremely difficult to state since the dips which would cause any considerable effects would be dips relative to the bottom, and not to the reference level. This is because the graph of \(T_{R_1}\) versus range accounted partially for slopes of the bottom. Dips of 2 degrees were determined by simplified calculations to be negligible for the methods of this investigation.
VI  GEOPHYSICAL AND PHYSICAL ASPECTS

Several times in the preceding section the need was felt to assign a 'type' of material to the velocity-depth structures shown by the profiles. There is considerable geological and physical importance attached to such an assignment, and more factors require consideration than were mentioned previously. Most of this section is associated with this discussion.

On all profiles it was observed that as the shot points moved away from the receiver, the low frequency content (below 300 cycles/second) of the bottom reflection $R_1$ decreased and became imperceptible, generally at a range of around 40,000 to 50,000 feet. (As the low frequency content of $R_1$ decreased, however, the sub-bottom arrivals became stronger with regard to low frequency energy, indicating good penetration by the lower frequencies). The high frequency components of $R_1$ (above 300 cycles/second) were not observed to decrease noticeably with range except occasionally at extreme ranges where $R_1$ became diffuse and weak. These observations constitute the first bit of evidence that there is a variable low velocity contrast across the bottom interface. It can be seen from the travel time graphs of all profiles that the sub-bottom arrivals do not cross the bottom reflection (in the figures this would be indicated by a negative travel time) but do approach it closely at the longer ranges. These arrivals would cross $R_1$ if the material immediately below the bottom had a sound velocity greater than that of the water just above the bottom for the frequencies observed.

Another universal result on all records was that, for a given arrival on a particular record, the peak amplitudes reached by the ar-
rival on each frequency band did not occur at the same time. For example, the peak amplitude on the band from 120-215 cycles/second was reached perhaps .05 seconds before the peak amplitude on the band from 21-47 cycles/second was reached. This feature led to an attempt to determine if the beginning of the arrival on each frequency band was a function of the frequency. This attempt involved two phases. First, it was necessary to determine the instruments' response to a multifrequency pip with regard to their frequency analysis of it. Second, it was necessary to accurately pick the beginning of the arrival on each trace (corresponding to a different frequency band). Great difficulty was encountered, however, in choosing the beginning of a particular arrival on each frequency band. Figure 32 is a composite picture showing the response to a pip and a typical moderate range record showing the arrival's effect on each frequency band. The same general relation is observed between the peak amplitudes of the pip as for the arrival. For the lower frequency traces (below 75 cycles/second) it is extremely difficult to choose with certainty the beginnings of the arrival.

It was hoped that the travel times could be picked for a particular arrival for each frequency band, plotted, and a theoretical curve fit to the plots to determine their velocity as a function of frequency. An attempt to do this was made but was defeated by the difficulty in picking the beginning on each band, by noise, and by topographic effects to be discussed below. The resulting graphs had a large scatter of points, most of which lacked confidence. It was concluded from the failure of this attempt that the best evidence for dispersion determined from
these profiles lay in the apparent dependence of reflectivity on frequency as described in the preceding paragraph. Further discussion of this point is given below.

The conclusion that the material just below the bottom interface has a sound velocity less than that of the water above (at least for low frequencies) requires investigation to determine the cause.

It was mentioned before that the sub-bottom materials just below the bottom interface are known to be of more or less typical deep-sea ooze type in most of this area (unpublished cores). Therefore a starting point is to assume that the near surface material is a gross mixture and study the theory of sound propagation in it. Chambré has treated the case of a mixture of fluid and solid particles. His investigation does not consider relative motion between the solid and the liquid, however. He finds that the velocity of a compressional wave in a mixture is given by

\[
\bar{c} = \sqrt{\frac{1}{\bar{\rho}}},
\]

where the compressibilities are given by

\[
\frac{1}{\bar{\rho}} = \frac{1}{\rho_1} + \frac{1}{\rho_2},
\]

with subscript 1 referring to liquid, subscript 2 referring to solid, \(\bar{c}\) the velocity in mixture, \(c_1, c_2\) the velocities in components, \(\rho_1, \rho_2\) the densities of components, and \(h\) the porosity, or percent of liquid.

By assuming several values in (17), one can plot theoretical curves giving the velocity in a mixture as a function of porosity. The density of the liquid (water) may be taken as 1.0. The velocities observed for the water at the bottom fluctuate with depth but an ap-
proximate value of 5,000 feet/second is a satisfactory average. A first curve was computed assuming the density of the particles to be 2.7 and the velocity \(c_2\) to be 8,000 feet/second. The velocity is taken from tables (Nettleton\textsuperscript{20}, for instance) and is a rough average of the velocities for clay, sandy clay, and shale. A second curve was computed based on data given by Laughton\textsuperscript{23} from laboratory velocity determinations on Atlantic Globigerina ooze. He gives the result that a specimen with uncompressed porosity of 64% and bulk density 1.62, when compressed by a pressure of 1,024 kilograms/cm\(^2\), has a sound velocity of approximately 10,000 feet/second, determined by 1 megacycle ultrasonic pulses and assuming no dispersion. From the porosity and bulk density stated, the average density of the particles is found to be 2.6. Using these two values a second curve was computed. Figure 26 shows the resulting curves plotted as the ratio of the velocity in the mixture to that in the water versus porosity. A short curve based on another assumption is included. Figure 27 shows the same curves plotted as the mixture velocity versus porosity. It is seen from these figures that the curves show an average velocity contrast of .96 to .97 for porosities in the range from 60 to 80%. Officer\textsuperscript{6} gives figures by Kullenburg stating the porosity of deep-sea sediments to range from 65 to 85%. Shallow sediments are naturally implied. Meinzer\textsuperscript{24} gives porosity values of 80 to 90% for Mississippi delta muds and Shaw\textsuperscript{25} gives porosity values for coastal muds from 40 to 90%. The above reasoning is the basis of the assumption of the ratio \(c_t/c_b = .97\) used in this investigation. It is interesting to
note that the curve based on Laughton's data gives a velocity contrast of .97 at the porosity value stated by him.

At the beginning of this section it was stated that the best evidence for dispersive materials lay in the apparent dependence of reflectivity on frequency for the bottom reflection. It is well known that for sound reflected from a boundary across which there is a velocity increase the relative amount of energy reflected increases from some small value at normal incidence to total reflection at the critical angle for the boundary and remains total for greater angles of incidence. In the case of a velocity decrease across the boundary, the relative amount of energy reflected decreases from some value at normal incidence to zero at nearly grazing incidence and then rises rapidly to total reflection. It was noted that the low frequency components of the bottom reflection disappeared at ranges in the neighborhood of 50,000 feet (corresponding to incidence angles of 60 degrees or larger) while the high frequency components (above 300 cycles/second) showed no noticeable decrease. This indicates that low frequencies (below 300 cycles/second) 'see' a decrease in velocity at the bottom, while higher frequencies 'see' an increase in velocity. This conclusion substantiates the dispersive nature of the materials.

Zwikker and Kosten\textsuperscript{28} have treated the case of a gross mixture taking into account the relative motion of fluid and solid particles. Morse\textsuperscript{29} and Ament\textsuperscript{30} have also treated the problem in a different manner. Officer\textsuperscript{6} gives a curve with the velocity contrast plotted against frequency (Fig. 28) which is based on Ament's treatment. He does not
specify a frequency scale, however. Of these two above mentioned treat-
ments, Zwiker and Kosten have perhaps the more versatile, but calcu-
lations based on either are complicated by the difficulty of assigning
values for particle radii, viscosity, and a certain structure factor,
a descriptive term of the array of the particles.

The ability of the instruments used in the present study to
analyze frequencies does allow an assignment of an approximate value
for the frequency at which the velocity contrast is unity on Officer's
curve. This value is approximately 300 cycles/second. Officer gives
an expression (based on Ament's treatment) for the velocity in the
following form.

\[ C = C_s \left(1 + F^2 \frac{\sqrt{\pi^2 h(1-h)\nu (\rho_s - \rho_f)^2 (\rho_2 + (1-h)\rho_1)}}{\sqrt{h\rho_s + (1-h)\rho_f}} \right) \]

where \( F = \) frequency,
\( r = \) particle radii,
\( \eta = \) viscosity, and
\( c_s = \) velocity from (17).

Revelle has tabulated the radii of particles from Pacific sediments
to range from less than \( 10^{-4} \) cm to greater than \( 10^{-2} \) cm. Using the
values \( F = 300 \) cps, \( \rho_1 = 1.0, \rho_2 = 2.6, c_1 = 5,000, c_2 = 10,000, h = 64\%\),
\( c_s = 4,850 \) (determined from (17) using these values), and an average
particle radius of \( 10^{-3} \) cm, the viscosity of the sediment is computed to be
\( 1.47 \times 10^{-3} \) cgs units. Little direct significance can be attached to
this value due to the methods of determining the factors used in its
calculation. However, it may be taken as an order of magnitude for the vis-
cosity of the Caribbean sediments subject to the assumption that these
sediments are of ordinary deep-sea type.
As a sidelight to the reflectivity discussion, it might be mentioned that the last two shots of profile 24 showed very strong low frequency bottom reflections. The range of these shots was 264,500 and 294,500 feet and the angle of bottom incidence was greater than 75 degrees. The shots preceding these two did not give any low frequency components for the bottom reflection.

So far it has been determined that the Caribbean sediments are dispersive and possess a low velocity contrast with the water. The above discussions have implied that the material is very fine grained, of clay or ooze type. All evidence indicates this to be true. Athy states that sandstones and limestones are virtually incompressible and that what compaction does occur takes place before cementation has progressed extensively. He states that compaction in clays and silts is considerable and continues as long as the pressure increases. Laughton's research shows that, in a deep-sea sediment core, the sound velocity is increased by pressure (compaction) alone. Several diagenetic processes besides lithification may also be a factor in increasing the rigidity and bulk density of a fine grained sediment. The first is expulsion of absorbed water and mechanical rearrangement of particles. The effects of these two processes were probably included in the results obtained by Laughton. Next would follow chemical combination with the pore-filling water and mechanical deformation of the particles. Considerable depth of burial would be necessary to produce this, probably of the order of a thousand feet or more. Finally, intrastratal solution and recrystallization would begin. All of these
steps would probably increase the sound velocity in the material. Relatively little cementation occurs in shales and nearly all changes in density or porosity are a direct result, with few exceptions, of compaction pressures.

Athy analyzed cores from near Ponca City, Oklahoma, in a thick shale sequence. His porosity-depth curve is shown in Figure 29. The dashed portion is hypothetical and, although it intercepts at a porosity of 50%, Athy states that surface clays have porosity values as great as 90% although lower values are more common. This curve also indicates that only very shallow sediments would have sufficient porosity to give a velocity contrast less than unity. At a depth of 3,000 feet, this curve shows a porosity of about 12.5%. The curve computed from (17) based on Laughton's data (Fig. 27) predicts a velocity of 7,100 feet/second for a mixture of this composition. If the velocity in the top of a hypothetical column having this porosity-depth structure were 4,800 feet/second, a parabolic approximation to the velocity structure would give a gradient of $3.86 \times 10^{-4}$ feet$^{-1}$ for this section. The resulting instantaneous velocity-depth curve is plotted on Figure 25 for comparison. A point by point comparison with the parabolic approximation shows that a linear approximation would have been sufficient to a depth of around 2,000 feet but the parabolic approximation is best below this depth. This does not indicate a fault in the parabolic method for two rather obvious reasons. The first reason is that the porosity values used for the upper part of the section are somewhat lower than those of deep-sea sediment. The second reason is that in
this case, no account is being made of any process other than decrease in porosity. Not even compaction is a direct factor in the curves of Figure 27. The agreement between this computed curve being discussed and those curves found from the Caribbean profiles is not as bad as might be expected. The lower portions of the profile sections diverge more rapidly but the upper portions are in fair agreement. It must be noted that in the derivation of this curve no account was made of any process or condition except a mixture of particles and water with different porosities. An indirect effect of pressure is present through the use of Laughton's data to derive the curve of Figure 27. The divergence of the observed curves from this theoretical one may indicate the order of magnitude of the effect of diagenetic processes on marine sediments with regards to bulk density and/or rigidity. Nettleton\(^20\) gives shale velocities as high as 13,000 feet/second, so considerable room for increase is present perhaps. Hedberg\(^21\) analyzed a shale section in western Kansas in a manner similar to Athy. For depths less than 2,000 feet the results agree with Athy's but for greater depths the Kansas shale does not decrease in porosity as rapidly.

The results of this quest seem to indicate that diagenetic processes have begun to some degree in the Caribbean sediments, especially in the deeper portions of the sections where they would be expected. If one attaches importance to the moderate parallel between the hypothetical curve based on Athy's data and the observed sections from the Caribbean, then the observed velocity structures might be used to indi-
cate the porosity-depth relation of the sediments.

Some of the travel time graphs do not show continuity of the arrivals for long ranges of observation. The range at which those arrivals become spotty is usually greater than 150,000 feet. The seeming temporary or permanent disappearance of these shallow refraction arrivals beyond this range is considered to be caused by very slight topographic undulations. At these long ranges, the bottom incident angle is very large, generally greater than 70 degrees. In all cases where the arrivals become spotty or disappear at the long ranges, the bottom reflection itself is very weak and may show several closely spaced peaks or have no sharp beginning. It would not require very great relief at these incident angles to cause several bottom reflections off of very slight topographic highs to be observed.

In keeping with this discussion, it was noted that on many records regardless of range several large amplitude arrivals occurred within a few hundredths of a second after the initial bottom reflection. These arrivals consisted chiefly of high frequency components (above 300 cycles/second). At first, an attempt was made to correlate these arrivals as being shallow sub-bottom reflections even though they consisted chiefly of high frequency components. Attempts to do this were unsuccessful and showed no continuity between these arrivals. Not only was there no continuity, but one record might show one of these arrivals while the next record might show two or three. The nature of these arrivals is demonstrated in Figure 5. It was finally concluded that they were also reflections from slight topographic undulations of the order
of 50 feet or less in amplitude. The frequency makeup of these arrivals is the best evidence for this conclusion. Hersey and Ewing\textsuperscript{3} carried out extensive reflection work in the North Atlantic and give a classification of their records based on the nature of the arrivals. In the present study, records were found representing all the types classified by them. Although no comparison will be made it is worth mentioning that they concluded as here that one of the causitive agents in the different nature of their bottom reflections was topography. During the present investigation, several records of each of their types were found at various medium to long ranges. The continued occurrence of these arrivals with predominant high frequency makeup at longer ranges lends increased weight to the conclusion that they represent secondary (not second order) bottom reflections. If these arrivals on a particular profile had represented a shallow sub-bottom horizon, they would have been relatively continuous out to the range where their curve met the curve plotted for the next lower horizon. Complete failure to do anything resembling this adds further evidence to the above conclusion. Officer\textsuperscript{6} shows an arrival beginning at about .050 seconds after the initial bottom reflection. He follows this arrival, which shows moderate scatter, out to a range of around 40,000 feet. This arrival seems to have been picked from frequencies below 150 cycles/second and disappears at the range where low frequency components of bottom reflections disappear as mentioned in the beginning of this section. It is possible that the phenomenon being discussed also explains this arrival.

The only feature observed during the analysis of the data
which could not be explained in some manner was a precursor or fore¬
runner appearing before $R_1$ at moderate to long ranges. These precursors
are plotted on the travel time graphs and are indicated by diamonds.

Several lines of approach were used in the attempt to explain
this phenomenon. Theoretical considerations did not account for them but
did reveal that they could not constitute a sub-bottom arrival preceed¬
ing the bottom reflection, since other arrivals followed them and the
bottom reflection. The precursors consisted chiefly of frequencies below
150 cycles/ second. At these frequencies, it has already been shown
that the bottom materials have a velocity contrast less than unity with
the water. Thus, the arrivals (true sub-bottom) could not cross the
bottom reflection.

Several attempts were made to obtain data on these arrivals.
From the general appearance of the travel time graphs the precursors seem
to follow, or better, parallel, the stronger sub-bottom arrivals following
$R_1$. This separation time difference decreases somewhat as the angle
of incidence on the bottom increased.

The angle of incidence computed for the range at which the first
precursor was observed is a rough function of the water depth but profile
27 is very anomalous in this respect, as is 25. However, it seems that
several ground waves (refractions) recorded for 25 complicate the deter¬
mination of the weaker precursors. Profile 25 agrees with the general
finding that the separation time (between the beginning of the precursor
and the beginning of the sub-bottom arrival) increases as the angle of
incidence (computed for the minimum range of precursor reception) de-
creases. Profiles 24 and 31 agree well with each other in all respects concerning the precursors. Profiles 32 and 33 agree well but 27 differs somewhat in that the observed precursors are much weaker and the angle of incidence on the bottom at the range of first precursor reception is greater than would be expected for this range. It is remembered that the first horizon seen on 32 and 33 was not found on 27. This was thought to be due to topography. Profiles 25 and 26 differ markedly in the range of first observation (and thus bottom incidence angle). One curious, though not universal, correlation was noted upon examination of the charge size and explosion depth data for the ranges of first observation. On five of the eight profiles no precursors were observed until the charge size was increased (and the corresponding explosion depth). The charge size increases were small, of the order of a few pounds, and the depth of firing increases were small, of the order of fifty feet. No other changes in record characteristics were observed except the usual change of the bubble pulse interval and a slight delay in the travel times of the surface reflected waves. Further increases in charge size caused no noticeable effect. The depths to which the explosions were changed still lay within the isothermal layer or so near it that the velocity varied from that of the layer by only a few feet per second. This seems to remove the slight possibility that the sound was channeled in some manner in the ocean itself due to some unknown effect of the isothermal layer.

In summation, empirical attempts were made to correlate between the following factors: water depth; separation time between the begin-
nings of the precursors and the beginnings of the sub-bottom arrivals; minimum range of ground wave reception; angle of incidence on bottom at minimum range of precursor reception; minimum range of precursor reception; charge size; shot depth; strength of precursors; maximum range of precursor reception; maximum range of sub-bottom arrival reception; thickness of the isothermal layer; and topography. The only noteworthy results are mentioned above with the exception that there is a very questionable relation between precursor strength and smoothness of the bottom topography. The stronger precursors tended to be associated with the smoother topography, but, as before, there were notable exceptions. It is regrettable that the precursors were not discovered until the tapes were played back in the laboratory and controlled experiments to determine their cause were impossible. It would be of interest to know if this phenomenon finds its origin in the sediments, as a coupling condition between the ocean and the sediments, or in the ocean proper. The results of this study tend to indicate that the precursors are not associated strictly with the sediments. Precursors were also noted on profiles from the Atlantic basin and Puerto Rico Trench which the author recorded.

It was desired to compute a curve giving the average velocity-depth function for the Caribbean profiles. A mean instantaneous velocity-depth curve was determined from Figure 25 for the seven profiles in the Venezuelan Basin. This curve is shown in Figure 30. This curve was then integrated by intervals to give the average velocity-depth function for this area. This curve is also seen in Figure 30. It is
Fig. 30 Average velocity structure curves.
remembered for this discussion (equation (2)) that the average velocity is a time average velocity.

Figure 31 is a composite of the approximations used by previous authors in describing the variation of velocity with depth in sedimentary sections. Officer's curve was determined in a manner similar to that used in deriving the present curve, which is also included in the figure. Hill's data showed only the shallow sub-bottom refraction depicted in Figure 12A. Laughton's approximation was determined by ultrasonic techniques on compressed cores in the laboratory. Nafe and Drake (unpublished private communication) determined their curve from a statistical study of sedimentary refraction arrivals from a large number of profiles in a variety of locales.

Due to the lack of control between the profiles and the surface geology of the islands, little can be said with confidence about the ages of the various layers found. The question arises as to what causes the reflections observed and this is probably connected with the dating problem.

The reflections come from velocity discontinuities. These discontinuities are probably not sharp. The method of analysis used assumed the velocity structure to be continuous across reflectors. Obviously this is not rigorously correct since something caused the reflections. However, the approximation is still valid if the discontinuities are not large. The validity of the method is witnessed by the good agreement of the Venezuelan Basin profiles. Its invalidity may be expressed by the anomalous results from profile 29.
Fig. 31: Comparison of velocity—depth approximations.
The reflections could represent periods of increased volcanic activity. If the material being deposited were fine grained ooze and mud and a large influx of tuff and volcanic ash of larger grain size were introduced, it is not unlikely that a velocity discontinuity of relatively minor proportions would result. Such an event is more a probability than a possibility in this area and may account for the reflecting horizons noted. It is not impossible on this basis that the section shown may date as far back as the later Eocene or Oligocene.

No further conclusions can be made concerning profile 29 other than to note two possibilities. One is that the column may represent more coarse grained material with advancing lithification. The other possibility, with perhaps the greater weight, is that this section of high velocity material may contain welded pyroclastic beds or thinly stratified lava flows. These could be interbedded with 'normal' marine sediments to give an overall effect of raising the average velocity considerably above that of the more usual sedimentary beds (assumed to be exemplified by the Venezuelan Basin sections). No sharp arrivals would be observed from individual layers of such a relatively thin-layered, heterogeneous section. Considerable random energy would be expected and such is found on the records of this profile.
VII REFERENCES


