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Seismic Measurements Made by H.M.S Challenger in the Atlantic, Pacific and Indian Oceans and in the Mediterranean Sea, 1950-53

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SEISMIC MEASUREMENTS MADE BY H.M.S *CHALLENGER* IN THE ATLANTIC, PACIFIC AND INDIAN OCEANS AND IN THE MEDITERRANEAN SEA, 1950–53

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H.M.S. *Challenger* made a round-the-world cruise during 1950–52, during which studies were made of the deep oceans. In 1953 this work was continued in the north east Atlantic. The seismic experiments which formed part of this oceanographic work are here described. Results are given for the geological structure, as interpreted from seismic refraction, and from some reflexion observations, for the North Atlantic, Pacific and Indian Oceans and for the Mediterranean Sea. A full discussion is given of the methods of analyzing the refracted wave arrivals observed in deep-water seismic experiments.

Introduction

A world cruise was planned by the Hydrographer of the Navy (Admiral Sir Guy Wyatt) during the period 1950–53. It was a happy chance that in 1949 successful trials of the sono-buoy seismic refraction method had been completed by the Cambridge University Department of Geodesy and Geophysics, and it was agreed that the world cruise would provide an excellent opportunity to collect a good harvest of results with the new technique. Two of the present authors spent $2\frac{1}{2}$ years in foreign parts studying the oceans (and some

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shore phenomena as opportunity presented), and after returning to England two of them (M.N.H. and J.C.S.) spent a further year in the north-east part of the Atlantic (Gaskell & Ritchie 1953; Gaskell & Ashton 1954).

The track of H.M.S. *Challenger* is shown in figure 1. The numbers along the track refer to the places at which seismic refraction observations were made. The ship left Plymouth on 1 May 1950, and steamed towards Bermuda. The Pacific was entered late in 1950 through the Panama canal, and after spending more than a year in the Pacific the homeward journey was made via the Indian Ocean and the Mediterranean. The large distances between seismic stations at many parts of the track underline the difficulty of making physical observations at sea. Seismic work is not possible in rough weather. Morever, a ship has only a limited range, and there are many times on a world cruise, when distance has to be covered with the minimum of stops, in order to reach the next refuelling base.

Experimental Methods

Seismic refraction experiments

The sono-buoy method described by Hill (1952) was used in all the deep water refraction work. The *Challenger* cruise provided the first opportunity for an extensive use of this method, and it turned out that, despite earlier fears that the layers immediately below the sea floor might escape detection in deep water, in most cases a fairly unambiguous picture of the structure could be deduced.

The sono-buoys were launched and recovered with the aid of a derrick, and were very suitable for working from a ship the size of the *Challenger*. However, their large size and weight (about 100 kg) made the buoys inconvenient to handle on deck and this type is now obsolete.

The explosions used were small depth charges (22 kg TNT) fired at about 300 m depth with a specially adapted depth charge pistol. Normal practice was to fire shots every 2 miles (3·7 km) with the ship steaming on a steady course at constant speed away from a line of four buoys, to a distance of about 28 km. Repeat shots were made, if required, on the return journey, and a few reverse shots were fired at suitable distances to give dip measurements after passing the buoys.

Shallow-water experiments

The sono-buoys were found to be very suitable for shallow-water work. The buoys were lowered into the water, from the ship at anchor, and towed into position by the ship's motor boat; each buoy was anchored to avoid drift due to wind and current. Charges ranged from single detonators at a few hundred yards from the hydrophones to 10 kg TNT at 10 km. The charges were made up with $1\frac{1}{4}$ lb. naval demolition charges.

The first shallow-water line was run in the lagoon of Funafuti atoll, where the water depth was 25 to 40 m. A line was marked out by taut-wire distance measuring, but the higher frequencies of the water wave (>300 c/s) were readable at all distances and at later stations the water-wave distance alone was used. The recording camera was operated in the *Challenger* at anchor, but it could equally well have been housed in a hut onshore, if, for example, atoll experiments were required and no ship was available. This technique was employed at Nukufetau atoll and at the Seychelles as well as at Funafuti.

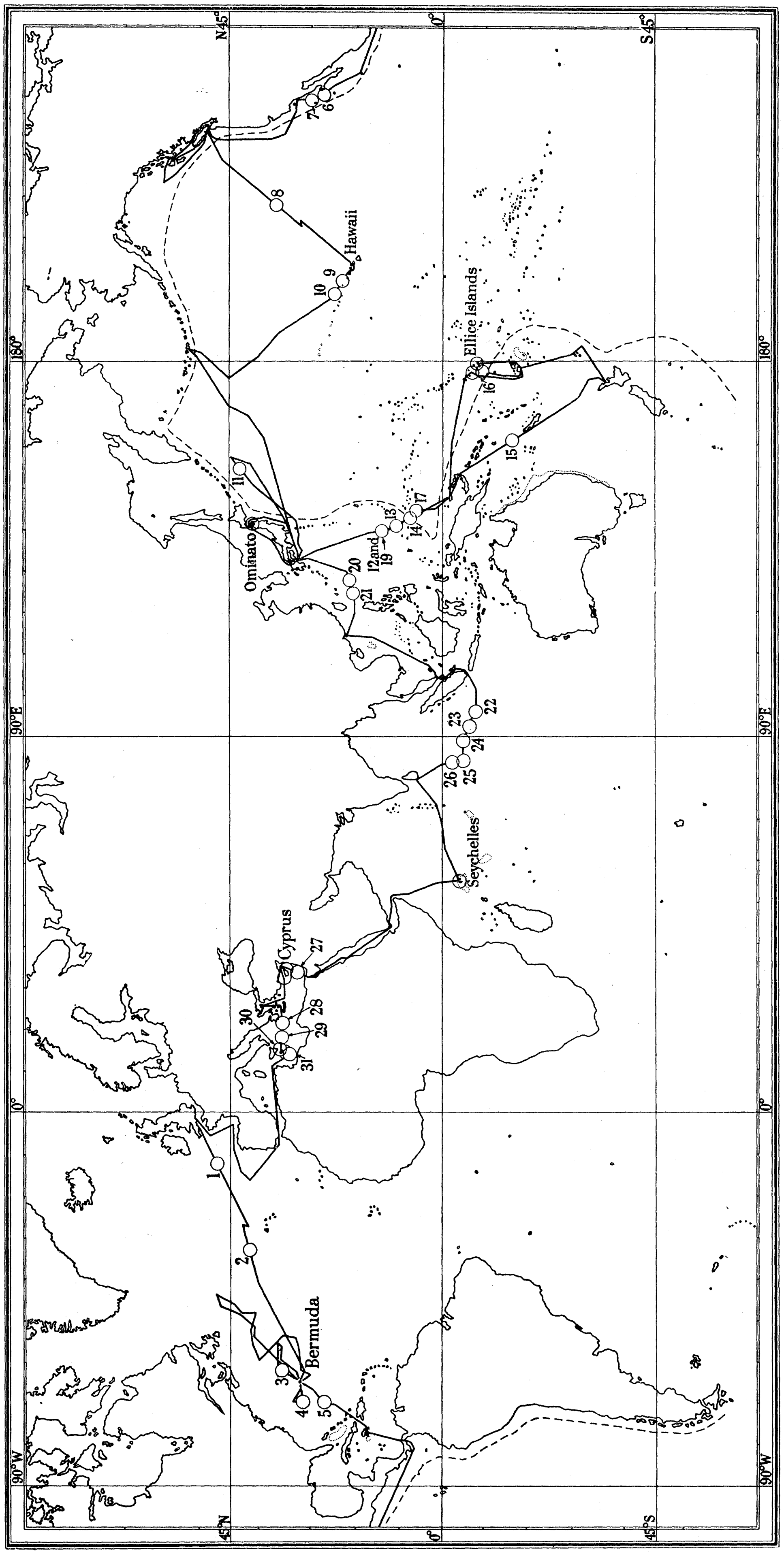

FIGURE 1. Track of H.M.S. *Challenger*. – – –, andesite line.

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In places such as the Famagusta station, where refraction lines were run close to the shore, the buoys were laid from the ship in about 400 fm. (0·7 km) of water, and the ship then stood off while a line of charges was fired from the motor-boat. This was found to be more suitable than the usual deep-water technique, because there was not much room to manoeuvre the ship and some small shots at short distances were necessary on account of the shallow water.

Reflexion experiments

Reflexion shots consisting of $1\frac{1}{4}$ lb. charges were fired at a depth of less than 1 m every day on passage, but few sub-bottom echoes were observed. Nevertheless, in some areas, clear and consistent sub-bottom reflexions could be seen, while in others, where apparently similar topography existed, the sound arriving after the bottom reflexion had the characteristics of slowly decaying random noises. There was some indication of a change in character between shots fired over a sea bed of red clay and those in places where the bottom consisted of globigerina ooze. The wide-angle reflexions that occurred during the normal refraction lines showed some interesting sub-bottom arrivals, but these were often confused by the high signal level produced by the large charges needed to give the refracted waves. At some of the later stations in the eastern North Atlantic, small shots were fired at several miles range for the specific purpose of obtaining wide-angle reflexions; these were sometimes successful. Officer (1955*a*) has shown that wide-angle reflexions obtained with small charges can sometimes be interpreted, but at the time of the *Challenger* cruise his method was not well established.

Reduction of observations

In the present work, all the quantitative results are derived from the travel times; amplitudes and frequencies are used only qualitatively in identifying the different phases. For these purposes, elementary ray theory is adequate.

Figures 2 (*a*) and (*b*) show some of the possible rays, and their time-distance diagram, for a series of uniform horizontal layers. In practice, only parts of these curves can be observed, depending on the characteristics of the corresponding waves and their relative times of arrival. These parts are drawn in firm lines in figure 2 (*b*). At longer ranges, the weak, low-frequency waves refracted through the ground arrive before the direct sound and the larger amplitude reflexions from the sea bed, and are therefore not obscured. In deep water, the direct sound is usually a short high-frequency pulse, and ground waves can normally be read if they occur in the interval between it and the reflexion from the sea bed. Second-arrival ground waves are discernible if their characteristic frequency is appreciably higher than that of the first-arrival or if their amplitude is relatively large. Second-arrivals are, however, less reliable, and a layer may be missed unless first-arrivals are obtainable. Where the reflected waves are incident at angles greater than critical, their amplitudes may be very large, and a sub-bottom reflexion may be stronger than that from the sea bed. At longer ranges the angles of incidence approach those of the refracted waves in the first layer and the deep reflexions become weaker.

Where the layers are of variable thickness over the line of shots and receivers, the refracted arrivals obtained at a series of hydrophones give, from different shots, separate straight lines in the time-distance diagram. Two cases are shown in figures 3 (*a*) and (*b*).

Where a uniform dip exists, the thicknesses of the layers and the true velocity for the ground waves may still be obtained (e.g. Bullard, Gaskell, Harland & Kerr-Grant 1940, p. 33). If the variations are irregular the results may be combined with those from shots on the reverse side of the hydrophones, giving the true velocity and thicknesses assuming only that the dip is uniform in the region under the hydrophones.

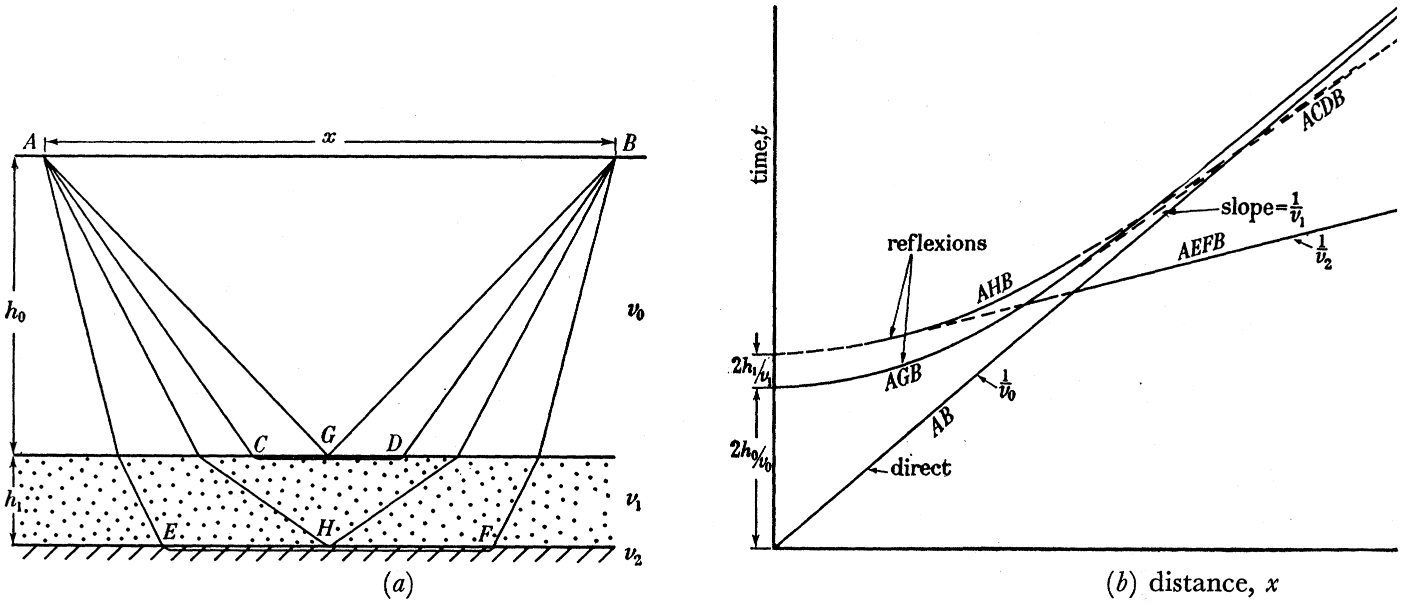

FIGURE 2 (*a*). Seismic ray paths. (*b*) Time-distance diagram corresponding to 2 (*a*).

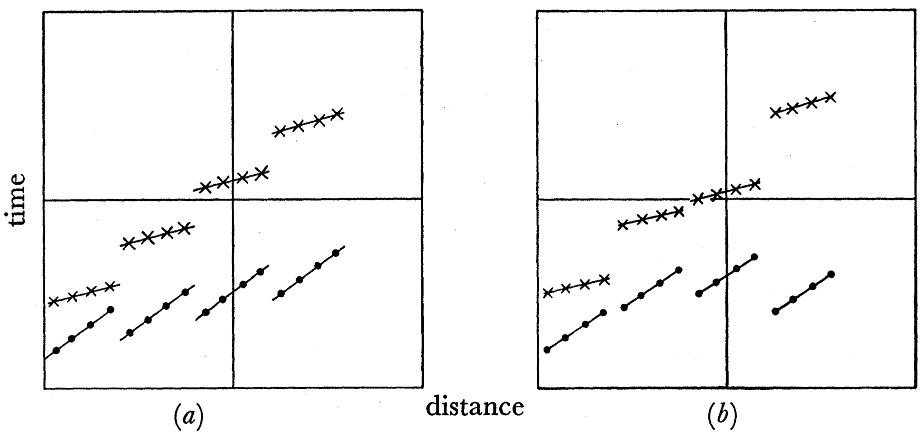

FIGURE 3. Time-distance diagram for four shots and four hydrophones: (*a*) with uniform dip, (*b*) uniform dip under hydrophones, variable dip under shots.

If the velocity of waves in the layer below the sea bed (usually unconsolidated sediment) increases with depth, curved-ray paths are possible (Hill 1952). The travel time curves are difficult to distinguish from the deep reflexion curve of figure 2 (*b*).

1. *Correction of travel times*

(*a*) *Shot instant correction*

The arrival times obtained from the records are measured relative to the first sound received from the explosion by the detector fitted in the ship. A correction has to be added for the travel time from the explosion to the ship, and the calculation of this correction has already been described (Hill 1952).

(b) Correction for depths of shot and hydrophone

Before the arrivals from different shots can be combined, the effects of slight variations in shot depths must be removed, and the travel times are corrected to those values they would have had if the shots and hydrophones were at the sea surface. For the ground waves from the nth layer, the term depending on the water depth in the expression for the travel time is $2h_0(1/v_0^2-1/v_n^2)^{\frac{1}{2}}$, where v_0 is the water velocity and v_n is the velocity in the nth layer; and the correction to allow for depths of shots and hydrophones d, d', respectively, is $(d+d')\ (1/v_0^2-1/v_n^2)^{\frac{1}{2}}$. The values of v_n need be known only roughly since these corrections are small. For reflexions from the sea bed the correction is $2h_0(d+d')/v_0^2t$, where t is the travel time of the reflected wave. In most cases this correction is also sufficient for the sub-bottom reflexions.

(c) Correction for water depth variation

This correction is intended to reduce the travel-time diagram to that which would be obtained if the water depth was constant; in applying it some assumption must be made about the way in which the deep layers follow the observed sea bed profile. Thin upper layers are usually assumed to show the same depth variations as the sea bottom, and deeper layers are taken to be horizontal. Any errors in these assumptions appear as departures of the corrected time-distance diagram from straight lines.

The travel time for ground waves from the second layer under the sea bed (velocity v_2) contains the terms $2h_0(1/v_0^2-1/v_2^2)^{\frac{1}{2}}+2h_1(1/v_1^2-1/v_2^2)^{\frac{1}{2}}$. In correcting for an elevation δh on the sea bed for a thin layer, h_1 remains unchanged and the correction is $\delta h(1/v_0^2-1/v_2^2)^{\frac{1}{2}}$. If the base of the first layer is assumed horizontal, however, the correction involves an increase of h_0 and an equal decrease of h_1, and is equal to $\delta h(1/v_0^2-1/v_2^2)^{\frac{1}{2}}-\delta h(1/v_1^2-1v_2^2)^{\frac{1}{2}}$. For reflexions, the water-depth corrections are obtained in the same way as those for the shot depth. For a single reflexion, the combined correction is $2h_0/v_0^2t(d+d'+2\delta h)$, and for an nth-order multiple reflexion is $2nh_0/v_0^2t(d+d'+2\Sigma\delta h)$, where $\Sigma\delta h$ is taken at all the n-points of reflexion on the sea bed. Sub-bottom multiple reflexions are corrected similarly; it is again usual to assume that the reflecting layer follows the sea bed profile and an approximate value of h_0+h_1 instead of h_0 in the above expressions is used. Wherever the sub-bottom reflexions have been considered in detail, these depth corrections are small compared with the thickness of the layers.

2. *Analysis of reflexions*

The time-distance curve for the reflexions from the sea bed, corrected to a mean depth h_0, is

$$(v_0t)^2=(v_sx)^2+(2h_0)^2,$$

where v_s is the velocity of sound and x is the travel time for a ray travelling in the surface layer of water. Plotting t^2 against x^2 gives a straight line of slope $(v_s/v_0)^2$, and since the vertical sounding velocity v_0 can be obtained from tables (Matthews 1939), this gives v_s. Since v_s/v_0 is always very nearly unity, it is more convenient to plot t^2-x^2 against x^2, giving $(v_s/v_0)^2-1$. This value of the surface water velocity is needed in converting the slopes of the ground-wave lines into velocities.

For the deep reflexions we have, approximately, for moderate angles of incidence,

$$(\bar{v}t)^2 = (v_s x)^2 + (2nh_0 + 2mh_1)^2,$$

for a ray which has made $n-m$ reflexions at the sea bed, and m at the deeper interface. Here $\bar{v}$ is the mean vertical velocity over the whole path, and is defined by the expression

$$\frac{2nh_0 + 2mh_1}{\bar{v}} = \frac{2nh_0}{v_0} + \frac{2mh_1}{v_1}.$$

Plotting $t^2 - x^2$ against x^2 gives lines of slope $(v_s/\bar{v})^2 - 1$, and hence v_1 and h_1 can be determined if n, m, h_0 and v_0 are known. The expressions for these two quantities are

$$v_1 = v_0 \frac{I_{nm}^{\frac{1}{2}} \bar{v}/v_0 - I_{n0}^{\frac{1}{2}}}{I_{nm}^{\frac{1}{2}} - I_{n0}^{\frac{1}{2}}}, \quad h_1 = v_0/2m\ (I_{nm}^{\frac{1}{2}} \bar{v}/v_0 - I_{n0}^{\frac{1}{2}}),$$

where I_{nm} is the intercept of the (n, m)th line on the $t^2 - x^2$ axis in plotting $t^2 - x^2$ against x^2.

Often, in the first-order reflexions, deep arrivals are obscured by the strong reflexion from the sea bed, but in the multiple reflexions of second and third orders a series of arrivals may be found, usually of increasing amplitude and decreasing frequency, corresponding to successively increasing numbers of deep reflexions. For each set of arrivals of a given order number (n) that has made the same number (m) of deep reflexions, a value of v_1 and h_1 can be obtained, and the agreement between the results is a measure of the certainty of identifying these arrivals as multiple reflexions from a single layer.

Where v_1 is found to differ appreciably from the velocity of sound in water the validity of the above approximation is checked by calculating the expected reflexion curves for the deduced values of v_1 and h_1; it may thereby be possible to determine whether there is a uniform velocity in the upper layer. It is sometimes found that the straight lines drawn in the $t^2 - x^2$ against x^2 diagram fit the observed points more closely than the exact curves calculated for a uniform layer. In such cases an alternative method of reduction may be applied. From the time-distance curves for the reflexions at the sea bed and at the deeper interface, a curve can be constructed which would have been observed if the water layer were absent. This is obtained by plotting the differences of co-ordinates of points on the two reflexion curves where equal gradients are found (see, for example, Jeffreys 1952). In general, however, where a simple curve cannot be fitted to the deep reflexions, the estimation of the gradient of the reflexion curves is too inaccurate for this method to be of much value.

3. *Analysis of ground-wave arrivals*

With uniform horizontal layers, the ground-wave arrivals fall on the series of straight lines

$$t = \frac{v_s}{v_n} x + 2 \sum_{k=0}^{n-1} h_k \left(\frac{1}{v_k^2} - \frac{1}{v_n^2} \right)^{\frac{1}{2}}$$

in the time-distance diagram, where x is again the time interval between the explosion and the arrival of the direct sound. The points obtained are assigned to straight lines by inspection, and the slopes and intercepts are fitted by least squares. Since v_s is known, the velocities v_n are obtained from the slopes, and combining them with the intercepts enables the thicknesses to be calculated successively. It frequently happens that no ground waves are obtained from the layer immediately below the sea bed. The observed ground-wave line cuts across the reflexion curve from the sea bed, and the calculated depth to the layer giving the ground waves exceeds the known depth of water. In such cases a velocity has to be assumed for the first layer, unless a value can be obtained from deep reflexions. Sometimes the deep reflexions indicate an interface between the sea bed and the layer giving the ground waves; in this case a velocity has to be assumed for the second layer, though the choice is usually limited to a fairly narrow range by the presence of the arrivals from the next deeper layer.

If second-arrival S-waves are observed from the layer giving the first-arrival ground waves, a further indication of a second upper layer may be obtained. If the cover thickness (assumed uniform) calculated from the S-waves is greater than that from the first-arrival line, the discrepancy may be accounted for by supposing that conversion of the wave from P to S has occurred at an interface in the cover material (Nafe & Drake 1957). The identification of second-arrivals as S-waves is based on the ratio of P to S velocities observed, and on the apparent depth to the layer giving the second-arrivals being at least as great as that for the first-arrivals.

Standard errors of the velocities are obtained directly from the least-square fitting; for the thicknesses, calculated standard errors would be unrealistic where assumptions about missing layers have to be made. In such cases, the effects of varying the assumed velocities, within the limits imposed by the observations, may be calculated instead.

4. *Examples of methods of reduction*

Because a straightforward calculation of velocities and thicknesses of layers cannot always be made from the ground waves, it is sometimes necessary to combine reflexion observations with the ground-wave results, to give a simple consistent model for a structure producing all the arrivals. Since each such case has to be considered individually, the method will be illustrated by working out three examples in some detail below.

(*a*) *Station 5* (figures 4, 5)

Seven shots (A to G) were fired at increasing ranges from a line of four buoys, and a reverse shot (H) was fired 7·4 km beyond the first buoy laid. The arrivals from each shot and buoy are designated A1 to A4, B1 to B4, ..., buoy 1 being nearest the line of shots A to G.

The direct sound arrivals were weak and of high frequency; they cannot be read at travel times exceeding 14 s. The arrivals corresponding to first and second reflexions at the sea bed can be identified at all ranges. Plotting their arrival times against horizontal travel time, where this is known, in the form t^2-x^2 against x^2, straight lines are obtained yielding a value 1·014 for the ratio of horizontal to vertical velocity of sound in water. Using this ratio, and the known depth of water along the line, horizontal ranges can be calculated for those arrivals where the direct sound cannot be read. A time-distance diagram is then plotted, the arrivals having been corrected only for the delay of the recorded shot break.

Reflexions are assigned to the first, second, third and fourth orders (from the known water depth). The first-arrival ground waves, except those from the two closest shots, indicate a velocity $v_s/0{\cdot}22$, and a conspicuous line of second-arrivals give a velocity $v_s/0{\cdot}38$.

For the purpose of applying depth corrections, the closer first-arrival ground waves (shots A and H) are tentatively assigned to a velocity $v_s/0{\cdot}35$. Corrections can now be applied to all the arrivals for depths of shot and hydrophones, and for water depth variation and a corrected time-distance diagram drawn (figure 4).

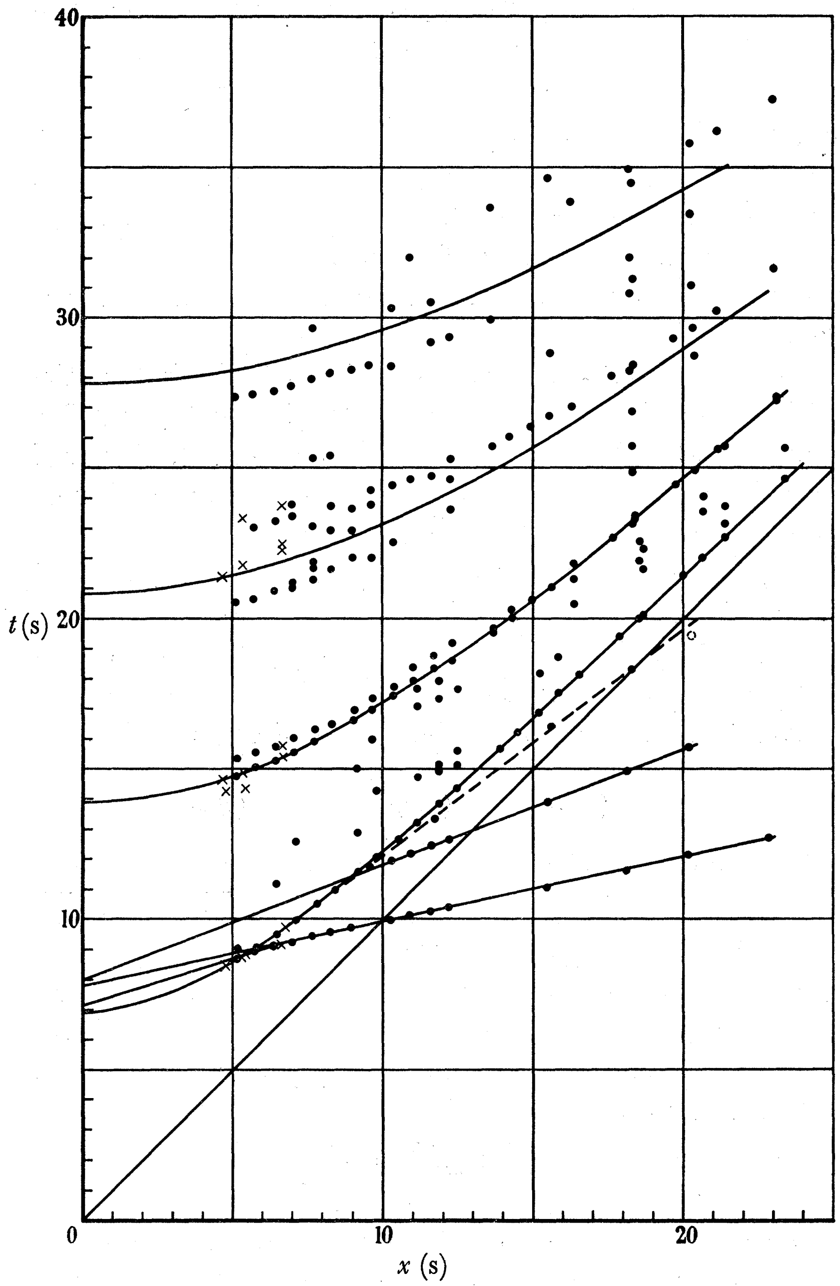

FIGURE 4. Time-distance diagram for station 5. ●, forward; ×, reverse shots; ○, doubtful observations.

The first-arrivals, except those for shot A and reverse shot H, fit the line

$$t = 0{\cdot}2144\ (\pm 0{\cdot}0018)x + 7{\cdot}800\ (\pm 0{\cdot}026), \text{ with residuals } (10^{-2}\text{ s})$$

B1	B2	B3	C1	C2	C3	C4	D4	E4	F4	G4
−1	+3	+2	−2	0	0	−1	−5	−5	+4	0

The tabulated vertical velocity of sound for this depth and area (Matthews 1939) is 1·516 km/s and hence the horizontal velocity will be $1{\cdot}014 \times 1{\cdot}516$, or 1·537 km/s. The velocity corresponding to the slope of the ground-wave line is therefore 7·16 ($\pm 0{\cdot}06$) km/s.

The second-arrival ground waves fit the line

$t = 0{\cdot}381\ (\pm 0{\cdot}003)x + 8{\cdot}05\ (\pm 0{\cdot}05)$, with residuals ($10^{-2}$ s)

B4	C1	C2	C3	C4	D4	E4	F4
+5	−2	+1	+2	−3	−4	0	+3

and the corresponding velocity is 4·04 ($\pm 0{\cdot}03$) km/s. The similarity of the intercepts of these two lines, and the ratio of velocities of 1·78 ($\pm 0{\cdot}02$) encourages the interpretation that the second-arrivals are *S*-waves from the same layer as the first-arrival *P*-waves.

The second arrivals cannot be *P*-waves from a layer deeper than the 7·16 km/s layer, nor can they have travelled as *P*-waves as far as the interface between the covering material and 7·16 km/s layer.

Assuming the cover material has a *P*-wave velocity of 1·6 km/s, the calculated intercept for the *S*-wave line differs from the observed value by 0·65 s, and for higher *P*-wave velocities in the cover material the discrepancy is even greater. Conversion from *P* to *S* must therefore have occurred at some boundary above the top of the 7·16 km/s layer, in order to make the *S*-wave arrivals late enough.

A likely boundary is suggested by reflexions and supported by the early ground-wave arrivals at shots A and H. A number of later arrivals can be seen after the calculated second and third-order reflexion curves in figure 4; plotting these in the form $t^2 - x^2$ against x^2 gives scattered results, but three fairly convincing groups can be picked out.

The results derived from these lines are given in the following table (see p. 29):

n	m	I_{nm}	$(I_{nm})^{\frac{1}{2}}$	$(v_s/\bar{v})^2 - 1$	$(\bar{v}/v_0)$	v_1 (km/s)	$2h_1/v_1$ (s)
2	0	192·4	13·87	—	—	—	—
2	1	207·2	14·40	0·002	1·013	2·06	0·53
3	0	434	20·83	—	—	—	—
3	2	478	21·86	−0·020	1·024	2·28	0·52
3	3	502	22·40	−0·080	1·054	2·28	0·52

The estimates of velocity in the upper layer are poor, depending critically on the slope of the reflecting boundary (an error of 0·5 km/s would be caused by a slope of 1°).

The values obtained for the vertical travel time $2h_1/v_1$ are much more concordant; these depend only on the intercepts since

$$\frac{2h_1}{v_1} = \frac{(I_{nm})^{\frac{1}{2}} - (I_{n0})^{\frac{1}{2}}}{m}.$$

Since there is some support for a velocity of 2·06 km/s from second-arrival ground waves emerging from the first-reflexion curve, that value will be adopted for the upper layer.

Vertical reflexion shots along the line indicate a reflecting boundary at 0·35 to 0·55 s delay after the first bottom reflexion, with a delay of 0·45 s in the area under the hydrophones and close shots. In figure 5 the close-range ground waves are plotted on a larger scale, together with a deep-reflexion curve calculated from the values 2·06 km/s for v_1 and 0·45 s for $2h_1/v_1$. It is clear that the early ground-wave arrivals could be accounted for by a layer immediately below the reflecting interface, and the velocity indicated is 4·5 ($\pm 0{\cdot}2$ approx.) km/s.

Assuming that a layer having this velocity extends down to the 7·16 km/s layer, the thicknesses are 0·4 to 0·5 km of 2·06 km/s material, followed by 1·65 km at 4·5 km/s. It seems most likely that conversion from P to S will occur at the 2·06–4·5 km/s boundary, where the P-wave velocity contrast is greatest.

On this assumption, the S-wave velocity in the 4·5 km/s (P) layer, calculated from the above thicknesses and the observed intercept of the known S-wave line, is 2·2 km/s. The accuracy of this velocity is hard to estimate, but it may be noted that if all the arrivals on the S-wave line had been read systematically 0·1 s late, the corrected value of the S-velocity in the 4·5 km/s layer would increase by only 0·2 km/s.

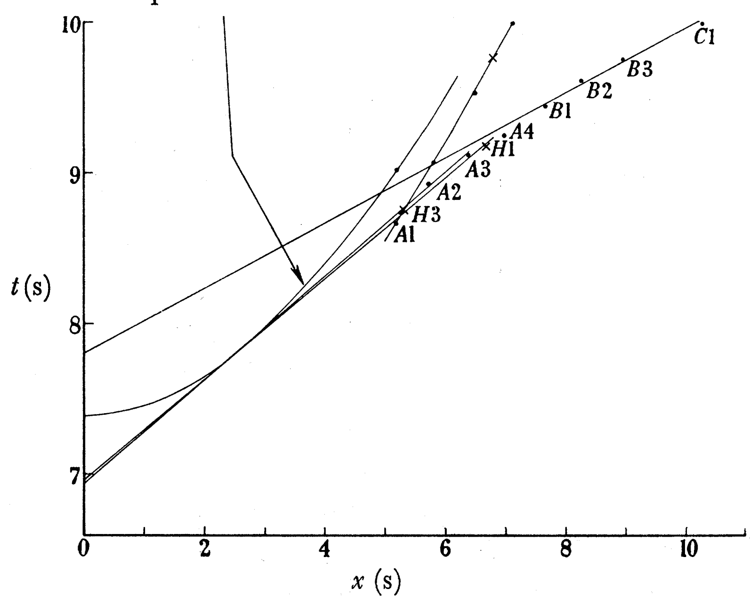

FIGURE 5. Close range observations for station 5.

It seems unlikely that conversion from P to S would occur at the boundary between the water and the upper layer. Experiments by Laughton (1957) suggest that S-waves are propagated only with difficulty in deep-sea sediments, until compacted to such an extent that their P-wave velocity is of the order of 3 km/s. The weakness of the reflexions from the sea bed (fading out after the second order) compared to the deeper ones, suggests that the lower interface is much sharper acoustically.

A minimum thickness of the 7·16 km/s layer can be obtained, if a velocity is assumed for the next layer. Taking 8·1 km/s as a plausible value for the next velocity, the thickness of the 7·16 km/s layer must be at least 2·8 km.

Summarizing the results at this station, therefore, it is possible to account for all the ground waves and several of the clearly defined deep reflexions by the following sequence of layers:

0·4 to 0·5 km at 2·06 (±0·2 approx.) km/s,
1·65 km at 4·5 (±0·2 approx.) km/s (P),
2·2 (±0·2 approx.) km/s (S),
+at least 2·8 km at 7·16 (±0·06) km/s (P),
4·04 (±0·03) km/s (S).

(*b*) *Station 15* (figure 6)

Four buoys were laid, and five shots, A to E, followed by one reverse shot (F) were fired.

This is the one station where the arrivals after the direct sound look like the multiple refractions in the sediment layer, described by Hill (1952). Except for the first reflexions, a systematic delay from the calculated reflexion curves, increasing at higher orders, is seen in the later arrivals (figure 6). The failure to observe the higher-order reflexions from the

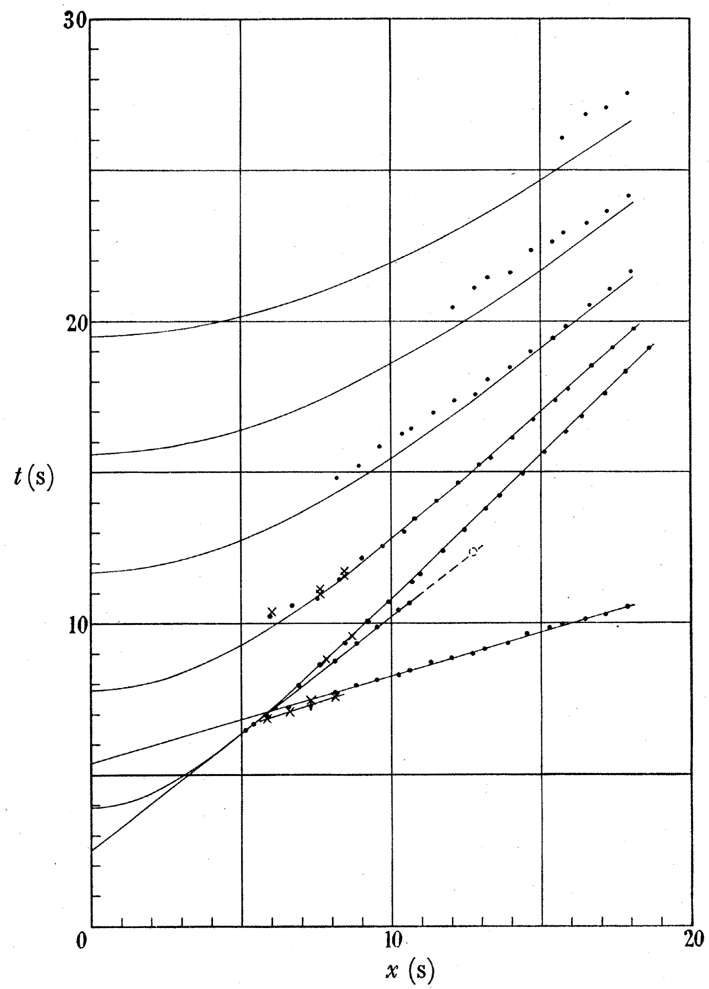

FIGURE 6. Time-distance diagrams for station 15. ●, forward; ×, reverse shots; ○, doubtful observations.

sea bed may be due, however, to a low reflexion coefficient there, and the later arrivals can, as will be shown later, be interpreted as reflexions from a discontinuity in the sediment layer and not necessarily as due to a gradient of velocity.

From the first reflexions, the ratio v_s/v_0 is 1·023, and to simplify the reduction of the multiple water waves in this example the horizontal ranges have been multiplied by 1·023, so that a uniform velocity of 1·494 km/s in water will be used.

The first-arrival ground waves, along the direct line, fit the relation

$$t = 0{\cdot}287\ (\pm 0{\cdot}004)x + 5{\cdot}39\ (\pm 0{\cdot}05),$$

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corresponding to a velocity 5·21 km/s, and having residuals (10^{-2} s)

B1	B2	B3	B4	C1	C2	C3	C4	D1	D2	D3	D4	E1	E2	E3	E4
0	+1	−1	−5	0	+7	+1	−6	+2	−2	+8	+4	+6	−3	−5	−2

The arrivals from shot A appear to belong to a lower velocity line and are omitted from this fitting.

There is a slight indication of dip, since the mean of the velocities given by the points from individual shots is 5·53 (±0·16) km/s.

From the reverse shot, F, three reliable ground waves were obtained, which lie almost parallel to but slightly below the forward line. Although the points from shot A, at the same range, do not appear to belong to the same line, it looks as if the arrivals at shot F are due to the deep layer having dipped upwards under the reverse side, so that arrivals from it could overtake those from a lower-velocity layer. Fitting a line through F's points gives

$$t = 0{\cdot}306\ (\pm 0{\cdot}006)x + 5{\cdot}05\ (\pm 0{\cdot}04),$$

with residuals zero at F1 and F4, and 0·01 at F3. An estimate of the true velocity in the layer giving these arrivals can be obtained from the mean value of the slope of lines in the time-distance diagram through the points from individual shots on the forward and reverse sides. For the forward shots the average slope of these lines is 0·270 (±0·008) and for the reverse shot it is 0·306 (±0·006) giving a true velocity of 5·19 (±0·09) km/s. This is almost exactly the same as the value found for all the points on the forward line, which indicates that the layer is flat under the forward shots, with a dip upwards under the buoys and the reverse shot. The dip required to give the observed differences is 1·8° (±0·7), assuming a velocity in the cover material of 2·4 km/s.

The remaining first-arrival points are those from shot A. The most likely interpretation of these is that A1 and A2 belong to a line giving a velocity of about 2·4 km/s, and that A3 belongs to the high-velocity line, with a slight dip-up already starting, in the same direction as that under the buoys and shot F. Alternatively, there could be a line giving a velocity of about 3·7 km/s passing through A2 and A3, but there seems little justification, with the existing points, for putting an extra layer in.

There is a very clear series of second-arrival ground waves, visible on shots B and C, with a characteristic frequency of 35 c/s. They fade out fairly sharply, on the most distant buoy of shot C, and the arrival at this buoy has not been included in the fitting. The line is

$$t = 0{\cdot}784\ (\pm 0{\cdot}010)x + 2{\cdot}49\ (\pm 0{\cdot}10),$$

with residuals (10^{-2} s)

B1	B2	B3	B4	C1
−3	+2	+3	+4	−4

The velocity corresponding to the slope of this line is 1·91 (±0·2) km/s.

In the multiple reflexions (or refractions), only one strong arrival corresponding to each order number is seen on the record for a given shot and buoy. Where the coefficient of reflexion at the sea bed is larger, one gets a series of arrivals, corresponding to reflexion at either the sea bed or the deep layer, but in the present case it is reasonable to assume that all the observed arrivals are from rays that have gone deep. Consequently, they can be reduced to a single curve by dividing the travel time and the horizontal range by the order number, after the corrections for depth of shot and hydrophone, and for variation of sea depth, have been applied. These reduced points can then be related to the ground-wave arrivals, since they will lie on the curve produced by first-order reflexions or refractions in the sediment.

Fitting travel-time curves with different values of the velocity gradient, but always starting from the same velocity as that in the water, the reduced points are consistent with a uniform velocity gradient of 3 s^{-1}. However, the gradient of velocity cannot stay constant at this value, or it would not be possible to account for the 1·91 km/s second-arrival line. In its upper part, the 'refraction' curve approaches the first-reflexion curve and the velocity in the surface layer of the sea bed must be less than 1·65 km/s, or one would have expected to find small ground waves from the surface layer overtaking the first reflexions, at the most distant shot. It seems most likely, then, that there is a consolidation from a velocity very near that of water, down to the level of the 1·91 km/s layer.

The reduced curve of multiple arrivals tends to a lower limit which, whether it is regarded as due to refractions or to critical-angle reflexions, indicates a velocity of approximately 2·4 km/s in the underlying layer. If the velocity in the sediment varies continuously with depth, there must therefore be a gradient of velocity greater than 3 s^{-1} below the 1·91 km/s layer (however thin it is) in order to reach the higher limiting value at the correct depth, since a mean gradient of 3 s^{-1} fits the reduced curve when the 1·91 km/s layer is ignored. Alternatively, there could be a discontinuous change from 1·91 to 2·4 km/s, and the curves obtained from these two hypotheses are indistinguishable, with the present observations.

The thickness cannot exceed 0·15 km because of the presence of the 2·4 km/s layer, and in order to allow arrivals to be seen at the observed range in such a thin layer, the velocity gradient in it cannot exceed 0·03 s^{-1}. Such a gradient would increase the velocity by only 0·2 % in going through the layer and the curvature in the ground-wave line would be insignificant. For calculation of thicknesses it will be sufficient to regard it as a uniform layer in which the velocity is 1·91 km/s.

The first-arrival ground waves A1 and A2 lie very nearly on the tangent to the reduced curve for the multiple reflexions at its limiting point. The line obtained by least squares from these ground waves and the reduced arrivals of third and higher orders near the end of the curve is

$$t = 0{\cdot}626\ (\pm 0{\cdot}003)\, x + 3{\cdot}25\ (\pm 0{\cdot}02),$$

but the standard errors are probably underestimated as too much weight is put on one point (A2). The velocity corresponding to this line is 2·39 (±0·01) km/s. On the refraction hypothesis, this is the limit of velocity reached when the gradient ceases, and with reflexions it is simply the velocity in the layer below the reflecting interface.

In seismic work on land with partially consolidated sediments, small gradients of velocity are frequently found, but interfaces between regions of different velocity are usually sharp. In the present case, it seems unlikely therefore that, once a fairly steady velocity of 1·91 km/s has been reached, there will be a further region in which a gradual consolidation occurs. More probably there will be a discontinuous change from the 1·91 km/s velocity to 2·39 km/s, and the arrivals observed after the direct sound will be deep reflexions.

The thickness of the layer immediately below the sea bed, in which it is assumed a velocity gradient of about 3 s^{-1} exists, is 0·14 km approximately, and this is followed by a layer 0·15 km thick in which the velocity is 1·91 ($\pm$0·02) km/s, with a very slight increase with depth (less than 0·03 s^{-1}).

Under this is a layer in which the velocity is 2·39 km/s, and from the first-arrival ground waves the thickness of this layer varies from 1·42 km under the reverse shot, to 1·69 km under the buoys and 1·97 km under the forward shots. The dip under the buoys and the reverse line, from these thicknesses, is 1·6°, which agrees well in size and direction with the 1·8° ($\pm$0·7) obtained independently from the slopes of the arrival lines.

Assuming a velocity of 6·5 km/s in the next layer, the thickness of the 5·19 km/s layer is at least 2·5 km.

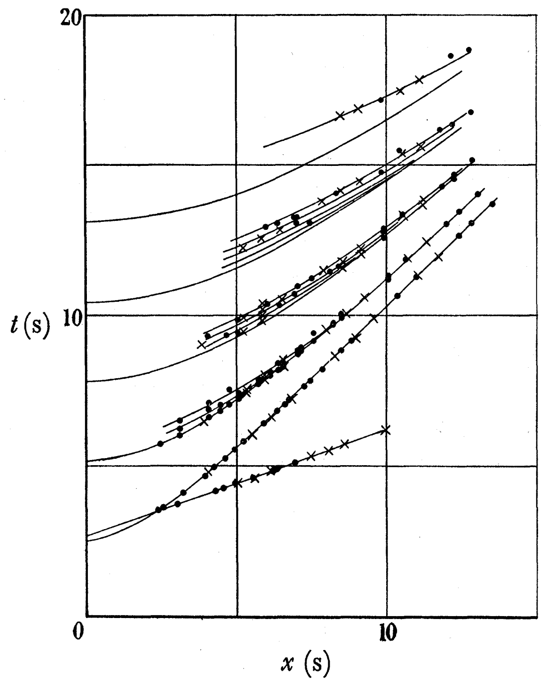

FIGURE 7. Time-distance diagram for station 27. (Deep reflexion curves are for 2·18 km/s.) ●, forward; ×, reverse shots.

It is possible that a layer of about 3·7 km/s velocity has been missed. Putting a line through the ground waves at A2 and A3 with this velocity gives the following thicknesses: 0·29 km at 1·91 km/s and below, then 1·07 km at 2.39 km/s, and 1·22 km at 3·7 km/s. One would not expect to see reflexions from the top of the 3·7 km/s layer, since the delay time would be about 1·2 s. The possible presence of such a layer cannot be excluded, but it is not required to account for the observed arrivals.

(*c*) *Station 27* (figure 7)

Four buoys were laid 0·9 km apart and five shots (A to E) were fired at 3·7 km intervals. Two more shots, F and G, were fired at 9 and 5 km range on returning, and three more shots (H to J) on the reverse side of the line of buoys.

Multiple reflexions (or refractions) were observed, up to the fifth order, the high-frequency bottom reflexion dying out after the second or third order leaving low-frequency arrivals delayed slightly from the calculated bottom reflexions.

The ground waves from forward and reverse shots show no systematic deviation from the single straight line

$$t=0{\cdot}355\ (\pm 0{\cdot}0025)x+2{\cdot}69\ (\pm 0{\cdot}016)$$

the residuals (10^{-3} s) being

A1	A2	A4	B1	B2	B3	F1	F2
+7	+11	−13	0	−20	−7	−13	−10
G2	H1	H2	I1	I2	I4	J2	J4
−2	−4	+28	−44	+9	+14	+13	+32

From the first reflexions, $v_s/v_0=0{\cdot}9953$, and since $v_0=1{\cdot}522$ km/s, $v_s=1{\cdot}515$ km/s. The velocity from the slope of the ground-wave line is therefore 4·27 (±0·03) km/s.

In the second-order multiple reflexions, two series of later arrivals can be seen, and the spacing of these suggests that they represent one, or two, reflexions from a deeper layer. The observed delays in this and higher orders indicate that the fifth-order arrivals, and the later group of fourth-order ones, have made all their reflexions at the deeper layer. They can therefore be reduced to the first order by simply dividing the distances and travel times by the order number. When this is done, the reduced points are found to lie on a curve touching the ground-wave line, and the multiple arrivals are therefore interpreted as reflexions from the layer giving the ground waves.

The only ground waves assignable to the sediment layer are a few weak second-arrivals, just emerging from the first reflexions at shot C and beyond. They indicate a velocity of approximately 1·62 km/s. It is unlikely that this is the average velocity for the whole of the sediment, and a better value of the average velocity in it can be got from the deep reflexions.

Since it seems clear that they come from the same layer as the ground waves, reflexion curves have been calculated for several average velocities, using the thicknesses given by the ground-wave line in each case. This involves less approximation than getting the velocity from plotting t^2-x^2 against x^2 for the reflexions, and although more tedious it shows the accuracy of the fitted velocity more clearly. Curves have been calculated for sediment velocities of 1·52, 1·73, 1·90, 2·18 and 2·54 km/s, and comparison with the observed points suggests an average velocity of 2·2 (±0·2 approx.) km/s (figure 7).

Although this may be the best average velocity, the sediment cannot be a uniform layer. The calculated deep-reflexion curve for a uniform 2·2 km/s layer crosses over the bottom-reflexion curve at a range of 3·3 s, so that one cannot get delayed reflexions at ranges greater than this with a uniform layer. Moreover, the bottom-reflexion would become very strong at 2·5 s range, where the critical angle for the 2·2 km/s layer is reached, and this would obscure later arrivals beyond this range. Neither of these effects are observed, however, and from the presence of delayed arrivals on the reduced curve at ranges beyond $3\frac{1}{2}$ s it is clear that a single velocity cannot fit the reflexions completely.

The arrivals could be accounted for by assuming a layer of, say, 1·62 km/s giving the weak high-frequency ground waves, and the longer-range deep reflexions could come from its interface with a 2·2 km/s layer beneath it. Alternatively, there could be a continuous gradient of velocity in the sediment, so that the short-range points are reflexions from the layer giving the ground waves, as before, but at longer ranges refractions in the sediment layer are obtained. Curves have been calculated with velocity gradients of 2·6, 3·6 and

$4{\cdot}7\ \mathrm{s}^{-1}$ (the velocities reached at the reflecting interface, starting from the water velocity, being 2·2, 2·5 and 3·0 km/s). Comparison with the observations shows that a gradient of about $4\ \mathrm{s}^{-1}$ is required, but the curve obtained is very insensitive to the choice of velocity gradient.

When a reflecting interface is not present, the position of the cusp in the sediment refraction curve is the most sensitive indication of the correct velocity gradient, but this does not apply here. From the present observations, one can only conclude that the average velocity through the sediments is 2·2 ($\pm 0{\cdot}2$ approx.) km/s, and that it starts with a lower value, probably about 1·6 km/s. Whether the changes in it are continuous or not cannot be decided.

The thickness calculated for the average velocity of 2·2 ($\pm 0{\cdot}2$) km/s, is 0·3 km. Assuming the 4·27 km/s layer is followed by a 6·7 km/s layer, its thickness is at least 2·4 km.

Results

(A) *The western Atlantic*

The western Atlantic measurements consist of three stations occupied while working from Bermuda in 1950 (Gaskell & Swallow 1951). The positions of the stations and the track of the ship are shown in figure 1.

Extensive work has been done in this area by Ewing and his associates, (e.g. Officer, Ewing & Wuenschel 1952; Katz & Ewing 1956; Officer 1955 *a*). It is reassuring to note that the present experiments, made by different observers using a different technique, gave results substantially similar to those obtained by the American workers. Table 1 (*a*)* gives the observational data for the stations and is self-explanatory except perhaps for the last column, which gives the ratio of horizontal to vertical velocities calculated from the arrival times of the multiple reflected water waves. The vertical velocity is taken from Matthews's tables. Table 2 (*a*)* contains a summary of the results that have been deduced from the measurements. Comments on the individual stations, to explain the adopted interpretation, are given below. The time-distance results have been interpreted in terms of three layers, the most important of which is the 'main refractor line', because it contains the majority of the observations. Since the time-distance line for the refracted wave from this layer controls to a large extent the thicknesses that are possible above it, the observations on this line have been fitted by least squares, and the standard errors in velocity and in intercept are tabulated. The material overlying the main refracting layer is divided into 'sediment layer' and 'layer above main refractor', and for these the velocity and thickness only are given, since there were rarely enough good observations to allow fitting of a time-distance line by least squares. When a velocity was assumed it is shown thus: (2·0).

The depth to the main interface below the sea bed is given in Table 2, because it is the information that results directly from the time-distance readings. The depth to the Mohorovičić discontinuity, the transition to a velocity near 8 km/s, from the sea surface is also tabulated, because this datum is more usual in comparing oceans and continents. The 8 km/s layer was recorded in only a few cases, and column 14 in most cases gives a minimum value.

* Tables 1 and 2 appear at the end of the paper.

The remarks column serves as a reminder of special features explained in the notes on the separate stations.

Travel-time graphs and structural models deduced from them for the western Atlantic stations are given in Figures 4, 5, 8 and 9.

Station 3 (figure 8*a*)

The mean line fitted to the seven readable arrivals on the main time-distance line indicates a velocity of 7·7 ± 0·4 km/s, but a more probable interpretation of the results gives 7·2 ± 0·2 km/s for the first five points and 8·4 km/s for the last two weak arrivals.

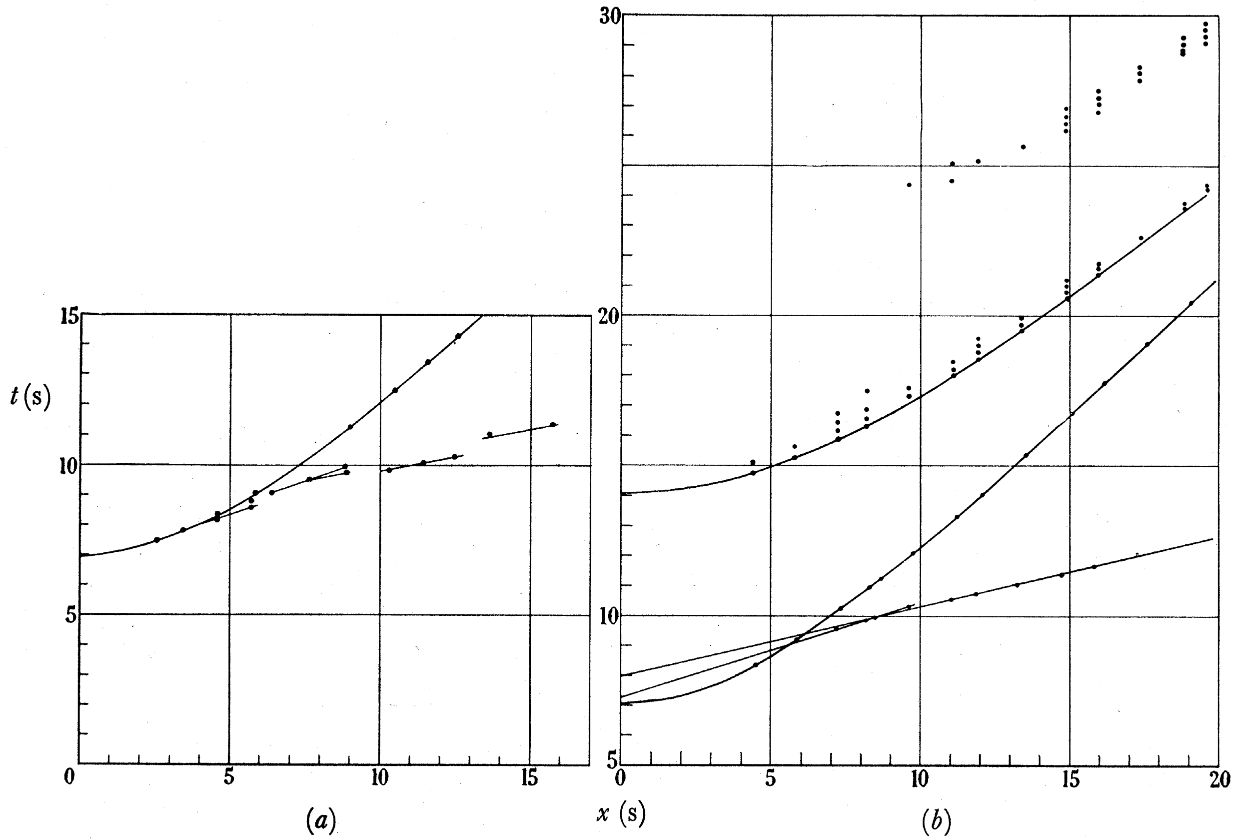

FIGURE 8. Time-distance diagrams for western Atlantic. (*a*) Station 3; (*b*) station 4.

Four first-arrivals determine an upper layer in which the velocity is 4·4 km/s, but the irregularity in depth of the ocean in the vicinity of the buoys makes the time intercepts vary from different shots.

The vertical profile given in table 2 (*a*) is that based on the 7·2 km/s interpretation. The large variation in thickness of sediment is caused by the combination of differences in intercept and in depth of water for the two closest shots, but is somewhat doubtful because of the rapid changes in depth in the area indicated by the different depth profiles along the line obtained when going out and when returning.

It is possible that the interface between the 4·4 and 7·2 km/s layers is not level (figure 9) and a lower velocity for the 7·2 km/s layer would be consistent with a slope downwards to the more distant shots. This slope down could be accommodated by thickening of the sediment layer or of the 4·4 km/s layer.

Station 4 (figure 8*b*)

The nine good first arrival refracted waves indicate two refracting layers, with velocities 4·84 and 6·58 km/s, so that the general form of the structure is similar to that at station 3. As with station 3, there are no reverse shots to check the main velocities.

Multiple reflexions provide some evidence of subdivision of the material overlying the 4·84 km/s layer. The good reflexions indicate 0·26 km of 1·6 km/s material. This leaves a gap (figure 9) before the top of the 4·84 km/s layer is reached and the interposed material may be anything from 0·3 km at 1·8 km/s to 0·8 km at 3·7 km/s. The strong reflexions from the bottom of the top sediment layer suggest a higher value; an upper limit of 3·7 km/s is provided by the first arrival time-distance points. The strong reflexions are in this case from a layer that is definitely above the 4·84 km/s layer.

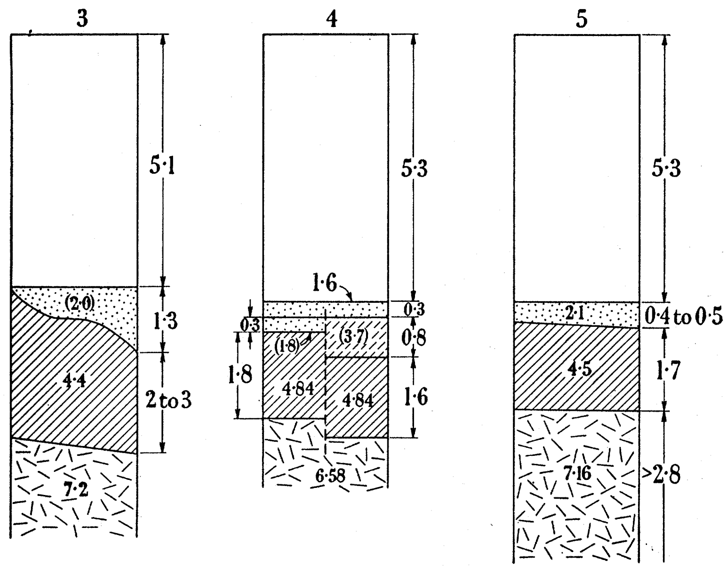

FIGURE 9. Vertical sections for western Atlantic. (Thicknesses in km; velocities in km/s; assumed velocities in brackets.)

Station 5

This station has been described as one of the examples in 'Reduction of observations' (p. 30).

Interpretation of western North Atlantic results

The three stations in this area show similar structures. The first-arrival refracted waves in each case indicate the existence of three layers. Reflexions at stations 4 and 5 provide some knowledge of the sediment layers. At station 5, the reflecting surface could be the top of the second layer, which is shown to exist by first-arrival waves, and which is inferred by the behaviour of waves identified as *S*-waves corresponding to the *P*-waves in the main deep refracting layer. However, at station 4 the reflecting surface is too shallow to be the junction between the sediment and the 4·8 km/s layer, and a subdivision in the sediment, with the lower part having a velocity less than 3·7 km/s may be present. The results are not conclusive, because the short range of distances over which the second layer gives first arrivals makes velocity and depth determinations uncertain. However, the refracted waves at the three western North Atlantic stations, and reflexions at these and at other places in the area, do show the existence of a second layer at depths from 0 to 1·2 km, and of thicknesses 1·8 to 2·3 km. The rocks corresponding to the second layer may be consolidated (or cemented) sediment or volcanic rocks, or a combination of the two.

The velocities from the deepest layers observed are all in the range of values obtained from basic igneous rocks. The values from stations 3 and 4 are less certain, both from calculated standard errors and possibility of uncorrected dip, than that of station 5. The differences in value may be associated with changes in composition of the layer; Officer *et al.* (1952) found a similar spread of velocities (6·53 to 7·53 km/s) in this area. Some high velocities recorded may be influenced by inclusion of time-distance points which should really be fitted to an 8 km/s line, (Gaskell 1954). The 8 km/s layer was not determined with certainty at any of the three stations described here. The lower limits for depth given in table 2 (*a*) have been calculated by fitting a high-velocity line through the most distant well-established observation. They are consistent with other measurements in the western North Atlantic.

(B) *The Pacific*

The Pacific observations were made during the years 1950–52 (Gaskell & Swallow 1952). The track of the ship is shown in figure 1, and the station numbers are marked in the positions in which seismic refraction experiments were conducted. In addition to the numbered stations, shallow-water experiments were made at the coral atolls of Funafuti and Nukufetau (Gaskell & Swallow 1953) and in a bay near Ominato in North Honshu. A summary of the coral atoll results will be given here because these results are relevant to the structure of deep oceans, and they will be needed for reference.

The position of the andesite line (Macdonald 1949) has been drawn in figure 1 and it will be seen that six stations 8, 9, 10, 11, 16, 17 lie on the oceanic side of this line, although two of these, 9 and 16, are close to islands. Stations 6 and 7 are near the American coast, and 15 is in the Australasian area. Station 13 is in the Marianas trench, in which a depth, 5940 fm (10·86 km), greater than those previously recorded for any area, was found by H.M.S. *Challenger* (Gaskell, Swallow & Ritchie 1953). Stations 12 and 19 are close together near the continental side of the Marianas trench, and stations 20 and 21 are at the north-western end of the Philippine Sea.

Table 1 (*b*) gives operational information relevant to each experiment, while table 2 (*b*) contains details of time-distance lines fitted to the observations. As in table 2 (*a*), the line with the majority of observations has been tabulated as the 'main refractor'. This leaves no 'layer above main refractor' for stations 13 and 14 and Ominato, and it puts 6·4 and 6·5 km/s as the 'layer above main refractor' for stations 12 and 19. These last velocities would normally be under 'main refractor', but good readings for the lower 8·5 km/s layer were obtained in this case. The time-distance diagrams are given in figures 10 to 12. The sections shown in figure 15 summarize the information obtained in the Pacific, except for the shallow-water stations, the geological profiles for which are in figures 13 and 14.

Station 6 (figure 10)

This station was about 150 miles from the coast of California, and although in deep water (2000 fm, 3·6 km) the depth varied by ±150 fm (0·27 km) along the 28 km of the seismic line, and the echo sounder showed that slopes of 1 in 4 existed.

The travel-time diagram suggests that two separate velocities are present. These indicate a break into two layers: the results cannot be explained by drift of the buoys over the irregular sea bottom because of the agreement between soundings on the outward and return trips. The first velocity gives some intercepts which are too small for the known water depths at buoys and shot points, and therefore there must be irregularities under the buoys such that a single dip cannot be fitted by combining forward and reverse shots. The

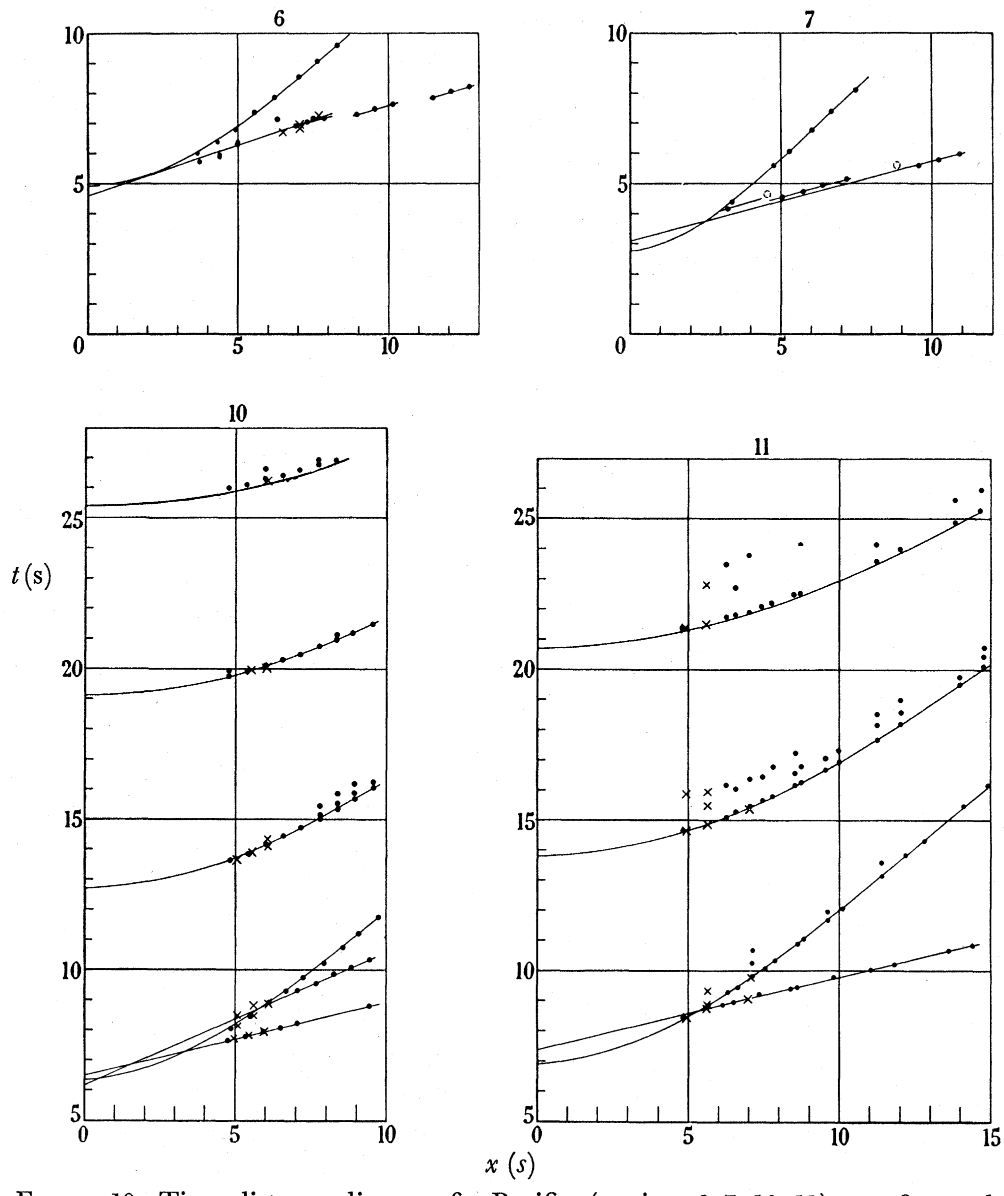

FIGURE 10. Time-distance diagram for Pacific, (stations 6, 7, 10, 11). ●, forward; ×, reverse shots; ○, doubtful observations.

layer corresponding to the first velocity has therefore been assumed to be on the surface, and the velocity is found to be 4·6 km/s. The arrival times for the waves belonging to this time-distance line have been corrected to a mean depth of 2000 fm (3·6 km) of water, assuming the irregularities in water depth to be formed of the 4·6 km/s material.

The second velocity is given by three shots, and a dip in the interface between layers 1 and 2 is indicated by the observations from the separate shots falling on lines arranged *en*

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échelon on the travel-time diagram. No reverse shots are available to give further definition, but an average result of 5·81 ($\pm$0·18) km/s is obtained by taking the mean of the slopes of the lines from separate shots (0·302$\pm$0·022) and from separate buoys (0·216$\pm$0·009). If the smaller slope was taken the velocity in the lower layer would have to be 7·0 km/s, and there would be a dip of 20° under the buoys. The other extreme slope cannot give the true velocity, since for one shot the intercept would be too small for the known depth of water. Adopting 5·8 km/s as the second layer velocity, with 4·6 km/s in the upper layer, the thickness of the latter varies from nearly zero under the buoys and under one shot, to about 1·5 km.

The uncertainty of the structure at this station does not allow much weight to be given to the 5·8 km/s value of the velocity in the lower layer. It does, however, appear that it is significantly lower than that in the deep oceans, and this fact combined with the irregularity of the area suggests that the structure at this station is similar to the continental structure.

Station 7 (figure 10)

This station is slightly closer to the Californian coast than no. 6 and again the seismic results differ from those in the deep oceans both in the low velocity of the lower layer and in the irregularity of the structure. The travel-time diagram (figure 10) indicates a single velocity and the value of 6·0 km/s is calculated from the velocity of 5·32 ($\pm$0·25) km/s obtained from separate shots and that of 6·88 ($\pm$0·32) km/s from separate buoys as for station 6, since here again sloping rock interfaces are present. There is no direct evidence of a 4·6 km/s layer as in station 6, but a reflexion 0·38 s after the wave reflected from the sea bed would indicate that a sediment layer is only 0·4 km thick. The 6·0 km/s layer must be at least 0·6 to 0·9 km below the sea bed, even if covered entirely by sediment of velocity 2·1 km/s, and it is possible that an undetected layer exists, similar in character to the 4·6 km/s layer of station 6.

Station 8 (figure 11)

The first-arrival waves all lie on a single time-distance line with slope corresponding to a velocity of 6·36 km/s, and with an intercept that indicates 0·3 km of sediment cover (assumed 2·0 km/s velocity). A single reverse shot indicates the possibility of a small dip and would give a velocity of 6·57 km/s with a depth of 0·39 km over the forward portion of the seismic line, but it is more probable that the misfit of the reverse shot is a local irregularity. However, there is evidence that the geological column is not so simple, and the overburden can be divided into 0·1 km of 2·0 km/s sediment and 0·6 km of 4·3 km/s material. The existence of the extra layer is presumed because (1) good sub-bottom reflexions with a delay time of about 0·1 s are observed in the area, and (2) second-arrivals indicating a velocity of 3·5 ($\pm$0·04) km/s are identified as delayed *S*-waves from the main refracting layer (see station 5, p. 30). It is assumed that the *S*-waves are initiated at the boundary indicated by the reflexions, that is at 0·1 km below the sea bed. The velocity in the medium between the sediment and the main refracting layer cannot exceed 4·3 km/s without conflicting with the short-distance observations. The *S*-wave velocity required to give the same layer thickness as is obtained from 4·3 km/s *P*-waves is 2·0 km/s. For a

P-wave velocity of 3·0 km/s the *S*-wave velocity must be 1·2 km/s. The thicknesses calculated from the latter velocities would be 0·1 and 0·4 km, and this gives a picture of depths intermediate between the extremes of no extra layer between sediment and 6·36 km/s material, and the maximum *P*-wave velocity of 4·3 km/s used in Table 2 (*b*).

Station 9 (figure 11)

The thickness of cover above the main refracting layer is much greater than for station 8 on any interpretation. Six good first-arrivals provide a measure of 4·3 km/s for the overburden velocity. The intercept of the corresponding time-distance line allows only 0·05 km of low-velocity sediment cover, so that no attempt has been made to divide the sediment into 2·0 and 3·0 km/s as was done for station 8. Station 9 was between two islands of the Hawaiian Island chain which are composed mainly of olivine basalt (Macdonald 1949). Laboratory measurements by Dr A. S. Laughton on samples of Hawaiian volcanic rock agree well with the velocity of 4·3 km/s. It is reasonable, therefore, to identify the second layer at this station with volcanic material. This same material could be present at station 8, but there is a large difference in the seismic result, in that at station 8 any 4·3 km/s layer must be much thinner than at station 9 and therefore does not show itself by first-arrival *P*-waves.

Station 10 (figure 10)

The velocity of 6·93 km/s for the main refraction line is calculated as a mean of the velocities from individual shots, because the line fitted to all the first-arrival points showed a regular trend in the residuals. As there are depth variations of ± 50 fm along the seismic line, with a flat area under the buoys, it seems likely, from the agreement between forward shot A and reverse shot D, that the individual shots are giving the true velocity and that the line fitted to all the points is incorrect because of unknown depth variations. However, the scatter of times for the same shot to different hydrophones is as large as the regular trend in the residuals, and since only three hydrophones were operating it is possible that the calculated 6·93 km/s velocity is in error. The velocity given by the mean line for all the points is $6{\cdot}25 \pm 0{\cdot}10$ km/s and its intercept is 0·16 s less than that given in table 2 (*b*) for the mean of the lines from separate shots.

If the overburden is assumed to be a single layer of sediment with velocity 2·0 km/s, the thickness of the sediment is 0·3 to 0·5 km, the smaller value corresponding to the 6·25 km/s velocity line. However, a sub-bottom reflexion, at 0·02 s after the arrival from the sea bed, was observed, and five second-arrivals give a time-distance line corresponding to a velocity of $3{\cdot}97 \pm 0{\cdot}22$ km/s, which is very reasonable for an *S*-wave in the main refractor. The large intercept for the *S*-wave line, 6·66 s, implies that *P*- to *S*-conversion has taken place above the main refracting layer. The choice of *P*- and *S*-velocities in the layer above the main refractor is not very critical, and a *P*-velocity of 4·3 km/s has been assumed. It seems unlikely that a sediment layer with a *P*-velocity of only 2·0 km/s will allow good propagation of *S*-waves.

Station 11 (figure 10).

The velocity of 6·69 km/s for the main refraction line is calculated from the mean of forward and reverse shots. The sea bed topography suggests that there may be a uniform dip in the area beneath the buoys, and the velocity of 6·53 km/s calculated by grouping the separate shots and separate buoys is in agreement with this value rather than with the value 6·15 km/s obtained from the time-distance line through all observations regardless of slope.

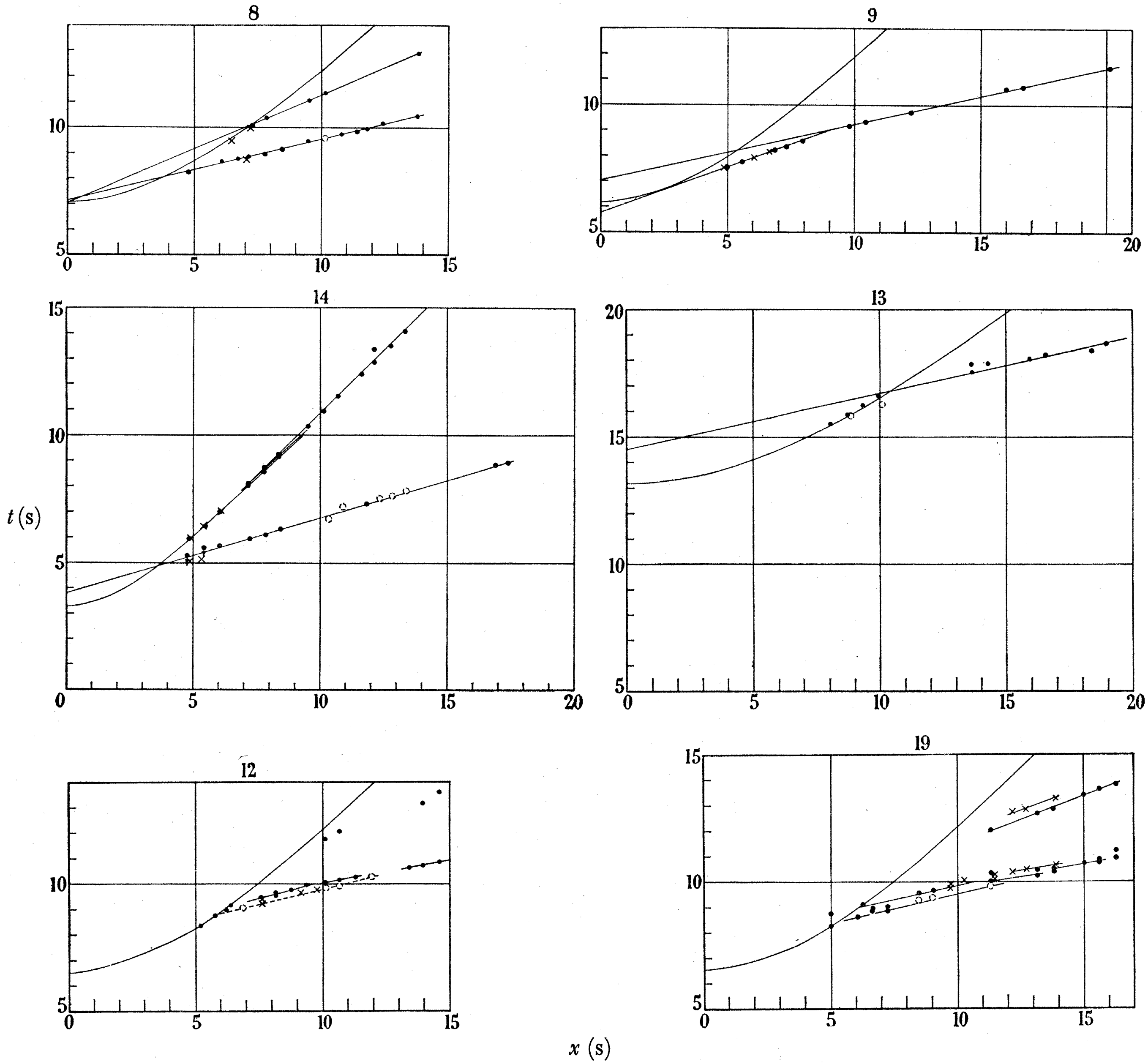

FIGURE 11. Time-distance diagrams for Pacific (stations 8, 9, 14, 13, 12, 19). ●, forward; ×, reverse shots; ○, doubtful observations; ●↓, arrival may be earlier.

Both wide-angle and vertical reflexions are observed with a delay (for vertical reflexions) of 0·52 to 0·55 s after the reflexion from the sea bed. The wide angle reflexions give a mean velocity of 2·1 km/s to the reflecting surface, but since the accuracy is very poor, the value of 2·0 km/s, which has been adopted for other stations, will continue to be used here. The depth of the reflecting interface (0·53 km) does not account for the whole of the intercept of the time-distance line for the main refracting layer, and an intermediate layer is

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assumed. There is no well-marked *S*-wave evidence as there was at stations 8 and 10, but the reflexion evidence for a discontinuity in the sediment layer is stronger than at the latter stations. The sediment layer is certainly much thicker here than at 8 and 10 on any interpretation.

Stations 12 and 19 (figure 11)

These stations are in the same position, station 19 being a repeat of 12, made in order to check the unusually shallow refracting layer having a velocity of about 8·5 km/s. The positioning by Loran ensured that the stations were within a mile of each other.

At station 12 the high velocity is indicated by two shots, and a velocity of 8·0 km/s is obtained as a mean of the two sets of refracted wave arrivals. The misfit of the separate observations from the two shots suggests a dip, and if this dip is uniform between buoys and shots the true refractor velocity is 8·5 ($\pm$0·5) km/s.

At station 19 one reverse and two forward shots give points which lie on a high velocity time-distance line. Fitting separate lines to these shots gives velocities of 8·1 ($\pm$1·7) and 9·0 ($\pm$1·4) km/s, the mean being 8·5 ($\pm$1·1 km/s). The spread of the buoys is approximately double the horizontal offset distance for the refracted ray paths in the forward and reverse directions, so that although the average of forward and reverse readings does not completely eliminate variations of depth beneath the buoys, it assumes uniformity of dip over a short distance only. The intercepts for the separate shots for stations 12 and 19 vary from 7·91 to 8·22 s along the two lines, indicating that there are dips in the area, so that the procedures adopted for both stations in obtaining the most probable velocities are in this respect plausible. On any interpretation of the arrival times there is certainly a refractor having a velocity of at least 8·0 km/s. If this was the true velocity the mean intercepts of the time-distance lines from the separate shots would be reduced by 0·17 s. This would not alter the general structural picture, because the contribution of the water path to the intercept is 6·38 s leaving nearly 2 s to be accounted for by the rock above the high velocity material.

The ground waves at the shorter distances at both stations indicate a velocity of about 6·5 km/s. Changes in the character of the waves and changes in intercept from the early group of shots to the later ones, suggest that refracted waves are being received in the first instance from a thin layer and later from a solid 6·5 km/s layer. At station 12 the three nearest shots, A, B and E, yield time-distance lines corresponding to 6·4 ($\pm$0·4) km/s, with intercepts 7·40 s for A and E and 7·64 s for B. Assuming 2·0 km/s as the velocity of the cover material, this would give 1·1 km as the depth to the layer under A and E and 1·4 km under B. This large increase seems unlikely in view of the flatness of the surface of the sea bed. An alternative possibility is suggested by the higher frequency of the ground waves observed at shots A and E, and the presence of very weak high-frequency forerunners on the ground waves of shot B. If a thin layer of the 6·5 km/s velocity material lay at a depth of 1·1 km, followed by lower velocity material, one would expect to get ground waves dying out at increasing range. This is observed in work on land, where limestone bands are found overlying semi-consolidated sediment (Bullard *et al.* 1940).

At station 19, weak higher frequency ground waves are observed, and these die out at the more distant shots. These arrivals from the three nearest shots correspond to a velocity

6·7 (±0·6) km/s, and an intercept of 7·2 s. The more distant shots have only two time-distance points each, so that lines cannot be fitted. The pair of points give velocities 6·34 km/s for the forward shot and 6·82 km/s for the reverse one, the mean being 6·5 km/s. The intercepts are 7·35 and 7·60 s, and the dip (1·5° approx.) is of the right magnitude and direction to give the observed change in intercept. If we interpret these results as due to a thin layer as at station 12, the thin layer will have a cover of about 0·8 km of assumed 2·0 km/s velocity material.

Some second-arrival waves indicate a velocity of 4·2 (±0·2) km/s, with an intercept which suggests that they may be *S*-waves that have travelled in the 8·5 km/s layer. Assuming conversion from *P* to *S* occurs on reaching the main 6·5 km/s layer, the velocity for *S*-waves in this 6·5 km/s layer can be calculated as 3·1 to 3·4 km/s. These values seem quite plausible, but a layer of 3·0 to 4·5 km/s could be present above the 6·5 km/s layer. There are, however, no well-marked reflexions that suggest a subdivision of the thick 2·0 km/s layer of sediment.

Station 13 (figure 11)

This line was intended to lie along the axis of the Marianas trench, and the ground waves were very feeble in such deep water. Uncertain drift of the buoys over unknown, but probably irregular topography makes correction difficult. However, the wind was nearly along the axis of the trench, so that depth errors due to drift may not be too serious.

Fitting a single line to the six reliable ground waves gives a time-distance line whose slope is 0·182 and whose intercept is 15·2 s, corresponding to a velocity of 8·4 (±1·1) km/s. The residuals are of the order of 0·1 s and show a systematic tilt, and the slopes of the separate lines fitted to individual shots are 0·60, 0·25 and 0·51, which are too scattered to be of any use and may imply that some arrivals have been misread. The residuals could be explained by a change in sea depth of 150 fm (0·27 km) between buoys. This is not impossible, since depths of 5320 to 5680 fm (9·73 to 10·39 km) were measured along the seismic line. Four of the six points fit a line corresponding to a velocity of 7·05 km/s, and if the velocity in the overburden is taken as 2·0 km/s, the intercept of 14·55 s corresponds to a sediment thickness of 1·3 km. This thickness increases to 1·9 km if the line through all six points is taken as the correct one.

There is no evidence from reflexions about a possible high-velocity layer above the main refractor because any deep reflexions were obscured by side-echoes, which were prevalent in this area. If a large part of the sediment material had a velocity of 4·3 km/s, as has been assumed for some of the other deep-ocean stations, the main refracting layer could be about 3 km below the sea bed.

Station 14 (figure 11)

A single reverse shot gave a reliable ground wave which lies 0·25 s below the main refraction line. If this misfit is due to a uniform dip, the true slope of the forward line should be reduced and the velocity increased to about 5·6 km/s. However, the three arrivals from forward shot B indicate the opposite tendency and it seems better, therefore, to assign these misfits to irregular depth variations and to take the velocity 5·15 (±0·07) km/s given by the fitted line.

Weak arrivals with a frequency of about 100 c/s are seen on the record of shot B, just before the first reflexions. They are interpreted as ground waves from the surface layer of sediment. The earlier, and weaker ones indicate a velocity of 1·66 km/s, and the later ones 1·68 km/s, and the depth to each of these low-velocity layers is 0·24 km below the sea bed.

A single reflexion was observed from a horizon 0·30 km below the sea bed, assuming 2·0 km/s for the sediment velocity. This value rather than 1·66 to 1·68 km/s is taken to conform with other stations, since the character of the arrivals that give the 1·66 to 1·68 km/s velocity suggests that they came from thin layers on the surface and the error in the calculated depth of these thin layers is large.

It is possible that the reflexion may occur at a change in material, and if we assume 3·0 km/s immediately below the sediment, the depth to the 5·15 km/s layer will be 1·0 km.

Station 15

This station has been described as one of the examples in 'Reduction of Observations' (p. 34).

Station 16 (figure 12)

There was no reverse shot at this station, but examination of the ground waves from separate shots shows no indication of dip in the main refracting layer.

The velocity 4·48 km/s for the intermediate layer is obtained by combining one good first-arrival point with a series of later arrivals which have been identified as double reflexions from the base of the sediment layer. Although this identification is not positive, the clear arrival of the refracted wave at the shortest distance requires a velocity of at least 3·5 km/s. The second point on the time-distance diagram requires that the velocity of any line fitted through the shortest distance point be less than 5·0 km/s.

A reflexion shot made near the end of the line showed no reliable sub-bottom reflexions.

Station 17 (figure 12)

The slope of the time-distance line for first arrival refracted waves for separate shots does not differ systematically from the line fitted to all points together, and therefore, although there were no reverse shots, it is assumed that there is no dip in the main refracting layer.

A reflexion shot at the end of the line showed a fairly clear sub-bottom reflexion at 0·38 s after the reflexion from sea bed. This reflexion cannot come from the top of the main refracting layer, and the depths in table 2 (*b*) have been calculated for an intermediate layer of velocity 4·3 km/s, as for station 8. The velocity could equally well be 3·0 km/s, in which case the depth to the main refracting layer would be decreased by 0·4 km.

Station 20 (figure 12)

The 8 points from two shots on the forward line, give a velocity of 5·75 km/s. The reverse points fit a line of very nearly the same slope, but with a different intercept, indicating that the area under the buoys is on the average, flat, though the large time residuals suggests that the buoys have drifted over irregularities in the sea bed.

The travel times for the various shots show that the sediment cover over the main refracting layer is of variable thickness.

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Station 21 (figure 12)

A peak standing about 0·8 km above the flat sea bed makes the detailed interpretation of this station difficult. However, an unusually large number of shots were fired in both forward and reverse directions. The forward shots suggest irregularities in depth under the shot points and so the mean velocity of 5·64 ($\pm$0·19) km/s for separate shots is taken as that appropriate to the refracting medium beneath the buoys, rather than the velocity 6·17 ($\pm$0·10) km/s obtained from all the forward observations together. The reverse shots

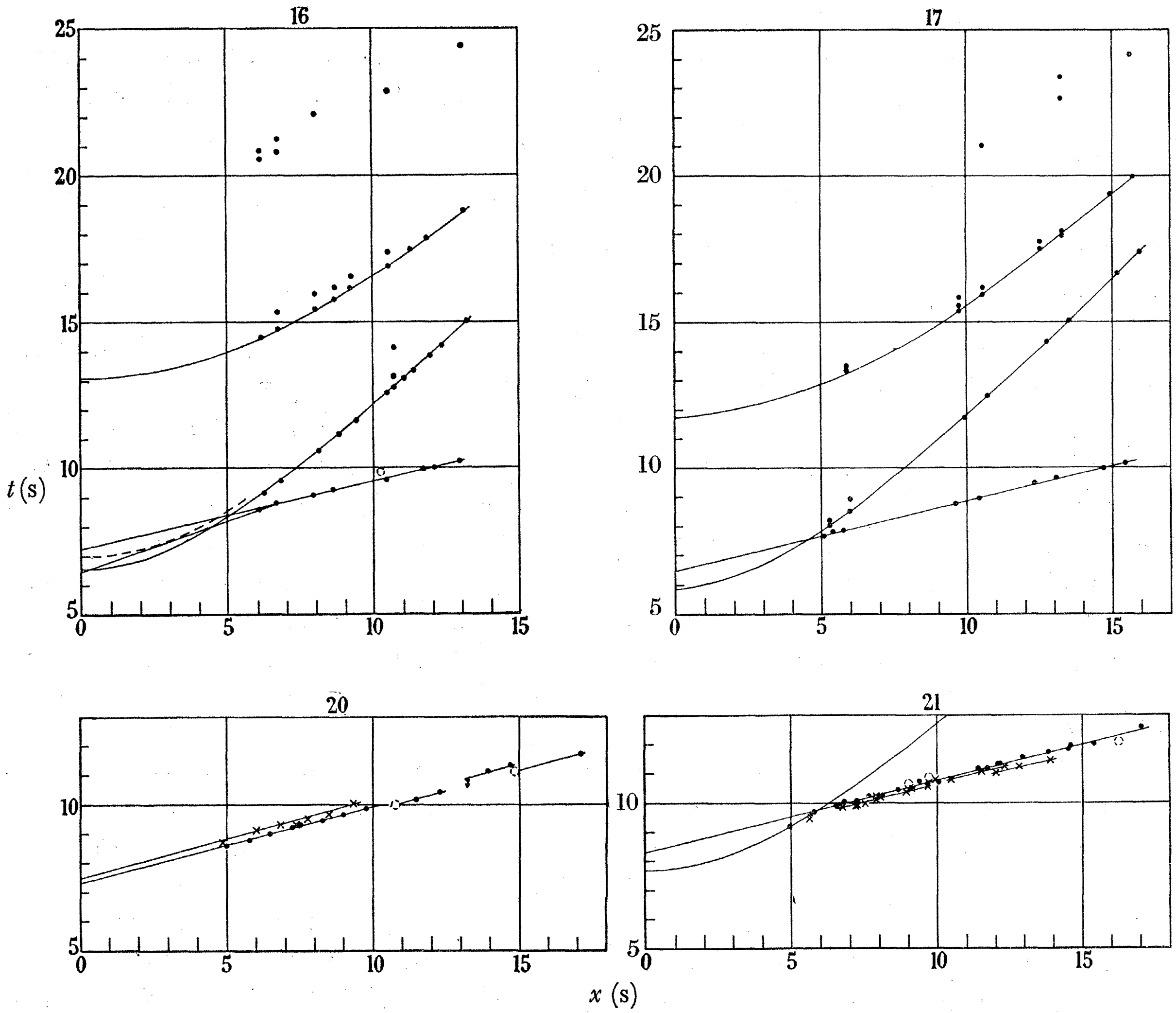

FIGURE 12. Time-distance diagrams for Pacific (stations 16, 17, 20, 21). ●, forward; ×, reverse shots; ○, doubtful observations; ⧭, arrival may be earlier.

taken separately give 5·77 ($\pm$0·02) km/s which with the forward shot value of 5·64 km/s, yields 5·70 km/s as the true velocity in the main refractor. In correcting the ground waves from the reverse shots, it has been assumed that the peak is composed of material in which the velocity is 4·0 km/s, with the 5·70 km/s velocity continuing underneath it. This seems more plausible than assuming a uniformly thick sediment layer over the peak, but the peak could be composed of material with the higher velocity. However, the method chosen to correct for depth variation has little effect on the result. The intercepts of time-distance lines corresponding to the true velocity, through the points from each shot are (running from left for K to right for E in the appropriate section of figure 15; the buoys in the centre):

reverse	K	J		I	L		H
	7·77	7·47		7·03	7·97		8·05
and forward	A	G	B	F	C	D	E
	8·12	8·18	8·07	8·02	8·06	8·03	7·91 s

If only unconsolidated sediment cover is present (2·0 km/s) its average thickness would be about 0·7 km. If the 5·70 km/s layer comes near the surface of the sea bed under the peak, there would have to be a concentration of 1·4 km of sediment under the buoys and consequently very little under the distant shots. This gives a possible picture, but more probably the peak is composed of some intermediate velocity material. For an extreme view a velocity of 4·0 km/s will allow zero sediment and 1·9 km of 4·0 km/s at the peak, and 0·4 km of sediment and 0·9 km of 4·0 km/s material under the buoys. Since the peak is about 0·75 km above sea bed, this makes the 5·70 km/s layer approximately level below the buoys, as indicated by the similarity of forward and reverse velocities. The 4·0 km/s layer may extend away from the peak, or it may peter out and all the material covering the 5·70 km/s layer under the forward shots may be unconsolidated sediment. The absence of first-arrival refracted waves from a 4·0 km/s layer does not give stringent limits to depth or thickness. The intercepts for the extreme shots (K and E) suggest that the 5·70 km/s layer comes nearer the surface as the distance from the peak increases, and the cover could equally well be 0·4 to 0·5 of 2·0 km/s sediment or a total of 0·6 to 0·8 km of sediment plus 4·0 km/s material.

Coral atolls

The results obtained at the atolls of Funafuti and Nukufetau have already been published (Gaskell & Swallow 1953). For convenience in comparing them with the rest of the Pacific work described here, a table of the thicknesses and velocities found is given in metric units, below.

(*a*) Funafuti:

Surface layer, known to be coral 1·75 ($\pm$0·06) km/s, 0·12 km thick.

Second layer, probably coral 2·43 ($\pm$0·02) km/s, 0·43 km thick.

These are followed by 3·11 ($\pm$0·15) km/s, 0·2 km (thinning); 3·51 ($\pm$0·15) km/s, 0·2 km (thinning); 3·96 ($\pm$0·24) km/s, 2·7 km thick and the deepest layer has a velocity 6·7 ($\pm$0·6) km/s. The total depth to this layer is about 3·7 km, but no reverse points were obtained on the highest velocity line, and since there is evidence of dip (probably not uniform) the estimate of velocity is uncertain.

(*b*) Nukufetau:

Surface layer, known to be coral 1·76 ($\pm$0·02) km/s, 0·11 km thick.

Second layer, probably coral 2·28 ($\pm$0·09) km/s, 0·66 km thick.

This followed by a layer of 4·67 ($\pm$0·13) km/s, 1·4–1·5 km thick in the centre of the atoll, but dipping downwards at both edges. The fitted velocity in the deepest layer is 5·58 km/s, but this is almost certainly in error due to unknown dip.

From the steep dips found in the 3·96 and 4·67 km/s layers at the two atolls, it is suggested that they are the upper parts of volcanic cones, and are probably composed of vesicular rock of low density. The profiles suggested by the seismic results are shown in figure 13.

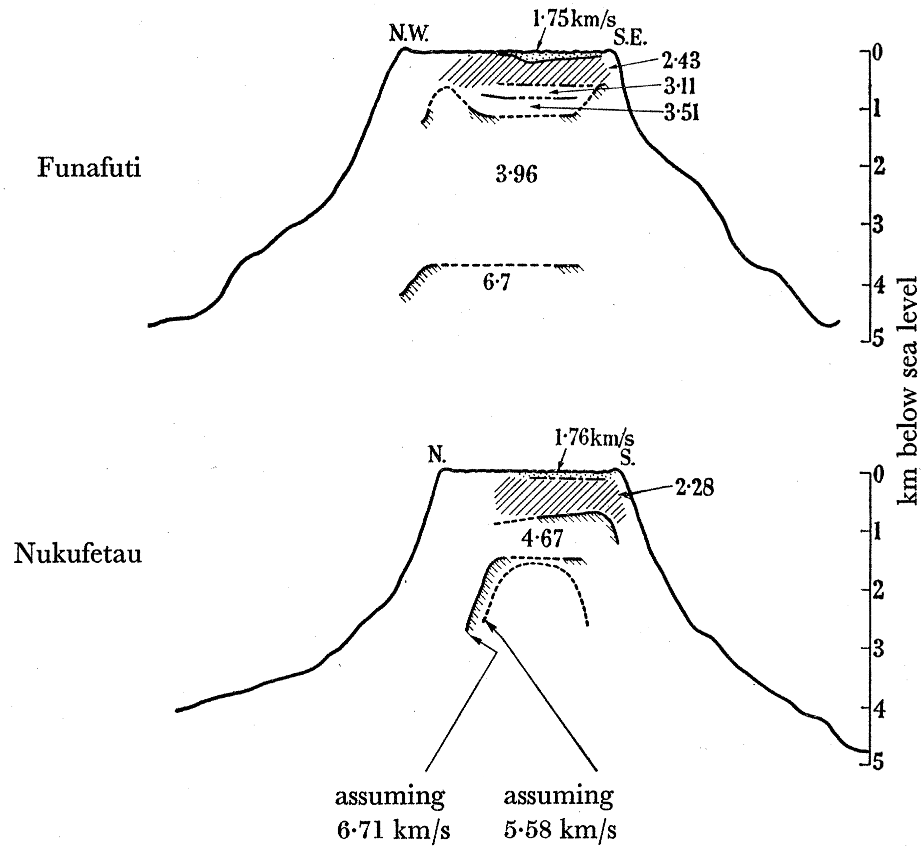

FIGURE 13. Section through Funafuti and Nukufetau atolls (vertical scale is five times horizontal).

Ominato (figure 14)

Three good days' shooting were obtained with the buoys anchored in two positions A and B, indicated in figure 14. A few early arrivals indicate a surface layer in which the velocity is 1·87 ($\pm$0·02) km/s. The main arrivals lie on time-distance lines of varying slopes, but the results from reverse shots and different buoy positions suggest that these all belong to the same refractor. Combining the slopes of lines obtained on two separate occasions a mean slope of 0·231 ($\pm$0·007) is obtained, which gives a velocity of 6·33 ($\pm$0·19) km/s and a strong dip (6·5°) under the position of the buoys. From the shots in both directions on a later date, the mean slope is 0·250 ($\pm$0·007) and the velocity 5·85 ($\pm$0·17) km/s, with a dip of 2·7°.

The first estimate of the high velocity is based on more degrees of freedom (11 forward + 3 reverse, against 10 forward and 1 reverse), but the buoys were in a more irregular area and the assumption of a uniform dip in the vicinity of the buoys is probably less valid. It seems unlikely that there would be a real variation of velocity in a given layer, over such a short distance, though this is possible. The profile shown in figure 14 (*b*) has been calculated using the mean velocity of 6·10 km/s and assuming that all the overlying material has the 1·87 km/s velocity given by the short-range shots. Having two buoy positions along the line enables the thicknesses to be determined without ambiguity, and the two separate days' shots in the southern half of the area show a rise in the basement layer to a depth of 1·1 km compared to the 2·1 km observed in the north. It is possible that this rise may be composed of material in which the velocity is intermediate between 1·87 and 6·1 km/s. Without putting the buoys directly over this area and making close shots, one cannot decide about this.

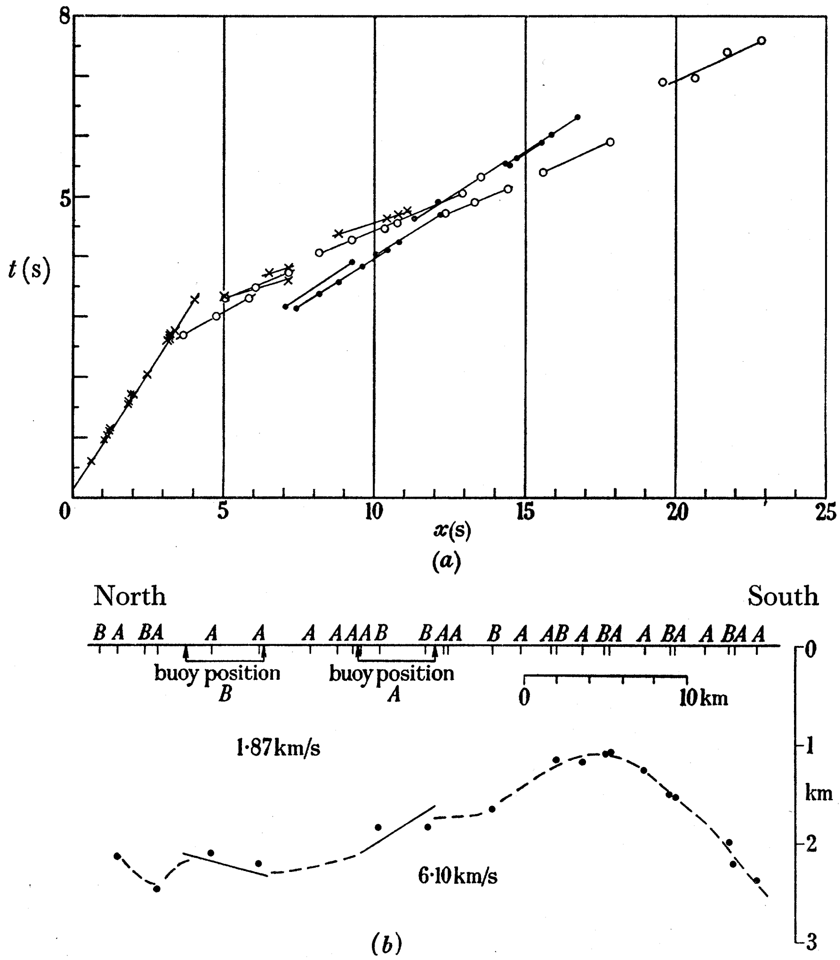

FIGURE 14. Ominato. The letters by the shot positions indicate whether the shots were made with the buoys in position *A* or *B*. Profile ——, definite; – – –, most probable. Time-distance diagram. ●, ×, buoys in position *A*; ○, buoys in position *B*.

Interpretation of Pacific results

The sections shown in figure 15 summarize the information obtained in the Pacific. Referring to the chart of station positions given in figure 1, it can be seen that the structures found are related to the kind of oceanic area in which the stations lie. Thus stations 8, 9, 11, 16 and 17 all lie in deep water of 2400 to 2900 fm (4·4 to 5·3 km) on the oceanic side of the andesite line, and show similar structures. They are similar also to the three western Atlantic stations already described, and this structure may well be regarded as typical of the deep ocean basins. On the other hand, stations 14 and 15 both show a much lower velocity in the deepest layer detected, and both are located on extensive banks with depths

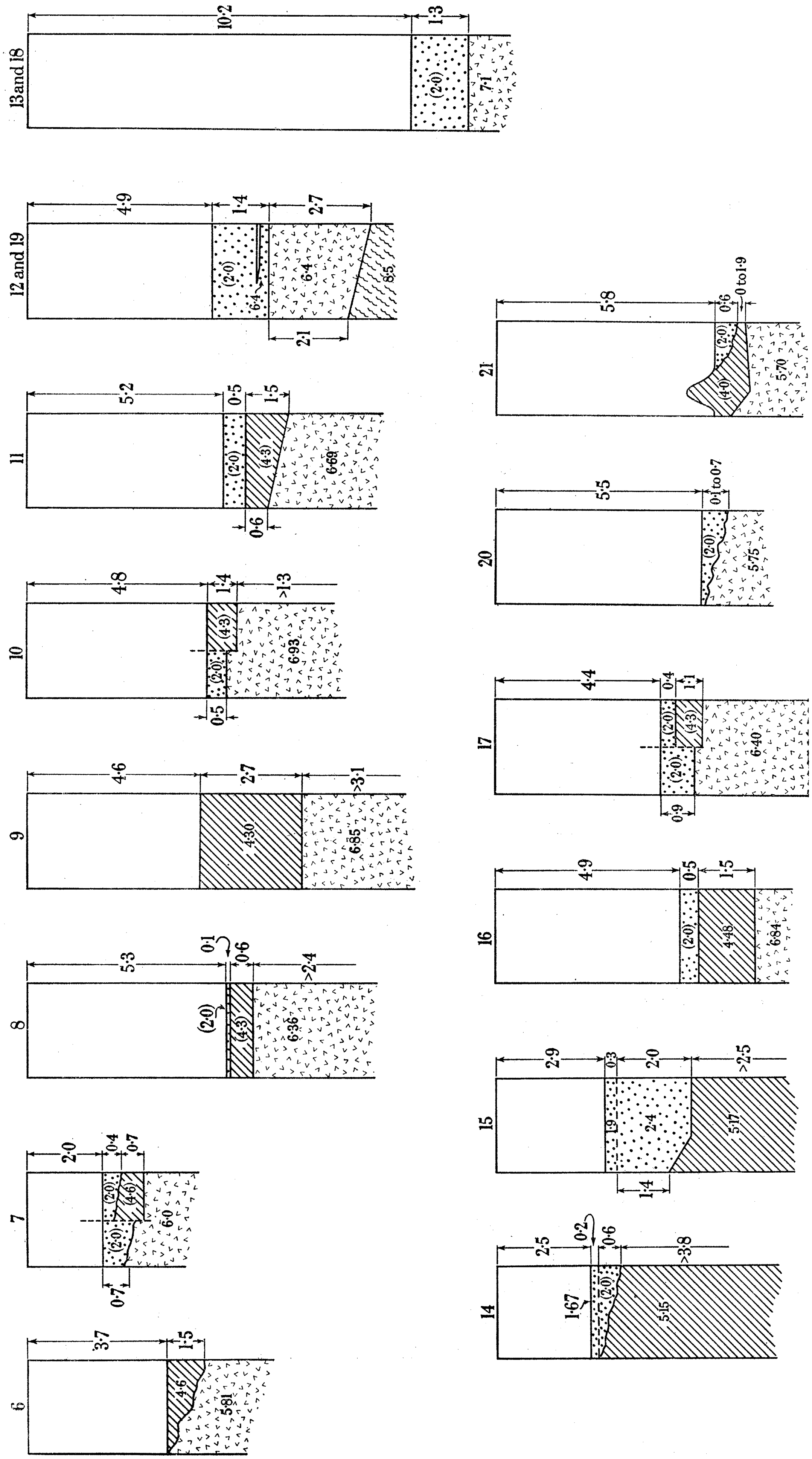

Figure 15. Sections for Pacific stations. (Thicknesses in km; velocities in km/s; assumed velocities in brackets.)

of about 1500 fm (2·6 km). Stations 20 and 21, in the Philippine Sea, both show layers with velocities of about 5·7 km/s, which is appreciably less than that in the first groups although the water is deeper (about 3000 fm or 5·2 km). Similar velocities are observed at stations 6 and 7, but their nearness to the American coast makes it natural to associate them with the continental structure.

The remaining stations 12 and 19, and 13, may also belong to the 'deep ocean basin' group, though they show some different features. At 12 and 19, a layer with a velocity in it of 8·5 ($\pm$0·5) km/s comes nearer the surface than at other places. It should have been detected, if present at a similar depth, at stations 9 and 11. At station 13, the basement velocity is uncertain, but probably belongs to the deep ocean group. A second layer of cover material, in which the velocity was from 4 to 5 km/s, could be present beneath the sediment at any of these stations.

(*a*) *Deep ocean stations* (8, 9, 10, 11, 16, 17, 12, 19 and 13). In this groups of stations, layers in which the velocity is 6·36 to 6·93 km/s are found at depths of 0·7 to 2·7 km below the sea floor. They differ markedly from continental results in showing such a high velocity so near the surface, and it seems fair to regard them as typical of the deep ocean.

None of the stations in this group give direct evidence from ground waves of an unconsolidated sediment layer, though its presence is known from coring and is inferred at some stations from sub-bottom reflexions. The reflexions, as in the Atlantic work, have been associated with the interface between the unconsolidated sediment and a layer with compressional velocity 4·5 to 6·0 km/s, though no direct evidence supporting this has been obtained from Pacific stations. The sediment thicknesses are slightly less than those in the Atlantic, and at three of the stations (8, 9 and 10) the probable thickness is very small. At station 9, where the refracted wave arrivals gave a definite indication of a 4·3 km/s layer near the surface, no sub-bottom reflexions were recorded; at stations 8 and 10 the sediment thickness is determined by reflexion. Station 16 is the only other location where ground waves indicate a layer in the velocity range 4·5 to 6·0 km/s, and here there are some reflexions which could fit the refracted wave evidence. Since station 16 is near the coral atoll of Funafuti, which we suppose to be a structure based on a volcanic cone, and as station 9 is situated between the islands of Kauai and Nihoa in the Hawaiian archipelago, it seems likely that for these two stations the 4·5 to 6·0 km/s layers observed are related to volcanic activity. However, it is not likely that this layer can everywhere be attributed to volcanism, and it may be a cemented or metamorphosed form of sediment. The velocity in it, where not observed directly, could not have exceeded 4·3 km/s, without giving first-arrival ground waves; and this value has been adopted in table 2(*b*) for computing the thicknesses of the various rock layers. Stations such as 8, 10, 11 and 17, where the 4·3 km/s velocity is assumed, are remote from islands or sea-mounts and should perhaps be distinquished from stations 9 and 16, where refracted wave evidence of a 4·3 to 4·5 km/s layer and proximity to volcanic manifestation go together. In the flat ocean areas it is not certain that there would be volcanic outpouring, but it is possible that altered sediment could be present. The seismic evidence, based on sub-bottom reflexions and on *S*-waves, is not very definite, and in stations 10, 11 and 17, the effect of interpreting most of the 'sediment travel time' as 4·3 to 4·5 km/s material produces vertical profiles very similar to that at station 16. This is because there are no means of determining whether the 0·5 km of sediment at station 16 should be subdivided or not, whereas at station 10 an equal 0·5 km of 2·0 km/s sediment could be interpreted as 1·4 km of 4·3 km/s rock on the evidence of sub-bottom reflexions. A direct comparison of the definite seismic evidence, that given by first-arrival waves from the 6·36 to 6·93 km/s layer, demonstrates that stations 16 and 10 differ considerably in intercept for the main refractor, and it would be misleading to make the cover thicknesses almost equal by applying different methods of subdivision of the sediment in the two cases. However, the seismic results on their own are not adequate to decide whether the differences between stations 8, 10, 11, 17 on the one hand and 9 and 16 on the other, are of degree only, or are real changes of character in the structure of the sea floor. More stations of both types, and more detailed following of the 6·7 km/s layer from island or atoll to deep flat ocean basin are desirable.

The velocities in the basement layer are in the range observed in samples of basic igneous rocks, and it is natural to interpret the layer as such. Other rocks are known, such as hard limestones, with velocities in this range, but they would be unlikely to show the uniformity of both velocity and distribution shown by this layer.

At stations 12 and 19 only, a still deeper layer was observed. Although the velocity determination, 8·5 ($\pm$0·5) km/s, is not very precise, there is no doubt that it is much higher than that of the 6·7 km/s layer and it probably indicates the layer below the Mohorovičić discontinuity. Raitt (1956) found this layer at from 5 to 10 km below the sea floor at several stations in the Pacific, whereas at stations 12 and 19 the depth is only about 4 km. This may be a peculiar feature of the area in which the stations lie, just inside the arc of the Marianas trench and separated from it by the southern end of the South Honshu ridge.

(*b*) *Stations on banks* (14, 15). These two stations are characterized by the presence of a thick layer in which the velocity is about 5·2 km/s. It might be thought possible to relate this to the second layer of the deep-ocean stations, but the velocity seems to be appreciably higher, and the thickness considerably greater. Both are situated to the continental side of the andesite line (Macdonald 1949), and possibly the different velocity is associated with this fact. The andesite line marks a geological boundary, on the continental side of which acid lavas are found, whereas to the oceanic side more basic volcanics predominate. However, the velocities found in samples of the two groups of volcanic rocks are too variable to allow any definite conclusions to be drawn.

The great thickness of the low-velocity material at station 15 is unusual; probably it is a layer of semi-consolidated sediment. The 5·2 km/s layer could well be a sedimentary rock. This would agree with geological ideas of the extent of the ancient Melanesian Continent (see, for example, Ladd 1934).

(*c*) *Philippine sea stations* (20, 21). This area is unusual in that its average depth is greater than that of the North Pacific basin, although it lies on the continental side of the andesite line. The basement velocity of 5·7 km/s found at the two stations in this area could belong to an acid igneous rock. Unfortunately, the thickness of this layer was not measured, but if the velocity in the next layer is 6·7 km/s, the minimum thickness of the 5·7 km/s material is 2·8 km.

Stations 12 and 19, which have been included with the deep-ocean stations on the basis of their 6·4 km/s velocity, also lie in deep water inside the andesite line. This makes the geological interpretation of the velocities less certain, though it could be argued that, since the andesite line is interpolated between isolated groups of islands, it may be incorrectly placed in some deep-water areas such as the Marianas trench. It is possible that the seismic method may be useful both in drawing a new andesite line and in throwing more light on the reason for the existence of the deep ocean trenches. Taking the seismic results as interpreted here, it seems that the deep trenches are formed from the floor of the deep-ocean basin rather than from the more acidic basement material which covers the intermediate zone between oceans and continents. This, however, poses the question of the structure of the Philippine trench.

(*d*) *American coast stations* (6, 7). The water was much shallower at these two stations than in the deep oceans and the basement velocities of 5·8 and 6·0 km/s obtained here are well within the range of typical continental rocks at similar depths and are appreciably lower than the values found in the deep ocean. The small probable thickness of unconsolidated sediment, so near land, seems remarkable. These results are consistent with the much more extensive work of Shor and Raitt (1956) in this area.

(C) *The Indian Ocean*

The Indian Ocean measurements were made during a 6-week period in 1952 (Gaskell & Swallow 1953). The track of the ship and the positions of seismic stations are shown in figure 1. In addition to the deep-water stations 22 to 26, a shallow-water line was shot off the island of Mahé in the Seychelles.

Tables 1 (*c*) and 2 (*c*) give summaries of the operational information and figure 16 the travel-time results.

Station 22 (figure 16)

The main time-distance line shows irregular misfits of the lines from separate shots, and the velocity given in table 2 (*c*) has been taken from a mean 6·78 ($\pm$0·27) km/s for parallel lines fitted to separate forward shots, and 6·61 ($\pm$0·11) km/s for the reverse line. Some irregularities between individual shots are expected because of the changes in water depth along the line. The agreement of forward and reverse velocities suggests that the main refracting layer is fairly flat beneath the buoys. The depth of sediment above the 6·70 km/s basement layer varies from 0·3 to 0·8 km.

There are no readable sub-bottom reflexions or *S*-waves to indicate the existence of an intermediate layer such as were found at station 8 in the Pacific. However, a layer about 0·8 km thick could be interposed between 0·4 km of sediment and the main refractor (6·70 km/s) without being observable from first-arrival waves.

Station 23 (figure 16)

The main refracting layer velocity of 5·09 km/s is obtained from a mean of forward and reverse readings. Some good second-arrival waves give a measure of sediment velocity of 1·86 km/s. This is one of the very few such determinations that have been possible in all the work.

There is some indication that sediment thickness varies from 0·6 km on the forward direction to 0·4 km on the reverse side, but the most distant reliable ground wave lies 0·36 s below the time-distance line fitted to earlier ground waves. This could indicate a sudden decrease to nearly zero thickness of the sediment layer, but the topography is very flat, and it is more probable that this distant observation is a refracted wave from a layer beneath the 5·09 km/s refractor. A minimum velocity of 7·1 km/s, giving a thickness of 2·9 km for the 5·09 km/s layer is obtained by fitting the distant reading with the neighbouring one. If the fitted velocity is 6·7 km/s, as observed at station 22, there would be 2·5 km of 5·09 km/s material, without much misfit of observations.

Station 24 (figure 16)

This station is located on a large flat-topped sea-mount. Only three sounding traverses were made across this sea-mount, so that its extent is not fully known. The buoys were placed approximately at the centre of one traverse in about 1600 fm (2·9 km) of water.

Four first-arrival refracted waves give a forward velocity of 3·92 ($\pm$0·09) km/s. The reverse points are three in number but two nearly coincide because of irregular drift of buoys. A velocity of 4·85 km/s is indicated but the accuracy cannot be estimated properly. A number of strong late arrivals can be read after the second reflexion from the sea bed, and as some of them are followed by another at approximately equal spacing, they are interpreted as having been reflected once from the sea-bed and once from a deeper layer. Plotting t^2–x^2 against x^2 for these points (see p. 29) leads to approximate estimates of thickness and velocity of 0·46 km and 2·1 km/s. The curve calculated for single reflexions at the deep layer based on these figures nearly touches the line through the forward ground-wave arrivals. This may be taken to indicate that the ground waves are from the same layer as gives the deep reflexions, and also that, after correcting the arrivals in the manner adopted at this station (i.e. with the deep layer assumed to follow the observed topography) the layering is approximately flat. If there was a downward dip along the line, the ground-wave points would give a line passing below the reflexion curve; one refracted wave arrival suggests the need for a higher velocity layer beneath the 3·9 km/s material, and a probable velocity of 6·7 km/s gives a thickness of 2·0–2·7 km for the 3·9 km/s layer.

Station 25 (figure 16)

The main refractor has a velocity of 6·74 km/s based on combined forward and reverse points together, since good observations are few in number. Three arrivals give a value of 5·09 km/s for a layer above the main refractor, and this layer, which is 1·1 km thick, is covered by 1·1 km of 2·0 km/s velocity sediment. Some later arrivals indicate a velocity of 2·44 km/s, and may correspond to refracted waves from a subdivision of the sediment layer. If this is so, the vertical profile will be altered very little from that given in table 2 (*c*).

Station 26 (figure 16)

The main refracted wave time-distance line is based on four readings in one direction only, since the background noise due to heavy swell was high as at all the Indian Ocean stations. Some second-arrivals indicate a layer with velocity 2·27 km/s situated very near the surface. Other possible time-distance lines indicated by second-arrivals, give velocities of 2·7 and 4·4 km/s and the thicknesses in table 2 (*c*) are based on these lines. Whatever interpretation of the results is taken, a large thickness of semi-consolidated material is found to be present.

Seychelles (figure 16)

Short distance measurements were made to determine surface velocities in the local granite rocks. The arrivals beyond 0·1 s indicate a high velocity, and the observations fall into two groups giving velocities 5·58 ($\pm$0·08) km/s and 6·02 ($\pm$0·06) km/s. Some close-

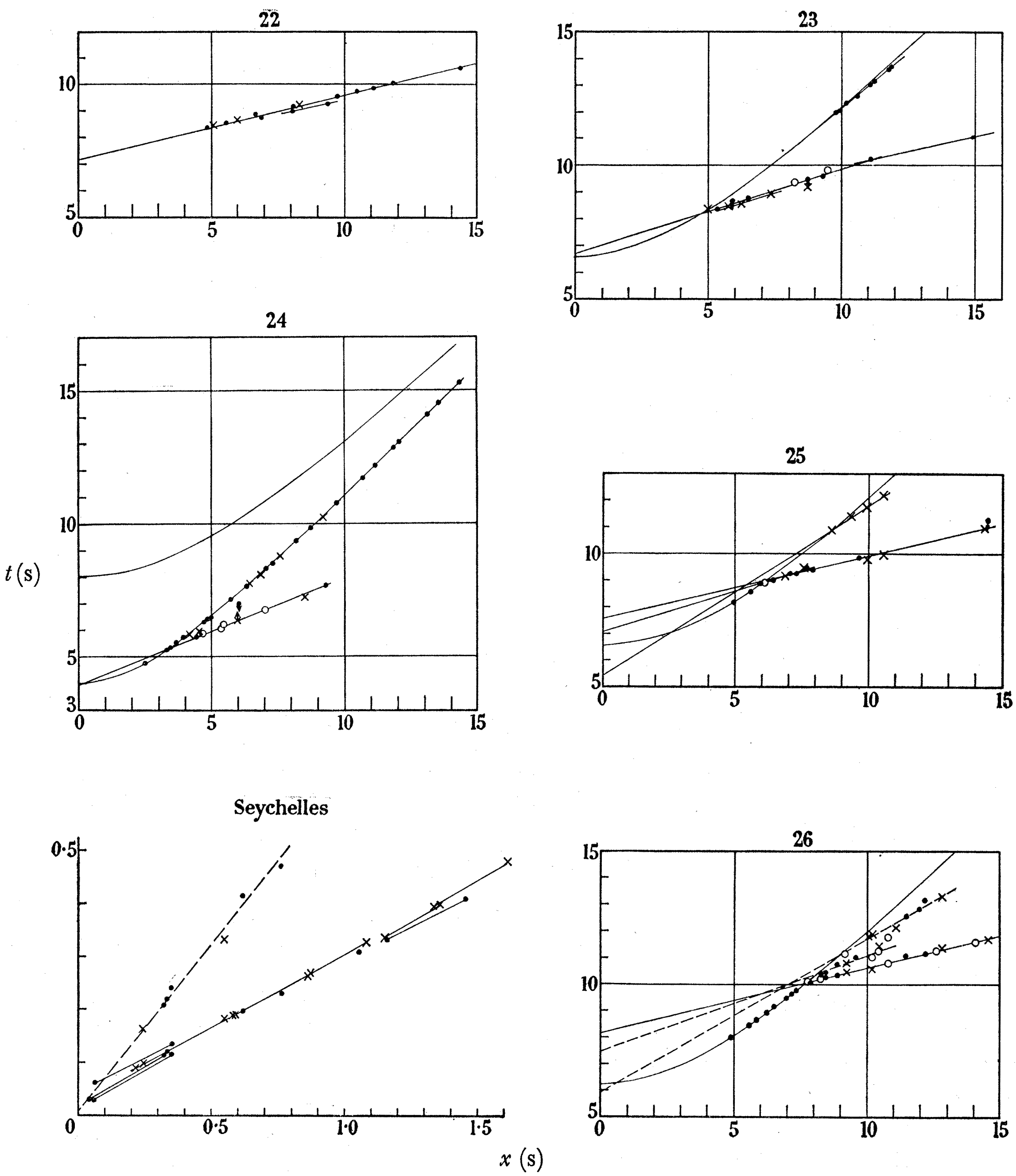

FIGURE 16. Time-distance diagrams for Indian Ocean. Stations 22, 23, 24, 25, 26 and Seychelles. ●, forward; ×, reverse shots; ○, doubtful observations; ⥿ (↕) arrival may be earlier (later).

range points and longer range second-arrivals show a considerable scatter about a line indicating a velocity between 2·1 and 2·7 km/s. Taking 2·4 km/s as a mean value, the depth to the 5·58 km/s layer is 0·023 km, and the thickness of the 5·58 km/s layer is 0·13 km.

The higher velocity of 6·02 km/s is reached within 0·15 km depth and is to be identified with granite. The few hundred feet of 5·58 km/s is also probably granite, because the latter outcrops within a mile or two of each side of the line.

Interpretation of Indian Ocean results

The four deep-water stations show (figure 17) structures similar to the Pacific deep-ocean type, though with some widening of the range of basement velocity. This may be partly due to the increased uncertainty of the time measurements caused by the poor weather conditions. The probable sediment thicknesses at stations 25 and 26 are greater than at other deep ocean stations. Both stations were on a vast plain, sloping upwards to the north, and extending about 1100 km, almost to Ceylon. The velocity of 5·09 km/s observed twice for the second layer is higher than was found in the Pacific in deep water,

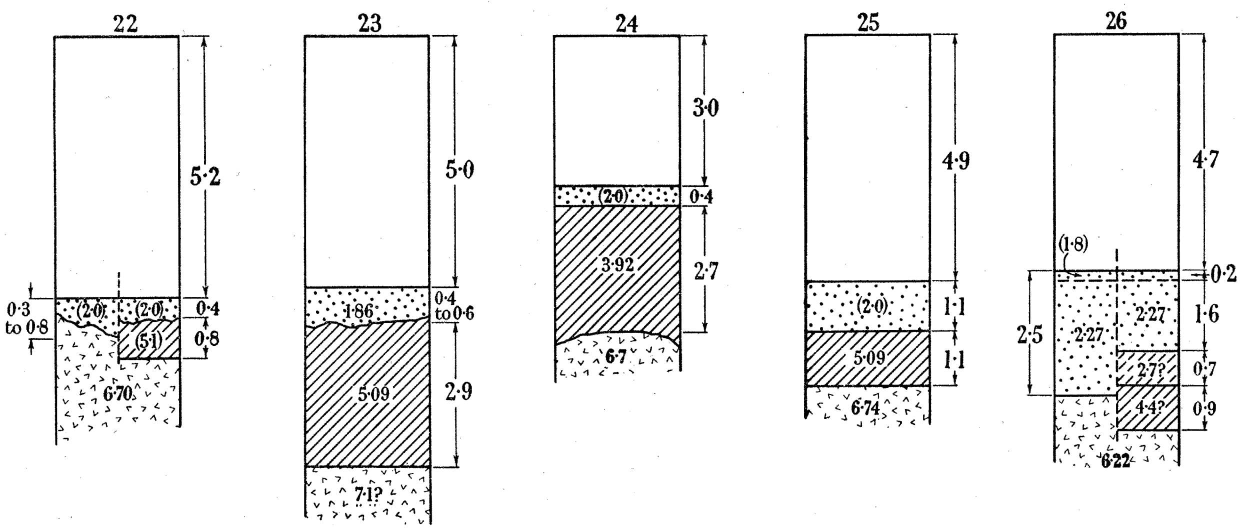

FIGURE 17. Sections for Indian Ocean stations. (Thicknesses in km; velocities in km/s; assumed velocities in brackets.)

though it may still be taken to indicate the same types of rock (volcanic rock or lithified sediments). The great thickness of this layer at station 23 may be an indication of a neighbouring sea-mount. The differences in depth to the 6·7 km/s layer at stations 22 and 23 are similar to the differences between the two groups of deep-water stations in the Pacific, and this may be in both cases a reflexion of the effect of nearby volcanic outpourings.

The second layer at station 24, on the top of a sea-mount, could very well be volcanic rock. It is clearly quite different material from that of the Seychelles bank, where 6·02 km/s was measured. This latter velocity is near the upper limit of the range usually associated with granite, but the identification of it is not doubted. Possibly the 6·22 km/s observed in the deepest layer at station 26 could be a similar granite, with the velocity raised slightly by the extra pressure of 7 km of water and sediment. It seems unlikely, however, that the 6·7 km/s layers at stations 22 and 25 could be accounted for in this way. More probably they represent a basic rock as in the Pacific and the western Atlantic.

(D) *The Mediterranean*

The measurements, made in 1952, consist of three deep-water stations, two stations near Cyprus, and three stations near Malta (Gaskell & Swallow 1953 *b*). The station positions were chosen to be of use in the interpretation of gravity measurements in the Mediterranean (Cooper, Harrison & Willmore 1952).

The track of the ship and location of stations are shown in figure 18 and details and summary of results are in tables 1 (*d*) and 2 (*d*) and figure 23. Time-distance diagrams are given in figures 19, 21 and 22.

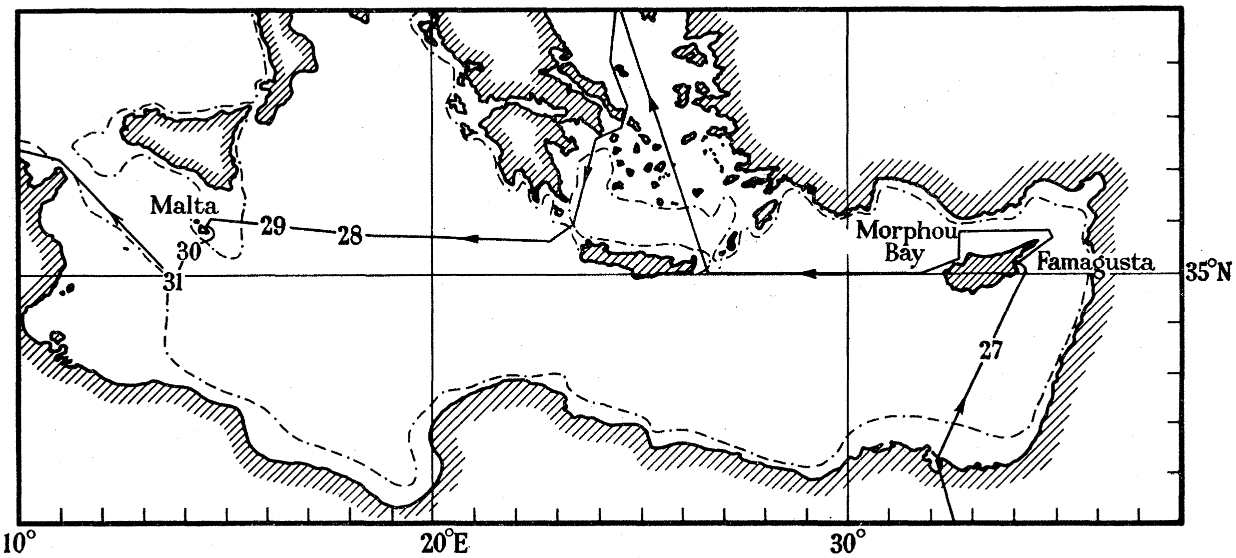

FIGURE 18. Location of stations in the Mediterranean, with 100 fm contour and ship's track.

Station 27

This has been described in detail in the section on 'Reduction of observations' (p. 37).

Station 28 (figure 19)

The results at this station are similar to those at station 27. The velocities calculated from forward and reverse observations are nearly equal, and the three reverse points indicate a slight deepening of the refracting layer under the shot points rather than a slope of the layer underneath the buoys. Good reflexions allow an average velocity of 2·1 km/s to be calculated for the upper layers, and give a thickness that agrees with the value obtained from the ground-wave readings. It is probable that the upper sediment layers have a velocity of about 1·7 km/s, and the reflexion measurements will allow either layers of uniform velocity, or a continuous gradient of velocity.

Station 29 (figure 19)

Only five reliable ground waves were recorded, and they show some variation of intercept with shot. A single line through these points gives the velocity of 4·30 km/s, and the structure is, therefore, similar to that found at stations 27 and 28.

Station 30 (figure 19)

The ground waves show irregular changes of intercept with shot position, and the absence of good quality reverse points makes it difficult to estimate the velocity. The slope of the line fitted to all the observations from the three closest shots agrees with the mean slope from all shots taken separately, and it is probable that this will give the true value of the velocity. If there was a dip under the buoys, it would have to reverse its direction under the first three shots to give the same straight line for all their arrivals.

Assuming that there is a single layer of 2·1 km/s covering the main 5·63 km/s layer, its thickness would be 0·7 km under the buoys and the first three shots, varying from 0·5 to 1·5 km along the rest of the line. Such variations seem very large for a single uniform layer, and the presence of deep reflexions, and two second-arrival ground waves, make the existence of a second layer probable. A line showing 3·49 km/s velocity, as found at Malta, would fit the second arrivals, and the results in table 2 (*d*) are based on this interpretation. The observed variations in intercepts may be due to variations in depth to the 3·49 km/s layer, or to the deep layer, and these cannot be separated with the present observations.

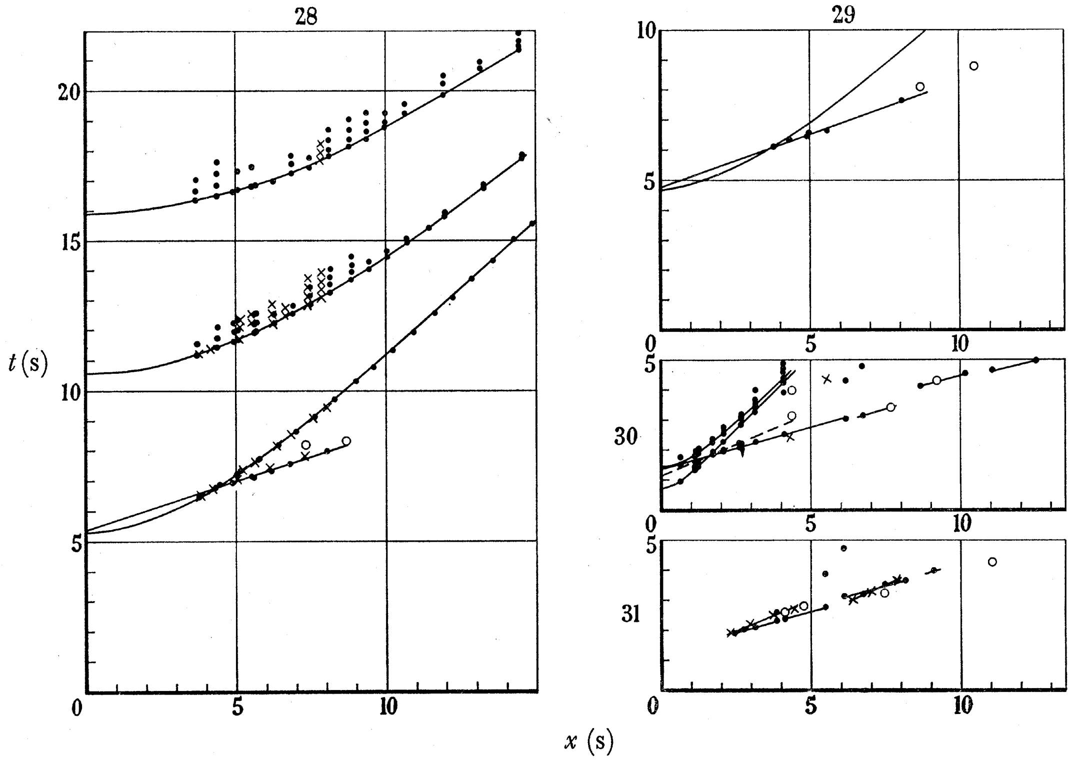

FIGURE 19. Time-distance diagrams for Mediterranean (stations 28, 29, 30, 31). ●, forward; ×, reverse shots; ○, doubtful observations.

Station 31 (figure 19)

The ground waves show irregular variations of intercept with shot point, and there is a considerable difference in the velocities calculated from forward (4·93 km/s) and reverse shots (3·76 km/s). If it is assumed that the buoys have not drifted, and that the dip in the region around the buoys position is uniform, the true velocity will be 4·26 km/s. Alternatively, the buoys may have drifted between making the forward shots and the reverse ones, and it may be better to take them separately. A single line through all the forward shots gives a velocity of 4·85 km/s which differs only slightly from that calculated from a series of parallel lines, indicating a small mean dip along the line. The two reverse shots considered separately show a mean velocity, from arrivals at a single buoy for the two shots, of 5·66 km/s and combining this with the 3·76 km/s for single shots, indicates a true velocity of 4·50 km/s for a uniform dip of 6° under reverse shots and buoys. It is possible for the offset distance for the refracted wave paths to give an apparent slope under the buoys from one direction and not from the other, or the buoys may have drifted. Whatever assumptions are adopted, there are large depth variations along the line, in the layer giving the ground waves. These variations are a minimum when the harmonic mean velocity from forward and reverse shots (4.26 km/s) is assumed. In this case the dip under the buoys is 4°, and the most likely profile is shown in figure 20, with the depth limits given in Table 2 (*d*).

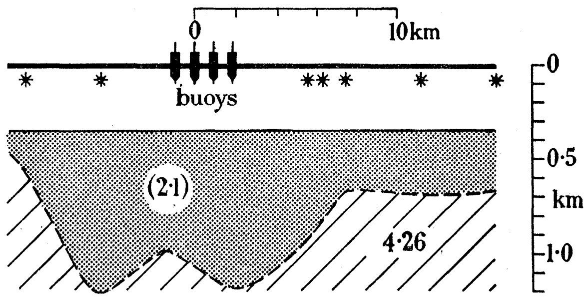

FIGURE 20. Profile and shot positions for station 31. *, shot points.

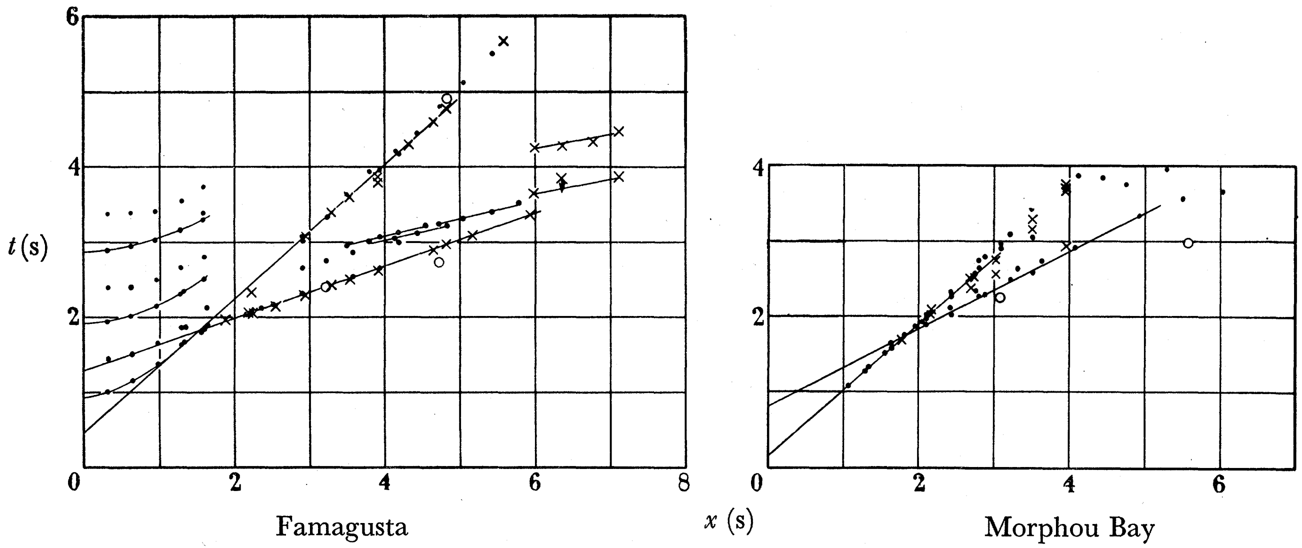

FIGURE 21. Time-distance diagrams for Famagusta and Morphou Bay. ●, forward; ×, reverse shots; ○, doubtful observations; ↕, arrival may be earlier.

Famagusta (figure 21)

Nine forward and eight reverse observations give the 4·40 km/s velocity for the intermediate layer in table 2 (*d*). At a distance to the south corresponding to water travel time of about 3 to 4 s. the 4·40 km/s arrivals change frequency from 20 to 40 c/s and become rapidly weaker with increasing distance. Arrivals from a deeper layer begin to come in, with a discontinuity in the time-distance diagram, (figure 21). This suggests a small thickness for the 4·40 km/s layer (Bullard *et al.* 1940). The 4·40 km/s refracted wave persists to much greater distances to the north, showing that the layer is thicker in the reverse direction, and no frequency change is noted. At the most distant northern shot, however, there is a discontinuous change into a higher-velocity line.

The 6·7 km/s velocity is obtained by combining results from one northern and two southern pairs of arrivals. The mean value agrees with that for a single line through the southern points, suggesting that the value is near the true one.

Some good second-arrivals show a velocity of 1·77 km/s for the upper layer of sediment, and fitting reflexion curves to the deep reflexion observations assuming different velocities, indicates an average velocity of 2·0 km/s.

If the 4·40 km/s layer continued right down to the 6·7 km/s layer its average thickness would be 2·4 km with a 2° dip down to the north. However, the die-out of energy in the refracted waves suggests a layer of the order of 0·1 km only in thickness, and the values in table 2 (*d*) have been calculated on this assumption, with a layer of 2·4 km/s material below the thin 4·40 km/s layer.

Morphou bay (figure 21)

The water depths varied from 75 to 120 fm (0·14 to 0·22 km) along the line. Ten ground-wave arrivals establish the 1·83 km/s velocity, but beyond a distance corresponding to 2·2 s water travel time the arrivals are scattered and there is a considerable difference between southward and northward shots. From the southward points a velocity of 2·96 km/s is obtained, and the northward points are scattered above this line, indicating a dip of this 2·96 km/s layer towards the north. The absence of any systematic trend in the residuals for the 2·96 km/s line shows, however, that the dip under the buoys is probably small. Two distant arrivals suggest that a higher-velocity layer, which could have a value of 4 km/s, exists below 1·1 km of the 2·96 km/s layer in the south. To the north the 2·96 km/s layer, on this interpretation, thins to 0·3 km. If 6·7 km/s was assumed for the lower layer instead of 4 km/s, the thickness of the 2·96 km/s layer would be 2·2 to 2·0 km. From the known presence of pillow lavas on the south coast of the bay it seems that the first assumption is more likely, in both velocity and depth variation.

Malta (figure 22)

The velocity in table 2 (*d*) of 3·49 km/s is from six forward and one reverse shots to a single buoy. The reverse shot indicates a small slope of 1°, but the assumption of a uniform slope along the line to explain the misfit of the reverse point from the line through the forward ones does not make a great deal of difference to the results. The 1·68 km/s velocity is calculated from five clear second-arrival waves, and from the intercept of the line through these points the layer must be on or just below the sea bed. The depth in table 2 (*d*) is calculated assuming an average upper layer velocity of 1·8 km/s. If the velocity in the layer below the 3·49 km/s material is 5·6 km/s, as observed at station 30, the thickness of the 3·49 km/s layer must be at least 0·7 km.

Interpretation of Mediterranean results

Velocity measurements have been made by Dr A. S. Laughton on rock samples collected in Malta, and from these results (figure 23) the deeper layers at the station north of Malta, and at stations 30 and 31 to the south, could be identified as limestones, though the 3·49 km/s layer north of Malta may be a calcareous marl (Harrison 1955). The results at these three stations are consistent with the faulting known on the south coast of Malta and assumed to exist at a submarine cliff about 8 miles south-west of Malta.

At Morphou Bay the deepest layer (assumed 4 km/s) probably corresponds to the pillow lavas that exist on the southern border of the bay (Bishopp 1952) and if this is correct it is clear that they have dipped steeply under the region covered by the experiment. The upper layers are identified as sediments in different states of consolidation, the lowest being probably Miocene sandstones and marls, such as are found inland in Cyprus in great thickness, and the upper layers being more recent unconsolidated material. At Famagusta

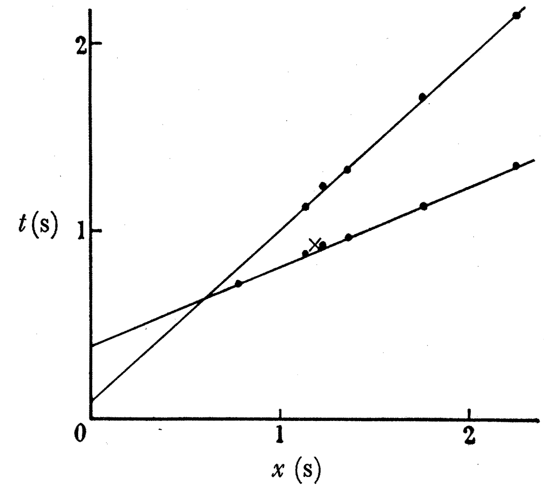

FIGURE 22. Time-distance diagram for Malta. ●, forward; ×, reverse shots.

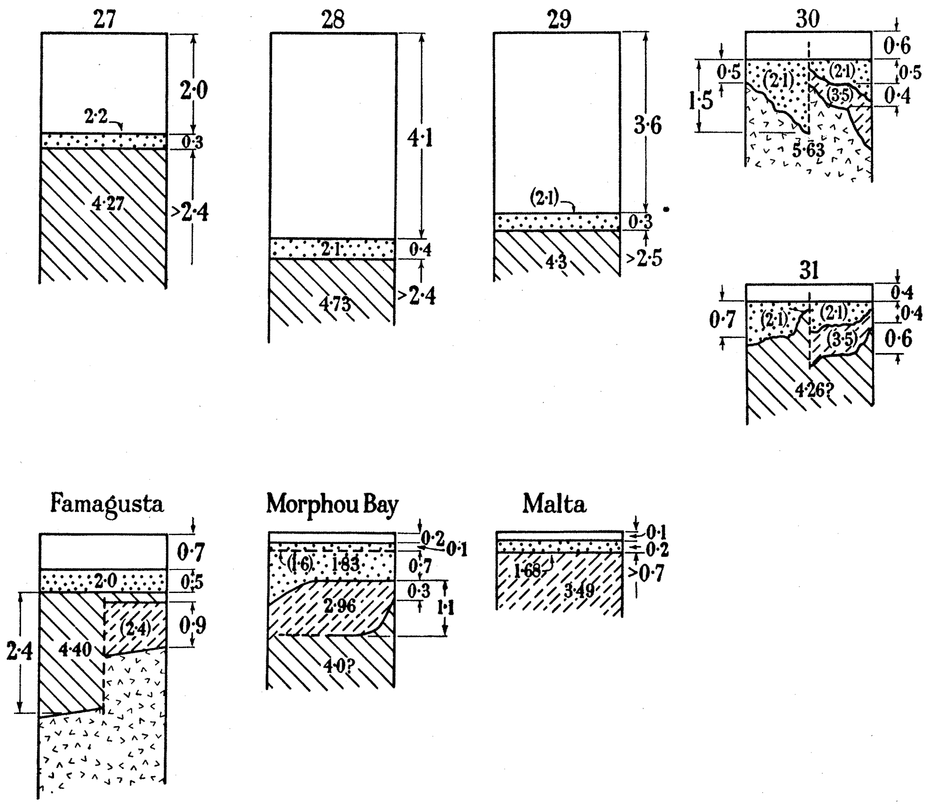

FIGURE 23. Sections for Mediterranean stations (thickness in km; velocities in km/s; assumed velocities in brackets).

the deepest layer, with velocity 6·7 km/s, may be connected with the diabase which forms the main mass of the Tröodos Mountains in the centre of Cyprus. The 4·40 km/s layer is probably a limestone band. The main refracting layers at stations 27, 28 and 29 (velocities 4·3 to 4·7 km/s) may also be limestone bands, but in this case they must be of considerable thickness in comparison with the 0·1 km assumed for the 4·40 km/s band at Famagusta. If a layer with 6·7 km/s velocity exists at stations 27, 28 and 29 it must be much deeper than the similar layer observed at Famagusta, whether the 4·3 to 4·7 km/s layer is assumed continuous downwards, or underlain by 2·4 km/s material as assumed for Famagusta. This is in accord with the large positive gravity anomalies extending out to sea from Cyprus in the direction of the Famagusta observations. It is unfortunate that the deep-water lines did not extend far enough to reach a high-velocity layer, since from the present evidence

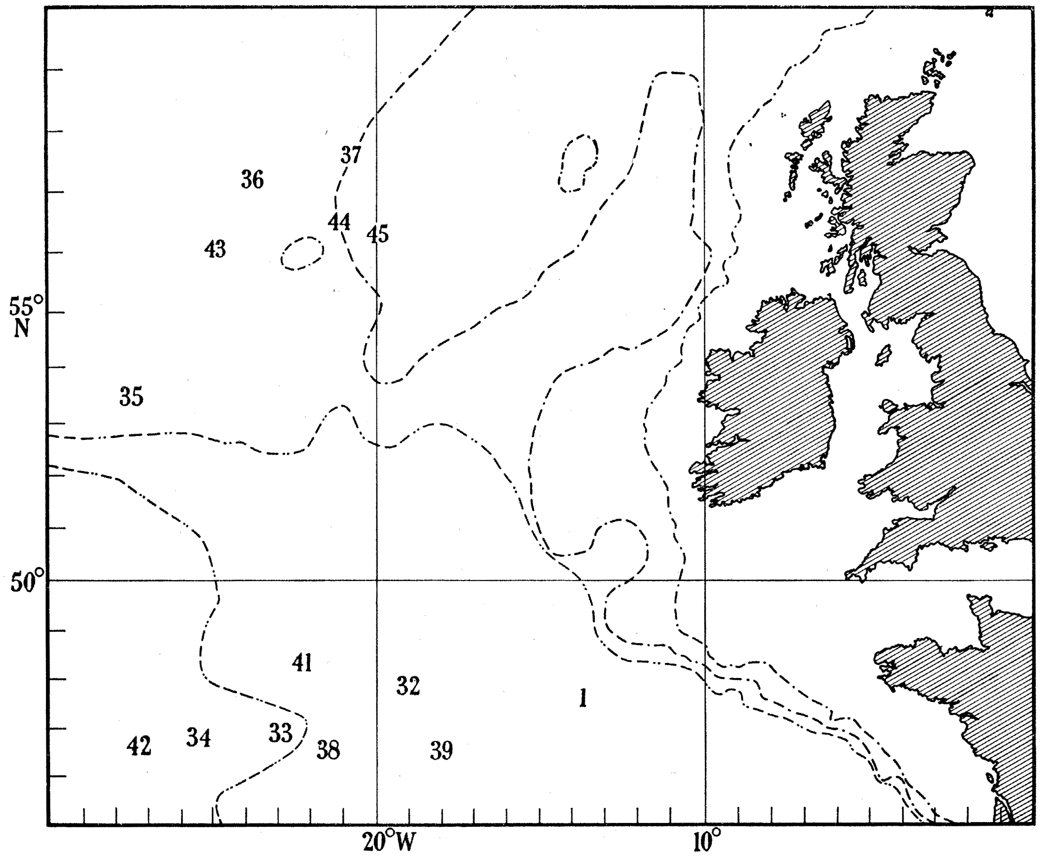

FIGURE 24. Station positions for eastern North Atlantic.

they could be classified as either continental or deep-ocean types. The high-velocity basement layer at Famagusta may be exceptional and a lower velocity might well have been found in longer lines in deep water.

(E) *The eastern North Atlantic*

All the stations except no. 1 were worked after completion of the world cruise, when *Challenger* was making surveys from Portsmouth and Londonderry. The station positions are shown in figure 24 and the operating details and results are given in tables 1 (*e*) and 2 (*e*) and Figs. 25, 27, 29 and 30.

Station 1 (figure 25)

The four good first-arrival ground waves from two separate shots show that there is a dip in the refracting medium. Since there were no reverse shots the dip has been assumed uniform under the buoys and shots and the velocity of 6·18 km/s is obtained from the mean of the slopes of the time-distance lines from separate shots and separate buoys. The over-burden above the main refracting layer has been divided into layers having velocities 2·0 and 4·5 km/s. The 'second-layer' velocity could have been 3·0 km/s with 2·2 km of total

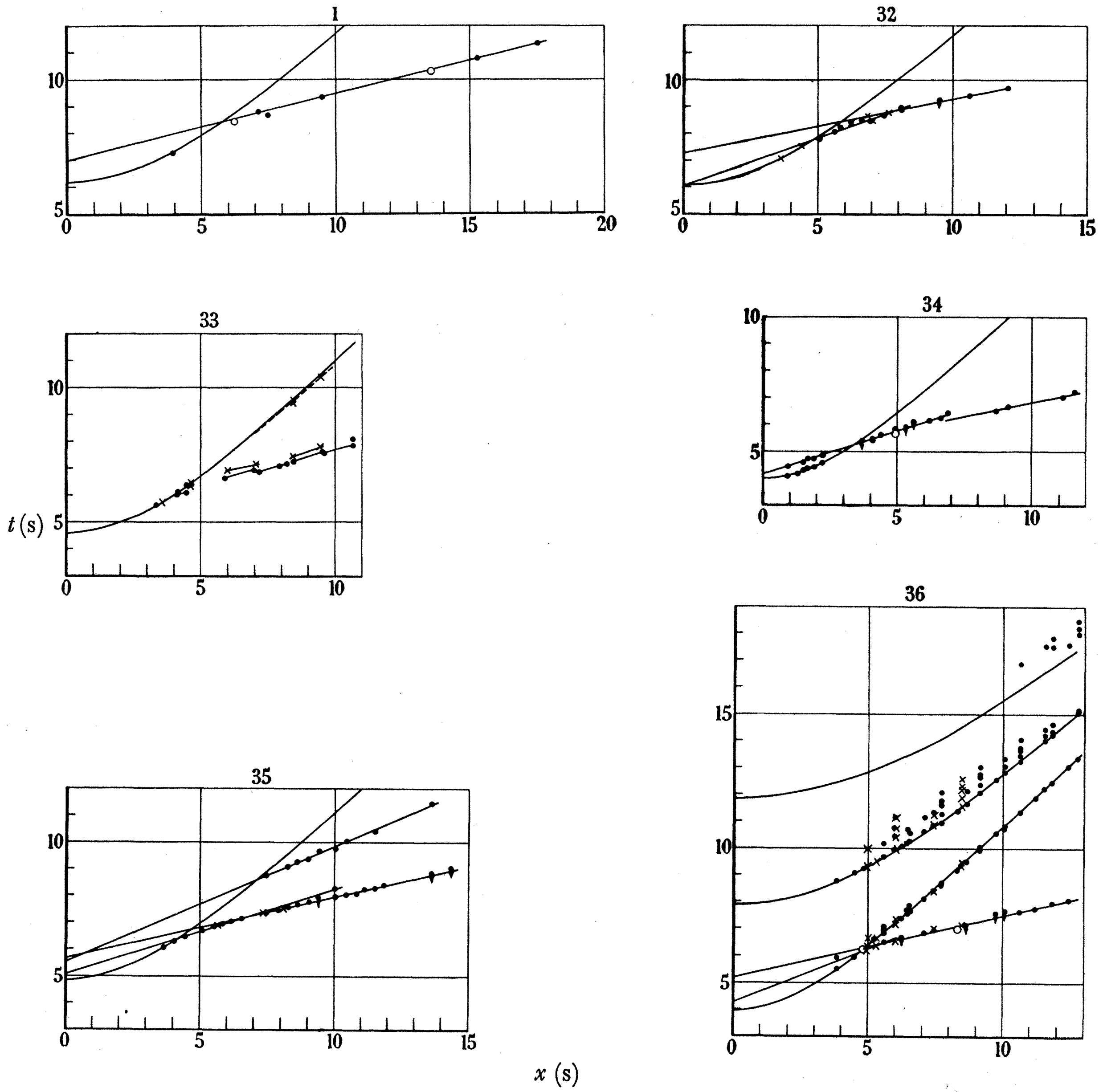

FIGURE 25. Time-distance diagrams for eastern North Atlantic (stations 1, 32, 33, 34, 35, 36). ●, forward; ×, reverse shots; ○, doubtful observations; ⧫, arrival may be earlier.

overburden. 4·5 km/s is the largest value of velocity the layer can have without showing as a first-arrival in the observations that were made, and is more probable from a comparison with other Atlantic stations.

Station 32 (figure 25)

Four forward and two reverse points establish the 4·36 km/s velocity. The existence of a higher velocity deeper layer is not in doubt, but the value of 7·15 km/s may be in error.

Station 33 (figure 25)

The main refracted wave velocity is taken as the mean of the slopes from forward and reverse shots fitted as a series of parallel lines in both cases. The forward shots are of better quality than the reverse, but the velocity for these alone is 5·13 km/s, which does not alter the general picture much. Some high-frequency second-arrival waves give a velocity of 1·84 km/s for the top of the sediment layer. The sea bed was not level at this station and the profile given in figure 26 has been drawn from the various intercept values from separate shots. It is apparent that the lower boundary of the sediment layer follows, in an exaggerated form, the variations in depth observed on the sea bed. This implies that horizontal transport of sediment has occurred.

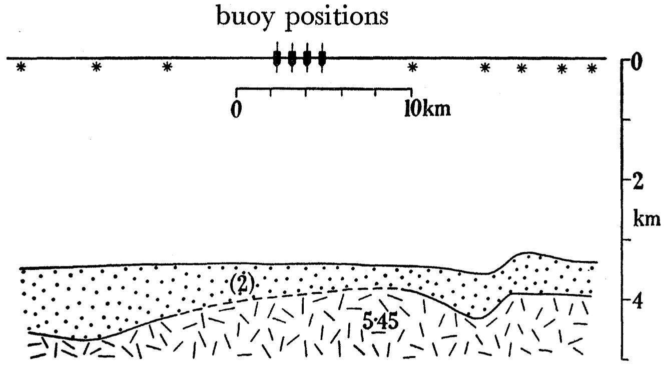

Figure 26. Profile for station 33. $*$, shot positions.

The delay time for deep reflexions from the lower boundary of the sediment would be 0·6 s near the buoys if the profile of figure 26 is correct. This agrees fairly well with the observed 0·45 to 0·55 s delays on vertical reflexion shots and does not leave much room for any intermediate layer.

Station 34 (figure 25)

The five ground waves that give the 4·68 km/s velocity have all been corrected for depth variation (150 fm or 0·27 km along the line) assuming that the deep layer follows the sea bed topography. The depth of assumed 2 km/s cover over the 4·68 km/s layer agrees well with deep reflexions at vertical incidence which have delay time 0·41 to 0·53 s. Four refracted wave first-arrivals determine the 6·65 km/s velocity in the main refracting layer. Since no arrivals corresponding to this velocity occur at the shot covering the 6 to 7 s equivalent distance, the main layer must be deeper under this shot than at greater distances along the line.

Station 35 (figure 25)

No reliable late reflexions were observed, but two main refracting layers are established by first-arrivals. The 4·75 km/s velocity is based on six readings. The main refractor velocity of 6·48 km/s is obtained from a fit of parallel lines to the observations from separate shots, since the variations of intercept are irregular, suggesting changes of depth of layer under the shots rather than a regular slope. However, there are not enough reverse shots to check the velocity. Nine clear second-arrivals give a velocity of 3·46 ($\pm$0·09) km/s, and this is probably the *S*-wave corresponding to the *P*-wave in the main refracting layer. The velocity ratio is 1·87:1. Assuming conversion of *P* to *S* at the top of the 4·75 km/s layer, the intercept of the 3·46 km/s line determines an *S*-velocity of 2·7 km/s (*P*/*S* ratio 1·76) in the 4·75 km/s layer.

Station 36 (figure 25)

Some good reflexions indicate an average velocity of 1·7 km/s for the material above the reflecting interface and assuming their strength is due to critical reflexion, the material under the interface will have a velocity of about 2·1 km/s.

There is a very slight variation of intercept with shot for the main 6·54 km/s line, but it is not systematic, and there is no sign of dip under the buoys from the reverse shots.

The earlier refracted wave arrivals are too close together to define a lower velocity accurately, though it is evident that a second layer exists. The velocity of 3·8 km/s given in table 2(*e*) could be raised to 4·3 km/s without conflicting with the higher-velocity line, but this change in velocity would not alter the thicknesses of the layers very much. By combining the reflexion results with the refraction evidence, it seems probable that the sediment layer consists of 0·4 km of 1·7 km/s and 0·3 km of 2·1 km/s.

Station 37 (figure 27)

The ground waves indicate two velocities, but the closer shots give varying intercepts. Since the sea bed under the buoys was flat, the mean of observations from separate shots may give the true velocity. This is supported by the fact that the more distant points lie on a single high-velocity line, which implies that there cannot be much irregularity under the buoys. The near shots then, established the 4·5 km/s velocity, and the more distant ones determine the main refracting layer velocity at 6·56 km/s. The profile along the line is a sediment layer of varying thickness with a flat main refractor.

Station 38 (figure 27)

The velocity of 4·52 km/s is taken from the reverse ground-wave arrivals. The four forward observations give 5·22 km/s, but there is a worse scatter than for the reverse points, and this may be due to irregular depth variation as the sea-bed topography is violent there but is fairly flat under the reverse shots. The thickness of sediment given in table 2(*e*) is that under the buoys, and this agrees with the vertical reflexion time of 0·32 s observed from short range shots.

If the velocity in the next deeper layer is 6·7 km/s the thickness of the 4·52 km/s layer must be at least 2·4 km.

Station 39 (figure 27)

Reliable ground waves were few in number, and it is clear that irregular variations of intercept with shot point occur. The water depth varies from 2100 to 2350 fm (3·8 to 4·3 km) along the line. A combination of the parallel lines fitted to forward and reverse shots is used to give the velocity of 5·4 km/s. However, it is possible that there are two refracted waves, because the longer distance shots show a higher velocity than the near ones. The velocities for these two waves are 4·9 km/s and 5·6 km/s, and the 4·9 km/s layer is 1·2 km thick, with a sediment cover of thickness varying from 0·4 to 0·8 km along the line.

Station 41 (figure 27)

The buoys were laid over a peak of about 2000 fm (3·7 km) in a surrounding area of 2400 fm (4·4 km). From the echo-sounder profiles along the line in both directions, little drift occurred during the experiment. Corrections for depth variation have been made

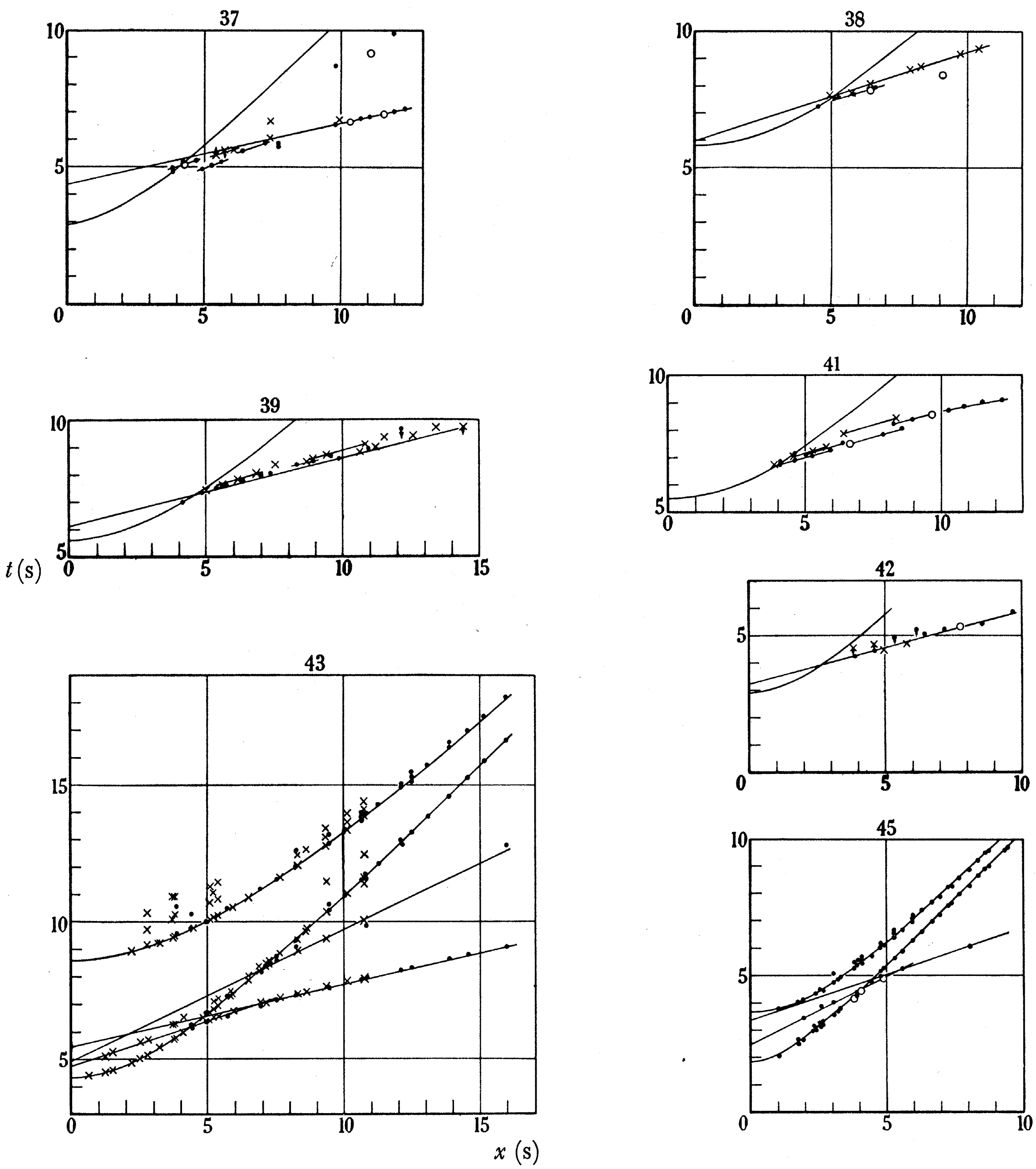

FIGURE 27. Time-distance diagrams for eastern North Atlantic (stations 37, 38, 39, 41, 42, 43, 45). ●, forward; ×, reverse shots; ○, doubtful observations; ↥, ⧫, arrivals may be earlier.

assuming that the ground waves and deep reflexions are from a layer which follows the sea-bed topography. The corrected ground waves still show variations of intercept with shot point, so that the true depth variations in the layer giving the ground waves are more pronounced than those in the sea bed. The velocity of 5·33 km/s given in Table 2 (*e*) is

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obtained from the mean of forward and reverse results, both fitted as a series of parallel lines to separate shots. Since the buoys are over a peak, the rays reaching them from forward and reverse shots have come from the downward slopes on each side, and taking the mean of forward and reverse shots, is, in this case, simply averaging two separate measures of the same thing. The two separate velocities differed by less than the standard error of either, which is reassuring. The actual velocity obtained depends on the assumption that the underlying layer follows the sea bed topography; if the underlying layer comes near the surface at the peak the 5·33 km/s velocity will be too high. The lowest possible value of velocity is 4·4 km/s, in which case the 4·4 km/s outcrops at the peak.

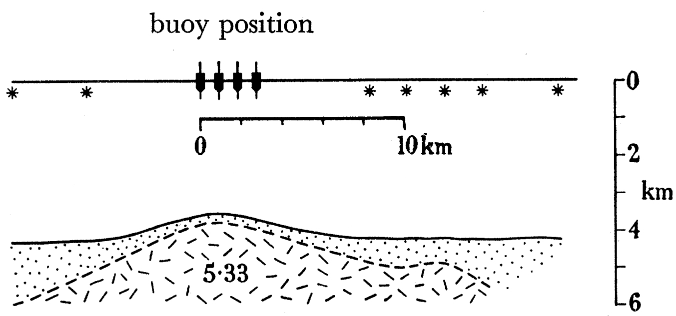

FIGURE 28. Profile for station 41 assuming a velocity below the sediments of 5·33 km/s. *, shot positions.

The most distant shot in the forward direction indicated a velocity of 7·7 km/s, and a thickness of 2·7 km for the 5·33 km/s layer. The value 7·7 km/s is, however, probably high, because of uncorrected dips, and a value of 6·7 km/s is more likely, with a consequent thickesss of 5·33 km/s of 1·7 km.

Station 42 (figure 27)

For this station, three buoys were anchored 0·9 km apart on piano wire, in a depth of about 1000 fm (1·8 km) on the top of a peak in the mid-Atlantic Ridge. The reflected waves were too much obscured by side-echoes to be of any use and the structural interpretation depends on ground waves only.

The arrivals have been corrected assuming that the layer giving them follows the topography observed on the ship's echo-sounder. Preliminary corrections were made to a mean depth of 1200 fm (2·2 km) assuming a ground-wave velocity of 4·5 km/s. Plotting these corrected points gave a reasonably straight line showing a higher velocity, approximately 5·5 km/s. A revised correction for depth was made using this velocity, though none of the corrections changed by more than 0·02 s. The final velocity is calculated as 5·74 km/s, and the corresponding time-distance line passes well above the calculated reflexion curve for the mean depth of water, so that there must be an undetected upper rock layer. This is not likely to be unconsolidated sediment, as hard rock is usually encountered in coring on similar peaks. The upper layer is restricted by the seismic results to a maximum velocity of 3·8 km/s and it is unlikely to be much less than 2·0 km/s. The thickness given in table 2 (*e*) is calculated from a mean value of 2·9 km/s.

It is possible that the ground waves should be separated into two lines, giving 4·5 and 5·9 km/s, but with so few good arrivals it is impossible to decide this. It is clear, however, that the 6·7 km/s layer commonly found in deeper water does not outcrop in these peaks, or the arrivals would have been about $\frac{1}{2}$ s earlier than observed.

Station 43 (figure 27)

The 4·74 km/s for the intermediate layer velocity is determined by 4 forward and 6 reverse points. The more distant arrivals in the forward direction fit the line of which the details are given in table 2 (*e*). The four rather closely spaced reverse points lie parallel to, but about 0·03 s above the forward line.

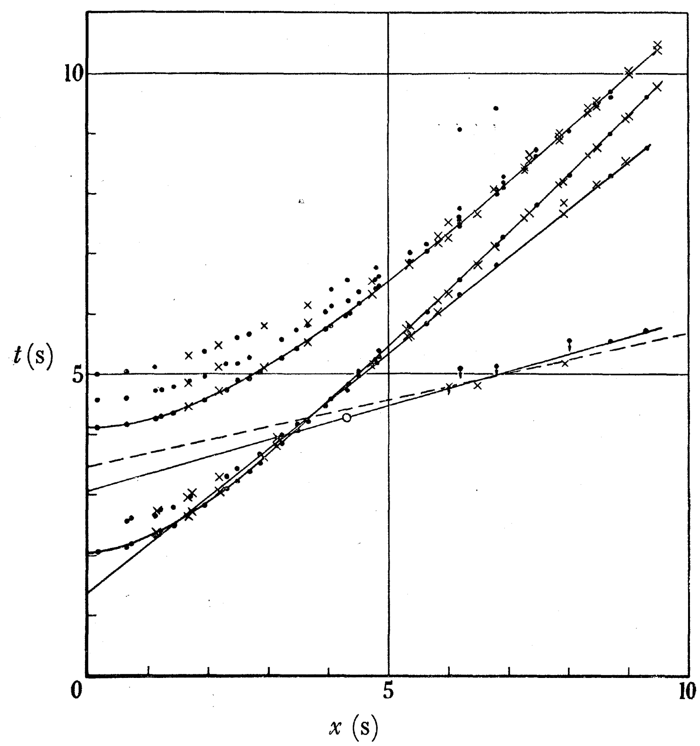

FIGURE 29. Time-distance diagram for eastern North Atlantic (station 44). ●, forward; ×, reverse shots; ○, doubtful observations; ↓, ↓, arrivals may be earlier; – – –, long-range line from station 44*a*.

A number of strong arrivals are observed in the records from the small shots. These lie on a curve touching the 4·74 km/s ground-wave line and they are interpreted as reflexions from the top of the intermediate layer. Some longer range second-order reflexions give additional information to show that the sediment consists either of two layers, 0·45 km at 1·75 km/s followed by 0·28 km at 2·4 km/s, or a single layer with a gradient of velocity of 1 s^{-1} in the upper part.

A group of second-arrivals indicates a velocity of approximately 3·5 km/s and an intercept slightly less than that of the high-velocity line. The ratio of the high velocity to this new value is 1·88 and the arrivals are probably *S*-waves from the main refracting layer.

Station 44 (figure 29)

This station was in the position of part of the 34-mile line shot with the assistance of H.M.S. *Bern* (44*a*). The long distance results are discussed in the next section.

First-arrival ground waves were particularly weak in this area, and a strongly reflecting layer is present, giving sub-bottom reflections at vertical incidence on all shots. These show delays of 0·42 to 0·52 s after the bottom reflexion, with the larger values to the south-east end of the line, and with 0·44 to 0·46 s along the greater part of the line. From oblique reflexions an average velocity of 1·9 ($\pm$0·19) km/s, and a vertical travel time of 0·46 s are calculated.

Some small high-frequency ground waves indicate a velocity of 1·88 km/s, with a cover of 0·17 km of material at an assumed velocity of 1·7 km/s or a velocity gradient of 2·5 s^{-1} in the cover layer. The mean velocity with 0·17 km at 1·7 km/s, and 0·24 km at 1·88 km/s is 1·78 km/s, which is within the estimate of the average velocity from the reflexions.

The longer range ground waves are very feeble, but they are evidently from a layer much deeper ($\frac{1}{2}$ to 1 s time difference) than the reflecting horizon. This suggests that the reflexions are from a thin layer of high-velocity material. Such a structure might be provided by a thin lava flow or a limestone band. The mean of forward and reverse ground waves gives the velocity of 5·5 km/s of table 2 (*e*), and the depth to this layer has been calculated assuming that the mean velocity of the material below the reflecting layer is 2·4 km/s.

Station 44 (*a*)

Shots were fired by H.M.S. *Bern* and recorded on a single hydrophone streamed over the side of H.M.S. *Challenger*. The line through the four good arrivals indicates a velocity of 6·69 km/s, but there was no possibility of detecting dip from reverse shots or from misfit of arrivals from a line of hydrophones.

distance	9·33	20·21	30·77	41·71 s
arrival time	5·44	8·03	10·20	12·82 s

The results in table 2 (*e*) have been calculated assuming that station 44 gives a true picture of the structure down to the 5·5 km/s layer. It is possible that the 5·5 and the 6·69 km/s arrivals all belong to the same line, in which case the thickness of the sediment layer of table 2 (*e*) (which includes the assumed 2·4 km/s material) becomes 1·7 km, and this is the depth to the main refractor, in place of the 2·4 km given in the table.

Station 45 (figure 27)

The ground waves were very weak at this station and it was decided not to attempt reverse shots. The only two reliable ground waves indicate the 4·7 km/s velocity given in the table. The 3·0 km/s layer above the main refractor is obtained from a group of three low-frequency arrivals appearing after the first sea-bottom reflexions and one doubtful first arrival. A few small high-frequency ground waves give a velocity of 1·92 km/s. These are from part of the upper layer, and the velocity agrees with the average of 1·8 km/s given by the deep reflexions. The assumed 2·2 km/s velocity given in table 2 (*e*) for the sediment is made up of this velocity and 2·4 km/s below the reflecting surface, as in station 44. Although the velocities are uncertain it is clear that there is a great thickness of low-velocity material here.

Interpretation of eastern North Atlantic results

The results in this area (figure 30) are remarkably similar to those obtained in the other deep-ocean basins, showing a similar range of unconsolidated sediment thicknesses, a second layer in which the velocity is generally between 4 and 5 km/s, and a basement velocity of about $6\frac{1}{2}$ km/s.

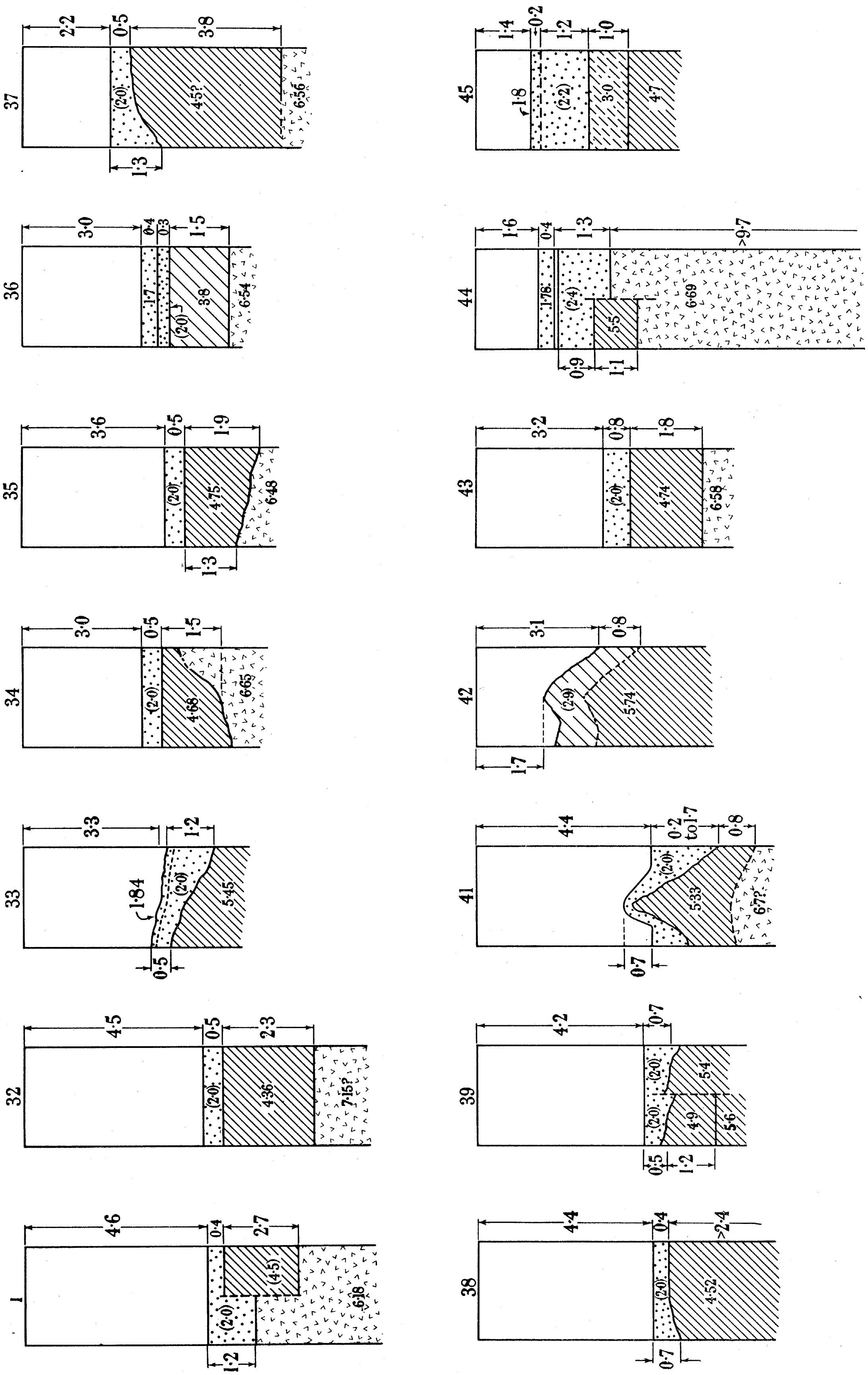

FIGURE 30. Sections for eastern Atlantic stations. (Thicknesses in km; velocities in km/s; assumed velocities in brackets.)

The northern group of stations (36, 37, 43, 44 and 45) lie in an area of less than average depth. This area is part of an extensive plateau stretching from Greenland to Scotland, and south from Iceland to about latitude 52°. Depths vary smoothly under the station positions from 700 to about 1700 fm (1·3 to 3·1 km), sloping away to the westward of Rockall bank. Sediment thicknesses are slightly greater in the shallower water of stations 44 and 45, though at both these there are uncertainties where velocities have had to be assumed. In the 1200 to 1700 fm region (2·2 to 3·1 km) sediment thicknesses of the order of 0·7 km are found, and reflexion shots in the area show sub-bottom arrivals consistent with this. None of these stations show as great a thickness of unconsolidated sediment as that found 200 miles to the south-east, 2·8 km at 2·5 km/s in 1300 fm of water (Hill 1952).

Velocities in the second layer are from 3·8 to 4·7 km/s with a possible 5·5 km/s at station 44. From the known presence of Tertiary volcanic rocks in Iceland and at Rockall, this layer might be identified as low-velocity volcanic material. From the velocity it may equally well be a consolidated sediment, or a mixture of lava flows and sediments. The reflecting layer 0·4 km deep at station 44 may well be a thin lava flow. The thicknesses of this second layer (1·5 to 3·8 km) are slightly greater than those of the western Atlantic and Pacific stations.

Velocities in the deepest layer, 6·54 to 6·69 km/s, are similar to those of the western Atlantic, the north Pacific basin, and the Indian Ocean. They are appreciably higher than the velocities found at comparable depths on continents, which makes it seem unlikely that this 'North Atlantic plateau' is a submerged continent.

It is possible, however, that in this northern area the high velocity may belong to a lava flow, and there could be continental rocks below such a layer, but the velocity range, and the thicknesses and velocities of the covering layers, are so similar to those in deeper water that it seems preferable to regard this layer as continuous with the floor of the deep ocean.

Further south, station 35 shows a very similar structure in slightly deeper water. Except for station 1, the southern group of stations are on the mid-Atlantic ridge and its approaches, and the more rugged topography makes the results less certain. The geological significance of the velocities 5·32 and 5·74 km/s for the second layer at stations 41 and 42, which are on peaks of the mid-Atlantic ridge, is uncertain. The surface material at station 42 is believed to be a hard rock, from attempts at coring in that area, and 3·8 km/s is the maximum velocity in the surface layer allowed by the observations. This could belong to a vesicular volcanic rock, and the rock beneath could also be volcanic.

At other stations, where coring or reflexions indicate unconsolidated sediment cover, the depths to the second layer are more variable than the observed depth changes, in the sea bed, suggesting that horizontal transport of sediment has smoothed out part of the relief of the deeper layer. A main refracting layer is observed at stations 32, 34 and possibly 41, with a considerable scatter in the velocities. The value of 6·18 km/s obtained at station 1 is uncertain, being based on only four points, with depth variations and no reverse shots. Hill & Laughton (1954) found 7·13 ($\pm$0·20) km/s near this position, and three other stations worked by them in deep water just to the west of this gave velocities from 6·49 to 6·75 km/s. The 6·65 km/s at station 34 and the suggestion of a 6·7 km/s velocity at station 41 make it seem unlikely that the mid-Atlantic ridge contains any appreciable thickness of granite.

Discussion of results

The study of earthquakes, and the sea seismic experiments of Ewing & Press (1955), Hill (1957) and Raitt (1956), show that a rock layer, characterized by a *P*-wave velocity of about 8 km/s, is present at a depth of about 10 to 15 km beneath the surface of the oceans. The sono-buoy technique, when employed with a single ship, does not allow adequate horizontal range to determine the depth of this layer in the deep ocean, and the results shown in tables 2 (*a*) to (*e*) are for the structure of the sea bed above the Mohorovičić discontinuity. The sono-buoys are, however, most suitable for determining the detail in the upper layer, because they provide several refracted wave arrivals for each shot and this assists in elucidation of dip in the various rock layers.

The results described here are not as comprehensive as could have been wished; there is nothing in the South Atlantic or the South Indian Ocean for example; but they do provide a link between the work of others, which for economic reasons is localized. The *Challenger* expedition carried the same apparatus and used the same interpretation methods in the main oceans of the world, and found results that are substantially in agreement with the few that were available at the time (1950–53) and with the many that have been reported subsequently.

There are three layers above the Mohorovičić discontinuity that are distinguishable by their seismic properties; a sediment layer, with velocity about 2 km/s; a 'layer 2', with velocity ranging from place to place from 3 to 6 km/s; a main layer with velocity of 6·7 km/s. (A summary of the evidence for this classification is to be found in Hill 1957.)

(*a*) *The* 6·7 *km/s layer*

The main refracting layer at most of the deep-ocean stations belonged to the 6·7 km/s velocity group. The mean and extreme values for the Pacific, Atlantic and Indian oceans are:

Pacific. Stations 8, 9, 10, 11, 16, 17: 6·36 to 6·93 km/s; mean 6·68 km/s.

Atlantic. Stations 1, 3, 4, 5, 32, 34, 35, 36, 37, 43, 44: 6·18 to 7·2 km/s; mean 6·71 km/s.

Indian. Stations 22, 25, 26: 6·22 to 6·74 km/s; mean 6·55 km/s.

The mean values are in good agreement with the value of 6·70 km/s computed by Hill (1957), from seventy-six observations (including the twenty given above), and it is probable that the seismic results refer to a similar rock layer in all the oceans. The value of the velocity could correspond to a basic igneous rock; it is certainly in excess of values found for acidic rocks or for sedimentary rocks except some hard limestones. Apart from the geological argument against the world-wide existence of a thick limestone layer, there are physical reasons why basic rock is more likely. The excellent propagation of refracted waves that is observed in all deep-ocean experiments suggests that the main refractor is some solid crystalline rock rather than a limestone. Limestones usually show a tendency to lose seismic energy due to bedding, shale-breaks and faults, and in any case have an inherently greater loss for seismic waves than do crystalline rocks. Moreover, on land, limestones show enormous variations in velocity, contrary to the close grouping shown for the 6·7 km/s layer in the oceans.

Table 2 shows that there is some variation within the group of velocities for the 6·7 km/s layer, and Ewing *et al.* (1954) point out that their stations that are in deep water far from sea-mounts, do give slightly lower velocities than those of Officer *et al.* (1952) on the Bermuda rise. A similar variation in the Pacific results described here was one of the reasons for the classification of deep-ocean structures into two types, depending on the presence or absence of layer 2, by Gaskell & Swallow (1952), and by Gaskell (1954), when the seismic results were first examined and reported from the ship. More detailed analysis has altered some of the most probable values of velocity, and evidence of more widespread occurrence of layer 2 has caused the two groups to merge. Raitt (1956), whose time-distance plots have a greater concentration of observations, does not find any subdivision of the 6·7 km/s group.

The results for the main refracting layer determine to a great extent the thickness of overlying material. This thickness will be discussed in two parts, 'sediment' and 'layer 2'.

(*b*) *Sediment*

There are very few measurements of sediment velocity in table 2 (*a*) to (*e*) and a value of 2·0 km/s has been assumed in computing depths for most stations. This value is reasonable, both from laboratory measurement on deep-sea sediments (Laughton 1957) and from values found by other observers.

The thickness of sediment (table 2) in the deep oceans ranges from 0 to 1·6 km with a mean of about 0·3. The Mediterranean values are of the same order. This is less than expected by Kuenen (1950), who has estimated that the total volume of deep-sea deposits should lie between 5×10^8 km^3 and $12{\cdot}5 \times 10^8$ km^3. These limits have been derived from a number of different considerations which include estimates of the present rates of deposition and of the sodium content of the ocean. These volumes of sediment if spread evenly over the ocean floor would result in thicknesses of between 1·5 and 3·8 km. There is some evidence from the Atlantic results that the sediment layer is thicker in shallower water, and this may be due to proximity to continental sources of material. Sediment can be produced by marine organic material and dust in all parts of the sea, and it can be transported from the continental shelves by slumping, turbidity currents, icebergs and tsunamis. Some care is needed, therefore, in calculating average sediment thicknesses from a few widely spread observations, because weight ought to be given to the area of ocean comprising the various types. An even greater difficulty in calculating total world sediment is due to the possibility of consolidation to form a hard layer with a higher seismic velocity.

(*c*) *Layer* 2

There are several stations at which a measure of velocity in a layer between the sediment and the main refracting layer has been possible. In the Pacific the two examples, stations 9 and 16, are both situated near volcanic islands or atolls, while in the Indian ocean the low velocity of 3·92 km/s is found on top of a sea-mount at station 24. The Atlantic stations 3, 4 and 5 are on the Bermuda rise, but are much farther from an island than are the Pacific stations 9 and 16. However, there may be some similarity in structure between the group of stations 23, 25, 26 round the Indian ocean sea-mount and the Bermuda group. The value of the velocity found at station 9 near the Hawaiian chain of islands is very close to that found in the laboratory for several pieces of olivine basalt ā-ā lava taken from a recent flow in Hawaii, and it is very likely that in the cases just enumerated 'layer 2' is volcanic in origin. The thickness of 'layer 2' near Funafuti and near the Hawaiian Islands suggest that a volcanic root exists in Pacific islands, and that the picture given by Woollard (1954) from gravity considerations is compatible with the seismic results.

In the first assessment of the results here described, the stations near islands were distinguished from those in the deep-ocean basins remote from known topographical features. (Gaskell & Swallow 1952; Gaskell 1954). A closer inspection of wide-angle reflexions and of later arrivals identified as *S*-waves suggest that 'layer 2' is always present but first-arrival refracted waves were not observed because of the thinness of the layer and the paucity of observations. This agrees with the conclusions of Raitt (1956) who has made many first-arrival observations in the critical distance range. Hill & Laughton (1954) did not at first report the layer 2 at stations in the eastern Atlantic, but reassessment of the results shows that, in two of the six stations, there is evidence from the *S*-waves of a layer interposed between the 2·0 km/s sediment and the 6·7 km/s main refracting layer. The evidence from *S*-waves alone is not positive, because it assumes that the conversion from *P* to *S* cannot take place at the sea bed and that a strong discontinuity must be present below the sea bed in order to form *S*-waves at all. There is some geological significance in separating the observations taken near known volcanic features from those in deep-ocean basins, since the layer 2 that is volcanic in one case is unlikely to extend over all the deep-ocean floor. There are undoubtedly more deep ocean sea-mounts and other possible volcanic outpourings than are marked on the charts, but it is improbable that they are so widespread as to provide a continuous volcanic cover to the sea bed. It is, therefore, plausible to ascribe a sedimentary origin to layer 2 where it is found in deep ocean basins.

(*d*) *The andesite line*

The concept of a division between one part of the Pacific and the remainder is not always accepted by seismologists. However, there is a large amount of geological evidence that cannot be dismissed, and the preliminary reading of the *Challenger* results did suggest (Gaskell & Swallow 1952) that the andesite line marked a boundary between two different seismic types of structure. The recent finding of layer 2 velocities as high as 5·6 km/s by Raitt in the Pacific and by Hill in the Atlantic, makes it possible that stations 20 and 21 are variants of the normal 'sediment plus layer 2 plus 6·7 km/s layer' structure.

There is clearly a difference between station 8 where the 6·7 km/s layer is within 0·5 km of the sea bed, and station 20 where a 6·7 km/s layer must be at least 3·0 km below a layer 2 of 5·75 km/s velocity. The layer 2 at station 20 must be explained as being due to volcanic material, or to compacted sediment, in which case the velocity and thickness are both abnormally high, or to a different structure for the earth's crust to the continental side of the andesite line. A good measurement of the depth of the Mohorovičić discontinuity in the Philippine sea would be most interesting; if it is 15 to 20 km as it is near New Zealand (Officer 1955 *b*), Eiby (1957), there may well be several kilometres of acidic rock resting on the basic 6·7 km/s material, to give a vertical column of rock whose character is intermediate between that of deep oceans and of continents. A similar difference between the sea-mount in the Indian Ocean (station 24) where there is a considerable thickness of material of 3·92 km/s, and the Seychelles, where granite of 5·9 to 6·0 km/s is at the surface, suggests that there are two types of ocean bed, one that forms acidic islands and one that forms the basic Hawaiian type of island.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

TABLE 1. OBSERVATIONAL DATA FOR STATIONS

station	date	buoy position lat.	buoy position long.	mean depth (fm)	number of shots	line extent (miles)	line direction	ratio of horizontal to vertical water velocity
				(a) Western North Atlantic				
CR 3	8. vi. 50	36° 08′ N	62° 16′ W	2770	6 × 50 lb.	13	000°	—
CR 4	16. vii. 50	32° 04′ N	69° 39′ W	2910	6 × 50	16	270°	1·006
CR 5	20. ix. 50	27° 48′ N	68° 28′ W	2870	8 × 50	19	032°	1·013
				(b) Pacific				
CR 6	23. x. 50	27° 42′ N	116° 50′ W	2000	7 × 50	9	135°	—
CR 7	25. x. 50	31° 12′ N	117° 22′ W	1110	3 × 50	7	350°	—
CR 8	20. ii. 51	35° 01′ N	143° 14′ W	2900	5 × 50	10	167°	0·996
CR 9	11. iii. 51	22° 35′ N	160° 23′ W	2530	7 × 50	16½	104°	1·009
CR 10	13. iii. 51	25° 42′ N	164° 34′ W	2615	4 × 50	8	134°	1·014
CR 11	15. v. 51	43° 35′ N	153° 14′ E	2827	6 × 50	12	335°	0·978
CR 12	12. vi. 51	14° 20′ N	140° 50′ E	2670	5 × 30	12	203°	1·022
CR 13	14. vi. 51	11° 16′ N	142° 05′ E	5580	4 × 50	15½	258°	—
CR 14	15. vi. 51	8° 40′ N	142° 58′ E	1343	7 × 50	14½	158°	1·021
CR 15	28. vi. 51	18° 13′ S	161° 25′ E	1595	6 × 50	14½	322°	1·023
CR 16	14. ix. 51	8° 51′ S	178° 55′ E	2670	4 × 20	11	113°	1·028
CR 17	23. x. 51	3° 49′ N	145° 54′ E	2410	5 × 20	13	180°	1·024
CR 19	31. x. 51	14° 20′ N	140° 50′ E	2660	7 × 20	13½	023°	1·022
CR 20	20. iv. 52	20° 36′ N	126° 49′ E	3020	7 × 50	14	090°	—
CR 21	21. iv. 52	20° 26′ N	124° 46′ E	3180	12 × 50	14	076°	1·017
				(c) Indian Ocean				
CR 22	18. v. 52	7° 58′ S	95° 13′ E	2840	10 × 50	12	150°	1·022
CR 23	20. v. 52	5° 14′ S	91° 19′ E	2720	9 × 50	13½	125°	1·022
CR 24	21. v. 52	3° 53′ S	89° 49′ E	1656	8 × 50	10	125°	1·028
CR 25	23. v. 52	3° 38′ S	86° 07′ E	2660	10 × 50	12	090°	1·023
CR 26	24. v. 52	2° 03′ S	84° 58′ E	2572	10 × 50	12	140°	1·022
Seychelles	13. vi. 52	4° 38′ S	55° 38′ E	16	12 × 1	3	020°	—
				(d) Mediterranean				
CR 27	2. vii. 52	33° 28′ N	33° 23′ E	1088	10 × 50	10	020°	0·996
CR 28	30. viii. 52	35° 46′ N	18° 08′ E	2220	10 × 50	7½	270°	0·983
CR 29	31. viii. 52	35° 57′ N	16° 09′ E	1950	10 × 50	9	096°	0·984
CR 30	5. ix. 52	36° 35′ N	14° 03′ E	300	2 × 1, 2 × 4, 5 × 50	10	315°	1·024
CR 31	6. ix. 52	34° 51′ N	13° 46′ E	190	8 × 50	9	050°	1·013
Famagusta	3. vii. 52	35° 13′ N	34° 07′ E	393	13 × 1 oz. to 9 lb.	5	000°	1·014
Morphou Bay	9. vii. 52	35° 17′ N	32° 51′ E	90	13 × 1 oz. to 9 lb.	5	180°	1·012
Malta	1. ix. 52	36° 06′ N	14° 38′ E	74	10 × 1 oz. to 4 lb.	2	135°	—
				(e) Eastern North Atlantic				
CR 1	4. v. 50	47° 40′ N	13° 40′ W	2535	4 × 50	15	345°	0·993
CR 32	25. v. 53	47° 49′ N	19° 05′ W	2460	9 × 50	10	270°	1·010
CR 33	24. vi. 53	46° 52′ N	22° 55′ W	1800	3 × 1, 10 × 50	9	270°	1·001
CR 34	25. vi. 53	46° 43′ N	25° 30′ W	1635	4 × 1, 8 × 50	9	090°	1·000
CR 35	28. vi. 53	53° 27′ N	27° 40′ W	1985	8 × 50	11	180°	0·997
CR 36	30. vi. 53	57° 11′ N	23° 54′ W	1625	9 × 50	9	000°	1·000
CR 37	2. vii. 53	57° 43′ N	20° 49′ W	1175	10 × 50	9	180°	1·000
CR 38	28. vii. 53	46° 26′ N	21° 33′ W	2390	10 × 50	8	270°	0·991
CR 39	29. vii. 53	46° 31′ N	18° 07′ W	2300	12 × 50	10	270°	0·995
CR 41	17. viii. 53	48° 22′ N	22° 14′ W	2250	7 × 50	10	218°	0·998
CR 42	19. viii. 53	46° 43′ N	27° 09′ W	1200	8 × 50	7	330°	—
CR 43	28. viii. 53	56° 05′ N	25° 08′ W	1760	9 × 1, 10 × 50	13	090°	1·000
CR 44	11. ix. 53	56° 34′ N	21° 06′ W	850	24 × 1, 8 × 50	8	130°	1·000
CR 44*a*	21. vii. 53	56° 37′ N	21° 12′ W	850	11 × 50	34	130°	1·000
CR 45	14. ix. 53	56° 24′ N	20° 07′ W	750	15 × 1, 5 × 50	9	360°	1·007

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Table 2

station	water depth (km)	sediment layer		layer above main refractor		main refractor						depth to main refractor from sea bed (km)	depth of 8 km/s layer below sea level (km)	remarks
		velocity (km/s)	thickness (km)	velocity (km/s)	thickness (km)	no. of good obs. fwd.	rev.	velocity (km/s)	standard error	intercept (sec)	standard error			
								(a) Western North Atlantic						
CR 3	5·07	(2·0)	0·1–1·3	4·4	2–3	5	0	7·2	0·2	7·66	0·1	3·7	13·1?	probably considerable changes in thickness of both 2·0 and 4·4 km/s layers along the line
CR 4	5·32	1·6 (2·0)	0·3 + 0·4	4·84	1·6–1·8	5	0	6·58	0·23	7·96	0·1	2·4–2·7	> 12·4	reflexions suggest division of sediment layer
CR 5	5·25	2·1	0·4–0·5	4·5	1·7	11	0	7·16	0·06	7·80	0·03	2·1	> 10·2	good *S*-wave velocity 4·04 km/s and reflexions
								(b) Pacific						
CR 6	3·66	(2·0)	0·1	4·6	0·0–1·5	8	0	5·81	0·18	5·01	0·09	0–1·5	—	irregular water depth by ± 150 fm; intermediate velocity well established
CR 7	2·03	(2·0)	0·4	(4·6)	0·5–0·9	8	0	6·0	0·24	3·23	0·06	0·6–1·3	—	irregular water depth by ± 70 fm. Sediment velocity < 2·8 km/s; 0·6–0·9 km sediment if no 4·6 km/s layer
CR 8	5·30	(2·0)	0·1	(4·3)	0·6	12	1	6·36	0·12	7·16	0·11	0·5	> 8·4	depth to main layer 0·3 km if no intermediate layer
CR 9	4·63	(2·0)	0·05	4·30	2·7	11	3	6·85	0·10	7·01	0·04	2·8	> 10·4	4·30 based on six first arrivals
CR 10	4·78	(2·0)	0·02	(4·3)	1·4	6	3	6·93	0·31	6·66	0·2	0·6–0·8	> 7·5	depth to main layer 0·3–0·5 km if no intermediate layer
CR 11	5·17	(2·0)	0·5	(4·3)	0·6–1·5	11	2	6·69	0·27	7·58	0·2	1·0–1·6	> 9·2	thickness of 2·0 km/s from reflexions
CR 12	4·88	(2·0)	1·4	6·4	2·1	13	3	8·5	0·5	8·20	0·2	3·5	8·4	the main refraction line is for layer below Moho;
CR 19	4·86	(2·0)	1·0–1·4	6·5	2·7–2·1	11	6	8·5	1·1	8·03	0·3	3·5–3·7	8·5	there could be a 4·3 km/s layer, but is unlikely
CR 13	10·20	(2·0)	1·3	—	—	6	0	7·1	0·8	14·55	0·1	1·3	> 12·1	no evidence about 4·3 km/s layer; depth uncertain
CR 14	2·46	(2·0)	0·7	—	—	14	2	5·15	0·07	3·83	0·04	0·7	—	irregular water depth by ± 75 fm; at least 3·8 km of 5·15 km/s
CR 15	2·92	1·5–1·9	0·3	2·4	1·4–2·0	19	3	5·17	0·09	5·39	0·05	1·7–2·3	—	probable increase of velocity with depth in sediment; at least 2·5 km of 5·17 km/s
CR 16	4·88	(2·0)	0·5	4·48	1·5	8	0	6·84	0·15	7·27	0·05	2·0	> 10·5	intermediate layer velocity from reflexions
CR 17	4·41	(2·0)	0·4	(4·3)	1·1	9	0	6·40	0·11	6·46	0·04	1·1	> 9·4	suggestion of 4·3 km/s layer by reflexion
CR 20	5·52	(2·0)	0·0–0·7	—	—	16	7	5·75	0·24	7·32	0·19	0·0–0·7	> 11·5	variation of sediment thickness along line of shots
CR 21	5·82	(2·0)	0·2–0·6	(4·0)	0·0–1·9	21	11	5·70	0·15	8·06	0·12	0·6–1·3	> 12·5	4·0 km/s introduced to fit 0·8 km sea-mount along profile
Ominato	0·05	1·87	1·1–2·4	—	—	21	4	6·10	0·18	1·6	(mean)	1·1–2·4	> 8·9	data for main refraction line is mean of observations at two different buoy positions

TABLE 2 (*cont.*)

								(*c*) *Indian Ocean*						
CR 22	5·19	(2·0)	0·3–0·8	—	—	12	3	6·70	0·15	7·28	0·12	0·8	> 9·3	irregular water depth (50 fm hump)
CR 23	4·97	1·86	0·4–0·6	see remarks		5	3	5·09	0·06	6·74	0·06	0·5	—	evidence of deeper 7·1 km/s layer 2·9 km below main refractor
CR 24	3·03	(2·0)	0·4	see remarks		4	3	3·92	0·09	4·02	0·05	0·4	—	evidence of deeper 6·7 km/s layer 2·7 km below main refractor
CR 25	4·86	(2·0)	1·1	5·09	1·1	3	1	6·74	0·35	7·59	0·11	2·2	> 9·3	5·09 km/s velocity from three good observations
CR 26	4·70	2·27	1·6	4·4	1·6	4	0	6·22	0·12	8·14	0·05	3·2	> 11·1	possible 0·2 km sediment above 2·27 km/s layer
Seychelles	0·03	2·4	0·02	5·58	0·13	3	3	6·02	0·06	0·045	5 × 10⁻⁴	0·15	—	6·02 and probably 5·58 are granite
								(*d*) *Mediterranean*						
CR 27	1·99	2·2	0·3	—	—	9	7	4·27	0·03	2·69	0·02	—	2·7*	4·27 km/s layer at least 2·4 km thick if 6·7 km/s underneath
CR 28	4·06	2·1	0·4	—	—	7	3	4·73	0·06	5·39	0·03	—	2·8	4·73 km/s layer at least 2·4 km thick if 6·7 km/s underneath
CR 29	3·57	(2·1)	0·3	—	—	5	0	4·30	0·31	4·76	0·15	—	2·9	4·30 km/s layer at least 2·5 km thick if 6·7 km/s underneath
CR 30	0·55	(2·1)	0·5	(3·49)	0·4	16	3	5·63	0·12	1·36	0·02	0·9	—	variation in thickness of overburden can be from 0·5 to 1·5 km along the line
CR 31	0·35	(2·1)	0·2–0·9	—	—	9	7	4·26	0·14	0·4–1·1	—	0·2–0·9	—	probable dip under buoys—velocity might be up to 4·85 km/s
Famagusta	0·72	2·0	0·5	4·40	(0·1)	4	2	6·7	0·3	2·17	0·03	1·7	—	4·40 km/s layer assumed thin with (2·4) km/s underneath
Morphou Bay	0·16	1·83	0·7–1·1	—	—	8	0	2·96	0·05	0·83	0·03	—	1·8	some evidence for (4·0) km/s 1·1 km beneath the 2·96 km/s layer
Malta	0·14	(1·8)	0·24	—	—	6	1	3·49	0·02	0·389	0·003	—	—	3·49 km/s layer at least 0·7 km thick
								(*e*) *Eastern North Atlantic*						
CR 1	4·64	(2·0)	0·4	(4·5)	2·7	4	0	6·18	0·18	7·08	0·2	1·2–3·1	—	could be 4·5 km/s or 3·0 km/s layer to give 2·2 to 3·1 km to main layer
CR 32	4·5	(2·0)	0·5	4·36	2·3	2	0	7·15	1·4	7·18	0·5	2·8	—	uncertain basement velocity
CR 33	3·29	(2·0)	0·5–1·2	—	—	10	5	5·45	0·56	5·02	0·12	0·5–1·2	—	room for not more than 0·2 km of (3·0) km/s at base of sediment layer
CR 34	2·99	(2·0)	0·5	4·68	1–2	4	0	6·65	0·82	4·58	0·3	2	—	the 4·68 km/s layer thins considerably along the line
CR 35	3·63	(2·0)	0·5	4·75	1·6	11	0	6·48	0·56	5·66	0·04	2·1	> 7	4·75 km/s layer has thickness variations of 0·3 km along the line
CR 36	2·97	(2·0)	0·7	3·8	1·5	7	3	6·54	0·08	5·23	0·03	2·2	> 7	evidence that sediment divides into 1·7 km/s and 2·0 km/s
CR 37	2·15	(2·0)	0·9	4·5	3·4	5	0	6·56	0·20	4·36	0·08	4·3	> 8	sediment varies 0·5–1·3 km along the line
CR 38	4·37	(2·0)	0·4	—	—	4	5	4·52	0·07	5·94	0·05	0·4	—	sediment increases to 0·7 km under reverse line
CR 39	4·21	(2·0)	0·5–0·9	—	—	6	5	5·4	0·3	6·01	0·12	0·7	—	maybe 4·9 km/s layer 1·2 km thick on top of 5·6 km/s layer
CR 41	4·11	(2·0)	0·2–1·7	—	—	11	5	5·33	0·21	5·81	0·15	0·2–1·7	—	the 5·33 km/s layer is probably 1·7 km thick and rests on 6·7 km/s material
CR 42	2·19	—	—	(2·9)	0·8	5	1	5·74	0·26	3·28	0·09	0·8	—	assumed hard rock rather than sediment on top of peak
CR 43	3·22	(2·0)	0·8	4·74	1·8	9	4	6·58	0·06	5·45	0·02	2·6	> 8	—
CR 44	1·55	1·78	0·4	(2·4)	0·9	3	2	5·5	0·25	3·10	0·04	1·3	—	sediment may be split up into 1·7 and 1·9 km/s layers
CR 44*a*	1·55	(1·78) (2·4)	1·3	(5·5)	1·1	4	0	6·69	0·12	3·46	0·12	2·4	> 13	cover material taken from result of station 44
CR 45	1·37	(2·2)	1·4	3·0	1·0	2	0	4·7	?	3·46	?	2·4	—	top 0·2 km of sediment has velocity 1·8 km/s

* This column, for the Mediterranean results only, is 'minimum depth to assumed 6·7 km/s layer'.