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

Crustal Structure between Kenya and the Seychelles

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Crustal structure between Kenya and the Seychelles

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A series of seismic refraction profiles has been shot between Kenya and the Seychelles Bank and in the neighbourhood of the Bank itself. Thick sediments have been observed for 300 to 400 km from the African coast. Near Kenya, great thicknesses of material of about 4·8 km/s velocity match closely the 9 to 10 km of Karroo beds expected on the coast at Lamu. The Mohorovičić discontinuity has been traced from 100 km off the African coast to the Seychelles Bank. West of the Bank the mantle is unusually shallow, rising to only 8·5 km below the surface, and the 6·8 km/s crustal layer unusually thin or absent. The absence of a gravity anomaly associated with this very shallow mantle raises a problem which has yet to be resolved.

Introduction

Between November 1961 and May 1963 the Naval surveying ship H.M.S. *Owen* carried out continuous underway bathymetric, magnetic and gravity measurements in the northwest Indian Ocean as part of the British contribution to the International Indian Ocean Expedition (Admiralty 1963). A detailed part of *Owen*'s work was in the Somali Basin between East Africa and the Seychelles (figure 1) and served as a reconnaissance for seismic work done by R.R.S. *Discovery* and H.M.S. *Owen* in September and October 1963. The most striking feature of the *Owen* profiles in this area is the absence of bathymetric, gravimetric and magnetic relief for at least 300 mi. out from the Kenya coast. This observation led to the suggestion that the area between the Kenya and a line halfway to the Seychelles is underlain by a thick wedge of sediments (Loncarevic & Matthews 1962). On geological grounds alone it is clear that the East African coast has been subsiding intermittently since about the end of the Karroo (Dixey 1960), so that the coastline may once have been much farther to the east. Baker & Miller (1963) go so far as to suggest that the Seychelles–Mauritius Ridge was once the eastern boundary of the continent.

The seven seismic refraction profiles between Lamu on the Kenya coast and the Seychelles Bank (the profiles were numbered 0, 1, 2, ..., 6 going eastwards) were planned to throw light on this hypothesis (figure 2). Further stations have been shot northeast and southwest of the Bank, and on the Bank itself. This work predominantly to the west of the Seychelles Bank is complementary to that carried out by the Scripps Institution of Oceanography to the east of the Bank in 1962, notably the line of stations occupied during the *Lusiad* Expedition running to the Chagos Archipelago along the 5° S parallel (Raitt & Shor, unpublished). On the *Lusiad* Expedition lines on the Seychelles and Saya de Malha Banks were shot (Shor & Pollard 1963). Hitherto, the northwest Indian Ocean had received little attention from refraction seismologists. Only the Seychelles Bank with its anomalous islands of granite had been investigated (Gaskell, Hill & Swallow 1958).

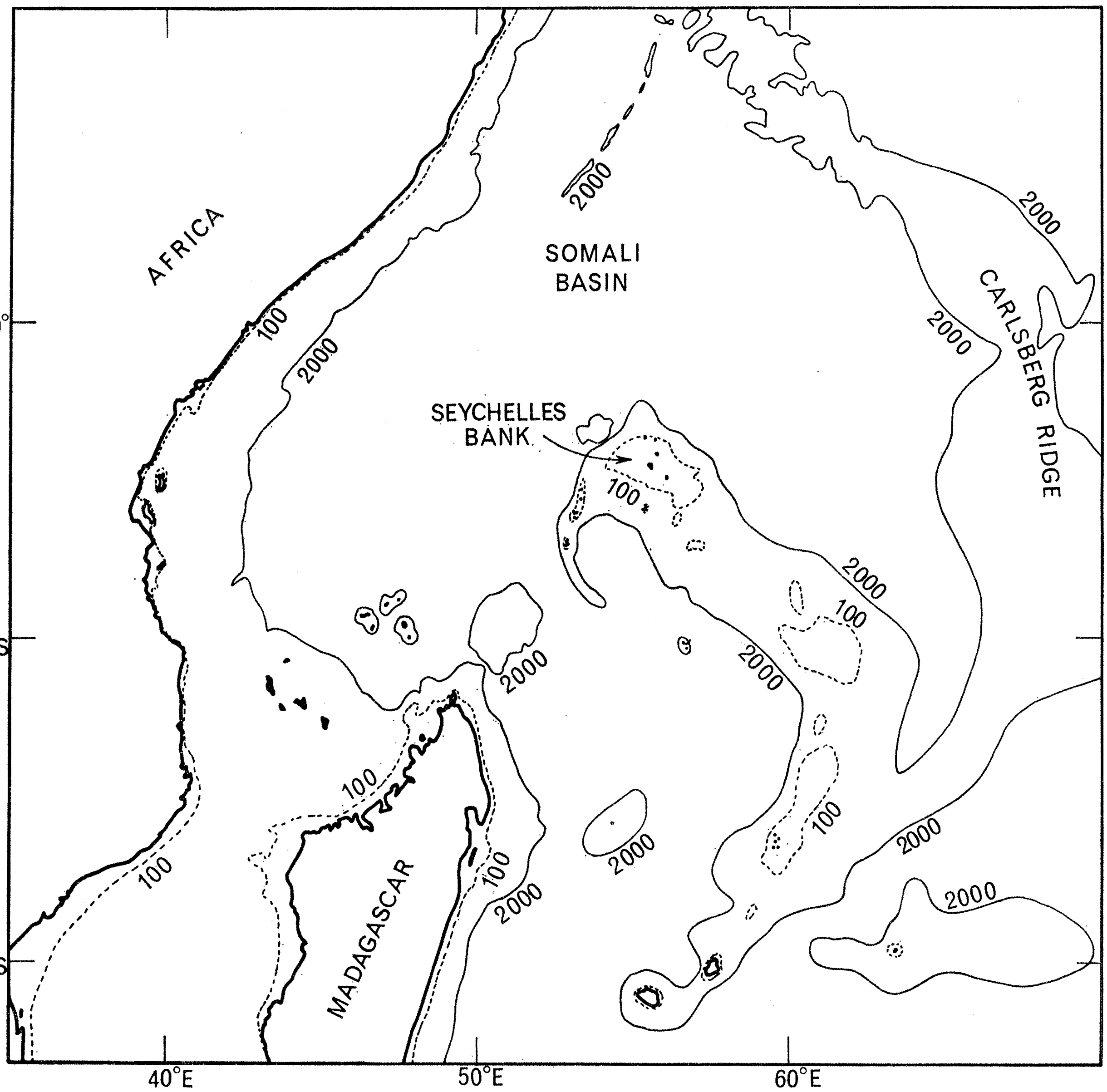

FIGURE 1. The major features of the North-West Indian Ocean. Depths in fathoms.

METHODS OF OPERATION

The receiving points were usually buoys, normally three of the sonoradio type (Hill 1963) and two of the internal-recording type (Francis 1964) being launched at 1 mi. spacings along the line of each station (Stations 5170, 5176, 5183 and 5191 (figure 2) were long-range single-ship stations relying on the internal-recording buoys for all arrivals beyond about 45 km range. Profiles 1, 2, 3, 5 and 6 were composite stations in which in each case buoys were laid twice, once for close range shots fired by *Discovery*, later for 300 lb. depth charges fired by H.M.S. *Owen* at long range. The remaining stations were likewise composite ones, but for which the buoys were launched only once.) Station 5210 has already been the subject of a paper (Davies & Francis 1964) and is also considered elsewhere in this volume; Station 5183 proved abortive as the result of very poor seismic propagation.

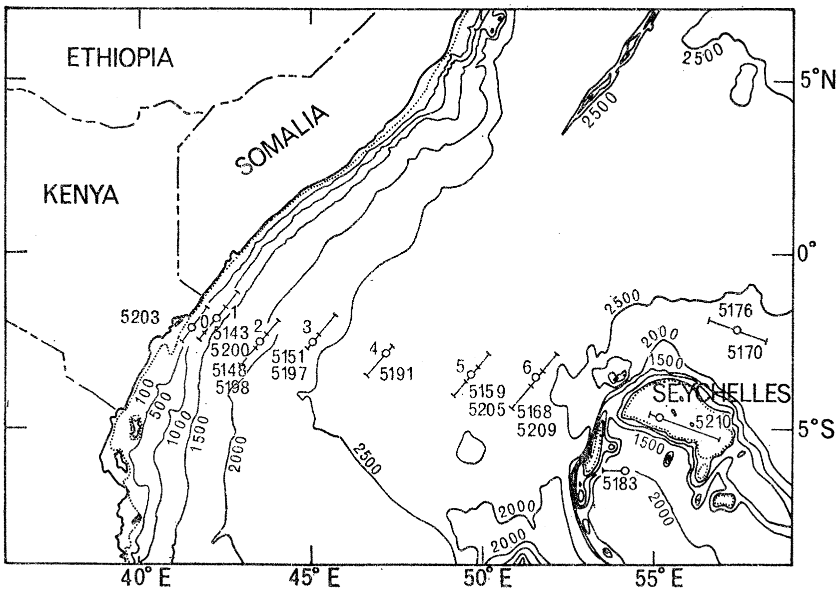

FIGURE 2. Positions of the seismic stations; the station numbers are marked. Depths on contours are in fathoms.

TABLE 1. SUMMARY OF SEISMIC REFRACTION STATIONS

profile	station	firing ship	max. range (km)
0	5203	*Discovery*	30
	5203	*Owen*	80
1	5143	*Discovery*	45
	5200	*Owen*	75
2	5148	*Discovery*	30
	5198	*Owen*	100
3	5151	*Discovery*	30
	5197	*Owen*	110
4	5191	*Discovery*	100
5	5159	*Discovery*	30
	5205	*Owen*	90
6	5168	*Discovery*	45
	5209	*Owen*	125
NE of Seychelles	5170	*Discovery*	80
	5176	*Discovery*	100
S of Seychelles	5183	*Discovery*	10
Seychelles Bank	5210	*Discovery*	40
	5210	*Owen*	200

METHODS OF ANALYSIS

Although many buoys were used at each station, it has not been considered worthwhile to deduce dip beneath them individually because the buoys usually drifted (on average at 0·5 to 1 kt.) several times their own spacing during a station. Dipping layer solutions (see, for example, Officer 1958) of the 'split' profile type, assuming a single mean receiving position, have been used where both dips and buoy drift were small. Corrections for variation in water depth were applied on the assumption of layering parallel to the bottom, but were only appreciable for profiles 0 and 1.

TABLE 2. RECEIVING POSITIONS, LINE DIRECTIONS, SEISMIC VELOCITIES AND LAYER THICKNESSES FOR INDIAN OCEAN STATIONS

profile	mean receiving position	line direction	velocity (km/s)					layer thickness (km)					depth to mantle (km)
			a	*b*	*c*	*d*	*e*	water	*a*	*b*	*c*	*d*	
0*	2° 23′ S, 41° 22′ E	040°	1·7†	2·88	4·71	7·04	—	1·46	1·0	3·4	9·3	—	—
		alternative solution	1·7†	2·88	3·49	4·71	7·04	1·46	1·0	2·3	1·5	9·0	—
1	1° 45′ S, 42° 07′ E	220°–040°	1·7†	3·54	4·80	7·16	8·1†	2·06	1·4	3·1	8·1	4·0	18·7
2	2° 40′ S, 43° 28′ E	220°–040°	1·8†	2·52	5·28	(7·00)	8·08	3·60	0·9	2·6	3·1	3·3	13·5
3	2° 31′ S, 44° 56′ E	220°–040°	1·93‡	2·53	6·56	8·14	—	4·17	1·0	2·7	4·6	—	12·5
4	2° 55′ S, 47° 02′ E	220°–040°	1·79	2·49	5·28	6·85	8·1† (8·54)	4·81	0·7	1·0	2·5	5·9	14·9
5	3° 28′ S, 49° 36′ E	220°–040°	I6·I	2·5† (2·63)	(4·20)	7·88	—	5·04	0·1	0·6	3·5 2·5	*Disc.* *Owen*	9·2 *Disc.*
6	3° 36′ S, 51° 29′ E	220°–040°	1·8†	6·24	8·18	—	—	5·06	0·3	3·1	—	—	8·5
NE of Seychelles	2° 12′ S, 57° 18′ E	290°–110°	1·78‡	4·86	6·86	8·14	—	4·38	0·3	1·8	4·7	—	11·2
Seychelles Bank§	4° 46′ S, 55° 04′ E	290°–110°	2·0† or 3·5	5·72	6·26	6·78	8·1†	0·05	0·3	3·3	9·4	18·9	32·0

* Shot in one direction only, but spread of buoys and their great drift (2·7 kt.) assumed to give average structure.
† Assumed velocity. The sediment velocities for profiles 0, 1, 2 were suggested by bottom seismic measurements (Shorthouse 1964).
‡ Velocities from bottom seismic measurements (Shorthouse 1964).
§ The full interpretation of this station has been published by Davies & Francis (1964).
( ) Velocity from a single run.
Water surface velocity everywhere 1·54 km/s; sounding velocities from hydrographic data.

Because of the sound velocity structure of the water in this part of the Indian Ocean the direct sound (D) could only be observed at ranges less than about 30 km and at long ranges even the first reflexion (R_1) was not observed. Fortunately, for many of the stations the velocity structure and depth of the water were such as to make $R_1 - D$ constant by the time D disappeared and $R_2 - R_1$ constant before R_1 disappeared. In these cases extrapolation to D was easy. By means of smoothed models of the velocity structures it can be computed that the differences do indeed, within the accuracy of measurement, become constant.

Table 2 summarizes the seismic results.

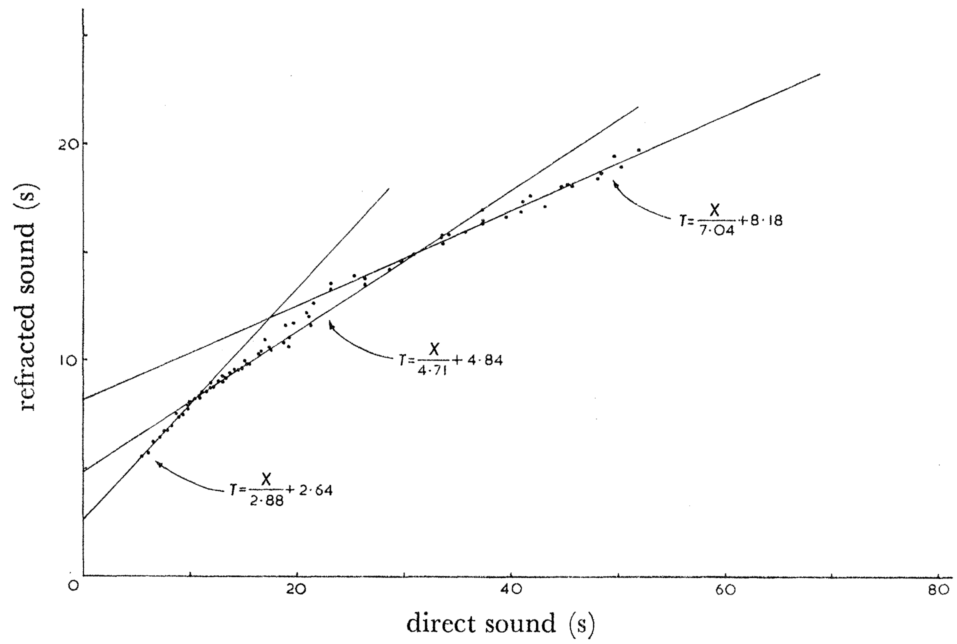

Figure 3. Profile 0: travel-time curve. The range may be expressed in kilometres by multiplying the 'direct sound' time by 1·540.

Results

(a) *Profile* 0 (figure 3*)

Station 5203 was shot over the canyons of the continental slope in the full strength of the Somali current. During the operation, the buoys drifted at 2·7 knots into deeper water. Shots were fired to the northeast only, but the spread of the buoys and their rapid drift has probably smoothed out much of the effect of dip so that an average structure has been obtained. First arrivals on the 4·71 km/s line beyond 14 s range were weak, but were followed by strong second arrivals lying, with some scatter, on a line of 3·49 km/s with 3·74 s intercept (not drawn on figure 3). An alternative solution is therefore possible and is shown in table 2. The delay in the first arrivals at ranges between 22 and 26 s might be evidence for a fault in the 4·71 km/s layer at about the 800 fm. contour, downthrown on the seaward side.

* On the travel-time diagrams the equations of the observed lines are marked; X is the range in kilometres, T the refraction travel time in seconds.

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

(*b*) *Profile* 1 (figure 4)

The surface current was again high for Stations 5143 and 5200, about 1·5 kt. to the northeast, and resulted in the movement of the buoys over a distance about 10 mi. for both stations. The differences in slopes and intercept of the various lines obtained from either side of the buoys is doubtless caused by the roughness of buried topography. The lines of lowest velocities obtained from late arrivals had poorly determined slopes and intercepts too small even for refractions along the bottom. The observations have been neglected and 1·7 km/s has been assumed as the velocity for the superficial sedimentary layer. The 3·54 km/s layer is confirmed by reflected-refracted arrivals to the southwest. Two arrivals beyond 40 s range to the southwest fall below the 7·40 km/s line and are interpreted as mantle arrivals. An assumed 8·1 km/s through their centre of gravity gives an intercept 9·15 s.

(*c*) *Profile* 2 (figure 5)

A dipping-layer solution has been provided for the layers with the two lowest velocities observed for Stations 5148 and 5198. The 2·52 km/s layer is confirmed by reflected refractions. The 7·53 km/s velocity measured to the southwest is probably incorrect because of changes in structure along the line. The 7 km/s velocity determined from first arrivals to the northeast agrees with reflected-refracted arrivals on both sides. For these reasons a horizontal 7 km/s layer is shown in figure 6. Mantle velocities are well observed each side, the apparent velocities and intercepts agreeing within their probable errors (7·99 ± 0·08, 8·16 ± 0·17 km/s; 8·68 ± 0·08, 8·92 ± 0·16 s). Since changes in the overlying structure have probably contributed more to the errors in this velocity and intercept than dip in the Mohorovičić discontinuity itself, the mean velocity 8·08 km/s is taken through the centres of gravity of each group of points to give intercepts for calculating the depth to the mantle. Horizontal layering throughout is assumed in the layer calculations for the 7 and 8·08 km/s velocities. The complete solution is shown in figure 6.

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

(*d*) *Profile* 3 (figure 7)

This profile (Stations 5151 and 5197) is outstanding in the number of reflected-refracted arrival times and the fact that the results from all buoys are entirely consistent. On this basis the structure can be said to be more uniform along the lines of shots than that of any other line occupied between Kenya and the Seychelles. The refractions from sedimentary layers only appear at the closest ranges as first arrivals, but are clearly distinguishable to more than 30 km as later arrivals. The complete dipping-layer solution (figure 8) shows the 2·53 and 6·56 km/s layers dipping gently to the southwest. The two-ship Station 5197 was shot only to the northeast, but the typical mantle velocity obtained, 8·14 km/s, together with the small dip of the overlying structures, makes the assumption of no dip reasonable. In addition, two arrivals to the southwest are earlier than can be attributable to the 6·39 km/s line. A line equivalent to a velocity of 8·14 km/s through the centre of gravity of these two points gives an intercept of 9·36 s; this is within the standard error of the intercept observed to the northeast (9·27 ± 0·09 s).

All the reflected-refracted paths have been identified and are shown in figure 9. The calculations are summarized in table 3. The clear observation of arrivals along these paths

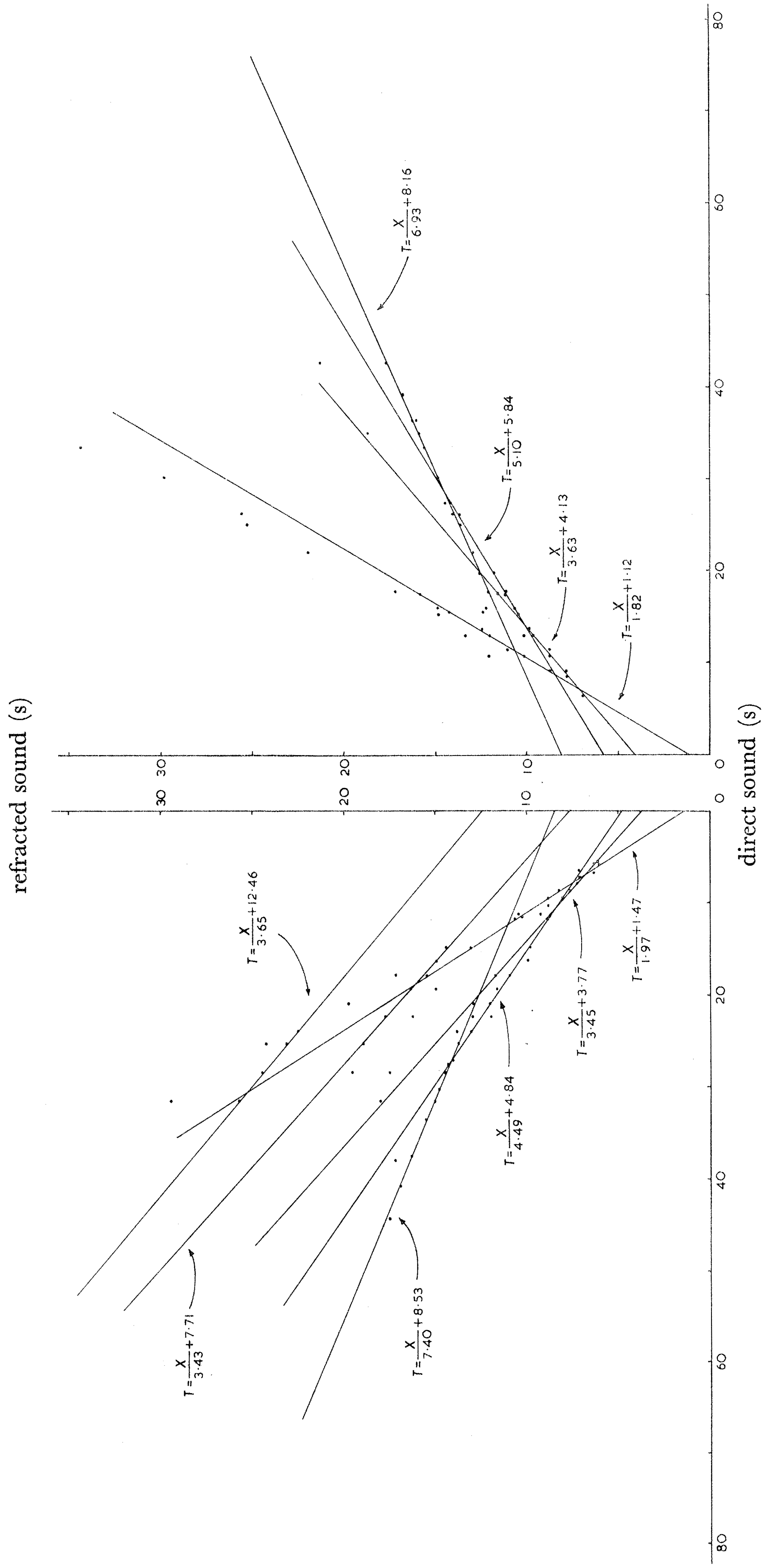

FIGURE 4. Profile 1: travel-time curve.

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

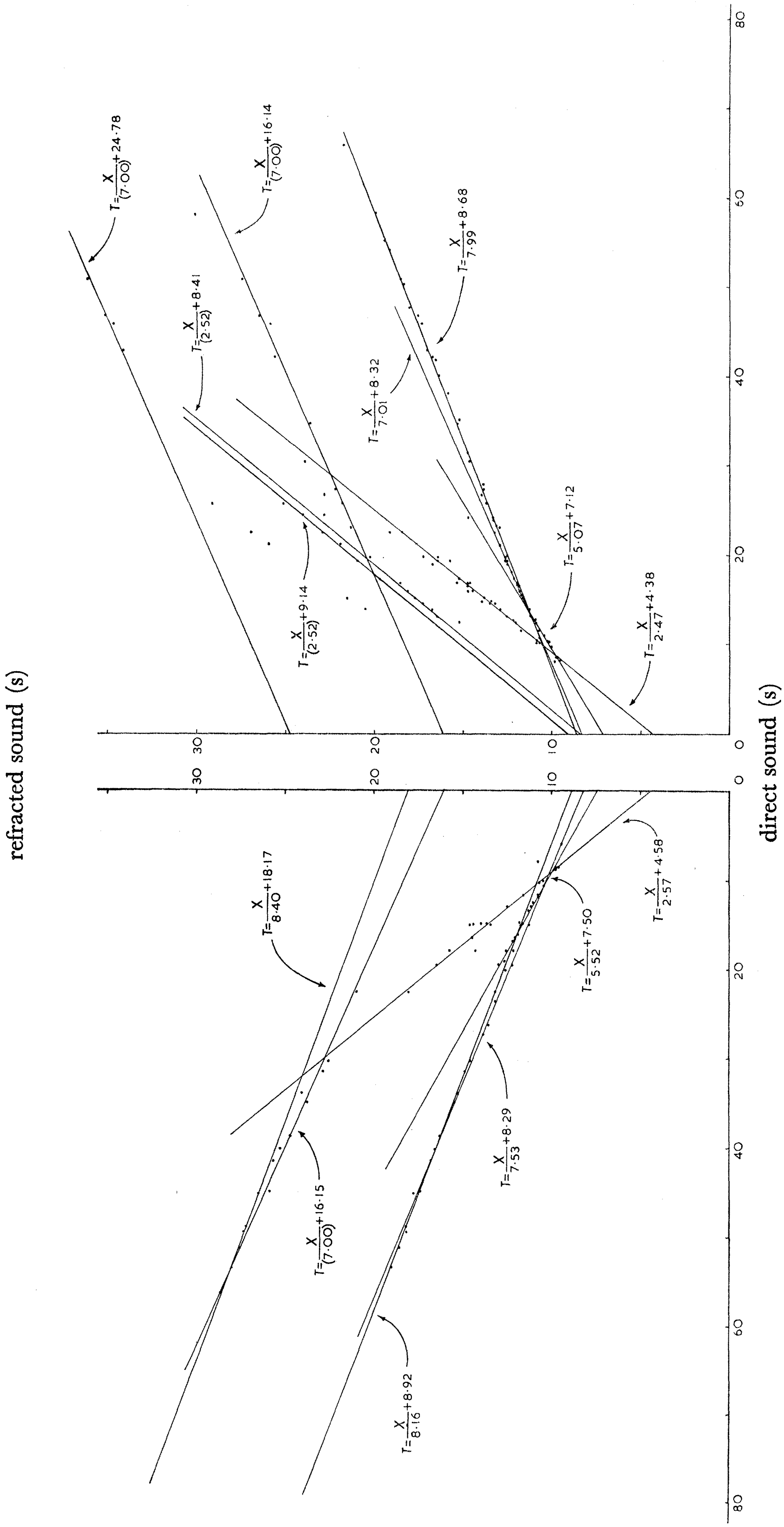

FIGURE 5. Profile 2: travel-time curve.

has doubtless resulted from the uniformity of structure along the lines. Only the slopes and intercepts obtained from first arrivals have been used in the determination of structure. The identification of the ray path is in general simple. The most interesting paths are *b* and *d*, involving respectively reflexion from below and above (at less than critical angle) the 1·93/2·53 km/s boundary. Figure 10 shows part of records obtained from the south-west by one of the recording buoys.

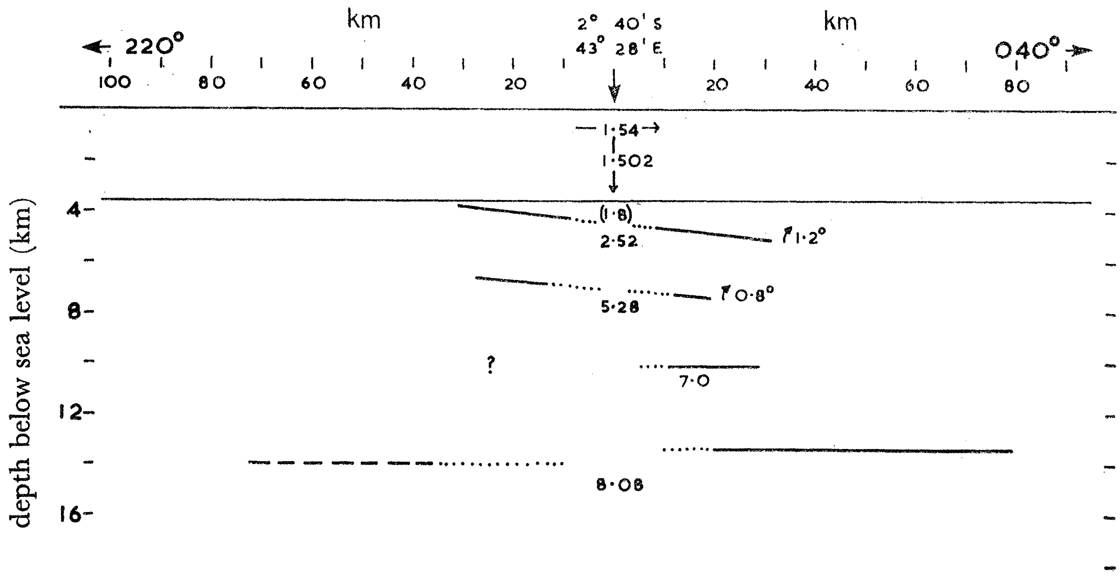

FIGURE 6. Profile 2: dipping layer solution. The seismic velocities are given in kilometres per second; the vertical exaggeration is 5:1.

(*e*) *Profile* 4 (figure 11)

This profile (Station 5191, figure 11) was carried to long range only to the southwest and was a single-ship operation. High frequency (50 to 60 c/s) arrivals lie on a line, tangential to the curve of the first reflexion from the sea floor. These were observed on both sides of the buoys and correspond to a velocity of 1·79 km/s at or very near the surface of the sediments. The lines of slope equivalent to 2·5 km/s observed on profiles 2 and 3 can still just be observed. The dipping-layer solution (figure 12) for the 2·49 and 5·28 km/s layers cannot be correct since the layers apparently interpenetrate. The thicknesses at the centre of the line are shown in table 2. The apparent velocities 6·89 and 6·72 km/s are combined to give a velocity of 6·85 km/s dipping 0·8° to the southwest. The 3·68 and 3·42 km/s velocities are both taken to be modes of propagation dependent upon the shear wave velocity in the layer in which the longitudinal velocity is 6·85 km/s.

The one determination of mantle velocity, 8·54 km/s is probably high because of structural variation rather than dip in the Mohorovičić discontinuity itself or a true change in mantle velocity. For this reason 8·1 km/s represents the slope of the line which has been forced through the centre of gravity of these points to give an intercept from which the depth to the mantle has been calculated assuming horizontal layering above.

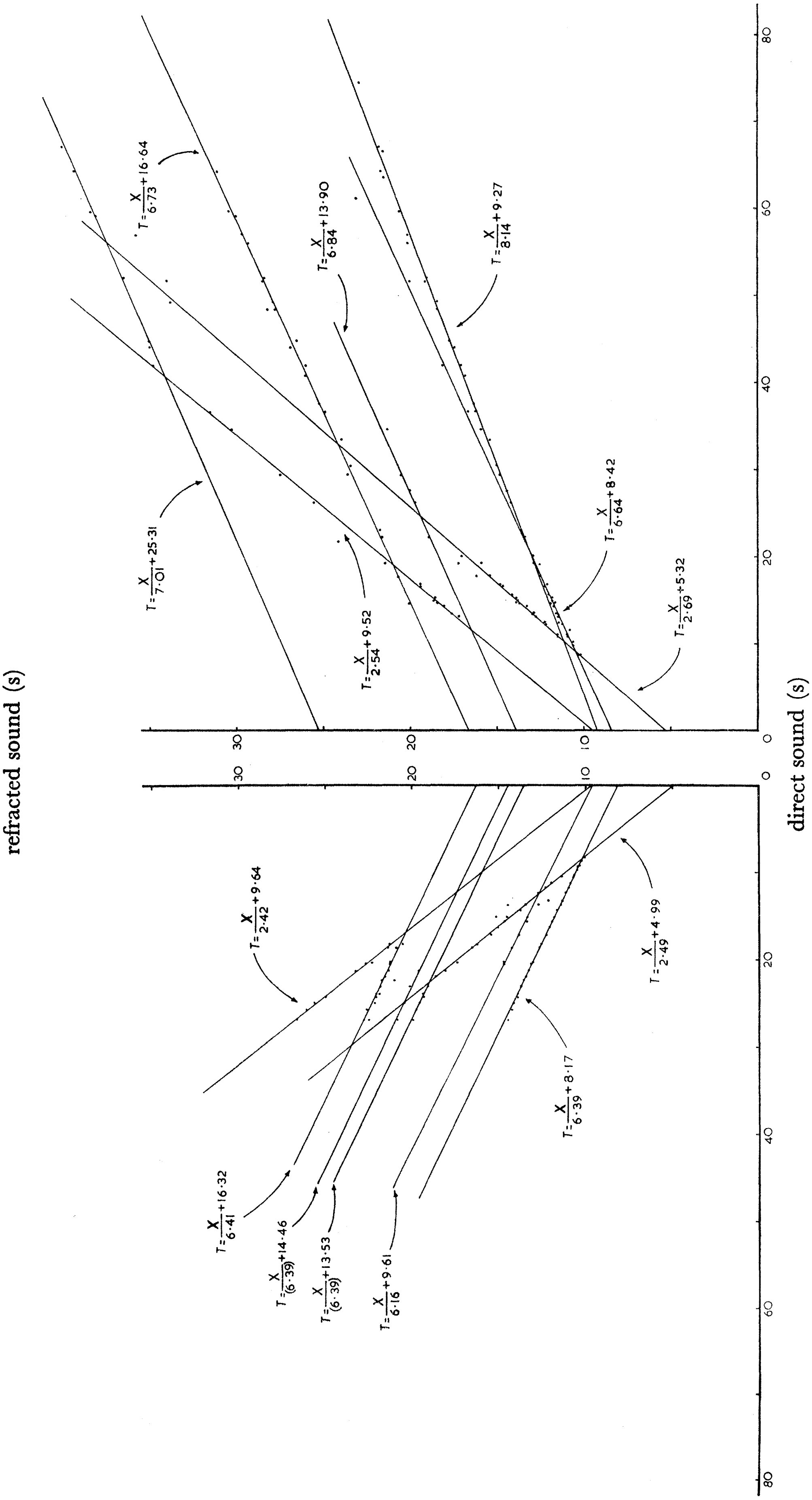

FIGURE 7. Profile 3: travel-time curve.

(*f*) *Profile* 5

This was the only profile on which the results from the *Discovery* and *Owen* stations (Stations 5159, 5205) did not dovetail well together. The *Owen* line was displaced about 5 mi. to the southeast of the *Discovery* one, but its arrivals appeared 0·3 to 0·4 s earlier

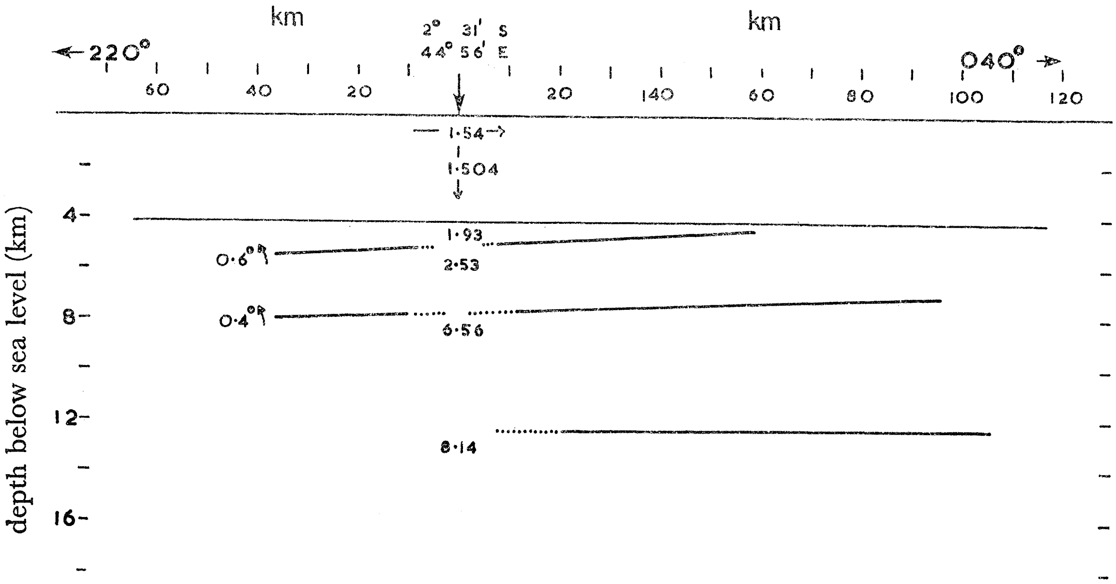

FIGURE 8. Profile 3: dipping layer solution.

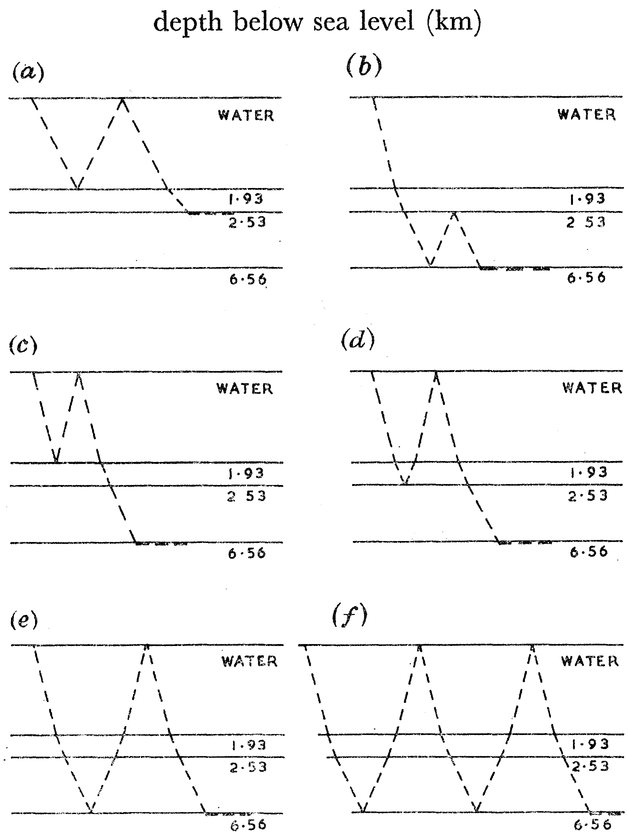

FIGURE 9. Profile 3: ray paths for reflected-refracted signals.

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

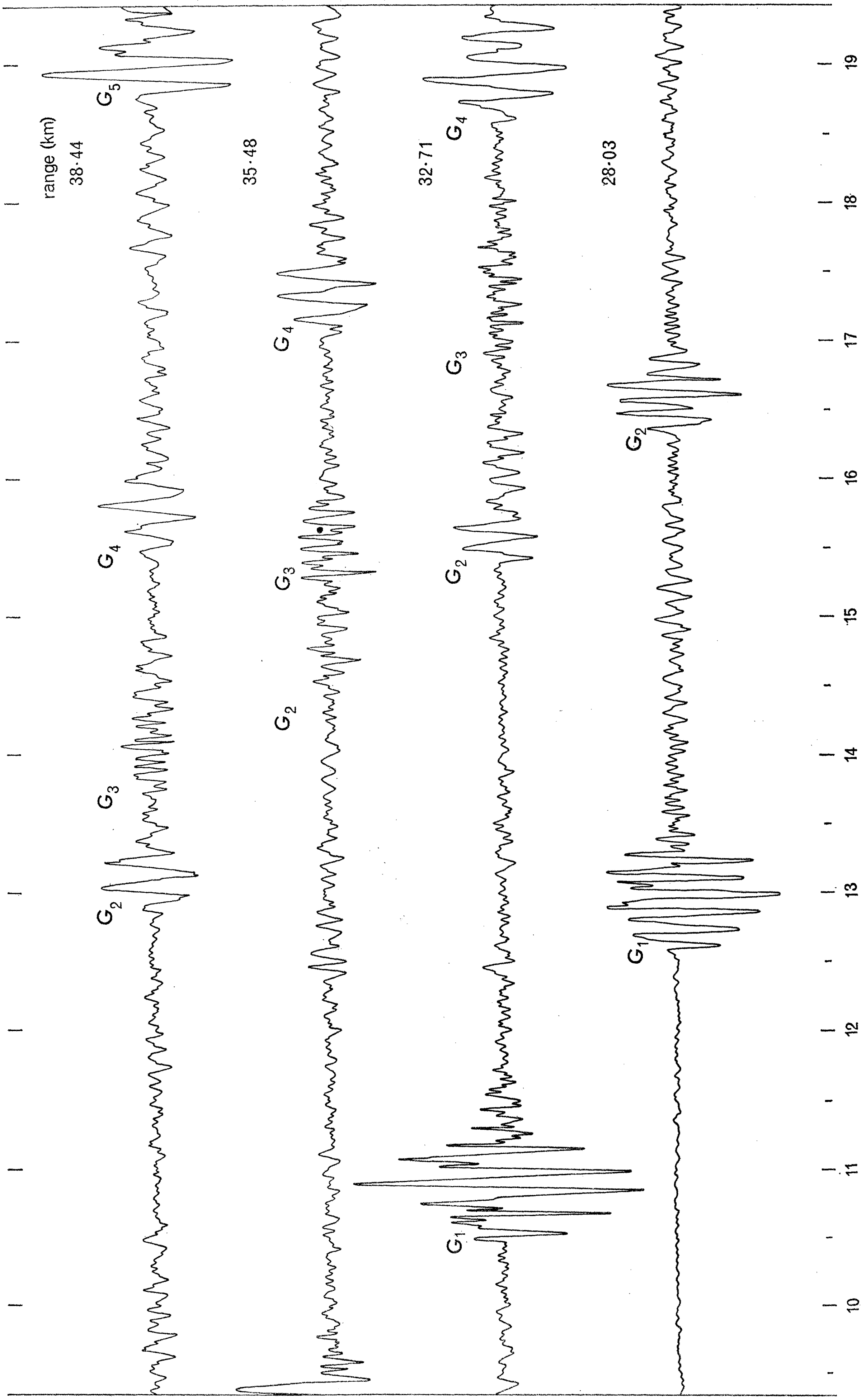

FIGURE 10. Profile 3: typical records from an internal-recording buoy showing large amplitude late arriving signals.

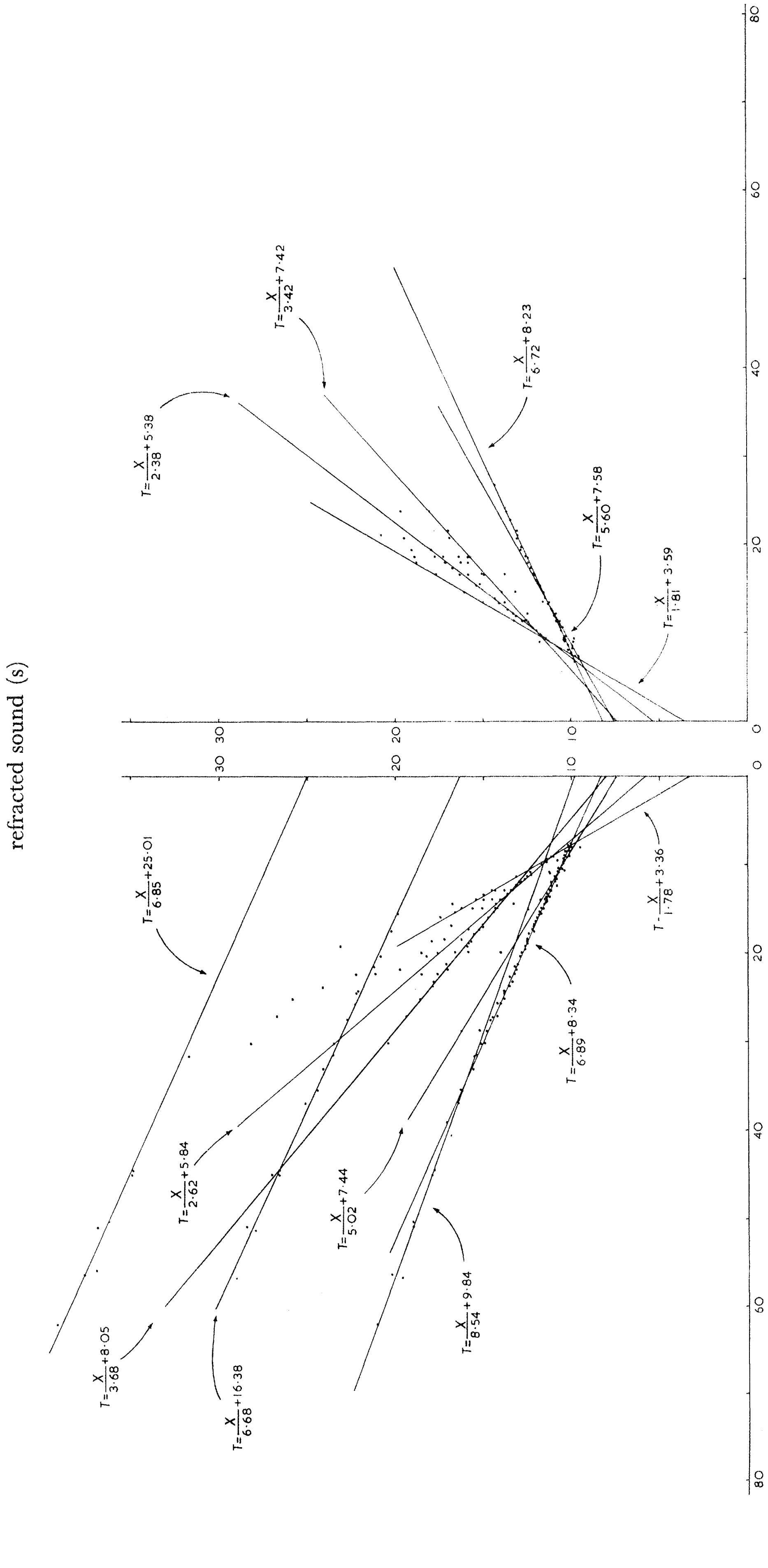

FIGURE 11. Profile 4: travel-time curve.

than would have been expected from the *Discovery* travel-time plot. The two stations have been treated independently, but all arrivals are shown in figure 13. The 7·80 and 7·99 km/s lines are from Station 5205, the remainder are from Station 5159.

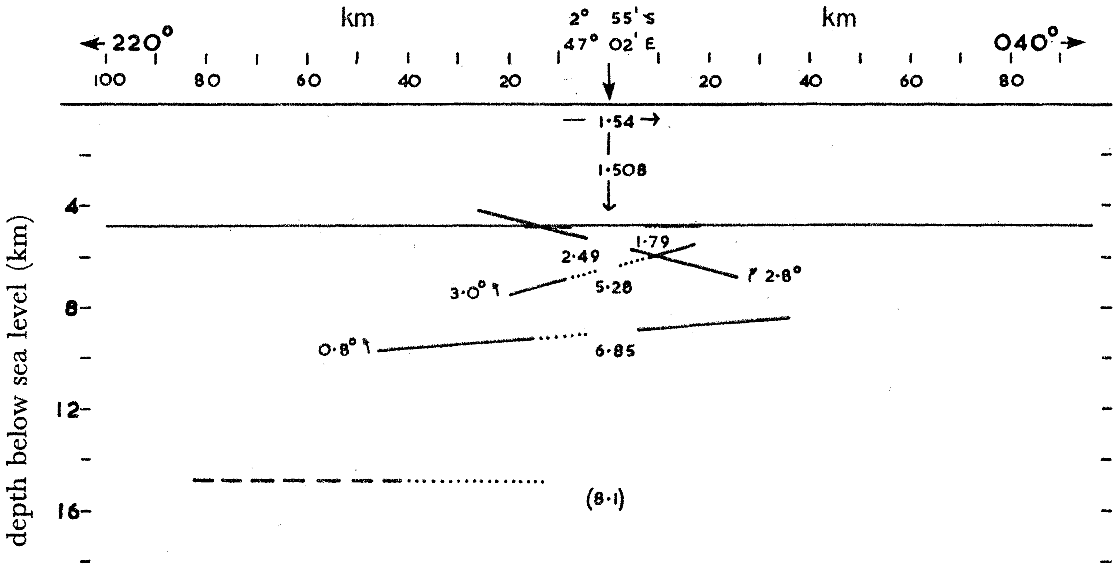

FIGURE 12. Profile 4: dipping layer solution.

TABLE 3. IDENTIFICATION OF REFLECTED-REFRACTIONS

observed velocity and intercept (see figure 8) (km/s)	(s)	ray-path solution (see figure 9)	calculated intercept
2·42 ± 0·04	9·64 ± 0·23	*a*	9·57
2·54 ± 0·02	9·52 ± 0·12	*a*	9·57
(6·39)	9·76	*b*	9·98
(6·39)	13·53	*c*	13·57
6·84 ± 0·32	13·90 ± 0·27	*c*	13·82
(6·39)	14·46	*d*	14·53
6·41 ± 0·27	16·32 ± 0·23	*e*	16·34
6·73 ± 0·07	16·64 ± 0·11	*e*	16·84
7·01 ± 0·13	25·31 ± 0·24	*f*	25·26

(Velocities in parentheses have been determined from second or later arrivals.)

High-frequency (*ca.* 50 c/s) arrivals lie on a line tangential to the first reflexion from the bottom. These give a 1·91 km/s velocity for the top of the sediments. Arrivals from Station 5159 to the northeast were much more scattered than those to the southwest. For this reason the shallow structure has been determined entirely from the shots to the southwest. The velocity of 2·63 km/s could be interpreted as arising from a mode of propagation dependent on the shear wave velocity in the layer whose longitudinal wave velocity is 4·20 km/s. However, an interpretation is favoured which assumes this velocity is obtained from longitudinal waves only since this is in better agreement with the bottom seismic observations in the same area (Shorthouse 1964) and with the results from profiles 2, 3 and 4.

A crustal layer of velocity 6·8 km/s is noticeably absent, and the mantle velocity (7·88 km/s) and the depth to the mantle are both unusually low, as figure 14 shows,

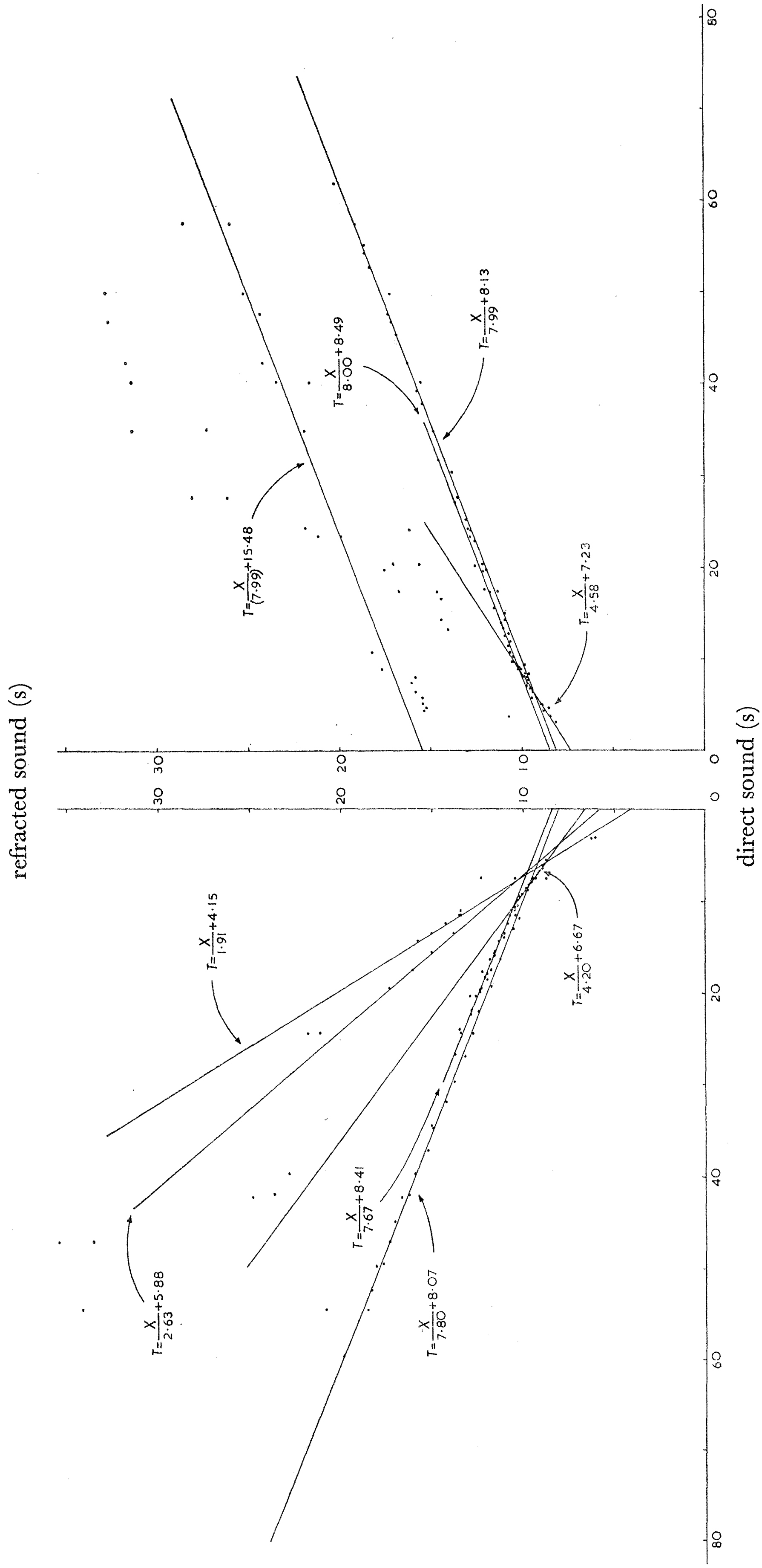

FIGURE 13. Profile 5: travel-time curve.

whichever station is considered. A masked 6·8 km/s layer up to 2·1 km thick can be present along the line of Station 5159 without producing first arrivals, but is not possible along the line of Station 5205. In conclusion, it is clear that the area is one of great structural change so that even the small difference in position between the stations confuses the travel-time plot. It is certain, however, that the mantle is shallow and the 6·8 km/s crustal layer thin or absent.

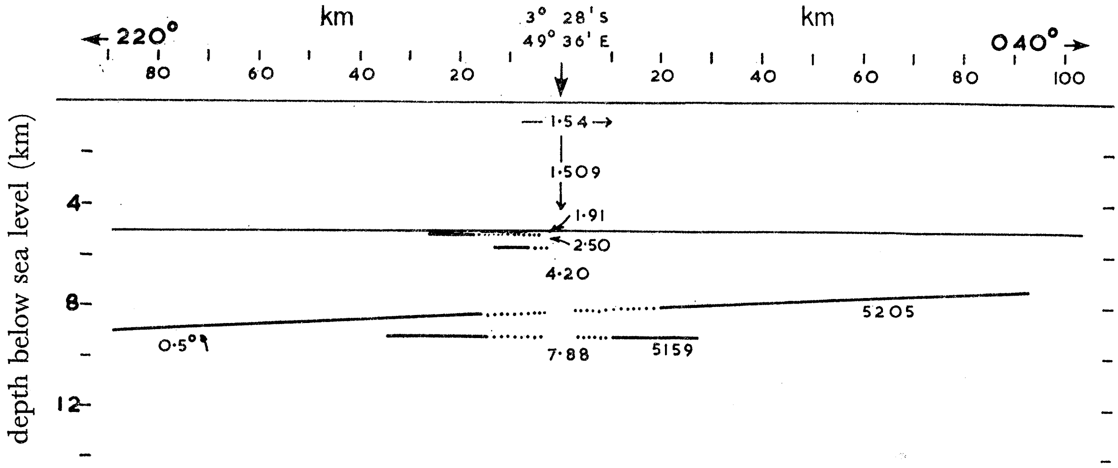

FIGURE 14. Profile 5: dipping layer solution.

(*g*) *Profile* 6 (figure 15)

In contrast to the neighbouring profile 5, buoy drift and differences in the buoy positions for the two Stations 5168 and 5209 were unimportant. Intercepts from each side agreed well and there was justification for a dipping layer solution. The lower velocities observed agree more closely than their probable errors and are averaged to 6·24 and 3·66 km/s. The 6·24 km/s represents longitudinal propagation in the layer immediately underlying the soft sediments. The velocity of 3·66 km/s is represented by a line of approximately the same intercept and a velocity ratio (6·24/3·66 = 1·70) suggesting a mode of propagation controlled by the shear wave velocity. However, a simple shear wave interpretation provides a thickness of the overlying layer inconsistent with the longitudinal wave interpretation. The latter interpretation is preferred. The next velocities observed each side are typical of the mantle, which is interpreted as dipping 0·8° to the northeast only 3·4 km below the sea bottom (figure 16). The apparent velocities may in fact reflect horizontal variations of velocities rather than dip, so that too much weight should not be attached to the mantle being less than 2 km below the sea floor at the southwest end of the line. As on profile 5, the 6·8 km/s crustal layer is absent. Even if it is assumed present it could at most be 2 km thick and would depress the Mohorovičić discontinuity by only 0·4 km.

The extraordinarily shallow Mohorovičić discontinuity makes a further examination of the mantle velocities worthwhile. To test the possibility that points from a lower velocity layer are included in the long lines, each long line has been split into two more or less equal halves and least squares lines calculated for each half. Table 4 shows the results of this. The southwest lines agree closely; to the northeast it is the outer half which has the lower velocity.

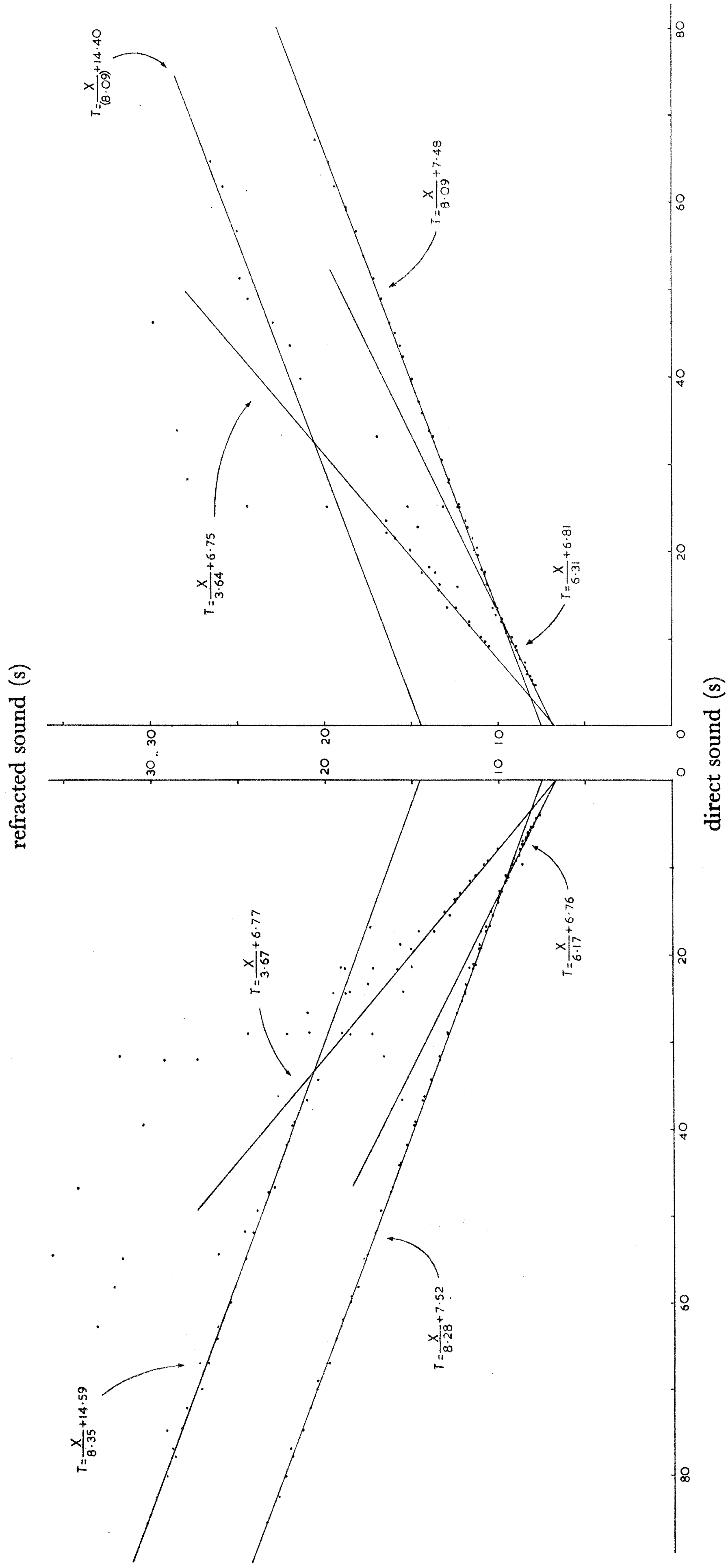

FIGURE 15. Profile 6: travel-time curve.

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

Finally, the reflected-refracted arrivals are interpreted as undergoing reflexion at the top of the 6·24 km/s layer and at the sea surface in addition to their refracted path in the mantle rocks. The results from this profile, while unusual for the deep ocean, are based on particularly reliable data.

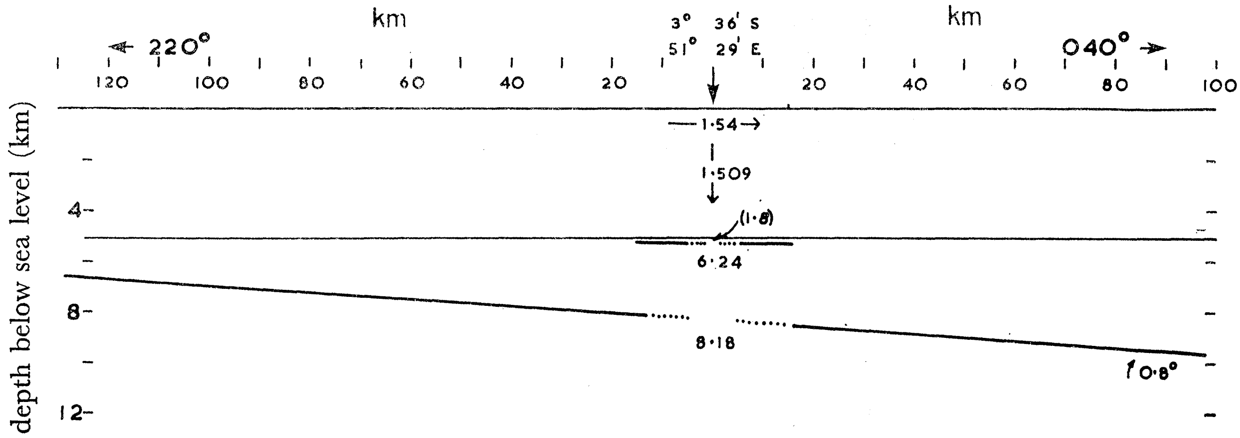

FIGURE 16. Profile 6: dipping layer solution.

TABLE 4. BREAKDOWN OF MANTLE ROCK VELOCITIES FOR PROFILE 6

range observed	velocity (km/s)	intercept (s)
SW > 11·5 s	8·28 ± 0·02	7·52 ± 0·02
11·5–50	8·19 ± 0·04	7·47 ± 0·02
> 50	8·25 ± 0·09	7·46 ± 0·14
NE > 13	8·09 ± 0·03	7·48 ± 0·03
13–40	8·10 ± 0·07	7·49 ± 0·04
> 40	7·84 ± 0·10	7·14 ± 0·13

(*h*) *Northeast of Seychelles Bank* (figure 17)

These two Stations 5170, 5176 form the two halves of a 'split' profile. Bottom seismic measurements in the area showed the sediment velocity to be 1·78 km/s (Shorthouse 1964). Because of the difference in the mean receiving positions for the two stations, a dipping-layer solution has been calculated from the observed velocities and related to the appropriate intercepts on each side. This approach results in the discontinuities in depth shown in figure 18. The lines representing the highest velocities on each side (7·85 km/s and 8·24 km/s) were combined to give mantle depths assuming horizontal layering above. It is unlikely that the Mohorovičić discontinuity rises all the way to the western end of the line. A rise in the westerly direction of the 6·86 km/s layer beyond about 40 km could produce the same apparent velocities.

CONCLUSIONS

Figure 18 shows the complete crustal section between Lamu on the Kenya coast and the Seychelles. The gravity and magnetic anomaly profiles were obtained by H.M.S. *Owen* during 1962 and 1963. The geological column at Lamu is inferred from nearby geological and geophysical work by B.P. Petroleum Development Limited.

The seismic results establish the existence of thick sediments out to profile 3. In

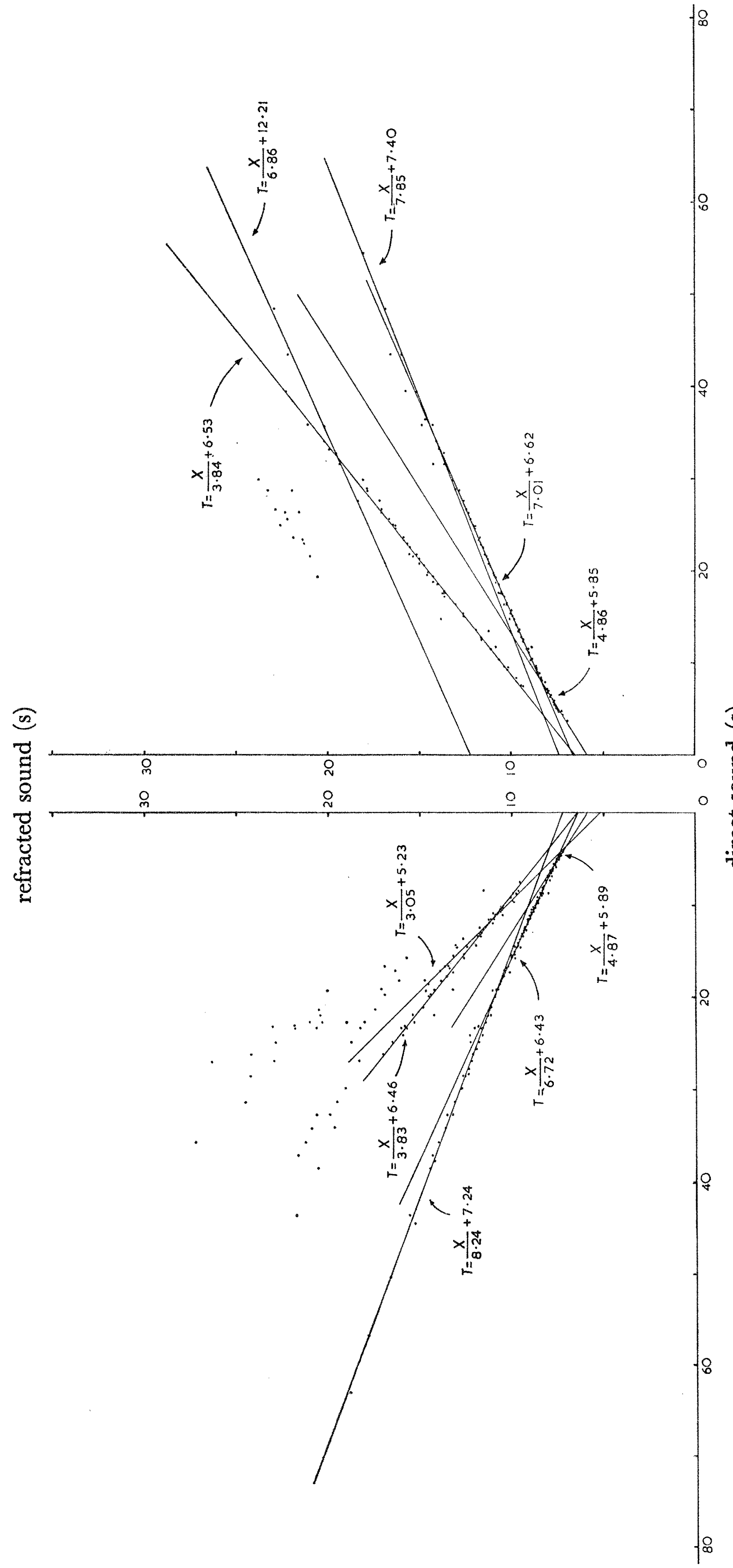

FIGURE 17. Northeast of Seychelles: travel-time curve.

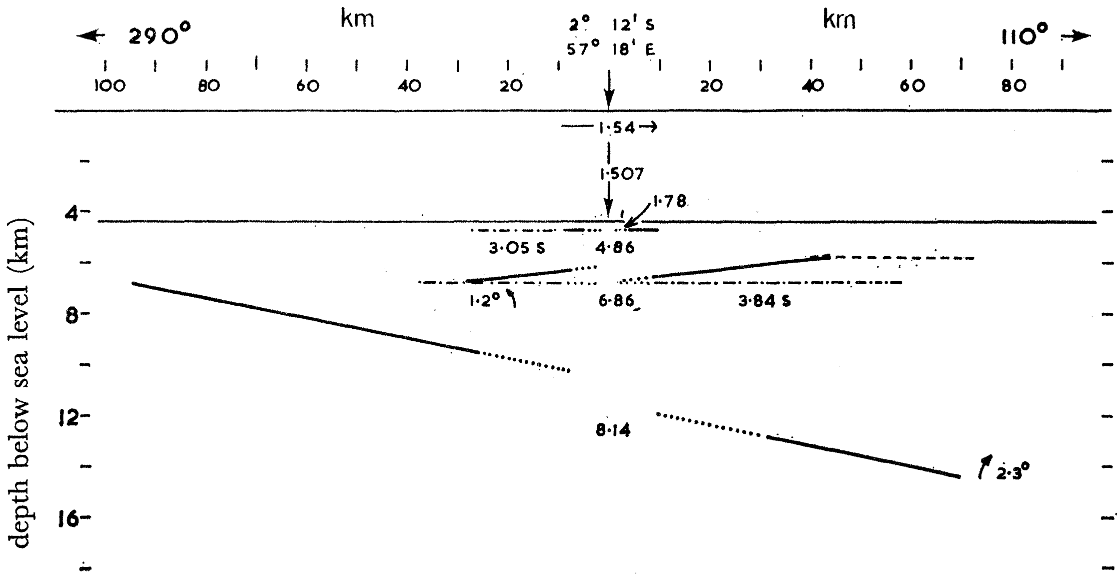

FIGURE 18. Northeast of Seychelles: dipping layer solution. Key to refracting horizons: —, first arrival *P* wave; – – –, reflected *P* wave; – · – · –, *S* wave.

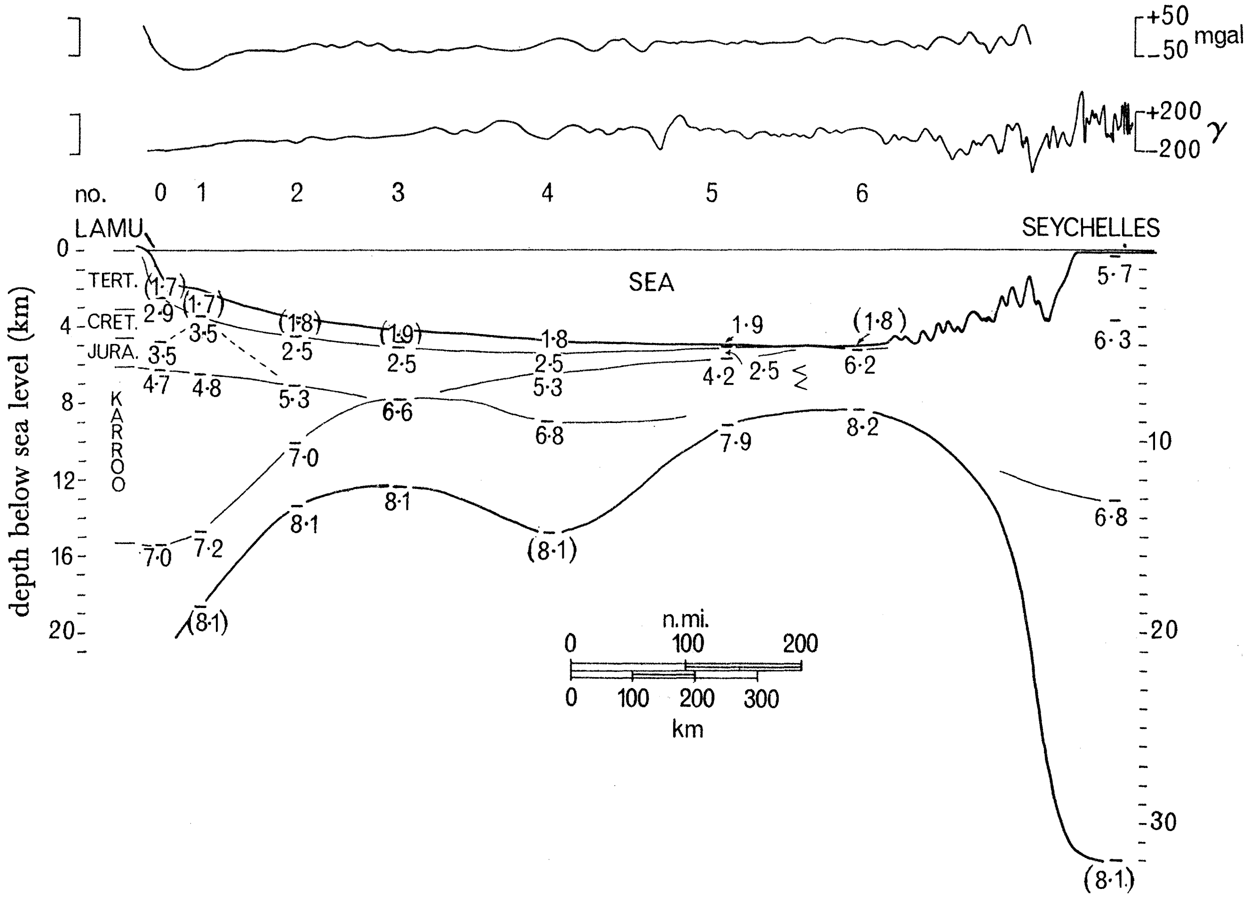

FIGURE 19. The seismic section from Lamu to Seychelles combined with the B.P. postulated geological column at Lamu. The seismic velocities are given in kilometres per second; the vertical exaggeration is 30:1. Gravity and magnetic profiles of H.M.S. *Owen* are included.

particular, the thicknesses and velocities of the 4·7 and 4·8 km/s material at profiles 0 and 1 correspond well with the Karroo beds inferred for Lamu (see figure 19). The 6·6 to 7·2 km/s velocities are typical for basic crustal rocks beneath both oceans and continents (Steinhart & Meyer 1961; Raitt 1963). The 2·5 km/s material, well established on profiles 2 and 3, is probably consolidated sediment of Jurassic and Cretaceous age, laid down perhaps when the water depth in these areas was not so great. The soft sediment probably started to form during the Tertiary.

The increasing magnetic relief from about profile 4 eastwards makes it probable that the 5·3 and 4·2 km/s velocities of profiles 4 and 5 are from volcanic material such as is usually supposed to exist in normal deep oceans. The 6·2 km/s velocity of profile 6 is rather high for such an interpretation and it is tempting to consider it as representing an extension of the Seychelles granite batholith to the west.

A comparison must be made of the profile from the East African coast with those obtained from the eastern seaboard of the United States (Drake, Ewing & Sutton 1959). There are two fundamental differences. First there is no magnetic relief in the region of the 'continental rise'. Secondly, there is no indication of a sedimentary trough beyond the continental shelf edge.

The most striking and unexpected result of the seismic work is the remarkable shallowing of the Mohorovičić discontinuity and absence of the basic crustal layer on profiles 5 and 6. The 8·5 km depth to the discontinuity on profile 6 is particularly well established. This is as shallow as any Mohorovičić discontinuity depth determinations for this water depth. The anomalous feature of this result is that it conflicts with the gravity measurements. The use of the normal Nafe–Drake relationship of the velocity as a function of density (Talwani, Sutton & Worzel 1959) for computing gravity anomalies, gives the free air anomaly at profile 6 of about 140 mgal higher than that at profile 3. The observed difference is only about 20 mgal. The structures of profile 6 and Stations 5170, 5176 to the northeast of the Seychelles Bank are, however, consistent with each other gravitationally. This is a problem which must be resolved. In general, seismically and gravitationally determined discontinuities agree well if one seismic station is used to start the gravity computation (Worzel & Harrison 1963). The solution of our problem probably lies in the rocks not following the usual velocity–density ratio exactly.

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

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