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Thickness of the Earth's Crust in Antarctica and the Surrounding Oceans

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Summary

Love waves and Rayleigh waves from eight earthquakes recorded at Hallett Station, Scott Base and Mirny have been analysed and the dispersion compared with that predicted by theory for simple model crusts. The average thickness of the crust in eastern Antarctica is found to be about 35 km, as is typical of continents, whereas Marie Byrd Land with an average thickness of about 25 km cannot be regarded as truly continental. Love wave dispersion indicates that the thickness of the solid crust in the oceanic regions surrounding Antarctica varies from about 5 km to 10 km, the smaller values being associated with the deeper basins. It is shown that the determination of oceanic crustal thickness from Rayleigh wave dispersion is in general subject to large uncertainties, nor can one usually rely on values of the thickness of unconsolidated bottom sediments obtained by this means.

1. Introduction

The broad structure of the land beneath the Antarctic ice cap can be determined only by indirect means. The ice cap is of continental size but this does not imply a single co-extensive land mass. Geological evidence points to the existence of a continental shield in eastern Antarctica whilst western Antarctica appears to be characterized by young folded belts, but the extent of these two geological provinces is uncertain. Much of the coastline is devoid of exposed rock and little is known of the region between the Weddell Sea and the Ross Sea, separating eastern from western Antarctica. Seismic reflection work in Antarctica has revealed that the rock surface lies below sea-level at many places in the interior, and often at a sufficient depth to remain below sea-level if the ice were to melt, even allowing for consequent isostatic uplift.

The installation of seismograph stations in Antarctica for the International Geophysical Year has provided an opportunity for determining the main features of the Antarctic crust by a study of guided earthquake waves. In a preliminary notice of the work described in this paper it was shown that the eastern Antarctic crust in the region from Victoria Land to Wilkes Land is about 35 km thick (Evison, Ingham & Orr 1959). This finding provided definite geophysical support for the presumption of a land continent in Antarctica, since the continents are characterized by a crustal thickness of about 35 km in contrast to thicknesses of 5–15 km in oceanic regions. Similar studies of the dispersion of Love and Rayleigh waves have also been carried out by Press & Dewart (1959), from seismograms obtained at Wilkes Station, and whilst they confirm the continental thickness of the area mentioned above, they report a much thinner average for paths through other sectors of Antarctica. This latter result is partly explained by the present study.

Hallett Station and Scott Base are well placed for distinguishing between eastern and western Antarctica, and separate determinations have been obtained for the crustal thickness in these two major sectors. Records from Mirny have been used mainly for measuring the dispersion of waves travelling across the South Indian Ocean. It appears that for most of the paths along which Press and Dewart found the average thickness to be less than continental much of the deficiency occurs in western Antarctica. The present results indicate, however, that the crust is continental throughout eastern Antarctica.

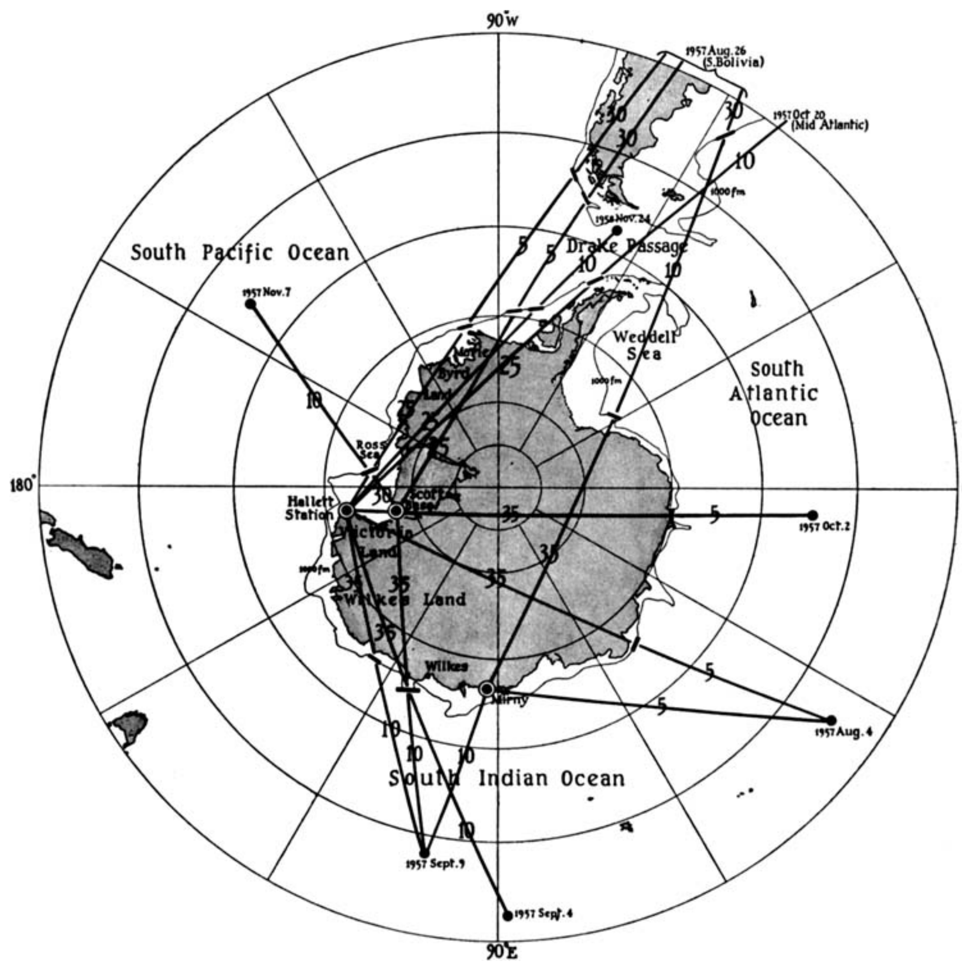

FIG. 1.—Wave paths, showing thickness of crust inferred for each segment.

2. Observations

Details of the eight earthquakes used in this study are listed in Table 1. Epicentres and origin times were taken from the monthly bulletins prepared by BCIS and USCGS. Earthquakes were chosen for which the wave paths would give good coverage of Antarctica, as illustrated in Figure 1. Epicentres close to Antarctica were preferred so that the contribution of the Antarctic segment of the path to the total dispersion would be as large as possible. Details of the seismographs that provided the records used in this study are as follows:

Hallett Station:	Columbia seismograph, 3 components $T_0 = 15$ s, $T_g = 75$ s.
Scott Base:	Benioff seismograph, vertical and E–W, $T_0 = 0{\cdot}6$ s, $T_g = 25$ s.
Mirny:	Kirnos seismograph, 3 components, $T_0 = 12{\cdot}5$ s, $T_g = 1{\cdot}2$ s.

The preference for epicentres close to Antarctica results in shorter paths being used than is usually the case in studies of this kind. Consequently the degree of dispersion on some records was rather limited. A majority of the records studied, however, came from the long period Columbia seismograph at Hallett Station, and a few of these are reproduced in Figure 2.

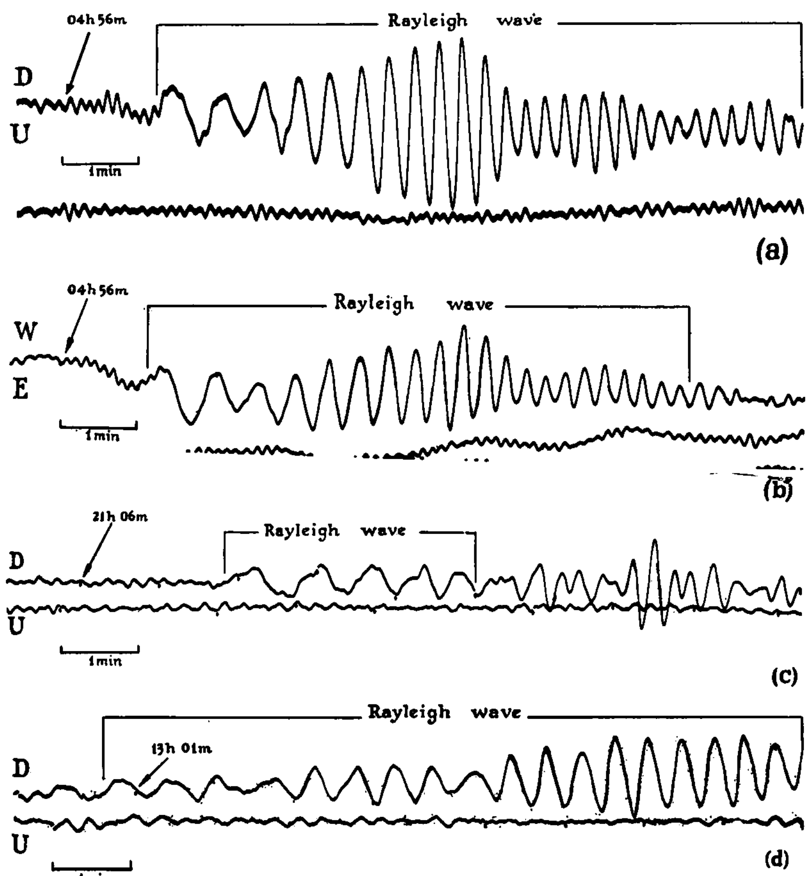

FIG. 2.—Rayleigh waves recorded at Hallett Station for earthquakes of 1957 Sept. 4 (a and b), 1957 Oct. 2 (c), and 1957 Oct. 20 (d).

Table 1

Particulars of Earthquakes

Date	Origin time h	m	s	Epicentre Lat.	Long.	Locality	Recording Station	Distance (km)	Wave	Component	Ocean segments, average water depth (km)	Figure
1957 Aug. 4	21	08	51	45°S	35°E	Prince Edward Is.	Hallett	6510	Love	N–S, E–W	Indian Ocean, 4·50	6
									Rayleigh	Z		8a
							Mirny	4120	Rayleigh	E–W, Z	Indian Ocean, 4·18	8b
Aug. 26	11	28	50	19°S	63°W	S. Bolivia	Scott	8805	Rayleigh	Z	S. Pacific, 4·21	13b
							Hallett	9140	Rayleigh	Z	S. Pacific, 4·45	11b
							Mirny	10315	Rayleigh	N–S, Z	S. Atlantic, 3·80	10b
									Love	N–S		12c
Sept. 4	04	33	52	42½°S	88½°E	Indian Ocean	Hallett	5295	Rayleigh	E–W, Z	Indian Ocean, 3·88	10a
Sept. 9	00	13	31	47¾°S	101°E	S. Indian Ocean	Mirny	2125	Rayleigh	N–S, Z	Indian Ocean, 3·72	9b
							Scott	4290	Rayleigh	E–W, Z	Indian Ocean, 3·80	9a
							Hallett	4350	Rayleigh	E–W, Z	Indian Ocean, 3·80	9a
									Love	N–S		7
Oct. 2	20	42	56	54½°S	5°E	Bouvet Is.	Hallett	5895	Rayleigh	Z	S. Atlantic, 4·35	11a
Oct. 20	12	04	22	11½°N	42°W	Mid Atlantic	Hallett	12915	Rayleigh	N–S, Z	Atlantic, 3·98	13a
											S. Atlantic, 3·81	
Nov. 7	06	21	56	57½°S	143½°W	S. Pacific	Scott	2920	Love	E–W	S. Pacific, 3·71	12a
1958 Nov. 24	06	48	57	57½°S	65½°W	Drake Passage	Hallett	4990	Love	E–W	Drake Passage, 3·80	12b
									Rayleigh	E–W, Z		11c

3. Method of analysis

The virtual absence of seismic activity in Antarctica makes it necessary to rely on waves that have first passed through some neighbouring oceanic region, and perhaps through some other continent as well. The recorded dispersion is therefore composed of two or more separate effects, of which one is of primary interest to us. The usual method of dealing with such composite wave paths is to assume that the dispersion due to an extraneous segment conforms with an empirical curve that has been derived for a known region of normal continent or ocean. When a correction has been made for this segment the remaining dispersion may also be assessed by comparison with the appropriate empirical curve. This is the method used by Press & Dewart (1959) in their analysis of Love and Rayleigh waves across Antarctica. The advantage of the method is that one does not have to postulate a simplified model crust and assume values for the various seismic parameters.

In the present study a different method has been adopted, in which the observations are compared with theoretical rather than empirical results. Theoretical dispersion curves have been computed from equations given by Stoneley (1948) for Love waves, by Lee (1932) for continental Rayleigh waves and by Jardetzky & Press (1953) for oceanic Rayleigh waves. The advantage of this method is that any departure from normal crustal thickness is readily accommodated. One finds that where a well-recorded dispersive wave has traversed a composite path the analysis reveals a value of crustal thickness for each segment, and surprisingly often there is a unique combination of values that will give reasonable agreement between observation and theory. Thus in the present study the results for Antarctica do not depend on assumed values of crustal thickness for the adjacent regions.

The models adopted for the purpose of computing theoretical dispersion curves consist simply of horizontal layers of uniform thickness, overlying a semi-infinite mantle. For the continental case a single crustal layer is postulated, and for the oceanic case a water layer and a single rock layer. The following seismic constants are assumed, incorporating the parameters used in Stoneley's (1948) computations for Love waves:

	Water	Crust	Mantle
Compressional velocity (km/s)	1·52	6·01	7·79
Shear velocity (km/s)		3·47	4·50
	Crust/water	Mantle/crust	
Density ratio	2·65	1·283	

Figure 3 shows the family of theoretical Love wave curves for selected thicknesses of crust. Since Love waves are not affected by a fluid layer the dispersion for any path, whether continental or oceanic, is given by an appropriate curve of this family. Figure 4 shows dispersion curves for continental Rayleigh waves.

In computing the theoretical dispersion of oceanic Rayleigh waves one has to assign a further parameter, namely the ratio of the thickness of the rock layer (H_1) to that of the fluid layer (H_0). Table 2 shows values of U and T/H_0, where U is the group velocity and T the period, computed for $H_1/H_0 = 1$, 2 and 3. Dispersion curves for selected values of H_1 are given in Figure 5.

In a wave path that is made up of a number of segments let m_n be the length of the nth segment, expressed as a fraction of the whole path length, and let U_n be the group velocity of a particular period traversing that segment. Then the group velocity of the period taken over the whole path is $U = 1/\Sigma_n(m_n/U_n)$.

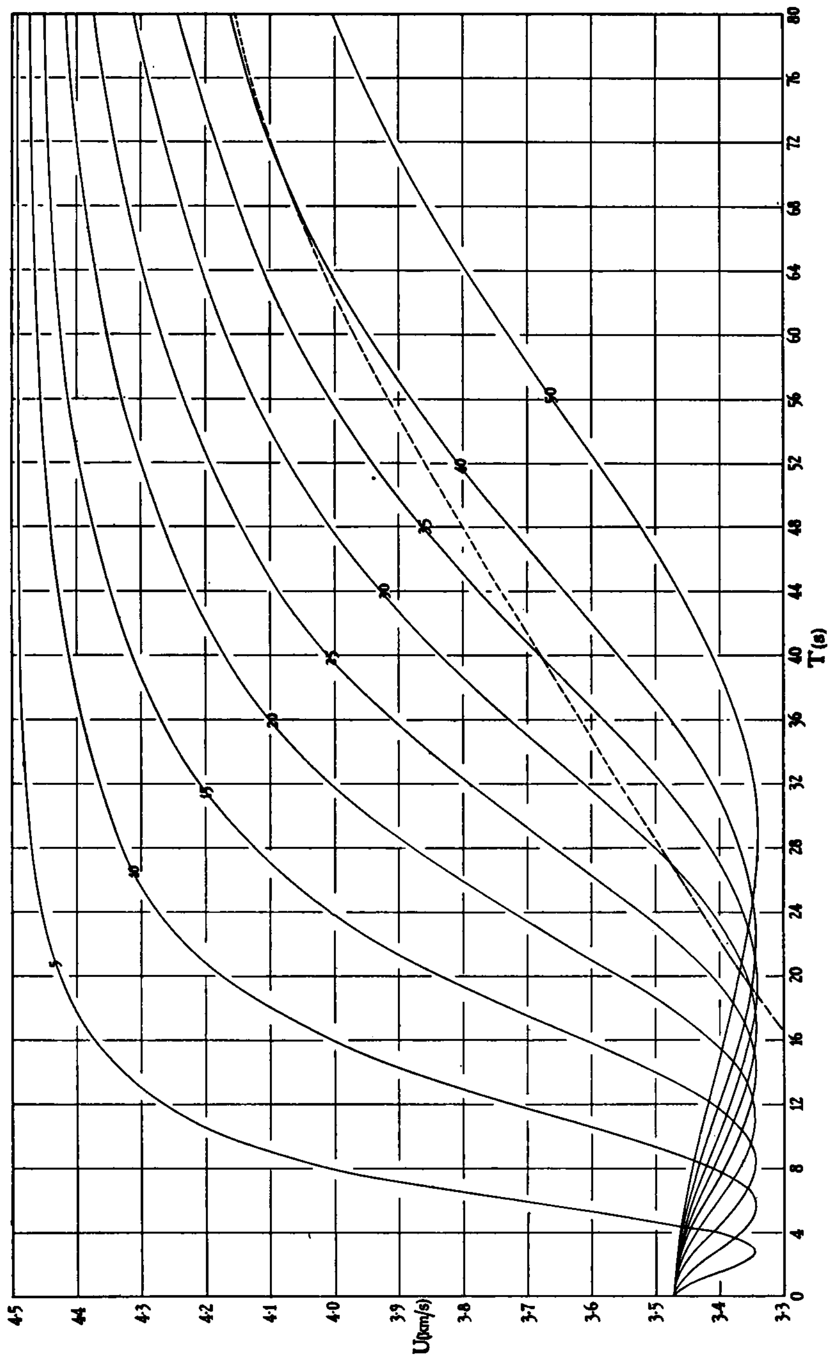

FIG. 3.—Theoretical Love wave dispersion for thicknesses of crust from 5 km to 50 km. Broken line shows empirical curve for North America. (Press & Dewart 1959.)

Thus we may construct theoretical dispersion curves for a composite path by assigning to each segment some curve from Figure 3, 4 or 5, making due allowance in

Table 2

Dispersion of oceanic Rayleigh waves

$H_1/H_0 = 1$		$H_1/H_0 = 2$		$H_1/H_0 = 3$	
U (km/s)	T/H_0 (s/km)	U (km/s)	T/H_0 (s/km)	U (km/s)	T/H_0 (s/km)
1·157	2·595	1·350	2·719	1·584	2·917
1·684	2·723	1·813	2·880	2·123	3·165
2·139	2·856	2·421	3·065	2·642	3·445
3·011	3·138	3·183	3·474	3·244	4·021
3·689	4·195	3·747	5·179	3·776	6·309
3·859	5·239	3·900	6·986	3·905	8·831
4·002	8·210	4·001	11·908	3·998	15·442

each case for the appropriate fractional length m_n. In measuring these lengths we have adopted the usual convention that the boundary between land and ocean is defined by the 1 000 fathom depth contour. In Figure 1 each wave path is shown divided into its segments; the captions to Figures 6–13 give the length of each segment as a percentage of the whole path. For simplicity, in a few cases a short stretch of water shallower than 1 000 fathoms has been included in an oceanic segment.

The recorded dispersion is represented by means of points on a graph; this is achieved by the usual procedure, in which a graph of arrival time against serial number is prepared for a suitable succession of recorded phases. The interpretation of the observed dispersion results for a particular path is then a matter of finding those theoretical curves which, when combined in the manner described above, provide the best fit to the plotted data.

The average depth of water along each oceanic segment has been calculated from bathymetric charts. This depth is useful, as will be seen later, in helping to resolve the indeterminacy that usually arises in interpreting the dispersion of oceanic Rayleigh waves.

4. Choice of parameters

The type of crustal model that one must be content to adopt in this kind of study, if the computations are to be performed in a reasonable time by desk calculator, is undoubtedly very much simpler than any real crust. Consequently it is not to be expected that the seismic parameters appropriate to the model will correspond precisely with particular values that might be determined by other means, for example by a study of body waves from earthquakes or artificial explosions. Such values usually pertain to a limited region of the medium—thus refracted waves are apt to indicate the velocity near the upper surface of the refracting layer—and they cannot well be adopted for theoretical purposes until more complex models can be readily analysed.

Even the simple models adopted here involve seven seismic parameters, apart from the ratio of fluid depth to crustal thickness that is required in the case of oceanic Rayleigh waves. Computations can be found in the literature for a variety

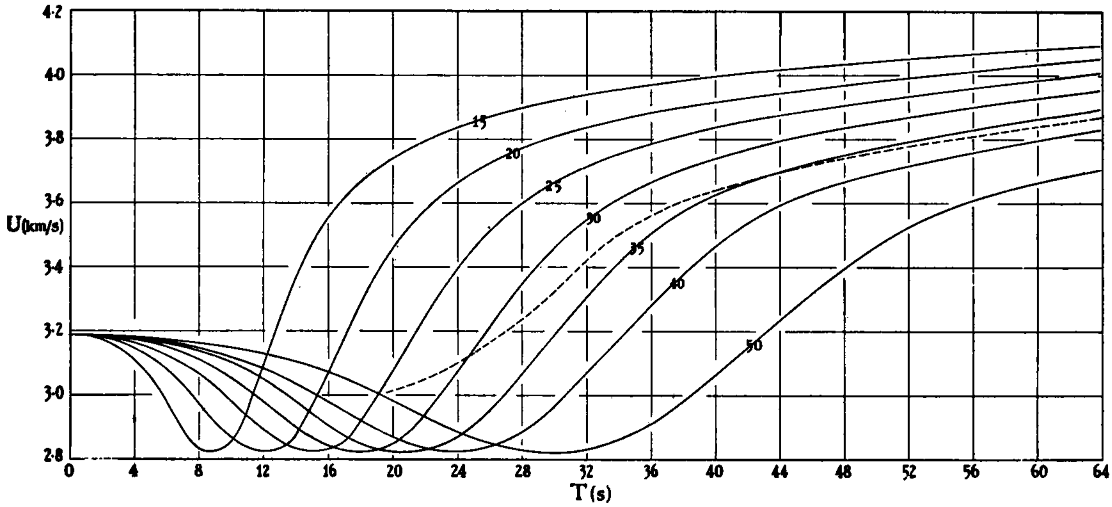

Fig. 4.—Theoretical Rayleigh wave dispersion for land paths, with thicknesses of crust from 15 km to 50 km. Broken line shows empirical curve for North America and Africa (Press & Dewart 1959).

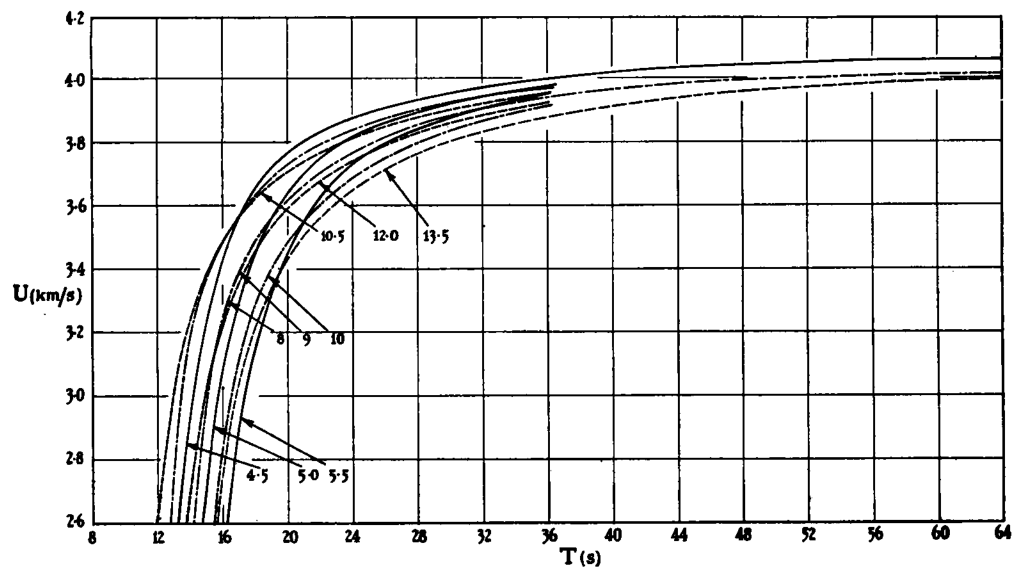

Fig. 5.—Theoretical Rayleigh wave dispersion for oceanic paths.

	Crustal thickness / Fluid depth	Crustal thickness (km)
————————	1	4·5, 5·0, 5·5
—·—·—·—·—	2	8, 9, 10
- - - - - - - - -	3	10·5, 12, 13·5

of parameter values, but a thorough study of the effect of each separate parameter upon the dispersion curve must await a systematic coverage of the problem by electronic computer. In the absence of any compelling reason for a more elaborate choice of parameters it has been thought desirable to use the same values for the continental and oceanic cases, and also for both Love and Rayleigh waves.

The values of compressional velocity (6·01 km/s) and shear velocity (3·47 km/s) chosen for the crust are close to those preferred by Press & Ewing (1955) for the continental case. For the oceanic crust these authors adopt much greater values, especially in their Rayleigh wave computations. According to Hill (1957), however, the evidence of seismic refraction work is that in water depths greater than 4 km the solid crust comprises on an average a layer 1·75 km thick with compressional velocity 4–6 km/s and a layer 4·7 km thick with a velocity 6·71 km/s. Our value of 6·01 km/s may be a little too low, but is not inconsistent with Hill's picture, even though the water depth for some paths is slightly less than 4 km.

The compressional velocity 7·79 km/s chosen for the mantle is at about the lower limit of the range of values that have been measured in various parts of the world by means of refracted waves. This low value, together with the corresponding shear wave velocity (4·50 km/s) gives a better fit in dispersion studies than do values such as 8·1 km/s and 4·7 km/s, which are more commonly indicated by refraction. This is a case where it seems inappropriate to attach more typical measured values of the parameters to our simplified models; conversely, it is not to be thought that a refraction survey would necessarily indicate the same values as those adopted here.

The general validity of the present choice of parameters may be tested by comparing the resulting theoretical dispersion curves with empirical curves that have been obtained for paths of known type. Such empirical curves, as given by Press & Dewart (1959) for continental paths, are included in Figures 3 and 4; it will be seen that they agree quite closely with the theoretical curves for a crustal thickness of 35 km, which is usually regarded as the average thickness for continents.

5. Results

Figures 6–13 show the plots of observed dispersion for each wave path and type of wave, together with the theoretical composite curves that appeared to give the best fit. Two or three such composite curves are presented in each figure so as to give some impression of the sensitivity of the method. In most cases the fit that would be obtained by any other interpretation is distinctly inferior, as may readily be checked by reference to the theoretical curves in Figures, 3, 4 and 5, taking into account the percentage of path contributed by each particular segment.

The most direct evidence that the thickness of the crust in eastern Antarctica averages about 35 km is given by the Love wave analyses in Figures 6 and 7. In both cases a wide range of periods was recorded and the analyses yielded independent determinations of thickness for the oceanic segments. The result was confirmed by analyses of Rayleigh waves from the same two earthquakes, as shown in Figures 8 and 9. Further confirmation from another earthquake is given in Figure 10a. A valuable determination of the same thickness is that of Figure 11a, since the path crosses Antarctica diametrically and the oceanic segment is small. Results for Rayleigh and Love waves recorded at Mirny for an epicentre in south Bolivia are included (Figures 10b and 12c) as offering an interpretation

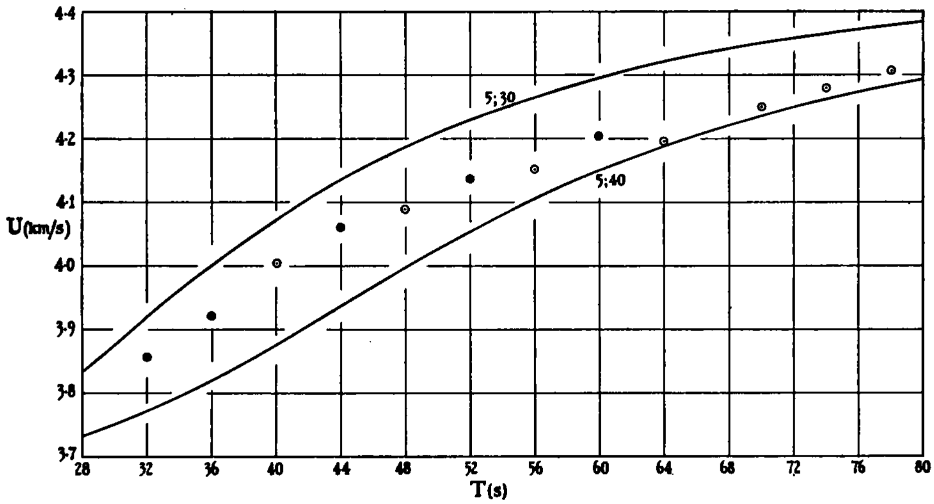

Fig. 6.—Love wave dispersion, Prince Edward Island to Hallett (40 per cent Indian Ocean at 5 km; 60 per cent E. Antarctica at 30–40 km). Components: ⊙ N–S; ● E–W.

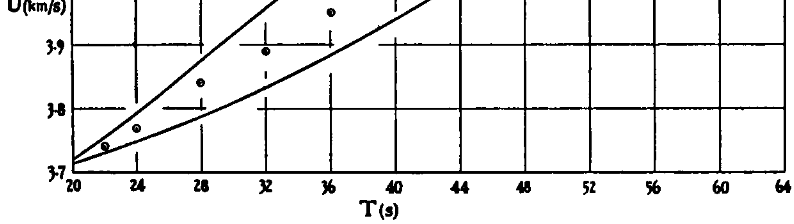

Fig. 7.—Love wave dispersion, S. Indian Ocean to Hallett (50 per cent Indian Ocean at 10 km; 50 per cent E. Antarctica at 30–40 km). Component: ⊙ N–S.

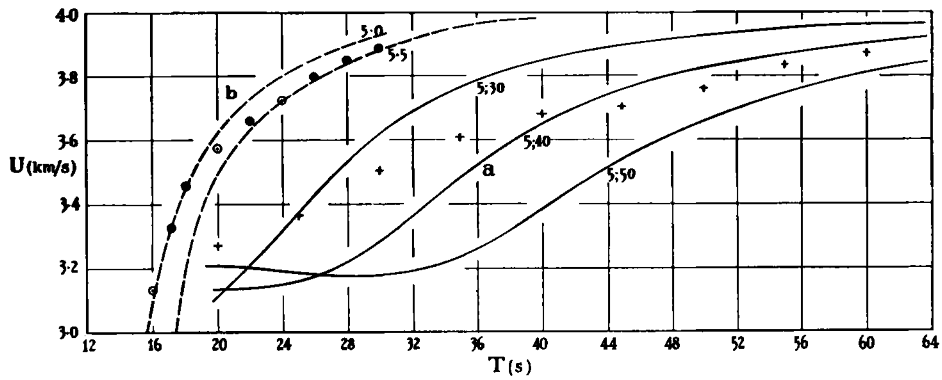

FIG. 8.—Rayleigh wave dispersion, Prince Edward Island to:
(a) Hallett (40 per cent Indian Ocean at 5 km; 60 per cent E. Antarctica at 30–40 km). Component: + Z.
(b) Mirny (100 per cent Indian Ocean at 5·0–5·5 km). Components: ⊙ E–W; ● Z.

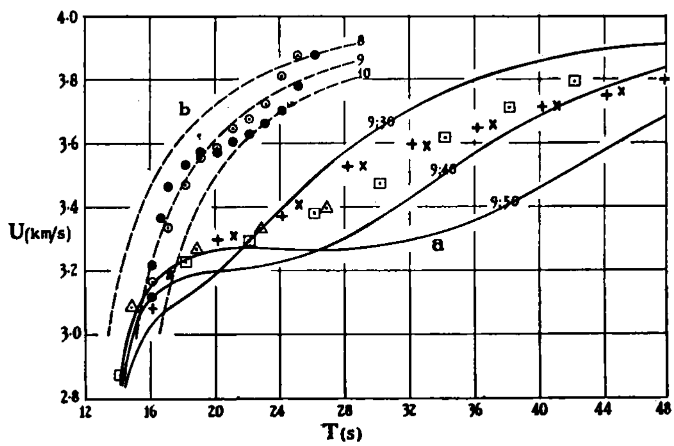

FIG. 9.—Rayleigh wave dispersion, S. Indian Ocean to:
(a) Hallett (50 per cent Indian Ocean at 9 km; 50 per cent E. Antarctica at 30–40 km,). Components: × E–W; + Z.
Scott (50 per cent Indian Ocean at 9 km; 50 per cent E. Antarctica at 30–40 km). Components: △ E–W; ⊡ Z.
(b) Mirny (100 per cent Indian Ocean at 8–10 km). Components: ⊙ N–S; ● Z.

consistent with that already put forward, although only a small range of periods was recorded.

A much thinner average crust is indicated for western Antarctica. Four wave paths have been studied, all traversing Marie Byrd Land, and although the observations did not provide so definite a determination as in the case of eastern Antarctica, it appears that the average thickness in this region is about 25 km. The simplest demonstration of this result is given by Figure 12b, which gives the dispersion of a Love wave from an epicentre in Drake Passage, recorded at Hallett Station after traversing some 1 500 km of ocean and 3 500 km in western Antarctica. A glance at the family of theoretical Love wave curves (Figure 3) will serve to show that these observations do not allow of a crustal thickness much greater than 25 km for the Antarctic segment.

The same conclusion arises from the Rayleigh wave analysis of Figure 11b for an epicentre in south Bolivia. This path traversed peninsular South America for 43 per cent of its length, and by allowing a crustal thickness of 30 km for this segment a very satisfactory fit has been obtained. This value seems rather thin for such a region and needs further verification; but if a thicker crust were assumed for the South American segment the western Antarctic crust would have to be taken thinner, and then also the degree of fit in Figure 11b would be inferior. Figure 13a also indicates a thickness of about 25 km for western Antarctica if we assume the normal continental value of 35 km for the Brazilian shield. Further Rayleigh wave data of a more limited kind are presented in Figures 13b and 11c, where they are shown to give a consistent solution for western Antarctica.

The thickness of solid crust beneath the surrounding oceans can be uniquely determined only from Love waves, which are unaffected by the water layer; furthermore, an accurate determination depends on the shorter periods. As we have seen, Figure 6 indicates a thickness of no more than 5 km for the southwest Indian Ocean, and Figure 7 indicates about 10 km for the southeast Indian Ocean. Values close to 10 km have been obtained from Love waves for Drake Passage (Figure 12b) and for the region northeast of the Ross Sea (Figure 12a). The results shown in Figure 12a also involve a short segment of path across the eastern Ross Sea, which appears to have a crust of almost continental thickness, and thus to belong to eastern rather than western Antarctica.

These values of crustal thickness for oceanic regions, obtained from recordings of Love wave dispersion, appear to be related to the depth of the ocean much in the manner that one would expect on the principle of isostatic balance. As Table 1 shows, the water was 4.50 km deep on an average for the path where a 5 km crust was indicated (Figure 6) and about 3·75 km deep for the paths with a crust of about 10 km thick (Figures 7, 12a, 12b). This relation has been used in the interpretation of oceanic Rayleigh waves, which otherwise, as will be discussed further below, do not yield an unambiguous solution. The major uncertainty has been resolved by taking $H_1/H_0 = 2$ for the water depths from 3·71 km to 3·98 km, and $H_1/H_0 = 1$ for depth of 4·18 km to 4·50 km (see Table 1). Thus, although a close fit has been achieved in most cases between the theoretical and observed Rayleigh wave dispersion for oceanic segments, this part of the analysis is essentially dependent upon the Love wave results and the estimates of water depth. The method is capable of further refinement by using fractional values of H_1/H_0, but this is not warranted by the limited quantity of data used in the present study.

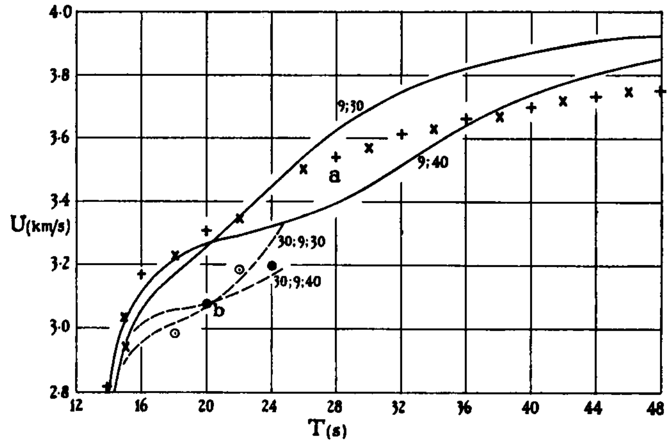

FIG. 10.—Rayleigh wave dispersion:

(a) Indian Ocean to Hallett (60 per cent Indian Ocean at 9 km; 40 per cent E. Antarctica at 30–40 km). Components: × E–W; + Z.

(b) S. Bolivia to Mirny (27 per cent S. America at 30 km; 35 per cent S. Atlantic at 9 km; 38 per cent E. Antarctica at 30–40 km). Components: ● N–S; ⊙ Z.

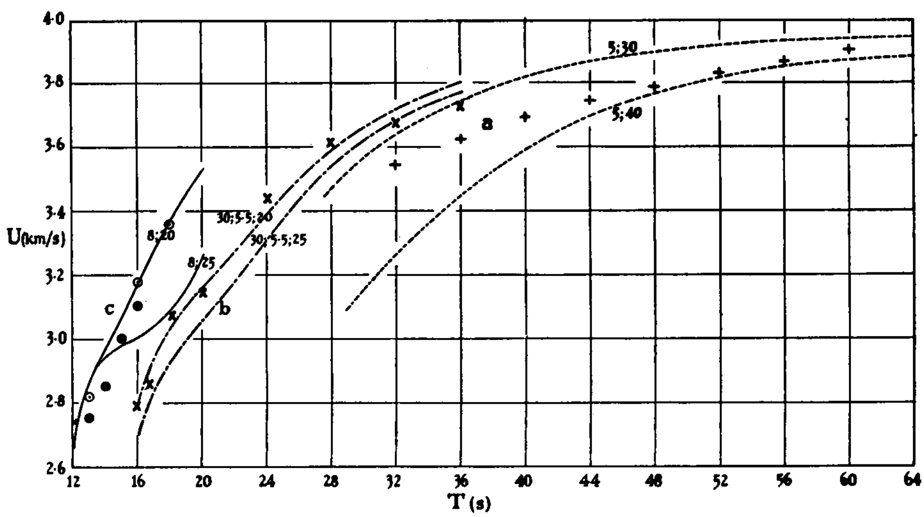

FIG. 11.—Rayleigh wave dispersion:

(a) Bouvet Island to Hallett (28 per cent S. Atlantic at 5 km; 72 per cent E. Antarctica at 30–40 km). Component: + Z.

(b) S. Bolivia to Hallett (43 per cent S. America at 30 km; 26 per cent S. Pacific at 5·5 km; 31 per cent. W Antarctica at 20–25 km). Component: × Z.

(c) Drake Passage to Hallett (30 per cent Drake Passage at 8 km; 70 per cent W. Antarctica at 20–25 km.) Components: ● E–W; ⊙ Z.

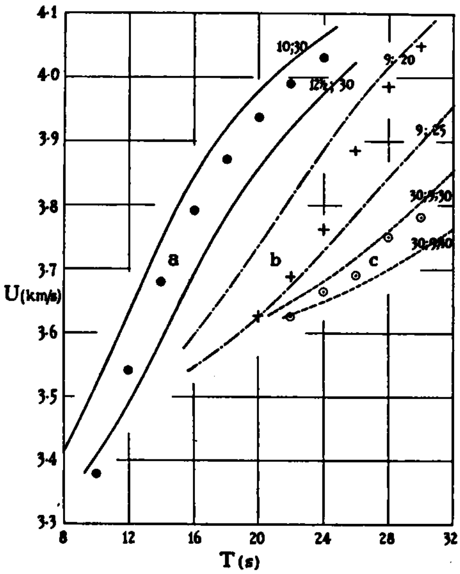

FIG. 12.—Love wave dispersion:

(a) S. Pacific to Scott (80 per cent S. Pacific at 10–12½ km; 20 per cent Ross Sea at 30 km). Component: ● E–W.

(b) Drake Passage to Hallett (30 per cent Drake Passage at 9 km; 70 per cent W. Antarctica at 20–25 km). Component: + E–W.

(c) S. Bolivia to Mirny (27 per cent S. America at 30 km; 35 per cent S. Atlantic at 9 km; 38 per cent E. Antarctica at 30–40 km). Component: ⊙ N–S.

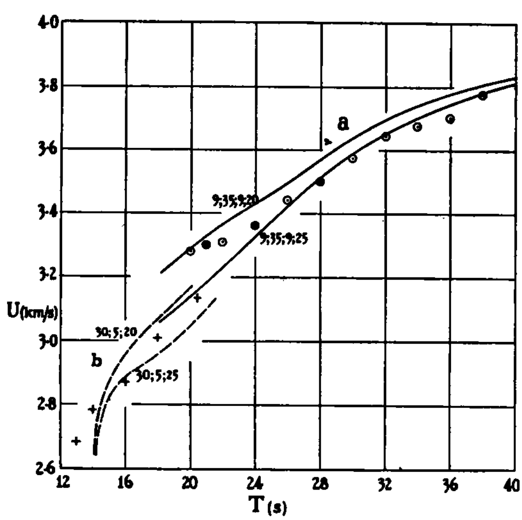

FIG. 13.—Rayleigh wave dispersion:

(a) Mid-Atlantic to Hallett (9 per cent Atlantic at 9 km; 28 per cent S. America at 35 km; 23 per cent S. Atlantic at 9 km; 40 per cent W. Antarctica at 20–25 km). Components: ● N–S; ⊙ Z.

(b) S. Bolivia to Scott (47 per cent S. America at 30 km; 19 per cent S. Pacific at 5 km; 34 per cent W. Antarctica at 20–25 km). Component: + Z.

Several wave paths in Figure 1 make rather small angles with the 1000 fathom depth contour. In such cases theory shows that the actual path is deflected from the great circle because of refraction at the boundary. The case where this effect would be expected to be most marked is the path from south Bolivia to Hallett Station. A careful study of this path has shown, however, that the result arrived at in Figure 11b would not be substantially altered by allowing for refraction.

6. Indeterminacy of oceanic Rayleigh wave solutions

The approximate thicknesses of oceanic crust shown in Figure 1 are compatible with the observed dispersion of Rayleigh as well as Love waves, but could not have been ascertained from Rayleigh waves alone, except between rather wide limits. It has been explained that the Love wave results support the idea of an inverse relation between water depth and crustal thickness, as is required by the principle of isostasy. The Rayleigh wave solutions have been obtained with the help of this added condition. In the Rayleigh wave theory, if the thickness of the fluid layer could be taken as equal to the known depth of water, an analysis of Rayleigh wave dispersion would yield a unique value of crustal thickness; the analysis would then consist of finding the value of H_1/H_0 that gave the best fit. It is generally found, however, that better agreement with other lines of evidence can be achieved by assuming a somewhat thicker fluid layer, the additional thickness being ascribed to unconsolidated bottom sediments.

Numerous studies appear in the literature in which estimates of the thickness of the oceanic crust have been based upon Rayleigh wave dispersion. Useful summaries may be found in review articles by Press & Ewing (1955) and Hill (1957). The claim that a thickness of about 5 km is normal for all oceanic areas is largely based on Rayleigh wave data. But these studies do not seem to take account of the fact that very similar dispersion may be produced by widely different crustal thicknesses, as readily follows from the theory if we allow that variations may occur in the ratio of crustal thickness to fluid depth (H_1/H_0).

The point is illustrated in Figure 14, which gives three different interpretations for a Rayleigh wave recorded at Mirny from the earthquake of 1957 August 4, the path being virtually oceanic throughout (Figure 1). The three theoretical curves are computed for the same seismic parameters, but H_1/H_0 is taken as 1, 2 and 3 in turn. To the accuracy that can reasonably be claimed for dispersion studies there is little to choose among the three solutions, yet the crustal thicknesses indicated are respectively $5\frac{1}{4}$ km, $9\frac{1}{2}$ km and 12 km. (The Love wave analysis suggests that the first of these solutions is nearest to the correct one.) Naturally any other value within this range could equally well be deduced by taking the appropriate fractional ratio of the thicknesses. The range of possible solutions might be less in cases where the observations extend over a greater range of velocity; but the later portions of most records bear signs of interference, indicating that energy has been propagated along paths other than the direct one, and hence making the analysis less reliable.

Rayleigh waves have also often been invoked as a means of estimating the thickness of the unconsolidated bottom sediments. Inferred values are usually in the range 0·4–1·2 km; thus the effect of the sediments is a second-order one. But the actual value that is obtained in any particular case is wholly dependent on the assumed ratio of crustal thickness to fluid depth. Thus in Figure 14 the three interpretations give the thickness of the fluid layer as $5\frac{1}{4}$ km, $4\frac{3}{4}$ km or 4 km. The average water depth for this path as determined from the bathymetric map is 4·18 km. Hence one inferred value of the sediment thickness is 1·07 km, another is 0·57 km, while the third interpretation would imply that not even all the water behaves as a fluid. It is clear that any thickness of sediment could be obtained, at least within the usual range of values, by varying the assumed ratio of crustal thickness to fluid depth.

Most authors have assumed, for purposes of computation, that the thicknesses of crust and fluid layer are equal. Curve fitting has then consisted of selecting the most favourable value of this thickness. The assumption is at variance both with

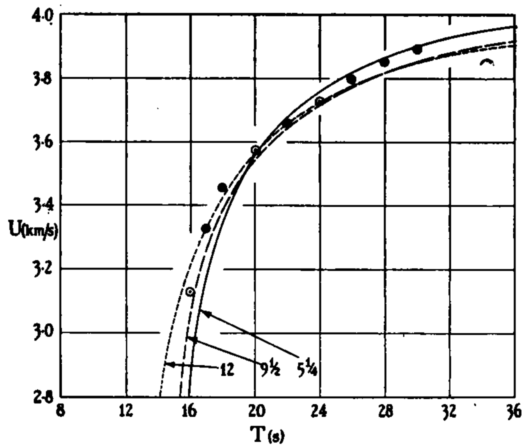

FIG. 14.—An example of the indeterminacy of Rayleigh wave solutions for oceanic paths. Dispersion from Prince Edward Island to Mirny (cf. Figure 8b), with three different interpretations.

	Crustal thickness / Fluid depth	Crustal thickness (km)
————————	1	5¼
— — — — — —	2	9½
- - - - - - - - -	3	12

the principle of isostasy (which seems to hold good in oceanic regions except for local anomalies), and with the evidence of seismic refraction results as summarized by Hill (1957). The case of a crust twice as thick as the fluid layer has occasionally been considered (see Press & Ewing 1955), but at the same time the very low value 5·5 km/s has been adopted for the compressional velocity in the crust, in place of the usual 6·9 km/s. This has obscured the effect of varying H_1/H_0. The refraction results actually show that the average compressional velocity in the oceanic crust is very nearly the same for a thickness of 10 km as for 5 km.

We thus see that Rayleigh wave dispersion does not, by itself, provide a reliable measure of crustal thickness in oceanic regions, much less of the thickness of fluid sediments on the ocean floor. The high degree of uniformity that has been attributed to the oceans may be illusory in as much as it depends largely on Rayleigh wave evidence. Indeed the growing amount of data from seismic refraction work at sea, and also the evidence of Love waves, suggests that thicknesses of 10 km or more are not uncommon. We have found that this is the case in the oceanic regions adjacent to Antarctica. A contrary view of the major oceans regards the Pacific as having an essentially different crustal structure from the other oceans.

Since the Pacific is appreciably the deepest ocean we must expect it to have the least average thickness of crust, but the difference is not such as would suggest any uniqueness of structure.

7. Structure of Antarctica

It is concluded that eastern Antarctica as a whole is continental, for the present study has given a good coverage of this large area, and a crustal thickness of about 35 km has been consistently obtained. By contrast, Marie Byrd Land has an average crustal thickness of about 25 km and cannot be regarded as truly continental in structure. The data do not extend to the remainder of western Antarctica, nor has it been possible to study the important transition zone which runs from the Ross Sea to the Weddell Sea.

These findings are evidently related to the known geological contrast between eastern and western Antarctica. The result for the western sector, however, requires further elaboration, for the average crustal thickness of 25 km could be made up in a variety of ways. Beneath the high mountain ranges of Marie Byrd Land one would expect to find crustal roots giving locally a total thickness of at least 40 km. If this is so there must be other zones where the crust is much thinner than 25 km, implying that the rock surface lies well below sea-level. The offshore depth contour at 1 000 fathoms generally lies much further from the coastline in western than in eastern Antarctica; this would account for some small fraction of the difference in average crustal thickness.

The picture of Marie Byrd Land as an archipelago made up of mountainous island chains finds support in recent seismic and gravity observations. A detailed survey of ice thickness has revealed extensive regions where the rock surface would undoubtedly be below sea-level if the ice were to melt. For example, along a traverse running close to latitude 77° S, between longitudes 87° W and 113° W, the rock surface was located consistently at between 1 km and 2 km below sea-level for a distance of some 400 km (Bentley & Ostenso 1959).

The conclusion that eastern Antarctica as a whole is continental and that the smaller average thickness of crust is confined to western Antarctica differs substantially from the conclusion of Press & Dewart (1959). For paths in all directions from Wilkes Station except to the southeast these authors obtained an average crustal thickness about as small as that indicated for Marie Byrd Land in the present study, and concluded that "at most only three-fourths of the Antarctic ice sheet is underlain by continent, the remaining area being oceanic in structure". The two exceptional paths, which passed close to Hallett Station, indicated a fully continental thickness. Six paths included approximately equal distances across eastern and western Antarctica, and traversed the Ross Sea–Weddell Sea zone. If it happens that this zone includes a wide belt of very thin crust, the average thickness obtained by Press and Dewart may prove to be consistent with the present results. Three further paths crossed eastern but not western Antarctica, and for these it is not easy to find agreement unless there is a large region of oceanic crust south-west of Wilkes Station, which seems unlikely since Wilkes itself is situated on rock and the value of gravity there is close to normal.

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