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CRUSTAL STRUCTURE OF ANTARCTICA

CHARLES R. BENTLEY

Geophysical and Polar Research Center, Department of Geology and Geophysics, University of Wisconsin, Middleton, Wisc. (U.S.A.)

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ABSTRACT

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Seismic refraction profiles completed in the past twenty years reveal that the top of the basement complex generally lies near sea level in East Antarctica but typically 2 or 3 km below sea level in West Antarctica. Throughout much of East Antarctica the thickness of the layer overlying the basement complex is less than half a kilometer, although a Phanerozoic sequence more than 1 km thick probably underlies the ice at the South Pole. Throughout central West Antarctica, on the other hand, a section one to several kilometers thick generally overlies the basement complex. The observed sedimentary section is no more than one half kilometer thick on either side of the Transantarctic Mountains. Rocks with high seismic velocities typical of the lower continental crust occur within a few kilometers of the surface on both sides of the Transantarctic Mountains. This occurrence lends support to the hypothesis of an abrupt increase in crustal thickness between West and East Antarctica.

In 1969, deep seismic soundings were carried out by the 14th Soviet Antarctic Expedition near the coast of Queen Maud Land. The crustal thickness was found to be about 40 km near the mountains, decreasing to about 30 km near the coast. In the top 15 km of the crust there is a gradual downward increase in P-wave velocity from 6.0 to 6.3 km/sec. The average velocity through the crust is 6.4 km/sec and the measured velocity below the M-discontinuity is 7.9 km/sec.

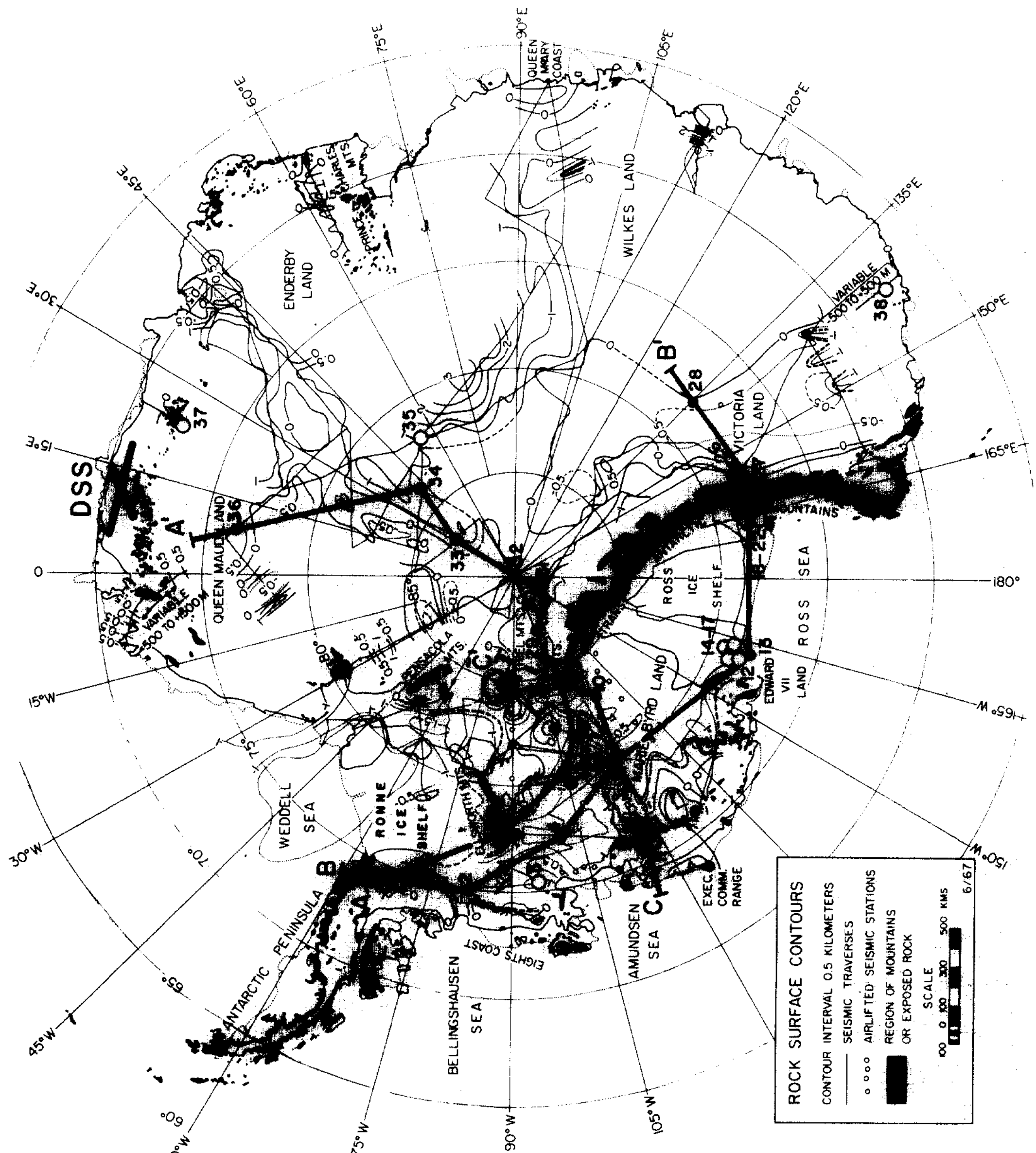
At the southwestern margin of the Ronne Ice Shelf, near-vertical reflections from the M-discontinuity have been recorded. A mean P-wave velocity of 6 km/sec in the crust was measured, leading to an estimated depth to M of 24 km below sea level.

Seismic surface wave dispersion studies indicate a mean crustal thickness of about 30 km in West Antarctica and about 40 km in East Antarctica. The dispersion data also show that group velocities across East Antarctica are much closer to those along average continental paths than to those across the Canadian shield. The results thus support other indications that central East Antarctica is not a simple crystalline shield.

P'P'-reflections beneath the continent support the existence of a low-velocity channel for P-waves, but show no significant difference in deep structure between Antarctica and other continents.

EXPLOSION SEISMOLOGY

In the past twenty years, some three dozen seismic refraction profiles long enough to provide information about seismic velocities beneath the ice have been completed on the antarctic ice sheet. Most of these have been carried out during reconnaissance exploration of the antarctic interior as part of the U.S. Antarctic Research Program. Since time and the


ROCK SURFACE CONTOURS
CONTOUR INTERVAL 0.5 KILOMETERS
SEISMIC TRAVERSES
AIRLIFTED SEISMIC STATIONS
REGION OF MOUNTAINS OR EXPOSED ROCK
SCALE
100 0 100 300 500 KMS
6/67
QUEEN MARY COAST
WILKES LAND
ENDERBY LAND
QUEEN MAUD LAND
VICTORIA LAND
ROSS ICE SHELF
ROSS SEA
EDWARD VII LAND
BYRD LAND
RONNE ICE SHELF
WEDDELL SEA
ANTARCTIC PENINSULA
BELLINGSHAUSEN SEA
AMUNDSEN SEA
EIGHTS COAST
EXEC. COMM. RANGE
VARIABLE 500 TO +500 M
DSS
A
A'
B
B'
C
0
180°
15°E
30°E
45°E
60°E
75°E
90°E
105°E
120°E
135°E
150°E
165°E
15°W
30°W
45°W
60°W
75°W
90°W
105°W
150°W
165°W

supply of explosives were strictly limited on the oversnow traverses, the profiles are not nearly as complete as would be desirable. Several comprise only a single shot, yielding, for each arrival path, a total travel-time and an apparent velocity across a detector spread which is generally about 700 m long. Profiles on which subglacial refracted arrivals have been recorded from three or more shots are the exception rather than the rule, and few of the profiles have been reversed. As a result, seismic velocities sections beneath the ice cannot be determined in detail. Nevertheless, the approximate upper crustal columns which can be deduced are invaluable in regions devoid of outcrops. For a summary of the profiles including a bibliography, see Bentley and Clough (1972).

In 1969, two deep seismic sounding profiles were completed by members of the 14th Soviet Antarctic Expedition in the vicinity of Novolazarevskaya near the northern coast of Queen Maud Land. P_n-arrivals and several intracrustal reflections were successfully recorded on these profiles for the first time in Antarctica, leading to a velocity/depth profile through the crust and into the upper mantle (Kogan, 1972).

Upper crustal seismic sections

Three rather irregular sections across Antarctica which include all pertinent upper crustal velocity data except those from the D.S.S.-profiles have been compiled (Fig. 1). Section *AA'* runs from the base of the Antarctic Peninsula along the west edge of the mountainous central spine of West Antarctica through the Horlick Mountains, past the South Pole, and across Queen Maud Land. Section *BB'*, also starting at the base of the Antarctic Peninsula, runs along the Byrd Subglacial Basin to the Ross Ice Shelf, across the Transantarctic Mountains, and out onto the plateau of Victoria Land. Section *CC'* is a shorter north–south profile from the Amundsen Sea across the Byrd Subglacial Basin to the Horlick Mountains.

Some preliminary remarks on the interpretation of the profiles are appropriate. The usual warning about low-velocity layers is particularly important because of the relatively high P-wave velocity in ice (3.9 km/sec). In the case of a layer immediately beneath the ice there is some evidence from the comparison of the ice thickness indicated by the first subglacial refracted-travel-time line with that measured by reflection shooting. But for refraction shooting on thick ice, the time intercept is usually not very well determined, since refracted energy begins to arrive only at large distances. Thus one often has considerable freedom in adjusting the inferred layer thickness. At the same time, the observed total travel-time must be fitted, so that the greater the layer thickness is taken to be, the faster the wave velocity in the refracting layer must be, and vice versa. Common use is made of this "trade-off" in the succeeding discussion.

Fig.1. Location of antarctic seismic refraction profiles superimposed on map of subglacial topography. Sections along *AA'*, *BB'*, and *CC'* are shown in Fig.2, 3, and 4. Open circles denote profiles not included in the sections. *DSS* marks the Soviet deep seismic sounding profiles. Dashed contour line indicates estimated position of pre-glacial shore line. Regions below sea level are denoted by dotted contour lines.

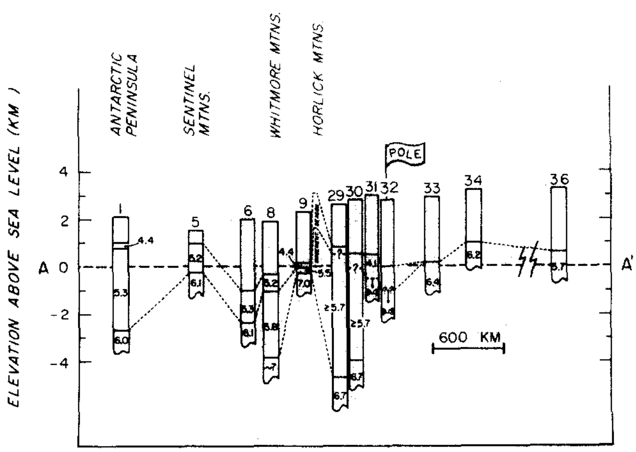


Fig.2. Seismic velocity columns along section *AA'*. In Columns 31 and 32 assumed velocities are enclosed in brackets, and minimum depths are indicated by downward arrows.

Section AA' (Fig.2)

The velocity of 5.3 km/sec in Column 1 is well determined, and is a typical value for granitic rocks such as the Andean intrusives exposed in the Antarctic Peninsula. The velocity of 6 km/sec is a poor determination, but still gives a likely approximate depth to the crystalline basement. For the reasons mentioned above, lower velocity sediments could exist beneath the 5.3 km/sec layer, which need be no more than a few hundred meters thick. The indicated depth to the basement is therefore probably an upper limit.

In Columns 5, 6, and 8, the velocity of 5.2–5.3 km/sec probably represents metasediments and/or felsic intrusive rocks typical of the Sentinel and Whitmore Mountains (Craddock et al., 1964; Craddock, 1970). The 5.8–6.1 km/sec velocity presumably represents the Precambrian basement complex, which thus lies 1 km or less below sea level near the mountains, but more than 2 km below sea level under the intervening basin (c.f. section *BB'*).

Column 8 shows the high velocity at depth which appears on several profiles near the great Transantarctic Mountains which separate continental East Antarctica from the borderland of West Antarctica (for a discussion of the subglacial topography, see Bentley (1964)). The velocity is not well determined, but nevertheless is probably 7 km/sec to one significant figure. A velocity of 6.8 km/sec was measured by Crary (1963) on a dolerite exposure in the Transantarctic Mountains near section *BB'* (see Fig.1), but any attribution to doleritic intrusives at Column 8 would be highly tentative. The velocity is also appropriate for the lower part of a continental crust.

The profile of Column 9 was located just a few kilometers north of the faulted front of the Transantarctic Mountains. The velocity of 5.5 km/sec, a minimum value as measured on the seismic profile, most likely corresponds to the granitic basement exposed at an elevation of about 1.65 km in the Ohio Range (Long, 1965). Apparently the fault displacement at the front of the range is about 1.7 km, and only a very thin sedimentary section remains above the basement on the down-thrown north side. The 7 km/sec velocity again appears to be real, suggesting either a doleritic intrusion within the basement or an extremely shallow occurrence of lower crustal rocks.

The profiles of Columns 29 and 30 each comprised a single shot so that the velocity of 5.7 km/sec for the upper part of the column is a minimum value. This material is almost surely the East Antarctic basement complex. If the true velocity in the basement is 6.0 km/sec, a thickness of about 0.5 km of overlying sediments is implied. The evidence for the deep, high-velocity (6.7 km/sec) material is poor here, but is supported by the occurrence of this high velocity in other columns bracketing the Transantarctic Mountains.

At the South Pole (Column 32) only negative information is available. No refracted arrival was observed from a 430-kg shot at a distance of 31 km (Robinson, 1964b). From this, a minimum depth of 5 km to a 6.0 km/sec basement can be calculated; this is such a large depth, however, that it seems more reasonable to assume that the ground wave energy was too weak to be observed. Nevertheless, a substantial thickness of low-velocity rocks overlying the basement is suggested, since the charge size was ample to have produced strong arrivals if the basement surface had been close to the base of the ice.

Columns 33, 34, and 36 in the interior of Queen Maud Land, display basement velocities directly beneath the ice with no evidence of any intermediate sedimentary layer. Such a layer, if present at all, must be thin.

In coastal Queen Maud Land where the Soviet D.S.S.-profiles were completed (not shown in Fig.2) there is also no evidence for a sedimentary section (Kogan, in preparation). Upper crustal rocks, in which the velocity is 6.0 km/sec, lie closely under the ice.

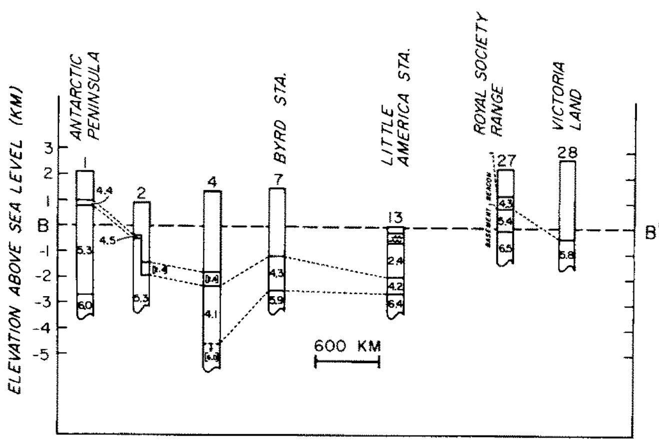


Fig.3. Seismic velocity columns along section *BB'*. In Columns 2 and 4 assumed velocities are enclosed in brackets; a minimum depth in Column 4 is indicated by a downward arrow.

Section BB' (Fig.3)

This section starts again at the base of the Antarctic Peninsula with Column 1, which we have already discussed. The profile of Column 2 was shot across what appears to be a faulted boundary between the extension of the Antarctic Peninsula and the edge (in the absence of ice) of the Weddell Sea. By analogy with Column 1, we would correlate the 5.3 km/sec velocity with Andean intrusives; the basement must then lie more than 2 km below sea level.

Columns 4 and 7 (and also Column 6 of Section *AA'*) are typical of the vast Byrd Subglacial Basin, which underlies the ice of central West Antarctica. Underneath a thick sedimentary cover the basement surface lies at a depth of 2.5–4.5 km or more below sea level. These columns are very similar to Column 13 on the continental shelf of the Ross Sea at Little America.

Crossing the Transantarctic Mountains into East Antarctica (Column 27) we find the basement surface at an elevation of about 800 m above sea level. There is again a deeper, high-velocity horizon; the question once more arises as to whether this layer represents the Conrad discontinuity or a basaltic intrusion within the basement complex. Column 28, 500 km beyond the Transantarctic Mountains in Victoria Land, is similar to the other central East Antarctic profiles. A maximum thickness of a few hundred meters of sediments overlying the normal basement complex is indicated.

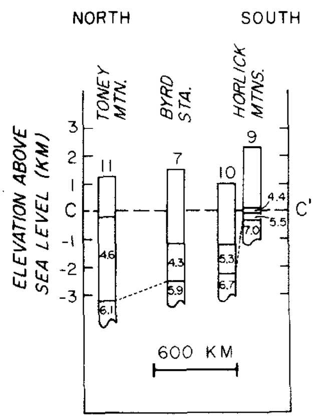


Fig.4. Seismic velocity columns along section *CC'*.

Section CC' (Fig.4)

This section runs southward from the volcanic mountains of Marie Byrd Land, across the Byrd Basin to the Transantarctic Mountains. Column 11 in Marie Byrd Land shows the basement surface 3 km below sea level, a depth also typical of the Byrd Basin. Column 10 is unique in the absence of any velocity attributable to "normal" basement. The "lower crustal" velocity, evidence for which is good at this location, occurs only a little more than 2 km below sea level.

The deeper crust

The recent work by Kogan (1972) provides the best information available about the deeper crustal structure of Antarctica. Upper crustal rocks, in which the velocity averages 6.1 km/sec, extend to a depth of around 20 km. The lower crustal zone (average velocity 6.7 km/sec) is also about 20 km in thickness, putting the M-discontinuity at an average depth of 40 km below sea level; it is a few kilometers deeper near the mountains, but shoals to only 27 km below sea level near the coast. The measured velocity just beneath M was 7.9 km/sec.

The only other determination of deep crustal structure from explosion seismology comes from an unpublished refraction profile 23 km long at 83°S 70°W near the head of the Ronne Ice Shelf (M. Hochstein, personal communication, 1964). Distinct reflections with travel times of 8.5–9.3 sec were recorded from all shots. An average velocity of 6.0 km/sec was calculated, leading to a reflector depth of 24 km below sea level in a region where the subglacial rock surface is 1 km below sea level, typical of the low-lying areas of West Antarctica. From comparison with surface wave dispersion studies (see below), it seems likely that the reflecting surface is the M-discontinuity.

EARTHQUAKE SEISMOLOGY

Surface waves

The study of Antarctic crustal structure by means of surface wave dispersion has been hampered by the complete absence of major earthquakes on the continent (Evison, 1967). Although local shocks do occur, associated primarily with volcanism or fracturing in the ice itself (Hatherton, 1961; Hatherton and Evison, 1962; Browne-Cooper et al., 1967; Adams, 1969), they are far too weak ($M < 3$) to produce transcontinental surface waves. It has therefore been necessary to make use of surface waves from earthquakes at a considerable distance from Antarctica, and to make correction for the non-Antarctic segments of the paths.

The first antarctic dispersion studies indicated continental structure in East Antarctica, but higher than normal group velocities along paths across the entire continent (Press and Dewart, 1959; Evison et al., 1959). Using Rayleigh and Love waves from earthquakes in Bolivia, the mid-Atlantic, and the oceans surrounding Antarctica, Evison et al. (1960) made the first analysis examining East and West Antarctica separately. Assuming shear-wave velocities of 3.47 km/sec and 4.50 km/sec for crust and mantle respectively, they estimated mean crustal thicknesses of 35 km in East Antarctica and 25 km in West Antarctica. However, several of the propagation paths, including three of the four across West Antarctica, were complicated by two or three separate crossings of a continent–ocean boundary. Furthermore, the structures assumed for the non-Antarctic segments of all paths, as well as the crust and upper-mantle velocities adopted for Antarctica, were open to some question (Kovach and Press, 1961; Bentley and Ostenso, 1962). Kovach and Press (1961) therefore re-evaluated the dispersion data, using only paths from earthquakes in the oceans surrounding the continent (Fig.5), and making use of computer modeling based on more realistic velocities. They found that the crustal-thickness estimates for both parts of the continent should be increased about 5 km, a conclusion also reached by Bentley and Ostenso (1962) from an analysis of the dispersion data combined with gravity data from West Antarctica. However, the 10 km difference in crustal thickness discovered by Evison et al. (1960), which indicates fundamentally different crustal characteristics in the West Antarctic borderland compared with those in continental East Antarctica, remains unchallenged.

No additional dispersion studies of West Antarctica have been forthcoming, so that the mean crustal-thickness estimate of that part of the continent is, unfortunately still based primarily on Love-wave group velocities from a single earthquake at periods between 20 and 30 sec. The coverage of East Antarctica on the other hand, has been much improved by a study of Love and Rayleigh waves, with periods between 15 and 70 sec, recorded at Wilkes Station from eight earthquakes in the South Sandwich arc (Dewart and Toksöz, 1965). The paths cover the shaded region in Fig.5. Correction was made for the oceanic segments of the propagation paths (20–30% of the total) on the basis of dispersion data from other oceans, assuming that ocean basins of similar depth have similar crustal and upper-mantle properties. The resulting continental group velocities are shown in Fig.6, together with average observed dispersion curves for North America and Eurasia (Kovach, 1965), and with the calculated model (CANSD) which best fit observed dispersion across the Canadian shield (Brune and Dorman, 1963).

The East Antarctic group velocities fall between those for Eurasia and North America and are markedly lower than velocities from CANSD. Thus the oft-repeated geological description of East Antarctica as a simple crystalline shield is not supported by the dispersion evidence, which points instead to a "typical continental structure". A complex structure is also suggested by the often rugged subglacial topography of the continent, which includes peaks beneath the ice rising over 3 km above sea level (Fig.1).

Dewart and Toksöz found a good fit to their observations from a model (A-1) consisting of a 39 km thick crust (underlying 3 km of ice) and fairly low shear-wave velocities in both crust (3.65 km/sec) and upper mantle (4.45 km/sec). A comparison of the velocities in their model with those of CANSD and those found in Kogan's (1972) D.S.S.-profile is given in Fig.7.

Early P'P' reflections

Adams (1971) has recently presented some evidence of deep Antarctic structure based on the study of early P'P' (PKPPKP) reflections from beneath East Antarctica, in the region between Enderby and Wilkes Lands. Using a technique previously applied to other continents (Adams, 1968) and arrivals generated by a group of nuclear blasts in Novaya Zemlya, he found good evidence for discontinuities around depths of 60–80 and 650 km, with

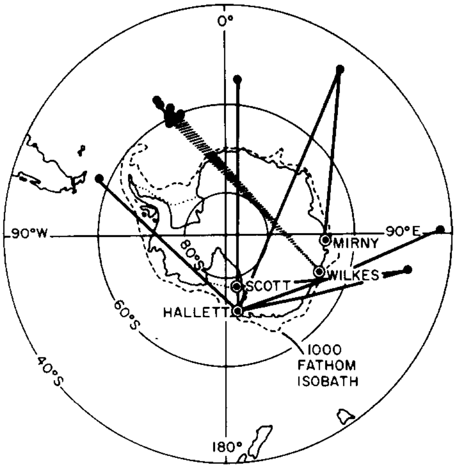
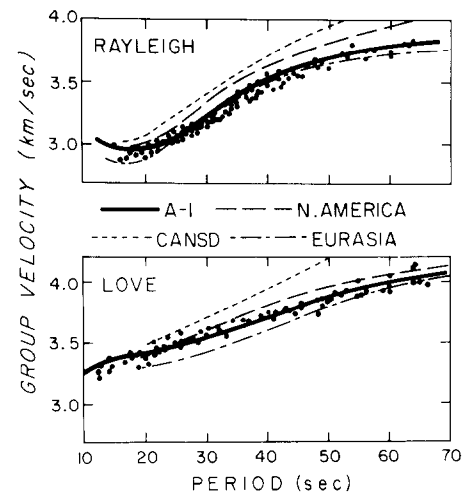


Fig.5. Surface wave paths for dispersion studies. Single lines indicate paths from Evison et al. (1960) re-evaluated by Kovach and Press (1961). Hachured area includes 8 paths studied by Dewart and Toksöz (1965). Group velocities along the latter paths are shown in Fig.6.



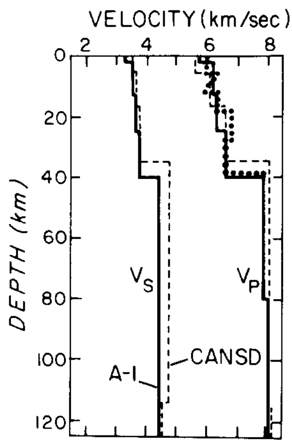


Fig.6. Group velocity dispersion curves for East Antarctica compared with average observed curves for North America and Eurasia (Kovach, 1965), and a model (CANSD) fitting observed velocities across the Canadian shield (Brune and Dorman, 1963). A-1 is the best fitting model from Dewart and Toksöz (1965).

Fig.7. Seismic velocities vs. depth for East Antarctica from dispersion studies (A-1: solid line) and deep seismic soundings (dotted line). Also shown are velocities fitting dispersion across the Canadian shield (CANSD: dashed line).

weaker reflections observed from a depth of about 420 km. The discontinuity at 60–80 km, also found beneath most other continents (Adams, 1968), probably indicates a low-velocity channel for P-waves with a rather sharp upper boundary. Adams (1971) finds no obvious differences between the deep structure of Antarctica and that of other continents.

SUMMARY

Throughout West Antarctica (including the base of the Antarctic Peninsula and the Ross Sea) except near the Ellsworth–Whitmore–Transantarctic Mountains axis, the surface of the basement complex apparently lies at least 2.2 km below sea level, dropping to at least 4 km below sea level beneath the deeper parts of the Byrd Basin. In contrast, the surface of the East Antarctic basement complex generally is found close to sea level, and the overlying section is typically no more than a few hundred meters thick.

Nowhere next to the Transantarctic Mountains on either side is there evidence for a thick sedimentary column. At stations within a few hundred kilometers of the mountains, on both sides, velocities typical of lower crustal rocks appear at elevations of 1–4 km below sea level. Although the deep high velocities are not all well determined, their persistent occurrence lends strong weight to the reality of the phenomenon. The velocities are similar to those which occur in the mountains, where their association with the Ferrar-type dolerites is unambiguous. Any correlation must, of course, be tentative, but it is interesting to speculate that normally deep-crustal basaltic rocks occur unusually near the surface here, and have provided the source of the dolerite intrusions in the Transantarctic Mountains.

The indication that high-velocity (and presumably high-density) rocks are found at comparable depth on both sides of the Transantarctic Mountains supports Robinson's (1964a) conclusion that the remarkable Bouguer gravity anomaly gradient across those mountains can best be explained by an abrupt change in crustal thickness, rather than by a rapid change in thickness of the lower-density, upper-crustal rocks. As Robinson demonstrated, the latter explanation would require a 15 km greater depth to the higher-density rocks on the East Antarctic side of the mountains. This is in direct conflict with the seismic evidence presented here.

The thickness of sedimentary rocks appears to increase from the Horlick Mountains toward the South Pole, reaching a probable thickness of more than 1 km under the Pole; no upper limit can be given. A sedimentary basin several kilometers deep could explain the –20 mGal regional free-air gravity anomaly under the South Polar plateau (Bentley, 1968), but in Victoria Land, where the gravity anomalies are even more strongly negative, the sedimentary section appears to be thin. In Queen Maud Land also, the sedimentary section appears generally to be no more than half a kilometer thick, and probably considerably less.

The fundamental contrast between East and West Antarctica which is seen from examination of subglacial topography and shallow crustal structure extends through the crust. The mean thickness of the West Antarctic crust as indicated by surface wave dispersion studies, is only about 30 km, compared with about 40 km in East Antarctica. Seismic refraction shooting also yields a 40 km thick crust near the coast of East Antarctica, but sug-

gests a crust only about 25 km thick in the low central regions of West Antarctica. On the basis of average crustal structure, East Antarctica is "continental" rather than a simple "Precambrian shield". The boundary between East Antarctica and the West Antarctic borderland is apparently abrupt.

A low-velocity channel for P-waves with a sharp upper boundary at a depth of 60–80 km probably underlies East Antarctica. Neither in this regard nor in other indications of upper-mantle structure is East Antarctica different from the other continents.

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