Reports

Extent of the Antarctic Continent

Abstract. Group velocities of earthquake-generated Love and Rayleigh waves for certain transantarctic paths are abnormally high when compared with data from other continents. For these paths, the data indicate that at most only three-fourths of the antarctic ice sheet is underlain by continent, the remaining area being oceanic in structure.

Explosion seismology and dispersion analysis of earthquake-generated surface waves are the two principal methods for determining crustal structure. The first offers the advantage of a point-by-point delineation of crustal layering, but requires considerable field efforts. The second reveals the average properties of segments of the crust having continental dimensions and requires only suitably disposed paths between earthquake epicenter and seismograph station. In Antarctica, explosion-seismology methods have been used primarily to determine ice thickness, which can then be indirectly related to crustal structure by interpreting ice-buried topography. Thus the significant result that extensive areas of Antarctica lie below sea level was the first indication that the Antarctic Continent may be less extensive than the ice sheet.

In this paper we report on crustal structure, along several profiles crossing Antarctica, as revealed by group velocity dispersion analysis of Love and Rayleigh waves. The segments of Antarctica to which the results apply are indicated by the propagation paths shown in Fig. 1. The materials for the study are the following: records from the Press-Ewing seismograph installed at the Wilkes Station in Antarctica for this purpose as part of the International Geophysical Year program (*1*); earthquake epicenters determined by the U.S. Coast and Geodetic Survey or the Bureau Central International Seismologique; and empirical group velocity curves for Love and Rayleigh waves (*2*) for oceanic and continental paths. The procedure is to obtain from the seismograms the travel times of dispersed Love and Rayleigh waves as a function of period. These times are then reduced for propagation across Antarctica by subtracting the travel time for the nonantarctic segments derived from the appropriate empirical group velocity curve. This procedure is made necessary because the scarcity of earthquakes in Antarctica forces us to use mixed paths. The method may be justified theoretically (*3*). It has been tested for mixed paths where the structure of the separate segments was known beforehand (*4*).

The results for the paths shown by heavy lines in Fig. 1 are presented in Figs. 2 and 3. They are in the form of antarctic group velocity data for Love and Rayleigh waves. For comparison, empirical curves for known continental paths are also presented. It is seen that for any given period, antarctic velocities are systematically higher than continental velocities.

The following sources of systematic error have been examined to see whether they could account for these results:

1) *Epicenter location*. It is necessary to assume a systematic error in epicentral distance of about +5 percent to reduce the antarctic velocities to continental values. The precision of epicenter determination is such as to make this unlikely, especially since data from the new antarctic stations were used.

2) *Proportion of antarctic and nonantarctic path*. The margin of Antarctica was taken to be the 1000-fathom contour on the continental shelf. Admittedly, this is imperfectly known. However, to eliminate the discrepancy between antarctic and normal continental group velocity would require an inadmissible error of about 1300 km in the location of this contour.

3) *Refraction*. Since the phase velocity of surface waves differs for oceans and continents, the possibility of propagation paths other than great circles exists. This was investigated, by use of the theory of R. Stoneley (*3*), and was eliminated as a source of systematic error. The direction of approach of the surface waves, formed from the orbital motion, was used as an auxiliary check for significant refraction effects.

4) *Effect of the ice sheet*. The presence of the ice layer serves only to decrease surface wave velocity and hence cannot account for the higher antarctic values. For wave periods of 20 seconds or longer, the effect can be neglected.

It is necessary, therefore, to explain the antarctic dispersion data in terms of crustal structure. When the continental data in Figs. 2 and 3 are used as a standard for comparison, it is seen that for a given group velocity the antarctic periods are approximately one-fourth shorter. This indicates that the average value for crustal thickness in Antarctica is three-fourths that of continents. Since no continental region is known with average crustal thickness so small, the continental areas of Antarctica appear to be significantly less extensive, and the oceanic areas more extensive, than indicated by the limits of the ice sheet. Taking the measured values of 35 km and 6 km, respectively, for normal con-

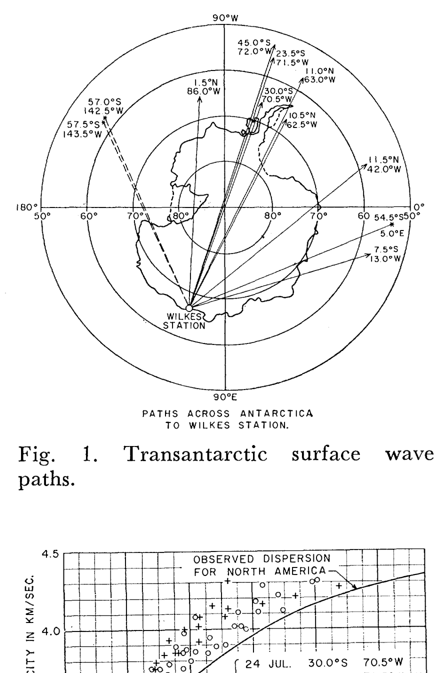

Fig. 1. Transantarctic surface wave paths.

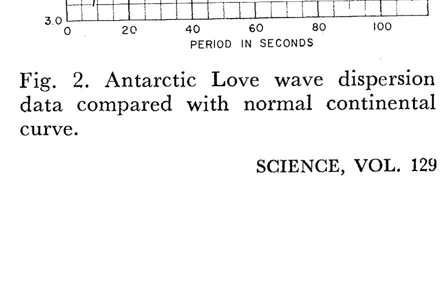

Fig. 2. Antarctic Love wave dispersion data compared with normal continental curve.

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Type manuscripts double-spaced and submit one ribbon copy and one carbon copy.

Limit the report proper to the equivalent of 1200 words. This space includes that occupied by illustrative material as well as by the references and notes.

Limit illustrative material to *one* 2-column figure (that is, a figure whose width equals two columns of text) or to *one* 2-column table or to *two* 1-column illustrations, which may consist of two figures or two tables or one of each.

For further details see "Suggestions to Contributors" [*Science* 125, 16 (1957)].

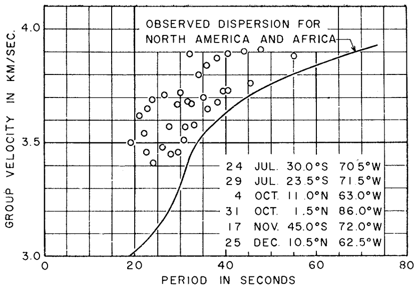

Fig. 3. Antarctic Rayleigh wave dispersion data compared with normal continental curve.

tinental and oceanic crustal thickness, the data indicate that for the profiles represented by heavy lines in Fig. 1, about one-fourth of the path is oceanic and three-fourths is continental. Had we assumed crustal thickness corresponding to shallow ocean, then the oceanic portion would have been much larger.

These results support the view that below-sea-level depths observed in measurements of ice thickness are primary features and not the result of crustal sagging under an ice load. They further show that more extensive areas of the antarctic land mass lie below sea level than have been reported.

Limited data available for the profiles shown by dashed lines in Fig. 1 suggest that the region is almost entirely continental. It may be possible to specify in greater detail the continental and oceanic areas of Antarctica when more surface wave data become available.

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References and Notes

1. This study was supported by funds from the National Science Foundation as part of the International Geophysical Year program. This report is contribution No. 914 of the Division of Geological Sciences, California Institute of Technology.
2. M. Ewing, W. S. Jardetzky, F. Press, *Elastic Waves in Layered Media* (McGraw-Hill, New York, 1957), chap. 4.
3. R. Stoneley, *Monthly Notices Roy. Astron. Soc., Geophys. Suppl.* 3, 262 (1936).
4. J. Oliver and M. Ewing, *Proc. Natl. Acad. Sci. U.S.* 44, 780 (1958).

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Theory of Ice Ages

In two recent papers, Ewing and Donn (*1, 2*) have presented a theory to account for repeated continental glaciation during the Pleistocene. This theory states that ice ages began when the North Pole migrated into the Arctic Ocean, the semi-isolated position of which causes climatic oscillations with a period and amplitude of the proper magnitude to account for all the observed environmental changes of the Pleistocene.

The oscillation is presumed to start with an ice-free Arctic Ocean warmed by water exchange with the Atlantic. Such an ocean would provide a rich source of precipitation for the circumarctic lands, inducing glacier growth there and increasing the earth's albedo enough to lower its mean temperature appreciably and cause further growth of glacier ice in northern regions and elsewhere. Ultimately so much water would be locked up in ice on the surface of the land that sea level would be lowered, the exchange of water over the Arctic-Atlantic sill would be materially decreased, the Atlantic would warm, and the Arctic would freeze, cutting off the polar precipitation source. The glaciers would then melt, interglacial conditions would prevail, the sea would rise, the Arctic ice pack would melt, and the whole cycle would start over again.

To me it is not clear why such a system should oscillate at all, let alone with the proper period and amplitude to cause glacial and interglacial ages. Rather, it seems probable that the system postulated would be a continuously self-regulatory one, that is, an ice-free Arctic Ocean would cause glaciers to form, which would immediately remove water from the sea, reducing the flow of warm Atlantic water into the Arctic basin and causing the formation of pack ice which would reduce snowfall on the adjacent land and shrink the glaciers. Apparently the authors of the theory (*1*, p. 1063) feel that the Arctic-Atlantic exchange of water would change abruptly, while the continental ice sheets would change gradually. As the decrease in interoceanic water exchange must be proportional to the reduction in sea level, and this in turn proportional to the volume of continental glacier ice, there does not seem to be any reason to expect such a lag of ice sheet behind ocean. The current temperature change is in phase throughout the world (*3*). Exact evaluation of the factors involved would be very difficult, but even crude mathematical models would be preferable to a subjective statement of the theory, and ought to show whether or not the postulated oscillations are likely.

It is not possible to examine in detail all the evidence on which the theory is based, for seven of the references, some of them very necessary to the argument, are to personal communications, articles in press, or unpublished observations. An examination of the published sources, however, reveals a very uncritical assessment of the relevant evidence. The theory demands that continental glaciers grow in the region around the Arctic Ocean and that the ice be very thick there during the height of a glaciation. This is in direct opposition to the prevailing opinion among glacial geologists that the principal nourishment and greatest thickness of ice were over the southern parts of the glaciers (*4*, pp. 313 ff.).

In attempting to satisfy this demand of their theory, Ewing and Donn refer to a map by J. Tuzo Wilson which is said to show that the glacial ice divide was much farther north than has previously been believed. The map has been published, in a form which shows the complete ice divide, only by Flint (*4*), as part of an exposition of what Ewing and Donn would have us believe is an "earlier" discredited view of the thickness distribution of the Laurentide ice, so one cannot scrutinize the evidence on which it, in turn, is based. It is, perhaps, significant that Wilson omitted much of the ice divide from the map when he published it (*5*). The inferred position of the ice divide appears to depend largely on aerial photographs of geomorphic features and, as Flint points out quite clearly, such features are most likely to represent conditions at the end of the ice age when the ice had retreated to the general region of the divide. Inferred ice divides based on reconnaissance studies of glacial geology are not very reliable, but this one, for what it is worth, is quite in accord with general geological opinion, and does not support the unorthodox views of Ewing and Donn.

The second line of evidence involves isobases. Ewing and Donn quote Charlesworth (*6*, p. 1321) to substantiate their idea of a northern ice divide. But if we turn to the page cited, we find a map from a paper by Daly showing the maximum uplift to be centered, not near the Arctic Ocean, but southeast of James Bay. Furthermore, the map depicts isobases of uplift since the postglacial marine transgression, and so tends to underestimate the crustal warping at the southern edge of the ice under full-glacial conditions. This map, even more than Wilson's, is subject to revision when more evidence is available about postglacial rebound in Canada, but it, too, supports the generally accepted view, and is, in fact, one of the classic statements of it.

Ewing and Donn's suggestion (*2*, p. 1160) that the crustal deformation data for the Great Lakes region be extrapolated through Hudson Bay is based on the assumption of a far-northern center of accumulation, and so cannot lead to any independent confirmation of it.

In no part of the theory is any cognizance taken of the fact that large parts of the land around the Arctic Ocean, far from being centers of glacier accumulation, were never glaciated at all. For example, the Glacial Map of North