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SCIENCE

Structure of West Antarctica

The results of U.S. IGY oversnow traverses reveal the nature of a large portion of ice-covered Antarctica.

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As part of its program for the International Geophysical Year and the IGY's successor, International Geophysical Cooperation, the United States is conducting an extensive traverse program in Antarctica. Seven major oversnow traverses, supplemented by several shorter trips and one airborne traverse, have thus far covered over 12,000 kilometers on the Filchner and Ross ice shelves, Marie Byrd Land, the Ellsworth highland, and the Victoria Land plateau of eastern Antarctica (Fig. 1). The scientific program of these traverses comprised glaciological investigations of the upper layers of the icecap and seismic, gravity, magnetic, and elevation studies to determine ice thickness, the physical characteristics of the icecap, and the nature of the rock floor beneath the ice. From this work a fairly clear outline of the structure of West Antarctica has now emerged.

Methods of Operation

Although there have been differences in the methods employed by the various traverse parties (*1*), the over-all procedure has been the same for all. Three Tucker Sno-cats were normally used by each party. The parties generally traveled 50 kilometers every day, stopping at regular intervals to read the gravimeter, the magnetometer, and the altimeters, and spent the alternate days making seismic and glaciological investigations.

The primary seismic measurements at each station were those of ice thickness and, on the floating ice shelves, of the depth of the water beneath the ice, made by reflection shooting. The travel time of the compressional wave echo served to locate the rock surface; in order to determine the thickness of floating ice, several methods utilizing multiple travel paths or shear waves, or both, were employed.

In addition to the reflection sounding, many short refraction profiles were shot to give a detailed determination of velocity variations in near-surface snow and ice. Travel times for both compressional and shear waves were recorded. This work was done to provide a comparison of the seismic wave velocities with the other physical properties of the ice, and to obtain corrections to the bottom-echo time for the low velocities near the surface.

At a number of locations long refraction profiles were shot to obtain information about the seismic velocities throughout the icecap and in the underlying rock. Both vertically and horizontally oriented geophones were used in order to record all possible phases. Shots were fired at distances up to 22 kilometers with charges as large as 870 pounds. These long refraction profiles provided, along with other valuable data, the wave velocities used for computing ice thickness.

Equipment

All traverses used the 24-trace Texas Instruments 7000B portable seismograph system with a basic frequency range of 5 to 500 cycles per second and with a selection of gain, filter, mixing, and automatic-gain-control settings that provided a large number of operating characteristics. Automatic gain control was very rarely used, and mixing only occasionally, with no appreciable improvement in the records. The parties were also equipped with two Vector geophone cables each having 12 takeouts at 30-meter intervals, and with a variety of geophones for measuring all components of motion over a wide frequency range.

Gravity values on the oversnow traverses were obtained with Frost gravimeters provided by Columbia University and the University of Wisconsin. A Worden geodetic meter was used at the airborne stations. The three Frost meters had been used for several years prior to the IGY, so their behavior was well known. Although the Worden meter was relatively new, and there was still some uncertainty about its drift rate, errors were minimized by the fact that ties back to the base at Byrd station were usually completed within 10 hours.

Magnetic measurements were made with an Arvela vertical-component magnetometer having a reading accuracy of about 10 gammas. Surface elevations were obtained with Wallace and Tiernan altimeters. A leapfrog or modified leapfrog method was used whenever travel conditions permitted.

Data Reduction

As has been discussed elsewhere (*2*), a low-velocity ice layer was discovered at the base of the icecap in Marie Byrd Land. Uncertainty about the thickness

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(or even the existence, in many places) of this layer and its wave-propagation characteristics diminishes the accuracy with which echo time can be converted into ice-thickness values. The maximum error in total ice thickness which would result from improper allowance for this layer is estimated to be 40 meters. The error in relative thickness between two neighboring stations would be considerably less than this but is difficult to reckon, owing to lack of information concerning the variability of the basal layer from place to place.

The gravity values measured between the seismic stations were used to provide detail in the topographic profile. Free-air gravity anomalies were used to compute ice thickness, although, with reflection shooting providing absolute depth control every 50 kilometers, Bouguer anomalies would have produced negligibly different results. The densities used for this interpolation were 0.9 gm/cm^3 for ice, 1.03 gm/cm^3 for sea water, and 2.67 gm/cm^3 for rock. From a consideration of the various sources of error, of which uncertainty about elevation is by far the greatest, the over-all accuracy of the computed gravity anomalies is estimated to be $\pm$ 10 milligals.

Considerable difficulty was experienced in trying to correct magnetic observations made by the traverse parties. The party was generally too far from a permanent station to permit effective control by means of the base-station magnetographs. For this reason the magnetic data have been used only to obtain a regional gradient and to give the general magnetic character of the basement rock.

Surface heights usually were calculated by the summation of elevation intervals measured between traverse vehicles as they traveled several kilometers apart. The normal corrections for temperature and humidity were applied, and also a correction for pressure gradient between vehicles, as estimated from the wind velocity two meters above the surface (*3*). The estimated maximum error of elevation determination at all traverse stations is 20 meters relative to the base station. This error decreases with decreasing distance between the field station and the base station. Another source of error in Marie Byrd Land elevations is uncertainty in the elevation of the base station, Byrd station. This uncertainty is estimated by the U.S. Weather Bureau to be 15 meters (*4*).

Ice-Surface Topography

The ice-surface contour map of the portion of West Antarctica which has been covered to date is shown in Fig. 2. Data from a short traverse to the Executive Committee Range conducted in February and March of 1959 were generously provided by William Chapman and have been used in constructing this map.

Two definite high areas are apparent, one in the east between the Sentinel and Horlick mountains and the other in the northwest in the vicinity of the Executive Committee Range. Between these areas is a saddle indicating converging movement of the ice from the high regions and outflow to the west and north. It is interesting to note the decided asymmetry of the icecap about the line between the Sentinel and Horlick mountains. To the east, where there are no obstacles, the ice surface slopes down rapidly to the Filchner Ice Shelf; to the west the converging flow has produced a relatively flat surface over the broad reaches of the interior of West Antarctica. Thus, the ice-surface contours suggest that the present ice sheet originated as separate icecaps in two mountainous areas, the Executive Committee Range and the area between the Sentinel and Horlick mountains, and that these two caps converged across the intervening low region.

Subglacial Topography

As the first step in the construction of a contour map of the subglacial rock topography, seismic reflection, gravity, and altimetry results were combined so that cross sections of the icecap along the various traverse routes could be drawn. Lines of mean depth were then estimated by eye in such a way as roughly to average out features less than 80 kilometers in extent. The resulting map is shown in Fig. 3. Ice-covered areas exhibiting a rock surface below sea level are hachured; the boundary of this zone was estimated where no direct evidence was available.

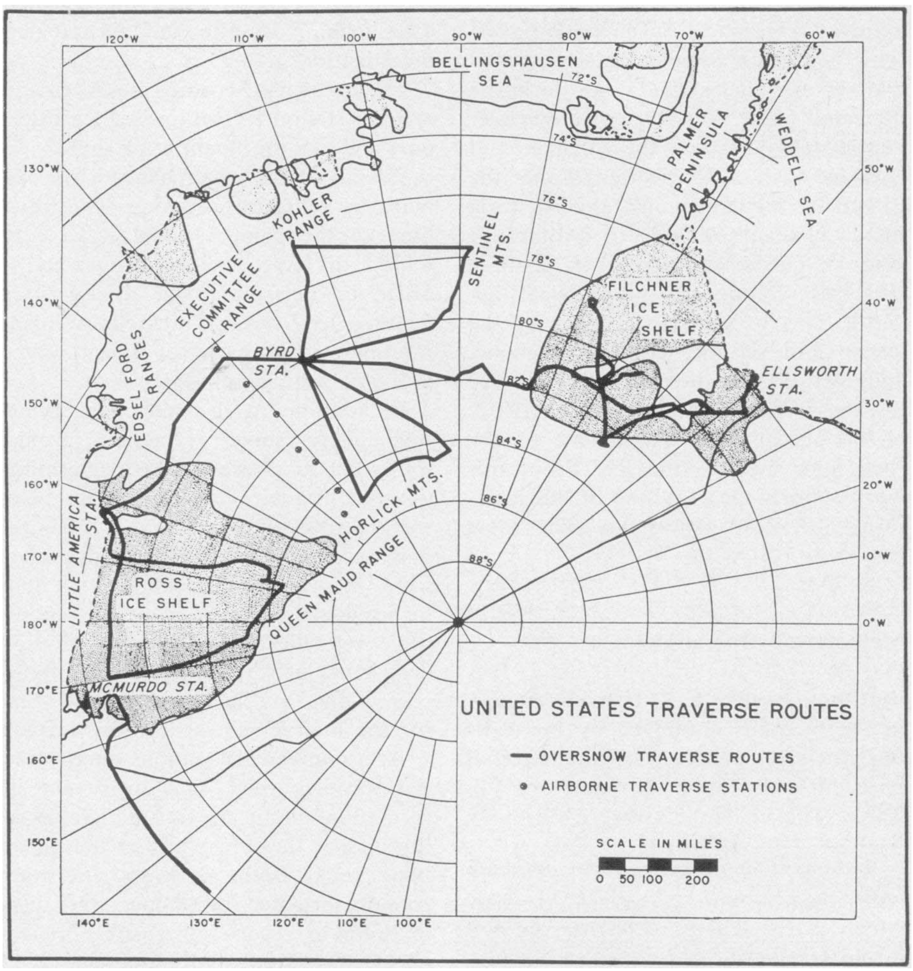

Fig. 1. Traverse routes in West Antarctica.

In considering the rock elevation beneath the thick, grounded ice of Marie Byrd Land, it should be remembered that the weight of the overlying ice has depressed the land surface on the order of 500 meters (up to 1000 meters in the deepest part of the central basin). Thus, sea level before the growth of the ice in western Antarctica should be fairly well represented by the −500-meter contour.

From this map it may be seen that, with the exception of Roosevelt Island near Little America station and the high spot centered around latitude 83°S, longitude 105°W, the region between the Sentinel, Horlick, and Queen Maud mountains to the south and the Kohler, Executive Committee, and Edsel Ford ranges to the north, is below sea level, most of it at least 500 meters below. Conspicuous within this region between Byrd station and the Sentinel Mountains is the deep basin whose maximum depth is more than 2500 meters. This basin, although becoming gradually shallower, broadens to the northeast and probably continues for some distance beyond the area surveyed. From this trend we infer that the rock surface below sea level extends northeast to the ocean, forming a vast channel across West Antarctica between the Ross and Bellingshausen seas.

Although, as previously mentioned, it was not possible to correct the magnetic data for temporal variations, a considerable change in their general character along the route appeared. North of the channel area the magnetic profile exhibits large variations which correlate qualitatively quite well with the variations in rock level. In the basin and along the Sentinel Mountains the variations are much smaller and show no relation to the subglacial topography. (Magnetic data from the Horlick Mountain region are not yet available.) The smoothest part of the magnetic curve is in fact found where the rock surface is the roughest. The magnetic evidence may therefore be taken to indicate that the rock immediately below the ice north of the channel possesses a relatively high magnetic susceptibility, whereas rock types with lower susceptibility exist under the basin and in the Sentinel Mountains.

Such a conclusion is in agreement with the limited geological evidence which is available. Rock samples collected just south of the Kohler Range and (during March 1959) from the Executive Committee Range by the Byrd traverse group now in Antarctica (*5*), as well as the shapes of the peaks themselves, indicate that these mountains are of volcanic origin. On the other hand, low-grade metamorphics were found in the foothills of the Sentinel Mountains (the main range was not reached) and in other nunataks on that traverse; visits to the Horlick Mountains and to neighboring peaks yielded samples of granite and sedimentary rocks (*6*). Granite and metasediments are known to occur along the coast in the Edsel Ford Range, but nowhere else northwest of Byrd station (*7*).

Long refraction shooting has given the wave velocities in the rock beneath the ice at several places. A value of 5.2 km/sec was found in the foothills of the Sentinel Mountains and on the eastern edge of the basin, whereas a significantly lower velocity of 4.3 km/sec was recorded at Byrd and Little America stations, both of which are within the channel.

Several lines of evidence are thus in agreement in indicating that the channel marks the dividing line between geologic provinces, separating the volcanic mountains on the north from the folded, metamorphic mountains of the Sentinel group to the east and the sedimentary, block-faulted Horlick group to the south.

The Filchner Ice Shelf reaches much farther inland than had been suspected prior to the IGY (*8*). It extends south for 650 kilometers from the ice front and has an area of approximately 330,000 square kilometers (exclusive of the large island) as compared with 540,000 square kilometers for the Ross Ice Shelf. This discovery, together with that of the large channel in Marie Byrd Land, has disclosed that West Antarctica consists, in fact, of a great southward extension of the Palmer Peninsula together with a mountainous island, or, more probably, series of islands, comprising the coastal ranges of Marie Byrd Land. Taylor (*9*) in 1930 postulated the existence of a downwarp or trough between the Ross and Weddell seas, and such a feature has been the subject of considerable

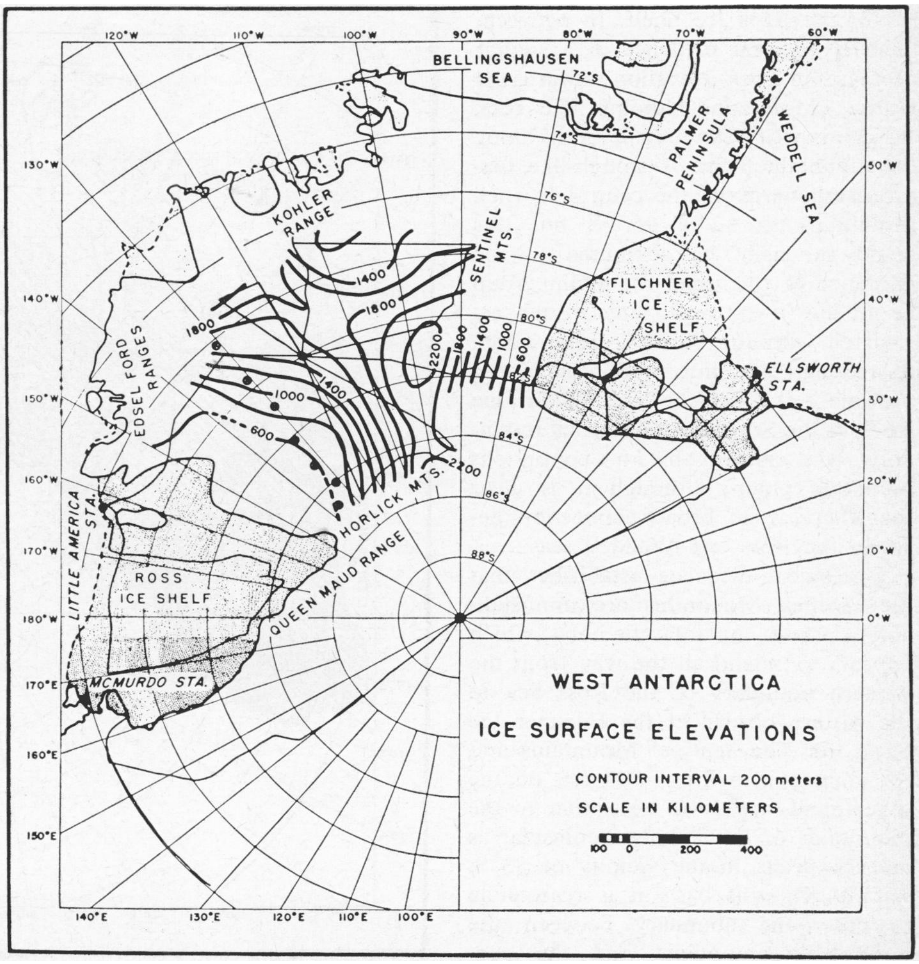

Fig. 2. Ice surface elevations in West Antarctica.

speculation since that time. In view of this it is worth while to consider briefly the continuity of the peninsula.

Although the area between the Sentinel Mountains and the base of the Palmer Peninsula has been seen only from a distance, some mountains are known to exist within the area, and there is at present no reason to doubt that there is a continuous land area across this region. From the traverse work it is virtually certain that the mountain chain continues unbroken to latitude 82°S. Between latitudes 82° and 84°S, along the 90°W meridian, mountains have been reported (see, for example, the 1958 edition of the map of Antarctica prepared by the American Geographical Society), but their positions are very uncertain, and in view of other evidence given below, their existence cannot be taken as proof of the extension of the peninsula to the Horlick Mountains.

A trough with depths greater than 1000 meters below sea level can be seen to extend from the edge of the Filchner Ice Shelf, near Ellsworth station, to the mountains at longitude 85°W. A trough is also shown along the entire western and southern boundary of the Ross Ice Shelf. In between, there is no clear evidence of a similar decrease in rock elevation toward the Horlick Mountains although the rock surface is well below sea level all along the mountain front. A trough-like feature is shown from the central Horlick Mountains to 82°S, 95°W, but this could as easily be attributed to the existence of the small mountain group to the northwest as to any trough associated with the Horlick front. From the topographic information it is not possible at present to determine whether the Sentinel and Horlick mountains are joined by a continuous mountain chain, although it is clear that there is no broad connection between the Ross and Weddell seas.

Geological evidence establishes that the Horlick Mountains are unmistakably a part of the antarctic horst, which appears to extend all the way from the western boundary of the Ross Sea to the eastern border of the Filchner Ice Shelf (*6*). The Sentinel Mountains and the nunataks to the southwest, on the other hand, appear to be similar to the mountains of the Palmer Peninsula, as are the peaks in the vicinity of 83°S, 105°W. On this basis it is reasonable to draw the boundary between the fault-block mountains and the geosynclinal, folded mountains just north of the Horlick Mountains (*10*). Therefore, the geological evidence tends to support the hypothesis of a topographic low expressing the break between folded mountains of the Palmer Peninsula type and the block-faulted mountains of the antarctic horst. However, even if this feature exists, it would be in no way comparable to the major channel between the Ross and Bellingshausen seas. An airborne traverse party under Thiel is now studying the area and should provide the data needed to resolve the question of the existence of such a trough.

Crustal Structure

The gravity results can be used not only to provide detail in the ice-thickness profile but also to obtain a rough picture of the crustal structure of West Antarctica. To remove variations due to changes of minor extent in the rock level, the free-air gravity anomalies have been averaged over 100-kilometer intervals. The resulting anomaly pattern shows that, by and large, West Antarctica is in isostatic balance, the average anomalies ranging between − 52 and + 49 milligals. The over-all mean anomaly of − 9 milligals is not significant when compared with the root mean square deviation from the mean of ± 23 milligals.

The discovery that most of the land surface under the ice of West Antarctica lies well below sea level has made it of particular interest to estimate crustal thickness in the area. This has been done by using empirical relations deduced by Woollard (*11*) which relate the elevation of the Mohorovičić discontinuity (*M*) to surface elevations and Bouguer gravity anomalies, respectively. These curves are based upon all available depths to *M* in North America and the associated Bouguer anomalies and surface elevations. Scientists of the U.S.S.R. have recently established the same type of relations based upon data for Europe and Asia (*12*). The independently determined curves are similar, so we may feel justified in applying the relations to the antarctic continent.

Tsuboi (*13*) has pointed out that only features 160 kilometers or more in

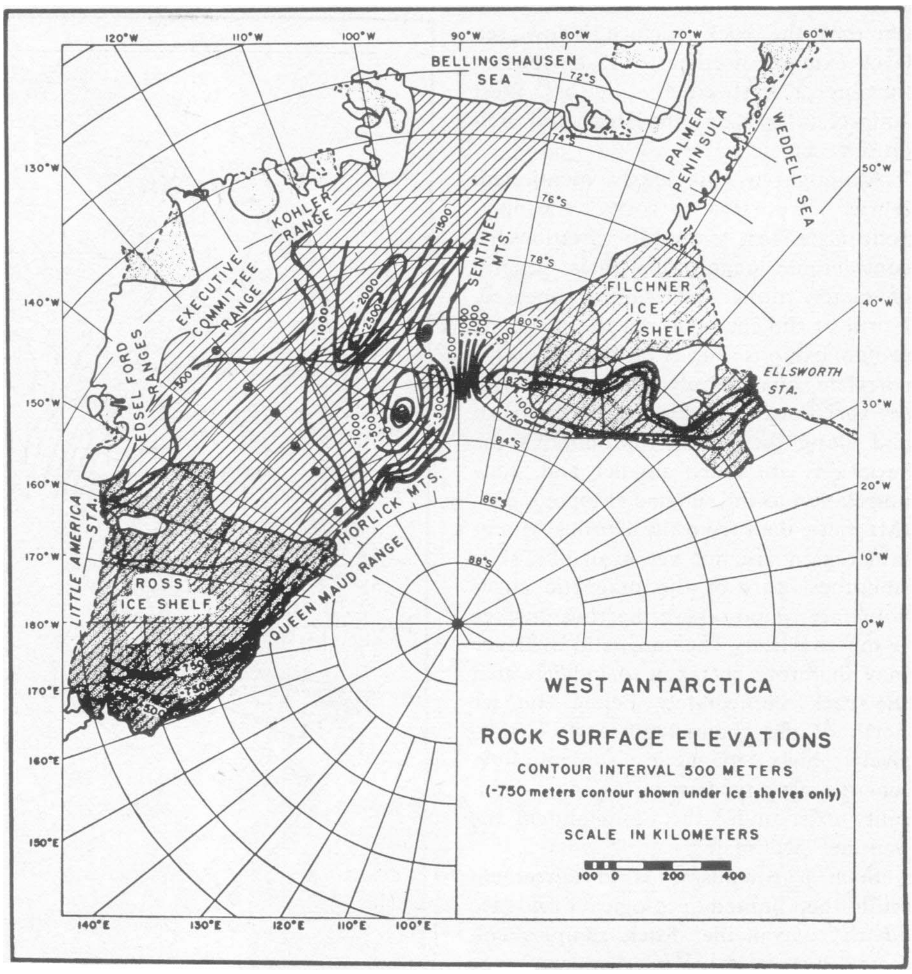

Fig. 3. Rock surface elevations in West Antarctica.

linear extent could normally be expected to achieve isostatic balance. To allow for this and also to minimize the effect of local departures of Bouguer anomalies and elevations from the regional values, both were averaged over intervals of not less than 400 kilometers. Since the relation between surface heights and the elevation of M given by Woollard is based on a normal crust with a near-surface density of 2.67 gm/cm^3, equivalent surface elevations in Antarctica were found by imagining the ice to be replaced by the same mass of crustal material.

Elevations of M obtained from Bouguer anomalies (M_b) and from surface elevations (M_e) have both been computed and are found to be in close agreement, differing by an average of only 0.5 kilometer. Since the values of M_e are based directly on the assumption of isostatic equilibrium whereas those of M_b depend upon the observed gravity values, the agreement between M_b and M_e provides further evidence that West Antarctica is in general isostatic balance.

A contour map based on the values of M_b is shown in Fig. 4. A deepening of M is seen toward all the mountain chains with the exception of the Kohler Range, for which sufficient data are not available. The tentative value of − 36 kilometers for the eastern edge of the Victoria Land plateau, based on preliminary gravity figures, corresponds well with the value of − 35 kilometers given by Evison, Ingham, and Orr (*14*), based on earthquake surface-wave data. The deep channel is marked by a consistently thin crust, and the M elevation under the channel in Marie Byrd Land is only slightly deeper than it is under the Ross Ice Shelf. The trend northeast from Byrd station of a thin crust supports the inference drawn from the subglacial topography that the channel extends to the Bellingshausen Sea.

The error to be expected in these determinations of crustal thickness should be examined. Since Woollard's curve has a slope of about 15 milligals per kilometer of crustal thickness, the estimated error in the gravity anomalies of 10 milligals corresponds to 0.7 kilometer in M elevation. From Woollard's work it is estimated that the error would be about ± 3 kilometers in M elevation by either method. This gives an error of about ± 4 kilometers in the determination of the absolute elevation of M. We may expect that the relative values of M_b and M_e will be more accurate than this, and that the shape of the contours on M in Fig. 4 is generally correct, although subject to a possible shift of a few kilometers up or down.

Summary

The following are the major conclusions reached concerning the structure of West Antarctica.

1) A major channel below sea level between the Ross Sea and the Bellingshausen Sea exists beneath the ice of West Antarctica. This connection is deep enough to have existed before the land surface was depressed by the weight of the overlying icecap. Between Byrd station and the Sentinel Mountains there is a deep basin within the channel in which a maximum depth greater than 2500 meters below sea level is found.

2) The combination of magnetic, geologic, and seismic evidence leads to the conclusion that the channel represents a fundamental division between geologic provinces, separating the volcanic mountains on the north from the folded, metamorphic Sentinel Mountains to the east and the sedimentary, block-faulted Horlick Mountains to the south.

3) The Filchner Ice Shelf is much greater in area and extends much farther to the southwest than had previously been realized. This discovery, together with that of the channel in Marie Byrd Land, has shown that the rock surface of the major part of West Antarctica is below sea level.

4) The Palmer Peninsula structures extend at least as far south as the 83rd parallel and may actually intersect the antarctic horst in the vicinity of 84°S, 80° to 90°W. There is no broad connection below sea level between the Ross and Weddell seas.

5) A deep trough extends inland for several hundred kilometers beneath the eastern area of the Filchner Ice Shelf. A trough is also found under the western and southern boundaries of the Ross Ice Shelf. These troughs may be connected by a narrow topographic low, expressing the break between the folded mountains of the Palmer Peninsula extension and the antarctic horst.

6) Free-air gravity anomalies show

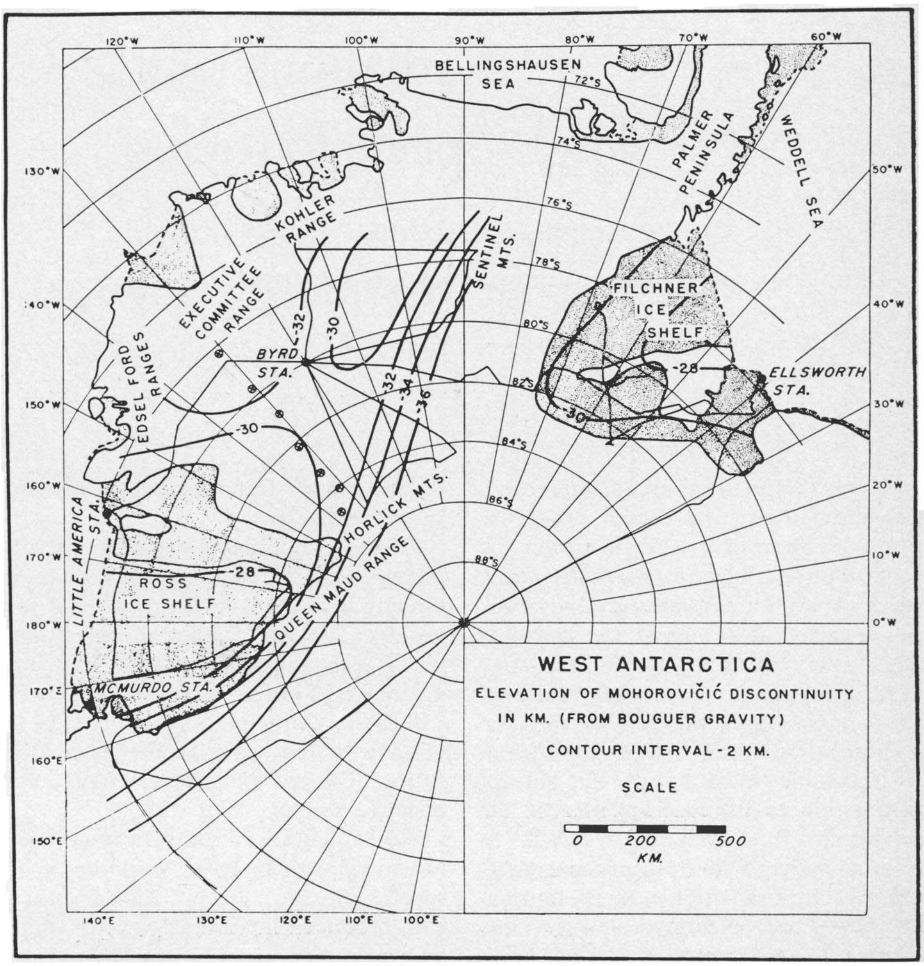

Fig. 4. Elevations of the Mohorovičić discontinuity (in kilometers).

West Antarctica to be in approximate isostatic equilibrium.

7) The crust of West Antarctica is continental in character, but the Mohorovičić discontinuity has the relatively high elevation (exclusive of the mountainous areas) of about 30 kilometers below sea level.

8) The Mohorovičić discontinuity deepens at least to − 36 kilometers, forming a continuous trough beneath the Sentinel, Horlick, and Queen Maud mountains and indicating their general topographic continuity with the Palmer Peninsula.

9) The thinnest crustal sections are found beneath the Ross and Filchner ice shelves, but the elevation of the Mohorovičić discontinuity in these areas is not greatly different from that beneath the large channel in Marie Byrd Land.

10) From the configuration of the ice and rock surfaces it is concluded that the ice sheet in West Antarctica originated as two separate icecaps in the two mountainous areas, one in the vicinity of the Executive Committee Range, the other between the Horlick and Sentinel mountains. As the caps expanded they converged over the open water between and were probably initially joined by a floating ice shelf which then grew thick enough to fill the trough completely and produce the present single-grounded ice sheet.

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Radiation from High-Speed Particles

Visible radiation that is shown to differ from luminescence phenomena has important applications.

P. A. Cherenkov

The experimental investigation and demonstration of the notable properties of radiation which appears during the motion of fast, electrically charged particles through a substance extends back some twenty-five years. As early as 1934, two reports were published—one by S. I. Vavilov and the other by myself (*1*)—in which it was shown that the gamma rays from radium produce a weak visible radiation of the solvent in addition to the luminescence of the solution.

In these reports, the universal character of this radiation and its unusual properties were described. and the conviction was expressed that the newly discovered radiation could not be a luminescence phenomenon because of its properties.

It was established by further experiments that this radiation is not released directly by the gamma rays, but by rapidly moving Compton electrons, which arise under the action of the gamma rays on the basis of the Compton effect. Attempts to produce a radiation with the same properties by the action of x-rays ($h\nu_{\max} = 30$ kev) gave negative results.

One might have thought that such radiation of the solvent would be of no special interest, since radiation phenomena, produced in various ways in solids and in liquids, represent a rather widespread effect. Aside from the generally well-known "classical" luminescence phenomena, one could, for example, mention the weak radiation of practically very "pure" liquids which arises under the action of ultraviolet radiation (*2*). Many liquids emit radiation upon the incidence of x-rays (*3*). Radiation has even been noted in liquids under the action of ultrasonic waves (*4*). Numerous cases of radiation from fluids and solids under the action of radioactive radiations have been well known from the time of Pierre and Marie Curie (*5*).

As a rule, such radiation phenomena are nothing else than ordinary luminescence and are emitted in the case of the so-called "pure" liquid as a result of the presence of a minute amount of luminescence-producing impurities. Therefore, one was inclined to believe that this radiation produced by the gamma rays was one of the many luminescence phenomena. This was presumed by Pierre and Marie Curie, who were undoubtedly among the first to have observed such radiation—of course, under conditions in which this radiation was rather strongly masked by ordinary luminescence.

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This article is a translation of the lecture he gave in Stockholm, Sweden, on 10 Dec. 1958, when he was awarded the Nobel prize in physics for 1958, a prize which he shared with I. Y. Tamm and I. M. Frank. It is published here with the permission of the Nobel Foundation. We are indebted to R. T. Beyer for translating the article from the German.

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