

Although the observations are not yet worked out, it is clear that large variations in accumulation occur from place to place. In particular, all surfaces with a west-facing downslope showed negligible accumulations. During the second year one could find weasel tracks in these areas that were a year old, together with remains of former camping sites up to 14 months old. In some places there was in fact ablation, a result purely due to wind erosion, so that the surface consisted of hard, smooth, crack-covered blue ice. It was, however, very seldom that we had to travel over bare ice in Dronning Maud Land; maps will show that 99 per cent or more of the surface layer of the area consisted of snow.

During sledging journeys ordinary glaciological work was carried out side by side with a detailed study of the first 2-3 m. depth of snow. This gave further information on the accumulation, since in a shaft dug at Maudheim (to a depth of 10 m. and down to snow from the year 1935) we had found a method of identifying the yearly snow layering.

In addition, temperature measurements in the snow were made at practically every camping place during the field season. By comparing these with the results obtained at Maudheim, we were able after the first summer's field work to calculate that the mean annual air temperature at a height of about 2000 m. above sea level in the main mountain area was  $-32^{\circ}$  C. During the second summer this work was continued, with the interesting result that at a height of about 2700 m. on the polar plateau we found that the mean annual temperature was  $-40^{\circ}$  C. Since the temperatures there were read to a depth of 12 m., this value can be considered very reliable.

Concerning the glacierization of Dronning Maud Land as a whole, it can be said that no glacial retreat corresponding to that in northern latitudes is at present taking place. The evidence for this is primarily that on even the very smallest nunataks (rocks which, in fact, project only a few metres above the inland ice) there is a comparatively rich covering of lichens. Since it is known that the migration of lichens takes a considerable number of years in a European climate, and since we have no reason to believe that plant migration in the unfavourable climate of Dronning Maud Land should proceed faster than it does in Europe, we can say that these rocks have lain bare for many years. Moreover, it is clear from these observations that the ice is not at present measurably in retreat. Detailed work in the mountain areas showed further that while there is no retreat in the glacierization there is also no increase.

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## II. SUMMARY OF SEISMIC SHOOTING INVESTIGATIONS IN DRONNING MAUD LAND<sup>1,2</sup>

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### INTRODUCTION

ALTHOUGH some seismic shooting measurements<sup>3</sup> of ice thickness were carried out by the Byrd Antarctic Expedition of 1933-35 around the region of the Bay of Whales, the order of magnitude of expected thickness over most of the Antarctic continent remained uncertain. Estimates varied from hundreds of metres to a few thousand. One of the tasks of the Norwegian-British-Swedish Antarctic Expedition, 1949-52 was to make a series of measurements of ice thickness along a line from the coast through the inland mountains and on to the high inland plateau. The main part of this task was carried out during an eleven-week journey from October 1951 until January 1952.

**METHOD.** Thickness measurements were made by seismic reflection shooting techniques, using equipment with six recording channels supplied by AB Elektrisk Malmletning, Stockholm.<sup>4</sup> The seismometers were normally spaced 10 m. apart in line with and separated from the shot point by distances of 10 to 200 m. according to the ice thickness. The shots consisted of T.N.T. charges ranging from 90 to 720 grams placed in hand-bored holes at depths from 2 to 12 m. Amplifier band pass filters were normally set to 90 c/s. Corrections to ice depths to allow for slower velocities in the surface layers were based on shots fired at the bottom of a 100 m. bore hole at Maudheim, and varied from 20 to 40 m. However, an accuracy of around 5 per cent in depth measurement is all that is claimed in view of independent checks of seismic results in other areas.<sup>3, 5.</sup>

With the technique used, all Rayleigh waves from the explosion passed the seismometers before the arrival of echoes from the underlying rock (Fig. 1, p. 211). This differs from the technique of Expéditions Polaires Françaises on the Greenland Ice Cap, as they used a much greater separation of shot point to seismometers.

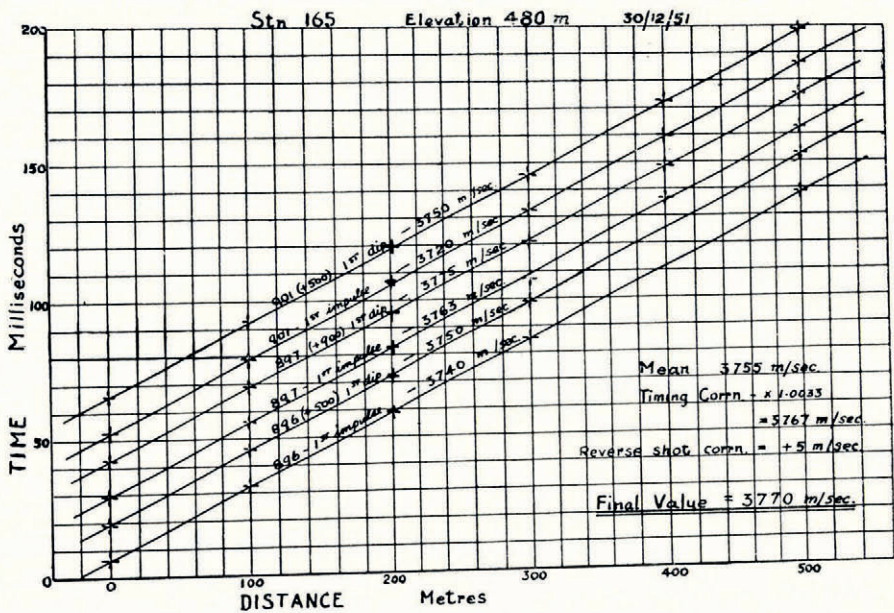


Fig. 2. A set of time-distance curves for determining the velocity of the longitudinal (P) wave in ice. These were taken 181 km. from Maudheim

Three distinct waves were produced by each explosion, the longitudinal (P) wave of around 3800 m./sec., a second wave of about 1650 m./sec. which may be a transverse (S) wave, and a Rayleigh wave at approximately 1050 m./sec. Refraction shooting techniques were used to measure the velocity of the P wave. For this the seismometers were spaced 100 m. apart, and shots fired at 100, 500, and 900 m. from the nearest seismometer along this line. A check shot at 100 m. from the opposite end of the seismometer line enabled a small correction to be applied for any apparent velocity difference in the reverse direction. The time-distance graph was plotted separately for each shot, thus eliminating any errors due to variation of propagation conditions around different shot points. Fig. 2 (above) shows these curves. As the 500 m. and 900 m. shots gave almost identical values of the velocity ( $V_p$ ) of the P wave, their mean was taken as the correct value. The measurements of  $V_p$  at the four main stations are shown in Table I.

TABLE I

Date	Seismic Station No.	Distance from Maudheim	Height above sea level	Ice Temperature	Velocity of P wave ( $V_p$ )
		km.	metres.	°C.	m./sec.
13.10.51	38(Maudheim)	0	37	-17	3760 $\pm$ 20
30.12.51	165	185	480	-19	3775 $\pm$ 20
13.11.51	97	413	1575	-27	3785 $\pm$ 20
25.11.51	119	615	2710	-40	3810 $\pm$ 20

The change in velocity of the P wave with altitude and ice temperature is less than has been found by other observers.<sup>6</sup>

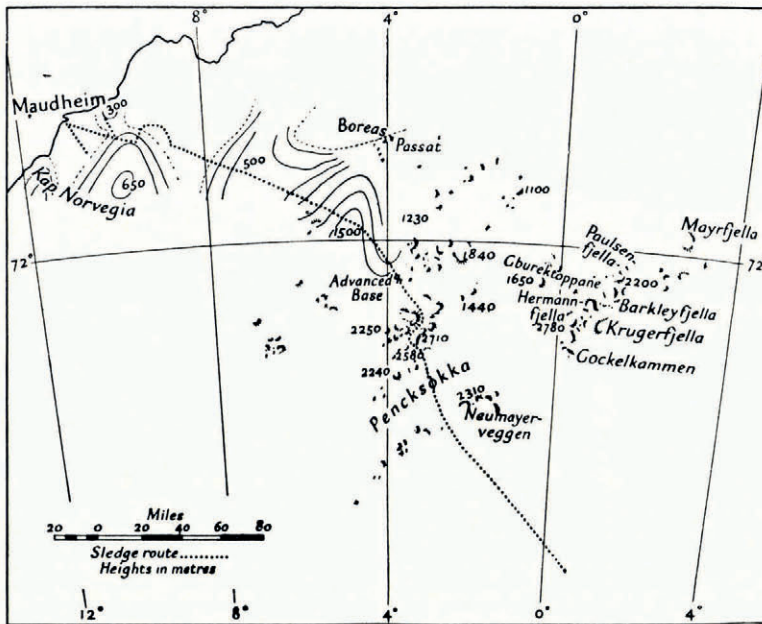


Fig. 3. The route of the main seismic journey

SNOW COLLAPSE. Some trouble was experienced at certain localities due to random impulses arriving at the seismometers for some time after the normal Rayleigh wave had passed, thus obliterating weak echoes (Fig. 1). These impulses were apparently due to a secondary collapse of the surface layers of snow caused mainly by the Rayleigh (surface) waves from the explosion. Running tracked vehicles around the area in which the seismometers were placed to cause preliminary collapse appeared to help, but the most effective method of reducing these impulses was to increase the depth at which the charge was fired. In general this random collapse became worse as the elevation increased and the ice temperature decreased. At an ice temperature of  $-40^{\circ}$  C., it would have been desirable to shoot at even greater depths than the 12 m. which was the limit of our hand boring gear.

The effect has been mentioned at some length, as it has not previously been found to be a serious and continuous obstacle to seismic shooting observations on ice, although similar effects have been noted. Techniques which failed to prevent this snow collapse included firing the shots

up to 8 m. above the snow surface, and increasing the separation of the shot point from seismometers to over one km. with the shot at 3 m. depth. So far no similar troubles have been experienced on the Greenland Ice Cap.

**SURFACE PROFILE.** Three aneroid barometers were carried on the main seismic journey, and the first half of that trip was along a regular route inland for which barometric heights from several other journeys are available. The heights noted in this paper are estimated to be  $\pm 30$  m. up to 315 km. from Maudheim, and  $\pm 60$  m. beyond that point. Distances were measured by sledge and weasel meters, and were adjusted to fit astronomical observations.

The maximum altitude reached on the inland plateau was 2710 m. above sea level, and it was still rising slightly at this point. The German claims<sup>7, 8</sup> that it rose to 4200 m. in this area proved to be incorrect. The route followed on the main seismic journey is shown in Fig. 3 (p. 207).

**ICE THICKNESS.** Fig. 4 (below) presents the main result of the seismic journey. As this profile is based on a series of spot soundings of varying quality rather than a continuous record of the

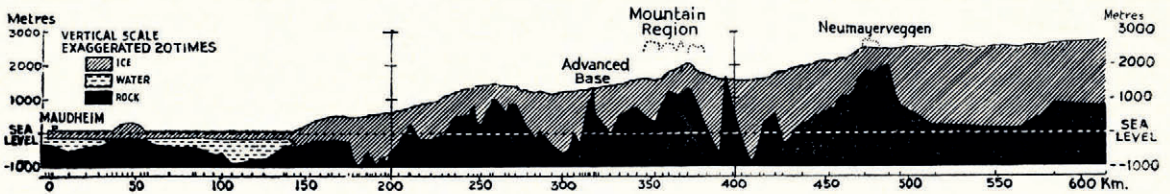


Fig. 4. The main seismic profile showing the ice and rock profiles along the route shown in Fig. 3. The vertical strokes above the distance scale indicate points at which seismic soundings were made

ice thickness, it is necessary to discuss the possible accuracy of the diagram. For this purpose we will divide the profile into regions with different characteristics.

(1) *The Ice Shelves.* The glaciologists' depth-density curve down to 100 m. below the surface, together with surface elevation and sea water density, gave the thickness of the ice shelf as  $186 \pm 5$  m. at Maudheim. This was used to evaluate seismic echoes which came from the ice-water interface at 5 stations. Elsewhere the thickness of the ice shelf has been taken as the mean of the five known values. Any error in the thickness of the ice shelf will produce an error in the depth of the sea bottom, but this is unlikely to exceed 50 m.

As Poulter has stated that the Ross Ice Shelf rests on moraine some 10 miles in from the front, the reasons for interpreting the results as showing that the ice shelf in Dronning Maud Land is floating should be stated.

- (a) Seismic shooting results at Maudheim indicate that for the layer shown as being sea water, the velocity of propagation of P waves is approximately that of sea water.
- (b) The character of the echo (Fig. 1).
- (c) No visible tidal rise and fall was taking place along the ice cliffs at the front of the ice shelf, but this was shown to occur at the junction with the inland ice (coastal ice hills).
- (d) Physical considerations, such as the hypotheses of Nye, make it necessary for some bottom or surface slope to be present to cause the flow of ice resting on rock. Such a slope is not present in ice shelves.

(2) *Coastal Ice Hills.* This term is proposed for the type of feature shown in Fig. 4 from 36 to 55 km. and 145 to 175 km.\* The term applies to the rounded hills typical of Antarctic coastal

\* This is a tentative name only.

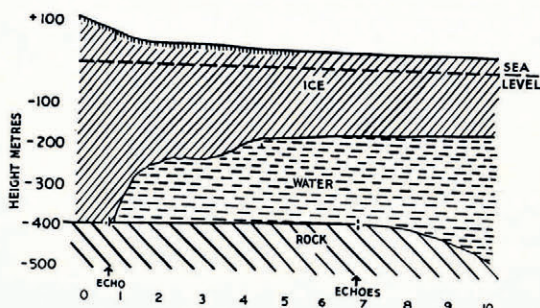
regions where the visible hill is due to the accumulation of ice on a relatively flat base and whose form is determined principally by the mechanism of ice flow rather than the underlying relief.

Seismic echoes were readily and reliably obtained in these regions.

(3) *Mountain Ice Sheet*<sup>9</sup> and *Mountain Region*. 175 to 480 km. In these regions the bottom relief changes to an alpine type covered by considerable thicknesses of ice except in the mountain region. The snow collapse started to give some trouble in these regions, and in five cases it was difficult to decide whether a recorded echo was due to the first or a multiple reflection from the subglacial floor. Although the distance between seismic stations was not large, several submerged peaks (the surface profile indicates their presence) could not be investigated in the time available. In particular the rise to Neumayerveggen is certainly more rugged than is shown by our profile.

(4) *Inland Plateau*. The snow collapse gave serious trouble here and greatly limited our work. Consequently the region is almost certainly more rugged than shown by our profile. There was considerable difficulty in obtaining echoes, but their general accuracy was indicated by recording both the primary and a double echo at two stations.

Fig. 5. *Inland ice to ice shelf junction 140 km. from Maudheim. The surface profile here was obtained by theodolite levelling. The bottom of the ice shelf is based on an echo at 6.8 km. and the assumption that a 1 m. change in surface elevation indicates a change of 8 m. in ice thickness*



#### DISCUSSION

(1) *The Ice Shelves*. In addition to the points mentioned above, two other points noted by the expedition should be remembered when discussing the mechanism of ice shelves. These are the constancy of height of the surface of the ice shelf with time, and its slow spreading out.<sup>10</sup>

In view also of the seismic profile at 140 km. from Maudheim (Fig. 5, above) and the relatively small variation in ice thickness at the five measured points, the following is put forward as an explanation of the mechanism of shelf ice. Floating ice which has a net annual accumulation (including loss or gain at both top and bottom surfaces) will tend to attain an "equilibrium thickness." This will then be maintained by the spreading out of the ice shelf so that

$$\frac{\text{Annual net accumulation}}{\text{Equilibrium thickness}} = \frac{\text{Increase in area}}{\text{Total area of ice shelf}}$$

If the ice is thicker than the equilibrium thickness, as may occur where a large glacier pushes into the sea, the spreading out would reduce its thickness accordingly. If the ice is below the equilibrium thickness, the spreading would be reduced or stopped. If, as seems reasonable, no differential movement takes place between different levels in an ice shelf, these assumptions could be checked by field observations.

The equilibrium thickness of the ice shelves around Maudheim is apparently around 190 m. As the sea temperature beneath ice shelves will never differ greatly from  $-1.8^{\circ}\text{C}$ ., and as large variations of density with location are not likely, this figure may not vary much around the Antarctic. A variation with latitude would, however, occur if the small forces due to the rotation of the earth play any appreciable part in the mechanism.

(2) *Coastal Ice Hills*. The ice hills shown in Fig. 4 and a third one also examined, approximately follow the form predicted by J. F. Nye <sup>11a, b</sup> from his equation

$$h = \frac{h_0}{\alpha}$$

where  $h$  is the ice thickness  
 $h_0$  is a constant  
 $\alpha$  is the surface slope.

In our case  $h_0$  takes the value of  $12\frac{1}{2}$  m., which differs only slightly from the value of  $h_0 = 10$  m. which Nye found in Greenland, and from the values it is given in Europe. As  $h_0$  is directly proportional to the shear stress in the lowest layers of ice, and as laboratory studies have shown the shear stress necessary to produce a given rate of strain varies rapidly with temperature,<sup>12, 13</sup> it follows that the ice at the bottom of these coastal ice hills cannot be much below  $0^\circ$  C.

(3) *Mountain Ice Sheet and Mountain Region*. The underlying relief here is too rugged for the application of a simple formula. It is, however, reflected in the surface relief on a much reduced scale, but the damming action of rock ridges complicates the picture. The valleys at 300 and 410 km. show cross sections of glaciers draining considerable areas of ice, where active erosion of fjord-type valleys is apparently taking place.

(4) *Inland Plateau*. The wide spacing of thickness measurements has resulted in the diagram showing a much less rugged underlying relief than is indicated by the surface profile. Nevertheless it is clear, from the profile in Fig. 4, and from Fig. 2, that the primary cause of this inland plateau is the damming action of the Neumayerveggen ridge, which forms part of a chain of peaks running from north-east to south-west. A main drainage channel for the ice from this plateau appears to run north approximately along the line of the Greenwich meridian. This is apparently the cause of the ice tongue on that meridian which projects northwards from the general trend of the coastline, but the direct connection from this glacier to the ice tongue was not traced right through.

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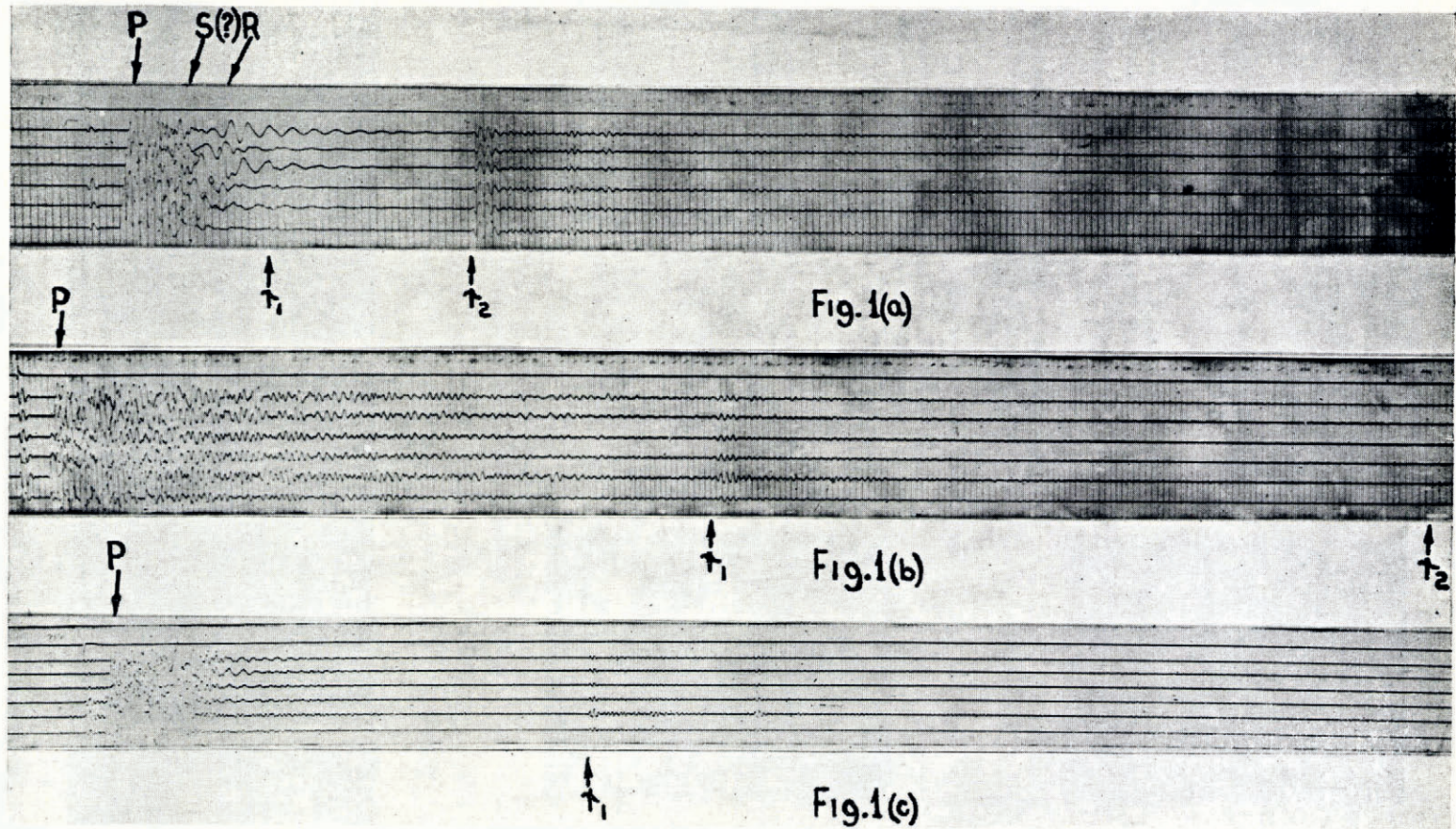


Fig. 1. Seismic reflection shooting records from Dronning Maud Land

- (a) Taken on the ice shelf near Maudheim. The direct P, S(?) and R waves are followed by the weak reflection from the ice-water interface ( $r_1$ ); the strong reflection from the sea bottom ( $r_2$ ) is followed by echoes from lower levels, then by multiple echoes
- (b) Record from the inland plateau 516 km. from Maudheim. The confused traces after the normal passage of the Rayleigh waves are due to snow collapse, the effect here being reduced by burying the charge at a depth of 12 m. A faint double echo ( $r_2$ ) 2.4 seconds after the explosion confirms that the one at 1.2 seconds is the primary ( $r_1$ ), the ice depth thus being 2380 m.
- (c) Record showing the deep fjord type valley at 392 km. from Maudheim. The impulses following the initial echo ( $r_1$ ) could be caused by rocks carried by the lowest levels of ice, lower sedimentary beds, or reflections from different sides of the steep-sided ice-filled fjord