The Omnsbre is a kind of "sheet" glacier (Fig. 11, p. 746) with its southern snout only some 5 km. north of Finse on the Bergen–Oslo railway. The highest part of the glacier is at 1600 m., it descends to 1500 m. to the south, and to 1350 m. to the north. At the time of the topographical survey of 1923–29 (Map D. 33, Hardangerjøkulen 1 : 100,000, stereophotogrammetric original 1 : 50,000) the glacier, as defined by the surveying party, covered some 10 km.[2].

The Omnsbre was thus an extremely flat glacier of considerable extent. Slight alterations in the firn line will work out much more sensationally than in an alpine glacier with perhaps 1000 m. altitudinal differences. Once the firn line rises above 1600 m., the Omnsbre is climatically dead.

Vertical wastage during the last few years has been very great. There are all kinds of marginal phenomena on a small scale, exactly like the dead inland ice in miniature. The ice is generally speaking very clean, and the melt water issuing from the glacier is now always quite clear. This is in enormous contrast to the melt water from the living glacier, which, when I worked on the lakes of the district in 1933, was frequently a real mud stream, blackish from the Ordovician shale below the glacier.

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THE DETERMINATION OF THE THICKNESS OF A GLACIER FROM MEASUREMENTS OF THE VALUE OF GRAVITY

Cambridge University Austerdalsbre Expedition 1955, Paper No. 2

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Abstract. A method is described of determining the thickness of a valley glacier from measurements of gravity. On a Norwegian glacier approximately 4 km. long and 1½ km. wide values of gravity were measured at points on four transverse lines. For comparison, values were measured at points on three lines in the valley below the snout of the glacier. The positions and altitudes of these gravity stations were determined by triangulation. After making corrections for the altitudes of stations and for the effect of the valley walls, the differences between the gravity values obtained on the glacier and those obtained in the valley below the glacier are attributed to the thickness of the ice. Four transverse sections of the glacier, obtained in this way, are given. Errors in the estimates of ice thickness should not exceed 20 per cent on the two lower cross-sections, nor 40 per cent on the upper two.

Résumé. On décrit une méthode pour calculer la profondeur d'un glacier de vallée en partant de mesures de gravité. En Norvège, sur un glacier long de 4 km et large de 1½ km environ, on a determiné des valeurs de gravité sur quatre lignes transversales. Et, par comparaison, on a mesuré des valeurs sur trois lignes en aval du front du glacier. La situation et l'altitude de ces stations de gravité ont été déterminées par triangulation. Quelques corrections faites, vu l'altitude de ces stations et l'effet des parois latérales, on a attribué à la profondeur de la glace la différence entre les valeurs calculées sur le glacier même et celles qui ont été calculées en aval. Par ce moyen on peut ainsi établir quatre sections transversales. Les erreurs des estimations de l'épaisseur de la glace ne devraient pas excéder 20% sur les deux sections transversales inférieures et 40% sur les deux sections supérieures.

https://doi.org/10.3189/S0022143000025028 Published online by Cambridge University Press

Introduction

The work of the Cambridge University Austerdalsbre Expedition, 1955, included a gravity survey of this small valley glacier and of part of the valley below the present limit of the ice. The programme for 1956 will probably include the direct measurement of the thickness of the glacier by seismic reflection methods. It was hoped that from the results of the gravity survey the ice thickness at some points could be estimated and that these estimates would be of value in the subsequent seismic experiments. In fact the estimates seem to be more reliable than was expected, so that it has been possible to draw four transverse sections of the glacier.

The idea of using a gravity survey for determining the thickness of an ice-sheet was suggested by Martin [1], and has been used with some success on the Barnes Ice Cap of Baffin Island [2] and elsewhere. However, the method has not been applied before to a valley glacier, so that a brief description of the work and its limitations may merit record.

The field work of the gravity survey was completed in three weeks of moderate weather in July, 1955.

The Reduction of the Observations of a Gravity Survey

To allow a useful comparison to be made of gravity measurements obtained in different parts of the world it is customary to reduce the data in one of several ways. For these reductions the following information is required: (a) the absolute value of gravity at each point of observation, (b) the absolute altitude of the point and its geographical latitude, and (c) a detailed and accurate map of the region, together with a knowledge of the density of the rocks.

The corrections which may be applied are the following:

(i) *The free-air correction.* This is to allow for the variation of the force of gravity with the distance between the point of observation and the centre of mass of the earth. Normally measurements of gravity are reduced to sea level and for altitudes up to several thousand metres the free-air correction is a linear function of altitude, being equal to 0·3086 milligals/metre.*

(ii) *The non-topographical Bouguer correction.* This correction accounts for the material between the point of observation and sea level, assuming that the same material extends in uniform infinite sheets in all directions around the station. The Bouguer correction is $0{\cdot}04185 \times \rho$ milligals/metre, where ρ is the specific gravity of the material.

(iii) *The terrain correction*, which allows for the varying altitude of the ground around the station, and for variations in the densities of rocks in the area.

The value of gravity, after the application of one or more of these corrections, is compared with the theoretical value at sea level given by the International Gravity Formula † for the variation of gravity with latitude. The difference is called the anomaly, being the free-air anomaly if the free-air correction has been applied, and the Bouguer anomaly if both the free-air and the Bouguer corrections have been applied.

For the free-air and Bouguer corrections the absolute altitudes of the points of observation are required. Unfortunately, no large-scale contour map exists of the Austerdal area. The determination of the absolute altitudes of the gravity stations would have involved levelling over considerable distances from the nearest point at which the altitude is known. Fortunately, for the immediate problem, it is not essential to know the absolute altitudes, as long as the height differences between the stations are known accurately. Therefore an altitude (of 280 m.) has been assumed for the starting point of the survey, based on a height of 822 ft. which is marked at an indefinite point in the valley below the starting point on the only available map of the area (Jostedalsbreen, 1 : 200,000, published by Norges Geografiske Oppmåling). The altitudes of all other points in the survey are based on this assumed altitude, which may be in error by ± 10 metres.

* 1 milligal = 0·001 cm./sec.^{2}

† Theoretical value of gravity on the international ellipsoid, $\gamma_0 = 978{\cdot}0490\ (1 + 0{\cdot}0052884 \sin^2\phi - 0{\cdot}0000059 \sin^2 2\phi)$ cm./sec.^{2}, where ϕ is the latitude.

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In a similar way the Bouguer corrections applied are incorrect in absolute value because of inaccuracies in these altitudes, and further errors are introduced by the assumption that all the rock in the area has the same specific gravity of 2·67. For example, in the centre of the valley below the snout of the glacier there is a considerable thickness of glacial drift, possibly as much as 30 m. in some areas. However, errors in the estimates of the glacier thickness caused by neglecting the lower density of this drift material are small compared with inaccuracies caused by other assumptions, probably being less than 7 m.

Since no large scale contour map of the area exists, it has not been possible to estimate the terrain correction. In a mountainous area the calculations are tedious in the extreme and the errors, even when altitudes are known, can be large. The procedure adopted in this survey is described later.

Measurements of the Value of Gravity

The instrument used in this survey was a Worden Geodetic Gravity Meter. Such an instrument does not measure the absolute value of gravity, but only the differences between the values at different points. Therefore, to obtain absolute values, it is necessary to start the survey at a point where the value has already been determined. No such point exists in the area of Austerdal. Because of the limited time available, and because the altitudes of the gravity stations could not be determined absolutely, only a relative gravity survey was made, in which the differences between the values at the points of observation are known accurately, but not the absolute value.

To allow for the drift of the zero of the instrument observations were taken at a gravity "base" immediately before and after a traverse, and at short intervals between carrying out the traverses. Four secondary gravity bases were established in the valley, at each of which the value of gravity (relative to that at the main base) was accurately measured by repeated linkages.

Seven traverses were made across the valley: three (A, B and C) in that part of the valley between the present snout of the glacier and the first large terminal moraine, the position of which corresponds approximately with the limit of the glacier marked on the map referred to above, and four on the glacier itself (D, E, F and G). The positions of all the traverses are marked on the sketch map, Fig. 5 (p. 761), and of D, E, F and G on the air photograph, Fig. 6 (p. 763). The number of points at which gravity was measured in each traverse varied between eight and thirteen. The total range of the station gravity values is about 80 milligals.

In the determination of the gravity values it has been assumed that the calibration constant of the instrument, determined by the manufacturers in tilt-table experiments, is correct. (Dr. M. H. Bott, Department of Geology, University of Durham, in work with the gravimeter immediately after this survey, has confirmed the makers' calibration.)

The maximum error in the gravity differences between the four gravity bases is 0·1 milligals. Two of the traverses were repeated and no error greater than 0·1 milligals was observed. In the other traverses, two readings were taken at most stations, and similar agreement was found.

Determination of the Altitudes and Co-ordinates of the Gravity Stations

As explained above, the altitudes of the gravity stations have not been determined absolutely. Neither are the absolute co-ordinates required. The liability to error due to the use of relative, rather than absolute, altitudes and co-ordinates is so small as to be negligible in comparison with the errors involved in the assumed terrain correction. This will be explained more fully below.

The computations of the co-ordinates of the stations are based on the measurement of the length and azimuth of a base-line made by C. Embleton and others. The accuracy of the base-line measurement is probably 1 : 3000, but due to the lack of accurate time readings the azimuth was determined only with an accuracy of 1°. The range of latitudes of the gravity stations is about 4′, the corresponding range in values given by the International Gravity Formula being 5 milligals, so that an error of 1° in the orientation of the base-line will not introduce any error in the reduction of the gravity data.

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To determine the altitudes and co-ordinates of the stations the following procedure was adopted. Bamboo poles were erected at each gravity station in a traverse, with marks at approximately theodolite telescope height. The stations in each traverse were aligned by eye on straight lines.

Suitable stations in each traverse were selected as control points and the horizontal angles necessary to join these in a triangulation network were observed, together with an extension of the base-line. To make firm figures in this network some intermediate control points, between the traverse lines, had to be set up. The co-ordinates of these control points were computed from this network after adjustment. The accuracy of these co-ordinates has been estimated from the size of the angular adjustments, and for control points on the lowest six profiles, assuming the azimuth to be correct, the co-ordinates are within 0·5 m. of their correct values relative to the origin. The connexions to the glacier profile G are less accurate and the corresponding figure for the accuracy of the co-ordinates of the control points in this profile is about 3 m.

The co-ordinates of the intermediate traverse stations were obtained by assuming them to be in straight lines between the control points, and measuring their separations with a linen tape, by tacheometry or, in a few cases, by subtense methods. Corrections for slope were made where necessary, and adjustments made to fit the total measured separations between control stations to the computed separations. From the size of these adjustments, and the errors in the control points, it is estimated that the co-ordinates of the intermediate traverse points are within about one metre of their correct relative position for the lower six profiles, and within 4 m. for the glacier profile G.

A scale error of 1 : 3000 throughout the survey would produce additional displacements of up to 1 metre in the co-ordinates of the gravity traverse stations.

Relative altitudes of the stations were obtained by measuring vertical angles from each station to adjacent traverse stations and to two control stations. Sufficient observations were taken from the control points to ensure that reciprocal readings could be used throughout, with one or two exceptions. Heights of the control stations were computed around a series of closed circuits, and adjusted. Heights of intermediate stations were then computed, using the most suitable set of reciprocal readings.

For the six lower profiles the altitudes of the control points are within about 0·25 m. of their correct value relative to the origin and those of intermediate stations within about 0·5 m. On the most northerly traverse, G, the uncertainty in the altitudes is about 1 m.

Reduction of the Field Observations

After the values of gravity at the traverse stations had been computed (relative to the value at Main Base), by correcting for the drift rate of the instrument, they were treated in the following way.

Corrections were made to the station gravity values according to the International Gravity Formula. Free-air and Bouguer corrections were then applied, assuming that all of the material under the station had a density of 2·67 gm.cm^{-3}. These corrected differences from Main Base value, which will be referred to as the "anomalies", contain the effect of the terrain, and of the difference in density of the glacier ice from the underlying material. The problem becomes one of differentiating between these two effects.

If the valley were straight and completely uniform in transverse cross-section, both in the section occupied by the glacier and beyond it, and there were no geological cause for gravity anomalies, the problem could be solved simply and accurately. In the actual valley, the walls are steeper near the head of the valley, and there is a bend in the valley near the present position of the snout. Corries and stream gullies cut deeply into the sides of the valley. The shape of the valley can be seen in the air photograph, Fig. 6.

The anomalies obtained at stations in the three traverses of the valley below the ice limit are shown in curves A, B and C of Fig. 1 (p. 759). Abscissae are distances measured along the lines of the traverses. The forms of these three curves are similar, and the similarity of the ordinates

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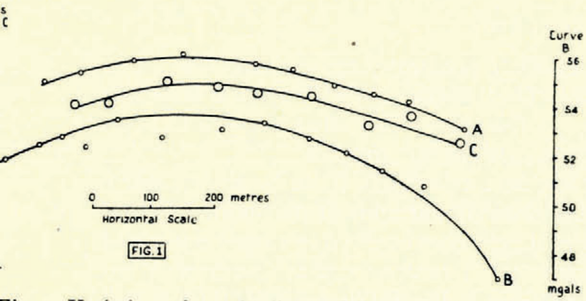

Fig. 1. Variations of gravity "anomaly" across the valley on three traverses below the snout of the glacier

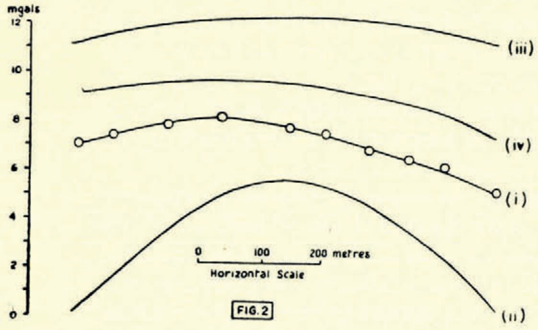

Fig. 2. Profile A. Calculated and observed "anomalies" across the valley

(i) Observed gravity "anomalies".
(ii), (iii) and (iv) Terrain effects of valley models I, II and III respectively.

(The ordinates of all curves have arbitrary zeroes)

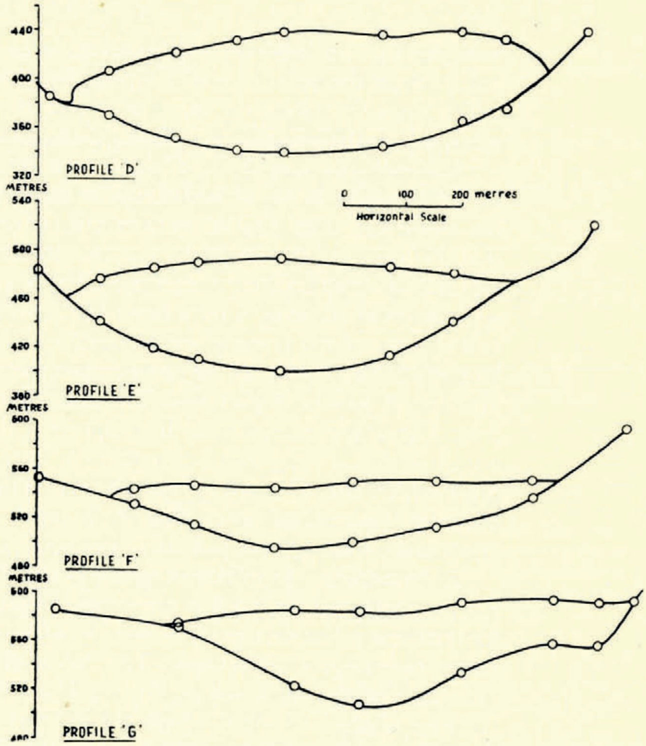

Fig. 4. Cross-sections of the glacier along profiles D, E, F and G, looking up the glacier

Vertical exaggeration: 2 times. Ordinates are approximate altitudes above sea-level

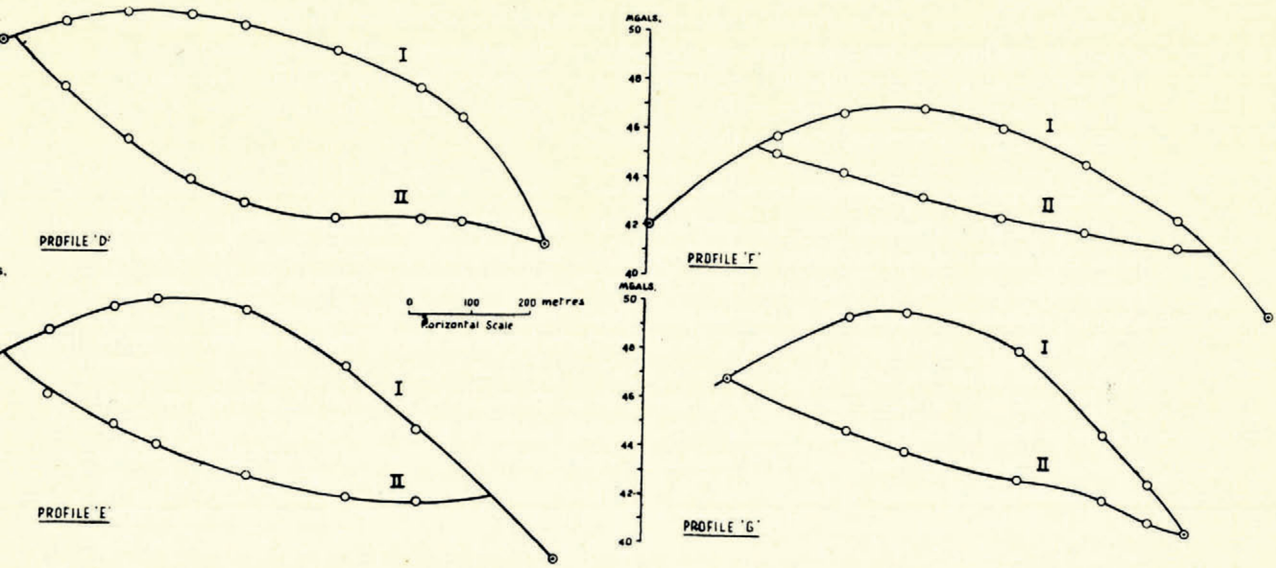

Fig. 3. Plots of variation of gravity "anomalies" across the glacier on the four traverses

Curves I are interpolated curves, and show the value of the "anomaly" expected if all the material under the point of observation had $\rho = 2{\cdot}67$. Thus the form of the curve gives the terrain effect across the valley. The form is estimated by comparison with the "anomaly" curves of profiles A, B and C. The values shown by a circle surrounding a dot are those found on rock at the sides of the glacier

Curves II are plots of measured gravity values, corrected for free-air and Bouguer corrections, assuming that all the material under the point of observation has a density of 2·67

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indicates that no large regional gradient of anomaly exists. The form of the curves is due to the attraction of the mass of rock forming the valley walls. These masses exert an upward attraction which tends to reduce the value of gravity at stations in the valley. This effect is greatest at the sides, and so the anomaly is reduced there, and the curves are convex upwards.

Although the magnitude of the terrain effect has not been calculated, it can be shown that it is of the correct order of magnitude to account for the observed variation of the anomaly across the valley. Fig. 2 (p. 759) shows the terrain effect of three simple model valleys. In each it is assumed that the walls are 610 m. high, and that the side slope is 45°. The density of the material of the side walls is 2·67 gm.cm.$^{-3}$, and the valley is assumed infinite in longitudinal extent. The station separations of traverse A have been used as examples. In the first model the western and eastern end stations of the traverse are assumed to be at distances of 60 and 50 m. respectively from the bottoms of the walls. In the second case the separations are both 610 m. and in the third they are 610 and 305 m. respectively. The actual curve of "anomaly" obtained on traverse A is repeated from Fig. 1 for comparison. It is apparent that the terrain effect from these models is of the correct order of magnitude, but there is little point in determining the form of a model which gives exactly the observed curve. The conclusion reached from this comparison is merely that the observed "anomalies" in profiles A, B and C can probably be accounted for completely by the effect of the local terrain, and that "geological anomalies", if they exist, are small.

In estimating the thickness of the glacier from the gravity traverses the following procedure has been adopted. Stations at either end of each traverse were situated either on rock, where the ice thickness is known exactly as zero, or where the thickness was so small that it could be estimated with a high degree of accuracy. The "anomalies" at these two end stations of each traverse were calculated in the same way as for the lower valley stations, and assuming that the form of the variation of the "anomaly" across the valley due to the terrain was the same as in the lower part of the valley, a curve of "anomaly" across the glacier has been interpolated. If this assumption is correct, this interpolated curve gives the values which gravity would have if all the underlying material had a density of 2·67 gm.cm.$^{-3}$. It is assumed that the difference between these interpolated values and the corrected station values is due to the lower density of the glacier. Assuming a value of 0·9 for the specific gravity of ice and that the sheets of ice and underlying rock are infinite in horizontal extent, the thickness of the ice sheet was calculated. In interpolating these curves some allowance has been made for the fact that the mountain walls become steeper at the head of the valley, but it is difficult to estimate the average slope. The interpolated curves assumed at these four traverses are shown in Fig. 3 (p. 759), curves D, E, F and G, together with the measured values of "anomaly" along these traverses.

Results Obtained, and their Accuracy

With the simplifications and approximations described above the thickness of the ice at any point on the four glacier traverses is directly proportional to the difference in the ordinates of the interpolated curve of anomaly and the curve of measured gravity corrected for free-air and Bouguer corrections, assuming all the material under the glacier is of specific gravity 2·67.

Based on this assumption, profiles of the glacier have been calculated, and are shown in curves D, E, F and G of Fig. 4 (p. 759).

It is essential that the main approximations and assumptions involved in arriving at these results be kept in mind. Errors arising from a wrong assumption for the mean density of rocks in the area are likely to be small. The maximum variation in the altitude of bedrock at the gravity observation points on any one traverse is 80 m. An error of 0·1 gm.cm.$^{-3}$ in the density assumed for the rock would produce an error of 0·32 milligals in the Bouguer correction. Since the difference in the ordinates of the pairs of curves in Fig. 3 is of the order of 6 milligals, errors from this cause are probably not greater than 5 per cent.

Errors of similar magnitude could be caused by neglecting the lighter layer of drift of unknown thickness lying in the lower valley.

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Obviously the largest error is introduced in interpolating the "anomaly" curves for the glacier traverses. The width of the valley is fairly uniform for most of the area of the survey, and for the lower two glacier traverses the slopes of the walls are quite similar to that in the lower valley, though for the upper two glacier traverses the slopes are steeper. In the valley below the glacier the variation of the terrain effect from the sides to the middle of the valley is about 5 milligals, and for the two lower glacier traverses curves of similar form have been assumed. However, it is not unlikely that in the centre of the glacier the error in the ordinate of the interpolated curve may be 1 milligal. This represents an error of about 16 per cent in the estimated thickness of the glacier, for the two lower traverses.

On the two upper glacier profiles, where the walls are appreciably steeper, the variation of the terrain effect across the valley will probably be greater, by an amount which is difficult to estimate.

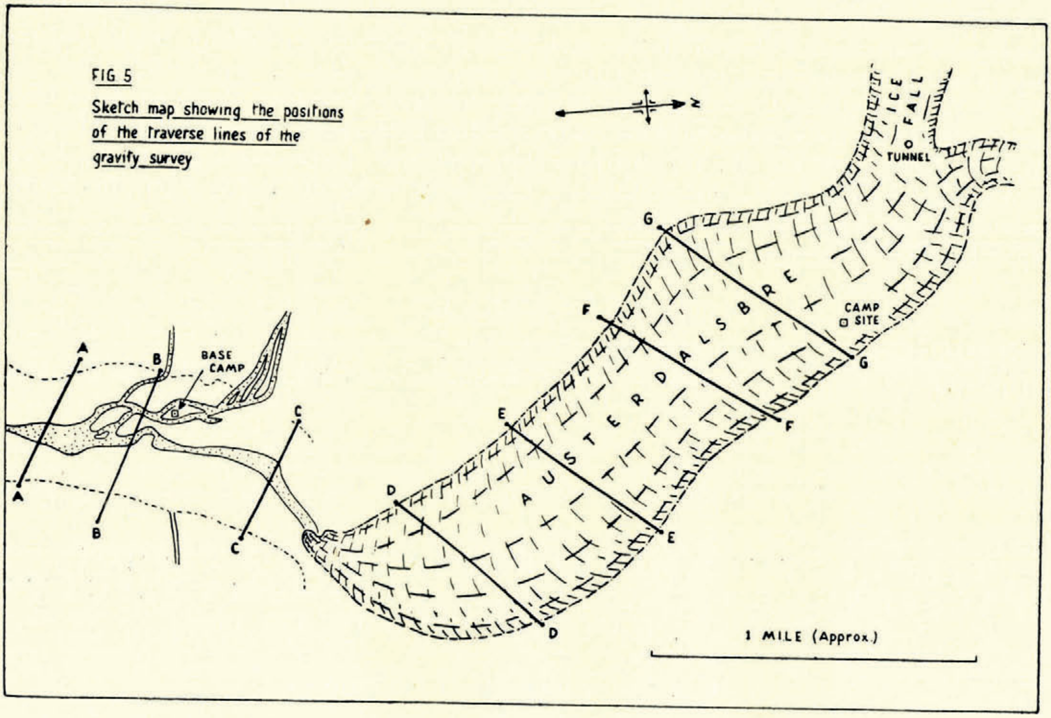

Fig. 5

Some allowance has been made for this in interpolating the anomaly curves across the valley, but errors of 2 milligals may be present in these curves. This represents an error of 40 per cent in the thickness for F and G profiles.

In determining the thickness of the glacier at any point it has been assumed that the thickness of the ice at all surrounding points is the same, so that infinite-sheet Bouguer corrections could be applied. Errors in the estimates of thickness introduced by this assumption will be appreciably smaller than the other errors discussed above.

The maximum thickness of the glacier determined by these measurements is about 100 m. In the two lower glacier traverses the shape of the bottom of the ice is a typical U-shaped valley, but in the two upper traverses there is some suggestion of a double valley. It is interesting to note that the ridge separating the valleys coincides with the position of the supra-glacial medial moraine.

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Conclusions

The method described, of using gravity values to determine the thickness of a glacier, has been shown to give reasonable results, with little expenditure of time in the field. Obviously, a direct measurement of the ice thickness is preferable, but that method is slower and more costly, so that when the seismic programme is undertaken, it is suggested that the gravity survey be continued. If the magnitude of the variation of the terrain effect across the valley can be accurately determined by finding the thickness by seismic methods at one point near the centre of each traverse, the accuracy of the estimates of the glacier thickness at other points along the traverse should be almost as high as that of the seismic measurements.

Acknowledgements

We are very grateful to Professor J. M. Bruckshaw of Imperial College, London, for the loan of the Worden Gravity Meter which was used in this survey. It is a pleasure to thank the other people who have been so helpful in the work. Miss A. Lathbury and Miss J. Hogbin, of the Department of Geography, Cambridge University, greatly assisted us during the field work and without their willingness to wade streams and jump crevasses the survey would not have been completed. During the working up of the results and their presentation, the interest and advice of Mr. J. E. Jackson and Mr. W. V. Lewis have been invaluable. To the Royal Society, the Royal Geographical Society, the Everest Foundation, Cambridge University and to others, the Expedition is grateful for financial assistance.

MS. received 2 *March* 1956

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TEMPERATURE MEASUREMENTS AT A CIRQUE BERGSCHRUND IN BAFFIN ISLAND: SOME RESULTS OF W. R. B. BATTLE'S WORK IN 1953

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(Arctic Institute of North America)

Abstract. Thermograph, thermistor, and thermometer readings at a 30 m. deep bergschrund from June 6 to July 22, 1953, showed that there was little direct relationship between air temperatures outside and at the bottom of the schrund. The air temperature inside ranged from −3·7° C. (25·3° F.) to +0·5° C. (32·9° F.), but from July 2 onwards it oscillated between −0·5° C. and +0·5° C., with a 3–4 day periodicity. The ice temperature at the bottom of the schrund behaved similarly, though it was about 0·5° C. colder. The oscillations may have been caused by the interplay of flowing melt water (source of heat) and air drainage in quiet weather (source of cold). The granite-gneiss headwall, where not sheathed by refrozen melt water, appeared to be chemically and mechanically unweathered, which supported the conclusions of Battle's earlier tests in deep bergschrunds and in the laboratory.

Zusammenfassung. Thermograph-, Thermistor-, und Thermometerablesungen an einem 30 m tiefen Bergschrund vom 6. Juni bis zum 22. Juli 1953 zeigten, dass zwischen der Lufttemperatur ausserhalb des Schrundes und der auf seinem Grund wenig Beziehungen bestanden. Die Lufttemperatur im Innern bewegte sich zwischen −3,7° C und +0,5° C; beginnend mit dem 2. Juli schwankte sie jedoch bei einer 3- bis 4-tägigen Periodizität zwischen −0,5° C und +0,5° C Obgleich ungefähr 0,5° C kälter, verhielt sich die Eistemperatur am Grund des Schrundes ähnlich. Die Schwankungen haben wohl in der Wechselwirkung von fliessendem Schmelzwasser (Wärmequelle) und abfliessender Luft bei ruhigem Wetter (Kältequelle) ihre Ursache. Die aus Granitgneiss bestehende Kopfwand war, wo sie nicht durch gefrorenes Schmelzwasser bedeckt war, chemisch und mechanisch unverwittert, welche Tatsache die Ergebnisse Battles früherer Untersuchungen in tiefen Bergschründen und im Laboratorium unterstützte.

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Fig. 6. Air photograph of Austerdalsbreen, showing the form of the valley, and the approximate positions of profiles D, E, F and G

Photograph by Widerøe's Flyveselskap og Polarfly A/S, Oslo

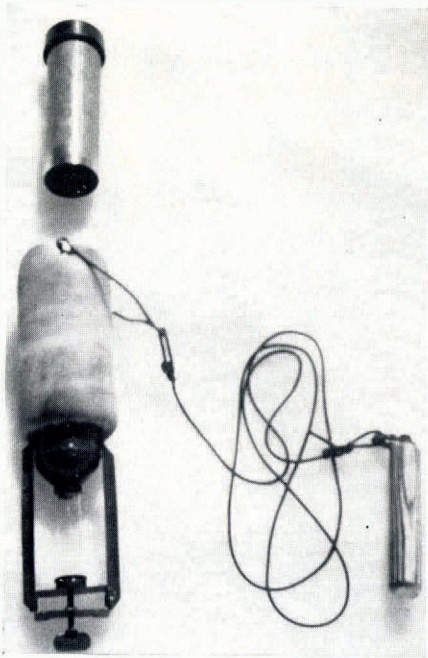

Fig. 1. Centrifuge for separating water from melting snow (see E. R. LaChapelle, p. 769)

Fig. 4. Summit of morainic arc of Litle Jiek'kevarribreen (see R. W. Galloway, p. 730)

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