GRAVITY AND MAGNETIC MEASUREMENTS ON STARBUCK AND STUBB GLACIERS, GRAHAM LAND

By P. KENNETT

DURING the course of reconnaissance survey work on the Larsen Ice Shelf in the southern summer of 1963–64 (Kennett, 1966), seven days were devoted to a detailed geophysical investigation of Starbuck and Stubb Glaciers on the east coast of Graham Land (Fig. 1). Geological and topographical surveys of the glaciers and surrounding country were conducted at the same time by M. Fleet and I. McMorrin.

The main object of the gravity and magnetic surveys was to provide information on the ice thickness of the glaciers and the configuration of the sub-ice topography. It was anticipated that measurements of gravity on rock sites would also improve the regional gravity map of Graham Land, which thus far had been based almost entirely on stations on the west coast (Griffiths and others, 1964).

PHYSIOGRAPHY AND GEOLOGY

Starbuck and Stubb Glaciers are situated on the east coast of Graham Land to the south-west of Cape Disappointment (Fig. 1). They are both valley glaciers which originate at the edge of the Bruce Plateau and flow in an easterly direction to merge with the Larsen Ice Shelf. The bulk of the Starbuck Glacier stream stems from a steep ice fall on the plateau wall about 32 km. inland from the junction of the glacier and the Larsen Ice Shelf. The upper reaches of the glacier follow a tortuous route for about 15 km. until the confluence with a major tributary, which appears to flow smoothly from the plateau with an increase in surface gradient but no ice fall. Stubb Glacier is shorter and it originates in an ice fall on the plateau scarp only 22 km. from its confluence with the Larsen Ice Shelf.

The dividing ridge between these two glaciers is broken in two places: by a snow col near its eastern end and by a gently sloping snow ramp in the central part. The southern wall of Stubb Glacier is also breached by two ice ramps leading to the lower-lying Flask Glacier. The walls of both Starbuck and Stubb Glaciers are scalloped by truncated cirques, many of which apparently contain less ice now than in former times.

Neither glacier is heavily crevassed, except in the areas immediately above its confluence with the ice shelf, where crevassing coincides with a steepening in the surface gradient. The ice shelf itself is buckled in the immediate vicinity of the glacier terminus but it otherwise appears to be undisturbed until a point 14 km. to the east, where the first of several rifts occurs (Fleet, 1965).

M. Fleet (personal communication) has examined the geology of the walls of Starbuck and Stubb Glaciers, and he has shown that they are composed mainly of crystal tuffs and agglomerates of presumed Upper Jurassic age. Outcrops of sandstone and mudstone occur near the head of each glacier and some of them contain badly fragmented plant remains. These are also considered to be of Jurassic age, but probably lower in the sequence than the volcanic rocks. In the central parts of the glaciers the dominant rock type is a massive white granite, which in places forms sheer cliffs at the glacier edges. Field relations indicate that the granite is younger than the volcanic rocks and Fleet has presumed, by analogy with other parts of Graham Land, that it is a member of the Andean Intrusive Suite. There are also minor intrusions of quartz-porphyry, pegmatite, and occasional basic sills and dykes.

It is interesting to consider the position of Starbuck and Stubb Glaciers in relation to the other glaciers of the east coast of Graham Land. Graham Land is at its widest between Crane Glacier and Churchill Peninsula, and the plateau scarp is set farther back from the coast than elsewhere along its length. The valley glaciers in this area, which include Starbuck and Stubb Glaciers, are all well developed with gentle surface gradients and many of them lead gently on to the plateau. Their general trend is from west to east and they are separated from one another by sharp ridges, which tend to be broken by cols in the southern part of the area.

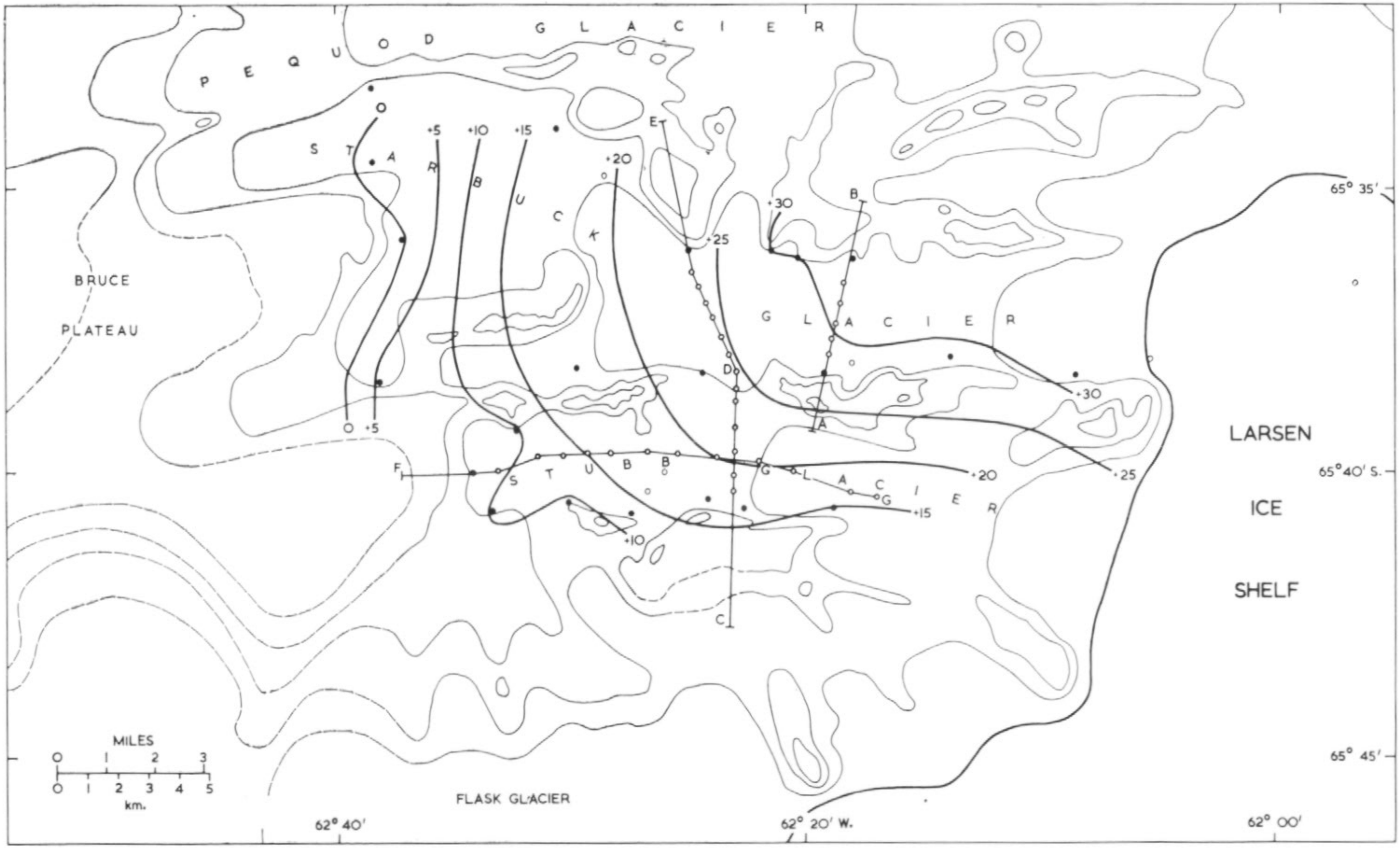

Fig. 1. Map of Starbuck and Stubb Glaciers, showing geophysical stations and lines of profile (A–B, C–D–E, F–G). Bouguer anomalies of stations on rock, reduced to ice-shelf level, are shown by heavy contours at 5 mgal intervals. Form lines of altitude above ice-shelf level are at 250 m. intervals.
○ Station on ice. ● Station on rock.

Linton (1964) has shown that these inter-glacier ridges are remnants of a former more extensive plateau. One of his photographs (Linton, 1964, p. 95, fig. 8) shows the series of glaciers north of Cape Disappointment, and Starbuck and Stubb Glaciers are just off the right-hand edge of the photograph.

North of Crane Glacier, the plateau margin is considerably nearer the coastline than elsewhere and most of the glaciers are less well developed, being steeper and badly crevassed. The coastline between Churchill Peninsula and the southern limit of the summer's work (in lat. 68°30′S.) is physiographically similar to the northern area.

M. Fleet (personal communication) has suggested that the physiographic contrast between these three areas is mainly due to variations in the geology; north of Crane Glacier the upper parts of the glaciers are cut in schists and granites, and they are controlled by a complicated system of faults. The glaciers are therefore themselves complex. In the area between Crane Glacier and Churchill Peninsula the glaciers are cut mainly in a thick succession of Jurassic volcanic rocks, which Fleet believes are faulted in a predominantly east–west direction. The volcanic rocks are relatively easily eroded and, because the suggested fault pattern is simple, the glaciers are correspondingly regular and well-developed. South of Churchill Peninsula intrusive rocks are again dominant and their erosion has been considerably slower.

Gravity Survey

Reduction of results

The gravity measurements were made with Worden Master gravity meter No. 556. Most of them were on the glacier ice, with control points on the adjacent rock walls where they were accessible (Fig. 1). Two profiles were measured across Starbuck Glacier, one of which was continued up the ice ramp and across Stubb Glacier (Figs. 2 and 3). A longitudinal profile was also measured from the head of Stubb Glacier to a point 8 km. from the Larsen Ice Shelf (Fig. 4). Stations on the cross-profiles were about 550 m. apart, while those on the longitudinal line were about 820 m. apart.

The station positions were determined from closed compass and sledge-wheel traverses. The whole survey was assigned geographical coordinates by reference to prominent points fixed from an earlier astronomically controlled traverse on the Larsen Ice Shelf.

Station heights were measured by aneroid barometer traverses relative to the average surface height of the Larsen Ice Shelf. In the absence of a local barograph to provide information about diurnal pressure changes, the regional synoptic charts of air pressure at sea-level, compiled by the Falkland Islands Meteorological Service, were used in the reduction of the data (Kennett, 1965). Since the recording stations on which the charts are based are very widely spaced, the pressure contours were used to provide an estimate of relative changes during each day's work rather than for direct calculation of heights relative to sea-level. Heights of all stations are estimated to be within ± 15 m. of their true height above ice-shelf level. Relative heights of stations along any single glacier profile are thought to be within ± 6 m.

Subsequent tentative correlation of pressures at ice-shelf stations with the meteorological charts showed that the average height of the ice-shelf surface above sea-level in the Cape Disappointment area is 66 ± 12 m. (Kennett, 1965).

Absolute gravity values have been derived for the area by means of a one-way overland traverse from Stonington Island (Kennett, 1966). Lack of knowledge of the drift of the instrument could result in a maximum error of about $\pm 5 \cdot 5$ mgal in the absolute gravity values in the vicinity of Starbuck and Stubb Glaciers. Relative values of stations are, however, accurate to about $\pm 0 \cdot 2$ mgal.

The latitude correction was obtained from standard tables compiled from the International Gravity Formula. The absolute latitudes of gravity stations could be in error by up to $\pm 0 \cdot 5$ km., corresponding to $\pm 0 \cdot 3$ mgal error in the latitude correction. However, relative latitudes of stations are accurate to $\pm 0 \cdot 1$ km., equivalent to $\pm 0 \cdot 06$ mgal error in the latitude correction.

The corrections for the surrounding topography were calculated by a two-dimensional method (Hubbert, 1948), in which cross-sections are drawn at right-angles to the strike of the topography and its effect calculated by reference to a series of standard land forms. On a glacier, the greatest part of the terrain correction is contributed by the steep side walls; the effect of distant relief is likely to exert a similar influence over the whole glacier rather than affecting different stations on a profile. The terrain correction computed by this method varies between 0 and +15·4 mgal. The relative error in the terrain correction across the glacier is expected to be of the order of ±2 mgal.

Values of rock density were measured by a Walker steelyard, using specimens collected by M. Fleet. The results for the predominant rock types are given in Table I.

TABLE I

Rock Type	*Number of Specimens*	*Density* (g. cm.$^{-3}$)	*Standard Deviation*
Granite	3	2·61	±0·02
Crystal tuff	5	2·67	±0·04
Sediments	2	2·79	—

The height reductions of the data have been treated in two separate ways. First, Bouguer and free-air reductions of stations on rock were calculated to a common datum at ice-shelf level solely in order to provide an estimate of the large-scale regional anomaly (Fig. 1). The local rock density was used in these reductions. Since absolute heights above ice-shelf level are probably within ±15 m. of their true values, the maximum error in the combined Bouguer and free-air correction is ±3 mgal.

Further error is introduced by the terrain effect of the sub-ice topography, which cannot be calculated in the same way as that of the sub-aerial topography, since it is obscured by the ice cover. Estimates at the cross-profiles show that the error there is between +5 and +7 mgal. Elsewhere it is unknown, although it is probably of the same order, so no correction has been applied. Since the sub-ice terrain correction is always positive, its omission will result in the anomalies (Fig. 1) being too low. The total root-mean-square error from all sources in the large-scale regional anomalies is thus about +9—6 mgal.

Secondly, Bouguer anomalies were calculated for each of the profiles separately, in order to provide a more accurate anomaly than the large-scale regional one for use in the estimation of ice thicknesses. Gravity values at rock and ice stations on each of the cross-profiles were reduced to the average altitude of the profile, using a density of 0·90 g. cm.$^{-3}$ for stations on ice and the local rock density for stations on rock. Changes in height between stations are very small and the altitude datum is close to the upper surface of the glacier. The sub-ice terrain is therefore largely beneath the datum level and its effect on the Bouguer anomalies over the glacier is estimated to be less than 1 mgal. On the longitudinal profile along Stubb Glacier, gravity values were reduced to the height of the rock station at the head of the glacier. Since relative height measurements on each profile are thought to be within ±6 m. of their true values, the maximum error in the Bouguer and free-air reduction of stations on rock is ±1·2 mgal, but for stations on ice it is ±1·7 mgal. The total error from all sources in the Bouguer anomalies of each profile is therefore about ±3 mgal.

Interpretation

Before the Bouguer anomalies can be used as a basis for interpretation, the "regional" anomaly along each line of profile must first be removed. On each cross-profile the "regional" anomaly was based on the gravity values at the rock stations at each end of the profile and its shape over the intervening ice stations was obtained from the contour map of the large-scale regional anomaly (Fig. 1). The measured anomaly was then subtracted, leaving a residual Bouguer anomaly, which was subsequently used in the calculation of ice thicknesses. On the longitudinal profile FG the "regional" anomaly could only be firmly established at one point, namely, the station on rock at the head of the glacier. For the rest of the profile the shape of the "regional" anomaly has been taken from the contour map of the large-scale regional anomaly (Fig. 1).

On each cross-profile an initial approximation to the depth of the glacier in its central part was obtained by assuming the glacier to be of parabolic cross-section (Corbató, 1964). Successive models of the glacier were then constructed and the gravity effect was calculated by a graticule method until a good fit with the observed anomaly was obtained. In every case a deeper section was necessary than that suggested by Corbató's method. The final profiles are shown in Figs. 2 and 3. In using the graticule method it must be assumed that the model extends to infinity in the direction at right-angles to the profile. This condition is almost fulfilled in the central parts of a glacier. It must also be assumed that the difference between the rock and ice densities is constant and that the anomaly is entirely due to the different distribution of ice and rock rather than some change in the underlying geology. Since the sediments are limited to the head walls of the glacier, the range in the density of the exposed rock in the central parts is only about 2 per cent, so the error involved in this assumption is not great.

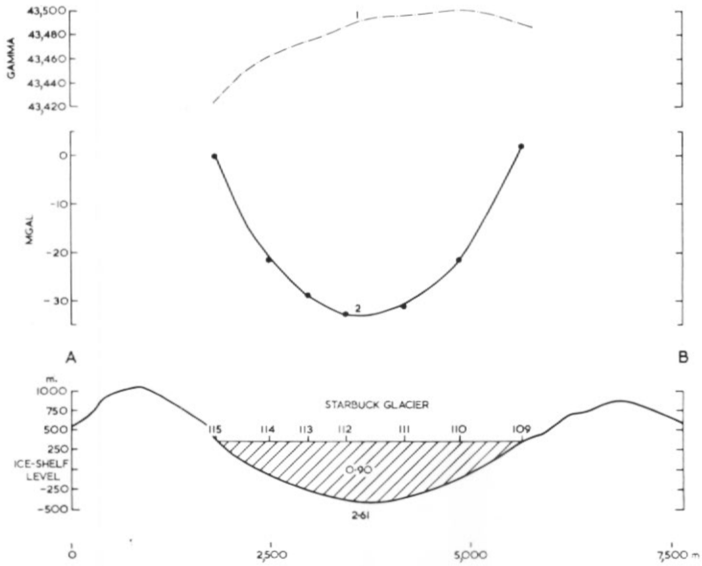

Fig. 2. Gravity and magnetic cross-sections along the line AB on Starbuck Glacier. The calculated depth profile provides a good fit to the Bouguer anomalies. Vertical and horizontal scales are equal.
1. Total field magnetic anomaly.
2. Residual Bouguer gravity anomaly.
● Calculated Bouguer anomaly for model shown.

The error in the ice-thickness determinations along the cross-profiles depends on the error between individual stations and the accuracy with which the "regional" anomaly along each profile can be interpolated. The former has been shown to be about ± 3 mgal and the latter is probably also about ± 3 mgal, which gives a total error of about $\pm 4 \cdot 5$ mgal. This is equivalent to an error of ± 14 per cent on profile AB, ± 18 per cent on profile CD and $\pm 12 \cdot 5$ per cent on profile DE.

In the case of the longitudinal profile for Stubb Glacier, regional control is less rigid than in the cross-profiles. Semi-quantitative methods have therefore been used in the interpretation. The residual anomaly was obtained by subtraction from the "regional" anomaly (as described above), and a profile of the glacier bed was calculated by assuming the anomaly at each station to be due to an infinite horizontal slab of ice. Considering only the shape of the glacier bed along the line of the profile, this would be a fair approximation to the truth, except for stations near the head of the glacier, where the calculated depth would be an underestimate. However, the glacier is limited in the third dimension and it is clear that the close proximity of the side walls introduces large errors into the ice thicknesses calculated by this method.

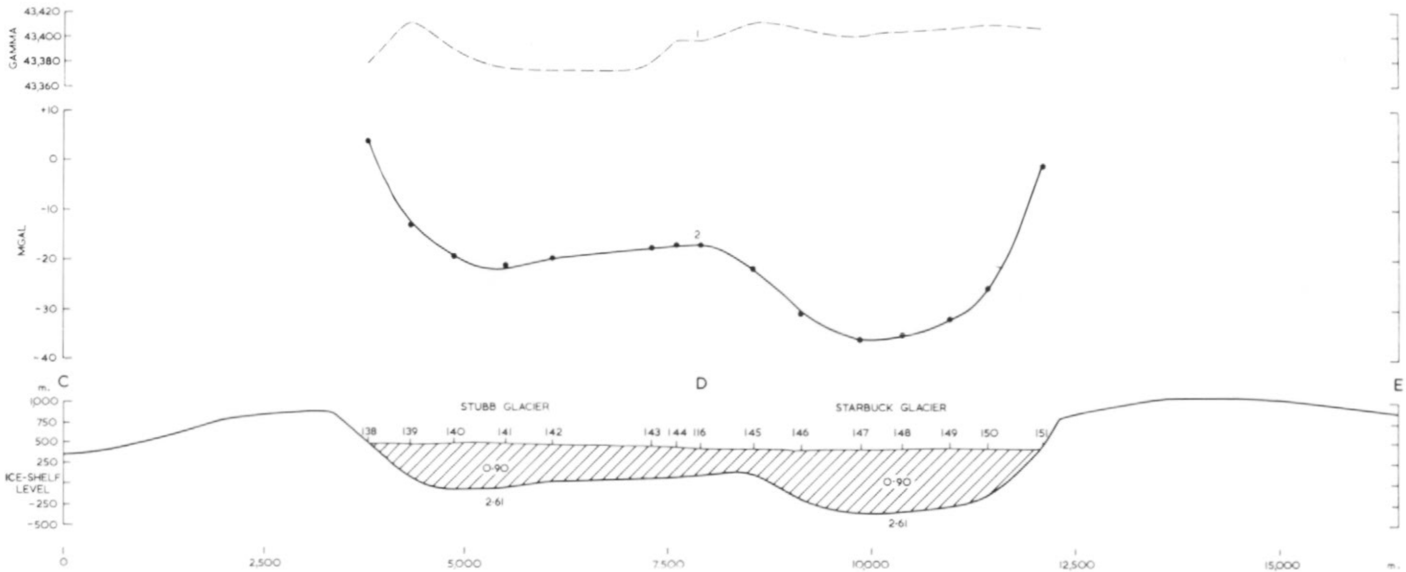

Fig. 3. Gravity and magnetic cross-sections along the line CDE on Starbuck and Stubb Glaciers. The calculated depth profile provides a good fit to the Bouguer anomalies. Vertical and horizontal scales are equal.

1. Total field magnetic anomaly.
2. Residual Bouguer gravity anomaly.
● Calculated Bouguer anomaly for model shown.

Nevertheless, the shape of the profile is not much affected, since the glacier walls are parallel to the line of the profile and roughly equidistant from it. The only point where independent control can be established is where the cross-profile CD intersects the longitudinal profile FG. Here, the depth to bedrock on profile CD has been found to be 38 per cent greater than that calculated by the slab method for profile FG. All depth values on the longitudinal profile have therefore been increased by 38 per cent in order to provide a more realistic configuration of the glacier bed. This profile (FG) is illustrated in Fig. 4.

Magnetic Survey

Reduction of results

Total field magnetic measurements were made with an Elsec proton magnetometer at the same sites as the gravity observations. Continuous records from the Argentine Islands, 80 km. away, have been used to make the diurnal corrections to the results. The estimated accuracy of this reduction is ± 2 gamma (Kennett, 1966). The secular variation has been allowed for by reducing all the values to 30 September 1963, assuming a change of 10·5 gamma/month, as at the Argentine Islands. The corrected total-field values are shown above each glacier profile in Figs. 2, 3 and 4.

Interpretation

The magnetic anomalies are, in general, very small. With the exception of rare basic sills, the exposed rock types appear to be relatively non-magnetic, and it is difficult to correlate the small anomalies with the geology on the basis of the existing magnetic information. The small disturbance around point D (Fig. 3) could largely be explained by a rise in bedrock corresponding to the feature determined from the gravity results, rather than by a change in polarization within the bedrock. The small positive anomaly on profile FG does not appear to coincide with any topographic feature. The rise in total-field values over the Starbuck Glacier profile AB is equally impossible to explain on topography alone, unless the glacier bed is composed of reversely magnetized material. It is more likely that the glacier is underlain at depth by a rock type with a greater intensity of magnetization than that exposed at the surface.

The only other feature of note is a single-point anomaly of about 200 gamma near the col at the eastern end of Starbuck Glacier. It appears to be associated with intense localized mineralization within the crystal tuffs but there are insufficient data to comment further.

Discussion

Although the gravity method often tends to present a smoother picture of the sub-ice topography than really exists, the glacier profiles shown in Figs. 2 and 3 should be substantially correct. The depth to bedrock for each of the Starbuck Glacier profiles is noticeably greater than that for the Stubb Glacier cross-profile. Since the surface of Stubb Glacier is also higher than that of Starbuck Glacier, it is possible that ice flows from the one glacier to the other through the gap in the separating ridge. Much of the Stubb Glacier flow is probably also deflected into the distributary channel near its head and thus into Flask Glacier. This diversion of ice may in part account for the shallower channel beneath Stubb Glacier in comparison with that of Starbuck Glacier, which is fed from many sources but which has no outlet up-stream of its confluence with the ice shelf.

Svensson (1959) has suggested that the cross-sections of many glacial valleys are parabolas. Tests on the cross-profiles of the glaciers investigated revealed that section AB is a close approximation to a parabola but that the equation of the regular part of profile DE is more nearly a cubic function. This difference may be due to the close proximity of profile DE to the confluence of the two major ice streams of Starbuck Glacier. With the exception of the breaching of the southern wall of Starbuck Glacier on profile DE, both profiles are almost completely symmetrical. This is clearly not the case with profile CD across Stubb Glacier, although this line must not be regarded as typical, because of the breached wall. The shape of the valley beneath the ice at the southern end of this section is truly parabolic.

In spite of the expected inaccuracy in the absolute estimates of ice thickness along the longitudinal profile FG, the qualitative shape of the glacier bed should be reliable. The most

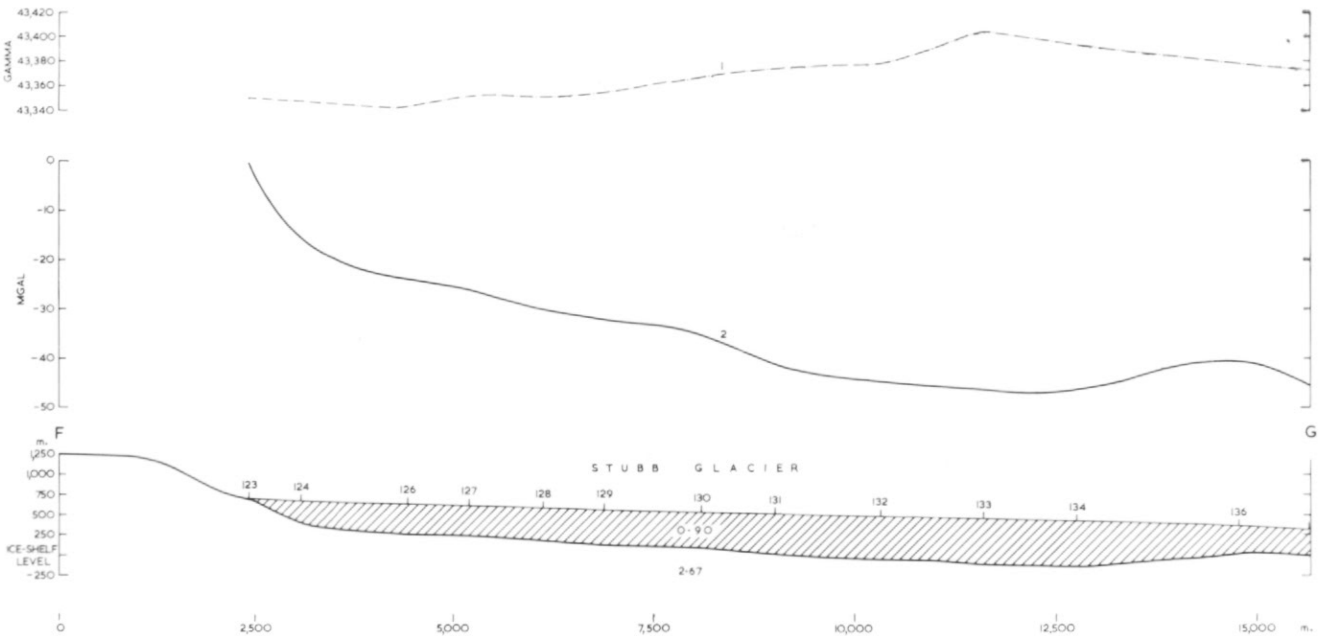

Fig. 4. Gravity and magnetic sections along the line FG on Stubb Glacier. The depth profile is only semi-quantitative. Vertical and horizontal scales are the same.
1. Total field magnetic anomaly.
2. Residual Bouguer gravity anomaly.

interesting feature is the rise in the rock floor two-thirds along the length of the glacier. This appears to be associated with an overdeepened basin on the up-stream side which possibly extends down to sea-level. Such basins and rises have been noted beneath other glaciers whose profiles have been examined, e.g. Athabaska Glacier (Kanasewich, 1963). No measurements were made along the length of Starbuck Glacier. However, the gradient of the valley floor, estimated between the deepest points of the two cross-profiles, is considerably less than that of Stubb Glacier along profile FG. Conjectural extrapolation of the bed of Starbuck Glacier to its confluence with the ice shelf shows that the depth to bedrock there is roughly 520 m. below ice-shelf level. This is of the same order of magnitude as the depth to bedrock determined on a traverse of the ice shelf 13 km. to the east (Kennett, 1966).

On each of the Starbuck Glacier profiles the deepest points in the valley extend below ice-shelf level and almost certainly below sea-level. It is, however, most unlikely that any part of the glacier is afloat, since there is insufficient depth for hydrostatic equilibrium until the immediate vicinity of the confluence with the ice shelf.

Comment on the large-scale regional Bouguer anomalies must inevitably be limited, because the information is so sparse and the possible error large. Since the height above sea-level of the surface of the Larsen Ice Shelf is still in some doubt, the regional Bouguer anomalies (Fig. 1) were reduced to ice-shelf level. However, for direct comparison with anomalies on the west coast of Graham Land, all values must be reduced to sea-level. This can be achieved by the addition of about 13 mgal, which is the Bouguer and free-air equivalent of 66 m. of rock of density $2 \cdot 67$ g. cm.$^{-3}$.

The trend in the regional anomaly over Starbuck Glacier is north to south, the value decreasing towards the centre of Graham Land. The average gradient is similar to that on the west coast of Graham Land (Griffiths and others, 1964), although it steepens locally at the head of the glacier. The gravity contour values on each coast are approximately symmetrical about the mid-line of the peninsula, and the marked swing to an east to west trend in the southern part of this area cannot easily be explained on the basis of the known geology. Further information will be necessary before any precise interpretation can be made.

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