Zeitschrift für Gletscherkunde und Glazialgeologie Bd. 14, H. 1 (1978), S. 1—16

ABHANDLUNGEN

GLACIER DISCHARGE IN THE SØR-RONDANE, A CONTRIBUTION TO THE MASS BALANCE OF DRONNING MAUD LAND, ANTARCTICA

By T. VAN AUTENBOER[1] and H. DECLEIR[2]

With 4 figures and 1 map supplement

SUMMARY

Mass transport and mass flux values for the different types of glaciers in the Sør-Rondane are calculated from computer models, based upon gravity data and geodetic stake velocity measurements. The results are interpreted in the light of a general flow line analysis, glacial geological investigations and of the ablation terms of the mass balance for Dronning Maud Land and Antarctica.

GLETSCHERABFLUSS IM SØR-RONDANE-GEBIRGE, EIN BEITRAG ZUR MASSENBILANZ IM DRONNING MAUD LAND, ANTARKTIS

ZUSAMMENFASSUNG

Werte des Massenflusses für verschiedene Gletschertypen im Sør-Rondane-Gebirge wurden nach Messungen der Schwere und der Fließgeschwindigkeiten eines Pegelnetzes mit einem Modell berechnet. Die Resultate dieser Berechnungen werden mit Hilfe von Bewegungslinienanalyse, glazialgeologischen Untersuchungen und Ablationsmessungen interpretiert.

1. INTRODUCTION

Gravity and movement surveys by the 1959 and 1960 Belgian and 1965 Belgian-Dutch Antarctic Expeditions led to the first assesment of the glacier discharge through the central part of the Sør-Rondane mountains (Van Autenboer and Blaiklock, 1966). The field work was continued in 1966: the already established movement markers were resurveyed and the gravimeter and movement observations extended to cover all glaciers in the range. These data — the earlier ones were recomputed using a more accurate method — allowed calculation of the discharge of all major glaciers in the Sør-Rondane. This allowed an evaluation to be made of the mass transport through a 220 km long section at right angles to the main flow from the polar plateau (between 21° 15′ E and 26° 30′ E). This regional contribution to the mass balance of the Antarctic ice sheet was the main purpose of the study.

The velocity values used in the calculations are a selection of the most representative data i. e. observations by the same surveyor covering the longest period of observations.

The observations on one of the glaciers (Gunnestadbreen) were repeated more frequently with the hope of establishing possible seasonal variations of the rate of movement. Further analysis of these data is planned.

[1] Belgian Antarctic Expeditions, Limburgs Universitair Centrum and Universiteit Leuven, Belgium.

[2] Observatorium van de Rijksuniversiteit Gent, Belgium.

The 1959, 1960 and 1965 surveys were carried out by K. V. Blaiklock and T. Van Autenboer, those in 1966 by T. Van Autenboer and the surveyors E. Lallemand and the late J. P. De Winde. The complete set of data (station numbers, period of observation, total movement, movement per day, reduced gravity values, computed gravity values for the adopted cross section, ice depth and elevation, subglacial relief and error analysis) can be found in Van Autenboer and Decleir (1974).

2. THE SØR-RONDANE

The Sør-Rondane forms a 250 km long, east-west wedge shaped mountain range some 200 km south of Princess Ragnhild Coast (Fig. 1 / enclosed map).
A map on a scale of 1 : 250.000, based upon US Navy air photographs (operation Highjump 1946/47) and published by Norsk Polarinstitutt in 1957, was originally used. A new series of 1 : 250.000 maps, based upon Belgian field work (K. V. Blaiklock) and Norwegian oblique air photographs (1959—1960), is being prepared for publication by Norsk Polarinstitutt and was used in the preparation of this report.
The Sør-Rondane mountains, belonging to the precambrian platform of East Antarctica, have been studied during the 1958, 1959 and 1960 Belgian and 1965 and 1966 Belgian-Dutch Antarctic Expeditions. The petrography of the metamorphic and igneous rocks of the eastern part of the range can be found in Picciotto and others (1967). Van Autenboer and others (1964) and Van Autenboer and Loy (1972) give a general synthesis of the geology and Van Autenboer (1969) a 1 : 500.000 geologic map of the area.

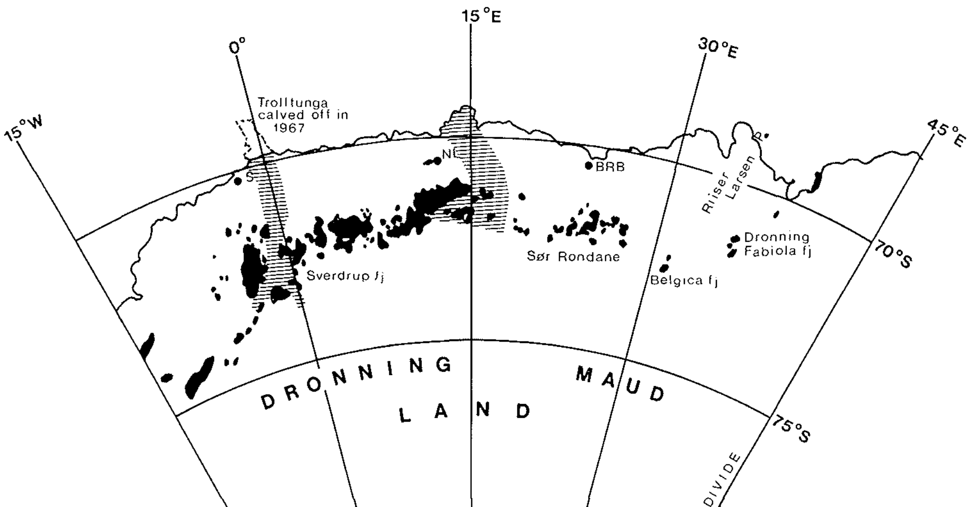

Fig. 1: Dronning Maud Land (compiled from different sources) : S = SANAE; NL = Novo Lazarevskaya; BRB = King Baudouin Station. The ice streams near Sanae and Novo Lazarevskaya are schematically represented.

Age measurements (mainly Rb/Sr on biotites) can be found in Picciotto and others (1967) and U/Pb zircon ages in Pasteels and Michot (1968). Zijderveld (1968) published the results of palaeomagnetic measurements. An outline of the glacial geology and glacierization of the range can be found in Van Autenboer (1964).

3. GRAVIMETRIC ICE THICKNESS DETERMINATIONS

Gravity profiles were measured at right angles to the main direction of flow of the glaciers. A Worden Geodetic Gravimeter, checked on Belgian and international calibration bases, was used. Transport was by dog sledge or by motor toboggan with the gravimeter suspended in a framework rigged on the back of the sledge.

The positions of the gravimeter stations were usually determined by resection from the trigonometric stations (see movement observations). At the resected stations, vertical angles were measured to provide the altitude of the stations which was calculated by taking into account the combined curvature and refraction correction. Over some of the minor glaciers position and elevation of the stations were obtained from sledge wheel readings and aneroid height determinations.

The ice thickness at each of the stations was computed from the gravimeter measurements using a method of which the first steps are similar to the one outlined by Van Autenboer and Blaiklock (1966).

I. An initial two-dimensional model is calculated for the glacier assuming that the gravity anomaly at each station results from the replacement of an infinite slab of rock by a slab of ice of identical dimensions (Martin, 1948). The gravity anomaly, used in this calculation, is the difference between the value at the glaciological station and the value at the reference station on rock.

The gravity measurements at the glaciological stations are first reduced to the same altitude and latitude and corrected for the regional variation of gravity.

This correction is first calculated by linear interpolation of the difference between the reduced gravity values observed at the reference stations on rock at both sides of the profile.

II. This model is then improved by computing the gravity effect of the calculated cross section at each of the stations. It has been shown by Hubbert (1948) that to evaluate the gravity effect of a two dimensional body, the areal integral can be replaced by a line integral following the periphery of the body.

Replacing the cross section of the two dimensional body with a n-sided polygon, Talwani and others (1959) adapted the line integral method for digital computers. The anomaly at each gravimeter station calculated by this method was compared with the observed anomaly as defined above. The difference between the two anomalies was then again converted into ice thickness with the infinite slab method, as outlined under I., and the shape of the cross section (i. e. the ice depths) altered accordingly. This process was repeated until measured and calculated anomalies coincided.

III. The model computed so far indicates the existence of a negative value at the reference stations where the anomaly, as defined, is supposed to be equal to zero. These negative values represent the effect of the computed glacier model on the reference stations on rock. In general these values are not identical, indicating a difference between the regional gravity gradient — or the gravity gradient when the glacier is replaced by rocks having the density of the country rock — and the gradient between the measured values on rock on both sides of the glacier.

This means that the values at the reference stations have to be corrected for the mass deficiency of the glacier and that the gravity anomalies at each glaciological station have to be recalculated.
In the final computing scheme an additional correction was therefore applied to the observed values at the reference stations. This correction, introduced at each step, represented the negative effect of the glacier model computed during the previous step. This iterative process converges rather rapidly towards a constant negative value at the reference stations and results in a deepening of the glacial floor especially near the side walls.
The computed ice depths of the surveyed glaciers have been given by Van Autenboer and Decleir (1974), while in table 1 of the present paper only the maximum values for each glacier have been retained. The errors are generally better than one tenth of a milligal after 10—20 steps of the iterative process. This indicates the degree of adjustment between the proposed model and the observed values. The accuracy of the mathematical fit does not however represent the accuracy of the calculated ice depths. These can be affected by unknown factors as local geologic or topographic anomalies, variations of the ice — rock density contrast, inclusion of morainic material within the ice . . . , the two-dimensional representation of a three-dimensional feature and the topographic effect of neighbouring glaciers (see below).

Table 1: Discharge, mass flux[3], maximum velocity and ice thickness.

	Discharge in $km^3\ yr^{-1}$	Mass flux in $10^{15}\ g\ km^{-1}\ yr^{-1}$	Max. velocity $m\ yr^{-1}$	Max. ice thickness m
Kreitserisen I	0.0412	0.003757	22.4	966
II	0.1521	0.009994	43.4	1408
Hansenbreen	0.7400	0.029344	38.1	1702
Teltet-Utsteinen	0.0024	0.000300	1.0	1271
Gunnestadbreen	0.1056	0.007475	12.0	1521
Gillockbreen	0.0017	0.000304	0.9	1111
Jenningsbreen	0.0025	0.000288	0.7	1446
Gjellbreen	0.0745	0.006063	10.2	1278
Nipebreen	0.0018	0.000268	5.6	1229
Byrdbreen	0.4704	0.018339	39.1	1085
TOTAL mass output[4]	1.5988	0.006686		

[3] Mass flux: discharge per km of width of cross section.
[4] Total mass output through Sør-Rondane area between Taggen and Vesthjelmen. This figure includes the discharge of the glaciers given here and estimated values for the local glaciers (Kampbreen and the local glacier between Utsteinen and Perlebandet). The latter are estimates based upon the very consistent mass flux values of the local glaciers.

The calculated model was fitted for as many points as originally measured on the glacier surface. The form of the subglacial valley is therefore very sensitive to small irregular variations of the gravity values at adjacent stations, which explains the rather angular subglacial relief found on some of the profiles. A smooth subglacial profile, generally associated with glacierized landforms, could have been obtained by reducing the number of points at which ice depths are calculated but without eliminating observational data (e. g. Corbato, 1965). However this method is not better justified mathematically and has the serious drawback of eliminating information on possible irregularities in the subglacial relief such as the meridional ridges described below.

Fig. 2 gives an example of the calculation of the subglacial profile of Gunnestadbreen indicating the differences between ice depths calculated by the infinite slab method (a) and the line integral method without (b) and with (c) the correction for the negative effect of the glacier on the reference values on rock.

IV. The topographic correction in a glacier covered area should not only take into account the effect of the visible "above ice" topography but also the mass deficiency represented by the surrounding glaciers. The former was calculated for a few stations and proved to be sufficiently small to be neglected as the profiles were situated at the northern end of the mountain massif where the relief tapers out.

The correction for the effect of neighbouring glaciers necessitates in general a three-dimensional analysis. In the case of two neighbouring glaciers with their long axis roughly parallel, the computing method as outlined under III. above, can be extended thereby treating the two glaciers as one profile. This method has been applied in the case of Jutulstraumen and Viddalen around the Greenwich meridian (Decleir and Van Autenboer, in press) and results in a significant deepening of the glacial floor due to the importance of these glaciers. In the Sør-Rondane the method was only readily applicable in the case of Kreitzerisen I and II. Fig. 3 illustrates the result and shows the further deepening of the glacier. This deepening is however

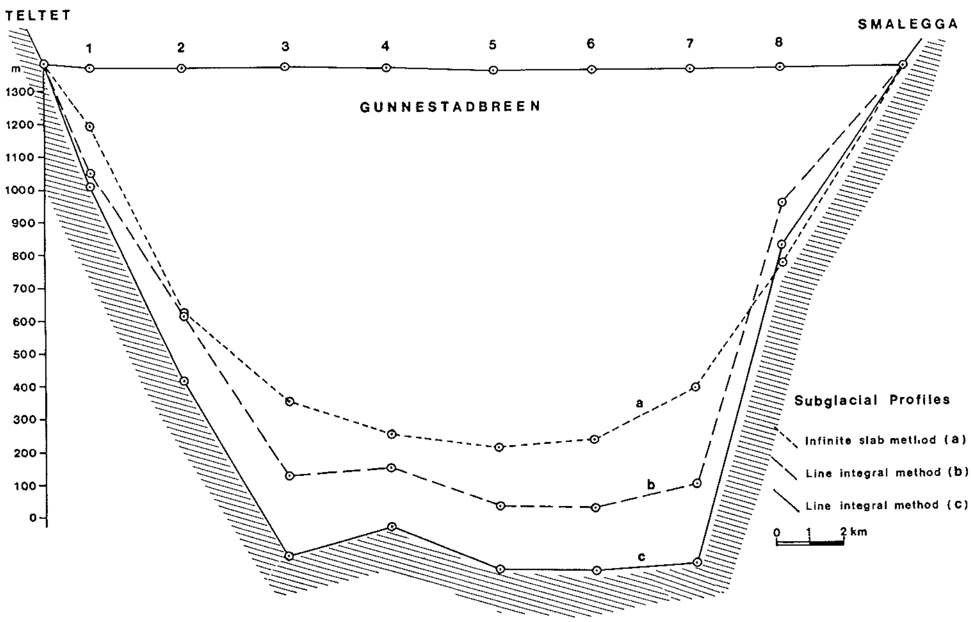

Fig. 2: Subglacial relief of Gunnestadbreen computed with the infinite slab method (a), the line integral methods without (b) and with (c) the correction for the negative effect of the glacier on the reference values on rock. A typical U-shaped cross-section is obtained with the infinite slab method. It deepens considerably and becomes more angular with the different polygonal approximations.

relative unimportant with a local maximum of 6 % so that no further refinement along this line was attempted.

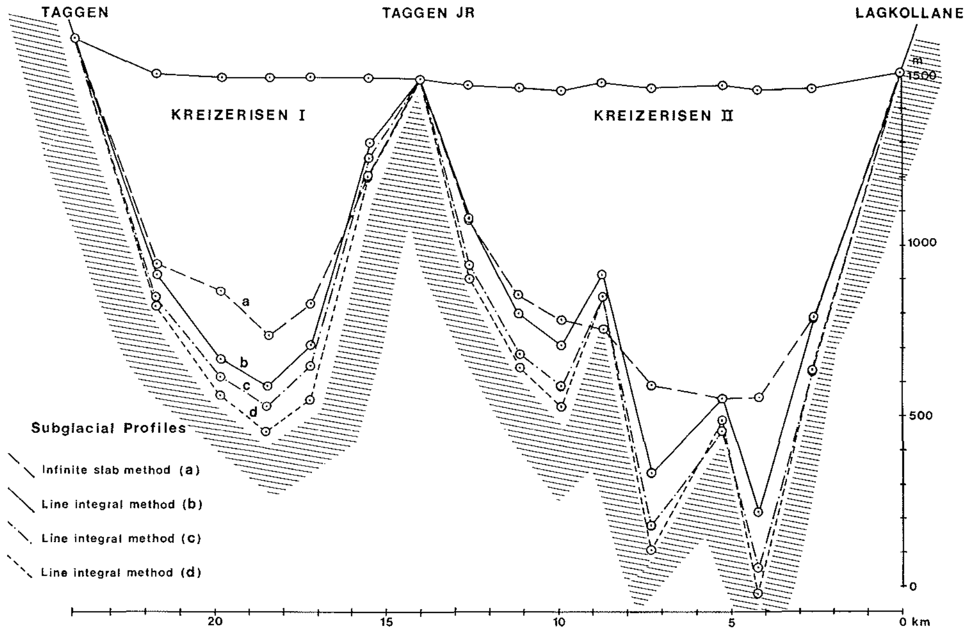

Fig. 3: Subglacial profiles for two neighbouring glaciers. Profiles (a), (b) and (c) have been computed for each glacier seperately as in Figure 2. Profile (d) represents the subglacial relief obtained by the combined computation of both cross sections in one profile, thereby taking into account the mutual terrain effect of both glaciers. Maximum deepening amounts locally to 6 %.

4. MOVEMENT OBSERVATIONS

The positions of the stakes were determined by theodolite resection from the main triangulation scheme, established by K. V. Blaiklock during 1959 and 1960.

At each station two or more sets of horizontal angles were observed with Wild T 2 or T 3 theodolites. The angles were measured between as many clearly identified peaks as possible with well known grid coordinates. The movement was measured over periods ranging from 205 to 1509 days. The 1959, 1960 and 1965 movement observations have been calculated with a semi-graphic method, an example of which is given by Van Autenboer and Blaiklock (1966).

The calculations of the grid coordinates from the 1966 observations were completely carried out by computer: an approximate position of the stake was first determined from two angles only. These provisional coordinates were then adjusted to give final values by fitting them to all observed rays using the method of least squares. When the standard error of the final result proved too big some observations were rejected after comparison of the observed directions with the computed ones. The whole process was then repeated until acceptable errors were obtained. The tabulated results of the movement observations can be found in Van Autenboer and Decleir (1974) and Van Autenboer and Blaiklock (1966), while table 1 lists the highest measured values on each of the surveyed glaciers.

5. ANNUAL DISCHARGE AND MASS FLUX

The annual discharge of the surveyed glaciers has been calculated using the above computed cross sections and the measured surface velocities. No correction has been made for the downward reduction of the glacier velocity seen that no data on which to base such a reduction exist[5]. In the calculation of the cross profiles the effect of the mass deficiency of the surrounding glaciers has been neglected. Both factors however might at least partially compensate each other when computing the discharge, as the use of surface velocities tends to maximize the discharge while neglecting the effect of neighbouring glaciers causes shallower ice depths.

Table 1 lists the annual discharge and the mass flux of the surveyed glaciers as well as the average flux through the 220 km long section between Taggen and Vesthjelmen. The values used for Kampbreen and for the local glacier between Utsteinen and Perlebandet are based upon an extrapolation of the very consistent mass flux of the measured local glaciers. The discharge and mass flux values of the different glaciers are schematically represented in Fig. 4.

6. FLOW ANALYSIS

The enclosed map represents the computed cross-sections and the observed movement vectors within the general pattern of ice flow in the Sør-Rondane area. The ice flow is schematized by flow lines, drawn as orthogonals to the surface contours and originating at equidistant points along an east-west line in 72° 40′ S. The flow of the local glacier system has been indicated in addition to the flow lines which represent the main directions of the flow of the ice from the polar plateau. In the construction of the flow lines, use has been made of the above mentioned maps being prepared for publication by Norsk Polarinstitutt. It has been remarked that the surface contours of the ice are locally weak (S. Helle, pers. comm.). A remarkably good correspondence however exists between the direction of the flow lines and the measured azimuths of the markers. Even local anomalous directions of the markers fit well in the flow line pattern (e. g. Hansenbreen Nr. 4) as does the orientation of local supraglacial morainic deposits. The ERTS imagery, which became available after this flow line analysis was carried out, confirms the overall picture.

7. REGIONAL DESCRIPTION

Hansenbreen, is the most important of the surveyed glaciers and its discharge ($0.740\ km^3\ yr^{-1}$) is as large as the combined mass transport of all other glaciers in the Sør-Rondane.

---

[5] Paterson (1969) reviews the available information on the ratios of surface to glacier bed velocities. These data, restricted to 7 temperate, wet based, alpine glaciers of reduced thickness, show that sliding over bedrock comprises roughly half the surface movement. Large variations can occur over comparatively short distances (between two drill sites, distant by 1.5 km and situated on the same flow line on Athabasca glacier (Canada), the ratio varies from 0.75 to 0.10). Two boreholes reach bedrock underneath the continental ice sheets, but no deep drillings have been made on outlet glaciers or on local glaciers in Antarctica.

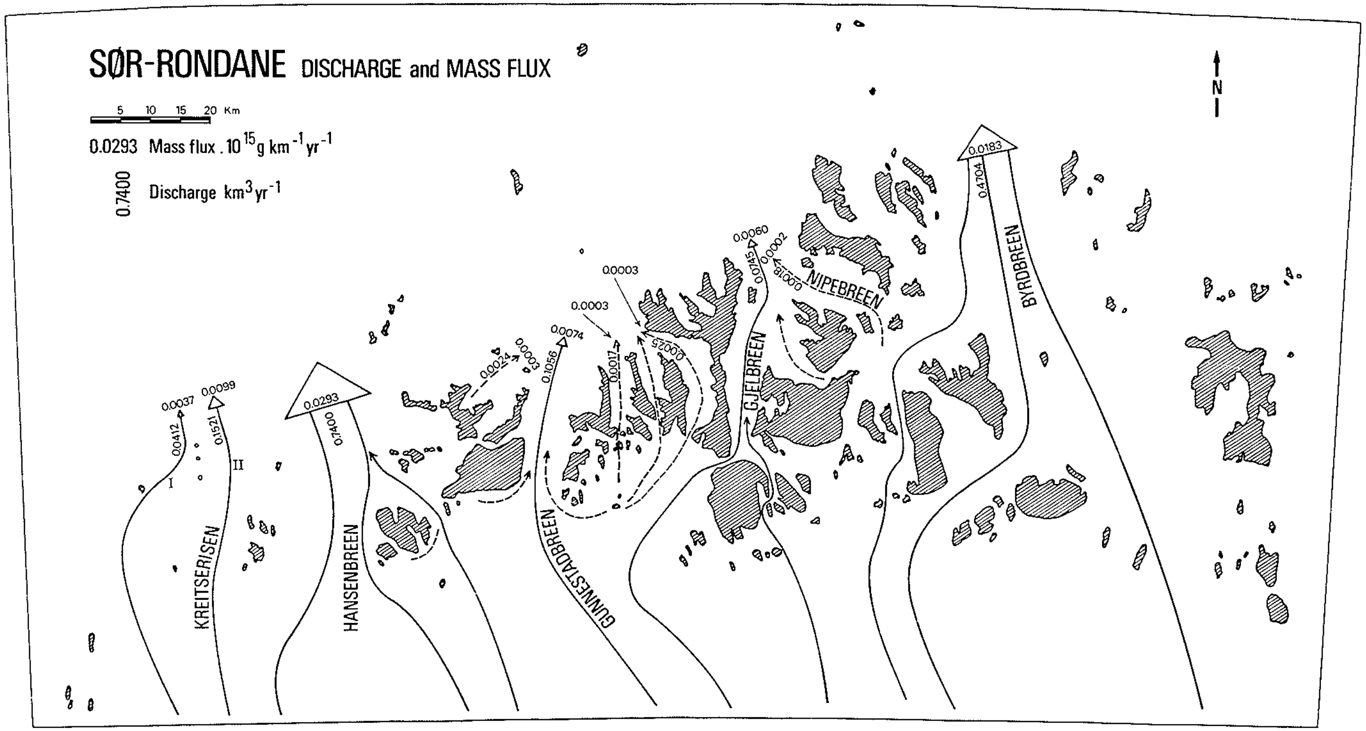

Figure 4: Schematic representation of measured mass fluxes and discharges through the Sør-Rondane Glacier flow on drainage glaciers is indicated by full lines. The flow pattern on local glaciers is given by dashed lines. Hatched areas represent mountain massifs. Total discharge through the entire section is calculated as 1.5988 km^3 yr^{-1}, mean mass flux as 0.006686 10^{15} g km^{-1} yr^{-1}.

High surface velocities (up to 38 m yr^{-1}) and the greatest ice depths in the Sør-Rondane (1980 m with the floor of the glacier at -311 m) were measured on this glacier. The mass flux attains 0.0293 10^{15} g km^{-1} yr^{-1}, again the highest value in the surveyed area.

Hansenbreen is situated immediately west of the apex of the wedge-shaped mountain area, which indicates that it is fed by a practically unobstructed flow of ice from the polar plateau. Its discharge might also be increased by the ice deflected to the west by the range.

A maximum depth of the floor of the subglacial valley (311 m below sea level) is measured on the southern profile; on the northern one the glacier floor is situated close to sea level. The subglacial relief seems therefore to become shallower to the north which corresponds to the increase to the north of the divergence of the flow.

The subglacial topography of the glacier valley is not a simple one: there is evidence for the existence of subglacial longitudinal ridges — locally substantiated by the existence of heavily seracced and crevassed areas — which divide the glacier. This seems to indicate that Hansenbreen, as the other important drainage glaciers in the area, is in fact a composite glacier.

Byrdbreen, with a discharge of 0.470 km^3 yr^{-1} and a mass flux of 0.0183 10^{15} g km^{-1} yr^{-1} is, in importance, the second glacier in the range. In its northern part it is a composite glacier divided in two by a subglacial longitudinal ridge. The existence of this ridge indicated by the gravimeter measurements is substantiated by the presence upstream of nunataks.

The greatest discharge takes place on the eastern side of the ridge where the highest surface velocities (up to 39 m yr^{-1}) and the greatest ice depths (up to 1085 m) are recorded. This part of Byrdbreen is directly fed by the ice flow from the polar plateau and has a weak and very regular surface gradient which explains the absence of crevasses.

The western side of the glacier is shallower and the surface velocities are lower (from 17 to 19 m yr^{-1}). It results from the coalescence of several narrow and steep glaciers cutting their individual gorge through the mountains. These glaciers originate from the edge of the plateau. The general geography of the area apparently indicates that they could originate from a local ice dome to the south of Gunnar Isachsenfjellet rather than from the polar plateau.

The vast mamillated surfaces of Balchenfjella to the east of Byrdbreen have been taken as proof of the former greater importance of this glacier and as an indication of the reduction of the main ice cover (Van Autenboer, 1964).

Gunnestadbreen and Gjelbreen have several similarities: their discharge (respectively 0.106 and 0.074 km^3 yr^{-1}) and mass flux (0.0075 and 0.0061 10^{15} g km^{-1} yr^{-1}) are of the same order of magnitude as are their surface velocities and ice depths (comparison with the northern profile on Gunnestadbreen). When passing through the mountains both glaciers cut a rather narrow gorge, the orientation of which deviates considerably from the general pattern of the ice flow.

When taking into account the effect of the mathematical method of calculating the ice depths, it is clear that both outlet glaciers have a subglacial profile which is strongly suggestive of a U-shaped valley.

Gunnastadbreen widens considerably north of Walnumfjellet and the velocity markers indicate a strong eastward component of the movement. In earlier papers (Van Autenboer, 1964; Van Autenboer and Blaiklock, 1966) this has been interpreted as the compensation by this active glacier for the disappearance of former tributary glaciers on Walnumfjellet. The subglacial profile between Romnaesfjellet and Dotten — obtained since — however indicates that the subglacial Gunnestadbreen valley deviates to the north-east. This means that the north-eastern direction observed at the markers of Gunnestadbreen indicate a general direction of flow rather than a local one. A comparison between the subglacial profiles of Gunnestadbreen on the Teltet-Smålegga line and its extension on the Romnaesfjellet-Dotten line indicates shallower subglacial relief to the north, which corresponds to the increasingly divergent flow in the piedmont area.

Kreitserisen I (west) is the plateau drainage glacier with the lowest mass flux rate ($0.0038\ 10^{15}$ g km^{-1} yr^{-1}). The very low discharge is explained by the existence to the south of a buried highland of which the highest peaks pierce the ice cover as granitic nunataks (Tertene).

Kreitserisen II (east) has a mass flux ($0.009994\ 10^{15}$ g km^{-1} yr^{-1}) which is of the same order of magnitude as Gunnestadbreen. This glacier also appears to be fed by an unobstructed flow of ice from the polar plateau. The subglacial profile is complicated, showing as in the case of Hansenbreen, the existence of subglacial ridges which seem to indicate that this glacier is a composite one.

Gillock, Ellis and Jenningsbreen are emissaries of a small ($\sim$ 175 km^2) local ice dome. The latter is situated on the edge of the polar plateau, south of Walnumfjellet and reaches an elevation of 2500 m. Part of the ice flow from the dome joins Gunnestadbreen and Gjelbreen while the rest cascades down into the three above mentioned glaciers. They can therefore be considered as local glaciers, which is confirmed by their very low discharge and their mass flux values ($0.0003\ 10^{15}$ g km^{-1} yr^{-1}) which are consistent with those of the other local glaciers. An indirect confirmation of this local origin could be seen in the composition of the hillocky morainic deposits on the east side of Jenningsbreen (Souchez, 1966).

Information on the surface elevations on the south side of the mountains has only recently become available and these glaciers were considered as plateau drainage glaciers in earlier papers (Van Autenboer, 1964; Van Autenboer and Blaiklock, 1966). The glacier smoothed surfaces of some isolated nunataks situated in the area south of Walnumfjellet and rising some 150 m above the present surface of the ice, had therefore been taken as a minimum indication of the lowering of the level of the plateau (Van Autenboer, 1964). It now appears that these glaciated surfaces can be explained by the reduction in thickness of a local ice dome on the edge of the plateau. Information on the surface elevations on the edge of the plateau in the Sør-Rondane area is unfortunately still too scant to decide whether this conclusion can be generalized for other glaciated nunataks south of the range. There is as yet no glacial-geological evidence in the Sør-Rondane to establish the relationship between local and plateau glaciation. It also appears that it will be necessary to obtain further information on the extension and role of the local drainage systems before concluding to the significance of some of the observed glaciated surfaces.

Both Nipebreen and the glacier between Teltet and Utsteinen have their drainage area entirely situated on the northern slopes of the mountains. Discharge values are rather weak, seen that they are based on few measurements (1 movement observation for Nipebreen and 2 movement and gravimetric stations on the glacier between Teltet and Utsteinen).

Discharge value are very low. The mass flux values (0.000268 and $0.000300\ 10^{15}$ g km^{-1} yr^{-1}) show a remarkably good agreement with those of the other local glaciers.

8. DISCUSSION

8.1. DRONNING MAUD LAND DRAINAGE SYSTEM

The Sør-Rondane are part of the coastal mountains of Dronning Maud Land extending between 15° W and 30° E. These mountain ranges follow the northern limit of a still poorly defined and largely unexplored drainage system (Dronning Maud Land Drainage system). The south-eastern limit of this system apparently corresponds to the northern part of the East Antarctic Ice divide which in Dronning Maud Land trends from the south-south-east to the north-north-west and locally culminates at 3.700 m in the Fuji divide (77° 40′ S and 42° E) (Fujiwara and others, 1971). Russian authors (Kapitza, 1967; Ivashutina and others, 1966) assumed that this part of the divide corresponds to the meridional trending, subglacial Vernadsky mountains forming the northwards extension of the subglacial Gamburtsev mountains better documented in the Vostok-Pole of Inaccessibility area (Evans and Robin, 1972; Drewry, 1975). Fujiwara and others (1971) however state that the results of the Japanese traverse, crossing the Fuji divide, do not substantiate the deductions made by the Soviet authors. A more balanced assessment of the available data on the subglacial relief is given by Bentley (1972).

To the south and to the west little is known about the limits of the drainage system. Mass transport measurements of Jutulstraumen (Decleir and Van Autenboer, in press) make it however clear that there is some doubt about the outline of an ice divide ending near the coast east of the Greenwich meridian, as indicated by Giovinetto (1964a).

Surface elevations on the South Pole—Queen Maud Land traverse (e. g. Beitzel, 1971; Picciotto and others, 1971) suggest that a large part of the continental ice sheet in Dronning Maud Land flows towards the Weddell sea and Filchner ice shelf. This indicates that an ice divide, situated in the unexplored area between the S. P. Q. M. L. traverse and the coastal mountains, forms the southern limit of the basin feeding the outlet glaciers of eastern Dronning Maud Land. South of the Sør-Rondane this divide might be situated quite close to the mountains as indicated by some isolated surface elevations in that area (G. De Rom, pers. comm.).

8.2. SØR-RONDANE

It seems very likely that the relative proximity of this ice divide influences the flow and the mass transport through the range. The Sør-Rondane, as the other coastal mountains in Dronning Maud Land, are more or less perpendicular to the main flow of ice from the continental ice sheet on which they have a damming effect. The general orientation of the ice flow in the Sør-Rondane area is from the south-east to the north-west. The damming of the ice flow by the range is clearly illustrated: only three main outlet glaciers — Gunnestadbreen, Gjelbreen and Byrdbreen — cut through the range. The direction of these glaciers — or of their tributaries in the case of Byrdbreen — deviates from the general orientation of the ice flow. Maximum flow is measured in the unobstructed area to the west of the range where mass transport through Hansenbreen alone is larger than the combined output of all the other glaciers in the range.

The obstruction of the ice flow by the Sør-Rondane might also be the cause of the increased surface elevations to the south of the range and of the existence of an undisturbed, crevasse-free zone extending northwards from Romnaesfjellet to the coast.

This also seems related to a rather sheltered area immediately to the north of the range, between Hansenbreen and Gunnestadbreen. No outlet glaciers cut through this area, entirely covered by local glaciers, and which probably corresponds to a glacierized highland forming the subglacial extension of the Wideröefjellet and Vikinghögda massifs.

Information on the subglacial topography is restricted to a few gravimeter profiles and a couple of seismic depth determinations (Dieterle and Peterschmitt, 1964). It is clear that the Sør-Rondane with the floor of the main glaciers below or close to sea level resemble an ice covered fjord landscape. There are furthermore indications (Hansenbreen and Romnaes to Dotten profiles) that the glacier valleys are deepest at the foot of the slopes rising to the plateau and become shallower to the north, underneath the progressively diverging flow. This local overdeepening is characteristic for fjord valleys (e. g. Sognefjord and Hardangerfjord in Norway, where rocky submarine thresholds are generally related to sounds or low lands where the spreading ice had less erosive effects [Holtedahl, 1967]).

Russian authors (Ravich and others, 1969; Ravich and Kamenev, pers. comm.) believe the ice flow in this range, as in other parts of the coastal mountains of Dronning Maud Land, to be completely controlled by tectonics: the major massifs of the mountains are delimited by vertical faults of mesozoic-cenozoic age forming horst and graben structures. Structural control of glacier flow in Dronning Maud Land is not to be excluded: the Jutulstraumen ice stream further west e. g. is situated on a down faulted block as inferred from geological (Roots, 1969) and geophysical (Decleir and Van Autenboer, in press) data. In the Sør-Rondane however there is no geological or geophysical information that points to the existence of a multitude of major faults. However, the ridge west of Gjelbreen (a long and steep rectilinear scarp) might be the morphological expression of a north-south oriented major fault and minor north-south faulting observed on the east side of Byrdbreen might be taken as an indication of a more important fault. The ice flow analysis adds no further information but certainly does not add weight to the postulated existence of multiple block faults controlling the entire ice flow system.

There is no evident relationship between the flow lines and mass transport. The enclosed map however shows a certain proportionality between the number of flow lines passing through a glacier and its measured mass transport. This relationship confirms the discharge measurements if we can assume a rather even distribution of the mass flow at the edge of the plateau. The survey has allowed measurement of the mass transport of all major glaciers in the Sør-Rondane and from table 1 and fig. 4 it can be concluded that there is a clear relationship between the mass flux values and the different types of glaciers under consideration.

The mass flux values of the local glaciers, including the ones originating from a local ice dome near the edge of the plateau, are very consistently similar (0.0003 10^{15} g km^{-1} yr^{-1}). The mass flux values of the drainage glaciers on the other hand vary from 0.0038 10^{15} g km^{-1} yr^{-1} (Kreitserisen I) to 0.0293 10^{15} g km^{-1} yr^{-1} (Hansenbreen), highlighting the complexity of the drainage pattern in the area.

The mean mass flux through the Sør-Rondane taken as a whole (between Taggen and Vesthjelmen) is 0.0067 10^{15} g km^{-1} yr^{-1}. The mass flux values for the Sør-Rondane are very low when compared with those given by Giovinetto and others (1966) for the glaciers in the Trans-Antarctic mountains, the western part of the Ross Ice Shelf drainage system. These authors conclude to the following values:

0.25 10^{15} g km^{-1} yr^{-1} (glaciers with large drainage basins)
0.05 10^{15} g km^{-1} yr^{-1} (glaciers with small basins and cirque glaciers)
0.02 10^{15} g km^{-1} yr^{-1} (piedmont glaciers)

The highest mass flux value in the Sør-Rondane area (Hansenbreen: 0.0293 10^{15} g km^{-1} yr^{-1}) falls between the two lowest estimates of the Trans Antarctic mountains. The mean mass flux in the Sør-Rondane (0.0067 10^{15} g km^{-1} yr^{-1}) is consequently also appreciably lower than the one given for the Trans-Antarctic mountains (0.04 10^{15} g km^{-1} yr^{-1}).

It is especially low when compared with the mean mass flux for the periphery of the grounded ice sheet in Antarctica which is estimated as 0.09 10^{15} g km^{-1} yr^{-1} (Giovinetto, 1964b cited in Giovinetto and others, 1966).

The only other mass transport measurements in Dronning Maud Land are those of Jutulstraumen ice stream (Gjessing, 1972; Decleir and Van Autenboer, in press). The discharge of this 49 km wide glacier has been given as 12.48 km^3 yr^{-1}, nearly 7 times the amount of ice flowing through the 220 km long section of the Sør-Rondane. The mass flux value for Jutulstraumen (0.233 10^{15} g km^{-1} yr^{-1}) on the other hand is close to that assigned to glaciers with a large drainage basin in the Trans-Antarctic mountains.

The comparison between the discharge of Jutulstraumen and of the Sør-Rondane confirms the view, already expressed in 1959 by Mellor (1959) that mass transport by ice streams, which occupy a small fraction of the drainage periphery are responsible for the removal of more ice from the continent than the sheet flow over the remaining length of coast. It also explains why only ice streams can still be recognized as individual geographic features within the coastal areas of high accumulation and why only the latter give rise to characteristic glacier tongues. In West Antarctica, radioglaciological surveys located several major ice streams feeding into the Ross Ice Shelf (Robin, 1975; Rose, in press). Ice streams are readily identified on large scale satellite imagery and Hughes (1977) estimates that they are responsible for 90 % of the mass wasting in West Antarctica.

There is much less information on East Antarctica and especially on Dronning Maud Land, where data on the large scale drainage pattern are speculative or absent. The low rate of discharge through the Sør-Rondane might mean that the outlet glaciers in this area are fed by a comparatively small drainage basin. This confirms the above made suggestion of the proximity of an ice divide to the south of the mountains. Wilson and Crary (1961) have shown that the Skelton glacier — which has a discharge comparable to that of Hansenbreen — is mainly fed by a local accumulation area on the plateau side of the Trans-Antarctic mountains and not by the main flow of ice from the plateau. These authors also suggest that this situation, related to the lowering of the surface of the plateau, is typical of most of the glaciers on the west side of the Ross Ice Shelf as far south as the Beardmore glacier. Drewry (in press) bases a similar conclusion on radioglaciological data when he shows that Taylor Valley in the McMurdo Sound area belongs to a local ice dome, west of the mountain range in Southern Victoria. The fluctuations of this dome and its drainage system might be controlled by local climatic effects and therefore not be representative of the main fluctuations of the ice sheet. This might lead to a reconsideration of the glacial history of this classic area. Does a similar situation exist behind the mountain ranges in Dronning Maud Land? In this case the flow from the plateau is channeled into at least two glacier streams: Jutulstraumen and the ice stream east of Novolazarevskaya (velocity measurements by Kruchinin and others, 1967). The other glaciers probably drain only marginal parts of the continental ice sheet.

Since Bull (1971) noted that the possible errors in the ablation terms of the total mass balance in Antarctica are far larger than the magnitude of the assessed mass balance, few more data have been presented. The paucity of data in Dronning Maud Land (where mass wasting has been measured only over 10 % of the total periphery) illustrates this once more. With the availability of large scale satellite imagery it will become possible to establish an overall picture of the drainage pattern so that with measurements on a few selected glaciers and their extrapolation it might become possible to end the successive speculations on the present increase or decrease of the Antarctic ice sheet.

9. ACKNOWLEDGEMENTS

This survey could not have been carried out without the initial trigonometric work by K. V. Blaiklock and without the field assistance of several companions in particular of E. Lallemand, J. J. Derwael and the late J. P. De Winde. Dr. T. Gjelsvik (Norsk Polarinstitutt) enabled access to unpublished cartographic material. Miss I. de Wispelaere (L. U. C.) kept smiling when she was presented with yet another drawing which we wanted finished before she had a chance to look at it. However, she managed and with the result the smile became ours.

Further thanks are due to Prof. Dr. P. Dingens, director of the Observatory of the Ghent State University, and last but not least to the chairman of the Belgian Dutch Antarctic Committee, Baron G. de Gerlache.

10. REFERENCES

Autenboer, T. Van, 1964: The Geomorphology and Glacial Geology of the Sør-Rondane, Dronning Maud Land, Antarctica. Mededelingen van de Koninklijke Vlaamse Akademie voor Wetenschappen, Letteren en Schone Kunsten van België, Klasse der wetenschappen, Jaargang 26, nr. *8*, 91 p.

Autenboer, T. Van, 1969: Sør-Rondane mountains, in Geologic Map of Antarctica. Sheet 8 Antarctic Map Folio Series, Folio 12, Geology. American Geographical Society, New York.

Autenboer, T. Van, and K. V. Blaiklock, 1966: Ice flow and thickness measurements in the Sør-Rondane, Dronning Maud Land, Antarctica. Journal of Glaciology *6*, 43: 69—81.

Autenboer, T. Van, J. Michot, and E. Picciotto, 1964: Outline of the geology and petrology of the Sør-Rondane mountains, Dronning Maud Land. In R. J. Adie, ed. Antarctic Geology. Amsterdam, North-Holland Publishing C°: 501—514.

Autenboer, T. Van and H. Decleir, 1974: Mass Transport Measurements in the Sør-Rondane, Dronning Maud Land, Antarctica. Preliminary Report. Service Géologique de Belgique. Professional Paper 1974, No. *6*, 25 pp.

Autenboer, T. Van, and W. Loy, 1972: Recent geological Investigations in the Sør-Rondane mountains, Belgicafjella and Sverdrupfjella, Dronning Maud Land, Antarctica. Proceedings SCAR-IUGS Symposium on Antarctic Geology, Universitetsforlaget, Oslo: 563—571.

Beitzel, J. E., 1971: Geophysical Exploration in Queen Maud Land, Antarctica. In A. P. Crary (ed.): Antarctic Snow and Ice Studies II. American Geophysical Union. Antarctic Research Series, Vol. *16*: 39—87.

Bentley, C. R., 1972: Subglacial Rock Surface Topography. In: B. C. Heezen, M. Tharp and C. R. Bentley: Morphology of the Earth in the Antarctic and Subantarctic. Antarctic Map Folio Series, Folio 16, American Geographical Society, New York.

Bull, C., 1971: Snow accumulation in Antarctica. In: L. O. Quam (ed.): Research in the Antarctic. American Association for the Advancement of Science. Washington, Publication No. *93*: 367—421.

Corbato, C. E., 1965: A Least-squares procedure for Gravity Interpretation. Geophysics, Vol. *30*, no. 2: 228–233.

Decleir, H. and T. Van Autenboer, in press: Gravity and magnetic anomalies across Jutulstraumen, a major geological feature in Western Dronning Maud Land. In: Proceedings of the SCAR-IUGS Symposium on Antarctic Geology and Geophysics. Wisconsin 1977.

Dieterle, G., and E. Peterschmitt, 1964: Sondages seismiques en Terre de la Reine Maud. Academie Royale des Sciences d'Outre-Mer (Bruxelles), classe des Sciences Techniques. Mémoires, Tome 13, fasc. 4: 101.

Drewry, D. J., 1975: Radio echo sounding map of Antarctica (90° E–180°). Polar Record, Vol. *17*, No. 109: 359–374.

Drewry, D. J., in press: Geophysical investigations of ice sheet and bedrock inland of the McMurdo Sound, Antarctica. In: Proceedings of the SCAR-IUGS Symposium on Antarctic Geology and Geophysics. Wisconsin 1977.

Evans, S., and G. de Q. Robin, 1972: Ice thickness measurement by radio echo sounding, 1971/72. Antarctic Journal of the U. S., Vol. *VII*, nr. 4: 108–110.

Fujiwara, K., S. Kakinuma, and Y. Yoshida, 1971: Survey and some considerations on the Antarctic Ice Sheet. In M. Murayama (ed.): Report of the Japanese Traverse Syowa–South Pole, 1968–1969. Japanese Antarctic Research Expedition. Scientific Reports, Special Issue, nr. *2*: 30–48.

Giovinetto, M. B., 1964a: The Drainage System of Antarctica: Accumulation. In M. Mellor (ed.): Antarctic Snow and Ice Studies. Antarctic Research Series, Vol. *2*. American Geophysical Union, Publ. nr. 1197: 127–157.

Giovinetto, M. B., 1964b: An estimate of mass flux Antarctica. Geological Society of America. Special Papers, Nr. *76*: 309.

Giovinetto, M. B., E. S. Robinson, and C. W. M. Swithinbank, 1966: The Regime of the Western part of the Ross Ice Shelf Drainage System. Journal of Glaciology *6*, 43: 55–68.

Gjessing, Y. T., 1972: Mass Transport of Jutulstraumen Ice Stream in Dronning Maud Land. Norsk Polarinstitutt, Årbok 1970: 227–232.

Holtedahl, H., 1967: Notes on the Formation of Fjords and Fjordvalleys. Geografiska Annaler *49*, Serie A: 188–203.

Hubbert, M. K., 1948: A line Integral Method of Computing the Gravimetric Effects of two-dimensional Masses. Geophysics *13*, 2: 215–225.

Hughes, T., 1977: West Antarctic ice streams. Reviews of Geophysics and Space Physics *15*, 1: 1–55.

Ivashutina, L. I., A. P. Kapitsa, and O. G. Sorokhtin, 1966: Thickness of ice sheet, 1 : 20.000, p. 94–95 in Atlas of Antarctica, Vol. *I*. Soviet Antarctic Expedition, Moscow-Leningrad: 225 p.

Kapitza, A. P., 1967: Antarctic Glacial and Subglacial Topography. In T. Nagata (ed.): Pacific-Antarctic Sciences. Japanese antarctic Research Expedition. Scientific Reports. Special Issue, nr. *1*: 82–91.

Kruchinin, Yu. A., S. Pinter, I. M. Simonov, 1967: Determination of the Rate and Direction of Movement of Glaciers in the Vicinity of Novolazarevskaya Station. Soviet Antarctic Expedition Information Bulletin *6*, 4: 290–294.

Martin, J., 1948: Gravimetrie. In: Rapport préliminaire de la campagne préparatoire au Groenland (1948). Publications des Expéditions Polaires Françaises *5*: 28–41.

Mellor, M., 1959: Ice Flow in Antarctica. Journal of Glaciology *3*, 25: 337–387.

Paterson, W. S. B., 1969: The Physics of Glaciers. Pergamon Press: 250 p.

Pasteels, P., et J. Michot, 1968: Nouveaux Résultats Géochronologiques obtenus par la méthode U-Pb sur les zircons des Monts Sør-Rondane (Antarctique). Annales de la Société Géologique de Belgique, T. 91: 293–303.

Picciotto, E., J. Michot, S. Deutsch, and P. Pasteels, 1967: Géologie et Annexe Glaciologique. Expédition Antarctique Belge 1957/58. Résultats scientifiques, Vol. *VII*: 299 p.

Piciotto, E., G. Crozaz, and W. de Breuck, 1971: Accumulation on the South Pole—Queen Maud Land Traverse, 1964—1968. In: A. P. Crary (ed.): Antarctic Snow and Ice Studies II. American Geophysical Union. Antarctic Research Series, Vol. *16*: 257—315.

Ravich, M. G., D. S. Soloview, and Y. E. Kamenev, 1969: Geological Investigations in the Eastern part of Queen Maud Land. Soviet Antarctic Expedition. Information Bulletin. Scripta Technica — American Geophysical Union, Washington: 58—65.

Robin, G. de Q., 1975: Ice shelves and ice flow. Nature *253*, January 17: 168—172.

Roots, E. F., 1969: Geology of Western Queen Maud Land. Geologic Map of Antarctica. sheet 6. In Antarctic Map Folio Series, Folio 12, Geology. American Geographical Society, New York.

Rose, K. E., in press: Radio echo studies of bedrock in Marie Byrd Land, Antarctica. In: Proceedings of the SCAR-IUGS Symposium on Antarctic Geology and Geophysics. Wisconsin, 1977.

Souchez, R. M., 1966: The origin of morainic deposits and the characteristics of glacial erosion in the Western Sør-Rondane, Antarctica. Journal of Glaciology *6*, 44: 249—255.

Talwani, M., J. L. Worzel, and M. Landisman, 1959: Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone. Journal of Geophysical Research *64*, 1: 49—60.

Wilson, C. R. and A. P. Crary, 1961: Ice Movement Studies on the Skelton Glacier. Journal of Glaciology *3*, 29: 873—878.

Zijderveld, J. D. A., 1968: Natural Remanent Magnetizations of some Intrusive rocks from the Sør-Rondane Mountains, Queen Maud Land, Antarctica. Journal of Geophysical Research *73*, 12: 3773—3785.

Manuscript received 28 September 1977 and in revised form 12 March 1978.

Author's addresses: Dr. T. Van Autenboer
Vijverstraat, 25
B-2800 Mechelen, Belgium
Dr. H. Decleir
Dr. W. Maststraat, 71
B-9030 Wondelgem, Belgium