DYNAMICS OF THE ANTARCTIC ICE CAP
Part I : Ice thickness measurements related to the damming effect of the Sør Rondane, Dronning Maud Land, Antarctica

Ludo DE VOS and Hugo DECLEIR

Vrije Universiteit Brussel
Geografisch Instituut
Pleinlaan 2 - 1050 Brussel
Belgium

Proceedings of the Belgian National Colloquium on Antarctic Research
Brussels, October 20, 1987
Prime Minister's Services - Science Policy Office

ICE THICKNESS MEASUREMENTS IN THE SØR RONDANE

Key Words : Ice Thickness measurements, Gravity, Ice Sheet, Damming Effect, Sør Rondane

Abstract : *Preliminary results of the 1986-87 Belgian Participation in the JARE 28 Expedition to the Sør Rondane , Antarctica, are presented. The principles of ice thickness calculations, based on gravity measurements, are given. The subglacial results illustrate the damming effect of a coastal mountain range and indicate an ice covered landscape in the process of being cut-off from the main plateau ice supply.*

1. Introduction

The East Antarctic Ice Sheet screens off most of the direct glacio-geologic information on the bedrock and restricts the observations to a few isolated mountain areas and the oceanographic sediments. Most of the information regarding the glacial history has come from investigations in the Trans Antarctic Mountains (Mayewski and Goldthwait, 1985). However a large body of information can also be found on the nunataks and in some dry valleys situated in the mountain ranges bordering the coast of Dronning Maud Land, Enderbyland and a few other marginal areas of the East Antarctic ice shield. In contrast with the Trans Antarctic Mountains some of these areas are quite close to the present ice divide. The recorded variations within the sediments of these mountains might therefore correspond quite closely to fluctuation in altitude and/or shifts of the position of the East Antarctic ice divide.

Apart from providing the necessary data on the dynamics of the ice cap the marginal coastal mountains constrain the ice movement and create typical outlet glaciers. As such they can be said to contribute to the stability of the Antarctic ice sheet. The Sør Rondane Mountains provide a particular beautiful example of the damming effect of such a coastal mountain range.

This paper presents some preliminary results from ice thickness measurements obtained in the central part of the Sør Rondane Mountains during the austral summer 1986-87 while participating in the 28th Japanese Antarctic Research Expedition. A complete survey of all the ice thickness profiles and an evaluation of the gravimeter ice thickness determinations as compared to radio echo sounding will be given elsewhere (De Vos and Decleir, 1988 ; Decleir et al., 1988). These ice thickness profiles will serve later as basis for reconstructing the subglacial relief in this part of the Sør Rondane and for interpretation of the glacier dynamics.

2. Ice Thickness Measurements

Over the vast ice covered areas of continental ice sheets -remote from steep mountain ranges and nunataks- the infinite slab method to calculate ice thickness from gravity measurements has been widely used in the past. The method was particularly useful for rapid ice thickness determinations between seismic reflection stations of oversnow traverses during and following the IGY.

The method became largely obsolete when airborne radio echo sounding was introduced in the late sixties. The latter method allowed for the first time rapid and accurate measurements to be made over terrain which is characterized by difficult and dangerous access. Since that time large scale mapping of the subglacial relief became possible and was carried out both over Eastern and Western Antarctica (Drewry, 1984).
However, within the mountain ranges, over narrow outlet glaciers, cirque glaciers etc..., both methods suffer largely from disturbing effects of the valley sides : e.g. side reflections and moraine cover for radio echo sounding, difficult topographic and subglacial modelling for the gravimetric method.

Van Autenboer and Blaiklock (1966) and Van Autenboer and Decleir (1974, 1978) applied the gravimetic method systematically in an approach to estimate the total glacier discharge through a 220 km long mountain range (Sør Rondane). Cross sections over the most important drainage glaciers were constructed using Talwani's method for modelling 2-D gravity anomalies.

During the 1986-87 JARE 28 Expedition a detailed investigation was planned of the subglacial morphology within the central part of the Sør Rondane by comparison of ice radar and gravity measurements. In that respect use was to be made of a newly developed "backpack" radio echo sounder (Scott Polar Research Institute). It was assumed that, especially near the valley walls and over the moraine covered ice surface, such a portable instrument would be advantageous.

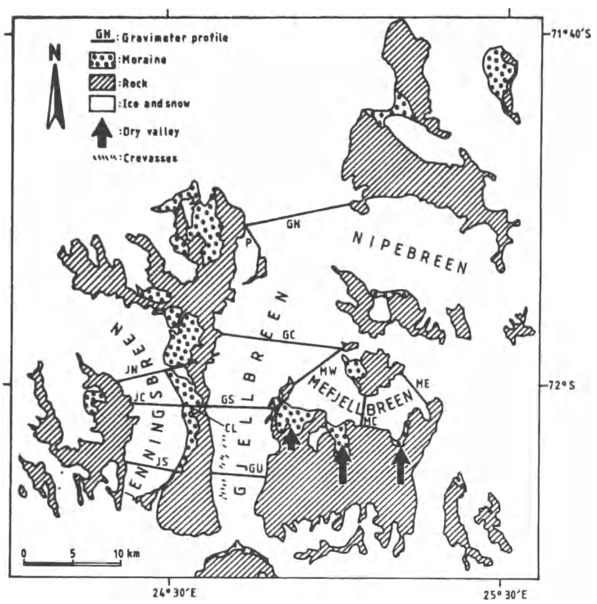


Figure 1 : Central Part of the Sør Rondane and Gravimeter Profiles

However due to stability and power problems with the radar system in the field, the ice thickness determinations were mainly restricted to gravimeter measurements. Gravity measurements were performed with a standard Worden gravimeter. 11 Gravimeter traverses were carried out across the glaciers of the central part of the Sør Rondane (fig. 1). As these profiles were chosen between well identifiable points on rock at both sides of the glacier location and distance between stations could be easily recorded on the mileage reader of the snow scooters. In the middle of the glacier spacings between stations were generally 0.5 or 1 km while altitudes were determined by aneroid altimetry. However near the valley-sides position and altitude of the gravimeter stations, both on the glacier and on the adjacent rock, were determined by theodolite tacheometry. Here the distance between stations varied between 100 and 500 m. As most of the profiles were measured to and fro, altitudes and gravimeter measurements were taken as the mean value, thereby automatically correcting for drift phenomena.

The gravity values were first corrected for latitude and height. To obtain a relatively fast and easy-to-handle calculating model the traditional Bouguer and terrain corrections were replaced by a "zonal" correction algorithm (fig. 2). The outer zones of the model (Topo $_{out}$) contribute a

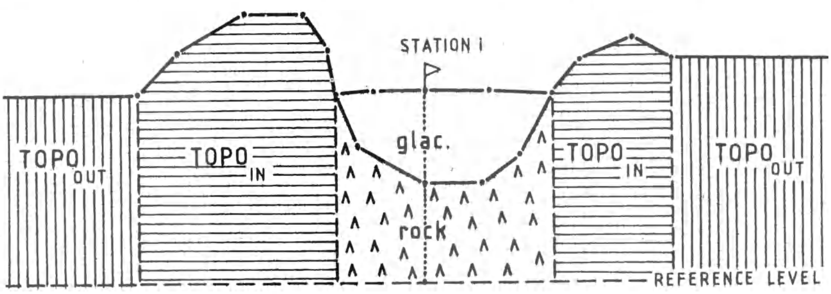


Fig 2. Zonal subdivision of terrain for ice thickness calculations

relatively minor amount to the total attraction values of the surrounding rock, therefore each outer zone can be approximated by a semi infinite slab, similar to the tradional Bouguer correction. The inner zones adjacent to the glacier (Topo$_{in}$) are much more important for the measured attraction forces. For this zone the total mass above the reference level was calculated by the Talwani method. The latter method allows the gravity effect of an arbitrary two-dimensional mass to be calculated by a polygonal approximation of the body (e.g. Telford et al.,). The surface profile of this body was digitized from existing topographic maps.

Finally the attraction of the two masses underneath the glacier surface ($g_{glac.}$ and g_{rock}) are calculated. The first mass is the glacier mass and the second one is the mass of rock which lies between the glacier bedrock and the reference level. The interface between these two masses is the unknown subglacial topography.

The true value G_i at station i can now be decomposed as follows :

$$G_i = \gamma_i - c_{h,i} + g_{topo,i} + g_i \tag{1}$$

where γ_i is the gravity underneath station i at the reference level.

$c_{h,i}$ is the altitude (free air) correction to pass from the reference level to the altitude of station i

$g_{topo,i}$ is the gravity effect at station i of all the masses between the reference level and the topographic surface except for the area covered with glacier :

$$g_{topo,i} = g_{topo,out} + g_{topo,\ in}$$

g_i is the gravity effect of both the glacier ice and the rock beneath the glacier :

$$g_i = g_{rock,i} + g_{glac,i}$$

On the other hand, the true value G_i at station i is also equal to :

$$G_i = g_{m,i} + g_{ref} + \varepsilon_i \tag{2}$$

where $g_{m,i}$ is the measured relative gravity value

g_{ref} is the unknown gravity corresponding to the zero of the scale of the gravimeter

ε_i is the error

Since the thickness of the earth's crust and the density of the crustal material may vary, both changes can be approximated by a linear variation of the gravity along the reference level :

$$\gamma_i = \gamma_o + rg\ \Delta x_i \tag{3}$$

where Δx_i is the linear distance along the profile reckoned from the reference station which is characterized at the reference level by a gravity value γ_o.

rg is the regional gradient in mgal/m

As the hight of the bedrock underneath the glacier is unknown, g_i can only be calculated from a model. If the model is not correct the gravity g_i will differ by an amount v_i,

$$g_i = g_{c,i} + v_i \tag{4}$$

Combining eqs. (1), (2), (3) and (4) and applying them to station i, and to a reference station i = o, one finds after substraction :

$$\Delta g'_i + (\varepsilon_i - \varepsilon_o) = rg\ \Delta x_i + \Delta g_{c,i} + (v_i - v_o) \tag{5}$$

Δ in general stands here for the value at station i minus the value at the reference station

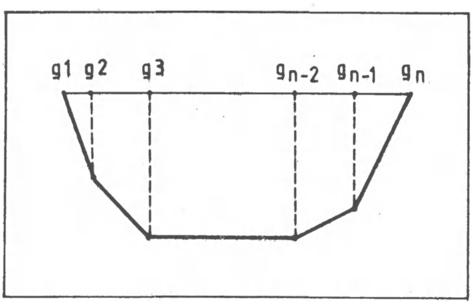
$\Delta g'_i$ combines the measured values plus correction terms :

$$\Delta g'_i = \Delta g_{m,i} + \Delta c_{h,i} - \Delta g_{topo,i}$$

Since the gravity is essentially vertical the numerical solution of eq. (5) can be split up in two parts :

(i) over rock, the ice depths are relatively unimportant and it will be assumed that $(v_i - v_o) \approx 0$. A least squares solution will then give an estimate for the regional gradient rg.

(ii) with the knowledge of the regional gradient and an estimate for the height of the bedrock underneath each station the correction terms v_i can be computed. With these v_i the bedrock altitudes can be inproved and a new regional gradient rg and new v_i can be calculated and so forth. This converges towards constant values of the bedrock altitudes underneath the stations on ice.



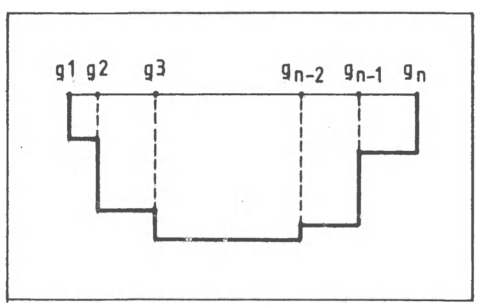


Fig 3. Polygonal (left) and prism (right) approach of subglacial relief.

The approximation of the bedrock by a polygonal line is one way to approximate the outline of the subglacial relief. One can also compose the ice mass and the rock underneath by a set of vertical prisms, extending from the bedrock to the ice surface and from the bedrock to the reference level (e.g. Børsting Pedersen, 1977). Each prism has a gravimeter station as boundary in the x-direction. Fig. 3 compares schematically the two methods. It is clear that both methods converge if the number of stations becomes large. However for a small number of measuring stations the methods diverge significantly. The negative effect of the vertical ice prism near the valley side results generally in a deeper glacier-bedrock profile. Fig. 4 illustrates the polygonal and prism method as applied to one of the profiles.

3. Results

Van Autenboer and Decleir (1974, 1978) have already emphasized the fact that the ice discharge of the glaciers of the central part of the Sør Rondane is very low as compared to the values obtained on the eastern and western side of the range. Although Jenningsbreen (for location see fig. 1) is still connected with the ice of the polar plateau, its mass flux (0.3 10^9kg/km/yr) is comparable to that of the very local glaciers. The same authors found the bedrock of Jenningsbreen to be situated at approximately -150m in the area where this glaciers enters the piedmont region north of the mountain range. Fig . 4 shows an ice thickness profile further up the glacier (Jenningsbreen JN)

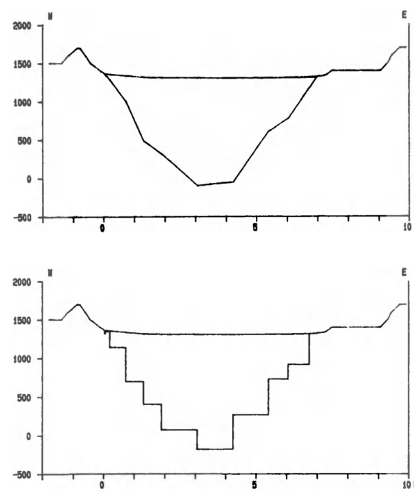


Fig 4. Polygonal (above) and prism (below) model for Jenningsbreen JN

and suggests that this low subglacial relief is continued following the glacier within the mountain range. It is only when approaching the head of the glacier that a steep bedrock rise occurs. This can be seen on fig. 5 where profile Jenningsbreen JS is shown. The latter profile -situated 10 km further upstream from profile JN- at the foot of the ice fall leading to the polar plateau, indicates an ice floor of more than 500m above sea level. Another interesting feature of this southern profile is its asymmetry. The deepest part of the glacier has clearly shifted to the east. This corresponds with a strongly eastward curving of the surface flow-lines as the glacier cuts its gorge through the southern border of the mountain range.

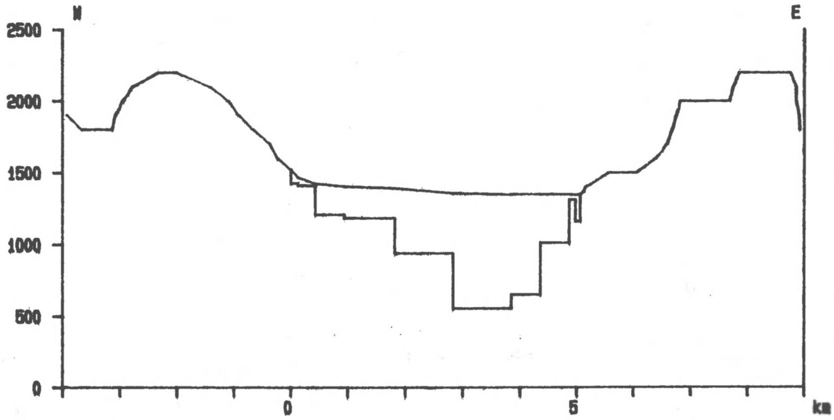


Fig 5. Subglacial Profile for Jenningsbreen JS

Noteworthy is the east-west gradient in the ice surface topography with the higher elevations occurring over the more shallow western part of the glacier. This higher glacier surface is characterized by an eroded snow cover and contrasts with the bare blue ice of the lower east side. Fig (6) shows the ice thickness results for Gjellbreen (profile GC). Although Gjellbreen flows

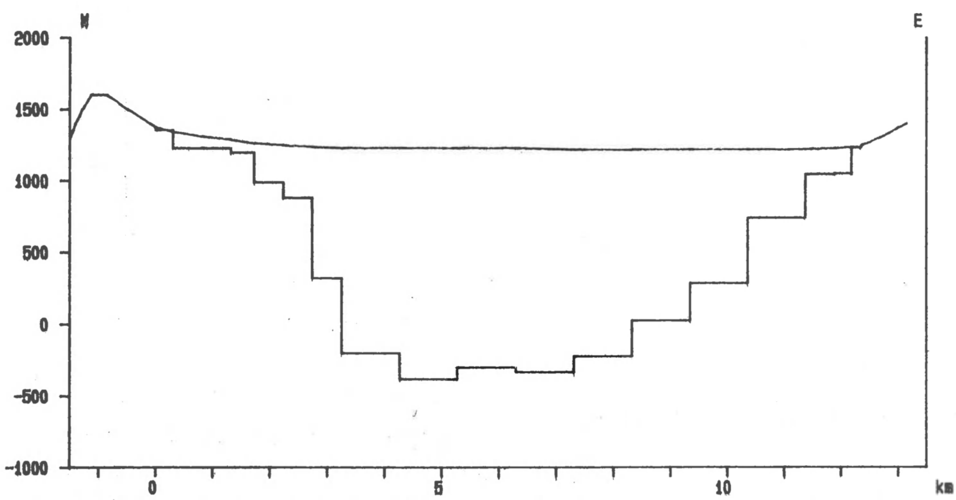


Fig 6. Subglacial Profile for Gjellbreen GC

parallel with Jenningsbreen it is fed not only by ice descending from the polar plateau but also from the east by two minor glaciers (Mefjellbreen and Nipebreen) which flow perpendicular to the main direction. Mefjell- and Nipebreen divide the central part of the Sør Rondane in multiple blocks. The cross section through Gjellbreen (GC) shows a subglacial depth of -500m which is deeper than the depth measured further to the north (Gjellbreen GN) where -100m is reached. This overdeepening of the glacier is confirmed on profile Gjellbreen GS where the subglacial floor lies also well below sea level. Such overdeepening has been typically attributed to fjordglaciers. Similar findings were reported by Van Autenboer and Decleir (1978) for Hansenbreen.

Three N-S cross-sections of Mefjellbreen show an interesting feature which contradicts somewhat the apparent block faulted appearance of this part of the range. As can be seen on fig. 7 both the eastern profile (ME) and the western profile (MW) are much deeper than the central profile (MC)

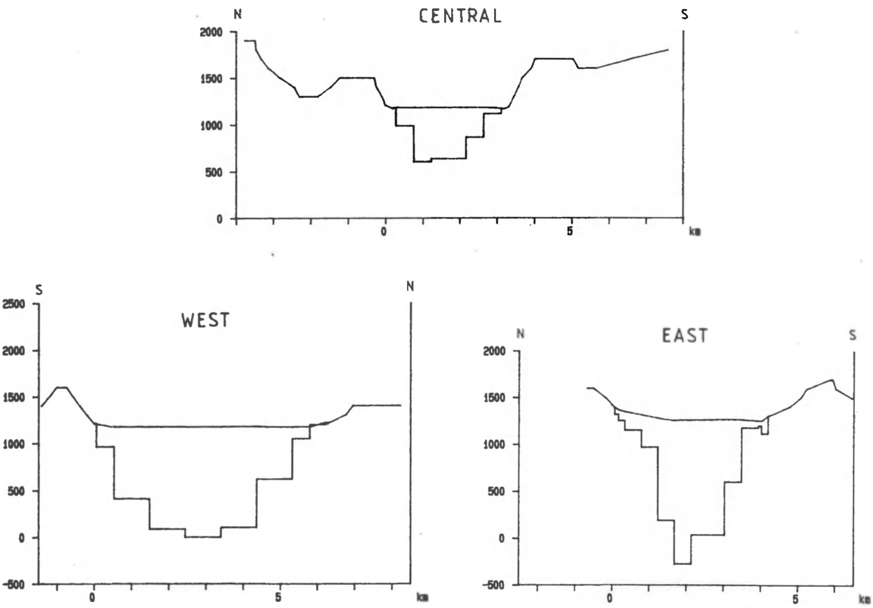


Fig 7. Subglacial Profiles for Mefjellbreen MW (West) Mefjellbreen MC(Central) and Mefjellbreen ME (East).

where the subglacial bedrock remains above 500 m and suggest a subglacial ridge connecting Mefjell and Menipa.

Further to the south on Gjellbreen the ice thickness decreases rapidly, although the very shallow profile of Gjellbreen GU is still being investigated for possible measuring and modelling errors. Anyway, an ice depth of less than a few hundreds of meters seems very likely. This underscores the damming effect of the southern threshold of the range on the ice flux towards the north. However, Van Autenboer and Decleir (1978) found a significant higher mass flux (6.0 10^9kg/km/yr) for Gjellbreen than for Jenningsbreen. This can only be partly explained by the additional inflow of ice through Nipebreen and Meffellbreen and needs therefore further investigation.

4. Conclusion

There is enough glacial evidence to conclude that two glaciers in the central part of the range, which in the past have developed characteristic glacial valleys similar to the major outlet glaciers, are in the process of being cut-off from the main ice supply. It is interesting to speculate that these on-going processes are similar to those which have led to the existence of the N-S trending dry valleys of neighbouring Mefjell area (fig. 1) and corroborate other glacial geological and geomorphological phenomena observed in the Sør Rondane (e.g. Van Autenboer, 1964). The consequence for possible related changes in position and altitude of the ice divide immediately to the south of the Sør Rondane and of the grounding line of the ice sheet to the north is currently being investigated by numerical modelling.

5. Acknowledgement

The authors are deeply indebted to Prof. T. Hoshiai, leader, and to all expedition members of JARE 28, especially their field compagnons of the Sør Rondane Party K. Hirakawa (leader), N. Matsuoka, Y. Osanai, Y. Takahashi, T. Sakiyama and K. Tanaka. This publication presented results of the Belgian Program "Scientific Research on the Antarctic" (Services of the Prime Minister - Science Policy Office). The scientific responsibility is assumed by its authors.

6. References

Børsting Pedersen L. (1977). Interpretation of Potential Field Data. A Generalized Inverse Approach. Geophysical Prospecting. Vol. 25. p. 199-230.

Decleir H., Nishio F., Ohmae H. (1988). A Comparison of Ice Thickness obtained by Radio Echo Sounding and Gravimetry in the Sør Rondane, Antarctica. Proceedings of the 9th Symposium on Polar Meteorology and Glaciology. National Institute of Polar Research. Tokyo.

De Vos L., Decleir H. (1988). Ice Thickness Profiles and Subglacial Relief in the Central Part of the Sor Rondane, Antarctica. Proceedings of the 9th Symposium on Polar Meteorology and Glaciology. National Institute of Polar Research. Tokyo.

Drewry D.J. (1984) Antarctic Glaciological and Geophysical Folio. Scott Polar Research Institute. Cambridge.

Mayewski P.A., Goldthwait R.P. (1985). Glacial Events in the Transantarctic Mountains : A Record of the East Antarctic Ice Sheet. Antarctic Research Series. Vol. 36. Paper 12, p. 275-324.

Telford W.M., Geldart L.P., Sheriff R.E. Keys D.A. (1976). Applied Geophysics. University Press. Cambridge.

Van Autenboer T. (1964). The Geomorphology and Glacial Geology of the Sør Rondane, Dronning Maud Land, Antarctica. Meded. Kon. Vl. Acad. Belgie. Kl. Wet., XXVI Nr.8. 91 p.

Van Autenboer T., Blaiklock K.V. (1966). Ice Flow and Thickness Measurements in the Sør Rondane, Dronning Maud Land, Antarctica. Journal of Glaciology. Vol. 6. Nr. 43. p. 69-81.

Van Autenboer T., Decleir H. (1974). Mass Transport Measurements in the Sør Rondane, Dronning Maud Land, Antarctica. Service Geol. de Belgique. Professional Paper Nr. 6. 25 p. Brussels.

Van Autenboer T., Decleir H. (1978) : Glacier Discharge in the Sør Rondane. A Contribution to the Mass Balance of Dronning Maud land, Antarctica. Zeitschrift f. Gletscherk. u. Glazialgeol. Bd. 14, H. 1, p. 1-16.