A Preliminary Study of Glacial Geomorphology in Area between Breid Bay and the Sør Rondane Mountains in Queen Maud Land, East Antarctica

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ブライド湾とセールロンダーネ山地間の氷床地形

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要旨：1983年2月12日から17日の期間，第23次および第24次南極地域観測隊は，セールロンダーネ山地における本格的な地球科学的調査の予備調査として，ブライド湾からセールロンダーネ山地の間の氷河地形学的調査を行った．その結果と過去のベルギー隊の得た結果を併せて下記のような推論を行った．

ブライド湾からセールロンダーネ山地の間の氷床は，セールロンダーネ山地によって内陸からのクィーンモードランド氷床流が阻止され，理論的に示される平衡氷床高度分布より著しく低く，セールロンダーネ山地の溢流氷河の涵養量は少ない．

ブライド湾周辺の棚氷の縁辺の形状は，1960年作成のベルギー隊の地図とほとんど変化がなく，同一形状の棚氷の位置の変位から棚氷の移動速度を求めると，北方へ56-126 m/a であった．1967年から1973年の間に旧ロア・ボードワン基地と棚氷の前縁との間に大きな断裂帯が形成されていたが，その原因は不明である．将来，この断裂帯が広くなり，ブライド湾の棚氷は氷山となって分離していく可能性が考えられる．

ブライド湾とセールロンダーネ山地の間の氷床の質量収支を近似的に求めた結果，この氷床の涵養源の一部は，現在の大量の積雪量であることが推定される．もし，現在の積雪量が著しく減少し，氷床表面高度の低下が発生すると，氷床の厚さが減じて現在の接地線 (grounding line) が後退するであろう．そして，氷床が氷山となって分離していく速さを加速するであろう．なぜならば，氷床底面は内陸深くセールロンダーネ山地近くまで海面下に位置すると考えられるからである．問題をはっきりさせるためには，氷床基盤の調査が重要である．

Abstract: During the period from 12 to 17 February 1983, a preliminary study of glacial geomorphology was carried out in the area between Breid Bay and the Sør Rondane Mountains by the 23rd and 24th Japanese Antarctic Research Expedition to implement earth science programs in the Sør Rondane Mountains.

The obstruction by the Sør Rondane Mountains to the ice flow is the cause of the elevated ice surface in the south of the mountains, and also the cause of the extremely low level in the north of the mountains, probably aided by the shelter effect of the mountains.

Outlines of the ice shelf front and the respective positions have indeed remained unchanged over twenty-three years, but the reentrant, a widely and deeply fractured

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zone, is formed in the ice shelf between the Base Roi Baudouin and the ice front. It was found that the reentrant was formed between 1967 and 1973, and further fracturing of the platform of this ice shelf may occur with the development of crevasses, and therefore the ice shelf may break off in not so far future.

A rough estimate of the mass budget of the ice sheet in the area between Breid Bay and the Sør Rondane Mountains suggests that the ice sheet may keep the present shape owing to the high accumulation rate over the ice sheet surface at present. If the present accumulation rate decreases, the lowering of the ice sheet surface may occur and, therefore, the thinning of the ice sheet may cause the retreat of grounding line, since most of the base of the ice sheet lies well below see level.

The detailed radio-echo sounding is essential for clarifying whether the ice sheet in this area is of a marine type or not. At least, it is grounding in the front of the ice shelf at present.

1. Introduction

The Princess Ragnhild Coast was discovered by ISACHSEN and RIISER-LARSEN in 1931, and a topographic map of "Princess Ragnhild Land" on a scale of 1:500 000 compiled from oblique air photographs was published by the Lars Christensen Expedition, Norway in 1936–1937. Thereafter, a map on a scale of 1:250 000, drawn on the basis of US Navy air photographs (Operation High Jump 1946/47), was published by the Norsk Polarinstitutt in 1957.

The Base Roi Baudouin (70°25′53″S, 24°18′38″E) was established by the Belgian Antarctic Expedition in 1958. The research program of the expedition included geological, gravitational and geodetic surveys, and these investigations dealt with the Sør Rondane Mountains approximately 200 km south of the Base Roi Baudouin. In addition, the glaciological survey in this area was conducted during the period between 1958 and 1961 by Belgian, and 1964 by Belgian-Dutch Antarctic Expedition (VAN AUTENBOER, 1964). Gravity and glacier movement surveys by the 1959–1960 Belgian, and 1965 Belgian-Dutch Expeditions led to the first estimate of the glacier discharge through the central part of the Sør Rondane Mountains (VAN AUTENBOER and BLAIKLOCK, 1966).

Subglacial topography determined by gravimeter profiles revealed that the floor of the main glaciers was below or close to sea level and the geomorphology of the Sør Rondane resembles an ice-covered fjord landscape. The Sør Rondane generally acts as a barrier and dams the flow of ice from the polar plateau. For the overall flow of the ice sheet, the drainage in the areas to the east and the west of the range, which are free from obstruction, is more important than the discharge through it. The low rate of discharge through the Sør Rondane Mountains might mean that the outlet glaciers in this area are fed by a comparatively small drainage basin (VAN AUTENBOER and DECLEIR, 1978).

In January 1961 a drilling to obtain ice specimens was undertaken at Base Roi Baudouin on the ice shelf of the Princess Ragnhild Coast. Detailed stratigraphic and morphological studies of the cores down to a depth of 115.72 m were made as well as chemical and isotopic investigations (TONGIORGI *et al.*, 1961). At that time core drillings in ice below a depth of 100 m were still rare in Antarctica. Only four drillings to a depth of 100 m were known. With respect to the core analyses, the first attempt was carried out with a view of establishing a direct correlation between the isotopic composition of a snowfall and its temperature of formation (PICCIOTTO *et al.*, 1960).

During the period from 12 to 17 February 1983, a preliminary study of glacial geomorphology was carried out by the 23rd and 24th Japanese Antarctic Research Expedition (JARE-23 and -24) in the area between Breid Bay and the Sør Rondane Mountains. The purpose of this study was to obtain some essential data for conducting main programs of earth sciences such as geology, geomorphology, geophysics, glaciology, meteorology and meteorite search in the near future in the area of the Sør Rondane Mountains.

2. Field Work

A reconnaissance survey of glacial geomorphology in the area from Breid Bay (70°S, 24°E) forward to the Sør Rondane Mountains was carried out by various methods to be described below from 12 to 17 February 1983. Morphology of the ice shelf

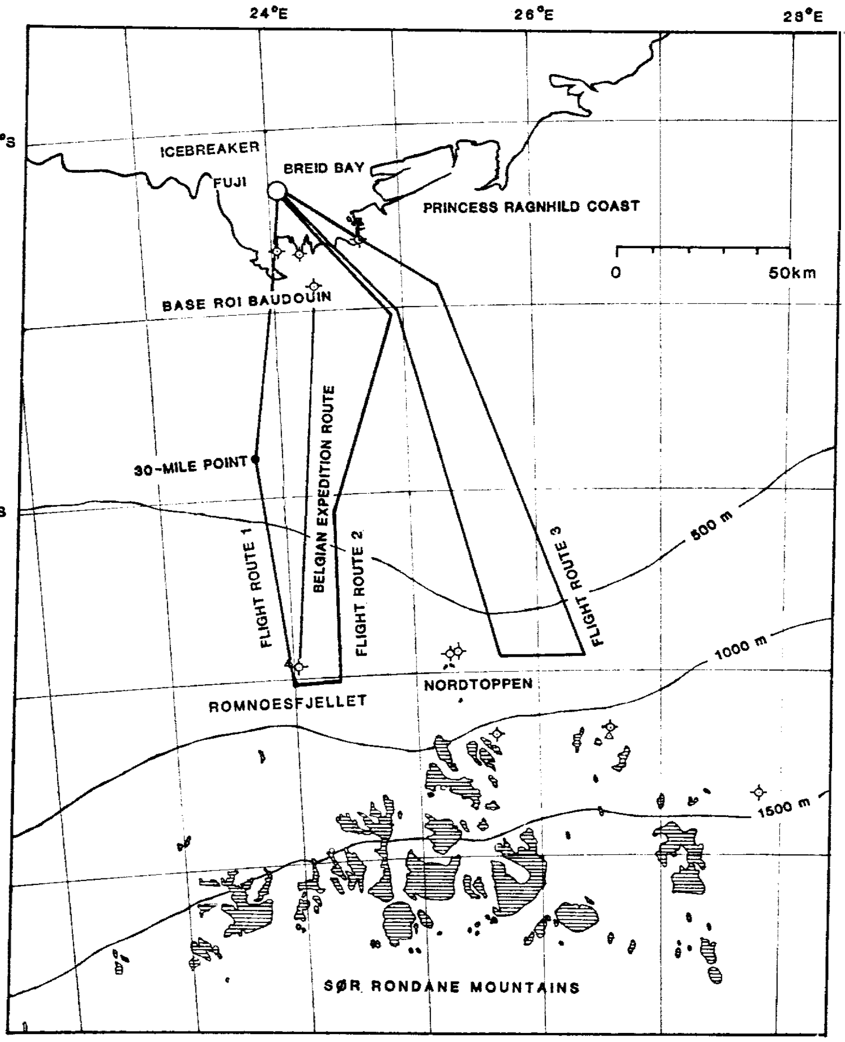

Fig. 1. Helicopter flight routes to observe surface elevation and morphological features with four flight lines from Breid Bay to 71.5°S.

edge in Breid Bay was obtained from oblique air photographs and depicted by radar sounding from icebreaker FUJI of which the location was determined by the satellite doppler positioning system. Four flight lines from Breid Bay to 71.5°S as shown in Fig. 1 were taken to observe the morphological features and surface elevation of the ice sheet using the radar altimeter of a helicopter carried by icebreaker FUJI.

Profiles of ice surface elevation along the helicopter flight routes were obtained by using both the barometric altimeter reading at every 30 s during the flight and the air-borne radar altimeter which was used to keep a constant altitude of about 300 m above the snow surface.

At about 55.6 km (70°53′13.6″S, 23°47′06.6″E; elevation 370 m) from the ice shelf edge as named 30-mile point in Fig. 1, the reading of the air-borne barometric altimeter was compared with that of geodetic survey, and it was found that the difference between them was 11 m. At the 30-mile point the surface snow study was made to estimate the accumulation rate of snow from the stratigraphy of ice cores. When weather did not permit reconnaissance flight by helicopter in the inland ice sheet area, sonic echo sounding in Breid Bay was carried out from FUJI to depict a submarine topographic map. This submarine topography was compared with the map published by the Belgian Antarctic Expedition (VAN AUTENBOER, personal communication).

3. Ice Sheet

3.1. Ice sheet of Queen Maud Land

The Sør Rondane Mountains are part of the coastal mountains of Queen Maud Land extending between 15°W and 30°E. These mountain ranges make the northern limit of a still undefined and largely unexplored drainage system in the East Antarctic ice sheet. The southeastern limit of this system apparently corresponds to the northern part of the East Antarctic divide which trends from the southeast to the northwest in Queen Maud Land and locally culminates at 3700 m in the Fuji Divide (tentative) (77°40′S, 42°E) (FUJIWARA *et al.*, 1971). However, the culminant location in Queen Maud Land is shifted to the west by a few hundred kilometers as shown in Fig. 2. Figure 2 indicates the detailed surface contour map of the East Queen Maud Land drainage system drawn from the data obtained by balloon-borne radar altimeters (LEVANON, personal communication). Although little is known about the limits of the drainage system and available data on the subglacial relief in the Queen Maud Land are lacking, the surface elevation map (LEVANON, 1982) suggests that a large part of the continental ice sheet in Queen Maud Land flows towards the Weddell Sea and the Filchner Ice Shelf. This indicates that an ice divide, situated in the unexplored area which locally culminates at about 3700 m in Fig. 2, forms the southern limit of the basin feeding the outlet glaciers of East Queen Maud Land.

In Fig. 2 the drainage system could be divided; a) Shirase Glacier drainage system, b) Belgica drainage system, c) Sør Rondane drainage system. The bald solid lines indicate the ice divide drawn along the ridge of surface elevation. The broken lines drawn perpendicular to the surface contour from the culminants are assumed to be stream lines of ice flow. Profiles of surface elevation along those broken lines in the respective drainage systems are shown in Fig. 3 in which the equilibrium shapes of the

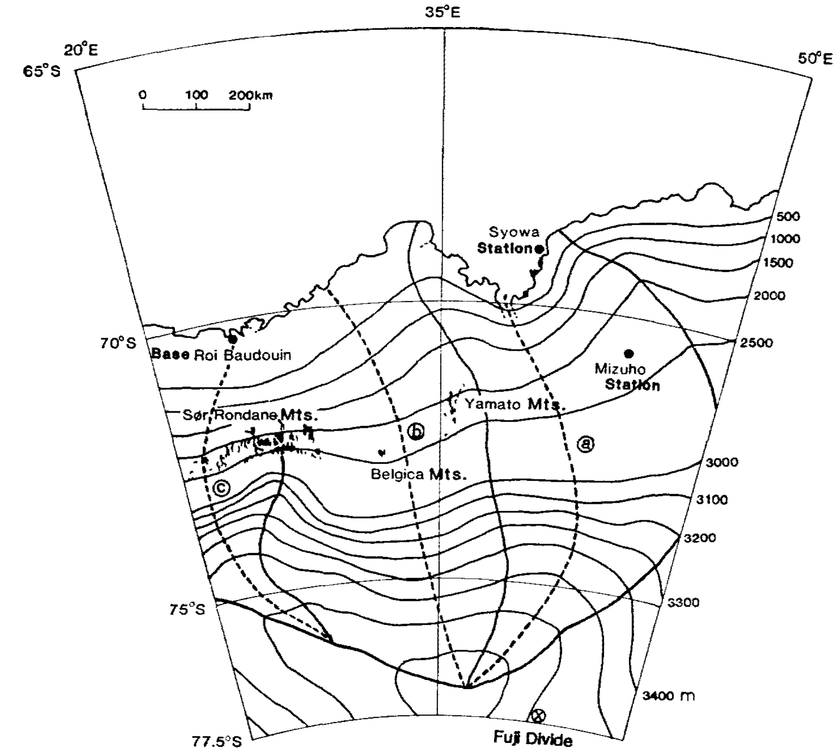

Fig. 2. Surface contour map of the East Queen Maud Land area obtained by balloon-borne radar altimeters (LEVANON, personal communication). The solid lines indicate the ice divide of subdrainage system of East Queen Maud Land and along the broken line and the profile of ice sheet is drawn in Fig. 3.

ice sheet predicted by WEERTMAN's equation (WEERTMAN, 1961) are shown by broken lines. It was suggested that the Shirase Glacier is in an unstable state since it flows very fast and the thinning of ice sheet is caused by basal sliding (MAE and NARUSE, 1978). The basal shear stresses along the flow line show high values of about 1.8 bar in the lower part of the Shirase Glacier and this means that the Shirase Glacier might be in a state of pre-surging according to ROBIN's theory (ROBIN and WEERTMAN, 1973). In the Belgica drainage basin, the surface elevation is lowered compared with the theoretical profile (broken line in Fig. 3) even though there are the Yamato Mountains and the Belgica Mountains. The Sør Rondane Mountains, as the other coastal mountains in Queen Maud Land, are more or less perpendicular to the main flow of ice from the continental ice sheet, and, therefore, they exhibit a damming effect to the ice flow by the proximity of many peaks. The general orientation of the ice flow in the Sør Rondane area is from the southeast to the northwest (VAN AUTENBOER and BLAIKLOCK, 1966). The damming effect is clearly illustrated in Fig. 3. The mountains' obstruction to the ice flow caused the elevated surface of ice in the south side of the mountains and the lowered surface in the north side. Existence of an undisturbed, crevasse-free zone extending northwards from Romnoesfjellet to the coast has resulted from the damming effect and also seems to be related to the shelter effect of the mountains.

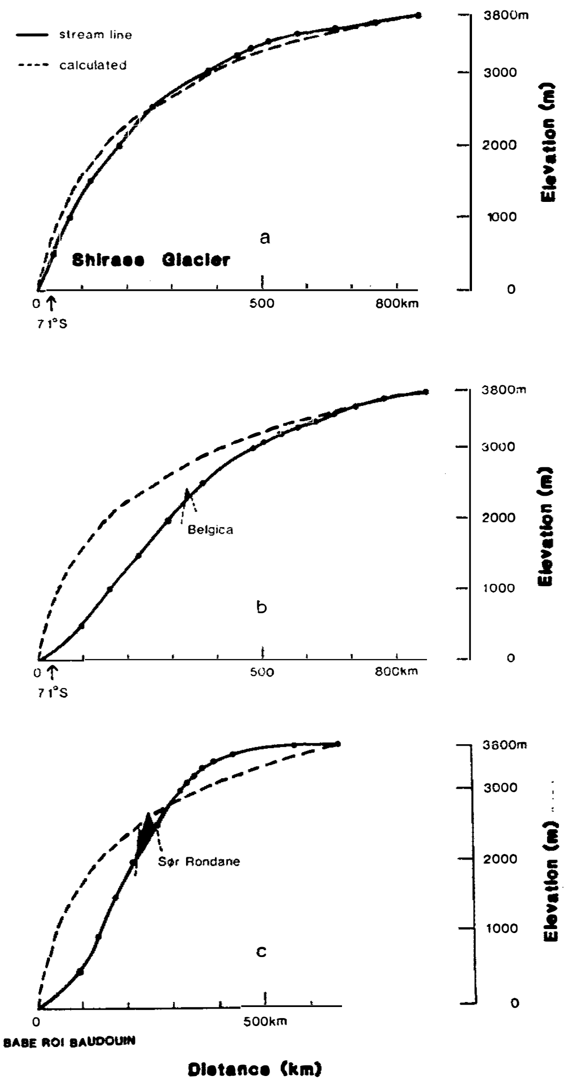

Fig. 3. Profile of ice sheet surface; a) Shirase Glacier drainage system, b) Belgica drainage system, c) Sør Rondane drainage system, compared with the theoretical profile (WEERTMAN, 1961). The solid line indicates the profile of surface contour along the stream line as shown in Fig. 2. The broken line is the theoretical profile calculated with the equation based upon the steady state.

3.2. Surface topography and surface features in the area between Breid Bay and the Sør Rondane Mountains

As mentioned in the previous subsection, the ice sheet in the area between Breid Bay and the Sør Rondane Mountains is fed by the outlet glaciers with a low rate of discharge through the Sør Rondane Mountains, and the profile of the ice sheet in this area, therefore, depends upon the rate of the discharge through the outlet glaciers.

Figure 4 shows the profiles of ice surface elevation along four helicopter flight routes as shown in Fig. 1 and also that obtained by the Belgian Antarctic Expedition in March 1958 from the Base Roi Baudouin to Romnoesfjellet. On the line from the Base Roi Baudouin to Romnoesfjellet, the profile shows a steadily rising and gently

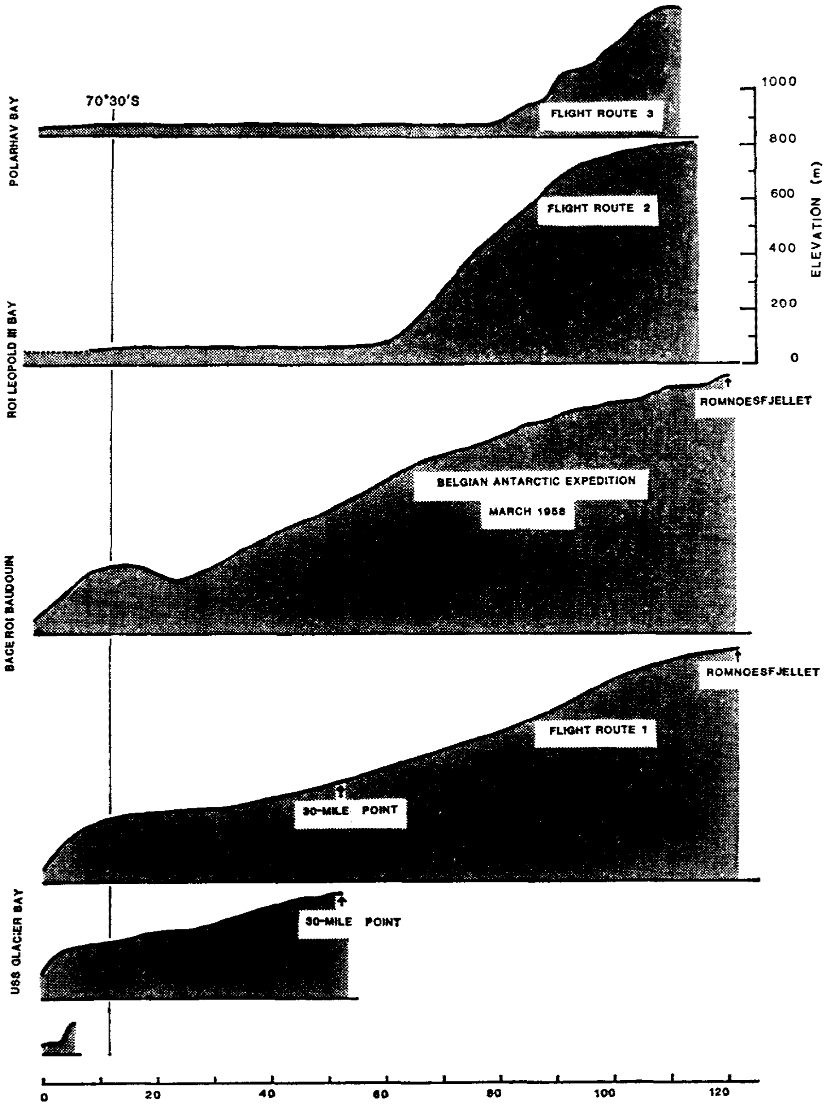

Fig. 4. Profiles of ice sheet surface along the helicopter flight routes (Fig. 1) by the Belgian Antarctic Expedition in March 1958 from the Base Roi Baudouin to Romnoesfjellet.

undulating slope, while the surface elevation to the east of this zone along flight routes 2 and 3 exhibit almost a flat shape from the ice shelf edge to the inland area, and it shows an abrupt steepening.

Figure 5 shows the distribution of blue ice fields and the surface features of the ice sheet in the area from Breid Bay on the Princess Ragnhild Coast to the Sør Rondane Mountains. On the line from the Base Roi Baudouin to Romnoesfjellet, no crevasses other than the ones at the foot of ice rise south of the Base Roi Baudouin have been observed, while to the east of this zone, snow-free and seracced areas have been seen from helicopter. This is probably a narrow zone with reduced movement protected by the Sør Rondane Mountains. The seracced areas to the east of this crevasse-free zone are formed by the contact between the more actively flowing zones of ice streams from the east side of the mountains.

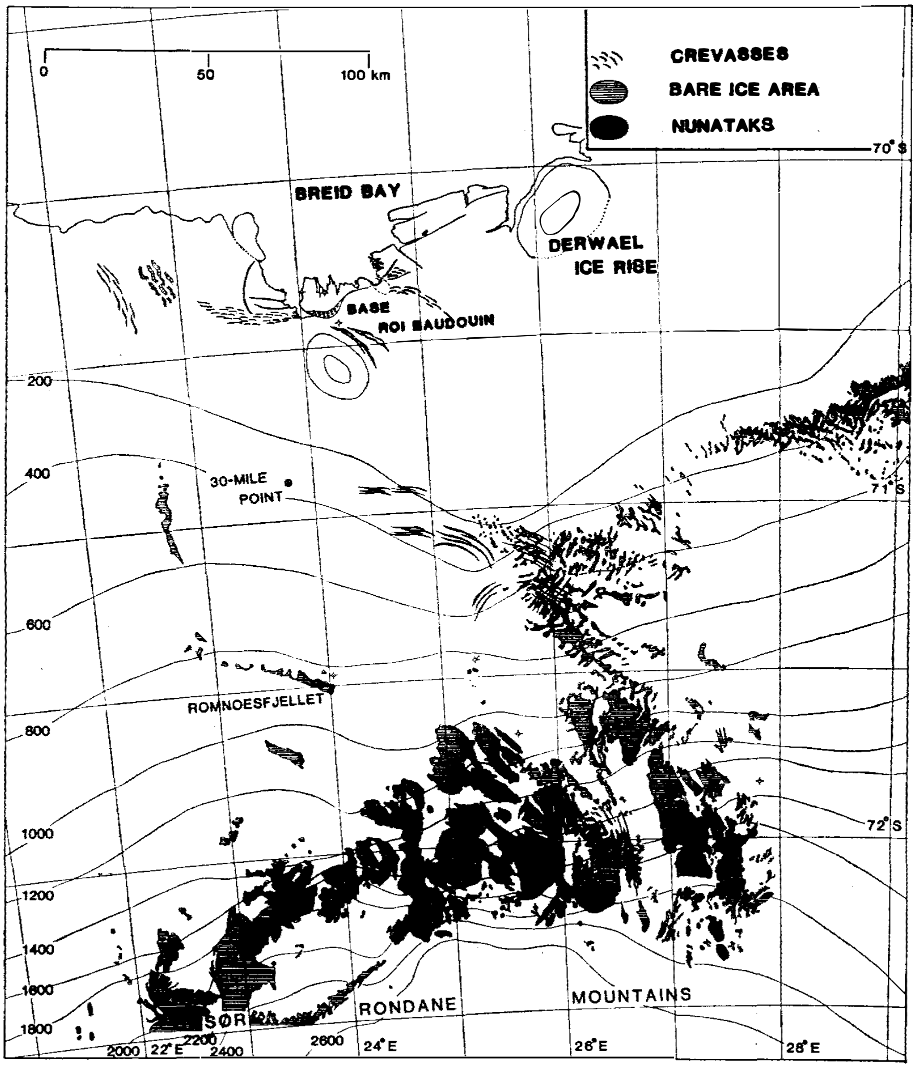

Fig. 5. Distribution of blue ice fields and surface features on the ice sheet in the area from Breid Bay on the Princess Ragnhild Coast to the Sør Rondane Mountains.

The approximate distribution of blue ice fields is shown in Fig. 5 as identified from the Landsat imagery taken in 1973. The shaded areas show the blue ice fields on the ice sheet and the dark areas indicate the exposed land area. The blue ice is widely distributed in the Sør Rondane Mountains, and from the northeastern area of the range towards the Riiser-Larsen Peninsula. The extensive blue ice fields are also existing in the upstream or south of the mountain range, and they indicate that the ice flow towards the mountain range should be forced to make an upward movement in the neighborhood of the mountains. Therefore, we may expect that a large number of meteorites could be found there as were the cases in the blue ice fields near the Yamato Mountains. It is also anticipated from the distribution of blue ice areas that the sub-ice mountains are existing under the blue ice area from the northeastern part of the Sør Rondane Mountains towards the Riiser-Larsen Peninsula.

3.3. Subglacial topography

Information about the thickness of ice as well as the subglacial topography is at

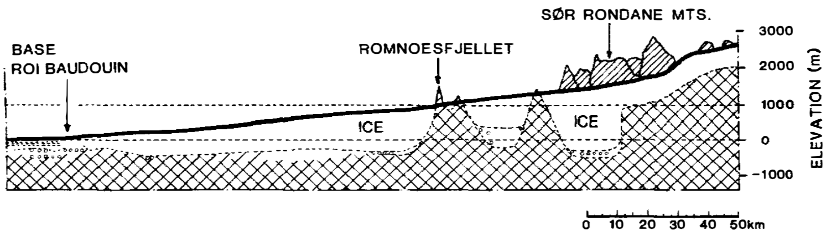

Fig. 6. Profiles of ice sheet surface and subglacial topography determined by gravimeter measurements (VAN AUTENBOER, 1964).

present restricted to a few gravimeter profiles and a couple of seismic depth determinations (VAN AUTENBOER and DECLEIR, 1978). The ice thickness was determined by gravity measurements along the surveyed line from the Base Roi Baudouin to the polar plateau through Romnoesfjellet (VAN AUTENBOER, 1964). Figure 6 reproduced from AUTENBOER's paper shows that the surface elevation is gradually increasing and most of the base of ice sheet lies well below sea level, that is, the ice sheet is grounding. It is also clear that the Sør Rondane Mountains with floor of the main glaciers below or close to sea level has a landscape which resembles an ice-covered fjord. Furthermore, there are indications that the glacier valleys are deepest at the foot of slopes rising to the polar plateau and become shallower to the north, underneath the progressively diverging flow. This local overdeepening is characteristic of fjord valleys (VAN AUTENBOER and DECLEIR, 1978).

4. Ice Shelf

Certain information on the change of the ice shelf in Breid Bay in a long period can be obtained by a comparison between the Norwegian map of 1937 and the Belgian map of 1960, and further by comparisons of these maps with the change of the ice

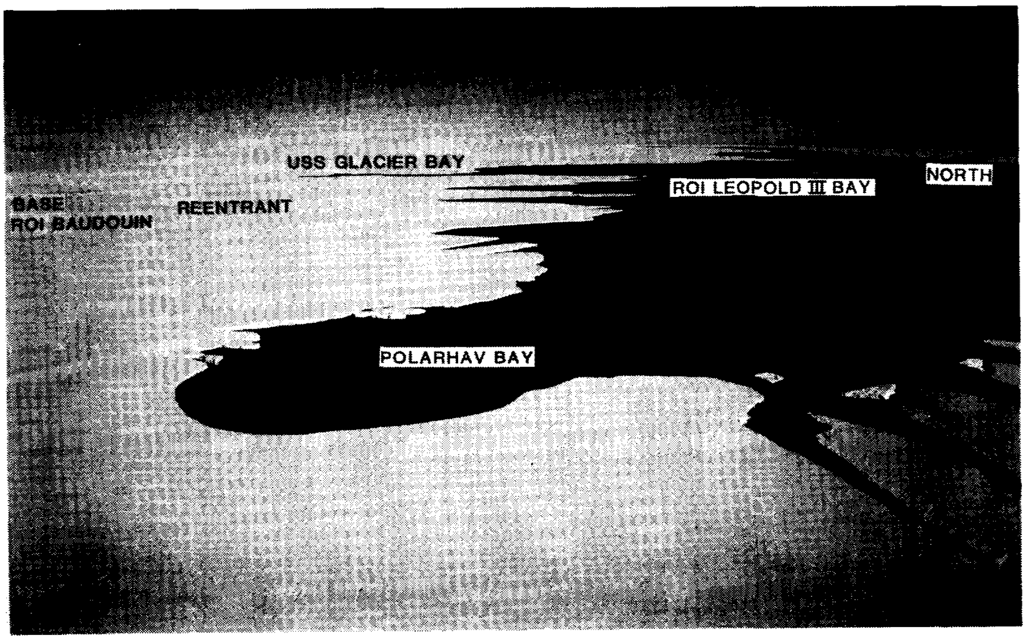

Fig. 7. Coastal feature of ice shelf in Breid Bay viewing to the west from air photograph taken on 12 February 1982.

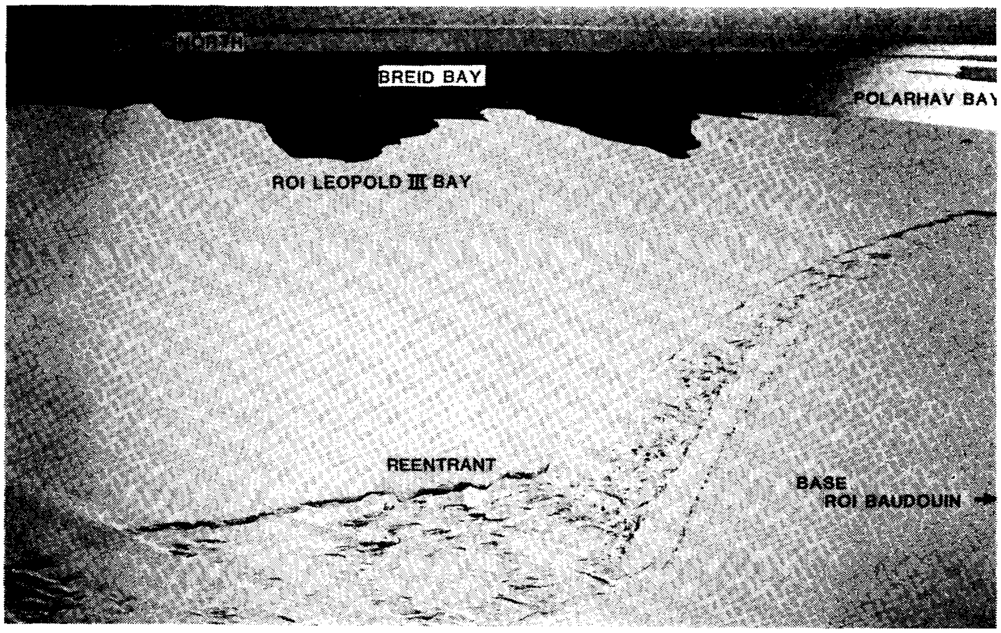

Fig. 8. Coastal feature of ice shelf of Roi Leopold III Bay and Polarhav Bay in Breid Bay, and reentrant (widely and deeply fractured zone) viewing to the northeast from air photograph taken on 12 February 1982.

shelf edge depicted by our oblique air photographs taken from a helicopter and by the radar sounding from Icebreaker Fuji. The oblique air photographs taken on 12 February 1983 are shown in Figs. 7 and 8. The similarity between the present coastline and that of twenty-three years ago on the Belgian map (Fig. 10) is most striking. The most distinctive features on the coast line can be clearly recognized on the both. The different feature appeared in the present ice shelf, not shown in the Belgian map, is the reentrant (widely and deeply fractured zone) formed between the Base Roi Baudouin and the ice shelf edge.

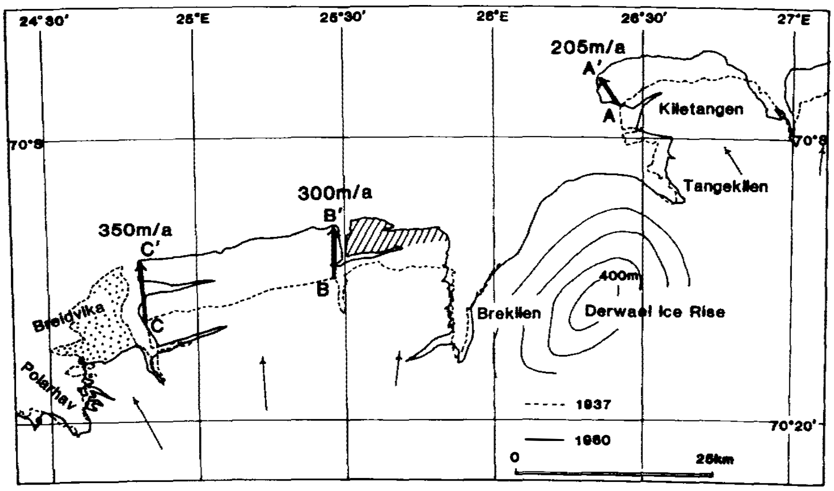

Fig. 9. Comparison of ice shelf between the 1937 Norwegian and 1960 Belgian maps and horizontal movement of the ice shelf front. The dotted area of large promontory to the northeast of Polarhav Bay broke off and disappeared between 1937 and 1960. The hatched area broke off and disappeared between January 1960 and January 1961 (Van Autenboer, 1964).

4.1. Change of ice shelf edge between 1937 and 1960

Figure 9 shows the 1937 map superposed on the 1960 one (VAN AUTENBOER, 1964). This figure allows a direct comparison of the respective positions of the two ice fronts. Although a large promontory of about 25 km² in area, to the northeast of Polarhav Bay (dashed area in Fig. 9) was completely broken off and disappeared, the head of Polarhav exhibits a fixed feature which may indicate that the ice sheet is grounding. A wide rectangular platform between this promontory and Brekilen is a distinct feature on both maps. The maximum horizontal movement has taken place in the central area of this platform, and also around Kiletangen at the eastern end of the map. The northward movements are estimated at 350, 300 and 205 m/a from the map. The smooth rounded cape between Brekilen and Tangekilen is an unchanged crevasse-free coastline formed on the northern slope of the Derwael Ice Rise.

4.2. Change of ice shelf edge between 1960 and 1983

The heavily indented coastlines such as USS Glacier, Roi Leopold III and Polarhav Bay, surrounded by ice cliffs of 10–30 m in height, as shown in the 1960 Belgian map, are still visible in Figs. 7 and 8. The coastlines of both the 1960 Belgian map

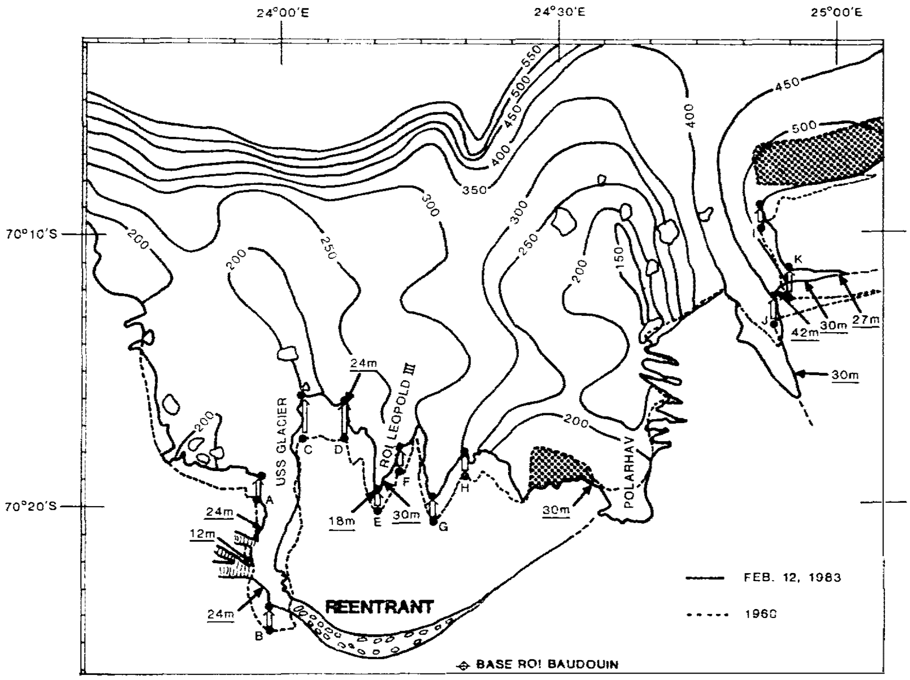

Fig. 10. Comparison of ice shelf between the 1960 Belgian map and the ice shelf edge measured from icebreaker FUJI on 12 February 1983. The reentrant, a widely and deeply fractured zone, is formed between the Base Roi Baudouin and the ice shelf edge, and is running from USS Glacier Bay to Polarhav Bay. The white grounded arrows show the movement of ice shelf of which velocities are tabulated in Table 1. The solid arrows indicate the height of ice cliff above sea level measured by the radar altimeter equipped on helicopter. The hatched area broke off and disappeared. The contour of submarine topography in Breid Bay is depicted from the sonic echo sounding by icebreaker FUJI and the Belgian Antarctic Expedition (VAN AUTENBOER, personal communication).

Table 1. The northward velocity of ice shelf edge in Breid Bay indicated by the white grounded arrows in Fig. 10 between the 1960 Belgian map and the ice shelf edge measured by icebreaker FUJI on 12 February 1983.

Point on ice shelf	Annual northward velocity	Remarks
A	63 $m \cdot a^{-1}$	USS Glacier Bay
B	70	USS Glacier Bay
C	126	USS Glacier Bay
D	112	Roi Leopold III Bay
E	63	Roi Leopold III Bay
F	70	Roi Leopold III Bay
G	70	
H	63	
I	56	
J	84	
K	91	

and our surveyed edge of ice shelf in 1983, after a slight scale adjustment, are shown in Fig. 10. The horizontal movements of the ice shelf edge were obtained by a direct comparison of the respective positions of the two ice fronts. The movements of the ice shelf edge at the respective points are northwards and ranging from 56 to 126 $m \cdot a^{-1}$ as tabulated in Table 1, while at the Base Roi Baudouin the horizontal movement of the ice shelf measured by the Belgian expedition was very small; the northward displacement component probably not exceeding 50 $m \cdot a^{-1}$ (VAN AUTENBOER and DECLEIR, 1978).

In Fig. 9 the northward movements of the ice shelf at a place indicated by C-C′ was 350 $m \cdot a^{-1}$ between 1937 and 1960, but the northward velocities measured at several points I, J, K in Fig. 10 (also see Table 1) at the same place between 1960 and 1983 were 56 to 91 $m \cdot a^{-1}$. The hatched area in the west and northeast of Polarhav Bay broke off and disappeared between the 1960 Belgian map and 12 February 1983.

Although outlines of the ice shelf front and the respective positions have indeed remained unchanged over twenty-three years, the reentrant, a widely and deeply fractured zone, has been formed in the ice shelf between the Base Roi Baudouin and the ice front. The reentrant, starting from USS Glacier Bay with a width of a few kilometers is running to Polarhav Bay gradually decreasing in width as seen in Fig. 8. This reentrant was not recorded in 1967 when the Belgian Antarctic Expedition traversed with oversnow vehicle between the Base Roi Baudouin and USS Glacier Bay. However, the present reentrant was seen in the Landsat imagery taken in November 1973. So the reentrant must have been formed between 1967 and 1973. Even though the reason of the reentrant formation is not clear as yet, at present, further fracturing of the ice platform may occur with the development of the reentrant, and consequently, the large ice shelf may break off.

In Fig. 10, the solid arrow indicates the height of the ice cliff measured by the radar altimeter equipped on helicopter. Then, the ice thickness d of the floating ice shelf can be estimated by the following equation:

$$d = h \cdot \rho_w / (\rho_w - \rho_i) \qquad \cdots\cdots\cdots \quad (1)$$

where h is the height of the ice cliff above the sea level, ρ_w the density of sea water (1.03 g/cm^3), and ρ_i the mean density of the ice shelf (0.90 g/cm^3). Since the ice thickness is approximately 8 times of the height of the ice cliff, according to eq. (1), the ice shelves of USS Glacier and Roi Leopold III Bay must be locally grounded (see the depth contour obtained by icebreaker FUJI in Fig. 10), but the ice shelf near Polarhav Bay to be 240 m thick must be completely grounded. This is consistent with the fact that the ice front of Polarhav Bay is unchanged.

4.3. Discharge of ice shelf

Annual discharge of the ice shelf in Breid Bay and that between the promontory of Polarhav Bay and the Derwael Ice Rise (see Fig. 11) were calculated using the above ice thickness of floating ice shelves and the northward velocity obtained by the com-

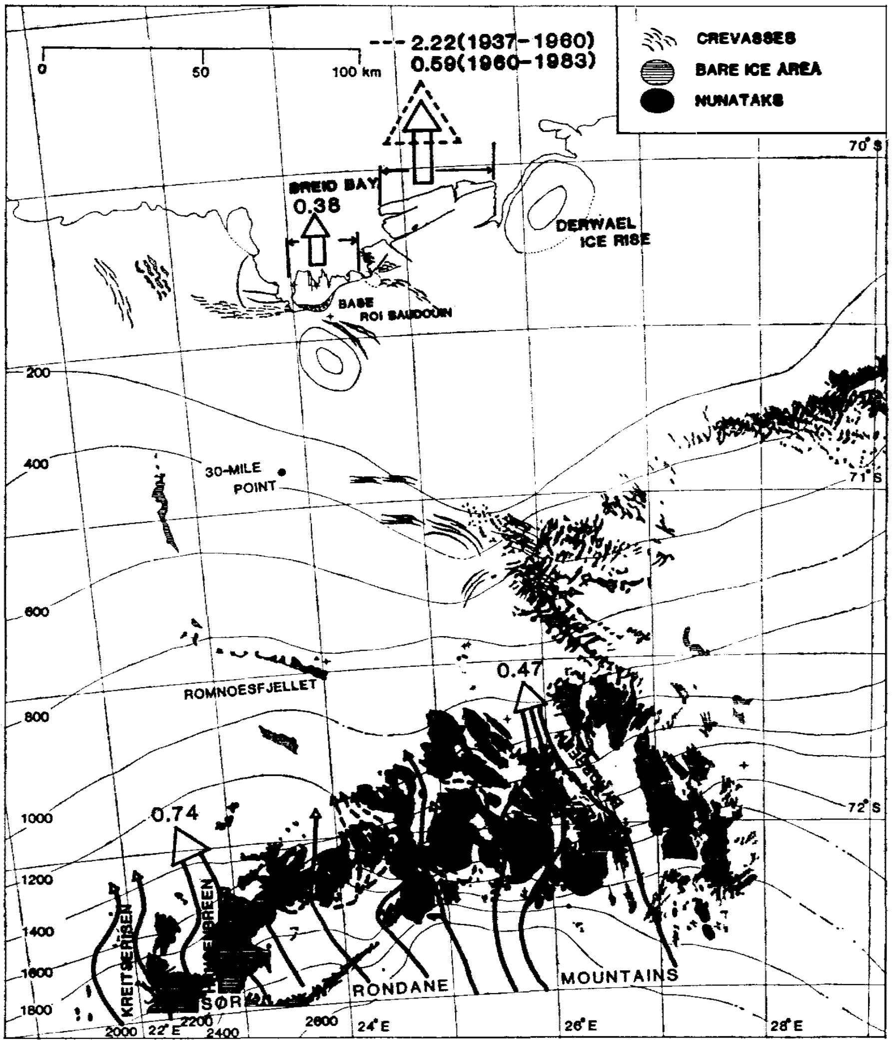

Fig. 11. Schematic representation of discharges from Breid Bay between 1960 and 1983, and the measured discharges through the Sør Rondane Glacier flow on drainage glaciers are indicated by full lines (VAN AUTENBOER and DECLEIR, 1978). The flow pattern on local glaciers is given by dashed lines. The numerals with arrow indicate the rate of discharge in unit km^3·a^{-1}.

parison of displacement of the ice shelf front. It is assumed that the average ice discharge per year along the long front of the ice shelf of Breid Bay (24 km), and that between the promontory of Polarhav Bay and the Derwael Ice Rise (37 km) both measured by the movement of the front is equal to the annual discharge of the ice shelf, neglecting a small amount of broken front of icebergs.

Figure 11 is a schematic representation of annual ice discharges from Breid Bay between 1960 and 1983. The numerals with arrow indicate the ice discharge in unit of km^3 per year. In Fig. 11, the measured discharges through the Sør Rondane drainage glaciers are shown by full lines, and the flow pattern on local glaciers is given by dashed lines (VAN AUTENBOER and DECLEIR, 1978). Total discharge through the entire section of the Sør Rondane Glacier is calculated as 1.5988 $km^3 \cdot a^{-1}$ (VAN AUTENBOER and DECLEIR, 1978). If we assume that the flow lines below the Sør Rondane Mountains are almost parallel and the glacier flow through the section of 220 km of the total width of the Sør Rondane Mountains feeds the locally grounded ice shelf which extends with the same 220 km width along the Princes Ragnhild Coast, the dis charge of 0.38 $km^3 \cdot a^{-1}$ for 24 km in Breid Bay gives the total discharge 3.48 $km^3 \cdot a^{-1}$ through the entire width of the ice shelf This value is about two times higher than the ice discharge through the Sør Rondane Mountains estimated above. Therefore, if the equilibrium state is established, the deficit of ice mass must be covered by high snow accumulation in the area between the mountain and the coast, and the average annual value of snow accumulation can be estimated at about 4 cm in ice. Otherwise, the lowering of the ice sheet surface in the area will occur. The low rate of discharge through the Sør Rondane Mountains might mean that the outlet glaciers in this area are fed by a comparatively small drainage basin on the plateau (VAN AUTENBOER and DECLEIR, 1978).

5. Accumulation

For the purpose of estimating the recent snow accumulation in the area as mentioned in the preceding section, the shallow ice coring down to a depth of 6 m was made at the 30-mile point. A preliminary stratigraphic profile is presented in Fig. 12. The horizontal stratification is marked by variations of firn grain sizes, ice layers and ice lenses produced by summer melting. Seasonal alternations are often discernible. Summer layers are characterized by larger grains, and by the presence of ice in impregnation, in strata or in lenses.

These seasonal alternations are clearly perceptible for the last eleven years and make it possible to calculate the annual accumulation values in snow as tabulated in Table 2 for the years between 1972 and 1983, with the average annual accumulation 47 cm in snow. Snow temperature in the borehole is also shown in Fig. 12 and the annual snow temperature at a 10-m depth is estimated as $-16°C$.

At the Base Roi Baudouin the average annual accumulation was estimated at 38.3 cm/a in water equivalent for the years between 1954 and 1959 according to the stratigraphic profile of the ice cores (TONGIORGI *et al.*, 1961). On the other hand, occasional accumulation measurements were made by the snow stake method in the Sør Rondane Glaciers by the Belgian expeditions, obtaining a few tens of cm in snow

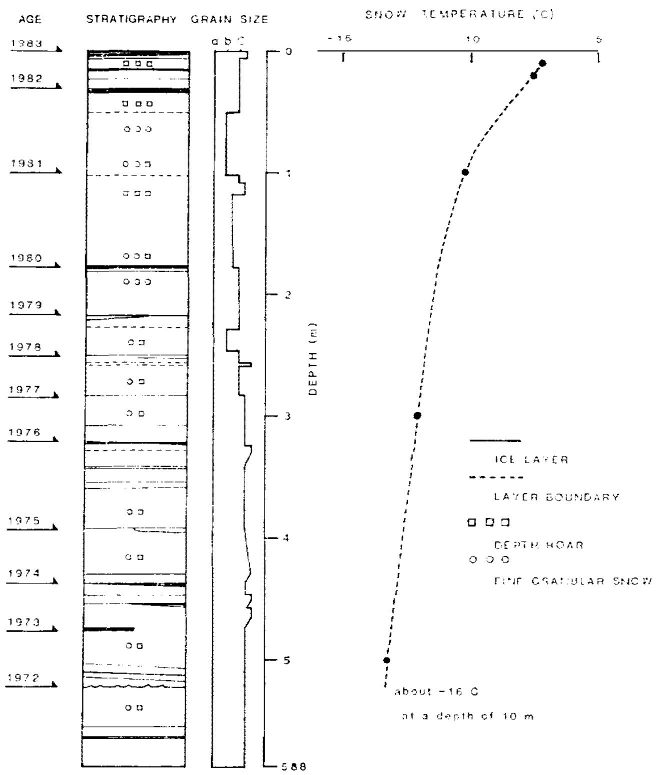

Fig. 12. Stratigraphic profile of ice core at the 30-mile point.

Table 2. Annual snow accumulation for a period from 1983 to 1972 at the 30-mile point.

Year	Depth in snow
1972–73	46 cm
73–74	38
74–75	44
75–76	72
76–77	36
77–78	34
78–79	34
79–80	38
80–81	78
81–82	70
82–83	30
Average	47

per year, while the ablation was measured on the blue ice fields. It is inferable that the high accumulation rate in the coastal region gradually decreases in the direction towards the Sør Rondane Mountains.

6. Submarine Topography in Breid Bay

A submarine topographic map of Breid Bay and the neighboring area on a scale of 1:3 200 000 was depicted by the Belgian Antarctic Experition (VAN AUTENBOER, personal communication). With reference to the Belgian map of submarine topog-

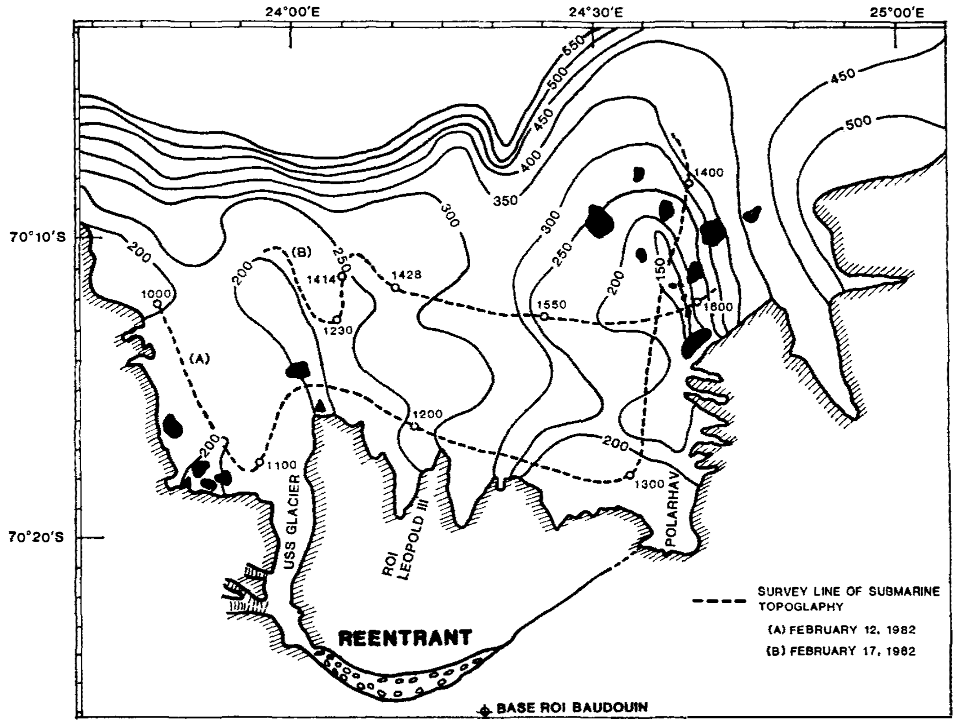

Fig. 13. Submarine topography in Breid Bay on the basis of the Belgian bathymetric chart and the sonic echo sounding by icebreaker FUJI *in 1983. Contour interval is 50 m. Solid area indicates the iceberg and the dotted line is the survey line of sonic echo sounding in Fig. 14.*

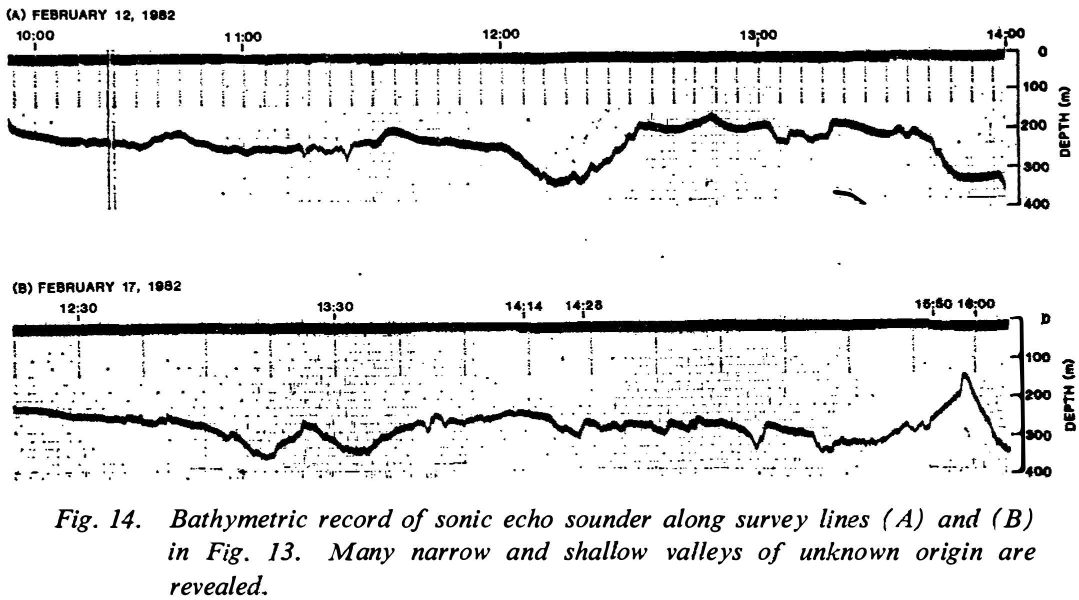

Fig. 14. Bathymetric record of sonic echo sounder along survey lines (A) and (B) in Fig. 13. Many narrow and shallow valleys of unknown origin are revealed.

raphy, sonic echo sounding was carried out from FUJI on four survey lines from the west to the east in Breid Bay. The survey line (dotted line in Fig. 13) designated by (A) is to clarify whether the ice shelf is grounded or not. The contours of submarine topography were drawn on the basis of the Belgian map, after a slight modification by the present sonic echo sounding.

The continental shelf off Breid Bay is extending from east to west with the depth of the edge approximately 350 m. On the shelf, there appear two ridges extending from the promontory of Polarhav Bay and the east side of USS Glacier Bay. These ridges 150–200 m deep are consistent with the existence of the ground icebergs broken off from the ice shelf and with the extension of the ice shelf to the north along the unchanged peripheries, which proves that the grounding of the ice shelf is obstructing the calving.

Figure 14 shows the bathymetric record of sonic echo sounder along the survey lines of (A) and (B) in Fig. 13. The bathymetry lines were run from west to east approximately perpendicular to the movement of the ice shelf. The record shows that no remarkable submarine valley of glacial origin has been developed, although the presence of many narrow valleys of unknown origin is observed.

7. Discussion

On the basis of the measurements of the height of the ice shelf edge in Breid Bay and the submarine topographic map, the annual ice discharge from Breid Bay was calculated as approximately 0.38 $km^3 \cdot a^{-1}$ between 1960 and 1983, while the discharge of floating ice shelf between the promontory of Polarhav and the Derwael Ice Rise was estimated at 2.22 $km^3 \cdot a^{-1}$ in the period of 1937–60 and 0.59 $km^3 \cdot a^{-1}$ in 1960–83 as shown in Fig. 11. Assuming that the rate of discharge through the periphery of locally grounded ice shelf is 0.38 $km^3 \cdot a^{-1}$ with the width of 24 km in Breid Bay, the discharge of the long section of 220 km through the periphery of the ice shelf on the Princess Ragnhild Coast is calculated as 3.48 $km^3 \cdot a^{-1}$. The ice discharge of 3.48 $km^3 \cdot a^{-1}$ is about two times higher than the ice discharge fed by the Sør Rondane Glacier of the same 220 km width. If the ice mass in the area between Breid Bay and the Sør Rondane Mountains is fed by the Sør Rondane drainage system, the deficit of mass budget must be attributed to heavy snow accumulation in the area, but information on the amount is still to be collected.

If the snow accumulation is not sufficient to make up for the deficit, the lowering of ice sheet surface may occur in the area between the Sør Rondane Mountains and Breid Bay. And then, the thinning of the ice sheet may cause the retreat of grounding line and the ice shelf may break off more frequently than in the present time. Since it is known that most of the base of ice sheet lies well below the sea level, almost the entire part of the ice sheet in the area is grounded at present. Average annual accumulation at Roi Baudouin was estimated at 38.3 $cm \cdot a^{-1}$ in water equivalent and average snow accumulation at the 30-mile point is 47 cm in snow. The occasional snow accumulation measurements in the vicinity of the Sør Rondane Mountains show a few tens of cm in snow. Thus, the high accumulation rate shows the surplus mass budget in the area between Breid Bay and the Sør Rondane Mountains. Future work on the correct estimate of the mass budget will show us the stability of the ice sheet in the area between Breid Bay and the Sør Rondane Mountains in relation to the ice discharge through the Sør Rondane Glacier and snow accumulation over the ice sheet surface.

It is very much desirable to obtain more accurate mass budget, more accumulation measurements, preferably over a number of years, ice sheet elevation profile and fluctuation of ice shelf edge. The radio-echo sounding will be a powerful tool to get information on the bedrock topography which is of essential importance for evaluating the mass balance.

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