Landforms of the Balchenfjella Area, the Sør Rondane, East Antarctica

Masamu ANIYA*

東南極セールロンダーネ山地バルヒェン山とその周辺のヌナタックの地形

安 仁 屋 政 武*

要旨：東南極セールロンダーネ山地の東端に位置するバルヒェン山とその周辺のヌナタックの地形について，バルヒェン山では現地調査と空中写真判読から作成した地形学図を，主なヌナタックについては空中写真のステレオグラムを使って記載した．ヌナタックは周辺の大陸氷床よりも高くそびえ，その多くはおもに山岳氷河の侵食による起伏の大きい景観を呈しているが，バルヒェン山は大陸氷床の侵食による，全体に起伏の緩い滑らかな地形である．またバルヒェン山の大部分は周辺の氷床より低く，その地形的な特徴と相まってセールロンダーネ山地では特異な地域となっている．

いくつかのヌナタックとバルヒェン山の東面は，風化した物質が載る斜面と新鮮な基盤岩の斜面が上下にきれいに分かれており，最近大陸氷床が数 10m 低下したことを示している．バルヒェン山では，風化した erratics や tills が広域にわたって新鮮な基盤の上に堆積している．これは，過去に周辺の大陸氷床から流れ下ってきた氷舌がこの付近で合流し，消耗したからと考えられる．これらの風化基盤と風化堆積物の分布に基づき解氷過程が推定され，バルヒェン山の西面が標高が低いにもかかわらず一番早く氷から開放され，東面が標高が高いにもかかわらず一番新しいと判断された．

最後に，解氷後の風化・侵食・堆積プロセスの作用とそれらによって作られる地形・地表状態について考察し表にまとめた．さらに，バルヒェン山やヌナタックではどのような地形・地表状態が分布するかを表にして，相対的な新旧が比較できるようにした．

***Abstract*:** Landforms of Balchenfjella (Balchen Mountain) and nunataks near it in the Sør Rondane, East Antarctica, were described using a geomorphological map compiled from field work and aerial photographic interpretation for Balchenfjella and aerial photographic stereograms for major nunataks. While the nunataks are in general standing out above the general surrounding ice surfaces and many of them show landforms of alpine glacier origin, Balchenfjella is characterized by landforms of areal scouring owing to continental ice-sheet glaciation and most of the area still lies below the surrounding ice surface. In this regard, Balchenfjella is found to be very unique in the Sør Rondane.

Distinctive demarcation lines between the surfaces of weathered materials and fresh bedrocks found at the eastern side of the several nunataks and Balchenfjella suggest a recent lowering of the ice-sheet surface by several tens of meters. Wide covers of weathered erratics and/or tills over Balchenfjella indicate that the mountain was once covered by ice tongues spilling and closing in from surrounding sides and ablation was very extensive there.

Based on the spatial distribution of weathered materials, the relative deglaciation sequence was inferred for Balchenfjella, finding that the eastern part, although higher, was most recently deglaciated. Schematic sequences of weathering, erosional

* 筑波大学地球科学系. Institute of Geoscience, University of Tsukuba, Tsukuba 305.

and depositional processes working after deglaciation and their effects on the exposed surface were tentatively presented and the surface characteristics were listed for parts of Balchenfjella and each nunatak.

1. Introduction

The ice-free mountain area, roughly bounded by 71°40′S and 72°30′S, and 21°45′E and 28°E, is collectively called the Sør Rondane and stretches about 215 km in the east-west and about 90 km in the north-south directions, occupying a large area of about 14000 km². The area is one of the few which are characterized by alpine landscape in Antarctica (SUGDEN and JOHN, 1976; p. 202). The Sør Rondane area was first scientifically studied by Belgian Expeditions (VAN AUTENBOER, 1962; VAN AUTENBOER and BLAIKLOCK, 1966; SOUCHEZ, 1966) and then the area has been taken up for systematic scientific investigations by the Japanese Antarctic Research Expeditions since 1985 (MORIWAKI *et al.*, 1985, 1986; HIRAKAWA *et al.*, 1987; ASAMI *et al.*, 1988). The mountain area actually consists of many individual massifs and numerous nunataks separated by the ice sheet and glaciers (inset, Fig. 1). Among these massifs, Balchenfjella (fjella = mountain) limits the eastern end of the Sør Rondane, at the location centered around 72°05′S and 27°30′E. There are numerous nunataks to the north and south of Balchenfjella and they are separated from the rest of the Sør Rondane by the Byrdbreen (breen = glacier, 20–30 km wide), the largest outlet glacier in this region (Fig. 1).

The author had an opportunity to spend one month in the Balchenfjella and nunatak area in January and February of 1988 and to examine landforms, finding that Balchenfjella was distinctively different from the rest of the Sør Rondane. It is the purpose of this paper, first to describe characteristics of the landforms in this area, and then to interpret their significance, particularly in conjunction with landforms and surface conditions found in the other parts of the Sør Rondane.

Although color aerial photographs at a nominal scale of 1:60000 have been available for this area since 1982, topographic maps have not yet been produced because ground control points had not been established until 1988 (ASAMI *et al.*, 1988), and any quantitative measurements over a wide area or map analysis could not be done. Consequently, the following discussion is largely restricted to the qualitative aspects of the landforms. Most elevations quoted in this paper were read with an altimeter which was set according to the elevation of the base camp determined by the NNSS (Navy Navigation Satellite System) positioning system while camping.

2. The Study Area

The study area, including the ice-sheet surface between the exposed bedrock areas, stretches about 80 km northwest-southeast and about 12 km across at the widest area (Fig. 1). By far the largest ice-free area is Balchenfjella, about 33 km north-south and around 12 km east-west at the widest section, with an area of little less than 300 km². Other ice-free areas are nunataks of up to few tens of square kilometers. There are two clusters of nunataks to the north, and one cluster each to the east and to the south of Balchenfjella. The southern and eastern clusters of nunataks were not

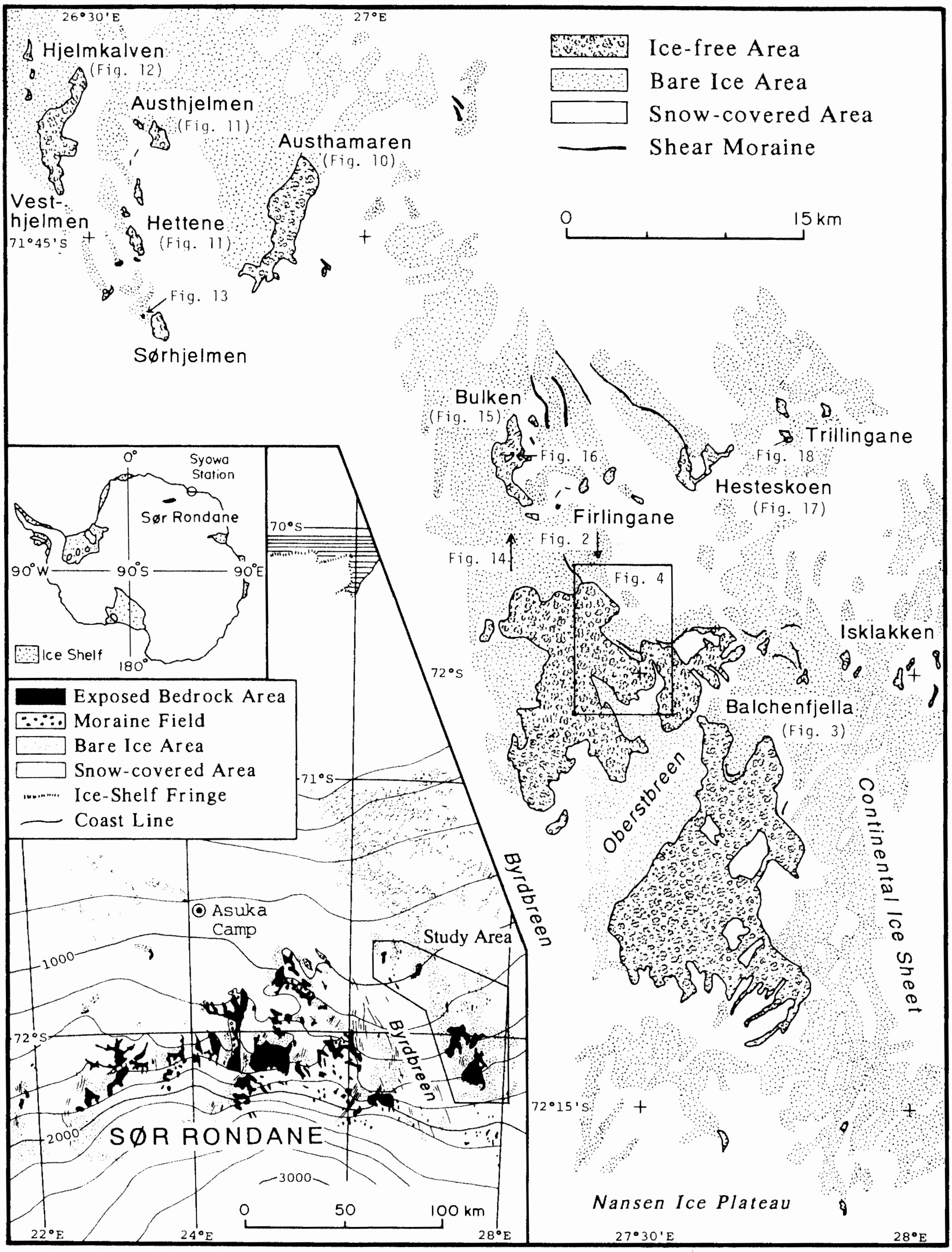

Fig. 1. Location of the study area: Balchenfjella and nunataks. Ice-free and bare-ice areas were delineated on a 1:250000 satellite map (Landsat) published by Geographical Survey Institute of Japan in 1985. The inset map was redrawn from a 1 : 2500000 map (East Queen Maud Land–Enderby Land) edited by National Institute of Polar Research in 1988. Locations and view directions of other figures indicated.

included in this study, because none of them were investigated.

The study area is limited by the Byrdbreen on the west and the continental ice sheet on the east. The elevation of the surrounding ice-sheet surfaces ranges from about 1000 m at the northern end near Austhamaren to about 1900 m at the southern end of Balchenfjella. The ice surface elevation on the east of the study area rises at three belts in a step-like manner. At the first rise located at a cluster of nunataks, Bulken-Trillingane, the elevation goes up by about a couple of hundred meters, forming ice cascades between some nunataks. The ice-sheet surface goes up, at the second rise near the nunatak, Isklakken, located east of Balchenfjella, also by a couple of hundred meters, and at the third rise located at the southern end of Balchenfjella, by about 500 m in a very steep gradient. Between these rises the ice surfaces are mostly gently-undulating. The Sør Rondane blocks the flow of the ice sheet, forming the high Nansenisen (Nansen Ice Plateau) to the south with the elevation of around 2000–3000 m, and force the ice streams to cascade between exposed bedrocks. The general flow direction of the ice sheet and glaciers is north or northwest in the Balchenfjella and nunatak area; however, local ice flows are very complicated as implied by complicated patterns of abundant shear moraines. Numerous crevasses can be seen in this region where bare-ice areas spread out extesively.

Balchenfjella can be divided into the northern and southern parts by the Oberstbreen, an offshoot of the Byrdbreen on the west. Around Balchenfjella, the surrounding ice-sheet surfaces have elevations about 1200–1700 m, and a large part of Balchenfjella lies below these elevations. Therefore, from a far distance, only very small top parts of the mountain can be seen (Fig. 2). This is one of the most notable characteristics of Balchenfjella, which is quite different from the rest of the Sør Rondane.

The study area is mostly underlain by metamorphic rocks, particularly biotite-hornblende gneiss. Although one nunatak of Firlingane is composed of diorite, igneous rocks are very rare; granite, pegmatite, aplite, occurring only as dykes in the metamorphic rocks (ASAMI *et al.*, 1988).

Fig. 2. Balchenfjella seen from north. Only top parts can been seen as much of the area lies below the surrounding ice-sheet surfaces. The ice-free area in the foreground is the northern Balchenfjella, and that in the background the southern Balchenfjella.

3. Geomorphology of the Balchenfjella Area

3.1. Balchenfjella

Northern Part

A large part of the northern Balchenfjella is almost level with or lower than the surrounding ice-sheet surface. Topographically speaking, numerous hollows, mostly shaped like ones scooped by a spoon, characterize this area (Figs. 3 and 4). Some hollows currently have frozen lakes on their bottoms due to ice/snow melt because of the insulation effect in the deep hollow. Many of these hollows are 100–200 m deep and elongated in the north-south direction, similar to the general flow direction of the ice sheet. Their sidewalls (E. and W. sides) are nearly vertical, and jagged owing to intensive frost-shattering because of active freeze and thaw process inside the hollow (Fig. 5), while the walls limiting north and south ends are usually less steep with some erratics; however, occasionally nearly vertical too. Talus slopes have developed below these steep cliffs. Since bedrocks are polished and smoothly rounded with scattered erratics and some striations on them, there seems to be no doubt that they have been primarily excavated subglacially by sliding glaciers and subsequently modified by weathering. Their longitudinal profiles appear similar to rock basins found in Hardangerfjord (Holtedahl, 1967). Holtedahl attributed these rock basins and thresholds to the glacier confluence and diffluence. Also these features are similar to the cirque-like valley head area of some Norwegian fjords, such as Flåmsdal. Although the exact mechanism which accounts for the excavation of these hollows is not known at present, some kind of positive feedback (King, 1970) probably worked in order to augment the relief by plucking. In a few of these hollows lie lobes of tills brought up by shears when the ice sheet had covered this area. The situation can be envisaged by the present condition found at an ice tongue located to the north of the hollow with two frozen ponds (indicated by A in Figs. 3, 4, and 5). This fact may suggest that the excavation of these hollows was in some way associated with a shear mechanism.

Protalus ramparts have developed very well in a hollow located near the central part of the northern Balchenfjella (B in Figs. 3 and 6). One protalus rampart has developed in front of a gigantic syenite dyke (width 10–20 m, see Fig. 6) with a distinctive reddish tint, and its surface is coated with this red rock, indicating that the formation of this ridge is by rock falls, although its morphology is very similar to lateral moraine.

Bedrocks in the central part are generally very fresh and the surface is highly polished and smoothly-rounded, *i.e.* whale backs, with relatively few erratics (Fig. 7), indicating relatively recent deglaciation. Contrastingly, bedrocks on the western part are in general more weathered with more till/erratic cover. On the color aerial photographs, usually patchy but sometimes extensive areas of darker tone can be recognized. At first glance, it appeared that this was due to different lithology; however, in the field it was recognized that this was because of much weathered erratic/till cover (occasionally bedrocks). Subsequent close examination of color aerial photographs has revealed that there are three shades of tones which are believed to be reflecting the degree of weathering, particularly in the southern Balchenfjella; however, only the

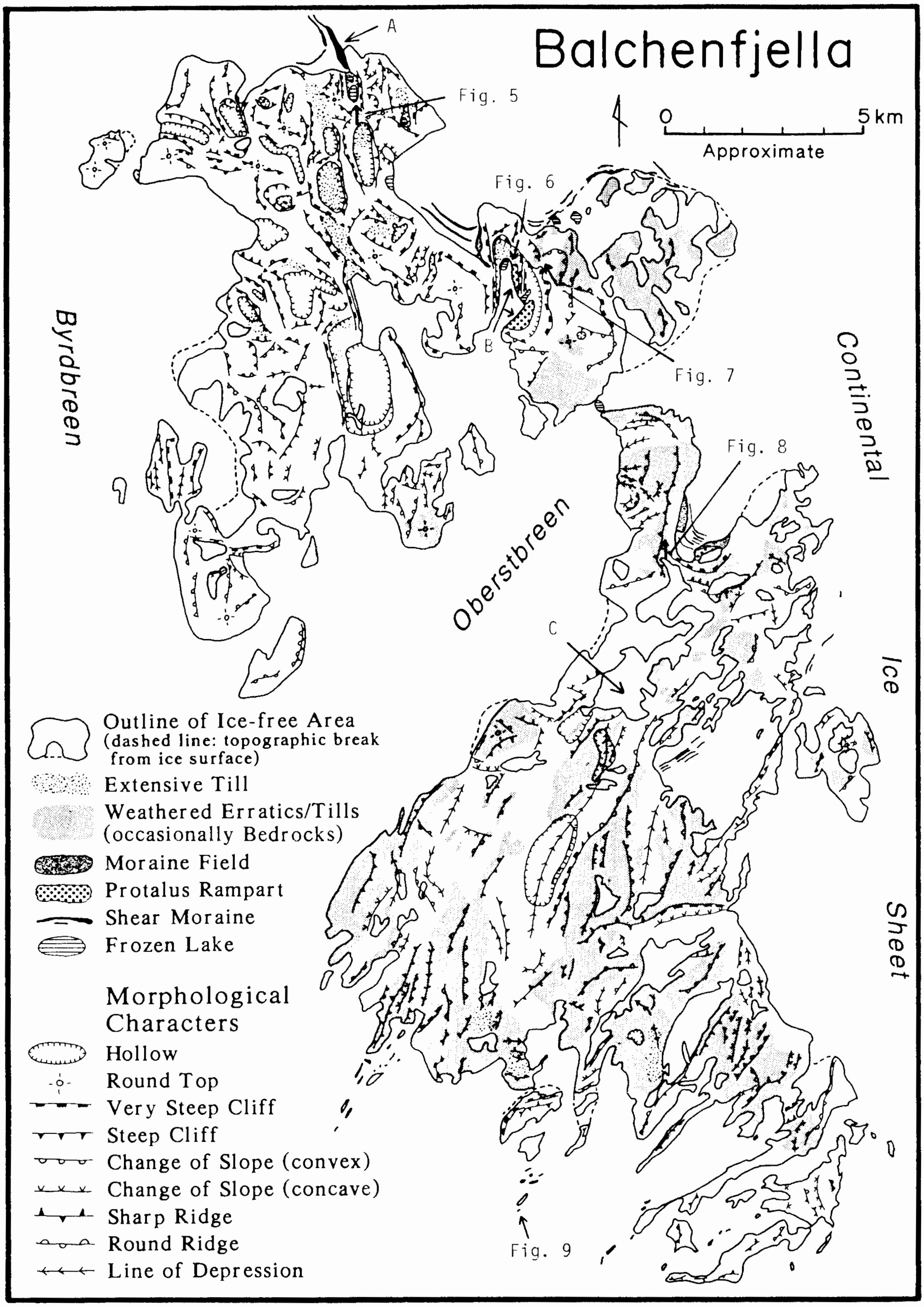

Fig. 3. Geomorphological map of Balchenfjella. Compiled from field work and interpretation of color aerial photographs taken in 1982 at a nominal scale of 1 : 60000. The outline of features was traced directly on aerial photographs and the planimetry is not necessarily correct.

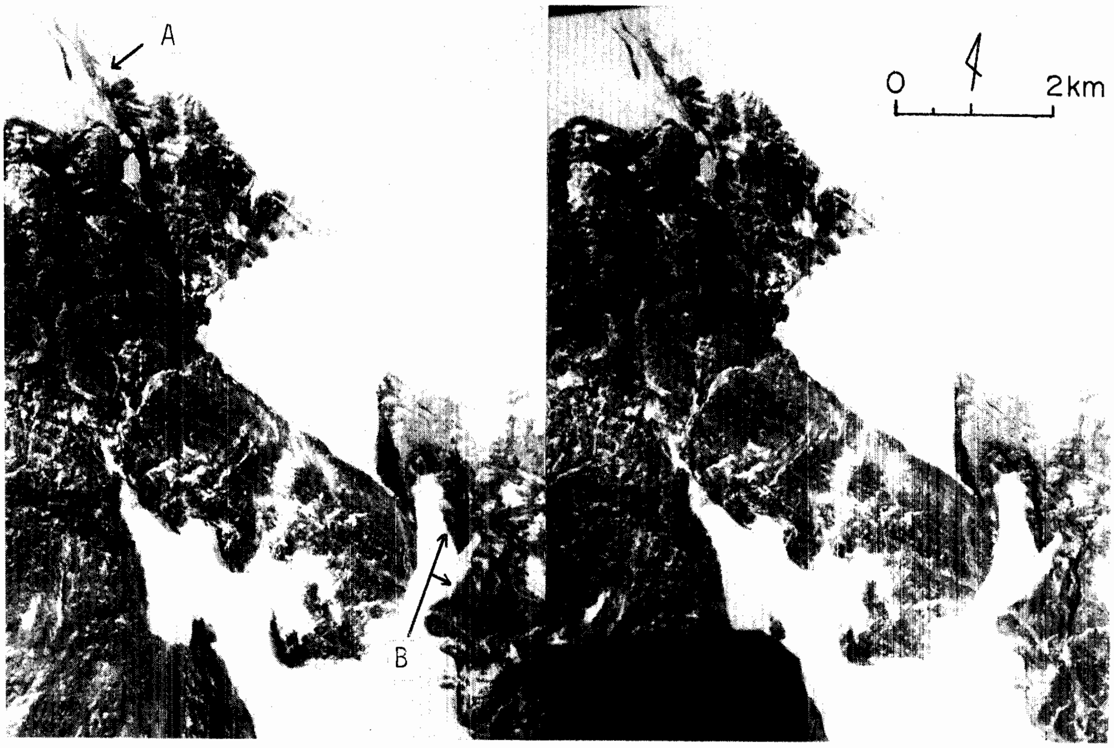

Fig. 4. Stereogram showing a number of hollows in the northern Balchenfjella. A: shear moraine currently being formed. B: protalus ramparts.

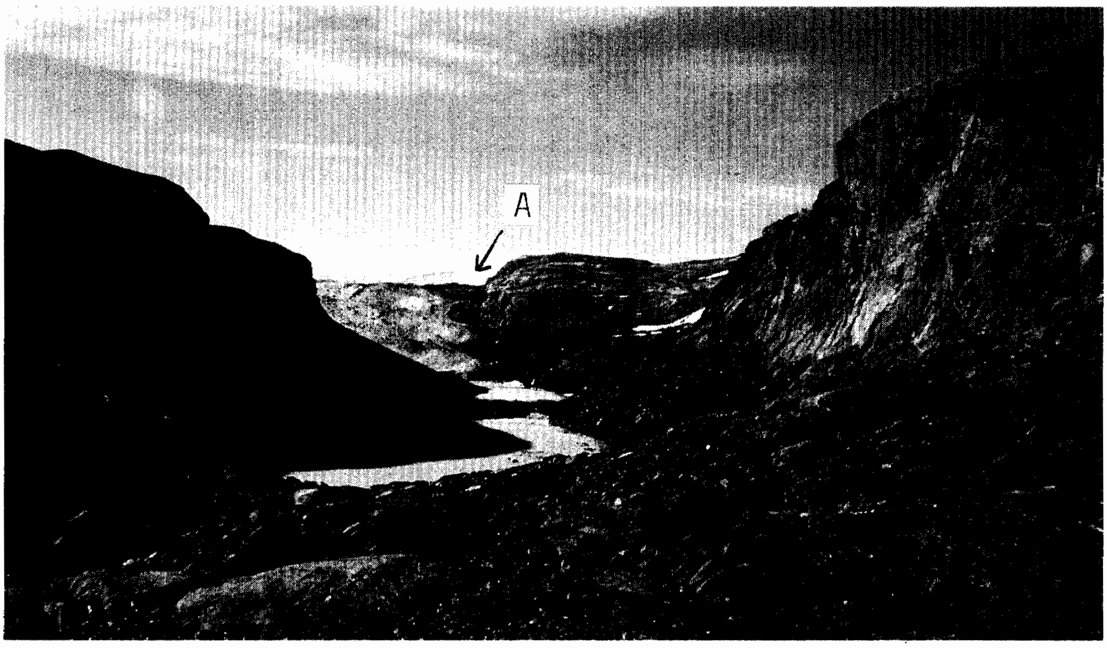

Fig. 5. A hollow with nearly vertical sidewalls and frozen lakes. Scattered erratics exist on the bottom. Looking northward. A: shear moraine currently being formed.

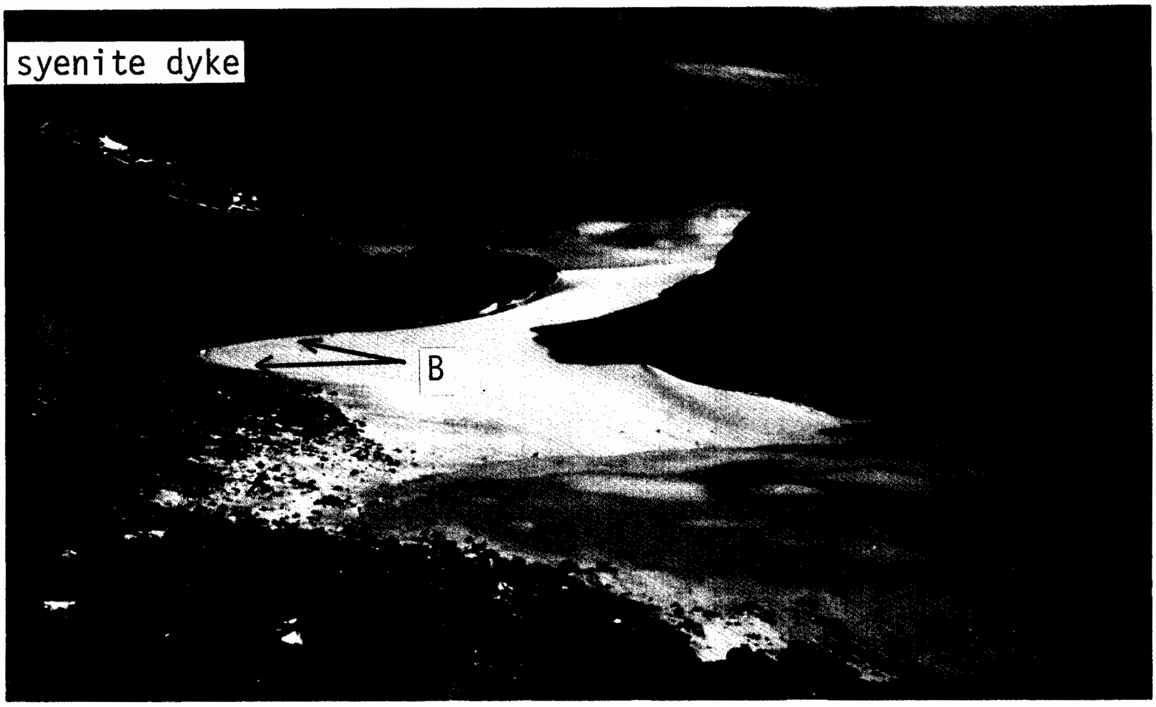

Fig. 6. *Two protalus ramparts (indicated by B) in a hollow at the eastern part of the northern Balchenfjella. An ice tongue from the Oberstbreen still spills into this hollow. A syenite dyke indicated.*

Fig. 7. *Fresh, smoothly-polished bedrocks with abundant striations at the eastern part of the northern Balchenfjella, indicating very recent deglaciation. Note: the bedrock surface is nearly level with or lower than the surrounding ice-sheet surface.*

darkest areas are indicated in Fig. 3 as they could surely be distinguished. These characteristics seem to be primarily related to the deglaciation period.

Southern Part

The topography of the southern Balchenfjella is characterized by the extremely low area near the middle (C in Fig. 3). Here the elevation is more than 200 m lower than the general elevation of the surrounding ice-sheet surface to the east. The top

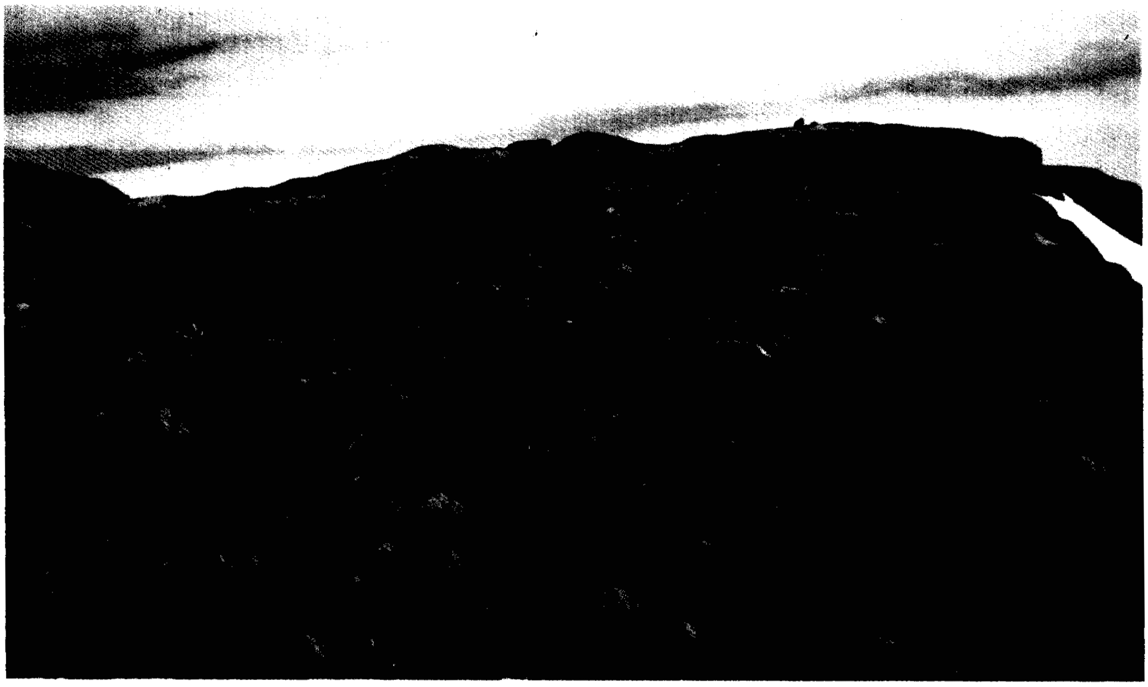

Fig. 8. Fresh bedrocks and the cover of very much weathered erratics at the northern part of the southern Balchenfjella.

Fig. 9. A tiny outcrop of the ice-free area at the southern end of the southern Balchenfjella. Persons for scale. The outcrop seems to have been caused by very recent deglaciation; however, bedrocks and rock fragments on them are very much weathered. The ice-free area in the back is Gunnar Isachsenfjellet.

part of peaks is often surrounded by frost-shattered cliffs. The southern Balchenfejlla is generally covered by very extensive, weathered erratics (Fig. 8), although there are only a few patches of till fields. Development of desert pavement is generally good near the southern end of the southern Balchenfjella, where bedrocks and erratics have been fragmented by frost-shattering. Occasionally, weak development of sorted patterned ground (mainly polygons) can be recognized on these desert pavements. Also there are a few ventifacts in this environment owing to strong, prevailing south-easterlies. As for the degree of weathering of bedrocks and rock fragments at the southern end of the southern Balchenfjella, there is an enigma. Figure 9 shows a very tiny outcrop of the bedrock which may suggest fairly recent deglaciation because it is only several tens of centimeters higher than the surrounding ice-sheet surface: however, bedrocks and rock fragments found there are very much weathered with a reddish tint. It is wondered whether or not they are products of the past exposure and preserved under the subsequent cover of the ice until recently.

From the eastern side toward the lower area in the middle, the degree of weathering, of both the bedrock and erratics, becomes progressively advanced. In general, bedrocks at peripherals of the southern Balchenfjella are most fresh, and have been plastically-moulded by basal sliding, with few erratics on the surface. This characteristic change of the degree of weathering can be explained by the deglaciation mechanism which is discussed in Section 4. From the observation of weathering pattern, it can be modeled that the degree of weathering is primarily related to the distance from the present-day ice margin, and that relation is modified by the height of the spot or the nature of bedrocks. With the similar distance from the ice margin, higher places have been released from the glacier earlier than the lower places, and subjected to a longer period of subaerial weathering and erosion. As for the nature of rocks, migmatite seems harder than rocks with well-developed gneissosity. Amphibolite dykes constitute sharp ridges and peaks. The abundance of erratics/tills near the low area has resulted from extensive ablation, where ice tongues spilling from four sides closed in and locked dead.

3.2. Austhamaren, Austhjelmen, Hettene, Hjelmkalven, Vestkalven, and Sørhjelmen

These nunataks constitute the northeastern corner of the Sør Rondane. A notable characteristic of this group is that except for Austhamaren all nunataks are surrounded by wind scoops, particularly on the eastern or southeastern side of the nunataks due to prevailing easterlies. However, development of wind scoops on other sides is also good, probably because of complicated wind patterns effected by clustering of these nunataks. In general, the snow surface on the east of a nunatak is much higher (around 100 m) than the surface of bare ice on the west. Contrasting to Balchenfjella, alpine glaciers seem to be primarily responsible for shaping the landforms of these nunataks as discussed below.

Austhamaren

Of these, Austhamaren (Fig. 10) is the largest with an aera of about 20 km^2, and the highest with an elevation probably exceeding 1600 m, with a relief of more than 400–800 m from the surrounding ice-sheet surface. The main divide runs north-south, separating steep free faces on the east and cirques and moraine fields on the west. Topography is characterized by a single arête at the northern one-third and double ridges at the southern two-thirds, and three empty cirques, one cirque glacier and two till fields on the western side of the divide (Fig. 10). The formation of the double ridges appears to be related to the gneissosity trending roughly north-south and dipping east. Excavation along weak gneissosity planes probably produced a central valley, thereby leaving two almost parallel ridges. There is an active cirque glacier on the western side of the southern part (A in Fig. 10), which is one of only two such glaciers (the other, on Hesteskoen) in the study area. The reason why this cirque glacier still exists is possibly as follows. There is a col on the eastern ridge (of the double ridges, B in Fig. 10), to the east of the headwall of this cirque glacier (western ridge). Strong easterlies can penetrate into the central valley through this col, drifting a lot of snow. After having filled the central valley with snow drift, easterly winds now blow upward all the way to the top of the headwall of the cirque and deposit drifted snow on the cirque glacier on the western side.

The ice-free area of the central valley and the southern part of Austhamaren are characterized by well-developed patterned ground of gelifluction lobes and polygons.

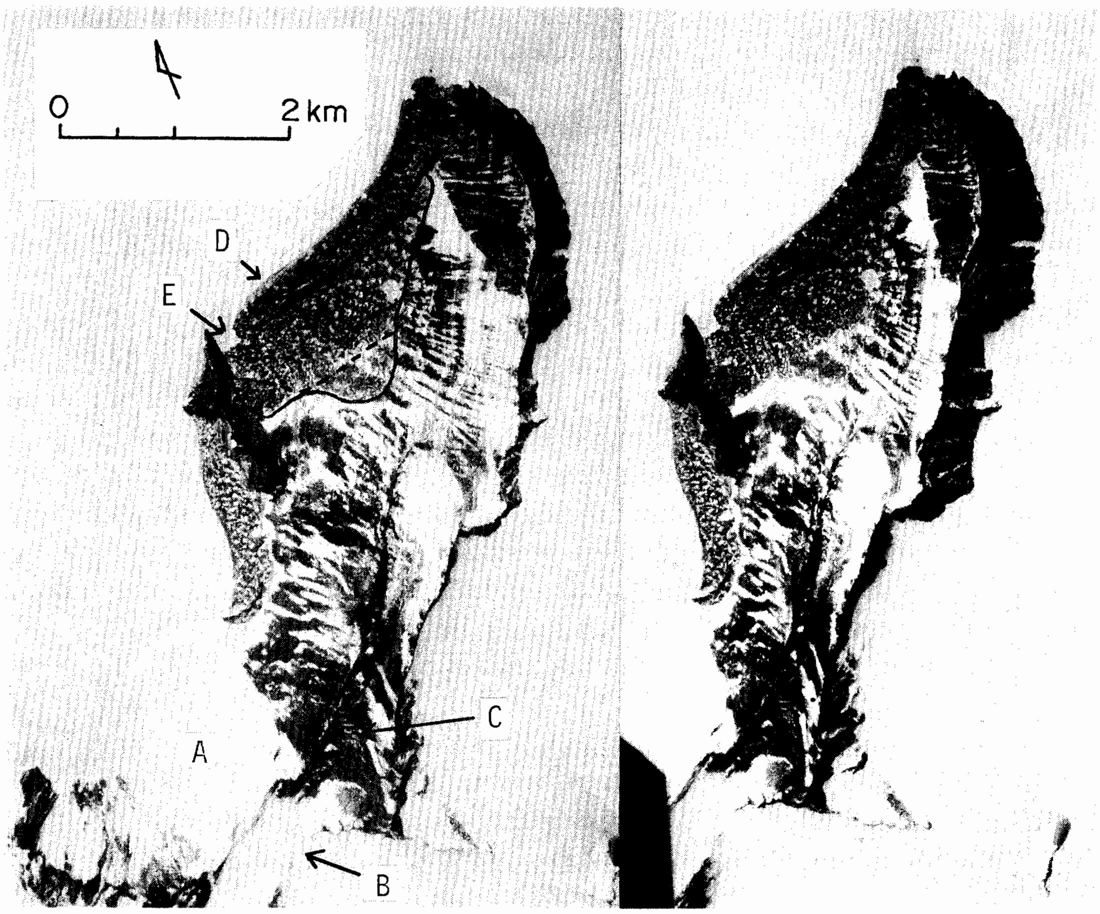

Fig. 10. Stereogram of Austhamaren. The southern part (south of the cirque glacier) is not shown due to irregular coverage of the photographs. A: active cirque glacier. B: col through which snow drifts in to nourish the cirque glacier. C: central valley where desert pavement is very well-developed on the frost-shattered till field. D: sorted lag deposits. E: small marginal lake (frozen). For the northern till field, the division between those deposited by the ice sheet and the local cirque glacier is indicated by a solid line, while the subdivisions within each are indicated by dashed lines.

Frost-shattering is very extensive, on both bedrocks and erratics. Desert pavement is developed very well on the frost-shattered till field in the middle of the central valley (C in Fig. 10), which has made the slope appear very smooth from a far distance. Tafoni are well-developed on erratics scattered at the southern end of the divide.

There are two large till fields on the western side, both showing typical pitted topography. Of these, the northern one is larger and consists of tills deposited by cirque glaciers and the ice sheet. Those deposited by cirque glaciers appear to be divided into three different periods from their surface roughness and elevation distributions. Those deposited by the ice sheet can largely be divided into two groups, the inner and outer ones (closest to the ice sheet). Of these, the southern part of the inner one consists of several conspicuous linear ridges running almost parallel to the present ice margin and composed of giant boulders whose diameters exceed a few meters. The outer line of the moraine hillocks is still ice-cored with a veneer of the till cover and stands 10–20 m higher than the adjacent ice surface. This feature suggests that the ice-sheet surface has lowered recently. Between this line of the moraine and the present ice-sheet margin, there are well-sorted lag deposits of rocks on the ice surface inclining toward the ice sheet (D in Fig. 10). Since the sorting pattern is parallel to the ice margin, with larger ones downward, it appears that the sorting was the results by wash in a marginal lake once existed here. There still exists a small marginal lake to the south of this moraine ridge (E in Fig. 10). In a marginal lake, tills were washed and finer materials were removed, so that big rocks became unstable and rolled down. In this manner, sorting was accomplished. The southern till field has probably been mainly laid by a cirque glacier, judging from their relative location to an empty cirque above.

Since the author did not have a chance to reach the top of Austhamaren, it cannot be ascertained whether or not the ice sheet had once completely buried the whole area. It is certain, however, from the existence of erratics of foreign rocks in the central valley around the elevation of 1250–1300 m that at least most area was once under the ice sheet. The empty cirque walls appear very much weathered, with many vertical grooves running parallel to each other at a rather regular interval and not retaining polished, smoothly-rounded bedrock forms. Together with extensive frost-shattering and good development of sorted patterned ground, these bedrock appearances imply that it has passed much longer time here since deglaciation than at Balchenfjella, probably comparable to other parts of the Sør Rondane.

Austhjelmen

Austhjelmen (Fig. 11) is a jagged nunatak with a single peak. Almost all sides are covered with tills and/or frost-shattered materials (hereafter referred to as debris), with slope gradients of 35–40°. The slope on the northeastern side shows a rectilinear form covered probably with debris (A in Fig. 11). Although the rectilinear form is very common in the other areas west of the Byrdbreen (IWATA, 1987), it is rather rare in this study area. There is a small cirque on the northwestern slope, where a small patch of ice/snow still exists on the headwall.

Hettene

Hettene consists of several nunataks, each heavily guarded by wind scoops (Fig. 11). Of these, the largest nunatak has three horns and one sharp ridge, with a till field on the western side of the divide. On the western side of the sharp ridge is a

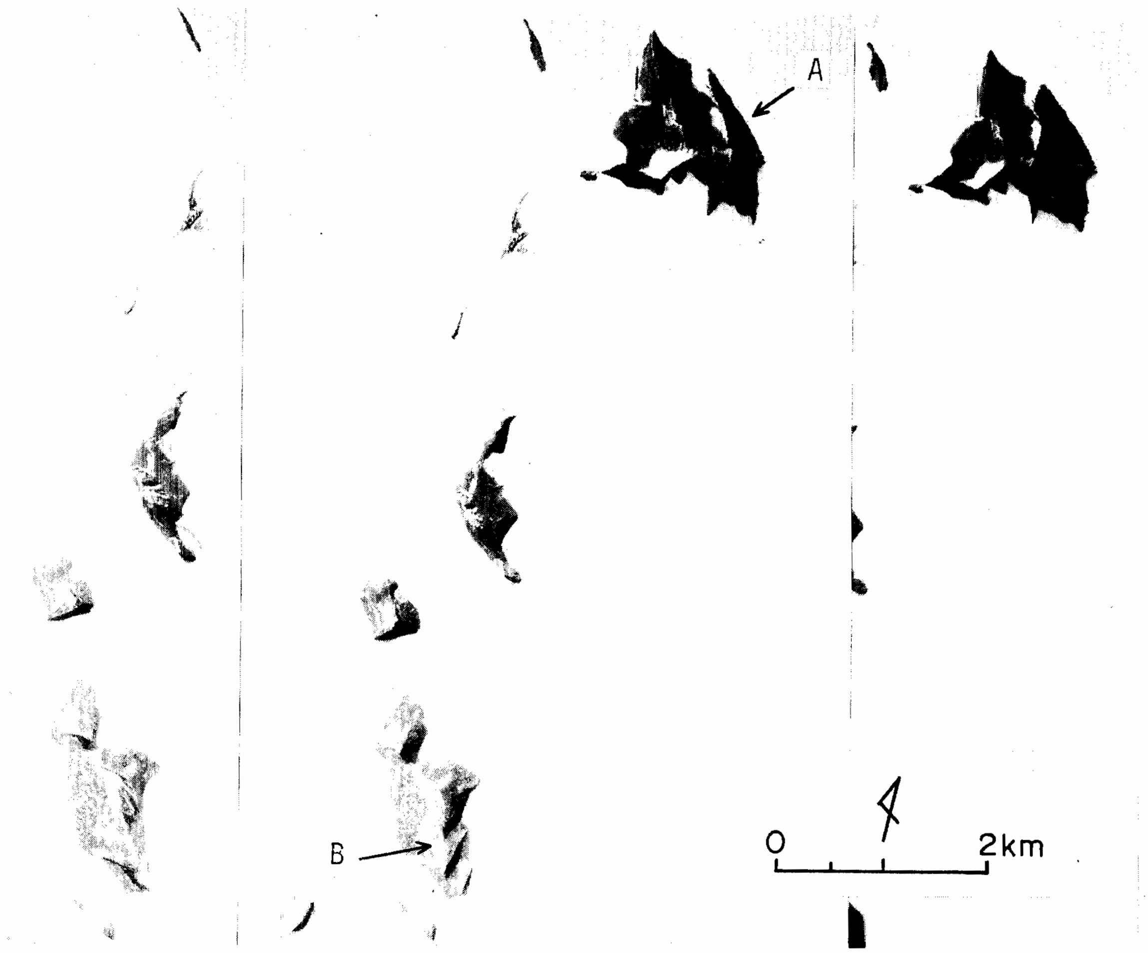

Fig. 11. Stereogram of Austhjelmen (a northern nunatak) and Hettene (southern nunataks). Note: very extensive development of wind scoops, particularly on the east. A: rectilinear slope at Austhjelmen. B: probable rock glacier at Hettene.

small cirque still with residual ice/snow at the lower section. Tills deposited by an old cirque glacier generally lie at higher elevations than those deposited by the ice sheet. The till laid by the ice sheet is still ice-cored, with numerous melt-out ponds in the field. Frost-shattering of erratics is not rare, and development of sorted patterned ground, particularly polygons, is good. Polygons are numerous on fine materials (about 5 mm or less) of the till deposited by an old cirque glacier, with generally small diameters (around 50 cm). There is a probable rock glacier starting from a col between the cirque wall and a horn to the south (B in Fig. 11). Its surface is a giant step-like slope with ill-sorted materials and as a whole it is convex upward, unlike usual till, talus or debris slopes.

Hjelmkalven and Vestkalven

Although two names are given, this is one continuous body of an ice-free area, with Hjelmkalven indicating the northern part and Vestkalven the southern part (Fig. 12). This nunatak is characterized by a long sharp divide running roughly northeast-southwest (Hjelmkalven) and north-south (Vestkalven). The eastern side of the divide is very steep with much exposed bedrocks, while the western side slopes are gentler with

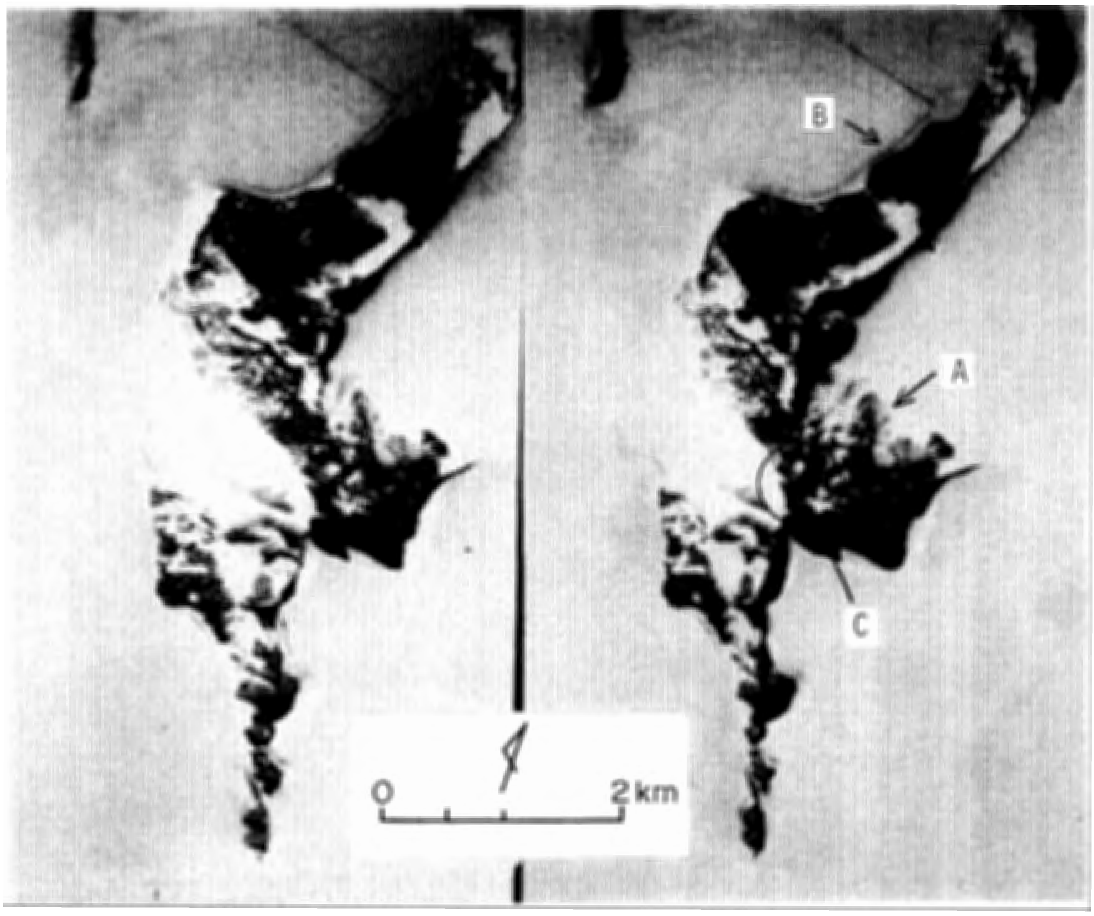

Fig. 12. Stereogram of Hjelmkalven (northern half) and Vestkalven (southern half). A and B: slope where patterned ground (mostly steps) have developed well. C: bedrocks with numerous tafoni.

the till/debris cover. There is one big spur extending to the east from the middle of the Vestkalven divide and the northern slope of this spur is covered by extensive surficial materials on which patterned ground primarily consisting of steps is well-developed (A in Fig. 12). Step patterns are also commonly found on the northwestern slope of Hjelmkalven (B in Fig. 12). Development of tafoni on bedrocks (biotite gneiss) at the eastern side of Vestkalven is conspicuous (C in Fig. 12).

Sørhjelmen

This nunatak is located southernmost in this group and is a blocky mass with a sharp ridge running in about the center of the mass, dividing it into almost equal-sized northeastern and southwestern sides. On the northeastern side of the ridge are hill slopes covered with debris/till, and these slopes merge into moraine and/or talus slopes near the glacier surface. The southwestern side is characterized by relatively extensive tills on the slope. These tills appear to have been laid down by glaciers developed on the mountain slope rather than by the ice sheet.

There is a very tiny bedrock exposure (a few tens of square meters) where tafoni have developed exceptionally well on hornblende gneiss, several hundred meters northwest of Sørhjelmen (Figs. 1 and 13). Here holes are mostly vertical and the diameter of the hole inside is generally larger than that at the mouth (about 10–20 cm most

Fig. 13. A tiny outcrop of very much weathered bedrock with numerous vertical tafoni, on the northwest of Sørhjelmen. Note: weathered skeletons of dykes (quartz) and an ice fall to the south from which direction the ice sheet flows.

common). Some holes are connected by tunnels and a lot of holes contain rock fragments. These observation suggests that these tafoni have been produced mainly by winds, using rock fragments as grinder. Right behind this bedrock exposure is an ice cliff, several tens of meters high. If the ice front advances a few tens of meters, this exposure would be buried under the ice. Yet, an extensive development of tafoni exists here. It is not certain whether this implies that the ice cliff has remained as today or less advanced for a long time of period, or the tafoni are products during the past exposure and had been preserved under the ice cover until recently.

3.3. Bulken, Firlingane, Hesteskoen and Trillingane

Aligning east-west, these nunataks block the ice-sheet flow, causing ice cascades and falls about 200 m high between them. The ice surface elevations are about 1000–1100 m to the north and around 1200–1300 m to the south of these nunataks. Firlingane and Trillingane actually consist of three nunataks each. Heights are about 1440 m for Bulken, 1470 m for Hesteskoen and 1460 m for the southernmost nunatak of Trillingane. The highest peak of Firlingane was not visited. Thus, they stand about 250–450 m higher than the surrounding ice-sheet surface.

Bulken, two northern nunataks of Firlingane and Hesteskoen have a characteristic form of cuesta, with precipitous cliffs on the western side and gentle slopes on the eastern side (Fig. 14). The two other nunataks of Trillingane, on the other hand, have a gentle slope on the west and cliffs on the east. The southernmost nunatak of Firlingane has a gentle slope on the south and cliffs on the northern side.

One of the most conspicuous characteristics recognized on the color aerial photo-

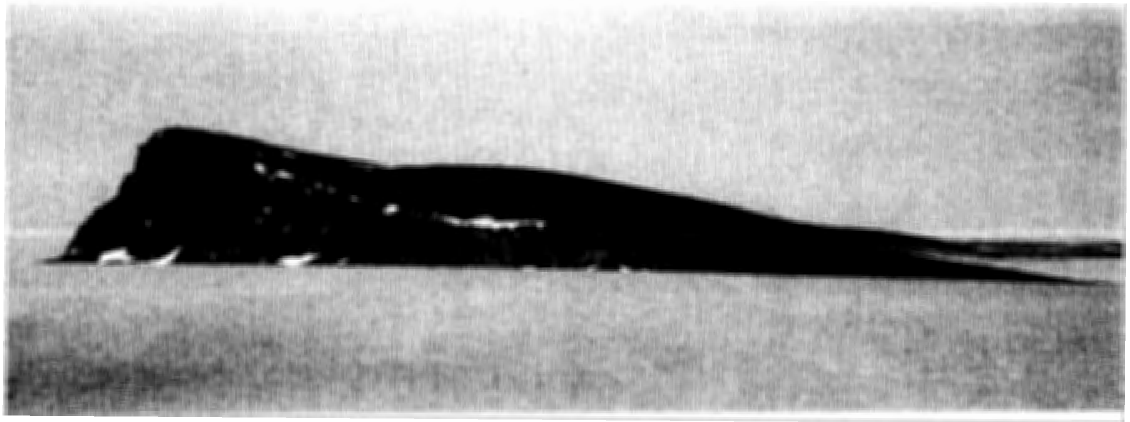

Fig. 14. Bulken seen from south, showing an asymmetric form. Note: smooth, gentle eastern slope.

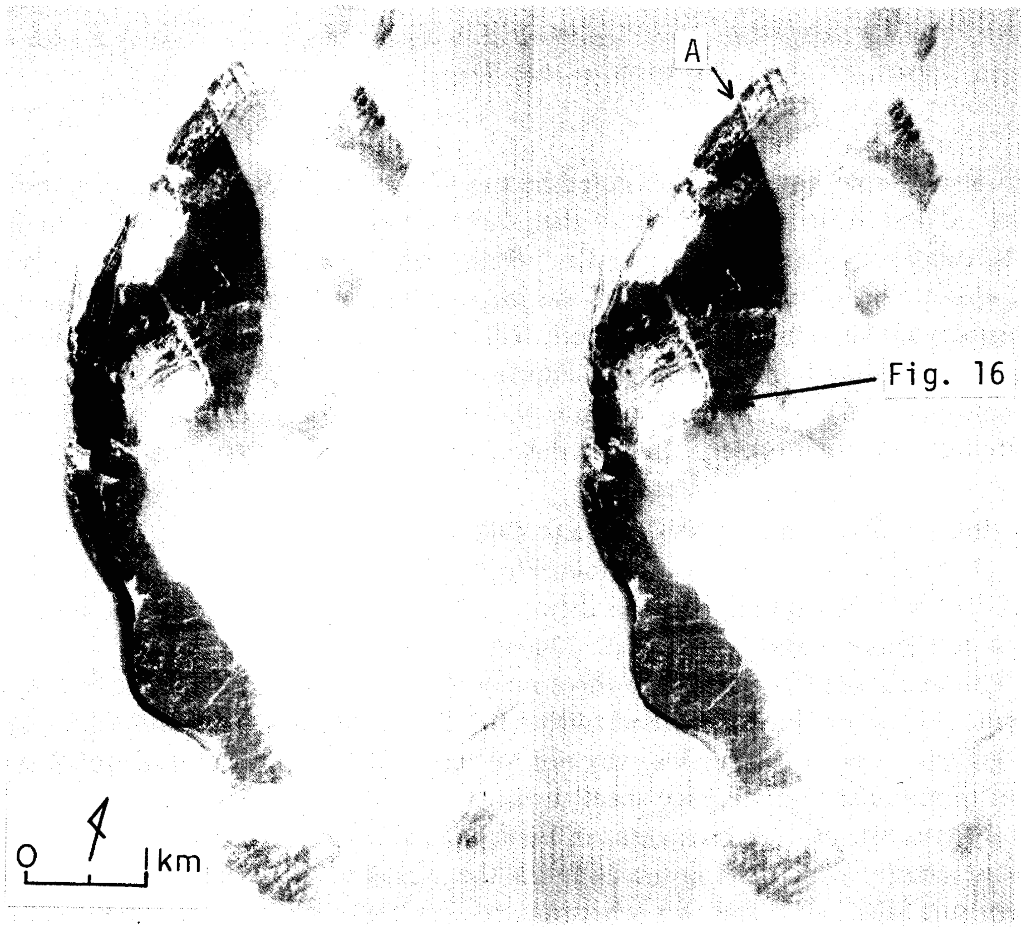

Fig. 15. Stereogram of Bulken, showing a remarkable demarcation line (A) between the slopes of fresh bedrock and weathered mantle. The freshness of the bedrock suggests fairly recent deglaciation. Photographic location of Fig. 16 indicated.

graphs and common to this group of the nunataks is that there is a very distinctive demarcation line running roughly north-south on the eastern slope, one side of which (usually west) appears reddish and the other side pale white (A in Fig. 15). In the field, it was found out that the pale white area was fresh bedrock devoid of weathered materials, while the reddish area was covered with weathered tills and debris. This suggests that the ice-sheet surface has lowered fairly recently.

The top part of Bulken is extensively covered with debris, on which gelifluction lobes and steps have developed well. There are a lot of snow patches and traces of water flows on the rectilinear, eastern (gentle) slope, indicating very active nivation processes (Fig. 16). Development of polygons is generally very poor, only a few at very favorable locations (*i.e.*, relatively flat and soft rocks which get easily weathered). At the lower section of the eastern slope, a remarkable demarcation line can be clearly recognized on the aerial photographs, indicating a few tens of meters lowering of the ice-sheet surface at the eastern side.

At Hesteskoen, there is still an active cirque glacier with ogive waves on the northern side, which almost splits the ice-free area into a small eastern half and a large western half (Fig. 17). It is evident from the low divide between the ice sheet and the cirque glacier, and freshness of the exposed bedrock there that the ice sheet had overflowed until fairly recently, and it has not passed a long time since the ice has become

Fig. 16. Gelifluction lobes and traces of water flows on the eastern (gentle) slope of Bulken, indicating very active nivation during summer.

a cirque glacier. Well-developed patterned ground of steps and polygons spread widely on the gentle southeastern slope of the western part, where moisture is abundant and fine materials prevail on the ground (A in Fig. 17). The top part is a slightly-inclined flat surface and covered with abundant erratics which show little weathering. Patterned ground was not found on this flat top surface.

The southernmost nunatak of Trillingane is characterized by extensive and in-

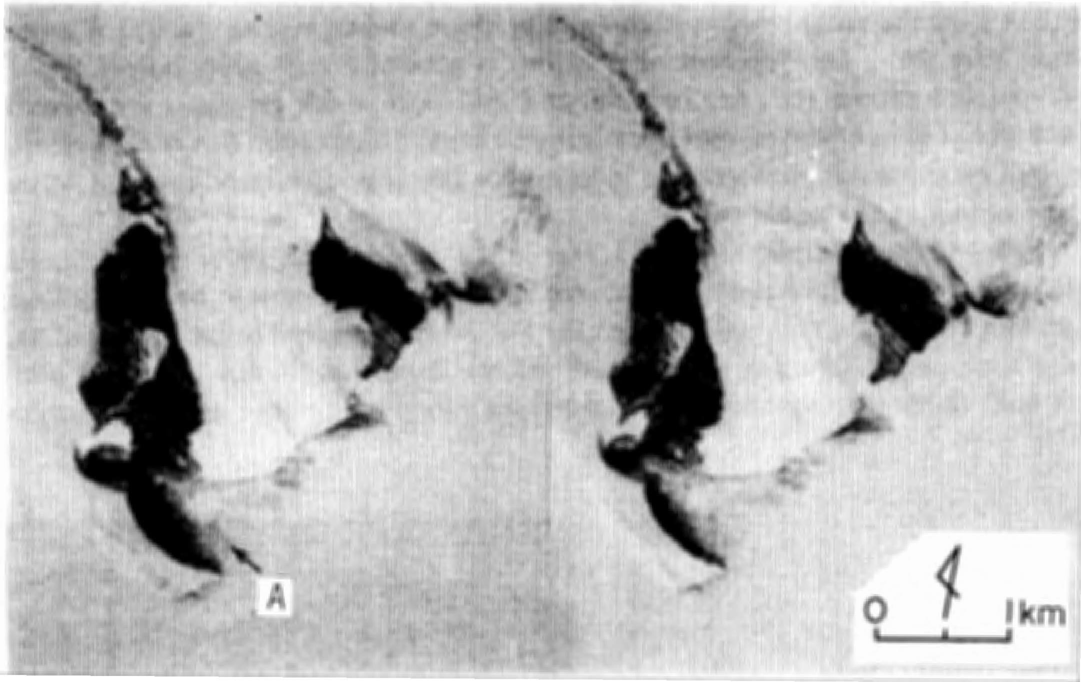

Fig. 17. Stereogram of Hesteskoen. A: slope where patterned ground has developed well.

Fig. 18. Cryoplanation terraces developed on the western slope of the southernmost nunatak of Trillingane. Strata of massive rocks and quartz sills/dykes constitute rises, while the area of platy biotite gneiss has become steps.

tensive frost-shattering of bedrocks. The western slope shows a step-like topography, with rises of a few meters high and slightly-inclined flat surface is several tens of meters long between rises. The flat surface is almost completely covered with angular, platy debris (biotite gneiss). It appears from these characteristics that this topography represents cryoplanation terraces (DEMEK, 1968, 1969); rises and steps probably controlled by the nature of rocks (Fig. 18). The existence of erratics, although few, indicates that this area was once completely buried under the ice sheet. Very well-developed tafoni were observed on bedrocks near the top on the northwestern side.

4. Deglaciation and Sequences of Weathering, Erosional and Depositional Processes after Deglaciation

4.1. Deglaciation

From the distribution of erratics/tills all the way up to the mountain tops, it is certain that Balchenfjella had once been completely buried by the ice sheet. Also the wide-spread of polished, smoothly-rounded bedrocks with abundant striations indicates that the basal sliding had been very active.

Deglaciation took place first near the central part of the area due to a decrease in the amount of spilling ice from the surrounding ice sheet and the spilling ice bodies became ice tongues. Subsequently, ice tongues receded toward south, west, north and east, exposing bedrocks and leaving tills and erratics. Once the ice became thin and a small part of bedrocks exposed, deglaciation was probably accelerated by a greenhouse effect (SOUCHEZ, 1966). Consequently, the relative amount of time passed after deglaciation becomes progressively shorter toward the present-day glacier margin, and so does the time period during which exposed materials have been subjected to subaerial weathering and erosion. This explains why the bedrocks and erratics near the eastern margin of Balchenfjella, although higher, are less weathered than those located near the center, the lowest part of the area. From the degree of weathering, it appears that the western part was deglaciated earlier than the eastern part in general, implying that the Byrdbreen and the Oberstbreen were more responsive than the ice sheet on the east to a decrease in the level of the ice-sheet surface to the south.

4.2. Sequences of weathering, erosional and depositional processes after deglaciation

Since it appears that the surface condition of the slope is indicative of the relative age after deglaciation in the Sør Rondane, schematic sequences of the resultant surface conditions produced by weathering, erosional and depositional processes are tentatively suggested in Table 1, which may naturally be subject to elaboration by further studies. Also shown together is a list of individual processes which can be thought to work in this environment.

Stage A

Upon deglaciation, two major types of ice-free surfaces emerge; 1) bedrock, and 2) till/erratic-covered surfaces. The till/erratic-covered surfaces may be divided into thick and thin covers. A thin cover indicates that bedrocks can be mostly seen through tills, whereas a thick cover means that bedrocks cannot be seen. If we consider the kind of geomorphic processes which would work after deglaciation, the surface on which tills were laid down can be divided into the level and the inclined. Therefore,

Table 1. Schematic sequences of weathering, erosional and depositional processes and their effects after deglaciation in Sør Rondane, East Antarctica.

Exposed Materials	Dominant Processes		Results: Main Products	Results: Others	Effective Processes	Results
A1 Polished, smoothly rounded bedrock (ex. Cq. Wall, Stoss and lee topo., Whale back, etc.)	1,2,3,9 4,12	Nature of Rocks	B1 Angular rock fragments and granular stones (1,2,3,12)	B2 coarse, uneven bedrock surface (still roundish) (1,2,3)	1,2,3,7,9	C1 very coarse, rough bedrock surface (not round) (1,2,3) C2 tafoni (7,9)
				B3 debris-mantled slope (1,2,3) B4 talus slope (14)	1,2,3,7,9 12,13,14	C4 desert varnish (7) C5 desert pavement (9) C6 tafoni (7,9) C11 patterned ground (12,13,14)
Loose materials						Compact and tight materials
A2 Thick till on level surface	1,2,3,9 most 4,12,13 ↕ 10,11 least			B5 lag deposits (9,10,11) B6 channel (10)	7,9	C7 desert varnish (7) C8 desert pavement (9)
A3 Thick till on inclined surface	1,2,3,9 4,12,13 10			B7 lag deposits (9,10) B8 channel (10)	12,13 14	C9 patterned ground (12,13,14)
A4 Thin till (bedrock can be seen)	1,2,3,9 4,12,13					C10 tafoni (7,9)

Processes

Weathering

Physical Weathering

1 Freeze and Thaw (shattering, joint-block separation)
2 Heating and Cooling (shattering, exfoliation, joint-block separation, granular disintegration)
3 Salt Weathering (granular disintegration, joint-block separation, shattering)
4 Wet and Dry (slaking)
5 Unloading (sheeting structure, exfoliation)
6 Biological Stresses
7 *Chemical Weathering*
8 *Biochemical Weathering*

Erosional and Depositional

9 Eolian
10 Glaciofluvial
11 Glaciolacustrine
12 Nivation
13 Cryoturbation
14 Mass Wasting

we have five types of the surface conditions to consider; however, when it is a thin cover, whether the surface is level or inclined does not matter as water does not play a significant role in either situation. So Table 1 lists only four as the initial conditions of the surface right after deglaciation.

Stage B

As soon as ice recedes, weathering processes such as freeze and thaw, heating and cooling, and salt weathering, and erosional and depositional processes such as eolian, glacio-fluvial, glacio-lacustrine, nivation, cryoturbation and mass wasting attack the exposed materials. Depending upon the type of the initial surface condition, the kind of the processes working on the surface and the degree of dominance among the processes differ slightly.

In any case, due to very favored periglacial conditions, *i.e.*, frequent and intense cycles of freeze and thaw and others, bedrocks are subjected to exfoliation, frost-shattering and/or granular disintegration, and erratics get broken to smaller pieces. The nature of rocks influences speed of this break-up. In this process, the polished bedrock surface becomes slightly rough, but retains rounded forms. Where frost-shattering is very active, the slope would be mantled with debris. If the bedrock surface is very steep, debris would not stay on the slope and fall down to the foot of the cliff, forming taluses by gravitational force.

In the erratic/till covered area, rocks are fragmented by processes such as frost-shattering, exfoliation and granular disintegration. In the level area, marginal lakes and moraine-dammed lakes may be formed and/or ice/snow melt water stream may be active during summer. These glacio-lacustrine and glacio-fluvial processes, together with strong eolian process, will wash or carry away fine materials and leave larger rocks behind as lag deposits. If a water stream is mighty enough, it forms a distinctive channel. When the till cover is on an inclined surface, lakes will not be formed. If the till cover is thin, the cover will not be extensive enough to form lag deposits or channels. By winds fine materials may be blown away and only large ones are left in place; however, their effectiveness in molding slope surface conditions is minimal, when the till cover is thin.

Stage C

Here processes are listed as effective ones, in order to emphasize their importance to the end products. As subaerial weathering and erosion continue, bedrocks become rougher and eventually their surfaces become very coarse and uneven with jagged edges. They no longer retain round forms, and in some cases tafoni develop on bedrocks. On the debris-mantled slope and talus slope, rock fragments become smaller and smaller, and due to general strong winds, desert pavement will probably be formed with/without desert varnish. Tafoni may develop on these rock fragments. At some favored locations, patterned ground may develop.

In the till-covered area, frost-shattering, granular disintegration and/or exfoliation may no longer be dominant due to small size of rock fragments. In this condition, winds are only dominant process, by which desert pavement is formed with/without desert varnish. Tafoni may develop on these rock fragments. After these developments, break-up of rocks and movement of rocks become minimal and the slope becomes very stable with a slow change.

5. Concluding Remarks

In the study area, we can find these characteristic surface conditions here and there. Table 2 lists them for parts of Balchenfjella and individual nunataks. The list was compiled from field observations and photographs. Since the places we could visit for investigation were of course very limited, listing is naturally not exhaustive of the surface conditions present in a particular nunatak or part of Balchenfjella, and is by no means complete: nonetheless they are indicative of the oldness or newness of the ice-free areas, although in a relative sense. From Table 2, it is evident that Balchenfjella has been deglaciated most recently among the ice-free areas in the study area: however, the list indicates that the southern side of the southern part is very much weathered, presenting an enigma to the general deglaciation pattern. If we compare Balchenfjella with the other ice-free areas in the west of the Byrdbreen (IWATA, 1987; HIRAKAWA *et al.*, 1988), Balchenfjella can be distinguished as a very unique ice-free area in the Sør Rondane. Whereas the other ice-free areas stand high above the surrounding ice-sheet surface, with landforms mostly of alpine glacier origin such as arêtes, horns, and cirques, and have been deglaciated for a much longer time, Balchenfjella is characterized by extensive low-lying areas which have become exposed to subaerial processes only recently and by the landscape of areal scouring resulting from ice-sheet glaciation.

Table 2. Examples of surface conditions found at Balchenfjella and nunataks. A1 through C11 correspond to those in Table 1.

Balchenfjella		
	Northern part	W side···A1, A3, B1, B2, B3, B4, C2
		Central and E side···A1, A2, B1, B2, B3, B4, C1*
	Southern part	N side···A1, A4, B2, B3, B4, C1**, C7, C10
		Middle···A1, B2, B3, C2, C4, C7
		S side···A1, B3, C1, C4, C5, C7, C8, C9, C10
Austhamaren		B1, B3, B8, C1, C5, C7, C8, C9, C10, C11
Austhjelmen		B1, B2, B3, B4, C1, C6, C11
Hettene		B1, B3, B4, C1, C9
Vestkalven		B1, C1, C2, C7, C11
Hjelmkalven		B3, C1, C11
Sørhjelmen		B1, B2, B4, C1, C9
Bulken		B1, B3, C1, C9
Firlingane		B2, B4, C1
Trillingane		B1, B3, C1, C2, C5

* sidewalls of hollows only.
** top part of peaks and cliffs only.

Acknowledgments

The author would like to thank Dr. O. WATANABE, leader of JARE-29, and Dr. Y. YOSHIDA of National Institute of Polar Research (NIPR), who provided an opportunity to study the Balchenfjella area. He is also grateful to the members of the summer field party who made the investigation enjoyable. Mr. K. MORIWAKI of NIPR and Mr. T. HAYASHI of Geographical Survey Institute of Japan made available color aerial photographs taken in 1982 and black and white aerial photographs taken in 1987, respectively, for this study. This research was supported by a project funding from the University of Tsukuba.

References

ASAMI, M., MAKIMOTO, H., ANIYA, M., HAYASHI, M., IIMURA, Y., HAYASHI, T., NARAOKA, H., YONEZAWA, Y., FUJITA, S. and GREW, E. S. (1988): Sêrurondâne sanchi chigaku chôsa hôkoku 1988 (JARE-29) (Report on the geological, geomorphological and geodetic field work and meteorite search in the Sør Rondane Mountains, 1988 (JARE-29)). Nankyoku Shiryô (Antarct. Rec.), **32**, 334–363.

DEMEK, J. (1968): Cryoplanation terraces in Yakutia. Biul. Peryglacjalny, **17**, 91–116.

DEMEK, J. (1969): Cryogen processes and the development of cryoplanation terraces. Biul. Peryglacjalny, **18**, 115–125.

HIRAKAWA, K., MATSUOKA, N., TAKAHASHI, Y., SAKIYAMA, T., OSANAI, Y. and TANAKA, K. (1987): Sêrurondâne sanchi chigaku chôsatai hôkoku 1987 (JARE-28) (Report on the geological, geomorphological and geodetic field party in the Sør Rondane Mountains, 1987 (JARE-28)). Nankyoku Shiryô (Antarct. Rec,), **31**, 206–229.

HIRAKAWA, K., MATSUOKA, N. and MORIWAKI, K. (1988): Reconstruction of maximum glacial extent in the central Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosic., **2**, 146–161.

HOLTEDAHL, H. (1967): Notes on the formation of fjords and fjord-valleys. Geogr. Ann., **49A**, 188–203.

IWATA, S. (1987): Debris-mantled rectilinear slopes in the western Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 178–192.

KING, C.A.M. (1970): Feedback relationships in geomorphology. Geogr. Ann., **54A**, 66–75.

MORIWAKI, K., SHIRAISHI, K., IWATA, S., KOJIMA, S., SUZUKI, A., TERAI, K., YAMADA, S. and SANO, M. (1985): Sêrurondâne sanchi chigaku chosa hôkoku 1985 (JARE-26) (Report on the geological, geomorphological and geodetic field work in the Sør Rondane Mountains, 1985 (JARE-26)). Nankyoku Shiryô (Antarct. Rec.), **86**, 36–107.

MORIWAKI, K., KOJIMA, H., ISHIZUKA, H., MATSUOKA, N., KOMETANI, T., SHIGA, S., MORITA, T. and KURIKI, S. (1986): Sêrurondâne sanchi chigaku chôsa-tai hôkoku 1986 (JARE-27) (Report on the geological, geomorphological and geodetic field work in the Sør Rondane Mountains, 1986 (JARE-27)). Nankyoku Shiryô (Antarct. Rec.), **30**, 246–281.

SOUCHEZ, R. A. (1966): The origin of moraine deposits and the characteristics of glacial erosion in the western Sør-Rondane, Antarctica. J. Glaciol., **6**, 249–254.

SUGDEN, D. E. and JOHN, B. S. (1976): Glaciers and Landscape; A Geomorphological Approach. London, Edward Arnold, 376 p.

VAN AUTENBOER, T. (1962): Ice mounds and melt phenomena in the Sør Rondane, Antarctica. J. Glaciol., **4**, 349–354.

VAN AUTENBOER, T. and BLAIKLOCK, K. V. (1966): Ice-flow and thickness measurements in the Sør Rondane, Dronning Maud Land, Antarctica. J. Glaciol., **6**, 69–81.

(Received June 12, 1989; Revised manuscript received August 31, 1989)