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DEBRIS-MANTLED RECTILINEAR SLOPES IN THE WESTERN SØR RONDANE MOUNTAINS, EAST ANTARCTICA

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Abstract: In the western part of the Sør Rondane Mountains, slopes in the ice-free area are classified into the following seven categories: cliff or free face, ice-smoothed steep slope, areal-scouring gentle topography, till-covered steep slope, debris- and/or till-covered areal-scouring gentle topography, debris-mantled rectilinear slope, and talus slope. Among them the last two categories are well developed. Debris-mantled rectilinear slopes especially occur on the north-facing slopes in gneiss rock areas. They are characterized by smooth surface, rectilinear profiles with angles of 29°–37°, and thin debris-mantled surface. They are thought to be a kind of the Richter denudation-slope, but intensive joints occurring in the gneiss bedrock control slope configurations.

1. Introduction

Slope development in the ice-free areas of Antarctica is related so closely with the ice-free period that it offers important information on the history of the Antarctic ice sheet. In the McMurdo dry valleys, conspicuous Richter denudation-slopes (*e.g.* YOUNG, 1972, p. 107) have been developed on the glaciated valley-walls as the result of the long-lasting ice-free conditions (COTTON and WILSON, 1971; SELBY, 1971, 1974). These slopes show long and rectilinear profiles at an angle of approximately 35° with thin boulder covers.

In the western part of the Sør Rondane Mountains, East Antarctica, at about 22.5° to 23.5°E longitude and 71.9° to 72.2°S latitude, many debris-mantled hill slopes were found, when the 26th Japanese Antarctic Research Expedition (JARE-26) conducted geomorphological investigations (MORIWAKI *et al.*, 1985). Some of these slopes have rectilinear profiles at angles around 30° and seem to be the same-type slopes as those reported in the McMurdo Sound region. Geomorphological investigation of the mountains had been conducted by Belgian expeditions during the period between 1958–1965 (VAN AUTENBOER, 1964a, b; SOUCHEZ, 1966, 1967), but relatively little attention was paid to the debris-mantled slopes.

This article represents first general features of slopes in the western part of the Sør Rondane Mountains, and then describes features of the debris-mantled rectilinear slopes and discusses briefly the origin of the rectilinear profiles of these slopes.

2. Study Area

The study area is bounded by Gunnestadbreen on the east, and by the western end of Tanngarden and Otto Borchgrevinkfjellet on the west (Figs. 1 and 2). The altitude of the ice sheet surface at the northern foot of the mountains is about 1000 m above sea level, whereas that of the inland plateau to the south is nearly 2000 m. Rugged large mountain massifs with steep rocky slopes and local mountain glaciers rise over 3000 m above sea level in the central part, but peaks in the surrounding areas do not exceed 3000 m. Small nunataks are scattered around the mountains (Plate 1b). Most areas of the mountains had been covered with the ice sheet and/or mountain glaciers, and subjected to glacial erosion in the early stage of the fluctuation of the Antarctic ice sheet. With the reduction in thickness of the ice sheet, ice-smoothed and/or till-covered mountain slopes were released by ice. In addition, outlet and mountain glaciers incised the massif and shaped steep rocky walls and nunataks. In ice-free areas, slopes have been developed by periglacial and gravitational slope processes with frost and salt weathering (VAN AUTENBOER, 1964a, b; SOUCHEZ, 1966, 1967).

The study area is composed of granite, migmatite, darkgreen schist, tonalite, and various kinds of gneiss (KOJIMA and SHIRAISHI, 1986).

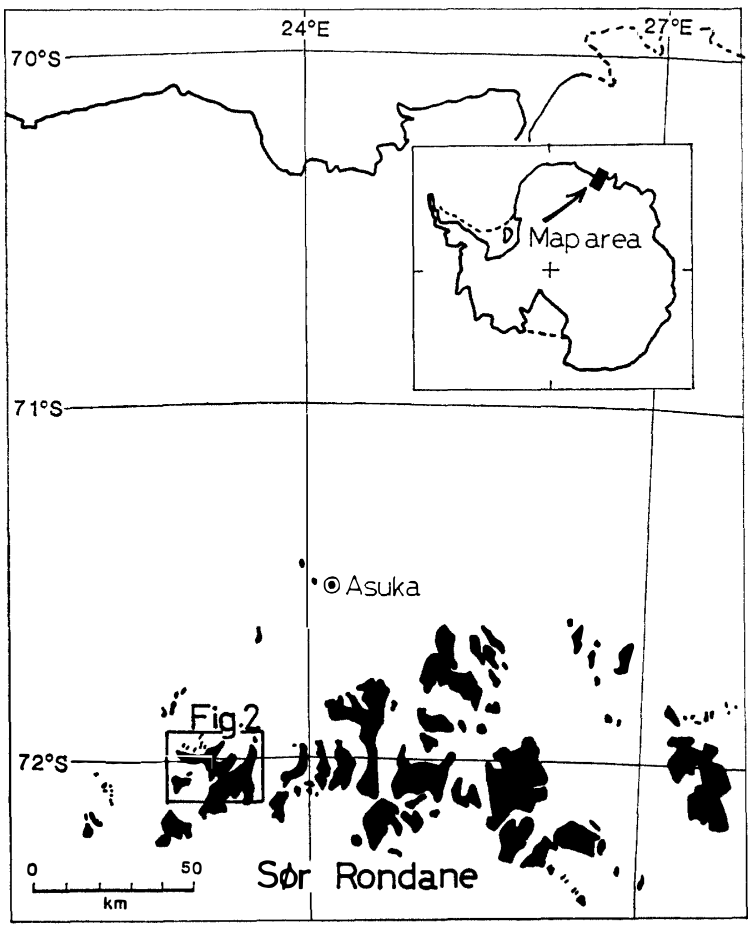


Fig. 1. Location map of the Sør Rondane Mountains showing the study area and the Asuka Camp.

Although two small-scale maps, the Sør-Rondane (1: 250000), Norsk Polar-institutt, Oslo, 1957, and LANDSAT MAP (1: 250000), Geographical Survey Institute, Japan, 1984, were completed, any large-scale map has not been published yet. Color aerial photographs, however, taken by JARE-22 (1: 50000–1: 60000 in scale) are available.

3. Debris-Mantled Slopes in the Study Area

Figure 2 shows the distribution of the debris-mantled slopes of the study area. The map was made by aerial photo-interpretation in addition to the field observations.

Slopes in the ice-free area are classified into the following types, based on the constituent materials and steepness:

1) Bedrock slopes,
   - -1. Cliff or free face,
   - -2. Ice-smoothed steep slope,
   - -3. Areal-scouring gentle topography,

2) Debris-covered slopes,
   - -1. Till-covered steep slope,
   - -2. Debris- and/or till-covered areal-scouring gentle topography,
   - -3. Debris-mantled rectilinear slope,
   - -4. Talus slope.

3.1. Bedrock slopes

3.1.1. Cliff or free face (Plate 1a, 1b)

Precipitous cliffs or free faces composed of exposed bedrock were originally formed mainly by erosion of the outlet and mountain glaciers. Some cliffs seem to maintain their original concave-features which were directly shaped by glaciers, while the others might have retreated due to glacial erosion at their feet and to weathering and rockfalls after emerging from the glaciers which covered the cliffs. The former two are called glaciated cliffs and the latter is called an exposed retreat cliff in this article. Although spectacular rock towers in the eastern and central parts and also small nunataks in the western part are considered to have been shaped by frost-action (VAN AUTENBOER, 1964b, p. 35), it is not easy to distinguish the exposed retreat cliffs from the glaciated cliffs, in the study area, so that the distinction is not indicated on the geomorphological map (Fig. 2).

3.1.2. Ice-smoothed steep slope and areal-scouring gentle topography

Some steep slopes, over about 35° in angle, with smooth concave and convex slope profiles and gentle topography composed of small-scale gentle slopes with a streamlined-relief shape are identified as glaciated landforms. In addition to these topographic configurations, the geomorphological situation which is suitable for glacial erosion is an important factor to distinguish them from other categories. Relatively smaller parts of these landforms are free from the debris-cover. Their flat or gentle bedrock surfaces, however, show completely fractured conditions where *in situ* well-weathered rock fragments were scattered and fresh bedrock surfaces could be rarely observed.

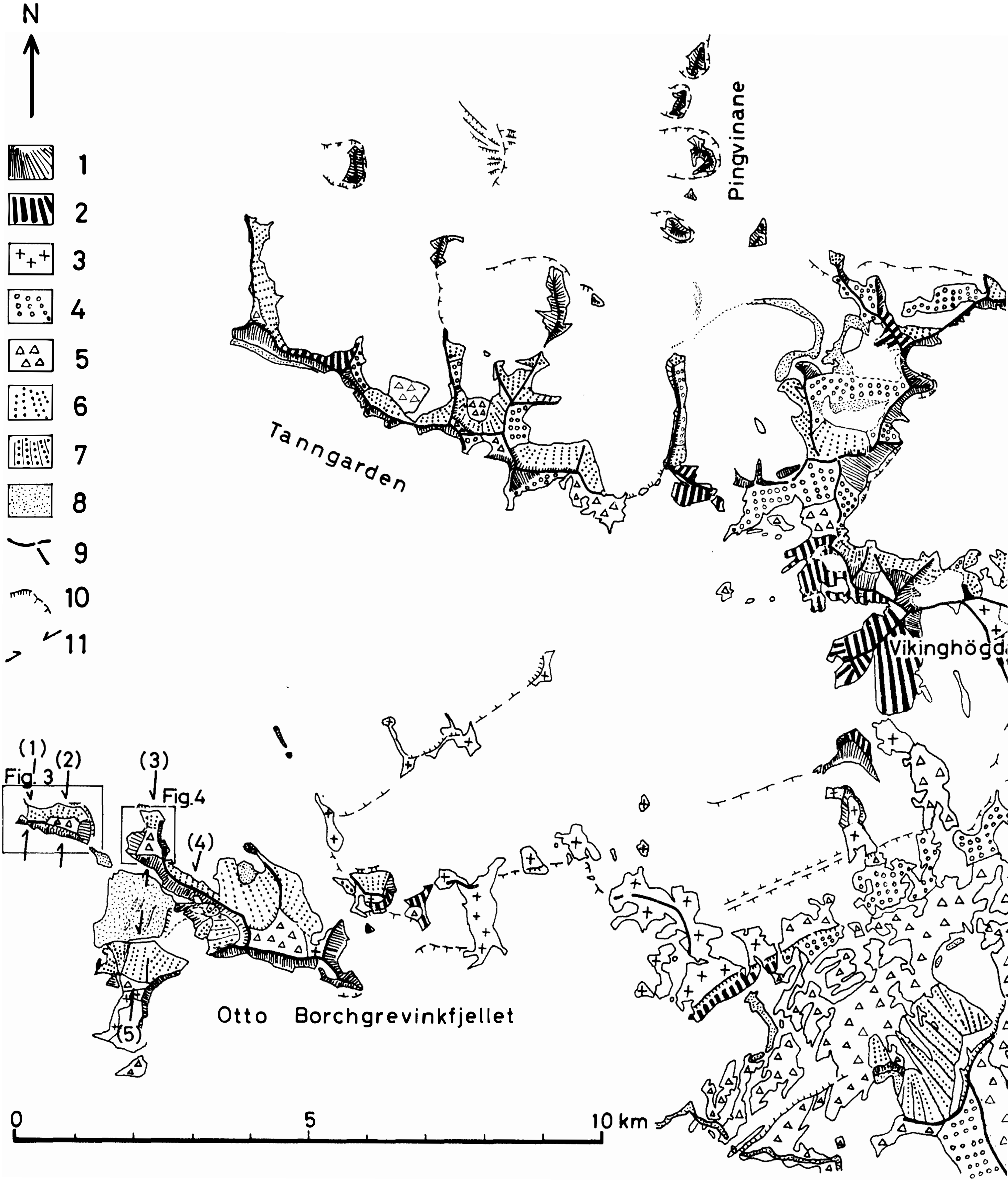
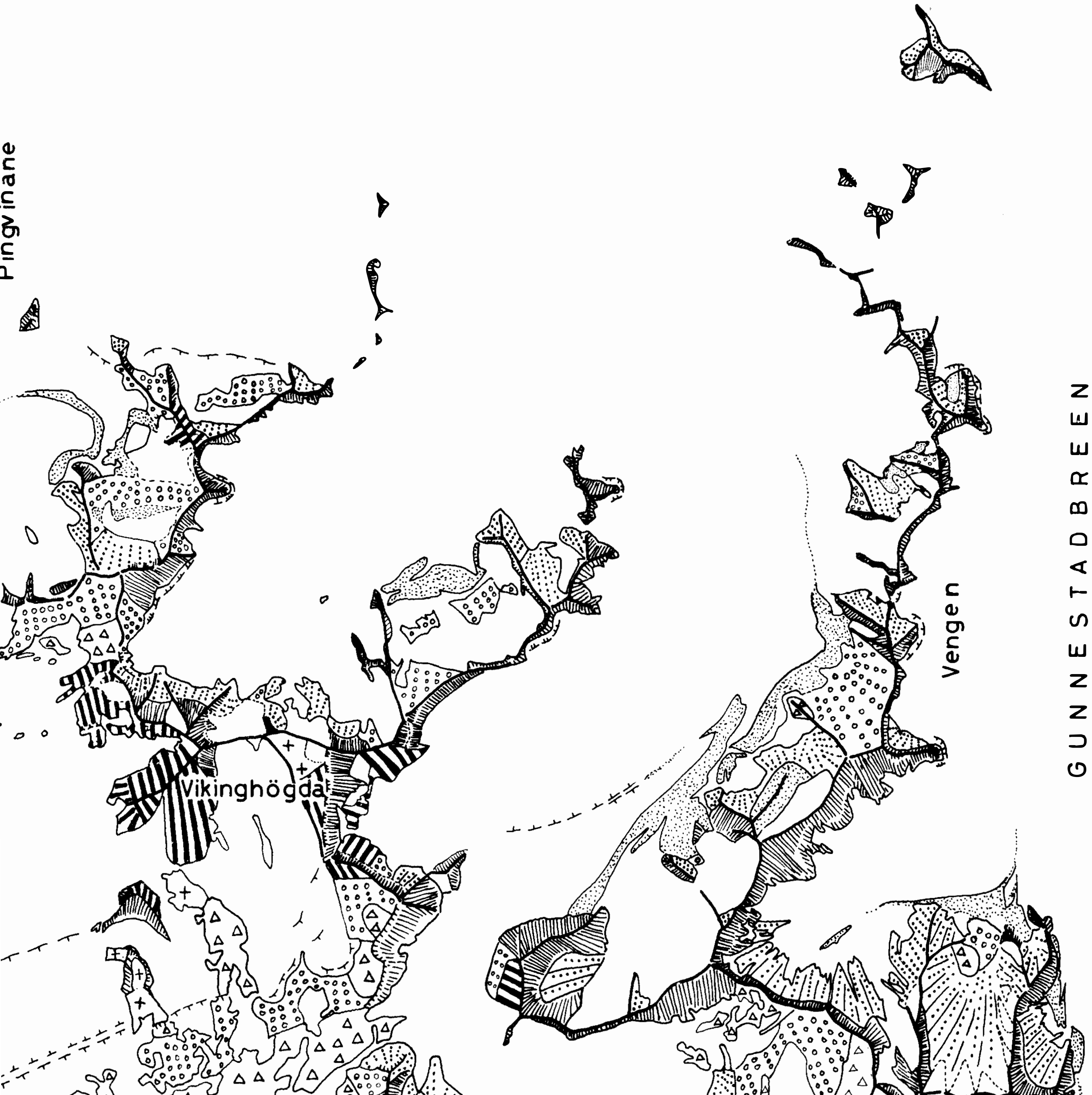


Fig. 2. Geomorphological map of the study area. 1: Cliff or free face, 2: Ice-smoothed s
4: Till-covered steep slope, 5: Debris- and/or till-covered areal-scouring gentle top
Talus slope, 8: Moraines, 9: Ridges, 10: Small cliff and change of slopes, 11: L



Cliff or free face, 2: Ice-smoothed steep slope, 3: Areal-scouring gentle topography,
ill-covered areal-scouring gentle topography, 6: Debris-mantled rectilinear slope, 7:
all cliff and change of slopes, 11: Locations of slope profiles indicated in Fig. 5.

3.2. Debris-covered slopes

3.2.1. Till-covered steep slopes and debris- and/or till-covered areal-scouring gentle topography

A greater part of the glaciated steep slopes and gentle topography is covered with glacial till or detritus which originated from the bedrock by weathering. In the field, to distinguish such weathering detritus from glacial till is not much difficult, but on the aerial photographs it is impossible to make clear distinction between these two cases.

3.2.2. Debris-mantled rectilinear slopes

Debris-mantled slopes characterized by a nearly rectilinear profile form are distributed in various places. In many cases, free faces stand at the upper end of the slopes. Figure 2 indicates that most of these slopes face to the north exposure.

3.2.3. Talus slopes

On the north-facing slopes of the high central parts of the Wideröefjellet massif, large talus slopes are formed below high free faces (Plate 1a).

According to the field observations in the western Sør Rondane Mountains and to the aerial-photo interpretation of the whole area of the Mountains by the author, the debris-mantled rectilinear slopes and talus slopes are best developed in the study area. In the other areas of the mountains, till-covered slopes are most common, while these slopes are observed in a few localities. A notable fact on the geomorphological map (Fig. 2) is that they are located on the north-facing side of the mountains, such as Wideröefjellet, Tanngarden, and Otto Borchgrevinkfjellet. On the other hand, considerable numbers of free faces and glaciated steep slopes are located on the south-facing side, on the nunataks and branch ridges in the northern part, and on the valley walls of Gunnestadbreen.

4. Debris-Mantled Rectilinear Slopes in Otto Borchgrevinkfjellet

The western part of Otto Borchgrevinkfjellet is composed of flat-topped mountains projecting 300–500 m in height from the glacier surface. On the north-facing side, debris-mantled rectilinear slopes occur nearly continuously (Plate 1c), while on the south-facing side, steep cliffs exist. These mountains represent a typical north-south asymmetrical feature (Figs. 3 and 4). Steep slopes or free faces formed by glacial erosion also occur on the eastern and western sides of these mountains. Relatively detailed observation was carried out on these slopes.

4.1. Slope form and surface features

The north-facing debris-mantled rectilinear slopes are characterized by smooth surfaces which are unfretted by gullies, and rectilinear vertical profiles (Plate 2a). Bedrock cliffs exist at the tops of some slopes, but rectilinear slopes without free face are common, where tors occurring at the tops of the slopes are observed (Plate 1c).

In the latter cases, the rectilinear slopes change to gentle convex slopes without abrupt breaks of slopes (Fig. 4).

Vertical profiles and mean inclination of these slopes are indicated in Fig. 5. The north-facing slopes represent nearly rectilinear profiles drawn by using a stereoplotter, and have angles of slopes which vary from 29° to 37°. On the other hand, the south-

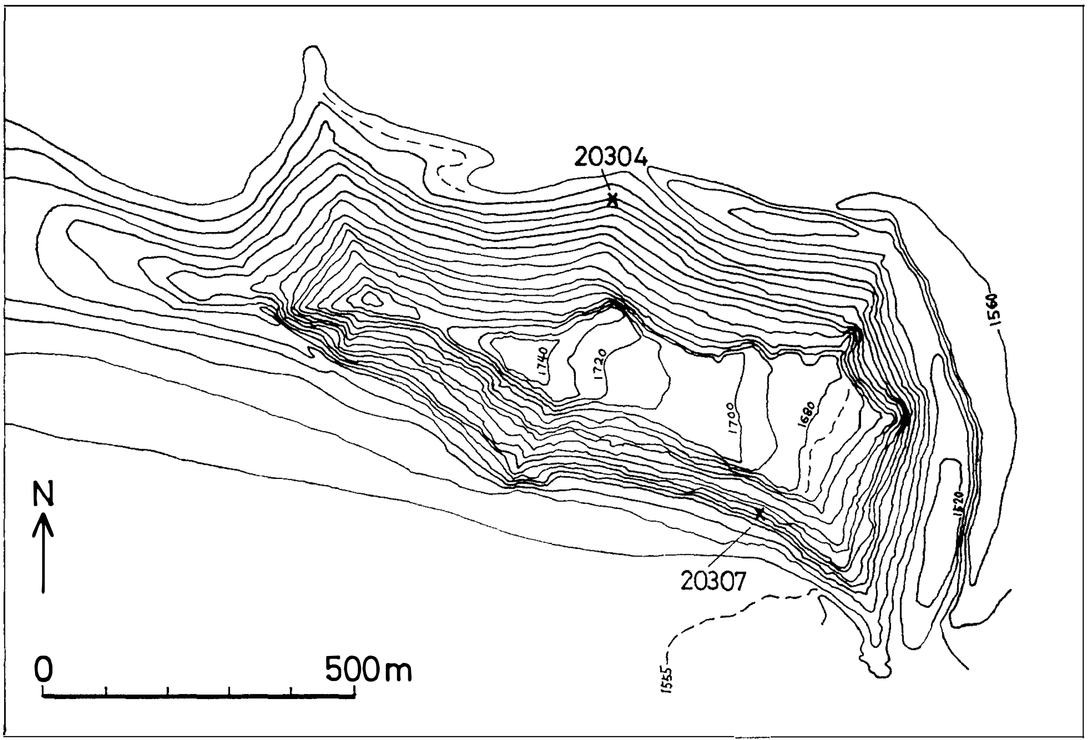


Fig. 3. Typical asymmetrical feature of slopes: showing north-facing debris-mantled rectilinear slopes with steep back wall and south-facing steep rocky slopes. Contour intervals: 10 m. The mapped area is shown in Fig. 2.

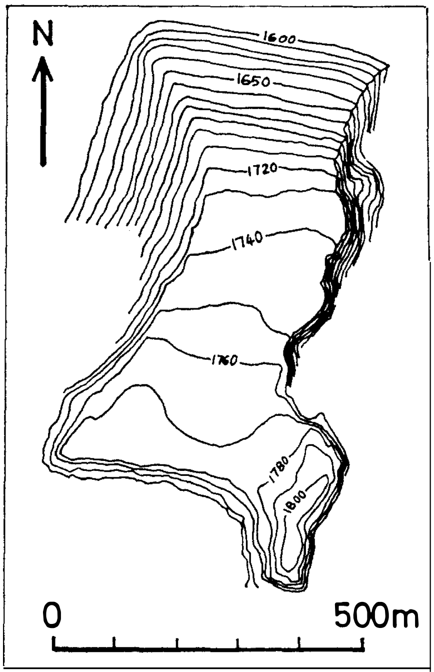


Fig. 4. North-facing debris-mantled rectilinear slopes without steep cliff. Contour intervals: 10 m. The mapped area is shown in Fig. 2.

facing slopes have concave profiles with mean angles of nearly 50°.

Horizontal shapes of the rectilinear slopes, which refer to curvature of contours, are rectilinear and slightly concave in form, as shown in Figs. 3 and 4.

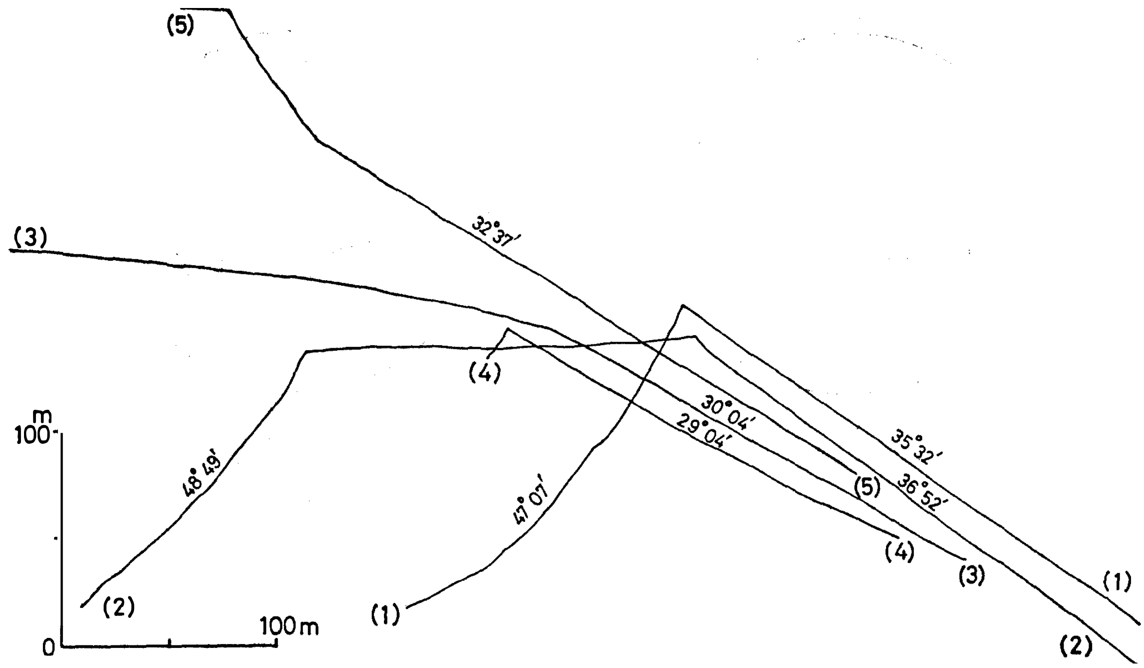


Fig. 5. Longitudinal profiles of slopes. Locations are indicated in Fig. 2.

4.2. Surface materials and bedrock structures

Detailed features of surface materials which cover the rectilinear slopes are indicated in Plate 2b. Rock fragments on the surface are angular in shape and exhibit various sizes ranging from pebbles to large blocks. Blocks larger than 1 m in size along the long axis occur abundantly. A small amount of finer materials exist below the rock fragments and in the interstices of them. Thickness of debris layers has not been measured yet, but debris layers seem to be thin veneers judging from observations at the margins of the slopes (Plate 3a, 3b). Small patches of smooth bedrock are exposed in several places and veneers of debris of only one boulder thick have been observed. These facts suggest that the debris layer is never more than 1 m thick.

The rock fragments are composed of gneissic rock derived from the bedrock in this western part, and erratic boulders and stones could be found on the slopes. The gneiss blocks represent relatively fresh features, but edges of blocks have been rounded off, and cavernous weathering features and coatings of ferric oxides are observed on the surface.

Foliations of the gneiss rocks strikes generally E-W with dips between 52° and 62°S (KOJIMA and SHIRAISHI, 1986), and various joint systems with different features are developed. Strikes and dips of the joints were measured in several points on and around debris slopes, and the results are indicated in Fig. 6. Dominant joints occur parallel to the gneiss foliation. Strikes and inclination of these joints coincide with the steep south-facing slopes (Plate 3a; Fig. 6), so that the steepness of the south-facing slopes may be controlled by these joints. On each north-facing slope, there exists a joint system corresponding to the strike and the inclination of the slope. These facts may indicate that the joint systems exert a strong influence upon the debris slope morphology.

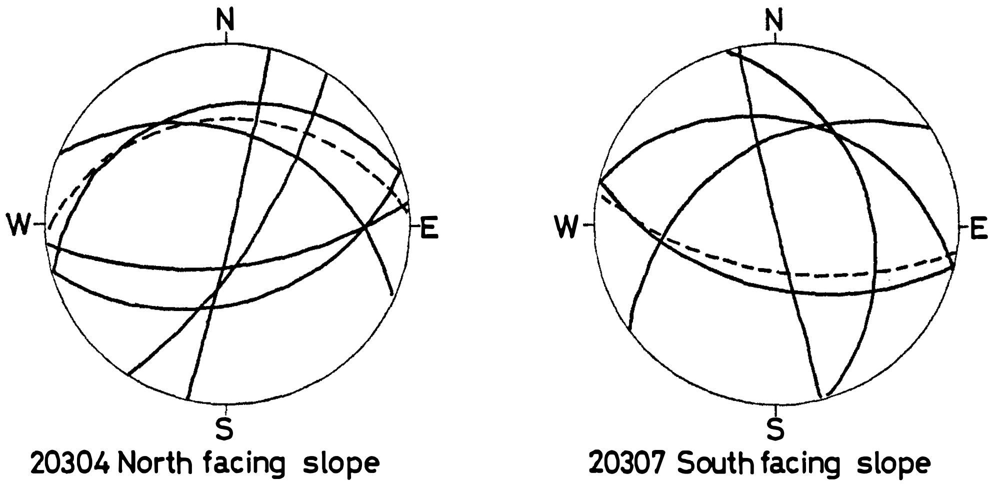


Fig. 6. Diagrams showing orientations of joints (solid lines) and slopes (broken lines) on the slopes in Fig. 3.

4.3. Surface processes on slopes

Although no quantitative measurement of slope processes has been carried out on the slopes in the study area, both observations in the field and some measurements of climatic conditions in the Sør Rondane Mountains suggest a present state of the surface processes on these slopes. It is safely stated that both salt and frost weathering occur in this region judging from the field observations, analysis of weathering materials, and measurements of the climatic conditions (VAN AUTENBOER, 1964a, b; MATSUOKA, 1986; MATSUOKA *et al.*, 1986). Rock fragments may be supplied mainly from the steep slopes above the debris slopes, but partly from the bedrock below the debris mantle in some places where the debris mantle is very thin. Downslope movements of the debris mantle surely occur, judging from clear lobate patterns of some talus surfaces (Plate 1a). The movement rate seems to be very low in most places because the debris reflecting the original bedrock structure is often observed, and large blocks are contained in the debris mantle.

At the lower ends, the debris-mantled rectilinear slopes border on glacier surface without any accumulation of debris. This suggests that the rate of debris transport from the rectilinear slopes to the glacier is very low and glaciers may remove them nearly completely.

5. Discussion

According to the distributions and features of the rectilinear debris-mantled slopes mentioned above, the origin of them is discussed below.

Rectilinear debris-mantled slopes in Antarctica are best developed on granitic rocks in the McMurdo dry valleys, as mentioned already. It is concluded that debris on slopes was supplied from back walls as the back walls retreated and the rate of salt weathering of debris on slopes is balanced with the ability of the wind to remove debris, and angles of the rectilinear sections are believed to be governed by the repose angles of the debris (SELBY, 1971, 1974). It is emphasized that there is no reason to doubt that the conspicuous development of these Richter denudation-slopes in the McMurdo dry valleys is due to the long lasting ice-free condition of the area. Initial smooth-curved slopes shaped by glaciers in the dry valleys had changed to the rectilinear debris-mantled slopes by slow but prolonged retreat of steep back wall during the entire period of Quaternary as illustrated by SELBY (1971, 1974), and COTTON and WILSON (1971).

In the Sør Rondane Mountains, glacial landforms are dominant in the central and eastern parts, while the distribution of the glacial landforms is limited in the western part. This suggests that glacial erosion was intensive in the former areas than in the latter one. In other words, the western part of the mountains, where the debris-mantled rectilinear slopes and talus slopes are developed, might have been released from the ice earlier than the other areas. The plan concavity represented by the contour lines (Figs. 3 and 4) may indicate a trace of the past glacial erosion.

The debris-mantled rectilinear and talus slopes are mostly distributed on the north-facing side of the ridges where frequent freeze-thaw cycles occur. This means the periglacial debris production is very important for the formation of these slopes.

In addition, the debris-mantled rectilinear slopes are best developed in the gneiss rock areas where intensive joint systems occur, while these slopes are less developed in the granitic rock area of which joint density is very low.

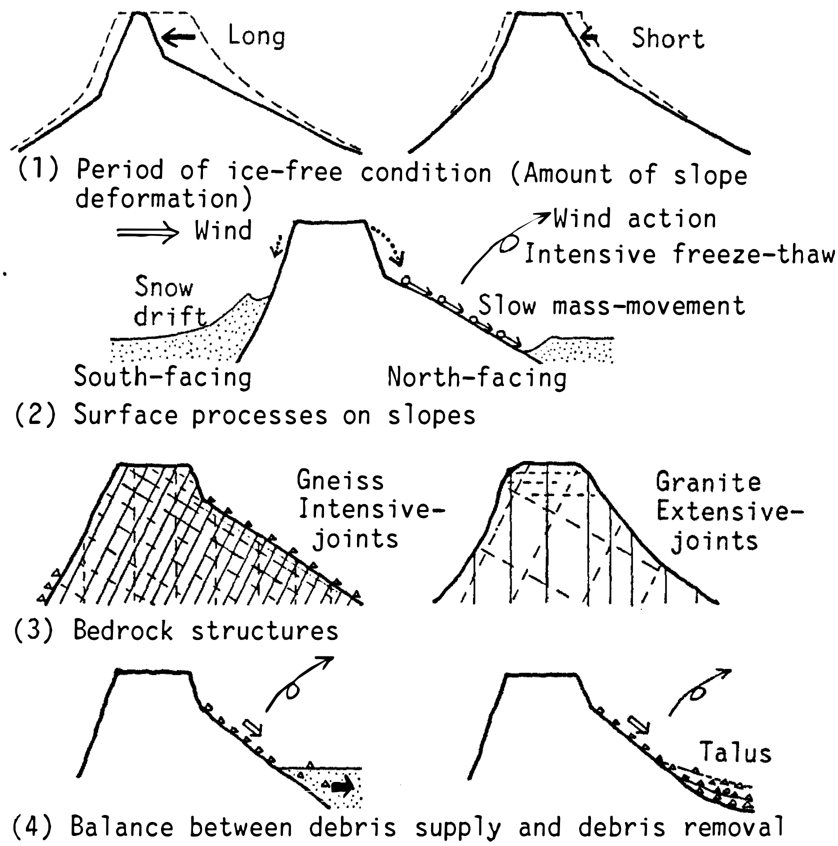


Fig. 7. Schematic situations of the debris-mantled rectilinear slopes and bedrock cliffs in the western Sør Rondane Mountains.

The facts mentioned above suggest that formation of the rectilinear debris-mantled slopes is likely to be related with the long lasting ice-free period, periglacial actions, and geologic structures. This geomorphological situation is indicated schematically in Fig. 7.

Among these, geologic structures may be most important: particularly the joint systems play an important role in controlling the configurations of the slopes. As in the case of the Richter denudation-slopes in the McMurdo dry valleys, the repose angles of the debris mantle may also govern those of the debris-mantled rectilinear slopes in the Sør Rondane Mountains. In some places on the slopes, however, the debris mantle is too thin to maintain the repose angle of the debris: sometimes only one-boulder thick debris lies on the bedrock. In such a case, inclination of the debris-mantled rectilinear slopes may be reflected by the orientation of a joint system (Figs. 6 and 7(3)). Significance of the joint orientation for the inclination of free faces and bedrock slopes has been emphasized by many authors (*e.g.* YOUNG, 1972, p. 119). KANEKO (1956) reported that inclination and profiles of debris-mantled slopes in Shirouma-dake of the Japan Alps are also controlled by the joint systems.

The importance of the joint system for the formation of the debris-mantled rectilinear slopes in the Sør Rondane Mountains is supported by that the distribution of these slopes is almost limited in the well-jointed gneiss rock area.

These slopes originated from the glaciated steep cliffs or ice-smoothed steep slopes. They developed as the Richter denudation-slopes, and the rectilinear segments spread as the steep back walls receded. It is necessary for these slopes to have enough time after they were released from the glacier ice, otherwise glaciated landforms would occupy the study area. Retreat of the rock cliffs above the debris slopes should occur by frost and salt weathering, and relatively balanced rates between the debris supply onto the slopes and the debris removal from the slopes must have existed. Relatively greater debris supply than debris removal may have formed talus slopes. Geologic structure such as a dense joint system with suitable orientations is thought to be dispensable for the formation of these slopes.

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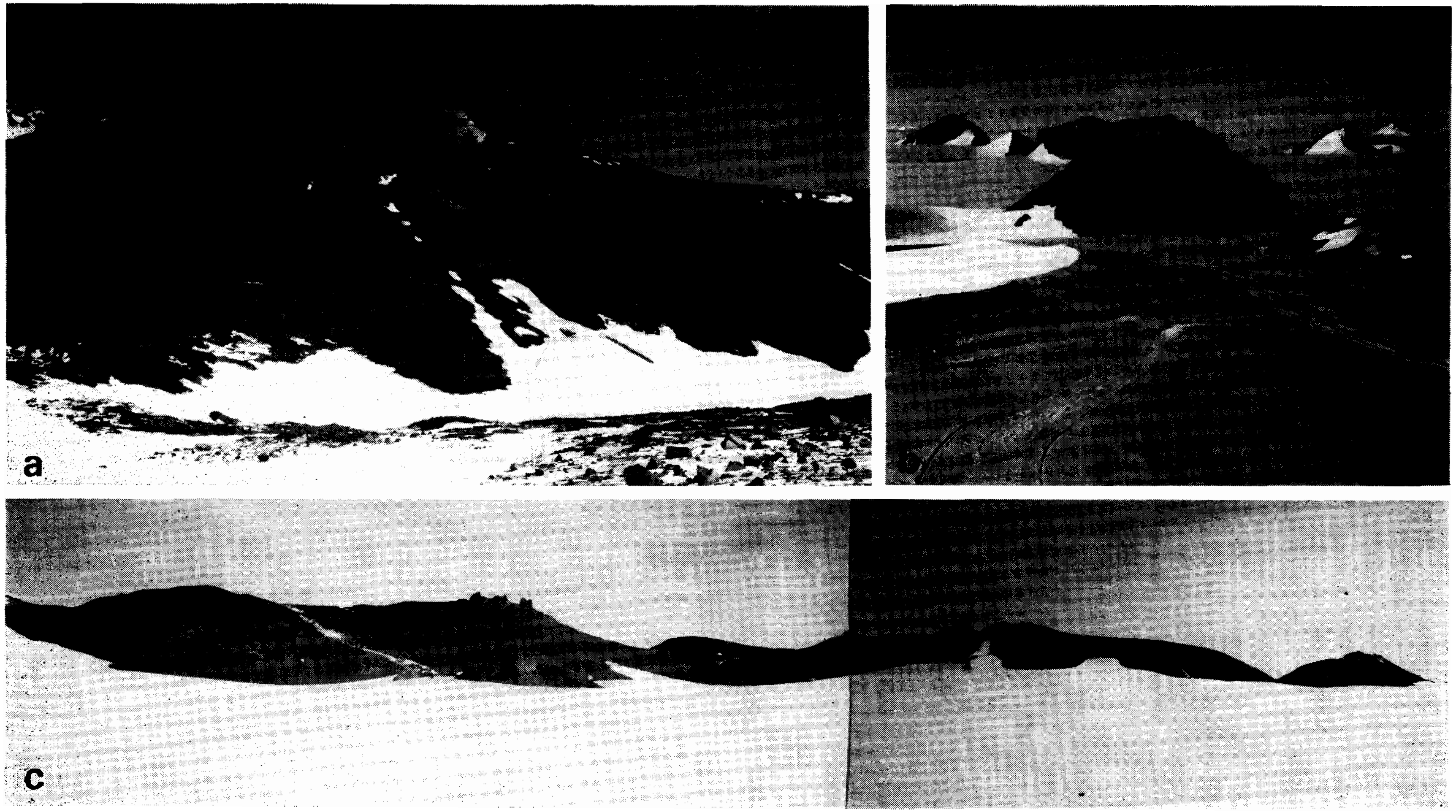

Plate 1. (a): Bedrock cliffs and talus slopes. North-facing slopes of Wideröefjellet. Lobate pattern can be recognized on the talus surface. (b): Granitic nunataks in Pingvinane. (c): North-facing slopes of the Otto Borchgrevinkfjellet.

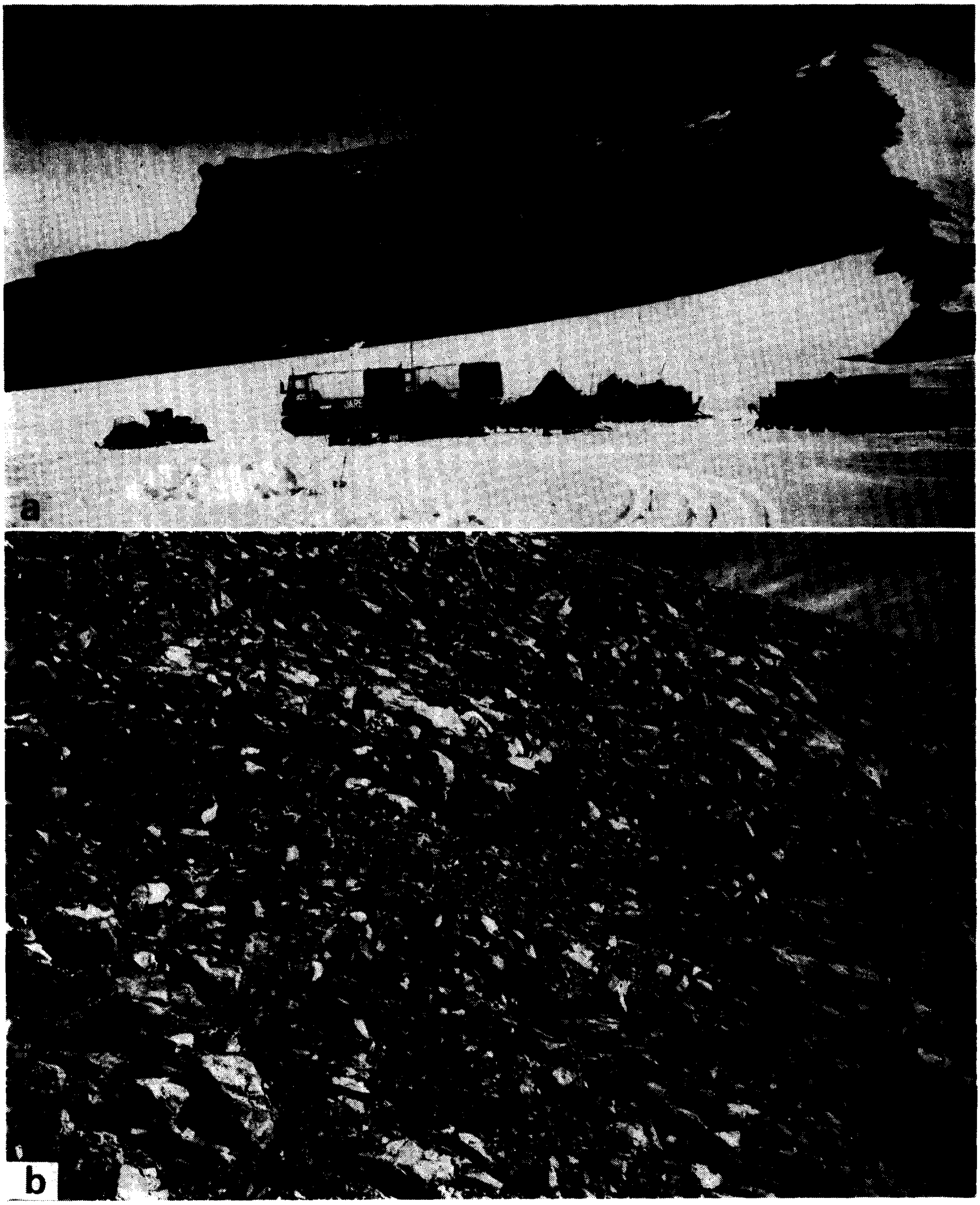

Plate 2. (a): Debris-mantled rectilinear slopes in Fig. 3. (b): Surface debris on the debris-mantled rectilinear slopes.

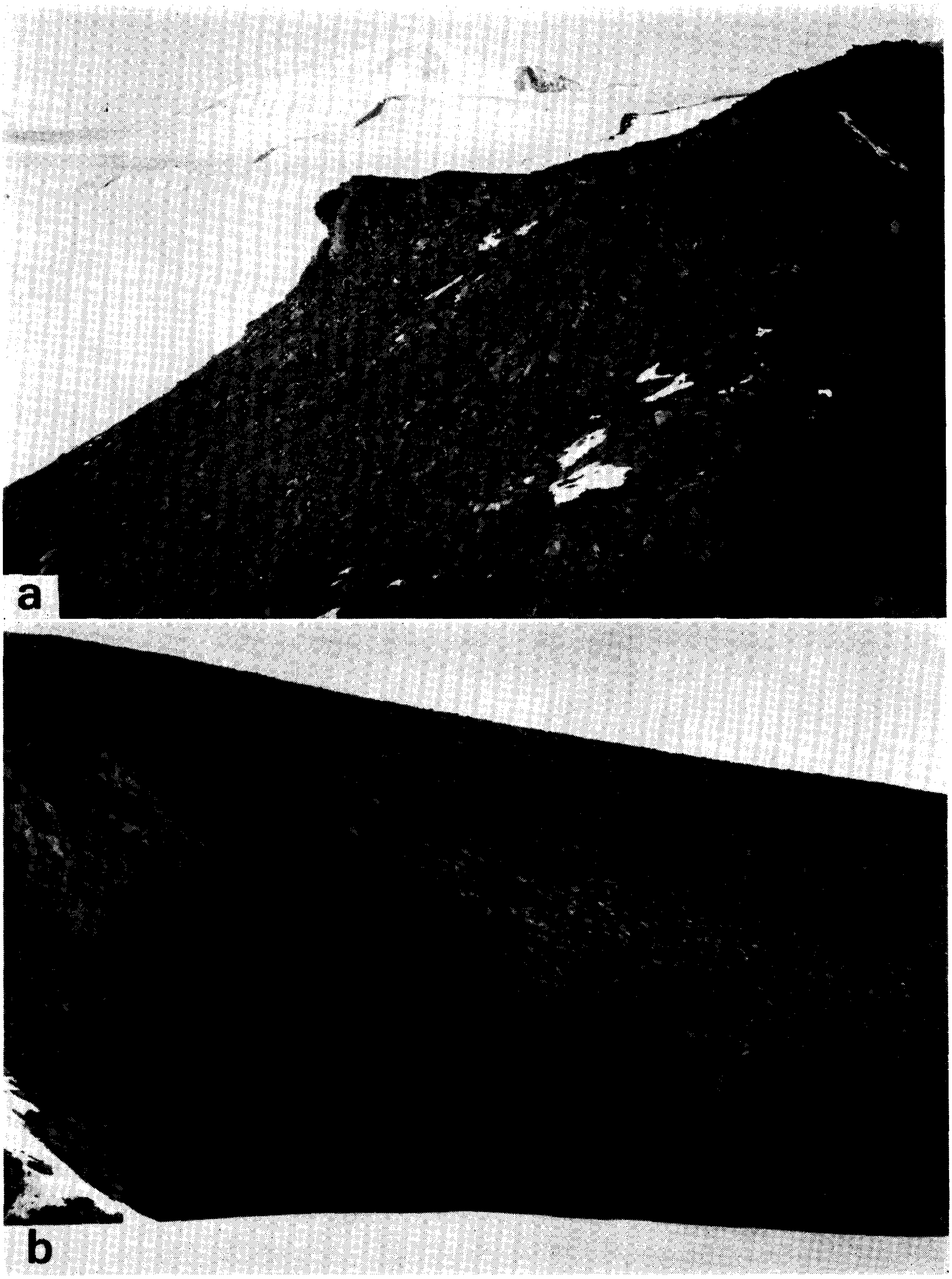

Plate 3. Bedrock structures and debris-mantled rectilinear slopes. (a): Top portion of slopes in Fig. 3. (b): The north-facing slope in Fig. 4.