HOKKAIDO UNIVERSITY

Title	Erosion of Bedrock by Subglacial Meltwater, Soya Coast, East Antarctica
Author(s)	Sawagaki, Takanobu; Hirakawa, Kazuomi
Citation	Geografiska Annaler, Series A: Physical Geography, 79(4), 223-238 https://doi.org/10.1111/j.0435-3676.1997.00019.x
Issue Date	1997-12
Doc URL	https://hdl.handle.net/2115/29664
Rights	The definitive version is available at www.blackwell-synergy.com
Type	journal article
File Information	GASA4-223.pdf

Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

Sawagaki, T. and Hirakawa, K. (1997): Erosion of bedrock by subglacial meltwater, Soya Coast, East Antaractica. Geografiska Annaler, 79A(4), 223-238.

Erosion of bedrock by subglacial meltwater, Soya Coast, East Antarctica

BY

TAKANOBU SAWAGAKI (1) and KAZUOMI HIRAKAWA (2)

(1) Research Fellow of the Japan Society for the Promotion of Science, National Institute of Polar Research, Tokyo, Japan

(2) Graduate School of Environmental Earth Science, Hokkaido University, Sapporo, Japan

Sawagaki, T. and Hirakawa, K., 1997: Erosion of bedrock by subglacial meltwater, Soya Coast, East Antarctica. Geogr. Ann.

Sawagaki, T. and Hirakawa, K. (1997): Erosion of bedrock by subglacial meltwater, Soya Coast, East Antaractica. Geografiska Annaler, 79A(4), 223-238.

Abstract

The formation of the glacial erosional bedforms at the Soya Coast of Lützow-Holm Bay, East Antarctica is discussed. The streamlined bedforms in the studied area are classified into crescentic transverse ridges and tadpole rocks, and these bedforms are accompanied by small erosional marks (s-forms) which support the interpretation of subglacial meltwater erosion. Some tadpole rocks are superimposed on a large roches moutonnée, and these two kinds of landforms are interpreted to have different modes of formation. Observations and interpretations of these bedforms are used to reconstruct the historical development of the glacial erosional bedforms, and to draw attention to the significance and implications of subglacial meltwater erosion on the marginal area of the Antarctic Ice Sheet in the past. An initial episode of glacial plucking and abrasion produced roches moutonnées and basic large-scale landforms. Subglacial meltwater flowing periodically into the Lützow-Holm Bay sculptured s-forms and streamlined bedforms in bedrock over much of the area. During this period, except for water flowing phases, ice again come in contact with the bedrock to form striations superimposed on the s-forms and the hillocks.

Introduction

The coastal ice-free areas along the Soya Coast, Queen Maud Land, East Antarctica (Figs. 1 and 2) are covered by scoured bedrock and represent zones of pronounced glacial erosion. Preserved morainic detritus is thin or limited to depressions between rockhills. In these areas, subglacial erosional bedforms have been discussed by several authors (cf. Yoshikawa and Toya, 1957; Tatsumi and Kikuchi, 1959a,b; Koaze, 1964; Fujiwara, 1973; Yoshida, 1973; Moriwaki, 1976; Omoto, 1977; Yoshida and Moriwaki, 1979; Yoshida, 1983). Yoshida (1983) reviewed these studies and summarized that most of the area had been exposed to areal scouring (Sugden and John, 1984). He also pointed out that the existence of a former wet-based ice sheet is demonstrated by glacial grooves, glacial striae, roches moutonnées and stoss-and-lee topographies. Thus, all previous studies have attributed the erosional bedforms along the Soya Coast to subglacial abrasion.

In the field surveys of the 34th and 35th Japanese Antarctic Research Expeditions (1991-1993), the authors found small-scale erosional marks and drumlin-shaped hills sculptured in bedrocks on ice-free areas along the Soya Coast (Fig. 2). While the sculptured bedforms have been recognized in the areas of previously glaciated terrain in the northern hemisphere, few similar features have been recognized in the Antarctic continent. The few and small ice-free areas in the vast Antarctic continent have made the investigation of Antarctic geomorphic development difficult. Since various debates regarding subglacial erosional bedforms and their formation processes have been discussed in the last decade (Menzies and Rose, 1989; Dardis, and MacCabe, 1994), it is also important to describe and discuss the origin of drumlins and related forms in Antarctica, which have received little attention in the previous studies.

In this paper, we first describe the classification and distribution of glacially sculptured landforms along the Soya Coast. Secondly, we assess a subglacial water erosion hypothesis accounting for the particular subglacial erosional bedforms along the Soya Coast. Finally, the historical development of the glacial erosional bedforms is discussed.

Study area

The areas of present interest are the Soya Coast and its inland area, in eastern Queen Maud Land, East Antarctica (Fig. 1).

The Soya Coast is the eastern coast of the large embayment of Lützow-Holm Bay bounded by the Riiser-Larsen Peninsula on the west and by the massive Enderby Land on the east (Fig. 2). The coast consists of a marginal slope of the ice sheet, ice streams, scattered ice-free areas, and a peripheral sea ice zone (Fig. 2). The bedrock of the ice-free areas is composed of crystalline gneisses including marble and skarn, with E-W or ESE-WNW trending structure (Yoshida *et al.*, 1976; Ishikawa *et al.*, 1977; Motoyoshi *et al.*, 1986). The bedrock surface is well polished, and these areas are inferred from their topographic features to have been covered by a formerly more extended ice sheet and subjected to glacial erosion (Yoshida, 1983).

Behind the coast, there is the second highest dome of the Antarctic Ice Sheet at 77°22'S, 39°37'E with an elevation of 3807 m (Shimizu *et al.*, 1978) (Fig. 1). The northeastern slope of the dome continues to the Mizuho Plateau.

Regionally, the present-day ice sheet at its margin flows approximately perpendicular to the coast line, from east to west or from southeast to northwest. Some outlet glaciers, such as Telen Glacier, Skallen Glacier, Rundvågs Glacier and Shirase Glacier, flow into the sea between the ice free areas (Fig. 2). Their flowing directions are SSE-NNW to SE-NW. Striations found on the deglaciated surface beyond the modern margin show that the flow directions of the formerly extended ice sheet were ranged northwestward to southwestward (Moriwaki and Yoshida, 1983; Yoshida, 1983) (Fig. 2).

The ice-free areas along the Soya Coast have been photographed several times by the Japanese Antarctic Research Expeditions, and the studied area is well covered by air photographs. Color prints were used to identify the glacial erosional landforms in a larger scale than a few tens of metres. The distribution and alignment of the sculptured erosional forms were mapped in the field, supplemented by aerial photograph interpretation.

Subglacial erosional bedforms

A number of different types of streamlined bedforms, ice-moulded depressions and smooth rock surfaces at scale ranging from less than a few metres to more than tens meters were found in the ice-free areas of Skarvsnes, Skallen, Skallevikhalsen, and Rundvågshetta districts (Fig. 2). These erosional bedforms are sculptured into bedrocks, mainly on the gneisses and less frequent in the calcareous rocks that have subsequently become more reshaped. They are generally better preserved along the southern part of the coast (Yoshida, 1983). We thus concentrated the study on these ice-free areas where the erosional bedforms are well developed.

The streamlined bedforms are ranging from less than one metre to several metres in height. A typical streamlined bedform is the rock hill with steeper stoss slope pointing up-ice. Judging from the morphology, the streamlined bedforms which we identified along the Soya Coast seem to be classified as drumlins. However, to avoid confusion with other drumlin-like features these bedforms should be called tadpole rock (Dionne, 1987) or crescentic transverse ridge (Kor *et al.*, 1991). Especially for tadpole rock, this form has a relatively similar form to that of roche moutonnée although the steeper slope is oriented in the opposite direction. This is the most important point which we note, because of the use of these forms in determining the direction of glacier movement.

Several kinds of small erosional marks were found on the streamline bedforms. Since they are similar to s-forms described by Kor *et al.* (1991), we describe the erosional marks using the terms defined by Kor *et al.* (1991). Assemblages of individual small erosional marks are closely related to the morphology of larger relief features. *Sichelwanne* and *comma-forms* (Kor *et al.*, 1991) are found on the steep stoss slopes of tadpole rocks or transverse rises. *Furrows* and *spindles* (Kor *et al.*, 1991) are found on the gentle lee slopes of tadpole rocks. In addition, *crescentic s-forms* (Kor *et al.*, 1991) tend to be replaced downglacier by longitudinal forms.

Rundvågshetta

The small erosional marks are especially frequent and well developed in

Rundvågshetta (Fig. 2). Similar features have been known to occur in Rundvågskorane (Yoshida, 1983). Figures 3, 4 and 5 show typical examples of theses features, consisting of a variety of s-forms and remnant ridges on the flat bed surface of a furrow. The furrow is approximately 20 m long and 50 cm wide and its surface gradient is less than 3 degrees. Lateral rims of the furrow are sharp and convex (Fig. 5). In contrast to this, upflow and downflow margins are merging imperceptibly with adjacent rock surface. The most remarkable s-form features are obstacle marks which consist of a proximal crescentic furrow (cf) wrapped around an upstanding obstacle of resistant bedrock, and a remnant ridge with rat-tail forms (rt) (Prest, 1983) (Fig. 3). The arms of the crescentic furrow extend leeward in a pair of furrows (f) that become shallow and wider downflow.

Skallen and Skallevikhalsen

Because the topography of these areas is rather smooth and low-relief, and because most of these forms are interpolated by geological fluctuations (Yoshida, 1983), the streamlined hills do not show distinctive stoss-and-lee forms presuming the upper reaches of the former ice flow (Figs. 6 and 7). Although it is thus rather difficult to identify the forms even from air photographs, site scale (1-10 m) forms are recognizable in the field, where the former ice flow direction can be inferred from spindle flutes (sf) on the lateral side. These forms point in the upflow direction and are broaden downflow (Fig. 8).

Individual hills are separated by troughs such as sichelwannen and comma-forms (Fig. 9) These troughs were quarried along the gneissic banding or foliation on the upper riser slope of the hills, which suggests a strong control on erosion by the bedrock structure.

The long axes of the streamlined hills show two distinctive directions; E-W and ESE-WNW. The smaller ESE-WNW trending forms seem to be superimposed on the E-W trending forms (Fig. 6). These cross-cutting relationships could be interpreted as a change both of glacial energy and the ice flow direction, during deglaciation (Rose

and Letzer, 1977; Rose, 1987; Mitchell, 1994). Beside of this, glacial striae are oriented S-N, ESE-WNW and SE-NW (Fig. 6). The S-N trending striations are thus perpendicular to the long axis of the larger streamlined bedforms.

The general trend of streamlined hills in Skallevikhalsen is E-W, perpendicular to the present-day ice movement and orientations of the glacial striae. Because of this, transverse ridges are significant streamlined bedforms in this region. On the transversely *riser slope* (rs) (Kor *et al.*, 1991) of these hills, *stoss-side furrows* (ssf) (Kor *et al*., 1991) with directions parallel to that of the striae were found (Fig. 10).

Skarvsnes

In Figure 11, the streamlined hills in Skarvsnes were mapped from interpretation of air-photographs and maps. More than 2600 examples of streamlined bedforms were found. In some cases these forms have been modified by the formation of smaller forms superimposed on the crest and flanks of the larger bedforms. These superimposed forms were also included in the population.

Most of the erosional bedforms are found in the gneisses, and the distribution of the streamlined bedforms in this region seem to be independent of the kinds of basement gneissic rocks. On the contrary to this, these bedforms were rare around the Maruyama Peak, within the eastern part of Skarvsnes (Fig. 11). This feature probably indicates that some kind of unfavorable condition for the formation of the erosional bedforms existed beneath the ice sheet on this area (e.g. basal ice would be frozen to the bedrock beneath cold-based ice sheet, which prevented the bedrock from glacial erosion).

The streamlined bedforms in Skarvsnes are classified as roches moutonnées, tadpole rocks and transverse ridges. The tadpole rocks are 5-1000 m long, and thus the larger ones are just recognizable on airphotos (Fig. 12). Longitudinal troughs parallel to the tadpole rocks form furrows. They appear on airphotos as a fluting pattern, 10-1000 m in length, 1-30 m wide, and up to 10 m deep.

Mt. Suribachi is a large rock hill, about 1500 m long and 300 m high, forming a

particular large roche moutonnée in the central part of this study area (Figs. 11, 12). The western and southwestern faces are cliffed, and talus slopes lie the foot of these cliffs. Some superimposed tadpole rocks were recognized on the southeastern flank of the stoss slope of Mt. Suribachi (Figs. 11, 12). Tadpole rocks and roches moutonnées are two glacial landforms both formed by erosion in bedrock, they display relatively similar shape, but the steeper slopes are oriented in opposite directions in relation to the ice movement. Thus, we believe that they have been formed in different way. Further interpretation of the two bedforms will be discussed later.

Large crescentic transverse ridges, 300-500 m long and 200 m wide, lie downglacier (west) of Mt. Suribachi, and a remarkable structural linear trough divides them (Fig. 12). Since the stoss side of the ridges curves gently, this ridges seem to be wrapped by a large-scale furrow. Tadpole rocks and furrows of medium-scale size (1-10 m) cluster on the stoss side of the ridges. Large tadpole rocks are found further downglacier.

In Figure 13, the population of streamlined bedforms was divided into smaller subgroups based on geological structure, and the orientations of their long axis were determined. The mean orientation is NW, but local mean directions vary from NNW to SW. Significant differences, however, are recognized in regions III and IV (Fig. 13) where the mean directions are SSE-NNW and ENE-WSW respectively ($p<0.01$, χ^2-2 sample test). In contrast, in region III, where the general geological structure trends north to south, the most of the streamlined bedforms are elongated perpendicular to the ice flow direction. They are thus classified as crescentic transverse ridges. The streamlined bedforms in the other regions are dominated by tadpole rocks, except in the transitional region (IV) where both types of streamlined bedforms exist. These features could be reflecting the geological structure of those regions carved along the gneissic banding or foliation. This fact indicates a strong control of the gneissic structure on erosion.

Discussion

The origin of the landforms

There is no doubt that the subglacial erosional bedforms in the Soya Coast are very similar features to drumlin-shaped rockhills which have been recognized in the formerly glaciated areas in the northern hemisphere (cf. Menzies and Rose, 1989; Dardis, and MacCabe, 1994), and that they show excellent examples of wet-based subglacial erosional forms. However, there have been considerable controversy surrounding the origin of drumlin-shaped bedforms or s-forms; some authors attribute them to the action of saturated till (Gjessing, 1965) and some to normal processes of subglacial abrasion (Boulton, 1974, 1979), or to meltwater activity (Dahl, 1965).

Besides this, we particularly note that the drumlin-shaped bedforms in the Soya Coast are accompanied by s-forms. Assemblages of individual s-forms are closely related to the larger morphologic features, on where they are superimposed, short and strongly curved forms are found on the steep stoss slopes of rock rises and tadpole rocks, and long and straight forms are found on the gentle slopes of rock rises and tadpole rocks. These features are similar to the morphologic relations stated by Kor *et al.* (1991) who classified erosional certain marks in bedrock in Canadian shield.

In seeking an explanation for origin for these bedforms, there have been some studies arguing in favor of a meltwater; using detailed morphological descriptions, experiments reproducing erosional marks, and analogies with bedforms created by turbulent flows (Dahl, 1965; Allen, 1982; Shaw and Kvill, 1984; Shaw and Sharpe, 1987; Shaw, 1988; Sharpe and Shaw, 1989; Shaw *et al.*, 1989; Shaw and Gilbert, 1990; Kor *et al.*, 1991; Shaw, 1994). Following Shaw (1983) and Kor *et al.* (1991), the distribution of erosional forms of several different scales is controlled by bed topography and the different scales of flow structure with some feedback between the two. In particular to the formation of drumlins in bedrock, following Allen's (1971) conclusion, Shaw (1983) proposed a local-scale (100-1000 m) flow structure of separated flows. Further more, Shaw and Sharpe (1987), Sharpe and Shaw (1989), Shaw *et al.* (1989) and Shaw (1994)

discussed horseshoe vortices in terms of several kinds of erosional bedforms. These studies rejected a glacial origin because the required vortex flow is unlikely in ice. These discussions are attributable to the bedforms along the Soya Coast.

In previously glaciated terrain, linear morphological forms aligned parallel to former ice flow are common. On the contrary to this, the trend of the streamlined bedforms in the Soya Coast regionally changes in response to geological structures, and it is clear that their directions do not always reflect the former ice sheet movement. This feature is thus also applicable to the Shaw (1983)'s model implicating that drumlins may not be oriented in the direction of glacier flow.

Consequently, the meltwater erosion may also explain the tadpole rocks, transverse ridges, s-forms and absence of drift in these areas, despite the erosional bedforms along the Soya Coast have been attributed to subglacial abrasion (Yoshida, 1983). The presumed subglacial water flow should be a regional scale sheet flow, because the streamlined bedforms occur over whole regions of the investigated areas. We thus propose an erosion model showing the development sequence of the streamlined bedforms (Fig. 14). In this Figure, the orientations of the streamlined bedforms are initially controlled by geological structure. The differences between tadpole rocks and crescentic transverse ridges are determined by the distinguished geologic lineation. These initial forms are modified by the subglacial water flow such as inferred by Shaw (1983) to form the rounded and smoothed surfaces of the streamlined bedforms.

Subglacial floods and landforms

There is a problem concerning the origin of the meltwater. In a theoretical study, Shoemaker (1991, 1992a, b) considered that the sources for large floods for the Laurentide ice sheet are thought to have emanated from a mega-subglacial lake in the Hudson Bay basin. Such water pondings or subglacial drainages are unlikely beneath the Antarctic ice sheet in the coastal zone, where the ice may be cold-based under thin ice. In contrast, subglacial lakes are known to exist beneath the interior of the Antarctic ice sheet, and presumably existed beneath Pleistocene ice sheets (Oswald and

Robin, 1973; Robin *et al*., 1977; Cudlip and McIntyre, 1987; Ellis-Evans and Wynn-Williams, 1996; Kapitsa *et al*., 1996).

Sugden *et al*. (1991), who investigated channels in part of Asgard Range in Antarctica, pointed out that it is improbable that discharges associated with steady state pressure melting can produce the volume required to cut large channels. They instead suggested that the meltwater could be produced by sudden outbursts reflecting periodic drainage of sub-glacial lakes beneath the thick ice or by sub-glacial drainage of surface lakes.

In particular along the Shirase drainage basin, the ice temperature was calculated by Nishio *et al*. (1989), and their result indicates that the base temperature is at pressure melting point between 20 km and 260 km from the coast, and the basal ice of the upper part of the basin beyond 260 km from the coast is frozen to the bed. Moreover, Mae and Naruse (1978) pointed out the possible basal sliding beneath the ice sheet of the Shirase drainage basin 200 km inland from the coast. It is also notable that unconsolidated deposits are poorly preserved in the ice-free areas along the Soya Coast. Overriding by a temperate ice sheet, and meltwater produced by sudden outbursts reflecting periodic drainage of subglacial lakes would most likely have removed any loose sediments.

Consequently, it may thus be possible to assume that ponded water in subglacial lakes in the upper reaches of the coast was evacuated to the margin by discrete subglacial floods along the basal sliding zone. Although such lakes have not been revealed up to now, we will made the further investigation on this matter in a separate paper.

Historical development of the landforms in Skarvsnes

We pointed out that the large roche moutonnée in the vicinity of Mt. Suribachi was sculpted in a way different from the superimposing tadpole rocks. The evaluation of these two kinds of bedforms gives information about temporal succession of the erosional landform generations.

In the evolution of large roches moutonnées, the link between plucking and subglacial meltwater is emphasized (Röthlisberger and Iken, 1981; Sugden *et al.*, 1992). On the contrary to this, subglacial water flow is emphasized for the tadpole rocks in this study. Accordingly, two processes can be recognized for the development of Mt. Suribachi: glacial plucking forming the steep lee slope pointing downglacier and subglacial meltwater erosion forming the superimposed tadpole rocks. Since the superimposed tadpole rocks are concentrated on the southern flank of Mt. Suribachi, the subglacial water flow forming the tadpole rocks should have been converged into this area. This feature indicates that the distribution of the erosional bedforms and the water flow pattern were controlled by the large scale bed topography (Mt. Suribachi).

Sugden *et al*. (1992) suggested that favorable conditions for plucking had existed in a zone of thin ice near the margin of ice sheets. Although they studied to mid-latitude ice sheets, their explanation also leads us to an assumption that the margin of the ice sheet was situated near the western edge of the present ice-free areas along the Soya Coast. Concerning the Holocene marine limit in this region, which reflects the regional isostatic rebound, Hayashi and Yoshida (1994) suggested that the ice sheet covering the present ice-free areas was not thick during the Last Glacial Maximum, and that the ice sheet retreated from the main areas during the period prior to 35000 yr BP.

Consequently, both processes took place near the margin of the ice sheet and these two processes must have been active almost simultaneously this large roche moutonnée could be interpreted as an older form than the superimposed tadpole rocks.

Historical development of the landforms in Skallen

The present-day movement of Skallen Glacier is northward, and three major orientations of glacial striae in Skallen had been changed from SE-NW to S-N. On the other hand, two trends of the streamlined bedforms were revealed, pointing westward for the larger bedforms, and northwestward for the smaller bedforms. Based on these features, the glacial flow direction was reconstructed to have changed from westward to northward.

The historical change of basal processes is also inferred. Thus, in the earliest stage, the bedrock was eroded by glacial abrasion and plucking beneath the wet-based ice sheet, in the same way as in Skarvsnes. In the following stage, subglacial meltwater was evacuated to the ice-margin and the pre-existed bedforms should have been destroyed or have been deformed into the larger streamlined bedforms and s-forms. This flow should be terminated in short period and was followed by glacial abrasion processes which formed the striations parallel to the larger bedforms. When the ice flow direction changed to the northwestward, another water sheet flow occurred again, which should have smaller energy than the former one, to form superimposed smaller bedforms. The last stage was dominated by glacial abrasion to form the striations parallel to the northward ice-flow directions of the present Skallen glacier. It is also assumed that the ice sheet flow in this stage has changed into a local ice stream as same as the present state of Skallen glacier. Thus, the Skallen district has been influenced by Skallen glacier until quiet recently.

The bedform evolution along the Soya Coast

Although the exact time when the erosional forms were created is still unknown, the fine preservations of the eroded bedrock along the Soya Coast probably represent the last major geomorphic activity of the Antarctic Ice Sheet, and strongly suggest an event of the subglacial water erosion of bedrock.

The above discussions are summarized in Figure 15, and we interpret and conclude bedform evolution along the Soya Coast as follows.

An initial episode of glacial plucking and abrasion produced roches moutonnées and basic large-scale landforms. Then till was probably deposited on the abraded and plucked bedrock. Later meltwater flowing into the Lützow-Holm Bay eroded s-forms and streamlined hillocks in bedrock of the greater part of the studied areas. Ice again came in contact with the bedrock, and striations were superimposed on the s-forms and the hills. Consequently, this region seems to have experienced single subglacial water flood. It is probably because the retreat of ice sheet from this region should be earlier

than Skallen.

It is expected that detailed examinations and observations are required to reveal historical change of basal thermal regime of the ice sheet which affects existence of the subglacial lake or subglacial water sheet flood in relation to the global climatic change. In addition to this, it is necessary that the distribution pattern of the bedforms is explained by subglacial water flow before we come to our final decision for subglacial meltwater genesis.

Conclusions

Followings are the revealed features and the reconstructed historical development of the erosional bedforms along the Soya Coast, in relation to the possible subglacial water erosion processes.

(1) The streamlined bedforms were observed over whole regions of in the southern part of the Soya Coast. They are composed of tadpole rocks, transverse ridges and roches moutonnées, and those are accompanied by s-forms.

(2) The streamlined bedforms are classified into several groups based on their orientation and scale, which are basically controlled by the basement rock structure and secondly modified by subglacial erosion processes.

(3) The sculptured bedforms strongly suggest the subglacial water erosion for their genesis, and the inferred subglacial water flow must have been a water sheet-flow, judging from the areal distribution of the erosional bedforms in the Soya Coast.

(4) The source of meltwater should be attributed to the subglacial lakes beneath the upper reaches of the Mizuho Plateau. However, existence of these lakes has not been revealed yet.

(5) The link between plucking and subglacial meltwater is emphasized in the evolution of the large roches moutonnée and the superimposing tadpole rocks. The subglacial condition required for the evolution of roches moutonnées supports the assumption that the former ice sheet that took part in the development of the drumlin-shaped hills extended to the western edge of the present ice-free areas along the Soya Coast.

(6) The bedform evolution along the Soya Coast was reconstructed as follows: An initial episode of glacial plucking and abrasion produced roches moutonnées and basic large-scale landforms. Meltwater flowing periodically into the Lützow-Holm Bay sculptured s-forms and streamlined bedforms in bedrock of the greater part of the areas. During this period, except for water flowing phases, ice again come contact with the bedrock to form striations superimposed on the s-forms and the hills.

Acknowledgements

This research was supported by a grant-in-aid for scientific research from the Japan Society for the Promotion of Science. We would like to acknowledge the members of the 33th, 34th and 35th Japanese Antarctic Research Expeditions for their kind collaboration in the field. We gratefully acknowledge the sincere advice and discussion of .Prof. Y. Ono, Prof. R. Naruse, Prof. T. Watanabe, and Dr. Y. Kurashige of Hokkaido University. Thanks are also due to Prof. Y. Yoshida of Rissho University, Prof. K. Moriwaki of Japanese National Institute of Polar Research, and Dr. D. Zwartz of the Australian National University for their help for improving this paper.

References cited

Allen, J. R. L., 1971: Transverse erosional marks of mud and rock: their physical basis and geological significance. *Sedimentary Geology*, 5, Spec. Issue Nos. 3-4, 167-385.

------- 1982: Sedimentary Structures, 2 vols. Amsterdam: Elsevier.

Boulton, G. S., 1974: Processes and patterns of glacial erosion. In D. R. Coates (Eds.), Glacial geomorphology (pp. 41-87) New York: State University of New York.

-------1979: Processes of glacier erosion on different substrata. *Journal of Glaciology,* 23, 15-37.

Cudlip, W. and McIntyre, N. F., 1987: Seasat altimeter observations of an Antarctic "lake". *Annals of Glaciology*, 9, 55-59.

Dahl, R., 1965: Plastically sculptured detail forms on rock surface in northern Nordland, Norway. *Geogr. Ann.*, 47A, 83-140.

Dardis, G. F., and MacCabe, A. M., 1994: Subglacial processes, sediments and landforms-an introduction. *Sedimentary Geology*, 91, 1-5.

Dionne, J. C., 1987: Tadpole rock (rocdrumlin): A glacial stream moulded form. In Menzies, J. and Rose, J. (Eds), Drumlin Symposium (pp. 149-159) Rotterdam: Balkema.

Ellis-Evans, C. J. and Wynn-Williams, D., 1996: A great lake under the ice. *Nature* , 381, 644-646.

Fujiwara, K., 1973:The landforms of the Mizukumi Zawa near Syowa Station, East Antarctica). *Nankyoku Shiryo (Antarct. Rec.)*, 46, 44-66 (in Japanese).

Gjessing, J., 1965: On "plastic scouring" and "subglacial erosion". *Norsk Geografisk Tidsskrift*, 20, 1-37.

Hayashi, M. and Yoshida, Y., 1994: Holocene raised beaches in the Lützow-Holm Bay region, East Antarctica. *Mem. Natl Inst. Polar Res. Spec. Issue.*, 50, 49-84.

Ishikawa, T., Yanai, K., Matsumoto, Y., Kizaki, K., Kojima, S., Tatsumi, T., Kikuchi, T. and Yoshida, M., 1977: Geological map of Skarvsnes, Antarctica.

Explanatory text. In Tokyo: Natl Inst. Polar Res.

Kapitsa, A. P., Ridley, J. K., Robin, G. D. Q., Siegert, M. J. and Zotikov, I. A., 1996: A large deep freshwater lake beneath the ice of central East Antarctica. *Nature*, 381, 684-686.

Koaze, T., 1964: The landform of the northern part of Prince Harald Coast, East Antarctica). *Nankyoku Shiryo (Antarc. Rec.)*, 20, 61-74 (in Japanese).

Kor, P. S. G., Shaw, J. and Sharpe, D. R., 1991: Erosion of bedrock by subglacial meltwater, Georgian Bay, Ontario: A regional view. *Canadian Journal of Earth Science*, 28, 623-642.

Mae, S. and Naruse, R., 1978: Possible cause of ice sheet thinning in the Mizuho Plateau. *Nature* , 273, 291-292.

Menzies, J., and Rose, J., 1989: Subglacial Bedforms - an introduction. *Sedimentary Geology*, 62, 117-122.

Mitchell, W. A., 1994: Drumlins in ice sheet reconstructions, with reference to the western Penines, northern England. *Sedimentary Geology*, 91, 313-331.

Moriwaki, K., 1976: Glacio-geomorphological observations in and around ice-free areas in the vicinity of Syowa Station, Antarctica. *Nankyoku Shiryo (Antarct. Rec.)*, 57, 24-55 (in Japanese).

Moriwaki, K. and Yoshida, Y., 1983: Submarine topography of Lützow-Holm Bay, Antarctica. *Mem. Natl Inst. Polar Res. Spec. Issue*, 28, 247-258.

Motoyoshi, Y., Matsueda, H., Matsubara, S., Sasaki, K. and Moriwaki, K., 1986: Geological Map of Rundvågskollane and Rundvågshetta. In Tokyo: Natl Inst. Polar Res.

Nishio, F., Mae, S., Ohmae, H., Takahashi, S., Nakawo, M. and Kawada, K., 1989: Dynamical behavior of the ice sheet in Mizuho Plateau, East Antarctica. Proc. *NIPR Symp. Polar Meteorol. Glaciol.*, 2, 97-104.

Omoto, K., 1977: Geomorphic development of Soya Coast, East Antarctica - Chronological interpretation of raised beaches based on levellings and radio carbon datings. *Sic. Rep. Tohoku Univ. 7th Ser (Geogr.)*, 24, 205-209.

Oswald, G. K. and Robin, G. D. Q., 1973: Lakes beneath the Antarctic ice sheet. *Nature*, 245, 251-254.

Prest, V. K., 1983: Canada's heritage of glacial features. *Geological Survey of Canada Miscellaneous Report*, 28, 119.

Robin, G. D. Q., Drewry, D. J. and Meldrum, D. T., 1977: International studies of ice sheet and bedrock. Philosophical *Transactions of the Royal Society of London, Series B* , 279, 185-196.

Rose, J., 1987: Drumlins as part of a glacier bedform continuum.form. In Menzies, J. and Rose J. (Eds.), Drumlin Symposium (pp. 103-116) Rotterdam: Balkema.

Rose, J. and Letzer, J. M., 1977: Superimposed drumlins. J*ournal of Glaciology*, 18(80), 471-480.

Röthlisberger, H. and Iken, A., 1981: Plucking as an effect of water-pressure variations at the glacier bed. *Annals of Glaciology,* 2, 57-62.

Sharpe, D. R. and Shaw, J., 1989: Erosion of bedrock by subglacial meltwater, Cantley, Quebec. *Geological Society of America Bulletin,* 101, 1011-1020.

Shaw, J., 1983: Drumlin formation related to inverted melt-water erosional marks. *Journal of Glaciology*, 29(103), 461-479.

-------1988: Subglacial erosional marks, Wilton Creek, Ontario. *Canadian Journal of Earth Science*, 25, 1256-1267.

-------1994: Hairpin erosional marks, horseshoe vortices and subglacial erosion. *Sedimentary Geology*, 91, 269-283.

Shaw, J. and Gilbert, R., 1990: Evidence for large-scale subglacial meltwater flood events in southern Ontario and northern New York State. *Geology*, 18, 1169-1172.

Shaw, J. and Kvill, D., 1984: A glaciofluvial origin for drumlins of the Livingston Lake area, Saskatchewan. Canadian Journal of Earth Science, 21, 1442-1459.

Shaw, J., Kvill, D. and Rains, B., 1989: Drumlins and catastrophic subglacial floods. *Sedimentary Geology*, 62, 177-202.

Shaw, J. and Sharpe, D. R., 1987: Drumlin formation by subglacial meltwater erosion.

Canadian Journal of Earth Science, 24, 2316-2322.

Shimizu, H., Yoshimura, A., Naruse, R., and Yokoyama, K., 1978: Morphological features of the ice sheet in Mizuho Plateau. *Mem. Natl Inst. Polar Res. Spec. Issue*, 7, 14-25.

Shoemaker, E. M., 1991: On the formation of large subglacial lakes. *Canadian Journal of Earth Science*, 28, 1975-1981.

------1992a: Subglacial floods and the origin of low-relief ice-sheet lobes. *Journal of Glaciology*, 38(128), 105-112.

------1992b: Water sheet outburst floods from the Laurentide Ice Sheet. *Canadian Journal of Earth Science,* 29, 1250-1264.

Sugden, D. E., Denton, G. H. and Marchant, D. R., 1991: Subglacial meltwater channel systems and ice sheet overriding, Asgard Range, Antarctica. *Geogr. Ann.*, 73A (2), 109-121.

Sugden, D. E., Glasser, N. and Clapperton, C. M., 1992: Evolution of large roches moutonneés. *Geogr. Ann.*, 74A (2-3), 253-264.

Sugden, D. E. and John, B. S., 1984: Glaciers and Landscape. New York: Edward Arnold.

Tatsumi, T. and Kikuchi, T., 1959a: Report of geomorphological and geological studies of the wintering team (1957-58) of the first Japanese Antarctic Research Expedition, Part 1. *Nankyoku Shiryo (Antarct. Rec.)*, 7, 1-16 (in Japanese).

-------1959b: Report of geomorphological and geological studies of the wintering team (1957-1958) of the first Japanese Antarctic Research Expedition, Part 2. *Nankyoku Shiryo (Antarct. Rec.)*, 8, 1-21 (in Japanese).

Yoshida, M., Yoshida, Y., Ando, H., Ishikawa, T. and Tatsumi, T., 1976: Geological map of Skallen. In Tokyo: Natl Inst. Polar Res.

Yoshida, Y., 1973: Geomorphology of the ice-free areas and fluctuation of the ice sheet, In K. Kusunoki (Eds.), Nankyoku (pp. 237-381) Tokyo: Kyoritsu Shuppan (in Japanese).

-------1983: Physiography of the Prince Olav and the Prince Harald Coasts, East

Antarctica. *Mem. Natl Inst.Polar Res. Series C (Earth Science)*, 13, 1-76.

Yoshida, Y. and Moriwaki, K., 1979: Some consideration on elevated coastal features and their dates round Syowa Station Antarctica. Mem. Natl Inst. Polar Res. Spec. Issue, 13, *Proceedings of the seminar III on Dry Valley Drilling Project*, 202-226.

Yoshikawa, Y. and Toya, H., 1957: Report on geomorphological results of Japanese Antarctic Research Expedition, 1956-57. *Nankyoku Shiryo (Antarct. Rec.)*, 1, 1-13 (in Japanese).

Figure Captions

Fig. 1 Index map and ice surface landforms of East Queen Maud Land.

Fig. 2 Index map of the Soya Coast modified from map of Yoshida (1983). The black arrows show former ice movement indicated by glacial striation. Dashed arrows show the present ice movement.

Fig. 3 S-forms sculptured along the lateral side of a streamlined bedforms in Rundvågshetta, and its vertical stereogramatic views. Furrows (f) are quarried around the bumps with a rat-tail remnant ridge (rt). Flow direction is indicated by an arrow.

Fig. 4 A furrow (f) sculptured into the genetic bedrock in Runvågshetta. Flow direction is indicated by an arrow.

Fig. 5 Sketches and vertical sections of a furrow composed of s-forms in Rundvågshetta (Fig. 3).

Fig. 6 Distribution of surficial deposits and streamlined bedforms in Skallen. The long axes of the streamlined hills show two distinctive directions (E-W and ESE-WNW). The E-W trending forms are superimposed by the smaller ESE-WNW trending forms.

Fig. 7 Streamlined bedforms in Skallen. The inferred ice flow direction is approximately from right to left.

Fig. 8 Spindle flutes (sf) and lateral furrow (lf) cut into a lateral side of a streamlined hill in Skallen. Former ice flow direction (arrow) is inferred from these marks which points in the upflow direction and broaden downflow.

Fig. 9 Sichelwanne with main furrow (mf), lateral furrow (lf) and median ridge (mr) in Skallen. Individual streamlined hills are separated by these furrows.

Fig. 10 Stoss-side furrows (ssf) are attached on the foot of the transversely riser slope (rs) in Skallevikhalsen. The general trend of streamlined hills in Skallevikhalsen is E-W, perpendicular to present-day ice movement and orientations of glacial striae. The direction of stoss-side furrows adjusts with the striations and they indicate that former ice movement was east to west as

same as present one.

Fig. 11 Distribution of streamlined bedforms in the Skarvsnes. Each form is shown by its plan form. Inner square indicates the area photographed in Fig. 12.

Fig. 12 An air photograph taken by JARE-34 showing the topography around Mt. Suribachi which is a large rock hill forming a particular large roches moutonnée. The western and southwestern faces are cliffed, and taluses are formed in the lee of these cliffs. Some superimposed tadpole rocks with steeper slopes points upflow are recognized on the southeastern flank of the stoss slope of Mt. Suribachi. A large crescentic transverse ridge, lies in the downstream of Mt. Suribachi, and a remarkable structural linear trough divides them.

Fig. 13 Regional variations in the long axis trends of the streamlined bedforms in Skarvsnes. The population of streamlined hills was divided into smaller subgroups based on geological structure. The mean direction is northwestward, and regional mean directions vary from northwest to southwest. Significant differences are recognized in regions III and IV where the mean directions are NNW and WSW respectively. These features could be reflecting the geological structure of those regions carved along the gneissic banding or foliation, which indicates a strong control of the gneissic structure on erosion.

Fig. 14 Idealized sketches of the development of streamlined bedforms considering the effect of geological structure (A) and subglacial water flow structure (B) to form the sculptured bedforms. The orientation of the streamlined bedforms are initially controlled by geological structure. The differences between tadpole rock and crescentic transverse ridge is determined by the distinguished geologic lineation. These initial forms are modified by the separated subglacial water flow to form the rounded and smoothed surfaces of the streamlined bedforms.

Fig. 15 Distribution of cross-cut bedforms and striations in relation to the ice sheet

geometry and subglacial condition of water. Under the wet ice sheet glacial plucked and abraded bedforms were created, which belong to the earlier phase of ice flow. In the following stage subglacial meltwater flood occurred to erode s-forms and streamlined bedforms. Ice came contact again with the bedrock, and striations were superimposed on the s-forms and the hillocks. In Skallen another water sheet flow occurred, which had smaller energy than the former one, to form superimposed smaller bedforms. The last stage was dominated by glacial abrasion to form the striations parallel to the directions of the present Skallen glacier. The ice geometry in this stage have changed into a local ice stream. The Skarvsnes region seems to have experienced single subglacial water flood, owing to the earlier retreat of ice sheet than the Skallen region.

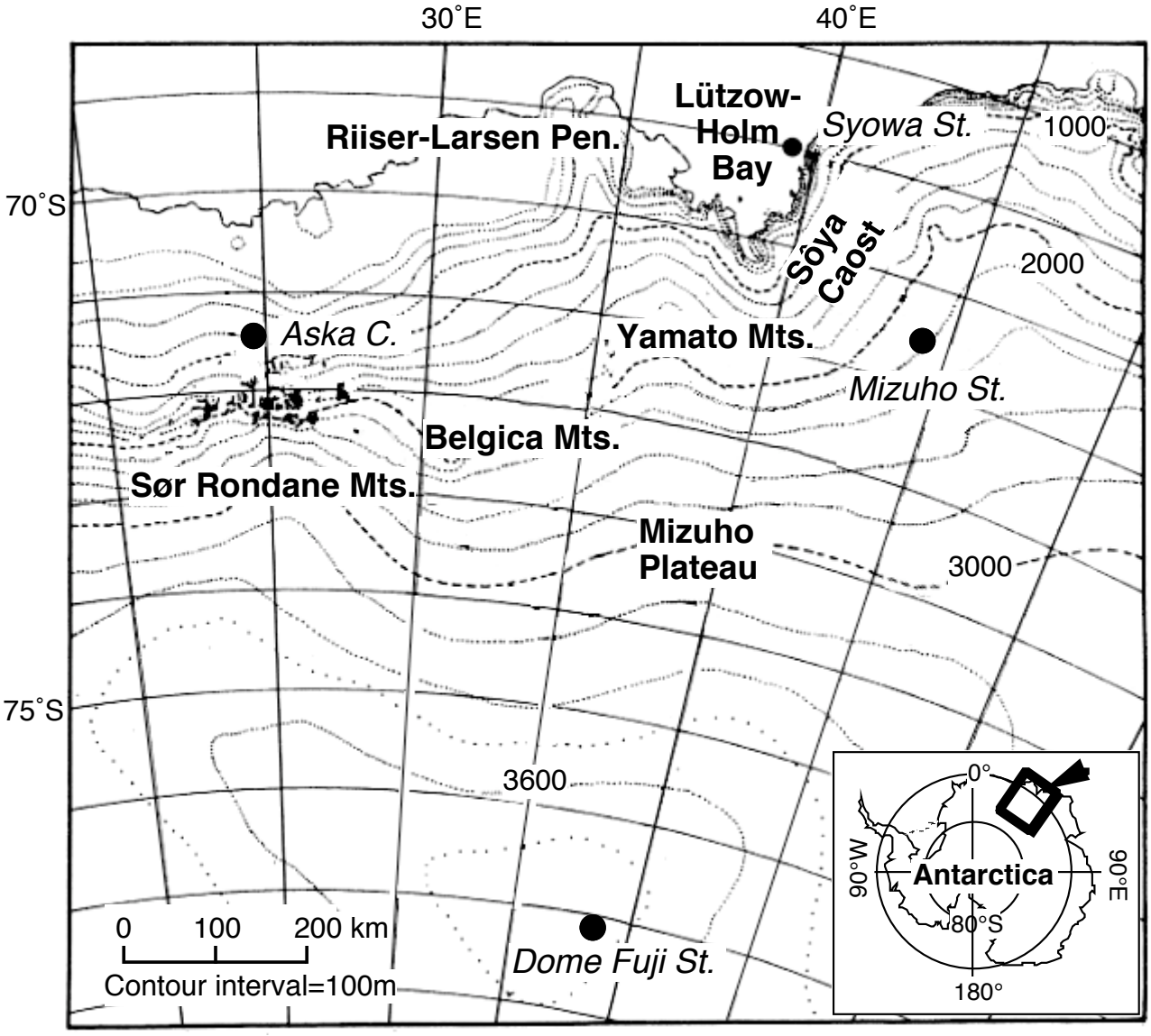


Fig. 1 Index map and ice surface landforms of East Queen Maud Land.

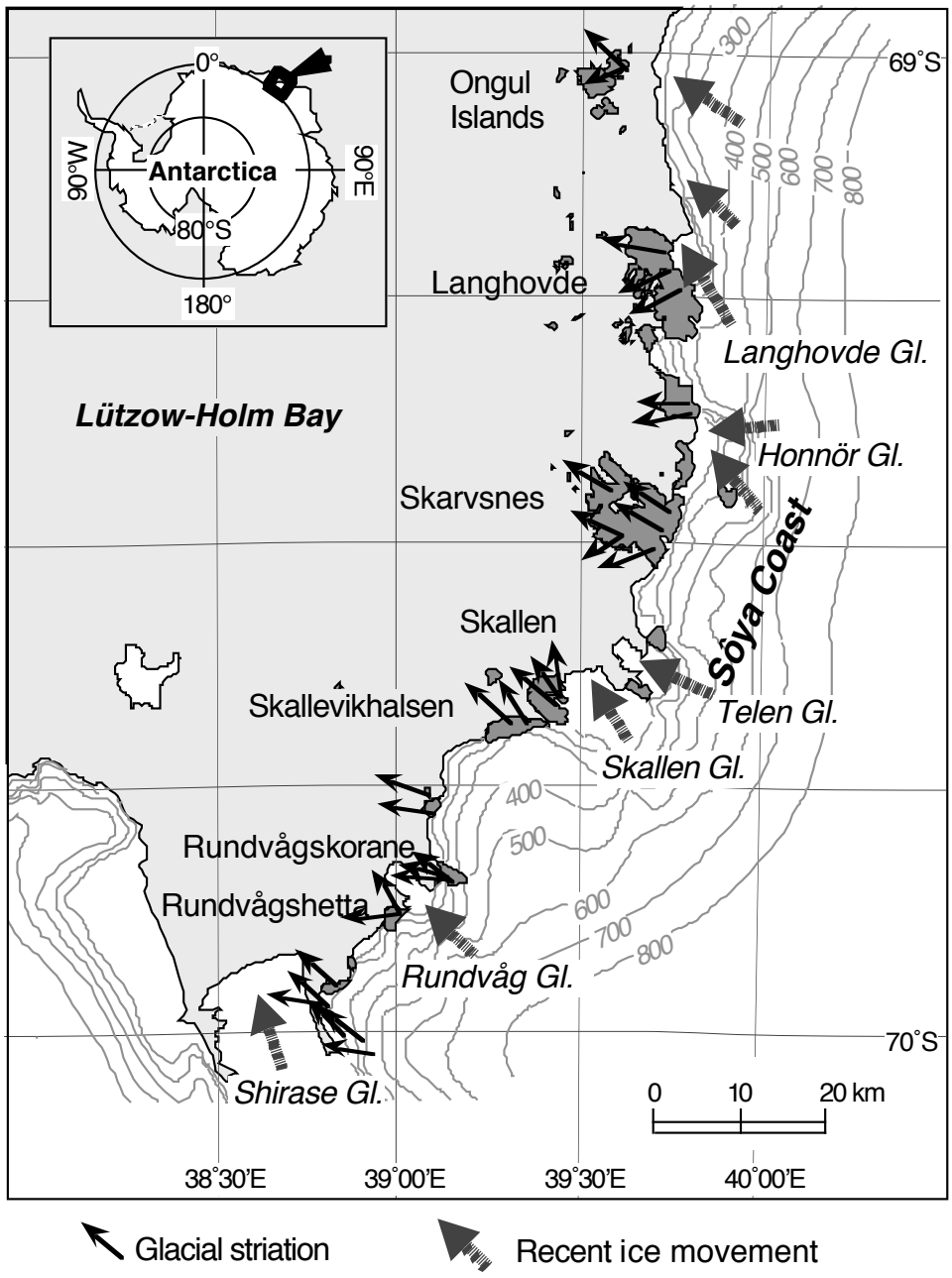


Fig. 2 Index map of the Soya Coast modified from map of Yoshida (1983). The black arrows show former ice movement indicated by glacial striation. Dashed arrows show the present ice movement.

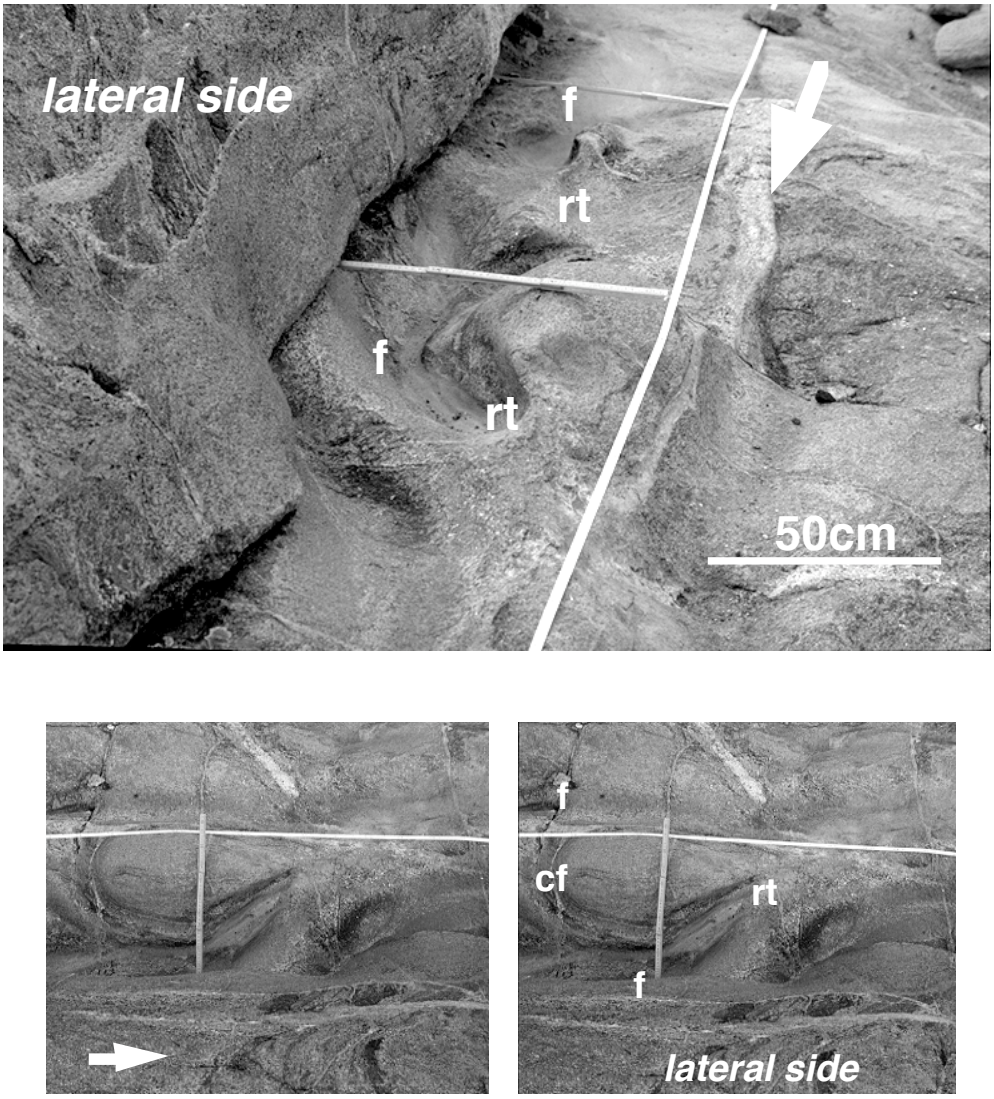


Fig. 3 S-forms sculptured along the lateral side of a streamlined bedforms in Rundvågshetta, and its vertical stereogramatic views. Furrows (f) are quarried around the bumps with a rat-tail remnant ridge (rt). Flow direction is indicated by an arrow.

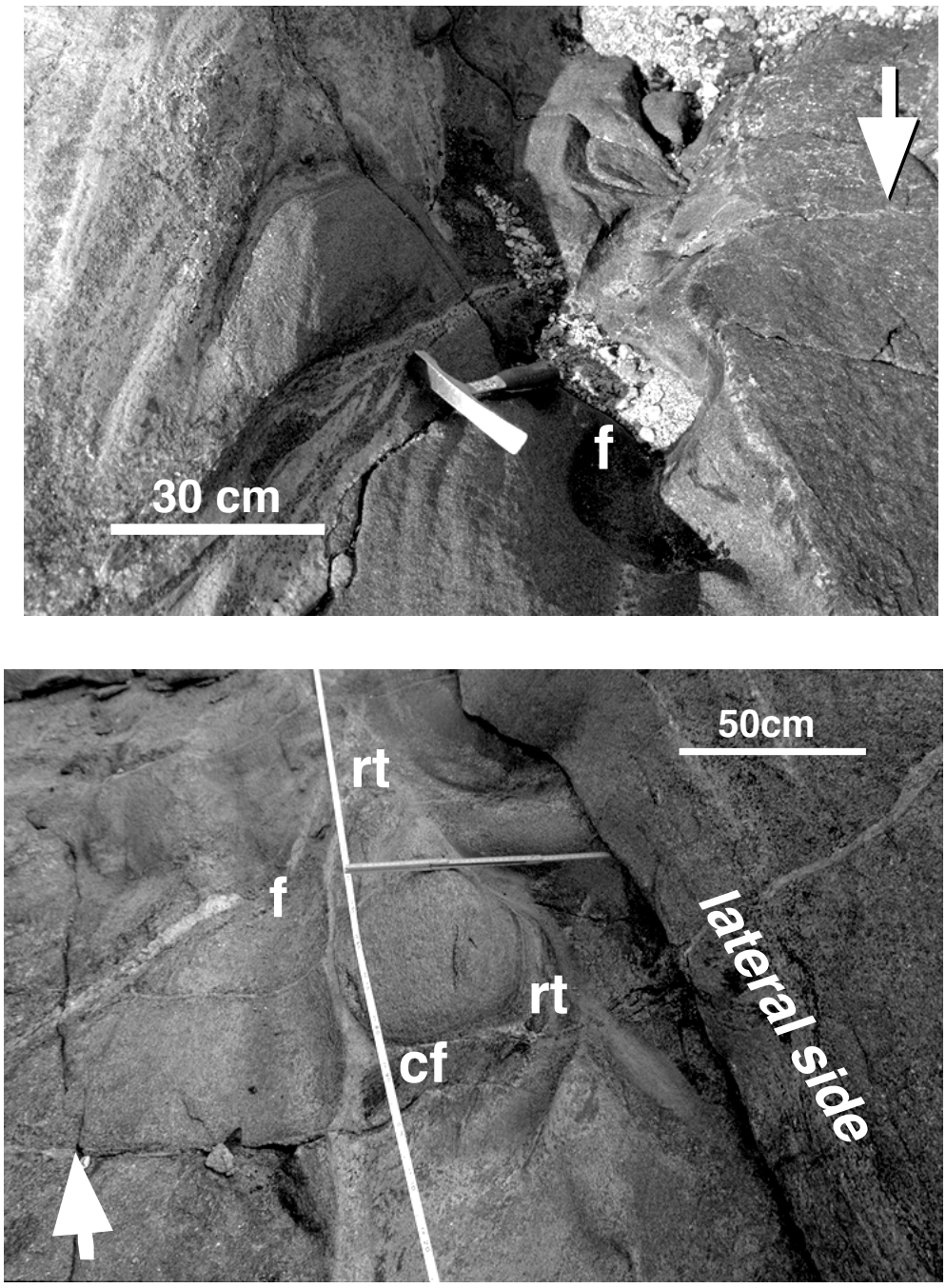


Fig. 4 A furrow (f) sculptured into the genetic bedrock in Runvågshetta. Flow direction is indicated by an arrow.

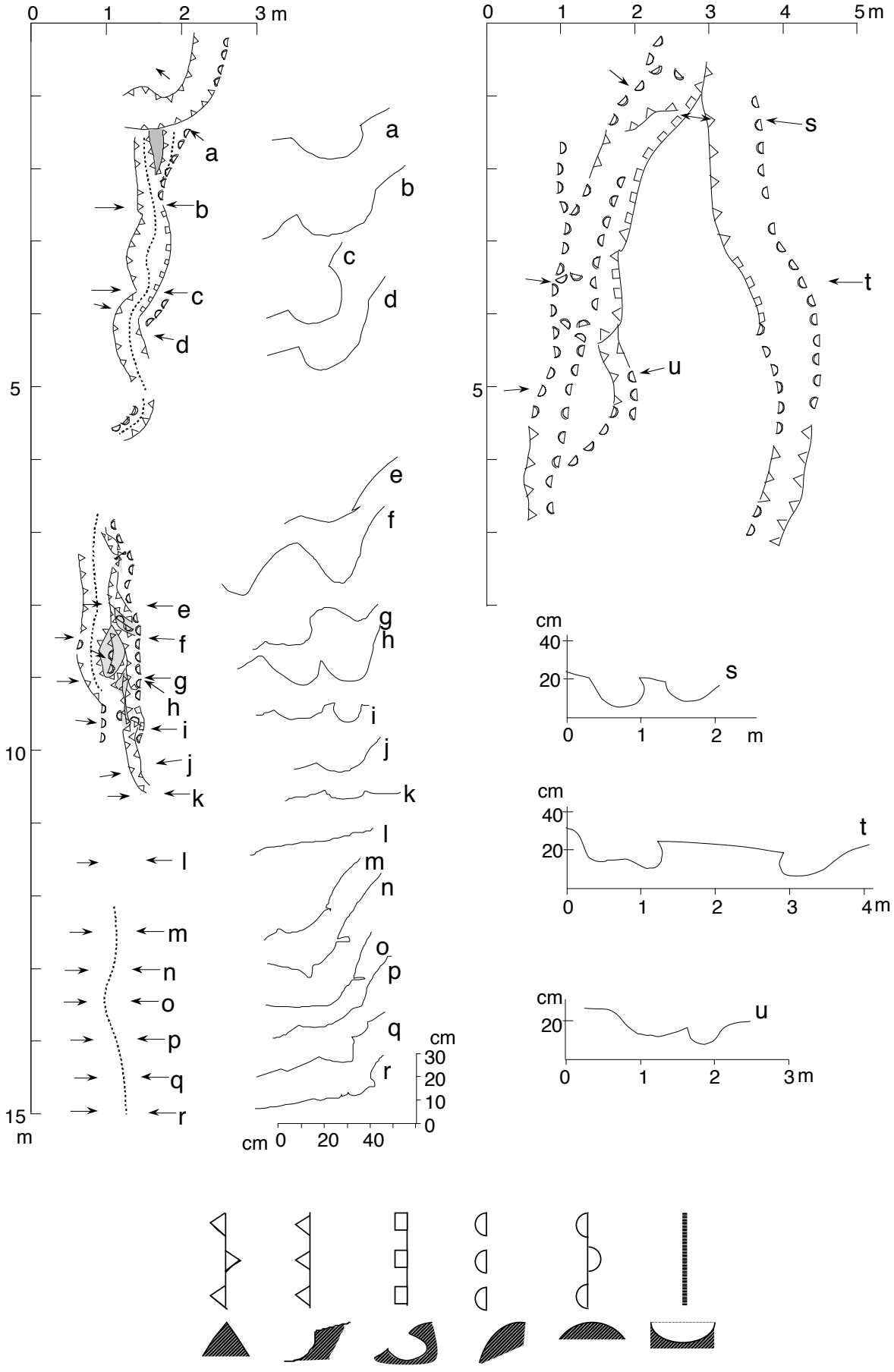


Fig. 5 Sketches and vertical sections of a furrow composed of s-forms in Rundvågshetta (Fig. 3).

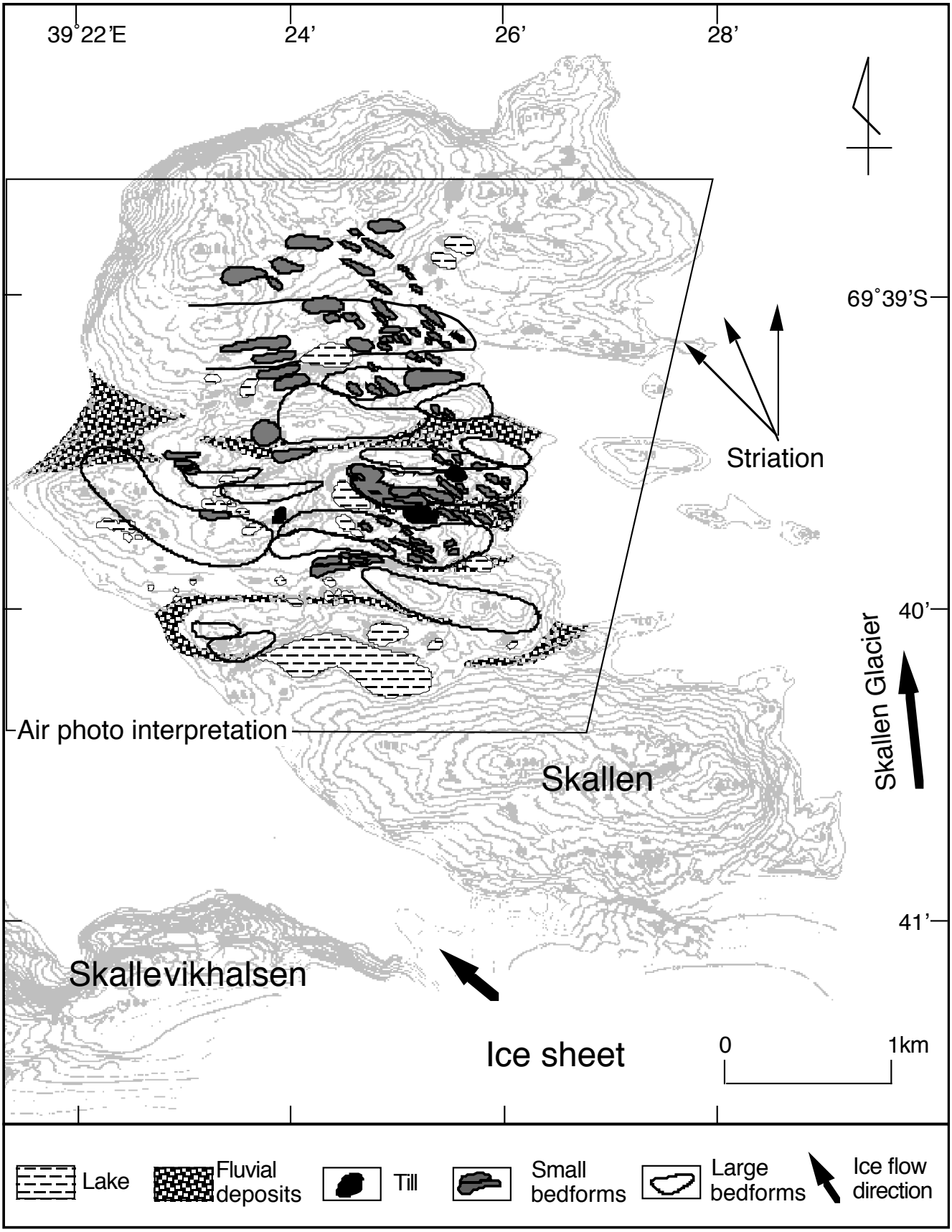


Fig. 6 Distribution of surficial deposits and streamlined bedforms in Skallen. The long axes of the streamlined hills show two distinctive directions (E-W and ESE-WNW). The E-W trending forms are superimposed by the smaller ESE-WNW trending forms.



Fig. 7 Streamlined bedforms in Skallen. The inferred ice flow direction is approximately from right to left.

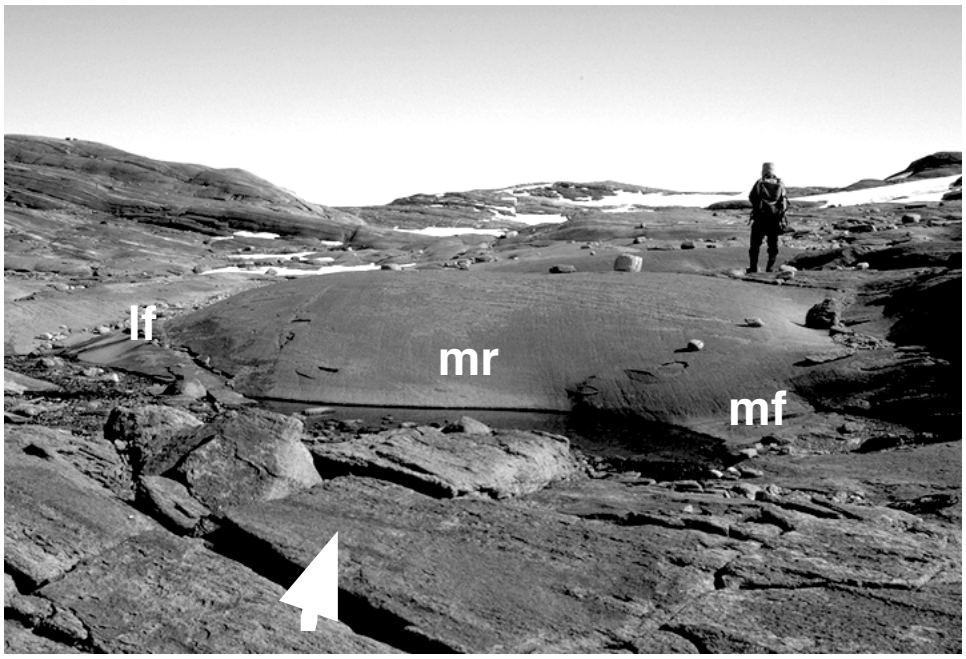


Fig. 8 Spindle flutes (sf) and lateral furrow (lf) cut into a lateral side of a streamlined hill in Skallen. Former ice flow direction (arrow) is inferred from these marks which points in the upflow direction and broaden downflow.

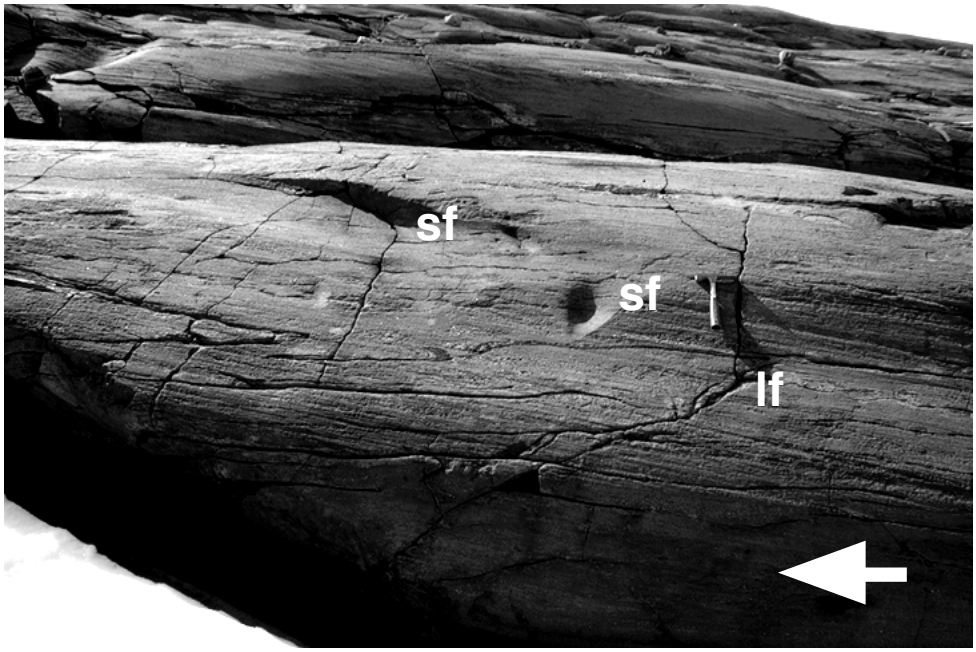


Fig. 9 Sichelwanne with main furrow (mf), lateral furrow (lf) and median ridge (mr) in Skallen. Individual streamlined hills are separated by these furrows.

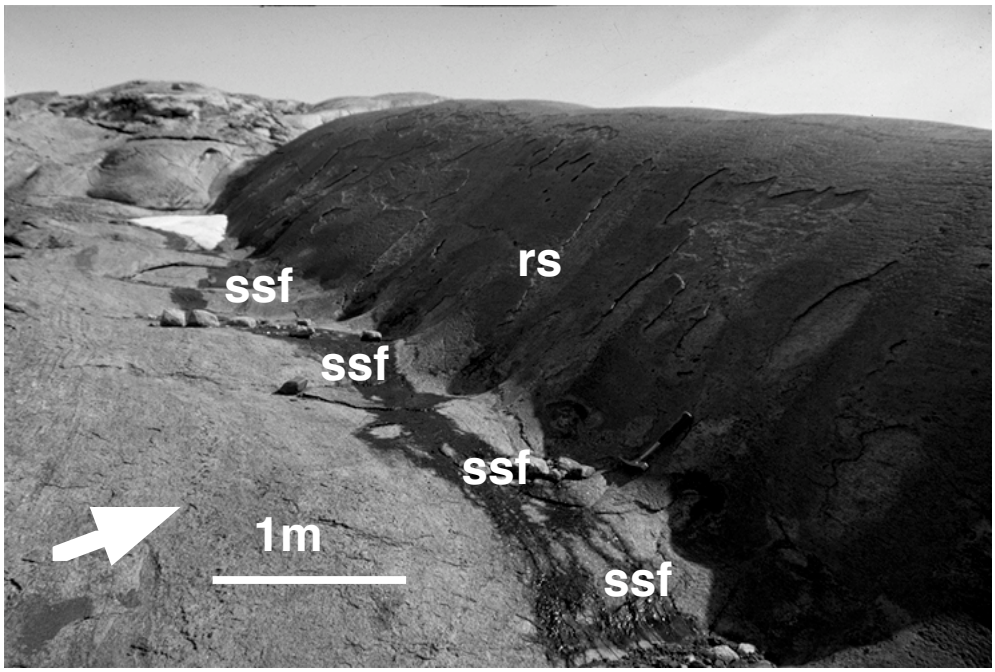


Fig. 10 Stoss-side furrows (ssf) are attached on the foot of the transversely riser slope (rs) in Skallevikhalsen. The general trend of streamlined hills in Skallevikhalsen is E-W, perpendicular to present-day ice movement and orientations of glacial striae. The direction of stoss-side furrows adjusts with the striations and they indicate that former ice movement was east to west as same as present one.

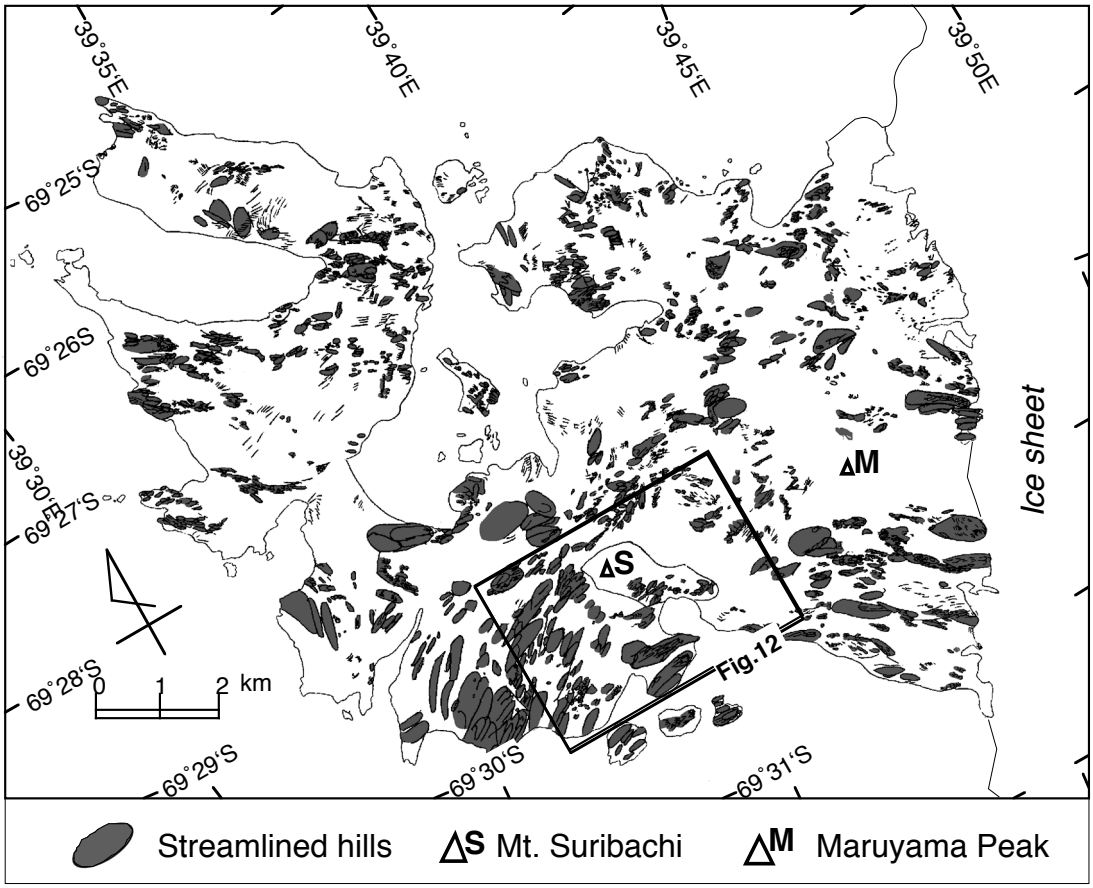


Fig. 11 Distribution of streamlined bedforms in the Skarvsnes. Each form is shown by its plan form. Inner square indicates the area photographed in Fig. 12.

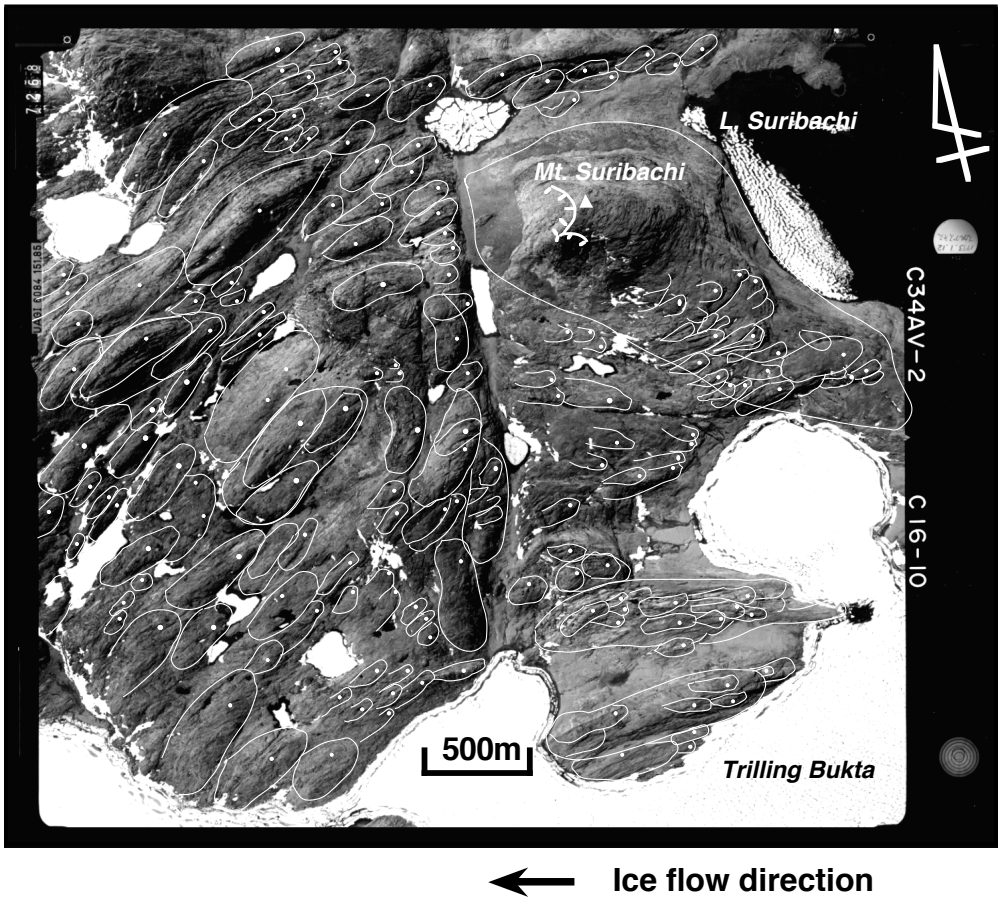


Fig. 12 An air photograph taken by JARE-34 showing the topography around Mt. Suribachi which is a large rock hill forming a particular large roches moutonnée. The western and southwestern faces are cliffed, and taluses are formed in the lee of these cliffs. Some superimposed tadpole rocks with steeper slopes points upflow are recognized on the southeastern flank of the stoss slope of Mt. Suribachi. A large crescentic transverse ridge, lies in the downstream of Mt. Suribachi, and a remarkable structural linear trough divides them.

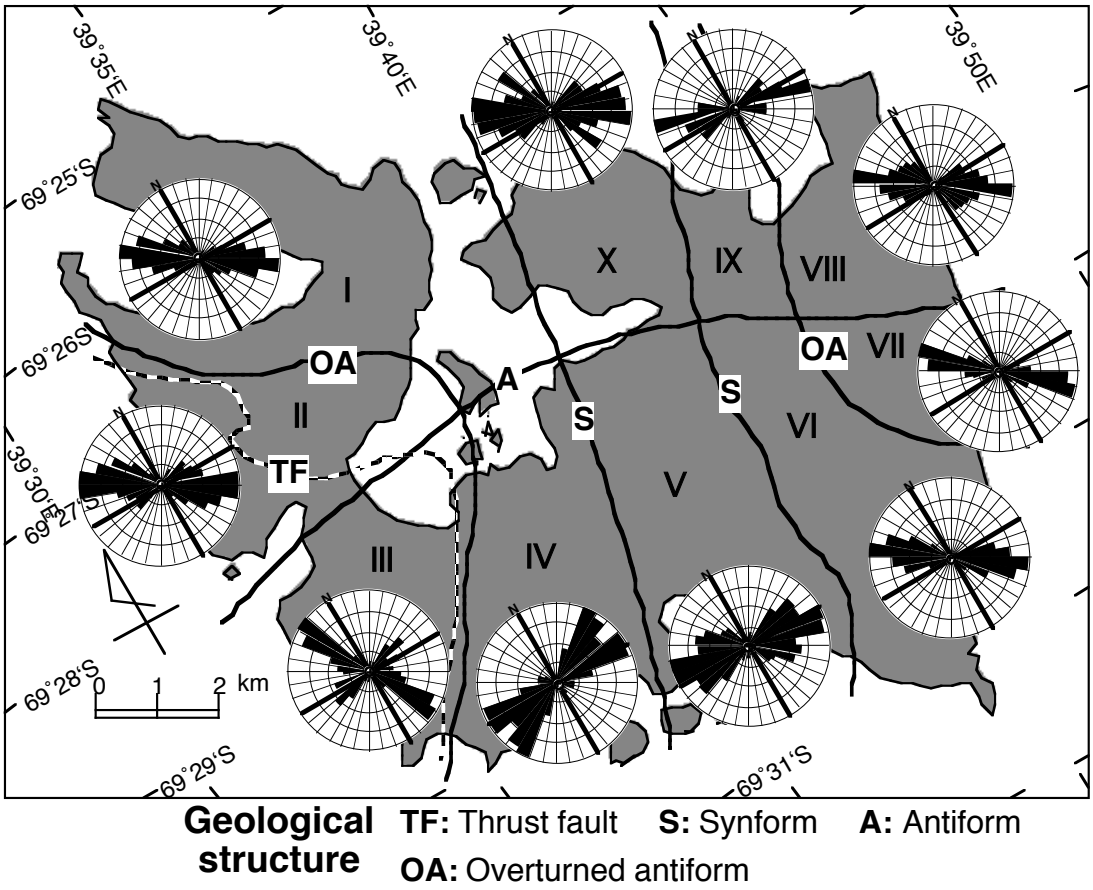


Fig. 13 Regional variations in the long axis trends of the streamlined bedforms in Skarvsnes. The population of streamlined hills was divided into smaller subgroups based on geological structure. The mean direction is northwestward, and regional mean directions vary from northwest to southwest. Significant differences are recognized in regions III and IV where the mean directions are NNW and WSW respectively. These features could be reflecting the geological structure of those regions carved along the gneissic banding or foliation, which indicates a strong control of the gneissic structure on erosion.

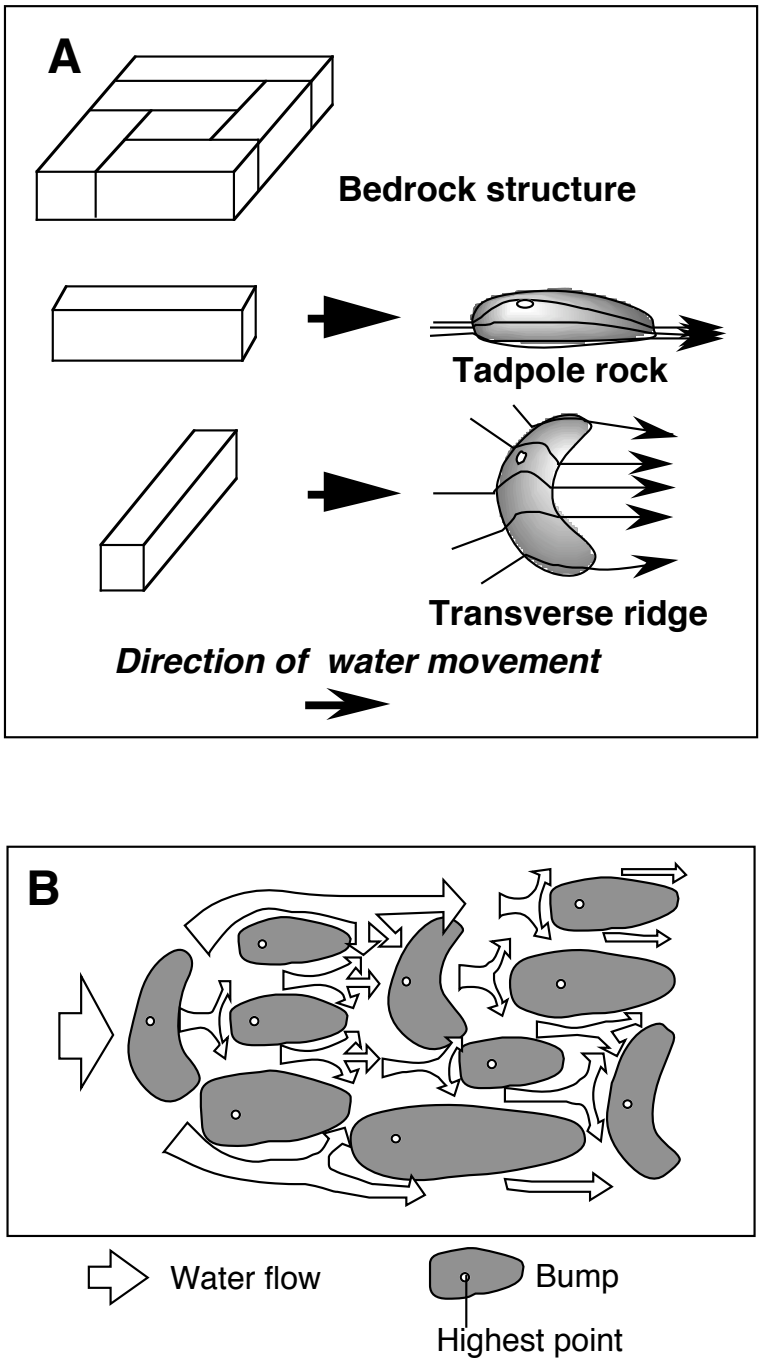


Fig. 14 Idealized sketches of the development of streamlined bedforms considering the effect of geological structure (A) and subglacial water flow structure (B) to form the sculptured bedforms. The orientation of the streamlined bedforms are initially controlled by geological structure. The differences between tadpole rock and crescentic transverse ridge is determined by the distinguished geologic lineation. These initial forms are modified by the separated subglacial water flow to form the rounded and smoothed surfaces of the streamlined bedforms.

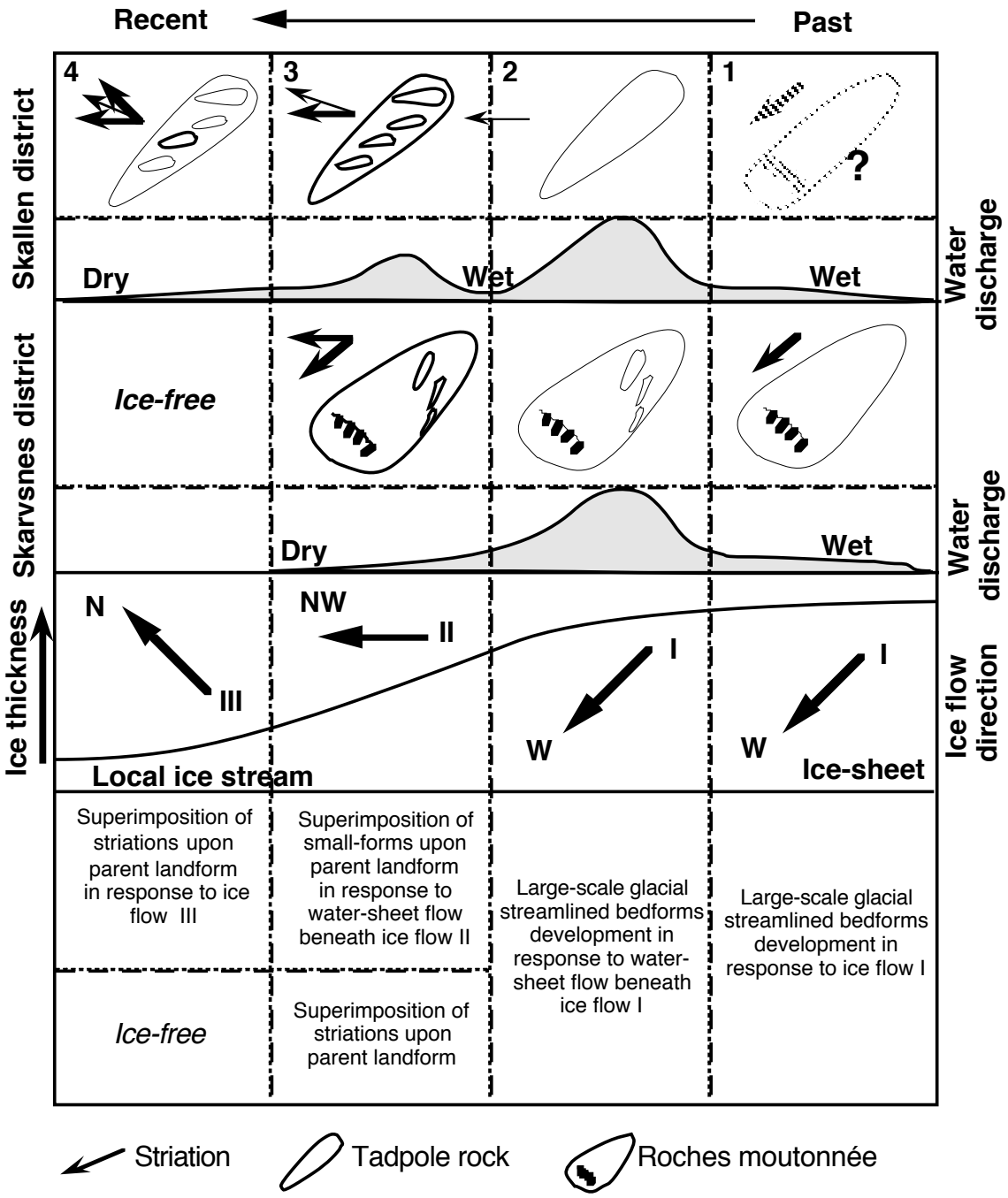


Fig. 15 Distribution of cross-cut bedforms and striations in relation to the ice sheet geometry and subglacial condition of water. Under the wet ice sheet glacial plucked and abraded bedforms were created, which belong to the earlier phase of ice flow. In the following stage subglacial meltwater flood occurred to erode s-forms and streamlined bedforms. Ice came contact again with the bedrock, and striations were superimposed on the s-forms and the hillocks. In Skallen another water sheet flow occurred, which had smaller energy than the former one, to form superimposed smaller bedforms. The last stage was dominated by glacial abrasion to form the striations parallel to the directions of the present Skallen glacier. The ice geometry in this stage have changed into a local ice stream. The Skarvsnes region seems to have experienced single subglacial water flood, owing to the earlier retreat of ice sheet than the Skallen region.