Antarctica at the close of a millennium 2002, 404-414.

TERRESTRIAL EVIDENCE OF MELTING OF THE ANTARCTIC ICE SHEET DURING THE LAST GLACIAL PERIOD

Takanobu SAWAGAKI[1] and Kazuomi HIRAKAWA[1]

Graduate School of Environmental Earth Science, Hokkaido University, N10, W5, Sapporo 060-0810

Antarctica at the close of a millennium 2002, 404-414.

Abstract

This article presents subaerial geomorphological evidences of significant melting of the Antarctic ice sheet during the last glacial period. Interpretation is based on glacial geomorphic features observed in the southern ice-free areas along the Sôya Coast, Lützow-Holm Bay, East Antarctica. Examples include glacial sculptured bedforms, glacio-fluvial landforms and subglacial till. Sculptured bedforms are composed of mammilated peaks, streamlined hillocks, and a variety of s-forms. The subglacial meltwater erosion model possibly best explains these forms and the absence of drift on the ice-free areas along the coast. Several fluvial valleys are more or less U-shaped with the lowest part of their cros-sections cut down showing a V-shape. Fluvial terraces are composed of large boulders. Huge amount of running water explain these features. The most notable till, containing a lot of oblique and bed-parallel shear planes, may have originated from subglacial meltout and deformation processes indicating a wet-based ice sheet. The North Atlantic sediment record demonstrates that much icerafted debris have occurred during the last glacial period as a succession of Heinrich events. This points to surges of the Hudson Strait ice stream discharging extreme volume of icebergs from the Laurentide ice sheet. Similar processes probably took place in Antarctica during the last glacial period.

Keywords: subglacial meltwater, s-forms, East Antarctica, glacio-fluvial landforms, subglacial t

Antarctica at the close of a millennium 2002, 404-414.

1. Introduction

The hypothesis of pulse-like surge events of the Antarctic ice sheet during the last glacial between 35 and 17 kyr B.P. has been presented by Labeyrie *et al.* (1986), according to several large isotopic anomalies in the surface waters of the Antarctic polar front. It was shown that the time of major isotopic anomaly is correlated with that of high ice rafted debris (IRD) in the sediments of the Southern Ocean. Thus, it was concluded that these anomalies are due to a large input of iceberg melt water during periods when the periphery of the Antarctic ice sheet was rapidly eroded. Labeyrie *et al.* (1986) thought that surge events occurred during maximum extension of the marine-based ice sheets or ice shelves.

Additionally, results of marine geological surveys in the Antarctic ocean (Herron and Anderson, 1988) are under controversy to discuss the vast ice shelf expansion in the last glacial period. Miura *et al.* (1998) recently proposed a considerable melting of the East Antarctic ice sheet during the period 30-46 kyr based on lower oxygen isotopic ratio of fossil shells and the occurrence of fluvial sediment intercalated with the raised marine sediments in the northern part of the Sôya Coast, Lützow-Holm Bay.

However, until now there has been little Antarctic land-based geological evidence for the collapse of the ice sheet. Vast ice shelves, peripheral sea ice, and few ice-free areas on the continent make investigations difficult. If there were massive purges of the Antarctic ice sheet evidence of them should be recorded, not only in marine and beach sediments but also in the ice-free continental margin. Therefore, we assess the geomorphological implications of the surge hypothesis in regards to the melting history of the Antarctic ice sheet. For this purpose, we present subaerial geomorphological evidence for significant melting of the ice sheet. This evidence is based on our own field survey and other results of the Japanese Antarctic Research Expeditions (JARE). We give information on particular glacial geomorphic features, such as glacial sculptured bedforms, glacio-fluvial landforms and subglacial till, observed in the southern ice-free areas along the Sôya Coast, Lützow-Holm Bay, East Antarctica.

Antarctica at the close of a millennium 2002, 404-414.

2. Study Area

Subaerial geomorphological evidence for the collapse of the Antarctic ice sheet is based on the interpretation of glacial erosional and depositional geomorphic features found in ice-free areas along the Sôya Coast in the marginal zone of the ice sheet. The ice-free areas close to the snout of Shirase Glacier are covered by scoured bedrock representing zones of pronounced glacial erosion (Fig. 1).

The regional, present-day ice sheet 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. 1). Outlet glaciers flow from SSE-NNW to SE-NW. From striations marked on the glaciated surface, we infer that the former ice sheet flowed northwestward and westward (Moriwaki and Yoshida, 1983; Yoshida, 1983) (Fig. 1). Yoshida (1983) concluded that at its maximum expansion the ice sheet probably extended to the outer edge of the continental shelf. Major retreat of the ice sheet from the region is estimated to have taken place prior to 30 kyr B.P. (Yoshida, 1983) or before the last interstadial (Miura *et al.*, 1998). However, the exact time when the erosional forms were created is unknown.

Theses areas are composed of crystalline bedrock of gneisses including calcareous rocks of marble and skarn with E-W or ESE-WNW trending structure (Yoshida *et al.*, 1976; Motoyoshi *et al.*, 1986). Polished bedrock is widely exposed in the ice-free areas. Erosional bedforms are found mainly on the gneisses, and are rare on the calcareous rocks that have weathered more intensely. Erosional bedforms are better preserved in the southern part of the coast (Yoshida, 1983).

Antarctica at the close of a millennium 2002, 404-414.

3. Interpretation

3.1. Glacial sculptured bedforms

Topographic features of the ice-free areas along the coast are characterized by mammilated peaks and undulating hilly land completely composed of bedrock. The distribution of morainic detritus is limited to some depressions behind hillocks. Some of the largest and most typical features are represented by Mt. Tyoto in Langhovde or Mt. Suribachi in Skarvsnes (Fig. 2). Mt. Tyoto is composed of three streamlined peaks about 400 m high steeper, moulded stoss slopes (Fig. 2-A). Mt. Suribachi is a large roche moutonnée, about 300 m high, with a gentle, abraded slope on the upstream side and cliffs with talus slopes on the downstream side (Fig. 2-B).

In addition to Mt. Tyoto and Mt. Suribachi, a number of streamlined hillocks, ranging from less than one meter to several meters in height were observed in the Skarvsnes, Skallen and Skallevikhalsen districts (Fig. 3). Sawagaki and Hirakawa (1997) classified these hillocks as "tadpole rocks" according to the classification by Dionne (1986). Some tadpole rocks are superimposed on the southeastern flank of the stoss slope of Mt. Suribachi (Fig. 3-A). Large crescentic transverse ridges, 300-500 m long and 200 m wide, lie downglacier (west) of Mt. Suribachi. Since the stoss side of the ridges curves gently, they seem to be embraced by a large-scale furrow. Tadpole rocks and furrows of medium-scale size (1-10 m) cluster on the stoss side of the ridges. The trough and furrows are quarried along the gneissic banding or foliation (Yoshida, 1983), indicating a strong control of the bedrock structure on erosion (Sawagaki and Hirakawa, 1997). The general trend of the hillocks in Skallen is E-W to ENE-WSW, parallel to the directions of the glacial striae (Fig. 3-B).

Individual hillocks in the both districts are separated by troughs such as sichelwanne and comma forms (Kor *et al.*, 1991) (Fig. 4-A). Stoss-side furrows (Kor *et al.*, 1991), whose direction change with those of the striations, are found on the transverse riser slopes of the hillocks in Skallevikhalsen (Fig. 4-B; Sawagaki and Hirakawa, 1997).

A variety of s-forms and remnant ridges occur on the flat bed surface of a furrow separating several whalebacks in Lundvågshetta (Fig. 5). Sawagaki and Hirakawa (1997) described the furrow is approximately 10 m long and 30 cm wide and its surface gradient is less than 3 degree. The most remarkable s-form features are obstacle marks, which consist of a proximal crescentic furrows wrapped around an upstanding obstacle of resistant bedrock and a remnant ridge with rat-tail forms (Prest, 1983) (Fig. 5). The arms of the crescentic furrows extended leeward into a pair of furrows that become shallower and wider downflow.

3.2. Glacio-fluvial landforms

Several remarkable fluvial landforms particularly in Langhovde appear to have been formed in relation to ice-sheet melting.

Fluvial landforms are particularly recognized along the Yatude, Yukidori and Yotuike valleys, where fluvial erosional landforms and related sediments are well developed. The Yatude and Yukidori valleys themselves show more or less U-shaped valley cutting down deeply from several tens of meters to more than 100 m as shown in Fig. 6. It must be noted that the bottom of the U-shaped valley is incised by a narrow V-shaped inner valley. In this V-shape valley floor, fluvial terraces are well developed and are mainly composed of large boulders up to 2-3 m in diameter. Signs of former fluvial activity are well preserved ancient braided channels on the terrace surface. Huge amount of running water are necessary for transportation of such large boulders. The terrace surface grades to two remarkable marine terraces at the mouth of Yatude Valley. Upper marine sediments are dated back to 5-7 kyr B.P. (Miura, *et al*, 1998). Thus the lower fluvioglacial deposits overlain by these marine sediments are older than these dates.

The Yotuike Valley (Fig. 7) is characterized by its surrounding mammilated gentle slopes and the extraordinally narrow deep gorge incised 80 m into basement rock (Fig. 7-C)at its mouth. This remarkable down-cutting was caused by violent running water.

3.3. Subglacial till

Characteristic tills indicating subglacial development are observed in some places along the Sôya Coast. The most notable till, first reported and named the Osen Till by Yoshida (1983), occupy the upper slope of a horseshoe-shaped depression in the Osen-Bay area of Skarvsnes (Fig. 8). Here, this till with a thickness of more than 5 m contains well striated cobbles and pebbles in a fine sediment matrix, with rhomboidal shear planes (Fig. 8).

In Skallevikhalsen, the bedrock is highly polished and partially covered with till, in addition to the wide development of glacialy sculptured bedforms described above. Figure 9-B is a sketch of a trench wall in the till. This till is mainly composed of silt, including cobbles and boulders. The finer part of the till include non-graded lamination and lenses of coarse sand and gravels as well as shear planes showing deformation. The upper part of till has been eroded. Almost all cobbles and boulders in and on the till are highly polished and striated. In Langhovde, we obtained a similar till facies by trenching as shown in Fig. 9-A. These thick tills may have been originated from the subglacial meltout and deformation process, indicating a warm based ice-sheet.

Antarctica at the close of a millennium 2002, 404-414.

4. Discussion

4.1. Subglacial water erosion

In summary, the sculptured bedforms observed in the Sôya Coast are composed of streamlined hillocks, sichelwanne, comma forms, stoss-side furrows, obstacle marks with a proximal crescentic furrow and a rat-tail remnant ridge. Other types of glacial erosional bedform have been reported from the coast since JARE was initiated in 1956 (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). In these studies, several erosional bedforms, such as glacial grooves, glacial striae, roches moutonées and stoss-and-lee topographies have been classified as the ice-abrasion forms or plucking forms. In a review article, Yoshida (1983) concluded that most of the Sôya Coast was underwent areal scouring (Sugden and John, 1976).

Despite these studies, the subglacial meltwater erosion model (Shaw and Sharpe, 1987) best explains the sculptured forms and the absence of drift on these areas (Sawagaki and Hirakawa, 1997), as has been shown in detailed morphological studies in the exposed bedrock areas of the Canadian Shield (cf. Shaw, 1988; Shaw and Gilbert, 1990; Kor *et al.* 1991). Although there is continuing debate concerning the importance of subglacial water and the plastic basal sediment in producing them (Menzies and Rose, 1987), the sculptured bedforms strongly suggest that the wet-based ice-sheet once covered the Sôya Coast.

4.2. Subglacial outburst flood

Shaw *et al.* (1989) argued that the sculptured bedforms in the Canadian Shield were caused by *subglacial outburst floods* beneath the Laurentide ice sheet. Shaw (1994) advocates that fast-flowing meltwater sheet eroding downwards into the glacier substrata was required to produce erosional marks in the bedrock. If subglacial outburst floods occurred, they may have been massive enough to leave a signal in the global climate record (Blanchon and Show, 1995). For instance, the North Atlantic sediment record demonstrates that much of IRD may have occurred as a result of succession of catastrophic events during the last glacial period (Heinrich, 1988). These Heinrich events may point to surges of the ice stream discharging a huge number of icebergs from the Laurentide ice sheet. Shaw (1996) suggested that the timing of a prominent and extensive Heinrich layer (H1) at about 14 kyr B.P. (Bond *et al.*, 1992) coincides with age estimates of the major Laurentide outburst floods, preceding the collapse of the Laurentide ice sheet. These two processes, outburst floods and collapse of the ice sheet, caused cooling and freshening of surface waters in the North Atlantic (Bond *et al.*, 1992; Shaw, 1996).

The hypothesis of pulse-like surge events of the Antarctic ice sheet presented by Labeyrie *et al.* (1986) and the geomorphological evidence presented in this paper suggest that similar processes occurred in Antarctica during the last glacial period.

The source for large floods for the Laurentide ice sheet is thought to have been a mega-subglacial lake in the Hudson Bay basin (Shoemaker, 1991, 1992a, b). Such water ponding and subglacial drainage seem very unlikely beneath the Antarctic ice sheet, particularly in the coastal zone where the ice may be cold-based under thin ice. However, Sawagaki and Hirakawa (1997) argued that ponded water on a subglacial lake in the upper reaches of the Sôya Coast was evacuated to the margin by discrete subglacial floods along the basal sliding zone. Their argument was based on the existence of subglacial lakes beneath the present Antarctic ice sheet, which presumably also occurred beneath Pleistocene ice sheets (Oswald and Robin, 1973; Cudlip and MacIntyer, 1987), and the possible basal sliding beneath the ice sheet of the Shirase drainage basin 200 km inland from the coast (Mae and Naruse, 1978). Although there is no evidence indicating basal melting of the present ice sheet along the coastal zone (Yoshida, 1983), the ponded water in a subglacial lake in the upper reaches of the Sôya Coast may have been evacuated to the margin by discrete subglacial floods along the basal sliding zone.

4.3. Melting of the ice sheet during the last glacial period

We now hypothesize that the whole ice-free area along the Sôya Coast once experienced erosion due to meltwater which had occurred in the subglacial and proglacial environments. Subglacial meltwater events could have led to the topographic development of the mammilated peaks, undulating hilly land. Outbursts in the proglacial environment, in relation to ice retreat, should have led to form v-shaped valleys, fluvial terrace landforms and deposition of large boulders. Although the thick subglacial tills are not necessialy related to the meltwater events, they must indicate warm based conditon of a former ice sheet at least.

^{14}C ages derived from fossil shells along the Sôya Coast are divided into two ages, younger than 7 kyr B.P. and older than 60 kyr B.P. (cf. Miura *et al.*, 1998, Hayashi and Yoshida, 1994). Labeyrie *et al.* (1986) dated hypothetical pulse-like surge events of the Antarctic ice sheet between between 35 and 17 kyr B.P. According to these dates, the surge occured between the two-aged beach sedimentations. Other studies on this area argued that major retreat of the ice sheet from the region have taken place prior to 30 kyr B.P. (Yoshida, 1983) or before the last interstadial (Miura *et al.*, 1998). Thus, we tentatively think that subglacial meltwater events occurred around 35 kyr B.P., which made the ice sheet unstable leading to surges of the ice stream discharging extreme iceberg to the ocean. After the main retreat of the ice sheet from the coast proglacial meltwater was activated to form the glaciofluvial landforms before 7 kyr B.P. These processes caused the cooling and freshening of surface waters of the Antarctic polar front during the last glacial between 35 and 17 kyr B.P.

4.4. Tele-connection between the Northern and Southern hemispheres

Recently, Blunier *et al.* (1998) have reported cross-dated isotope records in ice cores from Greenland and Antarctica. This is the first investigation allowing the relative timing of large climate changes between the Northern and Southern hemispheres. It appears that the south leads the north by a little more than a millennium (Blunier *et al.*, 1998; White *et al.*, 1998). Thus, if rapid melting or collapse of the Antarctic ice sheet during the last glacial period is confirmed, this phenomena is important for revealing the tele-connection of the global climate change between the Northern and Southern hemispheres. Consequently, further investigation into this aspect should be carried out.

Antarctica at the close of a millennium 2002, 404-414.

5. Conclusion

Form geomorphological interpretations we present the following features as terrestrial evidence for collapse of the Antarctic ice sheet during the last glacial period.

(1) Sculptured bedforms are composed of streamlined hillocks, sichelwanne, comma forms, stoss-side furrows, obstacle marks with a proximal crescentic furrow and a rat-tail remnant ridge. The subglacial meltwater erosion model possibly best explains the sculptured forms and absence of drift on these areas.

(2) Several fluvial valleys are U-shaped with bottoms cut down to show narrow V-shape. Fluvial terraces are composed of large boulders needing large amounts of running water for transfer.

(3) Tills on the glacially striated and polished bed surfaces and those occupying the upper slope of a horseshoe-shaped depression contain many oblique and straight shear planes indicating deformation. These tills probably originated from subglacial meltout and subglacial deformation process, indicating a wet based ice-sheet.

(4) The North Atlantic sediment record demonstrates that much of IRD may have occurred as a succession of Heinrich events during the last glacial period, which may point to surges of the ice stream to discharge extreme iceberg from the Laurentide ice sheet. If the hypothesis of pulse-like surge events of the Antarctic ice sheet and the geomorphological interpretations are correct, similar processes have occurred in Antarctica during the last glacial period.

Antarctica at the close of a millennium 2002, 404-414.

Acknowledgement

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. Yoshida of Rissho University, Prof. K. Moriwaki and Dr. H. Miura of Japanese National Institute of Polar Research. Comments from Prof. John Shaw of the University of Alberta improved greatly this manuscript. This research was supported by a grant-in-aid for scientific research from the Japan Society for the Promotion of Science.

References

Blanchon, P.; Shaw, J. 1995: Reef drowning during the last deglaciation: Evidence for catastrophic sea-level rise and ice-sheet collapse. Geology 23: 4-8.

Blunier, T.; Chappellaz, J.; Schwander, J.; Dälenbach, A.; Stauffer, B.; Stocker, T. F.; Raynaud, D.; Jouzel, J.; Clausen, H. B.; Hammer, C. U.; Johnsen, S. J. 1998: Asynchrony of Antarctic and Greenland climate change during the last glacial period. Nature 394: 739-743.

Bond, G.; Heinrich, H.; Huon, S.; Broecker, W.; Labeyrie, L.; Andrews, J.; McManus, J.; Clasen, S.; Tedesco, K.; Jantschik, R.; Simet, C.; Klas, M. 1992: Evidence for massive discharges of ice berges into the glacial Northern Atlantic. Nature 360: 245-249.

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

Dionne, J. C. 1987: Tadpole rock (rocdrumlin): A glacial stream moulded form. In "Drumlin Symposium" in :Menzies, L.; Rose, J. eds. A.A. Balkema Publishers, Rotterdam: pp. 149-159.

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

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

Heinrich, H. 1988: Origin and consequences of cycle ice rafting in the northeast Atlantic Ocean during the past 130,000 years. Quaternary Research 29: 142-152.

Herron, M. J.; Anderson, B. J. 1990: Late Quaternary glacial history of the South Orkney Plateau, Antarctica. Quaternary Research 33: 265-275.

Koaze, T. 1963: 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.; Sharpe, D. R. 1991: Erosion of Bedrock by Subglacial meltwater, Georgian Bay, Ontario: A Regional View. Canadian Journal of Earth Science 28: 623-642.

Labeyrie, D. L.; Pichon, J. J.; Labracherie, M.; Ippolito, P.; Duprat, J.; Duplessy, J. C. 1986: Melting history of Antarctica during the past 60,000 years. Nature 322: 701-706.

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

Menzies, J.; Rose, J. (1987) "Drumlin Symposium" A. A. Balkema publishers, Rotterdam.

Miura, H.; Maemoku, H.; Seto, K.; Moriwaki, K. 1998: Late Quaternary East Antarctic melting event in the Sôya Coast region based on stratigraphy and oxygen isotopic ratio of fossil molluscs. Polar Geoscience 11: 260-274.

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.; Yoshida, Y. 1983: Submarine Topography of Lützow-Holm bay, Antarctica. Memories of National Institute of Polar Research Special Issue 28: 247-258.

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

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

Oswald, G. K; 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 Missellaneous Report 28: 119.

Sawagaki, T.; Hirakawa, K. 1997: Erosion of bedrock by subglacial meltwater, Sôya Coast, East Antarctica. Geografiska Annaler 79A: 223-238.

Shaw, J. 1988: Subglacial Erosional Marks, Wilton Creek, Ontario. Canadian Journal of Earth Science 25: 1256-1267.

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

Shaw, J. 1996: A meltwater model for Laurentide subglacial landscapes. in MacCnn, S. B.; Ford, D. C. eds. Geomorphology Sans Frontieres. John Wiley & Sons: pp. 181-236.

Shaw, J.; 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.; Kvill, D.; Rains, B. 1989: Drumlins and catastrophic subglacial floods. Sedimentary

Geology 62: 177-202.

Shaw, J.; Sharpe, D. R. 1987: Drumlin formation by subglacial meltwater erosion. Canadian Journal of Earth Science 24: 2316-2322.

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

Shoemaker, E. M. 1992a: Subglacial floods and the origin of low-relief ice-sheet lobes. Journal of Glaciology 38: 105-112.

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

Sugden, D. E.; John, B. S. 1976: Glaciers and Landscape Edward Arnold, London.

Tatsumi, T.; 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).

Tatsumi, T; Kikuchi, T. 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).

White, J. W. C.; Steig, E. J. 1998: Timing is everything in a game of two hemispheres. Nature 394, 717-718.

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

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

Yoshida, Y. 1983: Physiography of the Prince Olav and the Prince Harald Coasts, East Antarctica. Memoirs of National Institute of Polar Research Series C: 1-76.

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

Antarctica at the close of a millennium 2002, 404-414.

Figure Captions

Fig. 1 Index map of the Sôya Coast modified from map of Yoshida (1983). Black arrows show former ice movement indicated by glacial striation. Dashed arrows show the present ice movement.

Fig. 2 Examples of mammilated peaks in ice-free areas along the Sôya Coast, showing typical streamlined glacial sculptured bedforms. A: Mt. Tyoto in Langhovde composed of three streamlined peaks about 400 m high of which the steeper moulded stoss slope points up ice. B: Mt. Suribachi in Skarvsnes, a large roches moutonnée about 300 m high with a gentle abraded slope on the upstream side and cliffs on the downstream side.

Fig. 3 A: An air photograph taken by JARE-34 showing the topography around Mt. Suribachi. B: Streamline bedforms in Skallen. The inferred ice flow direction is approximately from right to left.

Fig. 4 A: Sichelwanne with main furrow (mf), lateral furrow (lf) and median ridge (mr) in Skallen. B: Stoss-side furrows (ssf) attached on the foot of the transversely riser slope (rs) in Skallevikhalsen.

Fig. 5 S-forms sculptured along the lateral side of a streamlined bedforms in Rundvågshetta, with a plan view and vertical sections of a furrow. Furrows (f) are quarried around the bumps with a rat-tail remnant ridge (rt). Ice flow direction is indicated by an arrow.

Fig. 6 Yatude valley showing a U-shaped valley cutting down deeply from several tens of meters to more than 100 m. A: The bottom of the U-shaped valley (A) is cut down again to show the narrow V-shape. B: The fluvial terrace landform composed mainly of large boulders up to 2-3 m in diameter is well developed in this V-shaped valley floor.

Fig. 7 A: Four small depressions of the Yotuike Valley connecting the lower rock basins through a narrow deep gorge (C). Note that the surrounding slopes are gentle and mammilated. B: The bottom of the uppermost depression looking upstream toward the ice sheet. C: A narrow, deep gorge cut into a depth of 80 m into basement rock which connects the upper four depressions. This remarkable down-cutting should have been caused by violent running water.

Fig. 8 A: An air photograph of the Osen Till with a thickness more than 5 m occupying the upper slope of a horseshoe-shaped depression in the Osen-Bay area of Skarvsnes. B: An outcrop of the Osen Till, that shows widely striated cobbles and pebbles in a fine sediment matrix with many oblique and bed-parallel shear planes.

Fig. 9 Sketches of subglacial till in Langhovde (A) and in Skallevikhalsen (B). These tills are covered with lag cobbles and boulders of till origin indicating erosion by eorian process. Till consisting of laminated very fine sand and silt appear to have undergone glacial shearing.

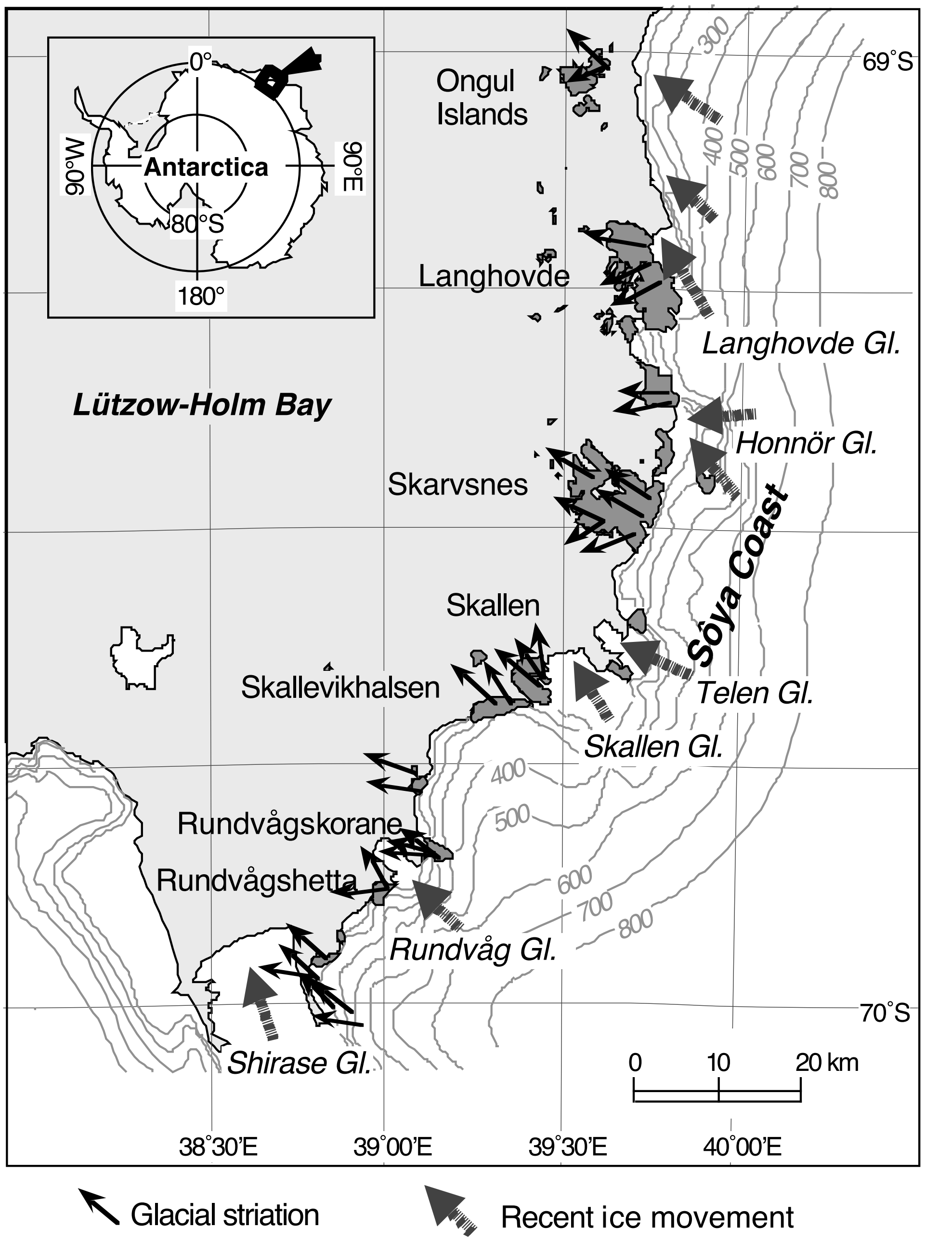

Fig. 1 Index map of the Sôya Coast modified from map of Yoshida (1983). Black arrows show former ice movement indicated by glacial striation. Dashed arrows show the present ice movement.

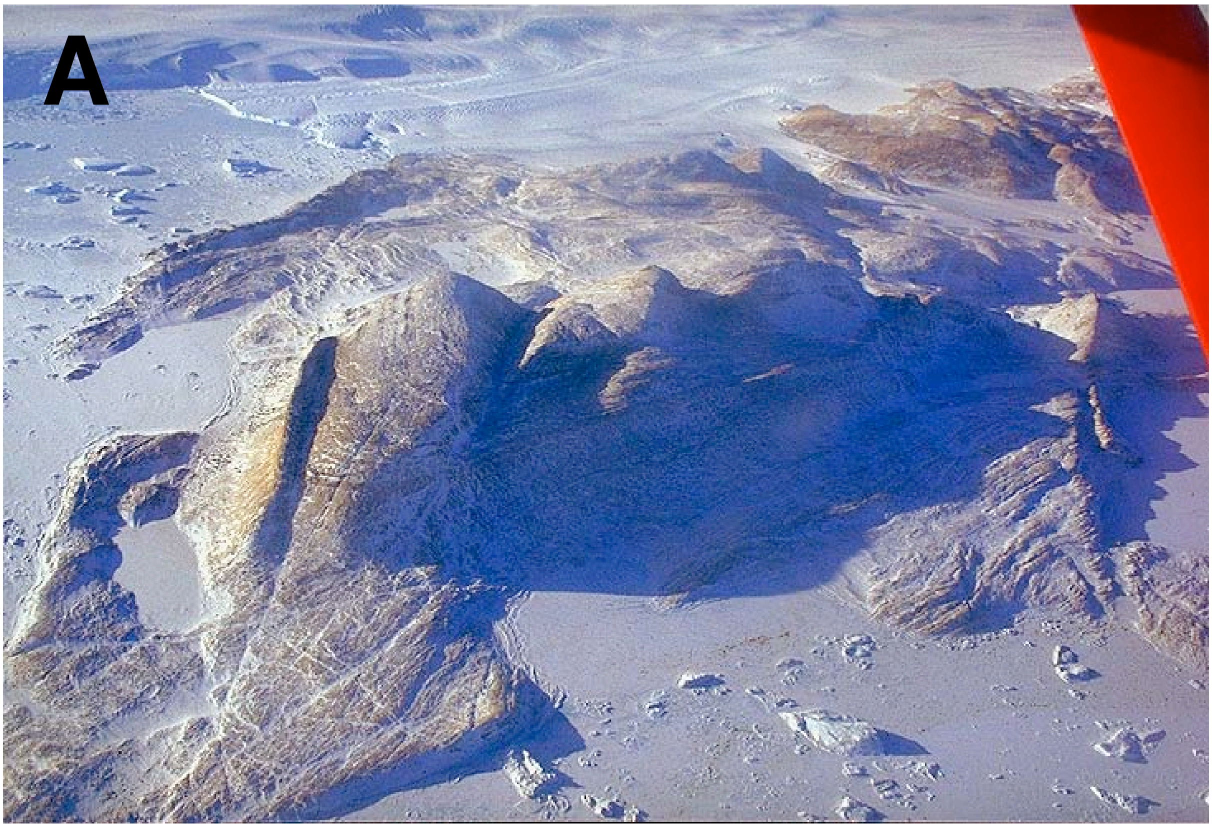

Fig. 2 Examples of mammilated peaks in ice-free areas along the Sôya Coast, showing typical streamlined glacial sculptured bedforms. A: Mt. Tyoto in Langhovde composed of three streamlined peaks about 400 m high of which the steeper moulded stoss slope points up ice. B: Mt. Suribachi in Skarvsnes, a large roches moutonnée about 300 m high with a gentle abraded slope on the upstream side and cliffs on the downstream side.

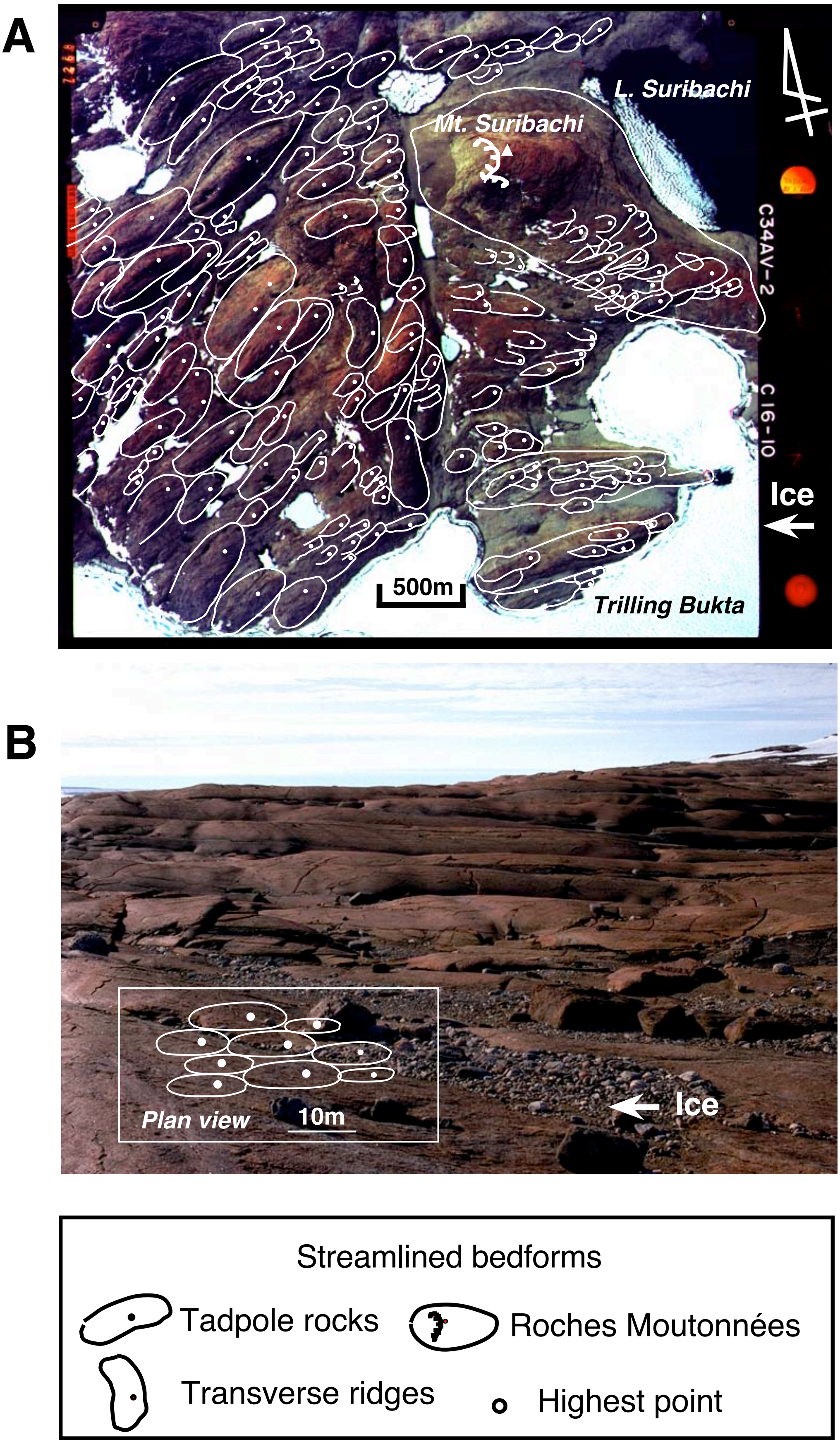

Fig. 3 A: An air photograph taken by JARE-34 showing the topography around Mt. Suribachi. B: Streamline bedforms in Skallen. The inferred ice flow direction is approximately from right to left.

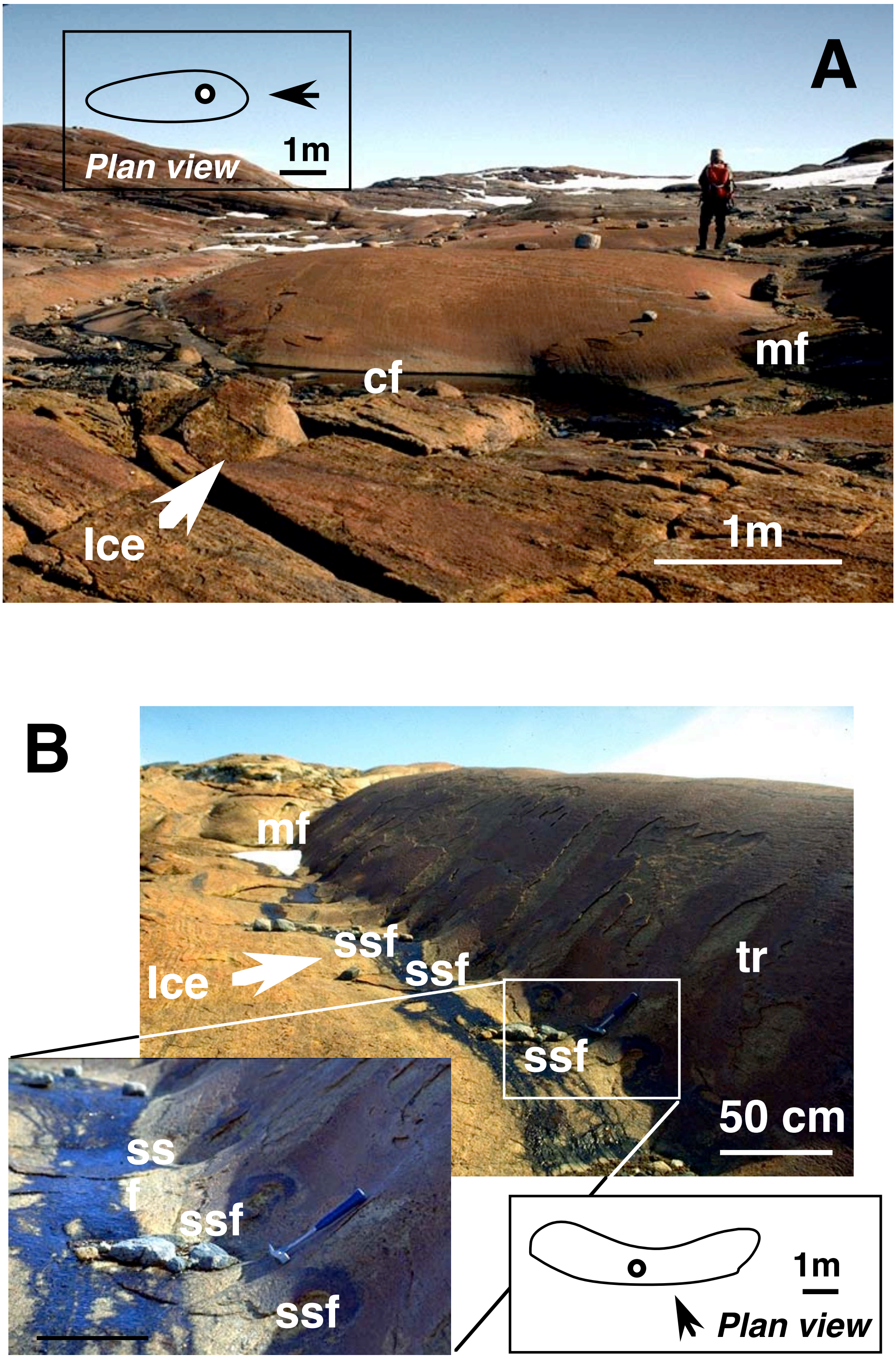

Fig. 4 A: Sichelwanne with main furrow (mf), lateral furrow (lf) and median ridge (mr) in Skallen. B: Stoss-side furrows (ssf) attached on the foot of the transversely riser slope (rs) in Skallevikhalsen.

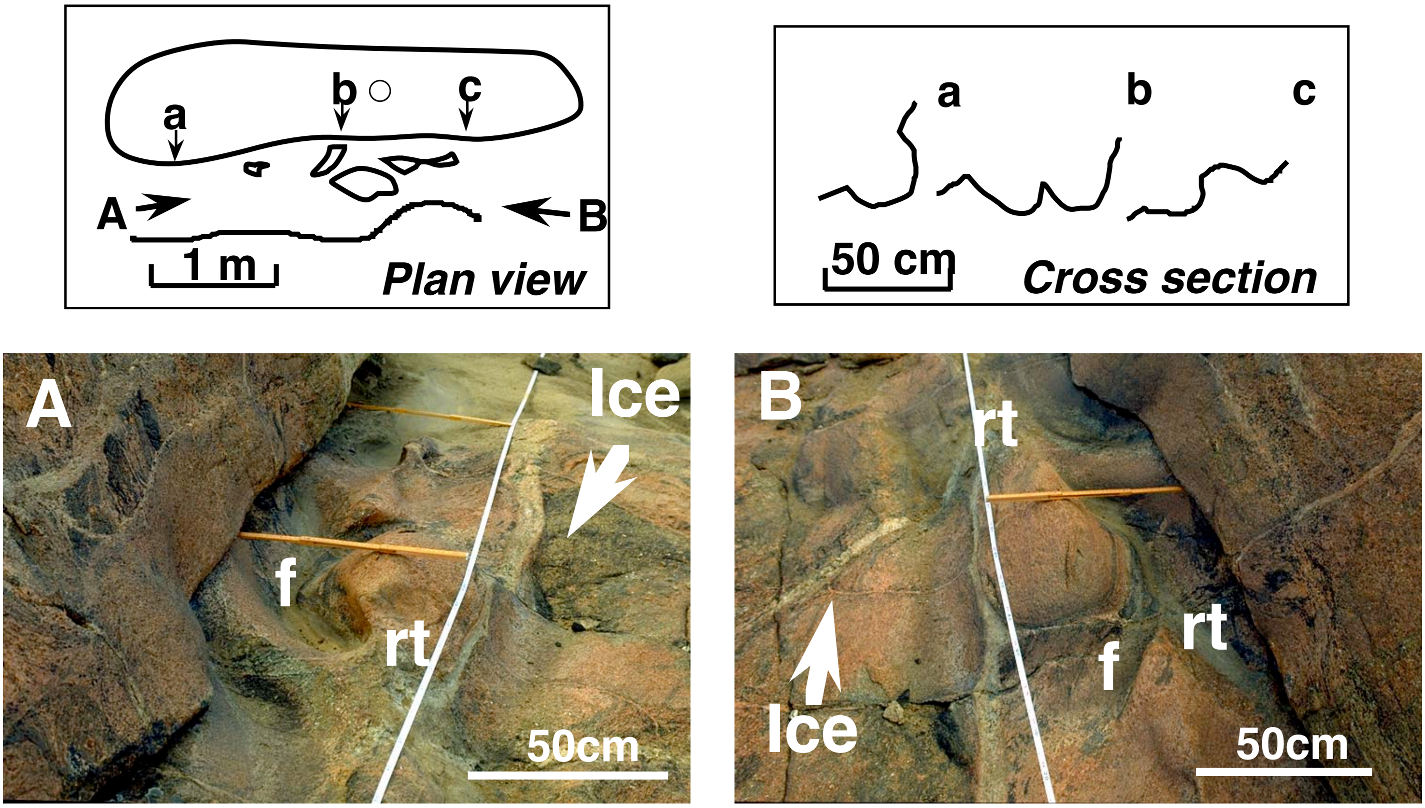

Fig. 5 S-forms sculptured along the lateral side of a streamlined bedforms in Rundvågshetta, with a plan view and vertical sections of a furrow. Furrows (f) are quarried around the bumps with a rat-tail remnant ridge (rt). Ice flow direction is indicated by an arrow.

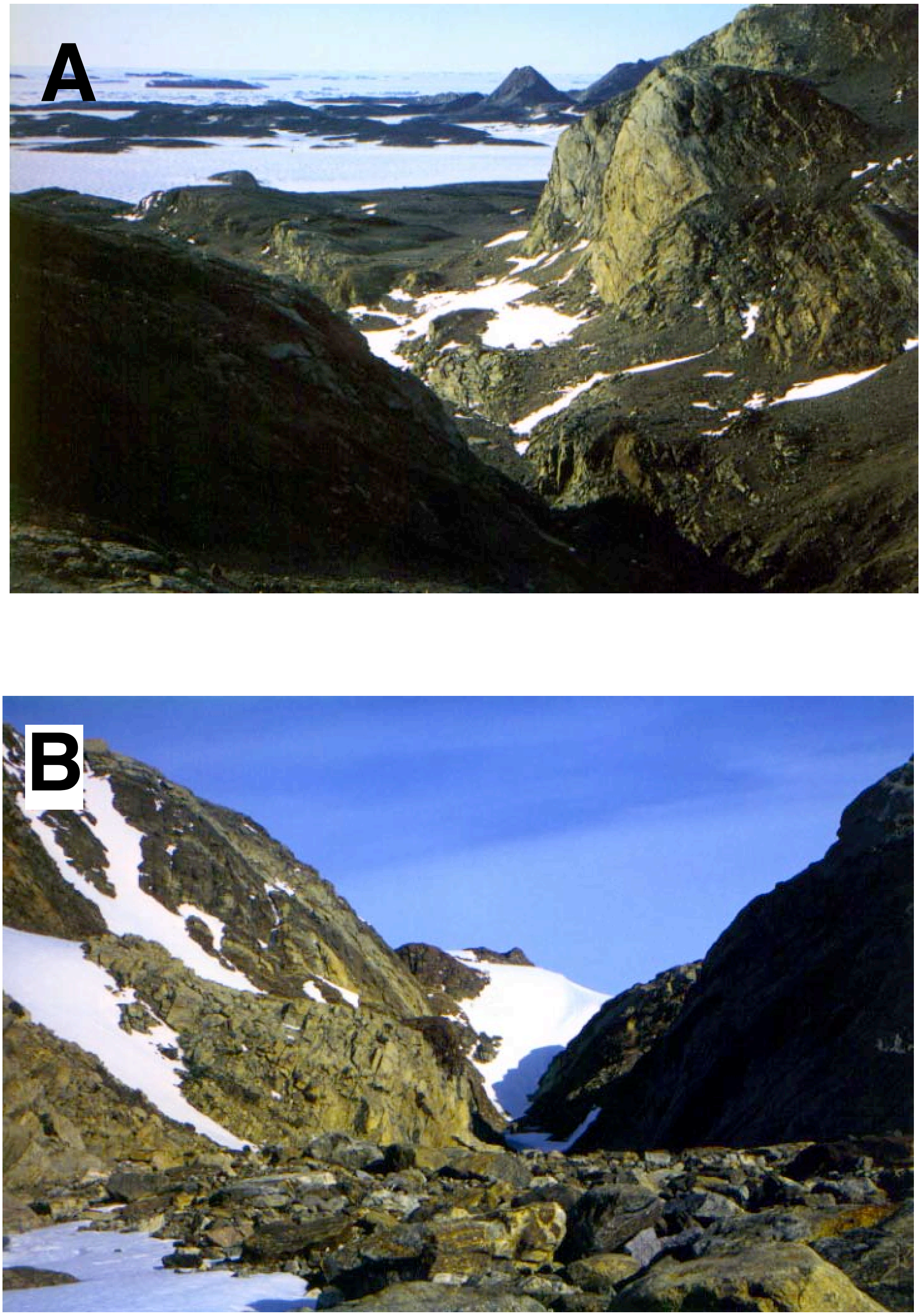

Fig. 6 Yatude valley showing a U-shaped valley cutting down deeply from several tens of meters to more than 100 m. A: The bottom of the U-shaped valley (A) is cut down again to show the narrow V-shape. B: The fluvial terrace landform composed mainly of large boulders up to 2-3 m in diameter is well developed in this V-shaped valley floor.

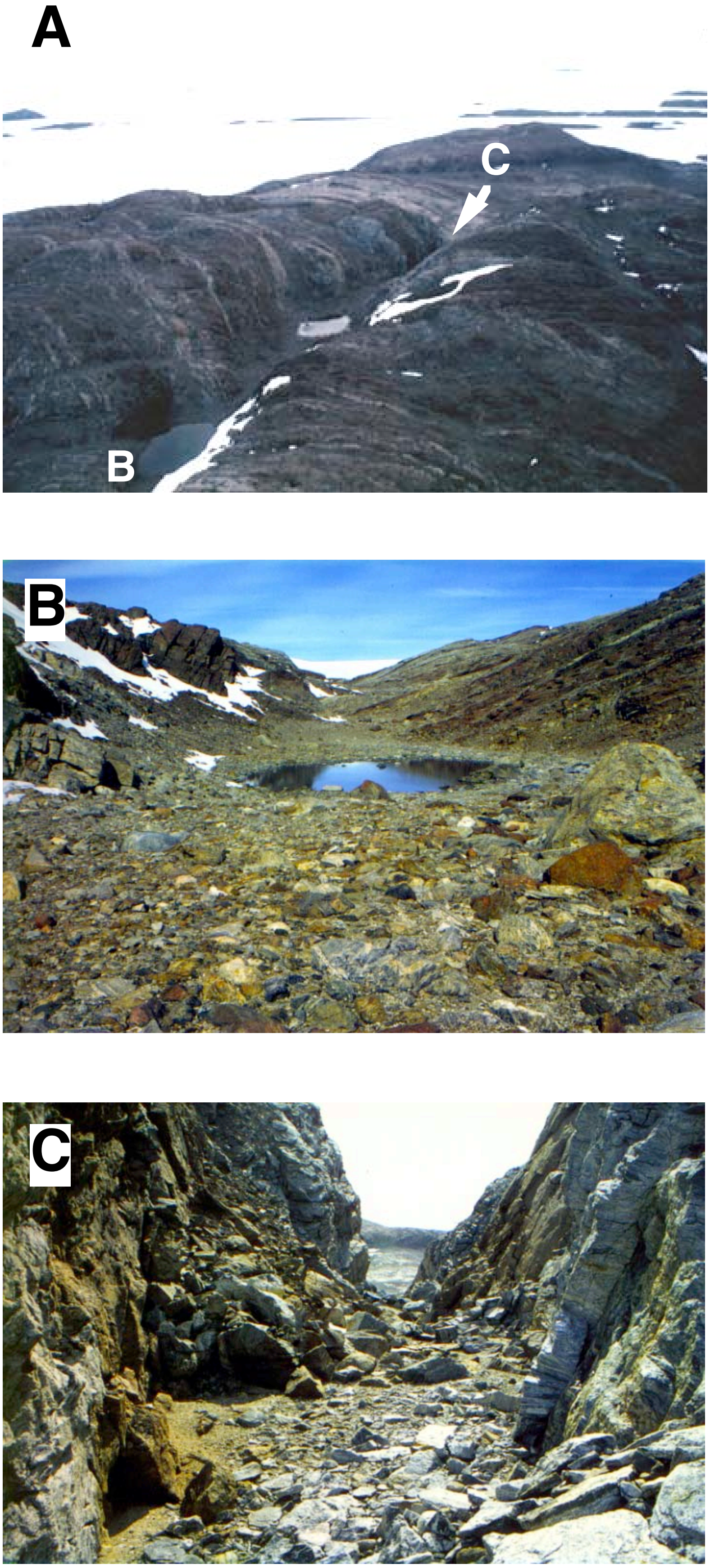

Fig. 7 A: Four small depressions of the Yotuike Valley connecting the lower rock basins through a narrow deep gorge (C). Note that the surrounding slopes are gentle and mammilated. B: The bottom of the uppermost depression looking upstream toward the ice sheet. C: A narrow, deep gorge cut into a depth of 80 m into basement rock which connects the upper four depressions. This remarkable down-cutting should have been caused by violent running water.

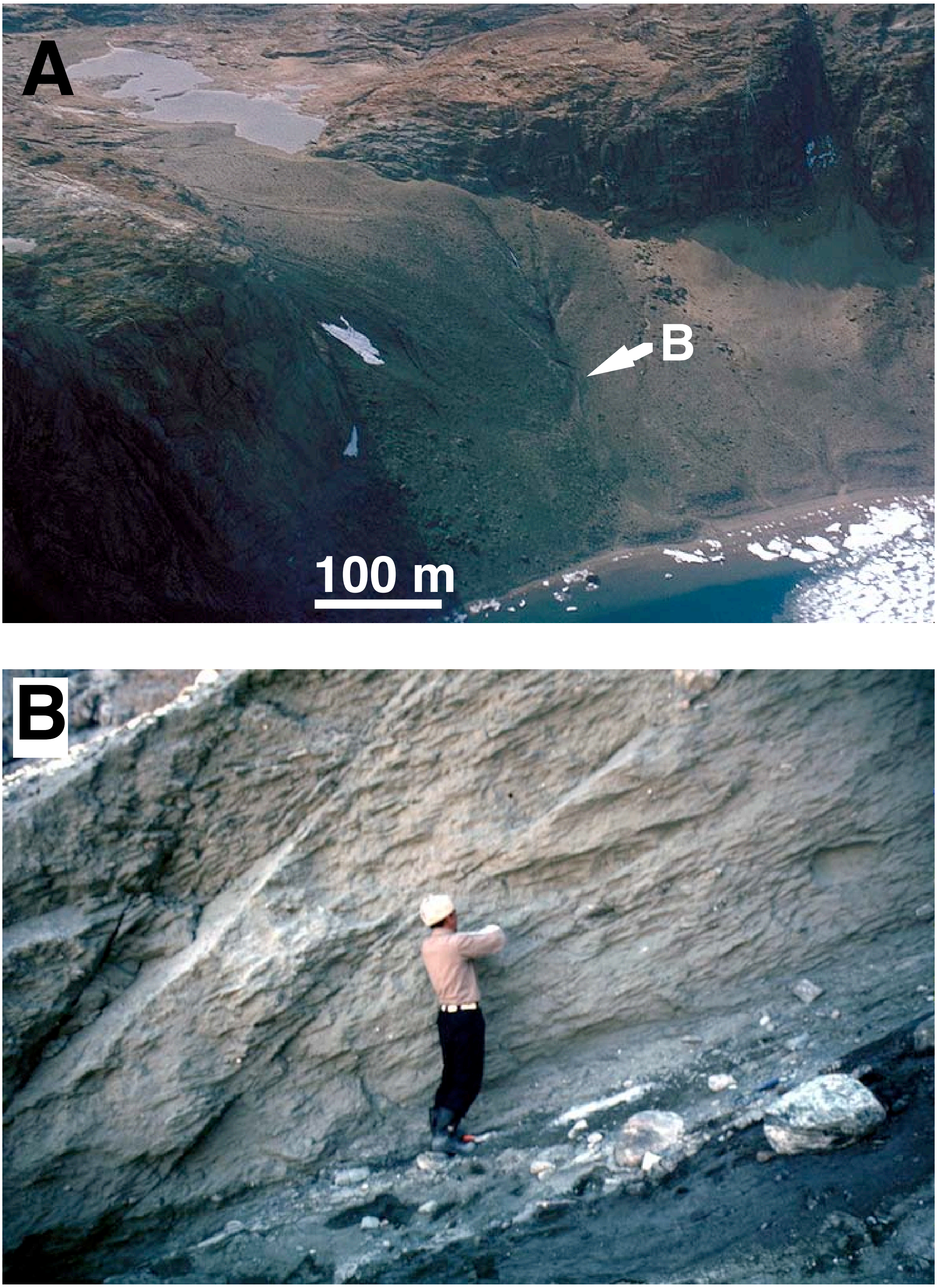

Fig. 8 A: An air photograph of the Osen Till with a thickness more than 5 m occupying the upper slope of a horseshoe-shaped depression in the Osen-Bay area of Skarvsnes. B: An outcrop of the Osen Till, that shows widely striated cobbles and pebbles in a fine sediment matrix with many oblique and bed-parallel shear planes.

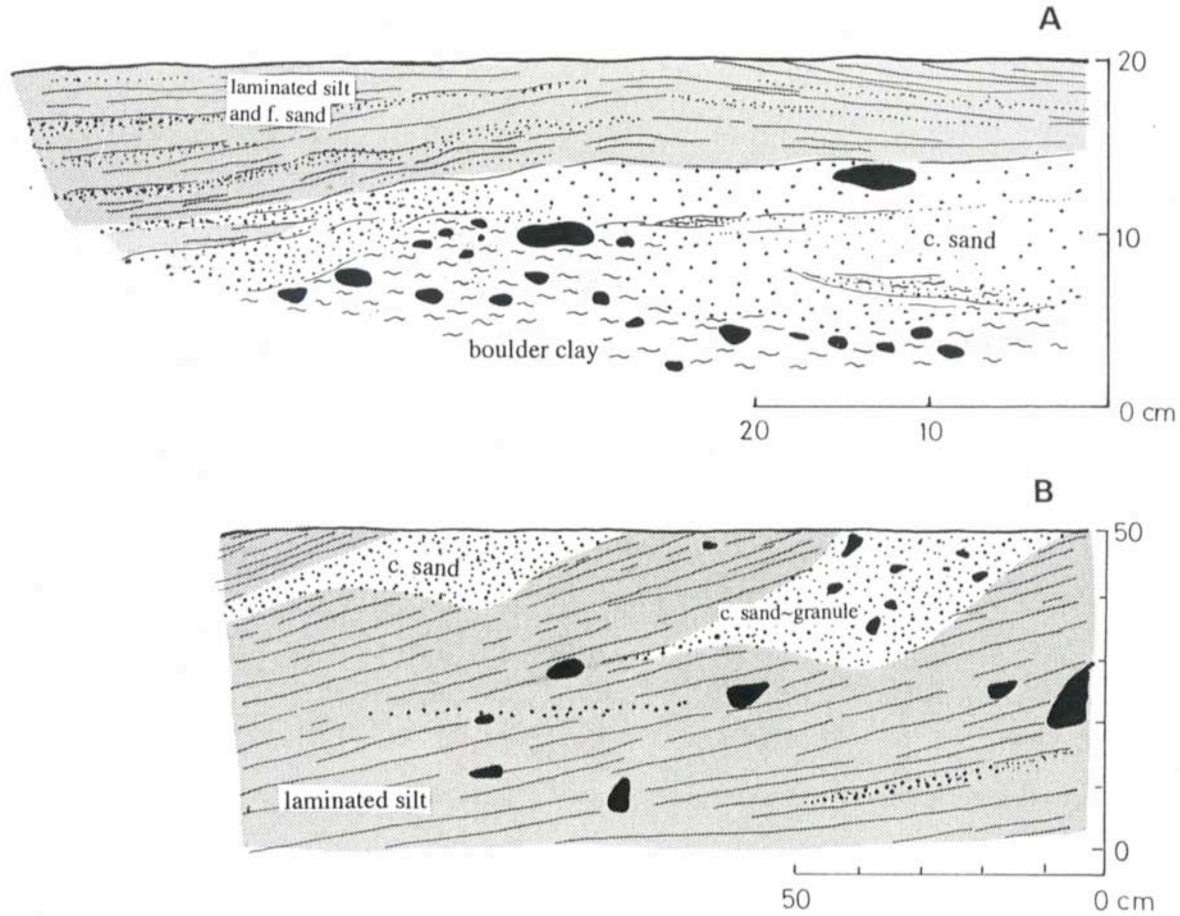

Fig. 9 Sketches of subglacial till in Langhovde (A) and in Skallevikhalsen (B). These tills are covered with lag cobbles and boulders of till origin indicating erosion by eorian process. Till consisting of laminated very fine sand and silt appear to have undergone glacial shearing.