Morphological evolution of the debris cover on Khumbu Glacier, Nepal, between 1978 and 1995

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Abstract The debris-covered area of Khumbu Glacier was topographically mapped in 1995 and the morphological evolution was determined by comparing the 1995 maps with those made in 1978. There had been significant changes in the surface morphology during this 17-year period: the area with a rough uneven surface with large relative relief had extended both upglacier and downglacier, and area of high ablation had increased. The glacier shrinkage in the ablation area where there was a thick debris cover was associated with an increase in surface relief and relative height, mainly caused by rapid ablation on exposed ice and lateral erosion at streams and ponds.

INTRODUCTION

There are many debris-covered glaciers which have ablation areas covered with supraglacial debris and till in the Khumbu region of eastern Nepal. Many aspects of the debris-covered area of Khumbu Glacier were intensively investigated in 1978 (Watanabe *et al.*, 1980). In particular, members of the project carried out a series of topographic surveys (Iwata *et al.*, 1980), and completed a topographic sketch map covering the whole ablation area and large-scale detailed 1:1000 maps of research areas I–IV (Fig. 1 in Watanabe *et al.*, 1980). After a 17-year interval, during the post monsoon season in 1995, the authors investigated the ablation area of Khumbu Glacier and constructed maps comparable to those completed in 1978. A series of glaciological and geomorphological observations was also carried out. The evolution of the surface morphology is in itself an interesting phenomenon for geomorphologists but observations of surface morphological changes also gives clues to the dynamic behaviour of the glacier, in particular the relationship between ice flow, ablation, and debris supply.

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This report describes the morphological evolution in the ablation area of Khumbu Glacier over a 17-year period obtained by comparing observations in 1995 with those in 1978, and discusses the significance for the evolution of ablating debris-covered glaciers.

KHUMBU GLACIER

Khumbu Glacier is a valley glacier originating from the southwest face of Qomolangma (Sagarmatha or Mt Everest, 8848 m), and flows in a southwest direction forming a 10-km-long, debris-mantled glacier tongue. The equilibrium line occurs at 5600 m a.s.l. (Watanabe *et al.*, 1980) in the icefall from whose foot the long and slender glacier tongue appears. Two main tributary glaciers join the mainstream: one is from the south of Lingtren and Khumbutse, and the other is from the western face of Nuptse (Fig. 1 in Fushimi *et al.*). The tributary glacier located just downstream of Gorak Shep is completely separated from the main glacier at present. Bare ice is exposed at Base Camp (5300 m a.s.l.) and extends downglacier 2–3 km below Base Camp as a slender bare ice band with ice pinnacles. The median part of the ablation area downglacier 5 km below Base Camp has a distinctive dark-coloured schistose debris cover supplied from the steep rock walls of the higher mountains (Fushimi *et al.*, 1980).

The ablation area is bounded by lateral and frontal moraines with distinct ridges formed during the Little Ice Age and Neoglacial periods (Iwata, 1976; Fushimi, 1981; Röthlisberger, 1986), and is mostly covered with a supraglacial debris mantle, except for limited areas in the upper part. The surface has a very complicated and chaotic topography: with striking glacier karst features, including funnel-shaped hollows with lakes, ice cliffs exposed on walls of hollows and on banks of lakes, and debris-covered cones (conical hills) and ridges. Khumbu Glacier is one of the most well-investigated debris-covered glaciers in the Himalayas. Various aspects of the debris-covered area have been described: surface morphology (Iwata *et al.*, 1980; Seko *et al.*, 1998); distribution, grain size, and production rates of supraglacial debris (Fushimi *et al.*, 1980; Nakawo *et al.*, 1986); ablation rates (Inoue & Yoshida, 1980; Nakawo *et al.*, 1999); and morphogenetic processes (Watanabe *et al.*, 1986).

METHOD

Field observations, measurements and surveys were carried out during the post monsoon season (October and November) of 1995. Sketch maps of the topography of the whole ablation area were made to clearly show the irregular morphology of the debris-covered glacier surface, and to compare the morphology in 1995 to that in 1978. Methods and data sources of the mapping in 1995 (the 1995 map) are as follows:

(a) stereoscopic observation of SPOT images taken in November 1995,
(b) field observation by Iwata in October 1995, and
(c) supplementary interpretation of stereo-pairs of vertical aerial photographs taken in December 1992.

The sketch map indicating the situation in 1978 (the 1978 map: Appendix, Separate Sheet 1 in Iwata *et al.*, 1980) was used as the base map. The completed map shows the distribution of sharp and gentle ridges, convex and concave slopes, valley lines, bare-ice areas, ice cliffs, ponds or lakes, and streams on the debris-covered surface (Fig. 1).

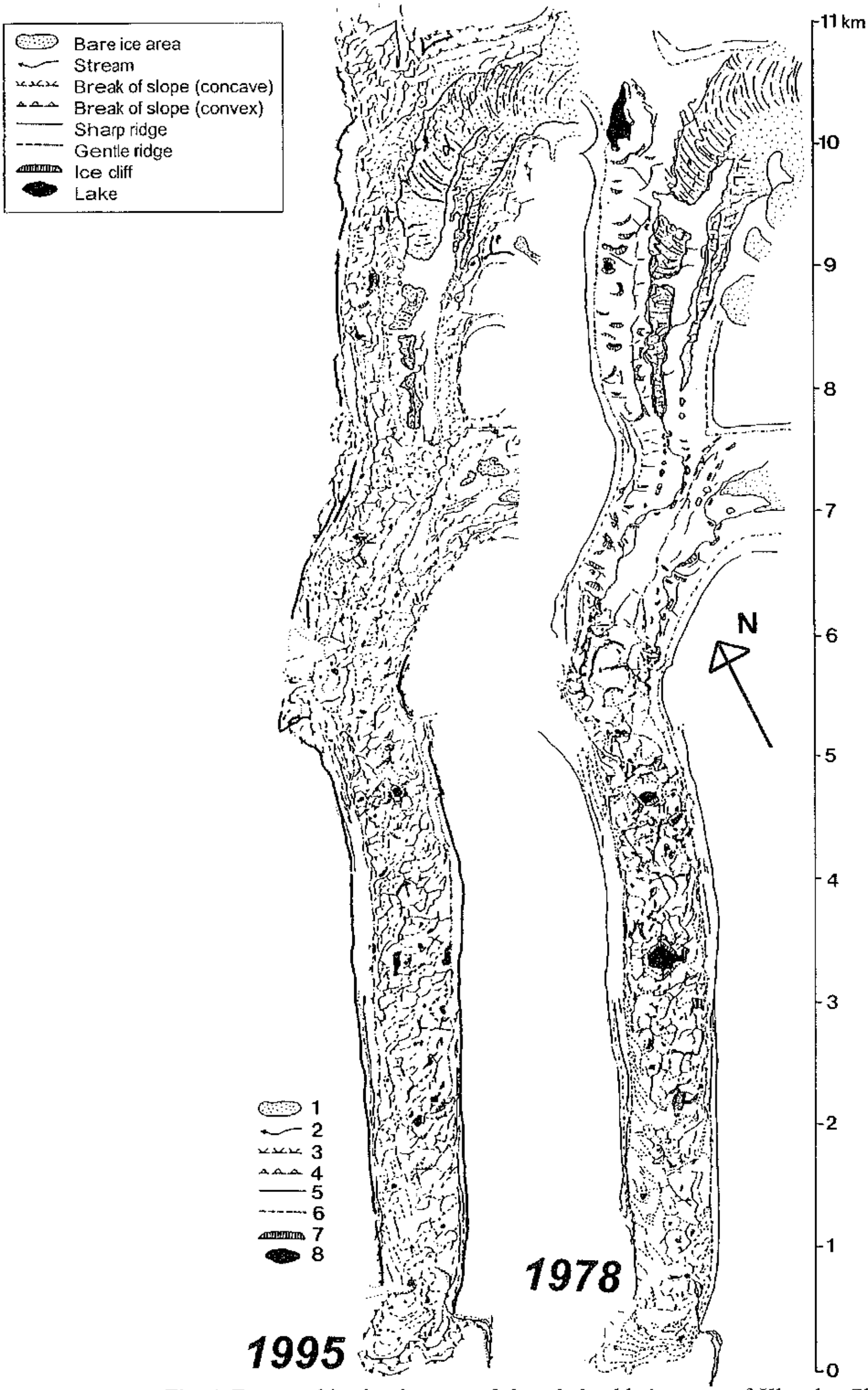

Fig. 1 Topographic sketch maps of the whole ablation area of Khumbu Glacier in 1978 (Iwata *et al.*, 1980) and 1995.

The 1978 map was mainly compiled by simple terrestrial photogrammetry of about 400 stereo-pairs of photographs taken from lateral moraine ridges (Iwata *et al.*, 1980). Therefore relative altitudes of the surface relief were well documented on the 1978 map, but accuracy of spatial positions was less precise. In contrast, the 1995 map, mainly made by SPOT images, represents a more precise positioning of each surface form, while the vertical forms such as small-scale ice-cliffs and elevations were not recognized with any accuracy, and are not represented on the map.

In order to find the morphological changes in research areas I–IV since 1978 (Iwata *et al.*, 1980; Watanabe *et al.*, 1980), each area was resurveyed in 1995. Details of the surveying method and the results are reported by Kadota *et al.* (2000).

RESULTS

Comparing the topographic maps between 1978 and 1995

The topographic sketch maps of the whole ablation area in 1978 and 1995 are presented in Fig. 1. A morphological change could be detected from the comparison of these two maps of the whole ablation area.

Upper part of the ablation area In the upper part of the ablation area, including Area IV, between 7.5 km upglacier from the terminus and Base Camp just below the icefall, the general features of the surface morphology were similar to those in 1978. A long and slender dark-coloured schistose debris-belt between the stretches of bare-ice belts with arcuate ridges or rows of ice pinnacles was found in almost the same location as in 1978, but the bare-ice surface had decreased in area by about 40%, and the debris gaps in the bare-ice belt on the right bank had moved about 0.5 km downstream (Seko *et al.*, 1998). In 1995, an apparent ridge was observed in the bare ice belt on the left bank along the dark debris band. The right bank of this part comprises a debris-covered ice-mass from Mt Lingtren and Khumbutse. This ice mass had changed significantly during the 17 years: many ponds and ice cliffs observed in 1978 had disappeared and the surface roughness had decreased.

Middle part of the ablation area This area comprises the glacier surface between 7.5 km and 2.0 km upglacier from the terminus. This mid-stream part of the ablation area changed greatly over the 17-year period. One of the authors (Iwata) carefully observed the surface features of this part from the lateral moraines in October 1995, but he could not identify the definite landforms that had been recognized in 1978.

The area between 5 and 6 km upglacier from the terminus, where Area III is located, is characterized by a deep valley on the right bank side and a line of large debris-covered cones. Most of this area had been covered with relatively thin debris, ranging from 10 to 30 cm thick, but part had been covered with debris more than 1 m thick. By 1995 more complicated landforms had appeared. For example, a large debris-covered cone had disappeared, and several circular hollows with high ice cliffs emerged; a large valley with a stream had shifted from the right bank to the centre of the glacier.

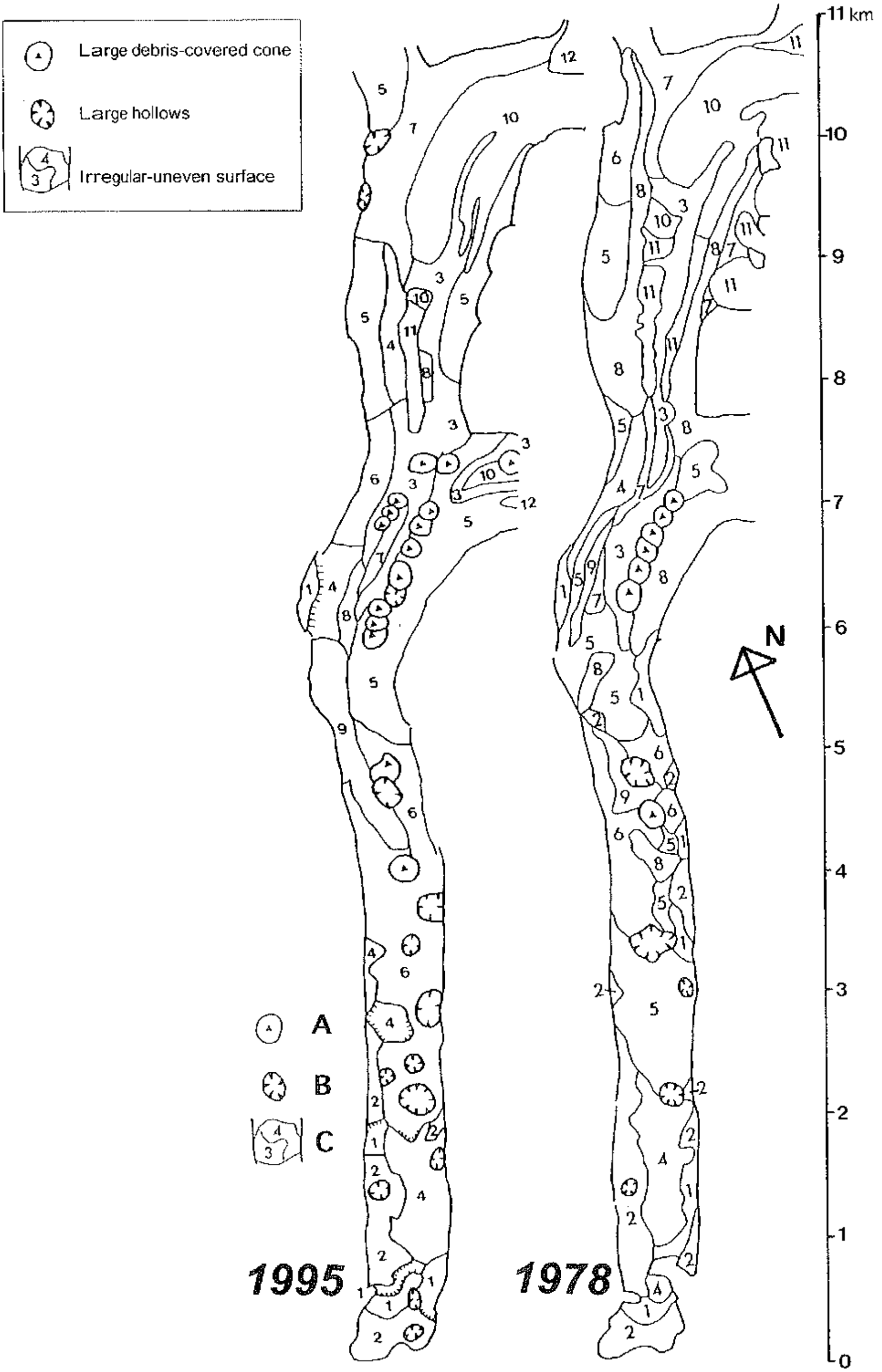

Fig. 2 Distribution of morphological units of the ablation area of Khumbu Glacier in 1978 (Iwata *et al.*, 1980) and 1995. The morphological classification was based on a combination of morphological elements: large debris-covered cones, large hollows and irregular uneven surfaces—the numbers correspond to those in Table 1.

The area between 3 and 5 km from the terminus has the largest relative height (60–80 m) from the surface of the glacier to the lateral moraine ridges. The observed rough and chaotic surface features were similar to those in 1978, but no recognizable landforms could be found, as the surface features had completely changed during the 17-year period. A notable large hollow with a nearly circular pond (0.2 m × 0.15 km) located 3.3 km from the terminus in 1978, had disappeared by 1995, but a small pond was seen near that location. In the lower part of the zone, between 2 and 3 km from the terminus, the rough topography had extended downstream. New hollows with small ponds and troughs occurred and on the right bank a low-relief area with parallel ridges had disappeared.

Lower part of the ablation area In the area within 2 km of the terminus, including Area I near Lobuche, many landforms such as gentle ridges and several small lakes observed in 1978 were still there in 1995. Notably, partially vegetated parallel ridges on the right-bank side which had been observed in 1978 were nearly the same in 1995. On the other hand, the left-bank side margin had changed to more or less rough topography. Some subsidence features such as small hollows and a trough appeared in some places at the lowest end of the glacier.

Evolution of morphological units

Glacier karst landforms in the ablation area of Khumbu Glacier (Fig. 1) were so complicated that Iwata *et al.* (1980) had made a morphological classification map (Fig. 2) based on a combination of the morphological features shown in the 1978 topographical sketch map. The surface topography of the ablation area was first classified into three remarkable morphological units as follows: large debris-covered cones, large hollows, and irregular uneven surfaces. The irregular uneven surfaces were then classified into 11 units given in Table 1.

In 1995 the glacier surface was similarly classified, and a map was made based on the 1995 topographical sketch map and our field observation (Fig. 2). A comparison of these two maps shown in Fig. 2 reveals a morphological evolution of the debris-covered glacier surface between 1978 and 1995, and reveals three significant changes:

Table 1 Classification of the irregular uneven surfaces.

Surface relief	Relative height (m)	Directional feature	Debris-cover (thickness)	Exposure of glacier ice	Pond	Stream	Number of units
Small	0–10	Nil	Thin	Large part	A few	Many	7
Small	0–10	Nil	Thin	Small part	Nil	Nil	3
Small	0–10	Exist	Thick	Nil	Rare	Nil	2
Small	0–15	Nil	Thick	Nil	Rare	Nil	1
Small	0–15	Exist	Nil	Whole	Rare	Rare	10
Medium	10–30	Nil	Nil	Whole	Rare	Rare	11
Medium	10–30	Nil	Medium	Large part	A few	Many	8
Medium	10–30	Nil	Medium	Large part	Many	Nil	5
Medium	10–30	Nil	Medium	Very small part	Nil	Nil	4
Large	20–40	Nil	Medium	Large part	Many	Nil	6
Large	20–40	Nil	Medium	Large part	A few	Many	9

- Several new large hollows had appeared in the middle and lower parts of the ablation area.
- The distribution of irregular uneven surfaces with large relative relief (units 6 and 9) had extended downstream in the middle part of the ablation area. This implies that the surface relief in the lower part of the ablation area had increased from medium (10–30 m in height) to large (20–40 m) between 2 and 3.5 km from the terminus.
- Large relief feature (units 9 and 6) emerged on the right-side bank in the upper middle part (4.5–5.5 km from the terminus) and the lower upper part (6.5–7.5 km) of the ablation area. On the right side in the upper part of the ablation area (9.5–10.5 km) where a tributary from Lingtren and Khumbtse joins the main glacier, two large hollows appeared and the surface units changed from units 5 and 6 to unit 7, indicating a decrease in surface relief which suggests a rapid decline of this thin ice mass.

DISCUSSION

Watanabe *et al.* (1986) schematically illustrated the morphogenetic processes on the glacier surface along the longitudinal section of the ablation area, based on detailed field observations in research areas I–IV on Khumbu Glacier. It was suggested that important factors in morphogenetic processes are the discharge of glacier (ice flow), sub-aerial and sub-debris ablation rates controlled by debris thickness, and surface and subsurface water which erodes the ice directly. Recently, Nakawo *et al.* (1999) estimated the ablation rates on the surface and beneath the debris layer and the ice flow rates along the longitudinal section of the ablation area of Khumbu Glacier. This estimation was conducted using a heat-budget approach derived from analysis of satellite data. Kadota *et al.* (2000) reports a lowering of the surface in the four research

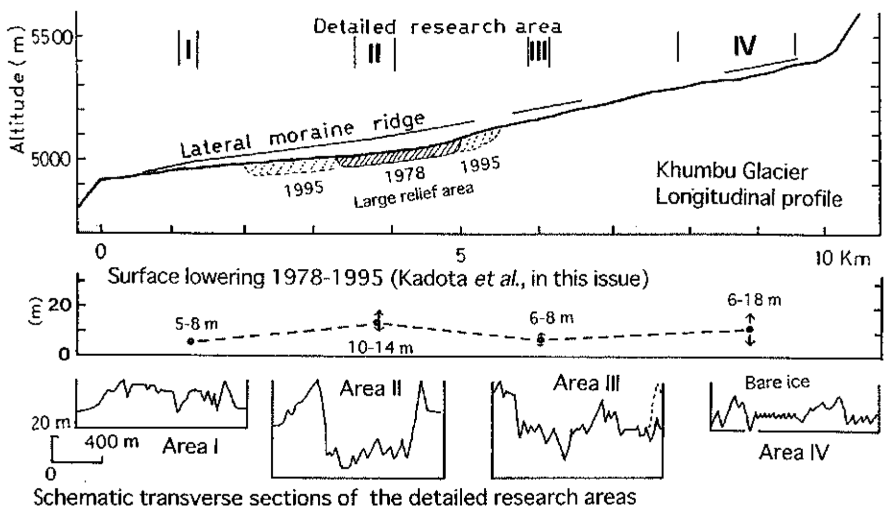

Fig. 3 Longitudinal profile of Khumbu Glacier ablation area showing expansion of large relief area, surface lowering, and transverse profiles.

areas between 1978 and 1995. This is illustrated in Fig. 3 which shows the morphological features of sections across the four research areas. The morphological evolution indicated by the detail mapping of the glacier surface in 1978 and 1995 reveals:

Upper part of the ablation area In and around Area IV, the surface features and distribution of bare and debris surfaces are mostly unchanged in the median part of the glacier. Kadota *et al.* (2000), however, found that the glacier surface had lowered by more than 10 m and that distinct longitudinal ridges had occurred in the areas of schistose debris on both sides of the band of bare ice. This nearly uniform lowering seems to be due to the thin dark-coloured debris cover (unit 3) and to the compression zone below the icefall. Although a relatively rapid ice flow was estimated in the area by Nakawo *et al.* (1999), this significant surface lowering suggests a recent rapid decrease of ice supply from upglacier.

Middle part of the ablation area In the area between 5 and 6 km from the terminus, the surface lowering is relatively small compared with the upglacier and downglacier areas (Nakawo *et al.*, 1999; Kadota *et al.*, 2000). It is probable that the morphological change including the shift of the valley is related to the decline of tributary glaciers from Lingtren and Khumbutse, and from Nuptse. This is likely to be related to the increase in the debris thickness.

The complete change in the rough and chaotic features from 3 to 5 km above the terminus is due to the large ablation rates (Inoue & Yoshida, 1980; Sakai *et al.*, 1998; Nakawo *et al.*, 1999) on the exposed ice cliffs which are eroded by running water in streams and still water in ponds. As the ice cliffs retreat by ablation and the debris-covered slopes evolve through stream erosion, the debris on the ice is redistributed to make an irregular debris cover with some nearly exposed ice surfaces. Apparent positive feedback relationships exist between high ablation rates, water erosion, exposed ice, and debris redistribution. As a consequence, irregular uneven surfaces appears and high surface lowering occurs in the area.

Lower part of the ablation area Fossil or stagnant ice in the lowermost 2 km from the terminus is covered with such thick debris that the ablation at the surface may be negligibly small (Inoue & Yoshida, 1980; Nakawo *et al.*, 1999). In spite of the occurrence of some subsidence features, the surface morphology and vegetation in this part have remained almost the same since 1978. Kadota *et al.* (2000) reports, however, that on the right bank side of Area I, the surface has lowered by 5–8 m since 1978. This suggests that the surface lowering is mainly due to subglacial and englacial meltwater, because many surface meltwater streams observed in the median part of the glacier are hidden in the lower end of the ablation area and this hidden water suddenly gushes out at the terminus.

The most important morphological change is that the area of large relief features in the middle part of the ablation area has expanded both the upglacier and downglacier. This means that since 1978 the areas of high ablation associated with large hollows, ice cliffs, and ponds and streams have spread. In ablation areas with a thick debris cover such as Khumbu Glacier, a glacial decline has occurred associated with the increase of the surface relief as well as the relative height. It thus follows that the existence of exposed ice cliffs and surface water is an important controlling factor for the morphological evolution of glaciers covered with a thick layer of debris.

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