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Debris-mantle formation of Wrputu Glacier, the Tianshan Mountains, China

Shuji IWATA[1], Shinjiro KURODA[1], and KADER Kezer[2]
1 Department of Geography, Tokyo Metropolitan University, Tokyo 192-0397 Japan
2 Xingchang Institute of Ecology and Geography, Chinese Academy of Science, Urumqi, China

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Abstract

A small valley glacier, Wrputu Glacier, in the Urumqi River basin, the Tianshan Mountains, has a tongue-shaped debris hill in front of a debris-free glacier snout. Two topographical maps, surveyed in 1983 and 2003, indicate that the debris hill surface lowered 5-10 m in elevation for the 20-year interval, and this subsidence occurred on the entire debris hill. The cause of the subsidence is ablation of the underneath glacier ice so that the entire debris hill contains ice. This means that the debris hill is a debris-mantled glacier-snout rather than an ice-cored moraine. The debris mantle has originated from the debris-rich basal-ice layer of the formerly advanced and overrode preexistent glacier. Its scenario is as follows: The preexistent advanced glacier-snout turned to a stagnant snout by the negative mass-balance of the glacier. In the following positive state, glacier thickened and increased its movement rates. The active snout with debris-rich basal-ice layer overrode on the debris-free stagnant-snout and continued to advance. The preexistent debris-free glacial snout turned to the debris-mantled glacier after the overridden glacier stopped its advance and retreated as leaving the residual debris-mantle on the underneath stagnant glacial snout.

1. Introduction

Debris-mantled glaciers with continuous supraglacial debris- and till-mantles are common in high-relief mountain environments, such as the Himalayas and the Central Andes. Many rock glaciers are thought to be deformed from debris-mantled glaciers. Debris-mantled glaciers and/or rock glaciers were found even on Mars recently (Head and Marchant, 2003). More understanding of the debris-mantled glacier is necessary to discuss cold environments in and outside of the earth. Thus importance of intensive discussion on the debris-mantled glacier increases in glaciology and glacial geomorphology.

A small glacier, called Wrputu Glacier, in the Tianshan Mountains was re-surveyed in 2003 by the present authors after a 20 years interval (Iwata, 2004). The results indicate that a tongue-shaped debris hill located in front of the present glacier snout is a debris-mantled glacial snout constructed recently. This tongue-shaped debris hill was thought to be an ice-cored frontal moraine. The main part of the present glacier snout is a typical debris-free snout on which only few boulders have emerged for 20 years between 1983 and 2003. It is quite peculiar that one glacier changed from a completely debris-mantled one to a typical debris-free one during the successive advances. No traces of large geomorphological changes such as landslides and rock avalanches were found in the upper glacial basin surrounding the accumulation area.

The present study describes the morphological change of Wrputu Glacier between 1983 and 2003, and discusses the processes for the buildup of the supraglacial debris mantle of the debris hill.

2. Research area and research method

2.1. Research area

The upper reach of the Urumqi River, the Tianshan Mountains in western China, is situated in an alpine zone located above forest lines. Many rock-peaks over 4000 m a.s.l. constitute the basin divides and many small cirques and valley glaciers occur on these mountain flanks. According to the meteorological data measured by the Tianshan Glaciological Research Station of the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Science Academy, located in the main valley bottom at 3546 m a.s.l., mean annual air temperature is -4.5℃, and annual precipitation, the 70% of total occurs in summer, is 468.6 mm (Ji, 1980). The lower limit of the permafrost is 3100 m a.s.l. (Ji, 1980).

Wrputu Glacier is one of many glaciers located at

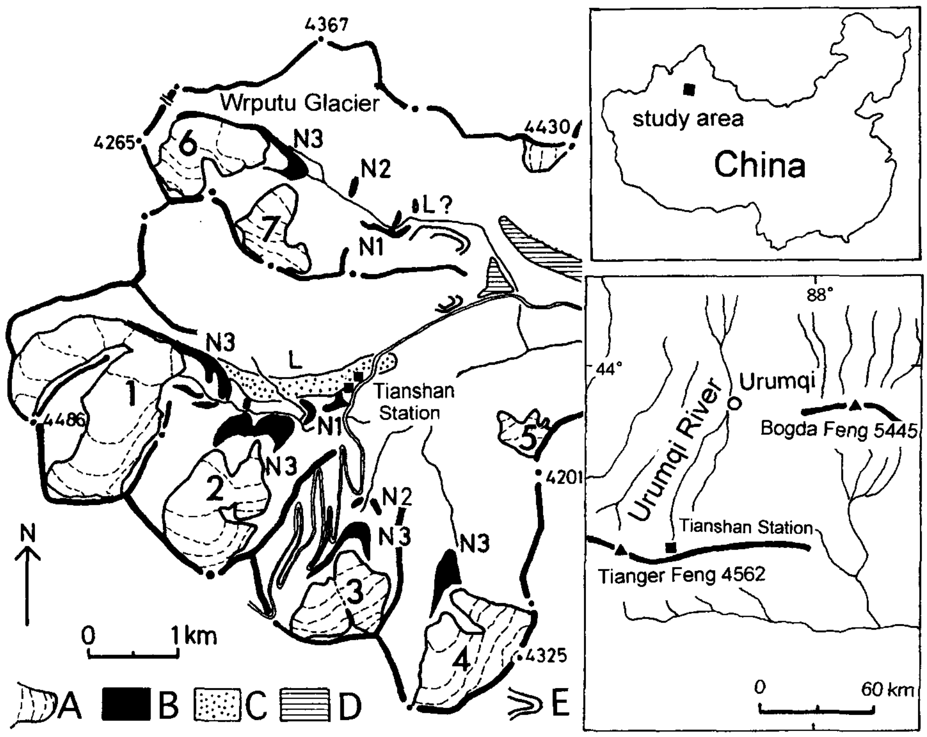

Fig. 1. Study area and Wrputu Glacier (No. 6 Glacier) in the upper basin of the Urumqi River, western China. A: glacier, B: Little Ice Age moraine, C: Holocene moraine, D: Last Glacial moraine, E: Rock glacier.

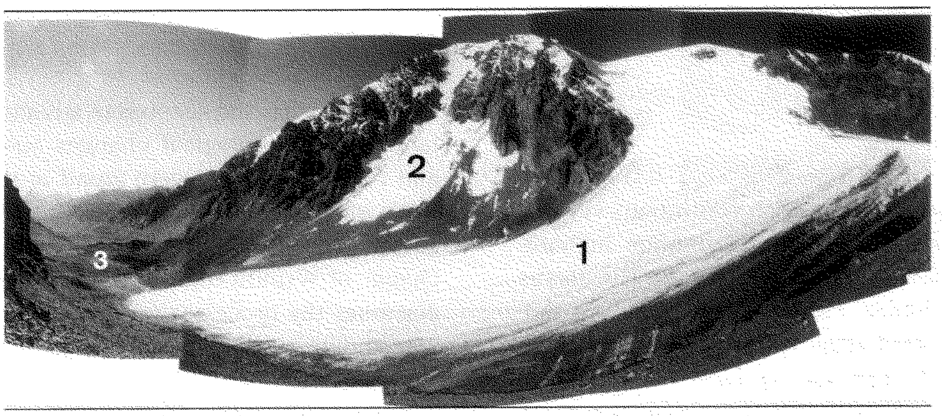

Fig. 2. Wrputu Glacier constitutes a debris-free main valley glacier (1), a small cone-type glacier (ice talus) (2) with a debris-mantle in the lower part, and debris hill (3) in front of debris-free main glacier snout. Taken in July 2003 from the north.

around the Tianshan Glaciological Research Station, and is named No. 6 Glacier by Chinese scientists (Fig. 1). "Wrputu" or "Wulupte" is the name used by local Kazakh people. This is a small valley glacier of 1.5 km in length, with 4300 m of the highest end and 3750 m of the present front. Glaciers in the area are classified into cold-type glaciers but parts of the glacier bottom of No. 1 Glacier attain at the melting point (Shi, 2000: 60-61). The glacier is composed of a main valley glacier (the north snout) and a tributary cone-type glacier (the south snout). The main one is a debris-free glacier which flows to the north on the north-facing steep slope and turns to the east in the valley, and the tributary one is a small cone-type glacier (ice talus) with a debris-mantle in the lower part (Fig. 2). A tongue-shaped debris hill with steep frontal slopes is located in front of the present glacier front. A central lower part is bounded by horseshoe-shaped higher marginal part. The higher marginal part was thought to be an ice-cored moraine (Cui, 1981), and one of the authors, Iwata observed that a large clear ice existed under glacial ice inside the higher marginal part in 1983 (Iwata, 2000). The tongue shaped hill seems to be a similar form of a terminal moraine or a rock glacier.

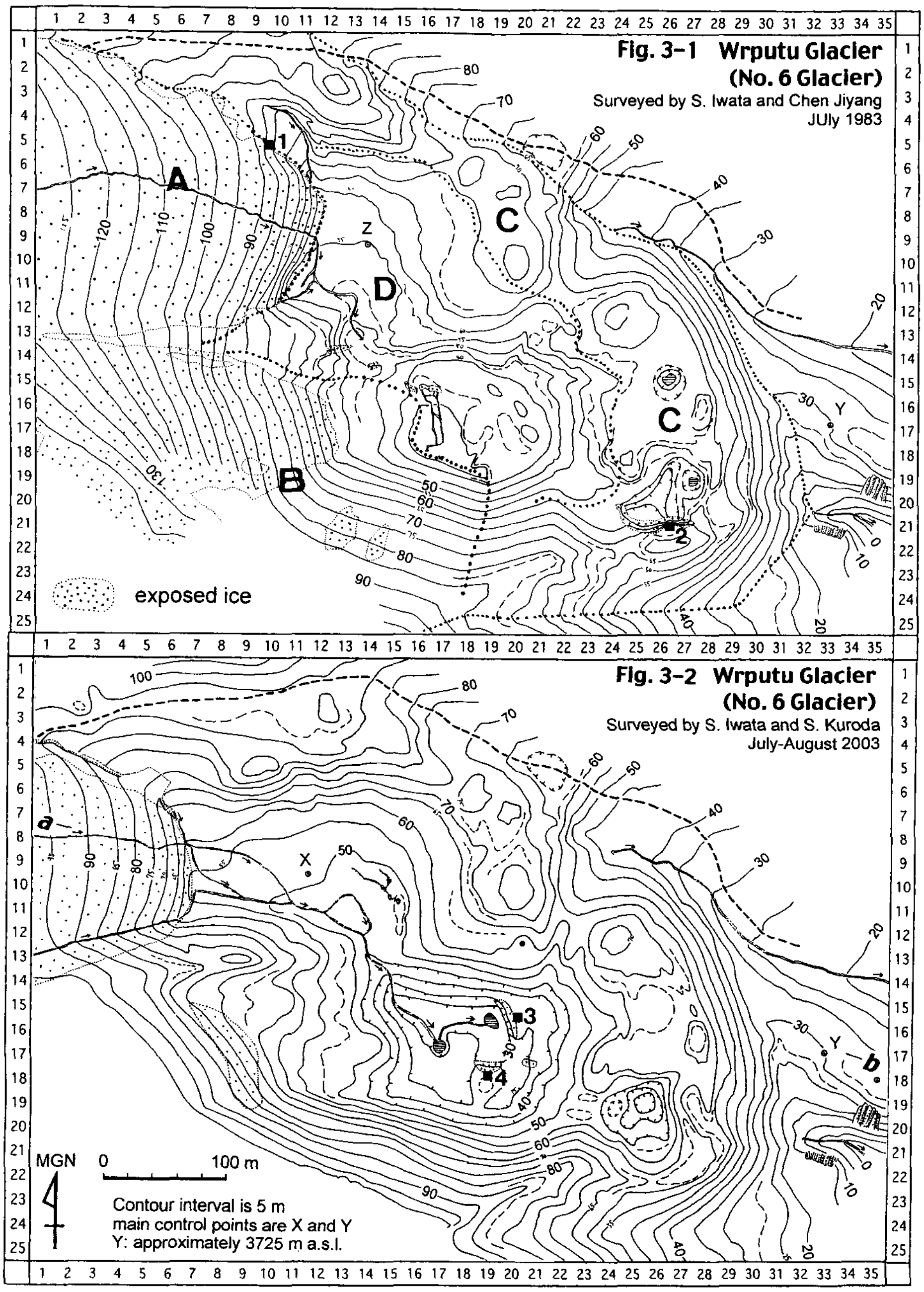

Fig. 3. Topographic maps of the Wrputu Glacier snout and the tongue-shaped debris hill. Fig. 3-1 was surveyed in July 1983 by Iwata and Chen, and Fig. 3-2 in July-August 2003 by Iwata and Kuroda. Contour interval is 5 m. Dotted lines in Fig. 3-1 are boundary of the following division A-D. A: main valley glacier snout, B: cone-type glacier snout, C: higher marginal part of tongue-shaped debris hill with steep frontal slopes, D: central lower part of tongue-shaped debris hill. Solid squares with numbers are locations in the text.

2.2. *Research method*

In July 1983, Iwata surveyed Wrputu Glacier and completed a geomorphological map by plane table surveying with an electron distance-meter (Fig. 3-1) (Iwata and Chen, 1987), when the Japan-China cooperative research was conducted in the area around the Tianshan Glaciological Research Station. After 20 years, in July-August 2003, the present authors carried out the resurvey by the same manner as that in 1983 (Fig. 3-2; Iwata, 2004). Point Y in Fig. 3 was set up on the bedrock in front of the debris hill as a common control point. The authors carried out field observations on debris production from the present glacier and on sedimentary features of debris on the tongue-shaped debris hill.

3. Results

3.1. *Morphological changes between 1983 and 2003*

Two topographical maps, surveyed in 1983 and 2003, indicate the morphological changes of the present glacial snout and the tongue-shaped debris hill of

Numbers are values of vertical lowering in meters
Numbers with underline are rising in meters

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	
1					4	5	4	3	0	1	4	5	2	0																						1
2	23	20	15	3	1	9	9	7	3	3	8	8	5	0	0																					2
3	30	27	22	21	4	15	7	2	0	0	1	3	10	7	3	1																				3
4	35	35	30	30	20	21	15	13	2	$\underline{7}$	$\underline{11}$	4	6	5	5	0	0																			4
5	35	35	37	38	13	30	30	16	3	$\underline{7}$	$\underline{9}$	$\underline{3}$	1	5	7	0	0	0	0																	5
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7	33	32	34	33	37	42	37	35	30	28	18	3	6	5	8	7	3	0	0	1	0	0														7
8	33	32	33	33	36	40	43	37	35	27	21	6	5	6	7	7	0	1	0	0	0	0	0													8
9	33	32	33	33	36	39	50	41	34	33	19	6	7	6	7	13	5	3	0	0	0	0	0	0	0											9
10	32	28	32	33	35	39	53	42	35	29	16	4	11	6	7	9	7	4	0	0	0	0	0	0	0	0	0	0								10
11	32	28	31	33	36	41	45	39	32	28	5	5	6	6	6	10	7	5	0	1	1	0	0	0	0	0	0	0	0							11
12	32	28	32	38	36	30	32	23	18	6	2	3	3	7	11	6	5	6	1	5	3	1	1	0	0	0	0	0	0							12
13	30	28	28	26	24	25	14	10	1	2	4	2	4	5	10	6	0	6	2	0	0	7	4	0	0	1	1	0	0							13
14	30	25	23	22	21	15	20	17	12	7	13	5	3	5	11	10	3	1	5	4	6	10	8	1	1	0	0	0	0							14
15			22	25	20	13	14	16	13	7	1	4	1	3	5	6	8	9	8	5	4	6	5	2	2	1	3	0	0	0						15
16					19	19	19	17	15	10	5	0	$\underline{2}$	$\underline{2}$	2	5	7	6	4	4	5	0	8	9	5	2	0	0	0	0	0					16
17					19	20	15	15	14	15	13	2	1	$\underline{4}$	$\underline{3}$	0	4	4	9	11	5	3	5	1	3	1	0	0	0	0	0					17
18						8	12	12	15	14	16	9	2	5	2	0	0	1	0	3	3	0	0	5	11	4	$\underline{2}$	0	0	0	0					18
19									5	7	10	4	$\underline{5}$	6	5	5	9	2	0	4	4	4	0	4	15	20	0	1	2	3	0					19
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22																$\underline{7}$	$\underline{5}$	$\underline{2}$	0	3	1	$\underline{4}$	$\underline{6}$	$\underline{4}$	$\underline{3}$	6	7	1	0	0	0					22
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Fig. 4. Vertical changes of the glacier and debris-hill surfaces were computed from the contour-line values on the two maps in Fig. 3. Values in meter show mean change in each cell (20 ×20 m). The frame (coordinates) of the figure is same as that in Fig. 3.

Wrputu Glacier for recent 20 years (Fig. 3). Vertical changes of the glacier and debris-hill surfaces are indicated by difference between the contour-line values on the two maps (Fig. 4).

3.1.1. Retreat and surface lowering of the glacier

The front of the main valley glacier (the north snout) retreated more than 100 m in distance, and the glacier surface lowered 30–40 m in elevation, the maximum value, obtained at the 2003 frontal position of the glacier, is 53 m.

The frontal positions of the tributary cone-type glacier (the south snout) are not clear because the snout is covered by supraglacial debris-mantle. The lower end of this cone-type glacier seems to coincide with the break of slope which is located roughly at the 35 m contour line both in 1983 and 2003. If this lower boundary is accepted, the frontal position has not change largely. The supraglacial debris-mantle is composed of relatively large and angular blocks and apparently increases its area for 20 years (Fig. 3). The steep back slopes of the glacier indicate that debris was supplied on the ice cone by avalanches and rock falls. This indicates that the debris has been accumulated by melt-out of the glacier.

Surface lowering of 15–20 m is observed in the frontal part of the debris-mantled cone-type glacial snout (Fig. 4). Four cells with 2–4 m surface rising are indicated in Fig. 4 (vertical 16–17, horizontal 13–15 of cell numbers in coordinates). They coincide with a wide ridge between 40 m and 55 m contours in Fig. 3-2. Apparently, a part of the cone-type glacier is advancing or rising its surface.

3.1.2. Morphological changes and surface lowering of the debris hill

The outline of the tongue-shaped debris hill shows the almost same form in these 20 years. This debris hill is topographically divided into three parts: the steep frontal slopes, the horseshoe-shaped marginal higher part, and the central basin bottoms. The position of the lower fringe of frontal slopes has not changed from 1983, and no surface lowering occurred on the frontal slopes. Figure 4 shows that most of the top surface of the marginal higher part keeps the same elevation, except the northwestern end (lowered) and southeastern corner (lowered and rose). Inner slopes of the marginal higher part partly decrease 3–7 m in elevation and the central lower part lowered 5–10 m. Vertical displacements of glacial and debris hill surfaces are shown in sections in Fig. 5. In *a-b* section (of the main valley glacier; the north snout), the surface lowering occurred in the part near glacial front and central part of the debris hill.

3.2. Features of surface debris on the debris hill

Based on features of debris, the debris hill is clearly separated into two parts: the north and south parts. In the north part, the surface relief is gentle (Fig. 6) and most clasts in the well-sorted debris layer are cobble in size. The surface clasts form a stable and compact ground-surface like a stone pavement. Many microforms indicating subsidence, such as step-like hummocky-forms on slopes and linear depressions

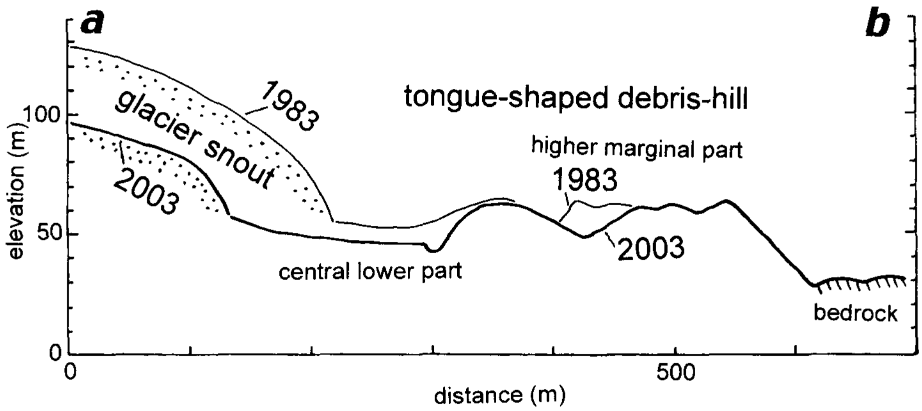

Fig. 5. Vertical displacements of the glacial and debris-hill surfaces in the section in *a-b* in Fig. 3.

Fig. 6. Surface features of the debris hill. 1: The north part of the debris hill. The surface relief is gentle and the debris is well sorted and most clasts are cobble in size. 2: Large clasts are cover the south part.

with cracks at the bottoms, were observed in this part. They occur even in the marginal higher part where the surveyed results show no apparent subsidence. The central basin-bottoms are mainly covered with pebbles and finer materials transported and deposited by melt-water from the glacier.

The south part of the debris hill shows rugged topography like glacier karst with hollows, ice cliffs, and linear depressions. The surface debris is ill sorted and includes many huge blocks of different lithology. These features are similar to those of the many debris-mantled glaciers in rugged mountains.

Three exposures of supraglacial debris-mantles were observed at ice cliffs during the field observation. In 1983, a 1 m-thick debris layer appeared at the top of ice cliff in the southeastern corner of the higher marginal part (see location 2 in Fig. 3-1). In 2003, two exposures were observed on the ice cliffs located at the eastern corner of the central basin (see locations 3 and 4 in Fig. 3-2). The thickness of these debris mantles is even, one section is 1.5 m and the other is 2 m. The latter case, a matrix-supported diamicton layer is covered with a thin fluvial gravel layer (Fig. 7). The diamicton contains a few large clasts, but is composed of relatively well sorted small clasts with abundant fine matrix. As far as the observed sections of surface debris indicated, the debris-mantle is thin and uniform in thickness, and the underneath glacier-ice is thick with over a few tenth meters.

3.3. *Observation at the main valley-glacier snout*

Frontal part of the main valley-glacier shows a convex bare-ice snout. Measurement of glacial-flow rates at 5 points on the surface around 100 m far from the frontal margin recorded average values of 0.32-0.93 cm per day from July 10 to 27 in 1983 (Iwata and

Fig. 7. Section of debris-mantle on the ice cliff located at the eastern part of the central basin (location 4 in Fig. 3-2). 2: Debris mantle with 2 m in thickness. The matrix-supported diamicton layer is covered with a thin fluvial gravel layer (1). 3: Glacier ice.

Chen, 1987), accordingly the snout is an active one. Frontal part of the main valley-glacier, however, has being retreated about 100 m in these 20 years. The authors observed that glacier release a small quantity of debris from the steep glacier front as the glacier front has retreated. Debris including clasts appeared along nearly horizontal shear-plains on the frontal ice by shear-up and melt-out, and fell down onto the foot in front of the glacier. Although more than 30 m surface lowering has occurred at the snout, no apparent supraglacial debris has appeared on the snout for this 20 years. This debris-free features distinctly contrast with the front of the tributary cone-type glacier (the south snout) of which surface has been largely covered with supraglacial debris (Fig. 3).

Basal debris-rich ice with 2-2.5 m thickness was observed at the bottom of the glacier snout near the front (Fig. 8). Clasts and fine materials occupy 40% in volume within clear ice which has attached by refreezing, and the clasts are cobble and pebble in average size, but large clasts with 0.2-0.3 m in size are included. The clasts in the basal-debris rich ice-layer show a planner structure parallel to the glacier bed. A number of these clasts have facets with striation. This suggests that basal sliding occurs at the interface of the glacier ice and the glacier bed. A slit between the basal debris-rich ice and the glacier bed was observed. The glacier bed is composed of clasts fell down from debris-rich ice and sediments moved by melt-water. On the ground in front of the glacier margin, clods of fine debris (silty clay with clasts) settled from the basal debris-rich layer were observed. Melt-water coming out from the glacier transports gravel and fine

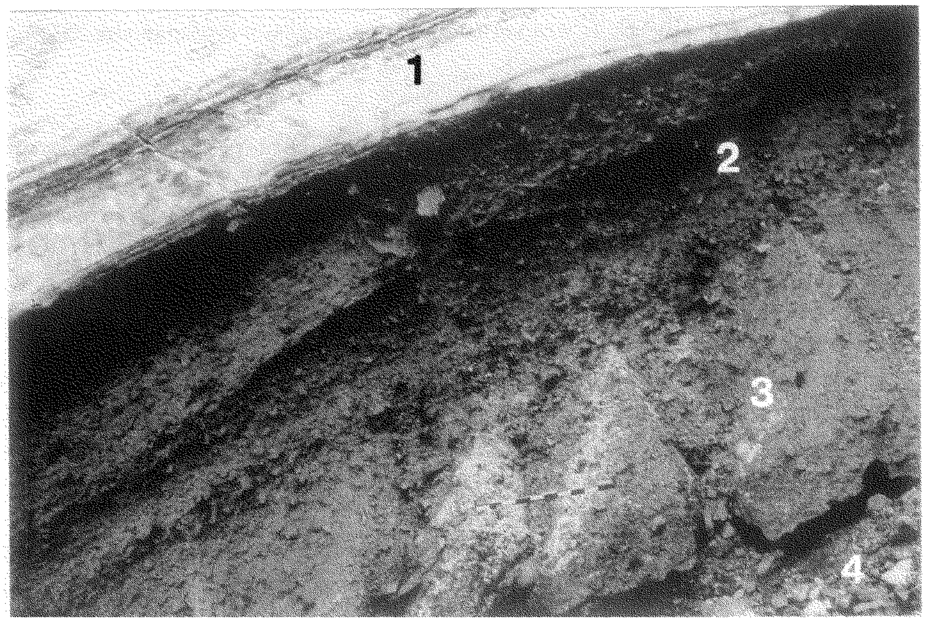

Fig. 8. Basal debris-rich ice at the bottom of the glacier near the front (location 1 in Fig. 3-1). 1: Glacier ice, 2 and 3: Basal debris-rich ice layers composed of clear ice and debris, 4: Glacier bed

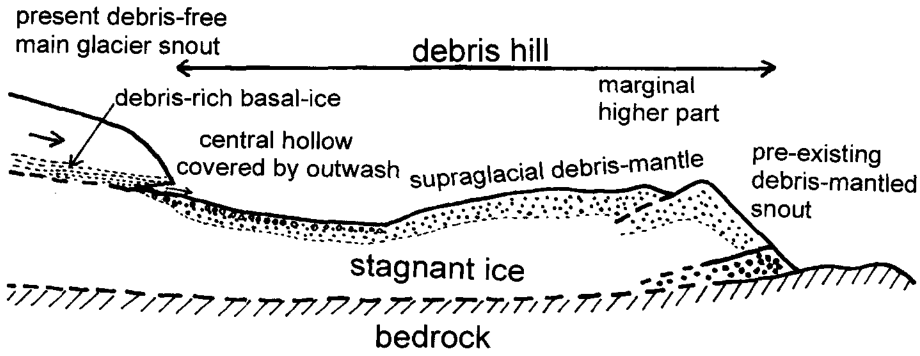

Fig. 9. Schematic section of the present debris-free snout and the debris hill (preexistent debris-mantled glacier).

materials and deposited downstream the glacier front.

4. Discussion

4.1. An ice-core moraine or a debris-mantled glacier?

The results show that distinct subsidence occurred on the debris hill in the upper (western) part near the glacial front (Figs. 4 and 5). Cause of this large subsidence is nothing except ablation of the underneath ice. As mentioned above, the existence of ice beneath the debris in the marginal higher part has already been known, and the marginal part was thought to be an ice-cored moraine (Cui, 1981). This subsidence, however, suggests that inside ice exists in the entire debris hill, even just outside of the present debris-free glacier front, and the ice may extend under the glacier snout. Although the existence of continuous ice beneath the glacial snout, existence of the debris-rich basal ice means that the ice of the present glacial snout separates from the ice-mass under the debris mantle in front of the snout. This means that the present glacier snout is independent from the underneath glacier bed that contains glacier ice. These features strongly suggest that the debris hill in front of the glacial snout is a debris-mantled glacier-snout rather than an ice-cored moraine (Fig. 9). The present debris-free snout overrides on the preexisting debris-mantled glacier.

4.2. Processes forming supraglacial debris-mantle

The debris-mantled glacier snout (the debris hill) gives a curious fact that the glacier shifted from a debris-mantled one (the debris hill) to a debris-free one (the present snout) at the next advance. It is quite peculiar that glacier-surface features change in a short interval. A reasonable cause of debris production should be discussed. Glacial geomorphological studies in present state recognize three processes for supraglacial-debris production (for example Benn and Evans, 1998): The first is supraglacial melt-out processes which include emerging and accumulating of englacial debris on glacier surfaces, and the second is direct debris-supply onto glacier surfaces in ablation areas by any geomorphic processes such as avalanches, landslides and debris flows. The third is debris sedimentation on glaciers by wastage of surging glacier snouts during repeated cycles of glacier surges. The first processes are ordinary ones occurring in most debris-mantled glaciers, and the second occurs in some accidental occasion such as the rock avalanche occurred in Mount Cook in 1991 (Chinn et al., 1992). The supraglacial debris mantle produced by surges was observed in many glaciers (Benn and Evans, 1998: 547) and glaciers in Kamchatka (personal communication from Dr. T. Sawagaki).

On the main valley glacier snout the melt-out processes enable to have formed the supraglacial debris in the past as well as at present, because its englacial debris is scarce as no debris-mantle has appeared due to the 30–40 m surface-lowering for these 20 years. In addition, any traces of mass-movement landforms such as landslides and slope failures could not be found on back slopes of the glacial basin so that the direct debris-supply onto glacier surfaces is not the cause of supraglacial debris-mantle of the debris hill. No surge has been recorded on Wrputu Glacier and features of glaciers and landforms show no sign of surging. Besides these processes some other processes are required to explain the debris-mantle production.

4.3. Possible cause of the debris-mantle

In discussing a possible cause of the debris-mantle, several facts and inferences are itemized as follows:

1) The main glacier snout has retreated for these 20 years and more years, and this means that it had advanced and occupied the large area of the debris hill in the past. The stable and compact surface of debris hill seems to be the result of the past glacier overriding.

2) The main glacier snout has a debris-rich basal-ice layer with at least a few meters in thickness. The features of debris-mantle such that are fine and relatively well-sorted in size, and thin and uniform in thickness are very similar to those of the debris-rich

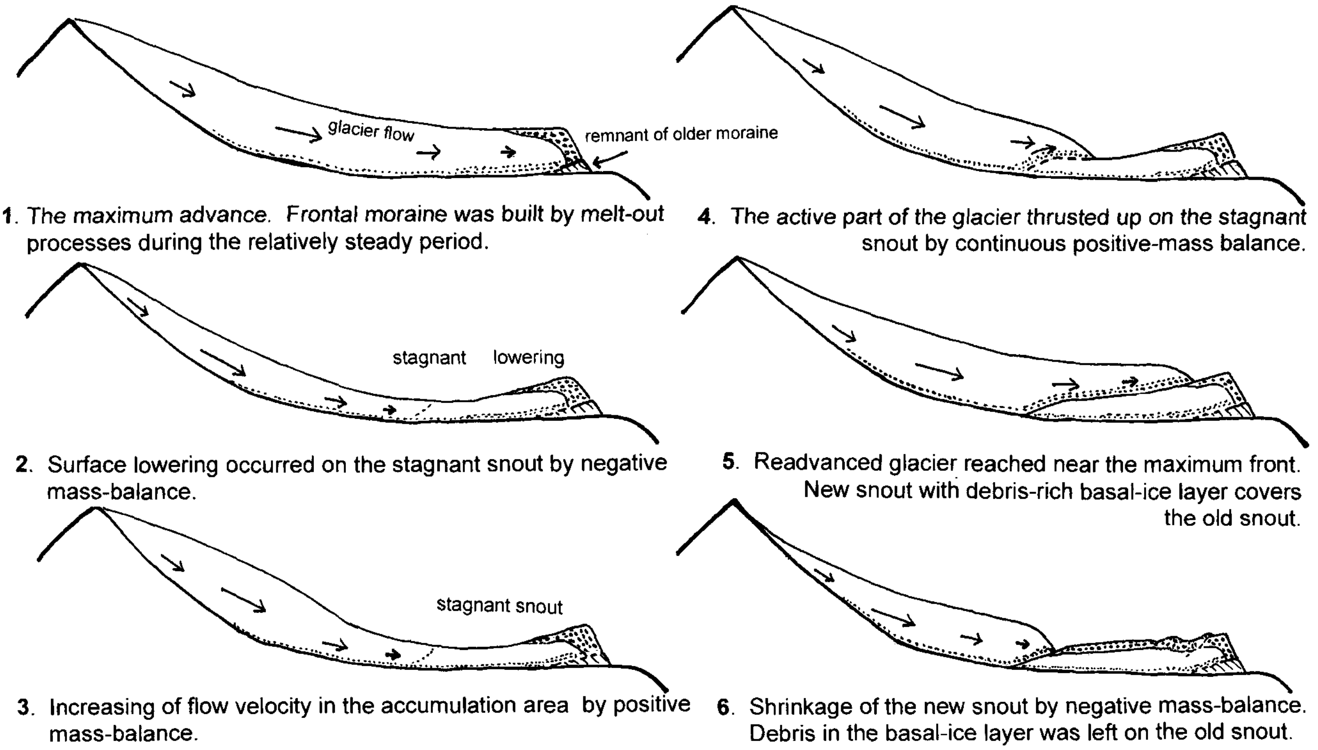

Fig. 10. Scenario of supraglacial debris-mantle formation by advancing and overriding glacier. The overrode glacier left debris in the debris-rich basal-ice layer after the glacier retreats.

basal ice layer underneath the present ice-free glacier snout.

3) Above 1) and 2) lead to a deduction that the debris in the debris-rich basal layer of the advanced glacier might been remained as a debris-mantle on the preexistent glacier-surface after the advanced glacier retreated (disappeared).

4) The 2.5–2.0 m thick debris-rich basal-ice layer, which is the observed value by authors, corresponds to a 1.0–0.8 m thick debris-mantle due to decrease in volume of the basal-ice layer by melting of interstitial ice. The decreased value is not far from the values of the debris-mantle on the debris hill.

Based on above 1)–4), the authors deduce that the debris-mantle on the debris hill was derived from the debris-rich basal-ice layer of the advanced glacier which left debris as the advanced glacier snout retreated. The whole scenario is schematically shown in Fig. 10. A maximum advanced glacier snout turns to a stagnant glacier snout by decreasing of the glacial mass. The following positive mass-balance of glacier thickens the upper and middle parts of the glacier and increases the movement. The moving-end of the glacier (active snout) flowed up on the debris-free stagnant-ice and continued to advance. After stopping advance and following retreat yielded the residual debris-mantle on the stagnant glacial tongue. Thus the debris-free glacial snout turned to the debris-mantled glacier. Although such glacial advance and override followed by retreat typically occur on surging glaciers, no evidence of past glacier surge has been recognized on Wrputu Glacier.

As mentioned already, the glacier advance and retreat in this scenario were not due to surge cycles. The features of glacier variation might have been reflected from the climatic change during the Late Holocene. The climatic change, however, have not been understood in this area.

5. Conclusions

Wrputu Glacier, a small valley glacier, in the upper reach of the Urumqi River, the Tianshan Mountains was surveyed in 1983 and 2003. A tongue-shaped debris hill with steep frontal slopes is located in front of the debris-free glacier snout.

Two topographical maps, surveyed in 1983 and 2003, indicate the morphological change of the present glacial snout and the tongue-shaped debris hill for recent 20 years. The front of the main valley glacier retreated more than 100 m in distance, and the glacier surface lowered 30–40 m, while frontal positions of the tributary cone-type glacier have not change largely and surface lowering of 15–20 m is observed.

Inner slopes of the marginal higher part of the debris hill partly decrease 3–7 m in elevation and the central lower part lowered 5–10 m. The distinct subsidence occurred on the debris hill in the upper part near the glacial front. Cause of this subsidence is ablation of the underneath ice, therefore the underneath ice exists in the entire debris hill. Thus the debris hill in front of the glacial snout is a debris-mantled glacier-snout of the previous glacial stage rather than an ice-core moraine. The present debris-free glacier snout has covered the debris-mantled glacier snout and is retreating at present.

The debris on the older debris-mantled snout was not accumulated by supraglacial melt-out processes, because contents of englacial debris are very scarce. No geomorphological change in the glacier basin has occurred so that this peculiar change from the older debris-mantled glacier to the younger debris-free glacier can not be explained by direct debris-supply onto the glacier. The authors conclude that the possible cause of the debris-mantle originates from the debris-rich basal-ice layer of the advanced glacier. A maximum advanced glacier snout turns to a stagnant glacier snout by the negative mass-balance of glacier. In the following positive state, glacier thickens and increases the movement. The active snout, moving-end of the glacier, with debris-rich basal-ice layer overrides on the debris-free stagnant-ice and continues to advance. The preexistent debris-free glacial snout turns to the debris-mantled glacier after stopping advance and following retreat yields the residual debris-mantle on the stagnant glacial tongue.

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