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Source: Arctic, Antarctic, and Alpine Research, 39(2) : 332-339

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(2007)39[332:IODCOO]2.0.CO;2

Arctic, Antarctic and Alpine Research, Vol. 39, No. 2, 2007, pp. 332–339

Influence of Debris Cover on Ogive-like Surface Morphology of Bilchenok Glacier in Kamchatka

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Abstract

Bilchenok Glacier is a surging glacier in the Kamchatka Peninsula, Russia, which most recently surged in 1982 and is currently in its quiescent phase. Field research in 1998 revealed an ogive-like repeated pattern of transverse ridges and intervening gently sloping ice at the surface of the ablation area of this glacier. It was also observed that most of the glacial surface was covered by volcanic rocks and ash, and the debris thickness on the ridges was more than 1 m, whereas the gently sloping ice was covered by thin debris. We posit that the pattern of the debris thickness is caused by the unique conditions of Bilchenok Glacier, namely, the restricted position of its debris supply at the foot of the rock walls beside the icefall and its surging behavior. The distance between the ridges might indicate the total horizontal displacement attributable to surges. The dependence of the ablation rate on the debris thickness can result in a highly undulating ice surface between the ridge and the gently sloping ice. We estimate the effect of the debris thickness on the ice surface profile using a simple model and this model successfully predicts that high ice relief can be caused by different ablation rates in the debris cover thickness.

Introduction

Regularly spaced arcuate bands on a glacier surface, known as ogives, are one of the most striking patterns in glacier morphology. Two basic types of ogives, the banded ogive and wave ogive, have been identified. Banded ogives are alternating dark and light bands on the ice surface. This banding pattern reflects different thicknesses of debris covering the glacier surface. Wave ogives are alternating ridges and troughs.

We found an ogive-like repeated pattern in the surface morphology of Bilchenok Glacier in the Kamchatka Peninsula, Russia. In this pattern, the dark bands represent arc-shaped transverse ridges, while the light bands represent gently sloping ice. Together, they give rise to a high ice relief which is similar in form to wave ogives, but with a considerably longer wave length and with a higher amplitude than that commonly reported for ogives. In addition, these forms appear only in the lower reaches of the glacier, and their amplitudes progressively increase down-glacier.

Several theories have been advocated to explain the formation of banded ogives. The most likely mechanism was proposed by Nye (1958), who argued that these ogives reflect seasonal variations in the passage of ice through icefalls. Thus, one ogive is formed every year, and the width of the ogives corresponds to the distance the ice travels in a year. Waddington (1986) made a mathematical analysis of ogive formation based on Nye's theory and explained that only waves generated in icefalls can survive, because the velocity gradient is large and localized. In fact, Bilchenok Glacier passes through an icefall, and the ogive-like repeated pattern appears below the icefall; however, the width of the pattern is too large to be considered as representing the distance of annual ice movement. Since Bilchenok Glacier is a surging glacier, with surges recurring at regular intervals, it is likely that the light-dark pair originates from one surge cycle composing an extraordinarily fast-flowing phase and a quiescent phase. We therefore propose that if the seasonal variations are replaced by the variations in the surge/quiescent phase, Nye's theory appears to be applicable to this glacier. However, the high ice relief with the darker bands is not satisfactorily explained by this theory.

Yamaguchi et al. (2000) suggested the possibility of the influence of the different debris distributions on the ice surface on glacial ablation, in addition to the relation between the surge cycle and the morphological pattern. They proposed the following processes for the formation of the characteristic repeated patterns: (1) most of the rock fragments on the glacier were derived from the steep rock walls beside the icefall, (2) during the surge phase, the passage of the glacier through the debris-supplying zone was very rapid and hence the debris was not deposited thickly on its surface, (3) in the quiescent phase, the glacier passed slowly through the zone with sufficient time to accumulate a large amount of debris on its surface, and (4) ablation was prevented by the thick debris cover, leading to ridge formation.

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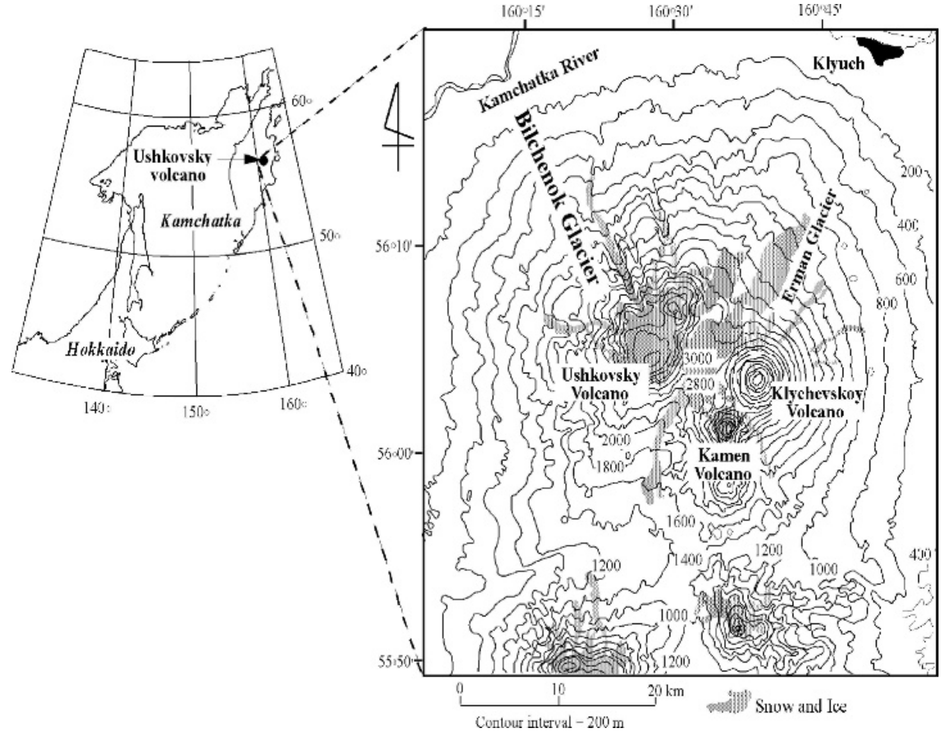

FIGURE 1. Location map of the studied area. Contour interval is 200 m.

In order to evaluate the above hypothesis, we present a model to reconstruct this type of ice surface profile. The reference parameters for the calculation included the observed ice surface topography and its debris distribution, in addition to the surface velocities measured by Yamaguchi et al. (2000).

Study Area

The highest (>3000 m a.s.l.) and most active volcanoes in the Kamchatka Peninsula in Russia exist in its central part (Fig. 1). The Ushkovsky volcano is one such active volcano; it has an altitude of 3900 m and an ice cap with a diameter of 4 km at the summit. Bilchenok Glacier, with a length of 19.5 km and an area of 24.4 km^2, is the main outlet glacier from this ice cap. It has a terminus altitude of 650 m and a firn line altitude of 2800 m (Dolgoushin and Osipova, 1975). The accumulation area is presently located between 3300 and 3900 m in the caldera of the Ushkovsky volcano, and the icefall extends from 2950 to 1420 m. The average surface slope below the icefall is about 5°, which increases to 9° near the glacier terminus. Dark debris composed of volcanic rocks and ash covers the glacier surface of the ablation area, and the debris thickness differs greatly from point to point.

Bilchenok Glacier is a surging glacier which most recently surged in 1982 and is currently in its quiescent phase (Muravyev et al., 1987). Some documents that reported the terminal altitude of this glacier were listed in Yamaguchi et al. (2000); this data can be used to reconstruct the glacial fluctuation during the 20th century. The first document on Bilchenok Glacier, presented by Tyushov, reported that the glacier terminus was located at approximately 900–920 m in 1900 (Bogdanowinsch, 1904). In September 1949, an aerial survey revealed that the terminus was at 800 m and that the glacier surface near the terminus was heavily crevassed, which strongly suggests that this glacier was very active around 1949.

The first reported surge occurred in 1959/1960. During this period, the altitude of the glacier terminus reached 615–630 m (Vinogradov, 1965). Unfortunately, the starting position of this surge is unknown. After this surge, in the 1970s, the active terminus rose to 930–950 m, near the icefall, leaving a vast field of "stagnant ice" downstream. In July 1980, Russian scientists in the field reported that a bulge of dirty ice with a height of 15–20 m had been advancing over the stagnant ice zone. The glacier continued to advance at low speed (some tens of meters per year) for 1.5 years. Finally, in February 1982, the glacier started to surge. The surge continued for about two years (a major advance occurred in 1982–1983) and stopped in autumn 1984. The terminus reached 400–500 m (Muravyev et al., 1987). The total horizontal distance of this surge advance is unknown, but we estimate the total distance between the terminus positions in the 1970s and in autumn 1984 to be 500 m. Therefore, the surge interval of Bilchenok Glacier was 23 years, from 1959 to 1982. If, as observed in many other surging glaciers, the surges of Bilchenok Glacier recur at more or less regular intervals, this glacier may be approaching the next surge, which appears likely to begin within 10 years from 2000.

Ice Surface Topography and Flow Velocity

DISTRIBUTION OF DEBRIS AND SURFACE MORPHOLOGY

Figure 2 shows the surface morphology of the ablation area of Bilchenok Glacier. Three repeated patterns are recognized up to a distance of 4 km from the glacier terminus. Each of these patterns comprises a transverse ridge followed by gently sloping ice. The relative height of the ridge from the surrounding gently sloping ice is about 30 m, and the distance between advanced ridges is 500–800 m. The longitudinal width of a ridge is some tens of meters at most. The lower end of the gently sloping ice makes a sharp contact with the transverse ridge. In some cases, the lower end of the gentle slope disappears into a large and deep moulin. Thus, the flanks of the ridges in the up-glacier side are steeper than those in the down-glacier side.

The glacier surface in the ablation area was covered with dark debris in 1998 (Fig. 3). The debris cover on the ridge was the

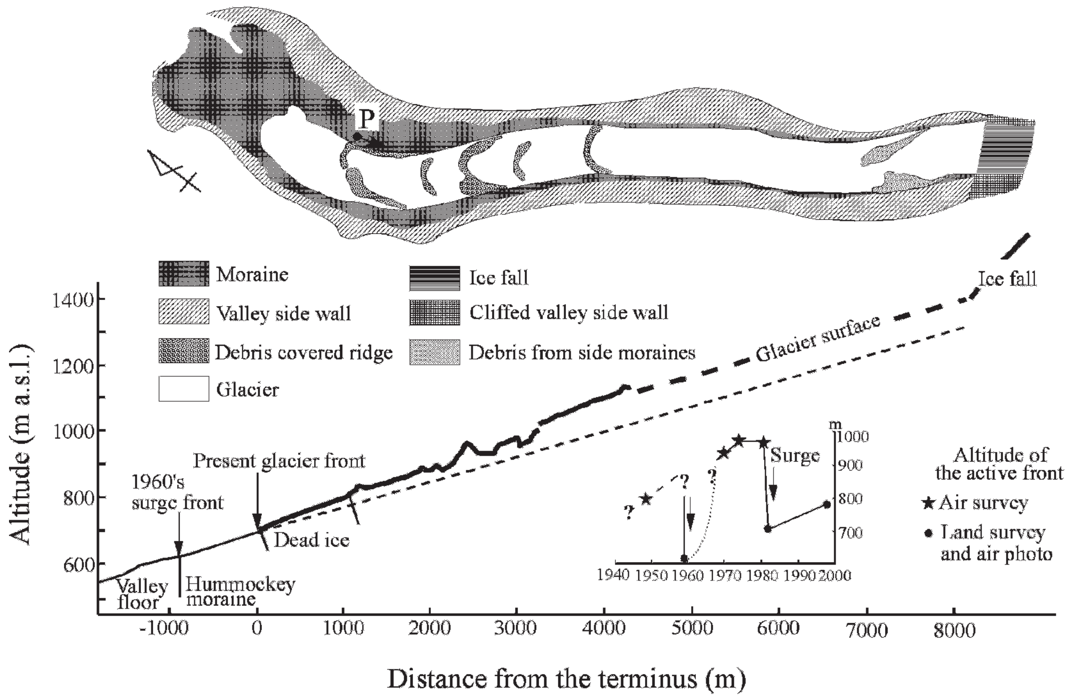

FIGURE 2. Geomorphology and ice surface profile of the ablation area of Bilchenok Glacier. "P" is the position where the photo in Figure 3 was taken, and the arrow indicates the direction of the photo. The fluctuation in the glacial terminus altitude during the 20th century is inserted in the surface profile.

thickest (>1 m) and was mainly composed of large and angular volcanic rock fragments. The debris cover on the gently sloping ice was thin or absent and was mainly composed of small rock fragments and pyroclastic fall deposits such as volcanic ash, pumice, and scoria. Bare ice was exposed particularly at the lower end of the slopes and steep cliffs on the flanks of the ridges.

The rock fragments on the glacier surface were probably supplied by (1) rockfall from the steep rock walls beside the icefall and (2) debris entrainment from the lateral moraines (Fig. 2). We believe that most of the rock fragments on the ridges were derived from the rock walls beside the icefall because the debris from the lateral moraines does not reach the central part of the glacier and is distinguishable from the debris on the transverse ridges. Although there are no significant geomorphic features such as landslide scars beside the icefall, which would suggest a few large landslide events, the possibility still remains that large amounts of debris were supplied within a short period by single large side-wall collapse in the melting season of a year. The icefall and surrounding rock walls are so steep that most of the rocks falling from the walls reach the foot of the icefall. Thus, the accumulation of debris might be concentrated on the ice near the foot of the icefall. The slower the passage of ice through this area, the thicker the debris cover that forms on the ice surface.

ICE FLOW VELOCITY

Yamaguchi et al. (2000) measured the ice flow velocities in the lower 2–3 km of the glacier between 18 July and 17 August 1998 using a global positioning system (GPS). Figure 4 is a scatterplot of the measured velocity against the distance from the terminus. There is a good correlation between the ice flow velocity (m a^{-1}) and its position, and the regression line between them is

$$V(x) = 0.012x - 1.60 \quad (R^2 = 0.86), \qquad (1)$$

where x is the distance from the terminus (m). Bilchenok Glacier shows compressive flow in the quiescent phase, with decreasing speed toward the terminus.

During the surge in 1982/1983, the velocities $V(x)$ (m a^{-1}) on the ridges corresponding to S4 and S9 in 1998 were measured as 98 m a^{-1} (at S4) and 100 m a^{-1} (at S9) (Muravyev, unpublished data). On the other hand, the non-surge velocities in 1998 were only 12 m a^{-1} (at S4) and 17 m a^{-1} (at S9). Based on these results, we approximate the flow velocity at these points to be 100 m a^{-1} during the surge period and 15 m a^{-1} in the quiescent phase. Applying these values, the ice advanced 200 m during the surge duration of 2 years, and 315 m in the quiescent phase of 21 years. Therefore, the total advance in one surge cycle of 23 years is 515 m. This value is close to the total observed advancing distance of the glacier terminus from the 1970s to 1984. On the other hand, the distance between neighboring ridges varies from 500 to 800 m. Thus, we can reasonably presume that the distance between the ridges may indicate the total horizontal advancing distance between surges.

Change in Debris-covered Ice Surface by Ablation and the Motion of Ice

The transverse ridges are so acute that morphological changes to the gently sloping ice are significant. The maximum relative height between the ridge and the gently sloping ice was about 30 m. In this section, we examine whether the difference in ablation rate due to debris thickness is attributable to such ice surface relief.

THE GLACIER BED

We have no actual data on the ice thickness and bed topography of Bilchenok Glacier. We thus estimate the bed profile [$G(x)$ m a.s.l.] as follows:

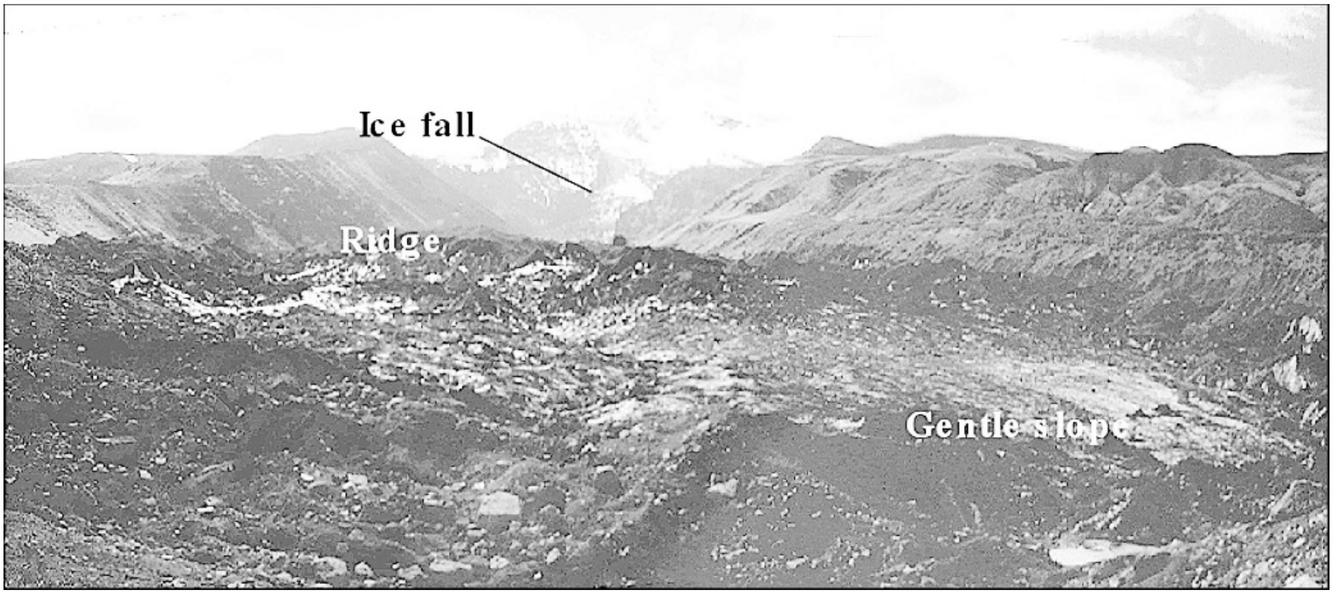

FIGURE 3. Transverse ridge and gently sloping ice on the glacier surface covered with debris and volcanic ash. The location and orientation of this photo are shown in Figure 2.

$$G(x) = I(x) - H(x). \quad (2)$$

Here, $I(x)$ is the ice surface elevation (m) fitted simply by a straight line,

$$I(x) = 0.1x + 600, \quad (3)$$

where the ice surface gradient ($\tan \alpha$) between the terminus and icefall is roughly 0.1. $H(x)$ is the ice thickness (m) determined by the surface flow velocity $V(x)$ assuming simple shear deformation of ice (Paterson, 1994).

$$H(x)^4 = [(n + 1)/2A](\rho g \sin \alpha)^{-3} V(x), \quad (4)$$

where g is the acceleration of gravity, ρ is the density of ice (900 kg m^{-3}), and A and n are the flow parameters. For Bilchenok Glacier, we used values of $A = 6.8 \times 10^{-15}$ (s^{-1} kPa^{-3}) and $n = 3$, which are appropriate for an ice body temperature of 0°C (Paterson, 1994).

EFFECT OF DEBRIS COVER ON ICE SURFACE MELTING

In general, the amount of melting on a clean glacier surface for a certain period (m_c) is estimated as proportional to the positive degree-day which is the sum of daily mean air temperature above the melting point (T_a) and is expressed as follows:

$$m_c = F_c \sum T_a, \quad (5)$$

where the coefficient F_c is the degree-day factor. Air temperature data have been measured at Klyuch station (30 m a.s.l.), which is the nearest meteorological station to Bilchenok Glacier. The distance between them is approximately 30 km. We estimated daily mean air temperature on the ice surface at the elevation I (m a.s.l.) as $[T_a(I)]$, using air temperature at Klyuch as follows:

$$T_a(I) = T_k - \gamma(I - I_k), \quad (6)$$

where T_k and I_k are daily mean air temperature and the elevation (30 m a.s.l.) at Klyuch, respectively. The coefficient γ indicates the temperature lapse rate in this area. We obtained F_c for the clean ice surface of Bilchenok Glacier as 4.2 mm day^{-1} $°C^{-1}$, using the ablation amount and daily mean air temperature determined during the research effort in 1998. The lapse rate (γ) in this region was estimated from a comparison between the data obtained at Bilchenok Glacier (780 m a.s.l.) and those at Klyuch station, and its value is 4.6°C km^{-1}.

Using data from Klyuch station, the monthly mean air temperatures over 30 years (from 1962 to 1997, excluding six years due to missing data) were calculated and compared with those in 1999 (Table 1). The comparison results reveal no large difference between these values; thus it may be reasonable to suppose that the air temperature in 1999 is normal. We calculated ΣT_a at every 50 m elevation of Bilchenok Glacier using the daily air temperature in 1999 at Klyuch station and the lapse rate, and the following regression was obtained between the ΣT_a and the ice surface elevation (I):

$$\sum T_a(I) = -0.70I(x) + 1660. \quad (7)$$

Some studies on debris-covered glaciers indicated that the debris thickness affects the ablation rate (e.g. Fujii, 1977; Driedger, 1981; Mattson et al., 1993). When the debris cover is relatively thin, a few centimeters, the rate of surface ablation can be larger than that of clean ice, whereas when the debris cover

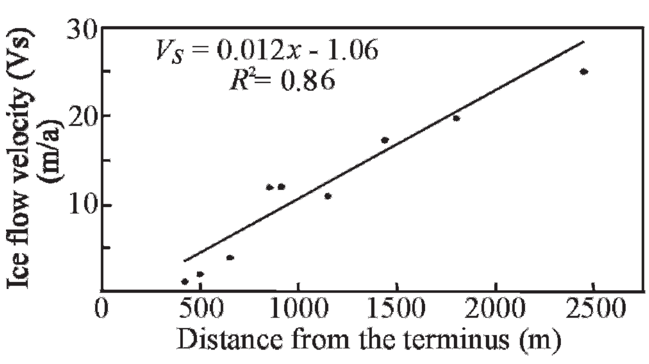

FIGURE 4. Plot of the ice flow velocity measured by GPS in 1998 against the distance from the terminus.

TABLE 1

Monthly mean air temperature (°C) at Klyuch station, the nearest meteorological station to Bilchenok Glacier.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
30 years' average	−16.6	−13.5	−9.5	−2.4	4.4	11.2	14.8	13.7	8.7	2.0	−6.9	−14.1
Standard deviation	±4.8	±3.8	±3.0	±1.7	±1.2	±1.5	±1.3	±1.0	±0.9	±1.2	±2.5	±4.2
Data in 1999	−13.9	−17.2	−10.9	−4.3	4.7	10.4	14.1	13.6	9.3	2.5	−5.4	−14.7

exceeds a critical thickness, the ablation rate is retarded (Mattson et al., 1993). We can estimate the amount of ablation on debris covered glaciers (m_d) by

$$m_d = R_m \, m_c, \quad (8)$$

where R_m is the ablation ratio of debris-covered ice to clean ice. For R_m, we referred to the case of Barpu Glacier in the Karakoram Himalaya (Khan, 1989; Mattson et al., 1993), where the critical debris thickness for ablation was about 4 cm (Fig. 5). We can determine R_m from Figure 5 when the debris thickness on the glacier is known.

CHANGE IN THE ICE SURFACE PROFILE WITH ICE FLOW AND DEBRIS COVER

In order to describe the surge and non-surge states, the ice flow velocity $V_S(x)$ (m a^{-1}) is considered to be

$$V_s(x) = V(x) + V_{add}, \quad (9)$$

where $V(x)$ is function (1) (see Fig. 4), $V_{add} = 0$ m a^{-1} for a non-surge state, and $V_{add} = 100$ m a^{-1} for a surge.

Assuming that the accumulation of debris on the ice is concentrated near the foot of the icefall, we define a portion of the ice passing through the foot of the icefall during Δt (years) as a calculation unit. The position of the upper part and the length of the unit at t years are shown as x_t and L_t, respectively, and the ice thickness [$H(x_t)$] and surface velocity [$V_s(x_t)$] are estimated from Equations 4 and 9, respectively (Fig. 6).

The first length of the unit [$L(x_0)$] is equal to $V_s(x_0)\ \Delta t$ because the ice moves with a velocity of $V_s(x_0)$ from the foot of the icefall during Δt; the length of the unit [$L(x_t)$] is then changed in proportion to the surface velocity gradient. In this case, $L(x_t)$ decreases down-glacier because of the compressive flow shown in Equation 1. The change in the ice thickness at each unit is determined from the balance between the increase due to the compressive ice flow and surface ablation.

The amount of ablation under debris [$m_d(x_t)$] is determined by using Equations 5, 7, and 8. Here, R_m in Equation 8 is available from Figure 5 as a function of the mean debris thickness along L_t, and D_t is defined as follows:

$$D_t = C\, L_t^{-1}. \quad (10)$$

Here, we assumed that the debris is supplied constantly at a rate C (m^3 a^{-1}) at the foot of the icefall in a year and that the total amount of debris on a unit is preserved in every age. Thus, D_t is concentrated down-glacier owing to the decrease in L_t.

The debris thickness (D_0) at the first unit during a quiescent period is thicker than that during a surge because $V_s(x_0)$ during quiescent periods is lower and $L(x_0)$ during quiescent periods is shorter than that during a surge.

The ice surface profile can be obtained by calculating the change in the ice thickness at the unit up to the glacier terminus and tracing the surface profile at each time point. In this model, the change in the ice thickness is not applied to the change in the ice flow velocity.

Results and Discussion

DEBRIS THICKNESS AND ICE SURFACE PROFILE

For convenience of calculation, we assumed that one surge cycle comprises a 2-year surge period and an 18-year quiescent period. The calculation was initiated from the beginning of a quiescent period and ended when the lowest unit had experienced three surge cycles (four quiescent periods and three surge periods) over a period of 78 years.

The calculated surface profile and debris thickness on the ice under three debris supply conditions (amount of debris supplied to the bottom of the icefall in one year), of 1.5 m^3 a^{-1}, 2.0 m^3 a^{-1}, and 2.5 m^3 a^{-1} are shown in Figures 7, 8, and 9, respectively. The profile of an ice surface without any debris cover is also plotted on each figure as a reference.

Each distribution of debris thickness clearly shows that the debris becomes thicker in the downstream area because of the

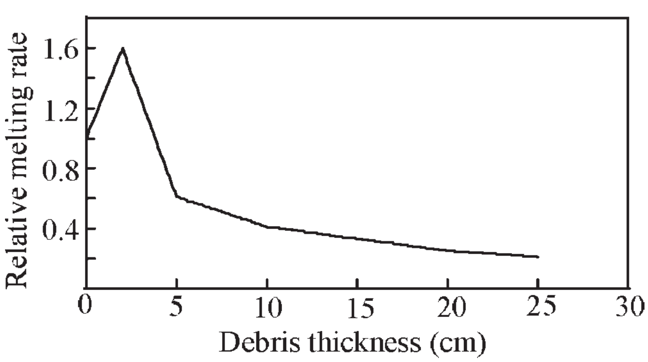

FIGURE 5. Change in ablation rate with debris cover thickness. From Barpu Glacier in the Karakoram Himalaya (Khan, 1989) *in* Mattson et al. (1993).

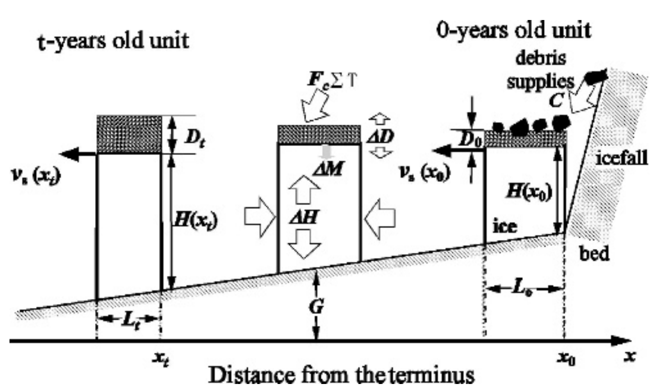

FIGURE 6. Schematic diagram of the model. Δ*H* and Δ*D* are the changes in the ice and debris thicknesses due to compressive ice flow during Δ*t*, respectively. Δ*M* is the surface lowering due to ablation during Δ*t*.

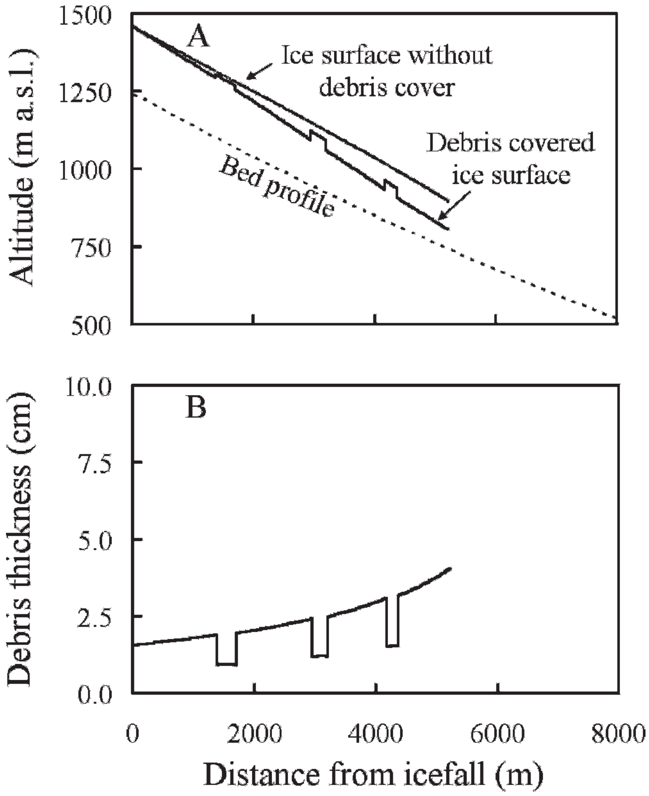

FIGURE 7. Calculation results for a debris supply amount of 1.5 m^3 a^{-1}. (A) Ice surface profile, bed profile, and the ice surface profile without a debris cover. (B) Distribution of debris thickness on the glacier surface.

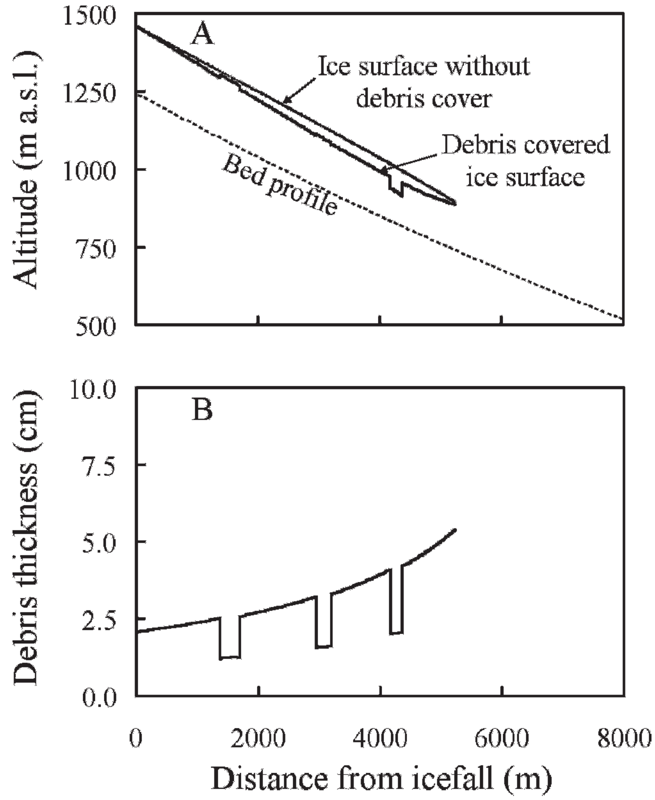

FIGURE 8. Calculation results for a debris supply amount of 2.0 m^3 a^{-1}. (A) Ice surface profile, bed profile, and the ice surface profile without a debris cover. (B) Distribution of debris thickness on the glacier surface.

compressive ice flow. Comparisons of the debris thicknesses of the units during the quiescent and surge periods indicate that the debris cover on the units is thinner during the surge period than during the quiescent period. These patterns result from the different velocity of ice passage through the foot of the icefall during the surge and quiescent periods.

All the calculation results excluding the case without any debris show a rugged pattern (high relief or deep concave depression) on the ice surface. They appear at the boundaries between the units with thin and thick debris cover.

Figure 7 shows the case in which ridges formed. The debris cover on each ridge is thinner than on intervening surfaces; this result indicates that the units that passed through the foot of the icefall during the surge developed relief. Figure 9 shows the case in which concave depressions were formed. The debris thickness in each depression is thinner than that on the other surface; the development of the concave depression can be ascribed to the units passing through the foot of the icefall during the surge. Figure 8 represents a transitional case, that is, relief was formed in the upper part, but was transformed into a concave depression in the downstream areas.

These results reveal that the general shape of the profile changes with debris thickness, that is, when the initial debris supply is low, the ice surface profile becomes convex (Fig. 7), while a large debris supply results in a straight or concave profile (Figs. 8, 9).

In this study, the melt rate is treated to depend on the debris thickness, and the critical debris thickness for ablation (melt rate becomes smaller than that on clean surface) is set at around 4 cm. Thus, if the debris on the units of the quiescent period is not sufficiently concentrated to reach the critical debris thickness (4 cm) down-glacier because of low initial debris supply, the melt rates of the units of the quiescent period are larger than those of the surge period; hence, the units of the surge period develop relief (Fig. 7). On the other hand, if the debris supply is sufficiently high to exceed the critical debris thickness (4 cm) on the units of the quiescent period, the melt rate is reduced, and the melt rates of the units of the surge period are larger than those of the quiescent period. The units of the surge period then become concave depressions.

In this study, although we used a simple model based on the hypothesis that the unique surface profile of Bilchenock Glacier is caused by the difference in the time taken for the ice to pass through the foot of the icefall between the quiescent and the surge periods, we succeeded in restoring similar patterns in the model. Further, the calculation results suggest a strong control of the debris thickness on the ice surface profile of a debris-covered glacier.

COMPARISON WITH ACTUAL ICE SURFACE PROFILE

The observations at Bilchenok Glacier show that the debris thickness on the ridges is thicker than that at other parts; thus, we infer that the relief was formed during the quiescent periods on the basis of the above calculation results. Here, we compare the calculation results (Fig. 9) with the actual features of Bilchenok Glacier.

In the calculation, we attempted to use a set of realistic parameters as far as possible; however, the calculated ice surface profiles are steeper than the actual one. We consider that this is

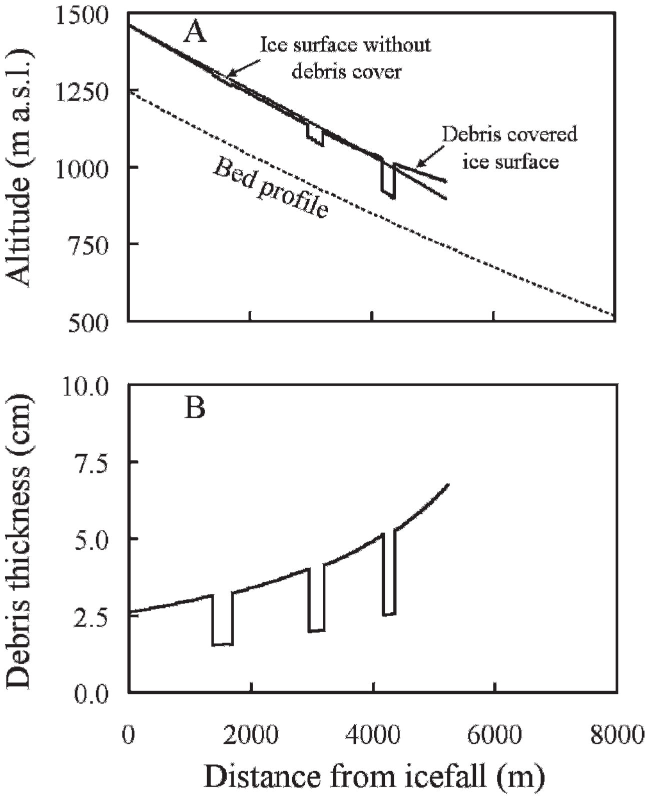

FIGURE 9. Calculation results for a debris supply of 2.5 m^3 a^{-1}. (A) Ice surface profile, bed profile, and the ice surface profile without a debris cover. (B) Distribution of debris thickness on the glacier surface.

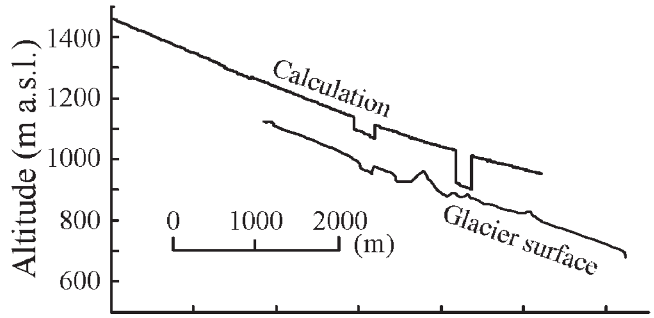

FIGURE 10. Comparison between the calculated and actual ice surface profiles. The actual profile is shifted horizontally to 1 km upstream.

mainly because we used assumed bed profiles obtained using Equation 2; in particular, the assumed ice surface gradient (tan α = 0.1) in Equation 3 is steep. Therefore, the resulting bed profiles become steeper than the actual ones.

For convenience of comparison, we shifted the actual ice surface profiles 1 km upstream in order to fit them to the calculated profiles (Fig. 10). Although the surface altitude estimated in the model is higher and the calculated glacier is smaller than the actual glacier, it seems that the calculation results reproduced the actual ice surface pattern, that is, the distance between each step in the model appears to correspond to that of the actual ridges.

This positive result suggests that the combination of the recurring surge behavior and difference in the ablation rate due to different debris thicknesses can create relief of the order of tens of meters in the ablation zone.

Since the model used in this study is a prototype, there is room for reconsidering each process in the model. Initially, the process of the debris cover effect should be improved. In order to simplify the debris cover effect in the model, the ablation rate between clean ice and debris-covered ice was adopted based on the case of the morainal materials of Barpu Glacier in the Karakoram Himalaya (Khan, 1989). However, the relationship between the debris thickness and ablation rate depends on several debris conditions and is therefore complicated. For example, Anderson (2000) explained the morphology of medial moraines as resulting from the relationship between the debris thickness, which is treated as a potentially decaying function, and mentioned the motion of the debris on the surface, which was driven down the topographic gradients arising from the differential ablation. This theory might be helpful in order to understand the cause of a sharp contact between the gentle slope and the transverse ridge at Bilchenok Glacier. In addition, the effect of accumulation of debris freed from the ice body is neglected in the model. Therefore, to discuss the behavior of Bilchenok Glacier in greater detail, we should determine an original relationship between the surface ablation and thickness of debris specific to Bilchenok Glacier, where the debris is composed of andesitic and basaltic rocks, and get information on the density of debris in the ice.

Moreover, the effect of volcanic ash, which is more likely to occur over large areas, has not been addressed satisfactorily in our model. We require more detailed studies of the critical thicknesses of debris and ash for enhancing/deterring ice surface ablation in the special case of volcanic regions.

For convenience of calculation, we assumed the difference between the ice flow velocities of the surge and quiescent periods to be constant, as shown in Equation 9. However, since surging behavior varies from one glacier to another, further examples are required to discuss the relation between the ice surface profiles and ice flow velocity of glacial surges.

Concluding Remarks

Bilchenok Glacier is a surging glacier with an estimated surge interval of about 23 years. GPS surveying revealed that the flow velocities in 1998 were considerably slower than those in 1982; the glacier may thus be considered to be in the last stage of its quiescent phase.

The surface of Bilchenok Glacier shows repeated patterns of transverse ridges and gently sloping surfaces. Most of the glacial surface was covered by volcanic rocks and ash, and the debris thickness on the ridges was more than 1 m, whereas the debris cover on the gently sloping ice was thin or absent. Assuming that the flow velocity on the transverse ridges is 100 m a^{-1} during a surge period and 15 m a^{-1} in a quiescent phase, the distance between the ridges may be considered as the total horizontal advancing distance between surges.

By using a simple model in which the ablation rate differs with the debris thickness, we constructed a calculation model to estimate the variation in the debris thickness and its effect on the ice surface profile. This model produces a high ice relief of the same order as that observed at Bilchenok Glacier. The unique condition of Bilchenok Glacier, where most of the debris is derived from the rock walls beside the icefall, makes this a particularly simple site.

This model suggests that Nye's theory on the formation of wavy ogives can be extended to explain the characteristic features of some debris-covered glaciers by replacing the seasonal variations in the passage of ice through an icefall with recurring glacial surges.

Acknowledgments

We would like to express our sincere gratitude to Dr. Alexander A. Ovsyannikov of the Institute of Volcanology, Russian Academy of Sciences, and Ms. Marina Vyatkina of Kamchatka Institute of Ecology and Nature Management, Far East Branch of Russian Academy of Sciences, for their logistical support in the field. We are also grateful to the following personnel for their support and valuable suggestions: Drs. Takayuki Shiraiwa and Toshio Sone of the Institute of Low Temperature Science, Hokkaido University, and Dr. Kotaro Yamagata of Joetsu University of Education. We are also indebted to the cooperation among the Institute of Volcanology, the Institute of Ecology of Russian Academy of Sciences, and the Institute of Low Temperature Science, Hokkaido University. Comments from Prof. Garry Clarke of the University of British Columbia and Prof. Yutaka Ageta of Nagoya University greatly improved an earlier version of this manuscript. The manuscript benefited greatly from reviews by Drs. R. S. Anderson and S. P. Anderson. This research was supported in large part by the Inoue Fund of Field Science, Japanese Society of Snow and Ice (awarded to S. Yamaguchi and T. Matsumoto).

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Ms accepted June 2006