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Influence of Sub-Debris Thawing on Ablation and Runoff of the Djankuat Glacier in the Caucasus

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Superficial moraines grew in size during the entire 32-year-long period of direct monitoring of water and ice balance of the Djankuat Glacier in the Caucasus. The total area of debris cover on the glacier increased from 0.104 km^2 (3% of the entire glacier surface) in 1968 to 0.266 km^2 (8% of the glacier) in 1996. Such rapid dynamics of moraine formation greatly influences the ablation rate and distorts fields of mass-balance components. Sub-debris thawing can be calculated by means of a model, which describes the role of debris cover for the thermal properties of a glacier. Its meltwater equivalent depends mainly on debris thickness. In 1983 and 1994 the debris cover was repeatedly mapped over the whole glacier portion that was covered with morainic material. Sub-moraine ablation increases (*vs*. pure ice surface) under the thin, less than ca. 7-8 cm, debris layer, whereas the thicker debris cover reduces the liquid runoff due to its shielding effect. Zones differing due to their hydrological effect are depicted on the glacier map and the degree of debris influence on ablation is estimated quantitatively. As a whole runoff from debris-covered parts of the Djankuat Glacier has diminished due to the dominant shielding effect. Variation of the terminus is also shown to be dependent on the evolution of superficial moraine.

Introduction

Snouts of alpine glaciers play an important role in the process of liquid runoff formation. Despite the fact that their areas are often much smaller than the rest of the glacier surface, the ablation rate here exceeds that of the accumulation area by a con-

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siderable amount. Besides, the melting season lasts much longer here than in the higher glacier belts. Therefore, a contribution from the significantly smaller lowermost part of a temperate glacier to the overall glacier bulk runoff can become unproportionally high. Sometimes (especially in the years of positive mass balance values) it can even be comparable with the total meltwater volume from the higher zones. These circumstances create special interest in the processes influencing the mechanism of meltwater drainage from the snout.

The present evolutionary stage of global glacierization can be generally characterised as pronounced deglaciation in most of the mountain systems of the world, with only a few rare exceptions. Deglaciation always causes the most striking alteration of glacial morphology for the snout zone. First of all, this alteration concerns changes in the spatial position of the snout (frontal and lateral retreat, glacier thinning) and development of debris cover on its surface. However, if spatial decrease of the snout obviously reduces liquid runoff, the role of the latter process is not so evident.

Debris Cover on the Glacier Surface

Superficial moraines on alpine glaciers are known to form as a result of 3 processes: a) the deposition of colluvial matter on the glacier surface; b) the melting-out of englacial moraines; and c) widespread development of thrust moraines, *i.e.* transfer of debris from the glacier bed to the surface along shear planes. Most often superficial moraines look like strongly pronounced lengthwise relief features (ramparts). However, the closer to the terminus, the more frequently ramparts transform into continuous debris cover, where bare the ice surface is no longer exposed. This transformation of initially longitudinal moraines into the solid lithogenic mantle is described in literature (Eyles and Rogerson 1978; Bozhinskiy *et al.* 1986; Aniya 1987; Benn and Evans 1998). Fig.1 illustrates this process with the example of the Bezengi Glacier, the largest in the Caucasus.

Apparently, explaining the formation of moraine cover solely as a result of the confluence of several medial moraines is too simple. An important role is played by ablation moraine on some glaciers and a continuous cover arises from the areal melting-out of debris dispersed randomly inside a glacier body. The existence of a continuous debris cover seems to be a characteristic feature of retreating glaciers. It essentially governs mass and heat transfers in their lower reaches and hence glacier-derived liquid runoff.

When morainic cover is thin (several centimetres) the sub-debris ice-thawing rate is known to increase. This effect has been known since G.Østrem's (1959) experiments with artificial blackening of a representative area on a glacier surface by dust. Moderate thicknesses of moraine covers result in a shielding or, armouring effect, which decreases the ice-thawing rate. Finally, melting practically ceases after the

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a) linear features (ca. 5 km upstream the terminus)

b) continuous cover (the lowermost part of the snout)

Fig. 1. Superficial moraine on the Bezengi Glacier, Central Caucasus.

moraine thickness reaches 1.5-2 m. During phases of glacier retreat debris has a non-stationary effect on runoff as the debris covered area and thickness increase with time.

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Formulation of the Problem

Bozhinskiy *et al.* (1986) have expressed the ablation rate, (α_m) under the moraine layer with the thickness h as

$$a_m = \frac{\lambda_m}{\rho_i(Q-cT_i)} \; \frac{Q_s(1-\alpha_m)+bT_a}{bh+\lambda_m} \tag{1}$$

Here λ_m is heat conductivity of morainic material; ρ_i is ice density; Q is latent heat of fusion of ice; c – specific heat of debris-containing ice as a volume-weighted average of specific heat of ice and debris (c_i and c_m, respectively), *i.e.*

$$c = c_i(1-\mu) + c_m\,\mu \tag{2}$$

where (is the mean bulk debris concentration inside ice; T_a and T_i and are air and ice (averaged over depth) temperatures, respectively; Q_s is total solar radiation; α_m is debris albedo; and b is the turbulent heat-transfer coefficient. For calculating sub-debris melting in terms of water layer equivalent in accordance with Eq.(1), three parameters may be considered as generally used physical constants (ρ_i = 880 kg/m^3, Q = 334 kJ/kg, b = 11.6 W/m^2 · deg), four others (λ_m, c, T_i, α_m) may be accepted constant for a given glacier under investigation, two meteorological parameters (Q_s and T_a) should be monitored at a nearby weather station and then extrapolated to any point by means of vertical and horizontal gradients, so that the final task is the estimation of moraine thickness h.

However, due to the mentioned non-stationary character of moraine layer formation, the value h for a given point changes permanently. During deglaciation, interaction between processes of internal mass exchange (debris thawing-out onto the surface) and external mass exchange (melting) tends to increase the debris-cover thickness. At the snout the horizontal component of ice flow velocity vector is low, and it cannot promote fast debris transportation towards the terminus and its further deposition in the periglacial belt. Thus, weakened surface-layer kinematics of the glacier motion can no longer compensate for debris outflux off the glacier ice, resulting in progressive piling up of the superficial moraine; the sub-debris ablation rate and debris-particle displacement along the surface then become comparable. Deglaciation also causes accelerated exposure of basal rocks on the steep slopes around the firn basin. The fact that fluctuations of glacier boundaries in the uppermost periphery are much faster than near the terminus was earlier revealed and confirmed in the course of geodetic monitoring (Popovnin 1996), and it is quite contrary to the traditional attention given mainly to frontal variations by glaciologists. Ice thickness on the steep revetment is small, and complete melting away of large portions of former glacier parts leads to much more rapid boundary dynamics here than on the snout. Consequently, colluvium begins to be piled up progressively in rear foothills of the firn cirques accompanied by steadfast growth of the debris cover on the snout.

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Meanwhile, Eq. (1) is valid solely for the stationary case. Only if we know the rate of debris layer increment with time and if setting of the correspondent function $h(\tau)$ is possible, then the sub-debris melting rate can be computed, according to Bozhinskiy *et al.* (1986), b

$$a_m = \frac{1}{\mu} (1-p)(1-\mu) \frac{dh}{d\tau} \quad (3)$$

where p is debris-cover porosity.

A realistic approach to this problem should be based on coupled application of modelling and direct measurements on the glacier. The easiest way here seems to include: a) observation of bare ice melting a_i by nearest stakes of the ablation network; and b) calculation of a_m with the help of a_m/a_i ratios. Since these ratios depend primarily on h and this dependence was earlier proved to be non-linear, the nomogram-like curve

$$\frac{a_m}{a_i} = f(h) \quad (4)$$

should be drawn first, using above considerations and either Eqs. (1)-(3) or statistical series of direct ablation measurements by means of stakes drilled closely both into clean and debris-covered ice. Its shape is peculiar for every glacier, being predetermined first of all by mechanical composition and petrography of surrounding

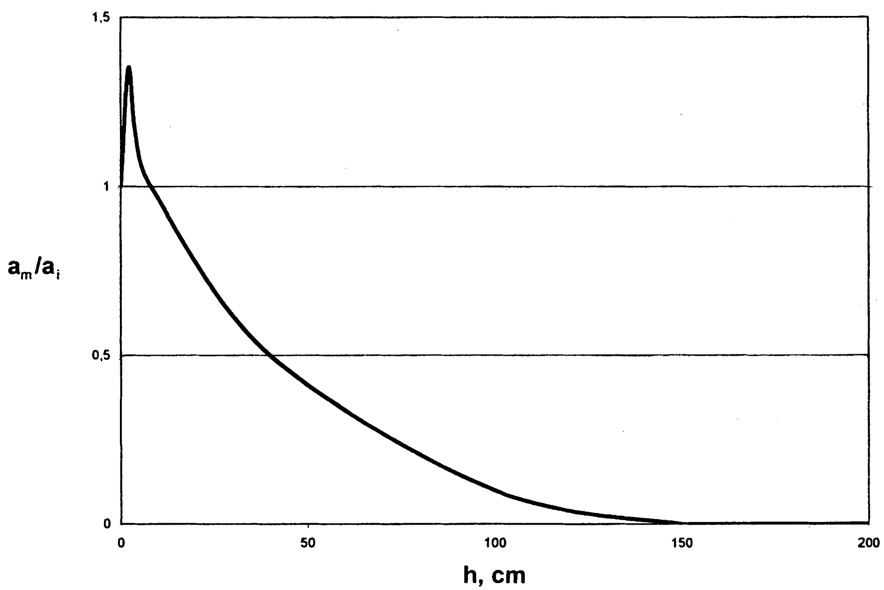

Fig. 2. Non-dimensional ablation rate a_m/a_i dependence on moraine-cover thickness h, cm, for the Djankuat Glacier.

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rocks as well as by the packing density, and the porosity of moraine cover, which affect thermo-physical properties of the lithogenic shield considerably. An example of such a curve for the Djankuat Glacier in the Caucasus is presented in Fig. 2. Numerous attempts at depicting the curve of function Eq. (4) revealing rather large deviations of input data from the approximation line

$$\frac{a_m}{a_i} \equiv \frac{1.3}{0.2h+1} \qquad (5)$$

were summarised by Khodakov (1972).

Furthermore, the standard programme of mass-balance measurements should be supplemented with surveying the thickness of debris cover over the whole area of superficial moraine on the glacier. Examples of such surveys are extremely rare. Bassin *et al.* (1983) wrote about such mapping on RGO, Podkova and Kuldzhilga Glaciers in the Pamirs. But many other mountain systems are completely lacking such information. Thus the posed task may be solved only on selected objects. The Djankuat Glacier as the best studied glacier in Russia could become such an object.

The Djankuat Glacier and its Present Evolutionary State

The Djankuat Glacier (Aleynikov *et al.* 2002; see their Figs. 1, 6a) is a valley glacier 3 km^2 large draining into the Caspian Sea via Adyl-su, Baksan and Terek Rivers.

Ice flows down via 4 main branches with independent catchments (see Fig. 4 in Aleynikov *et al.* 2002). The contact zones between adjacent branches are marked by medial moraine ramparts. Furthermore, the subglacial bed of the Djankuat Glacier is complex due to rocky ledges that give its longitudinal profile a stepped character. They serve as a principal source of subglacial moraine. In particular the left-hand margin of the snout is covered by a continuous envelope of debris on the last kilometre.

The general scheme of the recent evolution of the Djankuat Glacier is described by Baume and Popovnin (1994), Popovnin (1996) *etc.* After rapid degradation in the middle of the 20th century, it has become quasi-stationary since about 1980. Annual frontal fluctuations during the last 2 decades were negligible (several metres per year), and slight retreats alternated with slight advances. However, the last 3 years turned out to be tremendously unfavourable for the glacier state, and its retreating trend resumed. Such a behaviour is typical for most valley glaciers in the Caucasus during the past years. In general, the present evolutionary stage can be considered as slow deglaciation, with the average mass balance value over 1968-1999 being moderately negative: -120 mm of water equivalent per year, resulting from long-term accumulation and ablation values of 2,400 and 2,520 mm, correspondingly. The mean annual volume of liquid runoff is estimated as 8.3 million m^3.

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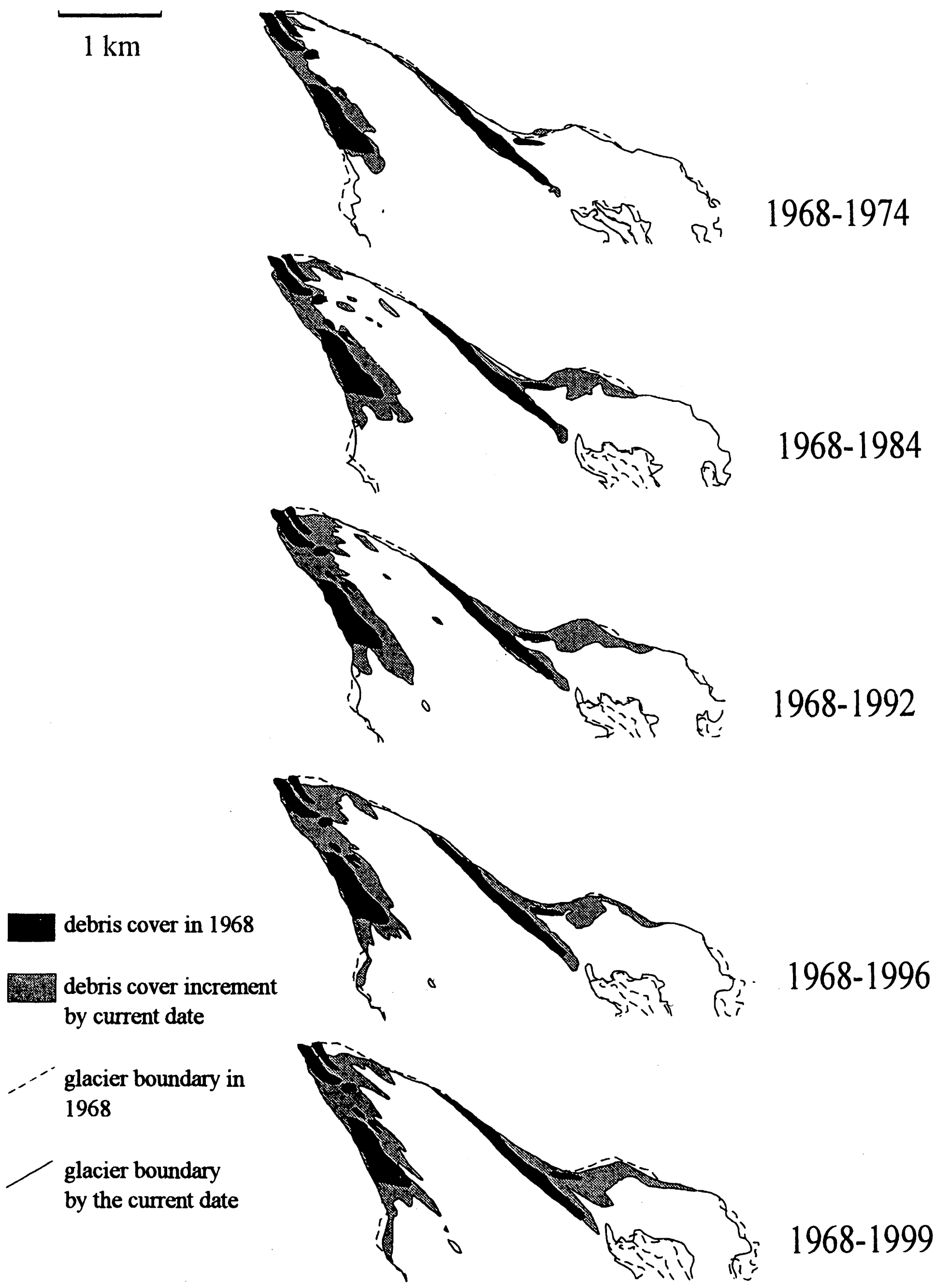

Fig. 3. Dynamics of debris cover areal growth on the Djankuat Glacier 1968-1999.

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Fig. 4. Scheme of alti-morphological zones of the Djankuat Glacier. Depicted are altitudinal boundaries of the zones and their numbers (in Roman numerals).

Debris-cover Area Expansion

During the last 32 years the Djankuat Glacier was remapped six times. The expansion of the continuous debris cover, as was to be expected during the deglaciation stage, can be easily traced in Fig. 3.

The debris-covered area increased more than thrice since 1968. Initially the supraglacial moraine occupied 0.104 km^2, or 3% of the entire glacier area, while by 1999 its share exceeded 10% (0.293 km^2). This increase rate was not constant, but

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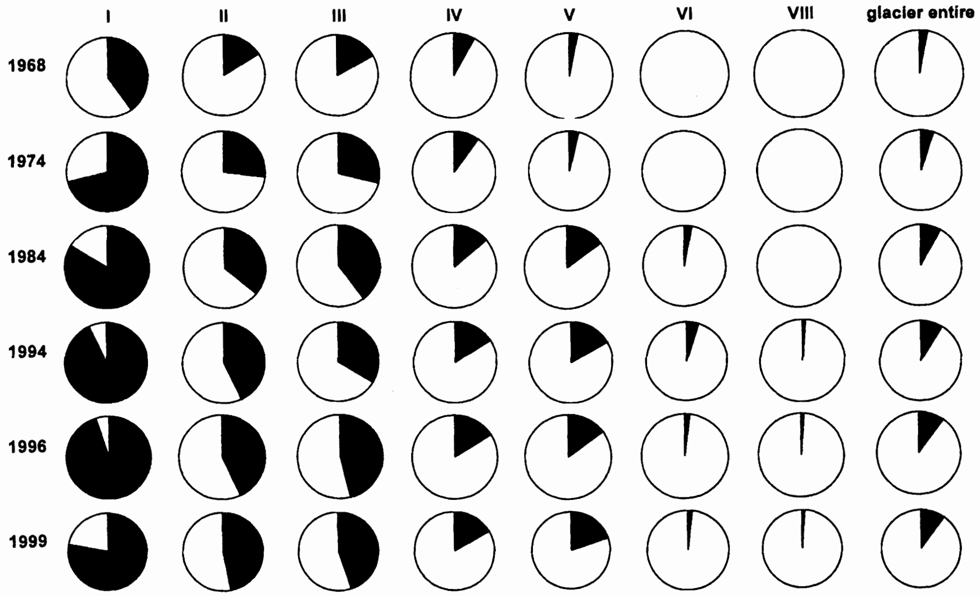

Fig. 5. Dynamics of debris cover areal growth 1968-1999 (by alti-morphological zones). Black sectors show the debris-covered part of a zonal area.

no strict correlation between the debris area increment rate and mass balance was revealed (especially for short intervals of the last period). Nevertheless, a general tendency can be detected: the more negative the mass balance, the higher the rate of debris areal increment. The least dynamics were registered between 1984 and 1994, when cumulative mass balance was positive.

For the Djankuat Glacier, the spatial distribution of various information is traditionally presented as systematised by 13 so-called alti-morphological zones (AMZ), *i.e.* parts of the glacier surface characterised by more or less uniform glacial morphology. Their numbers grow with height (Fig. 4). Fig. 5 allows one to trace back the dynamics of debris coverage in each of the lowermost AMZ, demonstrating the progressive propagation of debris cover towards the upper belts. In 1968 it was registered only up to the V AMZ, while at present superficial moraine spreads up to the VIII AMZ. Its percentage also tends to increase nearly everywhere. The lowermost I AMZ, where only about one third of its territory was under the lithogenic shield in 1968, was later covered almost completely. Rare exceptions in this growth tendency (such as the last time span for the I AMZ and some other cases) are explained either by complete melting of ice beneath and, hence, debris deposition outside the nominal glacier area, or by moraine movement to a lower neighbouring AMZ due to ice flow.

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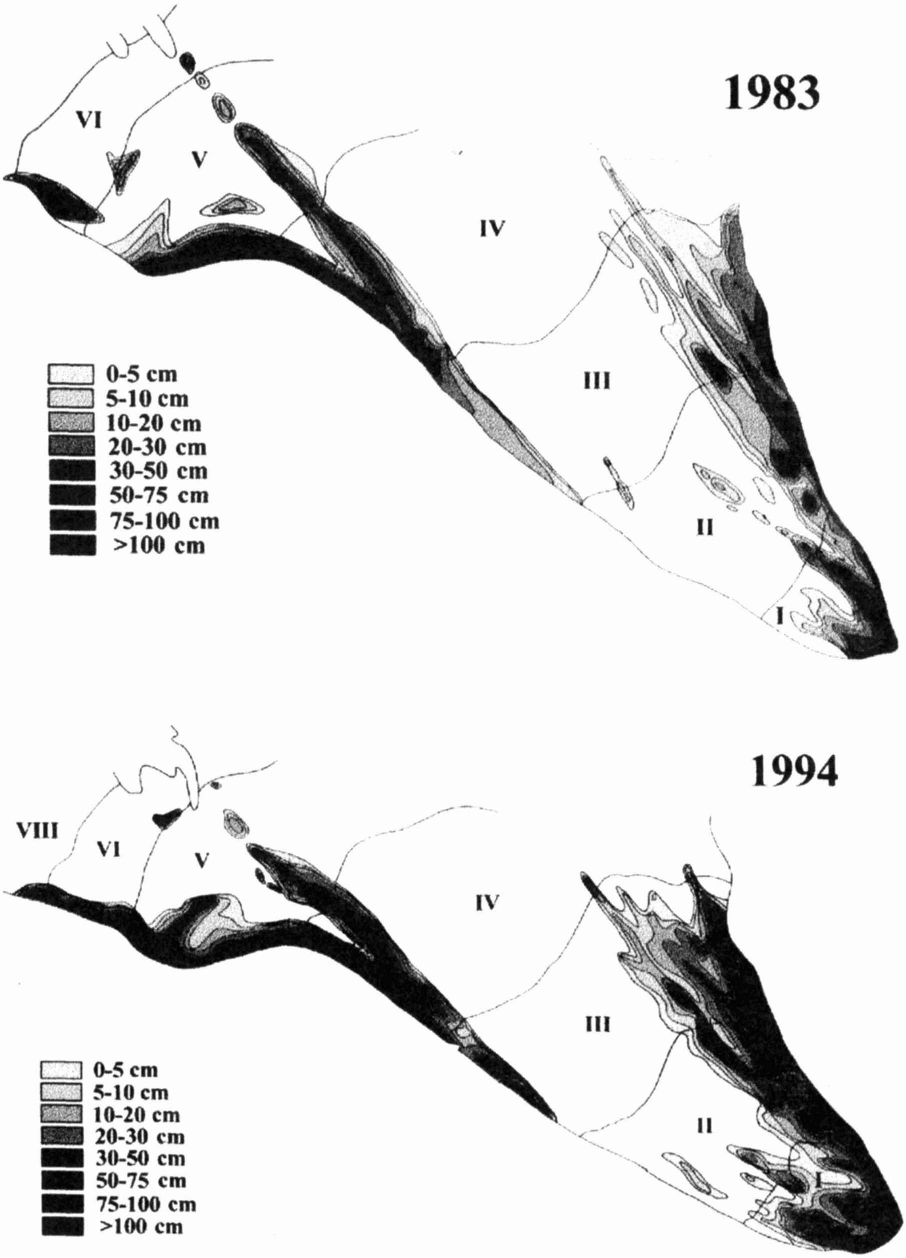

Fig. 6. Maps of debris layer thickness on the Djankuat Glacier: a) in 1983; b) in 1994. Boundaries of alti-morphological zones are also shown.

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Debris Thickness Surveys

For estimating the hydrological consequences of debris propagation the first complete survey on the Djankuat Glacier was achieved in 1983. Methodically it resembled common snow depth survey and *h* values were determined at measurement points dispersed over the whole moraine-covered area. Bassin *et al.* (1983) located such points in chess-board order. This does not seem to be the best option. Abundance of linear lengthwise geomorphological features of morainic meso-relief and extreme variation of *h* values on different parts of the snout requires either introducing the grid hierarchy of elementary spatial cells, or combining chess-board order with transect profiles across morainic ramparts whose measurement points are very close. Only the latter approach was applied at the Djankuat Glacier.

The measurement procedure complied of sticking metal rods in-between stones down to the buried icy surface or manual excavations. Debris thickness was estimated at 133 points distributed over the entire area, with projective morainic coverage close to 100%. Plots of glacier surface with thin debris layer, represented by chips or grus aggregates, even if not contacting each other, were admitted as continuous cover if their coverage was ≥80%.

In 1994 the debris thickness survey was repeated with increased accuracy and detail: this time it consisted of 240 measurement points. 2 maps (status 1983 and 1994) were produced, showing distribution of *h* values along the lower part of the Djankuat Glacier (Fig. 6).

The thickest debris layer gravitates towards axes of pronounced morainic ramparts and marginal segments of the snout where supra-glacial moraines unite with lateral ones. On the contrary, the least *h* values are registered along the inner peripheries of the debris-covered zone, but here a certain differentiation is outlined. Peripheric belts of ramparts, originating from the confluence of 2 adjacent ice streams and hereby consisting mainly of coarse colluvial material, are characterised by rapid increase of *h* values towards the axis of a rampart; peripheric strips of thin debris layer are narrow in such cases. Such are ramparts in the orographically right-hand side of the Djankuat Glacier. Apparently, higher shear strains between the adjacent ice fluxes cause flow-line convergence at this place. Hence, the in-glacier stream of debris containing ice is very localised in the cross-section of the glacier, so that after debris melts out, it turns out to be projected in a narrow band. However, if a rampart is composed of the material initially having been dispersed in the glacier body, now concentrated on the snout surface as a result of melt-out after passing ice-falls with subglacial rock ledges or riegels, horizontal gradients of debris thickness are small and ramparts are framed by relatively wide belts of a thin stony cover. This case was observed on the left part of the Djankuat Glacier. Shear strains are reduced here, causing parallel or even divergent character of ice-flow lines when mooring to the lateral boundaries of the snout. Therefore, it is just in this segment (in the II and III AMZ) where debris cover has a typical appearance of a continuous lithogenic enve-

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Table 1 – Moraine cover thickness frequency distribution (percentage of the total debris-covered area of a given alti-morphological zone AMZ) in 1983 and 1994.

AMZ	Year	Debris thickness *h*, cm							
		0-5	6-10	11-20	21-30	31-50	51-75	75-100	>100
I	1983	20.6	11.8	14.7	10.8	22.5	15.7	2.9	1.0
	1994	16.3	10.2	10.3	12.2	16.4	12.2	6.1	16.3
II	1983	18.6	15.8	22.9	13.1	25.5	4.1	-	-
	1994	14.5	10.9	11.0	7.3	18.2	20.0	12.7	5.4
III	1983	33.9	19.8	18.6	19.0	6.6	1.7	0.4	-
	1994	11.9	16.4	22.4	16.4	13.4	9.0	6.0	4.5
IV	1983	14.2	13.4	13.4	14.9	24.6	4.5	9.0	6.0
	1994	5.4	8.1	10.8	10.8	24.3	27.0	8.2	5.4
V	1983	24.4	14.1	16.3	13.3	10.4	4.5	8.9	8.1
	1994	18.7	14.5	16.6	10.4	16.7	12.5	6.4	4.2
VI	1983	7.7	7.7	23.1	7.7	19.2	23.1	11.5	-
	1994	11.1	11.1	11.2	11.1	22.2	22.2	11.1	-
VIII	1983	-	-	-	-	-	-	-	-
	1994	-	-	-	-	100.0	-	-	-
Glacier	1983	23.4	15.6	17.7	14.8	16.3	5.6	4.0	2.6
	1994	13.5	12.4	14.6	11.7	17.7	15.4	7.9	6.8

lope, *i.e.* with levelled meso-relief features, with the least horizontal gradients of *h*, and with moderate thicknesses of supraglacial moraine. Near the terminus the pattern changes: dominant here again are linear features with increased *h* values and higher areal differentiation in debris thickness. This is due to the fact that near the frontal margin basal ice layers outcrop with the highest debris concentration within the glacier body. Eyles and Rogerson (1978) consider that most of the medial moraine debris is transported englacially at depth and is only revealed close to the terminus. Debris material then characteristically accumulates along the flow-lines near the terminus.

Both surveys disclosed considerable values of supraglacial moraine thickness on the Djankuat Glacier: in 1983 the maximum *h* value reached 183 cm and in 1994 a point with 280-cm-thick debris layer was found. In 1983 modal *h* values for the entire glacier laid in the lowest interval gradation 0-5 cm (Table 1), while in 1994 they moved to the 31-50 cm interval. The distribution of *h* in different AMZs, obtained from digitalising maps of Fig. 6 in the knots of the detailed rectangular grid, shows that such a displacement of modal interval towards higher values took place nearly everywhere. This is particular for the lowermost AMZ, where contribution of the de-

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bris thickness utmost gradations increased drastically. All these facts testify clearly to the overall debris layer growth tendency, depicted in Fig. 6 as well.

Increments of absolute h values during 1983-1994 are also rather high, especially in the lower four AMZs (two-fold in the II and III AMZ). Average zonal debris thicknesses for both dates are summarised below in Table 2 (see next paragraph). On the average, h increased by one-third: from 26 cm in 1983 to 39 cm in 1994. But the initial idea to map h increments/decrements during the 9-year-long period by superimposing both maps of Fig. 8 had to be abandoned, because the morainic meso-relief features do not remain rigidly fixed in space – they move along with ice motion. Although ice flow on the snout is considerably decelerated in comparison with the rest of the glacier, geodetic monitoring shows that the horizontal component of the velocity vector can still reach 10 cm/day in some parts of debris-covered area (see Fig. 4 in Aleynikov *et al.* 2001). Resultant displacement of the whole morainic ramparts or isolated cones is large enough to make mapping h changes non-demonstrative at all.

Hydrological Effect of Sub-moraine Thawing

Heat conductivity properties of granite and gneissose granite rocks, surrounding the Djankuat catchment area, determine the values of three important points on the curve of Fig. 2:

- h_{cr}, or debris thickness causing the maximum rate of moraine-induced thawing is about 2 cm; the a_m/a_i value corresponding to h_{cr} = 2 cm, turns out to be approx.1.35;
- h_e, or debris thickness showing a hydrologically equivalent influence upon the thawing rate in comparison with clean ice (*i.e.* the case when $a_m=a_i$) is about 7-8 cm;
- h_0, or debris thickness where sub-moraine thawing can be assumed as negligible ($a_m=0$), is considered to be approx. 150 cm.

Values of h_{cr} and h_0 conform well to most similar estimates known in glaciological literature (Østrem 1959; Khodakov 1972 *etc.*). As for h_e, it may seem a bit higher than hitherto adopted. Perhaps this discrepancy springs from the packing features of the debris cover formed on the Djankuat Glacier. Three packing types of porous materials are known in physics: face-centred, cubic and rhombohedral. When simulating debris melt-out on the Djankuat Glacier, a characteristic porosity value was set as $p \equiv 0.43$ based on special measurements in the field and some theoretical considerations; this corresponds to an intermediate case between cubic and rhombohedral packing types. However, porosity may differ greatly on various glaciers. First of all, it depends on the size of stony aggregate, which in turn is predetermined principally

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by the way debris reaches the glacier surface. The largest boulders originate usually from gravitational redistribution (rock falls, avalanches, land-slides *etc.*). They compose mainly longitudinal moraine ramparts. Melt-out of the basal till beneath ice-falls or thrust moraines leads to finer granulometrical composition. Such a differentiation in the origin of debris matter was actually observed in the course of the debris survey on the Djankuat Glacier. One can also find signs of epigenetic transformation of debris granulometry after stones were already settled on the surface. The closer to the firn-line the stones emerge, or the more protracted the period of their slow motion with the moving substrate ice before their deposition in the periglacial zone, the longer the duration of weathering upon the debris. Hence, as stones are transported towards the terminus, the share of finer fractions tends to increase with time. A type of stratification can even be disclosed in excavations, dug in the lower reaches of the snout: fine-grained material in the bottom and coarse boulders above. Small (1983) reported a similar process observed at Tsidjiore Nuove Glacier in the Pennine Alps (Wallis, Switzerland): eventually granulometric fractioning takes place within the thick debris cover, resulting in its consolidation and compaction. Such a fine-grained debris layer on the buried ice insulates the ice not only from heat but from rainfall too. Obviously, different granulometry can therefore distort the shape of the curve describing function Eq. (4).

Fig. 2 as a basic nomogram allows to reveal the hydrological effect of debris cover in every AMZ where moraine cover exists. The contribution of sub-debris thawing in the true zonal ablation value A should be evaluated by means of normalising ablation, estimated by standard measurements on the bare ice surface, a_i, with a factor I, *i.e.*

$$I = \frac{A}{a_i} \tag{6}$$

Let S and S_m signify total and moraine-covered area, correspondingly, $a_m/a_i = m$ and j be the number of AMZ. Then for any AMZ

$$A_j \equiv \frac{a_{ij}(S_j - S_{mj}) + m_j a_{ij} S_{mj}}{S_j} \tag{7}$$

Now if we denote the percentage of debris cover in a given AMZ, shown on Fig. 3, by D (*i.e.* $D_j = S_{mj}/S_j$), we can easily combine Eq. (6) and Eq. (7) into

$$I_j = 1 - (1 - m_j)\,D_j \tag{8}$$

The main results are summarised in Table 2. Here h is the mean zonal debris thickness. For both years 1983 and 1994, and for every AMZ $h_j > h_e$. This indicates that the general hydrological effect produced by debris does not enhance the ablation rate but reduces it by screening therefore explaining why $m_j < 1$ in every zone. However, in order to calculate the zonal values of ratio m_j, simple application of the nomogram

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Table 2 – Calculation of the hydrological effect of debris cover on the Djankuat Glacier. See explanations in the text.

AMZ	1983				1994				1983-1994			
	h	*M*	*D*	*I*	*h*	*m*	*D*	*I*	Δ*h*	Δ*m*	Δ*D*	Δ*I*
I	29	0.80	0.84	0.83	45	0.73	0.93	0.75	+16	–0.07	+0.09	–0.08
II	22	0.86	0.36	0.95	43	0.74	0.43	0.89	+21	–0.10	+0.07	–0.06
III	14	0.98	0.40	0.99	30	0.81	0.34	0.94	+16	–0.17	–0.06	–0.05
IV	34	0.75	0.14	0.96	47	0.72	0.16	0.96	+13	–0.03	+0.02	–0.02
V	31	0.79	0.15	0.97	32	0.80	0.17	0.97	+1	+0.01	+0.02	0.00
VI	37	0.68	0.03	0.99	38	0.79	0.05	0.99	+1	+0.11	+0.02	0.00
VIII	-	-	-	-	32	0.80	0.01	1.00	-	-	-	-

h – mean zonal debris thickness, cm
m – mean zonal value of clean ice/sub-debris ice ablation ratio
D – percentage of debris cover in the zonal area
I – zonal value of correction factor for ablation estimates: $I=1-(1-m)D$

on Fig. 2 for a given h_j would be incorrect due to the non-linearity of the curve. Zonal values of m_j are not predestined by zonal debris thickness h_j as the arithmetical mean of thicknesses in every knot of a regular grid, but by the whole spectrum of their values over the area of an AMZ (or, in other words, by spatial distribution and quantitative ratio between ablation-enhancing and ablation-reducing thicknesses $h<h_e$ and $h>h_e$). The values of m_j given in Table 2 were therefore computed as area-weighted averages for *h* gradations much more fractional than presented in Table 1. For this reason, in spite of the fact that all h_j values grew during 1983-1994, one cannot affirm that all m_j values will therefore be sure to decrease. Look at (m_j values for V and VI AMZ to ascertain this.

Nevertheless, the reduction of runoff with time can be considered dominant in the deglaciation stage, judging by the dynamics of the correction factor I during the 11-year-long period. This coefficient expresses the ratio between actual ablation and some hypothetic ablation value for the case where there was no debris at all. Table 2 demonstrates clearly how this deviation increases towards the lowermost belts of the glacier snout. In 1983 it amounted to only a few per cent in nearly every AMZ, except for the I AMZ where it came to 17%, but by 1994 the role of debris in affecting runoff increased. Now runoff from the I AMZ is already reduced by one-quarter due to the screening influence of debris cover and for the II AMZ this reduction rate is 11%. These are zones where every year the ablation layer amount is the highest all over the glacier.

Dynamics of liquid runoff formation from under the supraglacial moraine is subjected to the influence of two opposite tendencies. On the one hand, sub-debris ablation rates tend to diminish during deglaciation. On the other, the spreading of the lithogenic mantle leads to the growth of the area »providing« runoff from under de-

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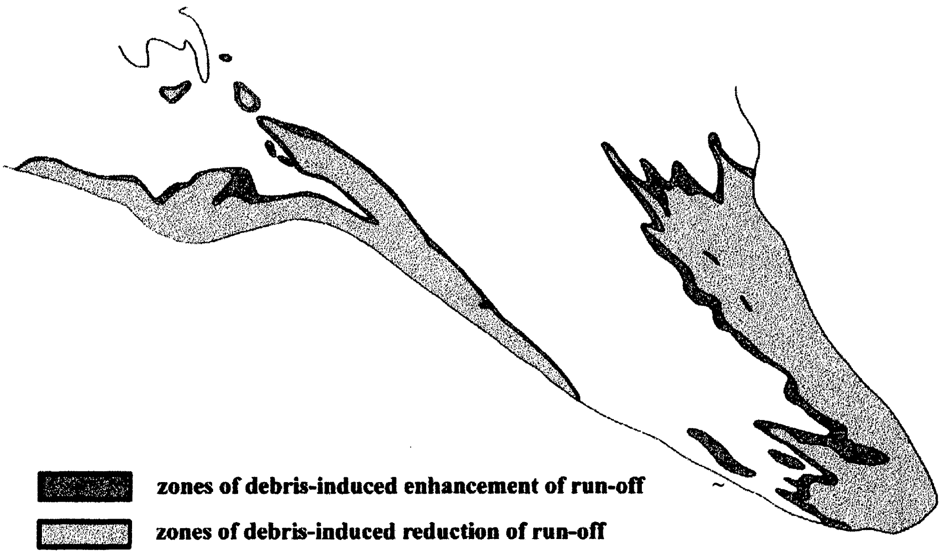

Fig. 7. Zonation of debris cover due to its hydrological effect (in comparison with clean ice surface).

bris. As a result, water yield turns out to be nearly steady: in 1983 1.06 km^3 of meltwater originated on the average from under debris cover and by 1994 this value did not change (1.05 km^3/yr). However, its share in the total amount of meltwater draining from the Djankuat Glacier rose a little between 1983 and 1994 from 12.5% to 13.5% of the glacier-derived runoff running means by the corresponding dates. Disregarding the slightly positive trend, the rather small share (only 2%) that has been deduced here by indirect and speculative considerations for the initial observation period 1968-1974 (Boyarskiy, 1978) seems to be greatly underestimated due to the lack of thorough studies during the IHD.

In each AMZ (except III AMZ) the contribution of sub-debris meltwater in the whole zonal volume of liquid runoff increased by 1994. For example, in the I AMZ it grew up to 92% in comparison with 79% in 1983. In 1994 its share in the II, III, IV, V and VI AMZs came to 37, 29, 12, 15 and 4%, respectively; in the VIII AMZ it did not reach 1% yet.

Zonation of the debris-covered part of the Djankuat Glacier by degree of moraine-induced perturbation of ice thawing, expressed by m criterion, may easily be accomplished by applying Fig. 2 as a reference curve to the maps of Fig. 6. Both maps may be interpreted in terms of m, taking into account that h isolines, limiting gradations on Fig. 6 in accordance with the accepted legend respond to some fixed values of m: h=5 cm corresponds to m=1.05, h=10 cm to m=0.95, h=20 cm to m=0.76, h=30 cm to m=0.60, h=50 cm to m=0.40, h=75 cm to m=0.22, h=100 cm to m=0.09, and fi-

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nally ablation under the moraine layer with h>150 cm may be reasonably assumed as coming to zero. In this connection, depicting the location of the isoline $h=h_e=7.5$ cm is of particular importance, since it separates glacier parts with runoff enhancement and runoff reduction (Fig. 7). Certainly most of the debris-covered part of the snout plays a runoff-reducing role. Areas of runoff enhancement are represented only by considerably smaller (less than 20% of the covered surface) marginal strips along the perimeter of continuous debris cover.

Continuous meteorological monitoring of the Djankuat catchment area since 1968 reveals a more or less pronounced positive trend for summer air temperature – about 1°C for a 8-year running mean. At the same time (at least until 1998) average overall ablation of the Djankuat Glacier remained nearly constant or even experienced a slight decline, which was noted earlier (Popovnin 1996) for the 1968-1993 period. This disparity in the glacier response to climatic tendency is most likely to be due to the described runoff »self-control« by debris-cover development that conserves glacier ice even under unfavourable natural conditions.

Geomorphological and Mass-balance Corollaries

Since the main hydrological effects of debris-cover development are shielding and ablation-reducing, this must inevitably become reflected in the glacier relief. Indeed, comparison of photo-theodolite surveys of 1968 and 1999 (Fig. 8) clearly demonstrate a considerable lag in lowering of the debris-covered surface as compared to clean ice. While the orographically right branch of the snout composed mainly of ice with scanty boulders lowered as much as 30 m at some points, degradation of the debris-covered left branch was much slower: typical values of surface elevation change are only –4 to –10 m and there are even segments with hypsometrical rising. The rampart of the medial moraine on the right part of the snout is also remarkable for its reduced lowering. As a result, the surface of the left branch is now 20-25 m higher than the right one along some transversal profiles, while during the IHD period this hypsometrical difference rarely exceeded 8-10 m. Furthermore, the thickest debris cover along the left-side margin of the glacier protected ice from melting in such a way that the mass influx due to ice flow from above caused the lateral advance of the snout periphery, whereas the terminus continued its retreat.

Accumulation, ablation, and mass balance maps are the main scientific products resulting from the research conducted on the Djankuat Glacier. Contrary to the firn basin, the isoline patterns on the snout follow the lengthwise features of ramparts and morainic relief. Thus, only the correct assessment of debris influence on melting permits an adequate cartographical representation of ablation fields on mass-balance maps. Such maps represent the modern level of providing glaciological information and are required for mass balance bulletins issued biennially by the World Glacier Monitoring Service (UNESCO 99).

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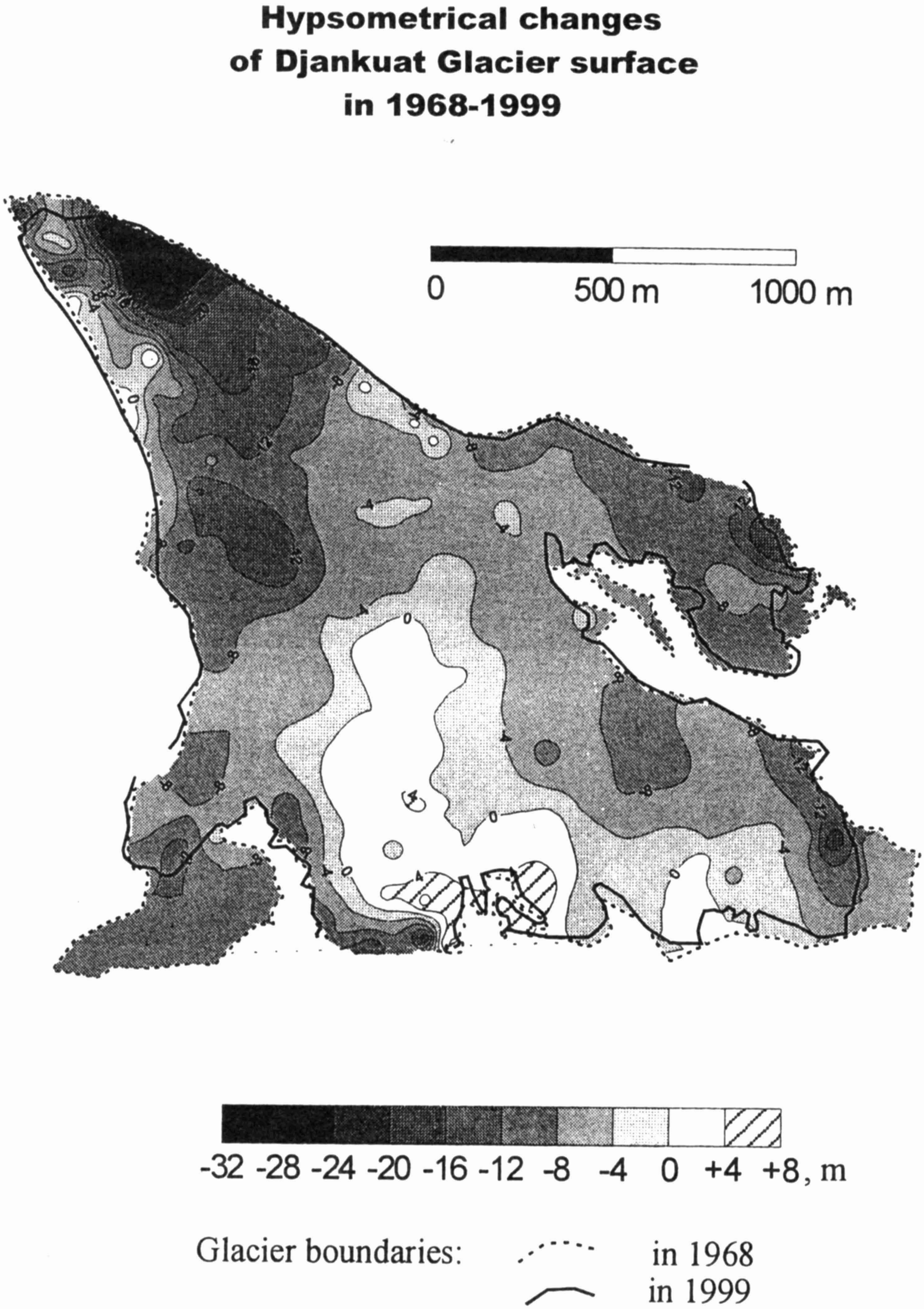

Fig. 8. Hypsometrical changes of the Djankuat Glacier surface 1968-1999.

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