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# SUPERFICIAL MORAINE EXPANSION ON THE DJANKUAT GLACIER SNOUT OVER THE DIRECT GLACIOLOGICAL MONITORING PERIOD

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A superficial moraine is an inherent attribute of the lower belts of active alpine glaciers at the currently prevalent regressive stage of their evolution. Debris on the glacier snout surface drastically influence ablation and the mass balance of a glacier and thereby the glacier runoff, as well. A superficial moraine at the Djankuat glacier, representative for the Central Caucasus, has been both examined in the course of direct fieldwork and mapped by means of remote sensing. Debris thickness was mapped thrice during the direct monitoring period as a result of three direct surveys, covering the entire debris-covered area of the snout. The study reveals evident debris expansion on the Djankuat snout: accounting for only 2 % of the entire glacier area in 1968, its share grew up to 13 % by 2010, resulting thereby in 6.5-fold enlargement during 42 years. The debris layer became thicker by 70 cm in some points near the terminus during 1983–2010, whereas the volume of the lithogenic matter over the whole glacier experienced 141 % increment. This process has changed the mass balance values and has affected its spatial pattern. In general, the debris cover renders a screening effect upon the melt-rate, and thereby the glacier-derived runoff turns out to be reduced annually by ca. 20 % on average.

*Glacier, superficial moraine, debris thickness survey, monitoring, mass balance, ablation, Central Caucasus*

## PROBLEM SETTING

A superficial moraine producing debris for lower parts of glaciers is currently their inherent component. The modern stage of the evolution of alpine glaciers is far and wide characterized by active background deglaciation, which is accompanied by intense accumulation of moraine material on the glacier surface and in the glacier belt. It is most commonly investigated in view of the mudslide hazard coming from the periglacial zone [*Tomashevskaya et al., 2013*]. However, deglaciation results in the growth of the surface moraine debris on the glacier itself both in terms of the area and thickness. Moraine debris primarily affects all the processes occurring within the limits of the glacier parts covered by it. It predetermines intensity of ablation in these parts and runoff from them and determines the pattern of the mass balance fields and of its discharge component on the snout: a thin (the first centimeters) moraine enhances sub-debris thawing, while a thicker moraine, on the contrary, diminishes it to the extent of complete disappearance [*Bozhinskiy et al., 1986*].

Having characteristics different from ice surface, a superficial moraine forms a special structure of heat exchange between a glacier and the atmosphere, while change in the morphology of the moraine debris eventually leads to a change in the glacier pattern as a whole. Yet, investigation of a superficial moraine is not currently an item on the program of traditional glaciological monitoring. The Djankuat Glacier, representative for the Central Caucasus, is a rare exception to the rule. Observations over expansion of the superficial moraine started simultaneously with deployment of the program of complex glaciological monitoring in [*Djankuat Glacier, 1978*]. Thus, studies of the superficial moraine have been conducted over 40 years, with consistency of the observation techniques and of the staff work ensuring comparability of the data obtained. This allows the researchers to estimate the development vector of the superficial moraine debris over the recent decades and the influence it exerts on the glacier mass balance and the glacier evolution, which is in fact the main goal of the study. It was assumed to achieve this goal by solving the following tasks: 1) to conduct repeated moraine survey over the entire debris-covered area of the glacier snout; 2) to make maps of the superficial moraine thickness at different times; 3) to evaluate changes of both the area and the debris thickness carried by the glacier; 4) to characterize the hydrological effect of development of the moraine debris on the glacier; 5) to assess representativeness of the conclusions regarding the role of the moraine in the evolution of the Djankuat Glacier in relation to the alpine glaciation of the entire Central Caucasus.

## DIRECT AND REMOTE METHODS OF STUDYING MORAINE DEBRIS

Now the mapping method and the method of direct field measurements are the two major methods of investigating the behavior of the superficial moraine on the Djankuat Glacier (Central Caucasus). So far, interpretation of the data obtained by the radar studies of the moraine conducted over the recent years has not yet been effected. In addition, it is planned to conduct accurate analysis of the behavior of the superficial moraine using the most recent surveying equipment, like laser scanners and profile recorders.

The mapping method of investigating morphometric changes is based on comparison of six large-scale (1:10 000) topographic maps with a 10 m interval, built according to the results of field photogrammetry of the glacier in 1968, 1974, 1984, 1992, 1996, and 2006, with the first and last photogrammetric surveys covering not only the glacier itself but also the entire alpine glacial basin. The surveys were conducted from fixed baselines [*Zolotarev and Popovnin, 1993*], while all the maps were made in a single conditional system of coordinates and altitudes. It was only recently, in 2009–2010, that transition was effected from this system to a geographic system, using the differential GPS-receivers Trimble. Besides, the most recent topographic basis was partly actuated in 2010 after updating the contour of the lower part of the glacier. Areas covered by the superficial moraine, the morphometry of which was evaluated with GIS analysis tools, were indicated on all the maps with a special symbol.

Based on this topographic foundation, for detailed analysis to be made, any glaciological information regarding the Djankuat Glacier is traditionally systematized regarding 13 altitudinal-morphologic zones (AMZ) – parts of the glacier surface isolated

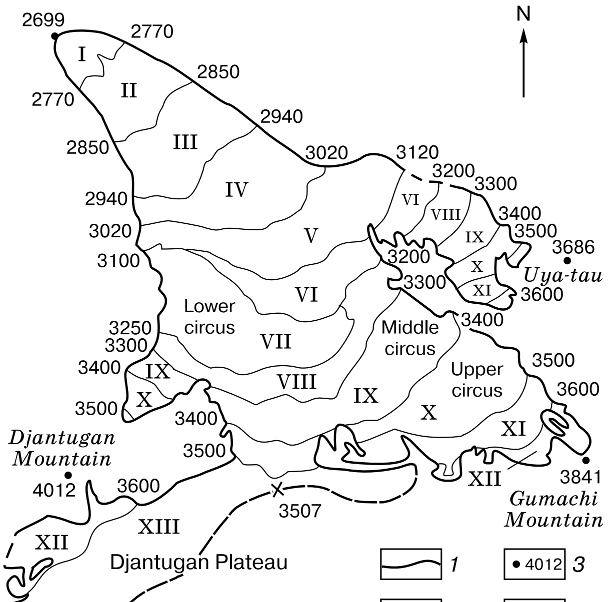


**Fig. 1. The altitudinal-morphological zones of the Djankuat Glacier.**

*1* – the glacier border; *2* – glacial divides; *3* – elevations and their absolute data; *4* – zone numbers and their borders.

according to the principle of relative homogeneity of their morphology. The zone numbers grow with the altitude, while their borders most commonly coincide with isohypses (Fig. 1). The lower four zones annually represent a typical ablation area, AMZ V and VI may be considered as a year-to-year migration belt of the firn line, while higher zones are mostly referred to the glacier alimentation.

However, the remote methods turn out to be unfit for detecting changes in the moraine material mass in time. Actual field survey of the lithogenic debris thickness is required, covering the entire debris-covered area of the snout. There are only few examples of such complete moraine survey on glaciers, and the Djankuat Glacier is one of such examples.

The first complete study of the debris thickness *h* on the Djankuat Glacier was conducted in 1983, to assess its hydrologic impact on the glacier's runoff. Methodologically, it was close to measuring the snow cover thickness and was carried out on the basis of determining *h* in discreet measurement points. With these points located on the Pamir glaciers of Schults, the Russian geographic society, Kuljilga, and Podkova, *N.S. Bassin et al.* [*1983*] organized them in staggered arrangement (chequerwise), which did not ensure due accuracy of the contour lines in the areas of the kame-and-kettle topography of the moraine surface. The abundance of linear elements of the moraine mesorelief, extended along the axis of the glacier movement, with *h* highly varied in different parts of the snout, requires other solutions. Therefore a landscape principle fits the purpose of moraine survey, when the staggered arrangement of the measurement points in the areas of complete debris with relatively monotonous mesorelief is combined with profiles across moraine lines, consisting of points, although arranged not too far from each other, but typical in terms of the landscape (bends, brows, tops, etc.). Then, depending on the specific shape of the moraine mesorelief, observed by a scientist in the location, a decision may be taken to condense the measurement points in complicated areas (for example, in crosswise profiling of the moraine lines) and to scatter them to the degree of being homogeneous (morainic mantles). It was this principle that was used on the debris survey of the Djankuat Glacier. The debris cover with the projective cover degree exceeding 80 % was taken to be "a complete debris cover". The measuring procedure included thrusting steel probes in-between the stones to reach the ice surface or manual excavation, with actual pits made. The observation had the accuracy of 1 cm, while the natural roughness of the debris cover was smoothened with a tin ring placed on the probe and by levelling off the debris roof. The debris thickness was thus measured in 133 points. In 1994, the study was repeated with increased accuracy and more details: the values of *h* were measured in 240 points. It was then that the topographic foundation was partly updated for the debris-covered part of the glacier snout. As a result, two maps were made for the debris cover thickness in the lower part of the Djankuat Glacier as of 1983 and 1994, the primary analysis of which had been conducted previously [*Popovnin and Rozova, 2002*].

Similar work was conducted on the Djankuat Glacier in the summer of 2010. The measurement method remained the same: penetrating the debris thickness with a steel probe or manual excavation, in order to see if the glacial ice roof buried under the debris layer had been reached. Measurements were conducted in 189 points all over the debris-covered part of the snout. The values of $h$ in each point were manually positioned on the topographic route map of the glacier. In addition, for each point to be positioned accurately, its coordinates were entered into the memory of a portable GPS-receiver Garmin eTrex Summit. Detailed direct field studies of the debris cover thickness, as opposed to the examples of determining this parameter on the basis of satellite data [*Mihalcea et al., 2008*], are complicated and labor-consuming. Measurements of the debris cover thickness of a superficial moraine on the Djankuat Glacier took 1.5 months; they were conducted within the range of absolute heights from 2,700 to 3,300 m. If the debris thickness in a point did not exceed 20 cm, the value of $h$ was averaged by three measurements.

Later, the data of the moraine survey as of 2010 performed with GIS analysis methods were interpolated using the method reverse weighted distance. As a result, the third map of the debris thickness was developed, allowing monitoring the mass of the lithogenic matter over the entire area of the glacier for a period of 27 years.

## THE GROWTH RATE OF THE SUPERFICIAL MORAINE ON THE DJANKUAT GLACIER

Comparison of the maps compiled at different time periods allows us to state that the part of the glacier area occupied by the superficial moraine is consistently growing: 1968 – 2 %, 1974 – 4 %, 1984 – 7 %, 1992 – 8 %, 1996 and 1999 – 10 %, and 2010 – 13 % (Fig. 2).

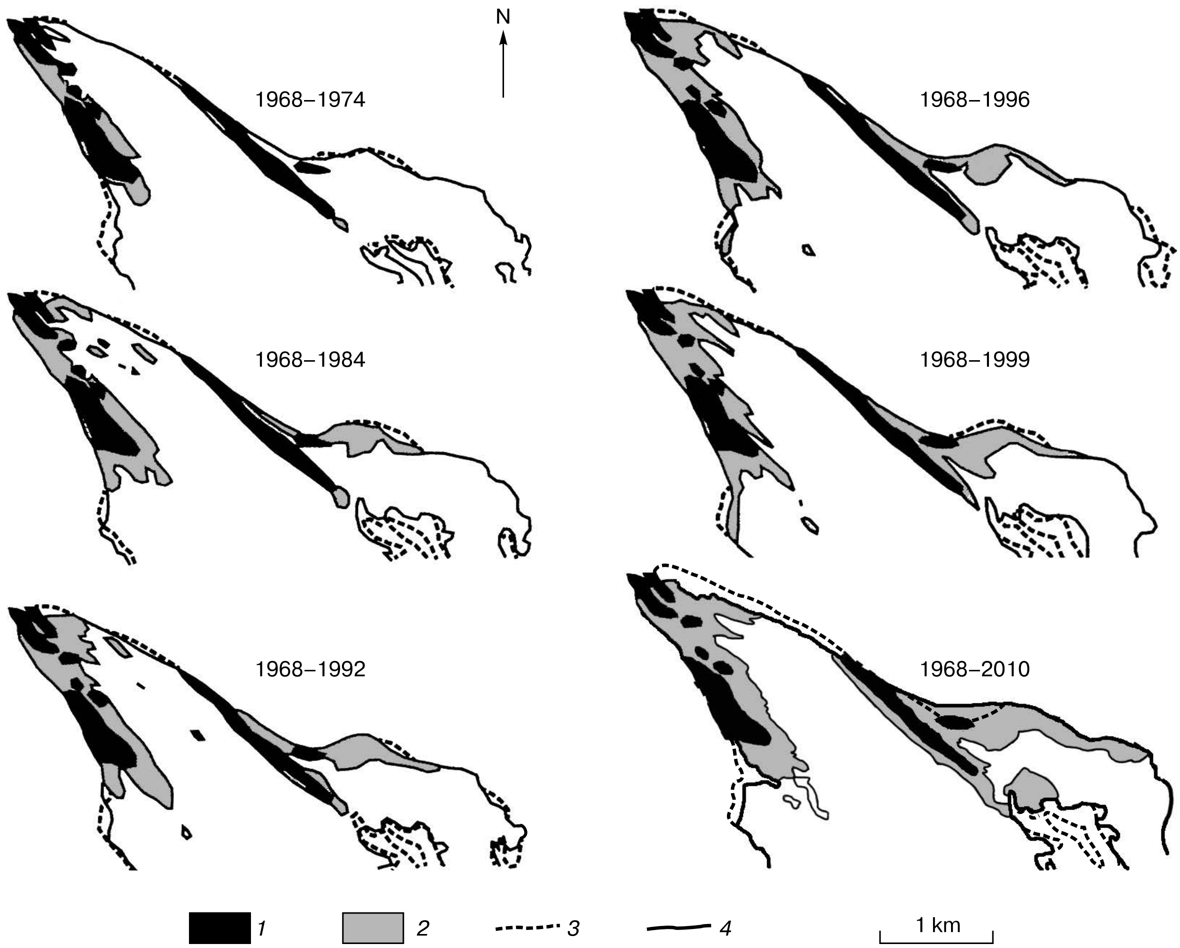


**Fig. 2. The increment rate of the debris-covered area of the Djankuat Glacier in 1968–2010.**

*1* – the debris cover in 1968; *2* – increment of the debris cover till the indicated date; *3* – the glacier border as of 1968; *4* – the glacier border at the given date.

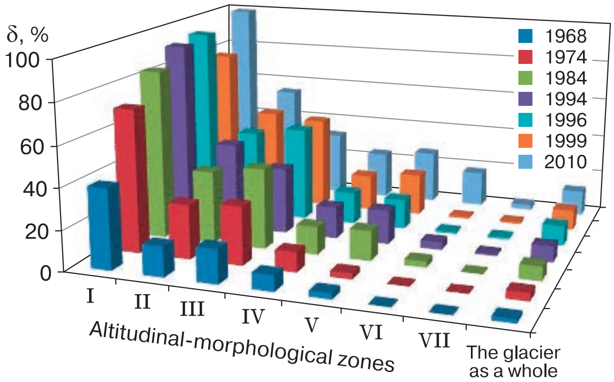


**Fig. 3. The increment rate of the debris-covered area of the Djankuat Glacier in 1968–2010 by altitudinal-morphological zones.**

AMZ: I – 2,700–2,770 m; II – 2,770–2,850 m; III – 2,850–2,940 m; IV – 2,940–3,020 m; V – 3,020–3,120 m; VI – 3,120–3,200 m; VII – 3,200–3,300 m; δ – coverage of the AMZ area with moraine, %.

Consider the process of expansion of the superficial moraine area on the glacier by the altitudinal-morphologic zones. A natural dependence is manifested: the closer a zone is located to the glacier front, the faster is the process of its screening by the lithogenic crust (Fig. 3). In 1968, the lowest AMZ I (absolute height of 2,700–2,770 m) was only 40 % screened by the superficial moraine, while currently it is practically fully concealed by the debris cover. Increment of the area occupied by the lithogenic matter occurred from 1968 to 2010 in the other AMZ, as well: in AMZ II (2,770–2,850 m) – from 15 to 55 %, in AMZ III (2,850–2,940 m) – from 17 to 32 %, in AMZ IV (2,940–3,020 m) – from 8 to 24 %, in AMZ V (3,020–3,120 m) – from 3 to 26 %, in AMZ VI (3,120–3,200 m) – from 0 to 18 %, and in AMZ VIII (3,200–3,300 m) – from 0 to 3 %. The rare cases of reduction of the zone area of a superficial moraine between two consecutive periods are accounted for either by complete melting of the ice kernel under the debris cover (indicating that this area has stopped being a glacier: for example, in AMZ I in the period between 1996–1999) or by movement of the moraine into the lower AMZ due to ice flow. The stepwise increment of the area covered by lithogenic matter is related, except regular processes, to melting of debris on the snout, which got carried to the glacier by rock slides in the area of the glacier alimentation in 2001–2002.

In 1968–2010, the orthogonal area of the glacier got reduced from 2.990 to 2.688 km$^2$, indicating that over 38 years the glacier had lost 10 % of its area. The physical area of the glacier remained practically the same in 1968 and in 1974 – 3.034 and 3.039 km$^2$, accordingly, while by 1984 it got reduced to 2.913 km$^2$ and later to 2.816 km$^2$ in 1992, 2.767 km$^2$ in 1996 and 2.740 km$^2$ in 1999. In this regard, it is to be noted that the migration process of the glacial divide on the Djantugan ridge firn plateau located in the territory of Georgia affects the fluctuations in the total area of the Djankuat Glacier, which in some periods caused accelerated area reduction, and in the other periods compensated the area loss on the northern macroslope [*Aleinikov et al., 1999*].

The glacier borderline on the snout is much less dynamic than on the rock margins of the firm basin. This is caused by the low thickness of ice on the facing, measured only by the first meters; as a result, the prevalence of the negative values of the mass balance at the degradation stage leads to complete melting of thin ice. This process became especially active in 1998, when the number of rock falls and slides from the rock ridges drastically rose [*Popovnin and Naruse, 2005*], causing increment in the thickness of the lithogenic matter and in the area occupied by it on the glacier surface.

The highest thickness of the debris cover was always recorded along the axes of median moraine lines and in the marginal parts of the snout, where the moving moraine gets connected with the deposited debris (Fig. 4). The thinnest layer of the superficial moraine has always been related to the internal periphery of the screened morainic zone. If the debris cover is composed of the matter dispersed in the glacier body and coming to the snout surface as a result of melting after passing ice falls and the irregularities of the subglacial relief, the horizontal gradients of the debris cover thickness are low, and the moraine lines are surrounded by the relatively broad strips of the thin stony debris cover. This was the case on the left part of the Djankuat Glacier. The vertical tensions are lower here; therefore the flow of ice strips when approaching the snout is parallel or even divergent. In the vast area in AMZ II–III, the moraine seems to be a single lithogenic body with smoothened features of the kame-and-kettle topography of the moraine surface mesorelief and minimum horizontal gradients *h*. Near the end of the snout, the situation changes: here again, prolonged shapes dominate, with increased debris thickness and different morainic variations, which is caused by the outcrop of basal ice with greater volume concentration of the lithogenic matter. In 1983, it was in that sector that the maximum height *h*, equal to 183 cm, was found [*Popovnin, 2003*], while in 1994 an area with debris thickness reaching 280 cm was found there.

In 2010, the highest value of debris thickness of the superficial moraine was recorded to be in AMZ I. Extreme were the points with debris thickness 260 and 245 cm, located in the immediate proximity from the glacier edge. At the same time, debris thickness values of 35–40 cm were recorded in AMZ I. The average thickness of the debris cover was 100 cm.

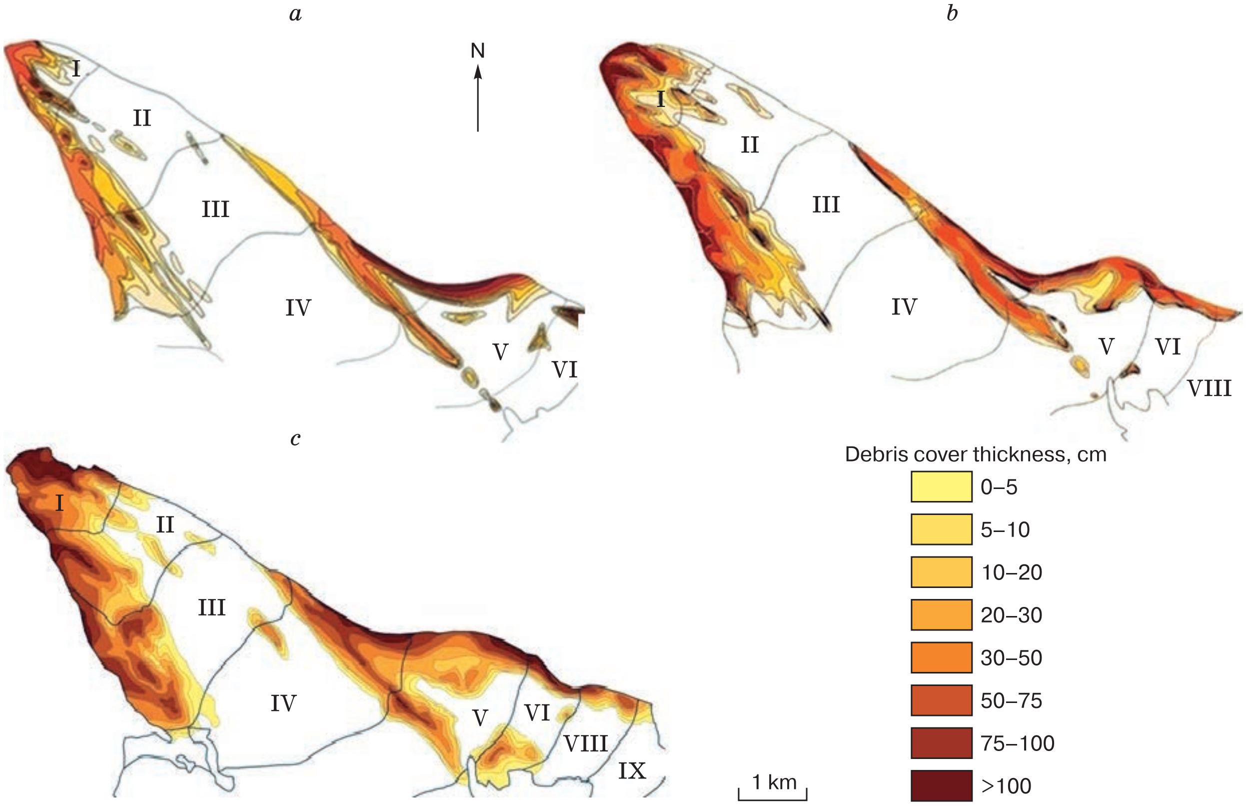


**Fig. 4. The debris cover thickness of the Djankuat Glacier by altitudinal-morphological zones (I–IX).**

*a* – 1983; *b* – 1994; *c* – 2010.

AMZ II of the glacier is characterized by lower values of *h* and by greater variety of the moraine relief manifestations, including moraine lines, a uniform debris cover, and thin newly formed moraine mantles. The main lithogenic matter in AMZ II is concentrated near the orographically left side of the glacier. The highest debris thickness value in 2010 was 119 cm. The lowest background values of *h* were 5–13 cm; they were recorded on the moraine mantles closer to the orographically right side of the glacier. On average, the moraine thickness in this zone was 51 cm.

The roof of the lithogenic matter of AMZ III forms rather homogeneous surface, in some places dissected by the melt-water channels, where the glacial ice is located under the lithogenic cover at the depth of at least 6–13 cm. The highest value of the debris thickness in this zone is 101 cm. The value of *h* rather uniformly and regularly decreases with the increasing distance from the orographically left side of the glacier. The average zonal debris thickness here (38 cm) is the lowest here – the lowest among all the AMZ of the glacier where there is debris cover.

The superficial moraine of AMZ IV is mainly located near the orographically right side of the glacier as a median moraine line, formed out of confluence of two ice flows (C and D in Fig. 5), and “a pocket” between this line and the glacier border. Currently its thickness does not exceed 79 cm, while the average zonal value of *h* = 51 cm.

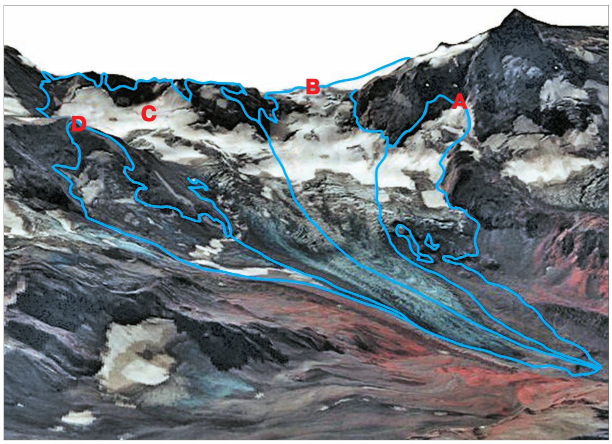


**Fig. 5. Ice flows composing the body of the Djankuat Glacier.**

A – from the northern slope of Djantugan Mountain; B – from the Djantugan firn plateau; C – from the upper circus under Gumachi Mountain; D – from the northern slope of Uya-tau Mountain.

The debris cover of AMZ V is associated with the foot of Uya-tau Mountain on the orographically right periphery of the glacier. The highest values of $h$ are associated here with the margin of the glacier body, perhaps due to the fact that, in addition to the rock slides coming from outside, the glacial flow, before rushing down, is forced against the steep side, leaving the main part of the debris material exactly there. The minimum value of $h$ among all the measurement points of the moraine survey of 2010 in this zone was 9 cm (the morainic mantle on the steep foot of the Uya-tau Mountain slope), while the maximum value was 73 cm (near the orographically right side of the glacier). The average zonal debris thickness was 40 cm.

In zone VI, the lithogenic matter is concentrated as a comparatively narrow strip, coinciding with very steep ice surface, hence its gravitational redistribution to the zone below in the nearest future is likely. In this case, it will come to the sector of the especially thick debris cover of AMZ V, thus increasing its thickness. In general, a rather thin morainic layer prevails in the territory of AMZ VI. Despite this, the value of $h$ becomes rather high in some places – 107 cm, thus ensuring the average zonal value of 42 cm.

In 2010, for the first time in the history of the morainic survey, the contours of the debris thickness entered the limits of AMZ VIII, where several measurements of $h$ were made. The debris material was also represented by a narrow strip, dividing flow D of the Djankuat Glacier and the Visyachiy Glacier. The debris thickness varied by the measurement points from 5 to 72 cm, on average equaling 40 cm in the zone.

Generally, it is to be noted regarding the glacier as a whole that in AMZ I–III the debris accumulation along the orographically left side of the glacier is ensured, in addition to direct rock falls from the valley slope, mainly by flow A (Fig. 5), which has significantly reduced recently. Back in 1970s, this branch accepted the flow of a small nameless glacier located above on the ridge of Djantugan Mountain; yet, now its hanging snout is separated from the lower circus of the Djankuat Glacier by a continuous belt of stripped bedrock. This leads to even greater intensification of the falls and slides from the surrounding rock slopes, which only recently got relieved of the glacier load and are therefore unstable.

Flow D, which, together with flow C, is the main supplier of the debris material for AMZ IV–VIII, flows from the steep slope of Uya-tau Mountain and is also significantly degrading, which results in excessive feeding of the mountain foot with colluvium. Besides, snow avalanches regularly move down from the slope of Uya-tau Mountain, carrying a large amount of rock and debris material. Sometimes they become catastrophic, like it was in April 1980 and in early May 1997, when the alluvial cone could be as high as 15 m. As winters are getting more abundant in snow and the winter temperatures are rising, which is has been observed in the Central Caucasus recently, the occurrence of avalanches from the slope of Uya-tau Mountain, including catastrophic ones, will be increasing.

Due to the above causes, one should expect fast intensification of debris accumulation in AMZ I–IV in the nearest future, and the thickness growth of the superficial moraine will be exponential.

## REPRESENTATIVENESS OF THE INVESTIGATION RESULTS FOR THE CENTRAL CAUCASUS

The Djankuat Glacier is one of the few glaciers, if not the only glacier in the world, where the debris thickness has been directly measured three times. The identity of the method applied and consistency of the staff who performed the works ensured due comparability of the results. It follows from comparison of the maps of debris thickness made in different time periods (Fig. 4) that over the recent 27 years there has not been any essential change in the mechanism of spatial distribution of the debris material. The major amount of the debris emerging in the process of melting tends to occur along the axes of linearly extended structures and the snout periphery, where the debris cover of the superficial moraine merges with the marginal ramparts. However, quantitatively, the mass of the lithogeenic mantle dragged by the glacier on its surface has significant increments (Tables 1, 2).

In zone I, the most intense increment in the debris thickness is observed, whereas the increment rate gradually goes down as the absolute height goes up. Thus, natural relocation of the debris material to the lower parts of the glacier occurs. Except the ending part of the glacier, certain proportionality can be seen in the regularities of the debris cover thickness increment (Fig. 6).

Based on the data shown in Table 2, one can speak about overall increment in the thickness of the superficial moraine on the glacier: nearly everywhere shifting of the modal values of the debris thickness to higher figures is observed. This process has been noted in all the altitudinal-morphological zones but it is especially noticeable in AMZ I, where the values of $h > 100$ cm account for 40 % of the measurements. In total on the glacier, in 1983 and in 1994, the largest areas of the zones (39 и 26 %, accordingly) were occupied by accumulations of the lithogenic matter of the lowest degree of thickness, 0–10 cm. By 2010, the largest amount of the debris (23 %) has thickness of 31–50 cm. This regularity is reflected in the increment of the average glacier debris thickness from the first survey to the last survey: in 1983, it was 28 cm, in 1994 – 39 cm, while in 2010 it was already 54 cm, i.e., nearly twice as much as at the beginning of the monitoring.

Table 1. **The average values of debris thickness in different altitudinal-orphologic zones of the Djankuat Glacier according to the moraine survey**

| AMZ zone | $h$, cm | | $\Delta h$, cm | $h$, cm | $\Delta h$, cm |
|---|---|---|---|---|---|
| | 1983 | 1994 | 1983–1994 | 2010 | 1983–2010 |
| I | 29 | 45 | +16 | 100 | +71 |
| II | 22 | 43 | +21 | 51 | +32 |
| III | 14 | 30 | +16 | 38 | +24 |
| IV | 34 | 47 | +13 | 51 | +17 |
| V | 31 | 32 | +1 | 40 | +9 |
| VI | 37 | 38 | +1 | 42 | +5 |

Table 2. **Distribution of the debris material thickness**

| AMZ number | Year | Debris cover thickness $h$, cm | | | | | | | Average moraine thickness in AMZ, cm |
|---|---|---|---|---|---|---|---|---|---|
| | | 0–10 | 11–20 | 21–30 | 31–50 | 51–75 | 76–100 | >100 | |
| I | 1983 | 32.4 | 14.7 | 10.8 | 22.5 | 15.7 | 2.9 | 1.0 | 29 |
| | 1994 | 26.5 | 10.3 | 12.2 | 16.4 | 12.2 | 6.1 | 16.3 | 45 |
| | 2010 | – | 6.7 | – | 16.7 | 20.0 | 16.6 | 40.0 | 100 |
| II | 1983 | 34.4 | 22.9 | 13.1 | 25.5 | 4.1 | – | – | 22 |
| | 1994 | 25.4 | 11.0 | 7.3 | 18.2 | 20.0 | 12.7 | 5.4 | 43 |
| | 2010 | 7.0 | 9.3 | 11.6 | 18.6 | 32.6 | 13.9 | 7.0 | 51 |
| III | 1983 | 53.7 | 18.6 | 19.0 | 6.6 | 1.7 | 0.4 | – | 14 |
| | 1994 | 28.3 | 22.4 | 16.4 | 13.4 | 9.0 | 6.0 | 4.5 | 30 |
| | 2010 | 16.3 | 18.6 | 9.4 | 27.9 | 16.3 | 7.0 | 4.6 | 38 |
| IV | 1983 | 27.6 | 13.4 | 14.9 | 24.6 | 4.5 | 9.0 | 6.0 | 34 |
| | 1994 | 13.5 | 10.8 | 10.8 | 24.3 | 27.0 | 8.2 | 5.4 | 47 |
| | 2010 | – | 15.7 | 19.8 | 19.8 | 32.3 | 7.3 | 4.1 | 51 |
| V | 1983 | 38.5 | 16.3 | 13.3 | 10.4 | 4.5 | 8.9 | 8.1 | 31 |
| | 1994 | 33.2 | 16.6 | 10.4 | 16.7 | 12.5 | 6.4 | 4.2 | 32 |
| | 2010 | 10.5 | 18.0 | 28.5 | 26.0 | 3.5 | 8.5 | 5.1 | 40 |
| VI | 1983 | 15.4 | 23.1 | 7.7 | 19.2 | 23.1 | 11.5 | – | 37 |
| | 1994 | 22.2 | 11.2 | 11.1 | 22.2 | 22.2 | 11.1 | – | 38 |
| | 2010 | – | – | 20.0 | 60.0 | 20.0 | – | – | 42 |
| Glacier in total | 1983 | 39.0 | 17.7 | 14.8 | 16.3 | 5.6 | 4.0 | 2.6 | 28 |
| | 1994 | 25.9 | 14.6 | 11.7 | 17.7 | 15.4 | 7.9 | 6.8 | 39 |
| | 2010 | 7.9 | 13.7 | 14.3 | 23.3 | 20.1 | 10.6 | 10.6 | 54 |

Thus, all the studies conducted indicate evident enlargement of the debris cover on the snout of the Djankuat Glacier. It is important that the results obtained could be referred to the other glaciers of Central Caucasus, as well. Representativeness of the Djankuat Glacier for the Central Caucasus for morphological and mass-balance characteristics was assumed before the beginning of the direct glacial monitoring [*Djakuat Glacier, 1978*], and now there are no grounds to question it. What is the degree of its representativeness in relation to accumulation of the debris material on the glacier surface?

To answer this question, data on the glaciers' areas and on the areas of the debris cover on them have been studied, available in the *Catalogue of Glaciers of the USSR* [*1967*]. Among the debris-covered glaciers,

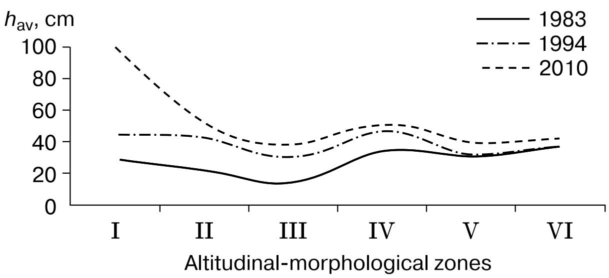


**Fig. 6. Changes in the average values of the debris cover by altitudinal-morphological zones ($h_{av}$) between moraine surveys of different years.**

AMZ: I – 2,700–2,770 m; II – 2,770–2,850 m; III – 2,850–2,940 m; IV – 2,940–3,020 m; V – 3,020–3,120 m; VI – 3,120–3,200 m.

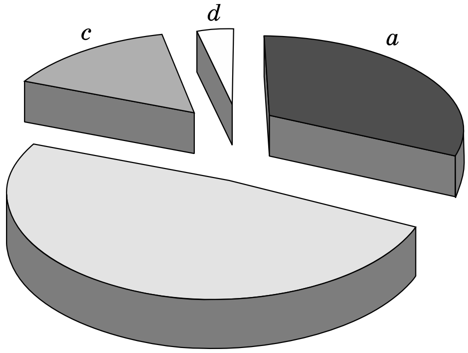


**Fig. 7. The total area of the debris-covered glaciers (*S*) of different morphological types in the Central Caucasus.**

*a* – $S$ = 119.6 km$^2$, complex valley glaciers; *b* – $S$ = 179.9 km$^2$, valley glaciers; *c* – $S$ = 59.4 km$^2$, corrie-valley glaciers; *d* – $S$ = 13.1 km$^2$, corrie glaciers.

simple valley glaciers are most common in the Central Caucasus, including the Djankuat Glacier, – 51 glaciers with the total area of about 180 km$^2$, while the complex valley glaciers account for about 120 km$^2$, and the corrie-valley glaciers cover about 59 km$^2$ (Fig. 7). Analysis of the average areas of the debris-covered glaciers belonging to different morphological types and of the areas of the debris cover on them also indicates representativeness of the Djankuat Glacier (Fig. 8). It area is 2.7 km$^2$, while the area of the superficial moraine on it is a little greater than 0.3 km$^2$ (according to the data of 2010), while for the valley and corrie-valley glaciers, making up the major mass of glaciation of the Central Caucasus, the average area is 3.6 and 1.6 km$^2$, with the average moraine area being 0.3 and 0.1 km$^2$, accordingly.

The typical nature of the Djankuat Glacier is evident when considering the geographical component of distribution of glaciers screened by superficial moraine, averaged for the local river basins (Fig. 9). Thus, the average area of the debris-covered glacier in the basin of the Malka and Baksan Rivers is 3.6 km$^2$ with the average moraine area on one glacier being 0.23 km$^2$ (the debris-covered glaciers constitute 26 % of the basin area); in the basin of the Cherek River the average area of the debris-covered glacier is 3.7 km$^2$, with the average moraine area being 0.5 km$^2$ (25 % glaciers of the basin are covered with debris); in the basin of the Chegem River, these values are 3.0 and 0.2 km$^2$ (23 %), accordingly, etc. In the Central Caucasus, the average area of a debris-covered glacier is 2.4 км$^2$, while the moraine covers 0.3 km$^2$ on it [*Catalogue…, 1967*]. Such representativeness of the Djankuat Glacier in view of development of superficial moraine on it allows us to generalize the results obtained on it regarding the regularities of the impact of the debris cover on the evolution of modern alpine glaciation to assess the behaviors of the other glaciers in this region.

Extreme scarcity of the data on direct measurements of sub-debris ablation on some glaciers of the Caucasus does not allow reliable evaluation of the degree of generalization relating to the hydrological effect of a superficial moraine. The prevalence of the debris-covered areas on the Djankuat Glacier with the debris cover thickness exceeding 5–7 cm clearly suggests that the screening action of the debris cover on sub-debris ablation and the glacier runoff prevails over the melting effect occurring under a thin layer of debris, with the background reduction of the general glacier ablation varying from year to year at the level of 20 %. The only in the Caucasus similar assessments of moraine impact on the glacier runoff have been made for the Zopkhito Glacier in Georgia [*Lambrecht*

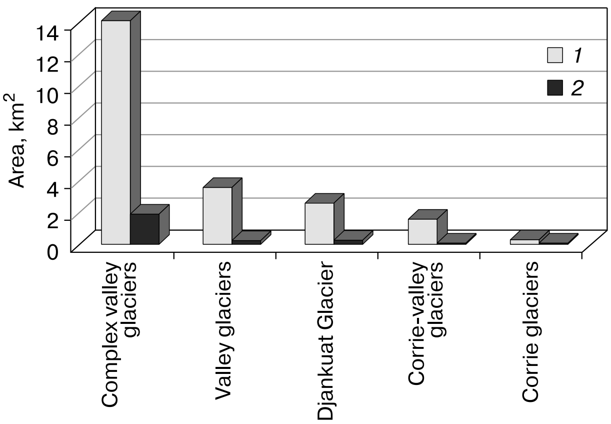


**Fig. 8. The average areas of the debris-covered glaciers (*1*) of different morphological types and superficial moraines on them (*2*) in the Central Caucasus.**

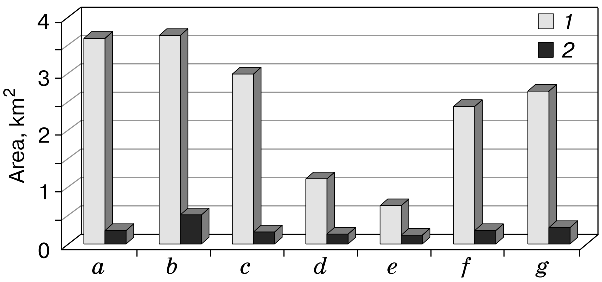


**Fig. 9. The average areas of the debris-covered glaciers (*1*) and superficial moraines on them (*2*) in different river basins of the Central Caucasus.**

*a*–*e* – basins of the rivers: *a* – Malka, *b* – Cherek, *c* – Chegem, *d* – Kuban, *e* – right tributaries of Sundja River; *f* – Northern Caucasus; *g* – Djankaut.

*et al., 2011*], where the values of melting reduction practically complied with those obtained for the Djankuat Glacier, although differences were noted between adjacent macro-slopes of the Caucasus in terms of expansion of the debris cover of the superficial moraine (the debris increment on the Georgian glacier recorded by satellite survey was reported to be slower).

## CONCLUSIONS

The results of monitoring the spatial attitude of the debris cover on the surface of the Djankuat Glacier indicate clear expansion of the area, volume, and mass of the debris material. For the first time in the world practice, three repeated surveys of the thickness of superficial moraine, covering the entire area of the debris-covered part of the glacier, were undertaken. The maps of its thickness, based on the direct measurement results, definitely demonstrate expansion of the debris cover over the previous 27 years both for the area (from 0.252 $km^2$ in 1983 to 0.344 $km^2$ in 2010) and for the thickness (increment from 10 cm in the upper part of the snout to 70 cm in its pre-frontal part), with the major spatial regularities of the expansion preserved. In 2010, the superficial moraine covered about 61 % of the snout area. It has been found that the volume of the superficial moraine increased in 1983–2010 by 141 % (from 70,330 to 169,590 $m^3$). It has been demonstrated that reduction or screening of ablation with a debris cover takes place on 93 % of the debris-covered part of the snout, and only on the remaining 7 % of the territory the debris cover contributes to intensification of sub-debris thawing. Every year, the glacier runoff under-receives about 20 % of its volume due to the growth of a superficial moraine on the glacier. Such vast expansion of the lithogenic cover on the day surface undoubtedly refers the processes of the growth of a superficial moraine to the number of the most important factors which predetermine further evolution of the Djankuat Glacier in terms of the balance of its mass and of its geometry.

In addition to the previously demonstrated glaciological (primarily mass-balance and morphometric) representativeness of the Djankuat Glacier for the Central Caucasus, now the authors have all reasons to consider it quite representative also in view of the debris cover formed on it. The typical nature of the degree of debris coverage of the basic glacier has been proven at the scale of the entire region's glaciation. Thus, the qualitative regularities of the modern mechanism of the debris accumulation process and the role of this process in external mass and energy exchange of glaciers may be spread to the other glacial objects of the northern macro-slope of Central Caucasus and even, to a certain degree, to the glaciers of Georgia.

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