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SNOW COVER AND GLACIERS

THE POLYTHERMAL STRUCTURE OF CENTRAL TUYUKSU GLACIER

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The article presents the results of field research carried out on the Central Tuyuksu glacier in 2013 by the scientists from the Institute of Geography of the RAS and from the Institute of Geography of Kazakhstan. The position of the glacier's contemporary boundaries has been defined using satellite imagery. Based on the obtained data on the terrestrial radio-echo sounding and DGPS-survey, the thickness of the ice has been determined. The ice thickness, the surface topography and the bed of the glacier have been mapped. The results of these studies confirm the previously made assumptions about the polythermal structure of the Tuyuksu glacier. Warm water-containing ice has been determined to occupy more than 40 % of the total volume of the glacier.

Tien Shan, Tuyuksu glacier, radio-echo sounding, DGPS-survey, polythermal glacier

INTRODUCTION

The central Tuyuksu valley glacier (Tuyuksu) is situated on the northern slope of the Ile Alatau mountain ridge (Tien Shan) in the upper reaches of the Malaya Almatinka River (Kishi Almaty) (Fig. 1). For its morphological characteristics, the Tuyuksu glacier is rather typical of the glacial system of the western slope of this ridge. It has northern exposure and has the size, morphometric, hypsometric and other characteristics which are average for this region. The major part of its surface is accessible for glaciological studies, which started in 1902 and continue now. After the International Geophysical Year (IGY, 1957–1959), the observations began to be made on an annual basis. The investigations involved different aspects of the glacier's existence: its regime and structure [*Makarevich et al., 1969; Solomina, 1997; Vilesov and Uvarov, 2001*], the alimentation conditions, ablation, and the mass balance [*Krenke and Bochin, 1984; Hagg et al., 2004; Eder et al., 2005; Makarevich and Kasatkin, 2011*], the glacier runoff [*Makarevich, 1989; Piven, 2013*], the temperature regime of the glacier mass, etc. In 1965–1974; K.G. Makarevich headed the investigations of the mountainous-glacial basin of the Tuyuksu glacier under the program of the International Hydrological Decade (IHD). After the decade was completed, regular observations over the glacier's mass balance and the trends in the glacier boundaries' movement were continued, and now studies are being conducted on the Tuyuksu glacier and in its basin under the International Hydrological Program (IHP) and in accordance with the glaciological monitoring plan. The Tuyuksu glacier is one of the last four glaciers preserved in the post-Soviet territory (two glaciers in the Caucasus, one on the Altay mountains, and one in Kazakhstan), on which a series of mass balance observations has been held over the recent decades. The field studies data collected over five year periods are regularly published in Fluctuations of Glaciers. In parallel, since 1988 the observation materials relating to the glacier's mass balance have been published in the Glacier Mass Balance Bulletin. Both journals are published by the World Glacier Monitoring Service (WGMS) (Zurich, Switzerland). At the time of this writing, the bibliography relating to the Tuyuksu glacier contains more than 400 titles.

Due to the above investigations and a long series of observations, the Tuyuksu glacier is one of the best studied glaciers of Asia. However, this does not mean that it has stopped being attractive as an object of glaciological studies. On the one hand, continuing the existing series of observations allows the scientists to use it as a natural indicator in solving the topical problem of determining modern trends of the climate change. On the other hand, the accumulated arrays of various data regarding the glacier's structure and regime provide an opportunity for honing the modern methods and technologies of glaciological investigations. For this purpose, in August 2013, joint works were conducted don the Tuyuksu glacier by the researchers of the Institute of Geography, RAS, and of the Institute of Geography, Academy of Sci-

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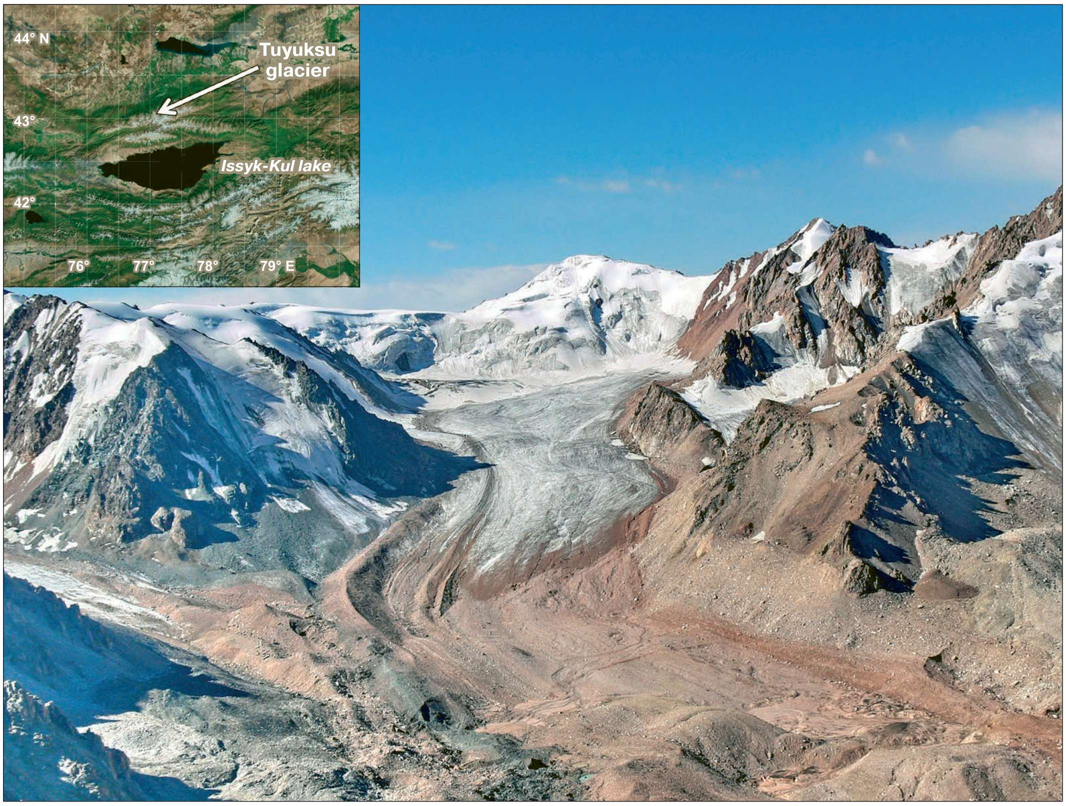


Fig. 1. The geographical position of the Central Tuyuksu glacier.
A photo by V. Vinokhodov (10.08.2007). The inset shows a fragment from Google Earth.

ences of Kazakhstan, which provided new information on the glacier's current condition and structure presented in this paper.

THE OBJECTIVES AND METHODS OF INVESTIGATIONS

For many years, scientists have taken numerous efforts to determine the thickness of the Tuyuksu glacier using different methods. For this purpose, they used both mathematical and geophysical methods. The first data on the glacier thickness were obtained during the International Geophysical Year in 1957 as a result of seismic studies [*Berzon et al., 1959*]. In 1960–1970, electric sounding was conducted in a number of positions, as well as boring using the pyric and thermoelectrical methods [*Borovinsky, 1963*]. In 1981, 1982 and 1985, radio-echo sounding works were conducted on the glacier in the decimeter and decameter ranges at the frequencies of 620, 8, and 720 MHz on several longitudinal and transverse profiles [*Bobrova et al., 1988*]. All these methods provided quite satisfactory and comparable results. Mechanical boring of ice on one of the profiles reached the glacier bed at the depth of 52.6 m, which agreed with the results of the geophysical measurements [*Krenke and Bochin, 1984*].

The subsequent years were not favorable for the life of the glacier [*Vilesov and Uvarov, 2001*]. In the whole world scientists recorded contraction of glaciation, which got accelerated in the recent decade. Since 1985, the snout of the Tuyuksu glacier has retreated by the distance of about 600 m [*Makarevich and Kasatkin, 2011*]. The location of the above-mentioned borehole turned out to be beyond the glacier limits on the glacier bed surface now free from ice. Accordingly, the height of the remaining glacier surface also changed, and the glacier volume contracted. Therefore, the main objective of the field works of 2013 was to obtain data on the current glacier thickness by conducting ground radio-echo sounding. It was also supposed to obtain new information about the structure of the glacier.

The Tuyuksu glacier is located in the area of negative mean annual air temperatures, and the temperature of the active ice layer (15–20 m from its surface) does not reach 0 °C even in its end part located at the altitude of 3500 m asl [*Krenke and Bochin, 1984*]. Zero temperatures were recorded only in the uppermost ice layer not more than 1 m thick in the period of intense summer thawing. At the same time, the results of temperature measurements in the boreholes located in different altitudinal zones of the glacier obtained in 1958 showed that the ice temperature increased with the ice depth. In one of the boreholes located at the altitude of 3800 m the zero value was recorded, which remained constant at the depth of 20 m for a year [*Makarevich et al., 1969*]. These data testified to the non-homogeneous temperature regime of the ice mass and to its possible manifestations in the glacier structure.

Assumptions regarding the presence of the second layer were made later when discussing the results of ground radio-echo sounding with the RLS-620 equipment in 1981. However, then the presence of a thick layer of a subglacial moraine based on a bed rock was meant. No signs of the glacier's the polythermal structure in the obtained radargrams of the field survey were found [*Bobrova et al., 1985*].

In the same year of 1981, on one of the transverse profiles 50 m above the borehole of 1958, A.V. Epov conducted an experiment to determine the spread rate of radio waves in ice by the method of oblique radio-echo sounding using the RLS-620 radar. The obtained value of the radio wave velocity at the depths below 40–60 m was 0.135 m/ns and was essentially different from the radio wave velocity in the above layers (172 m/ns), which corresponds to "warm" ice with moisture content of about 7 % [*Epov, 1984*]. However, the assumption made by the author regarding the presence of a layer of watered ice at these depths was found to be incorrect [*Bobrova et al., 1985*], and regular sub-surface reflections on the major part of the other profiles were interpreted as the border between ice and the moraine.

In our case, the technical characteristics of the VIRL-6 radar [*Macheret et al., 2006*] and the experience of its application in investigating the polythermal glaciers of Arctic [*Martín-Español et al., 2013*] and Tien Shan [*Petrakov et al., 2014*] allowed us to anticipate that these signs would be revealed. Of additional interest was evaluation of the possibility of using the DGPS-survey to develop a digital model of the glacier surface and its use in performing the subsequent balance observations.

The field investigations on the Tuyuksu glacier were conducted in late August of 2013, while direct measurements of the glacier thickness and of the height of its surface were made during the last three days – from August 27 to August 29. The time of measurement was as close as possible to the end of the ablation period of that year. Therefore, the major part of the glacier surface at the time of radio-echo sounding and of the DGPS survey was already free from the seasonal snow cover. An exception was constituted by the upper parts in the area of snow accumulation and by the slopes of the rear ridge, which restricted the glacier from the south. Survey of the steepest parts and zones of snow-covered crevasses was not conducted for safety reasons.

To measure the glacier thickness, we used a VIRL-6 radar with central frequency of 20 MHz and digital registration of the radar and GPS data with an interval of 0.2–1.0 s (the pulse rate was 20 kHz; the output power 9.6 kW; the pulse duration was 0.5 ns; the antenna type was a resistor-loaded dipole with input resistance of 600 Ohm and 5.6 m long) [*Vasilenko et al., 2003*]. The geodetic survey of the glacier surface was performed with a two-frequency differential GPS-receiver Topcon GB-500 in a kinematic mode with a 10 m interval. The error of the coordinate measurements in the plan view and by height did not exceed 10 and 15 mm, accordingly [*Topcon GB-500 Manual, 2007*]. Radio-echo profiling was conducted by a group of workers who went by foot with the average velocity of 2 km/hr. The measurement profiles included the stakes used annually for observations over the glacier mass balance by a traditional glaciological method, the coordinates of which were specially recorded.

RESULTS AND DISCUSSION

Resulting from the measurements made, two data arrays were obtained: records of a reflected radio signal and position data on the glacier surface for the profiles covered in a mapping projection WGS84/UTM зона 43N. Over three days of works, more than 25 km of transverse and longitudinal profiles were made, covering the maximum accessible area of the glacier. In addition to the glacier surface, an additional profile was made on the crest of the right lateral moraine to evaluate the possibility of determining the presence of the contained buried ice and its amount. The positions of the modern borders of the glacier and the survey routes are shown on a Google Earth satellite image (Fig. 2). Due to the high-quality geometric resolution of the image (sensor – GeoEye, resolution better than 1 m), a lucky combination of the time of the record (06.09.2012) and of the weather conditions, the specific features of the morphology of the glacier surface and the borders of the ice formation zones are distinct there.

It is to be noted that the investigation results and the quantitative estimates discussed in this paper are related only to that part of the glacier which was covered by direct measurements. It can be seen on the satellite image (Fig. 2) that the uppermost profiles of the survey are in close proximity with the borderline of perennial firns, which look like a dark edge coming from under the seasonal snow at an altitude of about 3800 m. Thus, the part of the glacier covered by the survey included the ablation area and the glacial alimentation zone. Extrapolation of the data obtained on steep and crevasses-cut slopes in the accumulation area is a special task, and its solution was not planned at the given stage of the works.

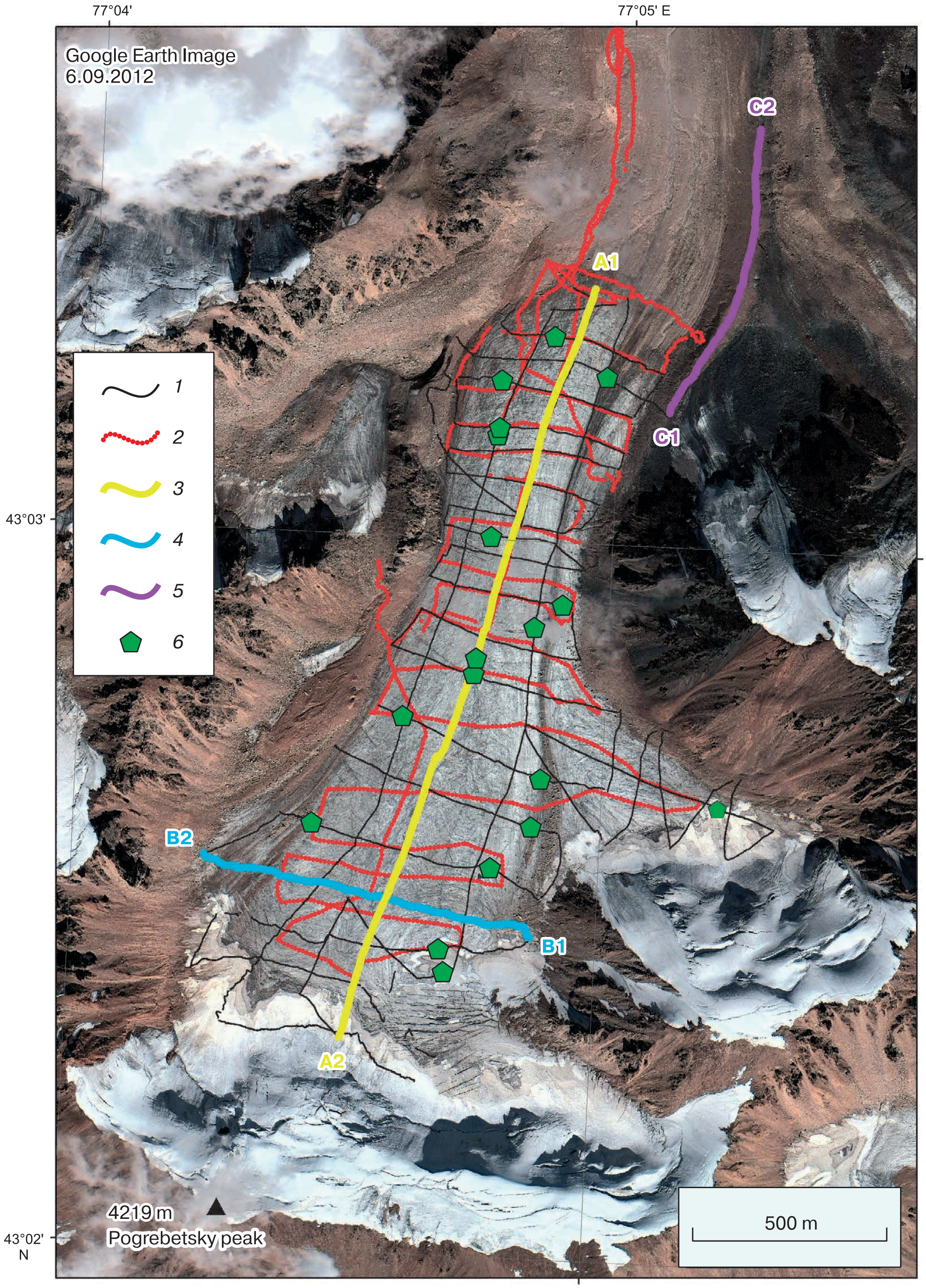


Fig. 2. Routes of instrumental measurements of the Tuyuksu glacier (as substrate, a satellite image as of 06.09.2012 from Google Earth was used).

1 – radio-echo sounding; *2* – DGPS-survey; *3* – longitudinal radio-echo profile A1–A2; *4* – transverse radio-echo profile B1–B2; *5* – radio-echo profile on the ridge of the right moraine C1–C2; *6* – positions of ice wells persisting from year to year.

The positions obtained by the DGPS survey were used for developing a digital model of the glacier surface. Interpretation was conducted in the software medium ArcGIS 10.0 with a Topo to Raster module. The error of the glacier surface height interpolation between the profiles did not exceed ±0.5 m.

To interpret the data of radio-echo sounding, the RadexPro 3.1. [*Kulnitsky et al., 2001*] software package was used. In calculating the ice thickness for warm and cold ice, the mean propagation velocity of radio waves was taken, equal to 0.168 m/ns [*Macheret et al., 2006*; *Glazovsky and Macheret, 2014*]. Evaluation of the mean-square deviation of the data on ice thickness performed by the intersection points of the profiles showed good agreement (±2 m).

Identifiable reflections of the signal from the glacier bed and from the intermediate horizon were obtained practically for all the profiles (Fig. 3). The presence of an internal reflecting horizon (IRH) is an indicator of polythermal glaciers, to which the Central Tuyuksu glacier may be reliably referred. The possibility of identifying the borderline between warm and cold ice allowed us to make the maps of their thickness distribution within the glacier surface covered by the survey (Fig. 4). Radio-echo sounding of the moraine separating the glaciers Central Tuyuksu and Igly Tuyksu revealed the presence of buried ice up to (40 ± 2) m thick (Fig. 3, *c*).

The digital model of the glacier surface and the results of radio-echo sounding were used to make a map of the glacier bed (Fig. 5) and to evaluate its volume (Table 1). The volume of ice was calculated using the approximation Topo to Raster ANUDEM [*Hutchinson, 1989*] in the ArcGIS software program, which considered the hydrological correctness of the glacier bed relief. The methodology of determining the error in evaluating the volume of the glacier using the radio-echo sounding data was described in [*Martín-Español et al., 2013*], and its value is 3.6 %.

It follows from the glacier bed map that this is a surface uniformly with a small gradient (about 8–10°) rising from the lower border of the glacier snout to its alimentation border. At the same time, it reflects the asymmetry of the glacier's alimentation area and the resulting differences in the intensity of the erosion activity of ice fluxes – the trunk of the glacier and its right branch. A hollow on the glacier bottom along its right edge seems to result from the higher degree of activity of the right ice flux, which is steeper before the confluence. The presence of a rock bar in the area of the crevasses in the narrowest place of the main ice flux may be inferred from the change in the pattern of the hypsographic curves at the level of 3540 m.

The glacier has maximum thickness in the area of the alimentation border (Fig. 4, *a*). Here it reaches 103 m. As the glacier moves downward, the ice thickness gradually reduces to several meters at the snout. Two more local maxima of the ice thickness up to 90 m were observed on the right branch of the glacier. The volume of ice within the area covered by the measurements (1.61 km^2) was (0.078 ± 0.003) km^3.

The maps of the distribution of thicknesses of the warm and cold ice over the area of the Tuyuksu glacier are more various, which reflects complex interaction between the cooling effect of the atmosphere and water in the glacier body (Fig. 4, *b*, *c*). Yet, regularities in its distribution may be identified with a certain degree of assumption. Thus, the thickness of the cold ice, which is the external mantle of the glacier, is rather uniformly distributed along the main ice flux. In the direction from the snout to the alimentation area, its value varies in the range of 25–45 m, slightly rising. Certain reduction of the thickness of the cold ice is observed in the rock bar area, where the surface torn by deep crevasses seems to contribute to that. Greater values of the thicknesses are shifted to the right side, where they exceed 65 m. This asymmetry is likely to be caused by the general northern exposure of the glacier and by the screening effect of the tall mountain framing of the right side, ensuring a longer time of the cooling of the glacier surface in the first half of the day. This also overlaps the increase in the duration of the cold period of the year as the absolute height of the glacier surface grows and contributes to penetration of a cold wave into the depth of the glacier.

Fig. 6 demonstrates the thickness and mutual position of the layers of cold and warm ice on the longitudinal A1–A2 and transverse B1–B2 profiles of the radio-echo sounding (their positions on the glacier are shown in Fig. 2). It follows from Fig. 6 that the lower borderline of the cold ice coincides with the borderline of the glacier snout. Over several hundred meters up the glacier, the cold ice has direct contact with the glacier bed, and only after that the signs of the warm ice and of its reflection from its separation from the cold ice appear. The upper borderline of the cold mantle ends at the altitude of 3800 m. Its area is 1.41 km^2, in which the volume of the cold ice contained is equal to (0.044 ± 0.002) km^3.

Wedging into the space between the cold ice and the glacier bed, the layer of the warm ice becomes thicker up the glacier, reaching maximum values in the area of accumulation – about 100 m. Here it reaches the glacier surface beyond the upper borderline of the spread of the cold ice and goes into the zone of near-surface crevasses and of the rising walls of the rear part. We can assume, looking at the pattern of the contours, that this lasts not long; however, we were unable to determine the position of the upper borderline of the warm ice for work safety reasons.

The lower part of the ice accumulation zone is the main cause of the origin of the warm ice in the

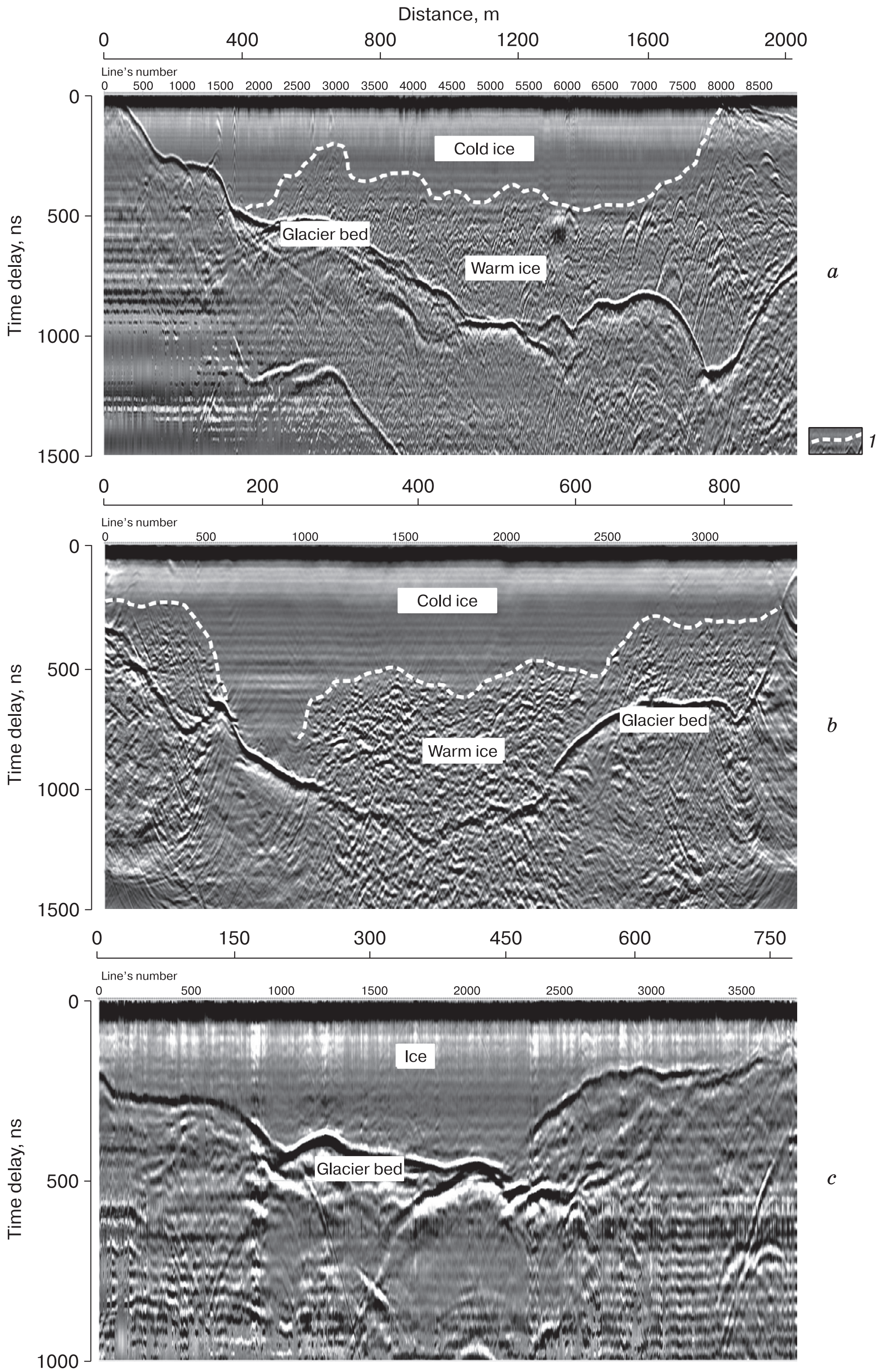
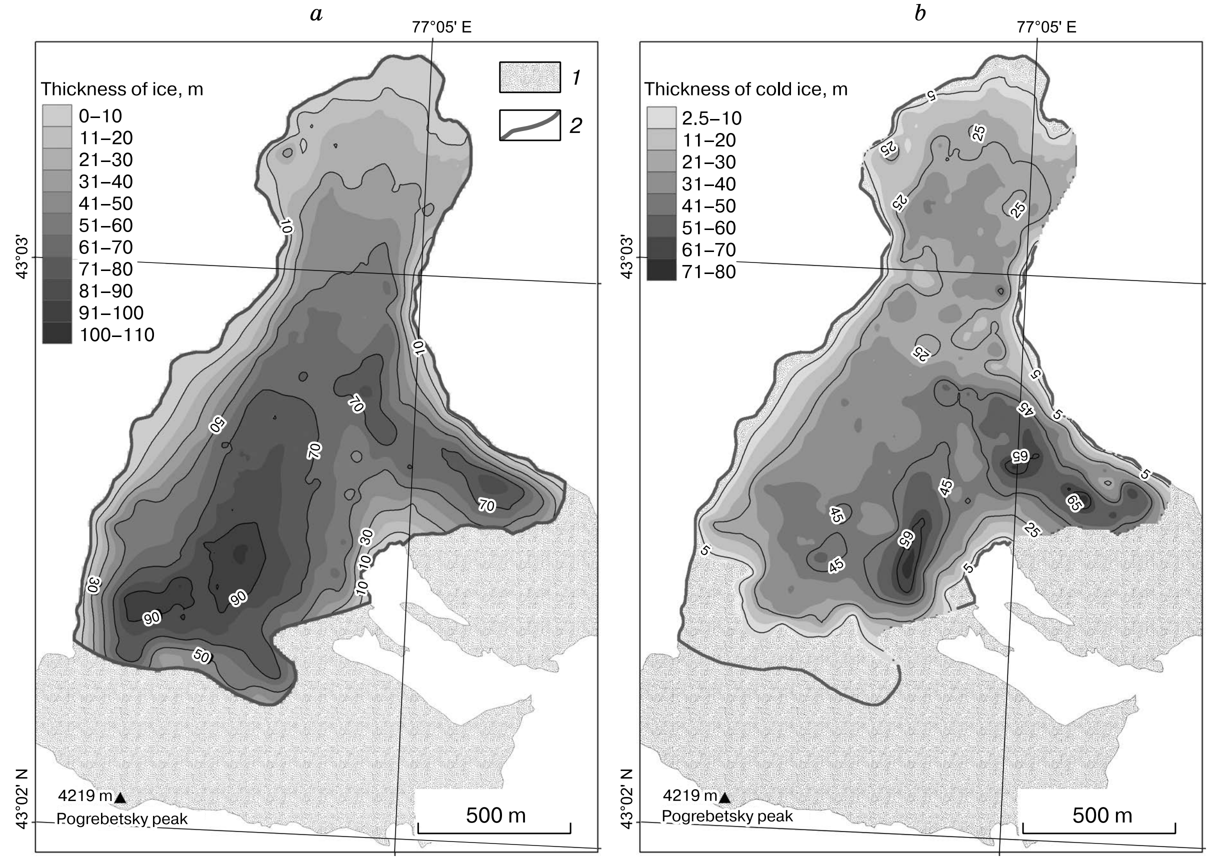


Fig. 3. Examples of radargrams obtained from the profiles of the Tuyuksu glacier:

a – longitudinal A1–A2; *b* – transverse B1–B2; *c* – on the crest of the right moraine C1–C2. *1* – the borderline between warm and cold ice. The upper scale is the distance covered from the beginning of the route, m.



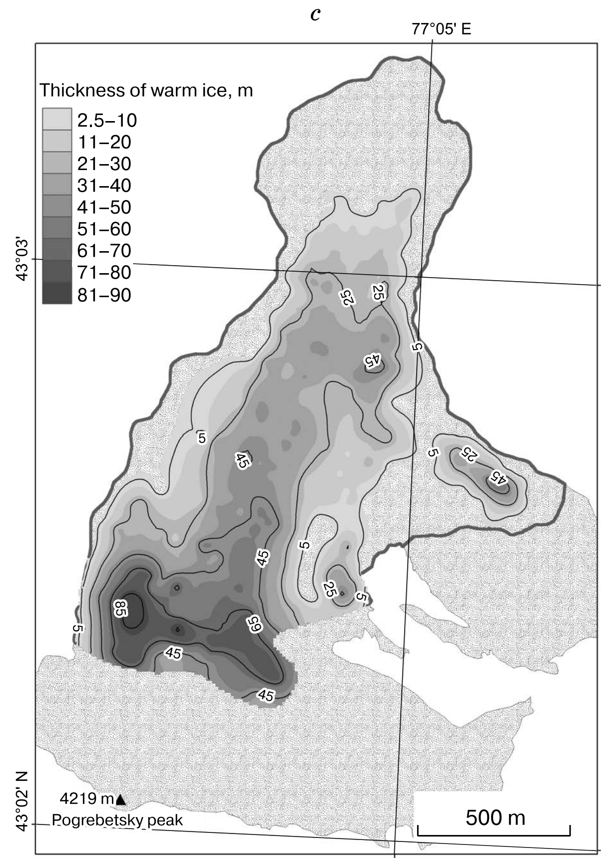


Fig. 4. Maps of ice thickness distribution:

a – total ice thickness; *b* – thickness of cold ice; *c* – thickness of warm ice. *1* – absence of data on ice thickness; *2* – borderline of glacier surface covered by survey.

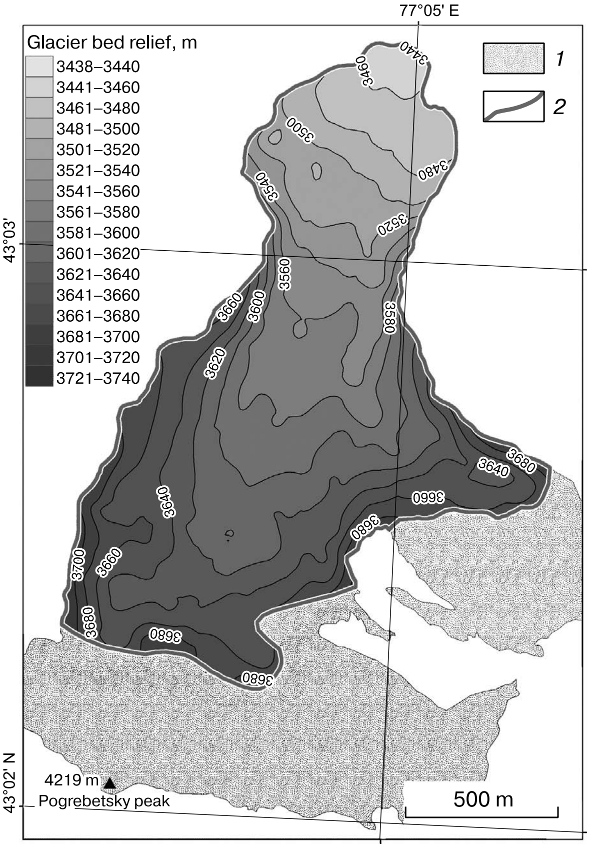


Fig. 5. Relief map of the Tuyuksu glacier bed.

1 – absence of data on ice thickness; *2* – the borderline of the glacier surface covered by survey.

glacier body. Located on the bottom of a large cirque, it is almost a horizontal surface, which contributes to the accumulation of thawed water in certain areas and to the formation of "snow bogs". Based on the previous studies, it was concluded that a sharp increase in the ice temperature observed in the accumulation area resulted from the impact of the firn mass, the thickness of which there exceeds 3 m, and the impact of thawed water in this period. Penetrating from the glacier surface into deeper layers of snow and firn, thawed waters get cooled to the freezing point, exuding heat, which contributes to destruction of the winter wave of cold and to heating of these layers to the zero temperature [*Krenke and Bochin, 1984*].

Table 1. **Thickness and volume of the glacier according to radio-echo sounding**

Object of study	Area, km^2	Ice thickness, m		Ice volume, km^3
		max	mean	
Glacier surface covered by survey	1.61 ± 0.06	103 ± 2	47 ± 2	0.078 ± 0.003
Cold ice	1.41 ± 0.05	74 ± 2	27 ± 2	0.044 ± 0.002
Warm ice	1.12 ± 0.04	96 ± 2	20 ± 2	0.034 ± 0.001
Right moraine	–	40 ± 2	24 ± 2	–

A developed drainage network, accelerating the process of heat transfer to lower horizons, exists practically on the entire surface of the glacier. Surface waters are captured by crevasses, the number of which is especially high above the rock bar, and form an internal drainage network. Many surface streams end in ice wells, the positions of which are preserved during several years (Fig. 2, *character 6*).

Distribution of warm ice over the glacier surface repeats the specific structure of the glacier bed, as it fills the bed, mostly due to the force of gravity. However, in certain places its distribution should be affected by the structure of the drainage network, caused by the relief of the glacier surface or inhomogeneity of the glacier mass. The drainage network by definition can not only account for the transfer but also for the drain of moisture and "drying" of certain spots, contributing to their freezing. It is probable that penetration of cold ice to the bed surface observed on the transverse profile B1–B2 (Fig. 6, *b*) has a similar cause.

To evaluate the change in the height of the glacier surface from the moment of the beginning of regular studies, reconstruction of its position was per-

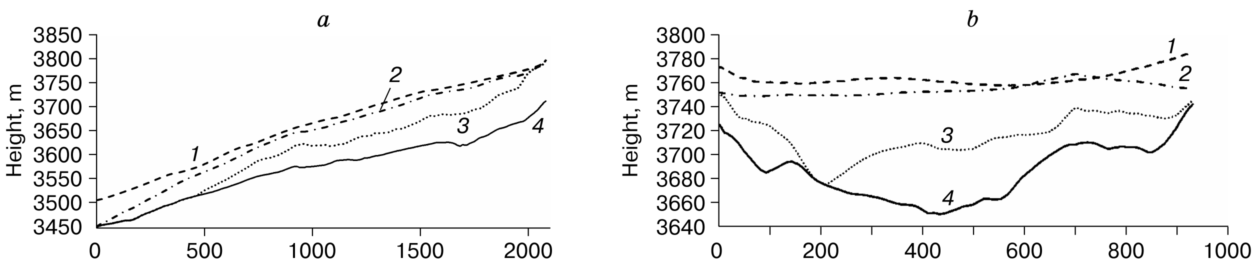


Fig. 6. Changes in the position height of the Tuyuksu glacier, the borderlines between warm and cold ice and the glacier bed surface on longitudinal A1–A2 (*a*) and transverse B1–B2 (*b*) radio-echo sounding profiles:

1 – the glacier surface in 1958; *2* – the glacier surface in 2013; *3* – the position of the internal reflecting horizon in 2013; *4* – the glacier bed.

formed using a map of 1958 [*Gletschergebiet Tujuksu, 1961*], which is shown by curve *1* on the longitudinal and transverse profiles of the radio-echo sounding (Fig. 6). At the beginning, the map was made on the scale of 1:10 000 in the local system of coordinates initiated from one of the old buildings of Almaty. Later the map was transformed to have the same system of coordinates which was used in conducting the DGPS survey, UTM WGS84 [*Hagg et al., 2004*]. Comparison of the position of the glacier in 1958 with the current position indicates that the maximum depression of the surface (about 50 m) is observed in the area of the snout. In the upward direction, the difference gets reduced to 10–20 m, remaining nearly constant for a long time, and, finally, these surfaces practically coincide in the area of the alimentation border. In some places, the difference is several meters, which is commensurable with the reconstruction error. Thus, despite the retreat of the glacier snout over the entire period of instrumental observations, the glacier surface height in the area of alimentation and, respectively, the ice thickness remained practically the same.

The most recent estimate of the volume of the Tuyuksu glacier measured from the end of the glacier to the height of 3800 m was given by [*Makarevich and Kasatkin, 2011*]. This study provides a figure of 0.095 km^3. The upper border of our measurements practically coincides with this contour line. Considering the fact that over the recent years the height of the glacier surface in the accumulation area has changed little and comparing this value with that we obtained (0.078 ± 0.003) km^3, a conclusion may be made that over 7 years the glacier has lost about (0.017 ± 0.001) km^3 of its volume.

CONCLUSIONS

The results obtained indicate that the Central Tuyuksu glacier has a polythermal structure. Inside the external mantle consisting of cold ice, there is warm moisture-containing ice, which occupies more than 40 % of the entire volume of the glacier.

The lower borderline of the cold ice coincides with the borderline of the glacier snout, and over several hundred meters up the glacier, the cold ice has direct contact with the glacier bed. The layer of warm ice wedges into the space between the cold ice and the glacier bed, its thickness increases upwards to reach maximum values in the area of ice accumulation (about 100 m). Here, beyond the limits of the upper borderline of the cold glacier spread located at the altitude of about 3800 m, it enters the glacier surface and goes into the zone of near-slope crevasses of the rear part of the glacier. The lower part of the ice accumulation is the main source of warm ice on the glacier body.

Currently the Central Tuyuksy glacier is continuing to contract. The front line is retreating over the entire period of instrumental monitoring, which started in 1956. Comparison of the height of the glacier's surface measured in 1958 with that of today indicates that the maximum reduction (about 50 m) is in the area of the glacier's snout. In the area of the alimentation limit, these surfaces nearly coincide. In certain places, this difference is several meters, which is commensurable with the reconstruction error. Thus, despite the retreat of the snout, the values of the surface height in the alimentation area and ice thickness remain practically unchanged. According to the results of the radio-echo sounding, thickness of the Central Tuyuksu glacier is 47 m, with its maximum value recorded in the area of the alimentation limit being 103 m.

The obtained data on the polythermal structure of the glacier may be used further to find new parameters of its response to the climate changes. In this regard, it is worthwhile to organize regular observations over the position of the internal reflecting horizon (IRH) in combination with the traditional monitoring of the glacier mass balance. Currently the insufficient amount of information about temperature distribution across the glacier mass and the results of previous radio-echo sounding have not allowed us to make adequate estimation of the dynamics in the position of the IRH over the period of observations made. However, the quantitative estimates obtained in the study may serve as a basis for further monitoring of these parameters.

An important fact is the fact that among polythermal glaciers, common are pulsating glaciers, as sudden destruction of the mantle of the cold ice may serve as one of the triggers of their movement. The causes of the destruction may be related to the change in the ratio between the masses of cold and warm ice in the glacier body, which occurs under the impact of both internal and external factors. It cannot be excluded that the movements of glaciers Shokalsky, Bogatyr, and Korzhenevsky recorded in this region are caused by their polythermal structure. Therefore, although up to the recent time the Central Tuyuksu glacier has not been discussed in this respect, discussing this glacier may be of methodological and practical interest under conditions of modern climate changes.

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