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Change of Chalaati Glacier (Georgian Caucasus) since the Little Ice Age based on dendrochronological and Beryllium-10 data

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Изменения ледника Чалаати (Грузинский Кавказ) с малого ледникового периода по данным космогенных изотопов (^{10}Be) и дендрохронологии

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Summary

Glacier variations over the past centuries are still poorly documented on the southern slope of the Greater Caucasus. In this paper, the change of Chalaati Glacier in the Georgian Caucasus from its maximum extent during the Little Ice Age has been studied. For the first time in the history of glaciological studies of the Georgian Caucasus, ^{10}Be in situ Cosmic Ray Exposure (CRE) dating was applied. The age of moraines was determined by tree-ring analysis. Lichenometry was also used as a supplementary tool to determine the relative ages of glacial landforms. In addition, the large-scale topographical maps (1887, 1960) were used along with the satellite imagery – Corona, Landsat 5 TM, and Sentinel 2B. Repeated photographs were used to identify the glacier extent in the late XIX and early XX centuries. ^{10}Be CRE ages from the oldest lateral moraine of the Chalaati Glacier suggest that the onset of the Little Ice Age occurred ~0.73±0.04 kyr ago (CE ~1250–1330), while the dendrochronology and lichenometry measurements show that the Chalaati Glacier reached its secondary maximum extent again about CE ~1810. From that time through 2018 the glacier area decreased from 14.9±1.5 km^2 to 9.9±0.5 km^2 (33.8±7.4% or ~0.16% yr^{-1}), while its length retreated by ~2280 m. The retreat rate was uneven: it peaked between 1940 and 1971 (~22.9 m yr^{-1}), while the rate was slowest in 1910–1930 (~4.0 m yr^{-1}). The terminus elevation rose from ~1620 m to ~1980 m above sea level in ~1810–2018.

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Для реконструкции колебаний ледника Чалаати в Грузии использовались космические снимки, старые карты, повторные фотографии, дендрохронология, лихенометрия и анализ космогенных изотопов. Максимальное наступание ледника в начале малого ледникового периода произошло в ~1250–1330 гг., второй максимум, когда ледник достиг почти такой же длины, датируется примерно 1810 г. С этого времени до 2018 г. площадь ледника уменьшилась с 14,9±1,5 до 9,9±0,5 км^2 (33,8±7,4%, или ~0,16% год$^{-1}$), а его длина сократилась на ~2280 м.

1. Introduction

Francois E. Matthes [1] was the first scientist to use the term Little Ice Age, which is globally known as one of the coldest periods of the last millennia. The Little Ice Age is a documented cooling event that began around the XIII or XIV century and peaked between the mid-XVI and mid-XIX centuries [2]. The spatial extent of this cold condition was mostly observed in the Northern Hemisphere, although the cooling phase was also noted in other regions with different intensities and time periods. Recent studies revealed strong spatio-temporal variations in this cooling with synchronous or asynchronous cool decades between regions suggesting a complex pattern of change [3]. Quantifying glacier change during the Little Ice Age is important when attempting to understand regional climatic changes and can also help to improve the understanding of any predictions of future glacial changes. Glacier variations themselves can be also used for the modelling studies [4].

Detailed records of variations spanning the past few centuries for glaciers on the northern slope of Greater Caucasus in the past few centuries were recently published [5–8]. These records were based on the analyses of satellite imagery and maps, old historical materials, lichenometry, tree-rings and ^{14}C dating. While some records of past glacier variations [9] are available for the glaciers located on the southern slope of Greater Caucasus [10–12], the status of Georgian glaciers during the Little Ice Age period is so far more poorly documented [13] compared to their northern counterparts. For this purpose, Chalaati Glacier was selected on the southern slope of the Greater Caucasus in order to assess its variations since the Little Ice Age. We use the same approach as for the northern slope such as combining the information from the old maps and figures, aerial images, historical data, lichenometry and dendrochronology [7] along with ^{10}Be in situ CRE dating.

We selected the Chalaati Glacier (43°07' N, 42°42' E) for several reasons: 1) Chalaati is an example of a well-documented glacier with a wealth of different historical sources (e.g. maps, photographs, anecdotal evidences) [13] that allow reconstruction of glacier length variations over the most recent centuries; 2) it is a typical valley glacier of relatively simple shape. This type of glacier is also climate sensitive and often used for climate modelling; 3) Chalaati is one of the most frequently visited glaciers in Georgia due its close location to the road, gentle valley inclination and low position of the terminus. Today this valley is used for the construction of the hydropower. Water and debris from Chalaati Glacier will be filling this reservoir, the rate of which is highly depends on the future state of Glacier, making this study especially relevant; 4) in addition, Chalaati valley is the best location on the southern slope of the Greater Caucasus where the well-preserved Little Ice Age moraines are covered by old conifer forest and, which are useful for dendrochronological purposes. The goal of our paper is to: 1) reconstruct the spatial variations of Chalaati Glacier; 2) assess the age of glacier deposits of the most recent centuries; 3) estimate the length and area changes; and 4) compare the variations of this glacier in the Little Ice Age with those of similar type and size from northern side of the Greater Caucasus and other mountain regions (e.g. European Alps). This will increase the knowledge of the more recent portion of the Holocene glaciation from the Greater Caucasus.

2. Study area

The Greater Caucasus is one of the world's highest mountain systems, containing over 2000 glaciers with a total area of about 1200 km^2. The Georgian side of the Greater Caucasus contains about 700 glaciers with a total area of about 370 km^2 [11]. These glaciers play a significant role in the ecology and economy of Georgia. They provide a freshwater source that feeds rivers in the mountainous area. This water is essential to river ecology, particularly during the summer months when rivers have lower flows. Georgian glaciers also have economic importance as a major tourist attraction with thousands of visitors each year. Local economies and livelihoods are connected to glacial input in these ways. Glacier meltwater also supplies several hydroelectric power stations. Understanding how glaciers in this region are changing is therefore important for these local considerations [10–13].

Chalaati is a compound-valley glacier and consists of two flows, which are fed from the slopes of over 4000 meter-high peaks: Ushba, Chatini, Kavkasi, and Bzhedukhi. Among the glaciers on the southern slope of the Greater Caucasus, this glacier has the lowest terminus (1980 m a.s.l. in 2018) and intrudes into the forest zone. Three icefalls on the glacier indicate a ledge under the glacier. The height of the largest icefall is ~300 m and its width is ~700 m. The two lower icefalls are relatively small. In the vicinity of the icefalls, the glacier tongue is rugged by the various fractures (serracs) going in different directions. The edges of the glacier tongue are covered with debris of a variable thickness. It is likely that these two flows will split in the near future. The middle part of the glacier tongue is strongly inclined and cracked.

The lateral moraines of Chalaati Glacier are well preserved. At their distal sides they are covered by forest, their proximal sides are bare and steep. The bottom of the valley stabilized in the XX century, and is now covered by young birch forest. Below ~1750 m a.s.l. there are older moraine walls in conifer forest.

3. Previous studies

A number of scholars visited and described Chalaati Glacier and documented the position of its front in the XIX and XX centuries [14–20]. Freshfield [14] was one of the first scientists to visit the glacier in 1868, provided the following description: «*Chalaati Glacier drains a double basin on either flank of Chatini. Owing to the steepness of the general inclination of its bed, it attains to a lower point in the valley than the larger stream of the Lekhziri. It reaches, indeed, a lower point than any other ice-stream on either side of the Caucasus. Not many years ago the two glaciers met at their extremity, now the Lekhziri terminates at 5600 feet* (1706 m a.s.l.)*, and the Chalaati at 5200 feet* (1585 m a.s.l.). *The descent from the Chatini Pass lies over the northern névé of the Chalaati Glacier*».

Déchy [15] also described Chalaati Glacier a few years later: «*Due to the steepness of its bed, the Chalaati Glacier terminates lower into the valley than a larger stream of the Lekhziri Glacier. In fact, at 1628 m, it reaches the lowest point of all the glaciers of the Greater Caucasus on both sides, while the Lekhziri Glacier terminates in 1734 m. Not many years back, the tongues of the two glaciers must have touched each other. The rocks of the moraines, which the Chalaati Glacier brings down from its surroundings, are gneiss granites, syenite, with fine grains consisting of feldspar and amphibolite, and pegmatites with quartz inclusions*».

Unfortunately, the measurements provided by scholars in XIX and early XX centuries are sometimes too obscure to be used to accurately identify the position of the front. For example, according to Freshfield [14] Chalaati Glacier terminated at 5200 feet (1585 m a.s.l.), and according the Déchy (1905), at 1628 m a.s.l. respectively, i.e. below the confluence to the Lekhziri River, ouside the Chaalaati valley. This contradict to the image of Chalaati Glacier at the map of 1887 and other evidences (see discussion below). This very detailed map, at a scale of 1:84 000, was used later by Podozerskiy [21] in his catalog of the Caucasus glaciers but unfortunately, he did not provide any indication of Chalaati frontal position. Detailed analysis of this map shows some defects in the shape of the glacier (see Chapters 4.4 and 5.4).

Rutkovskaya [16] studied the dynamics, ice thickness and velocity of the Chalaati Glacier during the 2nd International Polar Year (Fig. 1). She found that the glacier terminated at 1738 m a.s.l. and its total area was 11.3 km^2 in 1933. In the central part of the glacier tongue, the ice thickness was about 50 m and the daily ice velocity was 15.3 cm during the 30 days period in August 1933. According to Tsereteli, [17] Chalaati Glacier retreated over 1000 m from the 1890s through the 1960s [17], and in 1959 terminated at 1850 m a.s.l. and the snowline was located at 3050 m a.s.l. [18]. The mass balance observations at Chalaati Glacier measured in summer 1959 at 1980 m a.s.l. found an ablation rate of ~0.7 cm/PDD (positive degree days) in July. Between July 31 and September 1 in 1961, daily ice velocity at Chalaati Glacier was 18.2 cm [19].

R. Gobejishvili [20] was leading glacial-geomorphological studies between 1968 and 1995. The Chalaati Glacier terminus was surveyed by the phototheodolite method, and large-scale map (1:2 000) was created. According to his data the glacier terminated at 1880 m a.s.l. in 1980. Later these studies have continued by Tielidze [13]. The ablation rate was measured as ~0.6 cm/PDD (positive degree days) in July and ~0.4 cm/PDD in August 2011 at 2040 m a.s.l. Glacier terminated at 1950 m a.s.l. in 2011 (Table 1).

4. Data and methods

4.1. ***In situ ^{10}Be cosmic ray exposure dating.*** Three samples were collected with a hammer and chisel in September 2018 from the horizontal to sub-horizontal uppermost surfaces of large boulders (> 60 cm

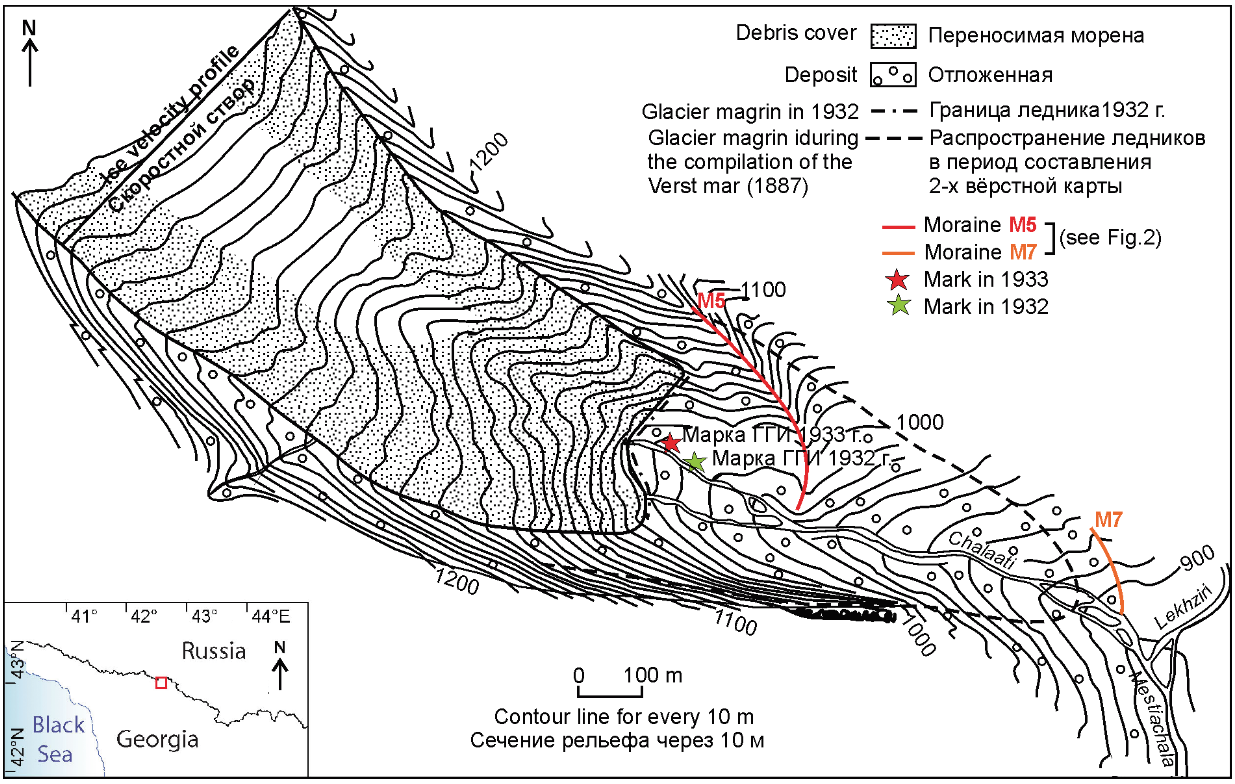

Fig. 1. Chalatai Glacier terminus position in 1933 [16] (modified by authors)
Рис. 1. Конец ледника Чалаати в 1933 г. [16] (с изменениями авторов статьи)

Table 1. **Front position of Chalaati Glacier according to various sources**
Таблица 1. **Положение конца ледника Чалаати по разным данным**

Years	Elevation, m a.s.l.	Reference
1868	1585	Freshfield, 1896
1905	1628	Déchy, 1905
1911	Unknown	Podozerskiy, 1911
1933	1738	Rutkovskaya, 1936
1959	1850	Tsereteli et al., 1962
1980	1880	Gobejishvili, 1995
2011	1950	Tielidze, 2017

high) located on the most external moraine on the left slope of the valley. The boulders were stable and without evidence of loss due to denudation processes. Sample locations and elevations were recorded using a handheld GPS, and topographic shielding was measured using a clinometer and a compass. The samples were processed at CALM lab (Cosmonucléides Au Laboratoire de Meudon – France) for in situ CRE dating. In situ-produced ^{10}Be was measured in the quartz mineral fraction separated from the rock samples. Samples were crushed and sieved (250–750 μm); magnetic components were eliminated using a Frantz magnetic separator. Quartz was extracted by dissolution of undesirable minerals in HF/HNO_3 acid mixture and atmospheric ^{10}Be removed through sequential dissolution (~10% in mass) in diluted HF. The obtained pure quartz was spiked with a commercial standard solution from the Scharlau Company (1000 mg l^{-1} of BeO) and then digested in 48% hydrofluoric acid. Beryllium was extracted using anion and cation columns and alkaline precipitation. The obtained beryllium hydroxides were dried, and finally oxidized for one hour at 800 °C. The final BeO oxides were combined with niobium powder for AMS measurements at the French 5 MV AMS national facility ASTER (Aix-en-Provence) [22]. Measurements were calibrated against the in-house standard STD-11 with an assigned ^{10}Be/^{9}Be ratio of $1.191 \pm 0.013 \times 10^{-11}$ [23] using a ^{10}Be half-life of $1.387 \pm 0.0012 \times 10^{6}$ years [24]. We calculated ^{10}Be ages using the CREP online calculator [25] and using the Arctic production rate [26] and the Lal/Stone time corrected scaling scheme [27, 28]. We did not make corrections for snow cover and denudation of the boulder surface.

Table 2. **List of the maps and satellite images scenes used in this study**
Таблица 2. **Список карт и снимков со спутников, использованных в настоящем исследовании**

Date	Resolution, m	Type of imagery/map	Scene ID
1887	12	1:84 000 topographic map	X_13_4
1960	5	1:50 000 topographic map	k_38_26_v
20.09.1971	2	Corona	DS1115-2154DF070_d
06.08.1986	30	Landsat 5 TM	LT51710301986218XXX02
12.08.2000	30		LT51710302000225AAA02
22.09.2018	10	Sentinel 2B	L1C_T37TGH_A008069_20180922T080212
17.11.2011	30	ASTER GDEM	ASTGTM2_N42E041

4.2. *Dendrochronology.* For moraine dating the standard procedures of measuring, cross-dating and indexation routinely used in tree-ring analysis [29] were applied. We cored the trees at the moraines and glacier forefields either at the breast height (1.5 m) or at the lowest possible level near the soil surface. In the first case, in order to assess the real age of the tree, the number of rings in the core was corrected by the addition of 15 years and samples cored near the surface this correction was 5 years. When the pith in the core was missing we used CooRecorder software which has a tool to measure «distance to pith». The number of missing rings was assessed using curvature of the last five rings. The trees growing on the moraines provide minimum age of the surface stabilization. Overall, we collected twelve tree ring samples within the two days (27–28 September 2018). Three long living species (Scots pine (*Pinus sylvestris L.*), Nordmann fir (Abies nordmanniana (*Steven*) Spach.), spruce (*Picea orientalis*) are growing at the Little Ice Age moraines of the Greater Caucacus glaciers and they can potentially provide ages of the surfaces up to five hundred years old. The eccesis (time lag for colonization) for pine used for the dating at the northern slope of the Greater Caucasus is 10–20 years as estimated from the analyses of the aerial photos and direct survey (e.g. [30]). The colonization by fir and spruce takes a few years longer. Thus, a minimum of 20 years should be added to the tree ring date to assess the minimum age of the surface (moraine) stabilization.

In Chalaati valley we used the oldest conifer trees growing on the moraines or between the ridges. In a few cases when the sampling (coring) was impossible due to the weak rotten wood we roughly counted the number of annual rings that would give us a rough estimate of the minimum age of the surface.

4.3. *Lichenometry.* Like at most other glaciers in the Greater Caucasus, the earliest map of Chalaati Glacier dates back to the late 19th century. The moraine deposits outside this contour clearly show that a set of advances occurred before the Chalaati Glacier reached this position. The lichenometry can be used to roughly assess the age of these deposits [31]. Although this dating tool was recently criticized by Osborn et al. [32], lichenometry is still in use in geomorphic studies as an express method of a relative dating of landforms (for further discussion see [7]).

Here we used this method only for the relative dating and an approximate assessment of the age of moraines [33]. We measured the maximum diameters of Rhizocarpon geographicum senso lato lichens at the surfaces, when there were enough large boulders at these surfaces and considered the largest (oldest) specimen as an indicator of the age of moraines. This method was criticized by Naveau et al. [34] and Jomelli et al. [33] as statistically incorrect and the GEV approach was suggested instead as a more statistically robust. Unfortunately we do not have original data from the growth curve constructed by Serebryanny et al. [9] for the southern slope of Greater Caucasus where single maximum diameters of lichens for five moraines from 14–15 years old up to 3360±90 years BP (TA-1233) in Khalde valley have been used for this purpose (see Discussion for further details). For this reason, we use the model suggested by Beschel [31] to obtain a rough age estimate.

4.4 *Maps and Satellite Imagery.* Old topographic map (1:84 000) from the second Caucasus topographic survey (1887) was used to evaluate the Chalaati Glacier outline (Table 2) along with the replaced and co-registered topographic map (1:50 000 scale) from the 1960s [11]. The projection of the 1887 map is different from the modern UTM system, as it was created by plane table survey using the old Russian unit of length such as the Verst (1 Verst = 1.07 km). In addition, the relief of this map is distorted (including the glacier shapes) compared to the map from the 1960s and satellite imagery (see 5.4. chapter for more details).

Corona image, dating from 1971, was obtained from Earthexplorer website (http://earthexplorer.usgs.gov/). We co-registered the 1887 map and Corona image using the 12 August 2000 Landsat 5 TM (Thematic Mapper) image as a master [10]. Offsets between the images and the Corona/archival map were within one pixel (30 m) based on an analysis of common features identifiable in each dataset. We reprojected Corona image and 1887 map to Universal Transverse Mercator (UTM), zones 38-north on the WGS84 ellipsoid, to facilitate comparison with modern image datasets (ArcGIS 10.2.1). Together with Landsat imagery, these older topographic maps and Corona image enabled us to identify century-long glacier change.

Two Landsat 5 TM georeferenced images dated 6 August 1986 and 12 August 2000, were supplied by the US Geological Survey's Earth Resources Observation and Science (EROS) Center and downloaded using the EarthExplorer tool (http://earthexplorer.usgs.gov/). We used a color-composite scene for both images – bands 5 (short-wave infrared), 4 (near infrared), and 3 (red).

High-resolution satellite instruments such as Sentinel 2B, with 20 m horizontal resolution available since March 2017, help in recognizing glacier margins. Cloud free image from 22 September 2018 was downloaded using the REMOTE PIXEL tool (http://remotepixel.ca). For Sentinel image, we used pan-sharpened tools in ArcGIS 10.2.1 software to enhance pixel size (20 m) to 10 m. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM, 30 m) version 2 (http://asterweb.jpl.nasa.gov/gdem.asp) was used to assess the Chalaati Valley longitudinal profile. Other datasets used in this study include the GPS measurements (terminus position) from a 2018 field survey.

4.5. ***Glacier mapping and uncertainty assessment.*** The Little Ice Age glacial extent was digitized manually, proceeding from the 1986 glacial extent, based on clear visible morphological evidence, e.g. terminal and lateral moraine systems. To avoid an overestimation of the Little Ice Age extent, larger rock outcrops (as included in the scenes from 1986) were preserved. Due to its higher resolution compared to Landsat 5 (30 m), data from Sentinel-2 (10 m) were also used for the mapping. We also crosschecked our mapped glacial extents with high-resolution data from DigitalGlobe and Google Earth images. Glacier areas were also measured from the maps and all satellite imagery by manual digitization. The time series of maps and satellite imagery resulted in glacier area values for each corresponding date since the 1880s (1887). The glacier boundary in the accumulation area for earlier glaciers than 1880s was taken from the 1986 ice divide and was kept constant over time. Based on the outlines of the different survey years, corresponding areas and area changes were calculated.

The length of glaciers was determined according to Global Land Ice Measurements from Space (GLIMS) recommendations (www.glims.com). The longest glacier's flow was determined manually as perpendicular to the altitude contours. Front variation measurements were conducted by using the glacier outlines for each date, along the ice front – perpendicular to the flow. We have determined glacier area uncertainty with a buffer method similar to Granshaw and Fountain [35], and adopted by Tielidze [10], Tielidze and Wheate [11]. This generated an uncertainty of the mapped glacier area of ±5.6% for 1960, ±6.3% for 1971 and 1986, and ±6.7% for 2000 (buffer size ±30 m), while the uncertainty was ±5.1% for 2018 (buffer size ±20 m).

Due to the different projection and distorted glacier shape, the map from 1887 was co-registered and digitized a second time by a different operator similar to Tielidze [10] in order to accurately access the uncertainty of the old glacier from 1887. To determine the precision of the digitizing, we used the Normalised Standard Deviation (NSD – based on delineations by multiple digitalization divided by the mean glacier area for all outlines). The difference between these two manually mapped outlines was ±10.3%. For glacier outlines earlier than 1880s and outlines for 1910–1940s we used a buffer size of ±60 m that generated an average area uncertainty of ±9.7% for 1810, ±10.2% for 1840, ±10.2% for 1910, ±10.4% for 1930 and 1940.

5. Results and Discussion

5.1. ***^{10}Be CRE ages.*** We collected all samples at the left side of the Chalaati valley while the right side was not accessible with no bridge over the river. We report individual in situ ^{10}Be CRE ages with their as-

Table 3. **Sample details. Cosmogenic nuclide concentrations and calculated cosmic ray exposure ages from the valleys. $^{10}Be/^{9}Be$ ratios were corrected for a process blank value of 9.11 × 10^{-15} ($^{10}Be/^{9}Be$ uncertainty: 8%) (samples Geo 1,3) and 5.31 × 10^{-15} ($^{10}Be/^{9}Be$ uncertainty: 15%) (sample Geo 2)**

Таблица 3. **Сведения об образцах. Концентрация космогенных нуклидов и рассчитанное время воздействия космических лучей. Соотношения $^{10}Be/^{9}Be$ были скорректированы для начальных точек процесса: 9,11 × 10^{-15} (ошибка определения соотношения $^{10}Be/^{9}Be$ – 8%) (образцы Geo 1 и Geo 3) и 5,31 × 10^{-15} (ошибка определения соотношения $^{10}Be/^{9}Be$ – 15%) (образец Geo 2)**

Sample ID	Latitude N	Longitude W	Elevation, m a.s.l.	^{10}Be conc, at g^{-1}	^{10}Be uncert, at, g^{-1}	Shielding factor	Density, g cm^{-3}	Thickness, cm	Erosion rate, mm yr^{-1}	Age, kyr	1σ, kyr	1σ without PR error
Geo 1	43.114097	42.737215	1843	10848	1657	0.9801	2.75	3	0	0.67	0.1	0.1
Geo 2	43.113806	42.738317	1820	59942	9913	0.9612	2.75	3	0	4.2	0.65	0.65
Geo 3	43.113630	42.738794	1812	12429	1284	0.9801	2.75	3	0	0.79	0.08	0.08

sociated uncertainties that include the standard deviations of both analytical (reported Table 3) and production rate uncertainties.

The three rock samples (Geo1-3) were collected on the external moraine ridge M8 to document the maximum extent of Chalaati Glacier during the last millennia in this upper part of the valley (Fig. 2). These samples show ages that range from 0.67±0.1 kyr to 4.2±0.65 kyr. Geo 2 dated at 4.2 kyr was rejected and considered as an outlier (possibly due to inheritance) compared to the other samples and rejected from the analysis. Geo 1 and 3 yield a mean ^{10}Be age of 0.73±0.04 kyr and suggest a formation of moraine M8 at the onset of the Little Ice Age. Because of the very limited number of samples it is still difficult to assess the age of this moraine. Here

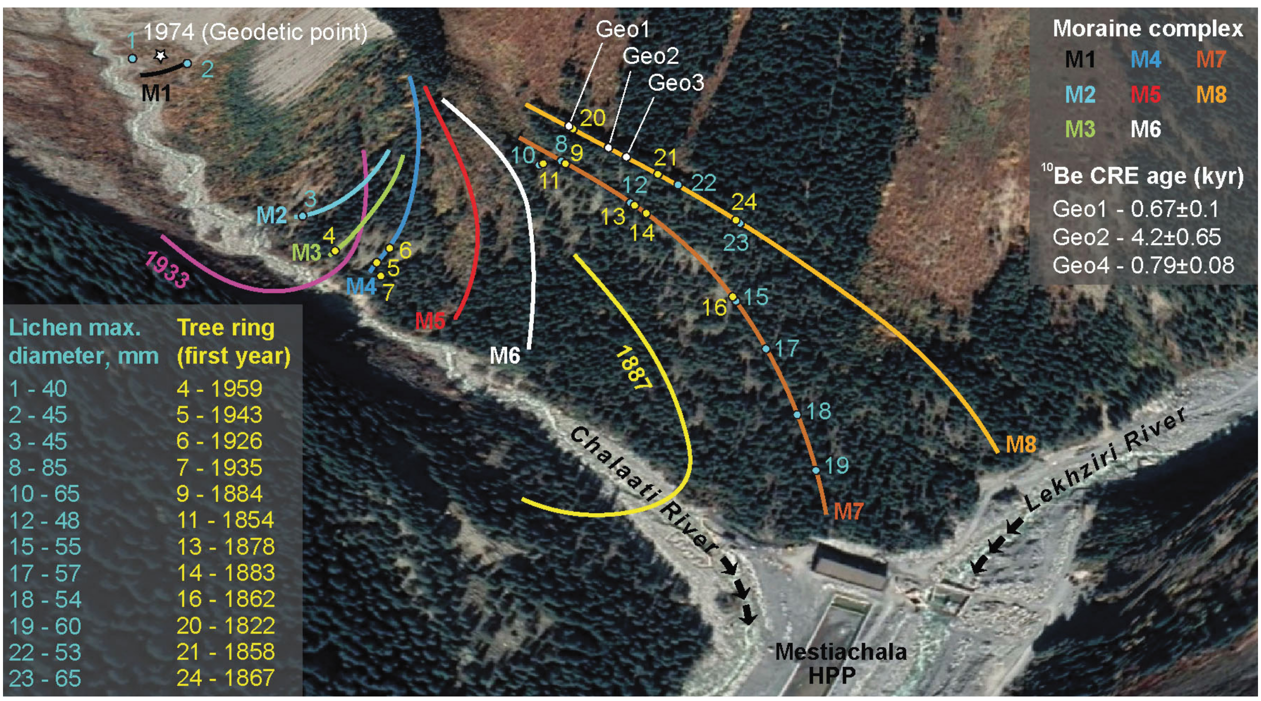

Fig. 2. Moraine ridges located on the left slope of the Chalaati valley; Locations of lichen measurements (diameter in mm) and dendrochronological sampling along with the in situ ^{10}Be CRE ages (kyr). Sizes of lichens and ages of trees by dendrochronology are given in Table 4. Google Earth image (21.10.2019) is used background

Рис. 2. Моренные гряды, расположенные на левом борту долины Чалаати; местоположения измеренных лишайников (диаметр в мм) и дендрохронологических образцов, а также возраст обломков по космогенным нуклидам ^{10}Be (тыс. лет). Размеры лишайников и возраст деревьев приведены в табл. 4. Изображение Google Earth (21.10.2019 г.) использовано в качестве фона

Table 4. **Minimum moraine age of the Chalaati Glacier based on dendrochronological measurement and maximum lichen diameters at the moraines**

Таблица 4. **Минимальный возраст морен ледника Чалаати по дендрохронологическим данным и размер максимальных лишайников на моренах**

Moraine	Name (Number) on the map (see Fig. 2)	Latitude N	Longitude E	Elevation, m a.s.l.	Lichens (maximum diameter, mm)	Dendrochronological measurement			
						the year of the first measured ring	last ring, year	presence of the core	correction (year) for the missing pith
M1	1	43.11533	42.72925	1829	40, 40, 40, 35, 30	–			
	2	43.11516	42.87320	1822	45, 45, 40, 40, 39, 39, 36, 35, 34, 33, 32, 32, 31, 31				
M2	3	43.11230	42.73430	1760	45, 40, 38, 35, 35				
M3	4	43.11213	42.77353	1783	–	1965	2018	+	6
M4	5	43.11209	42.73576	1752		1944	2018	+	1
	6	43.11209	42.73576	1752		1928	2018	+	2
	7	43.11176	42.73611	1739		1939	2018	+	4
M7	8-9	43.11355	42.73796	1812	85	1885	2018	+	1
	10-11	43.11357	42.73771	1820	65, 60, 55 50, 47	1857	2018	+	3
	12-13	43.11336	42.73876	1820	48	1879	2018	+	1
	14	43.11338	42.73906	1792	–	1887	2018	+	4
	15-16	43.11247	42.74066	1737	55, 52, 50, 50, 49, 45, 42, 40, 40, 40, 39, 36, 35, 32, 32, 31, 22	1865	2018	+	3
	17	43.11180	42.74117	1717	57, 52, 51, 50, 50, 42	–			
	18	43.11112	42.74171	1700	54, 52, 51, 50, 50, 47, 46, 46, 45, 45, 45, 43, 42, 41, 41, 40, 34, 35, 32				
	19	43.11012	42.74222	1670	60, 48, 45				
M8	20	43.06830	42.44266	1838	–	1825	2018	+	3
	21	43.11346	42.73917	1800		1859	2018	+	1
	22	43.11332	42.73957	1790	53, 52, 50	–			
	23-24	43.11316	42.74040	1698	65, 62, 62, 62, 60	1868	2018	+	1

the mean ^{10}Be age of 0.73±0.04 kyr has to be considered as a very preliminary estimate.

5.2. ***Dendrochronological measurements.*** Fig. 2 shows the locations of dendrochronological sampling sites and their position relative to moraine ridges. Minimum ages of moraines based on tree-ring data are presented in Table 4. The highest lateral moraines are clearly expressed in the Chalaati valley – unsodded in its proximal part and covered with forest - in the distal one. Their corresponding terminal moraine complex is more poorly preserved, but nevertheless it is discernible on both sides of the valley. At the Fig. 2 we mapped the moraine ridges from the M1 to M8 (from the youngest to the oldest) marking individual stages of the advances or stationary stages of the glacier.

1. Moraine M1 at an altitude of about 1820 m a.s.l. marks a location of the glacier position in 1960s (Instrumental measurement by Gobejishvili [20]).

2. The three moraine ridges – M2-M4 are located at an approximately 1730 m a.s.l., i.e. where the termination of the glacier was recorded in 1933 by Rutkovskaya [16] (see Fig. 1).

3. At an altitude of about 1710 m a.s.l., another, relatively older stage M5 is distinguished, which is also visible on the map of Rutkovskaya as a ridge going down to the river. Between the two moraine complexes M4 and M5, the distance is approximately 20 m vertically and 100 m horizontally.

4. The lower moraine ridge M6 is covered by forest and not very well shaped, especially in its lower part.

5. Two older lateral moraines in this complex M7 and M8 stretching parallel to the slope of the valley. They are partially destroyed by debris flows and avalanches coming from the left side of the valley. The slope processes keep renewing the surface of these moraines, erode them and damage the vegetation growing on their surface. These tracks are clearly marked at the

Google Earth image (see Fig. 2) by the lighter color of vegetation in the lower parts of these debris-flows.

So, the best undisturbed portion of moraines older than CE 1887 that we studied using bioindication approaches is located between the two debris flows at the left side of the valley. The map of 1887 shows that the space left unoccupied by the ice at that time was quite narrow. One moraine ridge descending to the Lekhziri River is marked on this map. In fact, there are at least two moraine ridges outside the glacier limits indicated on the 1887 map, which was not accurate enough to determine if it corresponds to M7 or M8.

The first tree-ring sample that we got from the moraine 3 that is located very close to the margins of the glacier marked at the map of Rutkovskaya for the year 1933 dates back to 1959. Taking into account the correction for the height of coring (approximately 5 years) and the time lag between the stabilization of the surface and its colonization by forest (10–15 years) the tree-ring minimum date of this surface is early 1930s, i.e. closely fit to the observations. At the foot of the M4 moraine ridge, at its distal side, two pines grow, which settled here in 1926 and in 1943. I.e. glacier terminated here in early 1900s and the moraine M4 (1750 m a.s.l.) was deposited slightly later, most likely in the 1910s (see Fig. 2, M4).

Unfortunately, the preservation of the moraine ridges in the lower part of the valley is poor. They are flattened and lost their clear outline, so it is very difficult to trace the contours of the glacier framed by them. It is likely that these surfaces are also constantly affected by slope processes and are partially eroded. We could not find old trees on the surface between moraine M6 and terminal moraines M7 and M8. However, fragments of moraines M7 and M8 that have survived the erosion, support that old trees are useful to estimate the minimum age of these generations. The oldest tree (live pine), settled on moraine M7 in CE 1854. Several other old trees grew on this moraine in CE 1862, 1878, 1883 and 1884. Thus, the minimum age of this moraine should be approximately 180 years, i.e. the moraine was formed in the CE ~1840. According to the dendrochronological data, moraine M8 is older, where the oldest tree (spruce) grew in CE 1822. Other pine dates are CE 1858 and 1867. However, as we learnt from the ^{10}Be date of this moraine this minimum age estimate is very far from the real one and tree rings in this case strongly underestimate the real age of the surface.

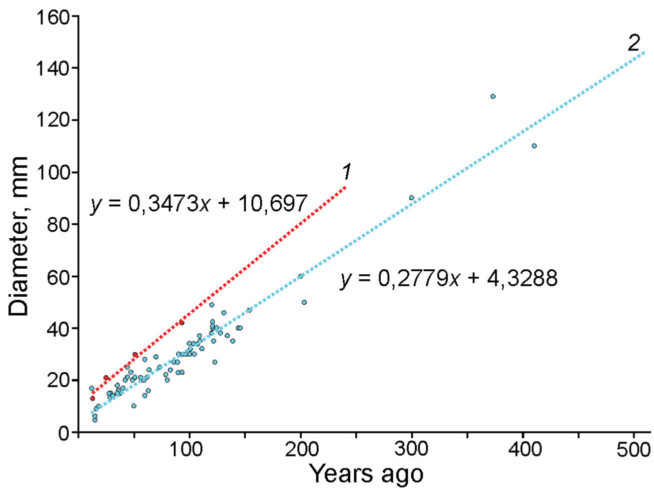

Fig. 3. Lichen growth curve developed:
1 – for the southern [9] (brown) and *2* – northern [7] (blue) slopes of Greater Caucasus

Рис. 3. Кривые роста лишайников:
1 – для южного [9] (коричневый) и *2* – северного [7] (синий) склонов Большого Кавказа

5.3. ***Lichenometric measurement.*** Although, for the reasons discussed above, we did not produce any systematic lichenometric studies in this valley, some data on the size of lichens seem to us worthy of discussion in this work. As it was described previously by Solomina et al. [7], currently there are serious reasons to discard all control points constraining the lichen's growth in Caucasus that are older than two to three hundred years old. In general, the rough estimate of the rate of Rhizocarpon geographicum growth in the past 100–150 years at the northern slope of the Greater Caucasus is around 0.25–0.30 mm per year. The past century period characterizes the stage of the fast growth of the lichens, however in the earlier time the growth rate of lichens should be slower [36], but there are no reliable control points to constrain the older part of the growth curve (Fig. 3). In Fig. 3 we indicated control points for the moraines of the northern slope of Greater Caucasus [7] and four points that Serebryanny et al. [9] identified for the southern slope of the Greater Caucasus. We discarded the oldest one for the moraine of Khalde Glacier (ca 3500 years old) that almost certainly supports the secondary generation of lichens and therefore is too old to be used for lichenometry. Moreover, it has been demonstrated that the mean of five largest lichens does not fit with the statistical extreme value theory and thus the mean value is not robust [33, 34]. Fig. 3 shows that the growth rates of the Rhizocarpon geographicum at the

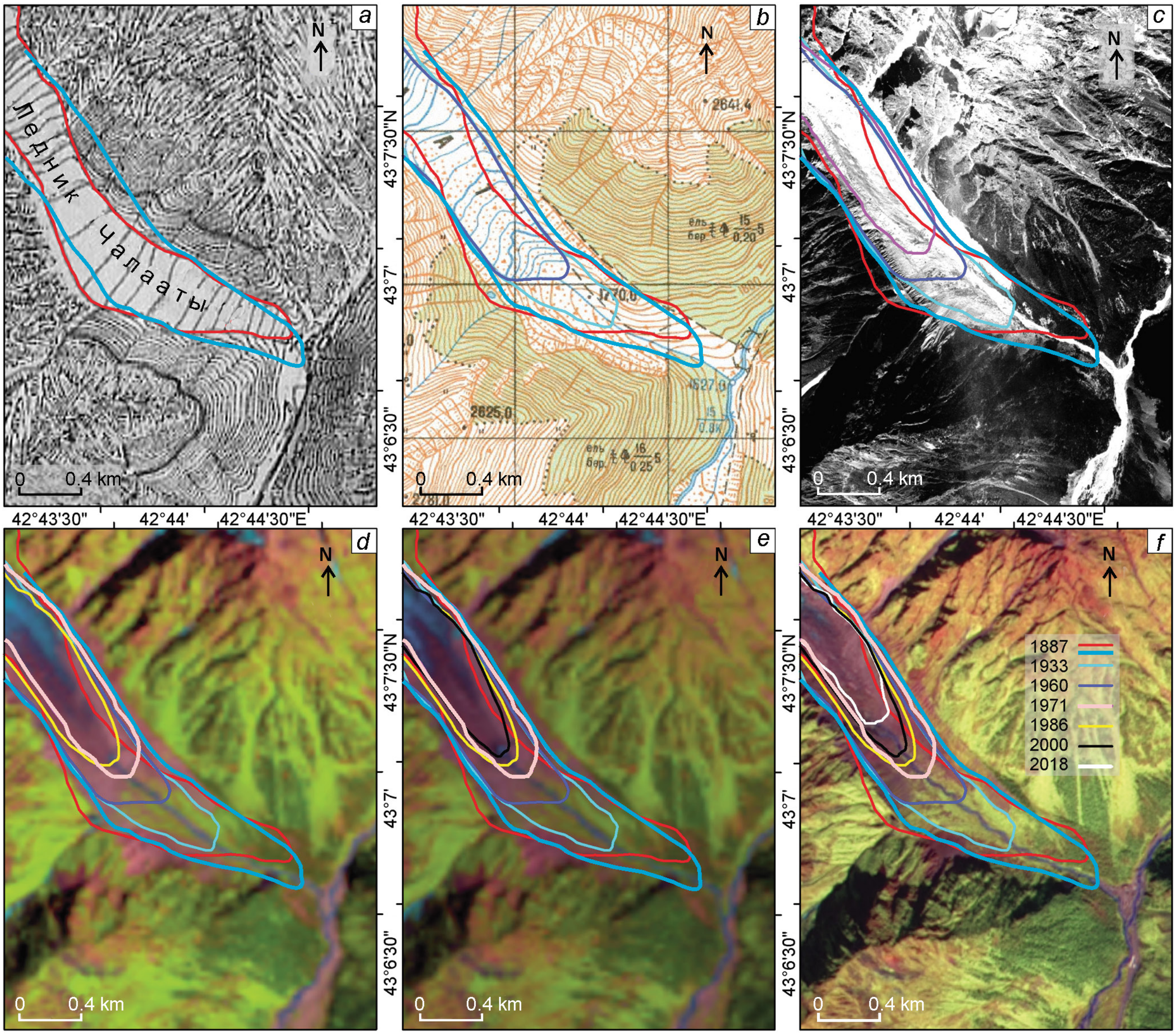

Fig. 4. Chalaati Glacier terminus change:
a – 1887 (1:84 000 scale topographic map); *b* – 1932 [16], 1960 (1:50 000 scale topographic map); *c* – 1971 (Corona, 20.09.1971); *d* – 1986 (Landsat 5 TM, 06.08.1986); *e* – 2000 (Landsat 5 TM, 12.08.2000); *f* – 2018 (Sentinel 2B, 22.09.2018)

Рис. 4. Изменения конца ледника Чалаати:
a – 1887 г. (топографическая карта масштаба 1:84 000); *b* – 1932 г. [16], 1960 г. (топографическая карта масштаба 1:50 000); *c* – 1971 г. (Corona,, 20.09.1971 г.); *d* – 1986 г. (Landsat 5 TM, 06.08.1986 г.); *e* – 2000 г. (Landsat 5 TM, 12.08.2000 г.); *f* – 2018 г. (Sentinel 2B, 22.09.2018 г.)

southern slope is similar, but slightly higher than at the northern one. This figure can be used for a rough estimate of the age of the moraines of the past one to two centuries that we are studying at Chalaati Glacier.

On the moraines M2 and M3, which were deposited about 90–100 years ago, judging by cartographic and dendrochronological data, the maximum size of lichens is 45 mm (see Fig. 2). According to Serebryanny et al. [9], the lichens as large as 45 mm on the Khalde Glacier moraines are also about 90 years old. Thus, the growth rate according to two independent studies is comparable. On the moraine M7, where it was possible to measure a sufficient number of lichens, their maximum sizes were up to 65 mm (see Fig. 2). According to the extrapolated linear growth curve for the southern slope, shown in Fig. 3, lichen reaches 65 mm in about 150 years. According to our dendrochronological data, the minimum age of this surface is 180 years. Serebryanny et al. [9] using the logarithmic curve claimed that the moraines supporting the lichens of 61–63 mm on

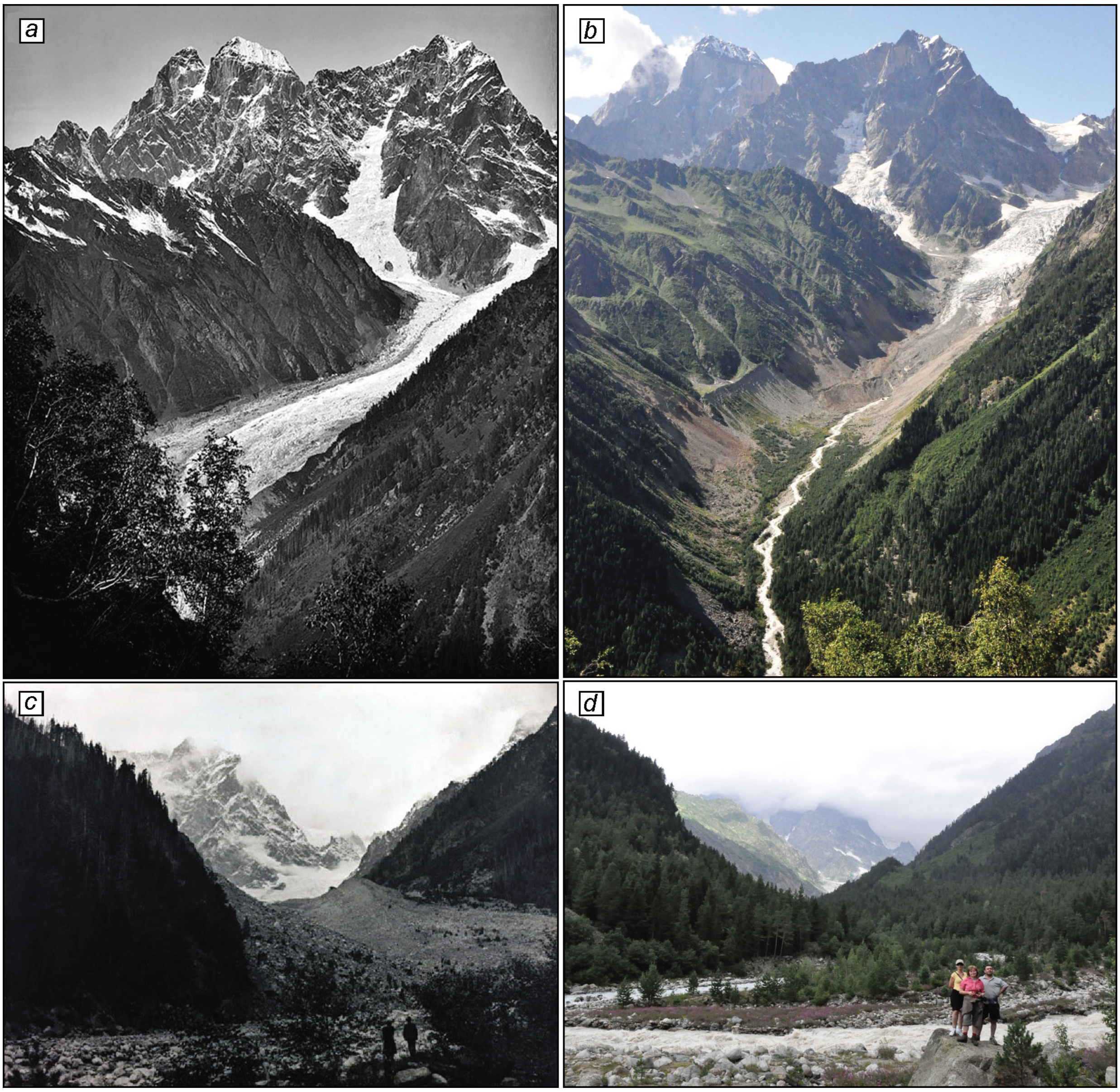

Fig. 5. Chalaati Glacier degradation between 1884 (*a* and *c*) (photos by V. Sella) and 2011 (*b* and *d*) (photos by L. Tielidze)
Рис. 5. Деградация ледника Чалаати между 1884 г. (*а* и *с*) (фото В. Селлы) и 2011 г. (*b* и *d*) (фото Л. Тиелидзе)

the southern slope dated back to the XVIII century interval of CE 1770–1780 years. Due to the lack of reliable data on the growth rate of lichens in this time range, no more accurate data have yet been obtained.

5.4. ***Old maps and repeated photos.*** The map of 1887 (Fig. 4, *a*) along with the moraine samples is the oldest records that we can use for the reconstruction of glacier fluctuations in XIX century. According to the map the glacier was terminating very close (about 200 m away) to the confluence of two rivers (Lekhziri and Chalaati). Its tongue occupied almost entirely the lower part of the valley covering most of moraines except for one lateral moraine ridge at the left side of the valley that can be seen at the map. Thus, most moraines located in the valley and covered by conifer forest by now were deposited later, after 1880s. The second attempt to co-register the 1887 map to the 1960 map (see Fig. 4, *b*) and satellite images (see Fig. 4, *c–f*) (see also chapter 4.4), showed that the shape of the glacier terminus of the XIX century (1887) does not fit into the valley. Moreover, is significantly higher than it is shown on the map of 1887, namely in the region of the younger lateral moraine. This is also clearly visible in Fig. 5, *b*, the treeless right side of the valley. Thus, we discuss

Table 5. **Chalaati Glacier area and terminus elevation since the ~1810 to the different years**

Таблица 5. **Площадь ледника Чалаати и высота его фронта с ~1810 г. за разные годы**

Year	Moraine	Area, km^2	Area uncertainty, %	Terminus, m a.s.l.
~1810	M8	14.9±1.5	±9.7	1620
~1840	M7	14.3±1.5	±10.2	1630
1887 (~1880s)	–	14.1±1.5	±10.3	1650±100
~1910	M4	13.8±1.4	±10.3	1720
~1930	M3	13.6±1.4	±10.4	1730
~1940	M2	13.6±1.4	±10.4	1740
~1960	M1	12.8±0.7	±5.6	1800
1971	–	12.3±0.8	±6.3	1860
1986		11.6±0.7	±6.3	1900
2000		11.0±0.7	±6.7	1920
2018		9.9±0.5	±5.1	1980

whether to take as the basis the assumption that 1) the terminus of the glacier on the 1887 map is correctly reflected (200 m away from the two rivers confluence) but the shape of the glacier tongue is distorted, or, 2) the glacier terminus was not 200, but 500 m away from the two rivers confluence. We suppose that the topographers of the XIX century accurately mapped terminus of the glacier relative to the two rivers confluence (i.e. 200 m away), while the shape of the tongue of the glacier could be distorted.

Photographs of Vittorio Sella of 1884, taken at about the same time as the map of 1887, could shed light on this issue, but unfortunately, we cannot see the terminus of the glacier from these positions due to the bushes and heavy debris cover (see Fig. 5, *a*, *c*). However, if we suppose that the white spot that is visible though the bushes is ice (see Fig. 5, *a*), the glacier should have been descend at least up to the lowest moraine that can be identified in a 2011 photo (see Fig. 5, *b*). This moraine is connected to the main crest of the lateral moraine and is located about 450 m away from the confluence of two rivers. However, we cannot rule out that the end of the glacier in 1884 was located even below this position, as we cannot see it in the 1884 photos. Thus, the historical material from 1880s does not provide precise evidence where the Chalaati Glacier was exactly terminated at that time. However, as no other data exist from this time, this map is the only source for this research to establish century-long trend glacier change.

Unlike the XIX century map, the large-scale topographic map from 1960 is consistent with all satellite imagery, which allowed us to define glacier change much precisely over the last half century (see more results in the 5.5. chapter).

Table 6. **Chalaati Glacier area and length change since the ~1810 according to the time periods between the dated positions of glacier terminus (the average error terms for length change are ±15 m)**

Таблица 6. **Изменение площади и длины ледника Чалаати с ~1810 г. за периоды времени между датированными положениями его фронта (средние значения погрешности для изменения длины составляют ±15 м)**

Time periods	Area change, %	Area change, ~% yr^{-1}	Terminus change, m	Terminus change, m yr^{-1}
1810–1840	4.4±9.9	0.15	215	7.2
1840–1880	1.1±10.2	0.03	185	4.6
1880–1910	2.5±10.3	0.08	470	15.7
1910–1930	1.2±10.3	0.06	80	4.0
1930–1940	0.2±10.4	0.02	110	11.0
1940–1960	5.6±8.0	0.28	440	22.0
1960–1971	3.9±6.0	0.35	270	24.5
1971–1986	5.8±6.3	0.39	135	9.0
1986–2000	5.0±6.5	0.36	80	5.7
2000–2018	10.2±5.9	0.57	295	16.4
1810–2018	33.8±7.4	0.16	2280	11.0

5.5 *Glacier change since the XIII century.* ^{10}Be CRE ages from the surface of the oldest Moraine (M8) suggest that the age of the upper glacial unit and of the corresponding glacial advance is at least CE ~1300. Neither lichen nor tree ring were able to provide a reasonably close age estimate of this surface. The trees were too young (up to 2 hundred years old) and we did not find any lichen larger than 65 mm on this surface (except the one single lichen 85 mm on the M7). The reason for this is either the lack of suitable material on the surface of the moraines, specific conditions for lichens slow growth (shade) or partly renovated surface of the moraines. If indeed the moraine is 600–700 years old as we identified by ^{10}Be the lichens should be almost 200 mm.

Since the ~1810 Chalaati Glacier area decreased by 33.8±7.4% or ~0.16% yr^{-1} from 14.9±1.5 km^2 to 9.9±0.5 km^2 while its terminus elevation rose from ~1620 m to ~1980 m during the same time (Table 5; Fig. 6). While area was decreasing, Chalaati Glacier retreated steadily over the past two centuries. The most intense retreats occurred in ~1880–1910, 1940–1971, and 2000–2018, while the slowest retreats have been recorded in ~1840–1880, 1910–1930, and 1986–2000 (Table 6). According to the

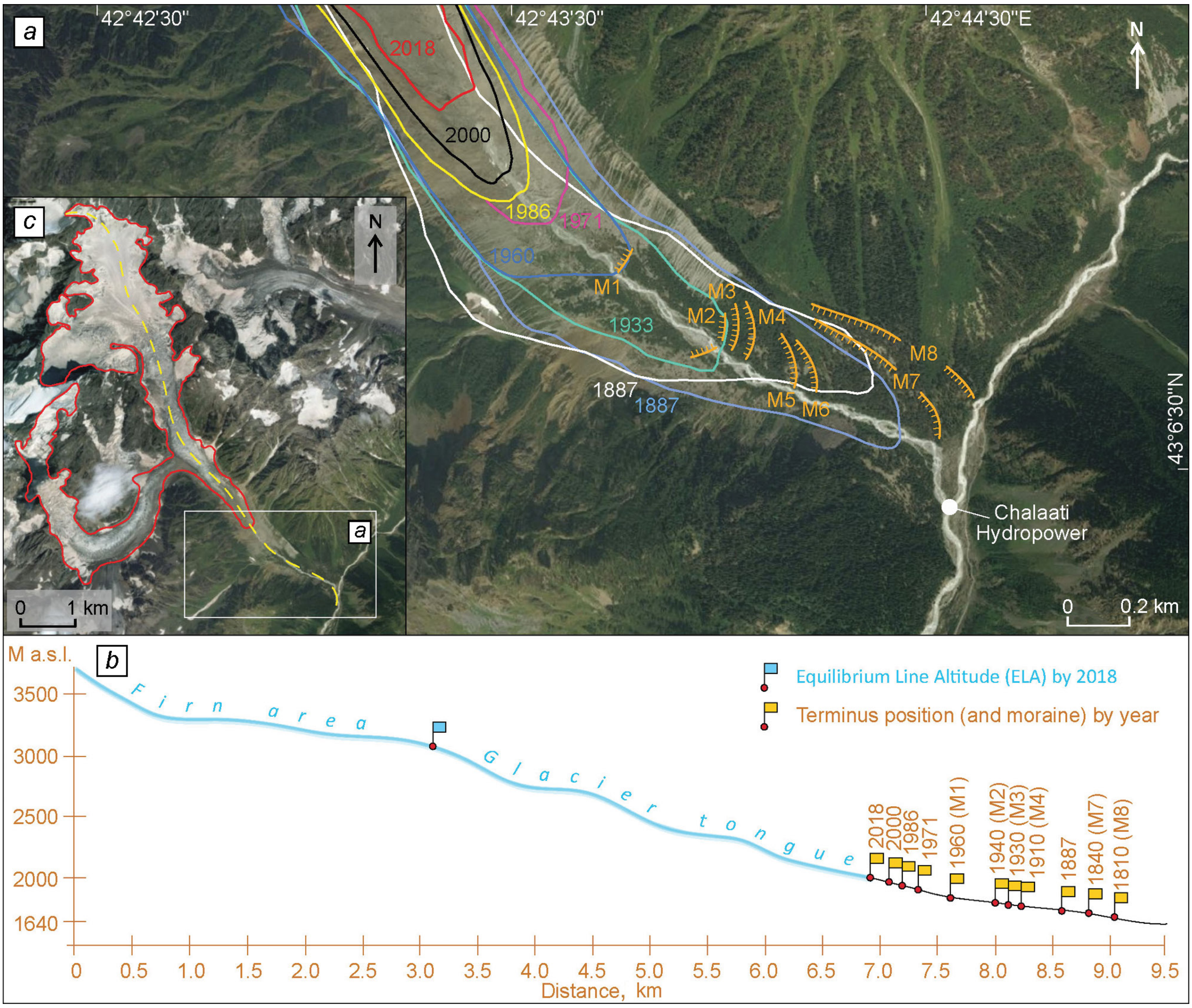

Fig. 6. Chalaati Glacier change (*a*) since the Little Ice Age (GeoEye 2014 image is used as background).
Different colors of outlines show glacier margins in different years. Moraine M8 corresponds to the CE 1810; M7 – 1840; M4 – 1910; M3 – 1930; M2 – 1940; M1 – 1960.; *b* – Chalaati valley longitudinal profile (based on ASTER GDEM, 2011) and Chalaati Glacier terminus positions according to the different years; *c* – yellow dotted line shows Chalaati valley longitudinal profile.

Рис. 6. Сокращение ледника Чалаати (*а*) после малого ледникового периода (изображение GeoEye 2014 использовано в качестве фона).
Различные цвета контуров показывают края ледника в разные годы. Морена M8 соответствует CE 1810 г.; M7 – 1840 г.; M4 – 1910 г.; M3 – 1930 г.; M2 – 1940 г.; M1 – 1960 г.; *b* – продольный профиль долины Чалаати (по данным ASTER GDEM, 2011 г.) и положение конца ледника Чалаати в разные годы; *c* – жёлтая пунктирная линия показывает продольный профиль долины Чалаати

previous detailed field measurement of the terminus position of Chalaati, the retreat in 1990s was interrupted by an advance. Microstadial moraines in front of Chalaati Glacier confirm ~20 m glacier advance during 1990–1993 [11] that gives a confidence in our measurements (small retreat rates between years 1986 to 2000). Moreover, Chalaati Glacier retreat between 1880s and 1960s (~1100 m) is in line with retreat measurement by Tsereteli [17], according to which, the Chalaati Glacier has retreated over more than 1000 m from 1890s to 1960s.

Unlike the other investigated periods, glacier area loss rates over the last three decades (since the 1986) are much higher compared to the relative terminus retreat rates (see Table 6), suggesting that the glacier area decrease over this time period progressing not

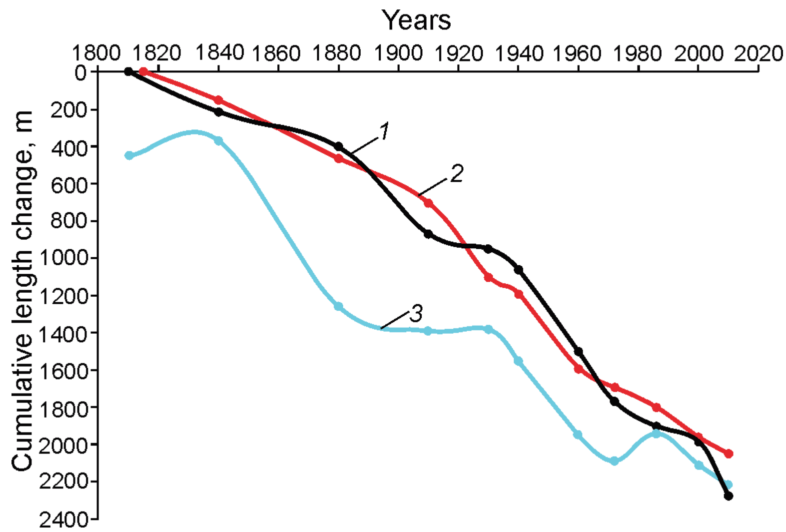

Fig. 7. Comparison of cumulative curves of terminus changes:
1 – for the Chalaati Glacier; *2* – for the Tsey Glacier in the northern Greater Caucasus [7]; *3* – Mer de Glace Glacier in the French Alps [40]

Рис. 7. Сравнение кумулятивных кривых изменения длины ледников:
1 – ледник Чалаати; *2* – ледник Цей на северном макросклоне Большого Кавказа [7]; *3* – ледника Мер-де-Глас во Французских Альпах [40]

only the terminus expense but also upper bodies of the glacier. This can be the result of the supra-glacial debris cover area and thickness increase near the terminus similar to some glaciers of the Greater Caucasus (e.g. Djankuat Glacier, [37]) which became more pronounced after 2000 [12]. We note that this requires more detail investigation and it can be the topic of the future study. Even though the century long trend of glacier retreat is global, and the rate of this retreat has increased in the past few decades, the retreat trend between 1940 and 1971 is unusual for Chalaati Glacier in the context of the past two centuries and it requires additional research.

5.6. *Comparison with other glaciers.* The ^{10}Be CRE ages are in line with global trends [2] of glacier advances in the second half of the Holocene and, in particular, during the Little Ice Age. The early advance of Chalaati Glacier 600–700 years ago is broadly consistent with minimum ^{14}C age for a moraine in the Bezengi Valley on the northern slope of the Greater Caucasus (CE 1245–1428) [9]. Chalaati advances are also in phase with other studies from the European Alps, where the general advance is documented in the late XIII century that culminated between CE ~1350 and ~1385 at Great Aletsch, Gorner (Switzerland) [38], and Mer de Glace (France) [39].

The dendrochronological data of this study also fits to other investigation from the northern slope of the Greater Caucasus. e.g. according to Solomina et al. [7] general glacier retreat on the northern slope started in the late 1840s. Four to five minor re-advances occurred in the period between CE 1860s and 1880s and three re-advances or steady states in 1910s, 1920s and 1970s–1980s, which again are agreement with lowest retreat rates or steady states between ~1840–1880 (~4.63 m yr^{-1}) and 1910–1930 (~4.0 m yr^{-1}) of the Chalaati Glacier. In addition, these recorded length changes of Chalaati Glacier are quite similar to changes observed in similar size Tsey Glacier (northern counterpart) over the past two centuries [7], while these are quite different to changes observed in the Mer de Glace Glacier (France) with several advance phases since the beginning of the XIX century [40] (Fig. 7). However, to be more robust, all these comparisons at the regional scale of the Georgian Caucasus need more data collection, observations, and enhanced chronology that had to be confronted to those obtained in other mountain ranges.

6. Conclusions

We present the first Chalaati Glacier variations analysis including multitemporal data sets covering the time period since the Little Ice Age. In situ ^{10}Be CRE ages, dendrochronology, lichenometry, along with the manual digitization from 1887 and 1960s topographic maps and satellite imagery from 1971 (Corona), 1986, 2000 (Landsat 5) and 2018 (Sentinel) were used to map the glacier surface area to substantially improve the regional existing knowledge.

The main study findings can be summarized as follows:

1) based on in situ ^{10}Be CRE ages, the Chalaati Glacier reached its maximum extent in the past millennium probably at the onset of an early Little Ice Age 0.73±0.04 kyr ago (CE ~1250–1330), even if more data are needed to get a better constrain on the age of this advance. This maximum extent recorded in this paper corresponds to moraine M8;

2) according to minimum tree-ring dates, the same oldest terminal moraine (M8) date back to the very beginning of the 19th century (~1810), while the second oldest moraine formed in the ~1840 (M7). Moraines from the 20th century were dated as ~1910 (M4) ~1930 (M3), ~1940 (M2), and ~1960 (M1);

3) since the ~1810, Chalaati Glacier decreased by 33.8±7.4% (~0.16% yr^{-1}) with highest decrease rates in 1971–1986 (~0.39% yr^{-1}) and 2000–2018 (~0.57% yr^{-1}), while the lowest rates in 1840–1880 (~0.03% yr^{-1}) and in 1910–1940 (~0.04% yr^{-1});

4) over the last two centuries glacier terminus retreated by about 2280 m with highest retreat rates in 1940–1971 (~22.9 m yr^{-1}) and in 2000–2018 (~16.4 m yr^{-1}), while the lowest rates in ~1840-1880 (~4.6 m yr^{-1}) and in 1986-2000 (~5.7 m yr^{-1}).

Future studies can be focused in collection of more data from other glacier valleys in order to better define the Little Ice Age glacier extend in regional context.

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Расширенный реферат

Лихенометрические исследования морен малого ледникового периода у ледников южного макросклона Большого Кавказа, выполненные Н.А. Голодковской в 1980-х годах [9], фактически, единственный источник информации о времени наступаний этих ледников в прошлом. В этой работе авторы приводят первые датировки морен ледника Чалаати в Сванетии, возраст которых определён с помощью космогенных изотопов бериллия ^{10}Be. Кроме того, для определения времени и масштабов колебания ледника Чалаати (Грузия) в прошлом были использованы космические снимки (Corona, Landsat 5 TM и Sentinel 2B), старые карты (1887, 1933, 1960 гг.), повторные фотографии, дендрохронология и лихенометрия. Исторические свидетельства о положении конца ледника имеются для 1868 г. [14] (1585 м), 1905 г. [15] (1628 м), 1933 г. [16] (1738 м), 1959 г. [18], 1980 г. [20] (1880 м), 2011 г. [13] (1950 м).

Три пробы на ^{10}Be были отобраны ручным молотком и долотом в сентябре 2018 г. с горизонтальных и субгоризонтальных верхних поверхностей крупных валунов высотой более 60 см, расположенных на самой внешней морене на левом борту долины. Валуны были устойчивыми и не имели признаков поверхностной эрозии. Координаты и высоты образцов регистрировались с помощью портативного GPS, а топографическую экранировку (линию горизонта) определяли с помощью клинометра и компаса. Образцы обрабатывали в лаборатории CALM lab (Cosmonucléides Au Laboratoire de Meudon-France). Длина ледников определялась в соответствии с рекомендациями GLIMS (www.glims.com). Самый длинный поток ледника определялся вручную как перпендикуляр высотным контурам. Измерения положения фронта ледника проводили с использованием контуров ледника для каждой даты, вдоль ледового фронта – перпендикулярно течению.

Мы оценили неопределённости вычисления площади ледника буферным методом. Ошибки определений площади ледника составили ±5,6% для 1960 г., ±6,3% для 1972 и 1986 гг. и ±6,7% для 2000 г. (размер буфера ±30 м), в то время как неопределённость составила ±5,1% для 2018 г. (размер буфера ±20 м). Три образца породы (см. табл. 3), которые были отобраны на горизонтальной поверхности дистальной левой береговой морены M8 (см. рис. 2) на анализ ^{10}Be, имеют возраст 4,2±0,65, 0,79±0,08 и 0,67±0,1 тыс. лет. Возраст 4,2 тыс. л.н. мы сочли аномальным (возможно, из-за наследования сигнала). Образцы Geo 1 и Geo 3 дают средний возраст ^{10}Be в интервале 1250–1330 гг. и означают образование морены M8 в начале малого ледникового периода. Однако из-за очень ограниченного числа проб средний возраст морены по ^{10}Be должен рассматриваться как предварительный. По своим масштабам это наступание в малом ледниковом периоде было максимальным. Второй максимум, когда ледник достиг почти такой же длины, датируется примерно 1810 г.

Таким образом, ледник Чалаати на южном склоне Кавказа наступал примерно в то же время, что и ледники в Альпах и других горных странах Северного полушария. С этого времени до 2018 г. площадь ледника уменьшилась с 14,9±1,5 км^2 до 9,9±0,5 км^2 (33,8±7,4%, или ~0,16% год$^{-1}$), а его длина сократилась на ~2280 м. Скорость отступания была неравномерной: она достигла максимума между 1940 и 1971 г. (~22,5 м год$^{-1}$), самая медленная скорость отступания была в 1910–30-х годах (~4,0 м год$^{-1}$). Высота конца поднялась с ~1620 м до ~1980 м в период с 1810 по 2018 г.

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