Research Paper

The Holocene
2022, Vol. 32(5) 468–481
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DOI: 10.1177/09596836221074029
journals.sagepub.com/home/hol
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Late-Holocene advances of the Greater Azau Glacier (Elbrus area, Northern Caucasus) revealed by ^{14}C dating of paleosols

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Abstract

Three paleosols buried in the left lateral moraines of the Greater Azau Glacier (Northern Caucasus) were identified in an excavated outcrop (43.2658 N, 42.4766 E, 2370 m a.s.l.). When the glacier was overlying the surface of the lateral moraines at this site, the thickness of the ice was 50 m and more above the valley floor. Fragments of charcoal from the uppermost soil (S1) buried 0.6 m below the surface yielded the radiocarbon date 130 ± 20 yr BP (IGAN$_{AMS}$-6826) (AD 1680–1939). The middle soil (S2), buried at the depth of 13 m yielded two ^{14}C dates 320 ± 20 yr BP (IGAN$_{AMS}$-8127) (bark of birch) (AD 1496–1641) and 1190 ± 20 yr BP (IGAN$_{AMS}$-8126) (AD 774–889) (charcoal). We suggest that the soil S2 has been formed between these dates during the Medieval Warm Period and in the early Little Ice Age. The lowermost (S3) unit lying 15 m below the surface is the thickest (0.4–0.6 m), well-developed paleosol. Charcoal collected at the top of S3, yielded the date 1300 ± 20 yr BP (IGAN$_{AMS}$-6826) (AD 663–773), indicating a prominent glacier advance occurred shortly before this date. Two dates from the charcoal buried at the bottom of S3 (2855 ± 20 yr BP (IGAN$_{AMS}$-8125) and 2880 ± 20 yr BP (IGAN$_{AMS}$-6827) mark the beginning of a long episode of restricted glacier extent that lasted for about 1600 years. The dates at the bottom of the S3 paleosol constrain the end of glacier advance that occurred before 2800–2900 ^{14}C yr BP. The timing of most prominent advances of the Greater Azau Glacier in the past 3500 years is in general agreement with the Late-Holocene glacial chronologies in the European Alps, Scandinavia and other regions of the Northern Hemisphere.

Keywords

glacier fluctuations, Little Ice Age, Medieval Warm Period, moraine, paleosol

Received 18 October 2021; revised manuscript accepted 30 December 2021

Introduction

Modern glacier retreat is one of the most unambiguous indicators of global warming (IPCC, 2021). Thus, the reconstruction of glacier variations in the past is a useful tool to assess the former climatic changes in order to disentangle the natural and anthropogenic forcings of climate variations.

The most common indicators of former glacier advances are glacial moraines that can be dated using historical descriptions, tree-rings, lichenometry, radiocarbon, optical luminescence, and terrestrial cosmogenic nuclides (TCN). The reconstruction of the chronology and magnitude of glacier recession periods are more complicated. Often proglacial lake sediments are used for this purpose (Larocca and Axford, 2021; Larocca et al., 2020; Leemann and Niessen, 1994; Nesje, 2009). Another way to reconstruct the timing, duration and the scale of glacier retreat in the past is the analysis of organic material primarily of in situ wood (e.g. Agatova et al., 2012; García et al., 2020; Joerin et al., 2008; Le Roy et al., 2015; Luckman et al., 2020; Nicolussi and Patzelt, 2000; Nicolussi and Schlüchter, 2012) and other plant macrofossils (e.g. Humlum et al., 2005; Miller et al., 2017) buried by advancing glaciers and later released due to subsequent glacier retreat.

The paleosols buried in till are among the records that can help to constrain the timing of former glacier fluctuations in the past and assess the environmental and climatic parameters during the periods of glacier recession and the development of the soils (Menounos et al., 2009; Reyes and Clague, 2004; Röthlisberger and Geyh, 1985; Röthlisberger et al., 1980).

In this paper, we report the results of the study of paleosols buried in situ in the left lateral moraines of the Greater Azau Glacier in the Northern Caucasus. Paleosols are of interest for understanding the history of glaciation, as they contain materials for radiocarbon dating. The ^{14}C dates provide information about both the duration of soil development, that is, the periods of glacier retreat, and the intervals of glacier advances.

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The section with the sequence of paleosols was exposed during the construction of the Azau Star Hotel. It was first described in 2018 by O. N. Solomina, T. M. Kuderina, and V. A. Shishkov, and re-examined in 2019 for a more detailed analysis of stratigraphy of paleosols by A. L. Alexandrovskiy.

These new records can shed light on the Late-Holocene history of this glacier, as well as on the environmental history of the Northern Caucasus in general, which is still very poorly known. The book by Serebryanny et al. (1984) remains the only comprehensive study of this topic. The Holocene glacier history of the Northern Caucasus is still largely based on four ^{14}C dates of organic material buried in the glacial and glacio-fluvial deposits in the Bezengi valley that broadly constrain the advances that occurred before 10.3–8.5 ka, 10.3–8.5 ka, and 8.3–6.2 ka, at approximately 4.5 ka (uncalibrated) and during 13th–19th centuries (Serebryanny et al., 1984). However, the correspondence of the stratigraphic data to the moraines of the Bezengi Glacier except for those of the Little Ice Age (LIA, 13th–19th centuries according to Serebryanny et al., 1984) remains unclear.

The main source of information that is used for the dating of moraines in the Caucasus is historical evidence, lichenometry and tree-ring dates (Solomina et al., 2016). Thus, the age of Caucasus moraines older than three to four centuries remains unknown. For this reason, the new set of AMS and LSC radiocarbon dates that we report in this paper might be an important contribution to the reconstruction of glacier and climate fluctuations in this region over the past three millennia.

The climate of the Caucasus largely depends on in the mid-latitude westerly winds. Therefore, there is a certain similarity in climate and glacier variations in the Caucasus and in Western Europe, which was noticed long ago (Solomina et al., 2016; Tushinsky, 1958, 1968). Moreover, the mass balance of the Greater Azau Glacier depends on climatic conditions on Elbrus, – the highest Mount in Europe, – and is indicative of free atmosphere conditions in the northern mid-latitudes of the Northern Hemisphere (Mikhalenko et al., 2020). Thus, this single-site study may be of a greater relevance in the context of larger-scale paleoclimatic processes.

Study area

The Greater Azau Glacier (43.28 N, 42.44 E), is located at the southern slope of Elbrus volcano (5642 m a.s.l.), in the central part of the Northern Caucasus (Figure 1). The climate of the Greater Caucasus is temperate continental. Westerlies as well as the proximity of the Black and Caspian seas affect the regional climate. At the elevation of 1800–2200 m a.s.l. the mean monthly temperature in July is +12°C to +14°C, in January −5°C to −7°C. The sum of precipitation in summer at Terskol meteorological station (2150 m a.s.l.) reaches 350 mm, in winter – 210 mm (Mikhalenko et al., 2020).

Granitoids and gneisses, as well as the volcanites of Elbrus (diabases and tuffs) dominate in the Elbrus region in general and as well as in the moraines of the Greater Azau.

Vegetation of the Northern Caucasus belongs to a moderately humid forest-meadow mountainous type with a pronounced altitudinal zonation. In the lower part of the Baksan valley, pine forests with an admixture of small-leaved forests and shrubs on the mountain-forest brown soils dominate. The soils are represented by underdeveloped (petrozem) and dernovo-podbur. The humus content of these soils ranges from 3% to 15.5%, pH 4.4–4.6 (Shishov et al., 2001).

Above the timberline, the vegetation is represented by subalpine and alpine mountain meadows on the regosols, leptosols, and folic cambisols (IUSS Working Group WRB, 2015). Gennadiev (1978, 1990) who studied in detail the soils developed at the Greater Azau moraines described the mountain-meadow and mountain-meadow-forest soils with no signs of podzolization. Pseudopodzolic soils (luvisols) were distinguished for the lower elevation zones in spruce, fir and beech forests on loamy loess-like rocks. According to the Russian classification (Shishov et al., 2004), mature soils on the moraines belong to the dernovo-podburs, and underdeveloped soils to petrozems. According to the WRB international classification (IUSS Working Group WRB, 2015), modern soils in the Greater Azau moraines are regosols. The paleosols that we discuss here belong to folic cambisol (loamic, humic), or haplic (or someric, if the humus horizon is less than 20 cm) umbrisol (loamic).

Fluctuations of Greater Azau glacier

State-of-the-art

The Greater Azau is one of the most easily accessible and well-studied glaciers in the Caucasus (see Figure 1). However, despite an almost two centuries-long history of investigations many important details of variations of the glacier before the 20th century remain unclear. The chronology of the Greater Azau fluctuations in the late 19th–early 21st centuries is based on historical documents, old maps, instrumental records and satellite images (see, e.g. Atlas of the Elbrus Glaciers, 1965; Baume and Marcineck, 1998; Solomina et al., 2021; Tushinsky, 1958; Volodicheva, 2013; Volodicheva and Voitkovskiy, 2004; Zolotarev, 2009; Zolotarev and Seinova, 1983). We used this to visualize the Greater Azau glacier retreat (see Figure 1). An image acquired by the WorldView-2 satellite on 16.10.2009 and uploaded in Google maps web-service was used as a master image. Using the control points we georeferenced Pleiades-1B image made on 08.09.2017 and the aerial images acquired by Soviet cameras on 26.09.1987, 25.09.1981, 12.08.1957. The same way, using the control points, we georeferenced the map by Burmester (1913). He marked the limits of the Greater Azau glacier in 1911 and the glacier front position from the map created by the Military Topographers in 1890. The digital elevation model used in this study was created based on Pleiades-1B stereo-pair acquired on 08.09.2017 (Shean et al., 2016). Based on this data we estimated the rates of the Greater Azau glacier retreat (Table 1 in Supplemental Materials).

According to the instrumental data and direct observations, in the 20th century the glacier was retreating with short re-advances in 1911, in 1930–1932, and in 1972–1981 (Volodicheva and Voitkovskiy, 2004). The retreat has been continuing in the past 40 years when the mass balance of the Elbrus glaciers decreased dramatically due to the summer warming and the increase of summer insolation (due to reduced cloudiness) despite the increase of winter snow accumulation. Since 1960s the Elbrus glaciers have lost almost 29% of their area (Mikhalenko et al., 2020). In 2017, the front of the Greater Azau Glacier was located at 2745 m a.s.l.

The positions of the glacier front before the early 20th century are much less certain. The first description of the glacier dates back to 1849 (Abich, 1875), but regular expeditions started visiting the valley only in the 1880s (Freshfield, 1896; Von Déchy, 1905). According to Volodicheva and Voitkovskiy (2004), who summarized the historical information and attempted to identify the location of former glacier front positions, from the frontal moraines at the bottom of the valley were deposited in 1849, 1876, 1884, and 1890 (see Table 1 in Supplemental Material and Figures 1 and 2). It is difficult to identify the precise positions of the glacier in 19th century due to the low accuracy of the measurements of contemporary front elevations. Due to the flatness of the valley, these measurements are of limited value, while the narrative descriptions allow various interpretations. However, the first photographs, for example, one taken by V. Sella in August 1889 (Figure 2a) show that the front of the glacier in 1880s was

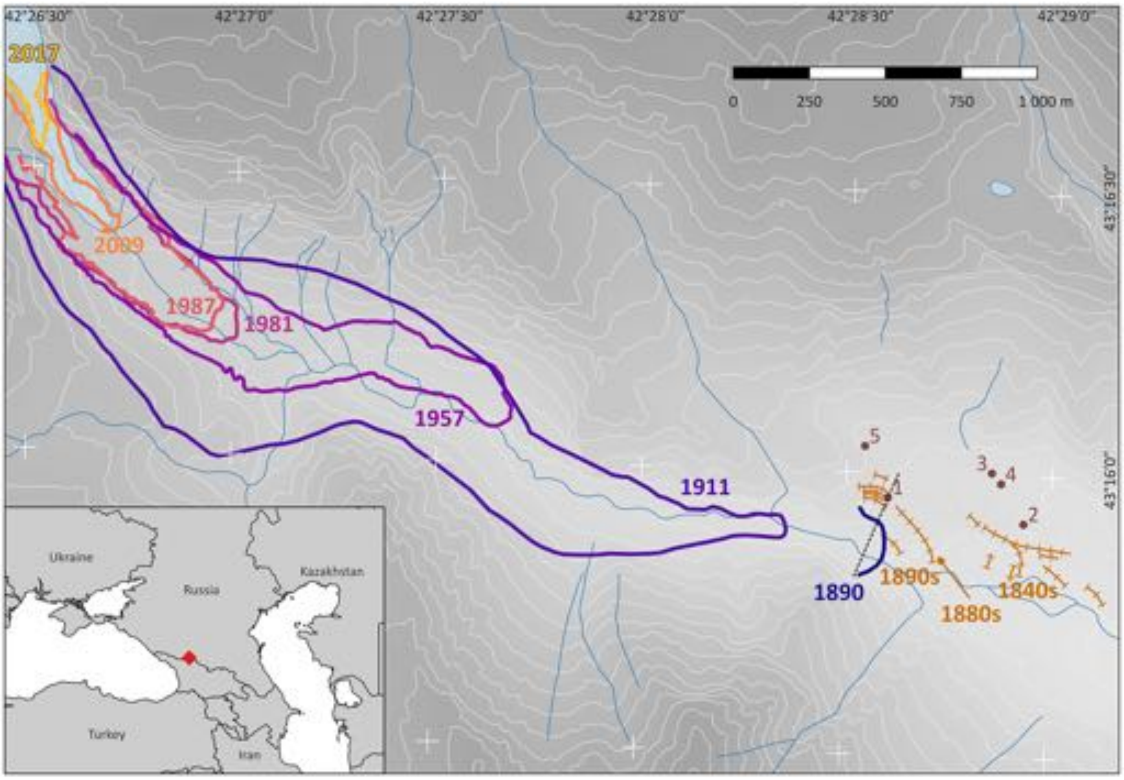

Figure 1. Location of the Greater Azau Glacier (red symbol at the overview map). The Greater Azau Glacier tongue positions reconstructed from the satellite images and the moraines of this glacier (brown) with their tentative dates. Dark brown numbers mark the locations of the sections with the ^{14}C dates of paleosols (see details in the text). Black dashed line indicates the cross-valley profile at Figure 3.

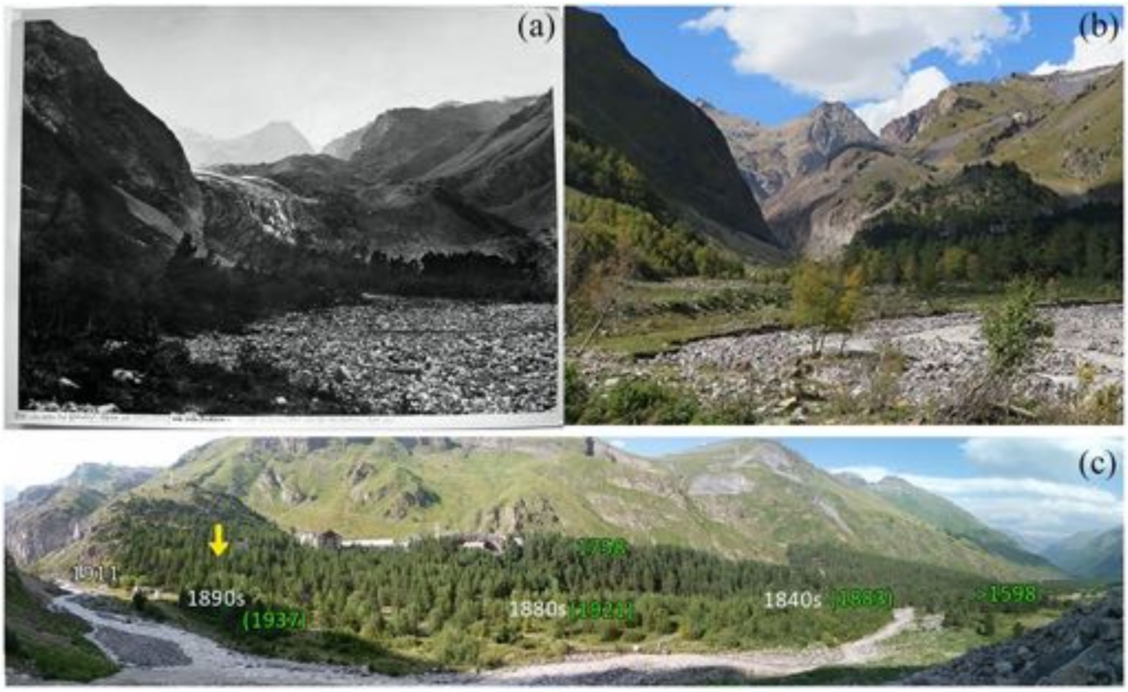

Figure 2. Photo of Greater Azau Glacier by V. Sella, 1889 (a). Repeated photo by V. Mikhalenko 2014 (b) Panorama of Greater Azau valley below "the gate" (by V. Mikhalenko and I. Bushueva). White numbers – the dated positions of the front of Greater Azau Glacier identified by historical data, green numbers – minimum limiting tree-ring ages of moraines. Yellow arrow marks the location of the "Azau Star" section (c).

located in the proximity of the narrow "gate," approximately across or slightly below the section with paleosols that we call "Azau Star" (see Figure 2). At that time ice was filling the valley and was up to 50 m thick at the front. Judging by the fresh surface of the left lateral moraines that one can see in Sella's photo, the glacier was previously even thicker and larger and covered the surface of these moraines a few decades before the 1880s.

Most intriguing is the location of the glacier front in 1849 when it was described for the first time (Abich, 1875). Many later visitors tended to use this position as a reference point. Ironically,

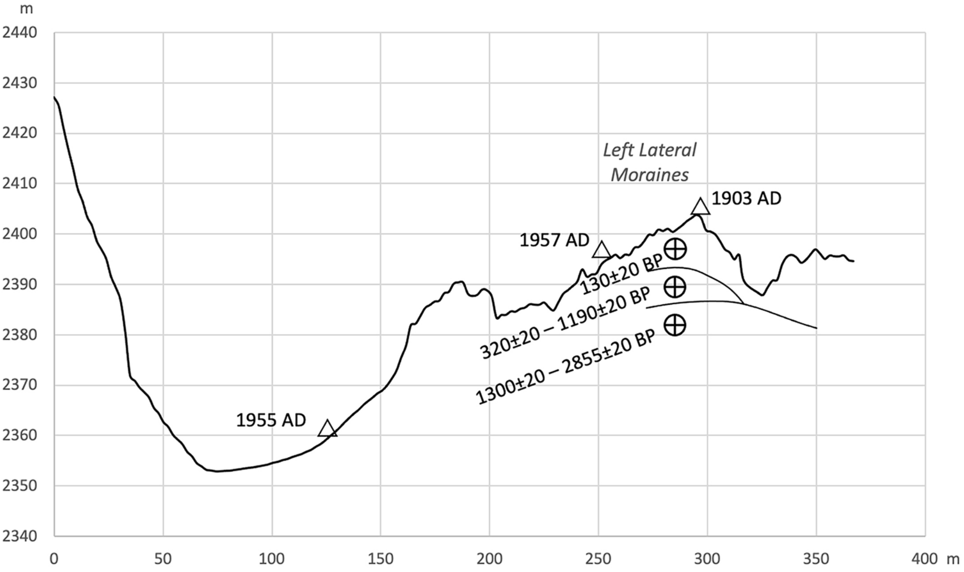

Figure 3. Cross-valley profile of Greater Azau left lateral moraines and stratigraphic position of paleosols (see Figure 1 for profile location).

despite a very detailed description and the existing drawing of the glacier by Abich, the location of the front in 1849 is still not clear (see discussion in Solomina et al., 2021; Volodicheva, 2013; Volodicheva and Voitkovskiy, 2004; Zolotarev, 2009; Zolotarev and Seinova, 1983). Volodicheva and Voitkovskiy (2004) believe that it was located at the elevation of 2320 m a.s.l. while Zolotarev (2009) places the front much higher, at the elevation of 2350 m a.s.l. The discussion originates from different interpretations of the drawing made by Abich from a long distance. Solomina et al. (2021) attempted to use the minimum limiting ages of trees growing on the moraines to solve this problem, but due to the large disturbances of the forest at the bottom of the valley by the avalanches in 20th century it turned out that this was not possible: the trees growing between 2350 and 2320 m a.s.l. are all young and do not confirm, but also do not contradict either of the two versions of glacier front locations (see Figure 1).

Figure 2c shows the minimum ages of the moraines of Greater Azau glacier. The highest lateral moraine, which was conventionally attributed to the 17th century by analogue with the European Alps (Volodicheva and Voitkovskiy, 2004), was formed before the end of the 16th century. The oldest tree (AD 1598) in the valley was found at the eroded frontal moraine located at 2294 m a.s.l. Judging by the size of maximum diameters of *Rhizocarpon geographicum* (120–130 mm) growing on this surface, the age of the moraine is underestimated (Solomina et al., 2016).

Materials and methods

Figure 3 demonstrates the profile of the valley and the stratigraphic position of the section "Azau Star" with paleosols. The 20 m-high section is illustrated in Figure 4. Two steps lined with large boulders are artificial. The boulders were removed from the overlying strata and stacked by builders on the flat artificial terraces for convenience. The exposed section composed mainly of diamicton which is poorly sorted in both texture and particle shape, grain sizes ranging from clay to boulders with different degrees of roundness. It also contains some layers of gravel and crushed stones, as well as buried paleosols. A description of the section is displayed in the Table 1.

In the Tables 1 to 4 and below we describe the stratigraphic units from young to old. The organic-rich and clay-rich horizons are interpreted as soils (marked as S1, S2, S3) developed on the moraine surfaces and subsequently buried by the tills as a result of the advances of the Greater Azau Glacier. These organic clay horizons are termed "paleosols." The layers between the paleosols are marked as T1, T2, T3, T4 (tills) and their ages are constrained by the ^{14}C AMS dates of the overlying and underlying paleosols. Moreover, since the time intervals of the deposition and development of some paleosols were quite continuous, the ages of the tills are further limited by the dates of the bottom layer of the covering paleosol and the top layer of the underlying one. Although macrofossil samples are not collected precisely from the contacts of the paleosols with the tills, we suggest that these dates bracket the beginning and the end of soil deposition and, hence, the maximum limiting date of the underlying till and minimum limiting date of the overlying till. This way we assess the timing of advances and retreats of the Greater Azau Glacier and the duration of periods of the lesser ice extent. We believe that all paleosols are intact and lie in situ.

Fragments of charcoal, plant remains (bark of birch), as well as the total mass of the humus horizon of the soil were collected from paleosols for radiocarbon dating. In total, 10 samples from the three paleosols were dated using LSC ^{14}C (Table 2). Radiocarbon dates were obtained by the liquid scintillation counting method (LSC) and by acceleration mass-spectrometry (AMS) technique at the Laboratory of Radiocarbon Dating and Electronic Microscopy of the Institute of Geography RAS, Moscow. For the charcoal and plant remains dating, an acid-base-acid (ABA) pretreatment technique was applied. For the humus horizons, the humic acids (HA) were separated and dated. The activity of ^{14}C (LSC method) was determined by using the Quantulus-1220 liquid scintillation counters. The sample preparation for AMS (i.e. graphitization, pressing and mounting on a target) was performed in the Radiocarbon Laboratory of the Institute of Geography using the AGE-3 graphitization system (Ionplus). ^{14}C AMS measurements were performed at the Center for Applied Isotope Studies, University of Georgia (Athens, USA) using the CAIS 0.5MeV AMS. The conventional radiocarbon ages were calibrated (2σ standard deviation) applying the CALIB Rev 8.2. program, with the IntCal20 calibration data set (Reimer et al., 2020).

The content of organic carbon (OC) and total nitrogen (TN) were determined using Vario ISOTOPE Cube CHNS-analyzer. In the soil samples, inorganic C was removed with 1M HCl treatment and then rinsing in deionized water. Samples were dried using a Scientz-10N freeze dryer and crushed for homogenization in Retsch Mixer Mill MM 400.

We also analyzed the granulometric composition of soils and diamicton, C and N content, and C/N ratio in the paleosols (Tables 3 and 4). In general, the increased values of the content of C and N indicate a duration of soil formation, moreover, in

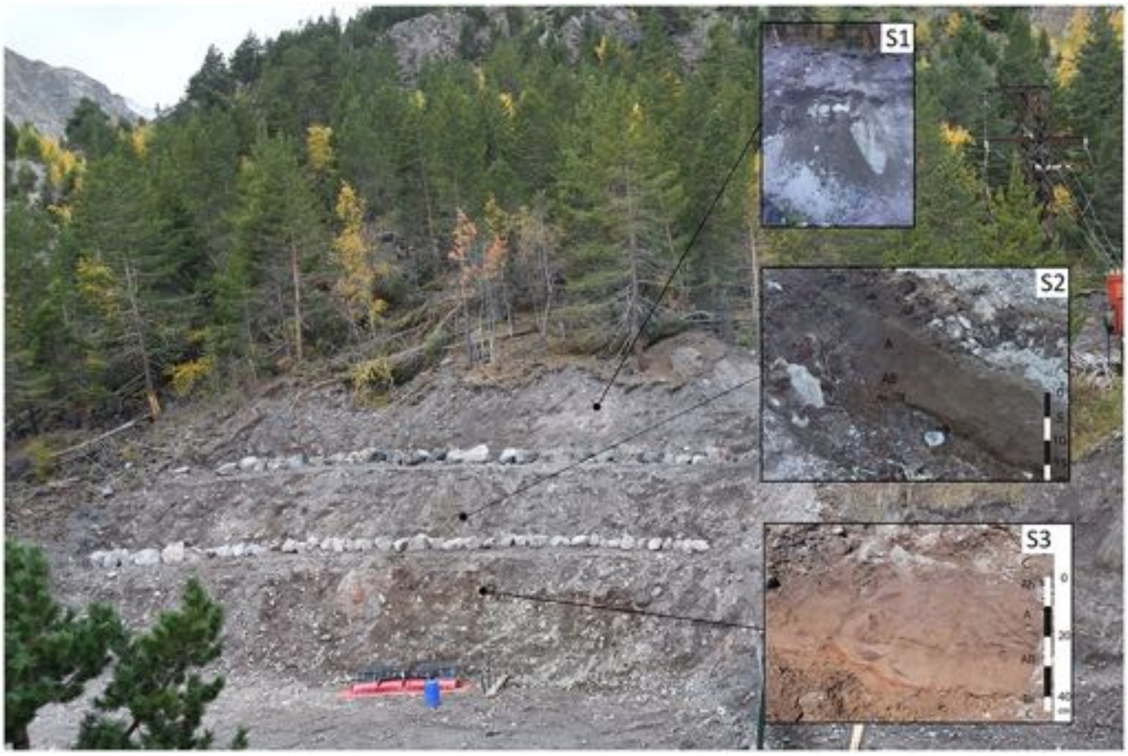

Figure 4. Section of the lateral moraines of the Greater Azau Glacier with S1, S2, and S3 paleosol profile. Photo by V. Mikhalenko, 2019.

favorable bioclimatic conditions. Grain size analysis was carried out using a combined method. Firstly, dry samples weighing 30 g were sieved on a sieve with an aperture of 2 and 1 mm. The content of fractions 1–2 mm and above 2 mm was determined by weighing. Grain size of the material thinner than 1 mm was determined by laser diffractometry using the Malvern Mastersizer 3000 particle size analyzer. Before measurements, the material was dispersed on the overhead shaker for 12 h with a 4% sodium pyrophosphate. After the initial preparation, the material was moved by pipette into a dispersing block of the analyzer. In the cuvette, the material was stirred for 100 s with a spinner at a speed of 2400 rpm and was exposed to the built-in ultrasound. After switching off the ultrasonic device, 10 repeated measurements were made. The results were averaged in the Mastersizer v.3.62 application. The calculation of the particle size distribution was carried out on the basis of the Fraunhofer approximation.

Results

Stratigaphy of the Azau Star section and it's interpretation

T1 glacier advance and S1 glacier retreat. The uppermost till (T1) exposed in the lateral moraine section is a 50–60 cm thick clast-rich diamicton embedded within a silty matrix (see Table 1, Figure 4). At the depth of 20 cm it includes a lens of loam darker and richer in organic material than the till although still too poor to be dated by radiocarbon. It indicates a potentially short period of glacier retreat from this site. Further re-advance, both occurred relatively recently, judging by the location of this layer very close to the surface of the moraine.

The S1 (see Table 1, Figure 4) paleosol is a loam layer buried in the till 60 cm below the surface. The S1 paleosol is similar in appearance to the lens of organic material described above, also extremely poor in carbon and nitrogen (see Table 3), but thicker and more continuous. The S1 has no clear evidence of proper soil development and, therefore, it would be more correct to consider it as leptosol – a lithological layer different from the till.

The date obtained from the humic acid from S1 paleosol (bulk sample collected from the entire unit) is characterized by $F^{14}C$ (fraction modern) > 1, most probably due to the input of modern carbon with soil solutions (see Table 2). The fragments of the charcoal spread out in the S1 yielded a young radiocarbon date 130 ± 20 yr BP (IGANAMS-6826) (calibrated as AD 1680–1939). The thickness of paleosol S1, its young ^{14}C age and poor C and N contents indicate that the time interval of the development of this stratigraphic horizon was short, not exceeding a few decades. It was deposited within one of the relatively warm intervals of the final stage of the LIA.

Additional tree-ring and historical data allow the calibrated date of the S1 paleosol to be constrained to the broad interval AD 1680–1939. The surface of the section represents at least six small lateral moraine ridges (see Figure 4) implying numerous minor re-advances of the Greater Azau Glacier each of smaller magnitude than the previous one. The moraines are overgrown with young birch and pine trees. The first rings in the oldest pines on these moraines date back to AD 1903 and AD 1909. Taking into account the corrections for the coring height and for the time of pine settlement in this area, the minimum age of stabilization of these surfaces is AD 1880s–1870s (Solomina et al., 2016, 2021). Judging by the early descriptions and photographs (Figure 2a) in 1880s these moraines had a fresh-looking surface. Thus, the uppermost till T1 was deposited shortly before the AD 1880s, but not much earlier judging by the unvegetated fresh surface of the moraines.

The most obvious candidate for the advance occurred in 1680–1880s is a glacier expansion that occurred in 1849 (Abich, 1875). Abich revisited the site 24 years later and observed the glacier in a retracted position. He described fresh-looking left lateral moraines where he identified 17 "moraines en retraite" (Abich, 1875: 102) that he interpreted as annual levels of the degradation of the glacier. Based on this hypothesis, he decided that the glacier retreat began in 1856–1857. Thus, the timing of the S1 paleosol deposition can be further bracketed by the interval between 1680 and 1849 or 1680 and 1856/1857 if we accept the Abich' hypothesis of the beginning of the glacier retreat.

Table 1. General description of the "Azau Star" section.

	Units	Depth from the surface of the section, cm	Thickness of the units, cm	Properties	Sub-units within the horizons	Datings
1	T1	0–60	50	Diamicton	Poor organic layer, 1–3 cm thick	n/a
2	S1	50–70	5	A pale-brown (10YR6/3) light loam with an admixture of sand and the inclusion of gravel, no evidences of humus paint. Lies horizontally, the length of the exposed visible fragment does not exceed 2 m.	None	The charcoal particles from S1 yielded the AMS date 130 ± 20 ^{14}C yr BP (IGAN$_{AMS}$-6826), that gives a wide range of calibrated ages 1682–1939 AD. The date obtained from the humic acid from this horizon is characterized by F^{14}C (fraction modern)> 1
3	T2	70–100	30–50	Diamicton		n/a
4	S2	100–120	15–20	Loam layer without inclusion of fractions larger than 2 mm; signs of soil development: dark humus color, lumpy structure, although poorly expressed. The layer is inclined from the river (the slope is 15%, up to 20% at the bottom).	Poorly developed grayish-brown horizon Ab10-1 cm thick lies under the upper lamella. Below there is a dark grayish brown (10YR 4/2) Ab2 horizon 1–10 cm thick, and ABb horizon 10–15 (20) cm thick (grayish brown 10YR 5/2).	In the middle part of the loam layer within this soil horizon, the fragments of birch bark were found. The color of the bark is the same (grayish-brown) as the color of the enclosing mass. The bark yielded the AMS date 320 ± 20 yr BP (IGAN$_{AMS}$-8127), the charcoal layer at the bottom of this unit dates back to 1190 ± 20 yr BP (IGAN$_{AMS}$-8126). The humic acid from the top of the S2 soil horizon dates back to 210 + 60 yr BP (IGRAN-8316).
5	T3	120		Diamicton		n/a
6	S3	150–190	30–60	Slightly inclined from the river (inclination about 5%). The visible length of the horizon is more than 10 m.	Separated from the till from the top and the bottom by thin (about 1–2 cm), dense ferruginous layers (lamellae). The profile includes the horizons Ahb – Ab – AB b – C. In the middle and lower parts of the S3, there are discontinuous charcoal layers.	Beyond the upper loam layer, bounded by the lamellae, there are transition horizons, represented by loam with an admixture of detrital material (coarse sand and stones). In the lower transition layer, the charcoal particles in some places, are as abundant as those inside the S2 layer. C-10–2 cm. Till with an admixture of loam material. Bsb-2-0 cm. Ochreous-brown, cemented sandy loam. Ahb 0–2 cm. Gray-brown loam (10YR4/2 by Munsell) with an admixture of sand and gravel, dense, fresh, with weakly expressed lumpy structure. It contains some charcoal particles, but their concentration was insufficient even for the AMS dating. Ab2-20 cm. Gray-brown loam (10YR4/2), dense, fresh to moist, cloddy, with gradual transition. In the lower part, the particles of charcoal were found. The ^{14}C sample from the charcoal layer returned the date 1300 ± 20 yr BP (IGANAMS-8124). The humic acid date is 680 + 80 yr BP (IGRAN-8314). ABb 20–35 cm. Brown medium loam (10YR5/3), moist, structureless, dense. At the base of this horizon, two charcoal dates 2855 ± 20 yr BP (IGANAMS-8125) and 2880 ± 20 yr BP (IGANAMS-6827) are very similar. The humic acid date is 1290 ± 70 yr BP (IGAN-8315). Bsb35-36 cm. Cemented lamellae, very dense, ochreous-brown, with inclusions of detrital material. C 36–50 cm. Pale-brown gravelly-sandy loam (10YR6/3), alternating with gravelly-clastic till, dense, moist. Contains little particles of charcoal.
7	T4	Diamicton				

The minimum limiting dates of the moraines deposited before the AD 1849 advance in the Greater Azau valley are 1801 and 1598 (see Figure 2c). While the 1598 minimum date is too old to fit to the calibration interval 1680–1939 we cannot rule out that the advance that occurred shortly before 1801 may correspond to the T1 till. However, the age of the 1801 advance is doubtfully due to excessively large lichens on the surface of this moraine.

Although it is difficult to trace the continuation of the left lateral moraine ridges that break off at the "Azau Star" section down to the bottom of the valley, one of them probably corresponds to the end moraine deposited at 2320 m a.s.l. (see Figures 1 and 2c). Volodicheva and Voitkovsky (2004) tentatively attribute it to 1880s based on historical information, while Zolotarev and Seinova (1983) believed that this was the position of glacier front in 1849.

T2 glacier advance and S2 glacier retreat. Paleosols S2 and S3 are attributed to the umbrisols (IUSS Working Group WRB, 2015). The S2 paleosol is buried at the depth of 13 m from the surface of the section. This is an intact, gently inclined sub-horizontal layer sandwiched between the tills T2 and T3. The S2 paleosol is thicker (15–20 cm) than the S1 and it possesses a better-developed profile (see Figure 4). The ^{14}C date obtained from humic acid from the S2 paleosol is 210 ± 60 yr BP (IGAN-1816) (calibrated as 1524–1950) (see Table 2). The ^{14}C date 320 ± 20 yr BP (IGAN$_{AMS}$-8127) derived from the bark of birch located in the middle part of the paleosol S2 (see Figure 4) yielded a calibrated age AD 1496–1641. A layer of charcoals located a few centimeters below the bark returned a much older ^{14}C date 1190 ± 20 yr BP (IGAN$_{AMS}$-8126) (AD 774–889). Although there is no inversion of the dates, a large difference between the dates of the bark and the charcoal needs explanation. We suggest that the date 1190 ± 20 yr BP (IGAN$_{AMS}$-8126) (AD 774–889) is close to the beginning of the S2 formation, while the date of the bark may indicate the final stage of the soil development. We suppose that the bark belongs to the birch growing on the surface of the stabilized moraine with already developed soil and hence the age of its death is closer to its final stage shortly preceding its burial by a glacier advance (see Figure 4). We use this suggestion as a working hypothesis, but do not exclude the possible relocation of the bark from the younger deposits.

Table 2. Radiocarbon dates of paleosols of the of the "Azau Star" section.

Lab. No. IGAN	Buried soil	Depth, cm	Material	^{14}C yr., BP (1σ)/F^{14}C	Calibrated age, 2σ
6826	S1	0–5	Charcoal	130 ± 20	AD 1682–1939
8127	S2	10	Birch bark	320 ± 20	AD 1496–1641
8126	S2	10	Charcoal	1190 ± 20	AD 774–889
8124	S3	10–20	Charcoal	1300 ± 20	AD 663–773
8125	S3	40	Charcoal	2855 ± 20	1109–931 BC
6827	S3	30	Charcoal	2880 ± 20	1187–940 BC
8140	S1	0–2	HA	1.028 ± 0.024	
8314	S3	10–25	HA	680 ± 80	AD 1219–1420
8315	S3	25–40	HA	1290 ± 70	AD 608–892
8316	S2	0–10	HA	210 ± 60	AD 1524–1950

Thus, we hypothesize that the S2 paleosol development was interrupted in 1496–1641 by the glacier advance that deposited the T2 till covering this paleosol. From the top, the age of the T2 is constrained by the date of S1 (1680–1850s). S1 date largely confirms the date of T2 advance (1496–1641), but does not help to get a more precise age. The tree-ring minimum limiting age of the oldest moraines at Greater Azau forefield is AD 1598. With the corrections for the time of colonization (15–20 years) and the height of coring (10–15 years) the minimum date of moraine stabilization is two to three decades older. This moraine is situated at the elevation 2290 m a.s.l. slightly below the hypothetical location of the front position described by Abich in AD 1849 (1875). It means that the advance older than AD 1598 was of a greater extent than the one that occurred in AD 1849, and hence the ice most probably covered the crest of the left lateral moraines of our section at the elevation of 2400 m a.s.l. For this reason the advance >AD 1598 can be a candidate to interrupt the development of S2 paleosol. However, Solomina et al. (2016) judging by the size of maximum diameters of Rhizocarpon geographicum (120–130 mm) growing on this surface, suggested that the real age of the moraine is much older than this minimum limiting tree ring date (1598). The growth curve for lichens is not very well constrained in the Caucasus for this old part. Serebryanny et al. (1984) reported that the lichens as large as 100 mm grow at the surface of a moraine deposited in 13th–14th centuries (younger that the ^{14}C date 650 ± 80 yr BP (TA-867)). Taking into account all the uncertainties, we provisionally accept the wider time interval AD 1496–1641 as a potential timing of T2 advance.

Since the S2 is a relatively well-developed soil (see Figure 4), containing a dark humus horizon with a high content of soil organic matter, the interval of its formation undisturbed by glacier advances should be at least a few centuries long (Gennadiev, 1978, 1990). In fact, we suggest that it lasted for almost 900 years according to our ^{14}C chronology and began as early 1190 ± 20 yr BP (IGAN$_{AMS}$-8126) (AD 774–889).

Table 3. Grain size of paleosols and till, fraction content by %, of the "Azau Star" section.

Soil	Horizons, depth,* cm	Size of fractions, mm									
		0.0001–0.001	0.001–0.005	0.005–0.01	0.01–0.05	0.05–0.1	0.1–0.25	0.25–0.5	0.5–1.0	1.0–2.0	>2.0
S1	C 0-5	2.0	6.5	2.1	18.2	15.0	19.2	7.3	2.0	3.5	24.2
Till	–	1.0	5.8	2.8	7.1	3.3	5.0	4.5	3.1	8.9	58.6
S2	Ab1 0–1	0.7	5.9	5.4	31.2	26.2	24.6	5.2	0.7	0.0	0.0
	Ab2 1–10	0.6	5.3	6.0	40.2	27.7	17.6	2.5	0.1	0.0	0.0
	ABb 10–15	0.7	5.7	7.3	47.7	21.1	12.6	3.9	1.0	0.1	0.0
S3	Ahb 0–2	0.4	4.8	5.2	36.4	28.9	18.5	2.9	0.1	0.4	2.3
	Ab 2–20	0.7	6.3	7.0	41.6	26.5	16.7	1.2	0.0	0.0	0.0
	ABb 20–35	1.1	6.5	6.7	40.0	24.6	17.7	2.9	0.4	0.0	0.0
	Csb 35	1.3	6.9	5.8	27.0	21.7	17.3	3.6	0.4	2.4	13.7
	C 36–50	1.2	7.1	5.9	25.3	17.6	15.1	5.1	1.3	5.3	16.1

Fractions: <0.001 – clay, 0.001–0.005 – fine silt, 0.005–0.01 – medium silt, 0.01–0.05 – coarse silt, 0.05–0.10 – very fine sand, 0.10–0.25 – fine sand, 0.25–0.5 – medium sand, 0.5–1.0 – coarse sand, 1.0–2.0 – very coarse sand, >2 – gravel.
*Depth from the surface of the soils.

Table 4. Carbon and Nitrogen in the paleosols and in the till of the "Azau Star" section.

Soil	Unit	Horizons, depth, cm	C (%)	N (%)	C/N atm
S1	3	C 0–5	0.09	(0.01)	21.131
Till	4	–	0.16	0.01	21.588
S2	5	Ab1, 0–1	5.37	0.44	14.244
		Ab2, 1–10	5.13	0.42	14.276
		ABb, 10–15	4.41	0.33	15.756
S3	7	Ahb, 0–2	4.96	0.4	14.577
		Ab, 2–20	3.22	0.28	13.408
		ABb, 20–35	2.47	0.2	14.461
		Bsb, 35	2.18	0.16	16.057
		C, 36–50	1.91	0.14	15.450
$S3_{2018}$	7	Ab 10	4.66	0.4	13.705
$S3_{2018}$	7	ABb 25	3.61	0.28	15.134

T3 and T4 glacier advances and S3 glacier retreat. The lowermost paleosol S3 deposited 15 m below the surface of the lateral moraine is the thickest, well-developed soil layer 40–60 cm thick. The deepest part of the S3 under lower lamella (Bsb and C horizons, see Table 1 and Figure 4) is represented by unevenly mixed loam and till, with some charcoal particles. Above this stratum, a layer of loam 30–40 cm thick with no admixture of detrital material is accumulated. The S3 paleosol is represented by humus Ab and weakly expressed surface coarse humus Ahb horizons. However, the total profile of the paleosol S3 is somewhat larger than the one of the loam layer. Here under the lamella (Bsb), in the transition horizon C, the content of carbon and nitrogen is increased, and the fragments of charcoal were collected for the ^{14}C analyses.

The two dates from this unit obtained from humic acids of soil material collected at the depth of 10–25 cm and 25–40 cm are 680 ± 80 yr BP (IGAN-8314) and 1290 ± 70 yr BP (IGAN-8315), respectively. The charcoal accumulated 10–20 cm below the top of the S3 paleosol, yielded the date 1300 ± 20 yr BP ($IGAN_{AMS}$-8124) (AD 663–773). The two dates from the charcoal fragments buried at the bottom of the S3 paleosol are 2855 ± 20 yr BP ($IGAN_{AMS}$-8125) and 2880 ± 20 yr BP ($IGAN_{AMS}$-6827) (cal 1109–931 BC and 1187–940 BC).

The ^{14}C date of charcoal from the upper part of S3 (1300 ± 20 yr BP), indicates that the soil development was interrupted by a glacier advance in the AD 7th–8th centuries. The age of this advance that deposited the T3 till is constrained from the top by the date of the S2 paleosol (AD 774–889), that is, lies in a very narrow time interval: the till T3 pre-dates the AD 8th–9th centuries and post-dates the AD 7th–8th centuries. No dates of moraines older than three-four centuries are available in the Greater Azau valley for a comparison with these results.

The glacier recession episode (marked by the paleosol S3) lasted from 2800/2900 ^{14}C yr BP to 1300 ^{14}C yr BP, that is was at least about 1500–1700 years long. The well-developed profile and the thickness of the S3 paleosol confirms the suggestion of a long interval when the site was ice-free. The dates of the charcoal particles at the bottom of the S3 paleosol constrain the end of the previous (T4) glacier advance that occurred before 2800–2900 ^{14}C yr BP (see Table 3).

In summary, in the section "Azau Star" we identified four discrete advances of Greater Azau Glacier and three to four periods of glacier recession. These most prominent advances occurred in 19th (most probably around 1849), between the end of 15th–first half of 17th, AD 7th–9th centuries, and shortly before 1187–940 BC. Between these dates, the glacier retreated from the site.

Discussion

Other ^{14}C dates of paleosols at the forefields of the Greater Azau glacier

Until now, mostly radiocarbon dates of bulk paleosol samples at the forefields of the Greater Azau glacier were reported in the scientific literature (Baume and Marcinek, 1998; Rogozhin, 2010; Solomina et al., 2013b). For this reason, the comparison between the bulk and more precise AMS dates from macrofossils is important to understand the values of the earlier dates obtained not only for the moraines, but also for colluvium, avalanche, debris flows (Solomina et al., 2013b), landslides, and earthquakes deposits (Bogatikov et al., 2003; Rogozhin, 2010) in the Caucasus.

As is known, soil organic matter is heterogeneous and represents a pool of different ages, which complicates the interpretation of the data (Geyh et al., 1985; Matthews, 1980; Reyes and Clague, 2004). These dates of the paleosols are traditionally considered as a minimum age of their burial (Chichagova, 2005).

From the data provided above it is clear that all ^{14}C dates of the humic acids from S1, S2 and S3 paleosols are younger that those identified by AMS dating of charcoal and wood particles embedded in these units. The difference between the bulk dates from humic acids and the AMS dates from charcoals coming from the same soils is irregular sometimes reaching several centuries. It means that any recalculation of the bulk ^{14}C paleosol dates into more realistic absolute ages is impossible.

Apart from the dates from the section described above, we are aware of four more sites of paleosols in the Greater Azau valley (see locations at the Figure 1).

A thin palesol located 100 cm below the surface at the Section 2 is overlaid by sediments that can be interpreted as debris flow deposits. The ^{14}C of the paleosol (humic acid) returned the modern date (110.36% ± 3.51% IGRAN-4611). It is possible that the debris flow event that isolated this young paleosol layer is the one recorded at the photo of AD 1932 taken by L.Ya.Frolov (Figure 1 in Supplemental Materials).

The Site 3 is located in the vicinity of the Section 2, across the road, at a foothill of a slope at the left side of the valley at the elevation 2340 m a.s.l. This is another artificial cross-section that exposes colluvial deposits (sandy loam) with three visible paleosols located at the depth of 115–119, 160–170, and 190–203 cm. The uppermost layer is not sampled due to its too young age for the ^{14}C dating that was obvious from a visual inspection (Solomina et al., 2013b). We speculate that the development of this paleosol was interrupted by the same debris flow that buried the paleosol at the Site 2. The two other paleosols in this section yielded the following ^{14}C ages (humic acids) 170 ± 50 yr BP (IGRAN-3939) (AD 1650–1890) and 380 ± 60 yr BP (AD 1430–1650) (IGRAN-3938). Solomina et al. (2013b) interpreted these dates as the periods of slope stabilization and low avalanche activity.

The Site 4 is an outcrop at the terminal moraine were Baume and Marcinek (1998) found a paleosol layer at the depth of 110 cm that returned the ^{14}C date (humic acid) 340 ± 95 yr BP (n22268, Hannover) (AD 1400–1850). Unfortunately, no other details about this paleosol are available. The age of the oldest tree growing on this moraine is AD 1640. Although it does not contradict the ^{14}C age of the paleosol, we believe that both dates represent the minimum age of the moraine that overlays this paleosol and it might be far from the real absolute date of the glacier advance, which deposited this moraine. The reason for this suggestion is the location of the site outside the Little Ice Age moraine complex. Most probably the origin of this paleosol is similar to the lowermost paleosol layer (380 ± 60 yr BP (AD 1430–1650) (IGRAN-3938)) described at the Site 1: the development of soil

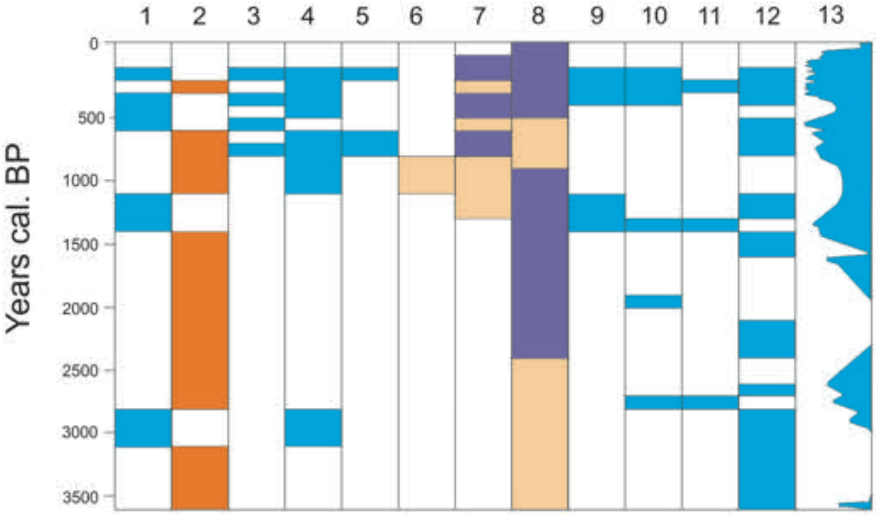

Figure 5. Comparison of the timing of glacier advances and paleosol development revealed from "Azau Star" section with other paleoclimatic proxies from the Caucasus and glacier variations in some other regions in the past 3500 years. 1 – advances of Greater Azau Glacier (this paper), 2 – periods of soils development at the lateral moraines of the Greater Azau valley (this paper), 3 – Lichenomentric dates of moraines at the northern slope of Caucasus (Serebryanny et al., 1984), 4 – Preliminary ^{10}Be dates of glacier advances in the northern Caucasus (personal communication of V. Jomelli, Solomina et al., 2019), 5 – glacier advances in the southern Caucasus (Georgia), Chalaati Glacier (Tielidze et al., 2020), 6 – "Arkhiz" warm interval (see references in the text), 7 – Warm (yellow) and cold (violet) intervals reconstructed by pollen and geochemical analyses in Karakel Lake, Teberda valley, the northern Caucasus (Alexandrin et al., submitted to Paleo-Paleo-Paleo), 8 – Warm (yellow) and cold (violet) intervals reconstructed by pollen analysis in Khuko Lake, western Caucasus (Grachev et al., 2021). Glacier advances 9 – in the Alps (Ivy-Ochs et al., 2009), 10 – in Scandinavia, Spitsbergen, Baffin Island, Iceland, European Alps, and Himalaya (Bakke et al., 2010), 11 – in Southern Norway (Griffey and Matthews, 1978), 12 – in the Northern Hemisphere (Solomina et al., 2015), 13 – Mer de Glace Glacier, Alps (Le Roy et al., 2015).

might be interrupted in both cases by a debris flow event that affected the two sites considering their very close locations, similar depth of the paleosol layers and close ^{14}C dates (340 ± 95 ^{14}C yr BP and 380 ± 60 ^{14}C yr BP).

The ^{14}C date 4420 ± 80 yr BP (n22268, Hannover) from the site 5 is reported by Baume and Volodicheva (2015, personal communication). These are charcoal particles from paleosol in a section of a soil-pyroclastic sequence covering the Elbrus volcanic deposits at the elevation 2480 m a.s.l., near the Unknown Solder Monument. The Site 5 is located at the inner flank of the ancient lava flow at the left side of the valley above the "Azau Star" section (Site 1 at Figure 1). The date indicates that the elevation 2480 m a.s.l., was ice free continuously at least for the past 5000 years, that is, neither the Greater, nor Maly Azau glaciers have been covering this surface since at least the Mid-Holocene.

Variations of the Greater Azau Glacier in comparison with other Caucasus glaciers and paleoclimatic proxies

We identified four separate glacier advances of large magnitude represented in the section "Azau Star" by T1, T2, T3, and T4 tills in 1680–1850s, 1490s–1640s, 7th–9th centuries as well as ca 12th–10th centuries BC, respectively. Between these dates, the glacier was smaller. Although there are no end moraines in Azau valley reliably dated to directly support or discard this reconstruction, available paleoglaciological and paleoclimatic context can be useful to discuss our findings (Figure 5).

Based on lichenometric data Serebryanny et al. (1984) identified the advances of nine glaciers at the northern slope of the Caucasus dating to AD 1957–1959, 1946–1949, 1925–1930, 1911–1913, 1885–1887, 1851–1860, 1790–1802, 1677–1683, 1492–1497, 1418–1425, 1270–1310. The growth curve for *Rhizocarpon geographicam sp.* used by these scholars was based on the historical and instrumental dates of the five youngest moraines mentioned above and the ^{14}C maximum limiting date of a moraine in Bezengi valley (650 ± 80 yr BP (TA-867) (AD 1240–1440)). The ^{14}C date comes from the charcoal at the bottom of peat sediments overlaying the "Naratlinskaya" moraine. According to these data, each moraine marks an advance of a smaller magnitude than the previous one. Although the lichenometric dates are not accurate, this study provides a general pattern of glacier fluctuations in the Northern Caucasus in the past millennium.

For further comparisons with our reconstruction, we used the tree-ring and preliminary TCN dates (V. Jomelli, 2018, personal communication, see also Solomina et al., 2019) of moraines from several other glaciers in the near-Elbrus area. At Kashkatash Glacier one of the largest advances occurred between the autumn AD 1839 and the spring of AD 1840 that is documented by a tree damaged by the advancing glacier (Bushueva and Solomina, 2012). Three moraines from the advances of a smaller magnitude were deposited in 1870s–1890s, 1910s, 1920s, and in 1970–1980-s. The maximum advance in Terskol valley occurred in the mid-19th century (Bushueva et al., 2016). This moraine is adjacent to the deposits that yielded the TCN ^{10}Be date 0.7 ± 0.06 ka, that is like in Bezengi valley it probably dates back to AD 13th–14th centuries. Donguzorun – a debris covered glacier – possesses a very simple moraine sequence consisting of three lateral moraines. The youngest one was formed in the early AD 20th century, the two others marking the most prominent advances of a similar magnitude are older than 200 and older than 350 years according to the tree-ring counts of juniper growing on these surfaces (Solomina et al., 2019). Jomelli reported a single TCN date 0.77 ± 0.1 ka for the outer moraine implying that the older advance (>350 years) occurred in 13th century.

Thus, one LIA glacier maximum in the Near-Elbrus area is documented at four glaciers in AD 19th century, not later than in its middle part. Numerous less prominent advances occurred later in 1870s, 1880s, 1890s etc. (Solomina et al., 2016). This pattern agrees well with our assessment of the date of the uppermost till T1 in the "Azau Star" section. Previous advances of similar magnitude probably occurred in 13th–14th century at Donguzorun and Terskol Glaciers, but the TCN dates constraining these advances are single and still very preliminary. Another date of

13th–14th century advance comes from the ^{14}C date at Bezengi Glacier.

Serebryanny et al. (1984) assessed the depression of the equilibrium line altitude in 13th–14th centuries as large as 145–160 m, while for the advances occurred in the early 17th–mid 19th centuries they estimated it as 50–60 m only. Seinova and Zolotarev (2001) also based on lichenometric data argued that in the Near-Elbrus area the advances of the first (13th century) and the second (17th–19th centuries) phases of the LIA were of similar magnitude. Almost equal magnitude of glacier advances in 13th and 19th centuries is reported for Chalaati Glacier in Georgia (southern slope of the Caucasus) by Tielidze et al. (2020) who used the preliminary TCN date of a moraine and identified the largest LIA advance at AD ~1280–1400. At the secondary LIA maximum that occurred about AD 1810 (tree rings) the Chalaati Glacier reached almost the same length as in 13th–14th centuries.

Collectively this evidence, although rather sparse, testify in favor of a similar magnitude for the two LIA maxima in 17th–19th and 13th–14th at least in the Caucasus. The absence of the till deposited during the first LIA maximum in our section can be hardly explained by the erosion of this till: we did not find any evidence of this in the section. Obviously new data is necessary to identify the scale of the advance of the early LIA stages.

The advance that is constrained by two ^{14}C dates – 1190 ± 20 yr BP (IGAN$_{AMS}$-8126) (AD 774–889) from the top and 1300 ± 20 yr BP (IGAN$_{AMS}$-8124) (AD 663–773) from the bottom of T3 – is identified for the first time in the Caucasus.

Serebryanny et al. (1984) suggested an advance at 2.8 ka (uncalibrated) in Bezengi valley, although this assumption was based on a climate deterioration period identified at that time by pollen analyses. Based on preliminary TCN sampling V. Jomelli identified an advance occurred ca 2.8–2.9 ka at Alibek, Terskol, and the Greater Azau glaciers (see also Solomina et al., 2019). The glacier expansion shortly before ca 3 ka is supported by two radiocarbon dates 2855 ± 20 yr BP (IGAN$_{AMS}$-8125) and 2880 ± 20 yr BP (IGAN$_{AMS}$-6827) (1109–931 BC and 1187–940 BC) in the “Azau Star” section.

Based on spore-pollen data Knyazev et al. (1992) identified a cold period between 3.0–2.9 ka and 2.3–2.2 ka (uncalibrated) and another cooling (probably three separated episodes) occurred at 1.0–0.7 ka in Northern Osetia. Kvavadze and Efremov (1996) in the Western Caucasus (Arkhiz region) dated the coolings at 1.2–1.3 ka and 0.35–0.4 ka (uncalibrated), but report about four warm and four cold episodes in the last 1600–1800 years that are derived from palynological records but are not dated. Based on the changes in pollen assemblages, content of organic matter and erosion rates in Khuko lake sediments in the Western Caucasus Grachev et al. (2021) identified warm periods at 3.5–2.4 and 0.8–0.5 ka BP and coolings at 2.4–0.8, and 0.5 ka BP–present (calibrated). In general, the stratigraphic data mentioned above do not agree with each other most probably due to a poor chronological control in the case of the early data (Knyazev et al., 1992; Kvavadze and Efremov, 1996; Serebryanny et al., 1984) or too large sampling interval for pollen analyses in the case of Khuko section (Grachev et al., 2021).

One relatively high-resolution paleoclimatic reconstruction covering the period of the past 1.5 ka is available for Teberda valley, where the Karakel lake sediment were sampled for pollen analyses every 1 cm and the reconstruction is chronologically controlled with 10 ^{14}C dates (Alexandrin, 2019; Chepurnaya, 2014; Solomina et al., 2013a, 2014). Based on spore-pollen and geochemical analysis of the deposits of Lake Karakel Alexandrin (2019) identified three distinct stages of cooling within the Little Ice Age at ca AD 1250–1400, ca AD 1500–1630, ca AD 1750–1880. According to this reconstruction, the cooling of the 13th century was sharp, but rather short. Similar in duration and amplitude was the cooling around AD 1400. While the cool episode at AD 1750s–1880s most probably coincides with the T1 till in our section, either (or both) earlier coolings and potential glacier advances might be expressed in the T2 till.

Within the period of AD 1596–2011 Dolgova (2016) identified the warmest summers (June–September) from the maximum density pine chronology in the Caucasus in 1714–1730, 1781–1806, 1939–1968, and 1985–2011. A warm period in Karakel lake sediments (Alexandrin, 2019) dates back to between AD 1630 and ca 1750. A shift of the dates of the warm episode in comparison to the tree-ring reconstruction in 18th century can be explained by less accurate chronology of the non-laminated lake sediments of Karakel deposits. We consider the 18th century as the most probable candidate for the warming, the retreat of Greater Azau and S1 paleosol deposition. This is indirectly confirmed by the evidence of Abich (1875) who described the glacier in 1849 as one advancing in the hundred years’ old forest. This means that in 18th century, the Greater Azau was in a retracted position and the valley was occupied by mature trees.

Some historical, archeological (Kuznetsov, 1993; Turmanina, 1988; Tushinsky, 1964) and palynological (Kvavadze and Efremov, 1996; Serebryanny et al., 1984) data provide evidence, although scarce and sometimes ambiguous, that the LIA cooling was preceded by a long warm interval with retracted glaciers and a lower avalanche activity called in the Caucasus the “Arkhyz hiatus in glaciation” between 6th and 12th centuries. However, the chronological control for this warm period is still very vague. Alexandrin (2019), using the Bromine content in the bottom sediment of Lake Karakel and its coherence with the broadleaved pollen identified the Medieval Warm Period lasting from ca AD 770 to AD 1250. The Medieval Warm Period warming included at least six multidecadal intervals of relative cooling, but on average the temperature in this period was much higher than in the LIA. The beginning of this interval correlates very well with the dates of S2 paleosol formation (AD 774–889).

Comparison of Greater Azau Glacier fluctuations with the global context of the late-Holocene glacier history

It is well known that the time and scale of glacier advances can differ not only between mountain regions, but also between neighboring glaciers. However, some periods of Holocene glacier advances tend to cluster at 4.4–4.2 ka, 3.8–3.4 ka, 3.3–2.8 ka, 2.6 ka, 2.3–2.1 ka, 1.5–1.4 ka, 1.2–1.0 ka, 0.7–0.5 ka, roughly corresponding to the coolings in the North Atlantic (Solomina et al., 2015). We found a certain similarity of our reconstruction with the global picture, especially with the Alpine and Scandinavian records (Figure 5).

Generally, in the Alps the LIA maximum dates back to the 17th–19th centuries, but the advances of almost the same magnitude occurred also in the first millennium in the AD 6th–early 7th century in the Swiss and French Alps (Holzhauser et al., 2005; Le Roy et al., 2015) and in the AD 9th century in the eastern Alps (Nicolussi et al., 2006). At the Sulden Ferner, the advance of AD 9th century is dated very precisely at AD 835 (Nicolussi et al., 2006). An advance from the AD 5th to the 9th century, is also recorded in the Italian Alps (Deline and Orombelli, 2005).

In our section the till T3 lying between the S2 and S3 paleosols is very closely limited by the radiocarbon dates (AD 7th–9th centuries), that is, the dates of advance is similar to the one that occurred in the Eastern Alps. Theoretically, it can also be a part of the Late Antique Little Ice Age – a cold interval identified for the temperate regions of Eurasia (e.g. in the Alps and in the Altay Mountains) from AD 536 to AD ~660 by Büntgen et al. (2016). However, Van Dijk et al. (2021) recently questioned a century-long cooling based on model experiments and the new Northern

Hemisphere (NH) temperature reconstruction by Büntgen et al. (2020) that shows a much shorter cold period lasting until about AD 560. Another cooling around AD 800 is also recorded by a new NH mid-latitudes temperature reconstruction (Büntgen et al., 2020). This implies that the advance of the Greater Azau should be rather attributed to the later, AD 9th century cold interval. Another possibility is that the T3 till includes the deposits of the two short but large-scale advances occurred between AD 7th and 9th centuries. This interval (AD 600–900) was also identified as a period of advances in Alaska and Coastal Ranges of Canada (Barclay et al., 2013; Reyes et al., 2006; Wiles et al., 2002, 2004; Young et al., 2009).

Two periods of glacier advances at 2.7–3.0 ka and 3.0–3.3 ka were reported by Solomina et al. (2015) in both the Northern and Southern hemispheres at high and mid latitudes. In the Alps the Tsjiore Nuove and Stein glaciers advanced between 3.3 and 2.8 ka as shown by ^{10}Be data (Schimmelpfennig et al., 2014). The dates of the advance preceding the S3 paleosol formation in "Azau Star" are close to these alpine advances.

Overall, in their comprehensive review of glacier fluctuations in the Alps Ivy-Ochs et al. (2009) mentioned three major periods of Neoglacial advances at 3.0–2.6 ka, around AD 600 and during the LIA. In Scandinavia, Spitsbergen, Baffin Island, Iceland, European Alps, and Himalaya Bakke et al. (2010) identified advances at 4.0 ka, 2.7 ka, 2.0 ka, 1.3 ka and during the LIA. These sequences are close to the chronology that we provided here for the Greater Azau Glacier. There is a similarity of our records with those presented by Griffey and Matthews (1978). Based on paleosols buried in the moraines (i.e. the same approach that we used in this paper) they identified that advances of largest magnitude occurred in Southern Norway at ca 2700 cal BP, 1300 cal BP and in LIA.

Conclusions

In this paper, we presented the chronology of the Greater Azau Glacier variations constrained by the radiocarbon dates of organic material from the paleosols buried in the tills of a lateral moraine. This is the first reconstruction that allowed identifying the absolute dates of four most prominent advances over the last 3500 years similar in magnitude to the Little Ice Age Maximum.

Novel key findings are:

1. The Greater Azau Glacier reached its maximum thickness during the advances in the AD 19th, AD 15th–17th-centuries, AD 7th–9th centuries, as well as shortly before 12–10 centuries BC.
2. The glacier retreat during the two long intervals allowed the deep soil profiles to develop between the AD 7th–9th and 15th centuries, and before the AD 7th–9th centuries.

Although this first numerical constraint on Neoglacial glacier advances in the Northern Caucasus has greatly clarified the glacier chronology in this region, we must admit that the dates obtained at one site are still preliminary. In addition to dating of glacial advances our records allowed us to determine the periods of glacier retreat and soil cover formation on stabilized moraine surfaces that implies a warmer climate. Two of these warmer periods were long and lasted 600–800 and 1500–1700 years. The advances, on the contrary, seem to have been shorter events, especially the one that occurred between the dates AD 774–889 and AD 663–773.

A comparison of our glacier chronology with those from the Austrian Alps and Southern Norway shows a similarity in the periods of glacier activity in these regions in the Neoglacial time. This is understandable since the climate in all these regions is largely driven by the westerlies. The similarity of decadal variations of summer temperature in AD 16th–21st centuries in the Alps and in the Northern Caucasus has been reported previously on the basis of the tree-ring analysis (Dolgova, 2016).

Our study highlights the need of more high-resolution paleoclimate records from various sites and different proxies in the Caucasus, including glacier variations because there is now a great disagreement between different proxy arrays and it is difficult to bring them all together into a complete and consistent picture. The reason for this is a poor chronological control of most records and a low temporal resolution of some biostratigraphic reconstructions. We hope that new TCN dates of moraines and the development of other stratigraphic records with stricter chronological control will help develop more robust multi-proxy paleoclimatic reconstructions in the Caucasus.

Acknowledgements

We are grateful to the colleagues V. Mikhalenko, E. Grabenko, A. Oleinikov who contributed to this studies in the field. The Pléiades stereo-pair used in this study was provided by the Pléiades Glacier Observatory initiative of the French Space Agency (CNES). We are most grateful to the reviewer for his enormous efforts to improve our manuscript.

Author contributions

Olga N Solomina was a principal investigator of this study and wrote the initial text for the paper, Alexander L Alexandrovskiy was responsible for additional sampling and the description and interpretation of the soil properties, Elia P Zazovskaya contributed to the interpretation of the ^{14}C dates, Tatyana M Kuderina and Vasiliy A Shishkov participated in the fieldwork and scientific discussions. Irina S Bushueva was responsible for the remote sensing data and support. Evgeniy A Konstantinov provided the results of the granulometric analyses.

Data availability

The authors declare that the data supporting the findings of this study are available in the article and its supplementary part. Additional datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The Field investigations were carried out within the framework (No 0148-2019-0004) of the State Assignment of Institute of Geography, Russian Academy of Sciences. The Megagrant project (agreement No 075-15-2021-599, 8.06.2021) of the Ministry of Highest Education of Russia "Natural And Anthropogenic Environmental Changes Inferred From Multi-Proxy Paleorecords In Russia" supported the analytical studies. V. Jomelli provided the unpublished TCN data (IRP DEGLAC project, IRP00008).

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Supplemental material

Supplemental material for this article is available online.

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