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The First Rock Glacier Inventory for the Greater Caucasus

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Abstract: Rock glaciers are an integral part of the periglacial environment. At the regional scale in the Greater Caucasus, there have been no comprehensive systematic efforts to assess the distribution of rock glaciers, although some individual parts of ranges have been mapped before. In this study we produce the first inventory of rock glaciers from the entire Greater Caucasus region—Russia, Georgia, and Azerbaijan. A remote sensing survey was conducted using Geo-Information System (GIS) and Google Earth Pro software based on high-resolution satellite imagery—SPOT, Worldview, QuickBird, and IKONOS, based on data obtained during the period 2004–2021. Sentinel-2 imagery from the year 2020 was also used as a supplementary source. The ASTER GDEM (2011) was used to determine location, elevation, and slope for all rock glaciers. Using a manual approach to digitize rock glaciers, we discovered that the mountain range contains 1461 rock glaciers with a total area of $297.8 \pm 23.0\,km^2$. Visual inspection of the morphology suggests that 1018 rock glaciers with a total area of $199.6 \pm 15.9\ km^2$ (67% of the total rock glacier area) are active, while the remaining rock glaciers appear to be relict. The average maximum altitude of all rock glaciers is found at 3152 ± 96 m above sea level (a.s.l.) while the mean and minimum altitude are 3009 ± 91 m and 2882 ± 87 m a.s.l., respectively. We find that the average minimum altitude of active rock glaciers is higher (2955 ± 98 m a.s.l.) than in relict rock glaciers (2716 ± 83 m a.s.l.). No clear difference is discernible between the surface slope of active ($41.4 \pm 3°$) and relict ($38.8 \pm 4°$) rock glaciers in the entire mountain region. This inventory provides a database for understanding the extent of permafrost in the Greater Caucasus and is an important basis for further research of geomorphology and palaeoglaciology in this region. The inventory will be submitted to the Global Land Ice Measurements from Space (GLIMS) database and can be used for future studies.

Keywords: rock glacier; glacier inventory; Caucasus Mountains; permafrost

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1. Introduction

Rock glaciers are landforms of frozen debris and supersaturated with ice. They creep downslope displaying forms of cohesive flow [1–3]. They are iconic features of the periglacial environment and have been investigated in the fields of geomorphology [4–7], alpine ecology [8,9], hydrology [10–12], natural hazard [13–15], and paleoclimatology [16–20]. Rock glaciers also serve as proxy for the spatial distribution of mountain permafrost [21–23] and as an indicator of its link with the climate system [24–27].

Understanding the processes controlling rock glacier dynamics at different time scales has improved due to geophysical and modelling studies [28–32]. At the same time, many studies have investigated their behavior at the regional scale, highlighting common global and regional patterns in their flow [27,33–35]. In addition, some studies have suggested that rock glaciers might be important sources of water, especially in dry and cold environments [28,36,37]. For all of these reasons, rock glacier inventories have become a priority in many countries around the globe and many studies are contributing towards the creation of regional and global databases, with thousands of rock glaciers identified and analyzed throughout entire regions [38–42]. Concurrently, important efforts from the rock glacier research community have been made to establish standards and guidelines for consistent mapping in order to minimize the uncertainties related to subjective decisions [43,44].

In the Greater Caucasus, rock glaciers provide hydrologic reserves and ecologic refugia with respect to ongoing and future climate changes as well as promoting vegetation communities and habitat for alpine terrestrial species [45]. Discharge of water from rock glacier springs and groundwater is a significant source of fresh water for the Caucasus countries [42]. They are specifically important reservoirs of water for the population living downstream, often providing meltwater during seasonal droughts, mainly for the eastern Greater Caucasus. Rock glaciers also play a significant role as a major tourist attraction for the economy of the Caucasus countries. For example, the prominent rock glacier in Juta River valley in the Kazbegi region, Georgia, is visited by thousands of tourists each year. Thus, the assessment of rock glaciers in the Greater Caucasus is crucial for both scientific and societal points of view.

In this study we present the first rock glacier inventory for the entire Greater Caucasus region obtained from various high-resolution satellite images (2004–2021) in combination with an ASTER digital elevation model (2011) along with various attributes (area, elevations, slope, and activity status) and location.

2. Study Area

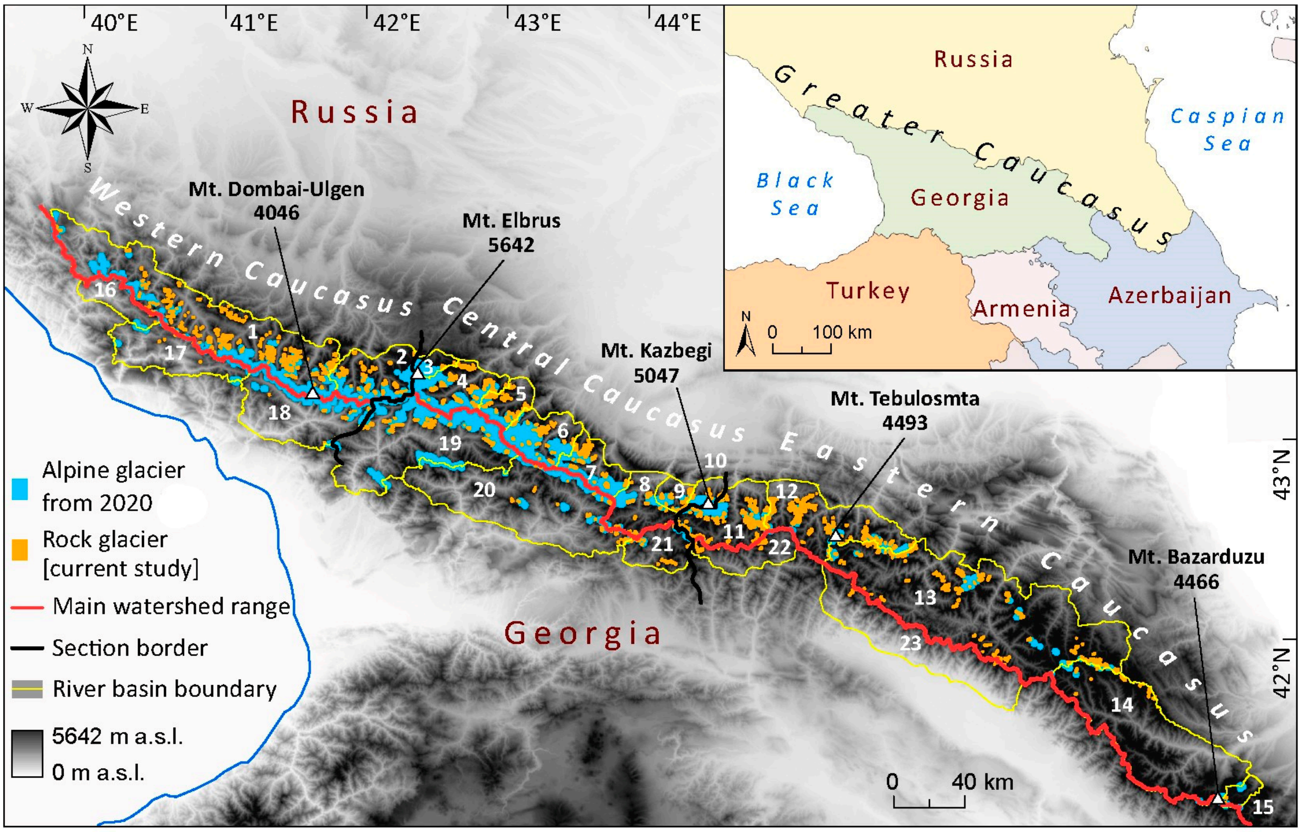
2.1. General Characteristics

The Greater Caucasus Range, located between the Black and Caspian Seas, extends approximately 1300 km from northwest to southeast (Figure 1). The width of the Greater Caucasus varies in different parts from 32 km to 180 km. The main watershed range with its northern and southern macro-slopes represents the largest structural element of the Greater Caucasus. Due to climatic and morphological features, the Greater Caucasus is traditionally divided into three parts—western, central, and eastern sections (Figure 1). The western Greater Caucasus is the lowest part of this mountain region, starting almost from the Crimean Peninsula (Black and Azov Seas) and extends to Mt. Elbrus (5642 m a.s.l.). Mt. Dombai-Ulgen, with an elevation of 4046 m a.s.l., is the highest peak in the western Greater Caucasus. The territory between Mt. Elbrus (5642 m a.s.l.) and Mt. Kazbegi (5047 m a.s.l.) is the highest part of the range and is called the central Greater Caucasus. There are about ten mountain peaks exceeding 5000 m a.s.l. in the central Greater Caucasus. The eastern Greater Caucasus starts from the Mt. Kazbegi and reaches almost the Absheron Peninsula (Caspian Sea). It is a relatively low range with the highest peaks reaching up to 4493 m (Mt. Tebulosmta) and 4466 m a.s.l. (Mt. Bazardüzü). The altitude of the eastern section gradually decreases to the southeastern direction, ranging between 2200–3500 m a.s.l. The Greater Caucasus has an asymmetric transverse structure with wide and gradual northern slopes, and shorter and steeper southern slopes.

The Greater Caucasus is part of the Alpine (Mediterranean) geosynclinal belt. Its modern appearance began to form at the beginning of the Neogene. Its axial part rose to 4000–5000 m during the Quaternary period [46]. This uplift was accompanied by manifestations of terrestrial volcanism in several areas (Mt. Elbrus, Mt. Kazbegi, and Keli Volcanic Plateau). Uplift and a cooling climate, as two main factors, led to the development of mountain glaciation in the Greater Caucasus [47]. Pronounced forms of mountain-erosion relief were created by snow and glaciers in the alpine zone—ridges, cirques, and trough valleys, which created favorable conditions for the formation of rock glaciers. The main watershed range and adjoining lateral ridges are composed mainly of crystalline rocks and shale. The tectonic activity of the area [48], including frequent earthquakes [49], enhances erosion, contributing sediment to cirques and valleys.

The main watershed range of the Greater Caucasus forms a barrier to the flow of moisture brought by the Mediterranean and Atlantic cyclones. It also prevents the transfer of cold air mass from the north to the south. The highest amount of annual precipitation falls in the southwestern slopes of the Greater Caucasus (up to 3300 mm). The climate becomes more continental from west to east. Annual precipitation in the central Greater Caucasus reaches 2000 mm, declining to 1000 mm in the eastern part [50]. The mean annual temperature of the mountain range depends on the altitude, while the seasonal amplitude depends on the distance from the Black Sea. The average regional lapse rate is −2.3 °C/km in winter, and −5.2 °C/km in summer [51]. However, recent instrumental measurements for individual glaciers also show that summer lapse rate can reach −7.8 °C/km (Zopkhito Glacier) or even −9.8 °C/km (Chalaati Glacier) [52]. Average annual air temperatures at an elevation of 3400 m a.s.l. are about −5.0 °C [53,54]. At the same time, the annual temperature on the southern slope is 1–2 °C warmer than on the northern slope [55].

On the southwestern slopes of the Greater Caucasus, snow avalanches often occur in late winter, mainly due to the persistence of snow cover for five or more months (November–April). In several regions of the western and central Greater Caucasus (e.g., northern Abkhazeti and Upper Svaneti in Georgia), snow depth often reaches 4–5 m [56].



River basin: 1 - Kuban left tributaries; 2 - Kuban headwaters; 3 - Malka; 4 - Baksan; 5 - Chegem; 6 - Cherek; 7 - Urukh; 8 - Ardon; 9 - Fiagdon; 10 - Gizeldon; 11 - Terek (Tergi) headwaters; 12 -Sunja Right Tributaries; 13 - Sulak; 14 - Samur; 15 - Kusarchai; 16 - Mzimta; 17 - Bzipi; 18 - Kodori; 19 - Enguri; 20 - Rioni; 21 - Liakhvi; 22 - Aragvi; 23 - Alazani.

Figure 1. The extent of rock glaciers relative to alpine glaciers in the Greater Caucasus. The location of the Caucasus region is shown in the inset map at the top right. Peak elevations are given in meters above sea level [57].

According to the latest inventory of the year 2020 [57], there are over 2000 alpine glaciers in the Greater Caucasus, with a total area of about 1060 km^2. About 70% of modern glaciers exist in the central Greater Caucasus.

2.2. Previous Studies

Studies of rock glaciers in the Greater Caucasus began after the 1960s when the first mapping of rock glaciers on the slopes of Elbrus Massif was carried out by Myagkov [58]. Later, Krasnoslobodtsev [59] provided a brief description of 229 rock glaciers from the Greater Caucasus. Rock glaciers of central and eastern Greater Caucasus on both northern and southern slopes were also studied by Brukhanda [60], Gobejishvili [61], Gobejishvili and Rekhviashvili [62], Rekhviashvili and Gobejishvili [63], Kozhevnikov et al. [64], Seinova and Mezhenina [65], Dokukin [66], Volodicheva and Labutina [67], and Tavasiev [68]. All of these previous rock glacier surveys are incomplete mainly because: (i) limited area coverage, i.e., none of these works provide comprehensive information about the total number and area of rock glaciers from the entire Greater Caucasus; and (ii) digital outlines of rock glaciers were not created during these studies. They only contain tables with incomplete glacier parameters (only number and area). A recently published near-global rock glacier inventory by Jones et al. [69] quantified Caucasus and Middle East as one region. However, their study provides a dataset from the Middle East (Turkey and Iran) and no data from the Caucasus Mountains. Recent regional glacier studies in the Caucasus Mountains aimed mainly on evaluating changes in alpine (or ice) glacier coverage [57] and mass balance [70] while the rock glaciers were always omitted.

Age-determinations on relict rock glaciers in the Greater Caucasus are very rare. The only study that reports such data provides an approximate age of Lichanishi rock glacier from Georgian Caucasus (43°0′24.29″ N 42°57′52.35″ E), where Rekhviashvili and Gobejishvili [63] explored peat deposits on the lower surface of this rock glacier. Using the radiocarbon technique (^{14}C), the age of this deposit was found to be 1460 ± 60 years (i.e., ^{14}C yr. ~560 BP). They also assumed that the relict rock glaciers which completely or partly covered with vegetation are older features compared to the active rock glaciers and were interpreted to have formed during Early or Middle Holocene period, while the active rock glaciers formed during the Late Holocene or Little Ice Age.

3. Data Sources

Using the Environmental Systems Research Institute's (ESRI) online service, such as ArcGIS [71], we used high-resolution SPOT and Worldview-1/-2 satellite images (2004–2021) and several Digital Globe products (up to 5 m resolution). Orthorectified high-resolution (1.5 m) SPOT-6 and -7 scenes (2019–2020) were also used to cover the individual parts of the central Greater Caucasus. SPOT images were obtained from Azercosmos facility (https://azercosmos.az/, accessed on 10 October 2022). About 90% of all high-resolution imagery was captured under cloud-free conditions between late June and late September when the rock glacier surfaces were mostly free of seasonal snow. In the case of cloud condition, shadow, or snow cover for individual places a 10 m medium-resolution Sentinel-2 imagery (visible/near-infrared/SWIR bands) from the 2019 and 2020 summer seasons was also used. The USGS EarthExplorer Sentinel collection (http://earthexplorer.usgs.gov/, accessed on 11 October 2022) was used as the main source for downloading Sentinel-2 images. Overall, Worldview, QuickBird, IKONOS, and SPOT images (ArcGIS, Digital Globe) served as a basis for rock glacier assessment, while the Sentinel-2 scenes were used as an extra tool. All images were loaded into ArcMap 10.8.2 software.

For 3D visualization, we also used Google Earth Pro software versions 7.3 [72] with high-resolution QuickBird and IKONOS images (2010–2021) superimposed upon the Shuttle Radar Topography Mission version 3 (SRTM v3) topography [73]. Furthermore, Google Earth Pro includes specific GIS tools, supporting the creation of separate layers exportable as KML formatted files in ArcMap software for further spatial analysis or data dissemination [74]. Google Earth is often used for identification of rock glaciers in various mountain regions [11,75,76].

To determine topographic parameters of individual rock glaciers such as elevation and slope distribution the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM, 2011) version 3 was used. The NASA LP

DAAC Collection (http://earthexplorer.usgs.gov/, accessed on 11 October 2022) was used as the main source for downloading the GDEM.

4. Methods

4.1. Rock Glacier Mapping

For mapped rock glaciers across the Greater Caucasus, a remote sensing approach was used based on geomorphological evidence such as lateral margins and steep front, ridges and furrows, collapse structures, flow structures, and distinct changes of the slope in the rooting zone [42,44,75] (Figure 2). Identification of the rock glacier snout was relatively simple while the accurate detection of the upper margin was sometimes challenging [43,77]. The upper boundary was defined according to the recommendations by Brardinoni et al. [43] and RGIK [44].

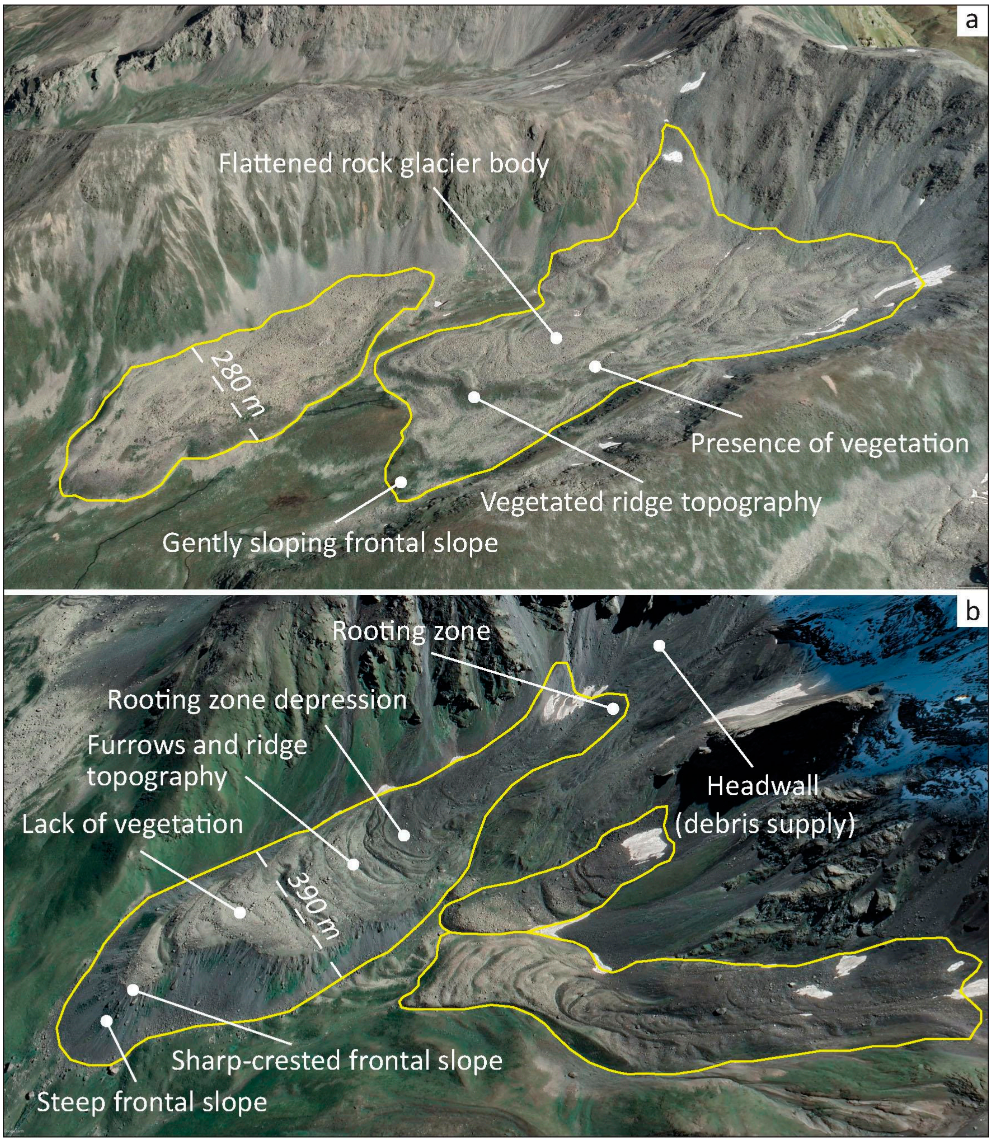


Figure 2. An example of rock glacier mapping and classification: (**a**)—relict rock glaciers (43°38′21.36″ N 41°5′53.19″ E); (**b**)—active rock glaciers (42°32′54.05″ N 44°46′31.21″ E). The yellow line corresponds to the boundaries of the rock glacier. The white dashed line indicates the width of the rock glacier. Google Earth imagery 16/08/2019 and 16/08/2022 is used as the background. © Google Earth 2022.

Delineation of rock glaciers is often challenging, especially distinguishing them from debris-covered glaciers and protalus and pronival ramparts [78,79]. Morphological similarities between these landforms may cause incorrect delineation of rock glacier margins and thus inaccurate area estimation of entire landforms. Although several approaches have been suggested [80,81], automatic mapping remains problematic and requires supervision [82,83]. We therefore used an optimal approach and digitized them manually to generate this inventory [11,42]. To reduce the misclassified areas, we carried out multiple adjustments of the outlines by at least two operators based on local and expert knowledge. However, this does not completely avoid the bias of the subjective interpretation of the operators. For this purpose, we used a buffer method, which gave us a certain $\pm$ uncertainty for each rock glacier outline (see Section 4.4 below).

4.2. Rock Glacier Classification

When classifying rock glaciers in their activity state, we used the morphological classification proposed by Barsch [84] and developed by the International Permafrost Association (IPA) Action Group on Rock Glaciers Inventories and Kinematics [44]. As a result, two categories of rock glacier activity were distinguished: relict, and active (Figure 2). Despite all our efforts, morphological characteristics remain a proxy for activity and the classification remains inherently challenging and uncertain [85,86].

Active rock glaciers present an over-steepened front, with an angle exceeding the angle of repose of the material and signs of ongoing erosional processes. This feature is often remarkable in remote sensing data due to its different colors or due to the existence of shadows and snow. The surface of active rock glaciers consists of large coarse clastic material. Moreover, furrows and ridges, which are formed as a result of cohesive flow of permafrost creep, are often distinguished on their surface [87].

According to the IPA guidelines [44], we interpreted relict rock glaciers as an evidence of past permafrost creep. Surface relief of relict rock glaciers is much more subdued than for active ones [84]. Often, they have a less steep front compared to active counterparts. Relict rock glaciers often present a vegetated surface but are recognizable in the landscape due to their morphology, sometimes still conserving distinct furrows and ridges. They are typically found at lower altitudes than active rock glaciers [44,84,88,89]. The expert-based discrimination from glacial moraines is completed by at least two expert interpretations, on the basis of the glacial and periglacial evolution of the landscape during the Holocene.

4.3. Topographic Features

We extracted and recorded topographic landform characteristics for each rock glacier, such as elevation (minimum, mean, and maximum), slope, and geographic coordinates (latitude and longitude) at the centroid. The topographic attributes were calculated in ArcGIS by draping the polygons over the DEM. The minimum elevation is the minimum value bounded by the polygons. The same applied to the maximum elevation. In a geomorphological sense, these two variables represent the lower point at the front and the higher point at the rooting zone, respectively. The mean elevation is finally the average between the minimum and maximum elevations. Surface area (km^2) of the digitized rock glacier polygons was calculated using ArcMap 10.8.2 software. According to the IPA guidelines [44], the area of the smallest rock glacier digitized during the inventory was 0.01 km^2. All of the parameters were entered in the attributes table (Table 1).

Table 1. Rock glacier attributes obtained during the inventory.

Attribute	Meaning
Latitude/Longitude	Coordinate
Area (km^2)	Rock glacier total area
Maximum elevation (m a.s.l.)	Maximum elevation of the rock glacier
Mean elevation (m a.s.l.)	Mean elevation of the rock glacier
Minimum elevation (m a.s.l.)	Minimum elevation of the rock glacier front
Mean slope	Mean slope (°) of the surface
Class	Active/Relict
River basin	Main and tributary river basins
Region/section	Western/Central/Eastern
Macro-slope relative to the watershed	Northern/Southern
Country	Russia/Georgia/Azerbaijan

4.4. Uncertainty Assessment

Mapping uncertainty is derived from the resolution of the aerial imagery in terms of visibility of features and by the contrast between the rock glacier and the surrounding area. We attempted to estimate this uncertainty using the buffer method as it is often used for alpine glaciers [55,90]. For debris-covered glaciers that are not obscured by clouds, a 2-pixel buffer was suggested [91,92]. Our primary satellite imagery has a pixel resolution of up to 5 m. Since rock glaciers are often more challenging to delineate than alpine debris-covered glaciers [78], we increased the buffer size to 3-pixel and a 15 m buffer was generated around the digitized rock glacier using ArcGIS 10.8.2 software. Thus, the average ratio between the area with a buffer increment and the original rock glacier area was calculated and interpreted as an uncertainty. Overall, calculated uncertainty of the total rock glacier area for the entire Greater Caucasus was $\pm 23.0\,km^2$ or $\pm 7.7\,\%$. However, the buffer method included the relative higher error of small polygons as a small rock glacier has relatively more edge pixels [90].

We used the standard deviation (or σ) method to estimate the spread of the elevation of the rock glaciers, as well as for the values of the slope angle. This method is a measure of how spread the data is in relation to the mean. For example, a low standard deviation means data are clustered around the mean (a short and compact rock glacier), and a high standard deviation indicates data are more spread out (a long rock glacier distributed over a large range of elevation—or slope). Uncertainty for elevation measurements was spread between ±80–100 m, while it was ±3–5° for the slope inclination

5. Results

Based on high- and medium-resolution satellite imagery from 2004–2021 we have identified and mapped 1461 rock glaciers in the Greater Caucasus. Our inventory covered 34 river basins, and the total area of all Caucasus rock glaciers was $297.8 \pm 23.0\,km^2$ (Table 2). Within this inventory, 1018 rock glaciers (67%) with a total area of $199.6 \pm 15.9\,km^2$ were classified as active, while the 443 rock glaciers (33%) with a total area of $98.2 \pm 7.2\,km^2$ were classified as relict. Active rock glaciers had an average area of $0.20\,km^2$, and the mean area of relict rock glaciers was $0.22\,km^2$.

Table 2. The distribution of rock glaciers in the Greater Caucasus by slopes and individual river basins in order from west to east. Please also see Figure 1 for locations of river basins.

Main River Basin	Tributary River Basin	Satellite Imagery 2004–2021		Mean Elevation (m a.s.l.)
		Count	Area km^2	
Northern Slopes				
Kuban left tributaries	Belaya	6	1.25	2232
	Malaya Laba	40	4.70	2570
	Bolshaya Laba	70	10.23	2507
	Bolshoy Zelenchuk	64	12.69	2705
	Maliy Zelenchuk	76	11.34	2849
	Teberda	57	12.26	2931
Kuban headwaters	Daut	10	1.96	2876
	Uchkulan	18	5.62	3005
	Ullukam	25	4.44	2986
	Khudes	4	0.98	3137
Malka		3	3.68	3090
Baksan		74	19.65	3149
Chegem		51	10.66	3228
Cherek		58	11.70	3164
Urukh		53	16.93	3139
Ardon		51	8.98	3046
Fiagdon		22	6.34	3074
Gizeldon		10	4.26	3032
Tergi (Terek) headwaters		185	35.19	3165
Sunja right tributaries	Assa	62	16.24	3006
	Arghuni	75	19.44	3075
	Sharo Argun	26	4.16	3146
Sulak	Andiyskoye Koysu	103	18.69	3183
	Avarskoye Koysu	96	21.88	3193
Samur		19	6.51	3185
Kusarchai		6	1.01	3484
Southern Slopes				
Mzimta		3	0.70	2268
Bzipi		6	0.33	2344
Kodori		12	0.89	2609
Enguri		74	12.70	2887
Rioni		34	4.79	2877
Liakhvi		30	3.36	2945
Aragvi		24	3.42	3105
Alazani		14	0.77	2940
Total, Greater Caucasus		**1461**	**297.80**	**3009**

The distribution of rock glaciers within the countries that occupy the Greater Caucasus shows that 974 rock glaciers (212.0 ± 16.0 km^2, 71.2%) were found in Russia, 481 (84.8 ± 7.0 km^2, 28.5 %) in Georgia, and 6 (1.01 ± 0.08 km^2, 0.3%) in Azerbaijan (Table 3).

Table 3. The distribution of rock glaciers in the Greater Caucasus according to countries, ordered by count.

Countries	Satellite Imagery 2004–2021		Mean Elevation (m a.s.l.)
	Count	Area km^2	
Russia	974	212.0 ± 16.0	2985
Georgia	481	84.8 ± 7.0	3052
Azerbaijan	6	1.01 ± 0.08	3484

Based on the physical geographical and climatological divisions of the Greater Caucasus we divided our dataset into five geographic subregions (westerns, central, eastern, northern, and southern). The northern slopes of the Greater Caucasus contained nearly 87% of all rock glaciers from the entire mountain range, or 1267 rock glaciers with a total area of 271.7 ± 20.5 km^2 (Figure 3). The number distribution by sections was inhomogeneous. The eastern Greater Caucasus contained 610 rock glaciers with the total area of 127.4 ± 9.7 km^2. The central and western sections had 460 and 391 rock glaciers with a total area of 103.1 ± 8.3 and 67.4 ± 5.4 km^2, respectively (Figure 3). The spatial distribution of active and relict rock glaciers for western, central, and eastern Greater Caucasus is shown on the color-coded map in Figure 4.

The average minimum elevation of all Caucasus rock glaciers was 2282 ± 87 m a.s.l., while the average maximum elevation was 3153 ± 92 m a.s.l. (Figure 5a). Relict rock glaciers had lower mean average snout position at 2716 ± 83 m a.s.l., while active rock glaciers had higher mean average snout positions at 2955 ± 98 m a.s.l. (Figure 5b).

The distribution of rock glaciers by mean elevation varied between western, central, and eastern Greater Caucasus (Figure 6). The mean elevation of the rock glaciers was lowest in the western section and mainly ranged from 2000 to 3200 m a.s.l., while it varied between 2600 and 3700 in the central, and between 2900 and 3700 m a.s.l. in the eastern regions, respectively. The mean average elevation for all Caucasus rock glaciers was 3009 m a.s.l. The spatial distribution of mean elevation for all Caucasus rock glaciers is shown on the color-coded map in Figure 7.

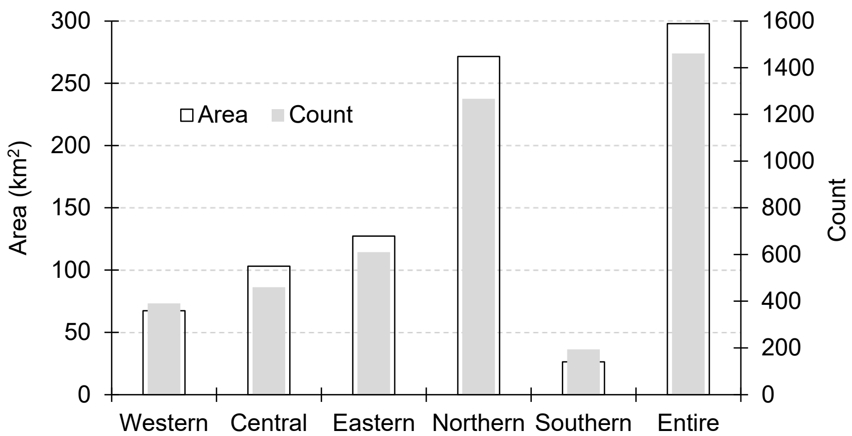


Figure 3. Rock glacier area and count comparison for the different sections and slopes of the Greater Caucasus.

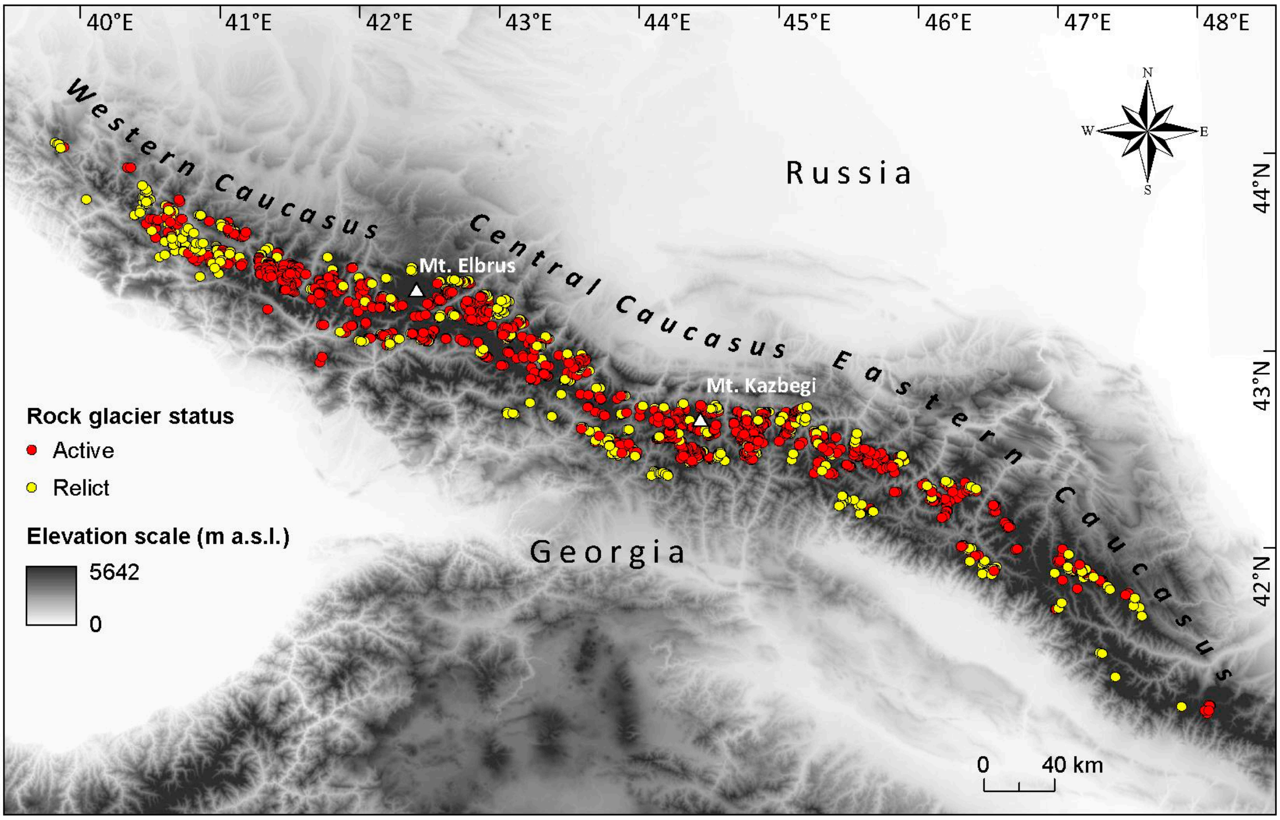


Figure 4. Color-coded map of active and relict rock glaciers for the Greater Caucasus.

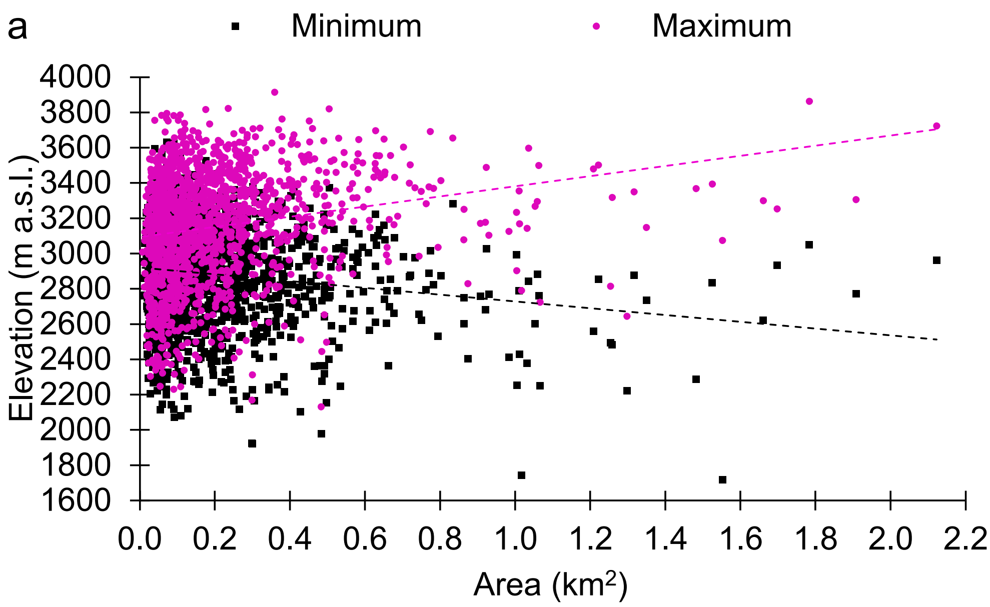


Figure 5. *Cont.*

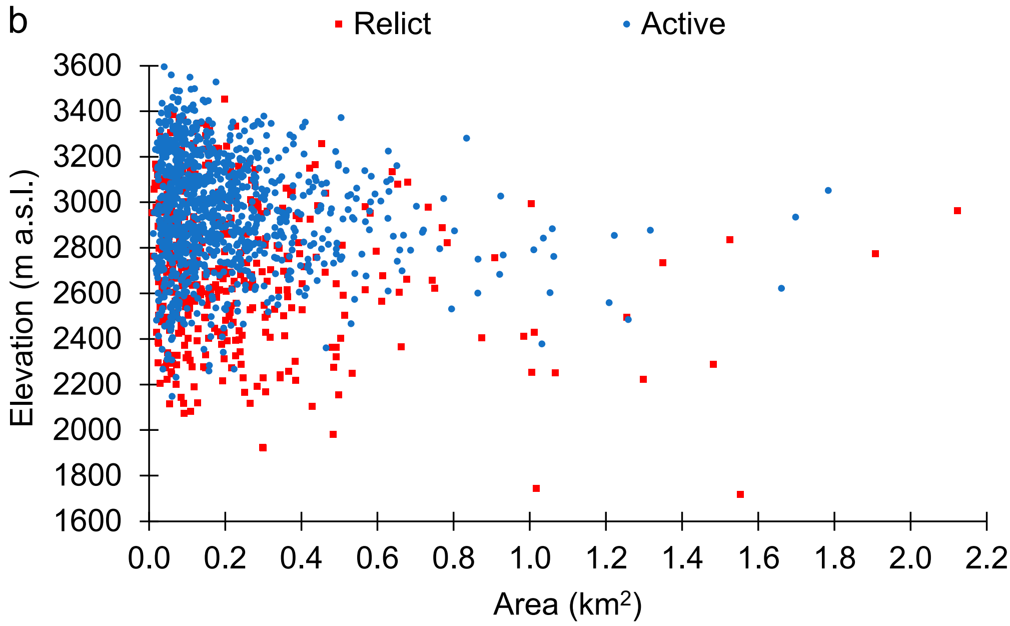


Figure 5. (**a**)—Individual rock glacier area versus maximum and minimum elevation for the entire Greater Caucasus. (**b**)—Individual rock glacier area versus minimum elevation (snout position) of relict and active rock glaciers for the entire Greater Caucasus.

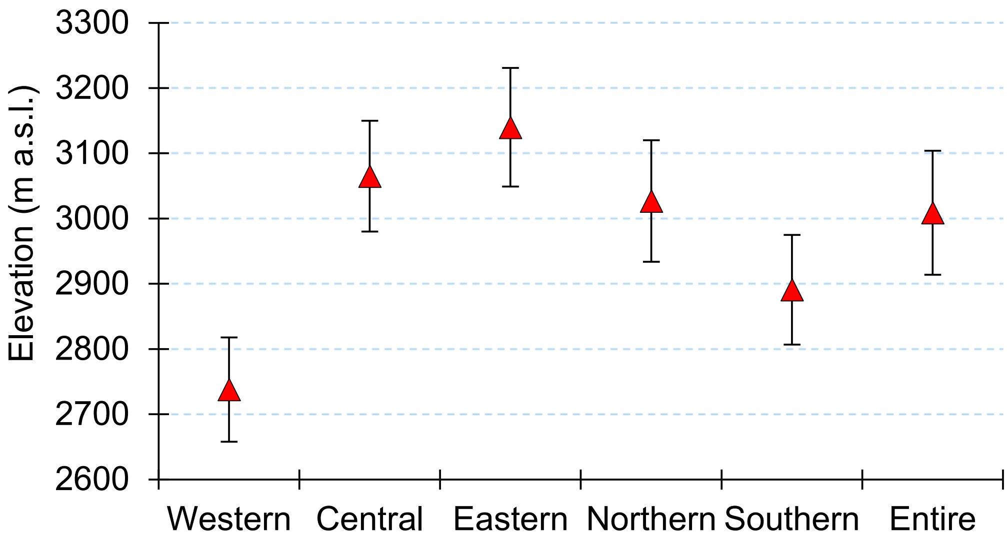


Figure 6. Mean average elevation of all rock glaciers inventoried across the Greater Caucasus according to the different sections (western, central, and eastern) and slopes (northern and southern). Error bars are based on standard deviation (1σ).

The difference between the mean average surface slope was minor between active (41.4 ± 3°) and relict (38.8 ± 4°) rock glaciers in the entire mountain region, as it is within the uncertainty. Some differences in slope were present between the different sections, e.g., rock glaciers in the western Greater Caucasus had the least inclined surface with the mean average slope of 35.9 ± 4°, while the central and eastern had relatively higher slope (42.7 ± 3° and 42.2 ± 3°, respectively). The difference in the mean average surface slope was also insignificant between southern and northern slopes. Rock glaciers found on the southern slopes had the mean average slope of 43.4 ± 3°, while the northern counterparts had the mean average slope of 40.2 ± 3° (Figure 8a). Figure 8b shows the spatial distribution of mean elevation versus average slope for all rock glaciers larger than 0.01 km^2 in the Greater Caucasus.

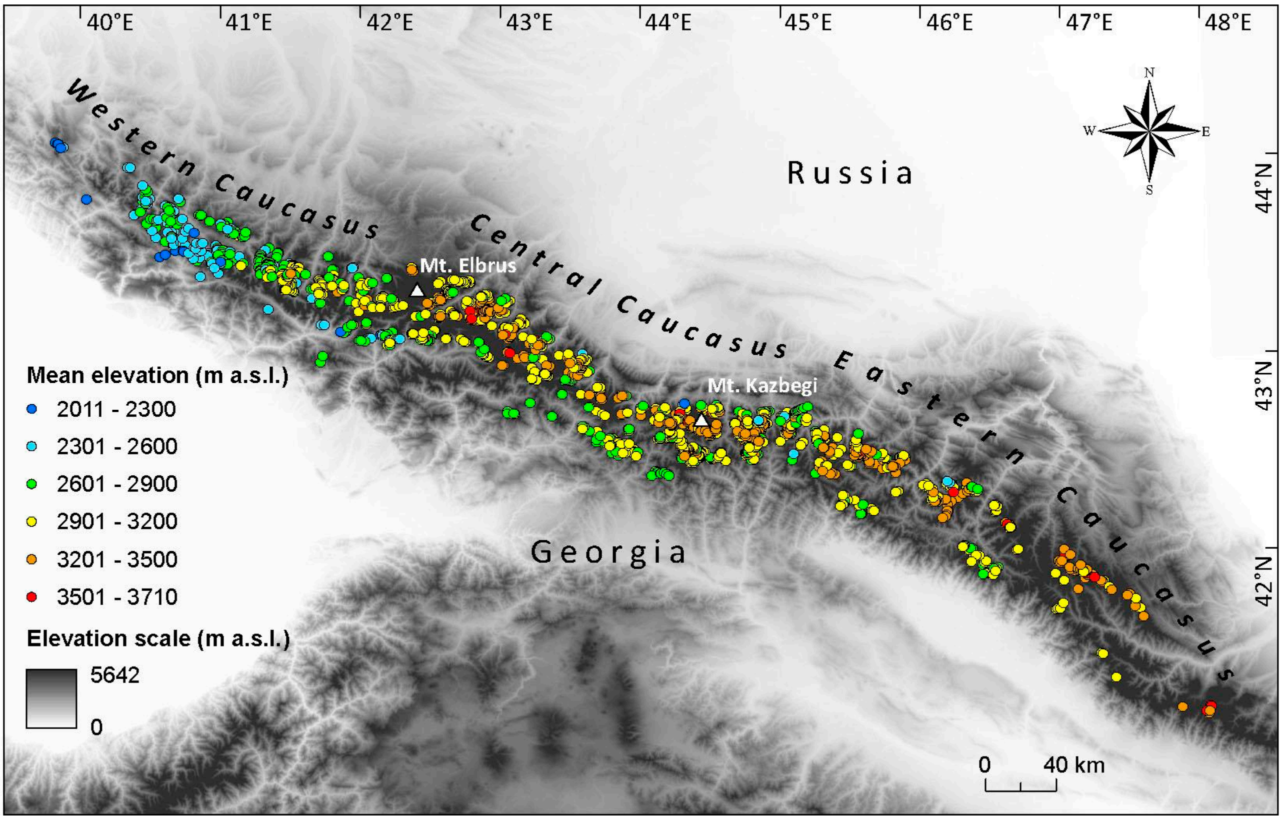


Figure 7. Color-coded map of mean elevation for all rock glaciers larger than 0.01 km^2 in the Greater Caucasus.

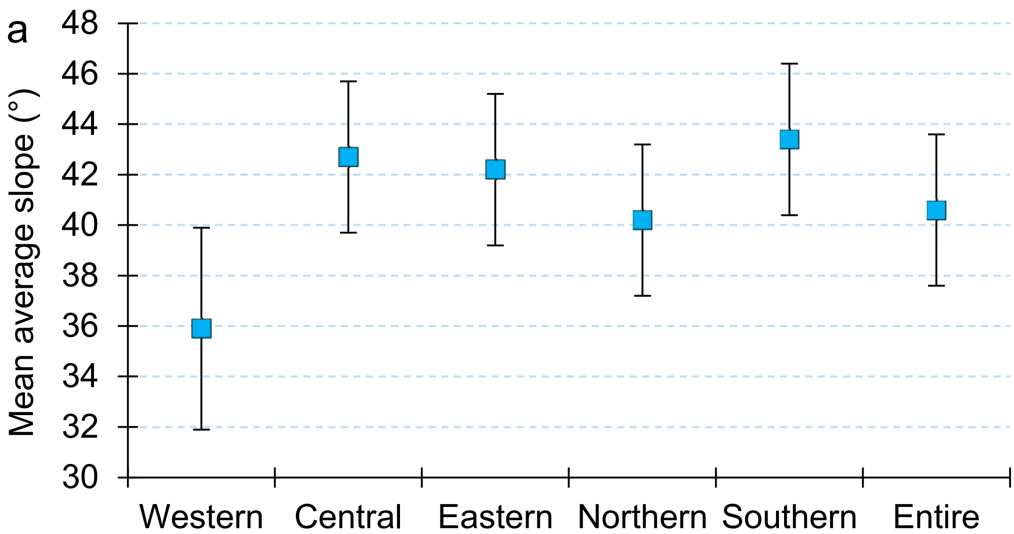


Figure 8. *Cont.*

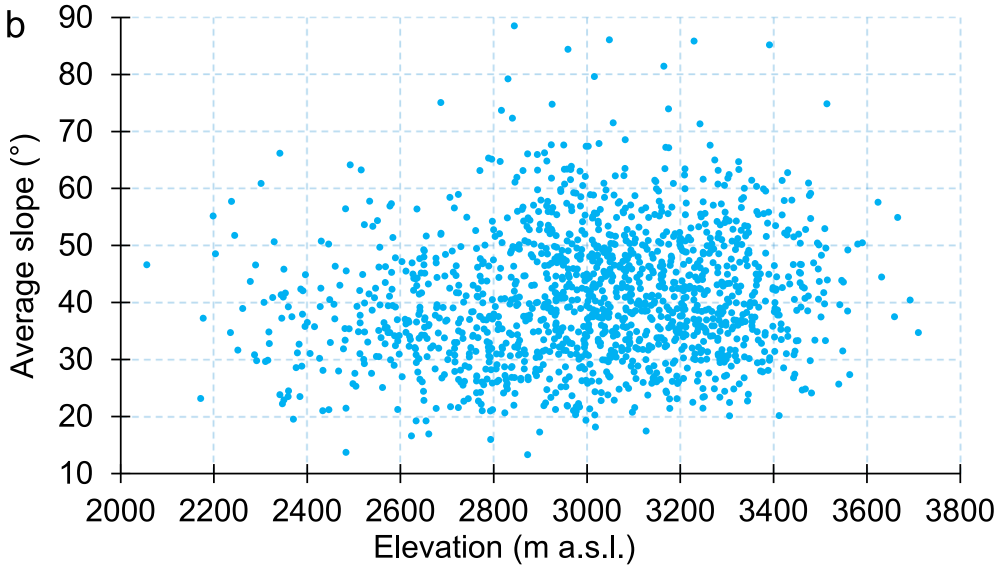


Figure 8. (**a**)—Mean average slope of all rock glaciers inventoried across the Greater Caucasus according to the different sections (western, central, and eastern) and slopes (northern and southern). Error bars are based on standard deviation (1σ). (**b**)—Spatial distribution of mean elevation versus average slope for all rock glaciers larger than 0.01 km^2 in the Greater Caucasus.

6. Discussion

This rock glacier inventory identified 1461 landforms, from which 1018 were classified as active, and 443 as relict. This number of rock glaciers in the Greater Caucasus and their existence at higher elevations emphasizes the importance of these landforms.

6.1. Possible Factors Controlling Rock Glacier Distribution

We interpreted the observed difference in the distribution of rock glaciers in the Greater Caucasus as a reflection of lithology, topography, climate, and its glaciation history [47,93]. The landscape of the central Greater Caucasus is mainly composed of crystalline slates, quartz diorites, Proterozoic and lower Paleozoic plagiogneisses, and plagiogranites [46], which are not prone to the formation of sediments and rock glaciers due to their resistance to erosion. Jurassic sedimentary rocks are dominated in lithology of some river basins in the eastern Greater Caucasus. These types of rock are characterized by relatively high erosion rates [47,94] and a better support formation of rock glaciers. The relatively low hypsometry of the western range can explain the lower number of rock glaciers and their lower average elevation and slope. In addition, higher precipitation rates in the western Greater Caucasus, due to closer proximity to the Black Sea, might promote the existence of more ice and thus lower elevations of the rock glaciers, although this topic needs further investigation.

6.2. Comparison with Other Mountain Ranges

Direct comparisons of our findings with other studies from the Caucasus are difficult due to the lack of previous data, i.e., none of the earlier works provide regional information of rock glaciers in digital form, which makes such a comparison impossible. Complete inventories for other mountain ranges are also relatively rare. However, similar rock glacier inventories based on high-resolution imagery using comparable methods have been recently published for the Austrian Alps where Wagner et al. [42] observed an average minimum elevation for all Austrian rock glaciers at 2276 m a.s.l. This is very similar with our data for all Caucasus rock glaciers (2282 m a.s.l.). In the Austrian Alps, the snout of the relict rock glaciers is situated at lower elevations than the active rock glaciers (median difference of 457 m for all rock glaciers) which is also comparable with the parameters inferred from the inventoried rock glaciers of the Greater Caucasus confirming that the relict rock glaciers have relatively lower (239 m) minimum elevation than those active rock glaciers.

We note that a more comparative analysis with results in any other mountain regions could be a topic for separate independent future research.

6.3. Mapping Uncertainty

The main sources of uncertainty, where the classification and mapping can potentially be improved in the next version, include but are not limited to: lack of clear geomorphological features of the object; errors of classification such as rock glaciers versus debris-covered glaciers; active rock glaciers versus relict forms (Figure 9); interactions with recent glaciations; talus slopes; truncated front in gullies. Uncertainties of mapping can arise mainly due to the insufficient quality of the initial data such as satellite imagery and DEM (cloudiness, snow, poor lighting, and coarse resolution), cartographic resolution of Google Earth Pro (distances, and elevation), and differences in resolution between dates of imagery. However, our total uncertainty (7.7%) does not exceed the recommended maximum uncertainty (approximately 10%) by the IPA Action Group [44] while mapping rock glaciers.

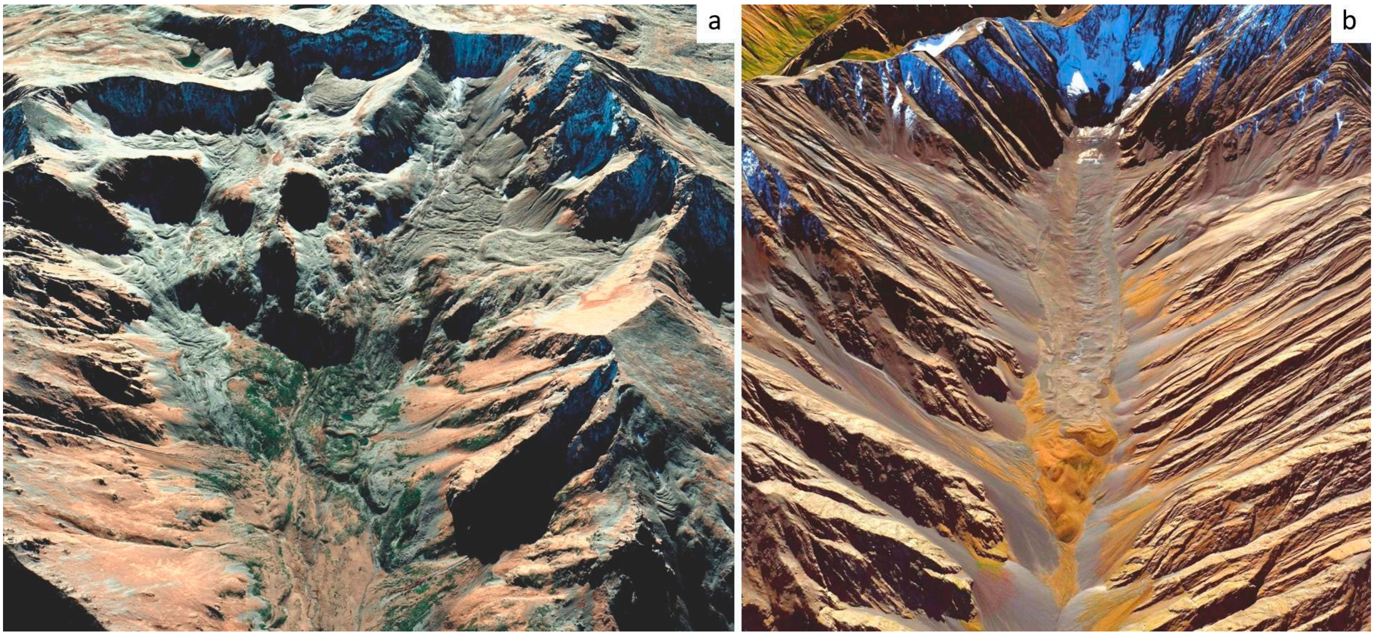


Figure 9. Examples of complex rock glacier terrain with hard-defined boundaries. (**a**)—active rock glaciers (upper part) versus relict rock glaciers (lower part) (43°30′6.58″ N 41°6′46.16″ E). (**b**)—debris-covered glacier (upper part) versus active rock glacier (lower part) (42°42′3.67″ N 44°50′44.61″ E). Google Earth imagery 26/10/2020 (**a**) and 22/09/2011 (**b**) is used as the background. © Google Earth 2022.

7. Conclusions

In this study, we present the first systematic inventory of rock glaciers for the entire Greater Caucasus region. The dataset includes polygons and characteristics of 1461 rock glaciers from different parts of this mountain region. Furthermore, it also enables the comparison of rock glaciers for different countries (Russia, Georgia, Azerbaijan), slopes—according to the location relative to the main watershed of the range (northern vs. southern), sections—based on physical geographical division (western, central, and eastern), and river basins—according to the hydrological catchment. A consistent attribution that was created during this study also enabled us to compare this with other inventories from different mountain regions and provided additional data for the modelling of the spatial distribution of permafrost in the Greater Caucasus.

Most of the landforms (1018 rock glaciers) were classified as active, while the remaining rock glaciers (443) were interpreted as relict. Active rock glaciers had a relatively smaller mean area than relict rock glaciers. Distribution of the rock glaciers were inhomogeneous according to the slopes and sections. Rock glaciers on the southern slopes had relatively lower mean elevation than those on the northern counterparts. Rock glaciers in the western Greater Caucasus reside at statistically significantly lower mean elevations than those in the central and eastern. We observed no significant difference in surface slopes between active and relict rock glaciers throughout the entire mountain region.

The main source of error in our database was related to the resolution of imagery, seasonal snow, shadows, and the classification strategy or interpretation. However, this rock glacier inventory is not a final product but only the first step towards a systematic approach for the entire Greater Caucasus, which will allow to improve these errors in the next version.

Future work should focus on more detailed field investigations; careful digitization and classification of rock glaciers; velocity measurements (in situ and from space), and classification of destabilized landforms, as well as their relationship with meteorological conditions along with climate analysis; measurement of ice and permafrost presence by ground-penetrating radar and electrical resistivity tomography; hydrogeological impact of rock glaciers, such as storage capacity and discharge dynamics. In addition, absolute age dating of the rock glaciers using the Terrestrial Cosmogenic Nuclide Dating has not yet been completed in this region; increasing interest in using this technique to better understand rock glacier role in palaeo-climate reconstruction.

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