
Rock glaciers in mixed lithology: a case study from Northern Pirin

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Received 14 November 2020; Revised 16 December 2020; Accepted 16 December 2020

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ABSTRACT

Rock glaciers are lobate or tongue–shaped assemblages of poorly sorted, angular–rock debris and ice, commonly found in high mountain environments, which move as a consequence of the deformation of internal ice (Giardino and Vitek, 1988; Barsch, 1996). However, in most research works, when discussing the formation of these features, the focus has been mainly on the past or present climatic conditions. The systematic observations of the distribution of relict rock glaciers in the mountains of the Balkan Peninsula indicate however that geological setting, represented by bedrock type and composition, and the pattern of fault lines, is not less important for the formation and evolution of these landforms.

The present article is focused on rock glaciers in the high mountain zone of the Pirin Mounains (Bulgaria), which are formed in mixed lithology, with participation of both silicate rocks (granite, gneiss) and carbonate rocks (marble). In fact, these rock glaciers are the only ones of a typical morphology that exist in the glaciokarstic marble area of Northern Pirin. What is common for all locations where such rock glaciers are found is that the marble layer, which is on top, is quite thin (few metres to few hundreds of metres). In such conditions, the rock glacier formation occurred following the mechanism typical for silicate rocks, but using marble debris and block material instead. The observed forms are characteristic only for marginal zones, along the contact line between silicate and carbonate high mountain environments.

KEYWORDS Pirin, rock glaciers, mixed lithology, marble, silicate rocks

1. Introduction

Rock glaciers are among the most prominent cryogenic landforms in the mountains of Southeast Europe. These are usually large deposits of rock debris of various sizes, often in form of a chaotic pattern of

ridges, furrows and lobes. In Bulgaria, rock glaciers are observed in high mountain areas, at altitudes between 2096 and 2710 m a.s.l. (Onaca et al., 2020). According to Washburn (1979) a rock glacier is “a tongue–like or lobate body usually of angular boulders that resembles a small glacier, generally occurs

in high mountainous terrain, and usually has ridges, furrows, and sometimes lobes on its surface, and has a steep front at the angle of repose". Berthling (2011) defined rock glaciers as "the visible expression of cumulative deformation by long-term creep of ice/debris mixtures under permafrost conditions". It is considered that they originate either from true glaciers (Ackert, 1998; Harrison et al., 2008), which during recession and deglaciation in warming conditions were gradually covered by debris (i. e. during warming), or from scree deposits (Haeblerli, 1985), in which permafrost developed during a subsequent cooling stage.

In general, rock glaciers have been categorized as either active, inactive or relict (Wahrhaftig and Cox, 1959). Active rock glaciers have a core of buried ice inside the debris. This makes them able to move downslope, forced by gravity. The heavy weight of the debris material exerts pressure on the ice and makes it plastic, and initiates the creep process. Similar to glaciers, rock glaciers are able to move on surfaces tilted 8–10 degrees. Therefore, the debris material can travel several hundreds of metres down and away from debris' source zone. In conditions of consequent warming/decrease of solid precipitation, rock glaciers may become inactive – they still have some ice inside, but no more move. If further warming occurs, ice can melt completely, and cause some subsidence on the surface of the rock glacier, which becomes relict. Rock glaciers in the high mountains of the Carpathian–Balkan area are considered mostly relict, but for 10 of the highest rock glaciers in Rila and Pirin Mountains still the presence of sporadic patches of permafrost is suggested (Onaca et al., 2020).

Since the pioneer work of Capps (1910), numerous studies of rock glaciers have been published (Wahrhaftig and Cox, 1959; Martin and Whalley, 1987, Barsch, 1988, 1997). In most of them, rock glaciers are researched as products of climate changes in the past, and as landforms which can successfully be used as proxies for paleoclimate reconstructions (Martin and Whalley, 1987). At the same time, less attention has been paid to the importance of topography, and especially of geological setting for rock glacier formation.

Along with appropriate climatic and topographic conditions, in order to develop, rock glaciers require a source of material to supply debris with a proper size (Martin and Whalley, 1987). Prevalent rock fragments need to be large enough to provide sufficient internal space (caverns, pores) for the snow accumulation and freezing of water. The possibility to produce such fragments depends on the structure of rocks and their way of weathering. Rocks which are not highly prone to physical weathering (such as limestone and dolomite), or have thin schistosity and disintegrate into tiles (for example some schists, phyllite) do not support formation of buried ice, as the screes produced in result of their weathering are very compact and provide too little pore space. Also inappropriate are all chemically highly soluble rocks, such as the mentioned limestone and dolomite, and also marble (despite that the latter is a crystalline rock which fragments into larger blocks than limestone), because of the development of karst features. Atmospheric waters that infiltrate in the scree accumulations of such rocks drain in the karst caverns and cannot be retained in the scree long enough to form ice (even if pores are large enough).

On the contrary, among the rocks which are especially supportive for rock glacier formation, are granite, gneiss, massive conglomerate, which naturally have lots of cracks, and fragment in relatively large and angular blocks.

The present article focuses on some specific cases of relict rock glaciers in the Pirin Mountains of Bulgaria, which blocky substrate is composed of marble. Contrary to limestone from which it descends, marble has a tendency to develop cracks at right angles, and defragment on larger angular blocks due to physical weathering, especially frost action) and because of this it is able to produce deposits for rock glacier formation. On the other hand, marble is a carbonate rock, chemically soluble in water. Usually marble surfaces are karstified, which results in a lack of surface runoff, as atmospheric (rain and snow) waters infiltrate in karstic caverns.

The studied rock glaciers are formed in conditions of mixed lithology (marble and granite/gneiss), and have distinct morphology and rock composition. Such forms can be considered unusual, being

determined both by the diverse bedrock with contrast chemistry (carbonate vs. silicate rocks) and by the appropriate rock stratification and sequences.

2. Study area

Pirin is the second highest mountain in Bulgaria and the third highest on the Balkans. It is located in southwest Bulgaria, between the rivers Struma, to the west and Mesta, to the east. The mountain is generally shaped as a rhomboid (70 x 35 km size) with its longer axis running in NNW–SSE direction (Fig. 1). The highest point, Mt. Vihren (2914 m a.s.l.), is situated in the northern part of the mountain. Two more locations in the central section exceed 2800 m a.s.l., and there are numerous peaks above 2500 m a.s.l.

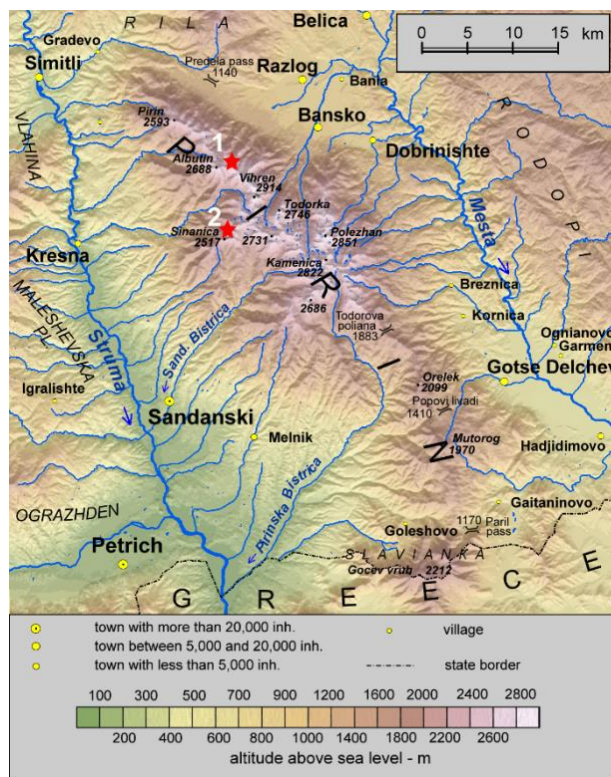


Figure 1 Map of Pirin Mountains with the study objects: 1 – Razlozhki suhodol rock glacier; 2 – Sinanitsa rock glacier

Like many other mountains within the Rhodope massif, Pirin has a complex geological structure. Three granitic bodies (intrusions) build up the core of the massif: one in the farthest north, one in the center, and one in the south. Around, and between them, the mantle of metamorphic rocks includes

gneisses, schists, amphibolites and marble. Sedimentary rocks are exposed in the periphery, which is surrounded from all sides by faults. The mountain represents a classical horst morphostructure. Volcanic rocks occupy the far east of the area. They are a result of eruptive activities along the Mesta graben during the Paleogene.

In Pirin, marble is found in two main zones: in Northern and in Middle Pirin. To the north, this is the highest section of the main ridge from Vihren peak on the south, to Okaden peak on the north, with the adjacent northeast slope (on the SW slope marble occupies only the highest altitudes). This is a high mountain section about 5 km long, which includes the highest peaks in Pirin: Vihren (2914 m a.s.l.), Kutelo (2908 m a.s.l.), Banski suhodol (2884 m a.s.l.) and Bayuvi dupki (2856 m a.s.l.). Five vast cirques were carved on the northern slope, which overlap over preglacial forms – in fact these are complex glaciokarstic depressions (cirques–uvalas, as mentioned for Pirin by Popov, 1962; and for Durmitor Mountains by Djurović, 2011). From SE to NW these are: Kazanite (Goliam Kazan and Malak Kazan), Kutelo, Banski suhodol, Bayuvi dupki, Kamenitica. This area is the only in Bulgaria where glaciokarst has been developed (Gachev, 2017). In Northern Pirin, marbles occupy also a small spot around Sinanitsa peak to the SW of Vihren.

The marble area is adjacent to silicate metamorphic rocks to the northwest, and with granite to the southeast, at altitudes up to 2600 m a.s.l., are favorable for the existence of fossil rock glaciers.

In middle Pirin marble is spread around Orelek peak (2099 m a.s.l.). Due to the lower altitudes, periglacial landforms are less common, and there are no rock glaciers found in that area.

The high part of Pirin was subjected to extensive glaciation during the Pleistocene. The equilibrium line altitude (ELA) during the maximum glacial stage (not dated) was at 2200–2300 m a.s.l. (Georgiev, 1991). Glaciers were of a valley type, descending 7–11 km to the foot of the mountain at 1100 m a.s.l., along the north heading valleys of Banderitsa and Demianitsa, which join shortly above the town of Bansko (Lilienberg and Popov, 1966). The area above 2200 m a.s.l. is dissected into several large and a number of smaller cirques. The most exten-

sive are those in the central (granitic) part of Pirin: Banderitsa cirque, the cirques of Valiavishki, Prevalski and Vasilashki lakes, Belemeto, Kremenski, Popovo lake cirque and many others (Mironski et al., 1970). Within this area there are around 110 glacial lakes which are scattered across cirque floors (Valkanov et al., 1964).

Apart from two tiny small glaciers (glacierets) in the marble cirques of Pirin, with a total area of 1.5 ha, and several ice patches (Gachev et al., 2016), all glacial landforms are a relict character. Nowadays the high mountain areas are subjected to cryogenic (periglacial in broad sense) activity. Frost weathering is especially intensive on rocky slopes, high summits and ridge tops.

Climatically, Pirin belongs to the sub-mediterranean zone (it is 110 km away from the Aegean Sea). The mountain has the highest range of annual air temperatures in Bulgaria, from +14°C at Kresna, to –1.4°C at Vihren peak (Velev, 2010; www.swu.bg). The 0°C annual isotherm is presently situated between 2650 and 2700 m a.s.l. In general, in high cirques (2400 m. a.s.l. and above) the period with negative temperatures lasts from November to April (and is associated with snowfalls), while between May and October average daily temperatures are mostly positive and rainfalls prevail (Grunewald et al., 2016).

The number of days with transition through 0°C ranges between 90 at 2000 m a.s.l. and 80 at 2900 m a.s.l., and the number of frost days (with minimum daily temperature below 0°C) range between 170 and 260 respectively (Grunewald and Scheithauer, 2008, 2011). In result, exposed ridges at altitudes above 2600–2700 m a.s.l. are strongly weathered. On the other hand, the great number of frost and icy days at cirque floors at 2200–2400 m a.s.l. 200–220 days with minimum temperature below 0°C and 110–130 days with only negative temperatures (Grunewald and Scheithauer, 2008) determines the 6–7 months of snow cover duration at these sites, and the restricted frost action there. Although Pirin is among places with highest annual precipitation amounts in Southern Bulgaria: around 1000–1100 mm for the high mountain zone, the overall sums are small compared to other moun-

tains in Southern Europe, due to the rain shadow that the Dinaric Mountain and Carpathian mountain ranges produce over of all the eastern part of the Balkans. Around two thirds fall in the cold part of the year (October to March) which provide relatively good snow accumulation.

The mentioned rain shadow effect should have occurred in a similar way in the past, during glacial and late glacial times. Especially in the latter period, the combination of low temperatures and modest precipitation supported the formation of rock glaciers and permafrost. Based on climate reconstructions, it is considered that the rock glaciers in the mountains of Bulgaria (Rila and Pirin) were originally formed during late glacial, in the course of deglaciation (Dimitrov and Gikov, 2011; Dimitrov and Velchev, 2012).

3. Methods of research

A detailed geomorphological mapping was done of those cirques in Northern Pirin, which lie on the zone of contact between the marble and the surrounding silicate intrusive and metamorphic rocks: Sinanitsa, Georgiitsa, Razlozhki suhodol and Okaden cirques (Fig. 2). Because of high portion of non-ice component, rock glaciers are usually able to retain much of their morphology long after the permafrost body has completely thawed (Hughes et al., 2003). This was used to identify relict rock glaciers on the field.

Topography maps of 1:10,000 scale were used as a base for the creation of a digital model in ArcGIS 10. Landforms were identified on the field and their main morphometric characteristics were measured with a laser range finder (900 m range). Lithology was diagnosed using geological maps and visually, on the basis of color, crystal structure and lichen cover. The state of lichens was used to make a relative dating of geomorphic activity of rock glaciers and screes. In situ climatic measurements were organized at several sites in the area: on Vihren peak –air temperature and humidity has been measured since October 2014.

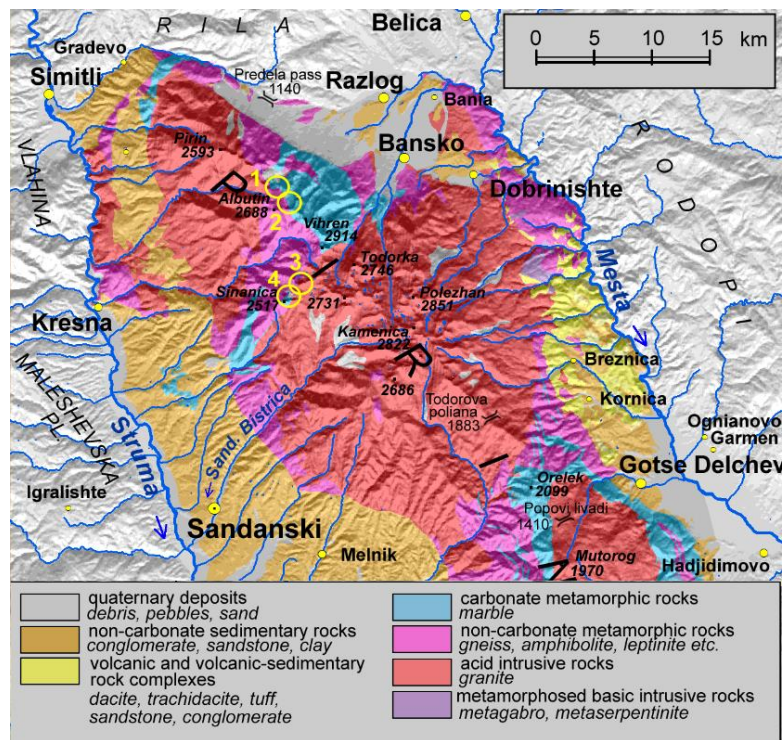


Figure 2 Geological map of Pirin, with the target cirques: 1 – Okaden, 2 – Razlozhki suhodol, 3 – Georgiitsa, 4 - Sinanitsa

4. Representative rock glaciers in mixed lithology

Our observations in the marble (glaciokarstic) high mountain area of Northern Pirin have shown that no rock glaciers have been formed in that area, despite the high altitude and the optimal climatic conditions that might have existed in the past. Only two rock glaciers have been described and studied in cirques where marble contacts with other silicate rocks. They are located in the cirques Razlozhki suhodol and Sinanitsa.

4. 1 Razlozhki suhodol rock glacier

The cirque of Razlozhki suhodol lies on the geological contact between marble (to the east) and gneiss (to the west) (Fig. 3 and 4). The cirque has a NNW aspect. The length from the main ridge to the lowest rim is 3.9 km. the uppermost section of the cirque is approximately 1.3 x 1.3 km, with an area of 2.78 km² (Mitkov, 2020). The highest point of that part of the cirque (Razlozhki suhodol peak) is at 2660 m a.s.l., and the lowest altitude is 2320 m a.s.l. The eastern slope of the cirque is higher, in fact a giant rock face of marble, which to the north de-

scends with several toothed peaks, known as 'The stairs'. A line of large screes runs along the slope foot. On the contrary, the western slope, carved in gneiss, is steadier, with a much lower altitude. The gneiss part of the cirque floor is filled with block material, which compose a chaotic pattern of ridges and furrows – a relict rock glacier. The eastern flange of the rock glacier (more than half) is made of marble blocks, which have originated from the marble rocky peak to the south. Descending north, the debris enter over the silicate terrain, where in fact the body of the rock glacier is (Figs. 3 and 4). The existence of the rock glacier in its shape is due to that silicate bed, which at the time of the rock glacier formation, hindered the escape of ground waters and allowed for the formation of permafrost.

The western, much smaller flank of the rock glacier, is entirely made of gneiss blocks. The rock glacier is situated at altitudes between 2410 and 2340 m a.s.l., and occupies an area of about 7.5 ha. In the lower end, debris accumulations are dammed by a ridge of deposits of mixed lithology and size with a steep front – probably a glacial moraine. A small pond (Suhodolsko Lake) is formed before the ridge.



Figure 3 Razlozhki suhodol cirque: a look towards south

4. 2 Sinanitsa rock glacier

Sinanitsa rock glacier is located in the cirque to the north of the 2517 m high Sinanitsa peak. The cirque is situated in Northern Pirin, on a side ridge descending to the southwest of the main crest of the mountain. The cirque has a NW aspect, and a staircase vertical cross section. The highest level reaches down to 2179 m a.s.l. at Sinanitsa Lake (Figs. 6 and 7). The lake itself has a length of about 140 m, width 90 m and 11 m depth.

In the area, marbles build up only the massif of Sinanitsa peak. They form “a marble cap”, which in this area is a sole remnant of the metamorphic mantle that once covered the granitic intrusion. The marble rock strata, which represent remains from the southern hip of the Sinanitsa anticline (Zagorchev et al. 2017) descend to southwest, forming a monocline structure. The very small thickness of the remaining marble cover (up to 200–250 m) is illustrated by the fact that in the base of the rock walls of Sinanitsa peak, rock start to change, and transition layers are observed. In fact all the cirque floor is on a silicate bedrock.

The rock glacier is developed on the NE, steepest slope of Sinanitsa peak (Fig. 6). It represents a large field full of scattered marble debris and blocks,

which have produced the familiar pattern of ridges and furrows, which is normally addressed as a rock glacier. The altitude of the rock glacier is 2250–2180 m. a.s.l., and the total area is about 9 ha.

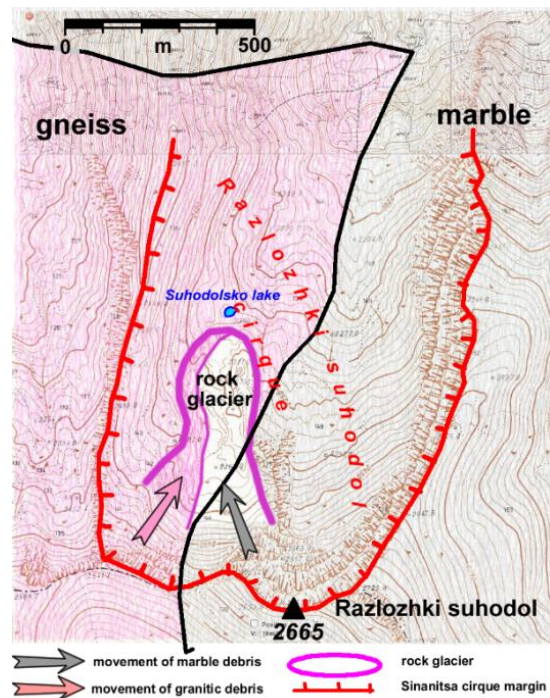


Figure 4 Razlozhki suhodol cirque. Topographic and geological setting of Razlozhki suhodol rock glacier



Figure 5 The rock glacier in Razlozhki suhodol cirque



Figure 6 Sinanitsa peak, with the rock glacier in its NE foot and Sinanitsa lake in the background

It seems that the NE slope of the peak provided best conditions for formation of abundant debris material – exposed shady rock walls, crossed by numerous tectonic dislocations. In normal situation it is difficult for atmospheric waters to collect in the marble block accumulations, because of the karstic features and the infiltration of waters in depth. But in this case the marble block materials from the slope of Sinanitsa peak have been deposited over a bed of silicate rocks, which allowed for preservation of accumulating of atmospheric waters and for a formation of an active rock glacier in the past, when climate conditions were appropriate.

Like the other of the studied rock glaciers, Sinanitsa rock glacier also has part of it made of blocks

of silicate rock (here it is granite). Debris material for this eastern rock glacier section, are originated from the granitic part of the cirque (see Fig. 7).

On the field, the two lithologically contrasting sections of the rock glacier, which are adjacent to each other, are easily recognizable by the differences in rock and lichen color (Fig. 8): white for marble (down right), greenish for granite (up left).

As it was mentioned above, the marble cap of Sinanitsa is quite thin and all the cirque floor is made of granite (Fig. 9). This has allowed for the formation of the rock glacier, and the permanent water body represented by Sinanitsa lake in the northern end of the cirque.

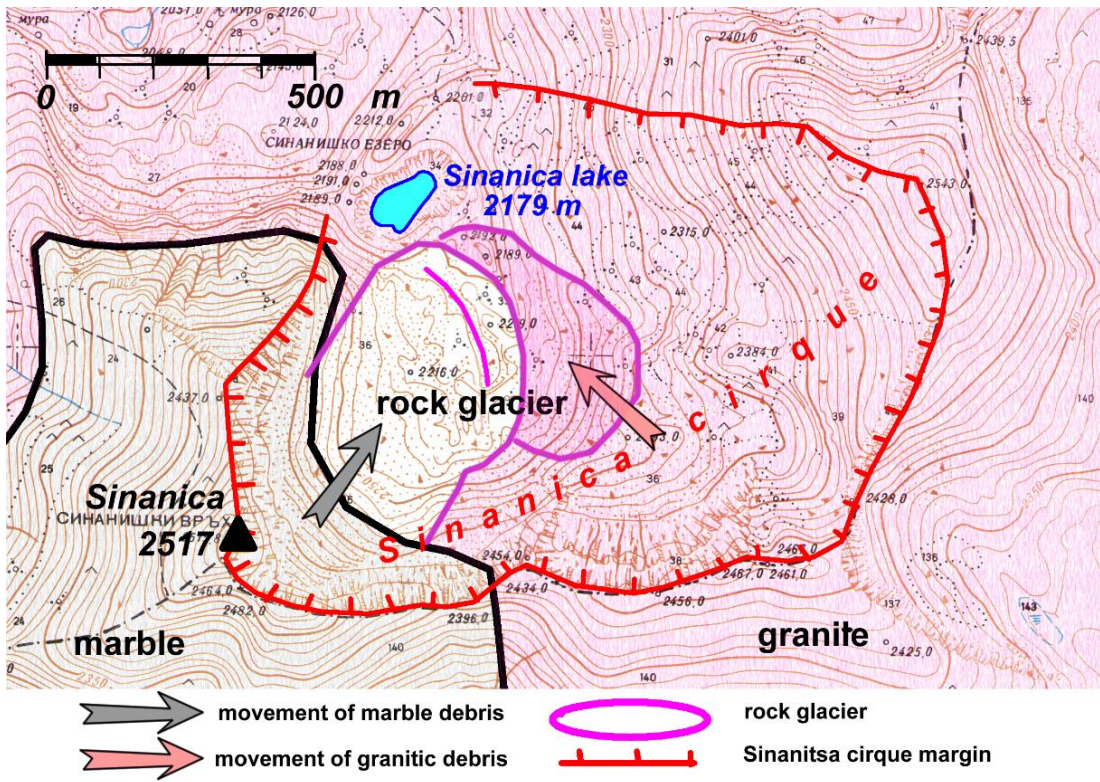


Figure 7 Sinanitsa cirque, with the location of the relict rock glacier



Figure 8 A view over Sinanitsa rock glacier: the marble section (in the foreground) is easily distinguished from the granite section (in the background) by the difference in rock coloring

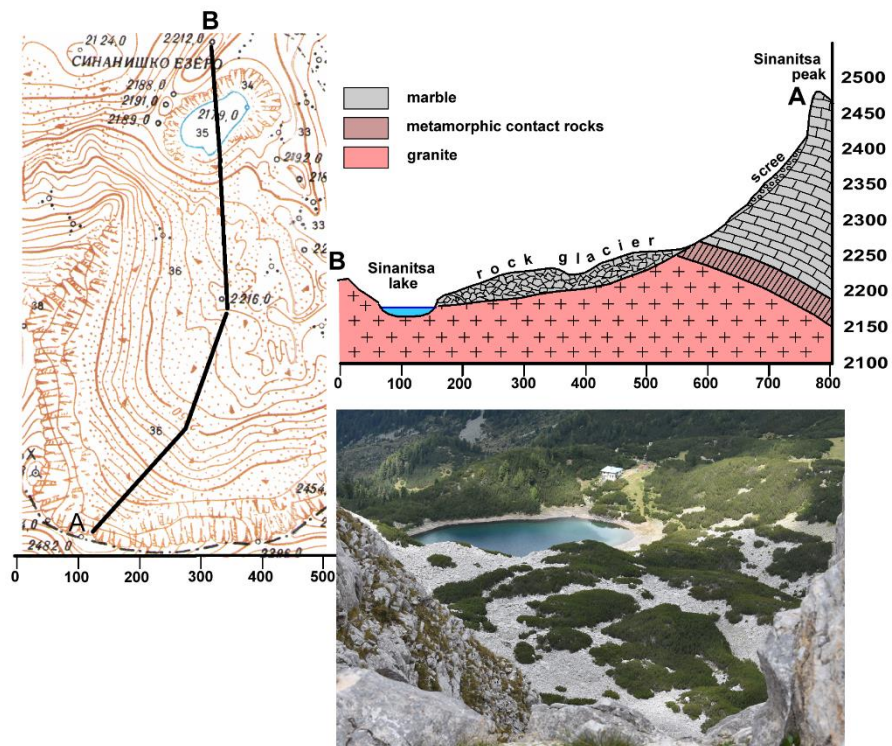


Figure 9 A profile (cross section) of Sinanitsa cirque and the rock glacier, and a view on the rock glacier from the slopes of Sinanitsa peak

5. Formation of rock glaciers in Pirin

According to Dimitrov and Gikov (2011) there are at least 55 rock glaciers in the high mountain zone of the Pirin Mountains, and after more recent studies their number has been increased to 83, at altitudes 2096 to 2710 m a.s.l. (Magori et al., 2017). Most of them are debris rock glaciers, but there are some of talus type (Gachev et al. 2017). Rock glaciers in Rila and Pirin Mountains are mostly considered relict at present (Gikov and Dimitrov, 2010; Dimitrov and Gikov, 2011). It is suggested that they were formed in the period soon after the last retreat of Pleistocene glaciers, i. e. at late glacial time, when the climate was much colder than present, but already unfavorable for classical glaciation (probably in the period Oldest Dryas – Younger Dryas, Dimitrov and Gikov, 2011; Dimitrov and Velchev, 2012).

Climate reconstructions (Bozhilova, 1978; Stefanova and Ammann, 2003; Stefanova et al., 2003) suggest that in general the late glacial in the mountains of SW Bulgaria was relatively dry. This enhanced glacier retreat, and by the middle of the period (Oldest Dryas) all glaciers were already in cirque phase (Mitkov, 2020). The cold dry conditions sup-

ported the enhanced frost weathering in the high mountain zone. Having in mind the present climate which provides optimal frost heave conditions for the open slopes and ridges at 2500–2900 m a.s.l., it would be suggested that during long time throughout the late glacial, similar conditions prevailed at altitudes 2100–2500 m, where most of Pirin rock glaciers are situated (including the two cases of the present work).

As it was already mentioned, almost all rock types in the high mountain zone of Pirin have potential to produce debris material suitable for rock glacier formation. Apart from the appropriate climatic conditions, which prevailed in the late glacial, proper topographic and geological settings were also crucial for the development of these landforms. Rock glaciers formed mainly at sites where shady or partly shady aspects combine with zones of weakened rocks. The latter are associated with tectonic disruptions of various orientation and size that formed as a consequence of intrusion buildup. In general, the rise of the Pirin granitic intrusions in the course of the Cenozoic caused the gradual folding of the metamorphic series, formed anticline struc-

tures, among which is the Sinanitsa anticline (Zagorchev et al. 2017). Moreover, in the course of multistage intrusion rise and cooling (Zagorchev 1995, 2001), vertical displacements occurred between major fragments within the granitic bodies. All these tectonic activities produced planes and strips of milonitized rocks which have been more easily eroded. Some weakened zones are associated to the magmatic dykes that cut through the cooling granitic and metamorphic bodies and contained still hot magma from the lower parts of magma chambers (Machev, 1993).

Some of the rock glaciers may have evolved from cirque glaciers, with their gradual burial by block and debris material. Others might have formed during subsequent cooling episodes, in re-

sult of freezing of atmospheric waters in the scree slope deposits. Most rock glaciers are found in the granitic part of Pirin, and a fewer number – in areas made of gneiss. Despite the abundance of produced debris material of a proper size, no rock glaciers have been recorded in the high mountain areas built of marble, the only exception being two lobes on the northern slope of Kutelo peak (Fig. 10), which do not possess classical rock glacier morphology. However, the two rock glaciers described in the present work (in the cirques Razlozhki suhodol and Sinanitsa) can also be considered exceptions – in fact they are the only ones that have classical ridge and furrow morphology, and are constituted by marble blocks and debris. This is due to their water impermeable silicate bed.

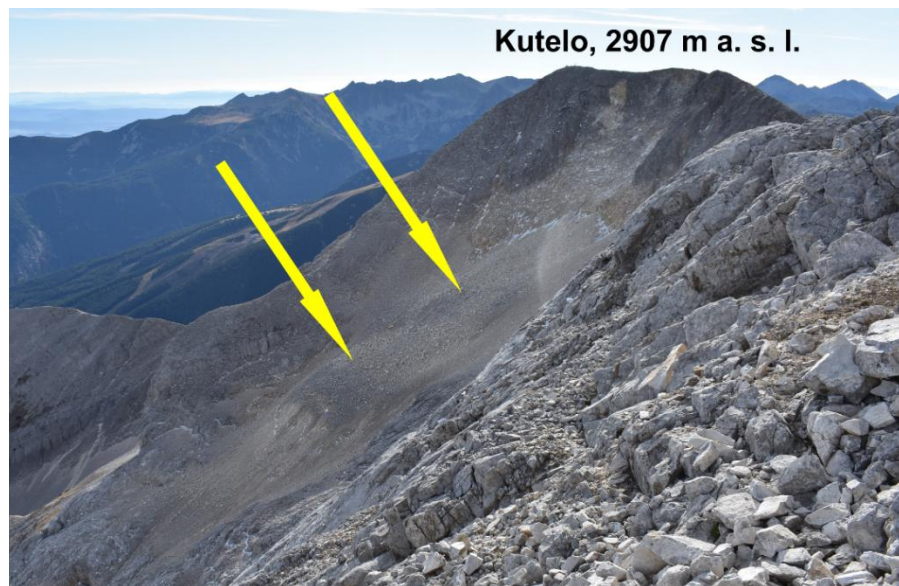


Figure 10 The debris lobes in marble, on the northern slope of Kutelo peak – the only landform in the glaciokarstic zone of Pirin which might have been formed due to former permafrost action

In the course of climatic warming throughout the Holocene, temperatures in the lower part of the high mountain belt (2000–2500 m a.s.l.) became too high to sustain permafrost, and all rock glaciers at such altitudes presently have a relict appearance – they are covered in lichens and are vegetated by grasses, junipers and dwarf (mugo) pine. No rock glaciers were formed during the Little Ice Age, although some minor displacements could have occurred at the highest rock glaciers (near the peaks Musala, Goliarn Kupen in Rila, Polezhan and Bunferishki chukar in Pirin). Some sporadic permafrost is

supposed to still exist at these sites even at present (Magori et al. 2017; Onaca et al. 2020).

6. Conclusions

Pirin is the mountain with the greatest number of rock glaciers in the high mountain zone of Bulgaria. These typical cryogenic landforms are suggested to have formed in late glacial time, in the course of the gradual retreat of Pleistocene glaciers in the highest parts of the Pirin Mountains. Out of over 80 rock glaciers in the massif, only two have been found and described in the highest mountain ridge of Pi-

rin, which is made of marble, as in general marble appears as a rock type which does not support rock glacier formation. In result of this study it has been found that those two rock glaciers were formed in result of favorable accidental combination of topographic and lithological factors, in cirques where the marble contacts with other silicate rocks. In both researched cases (in Razlozhki suhodol and Sinanitsa cirques) marble builds of the highest slopes, which have served as debris source zone for the rock glaciers; but the cirque bed further down is made of silicate rocks. In this way, due to lack of karstic caverns, at the time of rock glacier formation, atmospheric waters that entered the blocky marble material were prevented from escaping down, and were able to remain in the deposits and freeze there, forming the ice core necessary for rock glaciers to move.

In other words, on both sites, rock glaciers had the mechanism of formation typical for silicate geological environments, but with blocky and debris substrate made of marble. Nowadays, when the studied rock glaciers are no more active, the settled marble material is subjected to surface karstification.

Acknowledgements

This research was supported by South–West University “Neofit Rilski” through the project RP A4/18: Research of high mountain climate through cryospheric indicators: glaciers and permafrost – part 2 (2018), and project RP A 3/20. The high mountains on the Balkans in the conditions of climate change”.

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