S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
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CHARACTERISTICS AND EVOLUTION OF THE ROCK GLACIER NEAR MUSALA PEAK (RILA MOUNTAINS, BULGARIA)

Abstract. The article presents results from the first detailed study of the rock glacier near Musala Peak in the Rila Mountains (Bulgaria), performed in 2016–2017. Situated at 2600–2670 m a.s.l. the rock glacier is among the highest in Bulgarian mountains. It is made of granitic blocks derived from the northern slope of Musala Peak (2925 m a.s.l.). This paper presents a hypothesis on the formation and development of the rock glacier, based on detailed geomorphological mapping and rock weathering rate tests. First results from Schmidt hammer testing of rock glaciers in Bulgaria are presented and discussed. The values obtained from 782 tests show increase in rock strength from the lower to the upper part of the block accumulation, which indicates their sequential deposition over time. The rock glacier was formed in the period after the retreat of Pleistocene glaciers and most likely before the Atlantic optimum of the Holocene. Geomorphic evidence indicates at least two stages of rock glacier development. Recently it has been considered relict. However, some activity during the Little Ice Age, and even at present, is not completely excluded.

Keywords*:* rock glacier, Schmidt hammer, evolution, Musala Peak, Rila Mountains

INTRODUCTION

Rock glaciers are features typical for the high mountain environment of Bulgarian mountains Rila and Pirin. They are considered elements of the cryogenic relief (periglacial in the broader sense of the term; G l o v n i a 1959; R ą c z k o w s k a 2004). In Bulgaria they have been considered relict (G i k o v, D i m i t r o v 2010; D i m i t r o v, G i k o v 2011), formed in the past in climate conditions warmer than the glacial climate of the Pleistocene, and colder than the present-day climate. On global scale, two scientific views have been developed for the formation of rock glaciers. The views of the Continuum school (Ø s t r e m (1965) – ice-cored moraines; C o r t e (1976) – debris-covered glaciers; P o t e r 1972; A c k e r t 1998; H a r r i s o n et al. 2008; H a e b e r l i et al. 2006; J a n k e et al. 2015) are that rock glaciers are formed by degradation of real cirque or valley glaciers under conditions of climate warming (or decrease in precipitation), when ice moves too slowly (or not at all), and the intensified frost action leads to the gradual covering of stagnating ice mass with debris that break off from the slopes.

Thus the glacier gradually turns into a buried glacier (for example, Janke et al. 2015 outline 6 categories of transition between glaciers and rock glaciers). If stone blocks are sufficiently large and heavy, they start to move down the slope under their own weight, using the plastic properties of the ice core which is subject to pressure and by creep process, specific for polycrystalline ice. Under such conditions rock glaciers can "flow" over surfaces with very low gradients: 8–10° and even less, which is entirely impossible for debris in screes and fans formed solely by gravity (with critical angle of repose values of 30–35° above which motion of the material is triggered). In fact, the mixture of rocks and ice in rock glaciers acquires behavior of a jelly mass, which can travel several hundred metres from its initial position, and is eventually deposited in a typical pattern of ridges and furrows. Some of the depressions in the deposited block accumulations are considered to have resulted from suffusion during subsequent further climate warning, when the ice core melted.

Proponents of the other, periglacial origin (the Permafrost creep school) (e.g. Barsch 1978; Haeberli 1985; Harris 2004; Berthling 2011; Berthling, Etzelmüller 2011), consider that rock glaciers are permafrost features which evolve from slope or gully debris accumulations. During phases of cooling the infiltrating atmospheric water, and snowmelt water freeze in the cavities within debris accumulations deposited by gravity, and forms icy frozen cores – in fact, mixtures of debris cemented by ice. Then the ice cores provoke downslope movement of the debris mass and the formation of a pattern of ridges and furrows typical for rock glacier morphology. The formation of icy core occurs in a specific topoclimatic conditions, colder than the present one and warmer than those that prevailed in the glacial period.

A third view, which is accepted also by the author of this study, is that rock glaciers can actually form through both mechanisms (and under climate change of various trends), which leads to the formation of different morphology and development of contrasting genetic types of rock glaciers (like the "debris-covered glaciers" and "talus rock glaciers" mentioned by A. Corte (1980) and "debris rockglaciers" and "talus rockglaciers" by D. Barsch (1988)). As a landforms typical for the high mountain relief in Bulgaria, rock glaciers were mentioned for the first time by M. Glovnia (1959). In his summary about periglacial relief in the country he mentioned the presence of a rock glacier to the north of Musala Peak, near the Lake Bezimenno. Since then the term has been abandoned by Bulgarian scientists for a long time. The first detailed inventories of rock glaciers in Bulgaria were done by A. Gikov and P. Dimitrov (2010) for the Rila Mts., and P. Dimitrov and A. Gikov (2011) for the Pirin Mts. on the basis of satellite and aerial images. In these pioneer studies, 27 rock glaciers at altitudes 2140–2690 m a. s. l. were identified in the mountains of Rila, and 55 more in the Pirin at 2100–2700 m a.s.l. Descriptions of rock glaciers in the high mountain areas of the Rila Mounatins and the Pirin Mountains were also published by P. Dimitrov and A. Velchev (2011) and E. Gachev et al. (2017). The present study summarizes the results from expeditions in the Musala cirque in the Rila Mountains in August 2016 and 2017. Studies of morphology and the detailed mapping confirmed the presence of a rock glacier at the northern foot of the Musala Peak, and put forward the hypothesis for the stages of its formation.

With regard to their present activity rock glaciers can be active, inactive and relict (www.uibk.ac.at/projects/rockglacier). In active rock glaciers, like those in the Alps, the Scandinavian Mountains, the Rocky Mountains and other mountains with periglacial environment, downward movements are recorded on the order of several centimetres to several decimetres per year (Haeberli et al. 1979; Kääb et al. 1997, 2002, 2003; Serrano et al. 2006). Inactive rock glaciers show no movement, but still contain some patches of permafrost inside that have the potential for rock glacier activation in case of a slight change in climatic conditions. Relict rock glaciers are completely free of buried ice and experience no dynamic movement. In the previous studies all rock glaciers in the Rila and in the Pirin mountains were considered relict, or at least immobile, similar to those in the Tatra Mountains (Gądek, Kędzia 2008; Kędzia 2014). However, the discoveries of present existence of permafrost in the high mountains of Central and Southeastern Europe, like in the Tatra Mountains (Rączkowska 2008; Gądek et al. 2009) and the Southern Carpathians (Retezat, Parang), have raised doubts about present activity of some of the rock glaciers there (Urdea et al. 2008; Vespremeanu-Stroe et al. 2012; Onaca et al. 2013; Popescu et al. 2014). Results of these studies generate interest towards research of possible extent of permafrost in the alpine belt of Bulgarian mountains.

OBJECT OF STUDY – THE MUSALA ROCK GLACIER

The Musala cirque is one of the biggest and most representative in the Rila Mountains. (Figs. 1, 2). This complex relict glacial landform is situated in the eastern region of the mountain range. It has a total area of 2.3 km^2 and a general aspect to the north. The lowest point of the cirque is at the outlet of the Musalenska Bistritsa River from the lowest lake at 2386 m a.s.l., while the highest point is Musala Peak (2925 m a.s.l.). Cirque configuration is complex, the floor being of a staircase type with three distinct levels: at 2400, 2550–2600 and at 2710 m a.s.l. (Figs. 1, 3). Seven lakes are scattered throughout the area, at altitudes between 2386 and 2709 m. a.s.l. The lithology is relatively uniform: granite of Paleozoic age, of the Rila-West Rhodope batolith crossed by pegmatite dykes (Tueckmantel et al. 2008).

The climate in the area is subalpine and alpine, with average annual air temperatures ranging between 0.3°C (Musala hut, 2395 m a.s.l.) and –3.1°C (the Musala Peak, 2925 m a.s.l.) (data for 1951–1980 by Annual Bulletins of IHM) and annual precipitation about 1000 mm for the highest mountain areas of the Rila Mountains. (data based on analyses by P. Nojarov 2012). Precipitation regime

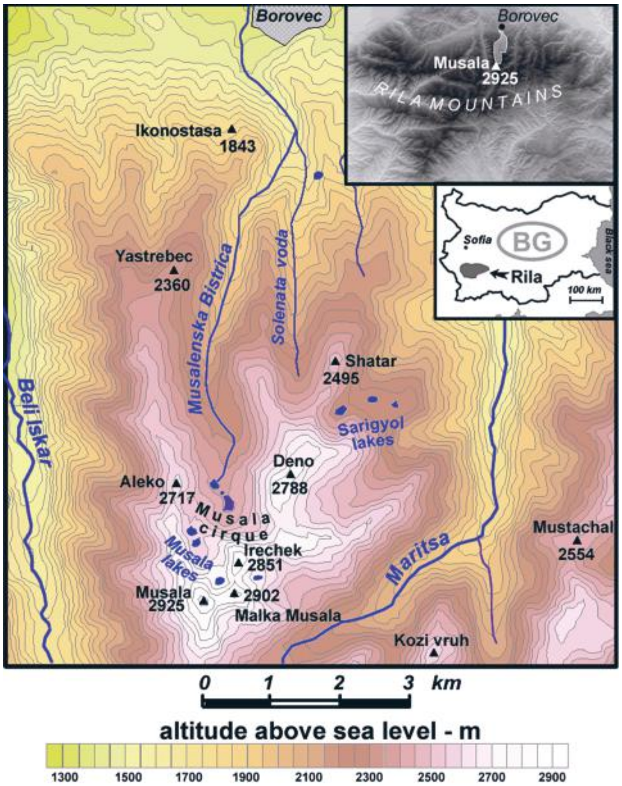

Fig. 1. Location of the Musala cirque.

has a transitional character between temperate and Mediterranean, with two maxima: in autumn-winter (November) and spring (May). Recently climate change has affected the region – the annual temperature at the Musala Peak for 1993–2017 is –2.2°C, and precipitation amounts have decreased by 5–15% (Grunewald et al. 2009; Nojarov 2012).

Fig. 2. A panoramic view of the Musala cirque – September 2006 (Musala Peak is to the left, the rock glacier is in the centre).

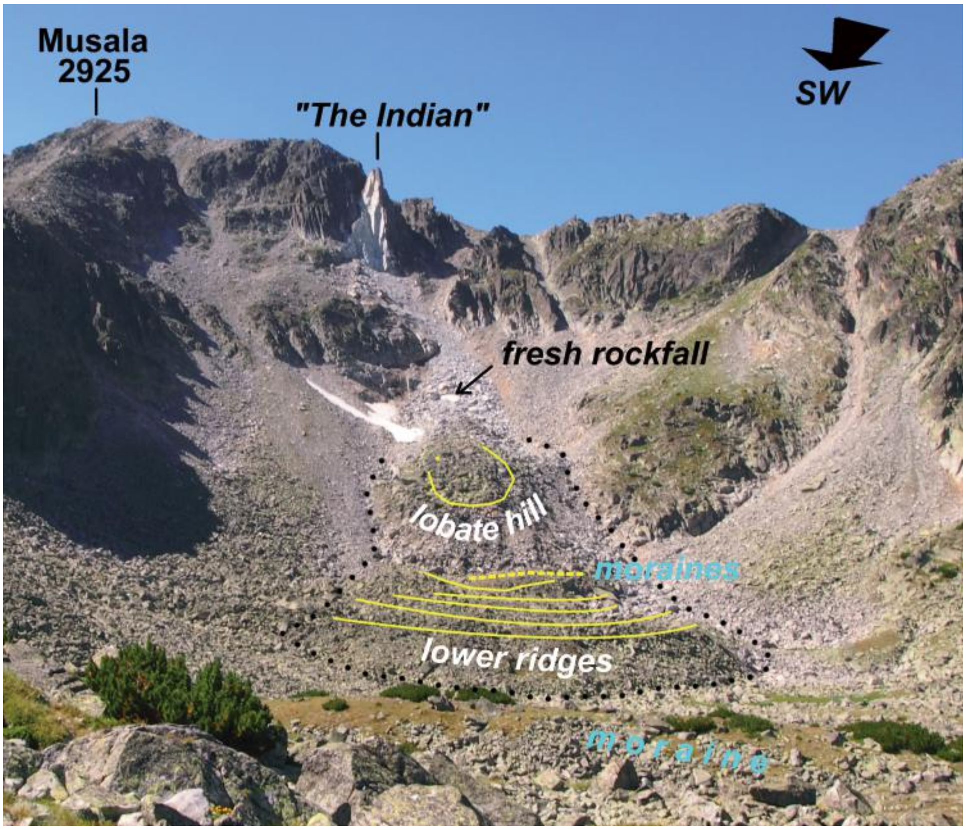

Fig. 3. The Musala rock glacier in August 2017 with the fresh rockfall from "The Indian".

The rock glacier near Musala Peak (named also *Musala rock glacier*) is the highest in the Rila Mountains and the second highest in Bulgaria (after the rock glacier under the Polezhan peak in the Pirin Mts. (G i k o v, D i m i t r o v 2010; D i m i t r o v, G i k o v 2011). It is situated in the vast Musala cirque, and lies on the northern slope of Musala Peak, at the foot of "Diavolskia uley" ("The Devil's Gully"), at 2600–2700 m a.s.l. (Figs. 1–3). It faces northeast and consists mainly of granitic blocks with traces of metamorphism and weakly expressed schistosity. The surface area it occupies is about 3 ha. Its lower section comprises five crescent shaped ridges parallel to each other, the first of which rises 14 m above the surrounding flat terrain (cirque floor). Above the lower ridges there is a lobe of stone blocks composed of two parts: a larger lower part of block debris covered with lichens, and an upper part, which is lichen free, obviously deposited relatively recently (Fig. 4). Between the lower ridges and the lobe above them a short ridge with a relatively low height (2–3 m) and a rounded grassy top is distinguished. Morphologically it resembles a stadial moraine, but it could be an exfoliated part of the subsurface, finer material layers of the rock glacier

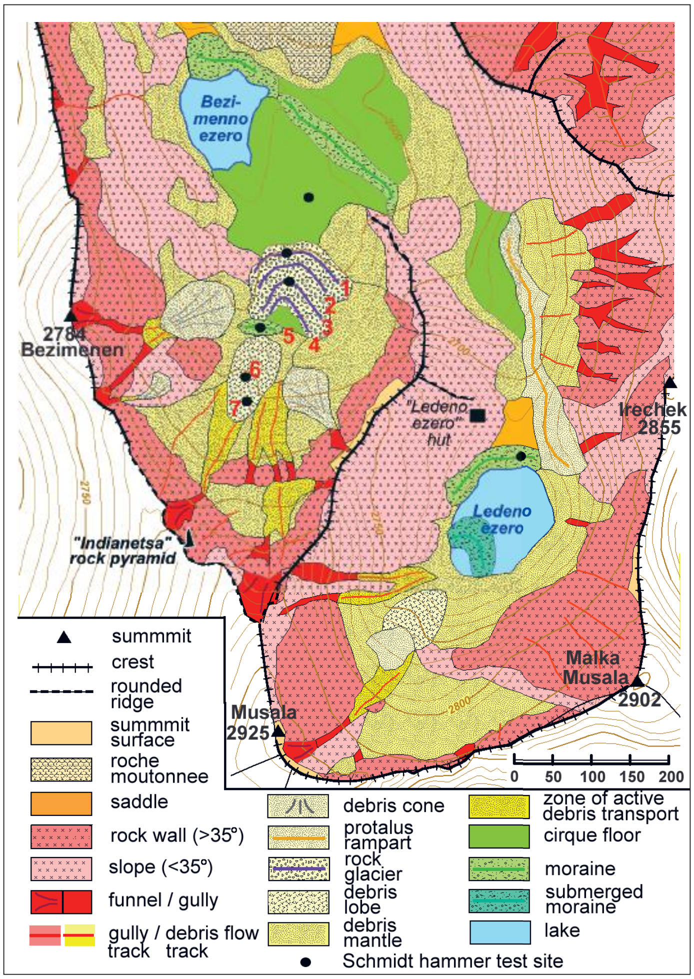

Fig. 4. A geomorphological map of the upper section of Musala cirque, focused on the rock glacier: 1–4 – the lower ridges; 5 – moraine (?); 6 – lobate hill, 7 – fresh debris accumulation.

(this is hard to distinguish, having in mind that moraines and rock glaciers can be genetically coupled (J a n k e et al. 2015): moraines often serve as a source of material for the rock glaciers). At the base of the debris lobe, and inside it, material of different fractions and sandy filament is found. On the top of the compound lobe there is a large accumulation of fresh block material, formed during the collapse of a part of a rock sculpture called “Indianetsa” (“The Indian”) in the autumn of 2016.

A prominent grassy moraine ridge is situated in the eastern section of the cirque floor, 110–120 m away from the front of the rock glacier. It runs parallel and close to the tourist trail to Musala Peak. Farther down is the Bezimenno ezero („Nameless lake”), which occupies the lowermost section of this part (step, terrace) of the floor of the great Musala cirque. The observed geomorphic setting could be explained with a hypothesis for a several stage formation of the rock glacier and its vicinity (it is presented in detail in the discussion part).

RESEARCH METHODS

For determining the exact position, spatial setting and geometry of the Musala rock glacier, we used aerial photographs and satellite images (Google Earth), and also the large scale geomorphological map of the Musala cirque done by Gachev (2007). Fieldwork activities during two expeditions (August 2016 and 2017) included morphometrical analysis – relative heights, slope angles, lengths and widths determined with a laser range finder (Hawke, 900 m range) – and recognition of the size, petrographic composition and structure, roundness and lichen cover of the deposited blocks. Lichen cover is used as an important proxy for determining relative and absolute age (Hughes 2007; Wilkinson 2011 and others). However, quantitative calculations of lichen cover were not performed in the present study.

An important part of the field measurements was the Schmidt hammer testing. The Schmidt hammer (sclerometer) is an instrument for the assessment of rock strength, from which weathering rates can be derived (Urdea 2006). Originally designed for testing the strength of building materials and constructions, this portable and relatively lightweight tool can be used for relative dating, in case of uniform lithology (like in the area around Musala Peak). In the latest decades Schmidt hammer has found successful application in geomorphology research for dating of moraines (McCaroll 1989, 1991; Winkler 2000, 2005; Kłapyta 2013), rock glaciers (Nicholas, Butler 1996; Humlum 1998; Kłapyta 2013), colluvial deposits (Clark, Wilson 2004), rocky surfaces and escarpments (McCaroll et al. 1995). In the present study we used a classical type N Schmidt hammer (Fig. 5).

Assessment of weathering rates is implemented via measurement of rock strength. The instrument records the strength of mechanical rebound from the rock surface of a piston provided with spring, and presents the strength on a display as “Rebound” (R) value in a range from 0 to 100. Testing is done always on horizontal or sub-horizontal surfaces, with a body of the instrument in a direction perpendicular to the rock surface. To obtain reliable results a large number of tests must be done from a relatively small area. These data are then statistically processed. In this study we present results form a total of 782 Schmidt hammer tests, done on rock surfaces larger than 25 cm in diameter on rock glaciers, moraines and rôche moutonnée in the Musala cirque. Test sites were natural rock surfaces free of dust, soil or lichens, not previously cleaned with the carborundum included in the instrument case. Obtained values were processed mathematically and statistically in Microsoft Excel.

Fig. 5. Schmidt hammer testing at the Musala rock glacier, August 2017.

RESULTS OF THE SCHMIDT HAMMER TESTING

In 2016–2017 a total of 782 Schmidt hammer tests were done in 9 locations throughout the Musala cirque (Table 1). Obtained results change slightly when values with the greatest deviation are excluded. This indicates reliability of the recordings. The Musala rock glacier (and its vicinity) was measured in six locations. Results (Table 1, Fig.7) confirm the increase of rock strength in upward direction. Along with the state of lichen cover this supports the idea of the formation of the rock glacier in several discrete stages. Excellent reference is provided by the fresh blocks in the uppermost part, which have a contemporary age of deposition (September 2016) (column 2 in Table 1). The R-values for the cirque floor to the NE from the rock glacier, for the moraine at Ledeno ezero, for the roche moutonnée near Alekovo ezero, as well as for the rock glacier at Karakashevo ezero, show older ages of deposition. The weathering rates of blocks throughout that lower rock glacier show slight variations. Therefore it is supposed to have been formed in a one, relatively discrete period (a single event). A general characteristic of all the testing is that with increasing age, the average values of the measured R-values decrease, while variation coefficients of the R-values, as well as their amplitudes, increase, because rock surface weathers unevenly and with the time passing differences within a single block become greater. This requires a greater number of tests to be done to obtain reliable results.

DISCUSSION: FORMATION AND DEVELOPMENT OF MUSALA ROCK GLACIER

FORMATION OF ROCK GLACIERS

As it was already mentioned, the climate that is favourable for rock glacier formation must be cooler than the present, with a great number of days with transition through 0°C, and enhanced occurrence of frost action. Annual temperatures should be low enough to provide conditions for the existence of buried ice (from 1 to 2°C; Haeberli 1985; Barsch 1996), and at the same time high enough not to sustain the formation of glaciers (for example, temperatures higher than those of a glacier climate, or fewer snowfalls). In fact, rock glaciers develop in continental or semi-continental climates where the lower limit of permafrost is situated below the glacier equilibrium line (Haeberli 1985). The type and structure of rocks are also important factors (Harrison et al. 2007; Johnson et al. 2007). Rock glaciers are formed in rocks which are prone to physical weathering, generating large (block size) debris material (Martin, Whalley 1987; Johnson et al. 2007). According to our observations on the Balkan Peninsula, the most favourable are silicate rocks with weakly expressed (or lacking) stratification, which generate large debris of a similar size. In case of a great heterogeneity in the size of rock pieces, the caverns between large blocks are filled with material of a smaller size, and very little space is left for air and water circulation inside the debris accumulation. In this context granites (such as the rocks in Musala area) are among the rock types that favour rock glacier formation (see also T. Uxa and P. Mida 2017). A third factor of major importance is the presence of tectonic disruptions, lines along which the rocks are weakened. In relief such zones are indicated by the presence of gullies and couloirs. They serve as sources of debris material supply. In our case such is the "Devil's Gully" that runs down along the northern face of Musala peak.

GLACIAL EVIDENCE IN THE MUSALA CIRQUE

According to J. Kuhlemann et al. (2013) the maximum glaciation in the Rila Mountains occurred during the Last Glacial Maximum, with two strongest phases: one at the beginning and one at the end of the LGM (24 ka and 18 ka BP respectively, evidenced by absolute dating). During that time the Musala glacier occupied the whole Musala cirque, and descended down the valley of the Bistritsa River. Retreat of the glacier in the Late Glacial resulted in the development of stadial moraines at Musala hut (2395 m a.s.l.), at Karakashevo ezero

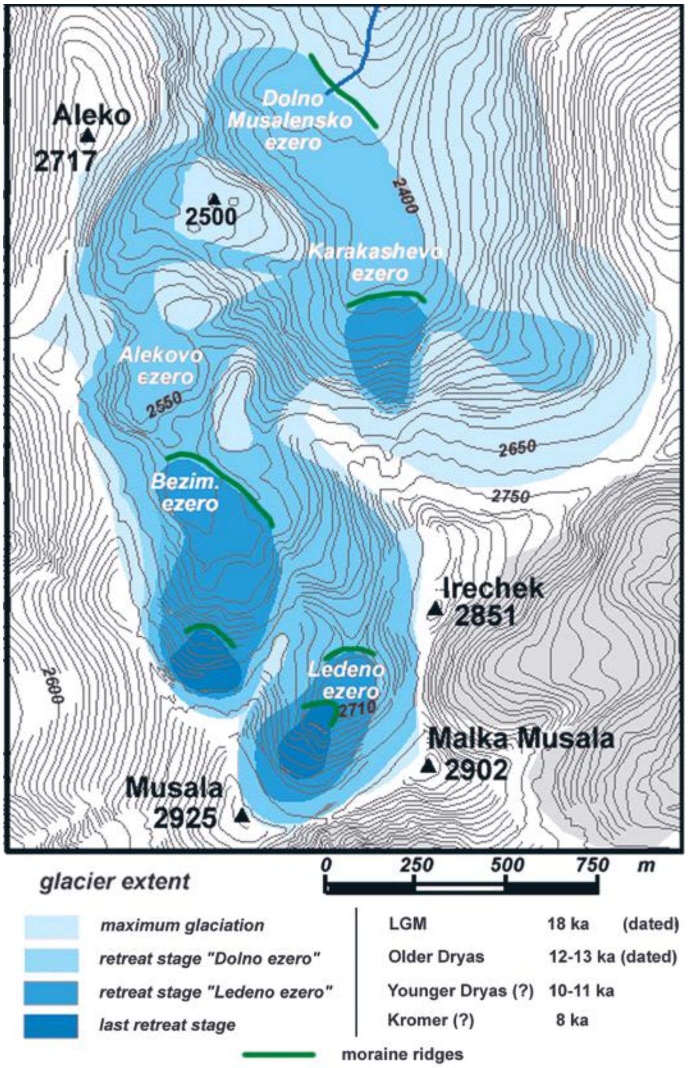

Fig. 6. Deglaciation stages in the Musala cirque.

(2400 m a.s.l.), near Bezimenno ezero (2540–2600 m a.s.l.) and at Ledeno ezero (2710 m a.s.l.). A thermoluminescent dating of the moraine near Musala hut at 2395 m a.s.l. showed an age about 15–13 thousand years BP (Baltackov, Kenderova 2003; Dimitrov, Velchev 2011), possibly correlating with the Older Dryas stage. The morphology of the highest parts of Musala cirque, the appearance of the moraines and also the similar results of the Schmidt hammer testing suggests that the two highest moraines (at 2540 and 2710 m a.s.l.) were formed simultaneously, i. e. during a single event, the next retreat stage after that at Musala hut (possibly Younger Dryas). During that stage the glacier was already separated in parts (cirque glaciers). One descended along the northern slope of Musala peak and stagnated in the cirque of Bezimenno ezero, and other was situated to the northeast of the peak and occupied the uppermost cirque section, where now is Ledeno ezero. Both glaciers were not connected to each other. At the same time a snow patch (or an ice patch as defined by E. Serrano et al. 2011) existed below the northern wall of Irechek Peak, above Karakashevo ezero. Its presence is supposed by the arcuate ridge (protalus rampart, Velchev 1999) that frames the southern shore of the lake (above it there is a small rock glacier). This might have been another small glacier, but the previous researchers (Glovnia 1962; Velchev 1999) reject the moraine character of that ridge. Results of Schmidt hammer testing of the ridge near Karakashevo ezero support the hypothesis that it was formed either simultaneously with those at Bezimenno ezero and Ledeno ezero, or at least within a short period of time (in a geological sense). There is no dating of moraines or other glacial landforms within the upper section of Musala cirque (a sample for ^{10}Be analysis was taken from the rôche moutonnée at Alekovo ezero in 2007, but the dating was unsuccessful). However, ages obtained from lower moraines indicate that the retreat stage at Bezimenno/Ledeno ezero should most probably coincide with the Younger Dryas cooling event (12.5 – 11.7 ka BP; Rasmussen et al. 2006). The last stage moraine in Musala cirque discovered so far, is the one at the bottom of Ledeno ezero (Gachev et al. 2008). The moraine found between the five curved ridges of Musala rock glacier, and the debris lobe, could possibly correlate with the one at the bottom of Ledeno ezero. Formation of those moraines might have occurred during the Piottino cooling (9.8 ka; Krasilov et al. 1985; Zubakov 1986)/Schlaten (9.4 ka; Grove 2004), a phase that was reflected in the vegetation history of the Rila Mountains (Bozhilova 1978).) Following the above explanation, and the work of E. Gachev (2009), the deglaciation history of Musala circue is summarized on Figure 6.

HYPOTHESIS ON THE FORMATION AND DEVELOPMENT OF THE MUSALA ROCK GLACIER

On the basis of this research and the obtained results, the rock glacier near Musala peak can be described as a compound landform, comprised of two parts with a different morphology (the lower ridges and the upper lobe), which have different origin and were formed during two respective stages. Morphologically, the lower ridges resemble a debris type rock glacier, while the upper lobe can be categorized as a talus type rock glacier (according to the genetic classification of D. Barsch 1988). While the lower ridges must have been formed by degradation of the cirque glacier in a period of climate warming (and/or a precipitation decrease), the most probable forming mechanism of the upper lobe was by redistribution of talus deposits under conditions of cooling and development of permafrost. Below, our hypothesis for the development stages of Musala rock glacier is described in detail with reference to Fig. 7.

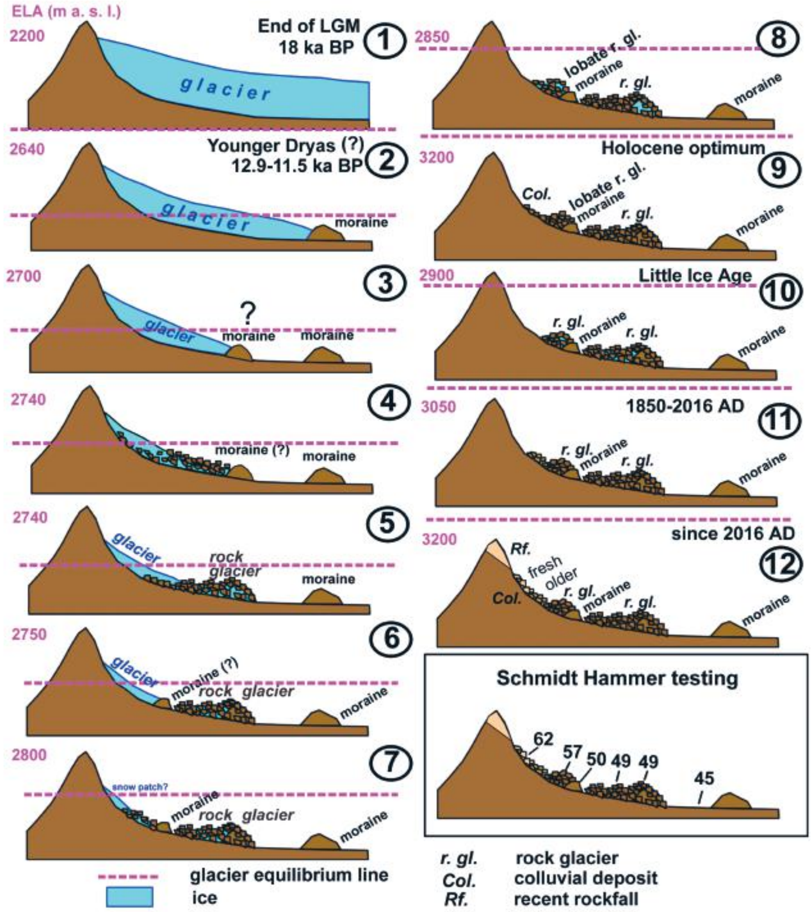

Fig. 7. The rock glacier near Musala Peak: a hypothesis for formation and development, and scheme of the location and results of Schmidt hammer tests. ELA levels are approximate, calculated using the AAR method (AAR = 0.67) from the reconstruction of glacier extent (Gachev 2009; Kuhlemann et al. 2013) and literature data (Kuhlemann et al. 2008; Messerli 1967). ELA levels are shown with indicative purpose – to demonstrate the prevailing processes in the different altitude zones. The exact determination of ELA for small glaciers could be problematic due to the very strong influence of topography (Grunewald, Scheithauer 2010).

During the Last Glacial Maximum (LGM) (1) the glacier occupied the whole Musala cirque, and descended down the valley of the Bistritsa River. In the Late Glacial the warming caused the Musala glacier to gradually retreat upwards. During a retreat stage the glacier stagnated in the cirque of Bezimenno ezero, forming a moraine (2). This was the last serious glacier advance, which can be suggested to have coincided with the Younger Dryas cold stage. At the beginning of the Holocene another warming phase started, the ELA shifted upwards and the glacier retreated (3). In this situation glacial conditions were still preserved in the upper parts of the cirque, but the lower part entered the periglacial zone (still it is not clear whether there was a moraine at the forehead of the present Musala rockglacier). During this phase, in climatic conditions still colder than present, the lower part of Musala rock glacier (the five ridges) was formed, while the glacier was limited in the upper part of the cirque (4–5). The glacier did not have the power to overcome the block barrier of the rock glacier, but was only able to push its rear section a little further ahead (5), and, at some stage, to deposit moraine material behind the block accumulation (6) (existence of small glaciers or glacierets over the permafrost body of rock glaciers is mentioned as typical by W. Haeberli 1985). The simultaneous formation of the lower rock glacier ridges and the moraine behind them is supported by the results from the Schmidt hammer testing. As the warming progressed, the glacier melted out and periglacial conditions prevailed all over the area. Increased intensity of frost weathering led to the accumulation of debris in the area of the former glacier (7), which were consequently transformed and reshaped into a lobe (a lobate rock glacier) (8). The initial formation of the lobate part of the rock glacier from talus deposits may have occurred under permafrost conditions during the Venediger (8.7–8.0 ka; Patzelt 1973), Kromer (Ivy-Ochs et al. 2009), or 8.2 ka event (Alley, Agustsdottir 2005). During the warmest phase of the Holocene (the Atlantic), permafrost diminished and the rock glacier turned to relict (or at least intact). Above the lobe a colluvial debris talus was deposited (9). During the Little Ice Age the debris lobe was probably active, and experienced some minor further movement (10). In the phase of the post-LIA warming a new quantity of rockfall debris was deposited behind the lobe (11). The last (present) stage is marked by new accumulation of a considerable amount of granite blocks in result of the collapse in the autumn of 2016 (12).

The idea that the debris lobe in the upper part of Musala rock glacier was formed entirely during the LIA is not supported by morphological evidence (similar to the findings of Kędzia 2014, for the rock glacier in Świstówka Roztocka, the High Tatras): the blocks on the top of the lobe are densely covered by lichens, and the lobe similar in morphology and position, which is on the slope of Musala Peak above Ledeno ezero, has a stabilized cover of soil and grass on it.

CONCLUSIONS

Rock glaciers are typical landforms for the high mountain areas of SW Bulgaria (the Rila Mountains and the Pirin Mountains). The rock glacier near Musala Peak is among the highest and the most representative in Bulgarian mountains. The complexity of the structure of the Musala rock glacier is used to reveal the main stages in its evolution and to raise a hypothesis for the development of the rock glacier and its adjacent areas after the period of maximum glaciation (the end of the LGM). The formation of the rock glacier started most probably after the Younger Dryas, with the degradation of the cirque glacier situated north of Musala peak. The main features of the rock glacier were most probably formed before the warmest phase of the Holocene. No considerable changes are expected to have happened during the Little Ice Age, except some redistribution of the debris in the upper section (the lobate hill). However, some permafrost occurrence and modern activity is still not completely rejected for this rock glacier. The rock glacier continuous formation on several stages is supported by the results of the Schmidt hammer testing, which clearly show increase of rock strength in an upward direction. The landscape continues to actively evolve at present, with rockfalls from the northern face of Musala Peak.

Results from this study demonstrate the ability of rock glaciers to serve as proxies for environmental reconstructions in high mountain areas, especially when results from their research are combined with those from the history of glaciation.

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