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Combining geomorphological approach and thermal monitoring for permafrost research in Rodna Mountains, Northern Romanian Carpathians

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Abstract

This paper aim to investigate the possibility of permafrost occurrence in the alpine area of Rodna Mountains by describing the rock glaciers distribution and characteristics and by monitoring the ground surface temperature and spring water temperature during late summer. Rock glaciers have a rather scarce distribution between 1670 and 1960 m a.s.l., their morphology is completely relict even at the highest altitudes which indicate they are inherited landforms. Thermal regime indicates improbable permafrost at Bila talus slope (1844 m a.s.l.) and an ambiguous outcome at Curmătura Buhăescului talus slope (1980 m a.s.l.) where average temperature during the BTS period was warmer than the -2°C threshold only in one year of the two monitored. Alpine spring water temperatures are above 3°C indicating absence of permafrost and they are moderately correlated with altitude. Iezeru Pietrosu cirque headwall is affected only by seasonal frost at 2100 m a.s.l. for almost 9 months. It seems that in Rodna Mountains the past and present climate conditions were and are milder in comparison to Southern Carpathians as the latitude increase does not compensate the lower altitudes.

Keywords: *rock glaciers, alpine permafrost, GST, geomorphological survey, Rodna Mountains, Romanian Carpathians*

Rezumat. Imbinarea abordării geomorfologice și a monitorizării termice pentru cercetarea permafrostului în Munții Rodna, Carpații Romanești de nord

Acest articol își propune să verifice posibilitatea prezenței permafrostului în Munții Rodnei prin studiul distribuției și caracteristicilor ghețarilor de pietre și prin monitorizarea temperaturii la suprafața solului și a temperaturii izvoarelor montane la sfârșitul verii. Ghețarii de pietre au o desitate scăzută între 1670 and 1960 m altitudine, au o morfologie complet relictă chiar și la cele mai mari altitudini indicând faptul că sunt forme de relief moștenite din alte perioade geologice. Regimul termic indică permafrost improbabil în trena de grohotiș din Valea Bila (1844 m altitudine) dar oferă un rezultat neclar în trena de grohotiș Curmătura Buhăescului (1980 m altitudine) unde temperature medie în perioada BTS este deasupra pragului de -2°C într-unul din cei doi ani monitorizați. Temperatura izvoarelor este de peste 3°C în toate siturile indicând absența permafrostului. Rezultatele termice din peretele circului Iezeru Pietrosu este afectat doar de îngheț sezonier pentru o perioadă de aproape 9 luni pe an. Condițiile climatice trecute și actuale au fost și sunt mai blânde în Munții Rodna în comparație cu cele din masivele înalte din Carpații Meridionali, efectul de latitudine nefiind complet compensat de altitudinile mai reduse.

Cuvinte-cheie: *ghețari de pietre, permafrost alpin, GST, cercetare geomorphologică, Munții Rodnei, Carpații Românești*

Introduction

Permafrost is a component of both the cryosphere and the lithosphere, and is defined as a matrix of rock and ice mixed in various proportions which occurs in areas where the mean annual air temperature is below -1°C (Dobinski, 2011). It can appear in rock glaciers, talus slopes and rock walls in mountains located in temperate regions (Jones et al, 2019; Scapozza et al., 2011; Magnin et al., 2015). However, as a result of global warming, significant changes are impacting high altitude and latitude areas, thus transforming the cryosphere. Consequently, permafrost was introduced as an essential climate variable by the Global Climate Observing System (GCOS), with thermal state and active layer thickness parameters regarded as key markers of climate change. Mountain glaciers are melting and in numerous instances they are transforming into debris rock glaciers as conditions transition from glacial to periglacial (Jones et al., 2019; Seligman et al., 2019).

Rock glaciers, both inherited and modern, are abundant periglacial landforms in high altitude mountains indicating past or present permafrost conditions: several thousand rock glaciers were mapped in the Alps (Cremonese et al., 2012), more than 10.000 active rock glaciers were mapped in USA (Johnson et al., 2021), and more than 4000 rock glaciers in North Yakutia (Lytkin, 2020). In lower mountains, a smaller number of rock glaciers are present, e.g. less than 400 in the Western and High Tatra Mountains (Uxa and Mida, 2017), more than 250 in the Cantabrian Mountains (González-Gutiérrez et al., 2019), and 224 in the entire Balkan Peninsula (Magori et al., 2019). In other formerly glaciated mountains, rock glaciers are very scarce, or their presence is questionable, as it is the case of Great Britain (Jarman et al., 2013).

Rock glaciers were mentioned for the first time in the Romanian literature by Ichim (1978), while the rock glaciers of the Southern Carpathians received a lot of attention in recent years indicating permafrost probability by thermal and geophysical investigations (Vespremeanu-Stroe et al., 2012; Onaca et al., 2015; Popescu et al., 2017). Studies centered on mountain areas with similar environmental conditions (e.g., Western Carpathians), indicated that rock glaciers are Late Glacial features with no activity at the present (Kędzia, 2014), but permafrost creep with very low movement rates was proved to exist in Southern Carpathians rock glaciers (Vespremeanu-Stroe et al., 2012; Necșoiu et al., 2016). However, permafrost persistence can occur even well below the apparent intact rock glaciers (Colucci et al., 2019). Rock glaciers density is in good relation with lithology as several studies indicated large rock glaciers densities in granitic mountain ranges (Urdea, 1998; Uxa et al., 2017) while in carbonate rocks lithology they can only form when other silicate rocks are available (Gachev, 2020).

Despite several studies dealing with past glacial reconstruction in Rodna Mountains, few studies mention and investigate rock glaciers (Ichim, 1978; László et al., 2013). As a consequence their occurrence and thermal characteristics are still poorly known. Therefore, this paper intends to describe the distribution of rock glaciers in Rodna Mountains and to present the results of several thermal measurements in talus deposits and rockwalls.

Study area

Rodna Massif is located in the northern part of the Northern Romanian Carpathians. It is delimited by Năsăudului Hills and Bârgăului Mountains to the south, by Suhard and Maramureșului Mountains to the east, by Maramureșului Depression to the north and Țibleș Mountains to the west (Figure 1).

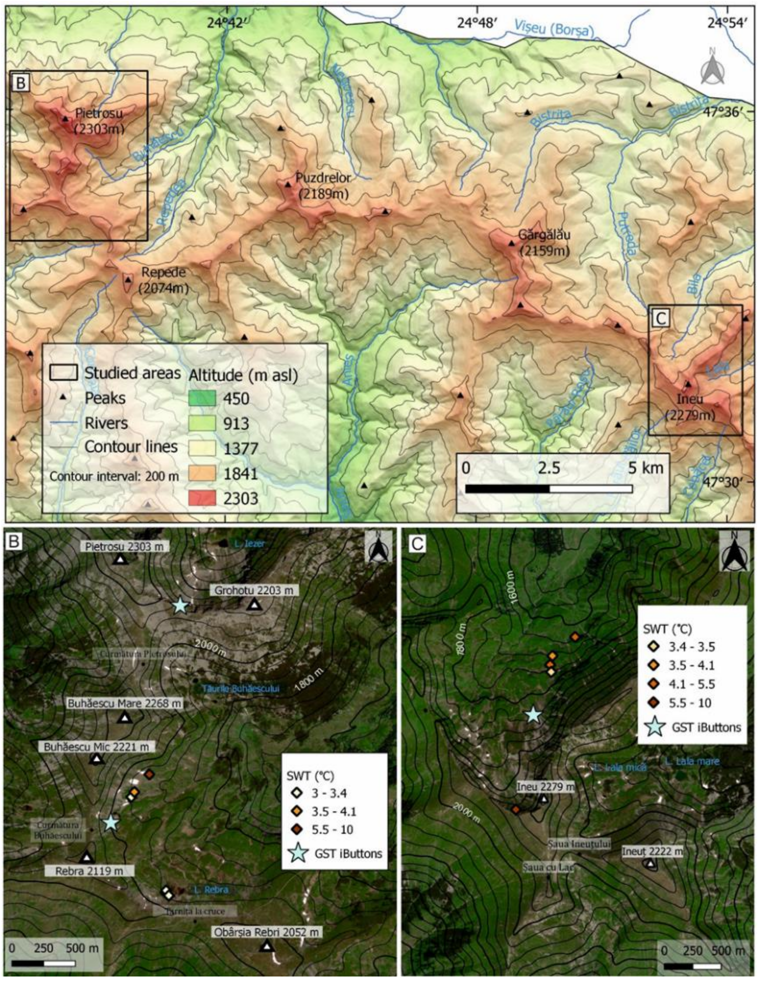

Fig. 1: Location of the two study areas in Rodna mountains: Pietrosu-Buhăescu area (B) and Bila-Ineu area (C)

The maximum altitude of the massif is of 2,303 m a.s.l. at Pietrosul Rodnei Peak. The massif is around 45 kilometers long from east to west and has a total area of 960 km2. The main ridge is generally oriented

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in a northwest to southeast direction. A more detailed orientation can be described in 3 sections: the sections in the east and west are oriented NW-SE, while the middle one is oriented WSW-ENE. The geology of the study area is dominated by pre-Hercynian crystalline schists and carbonatic Mesozoic formations (Mutihac & Mutihac, 2010). The massif has undergone asymmetrical tectonic uplift, resulting in a horst with steep slopes toward the northern Maramureșului Depression and gently inclined slopes in the south, towards the Someșul Mare valley. The main ridge is mainly made of schists, i.e. an intricate distribution of epi-metamorphic schists, mica schists and paragneiss. The western part of the ridge, corresponding to the highest area of the massif, is composed of phyllites and sericite-chlorite schists (Bleahu et al., 1968). The climatic setting of the Rodna Massif is directly influenced by wet air masses from the west and by polar air masses from the north and northeast (László et al, 2013). The multi-annual air temperature ranges from a minimum of -2°C on the highest peaks to 1°C at 1700-1800 m and the annual precipitation amount varies from over 1400 mm at the highest peaks to approximately 1300 mm at 1700-1800 m and 1000 mm at around 1000 m asl (Dragotă and Kucsicsa, 2011). The mean annual air temperature (MAAT) at Iezer meteorological station (1785 m asl) is +1.4°C (during the 1961-2001 time interval). Taking into consideration an average lapse rate of 0.65°C/100 m we can place the MAAT of 0°C at the altitude of 2020 m asl (increasing lately due to climate warming). Solid precipitation starts at the end of September and the last snowfall is usually in May. The landscape of the massif was shaped by glacier activity in the last glacial maximum (LGM) (Kłapyta et al, 2021), although pre-LGM ages were identified for some landforms (Gheorghiu, 2012; Urdea et. al, 2022). The presence of glaciers in Rodna Massif is a result of both high altitude and latitude. Here, regionally lower temperatures compensated for the lower altitudes (compared to the Southern Carpathians, which have altitudes up to 200 m higher) and led to the formation of 45 cirques, the largest in the Romanian Carpathians (Mîndrescu and Evans, 2014). The mountain range is characterized by altitudinal asymmetry manifesting itself in terms of the morpho-climatic zones (Ichim et al., 1979), the treeline (Mihaila et al., 2021) and the glacial relief (Mîndrescu, 2016), and is further reflected in the distribution and occurrence of periglacial landforms. The geomorphological setting of the range meets the basic conditions for permafrost development: high altitude and the presence of rockwalls and screes (Popescu, 2021).

Periglacial research in Rodna Mountains

In Rodna Mountains geographical studies were preceded by geological investigations, particularly due to the interest generated by mining in the area. The earliest geomorphological studies date back to 1891, when the first results regarding glacial landforms on the upper Lala valley (Lehman, 1891) were published. Subsequently, Géza (1896) published data on the glacial relief around Ineu Peak. A decade later Szilady (1907) introduced new geomorphological data regarding glacial cirques around Pietrosu, as well as a rather detailed map of cirques, while Orghidan (1909) published the first geomorphological considerations relating to the origin of Bistrița Aurie river. The scientific works mentioned in this section were mostly descriptive local-scale studies which included little graphical or morphometric data and focused mainly on glacial landforms (particularly glaciers), as well as periglacial forms.

After 1911, Rodna Mountains were also included in regional-scale syntheses focusing on glaciation and glacial landforms in the Romanian Carpathians. Based on the complexity of glacial and periglacial relief in this massif, Sawicki (1911) was able to bring solid contributions regarding the chronology of glacial phases, thus introducing the concept of three glacial phases in Rodna Mountains. However, Kräutner (1937) acknowledged the existence of a single glaciation with three phases of retreat. Both scientists (particularly Sawicki) likely included some periglacial forms into the category of glacial relief, understandably so for that era when mountain geomorphology research was still in its early stages and several researchers denied even the Pleistocene glaciation overall (Primics, 1884, Inkey, 1892).

Pawłowski (1936) published the first synthesis on glaciation and glacial landforms in the entire Carpathian Range comprising a nearly comprehensive map of the 23 glaciated mountain ranges, including Rodna Mountains. The map provided data on the extension of Pleistocene glaciers (e.g., glaciers with known or probable extension), thus allowing for a preliminary idea regarding the distribution of periglacial relief in the Late Pleistocene. Pawłowski also introduced the concept of glacial asymmetry, which is typical for Rodna Mts.

After a lengthy period during which only a small number of local studies were published (e.g., Donisă, 1968), a new stage in geomorphological research in Rodna Mountains was marked by the complex, more modern study carried out by Sîrcu (1978). Although the focus of this monograph is on the glacial relief, periglacial landforms are also granted considerable attention. Regardless of the terminology used in the study, which is a product of that period, the author brings to the forefront of the discussion a wide array of periglacial forms, including: blockfields, blockstreams, blockslopes, stone stripes; protalus ramparts; scree talus slopes; solifluction terraces; creep phenomena; frost heaving; thufurs (earth hummocks); nival niches; avalanche couloirs; fossil ice wedges; periglacial superficial deposits and associated processes (solifluction, creep, nivation). Most of these forms are briefly described in terms of traits and distribution, with the exception of fossil ice wedges that are viewed by the author, and rightfully so, as sackungs (trenches). Maps or other graphic representations are not available, apart from a thufur cross-section. According to Sîrcu (1978) the most significant periglacial landforms are scree accumulations and periglacial superficial deposits (primarily eluvia), whereas the main associated processes include solifluction and creep. The study does not mention residual forms, such as periglacial tors or rock glaciers. Just one year later, the paper of Ichim (1978) paves the way for progressive studies in geomorphology facilitated by the access to the scientific literature of the Western world. In his work dedicated to rock glaciers in the Romanian Carpathians, Ichim acknowledges the presence of fossil rock glaciers in Rodna Mountains on Cobășel and Negoiescu valleys and indicate that active rock glaciers should be present in Rodna Mountains above 2100-2150 m asl (Ichim, 1978). While Sârcu (1978) provided a map depicting the glacier and snowline distribution during the last glacial maximum in Rodna Mountains, which is useful for pinpointing the area of manifestation of periglacial processes, Ichim et al. (1979) published the earliest information on morpho-climatic dynamics in the massif during the Postglacial. The authors identified two major altitudinal morpho-climatic zones: fluvio-denudational and periglacial. Depending on the annual isotherms and the treeline, correlated with similar studies from other regions of Europe (e.g., the Alps, the Tatra Mountains), three subzones were delineated within the periglacial domain, including: the solifluction subzone (between +3° and 0° C); the complex periglacial processes subzone (between 0° and -2° C) regarded as the lower limit of rock glacier formation; and the intensive weathering subzone (below -2°C) where intensive cryoplanation, nivation and rock glacier activity are prevalent.

Further geomorphological studies targeted the glacial cirques of Rodna Mountains (Mîndrescu et al., 2010; 2014), sackung landforms (Mîndrescu and Cristea, 2011), glacial landforms (László et al., 2013) glacial reconstruction and deglaciation chronology (Gheorghiu, 2012, Kłapyta et al, 2021).

Methodology

In order to identify the most suitable areas for in-depth investigation, we performed an initial analysis on the distribution and main characteristics of the glacial and periglacial features in the study area, as these can help predict the spots with a high probability of current or past permafrost existence. This analysis was carried both based on ortophotos and in the field, the two approaches being complementary (for example, although other characteristics are easier to identify in situ, the ridges and furrows specific to the rock glaciers are more obvious on ortophotos). Ground surface temperature (GST) monitoring provides data regarding both the thermal regime of a specific feature (for example freeze-thaw cycles in rockwalls) and the characteristics of the heat transfer process between the ground and the atmosphere which are essential in permafrost detection especially in the case of porous screes that favour ground overcooling. GST was monitored at 3 sites: i) cirque Iezeru Pietrosu headwall, ii) Buhăescu Mare cirque moraine (bellow Curmătura Buhăescu) in the western part of the range and iii) cirque Bila rock glacier (at foot of Pleșcuța crest) in the eastern part. We used miniature digital data loggers (iButtons) manufactured by Embedded Data Systems (USA). The measurements were made from 2014 to 2018, with a sampling frequency of 4 hours. In order to compute the synthetic indices of mean annual ground surface temperatures, the data had to be completed for 24 consecutive months and for that purpose we used the offset between the mean monthly temperatures of ground and air from the intervals when both types of data were available and applied the method for the intervals without GST data. The low temperature of alpine springs water during late summer before first autumn frost is also an indicator for permafrost existence, as follows: temperatures below 1°C are specific for active rock glacier springs (Krainer and Mostler, 2002; Berger et al., 2004), thus indicating areas certainly underlain by permafrost, while temperatures in the range 1-2°C have been reported for areas with high probability of permafrost occurrence (Frauenfelder et al., 1998, Brighenti et al., 2021). We measured the temperature of 10 springs located in Buhăescu and Bila Valleys on 29-30 August 2018 using a hand-held thermometer Extech (0.5°C accuracy).

Results and discussion

Rock glaciers and other periglacial landforms in Rodna Mountains

Rock glaciers are found in the Rodna Mountains but their distribution seems to be rather scarce and their status completely relict. Their structure is fossilized with soil, grass vegetation and shrubs. Only small patches of openwork scree can be observed on their surface (Figure 2). On the northern slope, several rock glaciers were identified on Lala, Bila and Repede

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valleys. On Lala valley, a large rock glacier complex (1670 m - 1830 m asl) is covered almost completely with shrubs but present a typical rock glacier creep morphology of ridges and furrows. In Bila valleys two landforms were identified that can be attributed to rock glacier morphology: Bila 1 rock glacier (1770-1830 m asl) which has an expressive morphology and is completely vegetated, and Bila 2 rock glacier (1960-2000 m asl) which appears as an incipient fossilized rock glacier (protalus rampart) completely vegetated as well. On the northern slope of the Repedea peak, in the upper part of Izvoru Repede valley, there is an expressive tongue-shaped valley side rock glacier (1875-1965 m asl) that was also mentioned by Ichim (1978).

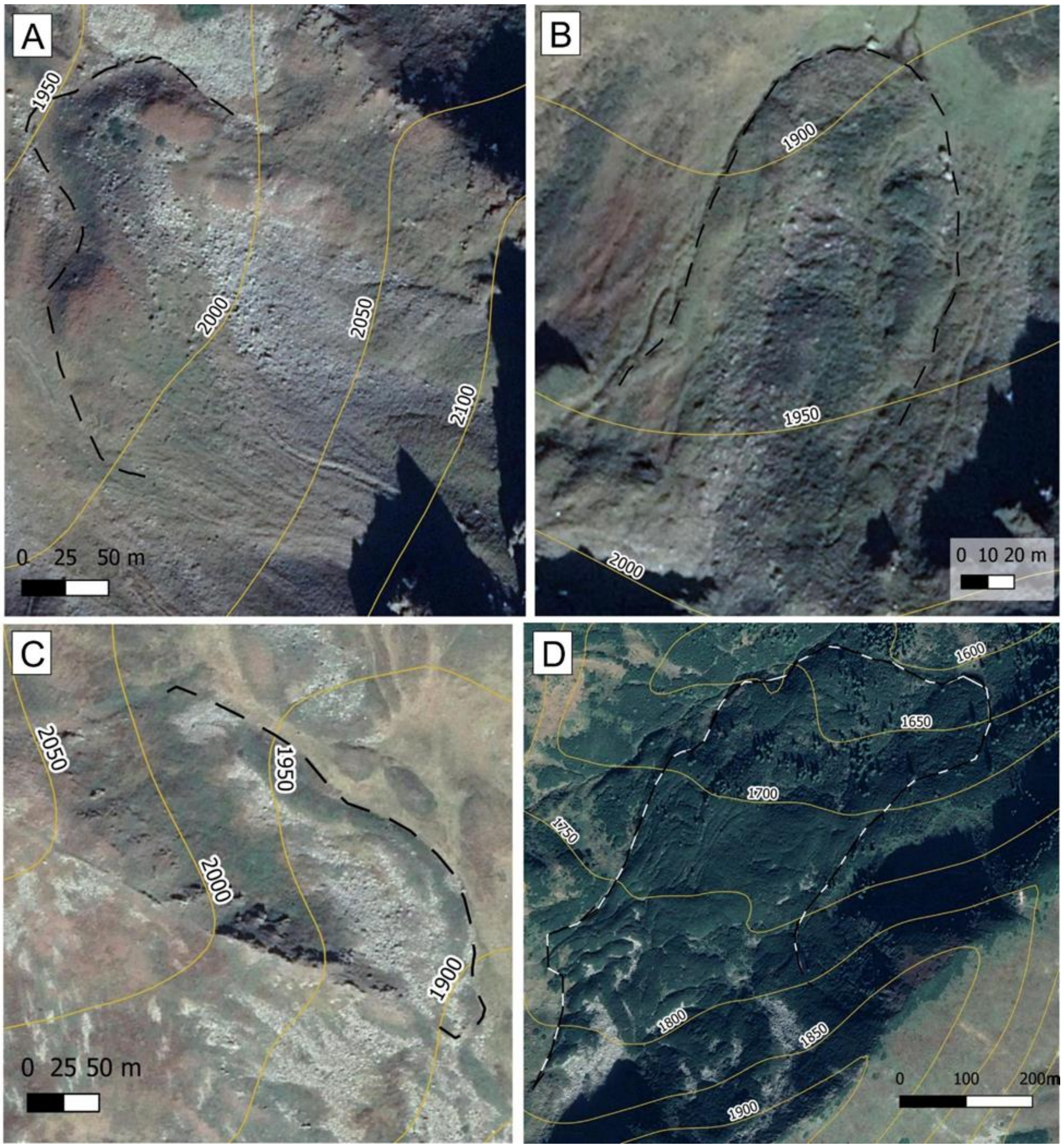

Fig. 2: Types of rock glaciers identified in Rodna Mountains: Bila 2 (A), Repedea (B), Cobășel (C) and Lala (D)

This rock glacier is completely fossilized and vegetated but has a clear spring at its front that has not been yet measured. Below Curmătura Buhăescului (2070-2080 m a.s.l), at the foot of the back wall cirque (Figure 3C) lies a small landform that has an arcuate morphology, no ridges and furrows and a low-lying surface behind a terminal crest. The latter has a symmetrical transversal profile with relatively steep slopes. These characteristics indicate rather a moraine morphology. The openwork debris comes from the slope in a new evolution phase that has nothing to do with permafrost creep in our view. This is in opposition to Gheorghiu (2012) that regarded this ridge as part of a periglacial protalus rampart. In Iezer cirque, the elongated landform parallel to the valley is considered a rock glacier by László et al. (2013) and an ablation moraine by Gheorghiu (2012); we are in favor of the latter as there is no rock glacier creep morphology visible there. On the southern and western slopes of Rodna, two valleys caught our attention, Cobășel and Pietrosu, which exhibit elongated lobes parallel to the lateral ridges of the valleys, regarded as either small rock glaciers/protalus ramparts or moraine ridges (Figure 2C).

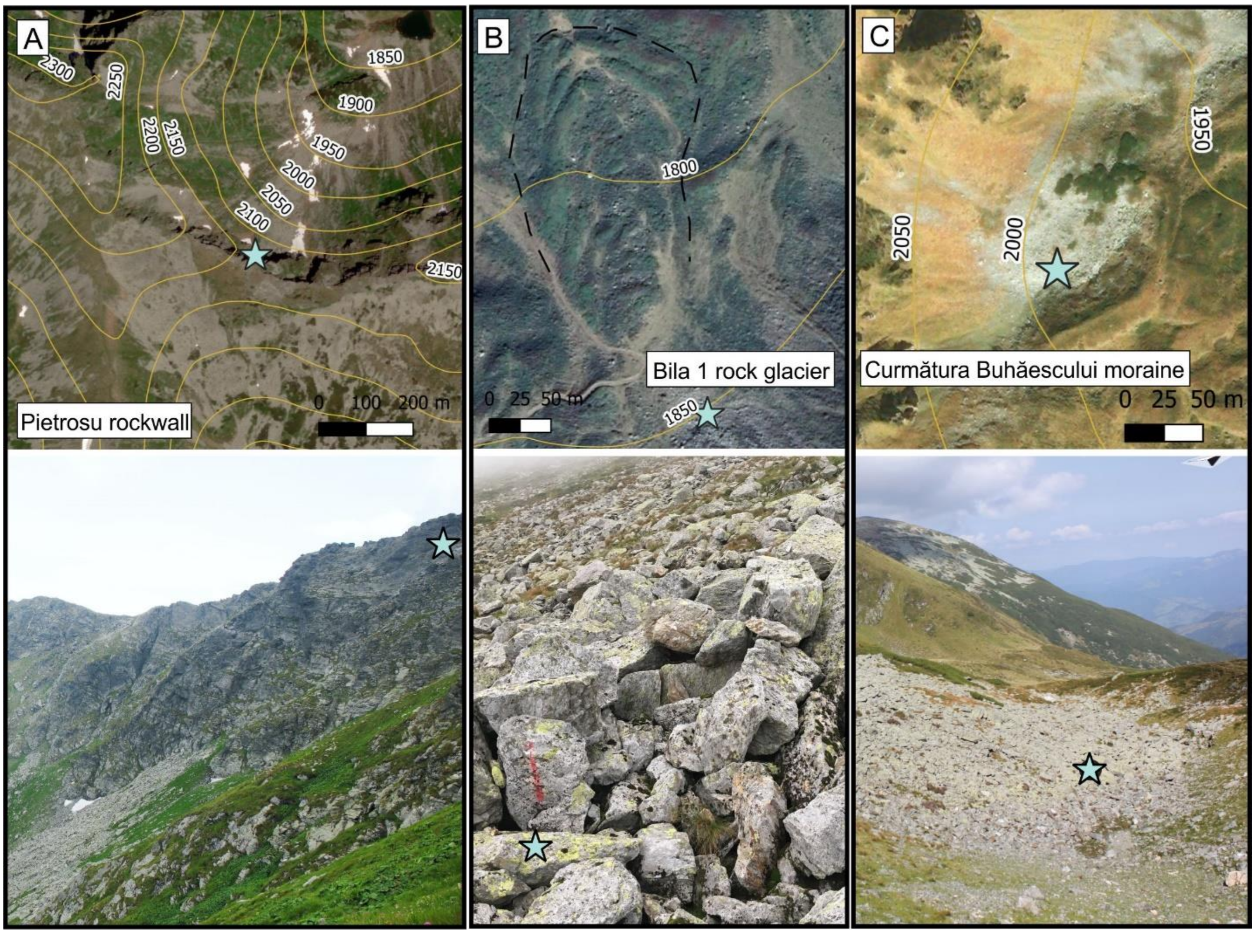

Fig. 3: The sites where thermal measurements were applied: Pietrosu rockwall – 2105 m asl (A), talus slope located above the Bila 1 rock glaciers at 1844 m asl (B), and talus slope below Curmătura Buhăescu in the back of a moraine ridge (C)

Other landforms with potential permafrost content are rockwalls and talus slopes. With some exception, the rockwalls are rather underdeveloped. The largest rockwalls in Rodna Mountains are those from the Pietrosu-Buhăescu Peaks and Ineu Peak areas which are also the highest ones (>2200 m asl). In these two areas the largest and most extended talus slopes can also be found, which as also the highest ones with openwork structure and still active today in terms of rockfalls supply (Figure 4). However, the largest scree landforms covering most of the slopes are debris-covered slopes. They are partially colonized by shrubs as well. Impressive protalus lobes mostly or totally vegetated, made of both boulders and fine materials were identified at Căldarea Putredu glacial cirque (north-facing), and below the Șaua Putredu on the southern slope. Other gravitational landforms that are typical and impressive from Rodna Mountains are the sackung trenches and the landslides, such as the one on the northern slope in the area of Negoiasa Mare Peak.

The scarcity of rock glaciers and their small surfaces (with the exception of the large rock glacier complex from Lala Valley) are probably related to the low amount of debris supply due to the marginal character of the glaciation (Mîndrescu et al., 2014) and the rockwall morphometry. The lower density of rock glaciers in Rodna Mountains is in line with the previous observations regarding rock glaciers formation metamorphic versus granitic rocks (Urdea, 1998; Uxa et al., 2017). There are major similarities between rock glaciers distribution and status from Iezer (Southern Carpathians) and Rodna Mountains (Popescu, 2018) in terms of scarcity and morphology of rock glaciers, as these landforms are relict to a higher extent and have an even lower density in Rodna Mountains. The seven rock glaciers identified in Rodna have their fronts between 1670 and 1960 m asl and their MAAT varies from +0.4 and +2.1°C (considering the MAAT reference from 1961-2001 at Iezer meteorological station) indicating that they formed in periods with MAAT lower by 2.4 - 4.1°C than the current MAAT. This thermal variation is beyond the Holocene range, therefore they could have only formed at the end of Pleistocene, in the late glacial period.

Fig. 4: A typical high altitude talus slope from Rodna Mountains located below the Ineu Peak in the upper Bila Valley. The talus slope base is at 2000 m asl.

Thermal regime of rock deposits and rockwalls

At Bila site the iButton was located in the lower part of an openwork talus slope above the Bila 1 relict rock glacier at an altitude of 1844 m asl. The GST regime (2014-2016) indicated cooler conditions in the first year in comparison to the second year (Figure 5) with: i) lower GST during autumn-early winter; ii) later partial insulating snow layer onset (8 December in comparison to 26 November); iii) lower temperature during the BTS period or late winter equilibrium temperature (around -1°C and 0°C in the first and second winters respectively, indicating that permafrost is improbable), iv) later entrance in the 0 curtain period (21 April in comparison to 30 March), v) earlier snow melting (17 May versus 6 June). These indicate that the first monitored winter was drier in comparison to the second one and the ground cooling was more efficient. Mean annual ground surface temperature (MAGST) was +4.1 and +3.3°C (average of October-September interval) while the local computed MAAT was +3.4°C and +2.8°C, respectively.

At Curmătura Buhăescului site the iButton was located in the lower part of a talus slope accumulating in the interior of a small arcuated ridge that we regarded as a moraine. We argue that between the talus slope and the ridge there is an evident discontinuity that cannot consistent with periglacial protalus ramparts. Also, the ridge has a rather symmetric transverse profile which is also an argument for the moraine origin of the ridge. The GST regime was recorded in the October 2016 - September 2018 period, showing a similar pattern as previously mentioned with a cooler first year and a warmer second year of measurements (Figure 5). The following observations were made: i) lower GST was recorded in the first autumn-early winter period; ii) later partial insulating in the first year (9 November compared to 28 October); iii) complete snow insulation of the ground after around 10-15 December in both years and consequent thermal adjustments in the following months; iv) relative stable temperatures during the BTS window indicating that the site is sufficiently insulated for BTS method application; v) average BTS is lower in the first year (-2.7°C versus -1°C) indicating possible permafrost in the first year and improbable in the second; vi) the stable temperatures during the BTS window are registered in 14.2-13.3 and 9.2-9.3; vii) the 0 curtain period is similar both years in terms of length and interval of occurrence (7.4-17.6 versus 13.4-22.6). MAGST was +1.7 and +2°C (same interval of October-September) while the local computed MAAT was +1°C and +1.7 °C, respectively.

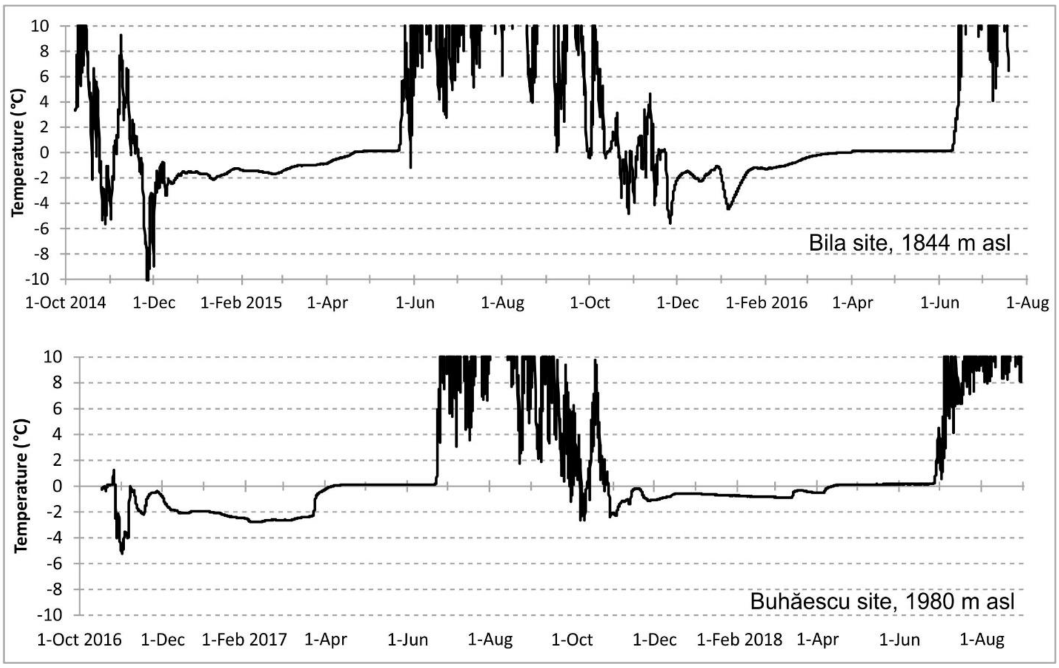

Fig. 5: GST regime of Bila and Curmătura Buhăescului talus slopes. Note the different time periods, i.e. 2014-2016 (up) versus 2016-2018 (down).

On Iezeru Pietrosu headwall the iButton recorded the rock temperature on a northern near vertical rock face. The thermal regime indicates a good overlapping between rock and air temperatures as a consequence of minor snow cover influence. Using the Berggren equation modified by Matsuoka and Sakai (1999), the timing and depth of freezing and thawing were calculated (Figure 6). The continuous freezing lasted 251 days from 16 November 2014 to 25 July 2015, indicating seasonal and not perennial freezing at 2105 m asl. The mean annual rock temperature (MART) was +1.5°C at a local MAAT of +1.8°C. The maximum penetration depth was 4.6 m.

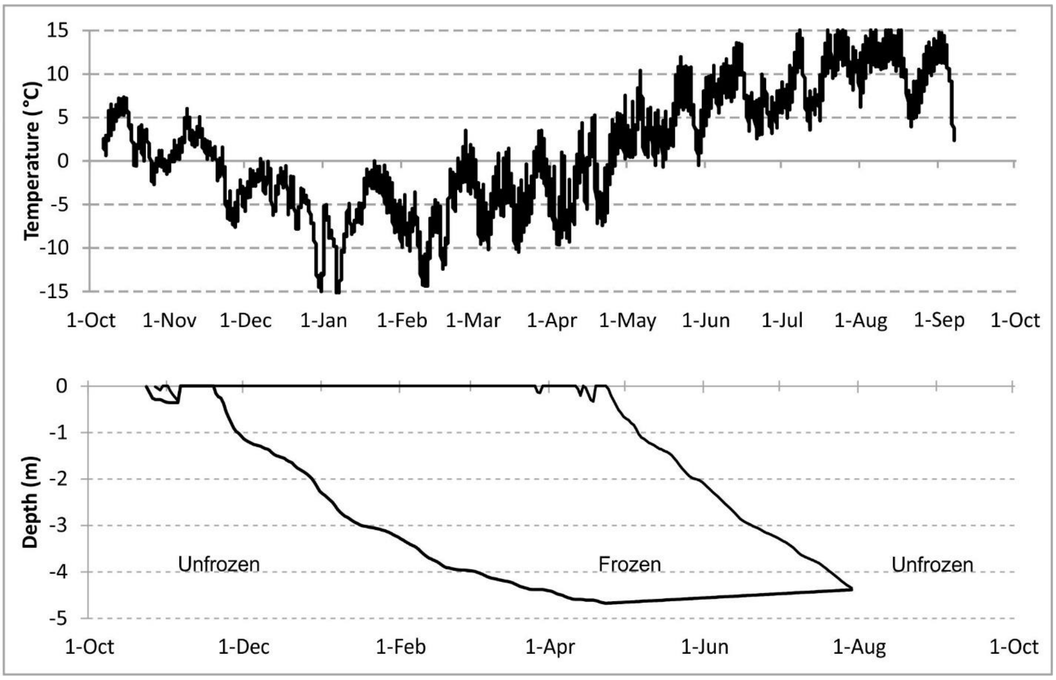

Figure 6: GST regime of Pietrosu rockwall at 2105 m asl during the 2014-2015 time period with the freezing and thawing regime computed using the thermal data and the Berggren equation modified by Matsuoka and Sakai (1999)

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The spring water temperature during late summer ranged between 3.5°C and 6.3°C on Bila Valley and between 3°C and 10°C in the upper Buhăescu Valley. The springs are located between 1555 and 2117 m asl (altitude measured in the field with GPS receiver). The highest two springs recorded the highest temperatures because they had rather stagnant water. If we exclude them from the analysis, the rest of 8 springs are moderately well correlated with altitude, which accounts for the water temperature decrease by 52% (Figure 7). In the upper Buhăescu Valley all springs are located at the contact between cirque headwall and cirque floor between 1922 and 1933 m asl: three (3-3.4°C) are located below the rock deposit (rock avalanche, moraines?) located west of Tarnița la Cruce lake, two are located westward below a rock cliff and displayed 3.4 – 3.8°C; and the remaining spring with stagnant water below a rock deposit exhibited 10°C. In the Bila Valley all the springs were measured on the eastern slope of the valley rising from rock outcrops or relict rock deposits from 1555 to 2117 m asl and with values between 3.5 and 6.3°C (Figure 2). All the values are way above the thermal threshold of permafrost presence of 2°C, indicating the lack of a frozen source. Similar results were reported in the Iezer lake glacial cirque by Popescu (2021).

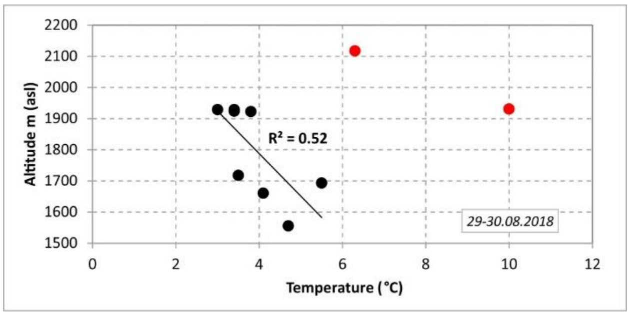

Fig. 7: Spring water temperatures measured at Bila and Buhăescului glacial cirques in late August 2018. The red dots were excluded from the linear regression because the water was rather stagnant at these sites

In the context of rock glacier relict morphology and positive MAGST even at higher altitudes rock deposits that indicate that all the rock glaciers are completely relict, we question why Ichim (1978) assumed that active rock glaciers should be present in the Romanian Carpathians including in Rodna Mountains? Firstly, the author took into consideration the air temperatures which were considerably lower during that period compared to the present day: in the 7th, 8th and 9th decades of the 20th century the mean decadal temperature at Iezer meteorological station was +1.2 - +1.3°C, considerably lower than the recent times. For example in the 2015-2020 period the mean temperature was +3.15°C. Secondarily, perennial snow patches were observed in the Romanian Carpathians at that time. Both aspects (temperatures and snow patches) are obvious indicators of active rock glaciers occurrence in a region; however, that was only a temporary cold climate anomaly similar to the Little Ice Age period and did not reflect the „normal" long-term conditions of the Romanian Carpathians. The same can be applied to rock glaciers from the Southern Carpathians which are also inherited landforms from colder past periods. Nevertheless, the lack of intact rock glaciers cannot exclude the possibility of small permafrost patches in relict rock glaciers (Colluci et al., 2019) or low altitude talus slope (Popescu et al., 2017).

Conclusions

Geomorphological investigations indicated the presence of several rock glaciers in Rodna Mountains, most of which are located in two areas: Pietrosu-Buhăescu in the west and Ineu in the east. Seven rock glaciers were mapped thus far, although an extensive rock glacier inventory should be carried out;

Most of the rock glaciers are small landforms indicating low debris supply and short periods favorable for permafrost creep in the past. This was related to the rockwall morphometry, metamorphic lithology and marginal glaciation;

All the rock glaciers are almost completely fossilized with small openwork areas unfavorable for typical alpine permafrost persistence;

Thermal investigations in openwork talus slopes areas indicated improbable permafrost at the Bila (1844 m asl) and bellow Curmătura Buhăescului (1980 m asl) sites with MAGST of 3.3-4.1°C. The latter site had BTS below -2°C in one of the two investigated years indicating possible permafrost due to overcooling, at least in some years. MAGST varied between 1.7 and 2°C;

Rockwall thermal monitoring at 2100 m asl showed MART of 1.5°C, continuous frozen regime for 251 days and a maximum penetration depth of 4.6 m.

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