
Permafrost investigations in Iezer Mountains, Southern Carpathians

Răzvan POPESCU^{1*}

¹Faculty of Geography, University of Bucharest, Bucharest, Romania

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*Correspondence to: Răzvan POPESCU, e-mail: razvan.popescu@geo.unibuc.ro

ABSTRACT

This paper assesses the possibility of permafrost occurrence in Iezer Mountains using field observations, GIS analysis and thermal investigations in the field. Rock glaciers as the main mountain permafrost footprint in the landscape are mapped using cross validation from two independent inventories, analysed and classified in terms of size, altitude, morphology, air temperature and vegetation cover. Measurements of spring temperatures, bottom temperature of snow (BTS) and continuous (near) ground surface temperature (GST) were applied to check for permafrost presence. Autumn temperature of 20 alpine springs are analysed and grouped by their source, temperature and apparent discharges. BTS was applied on 3 sites from the upper part of Colților Valley in 2012 and 2018 along GST in Tambura scree in 2012–2018 period. 16 rock glaciers are considered to exist in Iezer Massif, a much smaller number than previously assumed. We argue that several other landforms are rock–ice features and should be inventoried and analysed in corresponding with minimal past permafrost creep. Rock glaciers are poorly developed and have a faded morphology because of low debris availability, short periods of time with favourable climates and less supportive mountain morphometry. Alpine springs indicate possible permafrost occurrence in one rock glacier and one talus slope and BTS reveal sporadic patches of permafrost down to 1900 m asl in Colților Valley. GST supports the multiannual stability of permafrost indicating BTS on a multiannual scale and suggests the great importance of autumn–early winter temperatures and snow interplay for ground cooling and permafrost maintenance. We argue that 11 rock glaciers from Iezer Mountains are probably inactive. MAGST of 1.1 – 3.2 °C suggest a strong thermal gradient in the blocky layer if permafrost is truly present. Alpine screes possibly underlain by permafrost seem not to be disturbed by any modern climate changes.

KEYWORDS

mountain permafrost; rock glaciers; rock–ice features; talus slopes; Iezer Mountains

1. Introduction

Permafrost is ground understood as soil or rock and included organic matter and ice content that has a temperature of 0 °C or below for at least two consecutive years (van Everdigen, 1998). It is exclusively defined on the basis of temperature regardless the texture, water content, lithology and degree of induration (Washburn, 1979, p. 21). Permafrost is not a form but a thermal state of the ground without an explicit and direct appearance in the landscape (Dobinski, 2011). This phenomenon has been intensely studied in the last decades in the context of climate change because permafrost can release a large quantity of organic carbon that can accelerate global climate change (Schuur et al., 2015). The contemporary warming and degradation of permafrost is being documented both at high latitude and altitude and it is expected to continue (Etzelmüller et al., 2011; Hipp et al., 2012; Kokelj et al., 2017; Oliva and Fritz, 2018). Warming permafrost in mountain areas can be a source of hazards inducing an increase in slope instability (Ritter et al., 2012; Deline et al., 2015; Haeberli et al., 2017). On the other hand, mountain permafrost is a valuable resource of water that communities from arid and semiarid zones especially can rely on in the context of rapid glaciers retreat (Viviroli et al., 2011; Rangecroft et al., 2016; Drewes et al., 2018).

Striking geomorphologic features created by permafrost occurrence in mountain areas are rock glaciers which form by creeping of debris accumulated by rockfalls or deposited by glaciers and containing ice of glacial or periglacial origin (Barsch, 1996; Berthling, 2011; Knight et al., 2019). However, permafrost presence does not necessarily imply rock glaciers development if other environmental preconditions are not met (debris accumulation and ice formation) and also rock glaciers existence does not necessarily express the actual permafrost occurrence. The latter is the case of relict rock glaciers (no frozen content) that results from intact rock glaciers (active and inactive, i.e. with supersaturated and moving-/thin, under saturated, stable permafrost, respectively) subjected to permafrost thawing caused by the climate transition to a warmer phase. These rock glaciers can be used as palaeoclimate

indicators (Hughes et al., 2003; Aoyama, 2005; Kellerer-Pirklbauer et al., 2012; Moran et al., 2016).

Openwork debris deposits determine negative thermal anomalies in comparison to other land cover types and consequently are the most favourable structures for permafrost development (Harris and Pedersen, 1998; Gruber and Hoelzle, 2008; Otto et al., 2012). Discontinuous permafrost zone is restricted to the lowest altitude of the active (moving by the process of creep) rock glaciers while sporadic permafrost zone imply the presence of inactive or relict rock glaciers only with small patches of permafrost (Baroni et al., 2004; Kellerer-Pirklbauer et al., 2015). Talus slopes are also favourable to permafrost development in their lower sectors because of ground air circulation induced by density differences (chimney effect) occurring at both low (Morard et al., 2010; Stiegler et al., 2014) and high altitude (Scapozza et al., 2011; Kenner et al., 2017). In order to check for the presence of permafrost and to determine its spatial extent, an entire set of indirect and direct methods of detection should be used along multiple years in order to avoid short term climate effects.

Rock glaciers occurring in Romanian Carpathians were first assessed by Ichim (1978). Regional inventories (Urdea, 1992 and Onaca et al., 2017a) indicated the ubiquitous occurrence of rock glaciers in Southern Carpathians highest massifs that were used for palaeoclimate reconstructions (Urdea, 1998). Several studies indicate the relict state of rock glaciers supported by their subdued morphology and thermoclastic depressions in Făgăraş Massif (Nedelea, 2006; p. 189; Simoni, 2007, p. 293; Andra, 2008, p. 292). Other studies suggest the rather scarcity of rock glaciers in the alpine areas of Parâng Mountains (Săndulache et al., 2015). Indirect investigations (thermal and geophysical) proved more widespread potential distribution of permafrost in granitic massifs (Retezat and Parâng) in comparison to the crystalline ones (Făgăraş) (Urdea, 1993; Szepesi, 1998–1999; Kern et al., 2004; Nedelea, 2006, p. 195; Vespremeanu-Stroe et al., 2012; Onaca et al., 2013; 2015; Popescu et al., 2015). Continuous monitoring of temperature introduced the hypothesis of probable occurrence of perennially frozen rockwalls

above 2350 m altitude in Southern Carpathians (Vasile et al., 2014; Popescu et al., 2017a).

Low altitude permafrost was also investigated in Romanian Carpathians at Detunata Goală, Apuseni Mountains (Urdea, 2000; Popescu et al., 2017b).

The objectives of the present paper are to describe and analyse the geomorphological characteristics and significance of rock glaciers and to increase the knowledge on the potential permafrost distribution in Iezer Mountains.

2. Study area

Iezer Mountains are located in the eastern part of the Southern Carpathians between Făgăraş in the west and Piatra Craiului massifs in the east (Fig. 1). They have a total plane surface of 535 km² from which almost 14 % (74 km²) are located above 1800 m asl and a maximum height of 2470.2 m in Roşu

peak. The main ridge has a NE–SW orientation with two areas of high altitudes in the SW around Iezerul Mare peak (2461.8 m) and in the NE around Păpuşa peak (2391.4 m asl). The lithology of the massif is represented mostly by crystalline schists i.e., mica schists and garnet paragneiss, two mica paragneiss with garnets, gneiss, chlorite and muscovite–chlorite schists (Codarcea and Dimitrescu, 1968; Patruşiu et al., 1968). The massif has a pronounced asymmetry with elongated interfluvies and valleys on the SE side and short and abrupt slopes on NW side. The transversal profiles of most of the valleys are asymmetric with abrupt western/southern slopes and gentle eastern/northern slopes for the north–south and east–west oriented valleys respectively. Large sectors from the main ridge and other interfluvies of Iezer Mountains are represented by the remains of Borăscu peneplain.

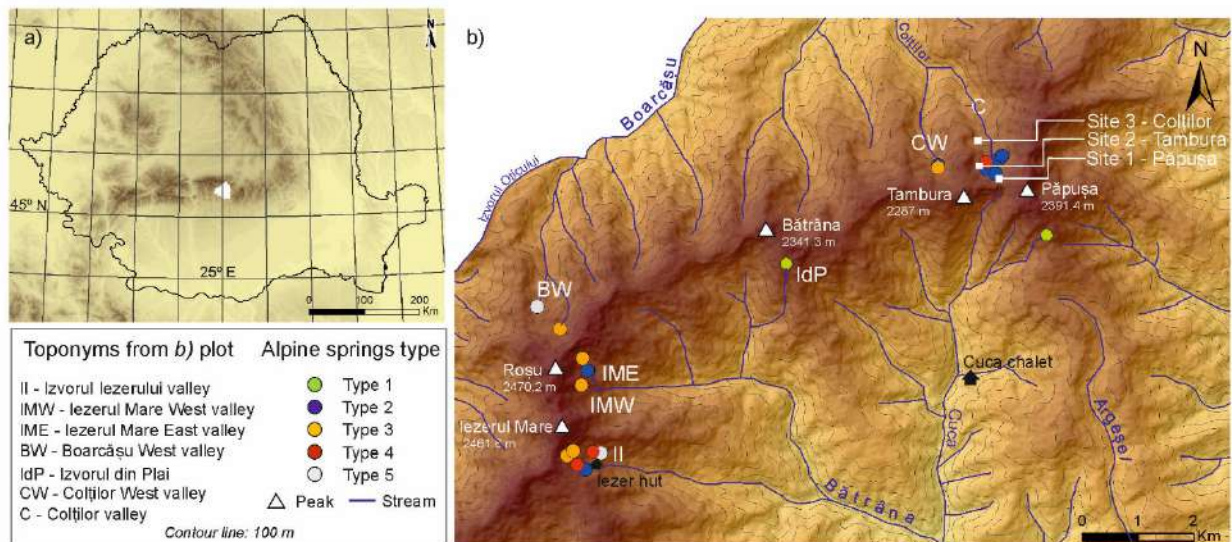


Figure 1 Study area. Location of Iezer Mountains in Southern Carpathians, Romania (a), study sites in Colţilor Valley and the distribution of alpine springs (b). Contour interval 100 m

The upper treeline does not surpass 1870/1830 m asl on the NW/SE slopes respectively as an effect of land cover (talus deposits) and anthropic intervention (deforestation) respectively, while the sub-alpine shrubs (*Pinus mugo*) climb usually up to 2100 m and exceptionally up to 2270 m asl (Săvulescu, 2014, p.122–129).

The past glacial erosion was less intense in Iezer in comparison with other massifs from Romania presenting a total of 38 cirques with a mean floor

elevation of 1880 m asl some of them clustered around plateaus (Mindrescu and Evans, 2017). The mean altitude of the end moraines was calculated to be 1395 m asl and the total surface of glaciers at their maximum extent 60 km² (Urdea and Reuther, 2009). From a structural point of view, the northern and north–western cirques are obsequent, the eastern ones are subsequent while the southern cirques are consequent (Szepesi, 2007, p.56). Rockwalls occur mostly on the western or southern slopes of

the valleys and they present a high degree of erosion. Talus deposits occur at the base of the rock-walls and also on the less inclined slopes. Large and compact areas of debris deposits can be found in the glacial cirques around the two highest areas of the massif of Păpușa and Roșu – Iezerul Mare peaks, respectively. The current active geomorphologic processes are solifluction, debris flows, snow avalanches and rock falls.

3. Methodology

3.1 Geomorphological mapping of rock glaciers

We mapped rock glacier landforms using orthophotos (produced by National Agency for Cadastre and Land Registration, 2012) and aerial images from Google Earth and field research. In mapping rock glaciers, we looked for their typical morphology signs like longitudinal ridges in the upper parts, transverse ridges in the lower parts and a terminal front. A difficult task is to differentiate between rock glacier fronts and late-glacial moraines not affected or only slightly affected by permafrost creep. We addressed this issue by assessing the continuity between the terminal crest and the talus slope behind it. For moraines there is a clear discontinuity between them while for rock glaciers there is a smooth continuation to the talus slope feeding it.

Taking into consideration that rock glaciers mapping can often be highly subjective (Marcer et al., 2017), we used the methodology proposed by Schmid et al., 2015 in order to avoid overestimation or underestimation of rock glaciers occurrence. This implies mapping to be done by two different persons independently and considering only those landforms identified by both. Thus, our rock glacier inventory was intersected to that of Onaca et al., 2017a kindly provided by the author. At the end, there were considered only those landforms identified in both inventories.

3.2 GIS analysis

ArcGIS software was used to compute several morphometric parameters of each rock glaciers, i.e. surface, length, width, altitude and orientation (including of the source rockwall area). Mean values of the pixels were considered for altitude and direction

while for length and width the average value of several longitudinal and cross profiles respectively were used (Kellerer and Pirklbauer et al., 2012). Mean annual air temperature (MAAT) was also computed using a thermal lapse rate of 0.57 °C (Săvulescu, 2014, p. 96) and a temperature of –2.2 °C (average in the 1941–2017 time interval) for the altitude of 2504 at the meteorological station Vârful Omu from Bucegi Mountains, located at 40 km east from Roșu Peak. The digital elevation model that was used for all calculations was obtained from topographic maps 1:25000 with contour lines interval of 10 m.

3.3 Thermal measurements

3.3.1. Temperature of alpine springs during late summer/early autumn

The water of alpine springs has multiple sources, e.g. deep underground water, rain and snow. If permafrost occurs, ice can be an additional source that alters significantly not only the temperature of spring but also its geochemistry (Williams et al., 2006; Harrington et al., 2017; Kürý et al., 2017). Thus, several studies indicated that spring water temperature indicate possible permafrost if temperature is between 1 and 2 °C or probable permafrost if temperature is <1 °C (Frauenfelder et al., 1998). Other studies revealed that active rock glaciers have spring water temperatures below 1 °C for the entire warm season (Krainer and Mostler, 2002). Springs temperature can also be used to model potential permafrost distribution in mountain areas (Carturan et al., 2016).

We measured the temperature of 20 springs from the alpine area of Iezer Mountains in 20–21 September 2018 at the end of the warm season. Air temperature was well above 0 °C even in the days and nights before the survey. Most of the measurements were performed at the very point of the spring location but for some of those rising from scree areas the measurements were done at a certain distance from the source (meters to tens of meters). Springs are located both on valley floors and mountain slopes and have multiple outcoming sources such as meadows, regolith and debris accumulations. An Extech handheld thermometer (TM20 model) with accuracy of ± 1 °C was used for

the measurements. The instrument was calibrated in alpine springs that were previously monitored with higher precision instruments (iButtons) and offered similar results with less than 0.3 °C differences.

3.3.2. BTS

BTS is amongst the most used methods for mapping and modelling the potential permafrost distribution in cold regions around the world (Ardelean et al., 2015; Blikra and Christiansen, 2014; Colucci et al., 2016; Seppi et al., 2015). The method is based on the finding that negative thermal anomalies in the underground induced by permafrost occurrence can be detected by measuring the temperature at the snow–ground interface at the end of the winter. Probable, possible and improbable permafrost are related to sites where BTS is below –3 °C, between –2 and –3 °C and above –2 °C respectively (Haeberli et al., 1973). A prerequisite for the relevance of this method is the snow cover of at least 60 to 100 cm depth installed sufficiently early in the winter to induce thermal stability. Itinerant BTS consists in measuring the temperature using a thermal probe of a few meters long by pushing it through the snow pack down to the ground level. Some authors apply the BTS concept to the continuous temperatures measured by in situ data loggers placed in the ground (Gądek and Kędzia, 2008; Krainer et al., 2015). We refer to this method as ground surface temperature (GST) measurements and the average temperature at the end of the winter as stationary BTS in comparison to itinerant BTS described in this chapter.

BTS investigations were performed in Colților Valley on a complex of landforms below the Păpușa Peak (Site 1 – Păpușa), below the Tambura Peak (site 2 – Tambura) and in the lower part of Colților Valley (site 3 – Colților). Site 1 corresponds to a talus slope and scree located down valley with two ridges of uncertain (moraines or structural?) origin with little probability of permafrost creep origin. Site 2 is related to a rock deposit that could be a rock glacier and site 3 on a “certain” rock glacier (both described in detail in the Results section). We performed BTS measurements in March 2012 on all three sites and in March 2018 at Tambura and Colților sites.

3.3.3. GST

The method consists in measuring the ground surface temperature continuously using miniature data loggers installed in the field that measure and store the temperature at specific time intervals chosen by user. The method was initiated in the '90s in the Swiss Alps (Hoelzle et al., 1999) and is largely used in permafrost studies since then. It allows not only to infer more precisely the permafrost probability at a specific location but also to understand and quantify the complex heat exchange processes at the ground–atmosphere and ground–snow interfaces during the warm and cold season respectively (Ishikawa, 2003; Ferreira et al., 2017).

GST was monitored at Tambura site in the upper part of the blocky deposit at 2162 m asl between 2012 and 2018 (T–1) with a sampling frequency of 4 hours using miniature digital data loggers (iButtons) manufactured by Embedded Data Systems (USA). The sensor was put at the upper part of a block into a 2 cm hole, sealed with sanitary silicon and covered by a 10 cm rock fragment. A data gap between 2016 and 2017 was caused by logger failure. In 2017 – 2018 an additional logger (T–2) was hung between the boulders about 1 m deep, in the same location like T–1 and another one (T–3) was placed in the same way in the lower part of Tambura scree at 2046 m asl (Fig. 1). The declared logger accuracy is ± 0.5 °C but judging by the values registered in the snow melting period (zero curtain), the error was not larger than 0.125 °C near 0 °C (Gubler et al., 2011). The resolution of the loggers is 0.0625 °C.

The annual regime of GST was divided in five intervals in accordance to permaNET handbook recommendations (available at www.permanet-alpinespace.eu): phase 1 of ground temperature oscillations quasi identical to air temperatures; phase 2 of ground cooling caused by negative air temperatures and overcooling because of thin snow layer albedo and long wave radiation emission; phase 3 of attenuated oscillations of ground temperature imposed by a thicker snow layer; phase 4 of complete ground isolation from atmospheric temperatures imposed by a thick snow cover that will determine GST tendency to reach an equilibrium state (4A interval) usually achieved at the end of the winter (4B interval); phase 5 of snow melting when

thermal regime enters the zero curtain period. Based on data measured in 2012–2016, we calculated for each phase the average period of occurrence, duration and mean temperature.

4. Results

4.1 Rock glaciers occurrence in Iezer Mountains and their characteristics

Our inventory (I–1) comprises 17 rock glaciers while the inventory of Onaca et al., 2017a (I–2) contains double (34 landforms). 15 rock glaciers are commonly identified in both inventories with some differences for their outlines and one landform from I–1 is considered as two separate rock glaciers in I–2. One additional rock glacier is considered only in I–1 and 17 only in I–2. Thus, 16 rock glaciers identified by both surveys are considered in this study. They are grouped in two areas located in the centre to south–west of the massif in the valleys of Izvorul Iezerului, Iezerul Mare, Groapele and Boarcășului (11 rock glaciers) and in north–east in the valleys of Colților east and west, respectively (5 rock glaciers) (Fig. 1). Based on morphology and general characteristics, the rock glaciers were grouped into three types:

- Type 1: Large rock glaciers, almost completely covered by shrubs located at the lowest altitudes (mean elevation between 1900 and 2000 asl) (Fig. 2a). Two subtypes can be differentiated: a) tongue shaped rock glaciers with more expressive morphology of longitudinal and transverse ridges and furrows sourcing from glacial cirques headwall. Two rock glaciers of this subtype are found in Groapele Valley; and b) lobate rock glaciers located at the base of secondary mountain ridges with lower density of ridges and furrows (Fig. 2b). Two rock glaciers in Colților West valley, one in Colților East valley and one in Iezer valley of this subtype are found;
- Type 2: Medium to small size rock glaciers located at high altitudes (mean elevation between 2146 and 2215 m asl) with a well–defined front covered mostly by herbaceous vegetation, parallel to the crest, and separated from the talus slope by a large furrow; ridges are more or less pronounced. Three rock glaciers of this type are found in Iezer valley and another one in Iezerul Mare east valley (Fig. 2c);

- Type 3: Small rock glaciers placed at relatively medium altitudes (2000 m asl) with expressive traces of past creep processes partially covered by shrubs and grass. Two rock glaciers of this type are found in Groapele and Colților West.

The remaining four rock glaciers could not be included in any group so they will be described individually from east to west. Tambura rock glacier (Fig. 2d) located in the Colților–east valley is a complex rock deposit with its roots in a suspended glacial cirque outflowing down–valley through two rock streams with a rock outcrop in between. Longitudinal furrows and the final front are well defined (Fig. 6a). Several creeping fronts are found in the upper part of the deposit and no vegetation is present there while herbaceous and shrubs vegetation occurs in the rest of the deposit. It is not a rock glacier *stricto sensu* but rather a large rock deposit with multiple source rockwalls along its length that it is affected in a certain degree of permafrost creep. Boarcășu deposit looks like a typical tongue shaped rock glacier with a small surface (c. 1.6 ha) but a relatively large length (c. 170 m) that would indicate intense past creep processes (Fig. 2e). Apparently, two generations of fronts are visible with their concavities being c. 170 m (the lower one) and 100 m (the higher one) in length. Roșu is a small (1.2 ha) but very expressive rock glacier with striking scree wrinkles located at the highest altitude from Iezer Massif (2329 m asl). The largest furrow is more than 10 m deep and all ridges are colonized by vegetation and even shrubs. The latter are present in spite of high elevation because of south–eastern exposition. Groapele 4 is a probable rock glacier with an intermediate state between type 1 and type 3 with a medium surface and less expressive morphology completely covered with shrubs. The supplementary landform identified only in I–1 in the upper sector of Piscanu valley is considered to be a rock glacier of type 2 (Fig. 2f).

The rock glaciers from Iezer massif (hereafter referred to as the 16 features commonly identified in both I–1 and I–2) have a mean elevation varying from 1919 to 2329 m asl., mean slope between 11 and 24° and surface between 0.7 and 9.5 hectares. The average values for altitudes, slope and surface are 2056 m asl, 20° and 3.5 hectares respectively.

Taking into consideration altitude, slope and direction, the MAAT was computed for every rock glacier according to Stanciu (1981) and Iancu (1982) both cited in Săvulescu (2014, p. 49 and p.96). Values at mean elevation for each rock glacier varied between -1.2 and $+1.1$ °C with an average of $+0.4$ °C. Roșu rock glacier has a MAAT of -1.1 °C, 4 rock glaciers from Izvorul Iezerului and Iezerul Mare east have negative MAATs, Tambura and Boarcășu rock glaciers have MAATs of 0.1 °C and the other rock glaciers have MAATs of $0.6 - 1.1$ °C. All landforms with MAATs below 0.1 °C present similar geomorpho-

logic characteristics like openwork structure, vegetated ridges and terminal front while the rest of rock glaciers are covered by herbs and shrubs in a larger degree but still present a partial openwork (matrix free) structure especially on furrows and micro depressions. Rock glaciers directions are north east (6), north and north-west (3/3), east and west (1/1) and south-east (2).

The lithology of rock glaciers is represented by mica schists with garnets (13 rock glaciers), mica schists with garnets and amphibolite (two) and two mica paragneiss (one).

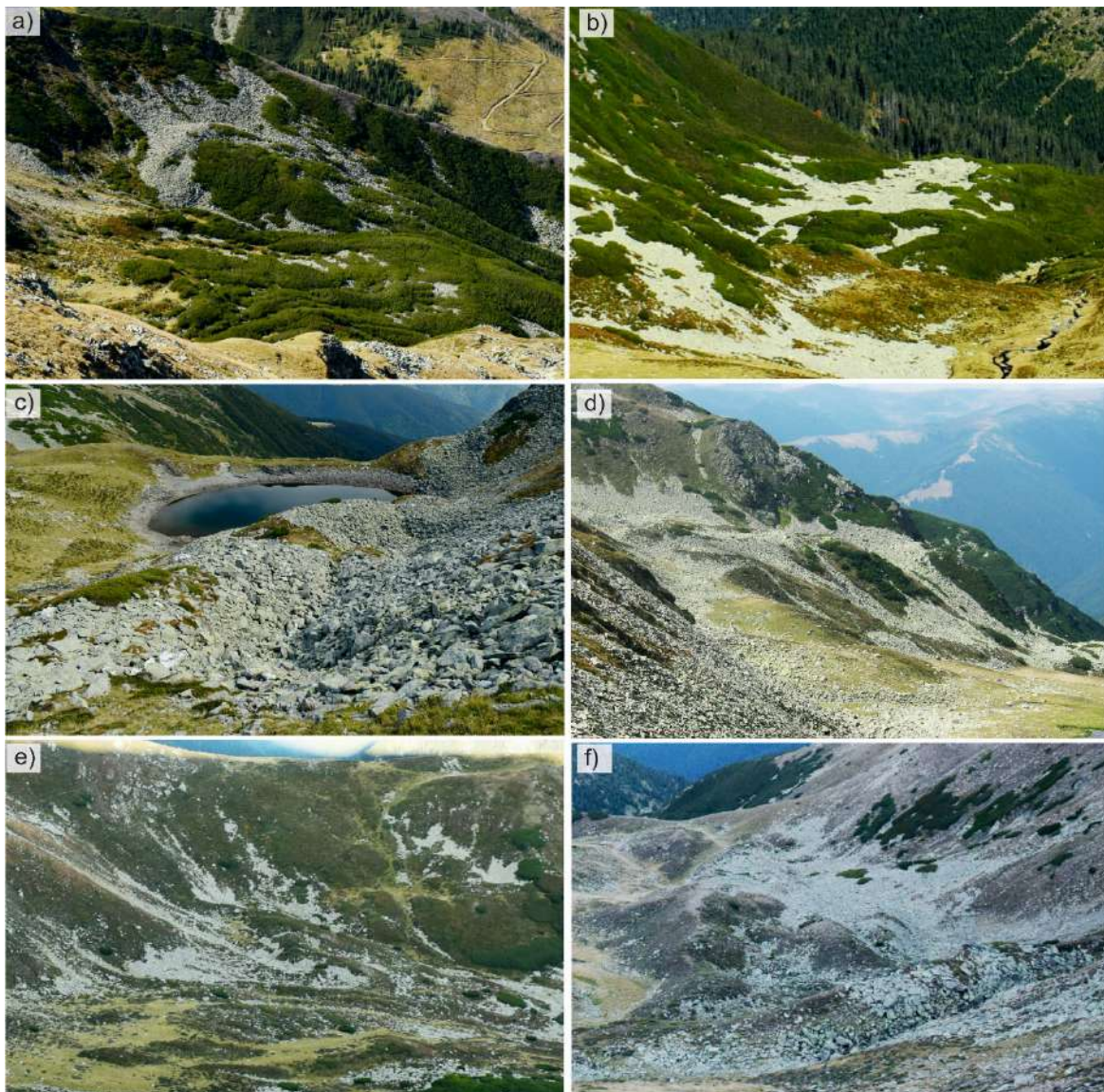


Figure 2 Rock glaciers types in Iezer Massif: Type 1a (a) and type 1b (b) rock glaciers from Groapele and Colților valleys; type 2 rock glacier from Iezer Valley close to the Iezer Lake (c); Tambura (d), Boarcășu (e) and Piscanu (f) landforms interpreted as atypical rock glaciers

4.2 Thermal characteristics of rock glaciers

4.2.1. Alpine spring temperature during late summer

The investigated springs are located at altitudes between 2050 and 2250 m asl and registered temperatures between 1.9 and 5.9 °C (Fig. 3). According to their position and source, the springs were classified into the following categories:

- Type 1 (2 cases): springs rising from slopes covered with meadows close to the mountain ridges and peaks (Păpușa South and Izvorul din Plai) with

altitudes of 2183 and 2250 m asl and temperatures of 3.4 and 4.6 °C (Fig. 4a).

- Type 2 (7 cases): springs rising below talus slopes, protalus ramparts or rock glaciers. They have altitudes between 2058 and 2172 m asl and temperatures between 1.9 and 5.3 °C. These springs have the lowest minimum and average temperatures. Two springs with temperature below the threshold of possible permafrost (2 °C) were measured in the Colților and Izvorul Iezerului valleys (Fig. 4b).

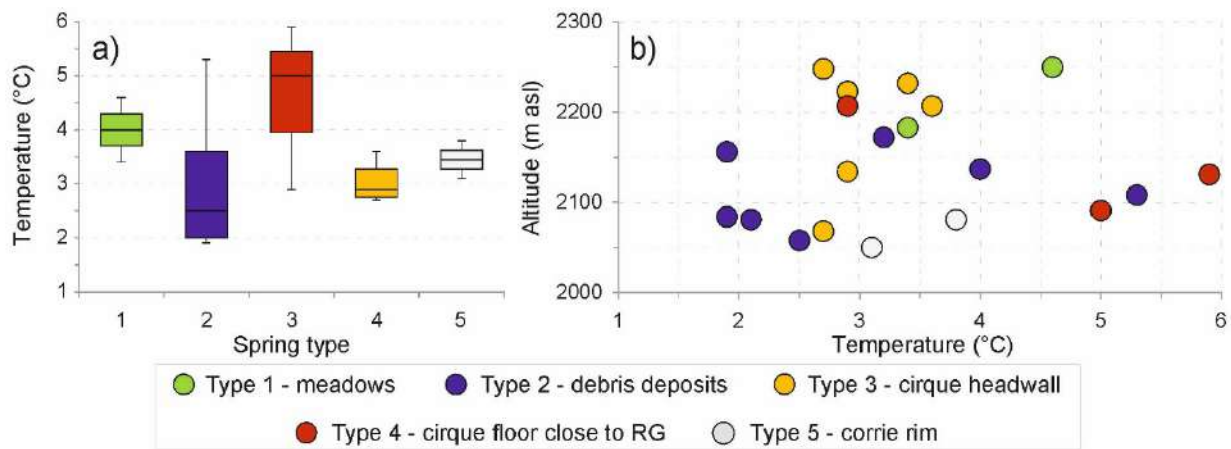


Figure 3 Temperature of alpine springs from Iezer Massif measured in 20–21 September 2018. Box plots of temperature variability of spring types from 1 to 5 (a) and temperature versus altitude (b). Spring types are discriminated by source as alpine meadows (1), screes (2), cirque floor close to rock glaciers (3), cirques headwall (4) and corrie rim (5) and are expressed by the same colour from plot a – c



Figure 4 Three examples of springs measured in the alpine area of Iezer Massif and their temperatures in relation to their source. Type 1 spring below Păpușa Peak rising from alpine meadow (a), type 2 springs in probable relation to talus slopes uphill in Colților Valley (b) and type 3 of springs rising from cirque headwall from Iezerul Mare East valley (c)

- Type 3 (6 cases): springs rising on the cirque headwall covered with more or less consistent scree deposits are located at altitudes between 2068 and 2248 m asl and have temperatures between 2.7 and 3.6 °C. Most of them are located in the lower part of the headwall and present the highest apparent dis-

charges. Such springs were measured in the Colților West, Boarcășu, Iezerul Mare East and West and Izvorul Iezerului valleys (Fig. 4c).

- Type 4 (3 cases): springs rising on the cirque floor close to rock glaciers have altitudes between 2091 and 2207 m asl and present temperatures

between 2.9 and 5.9 °C. Their lateral position to rock glaciers makes it unclear in what degree their thermal regime is related to rock glacier. Such cases are related to Tambura, Crucea Ateneului and Iezer 1 rock glacier.

- Type 5 (2 cases): springs rising at the lower limit of the glacial cirque (corrie lip) are located at altitudes of 2050 and 2081 m asl and have temperatures of 3.1 and 3.8 °C. This type of springs was measured in Boarcășu and Izvorul Iezerului valleys, the former is found below glacial and periglacial debris deposits while the latter is positioned below a rock glacier.

From a thermal point of view, relatively cold spring (two cases), below thermal threshold of permafrost presence (2 °C) can be found only below some talus slopes and rock glaciers, moderately cold springs (2 – 3 °C, seven cases) exist below some talus slopes and protalus rampart, lateral to rock glaciers and on the cirque headwall, moderately warm springs (3 – 4 °C, six cases) located at the cirque limit (corrie lip), on the cirque headwall, on the alpine meadow and below protalus rampart, and warm springs (4 – 5.9 °C, five cases) below warm

talus slopes, alpine meadow and at a lateral position from rock glaciers.

4.2.2. BTS investigations

Investigations at Păpușa site from March 2012 revealed two areas of low BTS, in the east and west corresponding with the lower sectors of talus slopes (Fig. 5). If we consider the classic BTS thresholds used for prediction, possible and probable permafrost occurs at 18 and 10 points respectively representing 44 and 24 % from the total measured points (Table 1). In 2012, measurements at Tambura site revealed possible and probable permafrost on 67 and 56 % from the total number of points (Fig. 6). In contrast, the BTS values corresponding to possible and probable permafrost were much fewer in 2018, i. e. 26 and 5 % respectively (Table 1). Colților rock glacier revealed possible and probable permafrost for 50 and 29 % of the measured points in 2012 in comparison to 11 and 0 % in 2018 (Fig. 7). At both sites, the averages and the minimum values of BTS were much higher in 2018 in comparison to 2012 the largest difference being registered at Tambura (Table 1).

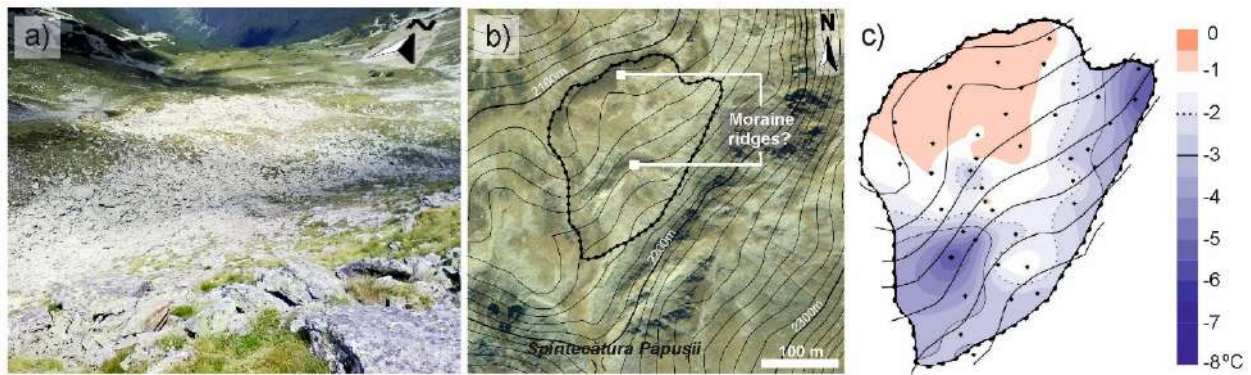


Figure 5 BTS investigations at Păpușa site from the upper part of Colților Valley from March 2012 indicating possible and probable permafrost in the upper part of the area at the contact to talus slope. The two ridges from the deposit might be rather small moraines than ridges induced by past permafrost creep

Table 1 Results from BTS field campaigns in Iezer Massif in the 3 sites from Colților Valley in terms of BTS values and predicted permafrost

Site	Area (ha)	Year	Min. BTS	Avg. BTS	Possible permafrost No. points	%	Probable permafrost No. points	%
Păpușa	4.6	2012	-5.7	-2.1	18	44	10	24
Tambura	7.2	2012	-9.3	-3.4	38	67	32	56
		2018	-3.2	-1.8	11	26	2	5
Colților	6.1	2012	-5.3	-2.1	17	50	10	29
		2018	-2.3	-0.9	4	11	0	0

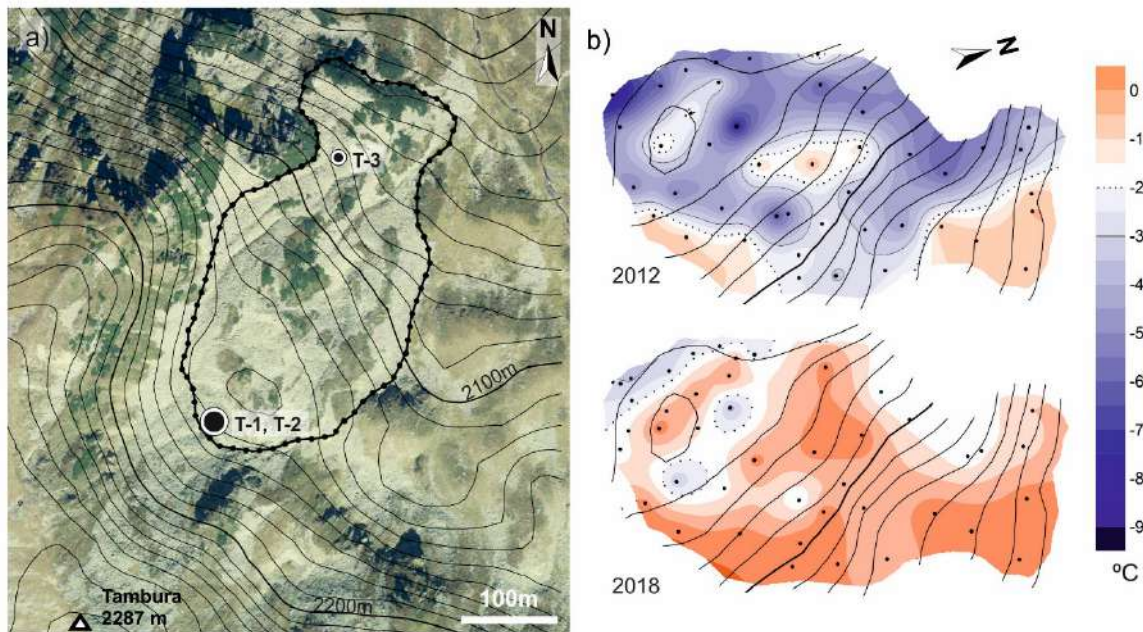


Figure 6 BTS investigations at Tambura site indicating probable (2012) and possible (2018) permafrost. The main rock outcrop is covered by shrubs and grass and the two rock streams present longitudinal furrows possibly induced by permafrost creep. Location of GST loggers is also shown in plot a

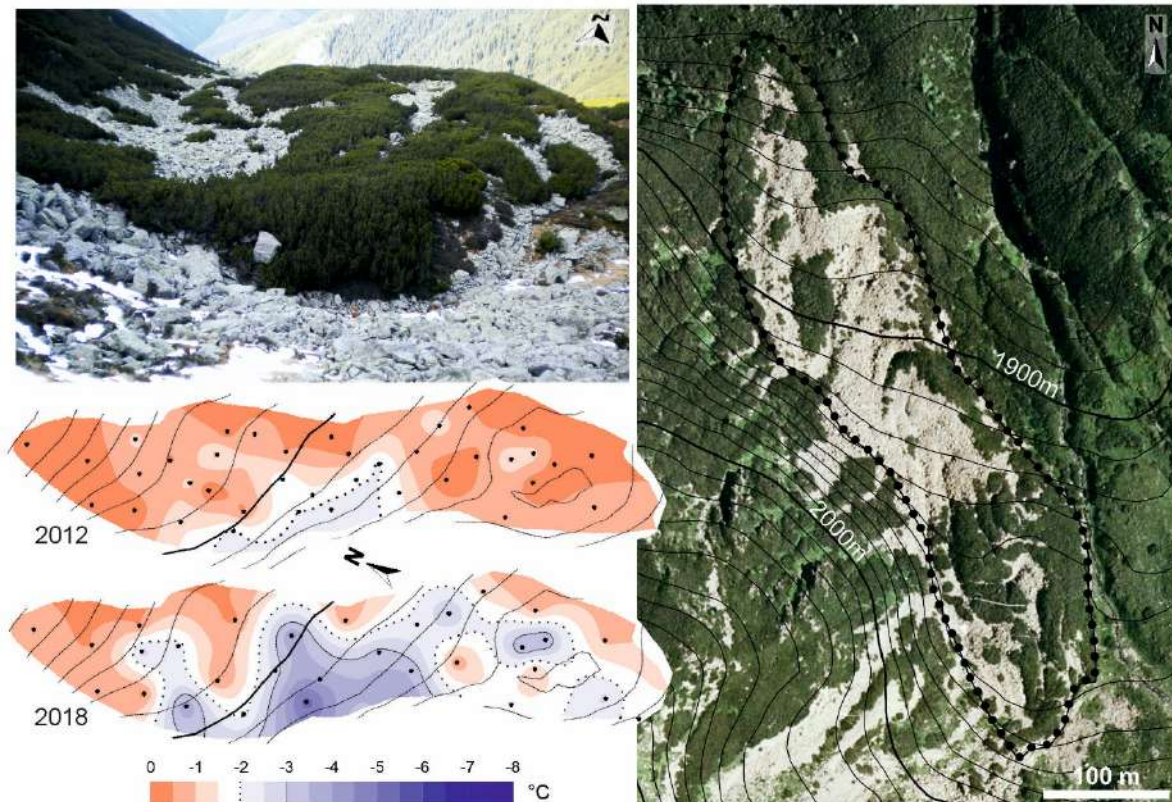


Figure 7 BTS investigations at Colților site from the middle part of Colților Valley from March 2012 and March 2018 indicating possible (2012, 2018) and probable (2012) permafrost in the middle part. Landform morphology clearly indicated past permafrost creep processes

Table 2 The average characteristics of the GST phases in terms of timing, duration, temperature and solid precipitations specific to Tambura scree possibly underlain by permafrost

GST phase	Avg. time interval		Avg. duration (days)	Avg. temp. (°C)	Avg. solid prec. (mm)
	Init.	End			
Phase 1	8-Jun	6-Nov	152	8.4	
Phase 2	6-Nov	20-Nov	17	-2.2	4.9
Phase 3	21-Nov	15-Dec	23	-4.1	48.2
Phase 4A	16-Dec	17-Feb	64	-3.4	152.2
Phase 4B	18-Feb	21-Mar	30	-2.0	75.3
Phase 5	22-Mar	10-Jun	83	–	–

Table 3 Methodology to define BTS interval. Timing and thermal oscillations are calculated for both BTS 1 and BTS 2. BTS 1 is defined as the longest interval without oscillations before the snow melting initiation while BTS 2 is defined as the longest interval before the snow melting onset with thermal amplitude less than 0.2 °C

BTS 1	Time interval		Duration (days)	Oscillations	BTS value (°C)
	Beginning	End			
2013	3-Mar	12-Mar	9	0	-2.13
2014	12-Mar	21-Mar	9	0	-2.39
2015	19-Mar	27-Mar	8	0	-2.01
2016	19-Mar	29-Mar	10	0	-1.19
Average	11-Mar	19-Mar	8.2	0	-2.02
BTS 2					
2013	20-Feb	15-Mar	23	5	-2.16
2014	26-Feb	21-Mar	24	8	-2.38
2015	3-Feb	10-Mar	36	22	-2.36
2016	25-Feb	2-Apr	38	23	-1.25
Average	18-Feb	21-Mar	30	8.8	-2.04

4.2.3. GST

The GST data and the main thermal indices are presented in Figure 8 and Table 2. Phase 1 (snow free interval) corresponds with the thawing season and it is the longest of the GST cycle of 136 – 156 days. Negative temperatures are possible but they are prevalent in phase 2 (ground cooling) that is characterized by thin and discontinuous snow cover that diminishes the amplitudes of ground thermal oscillations; the average solid precipitations are 5 mm and its duration varied between 9 and 25 days. In phase 3 (incomplete isolation) ground temperatures have no diurnal oscillations and follow air temperature only with time lag and lower amplitudes. The transition to this phase is marked by a snowfall event of >10 mm of solid precipitation, its length is highly variable (5 – 61 days) and the total solid precipitation is almost 50 mm. The progression to

phase 4A (tendency for thermal equilibrium) is marked by a heavier snowfall event (20–30 mm in the first 2–3 days) and its length varies between 31 and 90 days. The phase 4B (winter equilibrium temperature or BTS phase of the GST regime) needs a special attention in analysis and interpretation because the mean temperature during this period can be used to draw conclusion on potential permafrost occurrence at a site. Thus, in order to define objectively the limits of this period, it was calculated the frequency and magnitude of oscillations by subtracting each value from the next one and there were defined two types of 4B periods: BTS sensu stricto defined as the longest time period before the snow melt onset with no oscillations (BTS 1) and BTS in a broader sense defined as the longest period before the snow melting onset with a low number of oscillations but not surpassing an overall amplitude of 0.2 °C (BTS 2). BTS 1 lasts on average 8.2

days per winter in comparison to BTS 2 which lasts 30 days; however, the mean BTS values are virtually the same (Table 3). The time interval for one thermal oscillation of 0.0625°C (which is the resolution of the data loggers) during BTS 2 is 1.6 – 4.6 days (average of 3.4 days for one oscillation), thus, we propose to consider as BTS period the interval before the snow melting onset when temperature fluctuate less than 0.0625°C per day and the thermal amplitude is lower than 0.2°C during the entire period. The mean BTS value varied between -2.16 and -2.38°C indicating possible permafrost at Tambura site in 2012–2015 and -1.25°C in 2016 indicating improbable permafrost (Table 3). In what concerns precipitation, during this interval fall as snow on average an additional amount of 75 mm. Phase 5 (snow melting or zero curtain) is the second longest period of the GST cycle with its length only slightly varying between 77 and 87 days.

In 2017 – 2018 T-1 data revealed a similar mean BTS value of -2.38°C but a significantly warmer

thermal regime during the first part of the winter (Fig. 8b). Comparing T-1 and T-2, it can be observed a limited cooling of T-2 during autumn and the occurrence of a constant thermal difference of about $0.7 - 0.9^{\circ}\text{C}$ that maintains in the BTS period (mean BTS value at T-2 is -1.51°C). T-3 registers slightly colder ground temperatures in the first part of winter but a warmer mean BTS value (-1.22°C). Also, a much longer period of winter thermal equilibrium can be observed at T-3.

The MAGST at T-1 was mostly around $+2^{\circ}\text{C}$ in the interval of 2013–2015 and increased and remained quasi stable at around the value of 3°C (Fig. 9) in the rest of the interval. It varied between $+1.6$ and $+3.1^{\circ}\text{C}$ and the multiannual mean is $+2.4^{\circ}\text{C}$. Air temperature calculated for the same altitude (2162 m asl) had a multiannual mean of $+0.9^{\circ}\text{C}$ for the same interval and varied rather differently (Fig. 9). Mean ground temperature on almost 11 months in 2017 – 2018 were $+3.2^{\circ}\text{C}$ at T-1, $+1.4^{\circ}\text{C}$ at T-2 and $+1.1^{\circ}\text{C}$ at T3.

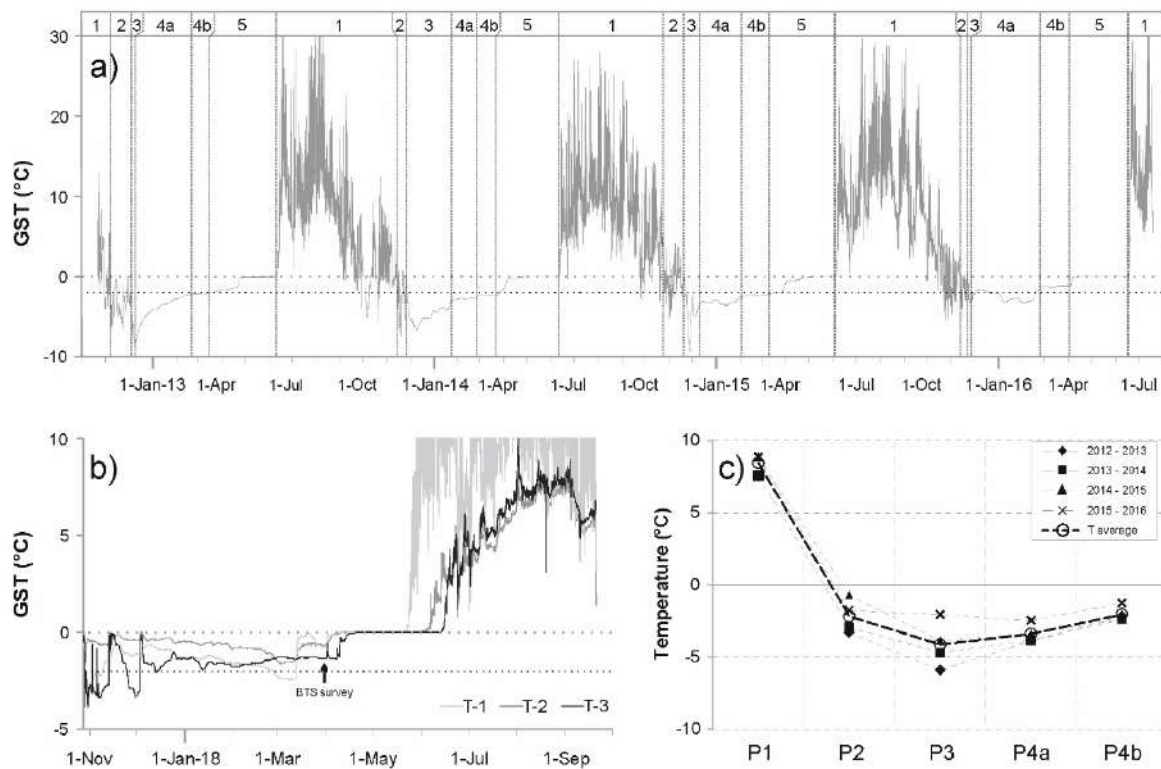


Figure 8 GST regime at Tambura site. Multiannual measurements in the upper part of the scree (T-1) at 2162 m asl with the specific annual 6 phases (a); one year GST regime at T-1 – T-3 locations with the time of itinerant BTS survey marked (b); mean temperatures of the 5 phases at multiannual level (phase 5 – zero curtain was excluded because it is close to 0°C every year) (c)

5. Discussion

5.1 Rock glaciers typology

Rock glaciers from Iezer mountains are small surface landforms (average of 3.5 ha, half of them are below this value), occurring on cirque headwalls and valley sides above the treeline. Their probable origin is mostly periglacial, i.e., talus derived. They are significantly smaller in comparison to those found in Italian Alps (5 ha) (Baroni et al., 2004), Central Alps (4.9 – 7.4 ha for talus-/moraine derived rock glaciers) (Scotti et al., 2013), Eastern Alps (6.1/7.5 ha for relict/intact rock glaciers) (Kellerer-Pirklbauer et al., 2012), Norway (10–20 ha for intact/relict and talus-/moraine derived rock glaciers) (Lilleøren and Etzelmüller, 2011), Patagonian Andes (3.6/9.2 ha for fossil/intact rock glaciers) (Falaschi et al., 2015). The main reason for such situation might be related to the type of rock glaciers that developed in Iezer Mountains which are mainly lobate talus derived rock glaciers located mostly on cirque headwalls and valley slopes. Only a few rock glaciers of type 1 occur on valley floors and have a considerable length and area (6.8–9.5 ha) in Groapele and Tambura valleys. The rest of landforms are lobate and relatively small with their surface decreasing with altitude (Fig. 10). They have a similar surface to valley wall rock glaciers (3 ha, type 2 of rock ice features) described in Sierra Nevada in comparison to cirque rock glaciers that are on average 5 times larger (Millar and Westfall, 2008). Mountain morphometry with round interfluvies and less inclined slopes did not favour the debris accumulation in large quantities but rather the spreading across large areas especially on eastern and southern slopes (subsequent and consequent). Below secondary ridges some rock deposits that formed parallel to the crest were subsequently affected by permafrost creep and formed rock glaciers of type 2. In opposition, on the western/northern obsequent slope (much steeper) rockwalls and talus slopes are considerably much better developed as well as several chaotic rock deposit of probable glacial origin. However, rock glaciers were detected just on one glacial cirque out of four in the Boarcășu basin and in two cirques out of six in Colților basin while the rest present only talus deposits under the headwall

that are partially fossilized. Such situation might be related to a reduced rockwall erosion rate in the postglacial period or a lack of debris availability in the period of climate favourability to permafrost development in Late glacial.

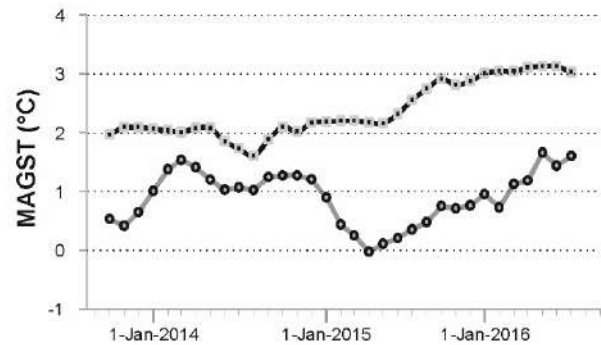


Figure 9 Multiannual variation of MAGST at Tambura site (grey squares line) along MAAT (black circles line) adjusted to the level of 2162 m computed using data from Vârful Omu meteorological station (2504 m asl) with a lapse rate of 0.57/100 m. Curves are moving averages and each point represents the mean value of the 12 previous months

The prevalence of northern direction of rock glaciers is typical because of the colder microclimatic conditions more favourable to permafrost development and creep (e.g. Kellerer-Pirklbauer et al., 2012; Scotti et al., 2013). In terms of grain size and texture most rock glaciers present medium blocks with diameters in the order of decimeters mostly matrix free that would include them in the category of bouldery type (Matsuoka et al., 2005). Grass and shrubs are embedded on convex ridges while lichens colonize the exposed parts of all blocks which indicate their lack of movement. However, this does not exclude the possibility to host permafrost, as talus rock glaciers are much more efficient in maintaining permafrost below the rock mantle in opposition to debris rock glaciers (Lilleøren and Etzelmüller, 2011).

The current inventory takes into account 16 rock glaciers, a much lower number in comparison to the previous works (Onaca et al., 2017a; Szepesi, 1998–1999). From the supplementary 17 landforms of I–2, we consider that seven are „certainly” misinterpreted as rock glaciers and are in fact scree slopes (1), lower talus slopes (2), moraine ridges (1), moraine deposits (1) and debris accumulations in cor-

respondence to structural rock outcrops (2). Two additional landforms are interpreted as incipient rock glaciers, i.e. protalus ramparts, a different landform type. For 8 landforms identified in I-2 some potential permafrost connection might exist because one morphological element that could be related to permafrost creep can be identified: an apparently well-developed front of deposits located below talus slopes (four cases), a chaotic structure of the deposit (two cases) or several longitudinal or transverse furrows (two cases). However, the resulting landforms cannot be considered rock glaciers in our view or at least not with an acceptable degree

of confidence only on orthophotos.. Some talus deposits are rather suitable for the more general term of rock ice features (RIFs) (Millar and Westfall, 2008). Such landforms are indeed more widespread in Iezer Mountains but do not fulfil the geomorphological demands to be interpreted as rock glaciers in our view. Other mass wasting forms included in RIF category like solifluction lobes are well represented in Iezer Massif and they seem to be active today. However they are only associated to seasonal frost and freeze-thaw action and not to permafrost (Fig. 11) (Onaca et al., 2017b).

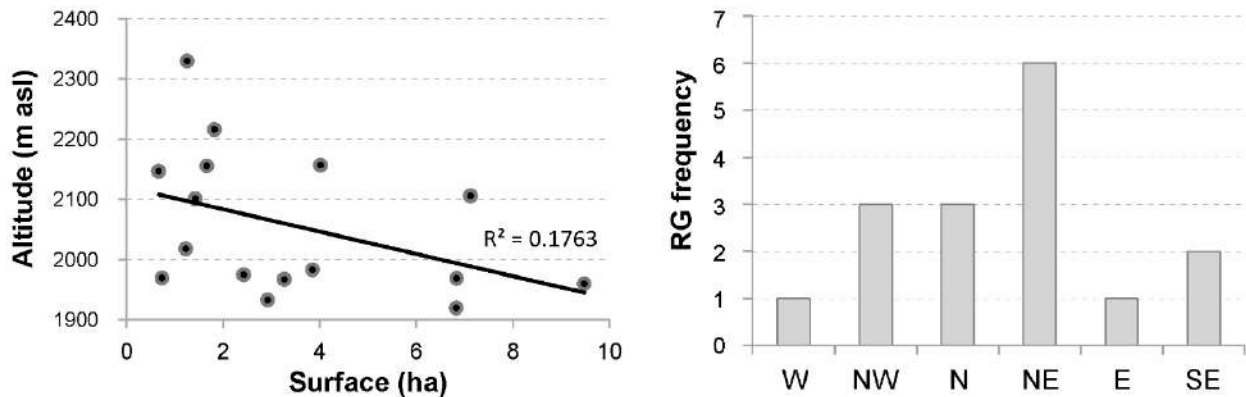


Figure 10 Rock glaciers characteristics and distribution. Relation between altitude and surface (a) and frequency on each cardinal direction (b)



Figure 11 Rock Ice features (RIFs) from Iezer Massif different from rock glaciers. Solifluction lobes on the western slope of Păpușa Peak related to seasonal frost (a) and a probable protalus lobe possibly related to incipient permafrost creep in the upper sector of Groapele Valley. The blue stick from picture a) is about 1.2 m high

Rock glaciers mapping in marginal periglacial mountain environments may be a difficult task as several problems arise from tracing the limits of the landforms especially in the areas covered by thick vegetation, differentiating them from other rock deposits like moraines, debris slopes and rock slope failures. Recent studies proved that some previously assumed rock glaciers were in fact other landforms like rock slope failures and debris drapes (Jarman et al., 2015) or “bedrock with clusters of locally derived boulders” and glacial deposits and solifluction lobes affected by fluvial processes (Wilson, 2011). This cancels previous palaeoclimatic inferences made on the basis of landforms interpreted as rock glaciers.

5.2 Thermal signature and possible permafrost occurrence

Spring water temperatures registered in the Iezer Mountains are more homogeneously distributed in comparison to Retezat (Vespremeanu–Stroe et al., 2012) and Parâng Massifs (Urdea and Vuia, 2000; Popescu et al., 2015). Also, their minimum temperatures are slightly higher. We assume that springs located on cirque headwalls, corrie rim and bellow some talus deposits have the typical temperatures for such a mountain environment, between 2.5 and 4.5 °C. Those with more vigorous discharges might indicate a better connection to the underground faults system and have probably a more stable thermal regime as well. Yet, three atypically cold springs were found in Colților and Izvorul Iezerului Valleys where temperature was 1.9 ... 2.1 °C, i.e. around the threshold of possible permafrost. They are related to a talus slope located 200 m uphill below the Păpușa Peak, and below a rock glacier front in the close vicinity of Iezer Lake. These two structures have a certain probability to host some low volume late summer frozen structures. Springs located in the lateral parts of rock glaciers are probably not connected to their runoff system and that is why their temperatures are so high. The warmest springs (above 5 °C) are among the weakest in terms of discharge and their temperatures could be related to warming caused by low flow velocity and enhanced heat transfer. That suggests that applying this method so late in the autumn could alter the results because of too low discharges. Our results confirm the investigations performed by Szepesi,

1998–1999 who suggests alpine springs temperatures below 2 °C in the summer.

Spring temperatures from Iezer Mountains are significantly warmer in comparison to other massifs where ice containing talus and rock glaciers lies in the vicinity of glaciers (Carturan et al., 2016). Also, the water from Iezer springs is clearly indicating motionless talus with no permafrost creep involved in comparison to other sites where active rock glaciers and rock ice forms present streams with suspended silt (Millar and Westfall, 2008). Also, active rock glaciers have lower temperatures (below 1.3 °C) for the entire warm season and their discharges are highly variable (Krainer et al., 2015). Because of missing massive ground ice and the presence of sandy to silty basal layer, relict rock glaciers were proved to have a great storage capacity acting as long term (in the order of months) aquifers with a regulating effect on hazards like floods and debris flows from mountain areas (Winkler et al., 2016). That is even more important as they are landforms with a long residence time in the landscape in comparison to glacial landforms (Knight et al., 2019).

BTS investigations at Păpușa site indicate two overcooled scree areas that might be related to the two cold springs from Colților Valley (Fig. 4b). This situation of low temperature springs rising tens to hundreds of meters from a potential frozen source is similar to that from Doamnei rock glaciers (Făgăraș Massif). Potential permafrost areas at Tambura and Colților sites vary significantly from 2012 to 2018 (Table 1). The GST regime proves however that this second BTS survey (31 March 2018) was performed at a time when BTS period was finished at T1 and T2 sensors locations and the temperature was 0.5 – 1.5 °C higher than in the BTS interval (Fig. 8a). Still, at T3 location, BTS period finished 5 days later. These facts indicate that BTS maps from 2018 are not completely relevant. An average situation, at the middle of the two estimations might be more appropriate because 2011–2012 winter induced atypical ground conditions as well but in the sense of a more intense cooling (Popescu et al., 2015).

GST measured in the upper part of Tambura scree (T–1) confirmed the potential permafrost occurrence suggested by BTS, with the exception of 2015–2016 when BTS was higher than –2 °C. The

latter was caused by the short durations of phase 2 and 3 and the early initiation of phase 4a before the ground cooled. In fact, the warmer temperatures in phase 2 and 3 are in power to increase the mean BTS value even though the opposite does not occur at our study site (Fig. 8c). A moderate correlation between ground freezing index and mean BTS was found for rock glaciers in Retezat Massif (Onaca et al., 2015). It was also shown based on borehole data that the more snow in the early winter the higher the temperature in March will be at the top of mountain permafrost (Vonder Mühll et al., 1998).

In 2017–2018 interval, GST at 1 m depth (T2) was warmer than at the surface (T1) for the entire winter especially at the beginning of monitoring period indicating a reduced ground cooling efficiency in spite of blocky layer. The thermal difference of 0.7 – 0.9 °C during most of the winter indicates a lack of air stratification below the insulating snow cover. However, the warmer temperatures at T2 in the BTS period do not indicate permafrost absence. Temperature increase with depth was also visible at other rock glaciers underlain by permafrost. For example in Swiss Alps Murtél rock glacier, temperature measured in boreholes in 1 April 2000 increased from approximately –4 °C at the surface to –2.7 °C at –1.5 m and –1.7 °C at –5 meters or in the Muragl rock glacier from –2.8 °C at the surface to –2 °C at –1 m and –1 °C at –2.5 m (Vonder Mühll et al., 2003). Thermal investigations in shallow boreholes in Scandinavia revealed the temperature increase with depths both in permafrost and seasonal frost areas and during the entire winter at sites with continuous winter cold air infiltration in the ground through a thin snow cover (Juliussen and Humlum, 2008).

MAGST values similar to those recorded at T1 in correspondence with BTS >-2 °C were attributed to relict rock glaciers in Retezat, Parâng and Făgăraș Massifs (Vespremeanu–Stroe et al., 2012; Onaca et al., 2013; Popescu et al., 2015) but in other marginal periglacial massif (Atlas, North Africa) it was suggested that they can still be attributed to permafrost if associated with BTS below –2 °C (Vieira et al., 2017). Positive MAGST (0.8 – 2.8 °C) was also found in a relict rock glacier subjected to probable permafrost in its rooting zones in Austrian Alps at a mean

annual air temperature of >4 °C (Kellerer–Pirklbauer et al., 2015) and creeping permafrost at positive MAGST (1–2 °C) in Italian Alps. In the latter case, however, rock glacier is derived from a former glacier (Seppi et al., 2015). The average surface offset (MAGST – MAAT) in 2013–2016 was 1.5 °C which is identical to that of Murtél rock glacier (Hoelzle and Gruber, 2008).

Taking into consideration that possible permafrost was documented at 1900 m asl in Colților rock glacier and that openwork coarse blocks can assure the thermal conditions for permafrost maintenance even at unexpectedly low altitudes, we suggest that most of rock glaciers (11) from Iezer Massif considered in this study are underlain by patches of permafrost and could be framed in the class of inactive rock glaciers. This assumption is supported by the findings of Kellerer Pirklbauer et al. (2005) who documented probable permafrost in a rock glacier located in conditions of MAAT of 1.6 °C in the eastern Alps. The causes of such low altitude distribution might be related to the openwork structure and porous debris availability and to snow cover conditions which is also crucial. Thermal processes in the blocky layer like funnelling through thin snow cover and hoarfrost crystal formation decrease significantly the MAGST (Bernhard et al., 1998; Kellerer Pirklbauer et al., 2015). However, we suggest that inactive rock glaciers from Iezer Massif are much closer to relict rock glaciers in terms of isolated permafrost occurrence in small spots and subdued morphology in comparison to those considered inactive in the Alps which seem to be much closer to active rock glaciers, presenting permafrost on their almost entire area but in a motionless state. Relict rock glaciers are considered those from Groapele Valley which are fully covered in shrubs and the one from Boarcășu cirque which has a matrix supported debris deposit of probable moraine origin (Onaca et al., 2017a). Moreover, we suggest that sporadic patches of permafrost might exist in other debris deposits and rock ice features like talus and scree slopes of non-glacial origin and with openwork structure. This is significantly more than previous assumptions of Onaca et al., 2017 who indicated the presence of 4 intact rock glaciers in Iezer Massif or from Szepesi, 1998–1999 who suggested that only

Roşu rock glacier might be inactive based on its altitude. In fact, this rock glacier might hold the record for the highest from Romanian Carpathians with an average altitude of 2329 m asl.

Geomorphological aspect of debris deposits in Iezer Massifs including rock glaciers do not show a recent acceleration of dynamics as it was documented in the Alps, they seem well settled while other mass movement processes like debris flow can be noticed to increase in occurrence. That is because coarse and porous deposits can assure great thermal anomalies at depths that protects efficiently the underground as it was documented at Murtél rock glacier for example (Schneider et al., 2012).

6. Conclusions

A lower number of rock glaciers (16) is assumed to occur in Iezer Massif in comparison to previous estimations based on two inventories independently produced. In mapping, we considered only landforms fulfilling at least two morphometric parameters to consider a rock glacier, i.e. ridges and furrows topography and a visible terminal front. Other eight additional landforms might be rock glaciers but field visits need to be done to check for the both criteria. Several other landforms that could be included in the more general term of rock ice features some affected by permafrost creep, can be found in Iezer Massif. Such landforms like protalus ramparts, protalus lobes, boulder streams and solifluction lobes need a better assessment, inventory and classification in the future. The small rock glaciers surface (3.5 ha on average) is related to the reduced debris production and accumulation imposed by morphometry of the valleys network but also on the relatively short period of climatic favourability.

Extensive investigations on alpine springs indicated two possible permafrost areas in a talus slope and rock glacier from Colţilor and Izvorul Iezerului glacial cirques with temperatures around the threshold of 2 °C during late September. Most of the springs are between 2.5 – 4.5 °C and only exceptionally above and below these values. We assume possible warming effects for all spring from the alpine area caused by low autumn discharges and associated lower water flow speed. Most rock

glaciers don't present a spring at their fronts, so this method cannot be used to check for permafrost presence.

BTS investigations indicate possible permafrost occurrence on Colţilor Valley down to an altitude of 1900 m which is equivalent to a MAAT of 1.1 °C. Multiannual GST proved the stability of BTS indicating possible permafrost in 5 out of 6 years of measurements. The specifics of intra-annual GST phases confirm the major role of ground cooling during autumn and early winter for inducing potential permafrost distribution in scree deposits. MAGST well above 0 °C at Tambura site indicate a large thermal gradient in the active layer above the potential permafrost. 11 rock glaciers from Iezer Massif are probably underlain by permafrost patches and could be considered inactive. This is much more than previously suggested. Other rock deposits and rock ice features like protalus ramparts and lobes, talus slopes and boulder streams located in shadowed conditions might also contain isolated patches of permafrost or at least prolonged summer ice remnants because of the cooling effect of coarse blocks and the favourable conditions of snow.

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