
Rock glaciers vegetation colonization in Retezat Mountains: implications for morphodynamics and palaeoclimate reconstruction

Răzvan POPESCU^{1*}, Alfred VESPREMEANU-STROE¹, Olimpiu POP², Nicolae CRUCERU³

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

² Babeş-Bolyai University, Faculty of Geography, Cluj-Napoca, Romania

³ Romanian Academy, Emil Racoviţă Institute of Speleology, Bucharest, Romania

Received 29 December 2021; Revised 30 December 2021; Accepted 31 December 2021

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

ABSTRACT

Vegetation is an important ecological indicator of rock glaciers' activity as its development marks the transition from active to inactive and relict states. Most rock glaciers in Retezat Massif are covered by vegetation, mostly *Pinus mugo* shrubs but also herbaceous and forestry vegetation. In this paper, 82 rock glaciers from Retezat are classified into six classes according to vegetation characteristics, rock glaciers' vegetation changes are assessed using old aerial and ground imagery, and the timing of shrubs vegetation growth is investigated by means of dendrochronology methods applied on three rock glaciers. The study's main purpose is to identify what caused the vegetation colonization, climate variation, or rock glacier inactivation. Results indicate that altitude is the dominant factor of rock glacier vegetation cover variability. In most cases, the vegetation patches increased in density and only slightly in surfaces. The last rock glaciers' vegetation colonization initiated in the 18th century, beginning with 1830s on all the three rock glaciers probably after the last local Little Ice Age cold spell. We conclude that the investigated rock glaciers were pseudorelict during the entire Holocene and that recent vegetation settling is not the first one in the Holocene. However, the scenario of rock glaciers inactivation that caused vegetation growth, previously advanced in the literature, cannot be excluded, especially in light of the recent discoveries of rock glaciers activity, and further investigations should be done to come to a less ambiguous outcome.

KEYWORDS rock glaciers, *Pinus mugo*, climate change, subalpine vegetation changes, Retezat Mountains

1. Introduction

Rock glaciers are harsh environments for vegetation colonization because of their openwork scree

structure that drain water efficiently, hinder fine material accumulation and soil formation, and favor snow persistence (Canone and Gerdol, 2003; Tampucci et al., 2015). As active rock glaciers can

sporadically allow lichens and plants adapted to surface blocks displacements, the inactive and relict ones have a more extensive and diverse vegetation cover favored by stable ground and more availability of areas with fine debris and soil (Burga et al., 2004). This observation allowed using the vegetation cover as an empirical indicator for the activity status of rock glaciers (e.g., Scotti et al., 2013; Onaca et al., 2017; Popescu, 2018; Jones et al., 2019). Fine materials are usually found on rock glacier front and lateral edges, which are generally less mobile than the rest of the body and are therefore the first to be colonized by vegetation. Lichens develop extensively on rock glaciers, even on the active ones, and that is possible because of the passive movement of gelifracsts that remain exposed to daylight with the same facets. Moreover, previous studies showed that *Rhizocarpon geographicum* agg. thalli are well correlated with the rock glacier age and that lichens cannot grow in areas with snow persistence of more than nine months in a year (Burga et al., 2004). Overall, the topoclimate, surface movement and fine sediments availability are the main controlling factors in vegetation distribution on rock glaciers.

Rock glaciers are landforms sensitive to climate changes and air temperature rising induces mostly dynamics acceleration, but as a final consequence, it can also inactivate them due the ice content reduction or disappearance (Fleischer et al., 2021). Reducing activity rates can increase floristic diversity on rock glaciers (Cannone and Piccinelli, 2021).

Several species of trees can be used as palaeoenvironmental indicators applying dendrochronology (Pearl et al., 2020). By analyzing tree rings one can determinate age, palaeoclimate changes or occurrence/variability in geomorphologic processes interacting with the growing plants. Since rock glaciers are mainly located above the treeline, the mostly used species in tree ring studies, i.e. spruce trees, are unavailable. Thus, alpine shrubs are the only ones that can offer palaeo-environmental information. Recent studies revealed that alpine shrubs like *Salix helvetica* (Gärtner-Roer et al., 2013) and *Linantus pungens* (Franklin, 2013) are sensitive to and can archive information about rock glacier activity or climate variation. Other species with a large occurrence above the tree line in the European

Mountains and Carpathians, in particular, is the dwarf pine (*Pinus mugo*), a common shrub belonging to the subalpine vegetation belt (Šibík et al., 2010), widespread also on relict rock glaciers (Kellerer-Pirklbauer et al., 2015; Popescu, 2018). Dendrochronology was applied on *Pinus mugo* in mountain areas (Palombo et al., 2010; Timiş and Popa, 2011; Dai et al., 2017) but rarely on rock glaciers so far (Urdea, 1998). Thus, the current paper aims at 1) presenting the ages of *P. mugo* shrubs located on rock glaciers and in their vicinity; 2) discussing the relevance of *P. mugo* ages in relation to rock glaciers dynamics and 3) assessing the rock glacier vegetation cover in Retezat Mountains and changes in the last 100 years.

2. Study area

Retezat Mountains is located in the western part of the Southern Carpathians as the first high massif (maximum altitudes of 2509 m asl in Peleaga Peak) facing the west wind masses (Fig. 1). It presents the marks of intense glacial erosion in the Pleistocene that left well-defined glacial cirques (Mîndrescu et al., 2014) and valleys (Urdea, 2000). Moraines from the Last Glacial Maximum are located down to about 1100 m asl on the northern and southern slopes (Urdea, 2000). However, repeated glacial cycles with a major cumulated effect manifested across the massif during the Quaternary period (Ruszkiczay-Rüdiger et al., 2016; 2021). The upper limit of the treeline is located at about 1800 m asl while above well-defined krummholz (subalpine vegetation level) and alpine levels are marked mainly by *Pinus mugo* and alpine meadows respectively. Other typical shrub vegetation consists of species like *Alnus viridis*, *Rhododendron ssp.*, *Juniperus sibirica*, *Vaccinium vitis-idaea*, *Vaccinium myrtifolium*, as well as the subalpine meadow communities. Glacial valleys have large and relatively flat valley bottoms with short and steep interfluvies. Several types of scree deposits like talus slopes, rock glaciers, debris-covered slopes, and block streams occupy a large part of the high altitude area of the massif (Onaca et al., 2017; Şerban et al., 2019) and are the result of frost weathering (Vasile et al., 2014; Vasile and Vespremeanu-Stroe, 2017). The dominant lithology is represented by granodiorite rocks but also by amphibolites and amphibolic gnei-

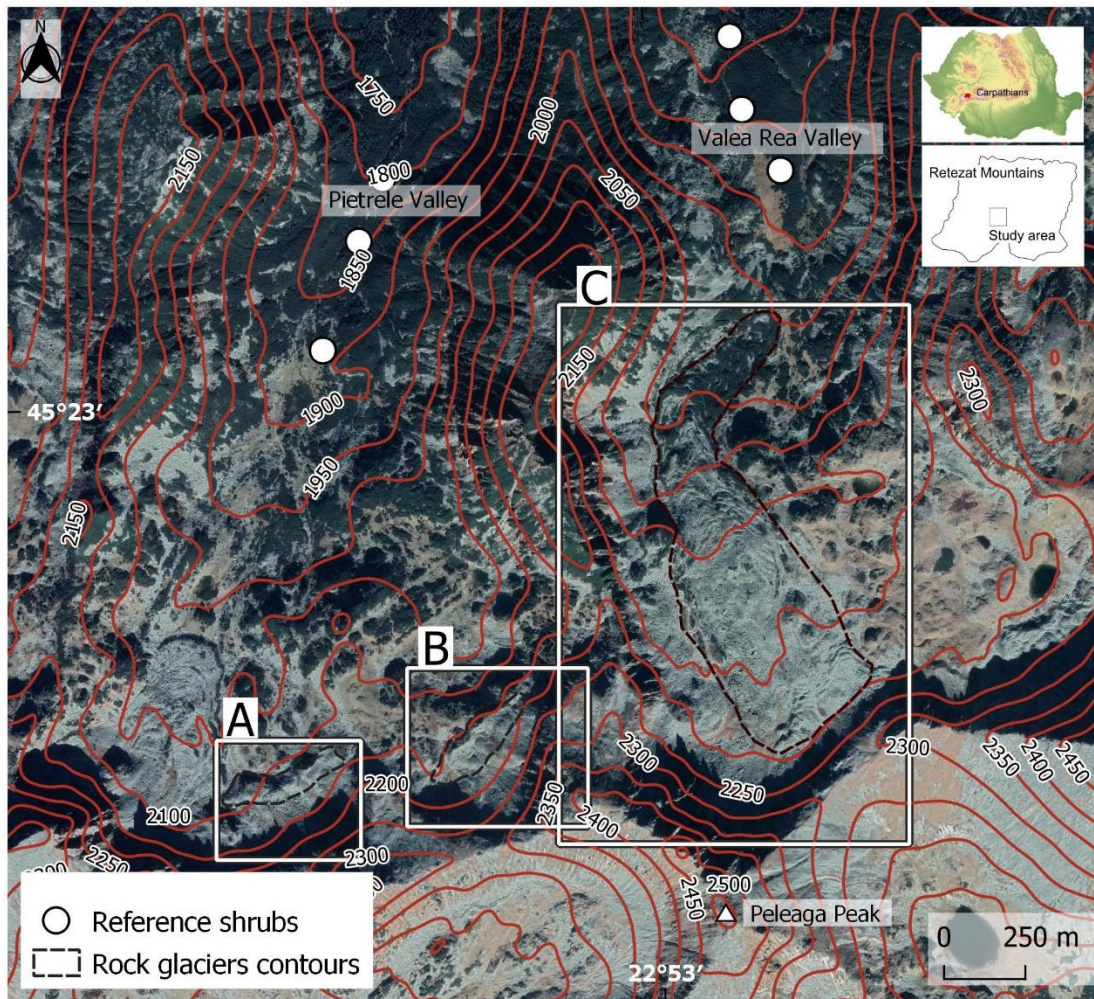


Figure 1 Study area in the central part of Retezat massif with Pietrele 2 (A), Pietricele (B), and Valea Rea (C) rock glaciers delineated. The shrubs sampled as reference are also visible here

sses in the SE of the massif in the Custura peak area, all of upper Precambrian age (Berza et al., 1989).

The climate is alpine specific to mountains located in mid-latitude temperate zones. The mean annual air temperature at the closest high altitude meteorological station (Vârful Țarcu, 2180 m asl) is - 0.5 °C for the 1961-2007 time interval (Onaca, 2017). The 0 °C isotherm of MAAT considered for the Southern Carpathians occurs at approximately 2050 m asl, (Onaca et al., 2017) and the precipitation above 2000 m is 978-1330 mm/year (Micu et al., 2015). Most precipitations come as rainstorms during summer, and snow is generally present from November to June. Several patches of snow can persist until August in the most favorable locations, but perennial snow is not documented in Retezat. Sporadic permafrost is

found above 1950 m asl mainly in debris deposits like rock glaciers and talus slopes (Vespremeanu-Stroe et al., 2012; Onaca et al., 2015; Popescu et al., 2017). A large part of the Retezat Massif is included from 1935 in the Retezat National Park, which is the oldest in Romania, and it was UNESCO biosphere reserve from 1979 until 2021. The Retezat Mountains comprise a third of Romania's biodiversity but seriously affected by overgrazing in the last decades (Kiss and Alexa, 2015). The Carpathian range is a biodiversity hotspot in Europe serving as a palaeorefugium for numerous continental, arctic and alpine taxa during the Pleistocene glaciation because of the relatively reduced glacial cover in comparison to other mountain ranges (Bálint et al., 2011; Pușcaș et al., 2021).

The three rock glaciers investigated by dendrochronologic approach are located in Pietrele and Valea Rea Valleys (Fig. 2). Pietricele and Pietrele 2 are relatively small talus derived lobate rock glaciers. At the same time, Valea Rea is the largest rock glacier of the Romanian Carpathians, with a total length of more than 1.3 km, a surface of 0.41 km² and a complex origin and evolution (Fig. 3).

3. Methodology

3.1. Age determination of *Pinus mugo* shrubs

The age of *P. mugo* shrubs from Valea Rea and Pietrele valleys was investigated based on a dendrochronological approach. During field campaign conducted in 2013 on Pietrele Valley, 7 sites from Pietrele 2 rock glacier and 7 sites from Pietricele rock glacier were selected for sampling (Fig. 2). Each site is composed of 1 to 7 shrubs, the total number of individuals sampled is 36; they are located only on the terminal fronts of the rock glaciers. Additionally, 3 sites with a total of 11 individuals were collected as a reference in the Pietrele Valley in 2015 (Fig. 1). On Valea Rea valley, 19 sites (one shrub per site) along a longitudinal transect from the front upwards on Valea Rea rock glacier and an additional 7 reference sites (one shrub per site) were also selected for sampling in 2015.

Regarding ages, all values are reported to the year 2012. The main stem of each *P. mugo* individual was sampled either by taking cores (two cores for each stem sampled) using a Pressler borer or by taking discs with a hand saw. Disks or cores were labelled and their sampling location was recorded with a GPS device. In each site, the larger individuals were considered the oldest ones intended to be sampled. In the laboratory, samples were air-dried and then sanded using a sanding machine with sanding belts of progressively finer grits (60, 180, 220 or 320, 600), until growth ring structures became clearly visible. Standard dendrochronological procedures for age determination were applied (Stoffel and Bollschweiler, 2008; Stoffel and Corona, 2014). Because the age determination technique by simple ring counting allows only to estimate roughly an individual's age, ring-width measurements and cross-dating of growth-ring series are needed when

the dating accuracy is required. Therefore, after preliminary age estimation by ring counting, ring widths were measured to the nearest 0.01 mm using a LINTAB 5 measurement station (a measurement table coupled to a stereomicroscope Leica DMS 1000) and TSAP-Win Scientific software (RINNTECH, 2021). The quality of cross-dating and measurement accuracy of ring-width series was assessed visually and statistically using COFECHA software (Holmes, 1983), enabling the detection of missing and/or false rings. However, the ages obtained are possibly slightly underestimated because the growth rings of *P. mugo* may not be continuous along the stem, and as the shrub grows, the rings tend to build up only towards the terminal part of the stem.

3.2. Assessment of the rock glaciers vegetation cover and its changes

We calculated the actual vegetation cover, including shrubs and herbaceous vegetation, using supervised classification on each rock glacier in ENVI software on RGB orthoimages of 0.5 m spatial resolution from National Agency for Cadastre and Land Registration (ANCP), collection 2012. One of the major sources of error is related to the steep frontal slopes that present shades and could sometimes be classified erroneously as vegetation. To overcome this, we used newer alternative aerial images that did not have this problem.

Diachronic analysis of vegetation changes is done in a qualitative manner by using old aerial photographs obtained by the National Center of Cartography, formerly called IGFCOT in the 1968-1980 period (Mărgărint, 2010, p. 59). These images are not orthorectified and georeferenced so conclusions on the surface changes were made only on very small areas where deformations are negligible. Other old photos from the ground found in the literature were also used.

4. Results

4.1. *Pinus mugo* growth rings analysis

In Pietrele 2 rock glaciers front, the samples are located at altitudes between 2073 and 2118 m asl, and the oldest age from all the sites was obtained at S1, 182 years. The oldest age from each cluster of samples is commented. Two shrubs are older than

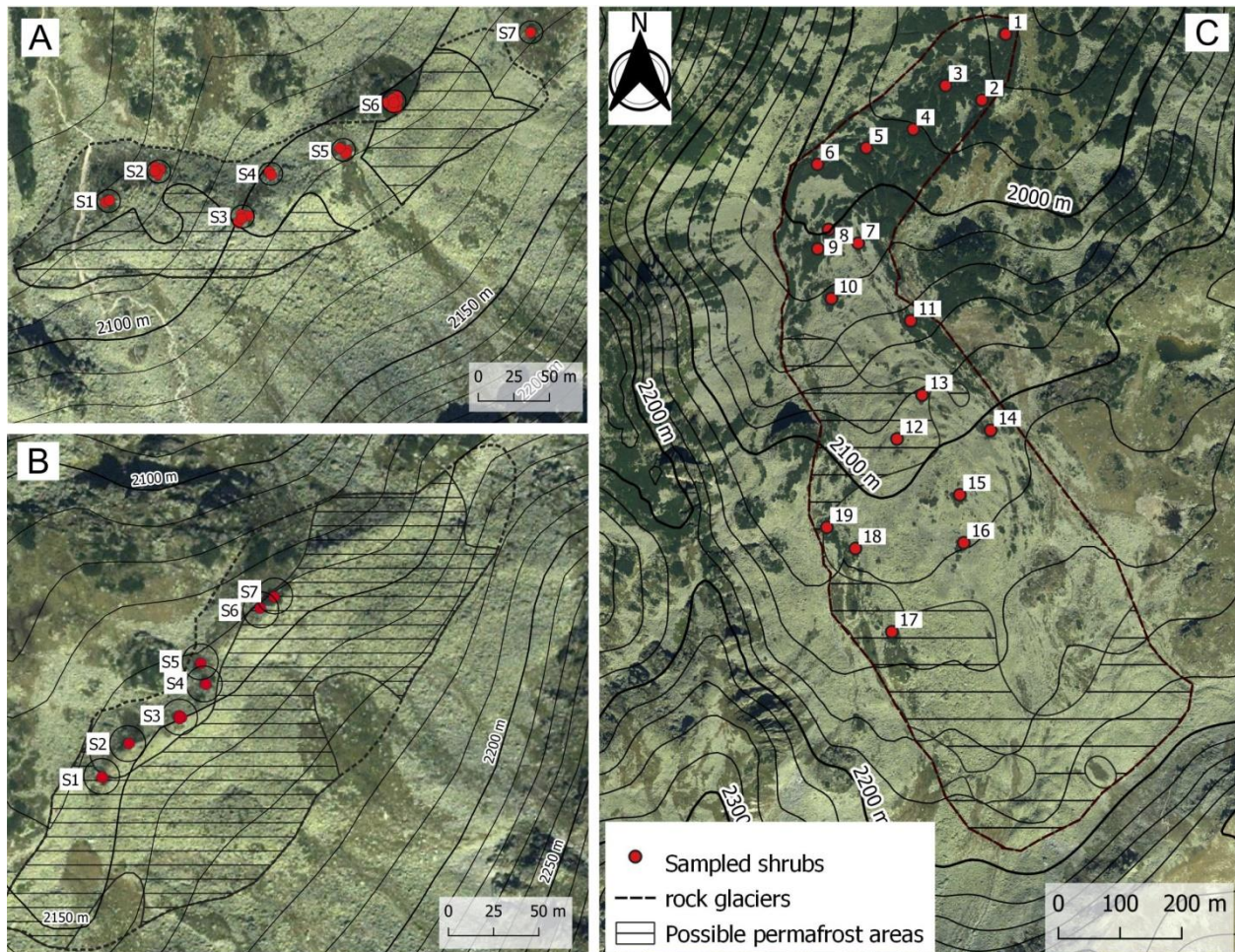


Figure 2 Location of sampled shrubs. In Pietrele 2 (A) and Pietricele (B) rock glaciers *P. mugo* shrubs were only located on rock glaciers fronts. In Valea Rea rock glacier (C) samples were collected on a transect from the lower to the upper part. The possible permafrost areas are determined by BTS measurements in 2011 (A and B) and 2013 (C)

150 years, five are older than 100 years, and six are older than 98 years (Figs. 4 and 5A). Only the one outside the rock glacier area is very young, of only 14 years. The shrubs and the sampling sites are distributed across the entire rock glacier front. In Pietricele rock glacier front, the samples are located in 2132-2150 m asl altitudinal interval, and one sample is older than 150 years, two are older than 100 years, and five out of seven are older than 50 years. The shrubs are only located on 2/3 of the entire rock glacier front length, while the remaining 1/3 is shrubs free (Figs. 2B și 3B). The distribution of values indicates a moderate tendency of shrub age decrease towards the northeast (Fig. 5B). In the Valea Rea rock glacier, the pattern of shrubs vegetation is represented by large cover in the lower terminal sector (2000-1950 m), with relatively low shrubs

vegetation mostly on ridges (1980-2140) only herbaceous vegetation above. The shrubs sampled are located between 1955 and 2133 m asl. The results indicate that two shrubs are older than 150 years, 11 are older than 100 years, 18 are older than 50 years, and only two are younger than 50 years. There is no spatial tendency of the age distribution. Comparing the entire data recovered from rock glaciers, age clustering at around 100 years with a larger number of cases towards higher ages can be observed (Fig. 5C). The reference shrubs are located at altitudes between 1790 and 1885 m asl and have, in general, younger ages in comparison to rock glaciers. They are clustered between 30-50 years old, but several shrubs are also old and comparable to those found on rock glaciers (Fig. 5D). The mean annual growth rate of shrubs located on the Valea Rea rock glacier

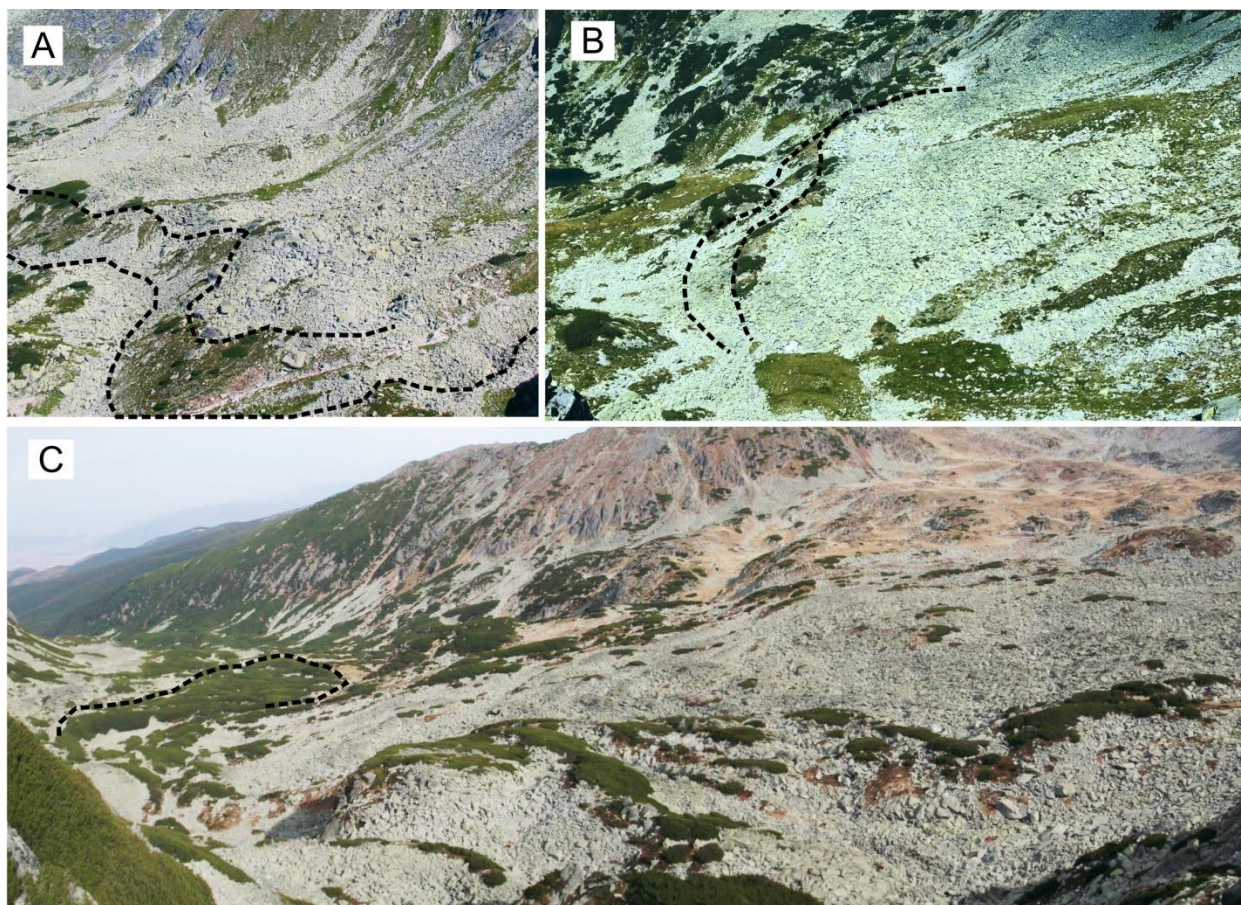


Figure 3 The three rock glaciers investigated by dendrochronological analysis with the terminal fronts delineated. Pietrele 2 (A), Pietricele (B) and Valea Rea (C- photo: Daniela Pascal, 2017)

is between 137 and 705 $\mu\text{m}/\text{year}$, and on the reference sites, it is between 205 and 1250 $\mu\text{m}/\text{year}$. There is a moderate to high correlation between growth rates and ages, with the older shrubs having lower values than the younger ones (Fig. 6). 63% of growth rates variability is related to shrubs' age.

4.2 Rock glaciers vegetation cover and its recent changes in Retezat Massif

An inventory comprising 82 rock glaciers from Retezat was used to analyze the vegetation cover and type visually. Six rock glaciers classes were distinguished (Fig. 7) and are described below.

1) Type 1 (e.g., Lower Ciulfu Mic) rock glaciers are mostly covered with shrubs, but also trees can be found on their surface (16 rock glaciers);

2) Type 2 (e.g., Lower Ana) rock glaciers have densely shrub/grass-covered fronts and moderate shrub/grass cover on the rest of their surface (29 rock glaciers);

3) Type 3 (e.g., Pietrele) rock glaciers have (quasi)continuous shrub-covered fronts and sparse shrubs/grass patches on the rest of their surfaces (13 rock glaciers);

4) Type 4 (e.g., Judele) rock glaciers present sparse grass- and/or shrubs on their fronts, absent or very sporadic shrubs/grass on the rest of their surface are possible (11 rock glaciers);

5) Type 5 (e.g., Știrbu 2) rock glaciers with continuous grass-covered fronts, no shrubs, and insignificant grass areas on the rest of their surfaces (6 rock glaciers);

6) Type 6 (e.g., Galeșu) rock glaciers with sparse to absent grass on front and sparse to absent grass on the rest of their surfaces (7 rock glaciers).

The large majority of rock glaciers present *P. mugo* shrubs on their surface (the lower ones on almost their entire surface) shrubs coverage decreasing with altitude. Rock glaciers vegetation cover variation can be explained by the altitude chan-

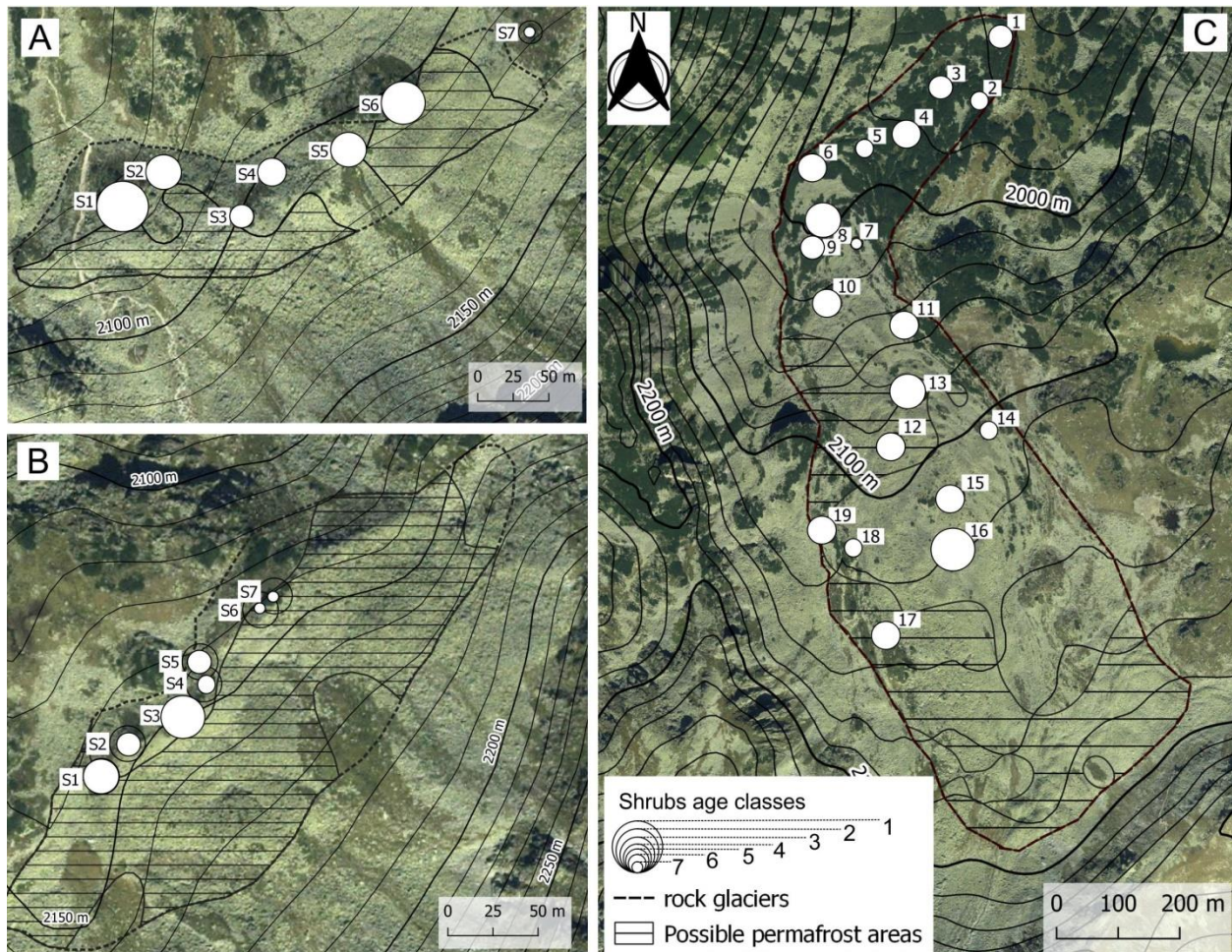


Figure 4 Shrubs age distribution at the studied rock glaciers. A - Pietrele 2; B - Pietricele; C - Valea Rea. Age classes in years are: 1 - >175; 2 - 151-175; 3 - 126-150; 4 - 101-125; 5 - 76-100; 6 - 51-75; 7 - <50

ge in proportion of 59% as revealed by the analysis of 40 rock glaciers (Fig. 8), simultaneously with MAAT decrease, snow cover persistence and wind intensity increase. The vegetation cover of more than 70% of the rock glacier surface can be found close to 1700 m asl, while less than 5% is encountered above 2150 m asl. The data are pretty scattered from the tendency line, especially at lower altitudes. For example, one rock glacier from about 1890 m asl has less than 28% vegetation cover, and another rock glacier as high as 2150 has nearly 80%. Other controlling factors that account for the rest 41% should be related to exposition that influences the input of solar radiation, debris size properties and availability of fines that allow plants to take roots but also the geomorphological processes that impede vegetation growth: snow avalanches, debris flows, rockfalls and debris dynamics (via rock glacier creep

and or dry creep). Quantifying the shrubs cover from krummholz is possible (Müllerová, 2005) as they have a higher contrast with the boulder mantle of rock glaciers from Retezat, while smaller shrubs and herbaceous vegetation areas need to be assessed with higher resolution images with better contrast.

The analysis of vegetation changes using old aerial imagery in the period between 1968-1980 and 2012 revealed that patches of *P. mugo* are relatively easy to distinguish from other land cover types, while grass cannot be separated from scree in most cases. Several rock glaciers from 1720 to 2130 m asl and from 1960 and 2180 m asl on the northern/southern slopes are presented (Figs. 9 and 10). In some cases, no identifiable modifications occurred (Figs. 9B, D; and 10B), while in other cases, the shrub areas increased their vegetation density but not their surface (Figs. 9A, C, and 10A, C). Only in one case stu-

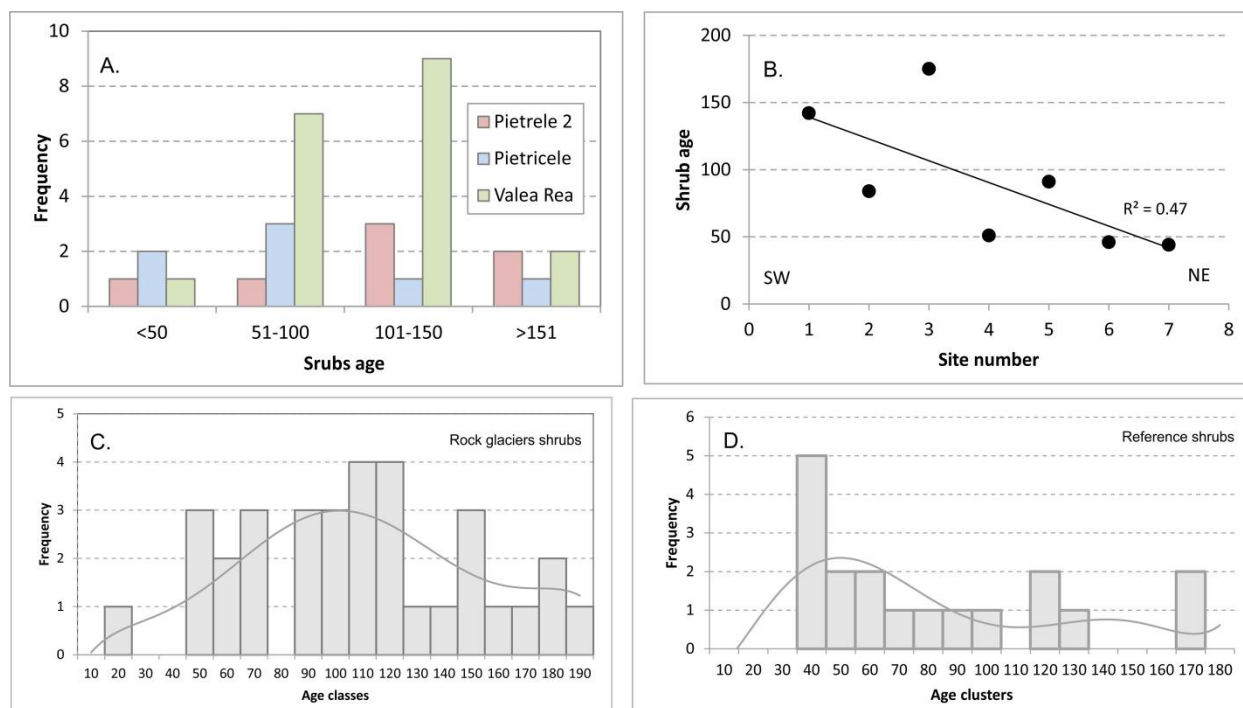


Figure 5 Statistic distribution of shrub ages on each rock glacier (A); the shrub age variation on the Pietricele rock glacier front from south-west to north-east (B); the absolute frequency of shrub ages on all rock glaciers classes (C) and on the reference sites (D); on the last two plots, the polynomial curve of 6th grade is added

dy was distinguishable the increase of shrubs area by the growth of new *P. mugo* small islands (Fig. 10A). In another place, we identified the first appearance of two trees within a compact shrub cover of *P. mugo* downhill the rock glacier front (Fig. 9A). For the Pietrele rock glacier, the current vegetation surface was compared with the one from more than 100 years ago using an old picture taken from Bucura pass (de Martonne, 1907). Across the rock glacier, the vegetation patches are at the same positions, but their extent seems smaller than in the present (Fig. 11). This is also visible at the rock glacier from 1950 m asl with the eastward exposition. In the background, on the steep slopes below the Stânișoara and Retezat peaks both the shrubs density and area seem to have increased considerably.

5. Discussion

5.1. Rock glaciers vegetation in Retezat Massif

Vegetation can be used as an indicator for rock glaciers activity and permafrost occurrence (Ikeda and Matsuoka, 2002). It is a good marker also for the activity of periglacial processes in high-altitude

mountains (Nedelea et al., 2012; Munteanu et al., 2012; Săndulache et al., 2015). Based on previous investigations in Retezat Massif, at type 1 rock glaciers permafrost is improbable, at type 2 permafrost is possible only at the rock glacier-talus slope contact but it is more a consequence of ground air circulation inside the talus slope, at type 3 rock glaciers permafrost is probable only at certain areas; at type 4-6 rock glaciers, permafrost is probable on almost the entire surface excluding the grass island (Vespremeanu-Stroe et al., 2012; Onaca et al., 2015; Popescu et al., 2017). According to vegetation indices, the 6th type rock glaciers are the only ones where permafrost creep could be likely. Their structure represented by numerous creep lobes with prominent ridges indicates a relatively fresh morphology even though lichens colonize all the exposed blocks except those located in depressions where snow persists more than 9 months/year (Burga et al., 2004). Rock glaciers from types 1-2 can be considered totally relict; types 3-5 could be considered pseudorelict (Onaca et al., 2017), and type 6 could be inactive. The latter seems to be of a younger chronological phase and with a morphology

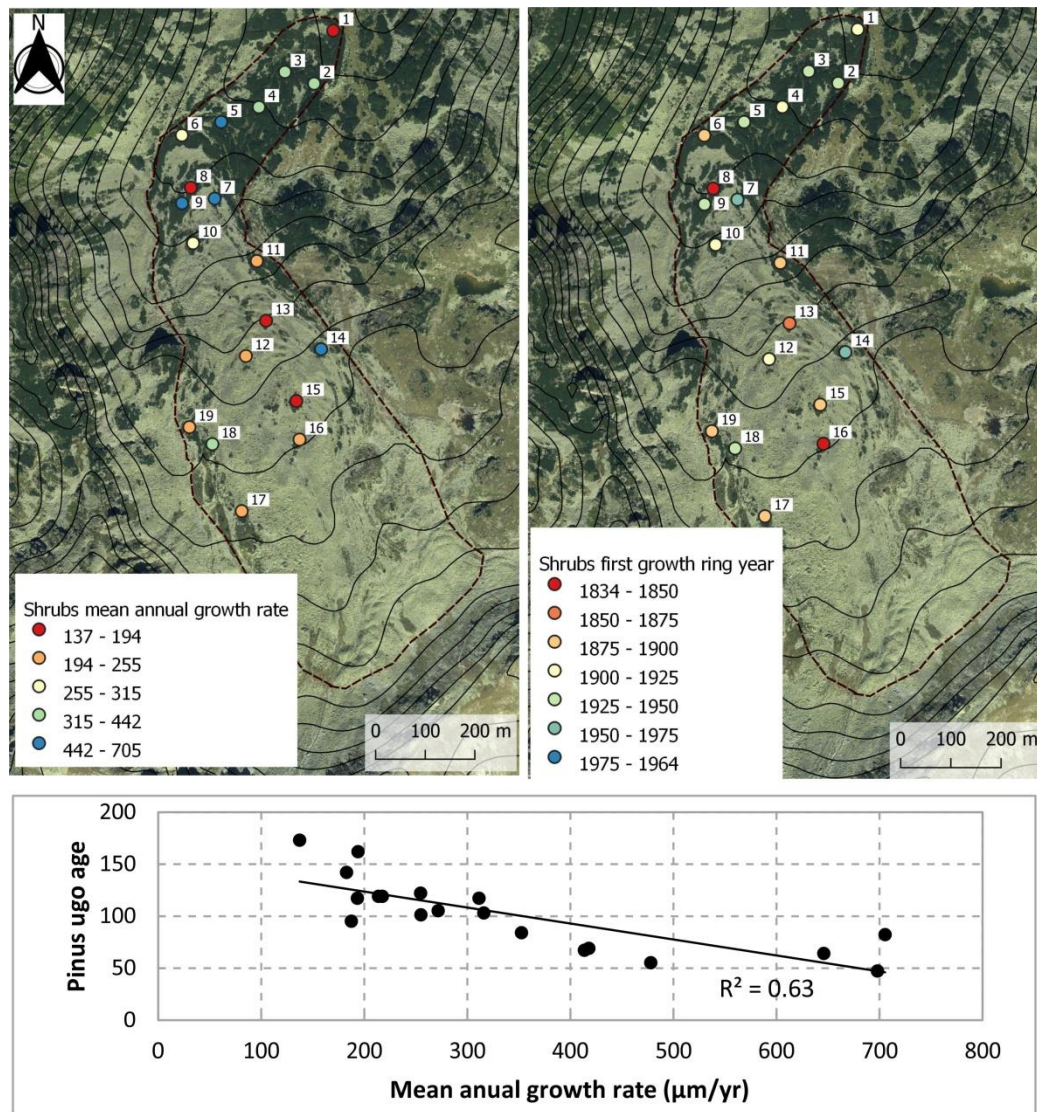


Figure 6 Mean annual growth rate and age of *P. mugo* from Valea Rea rock glacier along with the linear regression between the two parameters

that was probably more recently inactivated. Yet, age dating (relative and absolute) should be applied to distinguish between several generations of rock glaciers and verify this hypothesis.

5.2. Vegetation growth and changes in relation to rock glacier activity

Both Pietrele 2 and Pietricele rock glaciers belong to type 4 in terms of vegetation cover, presenting sporadic shrubs and grass on their frontal slopes and on the interior surface (Figs. 2, 3). Valea Rea rock glacier is a complex landform with progressive vegetation cover diminishing from its terminal front (1950 m asl) to its upper part (almost 2200 m asl) but

overall can be included in a type 3 rock glacier (Fig. 2).

Modern climate change causes the vegetation belts to increase in altitude and to decrease the intensity of periglacial processes that in turn allows a denser and wider vegetation cover. Rock glaciers are landforms restrictive to economic activities like grazing being less exposed to clearcutting. Thus vegetation colonization at these sites is impeded mainly by geomorphologic processes and climatic conditions. The oldest *P. mugo* shrubs from the three investigated rock glaciers date back to 1830-1839 and those from the reference areas date back to 1840 and 1888. The ages distribution indicates quasisynch-

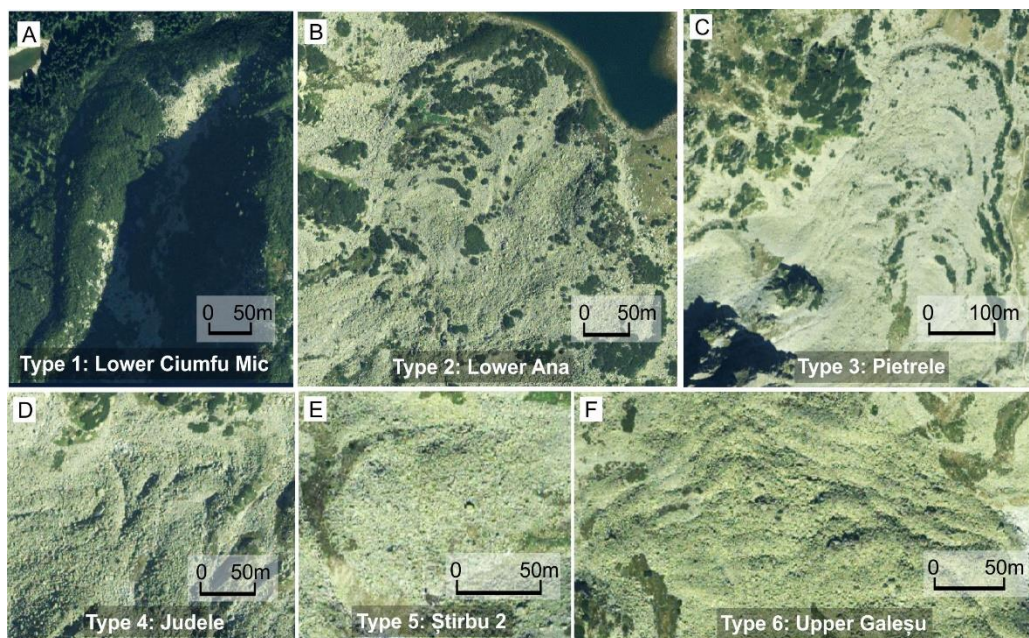


Figure 7 Rock glacier types in Retezat massif according to vegetation cover

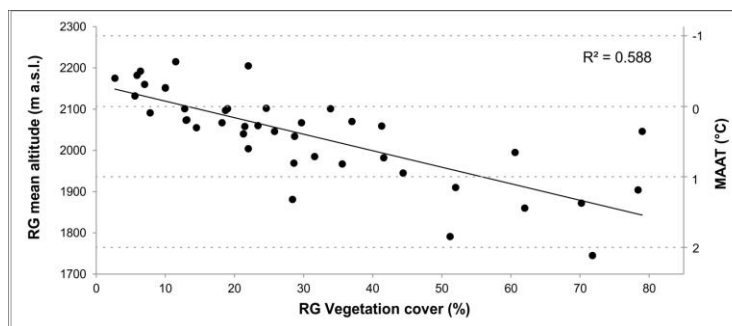


Figure 8 Rock glaciers vegetation cover, both shrubs and grass, in relation to their mean altitude

ronous colonization at Pietrele 2 and Valea Rea and relatively progressive colonization from SW to NE at Pietricele, where the northeastern most sector of the front is vegetation-free. Two scenarios can explain the shrub ages distribution and will be discussed below.

(1) In the climate influence scenario, the climate warming after the local Little Ice Age (LIA) allowed for the expansion of shrubs at higher altitudes starting with 1830 AD. A dendroclimatological study carried on in the Romanian Carpathians (Călimani Mountains) revealed that LIA last cold episode manifested between 1820-1840 AD after a long climate phase between 1370 and 1630 AD (Popa and Kern., 2009). In this case, rock glaciers were active in Late Glacial and probably early Holocene and stable

during most of Holocene, and only the moderate climate variations (e.g. LIA, Medieval Warm Period) could influence the *P. mugo* limit changes besides anthropic impact that is considered negligible on rock glaciers. The shrubs' age distribution pattern of the Valea Rea rock glacier supports this scenario.

(2) In the rock glacier movement scenario, the three rock glaciers were active in LIA and became inactive in the post-LIA period as a consequence of climate warming and subsequent permafrost degradation. That allowed the vegetation installation on the now stable rock glacier terminal fronts and internal creeping lobes. This is supported by the shrubs decreasing ages on Pietricele rock glacier front towards NE, but only if the northernmost sector would be active today, which doesn't seem to be the case considering the stable and weathered boulders

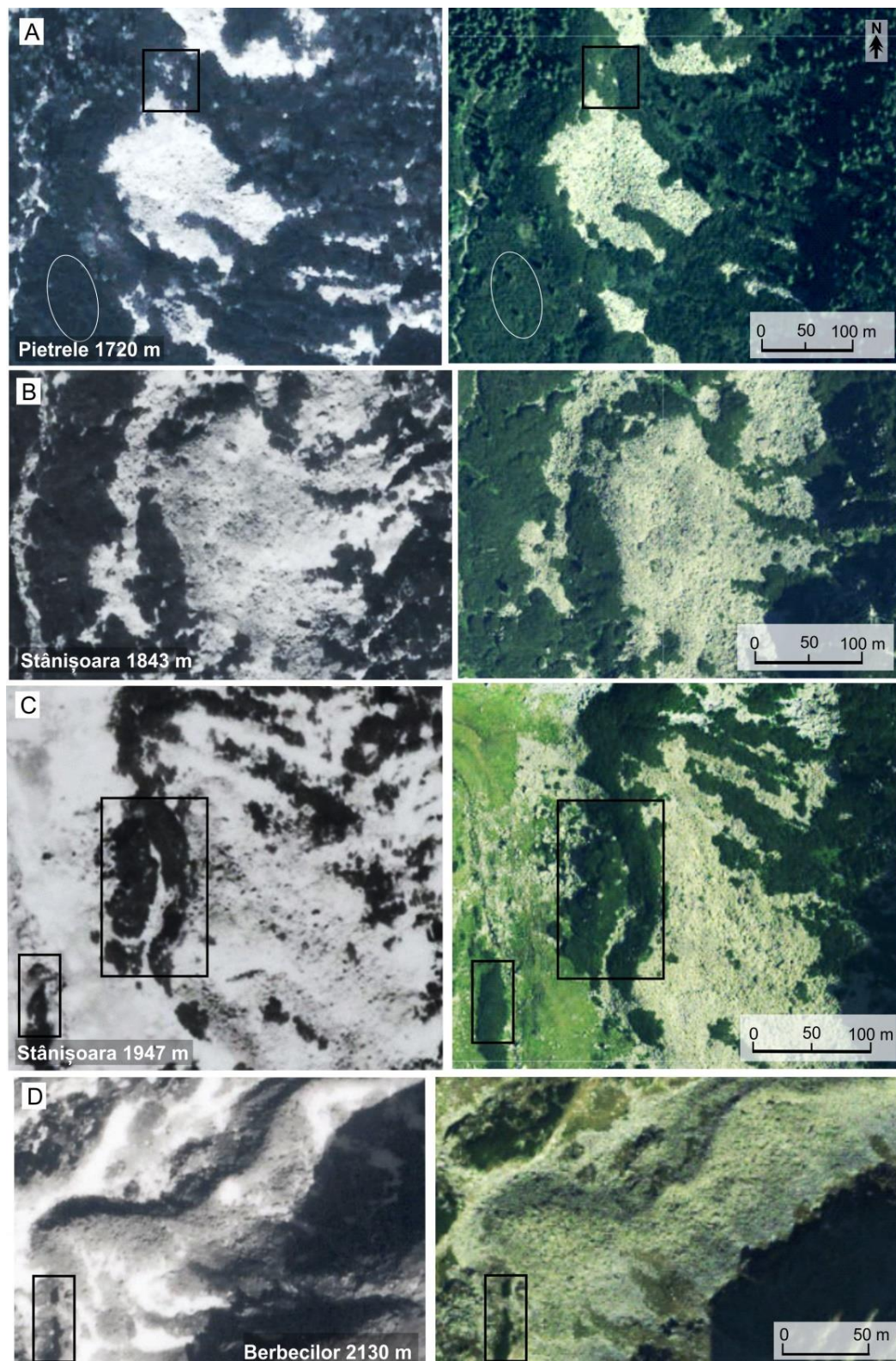


Figure 9 Vegetation changes on rock glaciers with northern aspects by comparing aerial imagery from 1968-1980 (left) and 2012 (right). The black rectangles indicate areas of increasing vegetation density. The old aerial imagery is the property of the National Center of Cartography (former IGFCOT) and was kindly provided by prof. M. Geanana (personal collection). The new images are the property of National Agency for Cadastre and Land Registration of Romania (ANCPI)

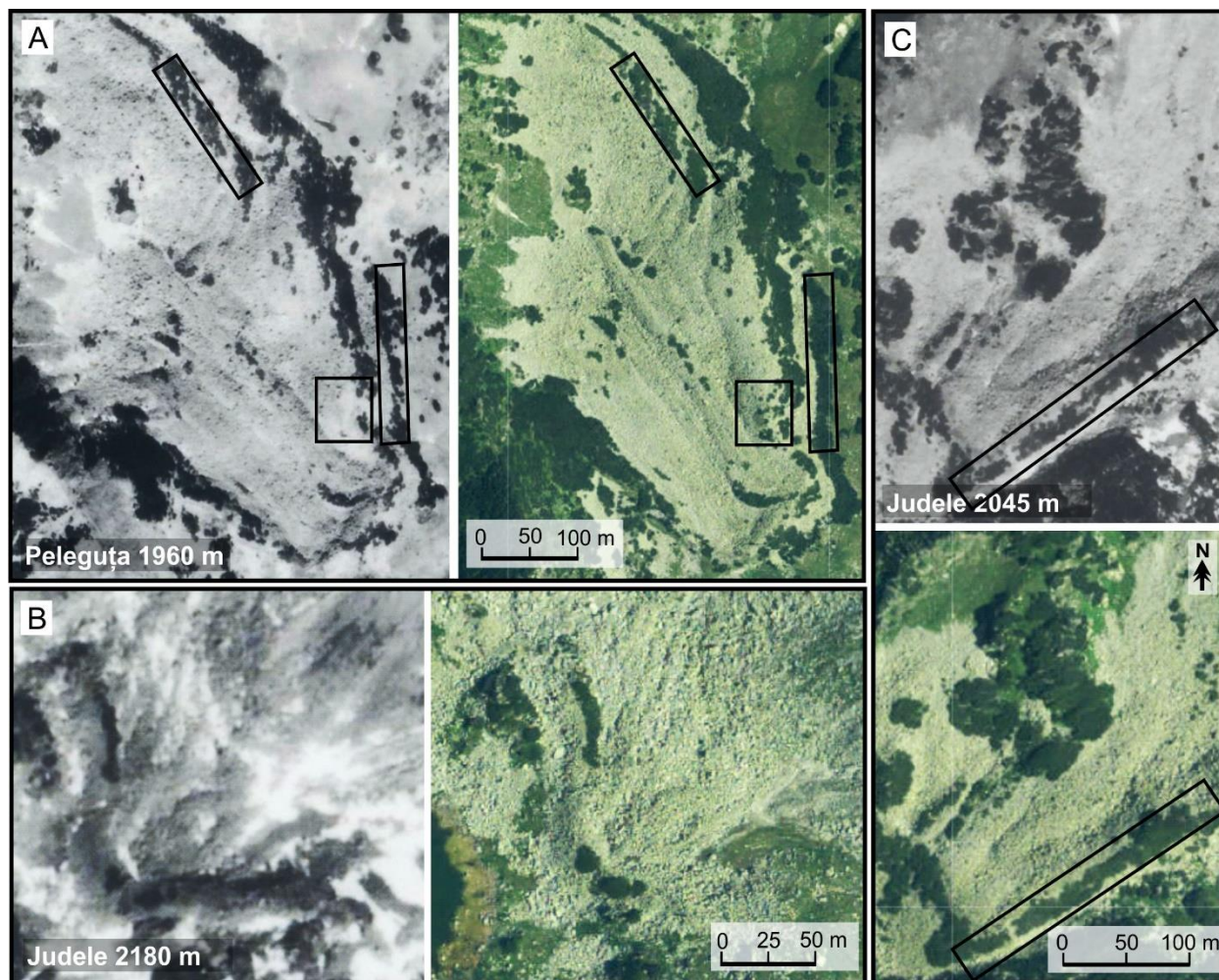


Figure 10 Vegetation changes on rock glaciers with southern aspects. The black rectangles indicate areas of increasing vegetation density and the appearance of new bushes (only on A). The old aerial imagery is the property of the National Center of Cartography (former IGFCOT) and were kindly provided by prof. M. Geanana (personal collection). The new images are the property of National Agency for Cadastre and Land Registration of Romania (ANCP)

even from this sector. This assumption is based on the fact that climate warming is immediate while the rock glacier dynamics decreasing response is delayed. This hypothesis was supported by Urdea (1998) that revealed a trend of decreasing ages of *P. mugo* from the main front inwards in the upper part of Pietrele rock glacier. In the south-eastern part of the rock glacier, the author indicates values from 137, 96, and 80 years old shrubs on three different set of ridges and 125 years in the central longitudinal ridge. That would correspond to 1860, 1901, and 1917 AD as years of shrubs development at these sites if we consider 1997 as the reference year. In Stânișoara Valley, the same author indicated the oldest shrubs developing at rock glacier/protalus rampart fronts

from 2130/2190 m asl in 1857 AD and 1895 AD, respectively interpreted similarly as a result of the progressive cessation of permafrost creep with altitude followed by subsequent shrubs colonization. If we assume an average lapse rate of $0.6\text{ }^{\circ}\text{C}/100\text{ m}$ and a $-0.5\text{ }^{\circ}\text{C}$ MAAT from Țarcu Mountain meteorological station to be valid for Retezat at 2180 m asl, in that case, the rock glaciers investigated in this study and those of Urdea (1998) would have a MAAT at their front of $-0.6\text{...}+0.9\text{ }^{\circ}\text{C}$. The necessary regional (average) MAAT for relict rock glaciers to be active was calculated to be $-1.6\text{...}-3.3\text{ }^{\circ}\text{C}$ in different mountain regions in Switzerland, even though local differences can be encountered (Frauenfelder and Kääb, 2000). Also, Haeberli (1985) indicated that acti-

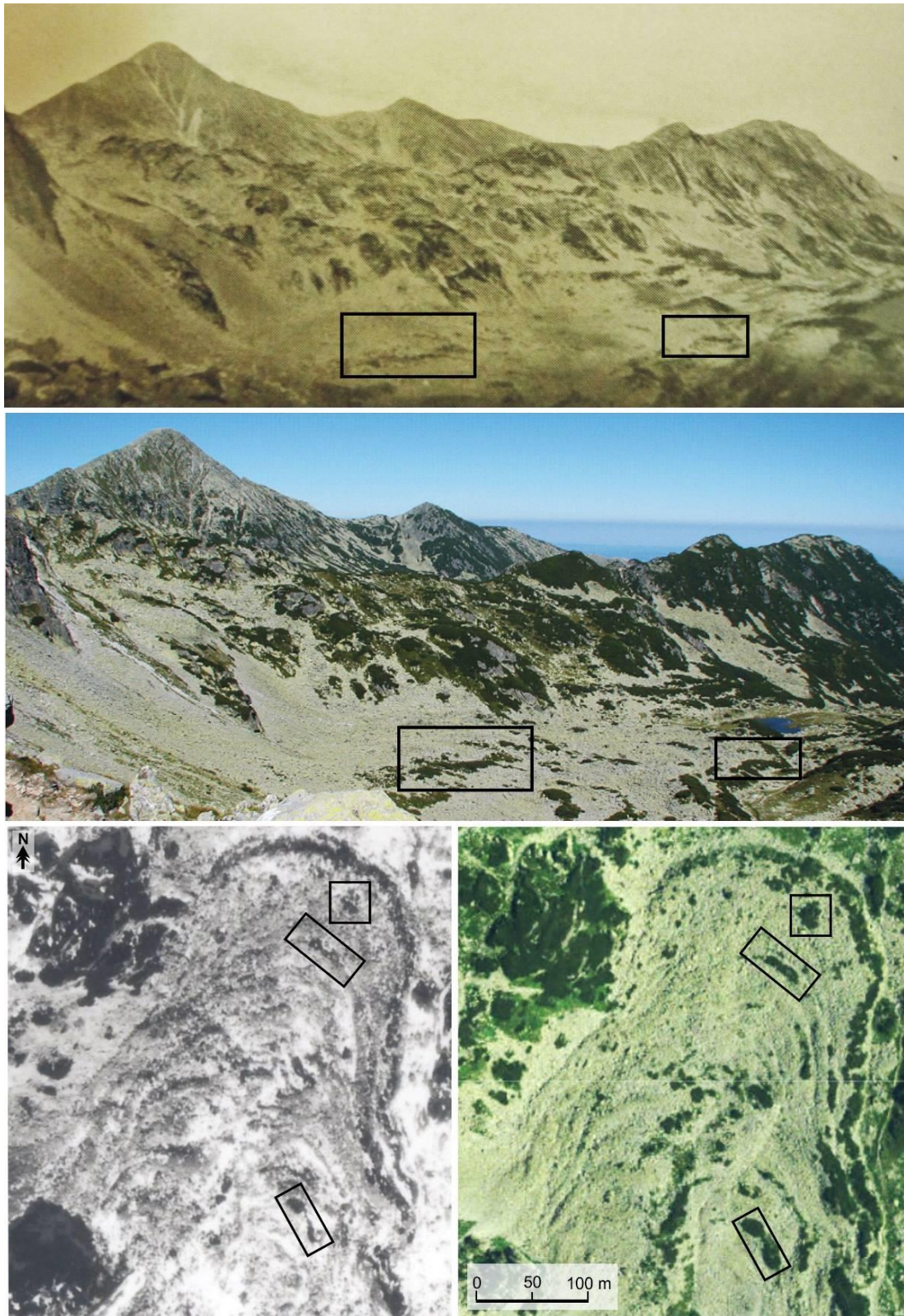


Figure 11 Vegetation changes on Pietrele rock glacier from 1907 to 2012 and from 1968-1980 to 2012. The black rectangles indicate areas of increasing vegetation density. The old picture of Pietrele rock glacier (up) is from de Martonne (1907)

ve rock glaciers typically lie above the MAAT isotherm of -2°C . Considering the relatively dry alpine climate of Southern Carpathians, it is expected that Retezat rock glaciers needed MAAT rather closer to -3°C . Thus, the temperature lowering of several degrees Celsius needed to allow rock glacier activity would then have been possible only in Late Glacial and Early Holocene (before 11.1 ka and during 8.2 ka cold event) as LIA climate conditions were insufficiently cold. However, Necşoiu et al. (2016) revealed that Pietrele rock glacier is active in the upper part and Judele rock glaciers is active on its entire surface with very low creep rate of a few cm per year. This is a much weaker dynamics, typical for marginal permafrost conditions, in comparison to what is traditionally considered an activity for a rock glacier, movement of a few tens of cm and m per year (e.g. Serrano et al., 2006) besides the recent rock glaciers acceleration caused by climate change (Kääb et al., 2021). In that case, shrubs growing seem possible in spite of small boulders movement. Suppose the permafrost creep was more intense in comparison to the recently discovered values as a consequence of colder LIA climate. In that case, it might be possible that the rock glacier movement scenario is valid for explaining the shrubs age distribution at the six investigated landforms. Recent studies indicate indirectly that climate was milder than at present in 8-3.2. ka BP as indicated by timberline at least 50 m higher than today at lake Lia in Retezat (Vincze et al., 2017). The fact that *P. mugo* ages are higher on rock glaciers despite of the more difficult conditions indicates the anthropic activity that manifested already beginning with 2.2 ka BP as indicated by the above mentioned study. This could also be the case for the lower, highly vegetated part of Valea Rea rock glacier. In any case, the Valea Rea shrubs age distribution presented in this study does not support a progressive upwards cessation of permafrost creep even though the conditions of this rock glacier are ideal (high altitudinal range of almost 250 m and numerous creep lobes systems that could move independently) for illustrating such a scenario. Based on the presented arguments, we incline more to the first scenario but the second scenario cannot be excluded. Future investigation like age dating of

landforms should give a clearer picture of the rock glaciers' past evolution.

The vegetation changes from 1907 to the present indicate the vegetation expansion of *P. mugo* on steep mountain slopes. However, on rock glacier ridges, the *P. mugo* was already in place more than a hundred years ago, but it increased its surfaces since. In the period between 1968-1980 and 2012, the rock glaciers shrubs seem to have increased the density and only sporadically it has colonized new debris areas across rock glaciers, which proves that vegetation colonization on rock glaciers was at its maximum immediately after LIA (1840-1880) or at the end of the 19th and first half of the 20th centuries. The tendency of *P. mugo* area growth is natural in the context of climate change even though in the Carpathians the clearcutting surpasses the shrubs' natural expansion (Roşca et al., 2019). In this context rock glaciers shrubs seem to be more useful in climate reconstruction than shrubs from surrounding areas.

6. Conclusions

In this study, rock glacier shrubs vegetation cover, the timing of colonization, and vegetation cover changes from the last century were investigated in Retezat Mountains. The following conclusions could be drawn:

- At all the three investigated rock glaciers, the earliest period of *Pinus mugo* colonization correspond to the fourth decade of the 19th century, matching probably the end of the last cold spell of Little Ice Age;
- The frequency of very old shrubs (>150 years) is much higher on rock glaciers in comparison to the reference areas indicating a probable less anthropic to non-existent impact on the former;
- Rock glaciers' vegetation cover increases with altitude, and it has changed slightly after 1907 AD, mainly by increasing vegetation density and slightly increasing the surfaces of existing patches. New islands of shrubs appeared only rarely on rock glaciers. Six types of rock glaciers were classified based on their vegetation cover that has relevance for potential permafrost content evaluation and activity status inferences;

- It is still debatable whether vegetation colonization of rock glaciers was caused by post LIA climate warming or by rock glacier inactivation. Our results indicate rather the first scenario as more probable as the vegetation growth was relatively

synchronous on the largest rock glacier from Romanian Carpathians. That invalidates the possibility of progressive inactivation of several creeping lobes that should have caused the gradual vegetation settling.

Acknowledgements

The research financing these results received funding from the Norway Grants 2014-2021 (project code RO-NO-2019-0415 / contract no. 30/2020), title "*The response of climate-sensitive environments to global warming, sea-level rise and increasing extremes: the Carpathians and Danube delta*".

References

- Ardelean AC, Onaca AL, Urdea P, Șerban RD, Sirbu F. 2015. A first estimate of permafrost distribution from BTS measurements in the Romanian Carpathians (Retezat Mountains). *Géomorphologie: relief, processus, environnement* **21**(4): 297–312. DOI: 10.4000/geomorphologie.11131
- Bálint M, Ujvárosi L, Theissinger K, Lehrian S, Mészáros N, Pauls SU. 2011. The Carpathians as a major diversity hotspot in Europe. In *Biodiversity hotspots* (pp. 189–205). Springer, Berlin, Heidelberg. DOI: 10.1007/978-3-642-20992-5_11
- Berza T, Dimitrescu R, Dimitrescu M, Tatu M, Strusievicz OR, Pop G, Szasz L, Popescu G. 1989. *Harta Geologică* 1:50.000, 105 D Retezat, L-34-94-D, Institutul de Geologie și Geofizică.
- Burga CA, Frauenfelder R, Ruffet J, Hoelzle M, Kääb A. 2004. Vegetation on Alpine rock glacier surfaces: a contribution to abundance and dynamics on extreme plant habitats. *Flora-Morphology, Distribution, Functional Ecology of Plants* **199**(6): 505–515. DOI: 10.1078/0367-2530-00179
- Cannone N, Gerdol R. 2003. Vegetation as an ecological indicator of surface instability in rock glaciers. *Arctic, Antarctic, and Alpine Research* **35**(3): 384–390. DOI: 10.1657/1523-0430(2003)035[0384:VAAEIO]2.0.CO;2
- Cannone N, Piccinelli S. 2021. Changes of rock glacier vegetation in 25 years of climate warming in the Italian Alps. *Catena*, **206**, 105562. DOI: 10.1016/j.catena.2021.105562
- Dai L, Palombo C, Van Gils H, Rossiter DG, Tognetti R, Luo G. 2017. Pinus mugo krummholz dynamics during concomitant change in pastoralism and climate in the Central Apennines. *Mountain Research and Development* **37**(1): 75–86. DOI: 10.1659/MRD-JOURNAL-D-14-00104.1
- de Martonne E. 1907. Recherches sur l'évolution morphologique des Alpes de Transylvanie (Karpates méridionales) (Vol. 1). *Revue de Géographie Annuelle*, Paris I (1906–1907).
- Fleischer F, Haas F, Piermattei L, Pfeiffer M, Heckmann T, Altmann M, Rom J, Stark M, Wimmer M, Pfeifer N, Becht M. 2021. Multi-decadal (1953–2017) rock glacier kinematics analysed by high-resolution topographic data in the upper Kaunertal, Austria. *The Cryosphere* **15**(12): 5345–5369. DOI: 10.5194/tc-15-5345-2021
- Franklin RS. 2013. Growth response of the alpine shrub, *Linanthus pungens*, to snowpack and temperature at a rock glacier site in the eastern Sierra Nevada of California, USA. *Quaternary international* **310**: 20–33. DOI: 10.1016/j.quaint.2012.07.018
- Frauenfelder R, Kääb A. 2000. Towards a palaeoclimatic model of rock-glacier formation in the Swiss Alps. *Annals of Glaciology* **31**: 281–286. DOI: 10.3189/172756400781820264
- Gärtner-Roer I, Heinrich I, Gärtner H. 2013. Wood anatomical analysis of Swiss willow (*Salix helvetica*) shrubs growing on creeping mountain permafrost. *Dendrochronologia* **31**(2): 97–104. DOI: 10.1016/j.dendro.2012.09.003
- Haeberli W. 1985. Creep of mountain permafrost: internal structure and flow of alpine rock glaciers. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie an der Eidgenössischen Technischen Hochschule Zürich*, **77**.
- Holmes RL. 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull.* **43**: 69–75.
- Ikeda A, Matsuoka N. 2002. Degradation of talus-derived rock glaciers in the Upper Engadin, Swiss Alps. *Permafrost and Periglacial Processes* **13**(2): 145–161. DOI: 10.1002/ppp.413
- Jones DB, Harrison S, Anderson K, Whalley WB. 2019. Rock glaciers and mountain hydrology: A review. *Earth-*

- Science Reviews* **193**: 66–90. DOI: 10.1016/j.earscirev.2019.04.001
- Kääb A, Strozzì T, Bolch T, Caduff R, Trefall H, Stoffel M, Kokarev A. 2021. Inventory and changes of rock glacier creep speeds in Ile Alatau and Kungöy Ala-Too, northern Tien Shan, since the 1950s. *The Cryosphere* **15**: 927–949. DOI: 10.5194/tc-15-927-2021
- Kellerer-Pirklbauer A, Pauritsch M, Winkler G. 2015. Widespread occurrence of ephemeral funnel hoarfrost and related air ventilation in coarse-grained sediments of a relict rock glacier in the Seckauer Tauern range, Austria. *Geografiska Annaler: Series A, Physical Geography* **97**(3): 453–471. DOI: 10.1111/geoa.12087
- Kiss I, Alexa V. 2015. Ecological restoration activities for long-term preservation of the alpine and sub-alpine habitats in the Retezat National Park. *TÁJÖKOLÓGIAI LAPOK*, **13**(1): 33–43.
- Mărgărint MC. 2010. *Utilizarea teledetecției în studiul geografic al teritoriului județului Iași*. Editura Universității "Alexandru Ioan Cuza", Iași. 301 p.
- Micu DM, Dumitrescu A, Cheval S, Birsan MV. 2016. *Climate of the Romanian Carpathians*. Springer, Cham. DOI: 10.1007/978-3-319-02886-6
- Mîndrescu M, Evans IS. 2014. Cirque form and development in Romania: Allometry and the buzzsaw hypothesis. *Geomorphology* **208**: 117–136. DOI: 10.1016/j.geomorph.2013.11.019
- Munteanu A, Comănescu L, Nedelea A. 2012. Altitudinal Zonation of the Morphodynamic Processes in the Piatra Craiului Mountains (The Carpathians, Romania). Case Study: Cheii de sub Grind and Șpirlea Valleys. *Revista de Geomorfologie* **14**: 95–102
- Müllerová J. 2005. Use of digital aerial photography for sub-alpine vegetation mapping: A case study from the Krkonoše Mts., Czech Republic. *Plant Ecology* **175**(2): 259–272. DOI: 10.1007/s11258-005-0063-3
- Necșoiu M, Onaca A, Wigginton S, Urdea P. 2016. Rock glacier dynamics in Southern Carpathian Mountains from high-resolution optical and multi-temporal SAR satellite imagery. *Remote sensing of environment* **177**: 21–36. DOI: 10.1016/j.rse.2016.02.025
- Nedelea A, Munteanu A, Oprea R, Comănescu L, Dobre R. 2011. Cryo-nival modeling system. Case study: Făgăraș and Piatra Craiului Mountains. *Revista de Geomorfologie* **13**: 83–90
- Onaca AL. 2017. *Procese și forme periglaciare din Carpații Meridionali: abordare geomorfologică și geofizică*. Editura Universității de Vest, Timișoara. 265 p.
- Onaca A, Ardelean AC, Urdea P, Ardelean F, Sîrbu F. 2015. Detection of mountain permafrost by combining conventional geophysical methods and thermal monitoring in the Retezat Mountains, Romania. *Cold Regions Science and Technology* **119**: 111–123. DOI: 10.1016/j.coldregions.2015.08.001
- Onaca A, Ardelean F, Urdea P, Magori B. 2017. Southern Carpathian rock glaciers: Inventory, distribution and environmental controlling factors. *Geomorphology* **293**: 391–404. DOI: 10.1016/j.geomorph.2016.03.032
- Pearl JK, Keck JR, Tintor W, Siekacz L, Herrick HM, Meko MD, Pearson CL. 2020. New frontiers in tree-ring research. *The Holocene* **30**(6): 923–941. DOI: 10.1177/0959683620902230
- Palombo C, Lasen C, Scire M, Garfi V, Lombardi F, Tognetti R, Marchetti M. 2010. Structural and dendrochronological characterization of mountain pine persistent woodlands on the Monti del Sole: Dolomiti Bellunesi National Park. *L'Italia Forestale e Montana* **65**(6): 737–749.
- Popa I, Kern Z. 2009. Long-term summer temperature reconstruction inferred from tree-ring records from the Eastern Carpathians. *Climate dynamics* **32**(7–8): 1107–1117. DOI: 10.1007/s00382-008-0439-x
- Popescu R. 2018. Permafrost investigations in Iezer Mountains, Southern Carpathians. *Revista de Geomorfologie* **20**(1): 102–122. DOI: 10.21094/rg.2018.033
- Popescu R, Onaca A, Urdea P, Vespremeanu-Stroe A. 2017. Spatial distribution and main characteristics of alpine permafrost from Southern Carpathians, Romania. In *Landform dynamics and evolution in Romania* (pp. 117–146). Springer, Cham. DOI: 10.1007/978-3-319-32589-7_6
- Puşcaş M, Ronikier M, Mráz P, Hurdu BI. 2021. Biogeography of the Carpathians: towards a better understanding of biodiversity patterns. *Plant Systematics and Evolution*, **307**(2): 1–3. DOI: 10.1007/s00606-021-01754-3
- RINNTECH 2021. Technology for wood and tree analysis. <http://www.rinntech.de/index-28703.html>. Accessed 11 December 2021
- Roșca S, Șimonca V, Bilașco Ș, Vescan I, Fodorean I, Petrea D. 2019. The assessment of favourability and spatio-temporal dynamics of Pinus mugo in the Romanian Carpathians using GIS technology and landsat images. *Sustainability*, **11**(13): 3678. DOI: 10.3390/su11133678

- Ruszkiczay-Rüdiger Z, Kern Z, Urdea P, Braucher R, Madarász B, Schimmelpfennig I, ASTER Team. 2016. Revised deglaciation history of the Pietrele-Stănișoara glacial complex, Retezat Mts, southern Carpathians, Romania. *Quaternary International* **415**: 216–229. DOI: 10.1016/j.quaint.2015.10.085
- Ruszkiczay-Rüdiger Z., Kern Z, Urdea P, Madarász B, Braucher R, ASTER Team. 2021. Limited glacial erosion during the last glaciation in mid-latitude cirques (Retezat Mts, Southern Carpathians, Romania). *Geomorphology*, **384**, 107719. DOI: 10.1016/j.geomorph.2021.107719
- Săndulache C, Săndulache I, Grecu F, Dobre R, Irimescu A. 2015. Geomorphological processes within the alpine level of Parâng Mountains. *Revista de Geomorfologie* **17**: 29–44
- Săvulescu I. 2014. *Forest vegetation in Iezer Mountains*. Editura Etnologică, București. 275 p. (in Romanian)
- Scotti R, Brardinoni F, Alberti S, Frattini P, Crosta GB. 2013. A regional inventory of rock glaciers and protalus ramparts in the central Italian Alps. *Geomorphology* **186**: 136–149. DOI: 10.1016/j.geomorph.2012.12.028
- Serrano E, San José JJ, Agudo C. 2006. Rock glacier dynamics in a marginal periglacial high mountain environment: Flow, movement (1991–2000) and structure of the Argualas rock glacier, the Pyrenees. *Geomorphology* **74**(1–4): 285–296. DOI: 10.1016/j.geomorph.2005.08.014
- Șerban RD, Onaca A, Șerban M, Urdea P. 2019. Block stream characteristics in Southern Carpathians (Romania). *Catena* **178**: 20–31. DOI: 10.1016/j.catena.2019.03.003
- Šibík J, Šibíková I, Kliment J. 2010. The subalpine Pinus mugo-communities of the Carpathians with a European perspective. *Phytocoenologia* **40**(2–3): 155–188. DOI: 10.1127/0340-269X/2010/0040-0436
- Stoffel M, Bollschweiler M. 2008. Tree-ring analysis in natural hazards research—an overview. *Nat. Hazards Earth Syst. Sci.* **8**: 187–202. DOI: 10.5194/nhess-8-187-2008
- Stoffel M, Corona C. 2014. Dendroecologic dating of geomorphic disturbance in trees. *Tree-Ring Research* **70**(1): 3–20. DOI: 10.3959/1536-1098-70.1.3
- Tampucci D, Boffa G, Mangili F, Gobbi M, Caccianiga M. 2015. Vegetation outlines of two active rock glaciers with contrasting lithology. *Fitosociologia* **52**(1): 9–18. DOI: 10.7338/pls2015521/02
- Timiș V, Popa I. 2011. Spatial variability of dendrochronological series from Rodna Mountains (Eastern Carpathians–Romania). *Proceedings of the Romanian Academy Series B: Chemistry, Life Science and Geoscience* **1**: 83–86.
- Urdea P. 1998. Considerații dendrogeomorfologice preliminare asupra unor forme periglaciare din Munții Retezat. *Anal. Univ. Craiova, Geografie* vol I: 23–28
- Urdea P. 2000. *Munții Retezat: studiu geomorfologic*. Editura Academiei Române, București. 272 p.
- Vasile M, Vespremeanu-Stroe A, Popescu R. 2014. Air versus ground temperature data in the evaluation of frost weathering and ground freezing. Examples from the Romanian Carpathians. *Revista de geomorfologie* **16**: 61–70
- Vasile M, Vespremeanu-Stroe A. 2017. Thermal weathering of granite spheroidal boulders in a dry-temperate climate, Northern Dobrogea, Romania. *Earth Surface Processes and Landforms* **42**(2): 259–271. DOI: 10.1002/esp.3984
- Vespremeanu-Stroe A, Urdea P, Popescu R, Vasile M. 2012. Rock glacier activity in the Retezat mountains, Southern Carpathians, Romania. *Permafrost and Periglacial Processes* **23**(2): 127–137. DOI: 10.1002/ppp.1736
- Vincze I, Orbán I, Birks HH, Pál I, Finsinger W, Hubay K, Marinova E, Jakab G, Braun M, Biró T, Tóth M, Dănaș C, Ferencz I, Magyari E. 2017. Holocene treeline and timberline changes in the South Carpathians (Romania): Climatic and anthropogenic drivers on the southern slopes of the Retezat Mountains. *The Holocene* **27**(11): 1613–1630. DOI: 10.1177/0959683617702227.