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Rock glacier dynamics in Southern Carpathian Mountains from high-resolution optical and multi-temporal SAR satellite imagery

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ABSTRACT

The dynamics of rock glaciers in marginal periglacial environments are poorly understood, especially in Eastern Europe where the enhanced continentality produces a distinct pattern of periglacial phenomena. Multi-temporal image analysis of high-resolution optical and radar satellite imagery of the Southern Carpathian Mountains, Romania revealed the small dynamic nature and a slow geomorphologic evolution of rock glaciers over a 46-yr period of record (1968–2014). Nine rock glaciers located in glacial cirques and troughs within the central area of Retezat Mountain were included in this study. Overall, the estimated displacement rates are extremely low (i.e., a few cm/year) compared with other active rock glaciers from all over the world. Despite their relative attenuated activity, it appears that Judele, Valea Rea, and Pietrele are still active rock glaciers, but in an evident disequilibrium/imbalance with the actual climate. These findings document the lowest altitude and easternmost active rock glaciers at this latitude from Europe. Quantitative investigations were concentrated on Pietrele rock glacier, subject of recent field campaigns. Optical data analysis indicated a slight acceleration of the horizontal velocities at the surface of Pietrele rock glacier in recent years. This acceleration appears to be caused by an increase in the temperature of permafrost, resulting from an evident warming of external air temperature. Radar data analysis suggested seasonal variability of surface motion, with higher deformation in autumn, whereas in early summer or spring the deformation is negligible. Overall, the results obtained with cross-correlation analysis, interferometric synthetic aperture radar (InSAR) coherence analysis, and Small BAseline Subset (SBAS) multitemporal interferometry, are consistent, displaying similar deformation patterns with the highest creep rates located in the southern and western portions of the glacier. These findings are supported by thermal and geophysical measurements, which suggest the probable presence of permafrost within these areas. The observed displacements were interpreted as permafrost creep, and their very low velocity rates suggest the deforming frozen layers are very thin. These results provide (i) baseline information and decadal-scale trends and a (ii) strategy for future monitoring of the health and integrity of the rock glacier environment in the Carpathian Mountains.

1. Introduction

Permafrost (perennially frozen ground) is defined as ground that remains below 0 °C for at least 2 years (Harris, 1988); hence, it is particularly sensitive to climate change (Haeberli & Hohmann, 2008). Permafrost is present at high altitudes in all major mountain chains around the world (e.g., White, 1981; Gorbunov, 1983; Haeberli, Guodong, Gorbunov, & Harris, 1993; Urdea, 1993; Strozzi, Kääb, & Frauenfelder, 2004).

Contradictory concepts have been formulated regarding the origin of rock glaciers. In the majority of the studies, rock glaciers were described as creeping permafrost masses of rock–ice mixture (Haeberli, 1985; Barsch, 1996; Haeberli & Vonder Mühll, 1996; Bolch & Gorbunov, 2014), whereas several authors state that the rock glaciers may also be related to glaciers in environments where permafrost is missing (Potter, 1972; Whalley & Martin, 1992; Humlum, 1996; Krainer & Mostler, 2000). Recent studies revealed that rock glaciers can develop as transitional landforms because they may incorporate both permafrost and glacier ice (Serrano, de Sanjose, & González-Trueba, 2010; Berthling, 2011; Monnier, Camerlynck, Rejiba, Kinnard, & Galibert, 2013). In either situation, these spectacular tongue-like or lobate creeping bodies are characterized by a distinctive microrelief of ridges and furrows on their upper surface (Barsch, 1996).

Increased recent interest in rock glacier dynamics (Haeberli et al., 2006) is due to the fact that they represent a major portion of the high alpine mass transport system and form an integral part of the landscape (Berthling & Etzelmüller, 2007; Azócar & Brenning, 2010). Rock glaciers are sensitive to climate change, but not as sensitive as true glaciers, because the course debris mantle produces a relative by large thermal inertia of permafrost (Haeberli et al., 2006). However, recent studies highlighted the increased sensitivity of permafrost when

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the temperature of the subsurface is close to 0 °C (Kääb, Frauenfelder, & Roer, 2007). Investigation of rock glacier dynamics contributes to understanding the evolution of permafrost related formations in both space and time, as well as under different climatic conditions (Frauenfelder & Kääb, 2000; Frauenfelder, Haeberli, Hoelzle, & Maisch, 2001). A recent estimate of the global permafrost area (i.e., permafrost area including Antarctic and sub-sea permafrost) was estimated to be 16–21 $\times$ 10^6 km^2, whereas the global permafrost region (i.e., exposed land surface below which some permafrost can be expected) was estimated to be 22 $\pm$ 3 $\times$ 10^6 km^2 (Gruber, 2012). Monitoring rock glacier dynamics is, in most cases, based on quantifying changes of three different components: horizontal velocities, vertical velocities, and the front advance. Horizontal velocity measurements have shown that movement rates are considerably slower (creep-like movement) than those of normal (ice) glaciers, ranging from a few centimeters to a few meters per year (Haeberli, 1985; Whalley & Martin, 1992; Kääb & Vollmer, 2000; Strozzi et al., 2004; Lambiel & Delaloye, 2004; Roer, 2005; Delaloye et al., 2008; Serrano et al., 2010; Liu, Millar, Westfall, & Zebker, 2013). Although most measured rock glacier velocities lay within these limits, there are a few studies reporting unusually fast velocities of up to 100 m/yr, reported by Corte (1987) in the Andes, Gorbunov, Titkov, and Polyakov (1992) in Asia, and Delaloye, Lambiel, and Roer (2010) in the Swiss Alps.

Globally, a large percentage of mountainous areas covered by rock glaciers either have not been surveyed, or the existing ground information is too noisy to derive trends in ground movement. This holds true for the Southern Carpathian Mountains, where field observations of rock glacier dynamics are scarce and do not provide a complete view of rock glacier movement and other processes. Because the permafrost exists in marginal conditions in the Southern Carpathians, specifically in Retezat Mountains (Onaca, Urdea, & Ardelean, 2013), it is important to determine if the autochthonous rock glaciers show the same kind of interannual variations in flow velocity as detected in the European Alps (Haeberli et al., 2006) and elsewhere (e.g., Janke, 2005; Liu et al., 2013).

The overall objective of this study was to quantify subtle landscape changes that are diagnostic of the health of near-surface permafrost of the mountainous environment of Retezat National Park (RNP), Southern Carpathian Mountains, Romania. Specifically, the dynamics of rock glaciers were assessed using complementary remote sensing techniques and satellite imagery acquired over almost half a century. Because field data measurements were only recently available, the study of the similarities and differences between results of the satellite-based techniques and field observations was essential.

2. Site description

The Carpathian Mountains are the most structurally deformed and fragmented mountain chain in Europe. They also are Europe's largest mountain range by area. The Retezat Massif is located in the RNP in the western part of the Southern Carpathians (45°20′N, 22°23′E) (Fig. 1). Urdea (1993) first reported the presence of permafrost in the Southern Carpathians and in the past few years has investigated the extent of permafrost in the Retezat Mountains by means of geophysical surveys (Urdea, Ardelean, Onaca, Ardelean, & Török-Oance, 2008). The high density of rock glaciers in the Retezat Mountains and the existing data on their characteristics, distribution, and internal structure (Urdea, 2000; Urdea et al., 2008) make this mountain range well suited for rock glacier dynamic measurements.

Retezat's landscape was shaped by Pleistocene glaciers and shows a typical alpine morphology with glacial cirques and U-shaped valleys or glacial troughs, well-preserved glacial shoulders and steps, and arêtes with very steep walls. A wide variety of relict and active periglacial landforms can be found above the tree line, including rock glaciers, block streams, scree slopes, talus debris, solifluction lobes and terraces, and earth hummocks. Climatic conditions have favored the occurrence and development of several periglacial phenomena, including 93 local rock glaciers (Urdea, 2000). Within the central area, nine rock glaciers are included in this study (Fig. 1). Recent studies have highlighted the occurrence of permafrost in rock glaciers from the central portion (Urdea et al., 2008; Onaca et al., 2013). The timber line is situated at 1700–1800 m a.s.l., higher altitudes are occupied by alpine meadows and subalpine dwarf shrubs. In the central sector, which is the subject of this research, the altitudes are well above the 2000 m a.s.l. for more than 56 km^2 (Urdea, 2000), with several peaks over 2500 m a.s.l. (Peleaga 2509 m a.s.l., Păpuşa 2504 m a.s.l.).

The surface morphologies of the investigated rock glaciers show well developed transversal furrows and ridges, and, on some of them, large thermokarstic depressions (e.g., Valea Rea). All the rock glaciers are located in glacial cirques and troughs, being fed by debris cones, scree slopes, and block streams found below steep, and heavily-weathered rock walls. In two cases (e.g., Pietrele and Valea Rea), the creeping permafrost bodies includes pre-existing morainic materials, whereas all other investigated rock glaciers are talus rock glaciers. According to their plan geometry, Pietrele, Valea Rea, and Judele belong to the tongue-shaped typology, whereas the rest have a lobate, or even a spatulate (e.g., Ana de Jos) shape. Coarse-grained blocky granodioritic and granitic rocks, including large boulders, are dominant on the surface of the rock glaciers. However, in the case of Pietrele, Ana de Jos, Pietricelele, or Valea Rea, fine materials and sparse vegetation occur on their frontal and marginal slopes. Previous geophysical and thermal investigations performed on these rock glaciers (Onaca, 2013) identified patches of permafrost, despite their superficial appearance as relict rock glaciers. The occurrence of permafrost within these landforms is strongly controlled by local topo-climatic factors and surface characteristics. Among them, the presence of large rocks on the surface is important because these surface features have a cooling influence on ground temperatures compared with finer grained materials (Harris & Pedersen, 1998).

Compared to the Alps, the Southern Carpathian climate is characterized by a more pronounced continentality. The mean annual air temperature at the nearby Ţarcu meteorological station (2180 m, 45°16′50″N, 22°32′00″E) is −0.4 °C and the highest peaks (at more than 2500 m) are estimated to have a mean annual air temperature (MAAT) of −2.5 °C (Voiculescu, 2000). This site is predominantly under the influence of western air masses. On the highest peaks, the mean annual precipitation varies between 900 and 1000 mm (959 mm at Ţarcu), with an obvious summer maximum. Between November and May, the precipitation falls primarily as snow. In the alpine area, the number of days with frost is around 250–275 days/year. The evolution of MAAT and precipitation are presented in Fig. 2. Specifically, the MAAT data indicates a minimum in 1980 at −1.8 °C, followed by a steady increase. Mean annual precipitation indicates a decrease in the precipitation regime until the mid-1990s, following a steady increase.

3. Data and methods

3.1. Satellite data

This study used a complementary set of optical and radar airborne and satellite imagery.

Optical imagery consisted of one stereo panchromatic dataset acquired by Corona KH-4B reconnaissance mission, a SPOT 5 satellite image, and a WorldView-1 image (Table 1). In addition, a set of Pléiades stereopair images was acquired synchronous with the field work and was used to derive a 4-m resolution digital surface model (DSM). This DSM was essential to the orthorectification and co-registration of optical and radar data.

For radar analysis, nine ascending Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) scenes were used, selected from those with no snow groundcover (i.e. June–October), no overcast conditions, and