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.

Index Terms: Rock Glaciers, Carpathian Mountains, Retezat National Park, Multi-Temporal Image Analysis, InSAR Coherence, Cross-Correlation, InSAR, SBAS, COSI-Corr

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43 **1. Introduction**

44 Permafrost (perennially frozen ground) is defined as ground that remains below 0° C for at least
 45 2 years (Harris 1988); hence, it is particularly sensitive to climate change (Haeberli and
 46 Hohmann 2008). Permafrost is present at high altitudes in all major mountain chains around the
 47 world (e.g., White 1981; Gorbunov 1983; Haeberli *et al* 1993; Urdea 1993; Strozzi *et al* 2004).

48 Contradictory concepts have been formulated regarding the origin of rock glaciers. In the
 49 majority of the studies, rock glaciers were described as creeping permafrost masses of rock-ice
 50 mixture (Haeberli, 1985; Barsch, 1996; Haeberli and Vonder Mühl, 1996; Bolch and Gorbunov
 51 2014), whereas several authors state that the rock glaciers may also be related to glaciers in
 52 environments where permafrost is missing (Potter 1972; Whalley and Martin, 1992; Humlum,
 53 1996; Krainer and Mostler, 2000). Recent studies revealed that rock glaciers can develop as
 54 transitional landforms because they may incorporate both permafrost and glacier ice (Serrano *et*
 55 *al* 2010; Berthling 2011; Monnier *et al* 2013). In either situation, these spectacular tongue-like
 56 or lobate creeping bodies are characterized by a distinctive microrelief of ridges and furrows on
 57 their upper surface (Barsch, 1996).

58 Increased recent interest in rock glacier dynamics (Haeberli *et al* 2006) is due to the fact that
 59 they represent a major portion of the high alpine mass transport system and form an integral part
 60 of the landscape (Berthling and Etzelmüller, 2007; Azócar and Brenning, 2010). Rock glaciers
 61 are sensitive to climate change, but not as sensitive as true glaciers, because the coarse debris
 62 mantle produces a relative by large thermal inertia of permafrost (Haeberli *et al* 2006).
 63 However, recent studies highlighted the increased sensitivity of permafrost when the temperature
 64 of the subsurface is close to 0 °C (Kääb *et al*, 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 and Kääb 2000; Frauenfelder *et al* 2001). A recent estimate of the global permafrost area (i.e., permafrost area including Antarctic and sub-sea permafrost) was estimated to be $16\text{--}21 \times 10^6 \text{ km}^2$, whereas the global permafrost region (i.e., exposed land surface below which some permafrost can be expected) was estimated to be $22 \pm 3 \times 10^6 \text{ km}^2$ (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 and Martin 1992;; Kääb and Vollmer 2000; Strozzi *et al* 2004; Lambiel and Delaloye 2004; Roer 2005; Delaloye *et al* 2008; Serrano *et al* 2010; Liu *et al* 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 *et al* (1992) in Asia, and Delaloye *et al* (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 *et al* 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) (Figure 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 *et al* 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 (Figure 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 km² (Urdea 2000), with several peaks over 2500 m a.s.l. (Peleaga 2509 m a.s.l., Păpușa 2504 m a.s.l.).

Figure 1. Geographical location of the test area within the Southern Carpathian Mountains, Romania (inset). Geographical distribution of the largest nine rock glaciers

located in the central part of the Retezat Massif. Background data: high resolution panchromatic satellite imagery acquired by WorldView-1 on July 20, 2012.

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 and 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 Țarcu 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 Țarcu), 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 Figure 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.

Figure 2. Climate data at Retezat-Godeanu mountain group over a 40-year period. Mean annual air temperature data (left) Mean annual precipitation data (right).

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.

Table 1. Optical Imagery*

Optical Image Dataset	Acquisition Date	Resolution/Nadir Angle
Corona KH-4B Black and White (B/W) Stereo Panchromatic Film (Mission: 114-04 Camera Resolution: High Film Type: 70mm Pan; Focal length: 610mm)		
1. 2155DA019	17 August 1968	1.2m / +/-15°
2. 2155DF013		
SPOT 5 Panchromatic Images	22 September 2007	2.5m / 1.80°
WorldView-1 Panchromatic Image	20 July 2012	0.5m / 20.31°
Pléiades Pan/MS/DSM	28 September 2014	DSM model resolution: 4 m

* all datasets have cloud cover less than 5%. No other historical satellite optical data were found to be suitable for this study.

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 no precipitation during acquisition (Table 2). No descending PALSAR scenes were acquired by ALOS over the study area.

Table 2. ALOS PALSAR Imagery (Path:620, Frame:900)

Date	PALSAR Granule
17 July 2007	ALPSRP078740900
1 September 2007	ALPSRP085450900
17 October 2007	ALPSRP092160900
19 July 2008	ALPSRP132420900
3 September 2008	ALPSRP139130900
19 October 2008	ALPSRP145840900
22 October 2009	ALPSRP199520900
9 June 2010	ALPSRP233070900
25 July 2010	ALPSRP239780900

* Fine-beam double (FBD) polarization; Off-nadir angle is 34.3°. Azimuth resolution (AR) is 4.5 m; slant range resolution (SRR) is 9.6 m. Only the horizontal transmit and horizontal receive (HH) polarized channels were used in this study.

3.2 Measuring Techniques

3.2.1 Optical Analysis

An accurate investigation concerning permafrost-related movements of rock glaciers requires several basic conditions: (i) existing information on dynamics over a large area in order to account for three-dimensional (3-D) effects, (ii) high resolution techniques to capture the low deformation rates, and (iii) multi-year investigations in order to capture slow temporal changes (Kääb *et al* 2003). Ground based approaches (i.e., simple techniques like repeated measurement of painted stones, or steel tapes and strain wires) (Chaix 1923; Pillewizer 1957, White 1987), differential global positioning system monitoring (e.g., Haeberli 1985; Barsch and Zick 1991; Berthling *et al* 1998; Koning and Smith 1999; Lambiel and Delaloye 2004), laser scanning or LiDAR (e.g., Paar *et al* 2001; Avian and Bauer 2006), and photogrammetry via optical image cross-correlation (e.g., Kääb and Vollmer 2000; Kaufmann and Ladstädter 2003; Kääb *et al* 2003; Kääb 2004; Frauenfelder *et al* 2004) are the methods typically used to determine rock glacier displacements.

Air- and space-borne methods are preferred because they can monitor large areas, including areas that are difficult to access. The repeated stereo pairs of optical images or LiDAR surveys are better suited than simple digital elevation model (DEM) differencing (Kääb *et al* 2003, Berthier *et al* 2005), provided glacial surface features remain coherent in the dataset. From the optical image cross-correlation techniques, a sub-pixel change detection technique, called Co-registration of Optically Sensed Images and Correlation (COSI-Corr) (Leprince *et al* 2007) is of

particular interest for this work. The technique has been successfully applied to terrestrial satellite images to measure seismic fault offsets, ice-flows, landslides, and dune migrations (for reference on other studies, see Necsoiu *et al* 2013). This method corrects offsets due to sensor distortions, attitude drifts, and orbital errors, enabling co-registration with a 1/20 pixel accuracy (e.g., the study on Mer de Glace glacier by Leprince *et al* 2008). The COSI-Corr technique does not require any external information when correlating images, thus allowing processing of any digital image acquired in any part of the electromagnetic spectrum (Leprince *et al* 2007).

Only a few studies have used COSI-Corr to measure glacial movement in mountainous terrain (Scherler *et al* 2008; Quincey and Glasser 2009; Herman *et al* 2011). Specifically, COSI-Corr also was used to derive 5-year surface velocity of the fast moving Tasman Glacier (Quincey and Glasser 2009). The rate of movement within this ice glacier is, however, orders of magnitude higher (i.e., tens to hundreds of meters per year) than is typical of rock glaciers. Tasman Glacier also was chosen by Redpath *et al* (2013), who developed a similar methodology to monitor flow dynamics using cross-correlation techniques implemented in the spatial domain. However, based on Heid and Kääb (2012), the most robust matching techniques for monitoring glacier velocities are the cross-correlation techniques implemented in a frequency domain (i.e., phase correlation) and the cross-correlation on visible and near-infrared satellite imagery (Rolstad *et al* 1997). Our study employs high resolution satellite imagery, the COSI-Corr and cross-correlation techniques to study rock glaciers and creeping processes, using a similar implementation to the one developed to monitor slow dune migration at Great Kobuk Sand Dunes, Alaska (Necsoiu *et al* 2009). In addition, this study is one of the first to apply COSI-Corr to Corona data.

Orthorectification and Co-Registration of Optical Data

High-precision orthorectification and co-registration of these images was performed on the optical imagery using the COSI-Corr technique with the 2012 satellite image as the reference. We carefully identified, selected, and optimized (i.e., through several iteration loops) stable tie points from the few available landscape features. Nineteen tie points were selected from relatively flat regions of the DEM to anchor the 2007 SPOT 5 and 2014 Pléiades to the 2012 WorldView-1 (WV-1) satellite image. Most tie points coincided with relatively stable features, such as wide (low height) boulders and dwarf shrubs (Figure 3). The resulting average misregistrations were a few millimeters for the SPOT 5 – WV-1 pair (e.g., $\sim 0.0022 \pm 0.3\text{m}$) and the WV-1 and Pléiades pair (e.g., $\sim 0.0045 \pm 0.22\text{m}$). Such levels of misregistrations and standard deviations are an improvement upon those reported elsewhere (e.g., Herman *et al* 2011; Brethier *et al* 2005). Brethier *et al* (2005) examined glacier dynamics using SPOT 5 images and achieved the best standard deviation of 1.55 m (absolute orientation) and 0.63 m (relative orientation) of different SPOT 5 scenes. Herman *et al* (2011) examined glaciers using 2002 and 2006 Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images with an average misregistration of 0.02 m, with a standard deviation of <3.5 m. Finally, cross-correlation analysis was performed on pairs of data sets using a Fourier-based frequency correlator engine with a window size of 32 x 32 pixels and a step of 4 pixels in X and Y directions. Frequencies were selected according to the amplitude of the log-cross spectrum based on a mask threshold set to 0.90.

Figure 3. Examples of a relatively stable feature (a and b – dwarf shrub, c and d – boulder) used as tie points to precisely co-register remotely sensed imagery. a and b: 2012 master image; c and d: 2007 slave image. Each image chip is ~180m x ~200m.

The film-based Corona satellite images were scanned with high spatial and radiometric resolution to accurately retrieve their information (i.e., 10-bit radiometric resolution, 7- μ m geometric resolution, and ~2–3 μ m stability). KH-4B Corona data, acquired in long 8.6 x 117 km film strips are subject to extreme spatial distortions caused by a cross-path panoramic scanning system not present in a typical aerial imagery [i.e., as panoramic, scan positional, and image motion compensation distortions] (Sohn 2004). Therefore, traditional two-dimensional (2-D) curve fitting techniques, such as higher order polynomials or spline-based methods cannot be used to correct these distortions because they cannot take into account distortions caused by the 3-D imaging geometry and terrain. The absence of camera information and a detailed orientation made the error correction process highly challenging. Furthermore, because our study area resides outside the overlapping segment (i.e., area is only present in the 2155DF013

image), the approach presented by Casana and Cothren (2013) was not applicable. Therefore, our approach was to slice the image into tiles (see Altmaier and Kany 2002; Casana and Cothren 2008; Galiatsatos *et al* 2011), making the assumption that locally, at the tile scale, the geometry is close to a regular frame camera. In these particular conditions, high-resolution orthorectification and co-registration could be performed. The potential effects induced by local topography were avoided by adopting tiles with size less than 2% of the width of the Corona scene. This selected threshold was more conservative than the one adopted in the above cited studies. For each pair of WorldView-1 and Corona images, five tie points were identified. Overall, this approach resulted in excellent average misregistration and standard deviation estimates, on the order of a few centimeters (e.g., $\sim 0.043 \pm 0.161$ m).

3.2.2 Radar Analysis

Interferometric synthetic aperture radar (InSAR) techniques are an alternative to optical-based remote sensing techniques. Intensity- and coherence-tracking, cross-correlation techniques, and differential radar interferometry (DInSAR) are examples of radar-based techniques used to produce 2-D velocity fields (Gray *et al* 2001). Rock glaciers are optimum targets for these radar-based techniques because they have little vegetation cover. Regarding DInSAR, a number of studies have succeeded in measuring rock glacier surface deformation at a cm-level accuracy (e.g., Mattar *et al* 1998; Rabus and Fatland 2000; Nagler *et al* 2001; Strozzi *et al* 2002; Strozzi *et al* 2004). Typical obstacles to overcome when using DInSAR are low coherence, steep topography, and the small size of rock glaciers. The low-coherence obstacle is especially significant when only ERS-1/-2 or ENVISAT satellite system data are available. In addition, low temporal resolution can prevent deriving glacier displacements (Berthier *et al* 2004).

Fortunately, spatial and temporal resolutions of synthetic aperture radar (SAR) data have significantly improved over the past few years. In addition, new SAR-based change detection techniques, such as persistent scatterer (PS) and SBAS interferometries (Ferretti *et al* 2000) and (Berardino *et al* 2002), can provide ground displacement accuracies on the order of a few mm and eliminate the DInSAR (as well as in the case of pairs of optical imagery) limitations, which estimate movement for a time-delimited period. Fortunately none of these errors are correlated in time, which makes the use of a multitemporal InSAR analysis very desirable.

The key to successfully applying the SBAS technique is that data pairs involved in the generation of interferograms be properly selected to minimize the spatial and temporal separation between the acquisition orbits, thus mitigating the decorrelation phenomena. SBAS is an attractive approach because it requires fewer SAR observations at a comparable precision to PS and is more sensitive to the nature of scattering mechanisms (i.e., distributed) that occurs in general, over rock glaciers. SBAS was recently used in studying fast (dm/year) moving rock glaciers in Sierra Nevada, California (Liu *et al* 2013).

Work was initiated by investigating the strength and coherence of the radar signal from rock glacier areas. Qualitative analysis was performed by InSAR coherence analysis in order to assess how rapidly decorrelation of radar data occurs over these sites. Rapid decorrelation is an indicator of (i) highly dynamic ground displacements, (ii) changes in the environment conditions of the target area, or (iii) presence of vegetation. The results of the coherence analysis were used to appropriately parameterize the SBAS InSAR analysis. SBAS is an area-based InSAR technique that can overcome some of the limitations of conventional interferometry. This method was specifically designed to identify and quantify mm-level movement of area-based natural features (e.g., rock outcrops and boulders). The dimensions of these reflecting objects

are usually smaller than the resolution cell and their coherence remains high for large temporal and geometrical bases. Preliminary SBAS analysis using a spatial baseline threshold of 50% of the critical baseline value was based on all nine ALOS PALSAR FBD images (only HH channel) acquired between 17 July 2007 and 25 July 2010. The entire InSAR processing was performed by applying a complex multi-look operation with one and four looks in range and azimuth, respectively. The ground range pixel dimensions of the resulting products are therefore about $20 \times 20\text{m}$ in the range and azimuth directions. This analysis identified 7 master and 23 candidate SAR image pairs (Figure 4).

Figure 4. Pairs (interferograms) processed of ALOS PALSAR images processed by SBAS. Time versus relative position. One dataset acquired on 17 July 2007 (i.e., yellow dot in the graphs) had been chosen as the super master dataset.

For each pair, the normal and temporal baselines were calculated. Overall, the mean, maximum, and minimum values are presented in Table 3.

329

Table 3. Normal and Temporal Absolute Baseline Values			
Absolute Baseline	Mean	Max	Min
Normal (m) (Critical value 6566 m)	1194	3071	303
Temporal (days)	480	1058	46

330

331 The refinement and reflattening step used initialization parameters from the orbital data and
 332 estimates based on the amplitude and coherence. Residual phase frequency was employed using
 333 a 512 x 512 window to eliminate those fringes that remain after the removal of the phase
 334 component due to topography (i.e., DEM) and/or flat earth. Unwrapped phase and coherence
 335 images were later used to identify and discard those InSAR pairs having large phase
 336 discontinuities and low coherence. These pairs were removed before the refinement and
 337 reflattening step because their presence could significantly decrease the precision in the first
 338 velocity estimation. Finally, 15 Ground Control Points (GCPs) were used to improve
 339 displacement estimates by removing the atmospheric phase components and eventually fit a
 340 quadratic displacement velocity model. By using a quadratic model, the chi-square estimates
 341 were significantly smaller when compared with the ones that resulted from linear or cubic
 342 displacement models.

343 Unfortunately, the spatial orientation of SAR acquisitions allowed limited exposure of the local
 344 slope to the satellite line-of-sight. Because of the complexity of the area, the quantitative
 345 analysis was focused only to a few representative rock glaciers, located outside radar layover or
 346 topographic shadow zones (i.e., steep rock walls and deep valleys). We also eliminated rock
 347 glaciers that had a slope direction close to the satellite flight direction, where the sensitivity of
 348 the interferometric phase to deformation is reduced. As a result, four rock glaciers were selected

for focused investigations. Judele and Ana de Jos were best illuminated by radar signal and therefore best positioned for analysis while Pietrele and Valea Rea rock glaciers were the less well-positioned (Figure 1). SBAS InSAR provided the following information, in raster and vector formats:

- Total displacement
- Displacement history, which consists of the displacement magnitude for each input file with respect to the reference acquisition
- Estimated displacement precision (i.e., standard deviation of the displacement error)

3.3 DEM Generation

Based on preliminary work, the resolution of the available public DEMs was found to be too coarse to generate solutions for capturing the dynamics of these rock glaciers. Therefore, two field surveys were conducted at the study site during Summer/Fall 2014 using Trimble GEO Explorer (GEO XH) 6000 coupled with an external Trimble Tornado antenna. GCP measurements were recorded at 15 locations with field accuracies between 0.50 – 1.5m (vertical) and 0.20 – 1.5m (horizontal). After post processing with Trimble Terra Sync software, the positional accuracies were 0.19 – 0.65m (vertical) and 0.12 – 0.35m (horizontal).

A 0.5 m stereo panchromatic Pleiades dataset was acquired in the proximity of our second field survey. Nine of the GCPs and 145 tie points were used to generate a high resolution 4 m DEM. The accuracy of the product generated by Astrium was horizontal: $RMSE\ X = 0.624\ m$, $RMSE\ Y = 0.528\ m$ with $CE\ 90 = 1.345\ m$, where RMSE is the Root Mean Square Error estimator; vertical: $RMSE\ Z = 0.475\ m$ with $LE\ 90 = 0.781\ m$ (Astrium 2014).

3.4 Field Assessment

In the field, the team assessed the activity status of rock glaciers based on visual observations and previous geophysical and thermal measurements (Onaca *et al* 2013, 2015). Several diagnostic morphological and ecological features were considered to differentiate between active/relict rock glaciers, such as: (i) surface micro-relief, (ii) steepness of the front and margins, (iii) extent and type of vegetation, and (iv) relationships with source rock walls (Baroni *et al* 2004).

In addition, geophysical (electrical resistivity tomography) and thermal measurements using miniature data loggers were performed to investigate the internal structure of rock glaciers and the ground surface temperature at specific sites. These data were compared with companion observations of rock glacier dynamics to detect if the deformations were occurring at sites where permafrost is likely, and thus are the result of permafrost creep.

4. Results

4.1 Rock Glaciers Areas - Optical Data

In theory, increasing the time interval between the images would improve chances that small dynamic phenomena can be detected. However, seasonal variations in the target dynamics can complicate the analysis. In order to overcome the temporal noise, we investigated the dynamics of the area using all four optical satellite datasets, paired to estimated short term (7 years) and longer term changes (44 years) (Figure 5).

Figure 5. Pietrele rock glacier (a) 1968 Corona (b) 2007 SPOT 5 (c) 2012 Worldview-1 and (d) 2014 Pléiades PAN images. To facilitate image interpretation, histogram matching was performed with reference to the 2007 image. For consistency, pixel size was set to 2.5 m. The size of the image chips is ~650 m x ~900 m.

By using all datasets, we also verified the consistency of results since each dataset was acquired using different sensors, geometries, and radiometric quality. The longest long term changes possible (i.e., 46 years) provided very similar results with 44 year changes and are not further discussed. The estimated displacement fields for the Pietrele rock glacier over 7 years (2007–2014) and 44 years (1968–2012) are presented in Figure 6. Areas located in the southern part of the rock glacier were not covered by vectors because of (i) absence of points with stable

geometries (which probably imply high local dynamics), (ii) inadequate geometry caused by local topography and geometry of satellite data acquisitions, and (iii) topographic shadow. The displacement estimates are very small, on the order of tens of cm for each investigated period, with half the displacements occurring in the past several years. As shown in Figure 6, apparent displacement also occurred outside the rock glaciers. These apparent displacements could be due to processes not related with the creeping of permafrost bodies, such as gravitational processes (e.g. gelifluction, soil creep) or may be simply noise in the image processing. For example, careful interpretation should be given to high slope gradient areas (e.g., darker areas located in the W, NW, SE) where estimated displacement vectors are picking up changes in the direction of shadow, as the pairs of analyzed images were collected by different sensors, and at different dates and times of the day. The validation of the displacement within the rock glacier was judged by their consistency in direction.

Figure 6. Estimated displacement field for the Pietrele rock glacier for (a) 7 years (2007–2014) and (b) 44 years (1968–2012). Vectors were determined by a 5 x 5 pixels moving average

window, with a step of 3 pixels. Background image: B1, B2, B3 Pléiades MS data acquired on 23 September 2014.

Figure 7 shows the probability density of the velocity measurements over active and stable areas of the rock glacier. The shape of the density plot reveals that the most likely rate estimates are between 0.8 cm and 2.2 cm/year, with peak velocities up to 1.44 cm/year. Stable areas revealed a mean velocity of $0.55 \text{ cm/year} \pm 0.56 \text{ cm/year}$ at 1σ , and uncertainty can be used as a proxy for the measurement noise.

It also can be noted that the noise density is approximately Gaussian, symmetrical. This was an expected result because the measurements were projected onto a local robust displacement direction (Necsoiu *et al* 2009). The shape of the velocity probability density over steady areas serves as evidence that our method delivers unbiased measurements. The negative velocity measurements are not physical; instead, they represent areas where Gaussian noise is higher than velocity. If the stable areas were truly unchanging, mean velocity should be zero and only noise should be measured. The mean velocity over stable areas is not centered at zero which is a result of a slight misregistration in the rock glacier vicinity. Thus, the corrected mean velocity for Pietrele rock glacier is slightly less than one cm/year, a result of subtracting the mean velocity of the stable area from the one estimated for the rock glacier.

Figure 7. Probability density of the velocity measurements over active and stable patches of Pietrele rock glacier. The negative values are a result of the projection operator, as we display the noise as Gaussian in this representation.

These small dynamics, close to the level of noise of the method, are not typical of mountain rock glaciers from the temperate zone (Haeberli, 1985; Delaloye *et al* 2008), which are rather warm (temperature close to 0 °C). In those regions, rock glaciers are expected to react more sensitively to even small changes in temperature (Ikeda *et al* 2008). Furthermore, the displacement rates measured for Pietrele rock glacier are smaller than those recorded for arctic rock glaciers (Berthling *et al* 1998; Isaksen *et al* 2000; Kääb *et al* 2002; Haeberli *et al* 2006; Kääb 2006), which are considered to creep, in general, slower than glaciers in warmer climates (Kääb *et al* 2007).

However, an “acceleration” of the surface horizontal displacement rates occurred over the last years (interval 2007–2014) when surface displacements of a few cm/year occurred at specific points within Pietrele rock glacier. This trend is likely the response to an increase in permafrost temperature as a result of warmer air temperatures (Delaloye *et al* 2008). Similar results were recorded in the Alps, showing that in the last 2 decades, the kinematics of rock glaciers have accelerated significantly (e.g. Delaloye *et al* 2008; Kääb *et al* 2007; Kaufmann and Ladstädter

2007; Roer *et al* 2005) because of shifts in temperatures. Both the climatic conditions and field data recorded at Țarcu meteorological station support this interpretation for the Pietrele rock glacier, if we consider that temperature increases considerably after 2000. Although the MAAT at Țarcu meteorological station for the interval 1961–2013 is -0.4 °C between 2006 and 2012, only positive MAAT values were recorded. The rise in both temperature and precipitation in the last decade contributed to the increase of liquid water content within the permafrost body or at its base, causing an exponential increase of rock glacier surface motion. As shown in other studies (Zhang *et al* 2001; Ishikawa 2003; Luetschg *et al* 2004; Gislås *et al* 2014) snow cover characteristics (duration, date of the first snow, thickness) and redistribution of snow by winds and snow avalanches (Haeberli 1975) could have an important impact on the temperature of the sub-surface and thus on the permafrost preservation. Because the snow cover is not uniform, internal ventilation may occur at particular sites contributing to a strong cooling/warming of the subsurface even below the thick snow cover in the Retezat Mountains (Onaca *et al* 2015). In some cases, at sites where permafrost is likely to occur, the reduced incoming solar radiation controls the snow cover duration, allowing the maintenance of snow until August. As a consequence, the snow-free cover interval with positive temperatures at sites where permafrost occurrence is probable, may last for less than 90 days (Onaca *et al* 2015).

The horizontal creep rates at the surface seem to decrease from the steep upper part to the flat lower part during both investigated periods. Higher values also were observed in the case of the individual flow lobe located in the western part and fed by a distinct debris cone with an eastern orientation. The measured creep rates and the transverse ridge-furrow topography point to compressive flow in the lower half of the rock glacier (Kääb and Weber 2004). The general flow pattern is a stream-like pattern, connecting the southern main rooting zone with the rock glacier

front. The arrangement of the flow vectors is mainly controlled by topography and the internal deformations of the frozen body. A different flow pattern is clearly visible in the southwestern and western part of the rock glacier between 2007 and 2014. Here, the movement is mainly from west to east and is probably controlled by the flow following the increasing slope of the underlying terrain from the lateral talus slopes to the center of the rock glacier. The lack of the transverse ridges and furrows from the upper half of the rock glacier seems to support this interpretation.

The maximum horizontal velocities during the interval 2007–2014 were in the southern and western parts of the Pietrele rock glacier and are related to the increase in surface slope. Both areas are located in the vicinity of the most active debris cones feeding this rock glacier and the displacements may be influenced to some extent by rock falls, rock rolling, avalanches, and debris sliding. According to previous studies (Vespremeanu-Stroe *et al* 2012; Onaca *et al* 2015) in the southern and western parts of the rock glacier, the mean annual ground surface temperature (MAGST) is negative and masses of rock-ice mixture are expected to occur in the subsurface, based on bulged morphology and geophysical results (Onaca *et al* 2015). The pattern of the displacements recorded for the 1968–2012 period is not very different, but reveals a less concentrated surface deformation distribution. The greatest displacements were observed in the southern and western parts, probably resulting from the combined effect of the deformation of frozen bodies and rapid mass wasting onto the surface, whereas the central-eastern portions of the rock glacier experiences exclusively permafrost creep.

4.2 Rock Glacier Areas – Radar Data

4.2.1 InSAR Coherence Analysis

Coherence was surprisingly high with the maximum available interval (~3 years) within the boundaries of the rock glaciers. Figure 8 presents the coherence channel of a pair of SAR images collected approximately 3 years apart (October 2007–June 2010). Masking was performed to the extent of the rock glaciers, eliminating areas subject to non-glacial processes. Areas within rock glaciers that have low coherence are indicative of local dynamics, vegetation, or geometric shadows. Patches of low coherence can be observed within all nine investigated rock glaciers. These results are in agreement with recent geophysical and thermal investigations (Urdea *et al* 2008; Onaca *et al* 2015), which revealed that patches of permafrost occur within Pietrele, Pietricelele, Ana de Jos, and Judele rock glaciers.

Figure 8. (a) InSAR coherence analysis based on a ALOS PALSAR FBD pair (HH channel) collected approximately 3 years apart. Low coherence is attributed to various factors, including the potential nonlinear dynamics of areas within the boundaries of the rock glaciers. Pietrele,

516 Valea Rea, Judele, and Ana de Jos seem to be least affected by radar layover and foreshortening
517 effects. Data are presented in slant range geometry. Coherence windows size is 5 x 5.

518 (b) Pléiades DEM slope of the area was provided for a visual comparison with the local
519 topography.

520 Furthermore, a good correspondence was observed between the results of the geophysical
521 measurements (direct current resistivity and ground-penetrating radar) and the “cold” areas
522 depicted by the ground surface temperature (Onaca *et al* 2015) and the bottom temperature of
523 snow cover (BTS) values (Ardelean *et al* in press). The electrical resistivity tomography (ERT)
524 and ground-penetrating radar measurements identified the occurrence of ice-rich frozen debris
525 underneath a thick active layer (7–10 m) (Onaca *et al* 2015). However the ice-rich frozen layer
526 in Pietrele rock glacier seems to have a thickness of 10 m (Onaca *et al* 2015). According to these
527 data, permafrost is likely to occur in Pietrele rock glacier in the southern part on the western side,
528 located in the shade of the Bucura Peak where the incident of solar radiation is reduced. On the
529 front and the eastern side, vegetation prevails suggesting the present inactivity of these areas
530 (Figure 9).

Figure 9. (a) BTS mapping (March 2013) and ERT profiles on the Pléiades satellite image, (b) InSAR coherence analysis indicating patterns with possible line-of-sight (LOS) dynamics for the Pietrele rock glacier V-possible effects of vegetation, (c) ERT inverted profile (after Onaca 2015) , and (d) correlation between coherence and BTS values.

The results obtained from BTS measurements and the InSAR coherence analysis are consistent because the areas that appear to exhibit high dynamics and low coherence correspond well with the areas with low BTS values during the late winter. On the eastern side of the Pietrele rock glacier, the low coherence was attributed to possible effects of vegetation, since the eastern marginal slope of the rock glacier is a part of a lateral moraine, completely vegetated by *Pinus*

mugo (dwarf mountain pine). Based on these findings, the inferred surface deformation is likely to be the result of the creep within the underlying permafrost.

4.2.2 Radar Interferometry Results (SBAS)

The results of the SBAS analysis (Figure 10) in the form of LOS differences between 2007 and 2008 show rock glacier speeds are not uniform over the area.

Figure 10. The SBAS InSAR result using a stack of ALOS PALSAR images. (a) The color of individual SBAS point locations corresponds to an LOS displacement difference between years 2007 and 2008. Colors denote rock glacier activity: blue and light green—active, red and orange—inactive. Same scale was maintained over each rock glacier.

We elected to calculate differences between these years because (i) each year had the same number of acquisitions and (ii) the months of SAR acquisitions were identical. The results revealed that surface deformations greater than 3 cm occurred on most of the Judele, on the southern part of Valea Rea, and only in isolated areas in the southern part of Pietrele. The results of the SBAS analysis for the Pietrele Rock glacier using the nine SAR images are shown in Figure 11.

Figure 11. The SBAS InSAR result from the Pietrele rock glacier using a stack of ALOS PALSAR images. (a) The color of individual SBAS point locations corresponds to the difference of 2007–2008 average LOS displacement rates. Negative values indicate motion away from the satellite. Background: Pléiades orthorectified image was acquired on 28 September 2014. (b) Direction of acquisition of satellite data (incidence angle = $\sim 34.3^\circ$, LOS azimuth = $\sim 14^\circ$). (c) Perspective view of the area. (d) Displacement trends of three representative SBAS point locations (displacements values are referenced to 17 July 2007).

567

568 Figure 11d shows the displacement of three selected points within the boundaries of the rock
569 glacier. Point 239 (blue) is located in the west side within one of the areas that shows the largest
570 displacement over 4 years. Point 592 is located in the moraine section, an area we expect to be
571 relatively static.

572 SBAS results and the ones obtained by InSAR coherence and cross-correlation analysis are
573 consistent, all displaying similar patterns of deformation, with the highest creep rates located in
574 the southern and western parts of the rock glacier. The observed displacements were interpreted
575 as creeping permafrost bodies, whereas very low velocity rates combined with MAGST close to
576 zero suggest the deforming frozen layers are very thin (Kaufman 1998).

577 According to the literature, the highest displacements are generally reached when the warm wave
578 has penetrated to the zone of highest displacement (Kääb *et al* 2007). Since our previous
579 geophysical and thermal measurements were unable to determine whether the active layer
580 becomes entirely frozen during the winter, it is difficult to evaluate the role of advective or
581 convective heat exchange.

582 Warmer ice is considered to be more ductile than a colder ice (Delaloye *et al* 2013); thus, higher
583 local strain rates are expected to occur in those shear zones that are very close to 0 °C. In the
584 2007 and 2008 warm seasons, higher velocities were detected for the Pietrele rock glacier in the
585 second part of the summer and in autumn, whereas in 2009, fairly high values were recorded in
586 October. In 2010, very low displacements were detected, probably because of a drier and colder
587 winter (Figure 12). In our case, the delay between the end of the “zero-curtain interval” and the
588 highest recorded velocities appear to be shorter than in other cases, probably as a result of an
589 accelerated melting of the snow at the beginning of the warm season, when high amounts of

precipitations are recorded. These results also seem consistent with Delaloye *et al* (2010), which noted that rock glaciers surveyed in the Alps, irrespective of size and velocity, respond sensitively and almost synchronously to interannual and decennial ground temperature changes.

Figure 12. Time series of the mean monthly air temperature (blue diamond) and the InSAR LOS displacement estimates and their associated error bars at SBAS point locations 239 on the Pietrele rock glacier (Figure 11).

5. Discussion

5.1. Methodology Discussion

This research provided insights into the evolution of permafrost-related formation and degradation in both space and time, providing the first documented assessment of dynamic range of rock glaciers in the Southern Carpathian Mountains over almost half a century. Although the analyses for this project were limited by the small number of archived SAR and high resolution optical data, the results demonstrate that InSAR coherence analysis, cross-correlation analysis, and multitemporal InSAR techniques (e.g., SBAS) can yield useful information for detecting

creeping permafrost bodies in a complex mountain environment, such as the Retezat Mountains.

Co-registration of optical satellite data imagery was particularly challenging due to a general lack of stable landmarks, but large boulders and small clumps of dwarf shrubs were relatively stable and therefore useful as tie points. Recognition of relatively stable landscape features during the timeframe of interest yielded a high-quality co-registration, which ultimately provided excellent average misregistration and standard deviation estimates (i.e., SPOT 5 – WV-1 pair $\sim 0.0022 \pm 0.3$ m; WV-1 and Pléiades pair $\sim 0.0045 \pm 0.22$ m). For newer high-resolution optical satellite imagery, the high-precision orthorectification and co-registration steps are relatively fast to implement; thus, it has potential for use in production mode to study the entire Carpathian Mountains rock glacier area, given an adequate supply of multi-temporal, very high-resolution imagery over large regional areas. The ability to accurately rectify and co-register Corona KH-4B imagery (average misregistration and standard deviation estimates were $\sim 0.043 \pm 0.161$ m) allowed us to expand the time horizon over which changes in this alpine environment could be analyzed. The estimated average of the displacement rates (i.e., few cm/year) correlate with variations in local slope of the rock glaciers, and the nature of the underlying material.

InSAR coherence analysis provided a fast qualitative way to detect stable areas that remain static over a large period of time, areas with high coherence being identified inside rock glaciers on pairs of SAR L-band data with a timespan of 3 years. Although decorrelation limits the ability to perform quantitative InSAR analyses, loss of coherence is useful for detecting subtle changes in active rock glacier environments. These results suggest that remote sensing techniques may be useful to detect other types of mass movements, including rock falls, rock avalanches, debris flows, permafrost creep, and solifluction.

SBAS InSAR analysis provided a way to quantitatively assess rates of change for unstable areas. The advantage of the SBAS technique is that it exploits phase unwrapping by (i) assuming a certain type of correlation (similarity) between the movement of one pixel and that of the neighboring ones and (ii) making no assumptions about the type of movement (i.e., slow or fast, linear or nonlinear motions). These movements are equally well reconstructed by the SBAS algorithm, given that the spatial unwrapping step can be carried out. SBAS analyses provided consistent millimeter-scale changes in ground surface displacements, mapped over the entire rock glacier areas.

Our analyses revealed that LOS displacements higher than 2 cm/year could be expected on most of the Judele surface and in the southern part of Valea Rea and Pietrele, whereas in the case of Ana de Jos, only a small surface located in the center of the rock glacier exhibit this pattern of deformations. This finding is consistent with Vespermeanu-Stroe *et al* (2012) classification, where Judele is considered active, Ana de Jos inactive/relict, and Pietrele and Valea Rea glaciers are complex.

5.2 Geomorphology Discussion

This study confirmed that in the Southern Carpathians active rock glaciers still exist above 2000 m, at more than 500 m lower than in the European Alps (Delaloye and Morand 1998; Lambiel and Reynard 2001; Baroni *et al* 2004; Nyenhuis *et al* 2005; Kellerer-Pirklbauer *et al* 2012; Krainer and Ribis 2012; Seppi *et al* 2012; Scotti *et al* 2013). This significant anomaly could be explained by the increased continentality effects towards the east, resulting mainly in lower precipitation and higher temperature amplitudes between cold and warm seasons. The evolution of ground surface temperatures and air temperature regimes recorded in Retezat

Mountains in the last years (Onaca *et al.* 2015) revealed that the lowest temperatures are generally recorded in December when the snow cover layer is missing or is too thin to prevent the conductive heat loss (Hoelzle *et al* 1999; Juliussen and Humlum 2008). In contrast, the snow melting occurs rather late in the midsummer because the heaviest snowfalls occur during spring in the Southern Carpathians, leading to air stratification and low conductivity of the ground. As a consequence, non-conductive heat fluxes prevail at the surface of the ground during the period of snowmelt, preventing the ground from heating up (Bernhard *et al* 1998). Compared to other rock glacier mean velocities reported internationally (Roer *et al* 2005), those measured in the study area are much lower, probably because the ground ice content is reduced. The geophysical investigations revealed the active layer is very thick in the Pietrele rock glacier (among others, see Onaca *et al* 2013). The unfrozen boulder mantle could reach 8–10 m, whereas the frozen core is thin, so the shear stress is much too weak to allow significant deformation (Barsch 1996). The reduced internal deformations could be determined by the high debris content within the rock-ice matrix, which could lead to an increase in the basal stress (Azizi and Whalley 1995). Based on our results, it seems that Pietrele is gradually becoming an inactive rock glacier, since displacements higher than 1 cm/yr on its surface only occur in isolated areas. This inactivation is likely the result of permafrost degradation through temperature increase since the Little Ice Age. In fact, Barsch (1996) reported other rock glaciers situated at the lower limit of discontinuous mountain permafrost, which became inactive during several decades in the 20th century (e.g., Val Sassa, Albana).

5.3 The Small Scale Spatial Variability

A clear explanation of the spatial variability, especially when coupled with temporal variability of horizontal velocities is extremely problematic since (i) a large number of factors influence rock glacier rheology and (ii) there are limited data available for this study (Haeberli 1985). Locally varying antecedent conditions, including lithology, ground ice distribution, hydrology, water body volume, vegetation, slope aspect, and topography—all could play an important role in setting up the dynamic patterns of the area in addition to large scale climatic patterns that alter ground surface temperature. While the higher displacements in portions of the studied rock glaciers could be due to higher slope and the accompanying enhanced geomorphological activity, we do not believe that mass wasting can account for all of the movement. It is generally accepted that the increase of ground temperatures has resulted in a significant immediate or a delayed acceleration of dynamics (Roer *et al* 2005).

According to Haeberli (1985), the creep rates are strongly controlled by composition and internal structure, surface slope, thickness of the ice-rich frozen layer, and ground temperatures. Because MAGST revealed interannual variation up to 1 °C, or even more in the investigated rock glaciers in recent years (Onaca 2013), it is possible that ground temperatures might also vary significantly from one year to another. Therefore, it is expected that ground temperature variations, as a result of air temperature rising/decreasing, or changes in snow cover characteristics to increase or decrease rock glacier deformations. Previous studies (Frauenfelder *et al* 2004) showed that a rise in rock glacier ground temperature leads to an approximately exponential increase in surface speed. More recent studies reveal that significant acceleration produced by air temperature increases of close to 1 °C are followed by stagnation, if the ground temperatures continue to rise (Kääb *et al* 2007). Therefore, displacements observed during

individual years may be highly variable and may not represent the long-term, average movement of the rock glacier.

The small scale variability in the topo-climatic factors controlling the ground surface temperature results in a patchy distribution of permafrost within the investigated rock glaciers (Pietrele, Valea Rea, and Judele). Based on our measurements and observations, the most favorable conditions for permafrost occurrence are limited to those parts of the rock glaciers in which the size of the boulders is large, the incident solar radiation is reduced, and a local lateral circulation of air within the boulder voids is present.

The surface motion is extremely variable from one season to another, with intervals of accelerated movement (Figure 11) common. Results presented in Figure 7 also seem to indicate that the motion of Pietrele rock glacier has slightly accelerated between 2007 and 2014, probably as a consequence of consecutive warmer years (Figure 2). A higher content of water within this rock glacier, already close to the melting point, might have played a decisive role in this acceleration. In the Swiss Alps, the highest annual velocities occurred after very warm winters (e.g., 2001 and 2003) (Delaloye *et al* 2008). In other studies, a direct influence of MAAT on surface velocities was observed (Schneider and Schneider, 2001). In our case, the MAAT for interval 2007–2012 (0.5°C) is 0.9°C higher than the corresponding for interval 1968–2012 (-0.4°C).

Liu *et al* (2013) found that seasonal variation of surface flow speed detected via InSAR was significant at the Mount Gibbs rock glacier, being more than double from the spring to the maximum in the fall. When modeling, the estimated seasonal variation was less than 10%; however, Delaloye *et al* (2010) found that "seasonal fluctuations could be high, sometimes

exceeding 50% of the annual mean” which also seem to be the case for the investigated rock glaciers in the Southern Carpathians.

Results of all these investigated methods appear to be consistent with field observations documented by Onaca *et al* (2013) and Vespremeanu-Stroe *et al* (2012) regarding permafrost occurrence at these sites. Because of intrinsic limitations (e.g., in case of radar, small SAR stack and detection only in line-of-sight direction; in case of optical assumptions in processing Corona data, limited acquisitions), complete characterization should involve future image acquisitions and field characterizations. However, it seems that local micro-topography and grain size of the surface substrate indirectly influence dynamics, since they control the ground surface regime and thus permafrost preservation in marginal periglacial environments. The open rock structures characterized by a high porosity favour ground cooling and permafrost occurrence, allowing an efficient cooling by air convection/advection in winter and causing relative insulation in summer.

6. Conclusions

The analytical approach based on a combination of optical and radar remote sensing technologies allowed characterization of the rock glacier movement in a mountainous area of Eastern Europe where information on glacier rock dynamics is scarce or completely absent. Specifically, our analysis provided temporal data showing that rock glaciers in the Southern Carpathian Mountains are experiencing very low movement velocities with mean annual speeds of only a few cm per year.

Displacement rates are extremely low compared with other active rock glaciers from all over the world, probably because the deforming frozen layers are very thin. Despite their relatively slow movement, it appears that Judele, Valea Rea, and Pietrele are still active rock glaciers, but are in

disequilibrium/imbalance with the current climate. These findings document the lowest altitude and easternmost active rock glaciers at this latitude from Europe.

An increase in horizontal velocities between 2007 and 2014 was captured for the Pietrele rock glacier. It seems this acceleration is mainly controlled by the persistence of warmer air temperatures since 2006. Our findings showed that permafrost from the Southern Carpathians is extremely sensitive to environmental changes and responds strongly to air temperature fluctuations. Our results also document intra-annual/seasonal variations in rock glacier dynamics. The seasonal fluctuations are high in several locations from Pietrele, where rates of movement may exceed 50% of the annual mean. The highest rates of horizontal velocities occur in late summer and autumn, similar to seasonal movement patterns previously identified in the Alps.

The link between climate change and rock glacier dynamics is complex and acts at various spatial and temporal scales. The results of this research could be widely applicable to other regions, with widespread implications for understanding the effects of climate change on rock glaciers around the world.

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1072 **List of Figure Captions**

- 1073 **Figure 1.** Geographical location of the test area within the Southern Carpathian Mountains,
1074 Romania (inset). Geographical distribution of the largest nine rock glaciers located in the central
1075 part of the Retezat Massif. Background data: high resolution panchromatic satellite imagery
1076 acquired by WorldView-1 on July 20, 2012.

1077 **Figure 2.** Climate data at Retezat-Godeanu mountain group over a 40-year period. Mean annual
1078 air temperature data (left) Mean annual precipitation data (right).

1079 **Figure 3.** Examples of a relatively stable feature [(a) and (b) – dwarf shrub, (c) and (d) –
1080 boulder] used as tie points to precisely co-register remotely sensed imagery. (a) and (b): 2012
1081 master image; (c) and (d): 2007 slave image. Each image chip is ~180m x ~200m.

1082 **Figure 4.** Pairs (interferograms) processed of ALOS PALSAR images processed by SBAS.
1083 Time versus relative position. One dataset acquired on 17 July 2007 (i.e., yellow dot in the
1084 graphs) had been chosen as the super master dataset.

1085 **Figure 5.** Pietrele rock glacier (a) 1968 Corona (b) 2007 SPOT 5 (c) 2012 Worldview-1 and (d)
1086 2014 Pléiades PAN images. To facilitate image interpretation, histogram matching was
1087 performed with reference to the 2007 image. For consistency, pixel size was set to 2.5 m. The
1088 size of the image chips is ~650 m x ~900 m.

1089 **Figure 6.** Estimated displacement field for the Pietrele rock glacier for (a) 7 years (2007–2014)
1090 and (b) 44 years (1968–2012). Vectors were determined by a 5 x 5 pixels moving average
1091 window, with a step of 3 pixels. Background image: B1, B2, B3 Pléiades MS data acquired on
1092 23 September 2014.

1093 **Figure 7.** Probability density of the velocity measurements over active and stable patches of
1094 Pietrele rock glacier. The negative values are a consequence of the projection operator, as the
1095 noise is kept Gaussian in this representation.

1096 **Figure 8.** (a) InSAR coherence analysis based on a ALOS PALSAR FBD pair (HH channel)
1097 collected approximately 3 years apart. Low coherence is attributed to various factors, including

1098 the potential nonlinear dynamics of areas within the boundaries of the rock glaciers. Pietrele,
 1099 Valea Rea, Judele, and Ana de Jos seem to be least affected by radar layover and foreshortening
 1100 effects. Data are presented in slant range geometry. Coherence windows size is 5 x 5. (b)
 1101 Pléiades DEM slope of the area was provided for a visual comparison with the local topography.

1102 **Figure 9.** (a) BTS mapping (March 2013) and ERT profiles on the Pléiades satellite image, (b)
 1103 InSAR coherence analysis indicating patterns with possible line-of-sight (LOS) dynamics for the
 1104 Pietrele rock glacier V-possible effects of vegetation, (c) ERT inverted profile (after Onaca
 1105 2015) , and (d) correlation between coherence and BTS values.

1106 **Figure 10.** The SBAS InSAR result using a stack of ALOS PALSAR images. (a) The color of
 1107 individual SBAS point locations corresponds to an LOS displacement difference between years
 1108 2007 and 2008. Colors denote rock glacier activity: blue and light green–active, red and
 1109 orange–inactive. Same scale was maintained over each rock glacier.

1110 **Figure 11.** The SBAS InSAR result from the Pietrele rock glacier using a stack of ALOS
 1111 PALSAR images. (a) The color of individual SBAS point locations corresponds to the
 1112 difference of 2007–2008 average LOS displacement rates. Negative values indicate motion
 1113 away from the satellite. Background: Pléiades orthorectified image was acquired on 28
 1114 September 2014. (b) Direction of acquisition of satellite data (incidence angle = $\sim 34.3^\circ$, LOS
 1115 azimuth = $\sim 14^\circ$). (c) Perspective view of the area. (d) Displacement trends of three
 1116 representative SBAS point locations (displacements values are referenced to 17 July 2007).

1117 **Figure 12.** Time series of the mean monthly air temperature (blue diamond) and the InSAR
 1118 LOS displacement estimates and their associated error bars at SBAS point locations 239 on the
 1119 Pietrele rock glacier (Figure 11).