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Slow-moving rock glaciers in marginal periglacial environment of Southern Carpathians

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Abstract. Rock glaciers, composed of debris and ice, are widely distributed across cold mountain regions worldwide. Although research on rock glaciers is gaining momentum, the distinct behaviour of rock glaciers in the marginal periglacial environments remains poorly understood. In this study, we combine remote sensing and in situ methods to gain insights into the characteristics of transitional rock glaciers in the Carpathian Mountains. We applied Persistent Scatterer Interferometry (PSInSAR) to Sentinel-1 images from 2015 to 2020 to identify areas with slope movements associated with rock glaciers and differential GNSS measurements (2019-2021) to detect the horizontal movement of 25 survey markers. Continuous ground temperature monitoring and measurements of the bottom temperature of the winter snow cover were used to examine the energy exchange fluxes characteristics of transitional rock glaciers in the Carpathians. The subsurface of one transitional rock glacier was investigated using geophysical measurements (electrical resistivity tomography and refraction seismic tomography), while petrophysical joint inversion was used to quantify the ice content. The PSInSAR methodology identified 110 moving areas (MAs) with low displacement rates (< 5 cm yr^{-1}). These MAs are generally located between 2000 and 2300 meters where solar radiation is minimal. Late winter ground surface temperature data from slow-moving rock glaciers point to permafrost conditions. Geophysical investigations reveal remnants of ice-rich permafrost within the Galeșu rock glacier, while petrophysical joint inversion modelling indicates a low ground ice content (~ 20 %) in its upper sector. The slow surface movement of rock glaciers in the marginal periglacial mountains is driven by the deformation of thin, frozen layers. Regarding activity status, the majority of rock glaciers in the Retezat Mountains are categorized as relict, with only 21% classified as

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transitional. The results of our study emphasize the benefit of combining Sentinel-1 SAR data with comprehensive field investigations, particularly in regions with slow-moving rock glaciers.

1 Introduction

In high mountains, ice-rich permafrost occurrence is usually associated with rock glaciers (Haeberli et al., 2006). Rock glaciers are masses of debris-ice mixture common in many cold mountains of the Earth (Kääb, 2013). The coarse debris surface of rock glaciers favours ground cooling and contributes decisively to preserving permafrost over long periods (Harris and Pedersen, 1998; Gruber and Hoelzle, 2008). Due to the insulating effect and thermal inertia of the thick coarse blocky layer, these landforms are more resilient to climatic changes than glaciers (Barsch, 1996; Kenner and Magnusson, 2017). This is the main reason why ground ice is sometimes present in rock glaciers occurring below the regional limit of permafrost in locations with positive mean annual air temperature (MAAT) (Popescu et al., 2017; Colucci et al., 2019).

The surface kinematics of rock glaciers have garnered significant interest from the international community in recent years (Bearzot et al., 2022) due to the growing need to better understand how mountain permafrost responds to ongoing climate change. While the response of rock glaciers to present-day air temperature rising is intricate in many instances, increased rock glacier velocities has been observed due to warmer climate (Wirz et al., 2016; Cicoira et al., 2019; Kenner et al., 2019; Kääb et al., 2021; Marcer et al., 2021). Annual rates of horizontal surface kinematics of rock glaciers range from a few millimetres to a few meters (Strozzi et al., 2020), though occasional accelerations can result in velocities exceeding ten meters per year (Vivero et al., 2022). Additionally, recent research has highlighted the increased sensitivity of permafrost to rising subsurface temperatures (Haberkorn et al., 2021; Etzelmüller et al., 2023). While the state of rock glaciers in discontinuous permafrost has undergone extensive study, the distinctive behaviour of rock glaciers in marginal periglacial environments has rarely been addressed (Serrano et al., 2010; Necsoiu et al., 2016). Here, rock glaciers exhibit no movement or considerably slower movement rates (a few cm yr^{-1}) and are also referred to as transitional rock glaciers (RGIK, 2023). Because the ice content in this category of rock glaciers is below a critical saturation threshold, the shear stress is too weak to induce fast creep-like movement (Barsch, 1996).

Many studies have demonstrated the feasibility of satellite radar interferometry (InSAR) for kinematic analysis of rock glaciers, capable of detecting motion at the millimetre scale (Liu et al., 2013; Necsoiu et al., 2016; Strozzi et al., 2020; Bertone et al., 2022;). This technique enables the mapping of land surface deformation with an appropriate spatial and temporal resolution over vast areas (Bertone et al., 2022). In marginal periglacial environments, low surface movement rates are observed mostly in small areas of limited extent within the rock glaciers (Onaca et al., 2017a). Identifying and delineating these relatively small moving areas is especially significant in regions with sporadic or isolated permafrost, as it may be strategically valuable for documenting the last areas bearing ground ice.

Despite the growing focus on rock glacier research, there is still a limited understanding of the transitional rock glaciers behaviour. Even if slow-moving rock glaciers were documented in various regions of the world (Brencher et al., 2021; Bertone et al., 2022; Lilleøren et al., 2022; Lambiel et al., 2023), the relationship between their velocity and ground ice content was rarely addressed (Serrano et al., 2010). Since borehole information is limited in high and remote mountains, a promising alternative to quantitatively estimate ground ice content is using petrophysical joint inversion (PJI) of seismic refraction and electrical resistivity data (Wagner et al., 2019).

The Southern Carpathian range is a key region in Europe where transitional rock glaciers are studied. Here, the enhanced continentality effects induce a distinct pattern of manifestation of periglacial phenomena compared with other mid-latitude mountains in Europe. In marginal periglacial mountains, permafrost occurrence is generally patchy (Popescu et al., 2024) and site-specific characteristics highly control its distribution (Stiegler et al., 2014; Onaca et al., 2015; Kellerer-Pirklbauer, 2019). Recent climatological analysis confirms that the Southern Carpathians are facing significant warming in the last decades (Micu et al., 2021).

The paper aims to present new results on the rock glaciers dynamics and permafrost characteristics in the Retezat Mountains and, more broadly, to better understand the behaviour of rock glaciers in marginal periglacial mountains. To achieve this goal, we will (i) locate and assess the kinematics of rock glaciers` moving areas using SAR-based persistent scatterers interferometry (PSInSAR); (ii) update the existing rock glacier inventory in the Retezat Mountains with information on the rock glacier dynamics; (iii) estimate ground ice content using petrophysical joint inversion based on electrical resistivity and seismic refraction data and (iv) characterise the thermal conditions at the rock glaciers surface.

2. Study area

The Retezat Mountains are among the highest massifs in the Romanian Carpathians, constituting a distinct part of the Southern Carpathians (the latter are also known as the Transylvanian Alps). Located in the western part of the Southern Carpathians (45°22' N and 22°53' E), the Retezat Mountains reaches elevation of 2500 m, revealing a typical alpine landscape (Fig. 1). The climate in this region can be characterised as a moderate temperate continental climate, classified within the subarctic or boreal category according to the Köppen classification system. At 2000 to 2100 m elevations, the mean annual air temperature hovers around 0° C, with annual precipitations typically around 1000 mm (Onaca et al., 2017a).

The mountain range is part of the orogenic units spanning two distinctive tectonic-structural regions: the Danubian Domain and the Getic Domain, both with the status of a thrust sheet. The Danubian Domain, referred to as the Danubian Autochtonous, is primarily characterised by two dominant granitic bodies, Retezat and Buta (Pavelescu, 1953). These granitic bodies are surrounded in the marginal area by epi- and meso-metamorphic schists, typifying the Getic Nappe. Specific Mesozoic rocks, particularly limestones, are prevalent in the southern part of this mountain range (Urdea, 2000). 87% of the rock glaciers in the Retezat Mountains have developed on granites (Fig. 2), while the remaining landforms are found on metamorphic schists.

The Retezat Mountains boast one of the most comprehensive and distinct arrays of glacial and periglacial landforms in the Romanian Carpathians. Notably, they host the largest glacial cirques in the Romanian Carpathians, with a combined area of

https://doi.org/10.5194/egusphere-2024-3262
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all glacial cirques amounting to c. 8 % of the massif's total area (Urdea, 2000). During the Last Glacial Maximum (LGM) (20.6 ka), glaciers in these mountains reached lower elevations ranging from 1000 to 1300 m (Ruszkiczay-Rüdiger et al., 2021).

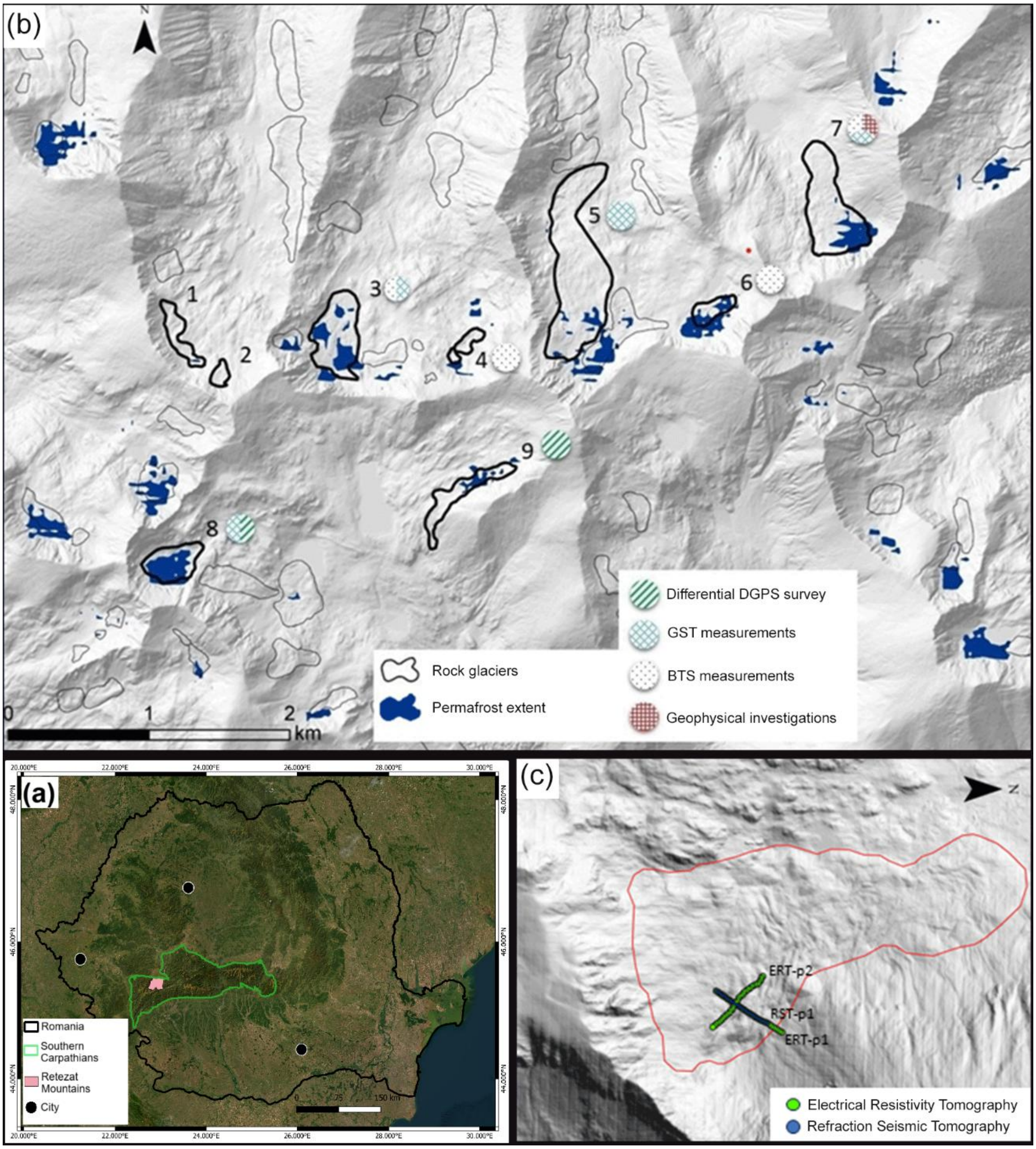

Figure 1: Study sites. (a) Overview map with the location of the Retezat Mountains in the Southern Carpathians and in Romania, background of the map: ESRI Satellite. (b) modelled permafrost distribution (Popescu et al., 2024) and spatial distribution of rock glaciers in the Retezat Mountains overlaid on a hillshade based on the LAKI II DEM (LAKI II MNT, 2024). The rock glaciers that are discussed in the present paper are numbered (1 - Stânișoara, 2 - Bucura, 3 - Pietrele, 4 - Pietricelele, 5 - Valea Rea, 6 - Păpușa, 7 - Galeșu, 8 -Judele, 9 -Berbecilor), and the ground based measurements that have been performed on each of them are represented by a composite symbol near the number. (c) A detailed map with the position of the geophysics profiles on Galeșu rock glacier; note: same background image as (b).

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

Subsequently, the Late Glacial period witnessed five phases of deglaciation. However, no glacial advance has been observed in the central part of the Retezat Mountains during or after the Younger Dryas (Ruszkiczay-Rüdiger et al., 2021). Permafrost associated with rock glaciers has been documented since 1993 in this mountain range (Urdea, 1993). A recent inventory described Retezat Mountains as the range with the highest number (94) and density (0.52 landforms/km^2, and 2.87 ha/km^2 at altitudes above 1540 meters) of rock glaciers in the Romanian Carpathians (Onaca et al., 2017b) (Fig. 1). Additionally, they harbour the longest Carpathian rock glacier, Valea Rea, extending 1.4 km (Urdea, 2000) (Fig. 2b).

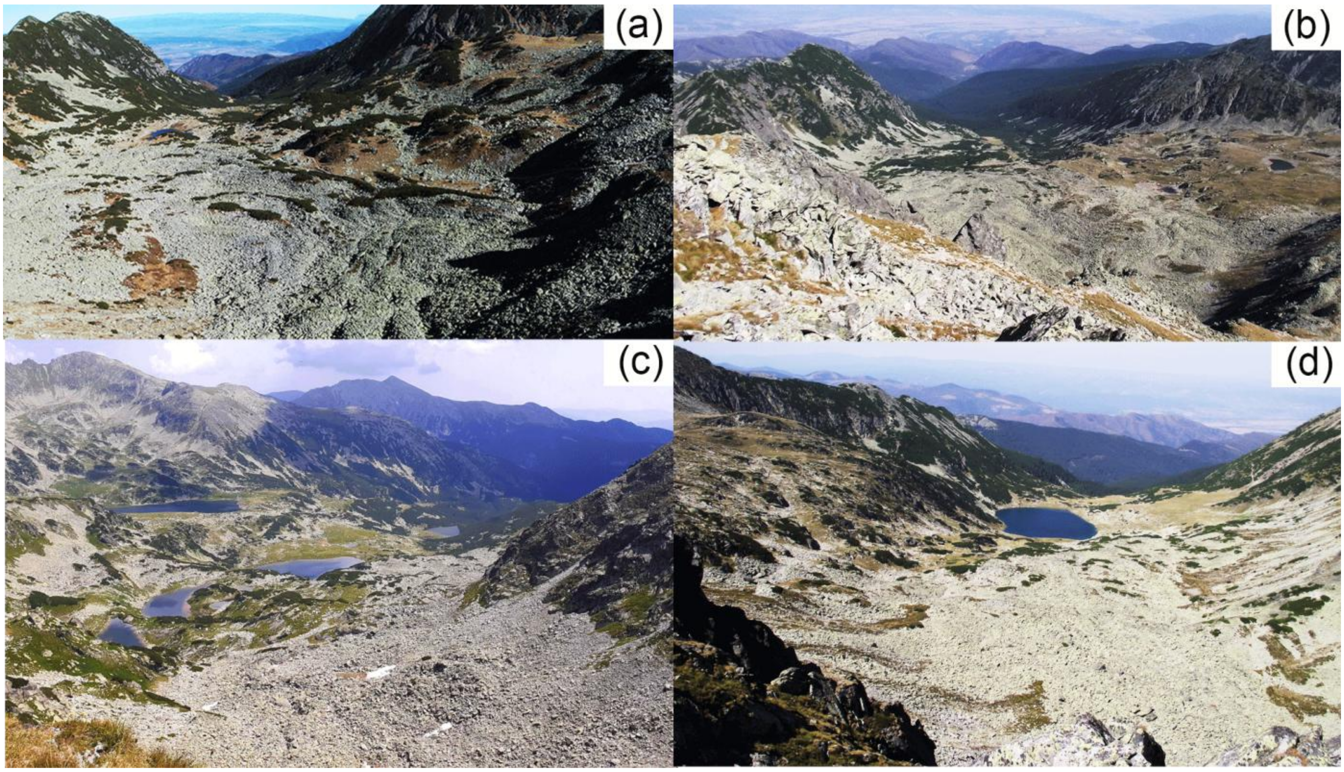

Figure 2: Pictures of the rock glaciers in the Retezat Mountains: (a) Pietrele; (b) Valea Rea; (c) Judele; (d) Galeșu. Photo credit: A. Onaca.

3. Methods

3.1. Rock glacier inventory

This study used the rock glacier polygons for the Retezat Mountains from the comprehensive inventory of the Southern Carpathians (Onaca et al., 2017b). The inventory involved mapping rock glaciers through fieldwork surveys and detailed examination of high-resolution aerial imagery. Due to the availability of kinematic information for only a limited number of landforms (Vespremeanu-Stroe et al., 2012; Necsoiu et al., 2016), the current inventory lacks data on the activity of rock glaciers. Information on rock glacier kinematics was only available for a few landforms (Vespremeanu-Stroe et al., 2012;

Necsoiu et al., 2016), while most of the rock glaciers were classified as either intact or relict based on geomorphological and ecological criteria.

Rock glaciers are categorised into three types based on their activity status: active, transitional, or relict, as outlined by (RGIK, 2023). Active rock glaciers exhibit horizontal displacements exceeding 10 cm yr^{-1} at their fronts and across substantial portions of their surface (Barsch, 1996). Rock glaciers with little to no movement (< 1 cm yr^{-1}) are classified as relict, while those with displacement rates between 1 - 10 cm yr^{-1} are considered transitional (RGIK, 2023).

3.2. Persistent scatterer interferometry using Sentinel-1 data

PSInSAR is a technique developed to measure displacements in the radar line of sight (SAR LOS) with millimetric accuracies, similar to GNSS (Rucci et al., 2012; Yu et al., 2020). Although Sentinel-1 (S1) SAR data does not offer the highest possible spatial resolution, its worldwide periodic coverage and open data policy have enabled wide-scale monitoring since 2014, leading to a thriving archive of ground-motion products with various applications.

Sentinel-1 serves as the backbone of the operational PSInSAR application development for the European Ground Motion Service (EGMS), openly available throughout the entire European area. The algorithms employed in this work closely resemble those described in EGMS Algorithms, with a few notable differences described below. Figure 3a illustrates the total coverage (from all available S1 paths from both the Ascending and Descending orbits) of the EGMS product in the area of interest, while Figure 3b illustrates the coverage of Terrasigna's PSInSAR analysis of the same area, derived in this study solely from one S1 path (Path 80 Descending). It is evident that EGMS coverage appears sparse and lacks dynamic areas (no areas red-coloured), whereas Terrasigna's PSInSAR coverage is notably dense, capturing dynamic areas comprehensively (depicted red colours).

In this study, the dynamics of the rock glaciers were assessed using 181 images acquired between May 15, 2015, and October 4, 2021, covering only the snow-free periods to avoid coherence loss. The motion was measured along the SAR LOS direction, but it could have also occurred along the slope or in the vertical direction. The PSInSAR algorithm, as described by Rucci et al. (2012), Crosetto et al. (2016) and Poncoș et al. (2022), preserved all displacement information to maximize the chances of detecting slow movements (mm yr^{-1}) in areas without vegetation cover. The process began by extracting linear deformation information before applying any spatial or temporal filtering, which is typically used to improve phase statistics. A key challenge is that the atmospheric phase is two orders of magnitude larger than the displacement signal (Poncoș et al., 2022), requiring meticulous phase unwrapping and correction of each residual interferogram. Due to significant atmospheric noise in steep terrain, a reference point at a similar elevation to the rock glaciers was chosen on the mountain plateau, reducing atmospheric differences and enabling PSInSAR measurements to cover the summits.

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

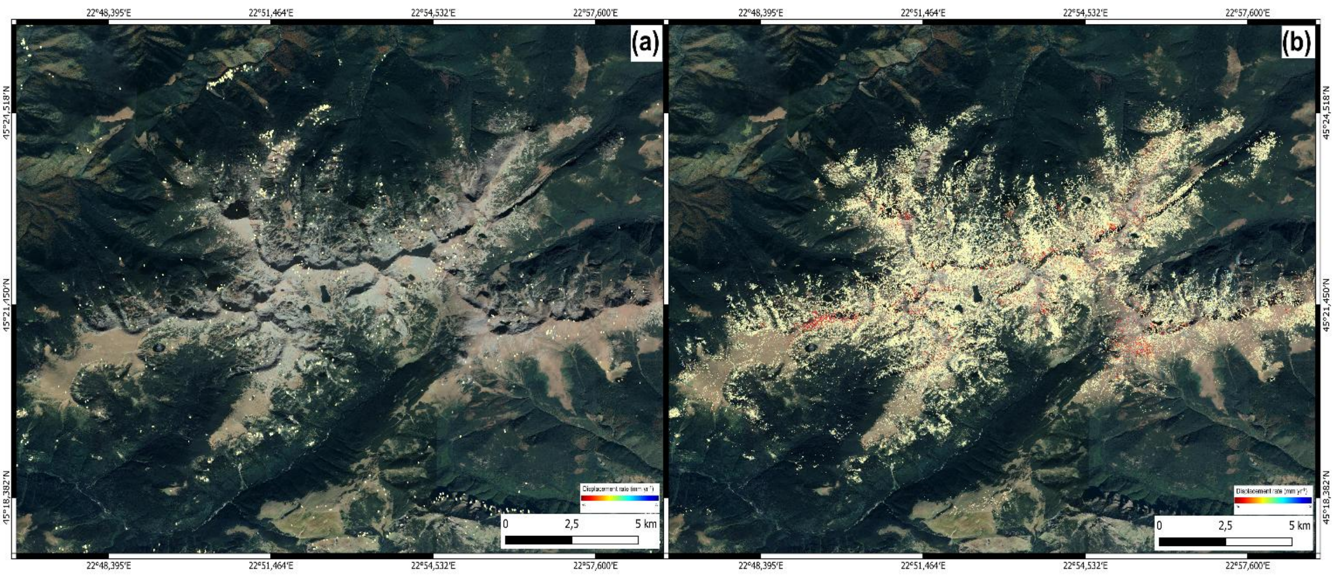

Figure 3: Comparison between the PSInSAR spatial density of measurements obtained by EGMS (a) and Terrasigna (b). Background of both maps: ESRI Satellite.

The PSInSAR results are analysed using the Persistent Scatterers Online Software Tool (PSTool), a web-based platform developed by Terrassigna Inc. (Poncoș et al., 2022), to exploit a large volume of ground displacement data. The PSTool platform can be used to inspect temporal characteristics of the ground motion, select areas of interest and extract temporal averages of displacement rates, export temporal profiles to standard formats for integration in the user's own platforms and upload user-specific layers on top of the displacement information.

3.3. Inventorying moving areas

According to previous studies, a moving area (MA) represents an area at the surface of the rock glacier characterised by relatively homogeneous velocity rates and consistent flow direction (Bertone et al., 2022). Based on the multi-annual surface velocity rates, MAs were identified and delineated within the inventoried rock glaciers (Onaca et al., 2017b). The next step was to assign velocity classes to moving areas considering the standardised velocity classes (Barboux et al., 2014; Bertone et al., 2022). In our case, MAs were attributed to one of the following SAR LOS deformation velocity classes: undefined, < 1 cm yr^{-1}, 1-3 cm yr^{-1}, and 3-10 cm yr^{-1} (Barboux et al., 2014) (Fig. 4). The undefined category was assigned to MAs characterised by heterogeneous velocity rates, such as areas affected by shadows and layover. PSInSAR-based surface displacement of ≤ 0.3 cm yr^{-1} were assigned to the "no movement" category, as this threshold was considered the lower limit of velocity detection on S1 interferograms in this type of approaches (Rouyet et al., 2021). Because the number of identified moving areas was relatively low in the study area, we have manually compiled the inventory of moving areas in ArcGIS 10.8. Although permafrost in marginal conditions may occur as patches with a relatively small extent, the minimum size of an MA considered in this study was 300 m^2. For the spatial analysis of the rock glaciers and MAs, we used a one-meter resolution digital elevation model generated from high-resolution LiDAR source data (LAKI II MNT, 2024).

3.4. Validation with GNSS measurements

Judele and Berbecilor rock glaciers have been surveyed by DGPS measurements every summer between 2019 and 2021. A differential dual-frequency Topcon Hiper V GPS has acquired high-precision positioning data in real-time kinematics mode. The DGPS device uses two receivers, one installed as a fixed base station, whereas the roving receiver is moved to different points of interest in the field. The mobile receiver gets the corrected position information calculated by the base station via a radio signal in order to measure a point with very high precision (i.e. < 1 cm accuracy in the horizontal plane). 25 survey markers were measured in October 2019 and remeasured in October 2020 and 2021.

3.5. Validation with ALOS-2 PALSAR-2 interferometry

To further validate the Terrasigna's PSInSAR analysis specifically developed for this study we considered a series of six ALOS-2 PALSAR-2 images regularly acquired between 2014 and 2019 at the end of the snow-free season in September and October. We computed wrapped differential interferograms with time intervals ranging from one to five years using a DEM with 10 m pixel spacing. For the interpretation of the interferograms, we followed the practical guidelines of the IPA Action Group Rock glacier inventories and kinematics (RGIK, 2023).

3.6. Thermal conditions

The bottom temperature of the winter snow cover (BTS) is an efficient method to map permafrost distribution in non-arid mountains (Vonder Mühll et al., 2002). If optimum snow conditions are met, the BTS values indicate probable permafrost at < -3 ºC, possible permafrost at -2 to -3 ºC and absence of permafrost at > -2 ºC (Haeberli, 1973; Hoelzle, 1992; Popescu et al., 2024). Two classical 2.6 m long BTS probes equipped with digital thermometers (0.5 ºC precision) were used to measure 140 thermal records at the snow-ground interface. The BTS measurements were acquired at the end of March 2022 on four rock glaciers in three north-facing valleys in the central part of the Retezat Mountains (Fig. 1). At all the sites where BTS values were recorded, the snow was sufficiently thick (> 80 cm) to insulate the ground from external air temperature fluctuations (Ishikawa et al., 2003). Previous studies in the Southern Carpathians (Vespremeanu-Stroe et al., 2012; Onaca et al., 2015) revealed that in March, BTS values remain nearly constant below a thick snow cover, which usually falls in November or December.

Minimal temperature data loggers became widely used in mountain permafrost terrain to get more detailed insights into the energy exchange fluxes at the surface of rock glaciers (Hoelzle et al., 1999). Four rock glaciers in the central part of the Retezat Mountains were selected to monitor the thermal regime at the ground surface (Fig. 1b). The evolution of ground surface temperature (GST) was recorded using iButtons DS1922L data loggers. According to the producer, the miniature thermistors used in this study have an accuracy of ± 0.5 ºC and measure temperatures between -40 and 80ºC. The sensors were indirectly calibrated at 0 ºC using the snow melting period ("zero curtain" interval), and GST data were measured and logged every 2 hours. In mid and late winter, the ground surface temperature remains stable under a thick insulating layer, and the subsurface mainly controls the energy flux. This is why the "winter equilibrium temperature" (WEqT) is considered an excellent empirical predictor of permafrost existence if temperatures are low (i.e., < -2 ºC) (Sattler et al., 2016). WEqT and mean annual ground surface temperature (MAGST) were calculated for each GST monitoring site.

3.7. Geophysical Methods and PJI Modelling

Geophysical methods, such as electrical resistivity tomography (ERT) and refraction seismic tomography (RST), are widely applied in mountain permafrost studies and have the potential to characterise subsurface structure and heterogeneity and detect and map ground ice occurrences (Hauck et al., 2011; Herring et al., 2023). Both methods are sensitive to differences between frozen and unfrozen subsurface conditions. As ice can be considered an electrical insulator as opposed to water, the electrical resistivity increases exponentially with decreasing temperatures below 0 °C. Similarly, the seismic P-wave velocity of ice is with 3500 m s^{-1} significantly higher than that of liquid water (~ 1500 m s^{-1}) or air (330 m s^{-1}), allowing to differentiate between frozen sediments (containing ice) and unfrozen sediments (pore space filled with water or air).

ERT is the most common geophysical technique applied in permafrost research and is used for mapping permafrost occurrence where no borehole information is available, as well as monitoring changes in the ice-to-water ratio (Wagner et al., 2019; Mollaret et al., 2020). The RST method is often used as a complementary method to ERT to reduce the ambiguity in the interpretation of ERT data, as the P-wave velocity v_p is mainly controlled by density, and variations in v_p allow to identify porosity changes, or discriminate between liquid (water) and solid (ice) pore fluid, as well as in determining the depth to the bedrock.

In the absence of ground truth information about the state of permafrost, another advantage of geophysical data is, that co-located ERT and RST data can be used to quantitatively estimate the content of the four phases (i.e., rock, ice, water and air) using the so-called 4-phase model approach, which is based on the petrophysical equations by Archie (1942) for the electrical resistivity and that of Timur (1968) for the P-wave velocity.

Recently, the approach has been further developed by Wagner et al. (2019), to the so-called petrophysical joint inversion (PJI) framework, permitting the joint inversion of ERT and RST data sets to simultaneously solve for the subsurface distribution of the 4 phases. The main advantage of the PJI is the increased accuracy of the parameters estimated, as the algorithms iteratively search for a subsurface model that simultaneously explains the seismic and resistivity measurements. This is especially relevant for the porosity model, which is represented more realistically in the PJI than in previous versions of the 4-phase model (Hauck et al., 2011). Mollaret et al. (2020) demonstrated the applicability of the PJI for data collected on different alpine permafrost landforms with different ice contents.

In the field, 2D ERT data were collected using a GEOTOM (Geolog) multi-electrode instrument equipped with 50 electrodes spaced 4 meters apart. By combining a multitude of individual measurements with different electrode combinations (i.e. quadrupoles) along a profile line, a 2-dimensional resistivity model of the subsurface is obtained. All measurements were

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

performed in the Wenner configuration to ensure an optimal signal-to-noise ratio, which is especially important in dry and coarse-blocky terrain.

2-dimensional RST data were obtained using a 24-channel Geode seismometer (Geometrics). An artificial seismic wave is produced by hitting a sledgehammer to the ground, and the waves travel along different paths through the subsurface and back to the surface, where they are registered by 24 geophones. The subsurface structure and composition can be derived from the travel time the so-called P-wave needs from the source (i.e. hammer) to the geophones. The wave velocity (v_p in m s^{-1}), and thus the travel time, is basically a function of the density of the subsurface material, and the obtained seismic velocity allows inferring the subsurface material. The pre-processing of the seismic field data (picking of first arrivals) was performed using the software *ReflexW* (Sandmeier, 2020). The individual ERT and RST data sets were first independently inverted using the PyGimLi framework (Rücker et al., 2017), and in a second step, the PJI was conducted to estimate ground ice contents using the approach developed by (Wagner et al., 2019).

4. Results

4.1. Inventorying moving areas

In the Retezat Mountains the MAs have velocities ranging from 0.3 to 5 cm yr^{-1} (Fig. 4 and 5). A total of 110 MAs covering 0.31 km^2 were inventoried in the Retezat Mountains rock glaciers. Most of the MAs are classified with the slow velocity class (< 1 cm yr^{-1} and 1-3 cm yr^{-1}) (Fig. 6), while only 8 % of the MAs are characterised by velocity class 3-10 cm yr^{-1} (Fig. 6a). Around one-third (38 %) of the total number of rock glaciers in the Retezat Mountains contains MAs, but the analysis revealed they usually occupy only a small portion (< 30 %) of the total surface of each rock glacier; in only three cases, the cumulated area of MAs represents more than 50 % of the rock glacier area (Fig. 6d). The mean area of MAs is 0.29 ha, ranging from 0.03 to 1.77 ha.

The number of MAs in each rock glacier varies between 1 and 9, but in most cases (69 %), 1 to 3 MAs occur in an individual RG. MAs characterised by velocities > 3 cm yr^{-1} were identified in 8 rock glaciers, whereas MAs classified in the velocity class 1-3 cm yr^{-1} appear in 19 (Fig. 6c).

The median elevation for each MA class falls between 1950 and 2295 m (Fig. 7). Specifically, 60 % of the MAs are found in the elevation band of 2100 to 2200 m, while 19 % lie between 2200 and 2295 m. Additionally, 15.5 % of the moving areas are situated in the range of 2000 to 2100 m, and only 5.5 % are below 2000 m. Among these, MAs categorised under velocity classes of 1-3 and 3-10 cm yr^{-1} generally occur at the highest elevations (Fig. 7a). Figure 7b illustrates the variability of slopes across the MAs velocity classes, revealing mean values ranging from 7 to 42°. The widest range of slopes is observed in the velocity class < 1 cm yr^{-1}, while median values are higher in the Undefined category. Around half of the MAs (51 %) face north (Fig. 8), despite that only 21 % of the inventoried rock glaciers in the Retezat Mountains stand out on the northern aspects. The NE and E slopes host more MAs (32 %) compared to NW and W aspects (22 %) in respect with the rock glacier distribution (Fig. 8). The MAs with velocities exceeding 3 cm yr^{-1} receive the lowest potential solar radiation (Fig. 7c).

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

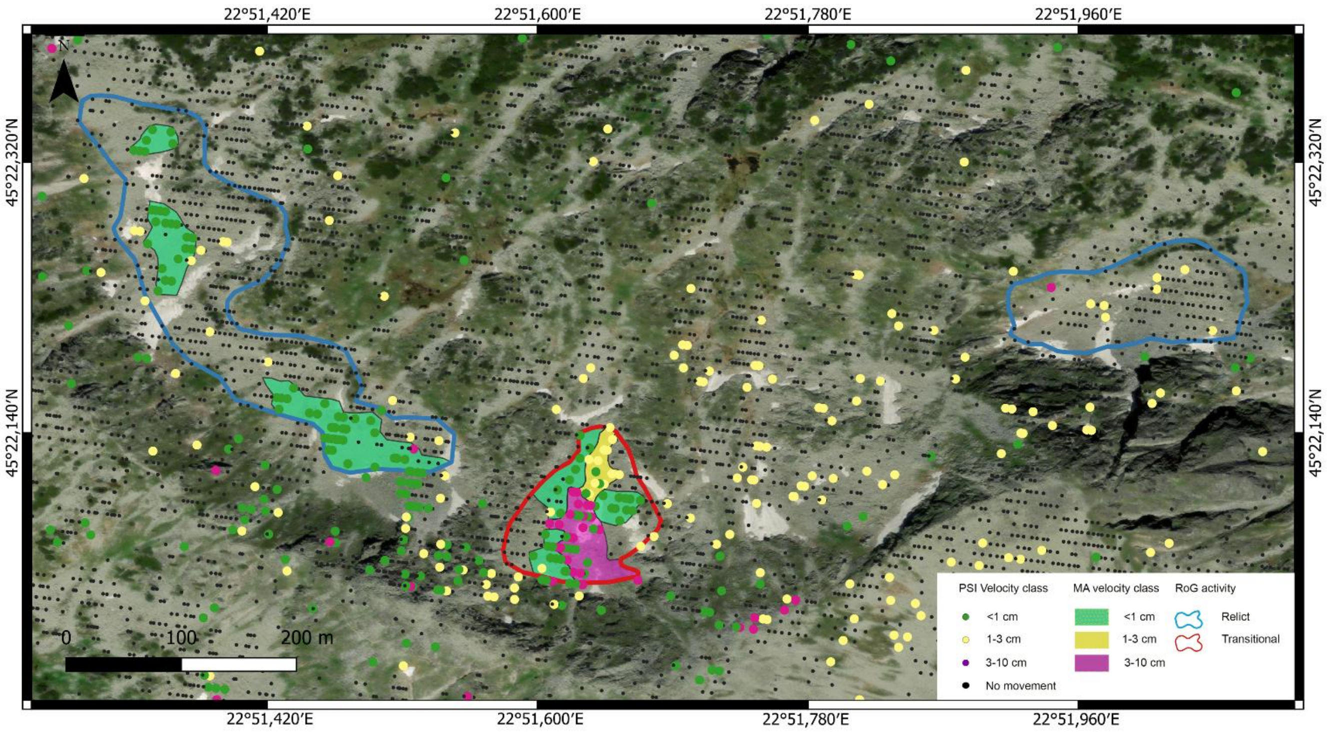

Figure 4: Example of moving areas and rock glacier activity for the Retezat Mountains. Background image: ESRI Satellite.

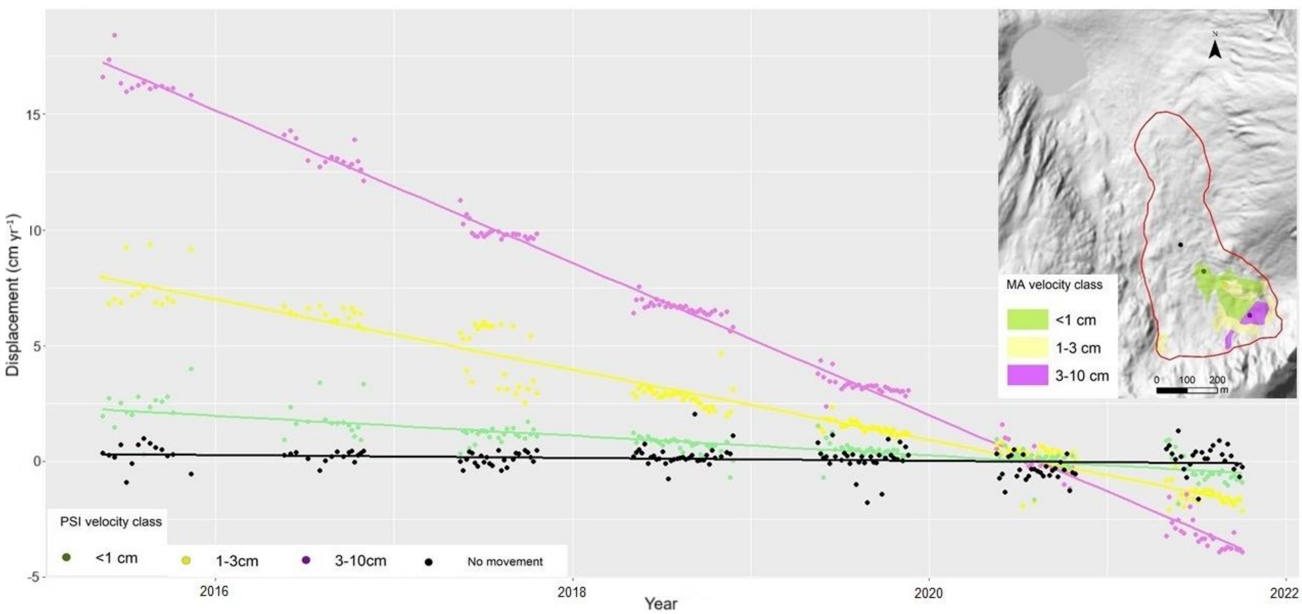

Figure 5: Average of 7 displacement profiles extracted from PSTool in the Retezat Mountains (Galeșu rock glacier).

https://doi.org/10.5194/egusphere-2024-3262
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For rock glaciers exhibiting no or minimal movement (< 1 cm yr^{-1}), the RGIK (2023), recommends assigning a relict activity class. The present analysis shows that only 21 % of the rock glaciers in the Retezat Mountains could be classified as transitional (Fig. 9a), encompassing areas with moving velocities ranging between 1 and 5 cm yr^{-1}. The transitional rock glaciers exhibit a median elevation of 2170 m, surpassing that of the relict ones by 150 m (Fig. 9b). Additionally, the median size of transitional rock glaciers is one-third larger than relict rock glaciers (Fig. 9c).

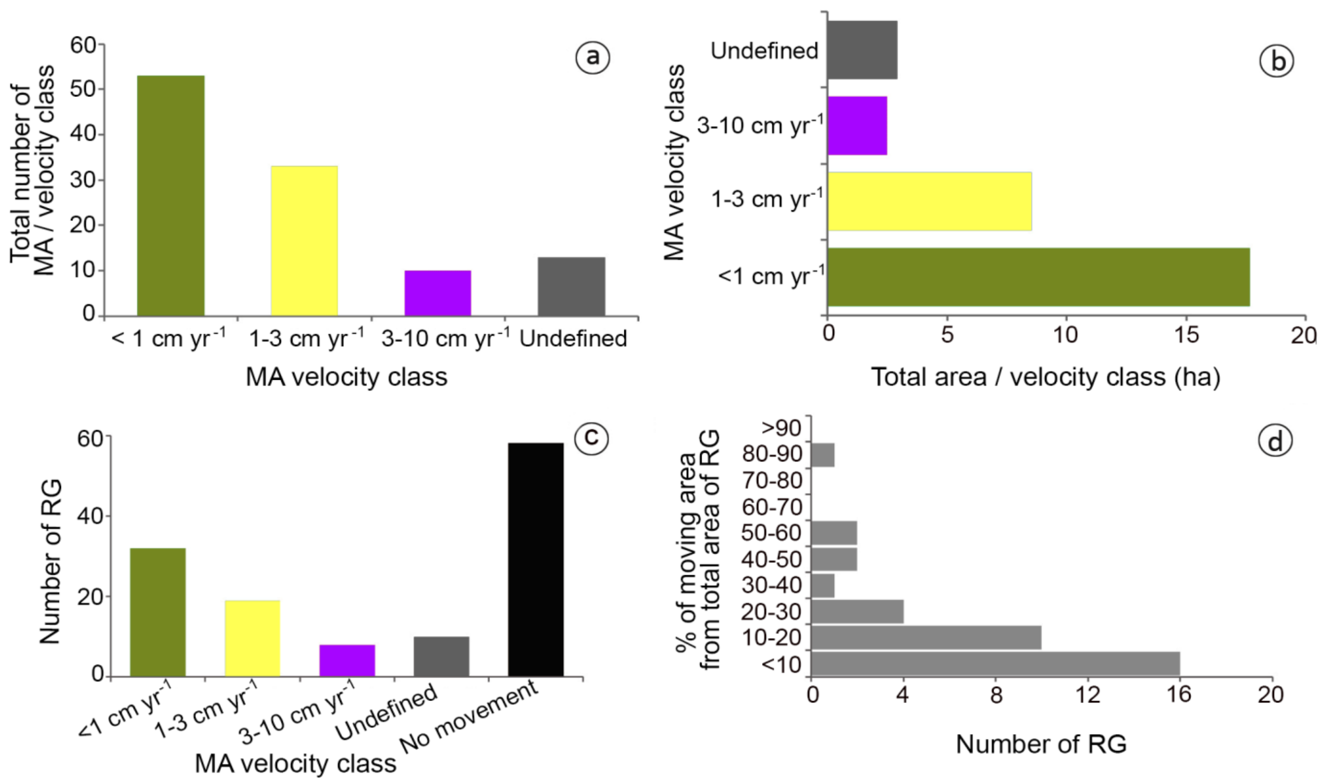

Figure 6: The moving areas classified by velocity classes (a) and their extent (b). The number of rock glaciers containing moving areas and without moving areas (c) and the percentage of the moving area cover within rock glaciers (d).

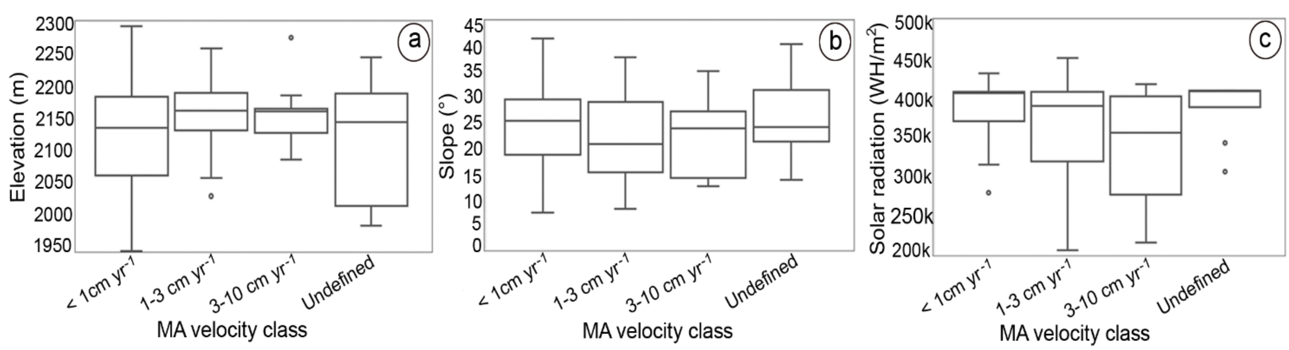

Figure 7: Elevation (a), Slope (b) Potential solar radiation (c) vs MA velocity classes

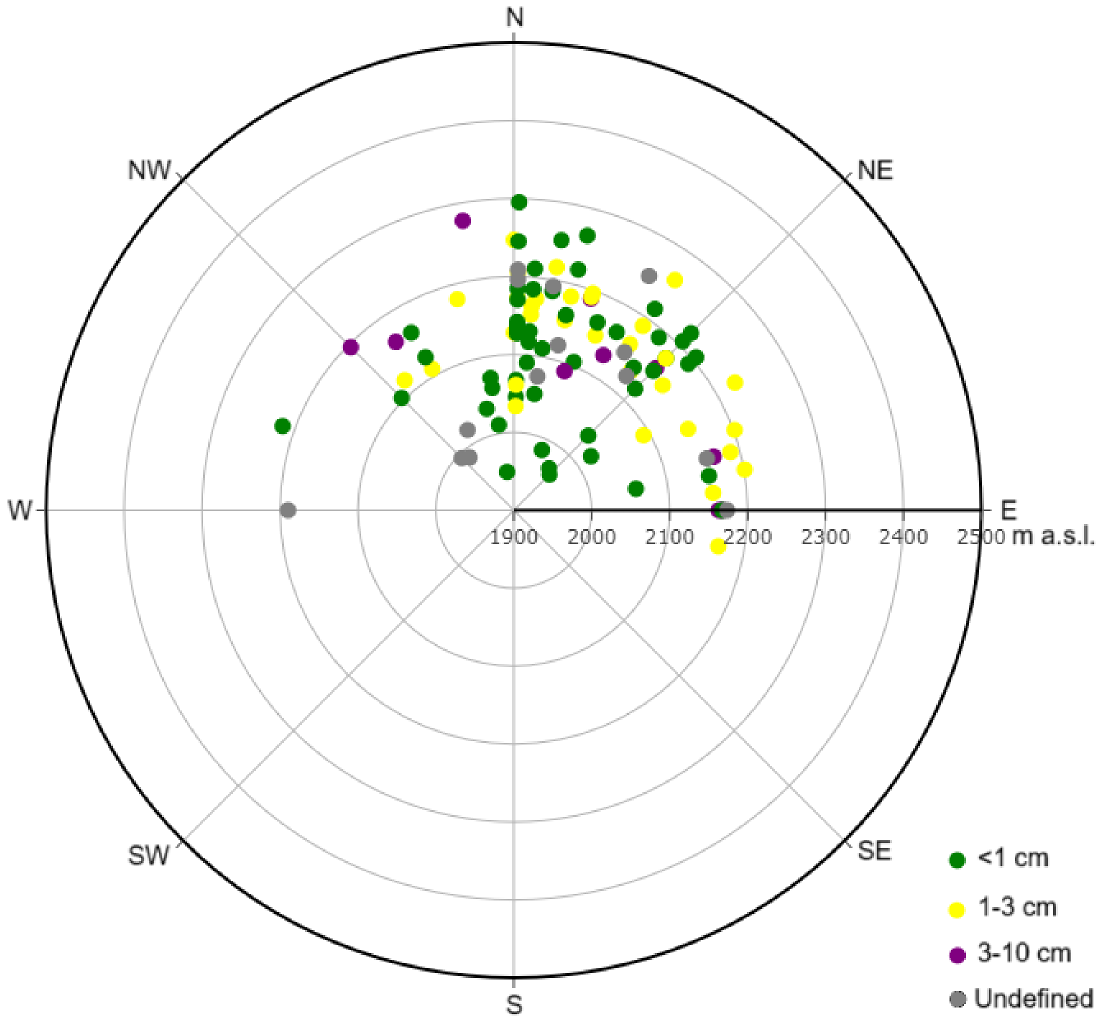

Figure 8: Distribution of moving areas, in the Retezat Mountains, in relation to slope aspect (angular axis) and elevation (radial axis).

Figure 10 presents a comparison between ALOS-2 PALSAR-2 interferogram and the Sentinel-1 PSInSAR results. Although the accuracy of the ALOS-2 PALSAR-2 is lower, both products exhibit similar signals. The main displacement areas are clearly visible and coincide on both maps. In the rock glaciers where on-site thermal measurements were conducted (Galeșu, Păpușa, Valea Rea, Pietricelele, Pietrele), both remote sensing techniques consistently revealed displacements in the same areas. The south-eastern part of the Galeșu rock glacier, where geophysical measurements were conducted shows displacements in both the ALOS-2 PALSAR-2 and Sentinel-1 data. Additionally, very good correspondence was observed for Păpușa, Valea Rea and Pietricele rock glaciers.

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

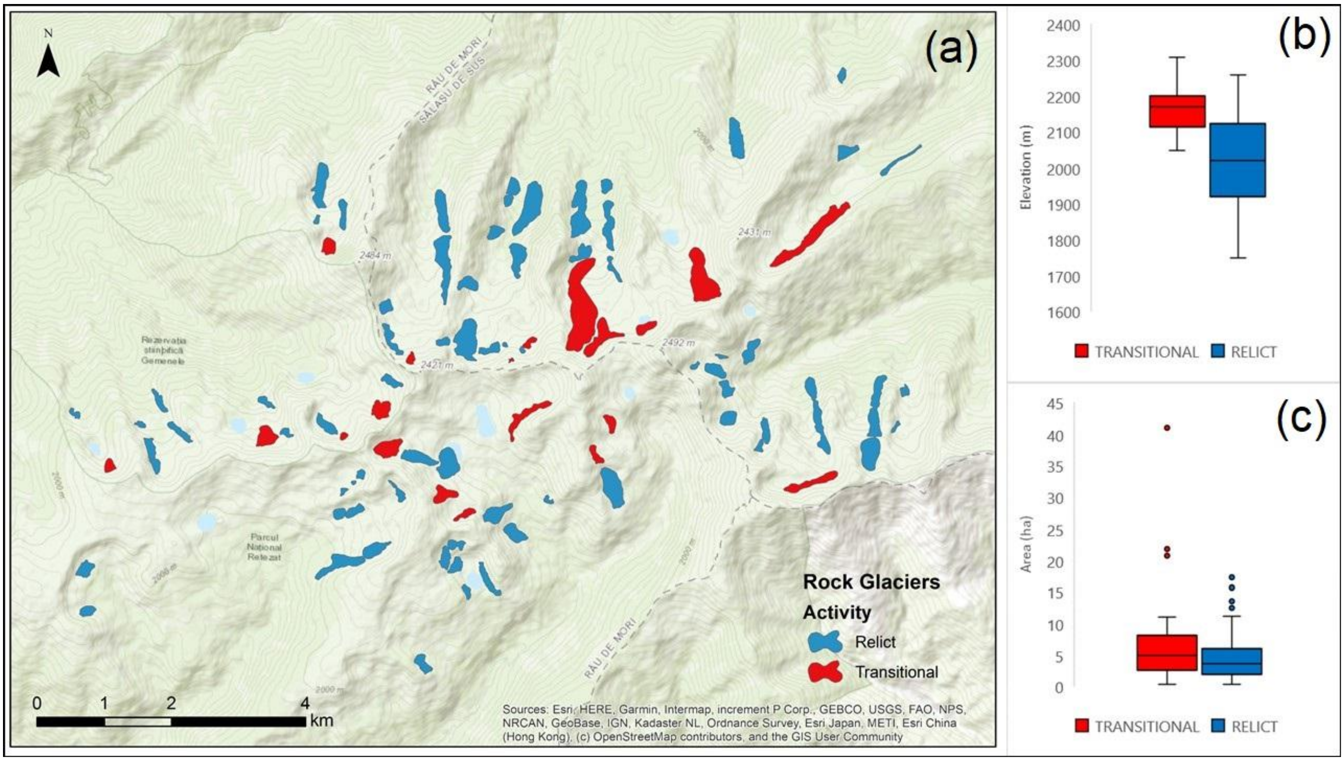

Figure 9: The spatial distribution of transitional and relict rock glaciers in the Retezat Mountains (a) and their median elevation (b) and size (c).

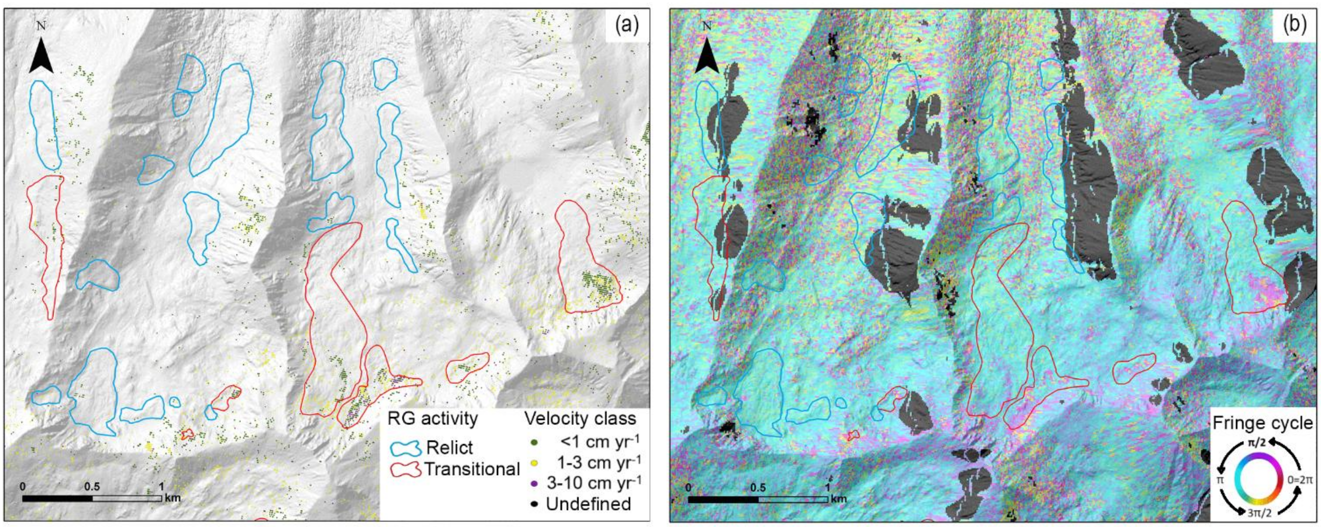

Figure 10: A comparison between multiannual PSINSAR from Sentinel 1 (a) and InSAR from ALOS-2 PALSAR-2 (b). Notice the same moving areas inside the RGs that are revealed by clustered pixels with movement from PINSAR (a) and the areas with fringe patterns (b). In (b) the shadow areas are masked out and the fringe cycle (bottom right) represents the change of colour.

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

4.2. GNSS measurements

The mean velocities measured by DGPS ranged between 0.4 and 2.8 cm yr^{-1}, with values exceeding 1 cm yr^{-1} for 56 % of the marker points (Fig. 11). In the Judele rock glacier, the velocity is higher in the central part and gradual decreases toward the peripheries. This zone is bordered by areas of significantly lower displacements (< 1 cm yr^{-1}). One marker point measured on the front of Judele rock glacier revealed very low rates of displacements (0.4 cm yr^{-1}). Four marker points on the Berbecilor rock glacier revealed velocities between 1 and 2.8 cm yr^{-1}. Most marker points with moving velocities between 1 and 2.8 cm yr^{-1} (89 %) were located within the MAs categorised under velocity classes of 1-3 and 3-10 cm yr^{-1} by PSInSAR analysis.

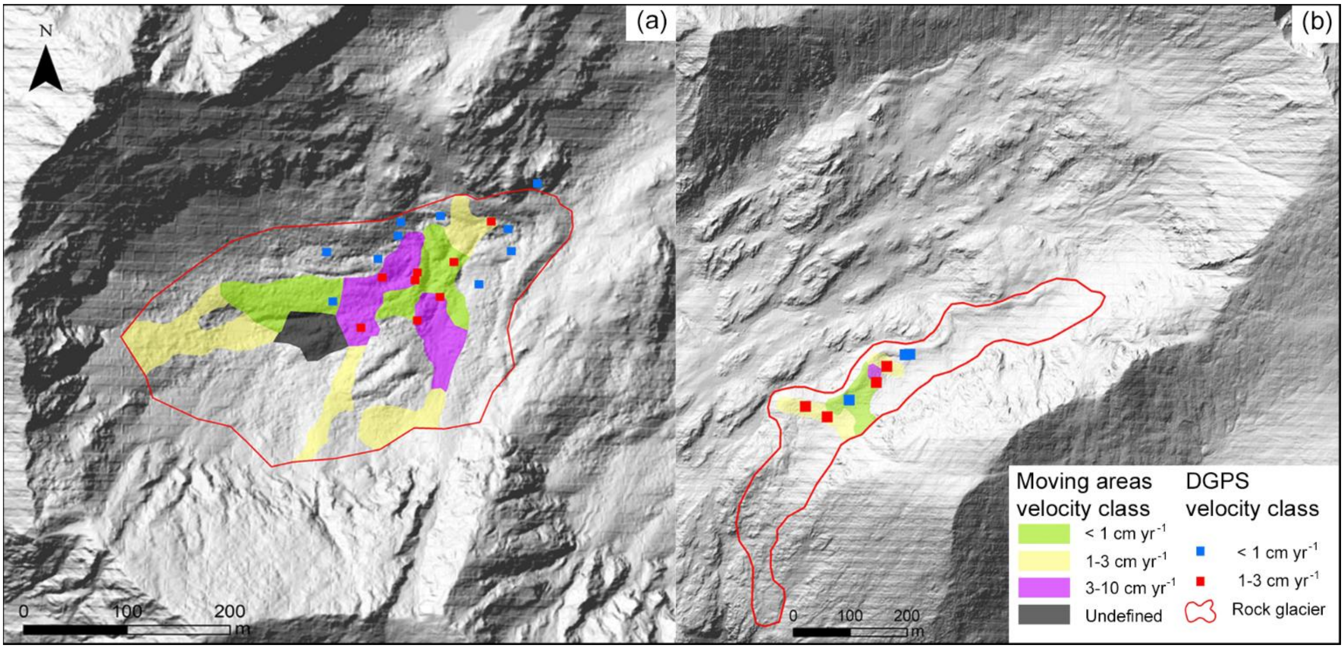

Figure 11: Horizontal displacements derived from GNSS measurements for 2019-2021 at Judele (a) and Berbecilor (b) sites.

4.3. BTS and ground temperatures

The BTS values indicate permafrost occurrence in the investigated rock glaciers (Fig. 12). The measured BTS data ranged between -7.7 and 0.3 ºC. Of the 140 measured BTS points, 107 indicate probable (54.3 %) and possible permafrost (22.1 %), while 23.6 % suggest the absence of permafrost. 50 % of the BTS measurements were measured on Pietrele rock glacier, which has the lowest front altitude and revealed the highest mean of BTS values (-2.9 ºC). At the Galeșu site, the mean BTS was -3.9 ºC, with all the points indicating probable permafrost clustered in the southeastern part. Păpușa is the highest rock glacier where BTS measurements were performed and revealed the lowest average of BTS values (-4.1ºC), whereas at Pietricelele, the mean BTS was -3.5 ºC. Six BTS points were measured in the vicinity of the rock glaciers, but only one of them was lower than -2 ºC. Overall, the mean elevation of probable and possible permafrost points, at these sites, was 2116 m (range 2021 –

2240 m), while for no permafrost points, a mean elevation of 2082 m was calculated. The snow depth varied between 80 and 260 cm at the probing points. In all the cases, the calculated median BTS in MAs was lower compared with the median of all BTS values in each site.

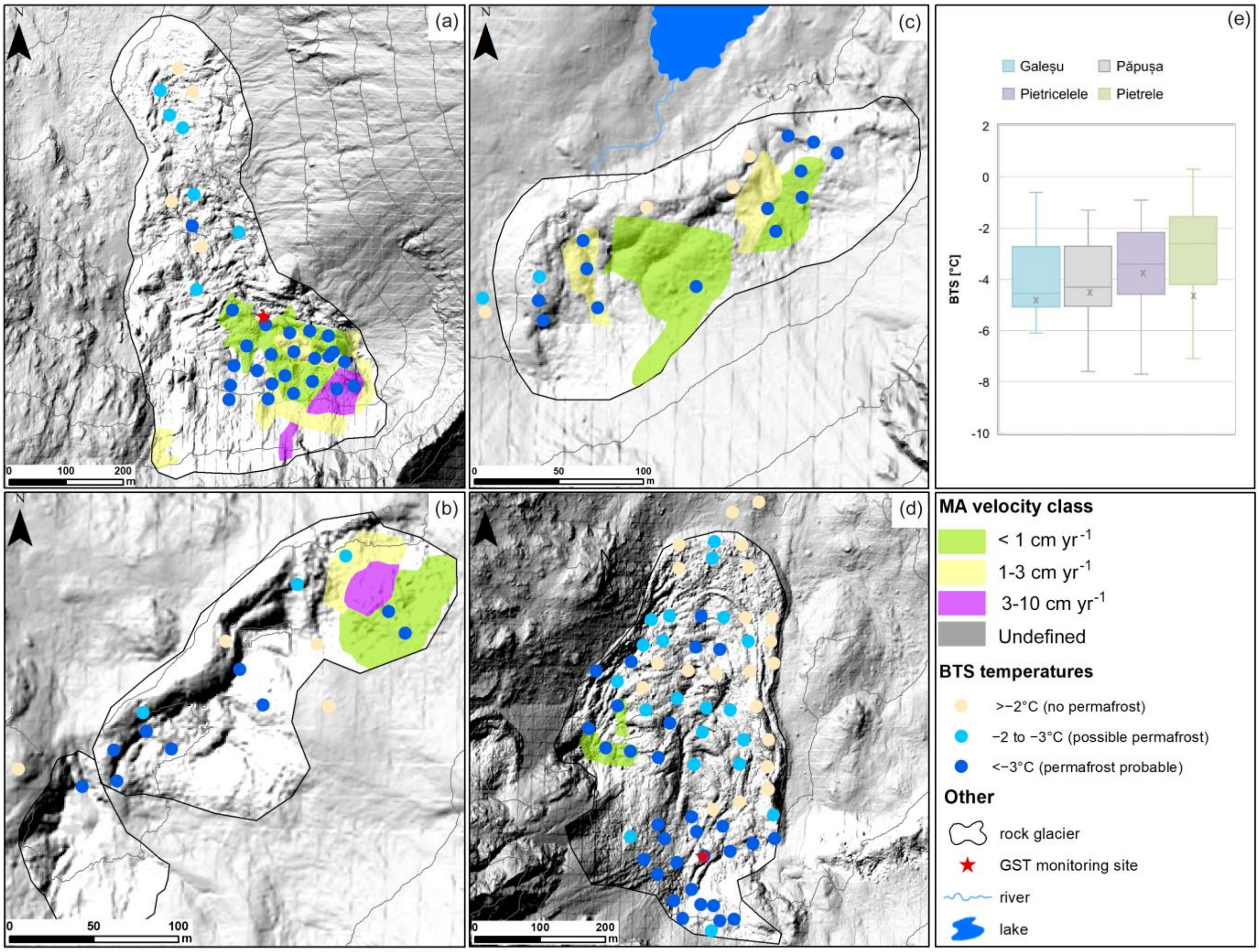

Figure 12: BTS measurements performed in March 2022 on four rock glaciers in the Retezat Mountains: (a) Galeşu, (b) Pietricelele, (c) Păpuşa, (d) Pietrele. (e) Summary box-plot diagram of the BTS measurements, the horizontal line drawn inside denotes the median BTS for each rock glacier, while the x represents the median BTS of the moving areas of each rock glacier). (f) the legend for the maps in (a), (b), (c) and (d).

In most cases, MAGST values were negative at the monitoring sites from 2012-2013 to 2021-2022 (Fig. 13a). MAGST values varied between -2.3 ºC and 0.6 ºC, with the lowest values recorded at site Galeşu and the highest at Pietrele. However, subzero MAGST values were recorded only at site Valea Rea in all the seasons, whereas at Galeşu, all the MAGST values were below 0 ºC except in 2015-2016. All the GST sites revealed negative values for the mean temperature of the entire monitoring interval.

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

Fig. 13c reveals the mean daily temperature at the GST monitoring sites. The lowest GST values (< -10 ºC) occurred in October-December under snow-free or thin snow cover conditions. This is because the insulating snow cover typically occurs in November/December, whereas the snow disappears in May or June. Usually, during March, ground surface temperatures are relatively stable and are mainly driven by conductive processes. In almost all cases, the corresponding WEqT were below -2 ºC, indicating possible or probable permafrost occurrence (Fig. 13b). WEqT values higher than -2 ºC occurred only at Pietrele in late winter 2013 and 2014. At Valea Rea and Judele, most WEqT values were between -2 and -3 ºC, whereas at Galeşu, the late winter temperatures were considerably lower.

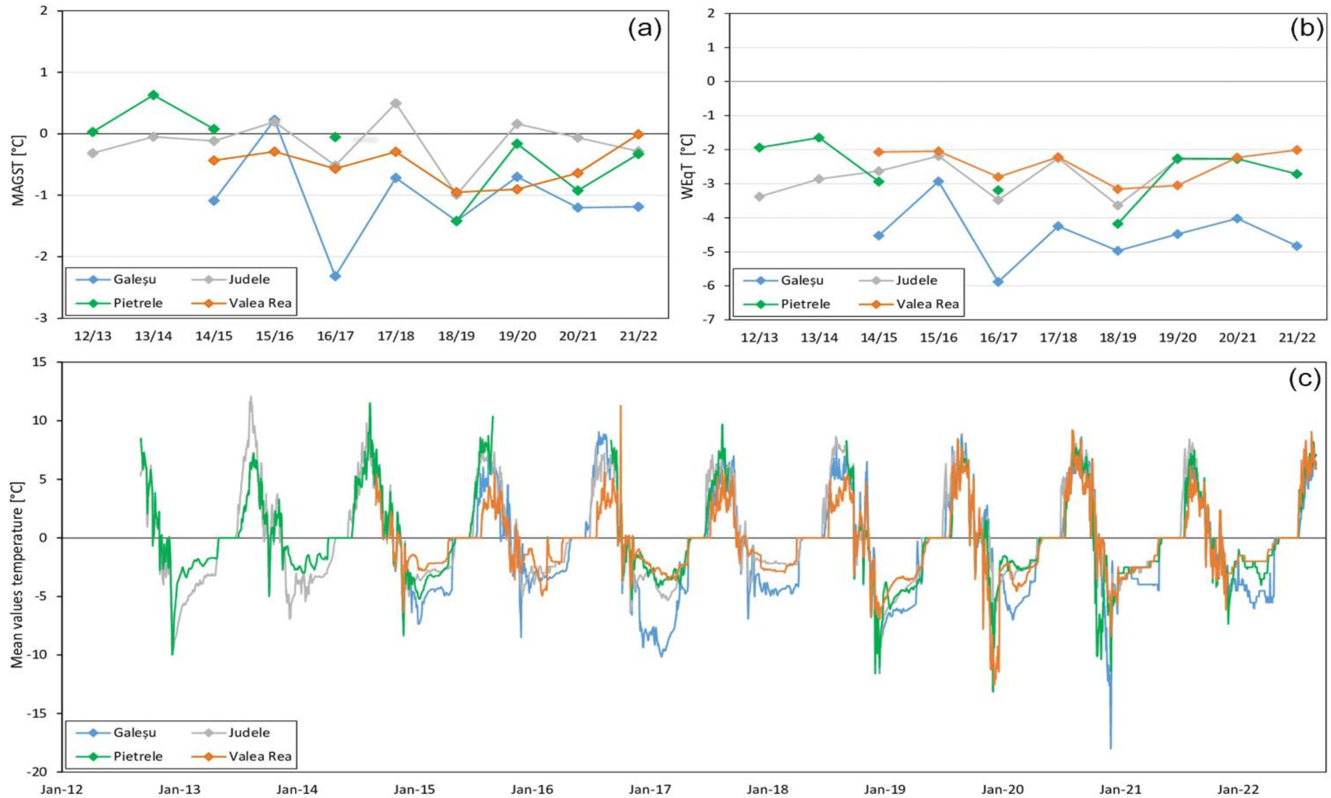

Figure 13: The evolution of (a) Mean Annual Ground Surface Temperature (MAGST), (b) Winter Equilibrium Temperature (WEqT) and (c) Ground Surface Temperature (GST) for the period 2012/2013 to 2021/2022 at four sites in the Retezat Mountains.

4.4. Geophysics results

The results of the geophysical surveys at Galeşu rock glacier are shown in Figure 14 (ERT, RST, PJI). Both tomograms reveal an uppermost 3-4 m thickness layer characterised by high resistivities (> 200 kΩm) representing the dry and coarse-blocky surface layer. A patchy layer with similarly high resistivities lies just underneath. This layer is mostly less than 5 m thick and could indicate remnants of ice-rich permafrost within the rock glacier. A homogeneous layer of resistivities around 20 – 30 kΩm occurs at greater depths, potentially indicating the rock glacier base (bedrock). The landform's overall thickness is

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

estimated at < 15 – 20 m. The eastern part of profile P1 (x < 50 m) is located outside the rock glacier and traverses into a partially vegetated talus slope. Here, the surface layer exhibits lower resistivities (< 100 kΩm, probably representing smaller
345 block size and organic material), and the underlying resistive layer (100-200 kΩm) has a thickness of about 10 m and a more homogeneous appearance than that of the rock glacier.

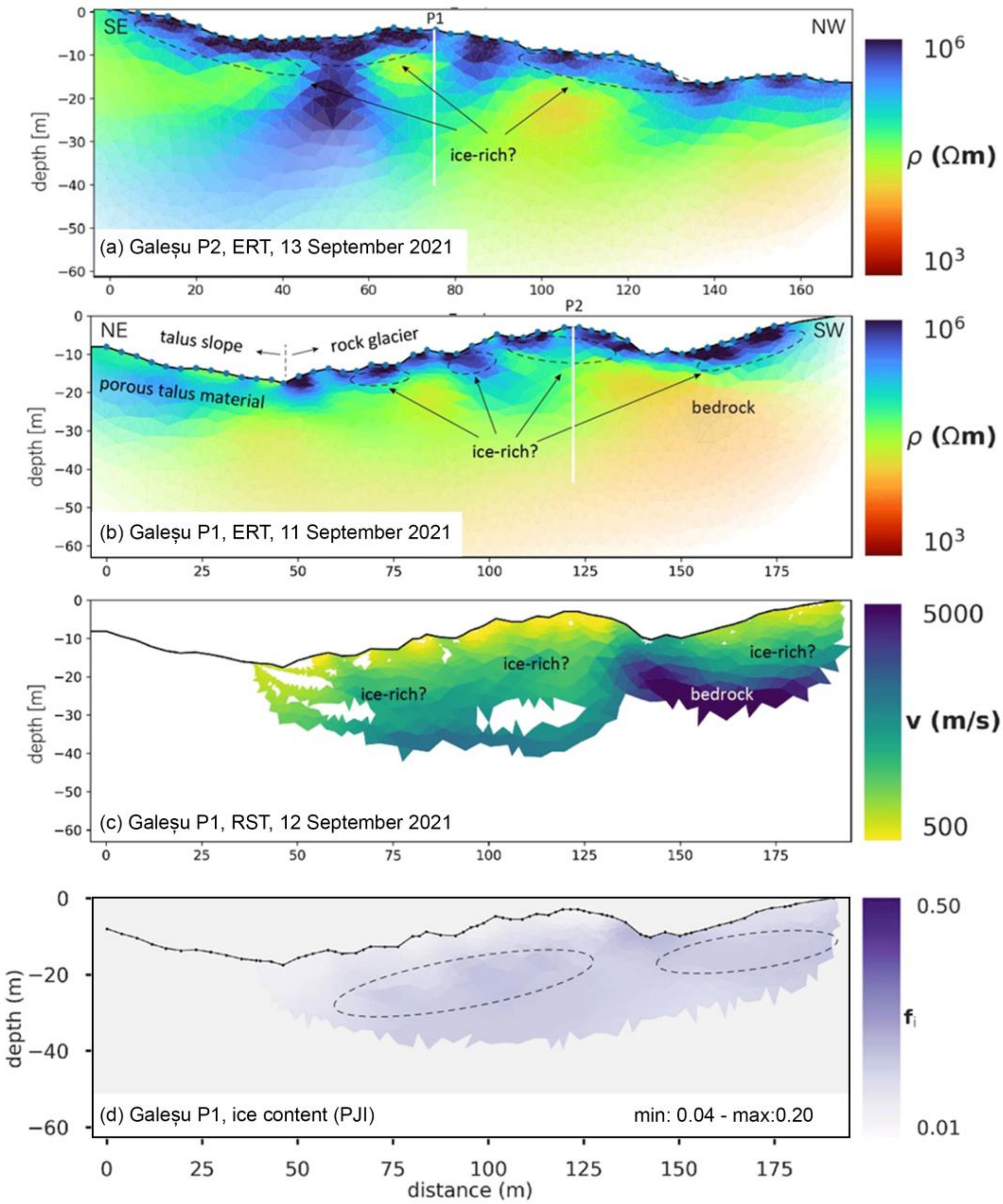

Figure 14: a) and b) ERT profiles P2 and P1 (see Fig. 1c for location), c) RST profile, and d) modelled ground ice content based on the PJI.

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

The seismic profile S1 (Fig. 14c) only covers the rock glacier part of the ERT profile P1 and shows a 5-10 m thick upper layer with P-wave velocities < 1500 m/s, indicating highly porous blocky material. The velocities are increasing with depth, reaching 4000 m/s at about 20-25 m depth in the central part of the rock glacier and at shallower depths (~ 15 m) in the last 50 m of the profile. According to the seismic data, ice-rich permafrost would be possible in large parts of the tomogram. In combination with the ERT data, ice-rich conditions seem only plausible in some parts of the tomogram, whereas seismic data seem to indicate relatively porous material rather than bedrock and point to an overall larger thickness of the rock glacier as indicated by the ERT profile.

The result of the PJI modelling (Fig. 14d) indicates a very low ground ice content in the upper sector of the Galeșu rock glacier, with maximum values of 20 %. The highest ice content occurs at 5 – 15 m depth in the central and right parts of the tomogram (see black ellipses in Fig. 14d).

5. Discussion

5.1. Assessing the velocity of rock glaciers in marginal periglacial environments

In marginal periglacial regions rock glaciers exhibit a minimal rate of motion (a few cm yr^{-1}) (Necsoiu et al., 2016) and evaluating their velocity can pose occasional challenges. Hence, the compilation of MAs inventory might be affected by limitations associated with radar interferometry (Bertone et al., 2022).

The PSInSAR measurements were provided in the SAR LOS direction, representing a 1-D rather than a 3-D measurement, capturing only a single component of motion. Due to the particular steep topography of the study area, it can be assumed that the movement direction of the actual motion is oriented along the mountain slope. Although PSInSAR does not produce the exact 3-D velocity vectors, this work was helpful in detecting areas of motion and refining the rock glaciers inventory.

Slow-moving areas (i.e., < 1 cm yr^{-1}; 1-3 cm yr^{-1}) are prevalent in this region, where only 8% of the MAs are characterised by velocities exceeding 3 cm yr^{-1}. The latter tend to occupy higher elevations and receive less solar radiation than slower ones. Overall, the median size of the MAs from Retezat Mountains is slightly smaller than other periglacial environments (Bertone et al., 2022), indicating the patchy occurrence of permafrost. The median size of the MAs, showing minimal variation across velocity classes, exhibits a slight peak among those moving at < 1 cm yr^{-1} (0.33 ha). The median size of MA velocity classes of 1-3 cm yr^{-1} and 3-10 cm yr^{-1} is 0.25 ha, roughly one-third smaller than those reported in Southern Tyrol (Bertone et al., 2024).

The examination of displacement measurements through the differential GNSS technique unveiled similarly very slow movements at specific points (ranging from a few millimetres to 2.8 cm yr^{-1}). A noteworthy correspondence between the outcomes was observed when scrutinising the displacements derived from the GNSS survey alongside the PSInSAR results (Fig. 11). Most GNSS survey markers that exhibited horizontal displacements exceeding 1 cm yr^{-1} were within the MAs.

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

The inter-annual variability of rock glaciers velocity is primarily related to changes in permafrost temperature and its associated effects (Kellerer-Pirklbauer et al., 2024). In the Judele rock glacier the annual movement rates based on PSInSAR results for all pixels (n=93) exhibited consistent movement between 2016 and 2021 and two distinct types of velocity were identified (Fig. 15). The pixels with faster movement have a mean velocity of around 3 cm yr^{-1}, while the ones with slower movement have a mean velocity of around 0.5 cm yr^{-1}. The inter-annual variability of the moving rates is low for both categories, with a slight drop in velocity of about 10% for 2017 and a rebound in the next years, with 2019 recording the highest velocity for both classes (Fig. 15). Similarly, in the European Alps, the interval from 2018 to 2020 was characterized by increased acceleration, with peak velocities occurring in 2019-2020 (Kellerer-Pirklbauer et al., 2024). Expanding this analysis over a broader timeframe and encompassing a more significant number of rock glaciers will help discern potential long-term trends in transitional rock glacier motion and their correlation with climate dynamics. However, the relationships between rock glacier kinematics and the driving factors are highly intricate, necessitating particular attention to local conditions.

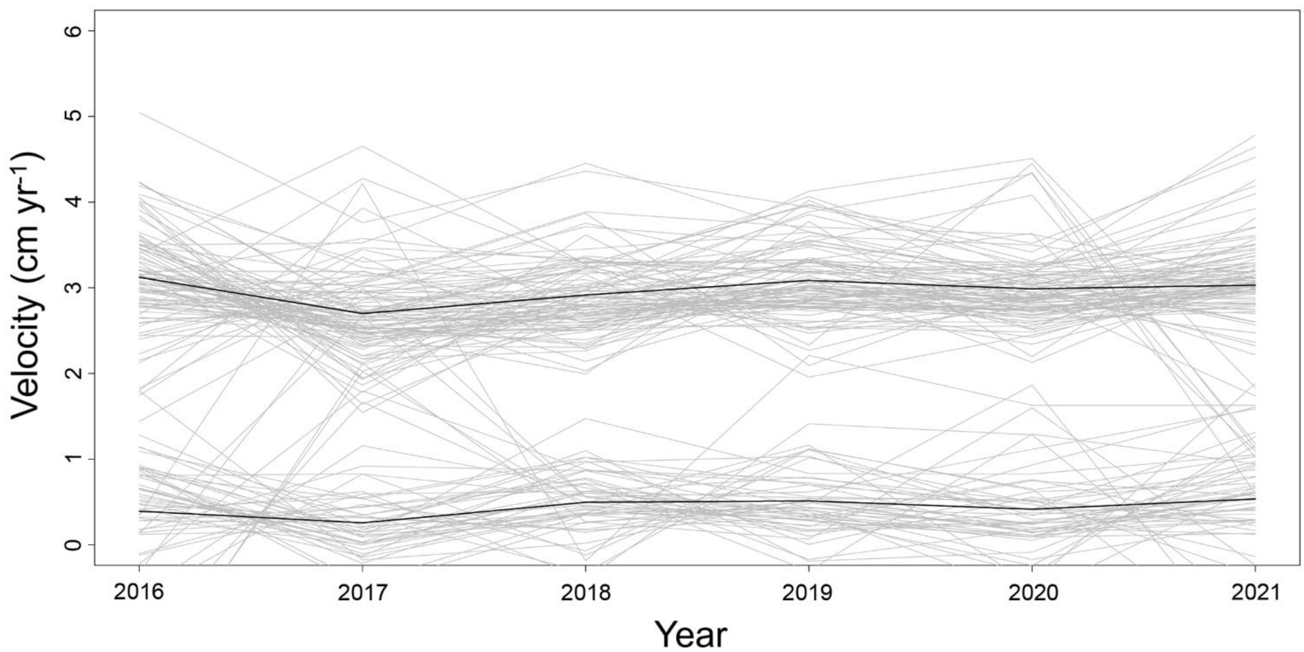

Figure 15: Annual PSInSAR-derived velocity of individual pixels within the moving areas at Judele site in mm/yr between 2016 and 2021.

The PSInSAR analysis enriches the existing rock glacier inventory with information about the activity status of rock glaciers in the Retezat Mountains. A previous study classified 30 rock glaciers in the study area as intact based on geomorphological and ecological criteria (Onaca et al., 2017b). Radar interferometry revealed that 20 rock glaciers exhibit surface displacements exceeding 1 cm yr^{-1}. In contrast, 14 rock glaciers showed minimal displacements (<1 cm yr^{-1}). Of these, seven were previously classified as intact, while the remaining seven were categorised as relict. Four rock glaciers, previously labelled as geomorphologically relict, show surface displacements exceeding 1 cm yr^{-1} and were categorised as transitional in our study.

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

Unlike other regions (e.g., Central Italian Alps, Eastern European Alps, Himalaya) where there is a considerable elevation difference between active/intact and relict rock glaciers (Kellerer-Pirklbauer et al., 2012; Scotti et al., 2013), the Retezat Mountains exhibit a significantly smaller separation. However, in some regions, there is also a minimal difference between active and relict rock glaciers (Brencher et al., 2021).

5.2. Permafrost occurrence revealed by geophysical and temperature measurements

The geophysical investigations revealed ice-rich permafrost bodies up to 5-10 m thick at 2130-2150 m in the upper part of the Galeșu rock glacier (Fig. 14). The frozen layer was suggested by geophysical measurements beneath a substantial active layer of approximately 5 m thickness. Similar results have been reported in other marginal periglacial environments (i.e., Făgăraș Mountains, Pirin Mountains, Italian Carnic Alps) where thick active layers indicate even greater thickness (Onaca et al., 2013; Colucci et al., 2019; Onaca et al., 2020). Due to the rock glacier's very dry and extremely coarse blocky surface, the ERT data only have limited quality which is also reflected by the high resistivities of > 200 kΩm on the rock glacier surface. However, we still assume that the overall resistivity pattern indicates the main structures and is representative for the site, whereas small-scale anomalies present in the tomograms as well as absolute resistivity values, should be interpreted with care.

The GST and BTS measurements confirmed the presence of permafrost at all the monitoring sites. Similar results have been reported for Judele, Pietrele, Valea Rea, Galeșu and Pietricelele rock glaciers in previous studies (Vespremeanu-Stroe et al., 2012; Onaca et al., 2015). Except for Pietrele, the other data-logger sites (Galeșu, Judele and Valea Rea) are located in areas with displacement velocities exceeding 1 cm yr^{-1}. In all cases, BTS values below -2 ºC are common even in seemingly stable areas. However, at Pietrele, despite the prevalence of low BTS values, almost no displacement was observed, except in the western part, where minor displacements (< 1 cm yr^{-1}) were detected. The Pietrele rock glacier is oriented along a south-north direction and the LOS orientation tends to underestimate displacements on north facing slopes (Liu et al., 2013). The lack of significant displacement in this rock glacier between 2014 and 2020 does not necessarily indicate complete ice melt, but likely suggests negligible ice content.

5.3. Rock glaciers behaviour in marginal periglacial environment

The rock glaciers in the Southern Carpathians generally move at slower rates than those in other mid-latitude high mountains, where rock glaciers' velocities range from a few centimetres to a few meters per year. But rock glaciers experiencing very low movement velocities were also documented in different periglacial regions (e.g., Pyrenees, Rocky Mountains, northern Norway, Southern Alps of New Zealand, etc.) (Serrano et al., 2010; Brencher et al., 2021; Rouyet et al., 2021; Bertone et al., 2022; Lambiel et al., 2023). In the Retezat Mountains, only 21 % of the inventoried rock glaciers display motion, whereas the rest are considered relict. Similar to the Uinta Mountains (Brencher et al., 2021), in most cases, only a relatively small portion of the rock glacier exhibits movements. An illustrative case in this regard is the Galeșu rock glacier, displaying movement solely in its uppermost section, for about 18% from its surface area, where a younger lobe overlies the main body. Similar younger lobes were identified in other valleys (e.g., Valea Rea, Pietrele) representing distinct phases of rock glaciers activity,

https://doi.org/10.5194/egusphere-2024-3262
Preprint. Discussion started: 3 January 2025

as observed in many other periglacial regions of Europe (e.g. Iceland, European Alps, Cantabrian Mountains, Pyrenees etc.) (Farbrot et al., 2007; Kellerer-Pirklbauer et al., 2008; Steinemann et al., 2020; Amschwand et al., 2021; Oliva et al., 2021; Santos-González et al., 2022).

Additionally, the PSInSAR analysis revealed that, in many instances, the fronts of the rock glaciers in the Retezat Mountains remain stable. Field observations also confirmed that despite steep and sometimes unvegetated slopes, the rock glacier fronts display no recent activity, and no ploughed grass occurs at their snouts. This type of rock glacier, called climatically inactive (Barsch, 1996), is also distinguished by a substantial unfrozen mantle and a low ice content (Onaca et al., 2013).

An explanation of the very low displacement rates in transitional rock glaciers is the reduced thickness of the ground ice (Onaca et al., 2015). For this reason, the internal shear stress would be too small to provoke substantial creep. The geophysical measurements performed in this study indicated the very low ice content present in the Galeșu rock glacier.

Various studies suggest that the volumetric ice content within active rock glaciers typically falls within the range of 40 % to 60 % (Barsch, 1996; Hausmann et al., 2007; Rangecroft et al., 2015). Conversely, for rock glaciers tending towards inactivity, Wagner et al. (2021) propose average ice content as low as 20 %. These estimates are commonly utilised to assess the water volume equivalent of ice content stored in rock glaciers (Wagner et al., 2021; Pandey et al., 2024). However, the geophysical investigations presented in this paper reveal even lower values for the volumetric ice content of the Galeșu rock glacier. This finding suggests that the ice content in transitional rock glaciers may be considerably lower than expected, emphasising caution when calculating water volume equivalent on a broad scale. Another key observation is that, despite lower ice content, slow permafrost creep is still possible in transitional rock glaciers.

The results presented in this study align with the coarse-rock glacier hypothesis (Onaca et al., 2015; Popescu et al., 2017), which suggests that permafrost occurrence in the Carpathian Mountains is patchy and limited to sites above 2100 m with low solar radiation. In these locations, very coarse rock glaciers, hosting numerous large boulders, facilitate strong cooling through density-driven airflow (i.e., the chimney effect) and air stratification (low conductivity) during summer or under thick snow cover.

6. Conclusions

This study leads to the following main conclusions:

- The majority of rock glaciers in the marginal periglacial environment of the Retezat Mountains are classified as relict, with only 21% categorized as transitional. The median elevation of transitional rock glaciers is 150 m higher than that of relict rock glaciers and their median size is approximately one-third larger. The PSInSAR methodology enabled the identification of new rock glaciers displaying movements, which were initially classified as relict features.
- A total of 110 moving areas were delineated within the rock glaciers of the Retezat Mountains, predominantly falling within the slow-velocity classes (< 1 cm yr^{-1} and 1-3 cm yr^{-1}). Moving areas exhibiting velocities between 1 and 5 cm yr^{-1} are typically located above 2100 m in regions with minimal solar radiation income. Higher movement rates are observed in the

upper, younger lobes compared to the well-developed lower parts. A six-year time series analysis of one rock glacier revealed a slight increase 2019 and 2021.

- Long-term ground temperature monitoring and BTS measurements confirm the presence of permafrost conditions at monitoring sites above 2100 m, where small velocity rates are observed. However, the lack of movement or absence of notable displacements over several years does not necessarily imply complete ice melt, but suggests negligible ice content.
- Geophysical measurements conducted on a transitional rock-glacier revealed notably low ice content (with maximum values of 20%) in its uppermost section. This reduced ice content within the rock-ice matrix contributes to decreased internal deformations in transitional rock glaciers, resulting in low displacement rates.

Our findings highlight the value of combining Sentinel-1 SAR data with extensive field investigation (such as DGPS, geophysical and thermal methods) and where possible, with other remote sensing data (like ALOS-2 PALSAR-2), particularly in regions with slow-moving rock glaciers. This approach could serve as a benchmark for similar studies in marginal periglacial environments.

Code/Data availability

The deformation data, obtained using PSI, and the temperature data, obtained using GST data loggers and BTS are freely available as a Zendo repository, at https://zenodo.org/records/14544941, DOI: 10.5281/zenodo.14544940
For further questions about data processing readers are encouraged to contact the authors.

Author Contribution

The study was conceptualized and managed by AO and FS. AO led the manuscript writing, with contributions from VP, CH, PU, TS and FS. VP, TS, DT, DB and FS contributed to the PSInSAR analysis. FA and IL produced the inventory of moving areas and performed the statistical analysis related to rock glaciers. AO, OB, RP, MV, IL and AVS contributed to the analysis of thermal measurements. CH, BE, SF, RP and AO were involved in conducting and analysing the geophysical measurements. AH and AO provided the GNSS measurements. All authors provided feedback on the final version of the paper.

Competing interests

The authors declare that they have no conflict of interest.

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