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~~ This study~~, we~~ combines remote sensing and in situ methods to ~~gain insights into the~~ ~~to~~ ~~characteristics~~ characterize ~~of~~ transitional rock glaciers in the Carpathian Mountains. We ~~applied~~ used Persistent Scatterer Interferometry (PSInSAR) ~~to~~ on Sentinel-1 images ~~from~~ (2015 -~~to~~ 2020) to ~~identify~~ detect ~~areas with~~ slope movements associated with rock glaciers and differential GNSS measurements (2019-2021) to ~~detect~~ track ~~the~~ horizontal movement of 25 survey markers. Continuous ground temperature ~~monitoring~~ and ~~measurements of the bottom temperature of the~~ winter snow cover bottom temperature (BTS) measurements ~~were used to~~ examined ~~the~~ energy exchange fluxes ~~characteristics of transitional~~affecting these rock glaciers~~ in the Carpathians. The subsurface of one transitional rock glacier was investigated using geophysical~~ Geophysical ~~measurements~~ surveys (electrical resistivity tomography and refraction seismic tomography), ~~while~~ and petrophysical joint inversion (PJI) ~~was used to quantify~~ quantified ~~the~~ ice content in one rock glacier. ~~The~~ PSInSAR ~~methodology~~ identified 92 moving areas (MAs) with slow displacement ~~rates~~ (< 5 cm yr^{-1})~~. These MAs were generally located~~ mostly between 2000 and 2300 meters, where solar radiation was minimal. Near-surface thermal ~~measurements~~ data ~~on~~ from four rock glaciers ~~indicate~~ suggest favourable conditions for permafrost persistence, largely driven by internal ventilation processes (e.g., advection heat fluxes) throughout the winter. BTS confirmed v~~V~~ery low ground surface temperatures ~~were detected by BTS measurements~~ over much of the investigated rock glaciers, particularly in their upper parts and within the MAs. Geophysical investigations reveal ~~remnants of~~ ice-poor permafrost remnants ~~within the~~in the Galeșu rock glacier, while ~~petrophysical joint inversion~~PJI modelling ~~indicates~~ estimated a low ground ice content (~ 18 %) in its upper sector. At this site, ~~the recorded~~ surface displacements ~~result from~~stems from ~~deformation within the~~ active layer deformation, not ~~and are not related to~~ permafrost creep. At two other sites, ~~The flow direction of~~ dGNSS markers moved- consistently ~~at two other~~toward rock glacier frontss, ~~indicated~~ indicating ~~consistent movement toward their fronts, a pattern typical of~~ permafrost creep. Regarding activity status, the majority of rock glaciers in the Retezat Mountains were categorized as relict, with only 21% classified as transitional. ~~Compared to relict rock glaciers, T~~transitional rock glaciers ~~ones are situated at a median elevation~~occur 150 m higher and ~~have~~ are slightly smaller ~~median size~~than relict ones.

1. Introduction

Rock glaciers are prominent periglacial landforms ~~in the periglacial environment~~, serving as indicators of permafrost presence at the time of their formation (Haeberli et al., 2006). ~~Generated through past or present~~Formed by permafrost creep, they are debris-dominated features typically identified by their front, lateral margins and occasionally ridge-and-furrow surface patterns (RGIK, 2023a). The geomorphic imprint of permafrost creep ~~is~~ often ~~preserved~~ persist even after the ice within the rock glacier has completely melted (Kellerer-Pirklbauer et al., 2022). Most rock glaciers in the Southern Carpathians are relict, though some retain isolated patches of permafrost ~~In the Southern Carpathians, rock glaciers mostly present as relict landforms, yet retain isolated permafrost in certain areas~~ (Vespremeanu-Stroe et al., 2012; Onaca et al., 2013, 2015; Popescu et al., 2015, 2024). Indicators such as extensive lichen cover, vegetated fronts and the overall morphological stability of many landforms suggest ~~that~~ greatly reduced permafrost creep ~~is significantly reduced compared to the colder climatic conditions of the~~compared to pre-Holocene conditions (Popescu et al., 2017). These rock glaciers are predominantly mantled by angular, coarse-grained blocks which facilitate ground cooling (Onaca et al., 2017a). The thermal offset associated with this blocky surface layer contributes to the maintenance of subzero temperatures in the subsurface over prolonged periods (Kellerer-Pirklbauer, 2019), ~~thereby enhancing~~supporting permafrost preservation even at ~~relatively~~ lower altitudes (Colucci et al., 2019). ~~In addition~~Additionally, the `chimney effect` - an advective heat flux process (Delaloye and Lambiel, 2005) - ~~significantly contributes to~~ enhances surface cooling in highly porous, openwork structures.

Permafrost creep ~~encompasses~~ involves both the internal deformation of ice within the frozen material and shearing at discrete planes within or just beneath the frozen structure (Cicoira et al., 2021). Surface displacement ~~can~~ may also result from active layer processes ~~occurring within the active layer~~, such as solifluction, or ~~the~~ block tilting and sliding ~~of blocks~~, which ~~may act~~can occur independently of ~~or in addition to~~ permafrost creep (Serrano et al., 2010; Cicoira et al., 2021). ~~The~~ Interest in rock glacier surface kinematics ~~of rock glaciers had~~ has ~~garnered~~ grown ~~significant interest from the international community in~~ recently ~~years~~ (Kellerer-Pirklbauer et al., 2024; Kääb and Røste, 2024; Pellet et al., 2024; Hu et al., 2025) ~~due to~~driven by the ~~growing~~ need to ~~better~~ understand ~~how~~ mountain permafrost ~~responds~~ response 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 have been linked to warmer climate (Wirz et al., 2016; Cicoira et al., 2019; Kenner et al., 2019; Kääb et al., 2021; Marcer et al., 2021; Kellerer-Pirklbauer et al., 2024). Rising temperatures within frozen debris enhance movement rates, as warming reduces the viscosity of the ice and promotes additional lubrication from infiltrating water (Kääb et al., 2007). Annual ~~rates of~~ horizontal surface velocities ~~kinematics of rock glaciers~~typically range from ~~a few~~ millimetres to a few meters (Strozzi et al., 2020), ~~though~~ but destabilization can ~~result in velocities exceeding ten meters per year~~raise them above 10 m yr^{-1} (Roer et al., 2008; Delaloye et al., 2013; Eriksen et al., 2018; Marcer et al., 2021; Hartl et al., 2023). Destabilization ~~typically~~ involves abrupt ~~sudden, pronounced~~ acceleration of a section of the rock glacier, ~~with displacement rates increasing~~often by up to two orders of magnitude, accompanied by ~~and~~ surface ~~manifestations~~ features such as cracks, scarps, and crevasses reflecting enhanced internal strain between stable and unstable areas (Marcer et al., 2021; Hartl et al., 2023).

~~Many studies have demonstrated the feasibility of satellite~~ Satellite radar interferometry (InSAR) has proven effective for analys~~z~~ing rock glacier kinematics, ~~analysis of rock glaciers, capable of~~ detecting ~~motion at the~~ millimetre~~-~~ scale motion (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). Surface displacements can be attributed to permafrost creep only ~~if the~~when flow direction and velocity are~~remain~~ spatially consistent and uniform over a documented period (RGIK, 2023a). Permafrost creep ~~typically~~ generally requires an ~~occurs when the thickness of the~~ ice-rich core ~~in rock glaciers reaches~~ at least 10-25 m thick (Cicoira et al., 2021). In contrast, displacements ~~observed~~ in rock glaciers with thinner ~~layers of~~ frozen debris are primarily driven by deformations within the active layer above the permafrost table.

~~While~~ Although rock glaciers in discontinuous permafrost have been ~~extensively~~ widely studied, ~~the distinctive behaviour of~~ those in marginal periglacial environments ~~has~~ have received far less attention (Serrano et al., 2010; Necsoiu et al., 2016). In such settings, rock glaciers exhibit significantly slower movement rates (a few cm yr^{-1}) and are often referred to as transitional rock glaciers (RGIK, 2023a~~).~~), largely due ~~This reduced surface velocity is attributed~~ to the high shear strength of the material, which inhibits fast creep movement (Cicoira et al., 2021). ~~Even if~~While slow-moving rock glaciers ~~were documented in various regions of the world~~have been reported globally (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). In remote, high-mountain environments where borehole data are scarce, petrophysical joint inversion (PJI) of seismic refraction and electrical resistivity offers a promising method to estimate ice content quantitatively~~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 E~~Eenhanced continentality in this range ~~effects~~ induced a distinct pattern of ~~manifestation of~~ periglacial phenomena compared ~~with~~ to other mid-latitude mountains in Europe (Onaca et al., 2017a). In such marginal periglacial ~~mountains~~settings, permafrost ~~occurrence~~ is ~~generally~~ typically sporadic or patchy, with its distribution strongly influenced by local site conditions ~~and site-specific characteristics highly control its distribution~~ (Stiegler et al., 2014; Onaca et al., 2015; Kellerer-Pirklbauer, 2019; Popescu et al., 2024).

This study presents new insights into rock glacier kinematics and permafrost conditions in the Retezat Mountains, with a focus on understanding their behaviour in marginal periglacial settings.~~The paper aims to present new results on the rock glaciers kinematics and permafrost characteristics in the Retezat Mountains and, more precisely, to better understand the behaviour of rock glaciers in marginal periglacial mountains. To achieve this goal~~Specifically, we aim to:~~will~~ (i) ~~locate~~ identify and ~~assess~~ ~~a~~analys~~z~~e ~~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~~with kinematics~~s~~ data; (iii) estimate ground ice content ~~using~~ through petrophysical joint inversion ~~based on~~ of electrical resistivity and seismic refraction data; and (iv) characterise the thermal conditions at the rock glaciers surface.

2. Study area

The Retezat Mountains, part of ~~are among the highest massifs in~~ the ~~Romanian~~ Southern Carpathians (also known as the Transylvanian Alps), ~~constituting a distinct part of the Southern Carpathians (the latter are also known as the Transylvanian Alps)~~are among the highest massifs in the Romanian Carpathians. Located in their western ~~part of the Southern Carpathians~~sector (45°22' N and 22°53' E), the ~~Retezat Mountains~~range reaches ~~an~~ elevations ~~of~~ up to 2500 m, revealing a typical alpine landscape (Fig. 1). The region has ~~climate in this region can be characterised as~~ a moderate temperate continental climate, classified ~~within the~~as subarctic or boreal ~~category according to~~under the Köppen ~~classification~~ system. ~~Between~~ At 2000 ~~and~~ –2100 m elevation, the mean annual air temperature is ~~approximately~~ around 0° C, with annual precipitation averaging ~~around~~ 1000 mm (calculated for the period 1961-2007) (Onaca et al., 2017a). Compared to the 1961-1990 baseline, ~~Above 2000 m in the Southern Carpathians,~~ the 1991-2020 ~~climatological~~ period was 0.8 ºC warmer ~~than the 1961-1990 baseline~~above 2000 m in the Southern Carpathians (Berzescu et al., 2025).

The Retezat M~~m~~ountains span ~~range is part of the orogenic units spanning~~ two major distinctive tectonic-structural ~~regions~~units: the Danubian ~~Domain~~ and ~~the~~ Getic Domains, both ~~with the status~~forming part of a thrust sheet system. The Danubian Domain, ~~referred to as the Danubian Autochtonous,~~ is ~~primarily characterised by two~~ dominat~~ed~~nt by two large granitic bodies~~,~~ — Retezat and Buta (Pavelescu, 1953) —, which are bordered by~~. These granitic bodies are surrounded in the marginal area by~~ epi- and meso-metamorphic schists~~, typifying~~ of the Getic Nappe. ~~Specific~~ Mesozoic rocks, ~~particularly~~ especially limestones, are ~~prevalent~~ common in the southern part of this mountain range (Urdea, 2000). Granite underlies 87 % of the rock glaciers in the Retezat Mountains ~~have developed on granite bedrock~~ (Fig. 2), while the remaining landforms are situated on metamorphic schists.

The Retezat Mountains boast one of the most ~~comprehensive~~ extensive and ~~distinct~~ diverse ~~arrays~~ assemblages of glacial and periglacial landforms in the Romanian Carpathians. Notably, they host the largest glacial cirques in the ~~Romanian Carpathians~~region, ~~with~~ which together ~~a combined area of all glacial cirques amounting to~~cover ~~c~~about. 8 % of the massif's ~~total~~ area (Urdea, 2000). During the Last Glacial Maximum (LGM) (20.6 ka), glaciers ~~in these mountains reached lower~~descended to elevations ~~ranging from~~as low as 1000~~ to~~–1300 m (Ruszkiczay-Rüdiger et al., 2021). Five deglaciation phases followed during the Late Glacial, but no glacial advance has been recorded in the central Retezat since the Younger Dryas, based on cosmic-ray exposure dating (Ruszkiczay-Rüdiger et al., 2021).

~~Subsequently, the Late Glacial period witnessed five phases of deglaciation. However, no glacial advance has been documented in the central part of the Retezat Mountains during or after the Younger Dryas based on cosmic-ray exposure dating (Ruszkiczay-Rüdiger et al., 2021).~~ Rock glaciers ~~in the Retezat Mountains~~ likely began ~~to develop~~forming during the Younger Dryas, ~~with~~ and have mostly ~~having~~ become relict or transitional since ~~the onset of~~ the Holocene. Permafrost associated with rock glaciers ~~had been~~ was first documented ~~since~~ in 1993 in this mountain range (Urdea, 1993). A recent inventory ~~described~~ identified the Retezat Mountains as ~~the range with~~having 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~~The range also hosts ~~harbour~~ the longest Carpathian rock glacier, Valea Rea, extending 1.4 km (Urdea, 2000) (Fig. 2b).

According to Necsoiu et al. (2016), slow-moving rock glaciers in the Southern Carpathians ~~exhibited~~ increased their velocities by 20% between 2007 and 2014, ~~attributed~~ likely due to rising permafrost temperatures. ~~They exhibited a velocity rise of 20% between 2007 and 2014.~~

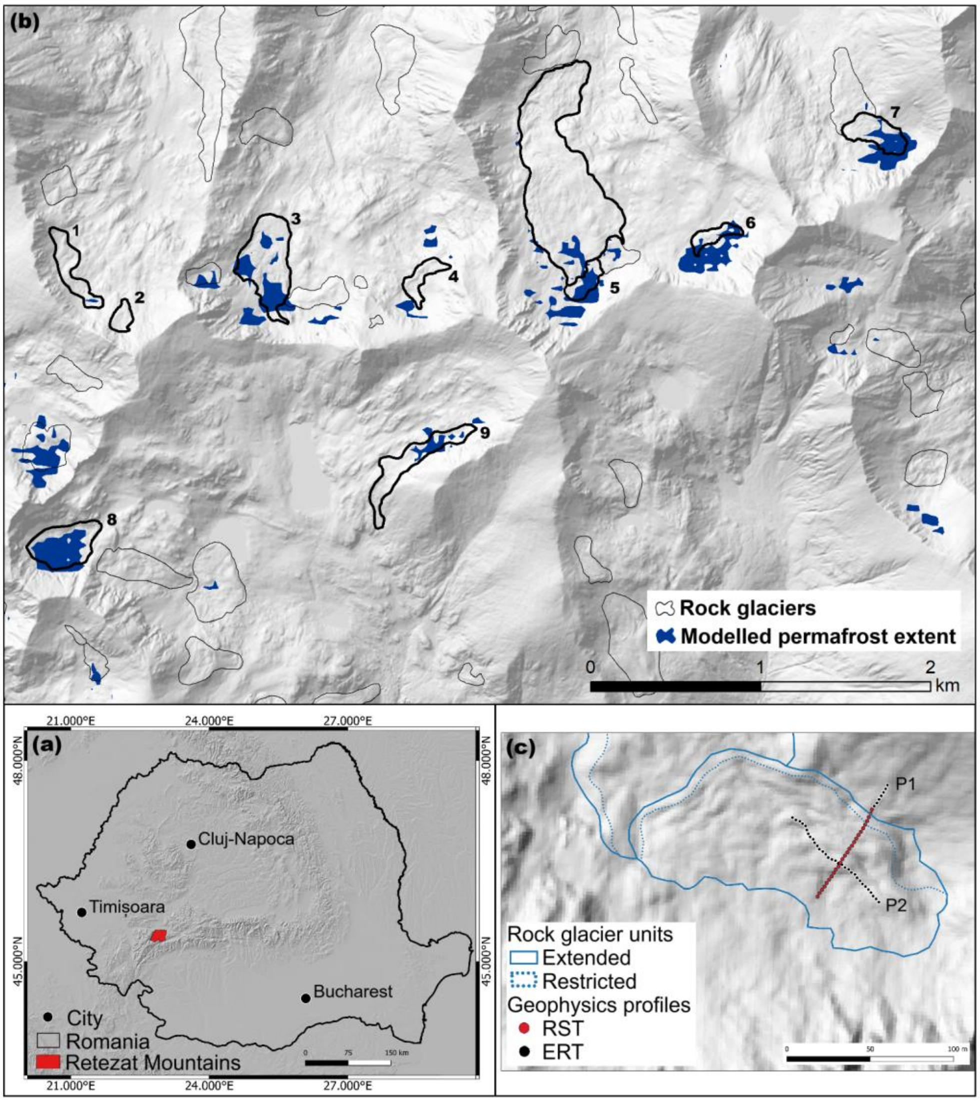

Figure 1: Study sites. (a) Overview map with the location of the Retezat Mountains in Romania, background of the map: hillshade based on FABDEM (Howker et al. 2022). (b) modelled permafrost extent (Popescu et al., 2024) and spatial distribution of rock glaciers in the Retezat Mountains overlaid on a hillshade based on the LAKI II DEM (LAKI II MNT, 2024). The rock glaciers that are discussed in the present paper are mapped with thicker lines and are presented in Table 1. (c) A detailed map with the position of the geophysics profiles on Galeșu rock glacier; note: same background image as (b).

Table 1 Rock glaciers investigated through ground-based measurements and/or discussed in this study (BTS = bottom temperature of snow cover; GST = ground surface temperatures ERT = electrical resistivity tomography; RST = refraction seismic tomography, dGNSS = differential GNSS measurements).

Number in Fig.1	RG name	RG activity	Ground-based measurements type
1	Stânișoara	Relict	-
2	Bucura	Transitional	-
3	Pietrele	Relict	BTS, GST
4	Pietricelele	Transitional	BTS
5	Valea Rea	Relict	GST
6	Păpușa	Transitional	BTS
7	Galeșu	Transitional	BTS, GST, ERT, RST
8	Judele	Transitional	GST, dGNSS
9	Berbecilor	Transitional	dGNSS

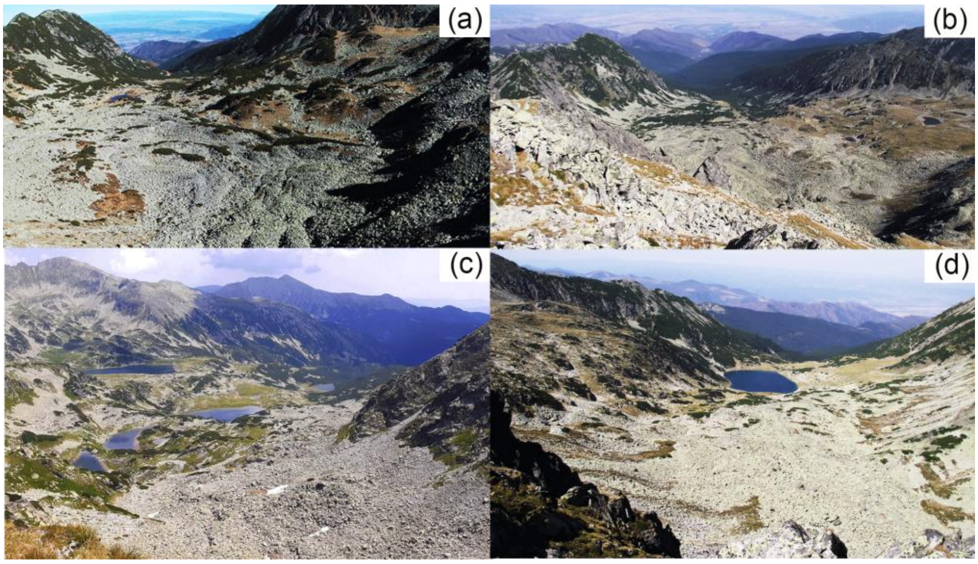

Figure 2: Pictures of rock glaciers from Retezat Mountains: a) Pietrele (3) – relict; b) Valea Rea (5) – transitional; c) Judele (8) – transitional; d) Galeșu (7) – relict. Photo credit: A. Onaca.

3. Methods

3.1. Rock glacier inventory

Rock glaciers are ~~categorised~~ classified into three ~~types~~ categories based on ~~their~~ activity ~~status~~: active, transitional, ~~or~~ and relict, ~~as outlined by~~ (RGIK, 2023a). Active rock glaciers exhibit consistent downslope movement across most of their surface, with displacement rates ranging from a decimetre to several meters per year (RGIK, 2023a). Most of the surface of a transitional rock glacier experiences little to no downslope movement, with annual average displacement rates generally falling below one decimetre (RGIK, 2023a). Rock glaciers exhibiting no detectable movement across most of their surface are classified as relict (RGIK, 2023a).

This study ~~revised~~ updates the existing inventory of ~~rock glaciers in the~~ Southern Carpathians rock glaciers (Onaca et al., 2017b) ~~in accordance with the guidelines provided by~~following RGIK (2023a) guidelines. The inventory involved mapping rock glaciers through fieldwork surveys and detailed examination of high-resolution aerial imagery. Due to the ~~availability of~~limited kinematic ~~information for only a limited number of landforms~~data (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 (e.g., degree and type of vegetation cover).

3.2. Persistent scatterer interferometry using Sentinel-1 data

PSInSAR is a remote sensing technique designed to measure ground displacements along the radar line of sight (SAR LOS) with millimetric accuracies (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~~global coverage, regular acquisition and ~~open access~~open access~~data~~ policy ~~has~~ have enabled large-scale ground motion monitoring since 2014, resulting in a growing archive of applications.~~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~~under the European Ground Motion Service (EGMS), which provides open-access~~ly available throughout the entire~~ground motion data across Europe~~an area~~. The PSInSAR analysis ~~employed~~ in this study, ~~was~~ developed by Terrasigna, ~~and~~ generally follows ~~the~~ EGMS specifications (EEA, 2025~~).~~), but differs in key areas, including ~~However, there are a few differences, particularly related to the choice of~~ reference point selections, ~~the modelling of~~ atmospheric ~~effects~~ modelling in steep terrain and ~~the selection of~~ SAR image selections. EGMS ~~products are computed~~ computes ground motion at the regional ~~level~~scale, ~~where~~ using reference points ~~are typically located~~mainly in lowland areas ~~covered by~~where infrastructure ensures~~, which provides~~ strong and stable radar backscattering~~ing~~. ~~Additionally, EGMS~~It also includes all available acquisitions, even those affected by snow cover at high altitudes. However, inspection of EGMS products reveals that extending the measurement network from lowland reference points to mountain summits ~~was largely unsuccessful~~has proven ineffective. This is mainly because the atmospheric path delay associated with steep topography was not adequately compensated for and acts like phase noise. Snow cover ~~f~~Furthermore~~, snow cover during winter significantly~~degrades ~~impacts~~ data quality~~. Non-homogeneous snow or snow with variable humidity~~ by scatterings radar signals and increasinges phase noise, especially when snow is non-uniform or has variable humidity. ~~If~~ Under ~~the case of~~ dry snow conditions, radar waves penetrate the snowpack, but because they propagate more slowly than in air, the interferometric phase experiences a time delay~~.~~ , that appears as ~~This delay produces apparent~~false subsidence (i.e., ~~false~~ ground displacement away from the radar sensor). ~~Combined these~~ These factors often result in the rejection of radar targets on mountain tops due to excessive noise.

To address these ~~issues~~~~challanges~~challenges, Terrasigna carefully selected reference points ~~located~~ on mountain summits, where the topographic atmospheric delay is similar to that of the areas of interest. Additional efforts were made to improve the accuracy of atmospheric delay modelling and compensation~~.~~ and limited analysis~~Furthermore,~~ to ~~only~~ snow-free acquisitions ~~were considered~~. ~~As a result~~~~Consequenlty~~Consequently, ~~the~~ a high density of radar targets ~~– formed by~~on bare rock surfaces at ~~the mountain~~ tops ~~of the mountains – is~~ was preserved in our measurements.

Both ascending and descending paths were processed for cross-validation, along with L-band ALOS data~~, which was analyzed for the same purpose.~~. Because descending passes occur in the early morning – when atmospheric conditions are generally more stable than in the evening – the resulting measurements tend to be less noisy. A 2D decomposition between ascending and descending passes is technically feasible; however, the steep topography introduces several challenges. First, areas that are clearly visible from one orbit may be in shadow or appear foreshortened in the other, reducing data quality and spatial consistency. Second, since the topography is steep, the preferential direction of ground movement is often dictated by the slope of the terrain. Additionally, the 2D decomposition estimates vertical and east-west displacement components under the assumption that there is no north-south movement – an assumption that is frequently invalid in mountainous regions, where north-south displacement is commonly observed. Based on these issuesGiven these challenges, it was decided to useonly the orbits that yieldedwith the best results was used for validation and mapping.

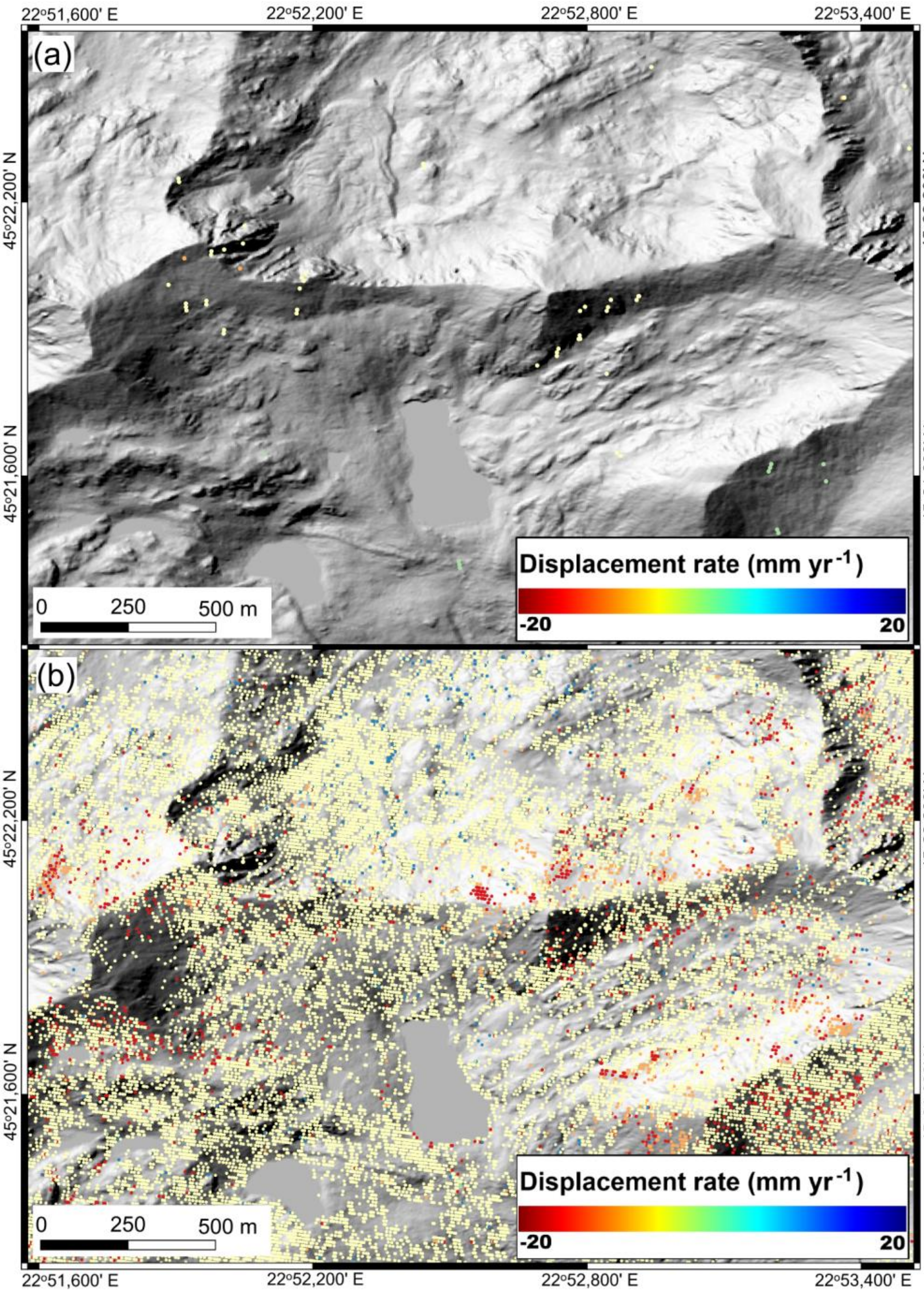

Figure 3: Comparison between the PSInSAR spatial density of measurements obtained by EGMS (a) and Terrasigna (b) in the central area of Retezat Mountains. Background of both maps: hillshade based on the LAKI II DEM (LAKI II MNT, 2024).

Figure 3a illustrates the total coverage ~~(~~from all ~~available~~ S1 paths ~~from both the~~ (Ascending and Descending orbits) in the study area ~~of the~~using the EGMS product, ~~in the area of interest,~~ while Figure 3b ~~illustrates~~ shows the PSInSAR analysis ~~of the same area, derived solely~~ from ~~one~~ a single S1 path (Path 80 Descending~~).~~), hereafter ~~In the following, this is referred to as~~called `Terrasigna PSInSAR`. It is evident that the EGMS coverage is ~~relatively~~ sparse and does not highlight dynamic areas – there are no zones marked in red, which typically indicate significant ground motion. In contrast, Terrasigna~~the~~ PSInSAR ~~results from Terrasigna show much~~offers denser coverage and clearly highlights ~~identify~~ dynamic areas, with red ~~colors~~colours ~~representing~~ denoting higher displacement rates.

~~In~~ ~~T~~This study assessed~~, the kinematics of the~~ rock glaciers kinematics ~~were assessed~~ using 181 snow-free S1 images acquired between May 15, 2015, and October 4, 2021~~, covering only the snow-free periods~~ to avoid coherence loss. ~~The~~ ~~M~~Motion was measured along the SAR LOS direction; however, the actual displacement of the rock glacier surface is expected to mainly occur along the slope or in the vertical direction. The PSInSAR algorithm (Rucci et al., 2012; Crosetto et al., 2012; Poncoș et al., 2022), ~~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 ~~unvegeted~~unvegetated areas ~~without vegetation cover~~. The process began by extracting linear deformation information before applying any spatial or temporal filtering, which was typically used to improve phase statistics. A ~~key~~ major 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. ~~An important number of~~Notably, 24 out of 94 rock glaciers in the area are oriented north-south or south-north, ~~which may lead to an~~potentially causing underestimation of ~~the~~ along-slope displacements due to ~~the~~ limited satellite sensitivity ~~of the satellite look angle~~ to slope-parallel motion.

The PSInSAR results were analysed using the Persistent Scatterers Online Software Tool (PSTool), a web-based platform developed by Terrassigna Inc. (Poncoș et al., 2022), ~~to exploit~~designed to handle ~~a~~ large volumes of ground displacement data. ~~The~~ PSTool ~~platform can be used to~~enables inspection of temporal ~~characteristics of the~~ ground motion characteristics, selection of areas of interest, ~~and~~ extraction of temporal averages of displacement rates, export of temporal profiles ~~to~~ in standard formats for integration ~~in the~~with user~~'s own~~ platforms, and uploading of user-specific layers on top of the displacement information.

3.3. Inventorying moving areas

~~According to~~Following RGIK (2023a) guidelines, a moving area (MA) represents an area at the surface of the rock glacier characterised by ~~relatively~~ homogeneous velocity rates and consistent flow direction. Based on multi-annual surface velocity from Terrasigna PSInSAR ~~rates~~, MAs were identified ~~and delineated~~ within the inventoried rock glaciers (Onaca et al., 2017b) ~~using Terrasigna PSInSAR results. The next step was to assign standardised velocity classes to moving areas~~and classified into SAR 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,~~ 0.3-1 cm yr^{-1}, 1-3 cm yr^{-1}, and 3-10 cm yr^{-1}, undefined (RGIK, 2023a) (Fig. 4). The velocity class characterizes the average yearly displacement rate recorded within a MA during the 2015-2021 period. The undefined ~~category~~ class was assigned to MAs characterised by inhomogeneous velocity rates. ~~PSInSAR-based surface displacement~~ Displacements ~~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 approach (Rouyet et al., 2021). The moving areas were manually digitized and compiled into an inventory using ArcGIS 10.8. MAs smaller than 1000 m^2 ~~Since many surface~~were excluded to avoid signals from active layer deformation unrelated to permafrost creep. ~~displacements in marginal periglacial regions result from active layer deformations (e.g., melt-induce subsidence), we have set the minimum area for an MA at 1000 m^2 to exclude those not associated with permafrost creep. For the~~ ~~S~~spatial analysis ~~of the rock glaciers and MAs, we~~ used a one-meter resolution digital elevation model ~~generated~~ derived from 2018 ~~from~~ high-resolution LiDAR ~~source~~ data ~~acquired in 2018~~ (LAKI II MNT, 2024).

3.4. Differential GNSS measurements

Judele (8) and Berbecilor (9) rock glaciers had beenwere surveyed by differential GNSS (DGNSS) measurements every summer between 2019 and 2021. A differential dual-frequency Topcon Hiper V GPS had acquired high-precision positioning data in real-time kinematics mode. The dGNSS device uses two receivers, one installed as a fixed base station, whereas the roving receiver was 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. Additionally, tTwo control points on stable bedrock outside the roc glaciers boundaries of the rock glaciers, located on stable bedrock, were also measured to assess DGNSS the horizontal accuracy, which ranged of the DGNSS. The difference between the yearly measurements in both cases indicated an accuracy range offrom 0.3 to 0.6 mm/yr^{-1}.

The Vvelocities used in the analysis were calculated as the displacement between the initial and final positions over a the two-year period.

3.5. Validation with ALOS-2 PALSAR-2 interferometry

To further validate 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 theduring snow-free season periods in (September and -October) were analysed. We computed Wwrapped differential interferograms were computed with for time intervals ranging fromof one to five years using a 10 m resolution DEM with 10 m pixel spacing obtainedderived from 1:25 000 scale topographic maps with a contour interval of 10 m contour lines. We masked aAreas affected by geometrical distortions were masked and used only reliable signals from descending paths were used.interferograms from snow-free periods. Kinematic attributes were assigned only when the signals were reliable (e.g., in descending mode). Moving areas were independently identified and delineated, and then linked associated to the existing Rock Glacier Units (RGUs) (RGIK, 2023b).

3.6. Thermal conditions

The bottom temperature of the winter snow cover is an efficient method to map permafrost distribution in non-arid mountains (Vonder Mühll et al., 2002). If Under optimum optimal 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). However, in on dry, porous bouldery surfaces - where air convection and advection occur, - this method lacks theBTS loses accuracy in preciseilyon needed to accurately mapidentifying permafrost occurrence (Bernhard et al., 1998). NeverthelessStill, the BTS methodit remains highly effective for distinguishing areas with colder ground surface temperatures from those with warmer ones. In March 2022, 140 BTS measurements were recorded using two classical 2.6 m-long probes with digital thermometers (±0.5 °C accuracy).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 Mmeasurements were acquired taken at the snow-ground interface end of March 2022 on four rock glaciers in across 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 Snow depths at all sites exceeded 80 cm, ensuring insulation from air temperature fluctuations (Ishikawa et al., 2003). Previous studies in the Southern Carpathians (Vespremeanu-Stroe et al., 2012; Onaca et al., 2015) revealed confirm that BTS values remain stable in March, BTS values remain nearly constant belowbeneath a thick snow cover, which usually falls inthat typically accumulates in November or December.

Minimal Miniature temperature data loggers became widely used in mountain permafrost terrain to get more detailed insights intobetter understand the surface 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 instrumented to monitor the thermal regime at the ground surface (Fig. 1b). The evolution of ground surface temperatureGST was recorded every 2 hours using iButtons DS1922L data loggers, which operate between -40 and 80 ºC with a manufacturer-stated accuracy of ± 0.5 ºC. ~~According to the producer, the miniature thermistors used in this study have an accuracy of ± 0.5 ºC and measure temperatures between -40 and 80 ºC.~~ 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~~ to late winter, ~~the~~ ground surface temperatures ~~remains~~ tend to stabilize ~~under a~~beneath thick snow, with subsurface processes ~~insulating layer, and the subsurface mainly controls~~ controlling ~~the~~ energy ~~flux~~exchange. This ~~is why~~stable phase, known as the "winter equilibrium temperature" (WEqT) is ~~considered~~ a reliable ~~an excellent~~ empirical ~~predictor~~ indicator of permafrost existence ~~if temperatures are low (i.e.~~when values are below~~, <~~ -2 ºC~~)~~ (Sattler et al., 2016). WEqT typically lasts ~~refers to stable ground surface temperature period lasting~~ at least two weeks~~, generally~~ and ~~occurring~~ occurs ~~in late winter, when~~under snow cover ~~exceeds~~ thicker than 50 cm ~~in thickness~~ (Schoeneich, 2011). Both 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 and refraction seismic tomography, are widely applied in mountain permafrost studies ~~and have the potential~~ to characterise subsurface structure and heterogeneity and to 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~~ Since ice ~~can be considered~~acts as 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) to be distinguished ~~and~~ from unfrozen ~~sediments~~ ones (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 (vp) is mainly controlled by density.~~, and~~ Variations in vp allow to identify porosity changes, or to 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~~relies 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~~ lies in its ~~the increased~~improved accuracy, ~~of the parameters estimated,~~ as ~~the~~ it ~~algorithms~~ iteratively ~~search~~ seeks~~for~~ a subsurface model that ~~simultaneously~~ fits ~~explains~~ both ~~the~~ seismic and resistivity ~~measurements~~data. This ~~is especially~~leads to a ~~relevant for the porosity model, which is represented~~ more realistic~~ally~~ representation of porosity ~~in the PJI than in previous~~compared to earlier 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~~ system 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~~ surveys ~~were performed in~~employed the Wenner configuration, ~~to ensure~~which provides 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 (vp 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~~initially inverted independently using the PyGimLi framework (Rücker et al., 2017), ~~and in a second step~~followed by a petrophysical joint inversion~~, 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 exhibited velocities ranging from 0.3 to 5 cm yr^{-1} (Fig. 4 and 5). The measured displacement between 2015 and 2021 remained constant for most MAs, with no significant ~~changes in velocity during this period~~temporal variations (see trendlines in Fig. 5). ~~Due to~~Given the relatively low velocities of the MAs, ~~tracking~~ seasonal variations ~~involved~~ were difficult to assess ~~high uncertainty~~reliably; ~~therefore~~thus, ~~we referred~~ only ~~to~~ annual or multiannual ~~displacement~~ rates were considered.

A total of 92 MAs covering 0.27 km^2 were inventoried ~~in the~~within the Retezat Mountains rock glaciers. Most ~~of the~~ MAs ~~are~~ fall ~~classified with the~~into the slow velocity class~~s~~es of ~~(~~0.3 – 1 cm yr^{-1} and 1-3 cm yr^{-1}~~)~~ (Fig. 6), ~~while~~ with only 10 % ~~of the MAs are characterised by~~exhibiting ~~velocity~~ velocities ~~class~~ of 3-10 cm yr^{-1} (Fig. 6a). ~~Around~~ About ~~one-third (~~37 %~~)~~ of the ~~total number of~~ rock glaciers ~~in the Retezat Mountains~~ contain~~s~~ MAs, ~~but the analysis revealed they~~which ~~usually~~ typically occupy ~~only a small portion (<~~less than 30 %~~)~~ of ~~the total surface of~~ each rock glacier`s surface; however, in six cases, the cumulated area of MAs represents more than 50 % of the rock glacier area (Fig. 6d). The mean MA area ~~of MAs~~ is 0.3 ha, ranging from 0.1 to 1.77 ha.

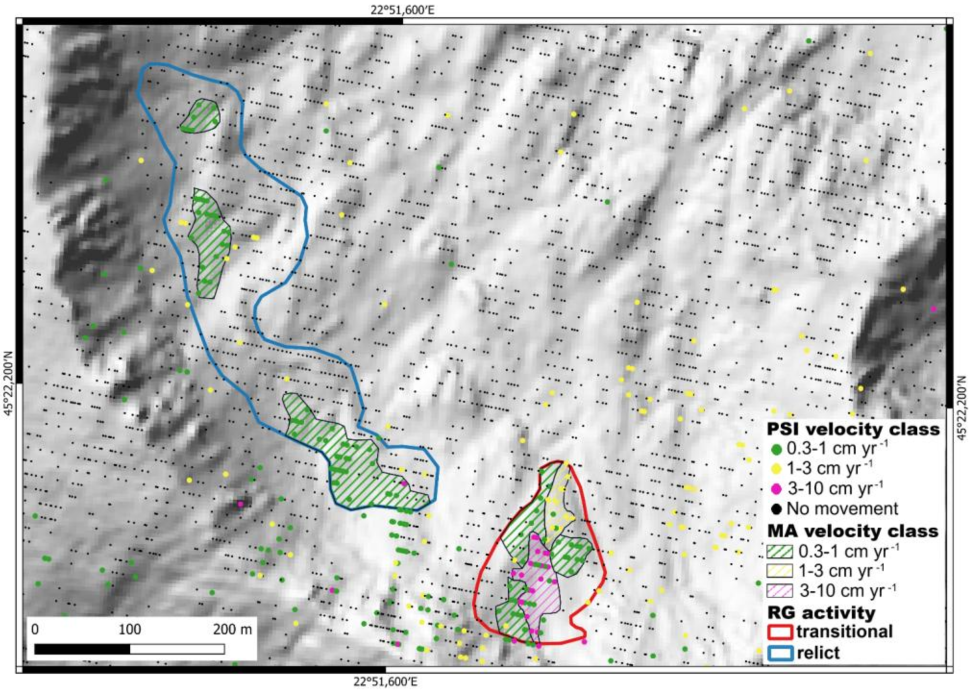

Figure 4: Example of moving areas and rock glacier activity for the Retezat Mountains. The two RGs are marked with numbers 1 and 2 in fig.1. Background image: hillshade based on the LAKI II DEM (LAKI II MNT, 2024).

The number of MAs ~~in each~~per rock glacier ~~varies~~ ranges ~~between~~ from 1 and 8, ~~but in most cases~~with the majority (69 ~~%),~~ %) containing 1 to 3 MAs ~~occur in an individual RG~~. MAs ~~characterised by~~with velocities > 3 cm yr^{-1} were identified in 8 rock glaciers, ~~whereas~~ while those ~~MAs classified in the velocity class~~in the 1-3 cm yr^{-1} class ~~appear~~ were found in 17 (Fig. 6c). The median elevation ~~for each~~of MAs by velocity class ~~falls~~ ranges ~~between~~ from 1950 and 2295 m (Fig. 7). ~~Specifically~~Most MAs~~,~~ (62 %) are located ~~of the MAs are found in the elevation band of~~between 2100 ~~to~~ and 2200 m, ~~while~~ followed by 17 % ~~lie~~ between 2200 and 2295 m~~. Additionally~~, 16 % ~~of the moving areas are situated in the range of~~between 2000 ~~to~~ and 2100 m, and only 5 % are below 2000 m. ~~Among these, MAs categorised under velocity classes of~~Higher velocity classes (1-3 and 3-10 cm yr^{-1}) ~~generally~~ tend to occur at the highest elevations (Fig. 7a Slope values across MAs vary between 8° and 42°, with the widest range observed in the 0.3–1 cm yr^{-1} class, which also shows higher median slopes (Fig. 7b).~~). Figure 7b illustrates the variability of slopes across the MAs velocity classes, revealing mean values ranging from 8 to 42º. The widest range of slopes is observed in the velocity class 0.3 – 1 cm yr-1, which also exhibits higher median values.~~ Half of the MAs (50 %) 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 %~~)~~ of MAs compared to 23% on NW and W aspects, ~~(23 %) in respect with the~~relative to rock glacier distribution (Fig. 8). Across the mountain range, ~~slopes with a~~ western aspects dominate in ~~terms of~~ surface ~~coverage~~area. ~~The~~ MAs with velocities >~~exceeding~~ 3 cm yr^{-1} receive the lowest potential solar radiation (Fig. 7c).

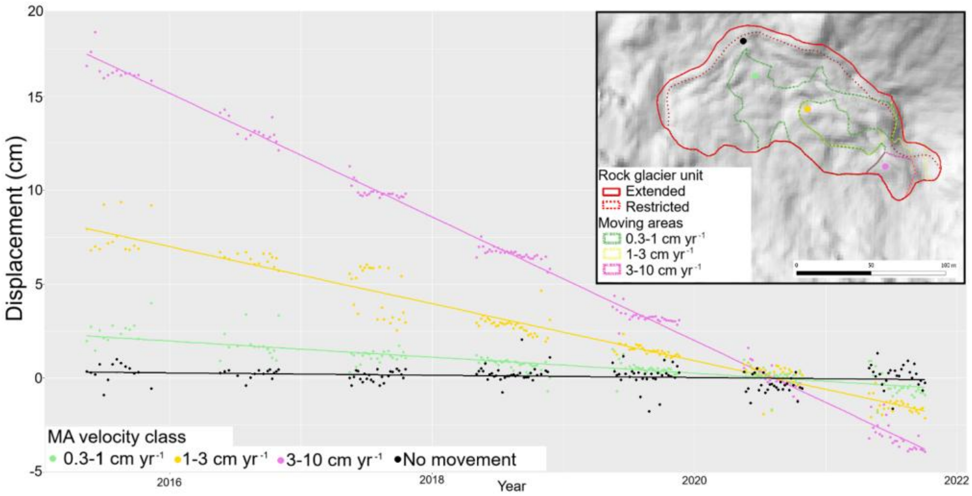

Figure 5: Displacement profiles over a period of 6 years (2015 – 2021) for 4 locations (identified in the location map with dots of corresponding colour) representing each velocity class and one for an area with no movement. The dots show the actual PSI displacement results, while trend lines (linear regressions) indicate long-term motion patterns. The displacement is measured relative to 2021. The downward trend can be interpreted as movement away from the sensor, which in our case represents a combination of vertical movement and horizontal downslope movement. The gap in point density along the trend line is due to the winter season, the measurements being performed in snow free conditions, usually from June to November.

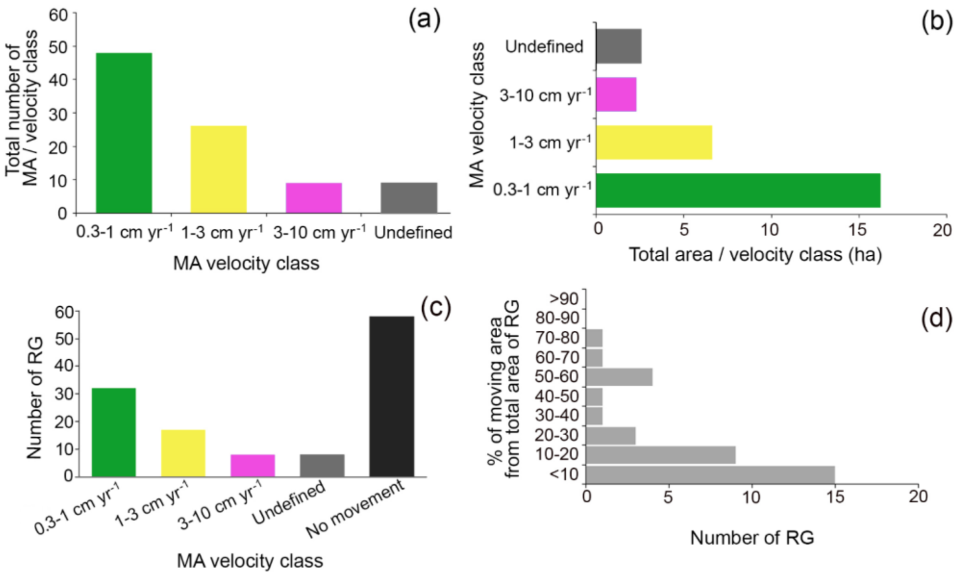

Figure 6: The moving areas classified by velocity classes (a) and their extent (b). The number of rock glaciers containing moving areas and without moving areas (c) and the percentage of the moving area cover within rock glaciers (d).

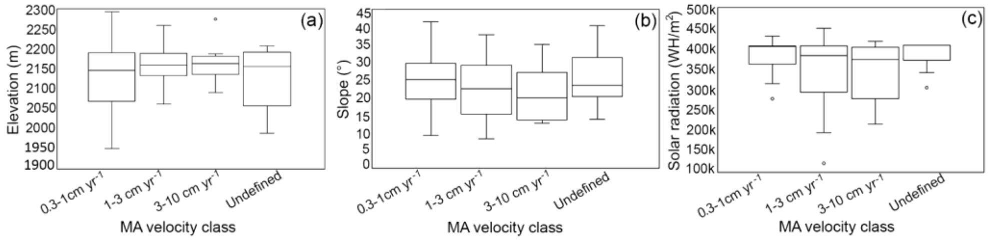

Figure 7 Elevation (a), Slope (b) Potential solar radiation (c) vs MA velocity classes

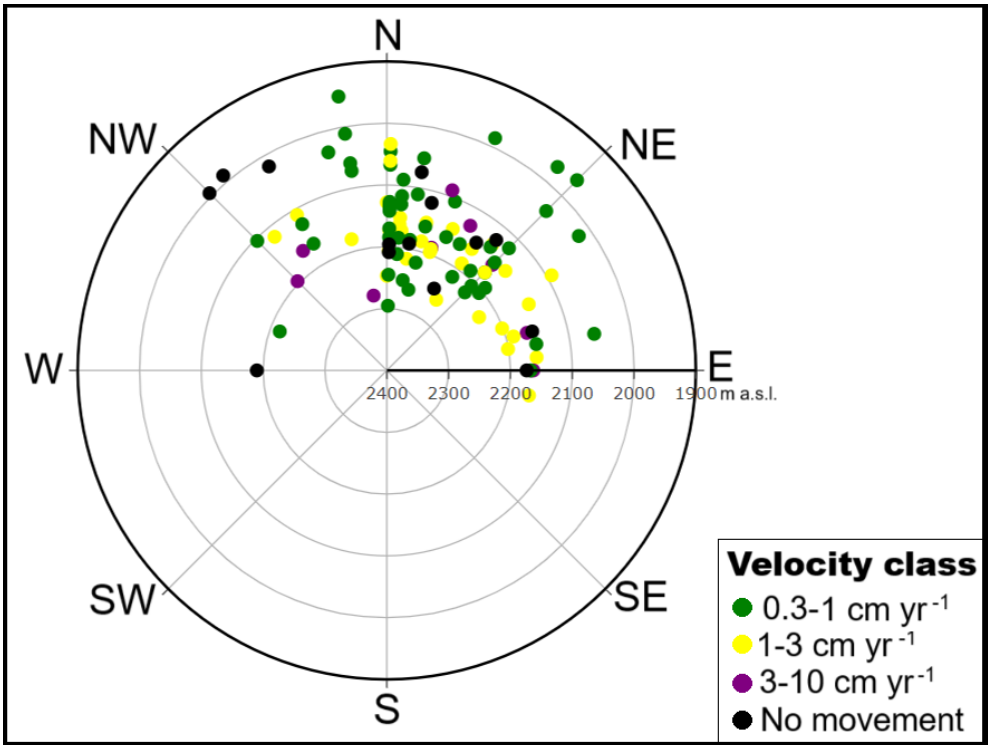

Figure 8: Distribution of moving areas, in the Retezat Mountains, in relation to slope aspect (angular axis) and elevation (radial axis).

For rock glaciers exhibiting no or minimal movement (< 1 cm yr^{-1}), the RGIK (2023a), recommends assigning a relict activity class. ~~The present analysis shows that~~Based on this criterion, only 21 % of the rock glaciers in the Retezat Mountains ~~could be~~are classified as transitional (Fig. 9a), ~~encompassing areas~~ with ~~moving~~ velocities ~~ranging~~ between 1 and 5 cm yr^{-1}. ~~The transitional~~ Transitional rock glaciers ~~exhibit~~ have a higher ~~a~~ median elevation ~~of~~ (2170 m), ~~surpassing that of the relict ones by~~about 150 m above the relict ones (Fig. 9b)~~. Additionally, the median size of transitional rock glaciers is~~and a slightly smaller median size ~~than that of relict rock glaciers~~ (Fig. 9c).

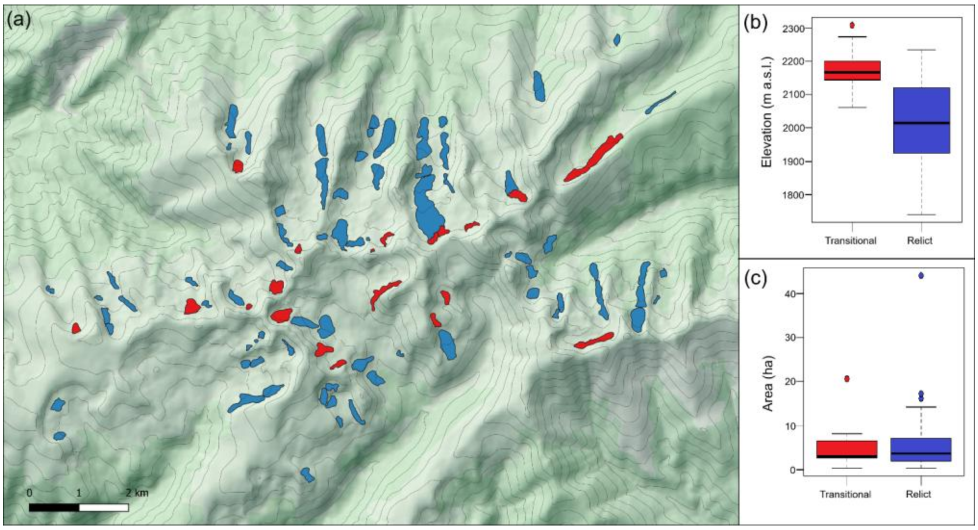

Figure 9: The spatial distribution of transitional and relict rock glaciers in the Retezat Mountains (a) and their median elevation (b) and size (c). Background imagery: Bing Maps © Microsoft, retrieved via QGIS (Version 3.34) using the QuickMapServices.

Figure 10 presents a comparison compares between ALOS-2 PALSAR-2 interferogram and thewith Sentinel-1 PSInSAR results at Galeșu (7) site. Although While the accuracy of the ALOS-2 PALSAR-2 hasis lower spatial resolution and accuracy, both datasetsproducts show consistent exhibit similardisplacement signals, with. The main displacement areasMAs are clearly visible and overlappingcoincide on both maps.

The comparison between highlights that PSI and InSAR performance reveals thatprovides finer spatial detail, particularly in areas with high spatial displacement variability in displacement, PSI provides more detailed mapping of the moving areas (MAs), allowing for the differentiation of relatively minor velocity differences. In Fig. 10b, a specific MA is clearly distinctly identified mapped and classified as having awith velocitiesy of <1 cm yr^{-1}. The same area zone appears in Fig. 10a shows a similar core of low velocity, where most of it is also mapped as <1 cm yr^{-1}; however,but includes adjacent zones areas are classified as 1–3 cm yr^{-1} and 3–10 cm yr^{-1}, indicating suggesting a broader range of motion detected velocitiesby ALOS-2 PALSAR-2 interferogram.

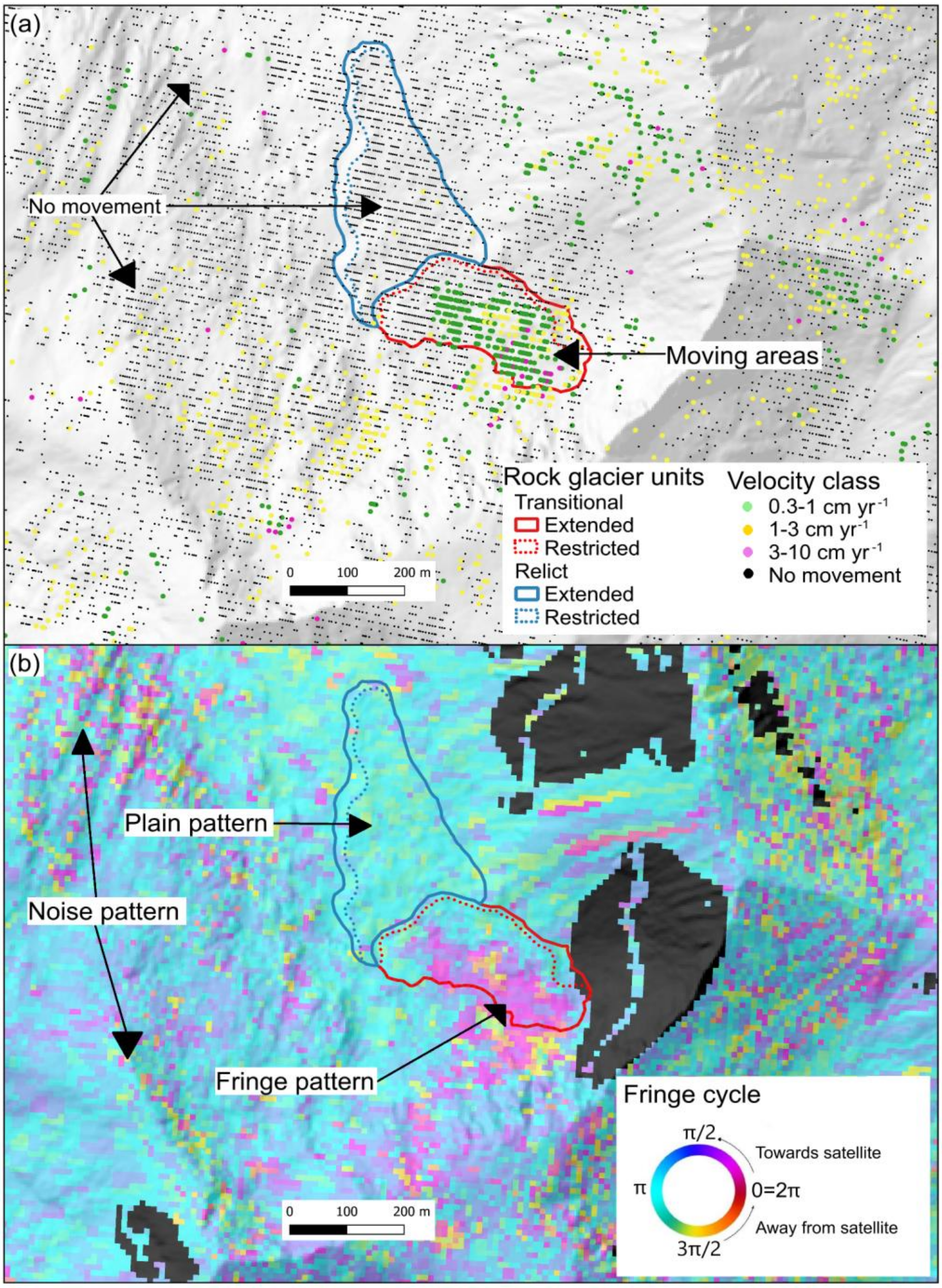

Figure 10: A comparison between multiannual PSINSAR from Sentinel 1 (a) and InSAR from ALOS-2 PALSAR-2 (b). Notice the same moving areas inside the RGs, that are revealed by clustered pixels with movement (green, yellow and magenta) from PINSAR (a) and the areas with fringe patterns (b). In (b) the shadow areas are masked out and the fringe cycle (bottom right) represents the change of colour. The interferogram presented in fig. 10b, over the Galeșu rock glacier unit, has a long temporal interval, over five years from September 2014 to October 2019, and it is computed only for the descending path.

4.2. GNSS measurements

The mean velocities measured by dGNSS 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). On the Judele (8) rock glacier, eight marker points recorded velocities between 1 and 2.6 cm yr^{-1}, while nine points showed velocities between 0.4 and 1 cm yr^{-1}. The highest velocities are observed in the central part, gradually decreasing toward the margins. One marker point measured on the front of Judele rock glacier revealed very low rates of displacements (0.4 cm yr^{-1}). Almost all marker points indicate consistent movement toward the front of the rock glacier. Four marker points on the Berbecilor (9) rock glacier revealed velocities between 1 and 2.8 cm yr-1 and three between 0.6 and 1 cm yr^{-1}. All the seven marker points indicate consistent movement toward the front. Most marker points with moving velocities between 1 and 2.8 cm yr^{-1} (89 %) were located within MAs categorised under the 1-3 and 3-10 cm yr^{-1} velocity classes by PSInSAR analysis. At Judele, five out of eight dGNSS markers recording velocities between 1 and 2.6 cm yr^{-1}, fall within the 1-3 cm yr^{-1} velocity class, whereas at Berbecilor the ratio is two out of four. At both sites, nine marker points with velocities between 0.4 and 1 cm yr^{-1} are located outside any designated MAs, while only three fall within the corresponding velocity class.

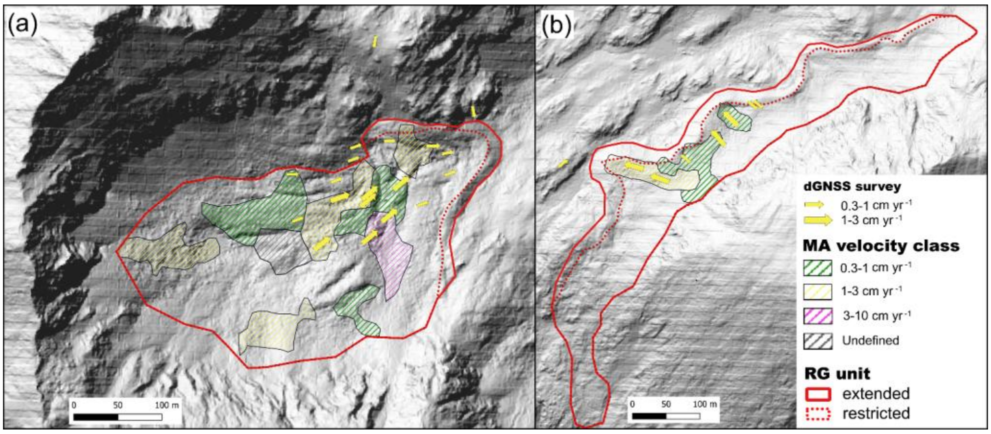

Figure 11: Horizontal displacements derived from GNSS measurements for 2019-2021 at Judele (a) and Berbecilor (b) sites, overlayed on the MAs derived from PSInSAR. Background of both maps: hillshade based on the LAKI II DEM (LAKI II MNT, 2024)

4.3. BTS and ground temperatures

BTS measurements ~~allowed the identification~~ identified ~~of~~ colder ~~versus~~ and warmer ground surface areas ~~in~~ across four rock glaciers (Fig. 12). Half of the 140 ~~measured~~ BTS points were ~~measured~~ collected on Pietrele (3) ~~rock glacier~~, ~~which has the lowest front altitude~~the lowest-elevation site, which ~~and revealed~~showed the warmest ~~mean o~~average~~f~~ BTS value~~s~~ (-2.9 ºC). The coldest ~~temperatures~~ values ~~at this site~~ occurred in ~~the~~ its upper~~most~~ ~~part~~section (mostly < –3 °C), ~~where~~ ~~whith~~with several ~~most BTS values were below -3 °C. Several BTS points measured on the~~low readings also on the feeding talus slope ~~feeding this rock glacier also revealed very low temperatures~~. In the western part, where a 0.3-1 cm yr^{-1} MA ~~in the 0.3-1 cm yr⁻¹ velocity class~~ is present, BTS values were consistently ~~fell~~ below -5 ºC. ~~At the~~ Galeșu, a multi-unit rock glacier, ~~the~~ had a mean BTS of~~was~~ -3.9 ºC, with the coldest values clustered in the southern unit and on the upslope talus. The BTS values within the MAs were all very low, below -5 ºC. In contrast, the northern rock glacier unit, which showed no signs of surface displacement, exhibited a highly heterogeneous distribution of BTS values. Păpușa (6)~~ is~~, the highest site, ~~rock glacier where BTS measurements were performed and revealed~~recorded the lowest average of BTS values (-4.1ºC), while~~ereas~~ ~~at~~ Pietricelele (4), ~~the~~ had a mean ~~BTS was~~ of -3.5 ºC. At Păpușa ~~site~~, a small central -zone had warmer ~~zone occurred in the central part, with~~

~~three~~ BTS values ~~warmer than~~ (> –2 °C), but all MAs showed very cold conditions. ~~-2 ºC; however, all BTS values within the MAs indicated very cold ground conditions~~ Similarly, at Pietricelele, ~~a~~ warmer ~~ground surface~~ areas were~~as~~ found~~identified~~ in the central and northeastern parts, while the western and southeastern areas revealed colder temperatures. Snow depth at the probing points ranged from 80 to 260 cm. ~~In~~ At all ~~the cases~~sites, the ~~calculated~~ median BTS in MAs was lower ~~compared with~~than the overall site median ~~of all BTS values in each site~~.

Between 2013 and 2022, MAGST values at the monitoring sites generally remained below 0 °C, ranging from –2.3 °C to +0.8 °C, with the coldest values at Galeșu and the warmest at Pietrele. ~~To illustrate long-term GST evolution,~~ Figure 13a ~~shows~~ illustrate the long-term evolution of GST using~~the~~ a running annual mean ~~of ground surface temperature~~. ~~However,~~Persistent subzero MAGST values were recorded only at ~~site~~ Valea Rea (5) in all the years, ~~whereas~~ while ~~at~~ Galeșu~~, all the MAGST values were~~ showed below 0 ºC values in all years except ~~one year (e.g.,~~ 2016~~)~~. All ~~the GST~~ sites recorded ~~revealed~~ negative ~~values for the~~ mean temperatures ~~of the entire~~ over the full monitoring period~~interval~~.

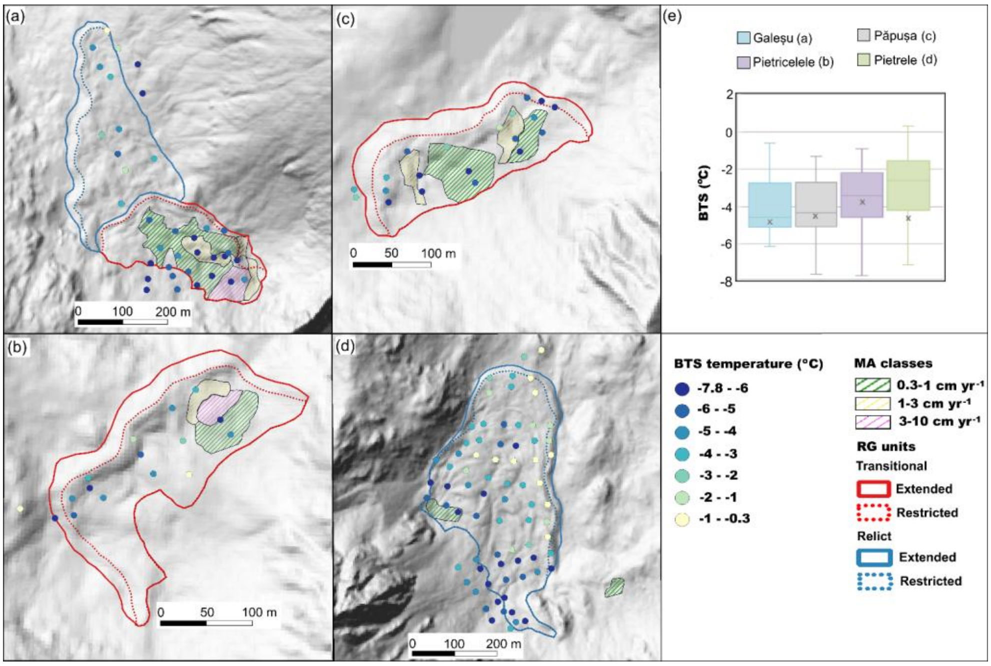

Figure 12: BTS measurements performed in March 2022 on four rock glaciers in the Retezat Mountains: (a) Galeșu, (b) Pietricelele, (c) Păpușa, (d) Pietrele. (e) Summary box-plot diagram of the BTS measurements, the horizontal line drawn inside denotes the median BTS for each rock glacier, while the x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

Fig. 13c reveals the mean daily temperature at the GST monitoring sites. The lowest GST values (< -10 ºC) occurred ~~in~~ between 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. Although snow depths are generally sufficient to insulate the ground by January, notable ground cooling still occurred between January and March at all sites.~~However, at all the sites, significant ground cooling was observed even during the January-March period, despite snow depths typically being sufficient to insulate the ground from air temperature fluctuations~~. ~~For example, at~~ At Galeșu, ~~almost~~ nearly every winter ~~exhibited~~ displayed ~~notable~~ short-term GST fluctuations indicating episodic ground-air thermal exchange ~~the GST regime~~. Similar, th~~r~~ough less pronounced, patterns were also observed at Judele (e.g., winters ~~of~~ 2013-2014 and 2017-2018), Pietrele (e.g., 2012-

2013, 2013-2014, 2014-2015, 2016-2017 and 2021-2022) and Valea Rea (e.g., 2015-2016 and 2019-2020). In a few instances, inverse thermal relationships between ground surface temperature and air temperature were recorded, confirming confirmed the presence of internal ventilation through the coarse debris during winter. These thermal anomalies, are likely driven by advective heat fluxes that remain active beneath thick snow cover and likely contribute to the cold low MAGST observed in the rock glaciers. Usually, duringBy March, ground surface temperatureGST typically stabilised, s are relatively stable and are mainly driven byreflecting conductive heat transferprocesses. In almost nearly all cases, the resultingcorresponding WEqT were below -2 ºC, indicating possible or probable permafrost occurrence (Fig. 13b). WEqT values higher than -2 ºC were recorded occurred only at Pietrele in late winters 2013 and 2014. At Valea Rea and Judele, most WEqT values wereranged frombetween -2 toand -3 ºC, whilecreas at Galeșu, the late winter temperatures were considerably lowerconsistently showed significantly lower values.

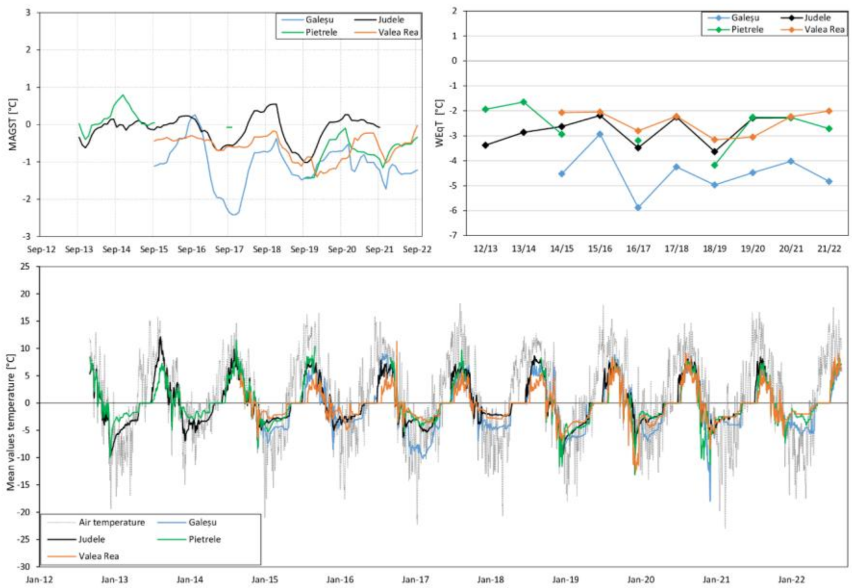

Figure 13: (a) Running 12-month average of mean annual ground surface temperature, (b) Winter Equilibrium Temperature (WEqT) and (c) Running 12 months average of Ground Surface Temperature (GST) for the period 2012/2013 to 2021/2022 at four sites in the Retezat Mountains and air temperature at Țarcu meteorological station (2180 m).

4.4. Geophysics results

The results of the geophysical surveys at Galeșu rock glacier are shown in Figure 14, for theincluding two crossing ERT profiles (P1 and P2) (Fig. 14a, b), as well as the RST and PJI results available for profile P1 (Fig. 14c, d). Both ERT tomograms reveal an up to 5 m thick layer characterised by high resistivities (> 200 kΩm) representing corresponding to the dry and coarse-blocky surface layer. Patchy occurrences with similarly high resistivities are observed in 5-20 m depth in both profiles, which could indicate remnants of former ice-rich permafrost within the rock glacier (labelled with `ice?` in Fig. 14). BelowBeneath, a more these zones, a more homogeneous layer of with resistivities around 10 – 30 kΩm may indicate the rock glacier base (bedrock) in the southwestern part of profile P1, however, the resistivity values do not exclude the possibility of frozen conditions and the interpretations of this zone remains ambiguous. The landform's overall thickness is estimated at < 20 – 30 m and potentially < 15 m in the southwestern part of profile P1. The eastern part of profile P1 (x < 50 m in Fig. 14b) is locatedextends outside beyond the rock glacier and traverses into a partially vegetated talus slope. Here, the surface layer exhibits lower resistivities (<

100 kΩm, probably representing smaller 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. Both the morphology and the resistivity values point to a potentially frozen ventilated talus slope, but this is not a focus of this study and will not further be explored.

The seismic profile P1 (Fig. 14c) ~~only~~ which covers only the rock glacier ~~part~~ section of the ERT profile P1, ~~and shows~~reveals a 5-10 m thick upper layer with P-wave velocities < 1500 m s^{-1}, indicating highly porous blocky material. The velocities are increasing with depth, reaching 4000 m s^{-1} 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~~toward the end of the profile. According to the seismic data, ice-rich permafrost would be possible in large parts of the tomogram. However, ~~in~~ when combined~~ation~~ with the ERT data, ice-rich conditions ~~seem only~~appear plausible in those parts of the tomogram that coincide with elevated resistivities. In contrast, areas with lower resistivities may reflect increased conductivity associated with ongoing ice melt, rendering their interpretation ambiguous. ~~Alternatively, the zones with lower resistivities could also indicate zones with increased conductivity due to ongoing ice melt, the interpretation therefore remains ambiguous.~~ The seismic data further indicate relatively porous material rather than firm bedrock and point to an overall larger thickness of the rock glacier than indicated by the ERT profile.

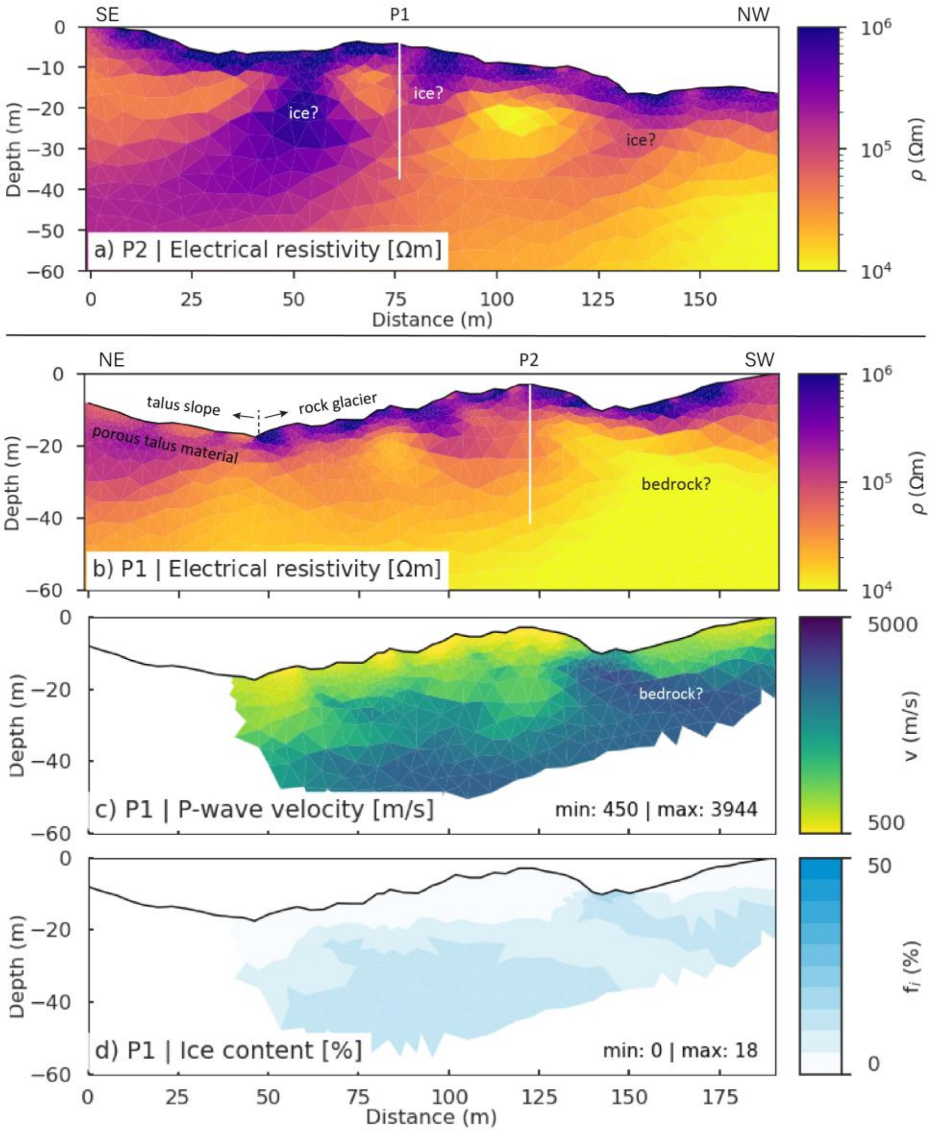

Figure 14: a) and b) ERT profiles P2 and P1 (see Fig. 1c for location), c) RST profile, and d) modelled ground ice content based on the PJI.

The result of the PJI modelling (Fig. 14d) reveals indicatesa generally very low ground ice content in the upper sector of the Galeșu rock glacier, with maximum values reaching onlyf 18 %. The highest ice contents coincide with zones with highest seismic velocity, partly contradicting the individual interpretation (bedrock). This can be due to the known rock-ice ambiguity of the current PJI formulation, as the rock and ice content are only directly constrained through the petrophysical equation of the seismic velocity. As a consequenceConsequently, the correctaccurate differentiation between rock and ice can beis problematic in some cases (see Mollaret et al., 2020 for details). The generally overall low ice contents modelled through the

PJI ~~therefore mainly confirm~~supports the interpretation that a ~~potential~~ formerly massive ice core is no longer~~t~~ detectable, ~~anymore and~~ pointing to an advanced ~~state~~ stage of degradation of this rock glacier. However, these results do not exclude the possibility of more confined ice-saturated or even supersaturated layers (as expected based on the analysis of InSAR data in section). Due to the limited resolution capacity of the geophysical profiles with 4 m sensor spacing, thin ice-rich or ice-supersaturated layers may not be resolvable as such, but - depending on their depth and extent - with strongly reduced spatial gradients of the ice content (as well as resistivity or velocity contrast in the individual tomograms). Therefore, t~~T~~he relatively homogeneous ice content distribution ~~modelled from~~in the PJI model may ~~therefore not only~~ reflect both the intrinsic rock-ice ambiguity ~~mentioned above~~of the inversion approach, and its limited ability ~~but also this limitation~~ to resolve small-scale subsurface structures.

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 (mm yr^{-1}~~a few~~ to 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~~ provides one-dimensional measurements along the satellite line-of-sight (LOS). ~~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~~Given the 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~~it proved effective ~~helpful in~~ for detecting ~~areas of~~surface motion and refining the rock glaciers inventory.

Slow-moving areas (i.e., 0.3-1 cm yr^{-1}; 1-3 cm yr^{-1}) are prevalent in this region, ~~where~~ with only 10% of ~~the~~ MAs ~~are characterised by velocities~~ exceeding 3 cm yr^{-1}. These faster MAs ~~latter tend to~~typically occur at ~~occupy~~ higher elevations and receive less solar radiation than slower ones. Overall, the median ~~size of the MAs~~ MA size ~~from~~ in the Retezat Mountains is slightly smaller than in other periglacial ~~environments~~ regions (Bertone et al., 2022). The largest median size (0.33 ha) occurs in MAs moving < 1 cm yr^{-1}, while those in the 1–3 and 3–10 cm yr^{-1} classes have a median size of 0.3 ha—approximately one-third smaller than those in South Tyrol (Bertone et al., 2024).~~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 0.3 ha, roughly one-third smaller than those reported in Southern Tyrol (Bertone et al., 2024).~~ Differential GNSS measurements revealed similarly slow movements at selected points, ~~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}~~)~~. Comparison with PSInSAR results showed limited agreement, likely due to the challenge both methods face in detecting such low velocities, as well as differences in the observation periods (2015–2021 for PSInSAR vs. 2019–2021 for dGNSS).~~A comparison between the GNSS survey and PSInSAR results revealed that there was not a very good correspondence between these outcomes. The discrepancy may be due to the difficulty both methods have in accurately detecting such slow movement. Additionally, differences between the velocity datasets may result from the distinct time intervals used for analysis - 2015-2021 for PSInSAR and 2019-2021 for dGNSS. However~~ Still, most GNSS survey markers ~~that exhibited~~with horizontal displacements exceeding 1 cm yr^{-1} were ~~still~~ located within the MAs. In terms of flow direction, the majority of these markers indicated consistent movement toward the fronts of Judele and Berbecilor rock glaciers, behaviour characteristic of permafrost creep.

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~~ identified 30 intact 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}., while In contrast, 15 rock glaciers showed show minimal displacements (0.3 – 1 cm yr^{-1}). Of Among these, eight were previously classified as intact, while the remainingand seven were categorised as relict. Notably, fFour rock glaciers, previously labelled asconsidered geomorphologically relict, now show surface displacements exceeding 1 cm yr^{-1} and were categorisedare classified as transitional in our study.

5.2. Permafrost occurrence revealed by geophysical and temperature measurements

The GGeophysical investigations revealed a frozen layer with overall low ice contents beneath a substantial thick active layer (~ 5m)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 greaterare often thickness thicker (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 though small-scale anomalies present in the tomograms as well asand absolute resistivity values, should be interpreted with carecautions.

The BTS measurements revealed very cold surface temperatures (< -4 ºC) across large portions of the rock glaciers, with particularly low values observedespecially within MAs, in the upper sections of the rock glaciers, and along the upper talus slopes. However, not all cold areas exhibited detectable movement in the PSInSAR results. Conversely, considerably warmer ground surface temperatures (-2 – -0.3 ºC) were also recorded in various parts of the rock glaciersseveral areas, supporting indicating the presence of internal ventilation. The GST results data suggest conditions favourable conditions for permafrost existence, but more notably highlight significant winter ground cooling episodes during the winter, likely driven by air advection. Similar results patterns have beenwere previously reported forobserved at Judele, Pietrele, Valea Rea, Galeșu and Pietricelele rock glaciers in previous studies (Vespremeanu-Stroe et al., 2012; Onaca et al., 2015). Except for Pietrele, all the other data-logger sites (Galeșu, Judele and Valea Rea) are located within areas MAs with displacement velocities exceeding 1 cm yr^{-1}. However, atAt Pietrele, despite the prevalence of low BTS values, almost no displacement was observed, except in the western part, where minor displacements (0.3 – 1 cm yr^{-1}) were detected. The As Pietrele rock glacier is oriented along a south-north direction and the LOS orientation tends tolikely underestimates displacements on its north facing slopes (Liu et al., 2013). The lack of significant displacement in this rock glacier between 2014 and 2021 does not necessarily indicate complete ice melt, but likely suggests an insufficient ice content for permafrost creep to occur., rather than complete ice melt.

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 slow-moving 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 detectable motion, whereas the rest are considered relict. Similar toAs in the Uinta Mountains (Brencher et al., 2021), in most cases, only a relatively reduced portion of the rock glacier exhibits movementsmovement is often confined to a limited portion of the landform. An illustrative case in this regard is the Galeşu multi-unit rock glacier, displaying movement solely in itswhere activity is restricted to the uppermost unit, where amarked by a younger lobe overlyingies the main body of the rock glacier. Similar younger lobes were identified in other valleys (e.g., Valea Rea, Pietrele) representing distinct phases of rock glaciers activity, 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 many rock glaciers in the Retezat Mountains remain stable. Notable examples of stable fronts include Judele (Fig. 11a), Berbecilor (Fig. 11b), Galeșu (Fig. 12a), Păpușa (Fig. 12c) and Pietricelele (Fig. 12b). Field observations support these findings, revealing no signs of recent activity—such as ploughed grass—despite steep and occasionally unvegetated slopes. 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. These characteristics are typical of climatically inactive rock glaciers (Barsch, 1996), which are often marked by a thick unfrozen surface layer and low ice content (Onaca et al., 2013).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).

The Our geophysical measurements performed in this study indicated the very lowrevealed a paucity of ice content in the Galeșu rock glacier, insufficient to support permafrost creep. For permafrost creep to occur, frozen conditions must extend to a depth of at least 10-25 m (Cicoira et al., 2021), which does not appear to be the case at Galeșu. Surface displacements at this site are more likely the result of ice-melt-induced subsidence, solifluction, or the tilting and sliding of blocks within the active layer. In contrast, the flow direction of dGNSS markers at Judele and Berbecilor showed consistent movement patterns, which are not typical of ice-melt subsidence or any other active-layer processesconsistent with permafrost creep. Additional Further geophysical and dGNSS measurements are needed to better distinguish differentiate between these mechanisms in marginal periglacial environments.

Various studies suggest estimate that the volumetric ice content within in active rock glaciers typically falls within theto range of between 40 % to and 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 values are commonly used to assess the water volume equivalent of ice content stored in rock glaciers (Wagner et al., 2021; Pandey et al., 2024). However, theOur geophysical investigations presented reveal 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 20 %expected, emphasising caution when calculating water volume equivalent on a broad scale.

Considering the current MAGST of approximately -0.5 ºC and assuming a climatic warming of about +1.5 ºC since the late 19th century (Allen et al., 2018), it is likely that these rock glaciers likely had a MAGST around -2 ºC during the pre-industrial period. At such low temperatures, widespread permafrost conditions would have been expected, and the presence of deep permafrost cannot be ruled out. However, recent accelerated warming in recent decades has resulted incaused permafrost temperature to rise, warming, particularly especially in ice-poor bedrock, at rates comparable similar to the increase in air temperature increases (Noetzli et al., 2024). BTS measurements and GST patterns observed during winter suggest indicate ongoing convective and advective air flow processes that maintain cold ground conditions and support the persistence of ice non-saturated permafrost in the Retezat Mountains.

The results presentedfindings ofin this study supportalign with the coarse-rock glacier hypothesis (Onaca et al., 2015; Popescu et al., 2017), which suggests posits that permafrost occurrence in the Carpathian Mountains is patchy and limited to sites above 2100 m with low solar radiation. In these locationssettings, very coarse rock glaciers, hosting numerouswithglaciers with abundant large boulders, enhancefacilitate strong internal cooling through internal ventilation processes, such as (e.g., advection and convection) (Wicky and Hauck, 2017; Amschwand et al., 2024), as well as through and air stratification (low conductivity) induring summer or under thick snow cover.

6. Conclusions

This study leads to the following main conclusions:

- The majority ofMost 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 slightly smaller. The PSInSAR methodology enabled the identification of new rock glaciers displaying movements, which were initially classified as relict features.

- A total of 92 moving areas were delineated within the rock glaciers of the Retezat Mountains, predominantly falling within the slow-velocity classes (0.3 – 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.
- Long-term ground temperature monitoring from 2012 to 2022 revealed low MAGST values at the observation sites, ranging from -2.3 ºC to 0.8 ºC. Internal ventilation processes (e.g., advection) occurring throughout the winter significantly contribute to surface cooling and appear to sustain permafrost conditions in coarse debris above 2100 m. BTS measurements ~~This is~~ further support this~~ed by BTS measurements~~, ~~which indicate~~showing very cold ground temperatures beneath ~~a~~ thick late-winter snow cover.
- Geophysical measurements conducted on an intact rock-glacier revealed ~~notably~~ low ice content (with maximum values of 18%) in its uppermost section. At this site, surface displacements are most likely driven by processes such as ice-melt-induced subsidence, solifluction or blocks sliding. In contrast, the consistent flow of dGNSS markers towards the fronts of the Judele and Berbecilor rock glaciers points to permafrost creep.

Our findings ~~highlight~~ underscore the value of ~~combining~~ integrating Sentinel-1 SAR data with extensive field investigation (such as DGPS, geophysical and thermal methods) and where ~~possible~~available, ~~with other~~complementary remote sensing data (like ALOS-2 PALSAR-2), particularly in regions with slow-moving rock glaciers. This multi-method 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.

Acknowledgements

This research was funded by the ESA Permafrost_CCI project (grant number 4000123681/18/I-NB), EEA Norway Grants 2014–2021, under project code RO-NO-2019-0415 / contract no. 30/2020, CNCS—UEFISCDI, project number PN-IV-P2-2.1-TE-2023-0603, within PNCDI IV and PNRR-III-C9 2022 - I8, CF 253/29.11.2022, 760055/23.05.2023. We would also like to thank

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Sabina Calisevici, Adrian C. Ardelean, Patrick Chiroiu, Trond Eiken, Romolus Mălăieștean, Ilie Adrian and Fabian Timofte for support in the fieldwork.

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