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Past glaciation of temperate-continental mountains: A model for a debris-charged plateau icefield/cirque glacier landsystem in the Southern Carpathians, Romania

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Abstract

Reconstructing the extent, style, timing and drivers of past mountain glaciation is crucial in both understanding past atmospheric circulation and predicting future climate change. Unlike in high-elevation mountains situated in maritime and continental climates, less is known of past glaciation in mid-altitude mountains, located in transitional climates, such as the Southern Carpathians of Romania. Despite these mountains harbouring a rich glacial geomorphology, this has never been systematically mapped according to well-established morphological criteria, nor confidently related to former styles of glaciation. Therefore, filling this gap is important for not only accurately identifying glacial extents but also for establishing past glaciation styles and relating them to past ice dynamics and climate. Here, we devise the first glacial landsystem model for the Southern Carpathians, to enhance our understanding of the glaciation style and dynamics of past mountain glaciers in temperate-continental climates. We present a geomorphological map, from which we infer the spatial and temporal evolution of glacial, periglacial and paraglacial landforms. We then assess the links between the mountain geomorphology and glaciation style and dynamics to construct a glacial landsystem model for debris-charged plateau icefields and cirque glaciers in temperate-continental mountain settings.

KEYWORDS
cirque glaciers, glacial geomorphology, glacial landsystems, glaciation, plateau icefields, Romania, Southern Carpathians

1 | INTRODUCTION

Reconstructing the extent, style, timing and drivers of past mountain glaciation is crucial for both understanding past atmospheric circulation and predicting future climate change (Li et al., 2016). Unlike high-elevation mountains situated in maritime (e.g., Federici et al., 2017) and dry-continental climates (e.g., Xu et al., 2010), less is known of the style, extent and dynamics of past glaciation in mid-altitude mountains located in transitional climates (e.g., temperate-continental/subarctic type), such as the Carpathian Mountains, Romania (Figure 1a,b). This climate zone is characterised by long, cold winters and short, warm summers because of its continental location and distance from the influence of oceanic air masses (Beck et al., 2018).

Although the Romanian Carpathians (particularly the Southern Carpathians) contain a rich glacial geomorphology (Urdea et al., 2022a, 2022b, 2022c, 2022d, 2022e; Urdea et al., 2022), these mountains have not been systematically mapped according to well-established diagnostic criteria (e.g., Chandler et al., 2018; Giles et al., 2017). Early (19th century) studies on the glacial geomorphology focused on landform descriptions in individual mountain ranges (e.g., de Martonne, 1900; Lehmann, 1881; Tietze, 1878). Later studies (20th century) provided more detailed inventories (e.g., Micalevich-Velcea, 1961; Nedelcu, 1967; Niculescu, 1965; Sîrcu, 1978). The most

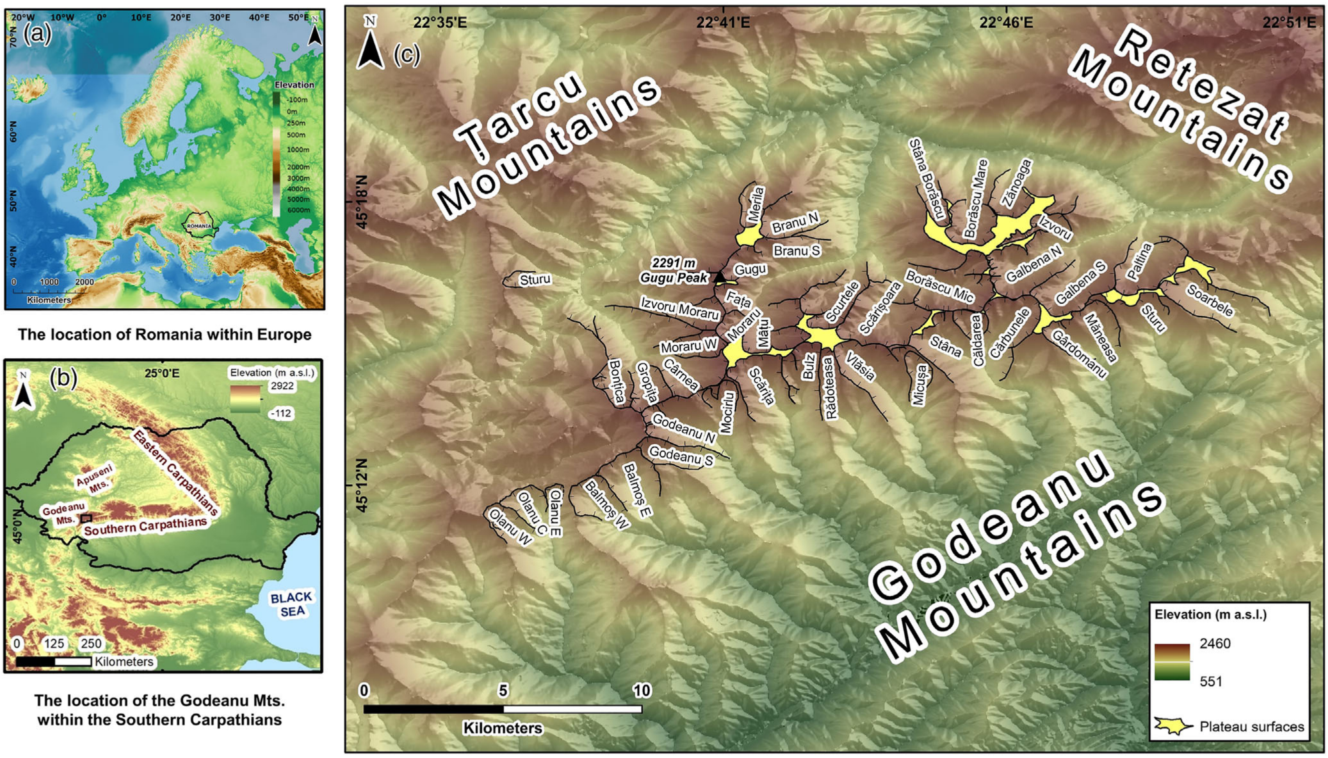

FIGURE 1 Location maps of the study area. (a) The location of Romania within Europe; (b) the location of the Godeanu Mountains within the Southern Carpathians; (c) large scale map of the Godeanu Mountains, showing the highest elevation point (Gugu Peak, 2291 m a.s.l.), plateau surfaces (highlighted in yellow), the names of the main cirques and valleys in the range, as well as the neighbouring mountain ranges: Țarcu Mountains in the West and Retezat Mountains in the East. Cirque and valley toponymy derived or adapted from Niculescu (1965) and Mîndrescu (2016). Digital elevation model for Europe (TOPO-WMS and TOPO-OSM-WMS), sourced from Terrestris, and that of Romania, Southern Carpathians, and the Godeanu Mountains sourced from EORC, JAXA.

recent studies consider an alpine (glacial, periglacial and paraglacial) geomorphological model as a framework for palaeoglaciation and palaeoclimate reconstruction. This has either focused on applying absolute/relative dating methods and/or numerical ice modelling (Balaban, 2018; Gheorghiu, 2012; Gheorghiu et al., 2015; Ignéczi & Nagy, 2016; Kłapyta et al., 2021, 2022; Kłapyta, Mîndrescu, & Zasadni, 2023; Kłapyta, Zasadni, & Mîndrescu, 2023; Kuhlemann, Dobre, et al., 2013; László, Kern, & Nagy, 2013; Reuther et al., 2007; Ruszkiczay-Rüdiger et al., 2016, 2021; Tîrlă et al., 2020; Urdea & Reuther, 2009), or conducting quantitative inventories of landform characteristics (Gunnell et al., 2022; Mîndrescu & Evans, 2014, 2017; Mîndrescu et al., 2010; Necșoiu et al., 2016; Onaca, Ardelean, et al., 2017; Onaca et al., 2013; Popescu, 2018; Popescu et al., 2021; Popescu, Urdea, & Vespremeanu-Stroe, 2017; Șerban et al., 2019; Vasile et al., 2022; Vespremeanu-Stroe et al., 2012). Despite this work, the relationships between palaeoclimate, geomorphology, and glaciation style and dynamics, particularly in a mountain landsystem context, remain poorly understood. Moreover, a glacial landsystems approach, informed by modern analogues, is necessary for assessing an alpine/cirque versus plateau icefield style of glacierisation in mountain terrains, to facilitate more accurate palaeoglaciological models (cf. Benn & Lukas, 2006; Benn & Owen, 2002; Bickerdike, Evans, et al., 2018; Bickerdike, Ó Cofaigh, et al., 2018; Carr & Coleman, 2007; Golledge, 2007; Hulton & Sugden, 1997; Rea et al., 1998; Rea et al., 1999; Rea & Evans, 2003, 2007).

In this paper, we compile the first glacial landsystem model for the Romanian Carpathians, in order to understand glaciation style and past glacier dynamics. Based on the Godeanu Mountains in the southwestern part of the Southern Carpathians, this is achieved through the following objectives: (1) identifying and interpreting the origin and spatial distribution of mountain landforms, based on a remote and ground-truthed geomorphological map; (2) determining the glacial debris transport pathways and genesis of selected glacial depositional landforms, using sedimentological analyses; (3) hypothesising on the relationship between the mountain topography and glaciation style and dynamics, based on the spatial relationships between the landforms (glacial landsystem) in the study area; and (4) assessing the value of the landsystem model as an analogue for similar glacierised uplands.

2 | STUDY AREA

The Romanian Carpathians occupy the centre of Romania and comprise three chains, including the Eastern Carpathians, the Southern Carpathians and the Apuseni Mountains (Figure 1a,b). They are composed of sedimentary, metamorphic and volcanic rocks (Urdea et al., 2011) and resulted from Mesozoic–Cenozoic continental collision and Pliocene–Quaternary erosion (15–2.6 Ma), including glaciation during cold climate cycles (Popescu, Urdea, & Vespremeanu-Stroe, 2017; Sanders et al., 2002; Sanders, Andriessen, & Cloetingh, 1999). Their position in Central–Eastern Europe marks a transition between the temperate-maritime climate of Western Europe, the Mediterranean climate of Southern Europe and their continental-arid counterpart of Central Asia (Mîndrescu et al., 2010; Reuther et al., 2007). The mountains are not currently glacierised but have numerous peaks above 2000 m a.s.l. (max: 2544 m a.s.l.—Moldoveanu Peak). In the present climate, the

0°C isotherm is situated at 1650 m a.s.l. in the Eastern Carpathians and 2050 m a.s.l. in the Southern Carpathians, and a mean precipitation above 2000 m a.s.l. of 1400 mm/year in the Eastern Carpathians and 1000 mm/year in the Southern Carpathians (Popescu, Urdea, & Vespremeanu-Stroe, 2017).

The Godeanu Mountains are a ~100 km^2, northeast–southwest-orientated mountain ridge located in the southwestern part of the Southern Carpathians (45°15′N 22°42′E; Figure 1c). Part of the Retezat–Godeanu group, the mountains form flat/rounded plateau surfaces overlooking ~70 cirques and short (3–4 km) U-shaped valleys with a range of orientations (Mîndrescu, 2016; Niculescu, 1965). The mountains are composed of gneiss, paragneiss, crystalline schist, amphibolite and pegmatite lithologies, with sparse limestone. With a maximum elevation of 2291 m a.s.l. (Gugu Peak; Figure 1c), these mountains are influenced by a sub-Mediterranean climate, with modern prevailing winds from the north, west and southwest (Dragomir et al., 2016; Niculescu, 1965). The climate is warmer (0–2°C average/year) and wetter (1000-1400 mm/year) than other areas of the Southern Carpathians (Dragomir et al., 2016; Niculescu, 1965). Therefore, although the geology and topography of the Godeanu Mountains are similar to other mountains in the eastern Southern Carpathians (e.g., Făgăraş and Iezer), the present climate characteristics are unique to it.

The Godeanu Mountains have previously been the subject of geomorphological and palaeoglaciological research. Early studies identified glacial landforms and produced the first topographic maps (Czirbusz, 1905; de Martonne, 1900; Schafarzik, 1899). More recent literature mapped landforms such as intact and relict rock glaciers (Onaca, Ardelean, et al., 2017; Urdea, 1992), cirques (Mîndrescu & Evans, 2014, 2017; Mîndrescu et al., 2010), block streams (Şerban et al., 2019) rock walls (Vasile et al., 2022) and rock slope failures (RSFs; Gunnell et al., 2022). The most comprehensive research has been that of Niculescu (1965), who produced the first field-based geomorphological map of the range. An electro-resistivity tomography profile of a moraine sequence in the Soarbele valley by Ardelean 2010; Figure 1c) confirmed a glacial depositional origin. Niculescu (1965) employed the glacial geomorphology as a morphostratigraphic tool, by relating the Soarbele valley moraine sequence to two ice advances, which he assigned to the Riss (MIS 8–6) and Würm (MIS 4–2) glaciations. The former yielded a palaeo-equilibrium line altitude (ELA) of 1750–1800 m a.s.l., and the latter 2050 m a.s.l. (Niculescu, 1965). However, this approach assumed a cirque/valley glaciation style, with little consideration for plateau icefield sources, despite widespread upland plateau surfaces.

This assumption was challenged by Ignéczi and Nagy (2016), who tested the hypothesis of a plateau icefield style of glaciation by performing numerical modelling of palaeoglacier extents. Using a steady-state plastic numerical model, they reconstructed 40 km^2 of ice over the range, constrained by the geomorphological map of Niculescu (1965). The reconstruction included plateau icefields, with an average palaeo-ELA of 1855 m a.s.l. on the northern slopes and valley glaciers predominant in the south-facing cirques in the west. These yielded an average palaeo-ELA of 1700 m a.s.l. Ignéczi and Nagy (2016) suggested that the discrepancy between the ELAs is related to missing geomorphological evidence of palaeoglacier extents in the northern valleys, possibly caused by postglacial erosion. This demonstrates that re-mapping of the area is necessary before further modelling and dating of past ice extents is attempted to derive paleoglaciological and palaeoclimate reconstructions.

3 | METHODS

3.1 | Geomorphological mapping

Guided by protocols for remote and field-based mapping of former glaciers (Chandler et al., 2018), we produced a geomorphological map of the Godeanu Mountains, at a scale of 1:120,000 in ArcMap 10.7.1. This was undertaken remotely for the entire range and field-checked in the area of the Scărişoara plateau and four surrounding valleys. Because of low-resolution digital elevation models (max = 30 m, ALOS DEM), mapping was undertaken on high-resolution (1 m) orthorectified aerial photographs from ANCPI, ArcGIS World Imagery, as well as on imagery viewed on Google Earth Pro.

The mapping focused on landforms and sediments of glacial depositional origin (moraines and till veneers/drift limits), glacial/glacifluvial erosional origin (ice-moulded bedrock and ice-marginal meltwater channels), periglacial origin (pronival and protalus ramparts, relict rock glaciers, rock-glacierised moraines) and paraglacial landforms (RSFs). Plateau areas were also demarcated to assess the possibility of former plateau icefields. Landforms were initially classified using descriptive terms (e.g., ridges and channels), avoiding premature genetic classifications (Darvill et al., 2017; Evans, Dinnage, & Roberts, 2018). Genetic classifications were subsequently made based on morphological diagnostic criteria, as outlined in Table 1. Field investigations in the area of the Scărişoara Plateau and four surrounding valleys (Bulz, Vlăsia, Scărişoara and Scurtele; Figure 1c) were employed as control sites for extrapolation to the remote mapping for the entire range.

3.2 | Sedimentological analyses

Landform origins and potential glacial debris transport pathways were assessed in the field via sedimentological analyses on natural exposures in depositional features in the ground-truthed area. Specifically, this entailed sediment logging and descriptions using a lithofacies approach, augmented by clast shape analyses (cf. Benn & Ballantyne, 1994; Lukas et al., 2013; Evans & Benn, 2021). Clast shape indices include clast roundness, quantified using the RA (percentage of A and VA clasts) and the average roundness (AvgR; cf. Evans, 2010), and clast form, quantified using the C_{40} index as an indicator of 'blockiness', and hence subglacial modification (Benn & Lukas, 2021). The degree of clast modification is then related to glacial debris transport pathways by employing the Type II RA-C_{40} covariance plot (Lukas et al., 2013) for anisotropic (foliated) lithologies, similar to those of the crystalline schists of the Scărişoara plateau.

3.3 | Glacial landsystems reconstruction

Glacial landsystems are assemblages of sediments and landforms that are representative of specific glacial processes, styles and dynamics in the context of the topographic and climatic characteristics of the investigated terrain (Evans, 2003). These characteristics, and thus, the landsystems, may change spatio-temporally in response to climate drivers (e.g., Benn et al., 2003; Bickerdike, Evans, et al., 2018; Bickerdike, Ó Cofaigh, et al., 2018). The importance of glacial landsystems lies in their integration with geochronology and ice

TABLE 1 Inventory of glacial depositional, glacial erosional, periglacial depositional and paraglacial landforms in the Godeanu Mountains, with details on their associated morphology, sedimentology, significance and key references.

Landforms	Morphology	Sedimentology	Significance	References
Glacial depositional landforms				
Latero-frontal terminal and recessional moraines	Linear, valley-side ridges with asymmetric cross profiles that descend downslope, sub-parallel to contours, and are linked to arcuate ridges crossing valley floors.	Poorly sorted, mostly rubbly diamicton with little to no significant matrix support. Clast forms change down-valley from VA/A and slabby to SA/SR and blocky, with increasing amounts of striation.	Demarcation of lateral and frontal, maximum and recessional glacier margins as well as vertical ice limits.	Benn et al. (2003); Lukas (2005); Glasser et al. (2008); Evans (2011, 2013a)
Drift limits and till veneers	Subdued mantles of debris above which slopes are characterised by bedrock and non-glacial regolith, or valley floor-based deposits.	As above	Demarcation of maximum elevations of lateral glacier margins in steep terrain.	Benn and Evans (2010); Rootes and Clark (2022)
Lateral moraines	Linear, valley-side ridges with asymmetric cross profiles that descend downslope, sub-parallel to contours.	As above	Demarcation of lateral, maximum and recessional glacier margins as well as vertical ice limits. Indicators of large extraglacial debris supply, often resulting in lateral moraine asymmetry.	Matthews and Petch (1982); Small (1983); Benn (1989); Bennett and Boulton (1993); Evans (1999); Quincey and Glasser (2009); Lukas et al. (2012); Boston and Lukas (2019)
Medial moraines	Subdued, valley-parallel, straight or slightly curvilinear ridges/ veneers on valley floors and/or at valley confluences.	Poorly sorted, mostly rubbly/bouldery diamicton with little to no significant matrix support.	Indications of ice flow unit confluences and/or rock avalanche input from backwalls; agents of supraglacial/englacial transport and deposition in valley and cirque glaciers.	Eyles and Rogerson (1978); Rogerson et al. (1986); Benn and Evans (2010); Evans (2013b); Giles et al. (2017); Ballantyne and Dawson (2019)
Glacial erosional landforms				
Ice-moulded bedrock	Striated and sometimes polished bedrock, with symmetric or asymmetric cross profiles (whalebacks and roches moutonnées) as well as abraded rock steps.	N/A	Indications of subglacial erosion and former ice flow directions; evidence of warm-based glacier thermal regime.	Gordon (1981); Evans (1996); Glasser (2002); Glasser and Bennett (2004); Benn and Evans (2010); Rea (2013)
Ice-marginal meltwater channels	Dry (relict) linear or sinuous channels on valley sides, often grouped *en echelon* and descending in altitude down-valley, crossing contours at oblique angles.	N/A	Large glacier meltwater volumes and high subglacial water pressures; indicate ice limits and recession patterns.	Maag (1969); England (1990); Evans (1990); Dyke (1993); Greenwood et al. (2007); Benn and Evans (2010); Livingstone et al. (2010); Evans, Hughes, et al. (2017); Giles et al. (2017)
Periglacial depositional landforms				
Pronival/ protalus ramparts	Discrete debris accumulations comprising single (protalus) and/or multiple inset (pronival), continuous ridges with asymmetric cross profiles. Maximum distance from talus foot ~30–70 m.	Openwork large clasts with pockets of poorly sorted finer debris but largely devoid of fine matrix.	Debris ridges deposited by perennial snowpatches, formed either outside or inside former glacial limits; not to be confused with moraines.	Ballantyne and Kirkbride (1986); Ballantyne and Benn (1994); Shakesby (1997); Shakesby and Matthews (1993); Shakesby et al. (1999); Matthews et al. (2011); Hedding (2011, 2016) Hedding and Sumner (2013)

TABLE 1 (Continued)

Periglacial depositional landforms				
Relict rock glaciers and rock-glacierised moraines	Discrete debris accumulations comprising spatulate or tongue-shaped assemblage of multiple lobate ridges. Rock glaciers emanate from cirques or plateau edge cliffs. Other rock-glacierised bodies occur within lateral or latero-frontal moraine ridges.	Poorly sorted, coarse, predominantly bouldery openwork debris with no fine-grained matrix. Clast forms predominantly VA/A in relict rock glaciers but becoming more A-SR in rock glacierised moraines.	Melt-out of debris-covered glaciers or creep of coarse debris bodies with interstitial ground ice (permafrost creep). Indicative of mountain setting with high debris turnover. Relict rock glaciers formed either inside or outside glacial limits. Rock-glacierised moraines formed within glacial limits.	Thompson (1957); Østrem (1964); England (1978); Wilson (1990); Ballantyne and Harris (1994); Hamilton and Whalley (1995); Harrison et al. (2008); Whalley (2009, 2012, 2015); Anderson et al. (2018); Jones et al. (2019); Leigh et al. (2021); Urdea et al. (2022)
Paraglacial landforms				
Rock slope failures	Discrete debris accumulations or partially intact bedrock masses comprising large debris mounds, often with no preferred orientation, but situated at the foot of failure-source rock walls. Arrested forms appear as slope deformations and/or *en echelon* antiscarps at the margins of plateaux and cirque backwalls.	Debris mounds are predominantly poorly sorted, matrix-poor, coarse and boulder-rich, with A/VA clast forms.	Deposits related to, but not exclusively diagnostic of, slope re-adjustment following deglaciation; not to be confused with moraines or periglacial landforms, which they may overlie.	Shakesby and Matthews (1996); Clark and Wilson (2004); Ballantyne (2002, 2013, 2018a); Jarman (2006); Coleman and Carr (2008); Jarman et al. (2013); Ballantyne et al. (2014); Gunnell et al. (2022)

modelling to produce a holistic understanding of glaciation style, dynamics and palaeoclimate through time. However, their compilation in ancient settings requires the recognition of geomorphological process-form regimes, informed by suitable modern analogues. Hence, we consulted modern analogue landsystems from similar climatic and topographic settings, such as those for plateaux (Rea et al., 1998; Rea et al., 1999; Rea & Evans, 2003, 2007) and glaciated valley (Benn et al., 2003; Benn & Owen, 2002) settings where paraglacial and periglacial process-form regimes interact with those of glacial systems (Knight et al., 2019; Leigh et al., 2021).

4 | LANDFORMS

4.1 | Moraines, drift limits and till veneers

4.1.1 | Morphology and genesis

The moraines mapped in the Godeanu Mountains are of several morphological and genetic types (Figures 1c and 2 and Table 1). The continuous linear valley-side depositional ridges and associated valley-floor arcuate ridges, forming inset sequences in an up-valley direction, are clearly latero-frontal moraines (Figures 3a and 4a). Occasionally, these are replaced by subdued, lobate-shaped glacial debris/till veneers (Figure 3b). Both landform types demarcate recessional, lobate glacier margins (Evans, 2013a). Terminal moraines and till veneers are more subdued than their recessional counterparts, which have sharper crests (Figure 3b and Table 1). Linear depositional ridges, perched on valley sides but not continuous with arcuate valley floor ridges, are regarded as lateral moraines, which underpin lateral glacier extents (Lukas et al., 2012; Figure 3c). Subdued, linear or sinuous bouldery deposits or veneers, which are situated on valley floors, usually at ice flow confluences, are interpreted as medial moraines, signifying supraglacial/englacial transport of debris in the glacial system (Eyles & Rogerson, 1978; Figures 3d and 4b).

Sedimentological investigations were undertaken on exposures through moraines in the Bulz, Vlăsia, Scărişoara and Scurtele valleys, surrounding the Scărişoara plateau (Figure 5a), including the lateral moraines BLZ1, BLZ2, BLZ4 and SCT1, and the frontal/recessional moraines BLZ3, BLZ5, VLS1, VLS2 and SCS1. The moraines are composed of coarse, bouldery, sandy-silty matrix or clast-supported diamictons (Figure 6a,b). The RA-C_{40} covariance plot (Figure 6c) reveals the relatively high C_{40} values, typical of anisotropic lithologies, indicating that roundness indices such as RA and AvgR are more appropriate in diagnosing clast modification within the former glaciers of the area. Down-valley trends can be assessed only in one location, the Bulz Valley, where the most intensive sampling was undertaken. Here, clast modification increases as expected in a down-valley direction (cf. Benn, 1989; Benn & Ballantyne, 1994; Evans, 1999; Matthews & Petch, 1982), with AvgR values increasing, and C_{40} and RA values decreasing, based upon valley head samples BLZ3 and BLZ2, valley side samples BLZ5 and BLZ4 and middle valley floor sample BLZ1 (Figure 5b–f). Overall, the moraine deposits and their sedimentological characteristics (Figures 5 and 6) indicate mountain glacier systems with limited active subglacial transport and predominantly passive, supraglacial debris transfer (Benn et al., 2003; Boulton, 1978; Evans, Roberts, & Evans, 2016; Evans, Roberts, et al., 2018).

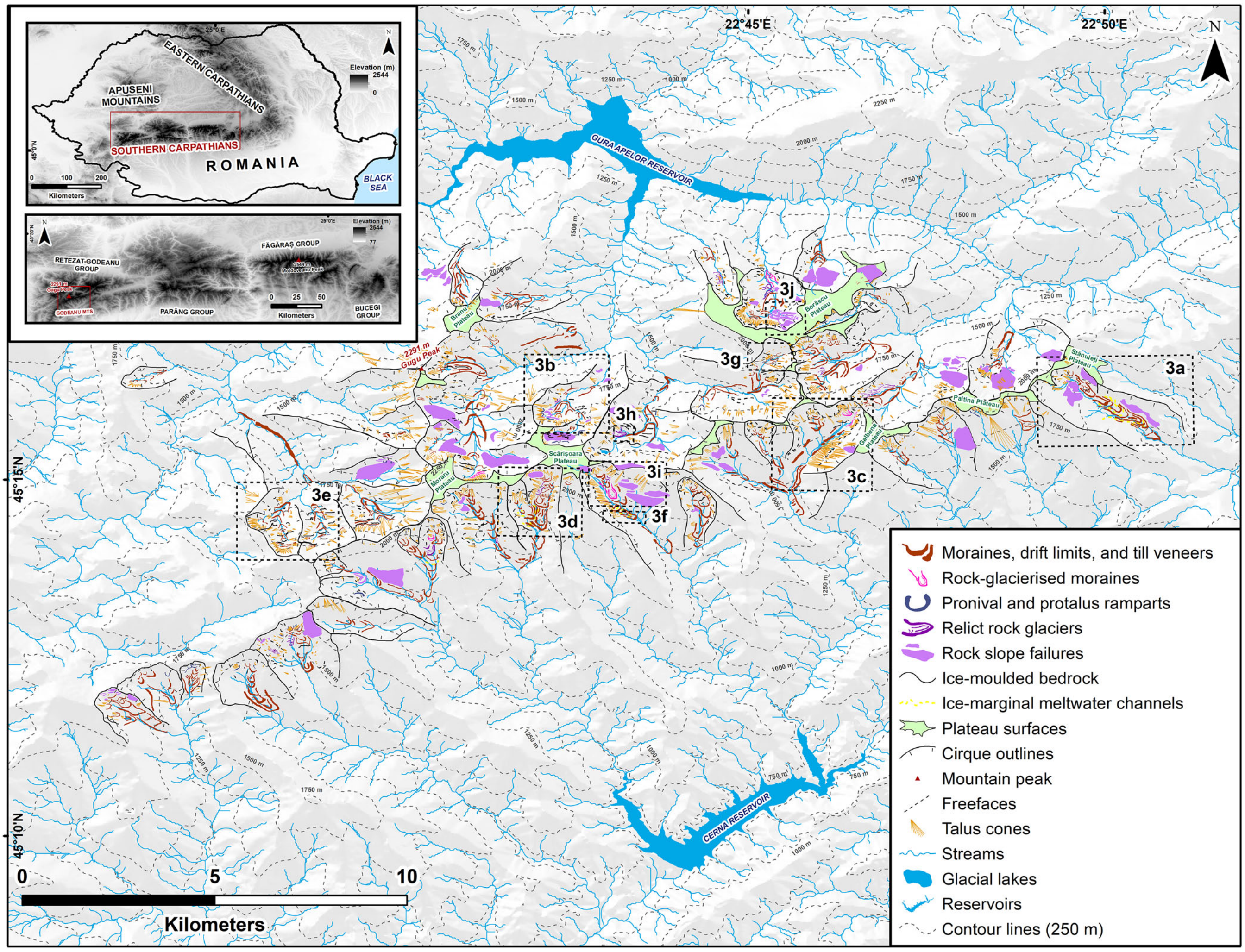

FIGURE 2 The mountain geomorphology of the Godeanu Mountains, Southern Carpathians, Romania, focusing on the main glacial, periglacial, paraglacial and contextual landforms. The numbered dashed line rectangles reveal the location of landform examples featured in Figure 3. Produced in ArcGIS, using two hillshade models (transparency = 95%, illumination angles = 180° and 315°), derived from the ALOS DEM (EORC, JAXA, resolution = 30 m). High-resolution version (without the numbered rectangles) is available to consult in the Supporting Information section in the online version of the article.

4.1.2 | Spatial distribution

Latero-frontal moraines occur in all glacial valleys and on the Borăscu plateau (Figures 1c and 2). Where they are scarce, particularly in north/northeast-facing valleys, such as Scurtele, Scărişoara, Borăscu Mic, Galbena North and Galbena South, former glacier extents are demarcated by drift limits/till veneers. Also diagnostic of a latero-frontal moraine genesis is the reduction in ridge lengths and widths between lower valley reaches (e.g., L = 617 m; W = 326 m) and upper valley heads (e.g., L = 100 m; W = 98 m) (Figure 3a), which reflects the reduction in former glacier size in an up-valley direction. In valleys with multiple cirques (e.g., Galbena North valley; Figures 1c and 2), recessional moraines can be traced back onto each cirque floor. With respect to valley aspects, latero-frontal and recessional moraines are smaller, more closely spaced (average = 189.5 m) and greater in number (average = 9.05 moraines/valley) in south-facing valleys than those in north-facing ones, which are larger, more widely spaced (average = 303.75 m) and lower in number (average = 7.16 moraines/valley). Additionally, the latero-frontal moraines reach lower elevations in south-facing valleys (average = 1477 m) than in the north-facing counterparts (average = 1648 m). The position and change in size of latero-frontal moraines from down-valley settings to valley heads reflect changes in palaeoglacier extents through time (e.g., Benn et al., 2003; Evans et al., 2010; Owen et al., 2001; Table 1). The predominance of subdued drift limits in north and northeast-facing valleys reflects lower glacier debris turnover, as well as relatively greater postglacial erosion and sediment reworking, promoted by the steeper, stepped bedrock valley profiles (Ignéczi & Nagy, 2016; Niculescu, 1965). The increased number of moraine ridges in proximity to cirques in valley complexes shows the separation of different ice sources and concomitant relative stabilization of the glaciers once they retreated to higher elevations (Glasser et al., 2006). Notwithstanding the differences in north- versus south-facing valley geometries, the difference in number, spacing and size of the latero-frontal and recessional moraines is possibly due to north-facing palaeoglaciers being larger (Ignéczi & Nagy, 2016) and less responsive to climate fluctuations. Aspects of valley topography that are likely influential in this respect

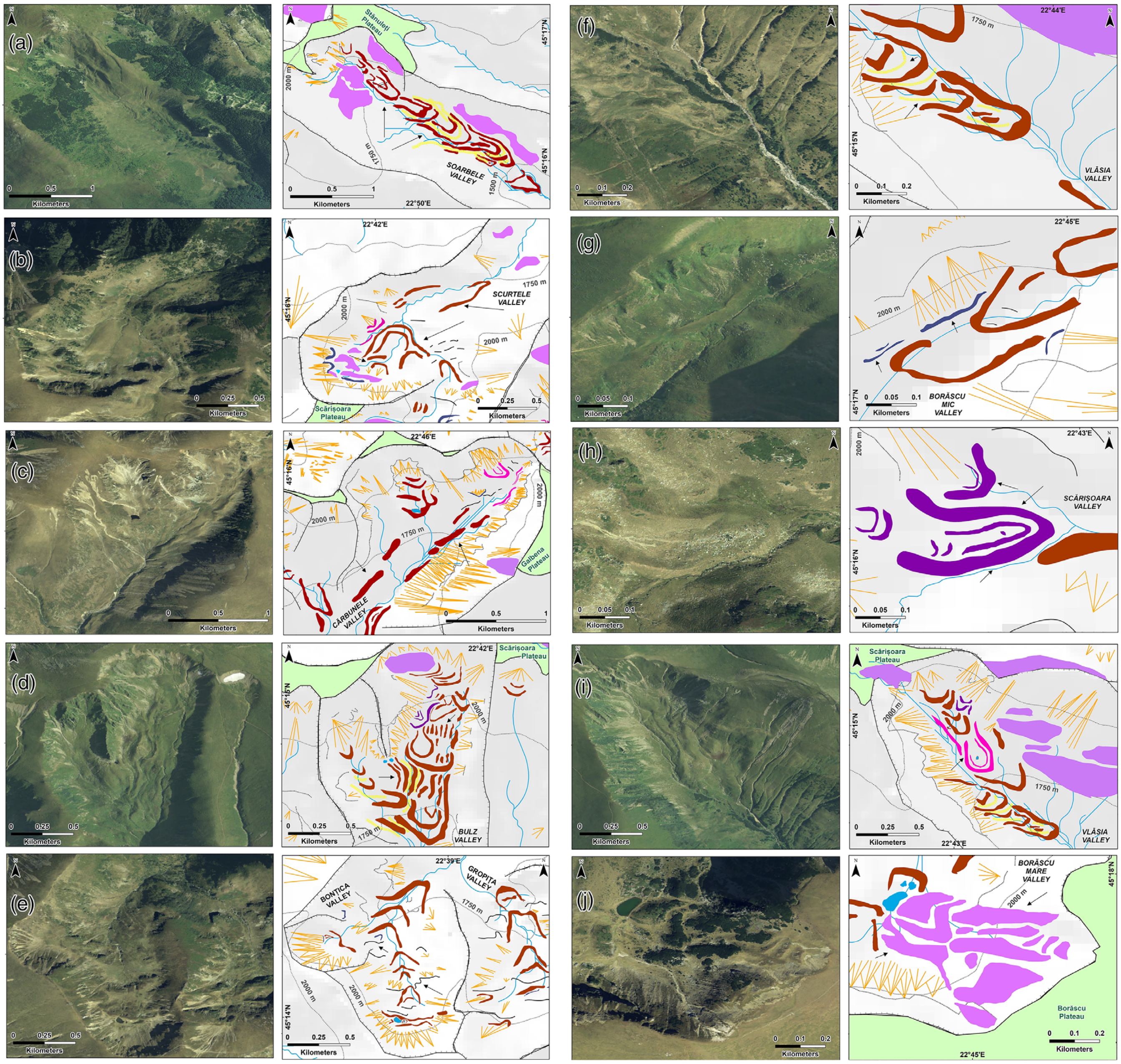

FIGURE 3 Orthophotograph–map pairs of mountain landforms in the Godeanu Mountains. Black arrows indicate examples of the relevant landform observed. The maps use the location names in Figure 1c, and the legend in Figure 2, and include specific examples for some of the statistics discussed in the text: (a) latero-frontal and recessional moraines in the Soarbele valley; (b) till veneers in the Scurtele valley; (c) lateral moraines in the Cărbunele valley; (d) medial moraines in the Bulz valley; (e) ice-moulded bedrock in the Bonțica valley; (f) ice-marginal meltwater channels in the Vlăsia valley; (g) pronival ramparts in the Borăscu Mic valley; (h) rock glacier in the Scărişoara valley; (i) rock-glacierised moraine in the Vlăsia valley; (j) rock slope failure (rockslide) in the Borăscu Mare valley.

are the bedrock steps, which can act as pinning points, solar insolation, and lee-side aspects relative to southerly winds (e.g., Barr & Lovell, 2014; Benn & Ballantyne, 2005; Coleman et al., 2009; Mitchell, 1996; Oerlemans et al., 1998).

Lateral moraines are uncommon, with more extensive examples occurring in the Olanu West, Vlăsia, Cărbunele, Măneasa, Scurtele, Mâțu and Branu North valleys. More fragmented examples occur in the Scurtele, Mâțu and Scărița-Bulz valleys (Figures 1c, 2 and 3c). In the Cărbunele (Figure 3c) and Soarbele (Figure 3a) valleys, there is a preferential slope aspect for the occurrence of large lateral moraines. For example, in the Cărbunele valley, a prominent lateral moraine occurs on the northwest-facing slope, where RSFs are also common, whereas there are no lateral moraines on the debris-poor southeast-facing equivalent. The variable occurrences and sizes of lateral moraines reflect the availability of paraglacial/supraglacial debris, resulting in lateral moraine asymmetry (Benn, 1989; Evans, 1999; Matthews & Petch, 1982; Table 1). This refers to the preferentially larger sizes of lateral moraines situated on steep, freeface-dominated and failure-prone valley sides (cf. Jarman, 2009), particularly in association with RSFs and talus cones, as observed in the Cărbunele and Soarbele valleys.

Despite their generally low preservation potential in glaciated terrains (Benn & Evans, 2010), medial moraines are present in the four south-facing valleys of Mocirlu, Bulz, Cărbunele and Soarbele and in

FIGURE 4 Field photograph example of mountain landforms in the Godeanu Mountains. The white arrows indicate examples in each landscape context: (a) recessional moraine in the Bulz valley; (b) 'ice-stream interaction'-type medial moraines in the Bulz valley; (c) ice-moulded bedrock in the Scărişoara valley; (d) ice-marginal meltwater channel in the Vlăsia valley; (e) pronival ramparts in the Scurtele valley; (f) relict rock glacier in the Scărişoara valley; (g) rock-glacierised moraine in the Vlăsia valley; (h) ice-moulded rock slope failure blocks in the Scurtele valley.

the northeast-facing Galbena North valley (Figures 1c, 2, 3d and 4b and Table 1). These features occupy a specific elevation niche at 1630–1950 m a.s.l., where they grade down-valley into recessional latero-frontal moraines (Figure 3d). Medial moraine production appears to have taken place via two distinct modes, based upon the models of Eyles and Rogerson (1978) and Rogerson et al. (1986). Firstly, 'ice stream interaction' (ISI)-type medial moraines are formed through the coalescence of lateral moraines of two tributary glaciers or ice flow units (Eyles & Rogerson, 1978). This model seems appropriate for the confluence between the two cirques comprising the Bulz valley, demarcated by three transverse ridges (Figures 2, 3d and 4b). Secondly, 'avalanche-type' medial moraines do not require the existence of coalescing ice flow units, but rather a supraglacial rockfall debris source, such as from a plateau or high cirque backwall nunatak (Rogerson et al., 1986). This model is most applicable to the eastern Bulz, Mocirlu, Cărbunele and Soarbele valleys (Figures 1c, 2 and 3a,d).

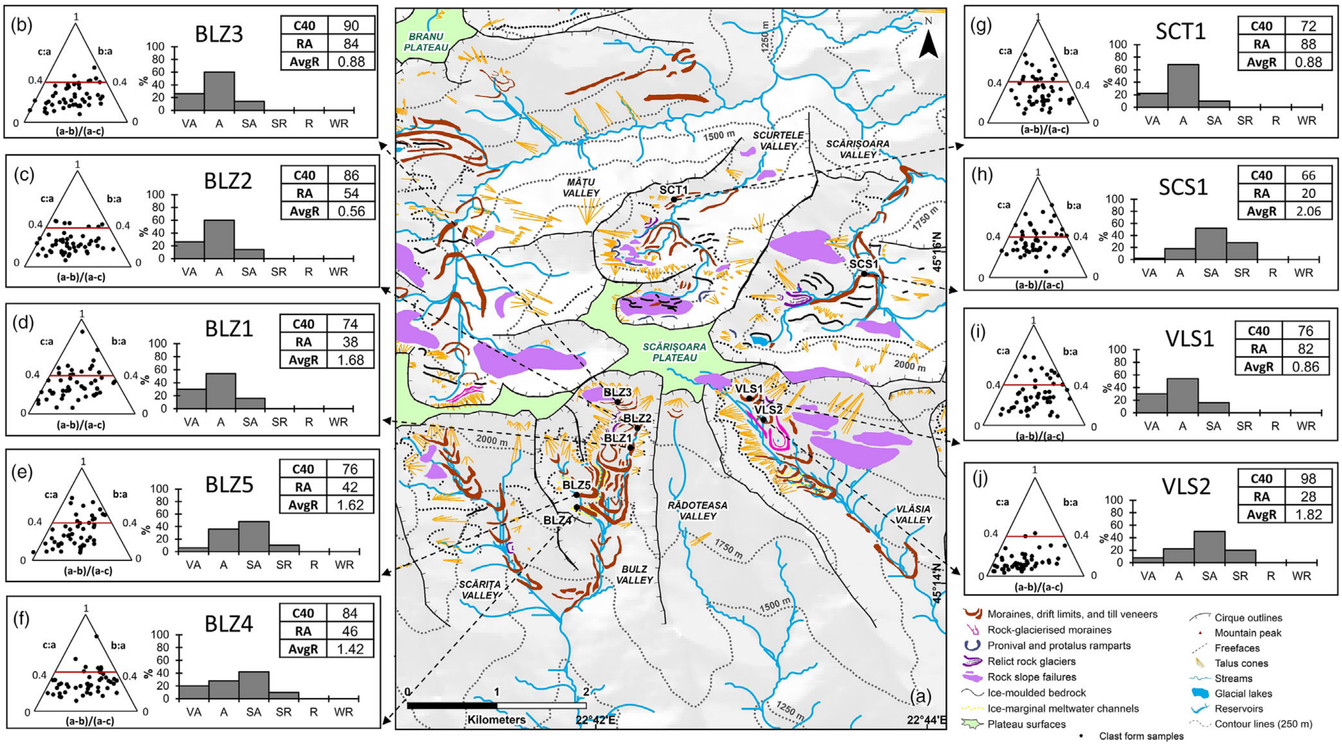

FIGURE 5 Clast sedimentological data on moraines in the valleys surrounding the Scărișoara plateau: (a) Bulz, Scurtele, Scărișoara and Vlăsia. Each sample is named after the valley of provenance and order of collection: (b) BLZ3, (c) BLZ2, (d) BLZ 1, (e) BLZ5, (f) BLZ4, (g) SCT1, (h) SCS1, (i) VLS1 and (j) VLS2. Various sedimentological statistics (clast form ternary diagrams, clast roundness, C_{40} index, relative angularity (RA), and average roundness (AvgR) are shown in individual boxes.The map legend can be consulted in the bottom right corner.

In both cases, with ice retreat and thinning, the debris position of each flow unit narrows and shifts towards the valley sides, forming inset ridges that represent parallel medial moraines in the main valley. The highly lobate bouldery ridge in the Bulz valley (Figure 3d) is more complicated in that it resembles the teardrop-shaped looped medial moraines of surging mountain glaciers (e.g., Ellis & Calkin, 1979; Gusmeroli et al., 2014; Meier & Post, 1969; Paul, 2015). Consequently, this reflects the differential speeds of individual flow units within the former valley glaciers of the study area rather than surging, as other features indicative of surging are lacking: for example, crevasse squeeze ridges, thrust moraines and zigzag eskers (Evans & Rea, 2003). We attribute the high preservation potential of medial moraines to large volumes of debris sourced supra-, sub-, and englacially (e.g., Eyles & Rogerson, 1978; Goodsell, Hambrey, & Glasser, 2005; Goodsell, Hambrey, Glasser, Nienow, et al., 2005; Small, Clark, & Cawse, 1979).

4.2 | Ice-moulded bedrock

4.2.1 | Morphology and genesis

Ice-moulded bedrock is represented by abraded and plucked outcrops that form roches moutonnées and whalebacks/rock drumlins. These features are indicators of subglacial erosion and former ice flow directions, and are generally reflective of a warm-based glacial thermal regime (Glasser, 2002; Glasser & Bennett, 2004; Rea, 2013; Table 1).

4.2.2 | Spatial distribution

In the Godeanu Mountains, ice-moulded bedrock is commonly found at altitudes of 1860–1920 m a.s.l. In areas of paragneiss and amphibolite in particular, roches moutonnées are widespread. Ice-moulded bedrock is common and prominent in the north-facing Bonțica, Gropița, Mâțu, Scurtele and Scărișoara, as well as the southern-facing Balmoș East, Scărița, Micușa, Stâna, Cărbunele and Soarbele valleys (Figures 1c, 2, 3e and 4c). Niculescu (1965) suggested that ice-moulded bedrock outcrops in areas where more durable lithologies, such as paragneiss, amphibolite and pegmatite, resist glacial erosion better than the weaker lithologies, such as crystalline schist. The prevalence of ice-moulded bedrock forms in north-facing valleys has been explained by Niculescu (1965) as a result of valley orientation, and hence ice flow being oriented in the opposite direction to the dip of the underlying strata.

4.3 | Ice-marginal meltwater channels

4.3.1 | Morphology and genesis

Relict channels indicative of former glacial meltwater incision appear as elongate depressions or interlinked channel networks, interpreted as ice-marginal meltwater channels. They are interspersed with bedrock and sometimes sediment ridges and are present in locations where their genesis is incompatible with a fluvial origin (Dyke, 1993). The ice-marginal meltwater channels are useful in identifying former

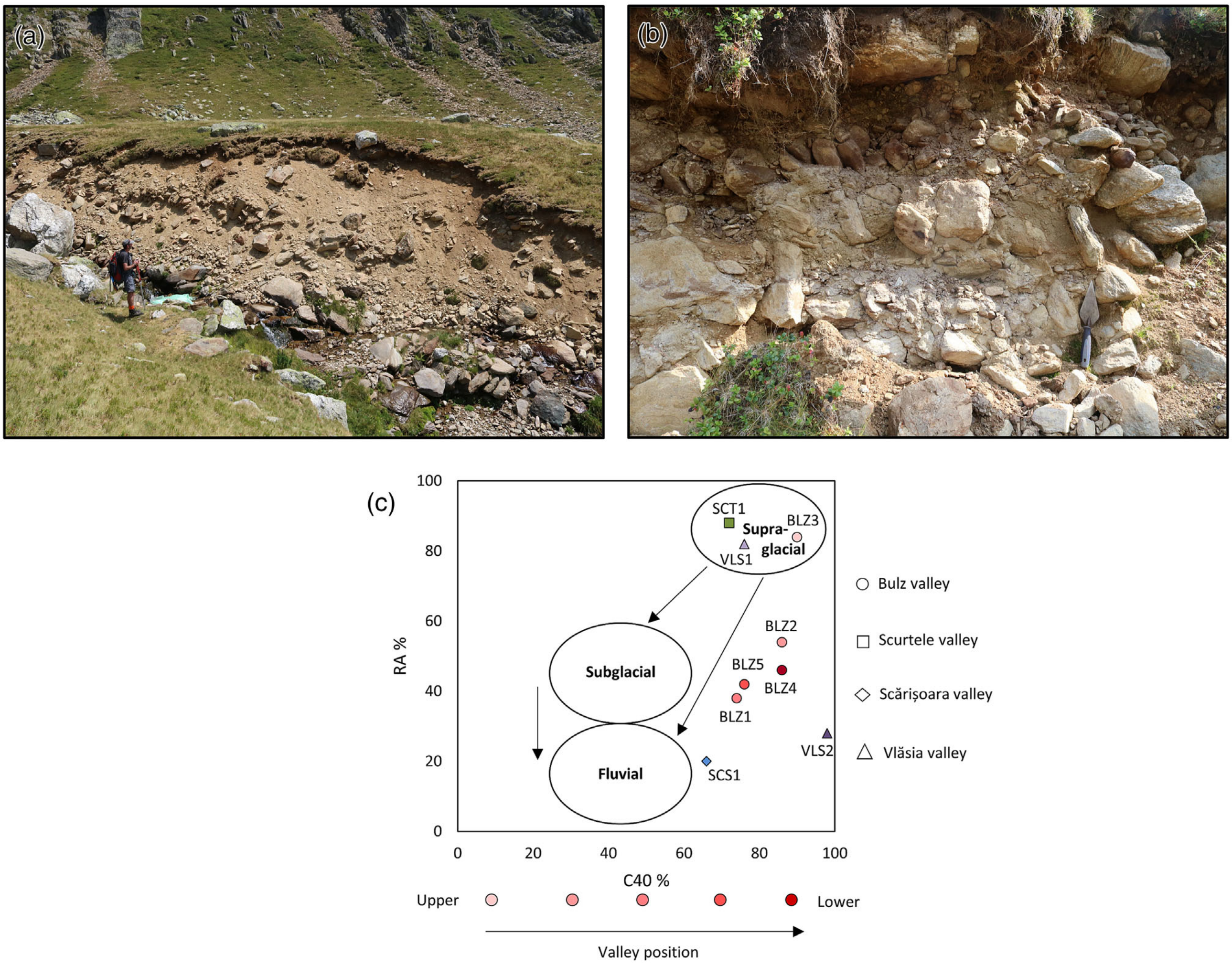

FIGURE 6 Key information for interpreting the glacial transport pathways in the study area. (a) Stream-cut exposure in moraine in the Bulz valley, where clast data for sample BLZ2 were collected. Note the poorly sorted, matrix-supported, predominantly A and VA clasts. (b) Close-up photograph into a stream-cut exposure in a till veneer in the Scărişoara valley, where the SCS1 sample was taken from. Notice the poorly sorted, clast-supported, sandy matrix, with predominantly SA and SR clasts. Trowel for scale. (c) Covariance plot, showing how the clast data samples in the study area plot in terms of transport pathways. Each sample can be correlated with the valley of provenance by a different symbology. The colour gradient indicates the samples' relative position in their associated valleys, from the lighter upper valley samples to the darker lower valley ones.

ice limits, and they offer insight into glacial thermal regime, meltwater volumes and subglacial water pressures (Table 1). Previous research has used meltwater channels as a diagnostic criterion for cold-based ice margins, whereby glacial meltwater is diverted along frozen margins, carving channels corresponding to their retreat positions (Dyke, 1993; Evans, Hughes, et al., 2017; Greenwood et al., 2007; Livingstone et al., 2010; Maag, 1969). However, Dyke (1993) and Syverson and Mickelson (2009) also acknowledged meltwater channel initiation in warm-based thermal settings.

4.3.2 | Spatial distribution

Ice-marginal meltwater channels are rare and specific only to the south-facing Mocirlu, Soarbele, Bulz and Vlăsia valleys (Figures 1c, 2, 3f and 4d). Their planforms can be employed to demarcate ice limits and glacier recession patterns, especially where they are nested and/or associated with recessional moraine ridges (Table 1). Located in the elevation range 1530–1890 m a.s.l., the meltwater channels range from 60 to 330 m long, with one exception in the Soarbele valley, of 823 m. Ground-truthed examples in the Bulz and Vlăsia valleys are 2–5 m deep. We cannot exclude a cold-based thermal regime in the Godeanu Mountains under specific conditions (elevation range and slope location). However, the association of meltwater channels with other landforms indicative of active deposition (recessional moraines), as well as warm-based thermal regimes (ice-moulded bedrock), indicates that an active temperate or polythermal setting was operating for at least some of the time.

4.4 | Pronival and protalus ramparts

4.4.1 | Morphology and genesis

Pronival and protalus ramparts are single, largely continuous ridges with asymmetric cross profiles, formed by the accumulation of rockfall debris at the foot of perennial snowpatches (Shakesby, 1997; Shakesby et al., 1999; Matthews et al., 2011; Table 1). Although some debate has surrounded a snowpatch versus glacial (morainic) genesis for many mountainside ridges (e.g., Shakesby, 1997; Shakesby & Matthews, 1993), there are specific diagnostic criteria for palaeo-protalus rampart interpretations (Table 1). Typically, the distance between a protalus rampart and the talus foot that it formerly covered can only be 30–70 m, otherwise the snowpatch would have turned into glacier ice (Ballantyne & Benn, 1994). Pronival ramparts, which represent ridges accumulating on mid-slopes, would thus be related to even smaller snow accumulations. The sedimentology of a pronival rampart should also typically be predominantly composed of open-work clasts in places, including a fine matrix (Table 1).

4.4.2 | Spatial distribution

We mapped 48 pronival and protalus ramparts in the Godeanu Mountains (Figures 2, 3g and 4e). Pronival and protalus ramparts are dominant in north-facing valleys ($n = 31$) in contrast to south-facing valleys ($n = 17$). They are situated at lower elevations in the south-facing valleys (1620–2100 m a.s.l.; average = 1790 m a.s.l), compared with north-facing ones (1710–2100 m a.s.l.; average = 1945 m a.s.l.). They also lie upslope of moraine ridges in many locations (e.g., up-valley distance between moraine and pronival rampart of 14.5 m in the Olanu West, and 15.03 m in the Cârnea valleys, respectively) (Figures 1c and 2). The spatial distribution of pronival and protalus ramparts offers potential insight into palaeoclimatic trends (Ballantyne & Kirkbride, 1986). Firstly, favourable conditions, such as shading and windward-facing basins, are reflected in preferential locations on north-facing slopes (Ballantyne & Kirkbride, 1986; Colucci et al., 2016). The lower elevations at which the ramparts are located in south-facing valleys might suggest these formed at a different time and climatic conditions than their north-facing equivalents. Secondly, the close association of pronival and protalus ramparts with recessional moraines reflects a spatio-temporal transition from small glaciers to snowpatches (Ballantyne & Benn, 1994; Niculescu, 1965). Indeed, Hedding et al. (2007) noted pronival and protalus ramparts forming under decreasing precipitation at the inception/demise of regional glacier activity.

4.5 | Relict rock glaciers and rock-glacierised moraines

4.5.1 | Morphology and genesis

Given the relict nature of the geomorphology and the absence of active permafrost in the Godeanu Mountains (Onaca, Urdea, et al., 2017), we refrain from subdividing rock glaciers by their hypothetical origin (rock glaciers or periglacial protalus lobes) (Harrison et al., 2008). Here, we employ the descriptive use of the term 'rock glacier', or a tongue-shape assemblage of multiple lobate ridges, composed of coarse, predominantly bouldery debris, regardless of their origin (e.g., permafrost/interstitial ice vs. glacier-derived genesis; cf. Ballantyne, 2018b; Berthling, 2011; Harrison et al., 2008; Humlum, 1996 Table 1). Hence, we endorse the concept of equifinality of rock glaciers (Knight et al., 2019; Whalley, 2009). Additionally, we follow the conventions of Thompson (1957), Østrem (1964), England (1978), Leigh et al. (2021) and Urdea et al. (2022) in recognising rock-glacierised moraines in situations where moraines appear to have been remobilized by creep, either due to interstitial pore ice accumulation or an initial glacier ice core (Table 1). In each case, rock glaciers and rock-glacierised moraines in the study area are relict features and, hence, are genetically classified based upon their more muted appearance after de-icing. This makes them difficult to distinguish from some other landforms, especially RSF run-out deposits and closely spaced, bouldery latero-frontal moraines (e.g., Ballantyne, Schnabel, & Xu, 2009; Whalley, 2009, 2012).

4.5.2 | Spatial distribution

We identified relict rock glaciers on valley sides, in association with talus cones (Figures 1c, 2, 3h and 4f), and rock-glacierised moraines (Figures 1c, 2, 3i and 4g) on the valley floors. We estimate that around 12 relict rock glaciers exist, with six located in the north-facing valleys of Scurtele, Scărişoara, Stâna Borăscu, Galbena North and Galbena South, and another six in the south-facing Balmoş East, Godeanu, Mocirlu, Scărița, Bulz and Vlăsia valleys. In contrast, rock-glacierised moraines are mainly found in south-facing valleys (six examples), with only two examples located in the north-facing Mâțu valley. Taken together, and similar to the distribution of pronival and protalus ramparts, the elevation ranges at which rock glaciers and rock-glacierised moraines are found are higher in the north-facing valleys (1690–2016 m a.s.l.; average = 1841 m a.s.l.) than in their south-facing equivalents (1650–1940 m a.s.l; average = 1786 m a.s.l.). Previous research on relict rock glaciers in the Southern Carpathians (Onaca, Ardelean, et al., 2017; Popescu, Urdea, & Vespremeanu-Stroe, 2017; Vespremeanu-Stroe et al., 2012) hypothesised that they formed as a response to either Lateglacial climatic warming during the Bølling–Allerød Interstadial (14.6–12.9 ka), precipitation starvation during the Younger Dryas (12.9–11.7 ka) or high humidity during the Early Holocene (11.7–8.2 ka), when glacier retreat was underway or complete, and slope destabilisation, permafrost development and rockfall occurred (Rasmussen et al., 2014; Walker et al., 2012). In terms of rock glacier distribution, Popescu, Onaca, Urdea, and Vespremeanu-Stroe (2017) and Şerban et al. (2019) noted a discrepancy in rock glacier and block stream elevation between north- and south-facing slopes in the Southern Carpathians, with the northern slope features located at higher elevations than their southern counterparts. Popescu, Onaca, Urdea, and Vespremeanu-Stroe (2017) and Şerban et al. (2019) attributed this to south-facing valleys receiving higher solar insolation, and thereby earlier glacier retreat and slope debutressing than in north-facing valleys. Because of their shading, the north-facing valleys might have preferentially supported higher elevation rock glaciers more recently. Although geochronology might constrain landform age and associated climate change, the incrementally polygenetic origin (glacial-to-periglacial) of many features makes their employment as palaeoclimatic indicators complicated (cf. Harrison et al., 2008; Jarman et al., 2013; Knight et al., 2019).

4.6 | Rock slope failures

4.6.1 | Morphology and genesis

Depending on the failure style, travel distance and degree of disintegration, RSFs are represented by a range of discrete debris accumulations or partially intact bedrock masses, situated on, or at the foot of, steep rock walls. They can be classified as follows: (1) rock avalanches—discrete debris assemblages on valley floors, whose transport path can be traced directly uphill; (2) rockslides—arrested rock masses showing little deformation due to their short-travel distance; (3) rock slope deformations—subtle ruptures, bulges, tension fault ridges and troughs (mini horsts and grabens) or antiscarps on valley sides and plateau edges (Gunnell et al., 2022). The lithology of RSFs can be traced to a source depression immediately upslope (Table 1; Ballantyne, 2013, 2021; Jarman, 2006). Such landforms are thought to relate to slope instabilities and isostatic adjustment following the removal of ice weight upon deglaciation (Table 1; Ballantyne, 2002; Ballantyne et al., 2014). Because of their similarity to, and juxtaposition with glacial landforms, RSFs can be misidentified as former glacier ice limits; they can also obscure them in cases of postglacial failures (Table 1). Additionally, RSFs that pre-date ice advance can be overrun and streamlined by glacier flow (Ballantyne, 2018a; Figure 4h).

4.6.2 | Spatial distribution

We identified 97 RSFs in the Godeanu Mountains. These landforms are predominantly distributed in north-facing valleys (65) rather than in south-facing ones (32; Figures 2, 3j and 4h). The RSFs cluster around valley heads and occur at a wide range of elevations (1650–2190 m). Compared with other features, RSFs are large (0.206–0.0005 km^2; average = 0.038 km^2) and classify as three rock avalanches, 39 rockslides and 55 rock slope deformations. Occasionally, RSFs appear to be associated with relict rock glaciers and rock-glacierised moraines, both in north- (e.g., Borăscu Mare) and south- (e.g., Vlăsia) facing valleys. However, a number of RSF-rich north-facing valleys are devoid of rock glaciers and rock-glacierised moraines, including the Izvoru Moraru, Branu North, Mâțu, Scurtele, Zănoaga, Galbena North and Paltina valleys (Figures 1c and 2). Our detailed mapping approach differs from that of Gunnell et al. (2022), which recognised only 21 RSFs in the Godeanu Mountains amongst 215 in the Southern Carpathians.

The work of Gunnell et al. (2022) and that of Vasile et al. (2022) constitute the first inventory and application of ^{10}Be cosmogenic nuclide dating of RSFs in the Southern Carpathians, respectively. These pioneering studies suggest that Neogene tectonic uplift and climate warming in the Southern Carpathians drove RSF development and that periglacial, fluvial and parafluvial triggers were more important than glacial and paraglacial processes. The dominance of Early Holocene (pre-9 ka) dated boulders in RSF deposits in particular supported these proposals (Vasile et al., 2022). Indeed, the spatio-temporal relationships between glacial, periglacial and paraglacial landforms may indicate a deglacial/postglacial (Early Holocene) development period for RSFs. Furthermore, the higher number of RSFs on the north-facing slopes and lower association with periglacial landforms on this aspect than on the south-facing ones re-inforces the hypothesis of a later deglaciation on the north-facing valleys, which may still be undergoing failure, whereas their southern counterparts have already completed the paraglacial cycle (Ballantyne, 2002). Over the longer timescales of multiple Quaternary glaciations, however, RSF operation likely initiates and/or contributes to cirque development through headwall erosion into plateau surfaces (cf. Evans, 2021; Turnbull & Davies, 2006), sourcing debris for the development of rock glaciers and moraines.

5 | GLACIAL LANDSYSTEMS

The spatio-temporal relationships between the mapped landforms and the sedimentological evidence provide a clear signature of past glaciation style, debris turnover and moraine construction in the Godeanu Mountains, thereby facilitating the compilation of a glacial landsystem model for the region of the Southern Carpathians. This landsystem model displays many of the characteristics of the conceptual plateau icefield (Rea & Evans, 2003), glaciated valley (Benn et al., 2003) and the cirque/niche (Bickerdike, et al., 2018) glacial landsystems, as well as elements of debris-charged geomorphology observed in a modern analogue in Norway (Leigh et al., 2021). Therefore, it is best classified as a debris-charged plateau icefield/cirque glacier landsystem. The most extensive phases of glaciation were characterised by simultaneous occupation of valleys by ice descending both from surrounding plateaux and from cirques, where narrow mountain ridges dominate. Conversely, phases of less extensive glacierisation were characterised by localised cirque and niche glaciers, detached snouts/reconstituted glaciers and perennial snowpatches (e.g., Benn & Lehmkuhl, 2000; Evans, Ewertowski, & Orton, 2016; Evans et al., 2006; Gellatly et al., 1986; Rea & Evans, 2003), whereas plateau ice may have been restricted to upland surfaces only or completely disappeared. The latter phases may have occurred initially on the more exposed south-facing slopes, with the more shaded north-facing counterparts possibly deglaciating later. Deglaciation unfolded in a landscape prone to rock glacier development, driven by rapid paraglacial debris accumulation and debris-covered glacier snouts, possibly compatible with the oscillating Lateglacial climate in the region (Magyari et al., 2012; Onaca, Ardelean, et al., 2017; Popescu, Urdea, & Vespremeanu-Stroe, 2017; Vespremeanu-Stroe et al., 2012). The spatial and temporal evolution of this complex mountain-based landsystem is depicted in a four-phase schematic model for the Godeanu Mountains in Figure 7.

5.1 | Spatio-temporal change in the Godeanu Mountains debris-charged plateau icefield/cirque landsystem

Using the most extensive moraine limits mapped, the first phase (Figure 7a) depicts the plateau icefield at its maximum extent, with ice descending into two neighbouring valleys. The valleys are separated by an ice-free nunatak, their bedrock slopes feeding extraglacial debris via talus cones to lateral and medial moraines of the outlet glaciers. Plateau icefields were developed on the Moraru, Branu, Scărişoara, Borăscu, Paltina and Stănuleți summits, where the lack of glacial landforms (except rare moraine ridges documenting ice recession from surrounding valley heads) indicates cold-based ice dispersal centres. Cirque glaciers accumulating in the more alpine terrain flow into the main valleys, coalescing with the plateau outlet glaciers. This results in the deposition of further medial moraines; the medial moraines on the cirque glaciers, created predominantly as avalanche types fed by couloirs at headwalls (Eyles & Rogerson, 1978; Rogerson et al., 1986), are also added to the valley glacier surface downflow of the coalescence zone. The transition from predominantly cold-based ice on the plateaux to warmer ice in the outlet glaciers was likely driven initially by the strain heating at the base of icefalls on the plateau edges (Rea et al., 1999; Rea & Evans, 2003; Whalley et al., 1996). Together with the subglacial modification of clasts down-valley, this explains the contrast between plateau summits devoid of glacial landforms and the widespread occurrence of glacial erosional landforms at lower elevations. Over time, the enlargement of cirque headwalls, as well as trough head development at plateau edges, promotes not only further

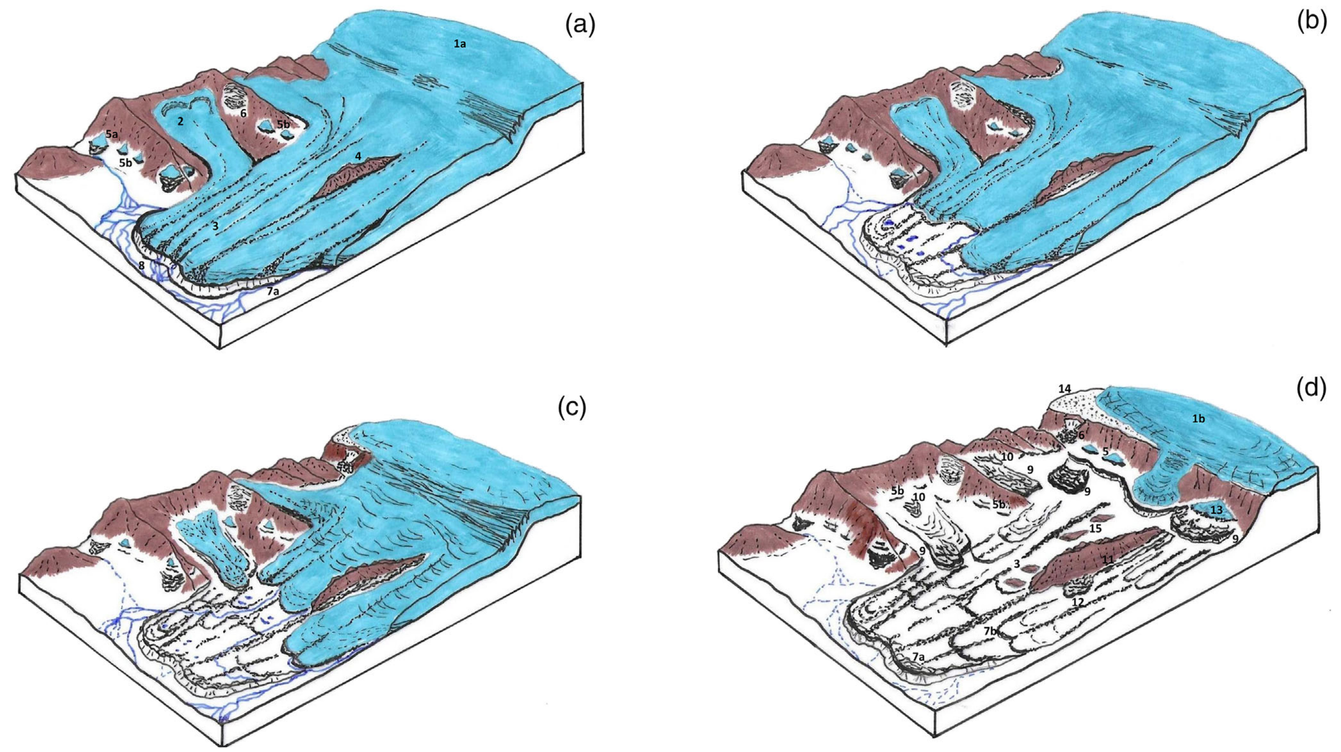

FIGURE 7 Conceptual model for the debris-charged plateau icefield/cirque glacier landsystem based on the Godeanu Mountains. The model is based on amalgamated elements from different valleys. Four phases (a–d) are represented to show how the landsystem signature changes spatio-temporally during deglaciation. Key features and landforms are as follows: (1a) plateau icefield dispersal centre; (1b) plateau icefield; (2) cirque glacier; (3) medial moraines; (4) nunatak; (5) snowpatches with protalus lobes (a) and protalus/pronival ramparts (b); (6) rock slope failure; (7a) latero-frontal end moraine; (7b) recessional moraine loops; (8) proglacial streams, ice-marginal meltwater channels and outwash deposits; (9) debris covered glacier snout developing into a rock glacier; (10) protalus rock glacier; (11) lateral moraines; (12) rock-glacierised lateral moraines; (13) reconstituted or stagnant glacier; (14) blockfield; (15) glacially scoured bedrock outcrops (roches moutonnées and whalebacks).

glacial erosion but also slope destabilisation, and the initial triggering of RSFs, sourcing large volumes of extraglacial debris to the glacial system. In turn, this creates increasingly more debris-charged mountain glaciers (Benn et al., 2003; Bennett et al., 2010; Evans, Ewertowski, & Orton, 2016, 2017; Rea & Evans, 2003). Based upon the landsystem extent and the general elevation of the outermost mapped moraines (≤1500 m a.s.l.), we suggest that this phase may be coeval with early post-Last Glacial Maximum deglaciation, especially as two moraine systems in the neighbouring Retezat Mountains at lower elevations (M1 at ∼1000–1100 m a.s.l.; M2a at 1200–1400 m a.s.l.) have been dated $21.0^{+0.8/-1.5}$–$20.6^{+0.8/-1.3}$ ka and $18.6^{+0.9/-0.8}$–$18.4^{+0.7/-1.1}$ ka, respectively, by Ruszkiczay-Rüdiger et al. (2016, 2021).

The second phase (Figure 7b) depicts initial ice retreat from the maximum extent. During this phase, the lowermost set of latero-frontal moraines were abandoned, and medial moraines were lowered onto the subglacial footprint. Also prominent are the looped latero-frontal and medial moraine signatures of constricted cirque glacier ice, flowing along the valley edge. Ice-marginal meltwater channels were excavated along lower valley slopes and the valley floor. Glacier snout thinning during retreat promoted further slope destabilisation and development of RSFs. The occurrence of continuous latero-frontal moraine ridges and ice-marginal meltwater channels indicates a (partially) coupled ice margin, with high ice and debris supplies, and the efficient meltwater transfer of glacial debris from the snout to proglacial outwash systems (Benn et al., 2003). Although ice-marginal meltwater channels typify cold-based plateau icefields, their lower valley position, the association with depressions and occasional intercalation with moraine ridges (Figure 3f) suggests a warm-based or polythermal basal thermal regime (Dyke, 1993). This is supported by ^{10}Be cosmogenic dating-inferred erosion rates in the Retezat Mountains, which indicate warm-based conditions at the ice margins and colder ice at the valley head during initial deglaciation (Ruszkiczay-Rüdiger et al., 2021). Additionally, the reconstructed coupled margin at this stage is a defining characteristic for glaciated valley landsystem settings with high debris turnover (e.g., New Zealand), whereby debris is efficiently evacuated from the margin by high subglacial meltwater pressures and volumes (Benn et al., 2003; Dyke, 1993). Phase 2 moraines are located at ∼1500 ≥ 1750 m a.s.l. and may correspond to the M2b moraine system (1600–1750 m a.s.l.) in the Retezat Mountains, which yielded early Lateglacial ages of $18.6^{+0.9/-0.8}$–$16.9^{\pm0.9}$ ka (Ruszkiczay-Rüdiger et al., 2016, 2021).

The third phase (Figure 7c) was characterised by continued recession of valley and cirque-based glaciers until the different glacier bodies became disconnected. Inset sequences of cirque moraines then started to record recession into localised alpine uplands. Overall recession was under active, warm-based conditions, as indicated by widespread ice-moulded bedrock and multiple inset latero-frontal moraines. Large longitudinal concentrations of supraglacial debris are indicated by the development of significant medial moraines, linked to tight arcuate or looped frontal moraines, each loop demarcating a separate flow unit within the valley outlet glacier (Eyles & Rogerson, 1978; Jennings et al., 2014; Roberson, 2008). As medial moraine preservation potential is usually very low after complete deicing (Benn & Evans, 2010), the prominence of such features in the Godeanu Mountains (especially in increasing numbers up-valley) indicates significant debris provision via extraglacial pathways. This was presumably derived from RSF sources, which began dominating large, steep areas of uncovered trough heads surrounding the plateaux upon ice recession (Ballantyne & Dawson, 2019; Evans, Ewertowski, & Orton, 2016, 2017; Rea & Evans, 2003). Examples of lateral moraine asymmetry (e.g., Figure 3c) reflect the uneven distribution of freefaces delivering such material during deglaciation. Over time, the uncovering of increasingly larger areas of such steep bedrock outcrops during glacier recession and downwasting resulted in enhanced debris production that locally overwhelmed glacier surfaces. This resulted in the formation of rock glaciers and rock-glacierised moraines and a transition towards an uncoupled snout (Benn et al., 2003). Unlike coupled ice margins, the meltwater produced in uncoupled systems is inefficient at removing sediment from the foreland, resulting in gradual ice burial by debris (Benn et al., 2003). This is specific to glaciated mountain valleys under drier climate conditions, with lower ice supplies (Benn et al., 2003). In summary, this phase underscores the evolving importance of topography and debris provision in this landsystem. Located between ~1750 and 1900 m a.s.l., Phase 3 moraines may have been deposited between the construction of the M2b and M3 moraines (1900–2000 m a.s.l.) in the Retezat Mountains, and hence likely date to $15.8^{+0.9/-0.6}$–$15.2^{+0.7/-0.8}$ ka (Ruszkiczay-Rüdiger et al., 2016, 2021).

The gradual increasing importance of debris supply and topographic confinement for spatio-temporal landsystem change becomes more evident in Phase 4 (Figure 7d). As ice retreats to the plateau margin, possibly under acute climate amelioration, glacier disconnections occur, leaving dead ice masses, niche glaciers and reconstituted glaciers at the valley/trough heads and at the base of valley walls (Benn & Lehmkuhl, 2000; Boston & Lukas, 2019; Davies et al., 2022; Evans, Ewertowski, & Orton, 2016; Evans et al., 2006; Gellatly et al., 1986; Rea et al., 1999; Rea & Evans, 2003; Whalley et al., 1996). The final stages of deglaciation renewed the paraglacial cycle (Ballantyne, 2002). In other words, RSF activity intensified, leading to increased supraglacial inputs, which altered the glaciers' responses to climate drivers, by insulating ice surfaces (Benn et al., 2003; Benn & Owen, 2002). Where buried ice persisted, obscured and/or modified glacial landforms, it led to creep, resulting in the formation of looped rock-glacierised moraines and rock glaciers on valley and cirque floors. The occurrence of freshly uncovered valley-side hollows, often bounded downslope by lateral moraines, became prime sites for the development of snowpatches, allowing pronival and protalus ramparts to accumulate. This phase is compatible with the cirque/niche glacial landsystem of Bickerdike, Ó Cofaigh, et al. (2018). Therein, the recession of topographically confined and small ice masses at valley heads and along valley sides is documented by sequences of recessional moraines, or single arcuate moraine ridges, and the gradual development of pronival/protalus ramparts, rock glaciers and RSFs (Bickerdike, Ó Cofaigh, et al., 2018; Ellis & Calkin, 1979). In the Godeanu Mountains, the cirque/niche glacial landsystem is found in the north-facing Șincu cirque and the south-facing Olanu and Balmoș cirques (Figures 1c and 2).

Also evident during Phase 4 is the role of topography in creating a geomorphic contrast between north and south-facing valleys. Some valleys contain far fewer recessional moraines and are devoid of medial moraines (e.g., the north-facing Cârnea, Mâțu, Scurtele and Scărișoara valleys and the south-facing Scărița and Micușa valleys; Figures 1c and 2). This contrast is likely a product of the variable occurrence of bedrock steps, which may act as topographic pinning points. Bedrock steps provide marginal stability, limiting variations in glacier accumulation areas when ELAs are coincident with them (Barr & Lovell, 2014; Dugmore, 1989; Oerlemans, 1989). Such topographic pinning points favoured the formation of rare, large moraines in north-facing valleys, contrasting with the small, but more numerous moraines that accumulated in shallower and smoother south-facing valleys (Barr & Lovell, 2014; Figure 2). Situated at ~1900–1950 m a.s.l., Phase 4 moraines may be equivalent to the M3 moraines in the Retezat Mountains (Ruszkiczay-Rüdiger et al., 2016, 2021). A further phase of moraine deposition (M4 at 2100–2150 m a.s.l.) was dated at $14.4^{\pm0.5}$–$13.5^{+0.5/-0.4}$ ka in the Retezat Mountains, which have a higher elevation than the Godeanu Mountains (max = 2509 m a.s.l.; Ruszkiczay-Rüdiger et al., 2016, 2021). This suggests that topography may have an inhibiting role in sustaining glaciers, lower elevations promote higher temperatures and lower precipitation, which are not compatible with glacier growth/persistence (DeBeer & Sharp, 2009). This is especially relevant for the cirques in the Godeanu Mountains, generally peaking at lower elevations (~1750–2000 m a.s.l.) than the plateau-fed valleys in the Godeanu Mountains (~2000–2250 m a.s.l.) (Figures 1c and 2) and the cirque/valley glaciers described for the Retezat Mountains (Reuther et al., 2007; Ruszkiczay-Rüdiger et al., 2016, 2021). Secondly, plateau-fed glaciers alter ice dynamics by either (a) depressing ELAs, leading to a lower elevation moraines than in cirque/valley settings (Aa, 1996; Dahl & Nesje, 1992; Rea et al., 1999), or (b) rapidly retreating to their plateau surfaces during a warming climate, leaving disconnected ice masses in the ablation area, which may or may not imprint geomorphological evidence (Rea et al., 1999; Whalley et al., 1996). Therefore, undated M4 moraines may be found at lower elevations in the plateau-fed valleys in the Godeanu mountains than in the Retezat, subject to confirmation by an absolute dating programme therein.

5.2 | Wider implications for the debris-charged plateau icefield/cirque glacier landsystem

The debris-charged plateau icefield/cirque glacier landsystem developed here is the first glacial landsystem devised for mid-altitude mountain ranges situated in temperate-continental climates. Considering the similarity of topographic characteristics, this landsystem model will have applicability to other glaciated landscapes in the Carpathians and beyond. In the Romanian Carpathians, plateau icefield styles of glaciation will likely be relevant to mountain areas with existing plateau surfaces above 1800 m a.s.l., for example, in the Rodna, Maramureș and Călimani Mountains (Balaban, 2018; Kłapyta, Mîndrescu, & Zasadni, 2023; Mîndrescu, 2001; Sîrcu, 1978; Urdea et al., 2011) in the Eastern Carpathians and the Țarcu, Retezat, Șureanu, Cîndrel, Lotru, Făgăraș, Iezer and Bucegi Mountains in the Southern Carpathians (Urdea et al., 2022d). In the central–eastern region of southern Europe, plateau icefields have been reconstructed, for example, in the Pindus Mountains, the Dinaric Alps, and Rila Mountains in the Balkans (e.g., Hughes et al., 2006, 2011, 2022; Kuhlemann, Gachev, et al., 2013), and in the Geyikdağ Mountains in Anatolia (e.g., Akçar, 2022; Çiner et al., 2015). However, the extent and timing of operation of these plateau icefields may differ from that of the Godeanu Mountains, and therefore, a careful assessment of topographic, lithological and climatic contexts is needed before making more direct comparisons. Likewise, the debris-rich cirque glacier component of the landsystem is not dissimilar to that of the majority of former cirque and valley glaciers in all the Romanian Carpathians (Urdea et al., 2022a, 2022b, 2022c, 2022d, 2022e; Urdea et al., 2022) and the Western Carpathians (e.g., Tatra Mountains) (Zasadni, Kłapyta, Kałuża, & Makos, 2022; Zasadni et al., 2022a, 2022b, 2022c; Zasadni, Kłapyta, Tołoczko-Pasek, & Makos, 2022; Zasadni, Makos, & Kłapyta, 2022). Indeed, previous research in the Romanian Carpathians highlighted a glacial geomorphology throughout the last deglaciation that was characterised by debris-charged palaeoglaciers (e.g., Balaban, 2018; Gheorghiu, 2012; Gheorghiu et al., 2015; Kłapyta et al., 2021, 2022; Kłapyta, Mîndrescu, & Zasadni, 2023; Kłapyta, Zasadni, & Mîndrescu, 2023; László et al., 2013; Reuther et al., 2007; Ruszkiczay-Rüdiger et al., 2016, 2021), but the exact timing and causes of glacial recession have not been assessed in detail (Popescu, Urdea, & Vespremeanu-Stroe, 2017). Consequently, there is a need to apply a landsystem approach to geomorphological mapping and couple it with radiometric dating programmes and numerical ice models to enable robust comparisons of spatio-temporal changes in glaciation style across a wider region.

6 | CONCLUSIONS

Drawing on geomorphological mapping and sedimentological investigations, we devise a glacial landsystem model for the Godeanu Mountains, Southern Carpathians, Romania, to understand past glaciation styles and dynamics of mid-altitude mountain glaciers located in temperate-continental climates. We derive the following conclusions:

Firstly, we identified glacial depositional (latero-frontal, recessional, lateral, medial moraines, drift limits/till veneers), glacial erosional (ice-moulded bedrock, ice-marginal meltwater channels), periglacial (pronival and protalus ramparts, relict rock glaciers and rock-glacierised moraines) and paraglacial (RSFs) landforms. The spatial distribution and association of landforms are compatible with a debris-rich glacier retreat, sourced from plateau surfaces/cirques.

Secondly, we performed sedimentological analyses on selected glacial landforms. These further support a debris-charged glacial environment, with transport pathways transitioning from passive to active with distance from valley heads and sides. Although active transport in the lower valleys relates to subglacial erosion from the bed mostly during the earlier stages of deglaciation, passive transport became more dominant in the latter stages, wherein abundant extraglacial sediment was sourced from cirque heads/valley slopes and transported via well-preserved medial moraines to the glacier foreland.

Thirdly, we produce a four-phase, time-transgressive, debris-charged plateau icefield/cirque glacial landsystem model. Phase 1 corresponds to the maximum glacial extent, when plateau ice coalesced with cirque ice, highlighting a transition from cold-based uplands to the warm/polythermal regimes in the valleys. Alongside material sourced from active bedrock erosion at lower elevations, extraglacial debris from RSFs at the valley heads was transported passively via medial moraines and deposited as latero-frontal ridges at the glacier snout. Phase 2 follows ice retreat from the maximum extent. The association of ice-marginal meltwater channels with recessional moraines is evidence of a warm-based/polythermal coupled ice margin, with a high debris turnover. Phase 3 underpins continual active but increasingly debris-charged recession and disconnection between cirque glaciers and plateau-fed outlets. This is supported by recessional moraines and looped medial moraines pertaining to individual ice flow units and asymmetrical lateral moraines, all of which reflect additional sediment supply sourced from fresh RSFs and the gradually uncovered ice-moulded bedrock ridges. Phase 4 illustrates the final retreat of the cirque and plateau outlets to their upland sources, the increased confinement of cirque glaciers to their niches and the more important role of debris and topography in driving landscape evolution. The likely climatic amelioration and abundance of extraglacial debris from debuttressed slopes led to the burial and uncoupling of glacial snouts from their foreland, which then became inefficient at removing the sediment load. This is supported by the development of pronival and protalus ramparts, rock glaciers and rock-glacierised moraines, which became more dominant over recessional moraines. Ultimately, the role of bedrock steps as topographic pinning points, and the elevation and topographic contrasts between plateau and cirque-fed glaciers explain the contrasts in moraine size, spacing and elevation between different outlets of the Godeanu Mountains and higher alpine summits in other areas of the Southern Carpathians.

Finally, the new landsystem model can be used as an analogue for other plateau/cirque-flanked mountains in Central, Eastern and Southern Europe that exhibit a debris-rich geomorphic signature on their former glacier beds but ideally in conjunction with absolute dating and numerical modelling of glacier extents.

AUTHOR CONTRIBUTIONS

Cristina I. Balaban co-designed the study, obtained funding for fieldwork, designed the methodology, conducted fieldwork and analysis and drafted the initial and final manuscript. David H. Roberts co-designed the study, supported the methodology and fieldwork, supervised CIB and helped draft the final manuscript. David J. A. Evans co-designed the study, supported the methodology, supervised CIB and helped draft the final manuscript. Stewart S. R. Jamieson co-designed the study, supported the methodology, supervised CIB and helped draft the final manuscript.

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DATA AVAILABILITY STATEMENT

A full resolution of the geomorphological map (without the dashed, numbered rectangles) is available in Figure S1 (Supporting Information). The shapefiles of the mapped landforms are available upon request.

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