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Geomorphology

Rock walls distribution and Holocene evolution in a mid-latitude mountain range (the Romanian Carpathians) --Manuscript Draft--

Manuscript Number:	GEOMOR-11671
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Keywords:	rock wall morphometry; lithology; rock slope failures; Romanian Carpathians
Abstract:	<p>Rock walls in high mountain areas are the expression of long-term slopes response (10³ –10⁵ years) to tectonics, weathering and denudation and a major source of sediment and hazard. Mountain rock walls (RW) characteristics and evolution at mountain-range scale is rarely discussed in the literature. Using a database of 791 RW mapped in the Romanian Carpathians, we present their distribution and morphometry in respect to lithological class, structural features and topography and relate them to post-Younger Dryas (Holocene) rock slope failure chronology. Morphometric data indicate that metamorphic and igneous RW (linked to a great extent to glacial valleys and cirques headwalls) are usually restricted to the highest sectors of the mountain slopes, are characterized by reduced relative heights and have an asymmetrical distribution, being common on the North-exposed slopes but extremely rare on the South. Statistical analysis results show the high significance of structural and tectonic control on RW distribution in sedimentary units which imposes the predominance of West and North orientations and RW dimensions up to a degree higher than in other lithologies. Based on 38 10 Be surface exposure ages obtained on metric boulders from the Southern and Eastern Carpathians, we hypothesise that metamorphic and igneous RW in the formerly glaciated Carpathian valleys were significantly shaped during Early Holocene (before 9 ka) by rock slope failures events that followed the deglaciation of the highest cirques and the intense RW permafrost degradation. We associate the long-term imprints of frost weathering to the significant North/South RW and rock glaciers distribution asymmetry, also identified in other mid-latitude mountain sites with similar topographic constraints.</p>

Rock walls in high mountain areas are the expression of long-term slopes response (10^3 – 10^5 years) to tectonics, weathering and denudation and a major source of sediment and hazard. Mountain rock walls (RW) characteristics and evolution at mountain-range scale is rarely discussed in the literature. Using a database of 791 RW mapped in the Romanian Carpathians, we present their distribution and morphometry in respect to lithological class, structural features and topography and relate them to post-Younger Dryas (Holocene) rock slope failure chronology. Morphometric data indicate that metamorphic and igneous RW (linked to a great extent to glacial valleys and cirques headwalls) are usually restricted to the highest sectors of the mountain slopes, are characterized by reduced relative heights and have an asymmetrical distribution, being common on the North-exposed slopes but extremely rare on the South. Statistical analysis results show the high significance of structural and tectonic control on RW distribution in sedimentary units which imposes the predominance of West and North orientations and RW dimensions up to a degree higher than in other lithologies. Based on $^{38} \text{Be}$ surface exposure ages obtained on metric boulders from the Southern and Eastern Carpathians, we hypothesise that metamorphic and igneous RW in the formerly glaciated Carpathian valleys were significantly shaped during Early Holocene (before 9 ka) by rock slope failures events that followed the deglaciation of the highest cirques and the intense RW permafrost degradation. We associate the long-term imprints of frost weathering to the significant North/South RW and rock glaciers distribution asymmetry, also identified in other mid-latitude mountain sites with similar topographic constraints.

1 **TITLE: Rock walls distribution and Holocene evolution in a mid-latitude**
2 **mountain range (the Romanian Carpathians)**

3

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23

24 ABSTRACT

25 Rock walls in high mountain areas are the expression of long-term slopes response (10^3 – 10^5
26 years) to tectonics, weathering and denudation and a major source of sediment and hazard.

27 Mountain rock walls (RW) characteristics and evolution at mountain–range scale is rarely
28 discussed in the literature. Using a database of 791 RW mapped in the Romanian Carpathians,
29 we present their distribution and morphometry in respect to lithological class, structural features
30 and topography and relate them to post–Younger Dryas (Holocene) rock slope failure
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33 the mountain slopes, are characterized by reduced relative heights and have an asymmetrical
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35 Statistical analysis results show the high significance of structural and tectonic control on RW
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39 Carpathians, we hypothesise that metamorphic and igneous RW in the formerly glaciated
40 Carpathian valleys were significantly shaped during Early Holocene (before 9 ka) by rock slope
41 failures events that followed the deglaciation of the highest cirques and the intense RW
42 permafrost degradation. We associate the long–term imprints of frost weathering to the
43 significant North/South RW and rock glaciers distribution asymmetry, also identified in other
44 mid-latitude mountain sites with similar topographic constraints.

45 KEYWORDS: rock wall morphometry; lithology; rock slope failures; Romanian Carpathians

46

47 1. INTRODUCTION

48 Mountain RW are landforms highly sensitive for mechanical weathering and erosional
49 processes (Hales and Roering, 2007; Matsuoka, 2008; Allen and Huggel, 2013; Phillips *et al.*,
50 2017), the rates of which are dictated by the interplay of lithology, climate and the local uplift
51 regime (Willett 1999; Seong *et al.* 2009; Bartosch *et al.* 2017). Tectonics and structure
52 significantly influence the extent and morphometry of the exposed rock surfaces in high

53 mountain areas (Lifton et al. 2009; Ellis and Barnes 2015; Sauchyn et al. 1998) which determine
54 differential resistance to weathering and erosion. In formerly glaciated European mountain
55 ranges, weathering and denudation rates are reported quantitatively after the Last Glacial period
56 (Curry and Morris 2004; Hughes et al. 2007; Messenzehl et al. 2017; Matthews et al. 2018). The
57 occurrence of numerous rock slope failures (RSF) in response to local deglaciation
58 debuitressing has been documented by absolute age dating (Soldati et al., 2004; Prager *et al.*,
59 2008; Ballantyne *et al.*, 2014) with responses varying from immediate to millennial time lags
60 (Ballantyne *et al.*, 2014). The reconstruction of RSF chronology in Tatra Mountains (Pánek *et*
61 *al.*, 2016) shows that lower magnitude events within steep topography occurred in the highest
62 sectors of slopes hundreds of years after glacier retreat and are likely triggered by ice mass
63 disappearance, whereas complex RSF producing at millennial time-scale in lower topography
64 are associated with climate changing to warmer and more humid conditions during the onset of
65 the Holocene and the Sub-Boreal period (Soldati et al., 2004; Ivy-Ochs *et al.*, 2009; Hermanns
66 and Longva, 2013).

67 High-mountain rock slopes are a continuous source area for geomorphic processes that trigger
68 natural hazards like debris flows, rockfalls or rock avalanches (Loye et al. 2009; Corona et al.
69 2013; Kromer 2017), especially when affected by permafrost degradation. RW stability is
70 responsive to climate variables such as changes of permafrost conditions (Krautblatter et al.
71 2013; Girard et al. 2013) and global climate change influencing periglacial processes (Gruber et
72 al., 2004; Messenzehl *et al.*, 2017; Phillips *et al.*, 2017), which has also been documented in
73 warming conditions during the Holocene in the European and Scandinavian Alps (Hormes *et al.*,
74 2008; Nagelisen *et al.*, 2015; Hilger *et al.*, 2021). This raises the question of RW evolution and
75 subsequent debris production induced by the post-Younger Dryas permafrost retreat, especially
76 in mid-latitude where permafrost in northerly slopes exists at lower altitudes than in southerly
77 slopes (Magnin *et al.*, 2015).

78 Range-scale morphometric studies in the Romanian Carpathians have been documenting the
79 distribution of glacial cirques by high-accuracy mapping (Mîndrescu and Evans 2014;
80 Mîndrescu et al. 2010) and object oriented image analysis (Ardelean 2013). Geochronology
81 studies based on absolute ages resume to deglaciation history, pointing to a Younger Dryas
82 glacial advance at 12.9–12.1 ka only in the highest massifs (Popescu et al., 2017a). During the
83 last decade, the intensive monitoring of the thermal regime of permafrost susceptible sites has
84 shown the restrictive conditions for permafrost preservation in RW and rock glaciers
85 (Vespremeanu–Stroe et al., 2012; Ardelean *et al.*, 2017; Onaca *et al.*, 2017; Popescu *et al.*,
86 2017b). Recent studies on RW present state, in terms of stability or thermal regime,
87 emphasized the rockfall hazard imposed by seasonal thawing in steep North-exposed RW
88 (Vasile et al., 2014; Onaca *et al.*, 2015; Vasile and Vespremeanu–Stroe, 2017).

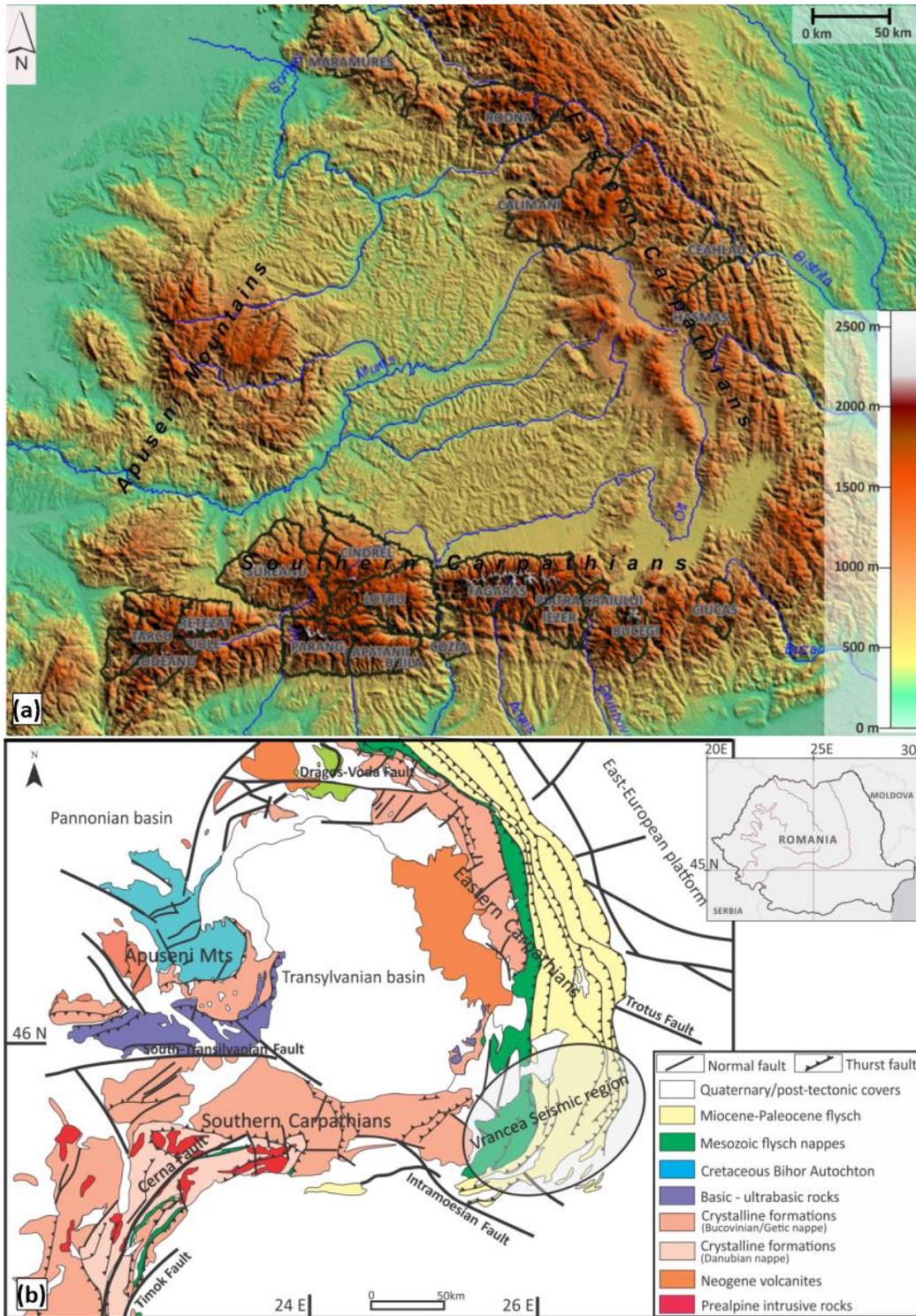
89 In this paper we i) present the distribution of RW in relation to lithology, structure and
90 topography for assessing differential RW retreat control factors and ii) provide a first insight on
91 Holocene RSF occurrence as the last major shaping agent of RW in the Romanian Carpathians.
92 The objectives are achieved by RW mapping and statistical analysis of distribution controlling
93 parameters, and by in-situ ¹⁰Be surface exposure data analysis in glacial cirques and valleys
94 from five different massifs.

95

96 **2. STUDY AREA**

97 The Romanian Carpathians stand as a geographical subdivision of the Carpathian Mountain Arc
98 that stretches in Central and Eastern Europe (44° 30' – 47° 45' N and 21° 30' – 27° 10' E). They
99 expand to a length of 900 km and reach the maximum altitude of 2544 m above sea level
100 (a.s.l.). The three main subdivisions (i.e., the Eastern and Southern Carpathians – abbreviated
101 EC and SC further on – and the Apuseni Mountains, Fig. 1a, b) show lithological and
102 topographic differences that reflect the complexity of the geological evolution, structural
103 characteristics, and influence of the Pleistocene glaciations.

104 The Carpathians are part of the Alpine Orogeny and include tectonic units dating prior to the
105 alpine event, in the Palaeozoic and early Mesozoic. The youngest exhumation phases
106 determined by thermochronology age patterns in the central part of the SC are Latest
107 Cretaceous – Middle Eocene. The south–western sector of the SC underwent Oligocene –
108 Miocene exhumation, whereas most of the EC correspond to Early – Middle Miocene phases,
109 except for the SE Carpathians (Curvature Carpathians) which started uplifting in both Miocene
110 and Latest Pliocene – Quaternary exhumation episodes (Merten, 2011). The EC are built on a
111 central Crystalline Unit (correspondent to present Rodna, Maramureş, Rarău and Hăşmaş Mts.),
112 Cretaceous Flysch (Ceahlău and Ciucaş Mts, extending towards the SC in Bucegi Mts) and
113 Palaeogene Flysch (Table 1, Fig. 1b). Internal volcanism during the Miocene led to the
114 formation of EC volcanic massifs while the Pliocene – Quaternary comprised both a rapid uplift
115 of 500–1000 m (which led to the formation of the most recent depression areas), and the
116 strongest volcanic activity in the area (Săndulescu, 1984; Linzer *et al.*, 1998; Mutihac, 2004).
117 The SC are comprised of three major Crystalline Units: the Getic Overthrust Nappe (Şureanu,
118 Căpăţanii, Lotru, Cindrel, Godeanu Mts), the Supragetic Overthrust Nappe (Făgăraş and Iezer
119 Mts) and the Danubian Nappes (Retezat and Parâng Mts), the latter being formed by granitic
120 and granodioritic batholiths in their central areas and marginal limestone massifs (Fig. 1a, b for
121 location, Table 1).



122
 123 **Figure 1:** (a) Location of Eastern and Southern Carpathians and Apuseni Mts., and outline of the units included in the
 124 RW inventory (digital elevation by 1 arc-second resolution ASTER GDEM). (b) Simplified geological map of the
 125 Carpathians (modified and adapted from Vaida and Verniers, 2005, and Merten, 2011. Small insert shows the
 126 Carpathian Arc position in Romania (please refer to the colour version)

	Unit name (max. altitude)	Lithology/ Structure*	Extent / Direction	Nr. of mapped RW	Glaciation**
Eastern Carpathians	Maramureş (1956 m)	Crystalline schist with peripheral limestone and sandstones Volcanic intrusions (basalts)	15 km long / NW–SE ridge	11	Yes
	Rodna (2303 m)	Crystalline schist, micaschists and paragneiss Horst, Dragoş Vodă Fault	40 km long / E–W ridge	19	Yes
	Călimani (2100 m)	Andesites (volcanic) Eroded craters	Volcanic cone	5	Yes
	Ceahlău (1969 m)	Conglomerates and flysch Suspended syncline	15 km / N–S	10	No
	Hăşmaş (1973 m)	Massive limestone West oriented syncline	3.5 km long / NW–SE ridge	6	No
	Ciucaş (1954 m)	Conglomerates and sandstones, flysch East oriented syncline	Two separated ridges 7 km / SW–NE and 3 km / NW–SE	37	No
Southern Carpathians	Bucegi (2505 m)	Conglomerates, sandstones Limestone with radiolarites N–S syncline, East oriented cuesta front slope	Reversed U–shape 30 km long ridge	49	Yes
	Piatra Craiului (2238 m)	Limestone with radiolarites Hogback	25 km long / NNE–SSW ridge	13	No
	Iezer (2459 m)	Micaschists and paragneiss Supragetic overthrust nappe	20 km long / SW–NE ridge	27	Yes
	Făgăraş (2544 m)	Micaschists and paragneiss, amphibolite Supragetic overthrust nappe Northern–Făgăraş Fault Line	70km long W–E ridge, and multiple secondary N–S ridges	248	Yes
	Cozia (1668 m)	Gneiss Horst	~70 km ² surface	3	No
	Buila–Vânturariţa (1885 m)	Massive Limestone Hogback	14 km long / SW–NE ridge	23	No
	Parâng (2519 m)	Granitoids Amphibolite (Danubian Unit)	25 km long / E–W ridge	40	Yes
	Şureanu/ Cindre/ Căpâţanii/ Lotrului (2130 – 2244 m)	Micaschists and paragneiss, amphibolite (Getic Unit)	15–25 km long / E–W ridges	8 / 10/ 4 / 5	Yes
	Retezat (2509 m)	Granodiorite intrusions Crystalline schist, amphibolite (Danubian Unit)	15 km long main / W–E ridge 2–5 km secondary N–S ridges	187	Yes
	Ţarcu (2196 m)	Conglomerates, sandstones, crystalline limestone Crystalline schist	20 km long / N–S then NE–SW ridge	26	Yes
	Godeanu/ Piule Iorgovanul (2291 m)	Micaschists and paragneiss, amphibolite / Recifal limestone	20 km long / NE–SW ridge	26 / 13	Yes
	Cerna Valley (1200 m)	Recifal limestone Graben	80 km long valley / NS	21	No

128 **Table 1:** Main lithological, structural and morphographic characteristics of the mountain units in which rock walls were
129 mapped

130 * according to the Geological Map of Romania, scale 1:200 000 (Geological Institute of Romania)

131 ** according to the Map of Glacial Cirques in the Romanian Carpathians (Mindrescu, 2016)

132 Present neo–tectonic movements show a differential uplift trend of the Carpathian orogeny with
133 mean values of 1–3 mm/yr, higher values up to 3–5 mm/yr reported in the Eastern Făgăraş,
134 Bucegi Mts. and the Curvature Carpathians which are associated with the activity from Vrancea
135 seismic region (Hoeven *et al.*, 2005).

136 The past glacial activity in the Carpathian area is expressed by well-preserved glacial cirques,
137 valleys and associated rock walls (Mîndrescu et al., 2010), most of which were modelled during
138 LGM and Late Glacial cold phases (Popescu et al. 2017a).

139 The Romanian Carpathians are characterized by a temperate-continental climate, the mean
140 annual air temperature (MAAT) ranging from -2°C at 2500 m a.s.l. (Vf. Omu meteorological
141 station) and -0.4°C at 2190 m a.s.l. (Țarcu station) to 3 °C at 1577 m a.s.l. (Cozia station). Using
142 a lapse rate of 0.63°C/100 m, the 0°C MAAT isotherm is around 2000 m a.s.l. on North-facing
143 slopes and 2100 m a.s.l. on South-facing ones. Moisture is supplied by the West and SW
144 dominating winds originating in the North-Atlantic and the Mediterranean, mean annual rainfall
145 above 2000 m is 1100–1300 mm, snow cover reaches 1.5–2.0 m during January–March, and
146 lasts in average 150–160 days per season (Micu *et al.*, 2015). In-situ RW thermal monitoring
147 above 2200 m a.s.l. (Vasile and Vespremeanu-Stroe, 2017) exhibits prolonged seasonal frost
148 (140–150 days/season with potential frost penetration depths reaching 2 m), and mean annual
149 rock temperatures (MART) of 0.5°C on the North-exposed slopes and 3–4°C higher MART on
150 the southern slopes, where daily temperature oscillations prevail, and continuous freezing rarely
151 sets within the -3...-8°C freezing window.

152

153 **3. METHODS AND DATA**

154 **3.1 Rock wall mapping**

155 RW were mapped based on the available time records of Google Earth satellite imagery.
156 Because some images were not clear enough for a good differentiation between the RW and
157 the adjacent geomorphological units, a comparison with higher resolution air photography was
158 undertaken (orthophoto images available for view only from the National Agency for Cadastre
159 and Land Legislation – ANCPI at 1–5 m resolution). Further, the 25 m resolution EU-DEM
160 digital surface model (EEA) was used to check slopes inclination and the inflection points within
161 longitudinal profiles at the contact with the talus or at the top of the glacial cirques. The term

162 rock wall refers herein to steep, bare and compact rock surfaces, with angles usually higher
163 than 37–40 degrees (Gruber, 2007). We took into account RW with areas larger than 200 m² in
164 order to avoid patchy rock surfaces partially covered with vegetation or sporadic discontinuous
165 outcrops. Considering these constraints, the analysis resumes to 21 mountain units in the EC
166 and the SC (Fig. 1a for location), where rock surfaces matching these criteria were identified on
167 satellite imagery. The geological map of Romania (scale 1: 200 000, Geological Institute of
168 Romania) was used to determine the rock type of each mapped RW, assuring a complete
169 spatial coverage over the entire range.

170 **3.2 Rock wall morphometry**

171 Mean RW area, total coverage, altitude, relative height, orientation and slope values were
172 computed for each mountain unit (Table 2) and per lithology types, using the values from all
173 units developed on the same rock class (sedimentary, igneous, metamorphic or volcanic). Each
174 RW was vectorized and the resulting polygons were overlaid on the DEMs and then used for
175 calculating the morphometric parameters in ArcGIS software. Mean RW orientation was
176 determined by averaging raster direction. The RW area was calculated for a 2D projection of the
177 RW polygons on the EU–DEM.

178 **3.3 Statistical analysis**

179 The statistical analysis was performed in RStudio (R version 3.4.0), and consisted in three
180 stages. First, a data normality check was performed using the Shapiro–Wilk normality test
181 (Shapiro and Wilk, 1965), which indicated the non-normality of the data. Then, for each
182 mountain unit, a Kruskal–Wallis one–way analysis of variance test (Kruskal and Wallis, 1952)
183 was performed in order to check if there are any statistically significant differences between
184 groups of quantitative parameters, namely the relations between exposures and morphometry,
185 and between lithology and morphometry. The Kruskal-Wallis Test is the non-parametric
186 alternative to ANOVA (one-way analysis of variance), which checks if the analysed groups are

187 subsets from the same population. The test computes the rank variance of the interest variable
188 for the combined groups, and then calculates the H statistic (Equation 1)

189
$$H = \frac{N-1(gn_n(t_i-T_j)^2)}{gsn_n(t_j-T_i)^2},$$
 Equation (1)

190 where n_n is the sample size of the group, g is the sum of the group n , sn_n is the sum of the
191 corresponding group n , t_i is the average observed rank sums for the group, t_j is the observed
192 rank for a value in the corresponding group, and T_i is the observed total average rank sums.
193 (McKight and Najab, 2010). The computed H statistic then indicates whether the groups come
194 from the same population by comparing it to a critical value, which for our analysis corresponds
195 to a 95% confidence or a p-value < 0.05. For H values beyond the critical threshold the Kruskal-
196 Wallis Test indicates strong differences between analysed groups. Finally a post-hoc Dunn's
197 Test (Dunn, 1961) for multiple comparisons was performed in order to identify which mountain
198 units have significantly different values of each pair of the analysed parameters.

199 **3.4 Surface exposure ages**

200 24 boulders (20 from Făgăraş and four from Bucegi Mts) were sampled for cosmogenic ^{10}Be
201 exposure dating. The samples are part of an extensive study regarding deglaciation and RSF,
202 which counts more than 120 rock surfaces (unpublished data). During sample processing, the
203 abundance of post-Younger Dryas resulting ages raised questions about RSF triggering the
204 detachment of such boulders, as documented in other European mountain ranges (synthesis of
205 studies in Pánek *et al.*, 2016). The samples included in the present study were collected along
206 7 glacial valleys in Făgăraş Mts and one valley in Bucegi Mts, ranging from 1205 to 2287 m
207 a.s.l., on metric-size boulders from both valley/cirque centre and peripheral. Sample size varied
208 from 2 to 3 cm thick and sampled rock surfaces were vegetation free. Additionally, we
209 accounted other 14 post-Younger Dryas boulder ages documented in the literature in Rodna
210 (Gheorghiu, 2012), Parâng (Gheorghiu *et al.*, 2015) and Retezat massifs (Reuther *et al.*, 2007;

211 Ruszkiczay-Rüdiger *et al.*, 2021) which were considered as outliers in studies regarding
212 deglaciation chronology, raising the database to 38 values from 16 valleys/cirques.

213 Secondary, we aimed for absolute dating of a rock glacier (Doamnei RG) surface in Făgăraș
214 Mts., where we sampled four boulders from the RG body on a longitudinal profile but also the
215 source RW area above; for comparing a North/South RW exposure, the corresponding South–
216 face of Doamnei RW was also sampled.

217 Dating procedure for Făgăraș and Bucegi samples is described below.

218 The sample purification followed the procedure of Merchel and Herpers, 1999. Samples were
219 crushed and sieved to the 0.25 – 1 mm fraction. Magnetic separation was performed on all
220 samples with a magnetic separator “Frantz LB-1”. The other minerals that are embedded in
221 samples were eliminated with mixtures of HCl and H₂SiF₆. Then atmospheric ¹⁰Be was
222 eliminated by HF (48%) dissolutions. Before the total dissolution, 150 mg of a ⁹Be carrier
223 solution (concentration 3025 ± 9 μg/g; Merchel *et al.*, 2008) manufactured in-house from a
224 phenakite crystal were added to the samples. The total dissolution of quartz was performed with
225 HF 48% (3.6 mL per g of quartz and 30 mL in excess). The resulting solutions were evaporated
226 until dryness and samples were recovered with hydrochloric acid. Subsequently samples were
227 precipitated with ammonia before successive separations through an anion exchange column
228 (Dowex 1X8) to remove iron and a cation exchange column (Dowex 50WX8), and to discard
229 boron and recover Be (Merchel and Herpers, 1999). BeO targets were prepared by mixing
230 Niobium powder with the BeO oxide for AMS measurements.

231 All samples were chemically performed at *Laboratoire National des Nucléides Cosmogéniques*
232 (LN2C) at CEREGE (Aix en Provence, France) and targets of purified BeO were prepared for
233 AMS measurement at *ASTER, the French National AMS Facility* (CEREGE, Aix en Provence).
234 The measurements were calibrated against an In-House standard (STD11) Braucher *et al.*,
235 2015 standard, using an assigned ¹⁰Be/⁹Be ratio of (1.191) × 10⁻¹¹ (1.09%). Analytical

236 uncertainties (reported as 1σ) included for all samples. The ¹⁰Be half-life of (1.387±0.01) × 10⁶
 237 years (Chmeleff *et al.*, 2010) was used.
 238 Production rates were scaled following Stone, 2000 with a sea level high latitude production rate
 239 of 4.02±0.36 atoms/g SiO₂/yr (Borchers *et al.*, 2016). Rock density of 2.5 g/cm³ was used for all
 240 samples. Topographic shielding was calculated using the CosmoCalc 2.2 Excel add-in of
 241 Vermeesch, 2007. Air pressure used is 1013 mBar. There was no quantitative information on
 242 the snow cover during the surface exposure duration, hence, no corrections for potential effects
 243 of snow cover or denudation were applied to the ages. ¹⁰Be exposure ages were calculated
 244 following Equation (2) using muogenic contributions of Braucher *et al.*, 2011.

$$\begin{aligned}
 245 \quad N(x, \varepsilon, t) = & \frac{P_{sp} * \exp(-\frac{x}{Ln})(1 - \exp(-t(\frac{\varepsilon}{Ln} + \lambda))}{\frac{\varepsilon}{Ln} + \lambda} \\
 246 \quad & + \frac{P_{\mu slow} * \exp(-\frac{x}{L_{\mu slow}})(1 - \exp(-t(\frac{\varepsilon}{L_{\mu slow}} + \lambda))}{\frac{\varepsilon}{L_{\mu slow}} + \lambda} \\
 247 \quad & + \frac{P_{\mu fast} * \exp(-\frac{x}{L_{\mu fast}})(1 - \exp(-t(\frac{\varepsilon}{L_{\mu fast}} + \lambda))}{\frac{\varepsilon}{L_{\mu fast}} + \lambda}
 \end{aligned}$$

248 Equation (2)

249 where:

250 N (x, ε, t) is the nuclide concentration function of depth x (g/cm²), denudation rate ε (g/cm²/y)
 251 and exposure time t(y). *P_{sp}*, *P_{μslow}*, *P_{μfast}* and *L_n*, *L_{μslow}*, *L_{μfast}* are the production rates and
 252 attenuation lengths of neutrons, slow muons and fast muons, respectively. *L_n*, *L_{μslow}*, *L_{μfast}*
 253 values used are 160, 1500 and 4320 g/cm², respectively Braucher *et al.*, 2003. λ is the
 254 radioactive decay constant. *P_{μslow}*, *P_{μfast}* are based on Braucher *et al.*, 2011.

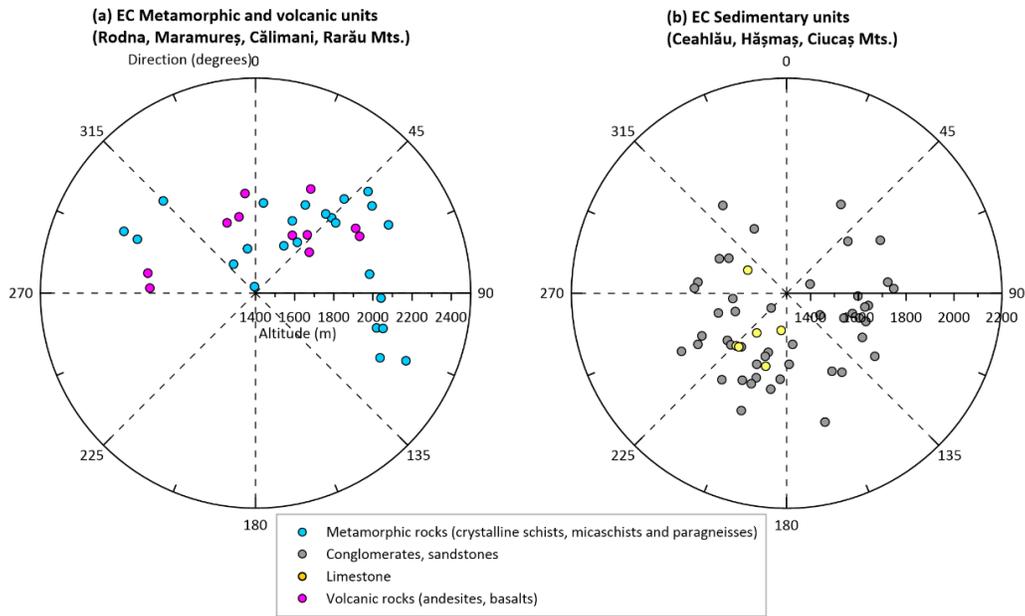
255

256 4. RESULTS

257 4.1 RW distribution

258 From the 21 units considered in this study, 11 preserve glacial landforms (Table 1). In the EC,
259 only Rodnei, Maramureș, and Călimani massifs present visible glacial landforms (cirques,
260 valleys and moraine deposits), most of which are in Rodnei Mts. (Mîndrescu 2016). The best
261 preserved landforms are in Făgăraș Mts., where 207 glacial cirques were mapped (Mîndrescu
262 et al. 2010), in Retezat Mts., which show extensive moraine deposits, glacial lakes and complex
263 glacial valleys (Urdea, 2000), and in Parâng Mts., which keep the largest glacial cirques in the
264 Romanian Carpathians (Iancu, 1970). The distribution of glacial cirques in the SC particularly
265 reflects the main ridge orientation, with moderate differences of frequencies between North and
266 South–exposed cirques (17% on North and 11% on South respectively, reported to 45 degrees
267 bins) and the most favourable conditions of cirque glaciers formation on the East–exposed
268 slopes of the valleys (19.5%) due to the strong eastward aeolian snow-transport acting on the
269 crests and plateaus (Vespremeanu-Stroe et al., 2012). In terms of area and height, the North
270 exposures preserve generally larger and wider cirques (Mîndrescu 2016).

271 A total of 791 RW were identified and considered as individual features, most of which were
272 mapped in the SC. In most of the mountain units considered here, the main ridges follow East–
273 West or NE–SW direction (Table 1), tracking the principal fault lines (Fig. 1a, b). The distribution
274 of the RW is further presented, based on mean orientation and RW altitude.



275
 276 **Figure 2:** Direction and mean altitude of the RW mapped in the EC: (a) the metamorphic schists – prevailing units;
 277 the andesitic and basaltic outcrops are represented as volcanic RW; (b) the sedimentary units (limestone and
 278 conglomerates prevailing). The radius of the graphs represents the altitude values, the general direction is expressed
 279 in sexagesimal degrees and each dot represents a RW (please refer to the colour version)

280 The units from the EC count 88 mapped RW in total. The RW found in the schist–prevailing
 281 massifs are distributed mainly on NE (23%) and secondary on North and East (Fig. 2a) with an
 282 average altitude of 1950 m a.s.l., the North–exposed ones being situated at slightly lower
 283 altitudes. The andesitic and basaltic rock outcrops mapped in the EC, are largely grouped on
 284 the North and NE (82%) similarly with the metamorphic ones.

285 In the sedimentary units, RW extend on all orientations, with a maximum frequency on the
 286 South (almost 40%) whilst just a few (7%) were mapped on the northern slopes (Fig. 2b), but
 287 are limited to altitudes lower than 1800 m, reaching an average of 1634 m a.s.l. which is
 288 considerably lower (> 300 m) than the metamorphic and volcanic RW.

289 Compared to the EC, the number of RW mapped in the mountain units from the SC built on
 290 metamorphic rocks is much larger, rising to 331 from which 275 are distributed in two large
 291 massifs (Făgăraș and Iezer), and the remaining are spread in 6 units characterized by gentler
 292 topography and lower altitude (Fig. 3a, Table 2). The northern direction clearly dominates in

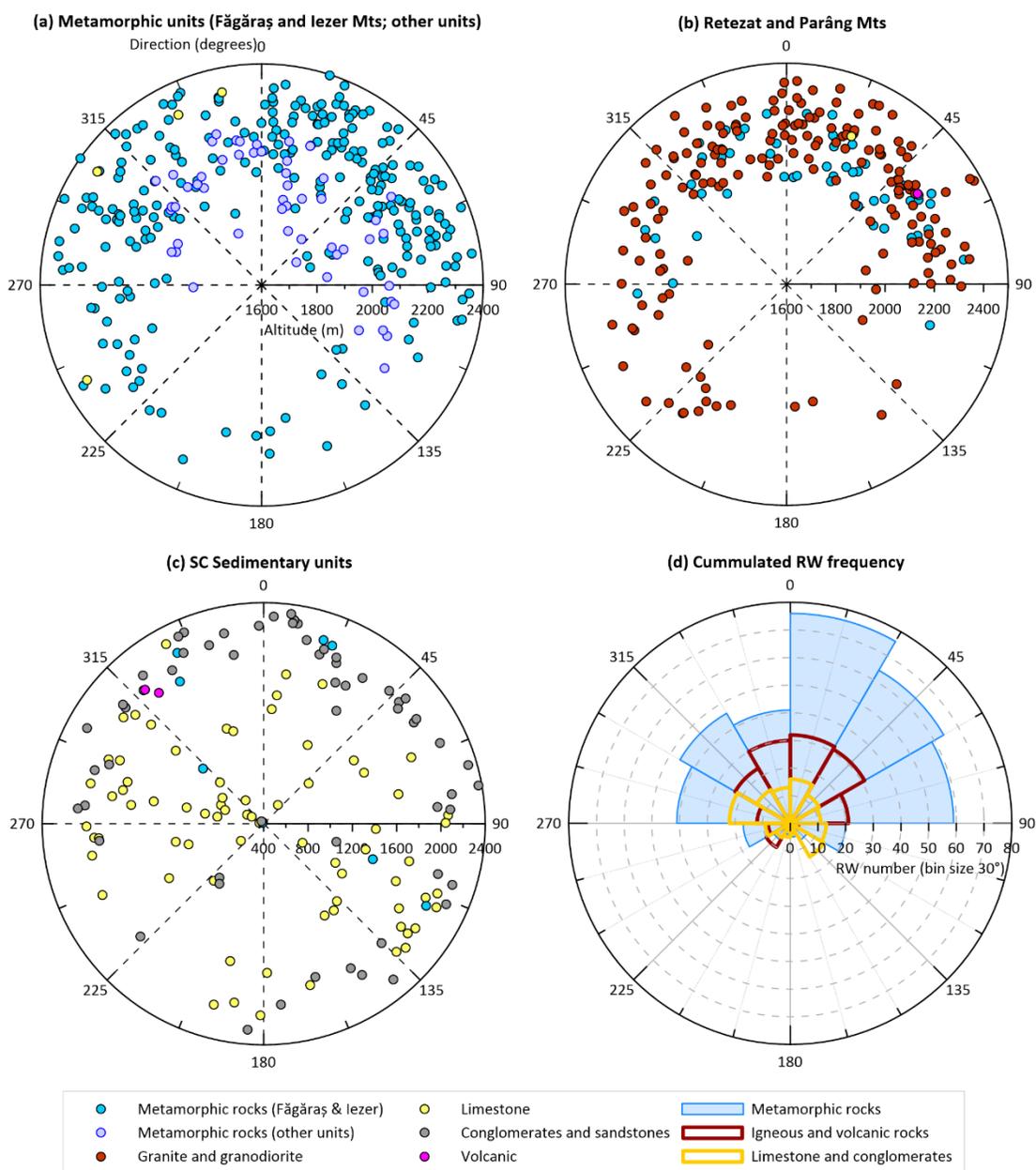
293 both clusters, summing 41% from the total RW number, with similar frequencies on the NW and
 294 NE bins (Fig. 3d). The second highest RW frequency corresponds to the eastern orientation
 295 (104 RW), followed by the western slopes (77 RW). RW mapped on the southern slopes are
 296 scarce and represent 5.4% from the total number. In the large metamorphic massifs of Făgăraș
 297 and Iezer the highest RW density is in the range of 2100 – 2400 m with a mean altitude of 2200
 298 m (Table 2), but 14 mapped surfaces are higher than 2400 m.

	Units	Main Rock Types	RW count	Mean Area (m ² x10 ³)	Total Area (m ² x10 ³)	Mean Height (m)	Mean Slope (degrees)	Mean Alt (m)
Eastern C.	Călimani	Volcanic	5	4.79	23.97	35.8	39	1984
	Ceahlău / Hășmaș / Ciucaș	Limestone	6	59.45	356.71	162.5	44	1546
		Conglomerate	47	41.82	1965.95	83.5	35	1645
	Maramureș / Rodna	Schist	24	15.81	379.55	55.4	44	1950
		Volcanic	6	7.60	45.63	69.7	38	1799
	Bucegi	Conglomerate	42	116.16	4878.94	221.1	46	2096
		Limestone	7	72.5	507.51	175.5	48	1935
	Piatra Craiului	Limestone	13	220.82	2870.74	266.5	44	1967
	Făgăraș / Iezer	Schist	275	8.0	2200.78	73.1	41	2200
	Parâng / Retezat	Granite	175	12.5	2162.87	68.0	38	2229
Schist		52	22.94	1193.22	95.7	40	2169	
Southern C.	Buila / Piule-Iorgovanul / Țarcu / Cerna Valley	Limestone	70	34.1	1909.46	124.2	46	1346
		Conglomerate	17	14.38	244.47	59.3	41	1748
	Cozia / Cindrel / Șureanu / Lotrului / Căpățanii / Godeanu	Schist	8	8.75	70.04	65.3	46	1666
		Volcanic	2	4.83	9.67	46.0	39	1967
			Schist	56	4.61	258.25	33.0	38

299 **Table 2:** The averaged values of the morphometric parameters and total cumulated area of the mapped RW in EC
 300 and SC

301 Parâng and Retezat Mts. in the SC (Fig. 1 for location) are two examples of mixed lithology,
 302 being composed mainly of granitoids plus granodiorites intrusions and of crystalline schist,
 303 micaschist, amphibolite (around 23% of the mapped surfaces) (Tables 1, 2) (Fig. 3b).
 304 Approximately 54% of the RW from Parâng and Retezat Mts. are North-oriented. Eastern and
 305 western exposures account for 25% and 15% of the total number, and only 5.7% of the mapped
 306 surfaces from the two massifs were identified on the southern slopes. More than half of the RW
 307 are concentrated in the 2100 – 2300 m interval and almost 18% extend above 2300 m, the
 308 northern ones reaching the highest altitudes. The RW on metamorphic rocks in the two massifs

309 range at slightly lower altitudes and occur almost evenly on the East, North and West-oriented
 310 slopes.



311

312 **Figure 3:** Direction and mean altitude of the RW mapped in the SC: (a) Făgăraș and Iezer Mts., with the secondary
 313 cluster of RW mapped in the lower altitude SC metamorphic units; (b) distribution of igneous and metamorphic rock
 314 surfaces in Parâng and Retezat Mts.; (c) distribution of limestone, conglomerate and sandstone RW mapped in SC;
 315 (d) Cumulated RW distribution on the four main rock categories represented on 30 degrees direction bins (please
 316 refer to the colour version)

317 In the limestone–prevailing units from the SC, (Bădescu and Tîrlă, 2020; see Fig. 1 for location),
 318 69 RW were mapped (Fig. 3c), of which almost 40% are exposed towards West directions, 26%
 319 to the East, 23% are on northern slopes, and 11% on the southern ones (Fig. 3d). In terms of
 320 altitudinal distribution, there are also major discrepancies between the massifs, imposed by the
 321 structural characteristics of each (Table 1). The highest mean altitude is recorded in Piatra
 322 Craiului (1970 m) while Cerna Valley reaches the lowest (771 m).
 323 Bucegi is the highest sedimentary massif (2507 m) from Carpathians, with most RW developed
 324 on conglomerates and sandstones, and 15% on limestone outcrops. RW are distributed mainly
 325 on the northern slopes (37%) and only 16% are South–facing. Maximum RW density is between
 326 2100 and 2300 m for the North and East–exposed slopes. East, South and West RW are
 327 situated at lower elevations and occur on a wider altitudinal range (1800 – 2200 m).
 328 The statistical analysis shows the clear dominance of West–exposed RWs for most of the
 329 considered morphometric parameters compared to the other main orientations (Table 3). This
 330 asymmetry is however case–specific and imposed by the particular orientation of many of the
 331 sedimentary units, respectively the NNE–SSW–oriented ridges and plateaus of Piatra Craiului
 332 and Buila hogbacks, Bucegi, Ciucaș and Hășmaș synclines (Mutihac, 1990) or Cerna Valley
 333 half–graben (Povară *et al.*, 2013), which together with the eastward and southward dipping
 334 strata contribute to the larger occurrence of West and North–exposed RWs (Fig. 1b).

Ratio	Mean area	Height	Altitude
N/E	2.38 (**)	2.36 (**)	3.19 (***)
S/E	1.11 (·)	1.33 (·)	-3.7 (***)
W/E	5.34 (***)	5.71 (***)	-2 (*)
S/N	-0.41 (·)	-0.17 (·)	-6.05 (***)
W/N	3.66 (***)	4.1 (***)	-5.27 (***)
W/S	2.76 (**)	2.83 (**)	2.18 (*)

335 **Table 3:** Results of the statistical analysis (Post–Hoc Dunn’s Test) of morphometric parameters for pairs of main
 336 exposures. Numbers represent the z-Score, which indicates whether the tested parameter pair has a value above the
 337 rank mean (positive value), or below (negative value). For example, the mean area of N/E pair has a z-Score = 2.38,
 338 meaning that North has a greater mean area than East. In a similar way, for z-Scores below the rank mean the

339 comparison is read inversely, as in the altitude for S/N pair which has a z-Score = -6.05, meaning that North has a
 340 higher altitude than South
 341 * p-value (0.05, 0.01]; ** p-value (0.01, 0.001]; *** p-value < 0.001. A p-value < 0.05 indicates a strong statistical
 342 significance at 95% confidence level

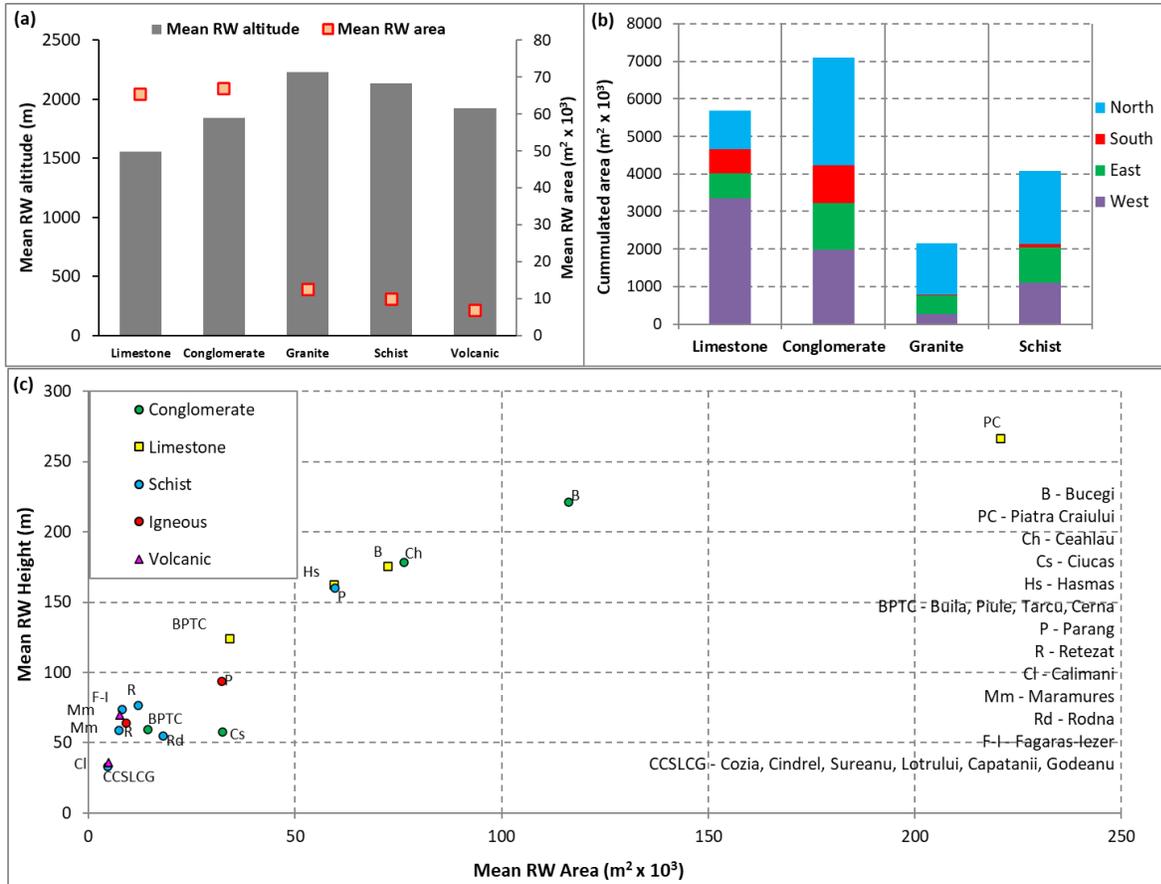
Ratio	Area	Height	Altitude
Conglomerate/ Limestone	-1.78 (*)	-3.9 (***)	2.93 (**)
Granite/ Limestone	-7.54 (***)	-6.9 (***)	12.89 (***)
Schist/ Limestone	-9.01 (***)	-8.36 (***)	10.9 (***)
Granite/ Conglomerate	-5.99 (***)	-2.79 (**)	10.31 (***)
Schist/ Conglomerate	-7.46 (***)	-3.87 (***)	7.91 (***)
Schist/ Granite	-0.77 (-)	-0.83 (-)	-4.53 (***)

343 **Table 4:** Results of the statistical analysis (Post-Hoc Dunn's Test) of morphometric parameters for pairs of main
 344 exposures. Numbers represent the z-Score, which indicates whether the tested parameter pair has a value above the
 345 rank mean (positive value), or below (negative value)
 346 * p-value (0.05, 0.01]; ** p-value (0.01, 0.001]; *** p-value < 0.001. A p-value < 0.05 indicates a strong statistical
 347 significance at 95% confidence level

348 In summary, our observations indicate that RW in metamorphic and igneous units are generally
 349 restricted to altitudes higher than 2100 m, show a high density on the North-exposed slopes
 350 and lack from the southern ones. In comparison, RW distribution in sedimentary units is spread
 351 over a larger range of altitudes but highly dependent on the structure and strata dip-direction
 352 which result in prevalent West and North exposures but not as large (asymmetric) as for the
 353 metamorphic and igneous rocks.

354 **4.2 RW morphometry**

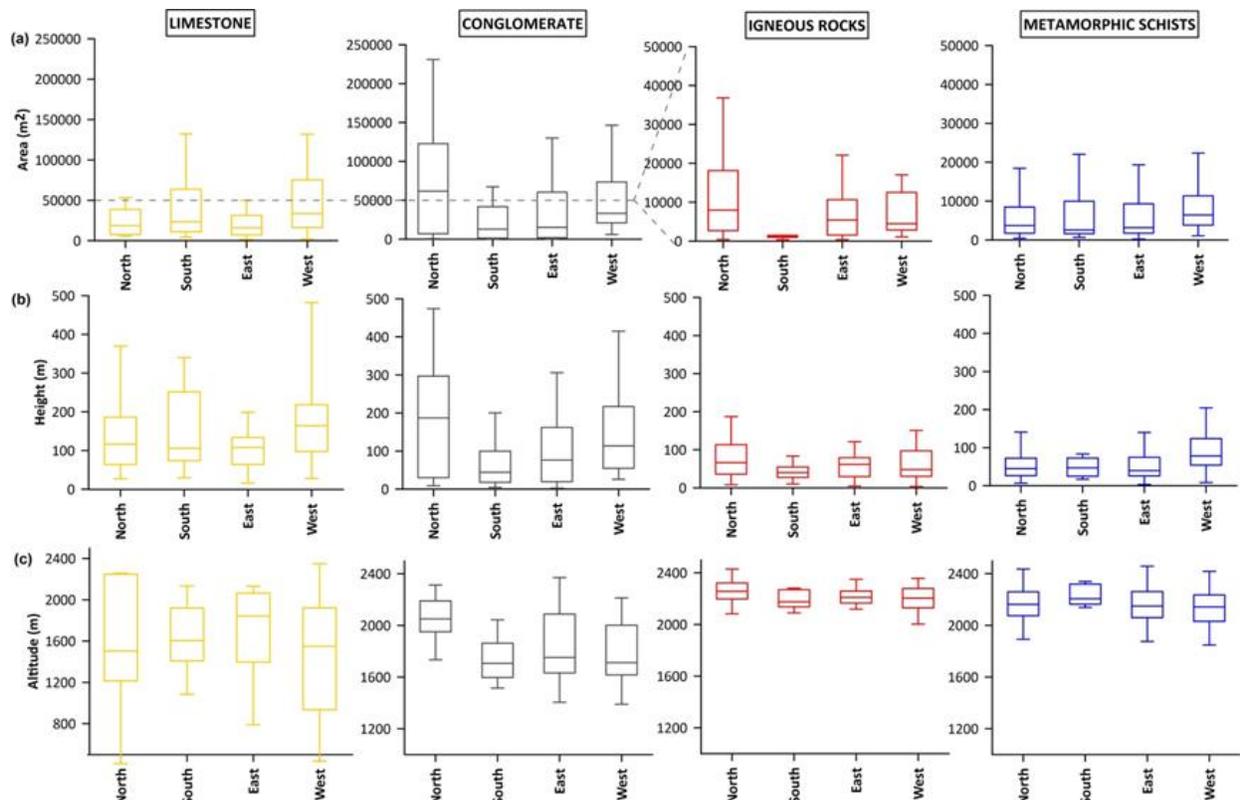
355 Although the most numerous RW were identified on metamorphic rocks, this group covers only
 356 21% of the total mapped surface. An even smaller cumulated area corresponds to igneous
 357 rocks which represent 12% of the total area. Comparatively, although counting less RW, the
 358 sedimentary massifs cumulate 67% of the total mapped area due to their large mean surface
 359 (Fig. 4a, b). Consequently, igneous and metamorphic RW are 5 to 6 times smaller than
 360 limestone, conglomerates and sandstone RW (Fig. 5a).



361

362 **Figure 4:** General RW morphometry on the main rock types (counting all features corresponding to the same rock
 363 type): (a) Mean RW altitude vs mean RW area; (b) Cumulated area of RW with the same lithology grouped on the
 364 four main cardinal directions; (c) Mean RW height and area derived for each massif (please refer to the colour
 365 version)

366 Metamorphic and igneous units are relatively similar in terms of RW vertical extension (around
 367 70 m in average) and show little inter-site variation whereas the sedimentary units both for
 368 limestone, conglomerate and sandstone RW reach almost double height values (Fig. 4c, 5b).
 369 This visible heterogeneity is imposed by Bucegi and Piatra Craiului, with RW of up to 250 m
 370 height. This is also consistent with the wider range of mean RW altitude, as limestone surfaces
 371 extend at much lower altitudes (Fig. 5c).



372
 373 **Figure 5:** Variability of the morphometry of the RW grouped in the main lithological classes in respect to the main
 374 orientations: (a) mean RW area; (b) mean height; (c) mean altitude. The boxes display the median values, the 25–75
 375 quartiles (lower – upper) and the caps show the minimum and maximum values (1.5 IQR)

376 Summing up, the high values of the z-scores in Table 4 (maximum -9.01 for schist/limestone
 377 area, 10.9 for mean altitude) support the high morphometric differences that exist between the
 378 sedimentary units and the metamorphic and igneous ones, which are more similar (-0.77 for
 379 schist/granite area, -4.3 for altitude). Although more numerous, metamorphic and igneous RW
 380 in the study area present typically small-size surfaces perched to the highest stands of formerly
 381 glaciated valleys and cirques. The sedimentary (limestone and conglomerates prevailing) RW
 382 are wider, steeper and cover larger areas than all the other lithological groups independent of
 383 glacial landmarks and with apparent homogeneity in respect to slope orientation. These
 384 characteristics thus reflect major differences between control factors over RW morphometry and
 385 distribution depending on geology.

387 4.3 Absolute ages

388 Sample locations, altitudes, ^{10}Be concentrations and ^{10}Be surface exposure ages determined in
389 this study and selected from the literature are presented in Table 5. Multiple values (3 to 5 per
390 valley) available in 8 of the valleys presented here, allowed an intra and inter-massif analysis of
391 age distributions. Values range between 0.97 ± 0.08 ka and 11.3 ± 1.0 ka (Table 5), clustering
392 between 11.3 and 9.1 ka (21 values), thus immediately following the Younger Dryas (12.9–11.7
393 ka, Rasmussen et al., 2006; 12.6–11.4 ka, Tămaş et al., 2005) and within time lags of up to 2.6
394 ka after. A second high frequency cluster was found between 9.0 and 7.0 ka, while younger
395 ages were identified with a frequency of 1.75 values/1000 yrs. There is not a clear correlation
396 between the absolute ages of the rock surfaces and the altitude. Such an attempt would be
397 hindered by the unequal sample distribution, given the fact that most of the boulders are
398 situated above 1800 m a.s.l. Nevertheless, most of the youngest ages (0.94 ± 0.08 ka, $4.51 \pm$
399 0.18 ka, 2.19 ± 0.12 ka, 1.27 ± 0.22 ka) were found in the lower or mid-sectors of Dejani, Bâlea
400 and Sâmbăta valleys (Făgăraş Mts.), between 1200 and 1500 m a.s.l., respectively. Although
401 few ages from the onset of the Holocene were also determined below 1400 m in the Retezat
402 and Parâng Mts., (10.7 ± 1.4 ka, Ruszkiczay-Rüdiger *et al.*, 2021, 10.5 ± 0.9 ka, Gheorghiu *et*
403 *al.*, 2015), most boulders dating between 11.5 and 7.0 ka are situated in the highest sector of
404 the valleys and on cirque floors (1800–2200 m a.s.l.). This distribution pattern is similar when
405 comparing both valleys within the same massif (e.g., Făgăraş) and valleys from the five different
406 massifs (Table 5).

407 The samples from Doamnei rock glacier yielded values of 12.97 ± 0.38 and 11.44 ± 0.34 ka in
408 the front sector, which gradually decrease to 9.91 ± 0.45 in the middle part and 3.37 ± 0.10 ka at
409 RW base. The exposure date of the source RW and the youngest rock glacier boulder age from
410 the upmost sector indicate rockfalls activity during Late Holocene (Table 5). Comparatively, the
411 South-exposed side of the ridge has returned a much older age (52.64 ± 0.89 ka).

412

LOCATION	Sample name	Lat	Long	Altitude (m)	Quartz mass (g)	[¹⁰ Be] atoms g ⁻¹ x 10 ⁴	t (exposure time) ka	Source
FĂGĂRAȘ								
Arpaș	AR01	45.60	24.67	2134	23.23	8.76 ± 0.33	4.07 ± 0.13	this study ^a
Bâlea Valley	BL	45.64	24.60	1205	24.39	4.92 ± 0.18	4.51 ± 0.18	
Dejani Valley	DEJ01	45.61	24.94	1300	23.05	1.13 ± 0.10	0.97 ± 0.08	
Dejani Valley	DEJ02	45.61	24.94	1287	26.72	8.15 ± 0.31	7.11 ± 0.26	
Dejani Valley	DEJ03	45.59	24.94	1929	26.00	16.91 ± 0.63	9.11 ± 0.34	
Dejani Valley	DEJ04	45.60	24.94	1401	25.77	13.36 ± 0.50	10.55 ± 0.39	
Fundul Caprei Valley	FC02A	45.60	24.64	1850	23.11	15.71 ± 0.59	9.04 ± 0.33	
Mioarele cirque	MIO01	45.58	24.83	2287	26.41	24.28 ± 0.91	10.14 ± 0.38	
Mioarele cirque	MIO02	45.58	24.83	2274	22.88	24.18 ± 0.76	10.14 ± 0.31	
Mioarele	MIO03	45.58	24.83	2285	24.74	24.33 ± 0.91	10.15 ± 0.38	
Orzâneaua cirque	ORZ02	45.60	24.72	1985	25.55	16.98 ± 0.64	8.79 ± 0.33	
Sâmbăta Valley	VS02	45.61	24.80	1823	25.11	16.60 ± 0.62	9.65 ± 0.36	
Sâmbăta Valley	VS01	45.61	24.80	1796	23.66	16.77 ± 0.57	9.95 ± 0.33	
Sâmbăta Valley	SA07	45.64	24.79	1215	26.22	2.46 ± 0.09	2.19 ± 0.12	
Sâmbăta Valley	SA05	45.62	24.79	1485	14.56	1.87 ± 0.07	1.27 ± 0.22	
Sâmbăta Valley	SA04	45.36	24.47	1820	-	-	10.00 ± 0.30	
Urlea cirque	U04	45.60	24.84	2077	25.44	16.00 ± 0.60	7.92 ± 0.29	
Urlea cirque	U01	45.60	24.84	2134	22.88	19.68 ± 0.59	9.36 ± 0.28	
Urlea cirque	U06	45.60	24.85	2062	27.87	22.14 ± 0.83	10.86 ± 0.40	
Urlea cirque	U01A	45.60	24.84	2130	23.07	22.94 ± 0.86	10.95 ± 0.41	
Doamnei RW N	DBEN	45.35	24.36	2230	20.48	3.59 ± 0.24	2.07 ± 0.13	
Doamnei RW S	DBES	45.35	24.36	2243	20.24	121.18 ± 2.06	52.46 ± 0.89	
Doamnei RG1	DBE1	45.36	24.36	2057	20.33	20.39 ± 0.94	9.91 ± 0.45	
Doamnei RG2	DBE2	45.36	24.36	2062	20.61	26.71 ± 0.79	12.97 ± 0.38	
Doamnei RG3	DBE3	45.36	24.36	2082	21.07	23.88 ± 0.71	11.44 ± 0.34	
Doamnei RG4	DBE4	45.35	24.36	2133	20.70	7.01 ± 0.22	3.37 ± 0.10	
BUCEGI								
Gaura Valley	Gaura05	45.43	25.40	1541	25.41	15.76 ± 0.61	10.78 ± 0.43	
Gaura Valley	Gaura06	45.43	25.40	1545	25.74	15.50 ± 0.46	10.62 ± 0.33	
Gaura cirque	Gaura03	45.44	25.43	2072	15.44	15.72 ± 0.49	7.49 ± 0.23	
Gaura cirque	Gaura01	45.44	25.43	2081	25.39	15.60 ± 0.53	8.00 ± 0.25	
PARANG								
lezer Valley	PR01	45.34	23.63	2034	10.99	24.34 ± 1.08	11.20 ± 0.50	Gheorghiu <i>et al.</i> (2015) ^b
lezer Valley	PR03	45.34	23.62	1970	14.33	13.61 ± 0.46	6.20 ± 0.20	
lezer Valley	PR05	45.34	23.62	2008	10.6	19.64 ± 0.63	8.80 ± 0.80	
Gâlcescu cirque	PR10	45.35	23.61	1990	8.21	24.29 ± 0.69	11.20 ± 0.30	
Zănoaga Mare cirque	PR15	45.35	23.59	2055	10.19	23.63 ± 0.70	10.20 ± 0.30	
Zănoaga Mare cirque	PR16	45.35	23.59	2055	10.56	23.94 ± 0.83	10.40 ± 0.30	

Table 5: Sampling locations, ¹⁰Be concentrations, and ¹⁰Be surface exposure ages for post–Younger Dryas dated boulders in the Romanian Carpathians

^a Analytical uncertainties (reported as 1-σ) included for all samples. No corrections for potential effects of snow cover or denudation were applied to the ages

^b Exposure ages calculated using Cronus-Earth 10Be - 26Al exposure age calculator v. 2.2 (<http://hess.ess.washington.edu/>). They assume zero erosion, scaling factors according to Stone (2000) and a spallation production rate of 4.49 ± 0.39 atom (g SiO₂)⁻¹ a⁻¹ (Balco *et al.*, 2008). Exposure ages are presented with the external uncertainties

RETEZAT								
Lăpușnicu Valley	Re15-29	45.31	22.78	1167	-	10.30 ± 0.13	10.70 ± 1.40	Ruszkiczay-Rüdiger <i>et al.</i> , (2021) ^c
Pietrele Valley	Pt-03-02	45.28	22.88	1902	-	23.9	11.40 ± 1.30	Reuther <i>et al.</i> (2007) ^d
RODNA								
Pietroasă Valley	RD 30	47.61	24.64	1379	25.11	16.32 ± 0.50	10.50 ± 0.90	Gheorghiu, (2012) ^{ee}
Zănoaga Mare cirque	RD 04	47.6	24.64	1669	28.95	21.65 ± 0.63	11.50 ± 1.00	
Zănoaga Mare cirque	RD 06	47.6	27.63	1767	24.24	22.83 ± 0.63	11.30 ± 1.00	
Zănoaga Mare cirque	RD 07	47.6	27.63	1767	25.85	22.50 ± 0.65	11.10 ± 1.00	
Zănoaga Mare cirque	RD 05	47.6	27.63	1753	24.36	10.89 ± 0.40	5.70 ± 0.50	
Buhăiescu Valley	RD 19	47.58	24.65	1718	23.01	21.61 ± 0.63	10.40 ± 0.90	

^c The measured $^{10}\text{Be}/^{9}\text{Be}$ AMS ratios were corrected for full processed blank ratios: $(3.30 \pm 0.50) \times 10^{-15}$. Age uncertainties: the 1st number is the internal uncertainty (AMS measurement, weighting, carrier, blank and half-life; $1-\sigma$). Every reported age was corrected for topographic- and self-shielding

^d Exposure age corrected for the effect of topographic shielding and surface geometry

^e Exposure ages calculated using Cronus-Earth $^{10}\text{Be} - ^{26}\text{Al}$ exposure age calculator v. 2.2 (<http://hess.ess.washington.edu/>). They assume zero erosion, scaling factors according to Stone (2000)

413 5. DISCUSSION

414 5.1 Structure and lithology influence on RW distribution

415 The RW inventory and morphometric analysis results have emphasized the significant influence
416 of the lithology and geological structure on the characteristics of metamorphic, igneous and
417 sedimentary RW in the Romanian Carpathians, the first two rock categories producing much
418 smaller RW, but developed at higher altitudes, than sedimentary massifs which account for the
419 greatest rock surface coverage overall. Our results also showed that the distribution of RW in
420 the Carpathians is very particular in respect to orientation, with an obvious asymmetry between
421 North and South exposures especially for metamorphic and igneous rocks, yet with extent RW
422 on all orientations in limestone or conglomerate massifs.

423 Despite the North / South balanced distribution of the glacial cirques (Mindrescu, 2016), we
424 showed that RW present a high asymmetry in the metamorphic and igneous mountain units
425 from the both SC and EC (Fig. 2a, 4b, d), where South-exposed slopes are much less frequent
426 whilst the total covered area is almost 30 times higher on the North-exposed RW.

427 Correspondently, the present rock glaciers distribution in these units accounts for 58% of the
428 mapped rock glaciers in the northern quadrant, and only 13% in the southern one (Onaca *et al.*,
429 2017), which also suggests a more intense/frequent debris accumulation on the North exposed
430 slopes during Younger Dryas and Early Holocene when presumably most of the rock glaciers
431 formed (Onaca *et al.*, 2013). A similar distribution is described in the Adamello–Presanella
432 massif (Italian Alps), where the main ridge follows the NE-SW direction of the North-bordering
433 fault and valleys radiate from the main ridge, covering all the cardinal directions. Here, based on
434 the inventory of 216 rock glaciers mostly consisting of intrusive granodioritic and tonalitic rocks,
435 Baroni *et al.*, (2004) show that both active and relict rock glaciers are predominantly facing the
436 North, NW and NE compared to the southern quadrant (which counts 18% of the active /
437 inactive, and 15% of the relict ones), and argument, by comparing front altitudes, that local
438 topoclimate makes northern slopes more favourable to rock glacier formation and preservation.
439 We further consider that RW preservation conditions are also more restrictive on the southern
440 slopes in igneous and metamorphic slopes, as commented below.

441 Both granite and schist RW in the study area are characterized by metric joints networks which
442 fit well with the dimensions of the boulders enclosed into the adjacent debris deposits (Vasile
443 and Vespremeanu-Stroe, 2017), supporting intense slope modelling which could have led to the
444 formation of large debris deposits, talus cones and rock glaciers. In a simulation of moisture
445 availability in alpine RWs, (Rode *et al.* 2016) highlight that the preconditions of water saturation
446 and temperature required for ice segregation are often recorded on the North-exposed slopes
447 but just rarely met on warmer South–exposed rock surfaces, which implies that the latter are not
448 prone for large–size debris production. Thus, South–exposed rock slopes would be subject to
449 small–scale flake and granular rock shattering under the effect of both superficial freezing
450 during snow melting intervals (Matsuoka, 2008) and of diurnal insolation thermal stress during
451 snow–free intervals (Eppes *et al.*, 2016). We assume that South–exposed RW in the Romanian
452 Carpathians were generally more stable than the other exposures whilst the northern were the

453 most active due to longer permafrost preservation. This is also supported by the old age (52.46
454 \pm 0.89 ka) age yielded by the South-exposed ridge outcrop above Doamnei rock glacier, which
455 was apparently unaffected by LGM, when it most probably stood as nunatak. Humification
456 process (i.e. humus formation in soil profiles) has been inferred to be more intense on South-
457 exposed mountain slopes, where warmer conditions intensify oxidation and create a more
458 optimal environment for microorganisms that degrade organic matter (Egli *et al.*, 2010),
459 compared to North-exposed mountain slopes which incorporate undecomposed or weakly
460 degraded organic matter and are subject to mineral leaching due to colder and wetter
461 conditions. Savi *et al.* (2015) reconstruct frost-cracking intensity and debris production during
462 the Holocene in the Eastern Italian Alps, and emphasizes that high debris accumulation
463 occurred during Early Holocene and also during Atlantic and Subatlantic periods when positive
464 MAAT would have promoted continuous superficial (up to 100 cm deep) frost cracking in the
465 highest peaks (around 3000 m a.s.l.). A similar pattern is supported in the SC by the surface
466 exposure ages that sustain production of large debris in all massifs during Early Holocene and
467 secondary debris production in subsequent phases.

468 The cumulated effect of these processes could explain a generally faster cover with soil and
469 vegetation on the sunny slopes of both metamorphic and igneous units from this study, whereas
470 on the North, colder thermal regime and the production of large-size boulders led
471 simultaneously to a better preservation of RW, which is reflected in present-day distribution and
472 morphometry.

473 The large synclines represented by Bucegi and Ciucaș Mts., with main North to South dip
474 direction of the conglomerate and sandstones bedding planes uplifted large RW on the North-
475 facing cuesta fronts, typical for sedimentary units formed as synclines, perched synclines, or
476 hogbacks which are generally dominated by the compactness and steepness of the cuesta
477 escarpments (Huggett, 2007). This is also the case in the NE-SW-dipping limestone massifs in
478 SC which enhanced the development of the largest RW on their western slopes. Limestone RW

479 in both EC and SC generally lack dense superficial joint networks which, along with increased
480 permeability, limits water availability within the first centimetres of rock and implicitly turns ice
481 segregation less probable, which implies reduced RW modelling by frost shattering and debris
482 accumulation in sedimentary massifs (Johnson et al., 2007). This is reflected by the low number
483 of rock glaciers formed / identified in the SC on sedimentary rocks (only 15 on limestone from a
484 total statistical population of 306 rock glaciers; Onaca et al. 2017). Therefore, we consider the
485 lithology and structure to play the major role in imposing the orientation-related homogeneity
486 which accounts as the primary control in RW distribution and dimensions in the sedimentary
487 units from this study. Secondary, post-glacial RW relaxation would have led to the detachment
488 of massive limestone and conglomerate blocks as sustained by the absolute ages obtained in
489 Bucegi Mts (Table 5). However, in specific cases, such as Piatra Craiului limestone hogback,
490 large debris deposits have accumulated at the base of the main tectonic slopes. For such
491 cases, we assume that the absence of transversal valleys and of the Pleistocene glaciers, both
492 caused by topography, could have created the conditions for the long-term (e.g. Middle to Late
493 Quaternary) debris accumulation, the formation of which is still to be deciphered.

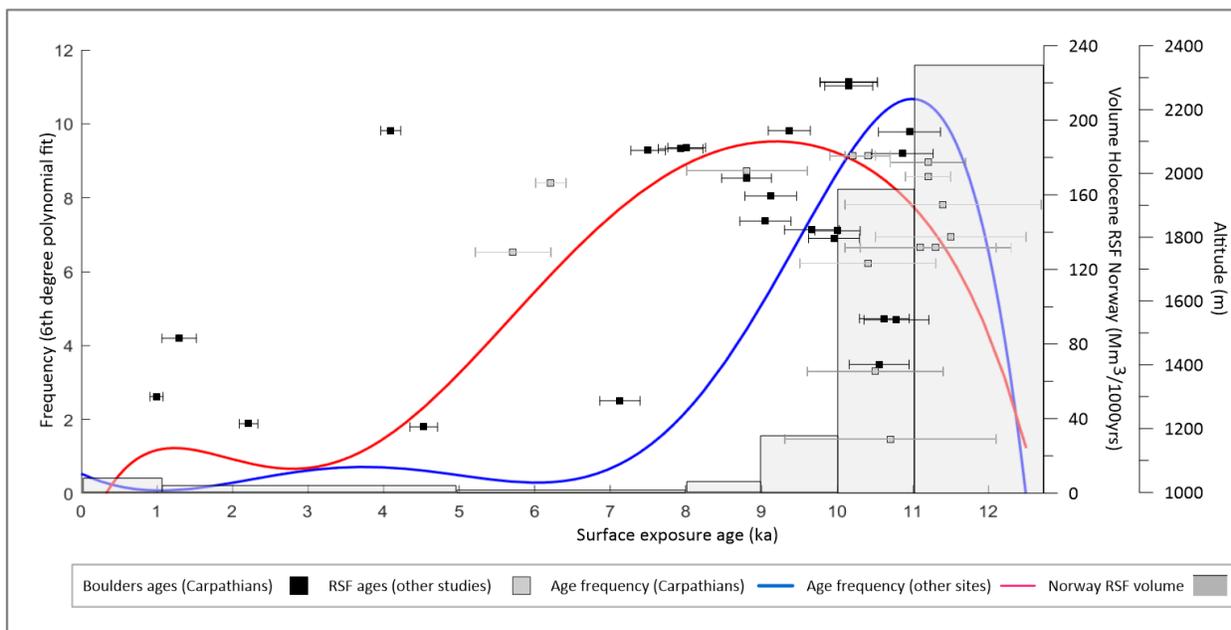
494 **5.2 Holocene dynamics of RW depicted by rock-slope failures**

495 Following Last Glacial Maximum deglaciation (19-14.5 ka), small glaciers re-occupied the
496 highest cirques (> 2050 m) during Younger Dryas excepting the southern ones (Gheorghiu *et*
497 *al.*, 2015; Popescu et al., 2017a; Pascal et al., 2018). The largest Younger Dryas glaciers are
498 likely to have lasted more than a millennium during Early Holocene (e.g. 10.2 ± 0.9 kyrs,
499 Gheorghiu *et al.*, 2015). Therefore, we consider that most of the boulders from high altitudes (>
500 2000 m) of early Holocene age dated in this study have originated by RW destabilization as
501 response of ice retreat which occurred mainly in the upper valley/cirques sectors where glaciers
502 were restricted (Fig. 6). High frequency of such events occurring several thousand years after
503 Younger Dryas period are well documented in the European Alps (Soldati et al., 2004; Cossart
504 *et al.*, 2008; Hormes *et al.*, 2008; Prager *et al.*, 2008; Ivy-Ochs *et al.*, 2009), Tatra Mts. (Pánek

505 *et al.*, 2016), in Scotland (Ballantyne *et al.*, 2014) and Scandinavia (Mercier *et al.*, 2013; Hilger
506 *et al.*, 2018, 2021; Vick *et al.*, 2022), but also in Karakorum (Shroder *et al.*, 2011) or the Andes
507 (Fauqué *et al.*, 2009). Many of these sites record re-activations or secondary clusters during the
508 Sub-Boreal period (Hermanns and Longva, 2013).

509 In Fig. 6 we compare frequency curves of the post Younger Dryas boulders dated in the
510 Romanian Carpathians and of the RSF ages compiled from these studies after excluding the
511 mountain ranges which are influenced by excess of humidity/dryness and correspondently by
512 their variability in time (e.g., Himalaya, Atlas or Cascade Mts). Overall, the Romanian
513 Carpathians show a similar general trend with the other world-wide catenae but with an
514 apparently more rapid and accentuated response to the Early Holocene warming and more
515 humid conditions, so that almost 3/4 of the dated RSF occurred before 8 ka with the highest
516 frequency window positioned during 11.6-9 ka. Conversely, the multi-sites curve reflects a
517 higher sensitivity of RW (deduced via RSF occurrence) to the Holocene Climatic Optimum,
518 which can be explained both by delays in local deglaciation momentum and topoclimatic
519 conditions. Given the relatively small number of samples used in our study (38), this first attempt
520 to assess the RSF evolution in the Romanian Carpathians might also be biased towards the
521 Early Holocene by the high frequency of the high-altitude samples (71% of the samples are
522 >1700 m). As future research, it is necessary to expand the RSF dating by including more cases
523 from the mid and low levels and to compare their histories in order to disentangle the influence
524 of deglaciation, permafrost thawing, thermal and humidity variation. However, some of the
525 European studies describe some similar results with the newly-obtained in the Romanian
526 Carpathians, such as Hermanns and Longva (2013) which give an estimation of Holocene RSF
527 magnitude in Storfjorden, Norway, showing that the earliest events (12.5 to 10 kyrs) generated
528 by far the largest detached volumes (Fig. 6), compared to the ones dating after 8 kyrs. Similarly,
529 reconstructed magnitudes of large landslides from the Alps (Soldati *et al.*, 2004; Ivy-Ochs *et al.*,
530 2009), place such events in the first millennia of the Holocene.

531 Independently of the absolute exposure ages used to assess the RSF probability occurrence
 532 during Holocene (Fig. 6), the other four surface ages from Doamnei rock glacier, in the central
 533 Făgăraș massif, indicate multiple phases of debris accumulation, and, in the same time, the
 534 high magnitude of early–Holocene debris production, which supplied at least the lower half of
 535 the rock glacier body, demonstrated by the rapid accumulation of massive boulders as well as
 536 their displacement between 12.97 and 9.91 ka ago. RW permafrost decay would have further
 537 enhanced subsequent rockfall or rock avalanches of smaller magnitude during the following
 538 warm episodes of the Holocene as also described in the Swiss Alps by Nagelisen *et al.*, (2015).
 539 The particularly large boulders in the lower half of Doamnei rock glacier are incompatible with
 540 frost-cracking intensities estimated for the Holocene (Savi et al., 2015) and were most probably
 541 produced by similar high magnitude (as described by Hermanns and Longva, 2013) slope
 542 failures induced by slope relaxation, permafrost degradation and overall weakened slope
 543 coherence. We consider this to be the ultimate process/interval of intense modelling in the
 544 alpine area of the Carpathians which defined the rock walls – rock glaciers/debris systems
 545 preserved until present.



547 **Figure 6** Cumulated distribution of surface exposure ages attributed to post-Younger Dryas RSF in the Romanian
548 Carpathians (blue line), and multi-site composed RSF distribution (red line) using absolute ages from the French Alps
549 (Cossart *et al.*, 2008), Swiss Alps (Ivy-Ochs *et al.*, 2009), Italian Alps (Hormes *et al.*, 2008), Central Andes (Fauque *et*
550 *al.*, 2009), Northern Iceland (Mercier *et al.*, 2013), Central Karakoram (Shroder *et al.*, 2011), Scotland and NW Ireland
551 (Ballantyne *et al.*, 2014). Grey-filled columns represent estimated volume of Holocene RSF in Norway (after
552 Hermanns and Longva, 2013)

553

554 **6. CONCLUSIONS**

555 The distribution of RW mapped in the Southern and Eastern Carpathians depends mainly on the
556 lithology, structure but also weathering processes. In the metamorphic and igneous units, it
557 ultimately relates to geomorphological context, being mostly associated with glacial cirques and
558 valleys headwalls. Most RW are therefore restricted to the highest ridge sectors, while their low
559 heights and areas are explained as a consequence of the lithological predisposition to debris
560 production, especially in permafrost degrading conditions during warming phases of the Early
561 Holocene. The North/South asymmetry in rock glaciers distribution (also signalled in other mid-
562 latitude ranges) is reflected by the lack of South-exposed RW. We assume more stable
563 conditions prone to fine debris and soil formation on the southern slopes due to insolation and
564 warmer conditions.

565 For the sedimentary RW, tectonics and the geological structure are the main controls to explain
566 the occurrence of the large (wide and high) limestone and conglomerate RW in the Romanian
567 Carpathians. Except for Bucegi Mts, which were high and large enough to host complex glaciers
568 during the last glaciation, most of the sedimentary units from SC and EC were not subject to
569 glacial erosion during LGM due to either steep topography (e.g., hogback ridges) or lower
570 altitude, although RW permafrost was probably widespread.

571 Absolute exposure ages confirm that an intense rock slope degradation via rock-slope failures
572 took place in the Carpathian metamorphic and igneous units in Early Holocene, similar with
573 other European sites, reaching the highest magnitudes 11.6 – 9 ka ago especially above 1800

574 m altitude. We associate the present distribution of RW with this periglacially-active period
575 which was the last time of rock surfaces substantial reshape.

576

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581

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