ROCK GLACIERS AND PERMAFROST RECONSTRUCTION IN THE SOUTHERN CARPATHIAN MOUNTAINS, ROMANIA

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Abstract

Rock glaciers are indicators of discontinuous permafrost which permits them to be used in the reconstruction of the development of mountain permafrost. The mapping of rock glaciers in the Southern Carpathians allowed a clear differentiation between talus rock glaciers and debris rock glaciers, as well as their spatial and morphological relations with glacial deposits. Given the significance of rock glaciers in the glacial-periglacial landscape continuum, geomorphological analysis has led to the outlining of three evolutionary models.

Two major periods of development of rock glaciers were recognised: Wurm III - Older Dryas for forms below 1600-1750 m, and the Medium and Younger Dryas for features over 1800 m a.s.l. During the Little Ice Age, features located above 2050 m were reactivated. Calculations were also made of the volume of mountain permafrost represented by the rock glaciers and the volume of ground-ice, as well as the evolution in time of the lower limits of continuous permafrost and widespread and patchy discontinuous permafrost in the Southern Carpathians.

Introduction

Knowledge of mountain permafrost in Southern Carpathians is very recent and is based on relatively few investigations (Urdea, 1992a, 1993a, 1993b, 1993c). Permafrost phenomena in this mountain area are a function of: mean annual air temperature, a function of altitude; direct solar radiation, a function of local relief and tophography; and snow cover thickness and duration, a function of wind drift and avalanche activity, (Haeberli, 1992; King, 1983). Rock glaciers are among the few geomorphological features diagnostic of alpine permafrost (Barsch, 1978; Haeberli, 1985). In the Southern Carpathians, relic rock glaciers are found in areas which had discontinuous permafrost during the last part of the Pleistocene glaciation (Ichim, 1978; Urdea, 1988, 1992a, 1993b) and therefore are regarded as useful paleoenvironmental indicators. Geomorphological mapping of these landforms may therefore be applied to the study of altitudinal and latitudinal limits of mountain permafrost (Dramis and Kotarba, 1994).

Study area

The Southern Carpathians form the most massive and highest part of the Romanian Carpathians, (Figure 1A) having 10 peaks above 2500 m and a maximum elevation of 2544 m in Moldoveanu Peak (Fgras Mountains). Ten percent of the mountain area lies above 2000 m. Pleistocene glaciers reached elevation of 1100-1200 m during their maximum extension, and carved an extensive suite of alpine glacial landforms (Figures 1B and 1C). The interaction of paraglacial processes and periglacial phenomena produced a variety of periglacial forms (rock glaciers, talus cones and scree slopes, block fields, rock streams, cryoplanation terraces and solifluction forms). The mean annual air temperature is -0.5°C at Tarcu (2180 m) and -2.6°C at Omu (2505 m) with an absolute minimum of -3 °C. The number of days with frost is 200-254 and the number of freeze-thaw cycles is more than 125, with frost possible at any time of the year. The mean annual precipitations 1180 mm at Tarcu and 1280 at Omu. The thickness of the snow layer can be between 50 and 370 cm and is highly variable according to wind action. The upper limit of the forest is generally between 1750 and 1800 m. The crystalline rock of the Southern Carpathians includes granites and granodiorites especially in the Retezat, Parg and Tarcu Mountains.

Alpine areas of the Southern Carpathians contain many periglacial features. Perhaps the most distinctive mezo-forms are the rock glaciers. As indicators of discontinuous permafrost, they can be used in the reconstruction of the development of mountain permafrost from the Late Pleistocene up to the present, especially in the most representative areas of the Retezat and Fgras Mountains (Figures 1B and 1C). Following the recession of the Pleistocene glaciers in the Carpathian
Mountains, the postglacial period has been dominated by periglacial and fluvio-torrential processes. In the deglaciated spaces during the so-called paraglacial period (c.f. Johnson, 1984) a quick adjustment of physical systems took place resulting in some relief meso-forms such as the rock glaciers. The large spreading rock glaciers in the Southern Carpathians are found in the alpine glacial landscape area, where they achieve a density of 76/100 km² in the Retezat Mountains and 36/100 km² in the Făgărăș Mountains. This high frequency of rock glaciers is explained by the fact that the walls of glacial cirques and valleys surrounding peaks provided large quantities of frost-shattered debris, favouring rock glacier formation. The great production of debris, incorporated either in rock glaciers or in talus cones and scree slopes in the immediate postglacial period, is due to the presence of rock sensitive to frost weathering, namely jointed granite, granodiorite, gneisses, amphibolites. The relative ease of joint-block separation is a function of pressure release as a result of liberation from the ice mass (cf. Summerfield, 1991) and is partly controlled by structural elements such as faults, joints, schistosity and bedding (Evin, 1987).

**Relation of rock glaciers to glacial deposits**

Mapping of rock glaciers in the Southern Carpathians allowed a clear differentiation between talus rock glaciers and debris rock glaciers, and clarified their spatial and morphological relationships with glacial deposits.

In many cases, the detailed topography of the valley floors and glacial cirques in Retezat, Făgărăș and Parang Mountains allowed the following evolutionary sequence of the latest glaciers to be identified: ablation complexes, ice-cored rock glaciers, debris rock glaciers, secondary rock glaciers (Corte, 1976), or ablation complex rock glaciers (Evin, 1987), like those in the Galesu (Figure 2), Valea Rea, Pietrele, Stevia in Retezat Mountains, Slveiu in Parng, or Arpsel, Cldarea Pietroas a Arpasului, Izvorul Grohotisului, Cltun, Litel, Burianu Mare, Podeiu, Cldarea Pietroas a Doamnei, Podrgel, Hrtopu Ursului, Smbta, Fundu Mogosului, Belia Mare, etc. in Făgărăș Mountains. For example in the Cldarea Grohotisului cirque, two generations of rock glaciers are present, both known to be coeval with stadial moraines in other areas. Here, the rock glacier development was curtailed at the debris-covered glacier stage. Three typical environments are found for rock glacier formation. The first involves glacial cirques and valleys
surrounded by high peaks, which provide significant quantities of frost-shattered blocks. The second involves glacial cirques and valleys cut into plateau margins, e.g., the cirques Bulzul, Vlsia Mic, Mocirliu, Stna Mare de Est from Godeanu Mountains. These areas are characterized by hummocky dead-ice topography, with irregular hummocks, arcuate ridges and convex furrows, separated by small lakes and/or hollows. In the third case, the evolutionary sequence was as follows: rockfall cones and/or avalanche cones, scree slope, pro-talus rampart, talus rock glaciers (lobate rock glaciers), and finally tongue-shaped rock glaciers. This evolution is possible because at the bottom of the walls of glacial cirques and valleys, the mixture of rock debris and ice derived from refreezing of meltwater, was favourable for the de-velopment of talus rock glaciers (Barsch, 1988). There are deposits of lateral moraines here, pushed to the axis of the valleys. A typical situation occurs within Vsiel cirque, where under the southern wall of the cirque corresponding on a fault-line escarpment, there is a 1.5 km long zone containing a series of lobate-linear type rock glaciers. The lobate part of these rock glaciers overlies the median zone of the lateral moraine from the Vsiel stage (Older Dryas), which provides some constraint on their age.

**Results**

The inventory of rock glaciers was based on field mapping and aerial photograph interpretation of 116 rock glaciers in the Fgras Mountains between 1680 and over 2300 m.a.s.l., and 93 cases from the Retezat Mountains between 1690 and over 2200 m.a.s.l. This

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Table 1. Distribution (%) of area occupied by rock glaciers in (a) Retezat and (b) Fagaras Mountains

<table>
<thead>
<tr>
<th>Altitude (m)</th>
<th>Total area a</th>
<th>Retezat</th>
<th>Fagaras</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1800</td>
<td>9.7</td>
<td>6.3</td>
<td>12.5</td>
</tr>
<tr>
<td>1800-1900</td>
<td>12.9</td>
<td>7.7</td>
<td>4.9</td>
</tr>
<tr>
<td>1900-2000</td>
<td>21.0</td>
<td>21.0</td>
<td>27.8</td>
</tr>
<tr>
<td>2000-2100</td>
<td>24.8</td>
<td></td>
<td>37.0</td>
</tr>
<tr>
<td>&gt;2100</td>
<td>40.3</td>
<td>40.3</td>
<td>17.9</td>
</tr>
</tbody>
</table>

Table 2. Altitudinal distribution (%) of rock glaciers in (a) Retezat and (b) Fagaras Mountains

<table>
<thead>
<tr>
<th>Altitude (m)</th>
<th>Total area a</th>
<th>Northern slope a</th>
<th>Southern slope a</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1800</td>
<td>47.9</td>
<td>47.9</td>
<td>46.6</td>
</tr>
<tr>
<td>1800-1900</td>
<td>54.3</td>
<td>7.0</td>
<td>4.8</td>
</tr>
<tr>
<td>1900-2000</td>
<td>14.0</td>
<td>7.2</td>
<td>8.6</td>
</tr>
<tr>
<td>2000-2100</td>
<td>17.2</td>
<td>6.4</td>
<td>3.8</td>
</tr>
<tr>
<td>&gt;2100</td>
<td>16.9</td>
<td>9.0</td>
<td>4.7</td>
</tr>
</tbody>
</table>

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Figure 2. Debris rock glaciers Galesu (Retezat Mountains) and their spatial relations with stadial moraines of Older Dryas (ODM) and Middle Dryas (MDM).

Figure 3. Talus rock glaciers in Papusii cirque (Retezat Mountains) and fossil debris rock glaciers Bărloa Ursului.
Figure 4. Orientation of rock glaciers (azimuth of median axis) in Retezat and Fagaras Mountains for: a - total area; b - northern slope; c - southern slope.
distribution gives an impression of the zone of discontinuous permafrost within these mountain areas. To clarify the time evolution of the limits of discontinuous permafrost, it is necessary to establish the major periods within which rock glaciers formed. We consider that during the Würm III - Younger Dryas period of deglaciation in the Southern Carpathians up to the Boreal period, climatic conditions favoured the development of rock glaciers. This is documented by palynological data (Ciobanu et al., 1967; Diaconeasa, 1968; Pop et al., 1971; Boscaiu and Lupsa, 1984). Taking into account the spatial relations with the moraines and the palynological data, we consider there to be two major periods of rock glacier development: Würm III - Older

Dryas for the forms located below 1600-1750 m, and Middle and Younger Dryas for the forms located over 1800 m. Most recently, during the Little Ice Age, rock glaciers located above 2050 m.a.s.l. were reactivated, as shown by dendrochronological and dendroecological data (Soran et al., 1981; Urdea, 1998).

During the Younger Dryas, the permafrost area, as represented by the rock glaciers, is estimated to have been 15 km² in Fgras Mountains and 6.1 km² in Retezat Mountains. These areas are 4.6% and 5%, respectively, of the highest parts of the two mountains areas. It is worth underlining the present differences between the north- and south-facing slopes (Table 1, Figures 4 and 5). The percentage of the total rock glacier areas found on the north-facing slope is 62% in Retezat Mountains and 59% in Fgras Mountains. These figures represent 10% and 3%, respectively, of the total surface alpine zone. Also notable is the altitudinal spread of the rock glaciers and therefore of discontinuous permafrost, indicating differences between the two researched mountain areas (Tables 2 and 3).

Assuming a mean thickness for rock glaciers of 20 m and a mean ice content of 40% (cf. Barsch, 1996), the volume of the permafrost and its ice volume was calculated (Table 4). Including the Parng Mountains, where rock glaciers occupy a surface of about 3.1 km², and other small rock glacier areas in Tarcu and Godeanu Mountains, the total permafrost area in the alpine belt of the Southern Carpathians is about 26-28 km², or 1.1% of the total alpine area.

The results of the reconstruction of the development of Quaternary glaciations in the Retezat Mountains (Urdea, 1993a), and the postglacial development of the same mountain area (Urdea, 1992a), have been used to sketch the evolution of the lower limits of the continuous, widespread and patchy discontinuous permafrost (Table 5). The lower limit of continuous per-

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Table 4. Estimated permafrost volume (PV) and ground ice (VPI) (40%) for Retezat and Fagaras Mountains at the Younger Dryas level

<table>
<thead>
<tr>
<th></th>
<th>Total area</th>
<th>Northern slope</th>
<th>Southern slope</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Retezat</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV (km²)</td>
<td>0.12</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>VPI (km³)</td>
<td>0.05</td>
<td>0.03</td>
<td>0.19</td>
</tr>
<tr>
<td><strong>Fagaras</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV (km²)</td>
<td>0.30</td>
<td>0.18</td>
<td>0.12</td>
</tr>
<tr>
<td>VPI (km³)</td>
<td>0.12</td>
<td>0.07</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 5. Evolution of lower limits of continuous, widespread and patchy discontinuous permafrost in the Southern Carpathians

<table>
<thead>
<tr>
<th>Lower limit</th>
<th>Würm III</th>
<th>Old Dryas</th>
<th>Medium Dryas</th>
<th>Younger Dryas</th>
<th>Boreal</th>
<th>Little Ice Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>1975</td>
<td>2030</td>
<td>2095</td>
<td>2130</td>
<td>2650</td>
<td>2650</td>
</tr>
<tr>
<td>Widespread</td>
<td>1825</td>
<td>1885</td>
<td>1925</td>
<td>1985</td>
<td>2770</td>
<td>2510</td>
</tr>
<tr>
<td>Patchy</td>
<td>1490</td>
<td>1675</td>
<td>1720</td>
<td>1780</td>
<td>2050</td>
<td>2265</td>
</tr>
</tbody>
</table>
mofrost is situated at the altitude of the -6°C isotherm of the MAAT, the limit between the widespread and patchy discontinuous permafrost at the level of -4.5°C isotherm, and the lower limit of the discontinuous permafrost at the elevation of the -1.5°C isotherm (King, 1983, 1986). The values obtained for the lower limit of discontinuous permafrost and the limit of perennial snowcover involve an average altitude difference of 431 m, a value close to the 460 m figure typical of the Bernina zone (Belloni et al., 1993).

Today the presence of segregation and cementation ice, BTS (the bottom temperature of winter snow cover; cf. Haeberli, 1973) results and the summer temperatures of springs situated at the front of rock glaciers and at the foot of talus cones, indicate the existence of patchy and sporadic permafrost in the Southern Carpathians above 2100-2200 m.a.s.l. (Urdea, 1993b, 1993c). This present distribution of permafrost is closely related to topographic and microclimatic conditions. Segregation and cementation ice have both been documented within debris rock glaciers and with talus rock glaciers (Urdea, 1993b). In the case of debris rock glaciers, it is likely relict permafrost, while within the talus rock glaciers situated in shady places, it is regarded as modern permafrost. We believe that the model of rock glacier evolution and permafrost reconstruction in the most representative parts of Southern Carpathians, the Retet and Fgras Mountains, may be applicable to the remainder of the Carpathians alpine belt.

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References


