DIFFERENTIATION OF PRESENT-DAY PERIGLACIAL RELIEF IN THE HIGH MOUNTAINS OF EUROPE[1]

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Key-words: high mountains, present-day periglacial processes, periglacial landforms, Europe.

La différenciation du relief périglaciare contemporain des hautes montagnes de l'Europe. L'objet de l'article est la présentation de la différenciation du relief périglaciaire contemporain des hautes montagnes de l'Europe, fondée sur l'analyse de la distribution et du développement des formes de relief périglaciaire en considérant les données quantitatives qui caractérisent le taux de processus. Les résultats de l'analyse indiquent les traits caractéristiques du relief périglaciaire de même que le type dominant des formes de relief périglaciaire pour chaque massif de haute montagne.

INTRODUCTION

Periglacial processes are one of the most significant geomorphological processes involved in the recent transformation of the high-mountain relief. Their activity is concentrated in the climatic periglacial zone. The upper timberline is generally accepted as lower limit of the mountain periglacial zone (e.g. Troll 1944, Höllerman 1967, Jahn 1975). In mid-latitude mountains, the periglacial zone comprises areas above the isotherm of –1°C – +5°C, as the altitude of this isotherm and the upper timberline are usually parallel. Snowline is considered the upper limit of this zone. Altitudinal extension and division of the periglacial zone varies much (from 500 to 1100 m) particularly in the high-mountain group, but no differences in its vertical extension between glaciated and unglaciated mountains.

The paper aims to examine regional differences in the present-day periglacial relief of high-mountains in Europe. The following high mountains, located in different climate conditions, were taken into consideration: the Scandinavian Mountains, the Cairngorms, the Tatras, the Southern Carpathians – Făgăraş and Retezat massifs, the Alps and the Pyrenees (Fig. 1).

Analysis of the distribution and development of contemporary periglacial landforms, assumed to be the result of present-day periglacial processes activity, together with the quantitative data characterising the occurence rate of these processes is a base for the evaluation of regional differentiation of the recent periglacial relief in the studied high-mountain areas. Effectiveness of periglacial processes in comparison with other geomorphic processes is also evaluated. Characteristic features of periglacial relief and of the spatial pattern of periglacial landforms, as well as the dominant type of periglacial landform are specifying for particular mountain groups. The analysis of periglacial relief is based on the results of the author's studies and findings of former approaches collected from relevant references. The weathering, the permafrost-related landforms, frost sorting processes and landforms, solifluction processes and landforms as well as nivation processes and forms are taken into consideration. The lack of distinction between active and non-active periglacial forms in many former studies made difficult this analysis. The assumption that development of present-day periglacial relief belongs to the local climate and substratum was accepted in this analysis. The climatic conditions and their variability in the periglacial zone of particular high-mountains are discussed (Rączkowska 2007).

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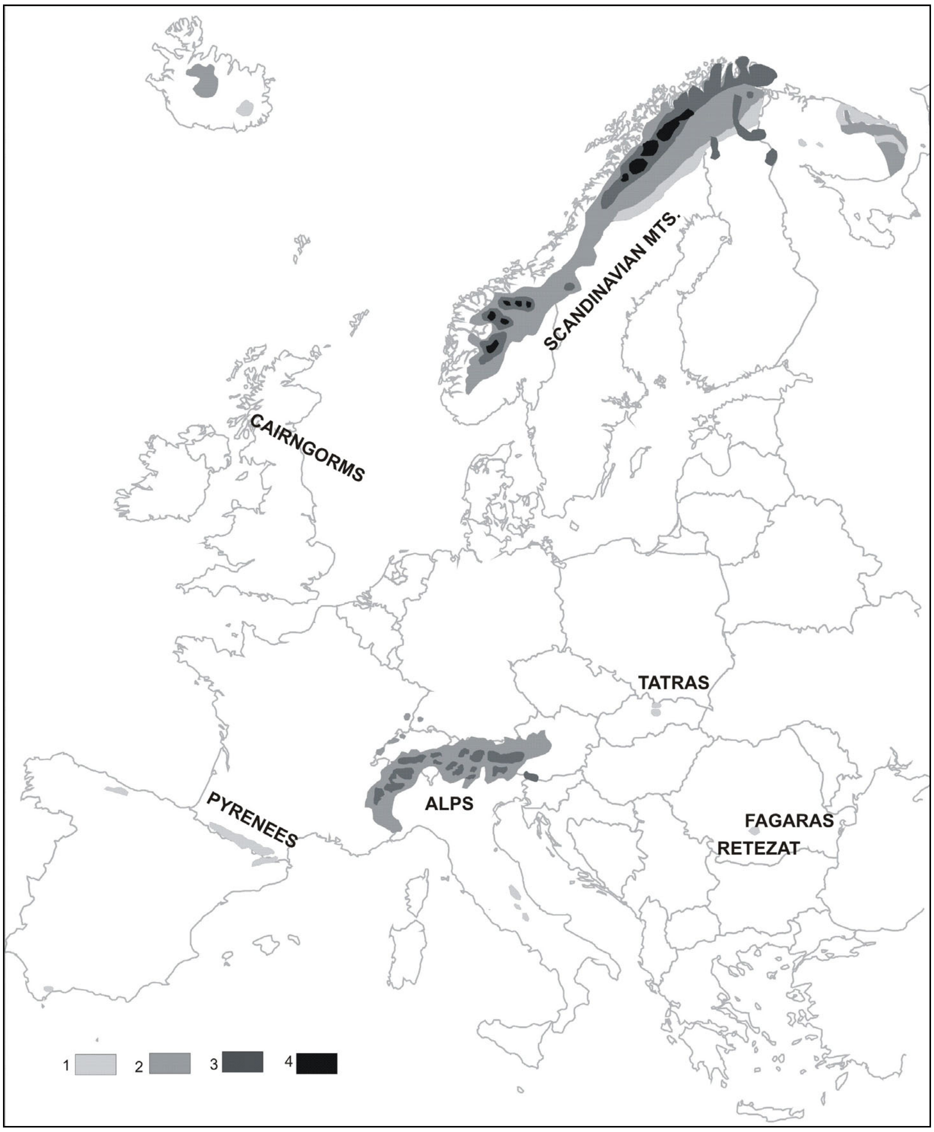

Fig. 1 – High-mountains of Europe against a background of mountain permafrost occurrence after J. Brown *et al.* (1997) (modified). *1,* Isolated patches of permafrost; *2,* sporadic permafrost (10–50%); *3,* discontinuous permafrost (50–90%); *4,* continuous permafrost (>90%). Location maps of particular high-mountain areas in Chapter 6.

The most important elements of the natural environment, which influence formation and differentiation of the present-day periglacial relief are the presence and distribution of permafrost, present-day glaciation in the mountains, the climate and its differentiation due to vertical and latitudinal zonality, as well as continentality and asymmetry. Table 1 presents some of these features in the mountains taken into consideration.

CHARACTERISTICS OF PERIGLACIAL PROCESSES AND LANDFORMS

Analysis results evidence that present-day modelling of high-mountains is regionally differentiated (Rączkowska 2007), both in the resulting periglacial forms and in the course and the effects of particular periglacial processes. However, no distinct differences were found in the intensity of particular periglacial process. For example, the rates of solifluction in the Alps and in the Scandinavian Mts. are similar, 2.9–3.1 and 2.9 cm/year, respectively (Gamper 1987; Rapp, Åkerman 1993), likewise the rates of frost creeping average 1.0–1.7 cm/year in the Alps (Coutard *et al.* 1996) and 0.1–1.6 cm/year (Rudberg 1964). The type of periglacial processes dominant in present-day relief development also differs in the high mountains of Europe studied.

Table 1

Elements of natural environment influencing periglacial relief development

Features	Tatras	Alps	Scandinavian Mts.	Pyrenees	Cairngorms	Southern Carpathians
Permafrost Lower limit m a.s.l.	sporadic 2000 (1930)	continuous 2400	continuous 1000	continuous 2700	no	probable 2000
Glaciers	no	yes	yes	yes	no	no
Type of relief	alpine	alpine	plateaux	alpine	plateaux	alpine

Differentiation of present-day periglacial landform is expressed by detailed geomorphological maps. The maps were made for fragments of each high-mountains discussed. For example, maps presented on Figures 2 and 3 display differences between the character of periglacial relief in the Italian Alps and the Scandinavian Mts. The types, morphometry, morphology and location of periglacial forms also reflect variation of periglacial relief. In Tables 2 and 3 are presented features of solifluction landforms in the Alps and in the Southern Carpathians, as a sample confirmation of such variation. Similar variation is stated within the other types of periglacial landforms.

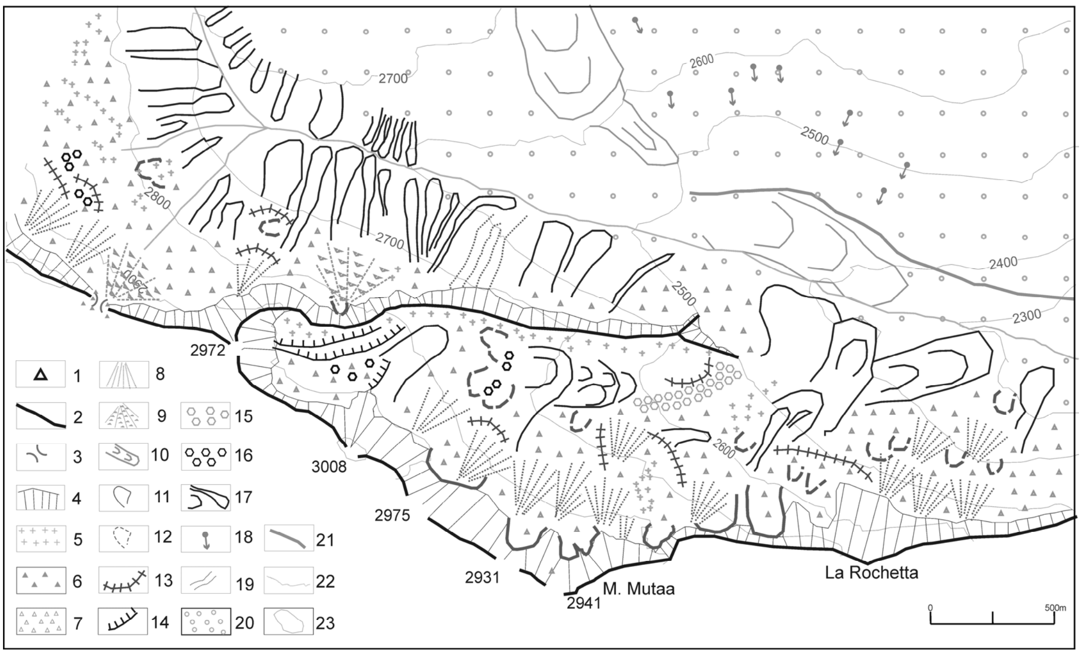

Fig. 2 – Geomorphological sketch of the upper part of the Madriccio Valley in the Ortles-Cevedale Massif (the Italian Alps). *1,* Summits; *2,* ridges; *3,* passes; *4,* rockwall; *5,* rocky slopes; *6,* slope cover with blocks produced by in situ weathering; *7,* talus slopes; *8,* talus cones; *9,* rockfall cones; *10,* relict rock glaciers; *11,* nival niches with rocky edges; *12,* nival niches cut in debris cover; *13,* active protalus ramparts; *14,* structural escarpment; *15,* non-active sorted polygons and circles; *16,* active sorted polygons and circles; *17,* solifluction lobes; *18,* ploughing bloulders; *19,* erosion gullies; *20,* valley bottom filled with moraine deposits; *21,* moraine ridge; *22,* streams; *23,* contour lines.

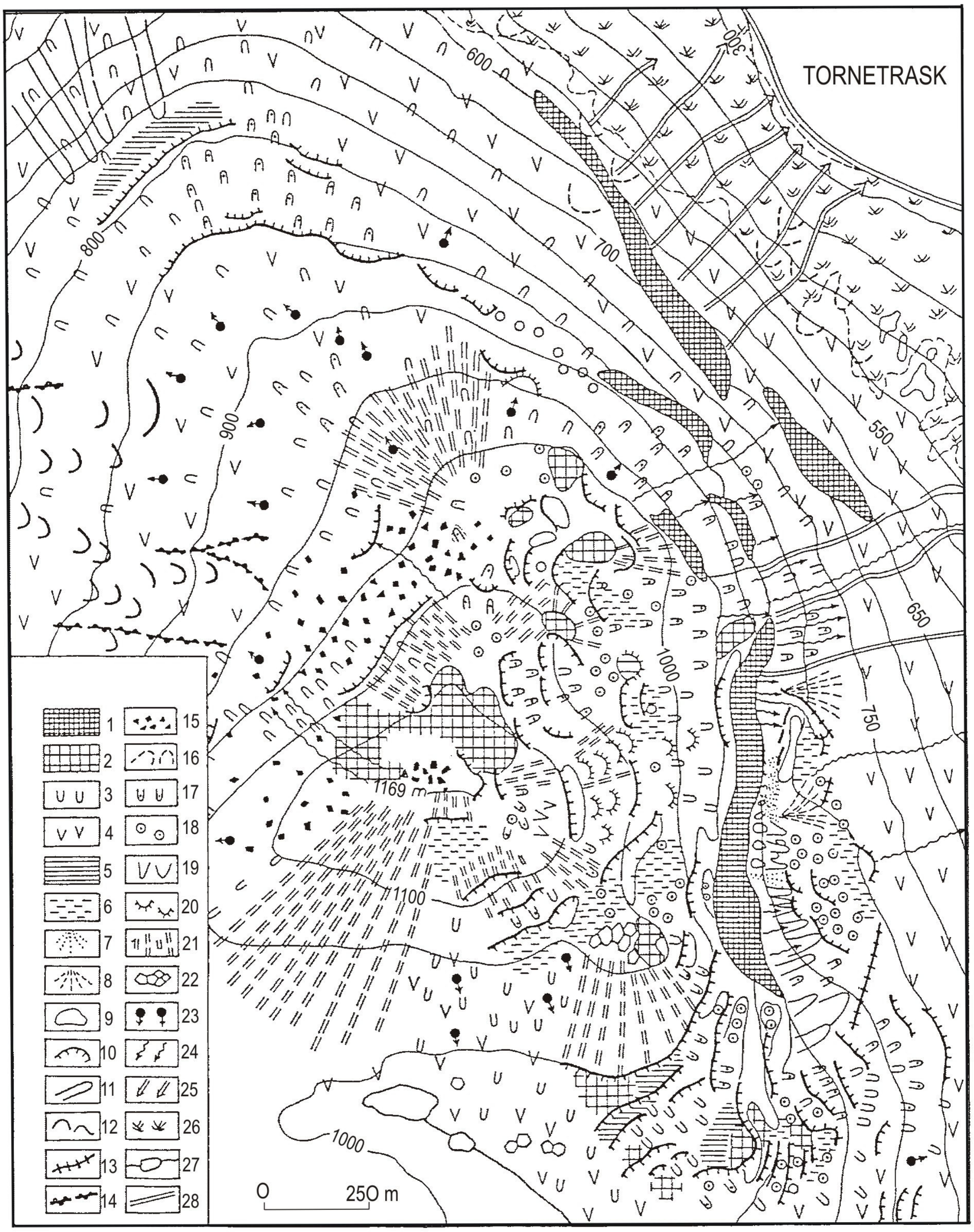

Fig. 3 – Geomorphological map of the Njulla Massif, the Abisko Mountains, Swedish Lappland (Rączkowska 1990). *1,* rockwalls and rocky slopes; *2,* rocky outcrops; *3,* debris-mantled slope remodelled by solifluction and soil creep; *4,* debris-mantled slope stabilized by vegetation; *5,* surface of planation; *6,* zone of highly saturated weathering cover (swampy area); *7,* snow patches; *8,* edges of transverse nivation hollows or cryoplanation terraces; *9,* depression without distinct edges; *10,* longitudinal nivation hollows; *11,* protalus ramparts; *12,* structural escarpments; *13,* gravitational talus cones; *14,* alluvial talus cone; *15,* blockfields; *16,* soil creep niches; *17,* solifluction due to meltwater; *18,* creep of highly saturated waste; *19,* solifluction tongue; *20,* solifluction terracettes; *21,* non-sorted strips; *22,* polygons; *23,* ploughing boulders; *24,* linear erosion; *25,* debris flows and avalanche gullies; *26,* birch forest; *27,* lake; *28,* road from Kiruna to Narvik.

Table 2

Characteristics of active solifluction forms in the Alps

Location	Length (m)	Width (m)	Height (m)	Morphology	Altitude (m a.s.l.) Gradient and aspect of slope	Lithology	Author
Col du Vallonnet, Chambeyron, Ubaye	15–22			turf-banked debris lob	2737–2727, NE, 14–27°	limestones, flysch	Coutard i in. (1988a)
Lac Premier, Chambeyron, Ubaye	60	10		debris lobe, small lobes on surface	2600–2640, SSW, 35–19°	limestones, flysch	Coutard i in. (1988a) Coutard i in. (1996)
Aoupets, Chambeyron, Ubaye	9.2	3–6		vegetated lob	2480–2506, NNW, 7–35°	limestones, flysch	Coutard i in. (1988a) Coutard i in. (1996)
Cirque Grande Ruine, Etançons valley, Massif Écrins	50–70	10–15	3–5	debris lobe, hollows on the surface	2450, W	granite,crystallinesc hists	Rączkowska (2007)
Lanserila, Massif Vanoise	few do 50		few dcm	asymmetric	2350–2800, NW	dolomites	Kaiser (1980)
Vallon de la Rocheure, Massif Vanoise	40–50	5–10		without vegetation, fresh debris on surface	2800, SE, 5–20°	without granite	Marnezy (1977a)
Vallon de la Rocheure, Massif Vanoise	5–10	40–50			2300–2800, NW, 5–20°	without granite	Marnezy (1977a)
Munt Chavagl, E Swiss Alps	50	10–15	0.6	lobes of bound and free solifluction	2400, 14°		Gamper (1987)
Upper Engadin valley, Swiss Alps	0.4–2.2	0.7–2.1	0.1–0.2	low lobes	2600–2820, 11°	limestones	Matsouka i in. (2005)
Upper Engadin valley, Swiss Alps	0.9–62.0	1.6–37.0	0.2–1.5	high stone-banked and turf-banked lobes	2300–2820	limestones	Matsouka i in. (2005)
Val Madriccio, Massif Ortles-Cevedale	150	10–12	1.0	debris lob, front 60 °	2640, N, 14°	crystalline schists	Rączkowska (2007)
Val di Pozzo, Massif Ortles-Cevedale	200		1–2	debris lob	2820, S, 15°	crystalline schists	Rączkowska (2007)
Massif Glockglokner, Austrian Alps	few		0.5	lobes of bound and free solifluction	2640–2680, N, NE, 30–10°	crystalline schists	Jaesche i in. (2003)
Kapall, Lechtaler Alps	few	0.3–0.7	0.05–0.2	garlands, turf-banked, debris surface	2300, E	limestones	Höllerman (1967)

Table 3

Characteristics of active solifluction forms in the Southern Carpathians

Location	Altitude (m a.s.l.)	Gradient and aspect of slope	Form	Author
Făgăraş, Paltinu Mt.	2300	W	terraccettes below nival niche, width 0.2–0.5 m, height of front 0.1–0.2 m	Rączkowska (2007)
Făgăraş, Paltinu Mt.	2300	15–20^o	solifluction lobe, 3 m wide, 3–4 m long, 0.7–1.0 m front height, fine material with few coarse debris	Rączkowska (2007)
Făgăraş, Lăiţel pass	2320	10–20^o	garland-terrace, width 2 m, height ~1m, flat and wet debris surface, turf-banked, slope of front 30–40^o,	Rączkowska (2007)
Făgăraş	2300–2100 2100–1900		terraces 0.5–1.5 m width	Nedelcu (1964), Florea (1998)
Retezat	>1600	1–3^o to 20–25^o	micro- and mezorelief – terraccettes below talus slopes	Urdea (2000)
Retezat, Zlata Valley, Ştirbu	2110	SW slopes 20^o	turf-banked terraccettes, debris on surface, width 0.5 m, front height 0.3–0.5 m	Rączkowska (2007)
Godeanu	2000–2500	SW slopes <15–20^o	irregular garlands, width 0,5–1,5 m, tens to hundreds of meters long; terracettes	Niculescu, Nedelcu (1961)
Muntele Mic	1600–1700	15–20^o	ploughing boulders, 4–8 m^3, gully 3–5 m long	Niculescu, Nedelcu (1961)

Yet, apart from the commonness of occurrence and diversity of periglacial landforms, a mosaic pattern is the main feature of their distribution inside the climatologically conditioned periglacial zone. It reflects the mosaic structure of the high-mountain environment. Therefore, periglacial features develops only in fragments of the mountain periglacial zone.

Table 4 presents the intensity of periglaciation of the high-mountains taken into consideration. Based on analysis results, active periglacial landforms are grouped according to their occurrence as follows: 1. lack of form; 2. form occurs rarely (or there are doubts of its occurrence or present-day activity); 3. form occurs, 4. form occurs in great number.

Table 4

Occurrence of active periglacial landforms in the high-mountains of Europe
(after Rączkowska 2007, modified)

Forms	Tatras	Scandinavian Mts.	Alps	Retezat	Făgăraş	Pyrenees	Cairngorms
Blockfields	–	±	+	–	–	±	–
Rock glaciers	–	+	++		–	+	–
Ice-cored moraine	–	+	±	–	–	–	–
Palsas	–	+	–	–	–	–	–
Non-sorted polygons	–	+	±	–	–	–	–
Sorted polygons	±	++	++	–	–	+	±
Sorted circles	±	++	++	±	±	+	±
Sorted strips	+	++	+	–	–	+	±
Miniature patterned grounds	+	+	+	+	+	+	+
Thufurs	+	+	+	+	+	+	+
Solifluction lobes	+	++	++	±	+	+	+
Solifluction sheets	–	+	–	–	–	–	+
Solifluction garlands	+	+	+	+	+	+	+
Terraccettes	++	+	++	+	++	+	+
Ploughing blocks	+	++	+	+	+	+	++
Gelideflation forms	±	+	+	–	–	±	++
Nival niches	+	++	+	+	+	+	+
Protalus ramparts	±	+	+	±	±	+	–

„–” – do not occur, „±” – occur rarely, „+” – occur, „++” – occur very often

THE ALPS

In the Alps, the periglacial zone (above 1500–2400 m a.s.l.) is significantly diversified due to the occurrence of continuous and discontinuous permafrost, glaciers and a variety of inherited landforms. The presence of glaciers generates additionally two spatial zones within the periglacial zone – unglaciated summits and ridges rising above glaciers, and the zone in front of glaciers and along their tongues. Frost processes, like weathering, frost sorting and frost creeping related to both annual and diurnal freeze-thaw cycles, as well as gelifluction and solifluction are widespread active. Data obtained from direct measurements evidence the activity of all periglacial processes. The course and intensity of periglacial processes result there in distinct and well-developed periglacial landforms. Periglacial landforms are widespread and rich in types and sizes. Landform types vary from rockglaciers – permafrost indicative landforms to miniature patterned-grounds and solifluction terracettes (Table 4). The number of active rockglaciers and the development of blockfields resulted from weathering *in situ* are conspicuous features of the area. The activity of periglacial processes effects the types of slopes undergoing modelling. Sorted strips and patterned grounds, as well as blockfieds *in situ* enlarged on broad fragments of slope develop on wide ridges and passes. Rockwalls and rocky slopes are modelled by rockfall and frost weathering. Solifluction lobes of different size develop on debris slopes beyond rockwalls and rocky slopes as is the case on slopes with debris covers.

Lobes of free or bound solifluction depend on altitudinal zone and slope aspect. Numerous nival niche and protalus ramparts occur both on the slope and in valley bottoms. At the contact between debris slopes and valley bottoms as well as within valley bottoms, rockglaciers exists in the permafrost zone (Photo 1). The patterned grounds of different types and sizes are often on flat fragments of slopes or within the valley bottoms.

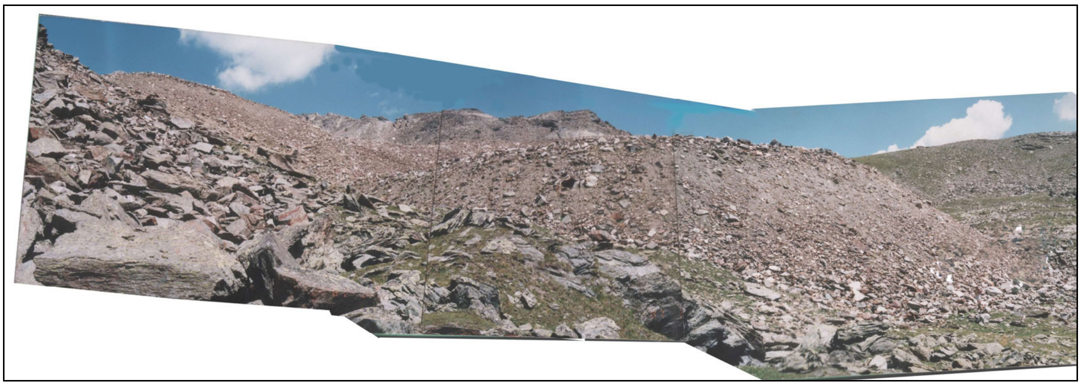

Photo 1 – Front of inactive rock glacier in the Livi Valley, altitude ~2800 m a.s.l. (the Ortles-Cevedale Massif, the Italian Alps).

Great spatial variability of periglacial relief, the occurrence of a number of active rock glaciers and the presence of proglacial zone are conspicuous features of the area.

THE SCANDINAVIAN MOUNTAINS

In the Scandinavian Mountains periglacial processes, especially solifluction, play the main role in the present-day modelling of their relief. The activity of periglacial processes is conditioned by the presence of glaciation and permafrost. Solifluction is widespread and a dominant geomorphic process, however, frost creeping, frost sorting and nivation also significantly participate in the present-day modelling of relief. Plastic creeping or the slow flowing of the surface layer of the weathering cover on frozen ground dominate the solifluction movement. It results in development of large, numerous solifluction lobes and sheets. Overlapping solifluction forms of different shape (lobes, sheets, and terracettes) and size very often covers the whole valley slopes (Photo 2). Patterned grounds are common landforms as well. Sorted polygons, circles and strips occur both on summit plateaux (fields) and within the valley bottom, however, palsas and tundra polygons, which are a feature that distinguishes the Scandinavian Mountains from the others mountains, develop mainly the valley bottom. Nowadays, weathering is less important than in the past when blockfields and rock glaciers were formed.

Photo 2 – The eastern slope of the Låkktavagge Valley, modelled by solifluction (the Abisko Mountains, northern Sweden). Fresh snowfall in mid-summer (August) is visible above 1100 m a.s.l.

All kinds of periglacial forms exist in the Scandinavian Mts. (Table 4). The spatial pattern of their occurrence resembles a mosaic reflecting local differentiation of the natural environment, however, patches of mosaic with periglacial landform are larger than in other high-mountains examined.

Periglacial modelling resulted mainly in the occurrence of large and numerous lobes and sheets of solifluction, as well as in patterned ground.

THE PYRENEES

The periglacial zone in the Pyrenees is also different due to the presence of glaciers and permafrost. The periglacial relief is developed but all periglacial forms are not so large and frequent as in the Alps (Table 4). In the Pyrenees periglacial forms are developing at present mainly in the uppermost part of the mountains. The effects of physical weathering (macro- and microgelivation) occurring within rockwalls and rocky slopes are characteristic features (Photo 3). Active periglacial landforms are concentrated above 2500 m a.s.l., where different forms, like rockglaciers, solifluction forms (lobes, garlands and terracettes), patterned grounds (sorted polygons and strips), nival niches and protalus ramparts develop. The landforms very often occur at the bottom of glacier cirques. However, glaciers are small, usually not extending over glacier cirques, and the paraglacial zone there is not like it is in the Alps.

Generally, forms of solifluction and nivation are often seen in the Pyrenees, yet active rock glaciers and patterned grounds rarely occur.

Photo 3 – The effects of weathering on ridge crest in Maladett Massif, Central Pyrenees.

THE CAIRNGORMS

The presence of well-developed and diverse relict periglacial landforms, like tors, blockfields, large sorted polygons and strips, solifluction lobes and others make periglacial relief to dominate the landscape of the Cairngorms Mts. Yet, active periglacial landforms are mainly related to solifluction and wind action (Table 4). The activity of solifluction forms lobes, sheets and terracettes. Nivation hollows occur often, while patterned grounds are rare and small. Active rockglaciers and protalus ramparts are not found. Wind activity results in the development of specific landforms like wind scars, garlands and terracettes. It also caused significant degradation of slope surface on summit plateaux and of periglacial landforms, especially those located on W, SW and NW slopes oriented towards the wind (Photo 4).

The Cairngorms area with maritime type of periglacial climate is conspicuous by a predominant wind activity, which lead, to the degradation of large fragments of summit plateau and solifluction forms as well.

Photo 4 – Solifluction lobes and terraces on SW slopes of the Cairngorms Summit (~1150 m a.s.l.). Vegetation cover on the surface of solifluction forms is degraded by wind activity, resulting in development of wind terracettes and garlands.

THE SOUTHERN CARPATHIANS

In the Southern Carpathians (Retezat, Făgăraş), frost-related processes, such as weathering, frost heaving and frost creeping are active in the periglacial zone i.e. above 1700–1900 m a.s.l., from autumn to spring. The effect of their activity is development of sparse sorted circles and miniature patterned grounds and weak transportation of slope covers. Solifluction is the most widespread process on slopes with weathering covers in the area. The type of landforms produced by this process depends on the local features of the natural environment. Distinct, well-developed solifluction forms – lobes and garlands occur on slope flattening in the uppermost parts of slopes or on wide ridges and passes (Photo 5), while in the lower parts small terracettes are more often seen. Active nival niches and partly active protalus ramparts occur relatively frequently. Avalanches play a significant role in relief modelling. Despite the suggested presence of isolated patches of permafrost, no landforms indicative of permafrost were found, e.g. active rockglaciers.

Photo 5 – Solifluction lobes and terraces at altitude of 2330 m a.s.l., on the Lăiţel Pass, in the Făgăraş Mts. (the Southern Carpathians).

THE TATRA MOUNTAINS

In the Tatras like in the Southern Carpathians (Făgăraş, Retezat) the activity of periglacial processes is limited in space and time, therefore active periglacial landforms are small and relatively sparse (Table 4). Moreover, many of them are not complete. Their development is related to seasonal or diurnal freeze-thaw cycles not to permafrost (Rączkowska 2007). However, sporadic permafrost was documented in the area (i.e. Mościcki, Kędzia 2001), any permafrost indicative landforms are not active. Periglacial landforms develop in the Tatras within the whole periglacial zone i.e. above 1500 m a.s.l., but the greatest variability of periglacial landforms occur between 1850 and 2050 m a.s.l. It is conditioned by topography, and especially by the location at the bottom of most glacial cirques. The altitudinal belt 1900–2000 m a.s.l. limits from below zone of active periglacial landforms formed mainly by frost-induced processes. These are sorted polygons (Photo 6), sorted circles, lobes of free solifluction and lobes of bound solifluction. Periglacial landforms, developing due to the activity of different geomorphological processes, occur in the lowermost belt limited by the upper timberline. Frost, as geomorphic agent, significantly influences their development, yet the other geomorphic factors (e.g. water, gravitation) also play an important role in their formation. For example nival niches, solifluction terracettes, thufurs and ploughing boulder gullies belong to this group.

Photo 6 – Active sorted polygons, Hińczowe Oko Lake, in the Mięguszowiecka Valley (altitude 1950 m a.s.l.). Colour lines painted on the polygon surface were used to monitor changes in a polygon surface.

DISCUSSION AND CONCLUSION

Types of periglacial processes dominating the present-day relief development, as well as suites of periglacial forms differ in the studied high mountains of Europe.

Generally two types of present day periglacial relief could be singled out: present-day periglacial relief *sensu stricto* and *sensu lato*. The first could be attribute to mountains where continuous and discontinuous permafrost is present. In these mountains almost all types of periglacial landforms develop at present and their development could be characterised using quantitative data. The periglacial relief *sensu lato* is present in mountains where permafrost does not exist, or only isolated patches could be found. In this areas, the activity of periglacial processes does not always result in the development of distinct periglacial forms. Only some periglacial landforms occur. The first type of present-day periglacial relief is found in the Alps and the Scandinavian Mountains, and partly in the Pyrenees. The periglacial relief *sensu lato* could be found in the majority of the high-mountains of Europe.

The periglacial landform of the discussed areas, regardless of the specificity of each of them, is similar to other high-mountains areas in Europe i.e. the Alps, the Caucasus, the Scandinavian Mountains – the Ural, the Cairngorms – the Monte Dors. Taking into consideration the number and diversity of active periglacial landforms, similarities between the Alps and the Scandinavian Mts., as well as partly the Pyrenees, are found. The occurrence of permafrost, continuous and discontinuous not only sporadically, is the common feature of these high-mountains. Then, there is the severity of climate, regardless the climate zone, the most significant factor conditioning periglacial relief development. The influence of climate zonality is manifest in the abasement of the lower limit of periglacial landform occurrence, conversely to the increase of latitude.

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