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LANDFORM EVOLUTION IN MOUNTAIN AREAS

ZOFIA RĄCZKOWSKA (KRAKÓW)

PERIGLACIAL LANDFORMS OF NORTHERN SWEDEN MT. WITH THE TARFALA VALLEY AS EXAMPLE

Abstract. Characterization of relief of upper Tarfala valley (Kebnekaise massif — 68°N) is presented based on geomorphological mapping in scale 1 : 10,000. Special attention was paid to periglacial landforms. Environmental features important for periglacial processes and forms development are discussed. Regularities of distribution and altitudinal zonation of periglacial landforms in the Tarfala valley and in the whole mountains of northern Sweden are presented. Distribution of periglacial landforms strongly depends on permafrost presence. Patterned grounds and solifluction forms are indicative elements of periglacial landforms of the northern Sweden mountains. Role of periglacial processes in recent modelling of the relief is rather small.

Key words: northern Sweden mountains, periglacial landforms and processes, altitudinal zonation

INTRODUCTION

A variety of small-scale periglacial features occur above the tree-line in the Scandinavian mountains (Lundquist 1962). Their distribution is related to regional climatic factors, mainly mean temperatures, number and intensity of freeze-thaw cycles, and site-specific factors such as microclimate, relief, regolith, vegetation and drainage (Harris 1982). Snow cover depth, duration as well as orientation towards a dominating wind direction are also important. An extensive influence of climate is indicated by a fall in altitude of the lower limits of many periglacial features from south to north in the Scandinavian Caledonides (Lundquist 1962; Rudberg 1977). Altitudinal zonation of periglacial phenomena, i.e. form and processes, is a characteristic feature (Karte and Liedtke 1981; Harris 1982; Niessen et al. 1992).

In this paper the activity of periglacial processes and their role in landforms evolution is discussed based on the Tarfala valley as example. The Tarfala valley floor lies at 1,130 m a.s.l., at the base of Kebnekaise (67°55′ N) — the highest peak of Sweden (Fig. 1).

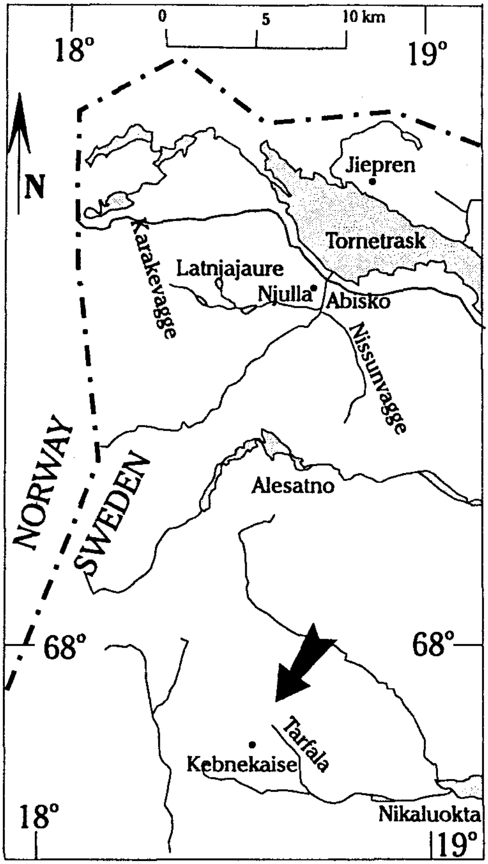

Fig. 1. Location of examined area

Kebnekaise region belongs to Caledonian system. The Tarfala valley is located within the Seve belt, where the bedrock is generally identified as amphibolites. The Kebnekaise massif is built of dolorites dyke complexes and underlying units consisting of gnesis and schists (Kulling 1964; Andersson and Gee 1989). Geology controls the relief. Eastern slopes are steep, western are gentler.

Detailed field mapping was done twice during two weeks stay in Tarfala Scientific Station in the first half of 1990s. Based on it a geomorphologic map in scale 1 : 10,000 was drawn. Field mapping was supplemented by site descriptions, including altitude, aspect, gradient and size of landforms. Periglacial landforms were also described and mapped in the surroundings of Abisko, about 100 km to the north (Fig. 1). The analysis of the published research results was a source of complimentary data about periglacial landforms in northern Sweden mountains.

The aim of this paper is to show regularities in the distribution and altitudinal zonation of periglacial landforms and the role of periglacial processes in present-day functioning of slope and valley systems in mountains of northern Sweden.

ENVIRONMENTAL CONTROLS OF PERIGLACIAL LANDFORMS DEVELOPMENT

There are some features of natural environment, specific of northern Sweden mountains, which strongly influence periglacial landforms evolution in this area. The first group comprises geomorphologic-geological features. Among these features the following influence a course and intensity of present-day periglacial modelling; 1. Presence of extensive summit surfaces — fjells — approximately above 1,200 m a.s.l., with gentle relief and higher summits, like Kebnekaise, rising above it. Deep glacial troughs with relatively wide flat floors, steep rockwalls and rocky slopes dissect the fjells. 2. Presence of rather thin mantle (0.5 to few meters depth) of loose material (mountain-top detritus or glacial drift deposits) or very often exposed solid bedrock. 3. Morphology of steep rock slopes and rocky steps is very similar to those in young mountain of alpine system where gravitational processes and debris flow activity are common.

Climatic conditions are also important for activity of periglacial processes. Climatic characteristics of mountains of northern Sweden are summarised in Table 1. A characteristic feature of the northern Sweden mountains is precipitation mainly in a form of snow. The rates are rather high. Wind plays an important role in snow distribution. Snow accumulates mainly on east-facing slopes. MAAT ranges from

Table 1

Climatic characteristic of northern Sweden mountains

Name of station		Oksti-dan	Kkatter -jakk	Lakkat -jakka	Abisko	Paptet-jakka	Tarfala	Nikko-luokta	Kiruna
Altitude m a.s.l.		1,800	508	1,228	388	1,834	1,130	470	470
Mean air temperature °C	Year	-4.0	-1.5	< -5.0	-0.9	-8.1	-3.9	-2.0	-1.5
	January	-9.6			-10.5	-14.4	-12.0	-14.3	-12.7
	July	10.6			12.3	5.4	7.1	13.1	12.8
Number of months with mean month temperature > 0°C			6		6	2	4	5	5
Precipitation mm (% falling as snow)			940 (51%)	1,750 (80%)	322 (40%)	—	1,000	456	505

After B. Eriksson (1982); L. King (1986)

–1.5°C to –8.1°C. The warmest month is July, the coldest January. The mean monthly temperature is more then 0°C for four month (July-September). There are only two seasons: summer with 24-hours daylight and winter with 24 hours nights.

In periglacial modelling of the area it is very important that there is much more freeze-thaw cycle in comparison with mountains of middle geographical latitudes (Rapp and Rudberg 1960). Daily amplitudes of air temperature are small, 1–2°C, while the annual amplitude of air temperature in Tarfala valley is about 24°C. Daily freeze-thaw cycles are less intensive and rarer on fjells than in valley bottoms.

Nowadays, glaciers are mainly found in the central part of northern Sweden mountains. The Tarfala valley is one of those glaciated valleys and is located at a maritime and continental climatic boundary. Precipitation measured here is relatively high, 1,000 mm in the valley (mean for period 1965–1985) and 3,000 mm in accumulation part of glaciers. Therefore glacial cirques occur at low positions (Holmlund 1991).

L. King (1986) presented the scheme of altitudinal zonation of high-mountain permafrost, based on the data form Kebnekaise massif. According to this scheme, continuous permafrost exists above 1,600 m a.s.l. Between 1,600 and 750 m a.s.l. discontinuous permafrost appears. Below, only sporadic permafrost occurs in small patches. Geomorphic evidences of permafrost are palsa and tundra polygons (Rapp 1983). Most often they are found in the valley bottoms and/or in the foreland of the mountains in places where the snow cover is wind-thinned. Palsa develop in the areas with MAAT –1°C, located even lower then 600 m a.s.l.

CHARACTERISTIC OF RELIEF OF THE TARFALA VALLEY

Main geomorphologic features of the Tarfala valley are presented in Figure 2. The asymmetry in relief is visible. On western slopes of the valley glaciers exists. Above them, steep, almost vertical rocky walls and slopes of Kebnekaise rise up to 2,100 m a.s.l. Summit of Kebnekaise rises also above the fjells plateau level, which is best developed at altitude about 1,800 m a.s.l. and then descends toward the mountains outer limits to about 1,000 m a.s.l. Eastern slopes of the valley are gentler. Only small fragments of this slopes are occupied by rockwalls. Most often they are mantled by detritus or till. The south-facing slopes are much more dissected by gullies and rocky niches with talus cones developed below. North oriented slopes are rocky slopes deeply dissected by chutes.

Recent development of the Tarfala valley relief results from glacial and periglacial processes activity. The last one should be rather called cryogenic or cold climate processes as was suggested by H. French (2000).

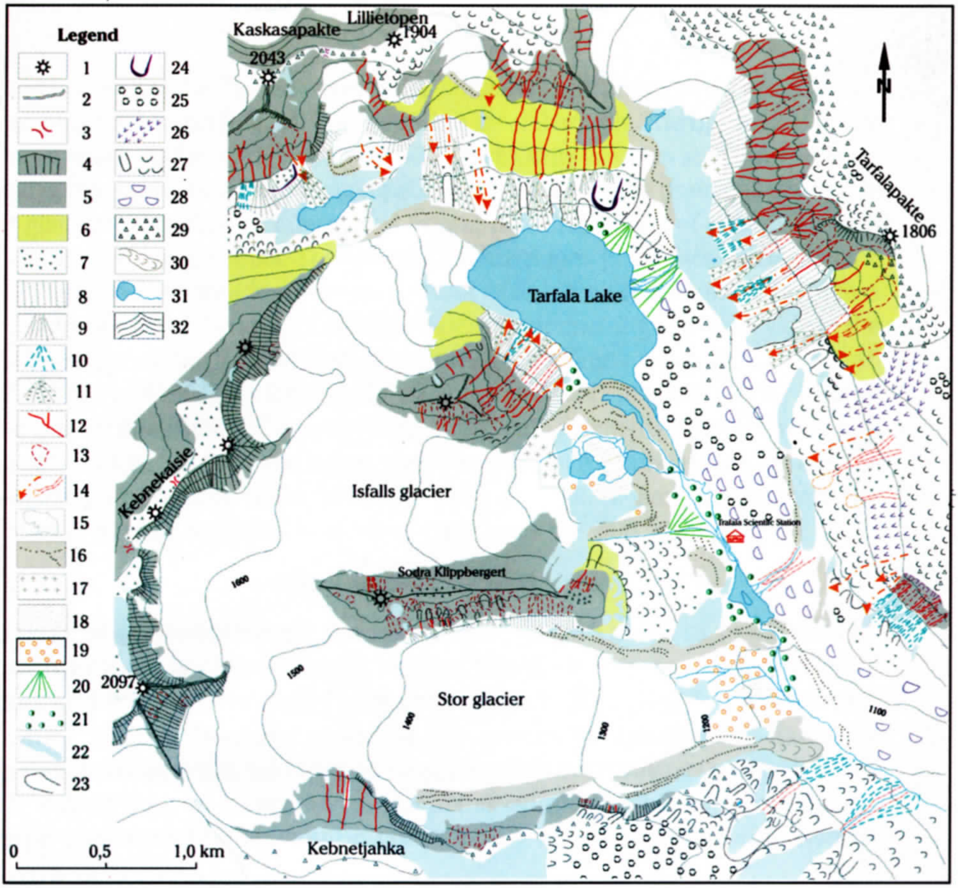

Fig. 2. Geomorphological map of the Tarfala valley. 1 — summits, 2 — ridges, 3 — passes, 4 — rock-walls, 5 — rocky slopes, 6 — debris mantled slopes, 7 — rockfall/rockslides deposition, 8 — talus slopes, 9 — talus cones, 10 — alluvial cones, 11 — avalanche cones, 12 — chutes, 13 — denudation niches on rocky, 14 — debris flows, 15 — glaciers, 16 — moraine deposits and moraine ridges, 17 — roche moutonné, 18 — fluted moraine, 19 — glacial deposits, 20 — fluvioglacial cones, 21 — alluvial/fluvioglacial plain, 22 — permanent snow patches, 23 — nivation niches, 24 — protalus ramparts, 25 — sorted and non-sorted circles and polygons, 26 — sorted and non-sorted strips, 27 — solifluction lobes and terraccettes, 28 — thurf-banked solifluction lobes and sheets, 29 — block fields, 30 — rockglaciers, 31 — lakes and streams, 32 — contour intervals 100 m

GLACIAL RELIEF

Main features of the Tarfala valley relief, similarly to all northern Sweden mountains, are of glacial origin (Fig. 2). The valley is a glacial trough. The upper part of this valley has a relatively flat, wide floor at 1,100 m a.s.l. On its western side three cirques filled with glaciers exists. All are hanging about 100 m above the main valley floor. In front of glaciers, a system of lateral and frontal moraine ridges of different age is formed. Most of them are relict. The lateral moraine ridges of the Stor glacier, which consist of very mobile boulders, almost without of fine material, seem to be active. Surface morphology of the lower end of the lateral moraine ridges at right side of the Stor glacier suggests that it could have been transformed into rockglacier, as according to G. Ostrem (1964) it is ice-cored moraine. In front of the Isfalls glacier a fluted moraine built of fine material, mainly silt and clay, with single big boulder is formed. Its surface is almost flat, 0–6° and is very wet. The nearest moraine ridges are of similar grain-size composition, while the upper ones are built of giant boulder without fine material. Similar regularities are observed near the Stor glacier.

PERIGLACIAL LANDFORMS

Activity of geomorphologic processes in mountain areas of periglacial alpine environments is characterized by frost related processes. Sub-zero temperatures and freeze-thaw cycles play an important role in the denudation process, either directly because many of the processes concerned, like frost weathering, frost heaving, talus creep or gelifluction can only occur due to such climatic conditions, or indirectly through the climate influence on relevant landscape attributes like vegetation cover, soil properties and ground hydrology (Jonasson 1991).

Periglacial forms representing almost all non-glacial phenomena that function in cold-climate (Washburn 1973) could be found in the Tarfala valley.

On the summit surfaces, fjells — block fields are developed what is a common phenomenon in northern Sweden mountains. They dominate on Tarfalapakte, Lilientopen or Kaskasapakte tops in the study area, but often also patches of block fields are found, in lower positions. Although block fields are common periglacial features not only in northern Sweden mountains, their origin is still discussed. There are two different groups of opinions: 1. Block fields were formed during and just after glacial period (Svenonius 1909; Lundquist 1962; Dahl 1966). 2. They originate from pre-glacial period (Peulvast 1989; Rapp 1992). Both suggest that these forms are relict now. However, results of macrogelivation i.e. fresh broken boulders 0.5 to >1 m in diameter are observed in the study area very often. According to R. Nyberg (1993), recent weathering and shattering are connected with annual freeze-thaw cycles, especially with spring thawing. It is confirmed by maximum amount of falling materials measured in spring (Rapp and Nyberg 1988). L. Strömquist (1973) has proved that frost might penetrate to 0.5 m into ground on fjells.

Table 2

Well-documented sites of patterned grounds occurrence in mountains of northern Sweden

Location	Altitude m a.s.l.	Climatic features	Geomorphology and geology	Process	Type of pattern ground	Autor
Abisko (68°N)	340–440	MAAT –0.9 °C	valley bottom, wind-thined snow	active frost heaving	non-sorted circle and stone pits	M. Josefsson (1988)
Latnjajaure (68°N)	1,000–1,300	MAAT 1.7 to –5.1°C, annual total of precipitation 320 –1750 mm, 70% as snow	flat plateaus or valley bottoms, in front of snow patches, garnet micaschists	frost heaving and sorting	polygons 2.0 m × 2.63 m sorted circles 1.15 m × 1.69 m	J. Kling (1996)
Kuotekjakka (East of Sarek Mt.) (67°N)	1,000–1,300	MAAT–1.6 to –5.1°C, annual total of precipitation 440–547 mm, 70% as snow	flat plateau with blockfields or valley bottoms, in front of snow patches, granite	frost heaving and sorting	polygons 3.0 m × 4.41 m sorted circles 0.98 m × 2.54 m	J. Kling (1996)
Northern Finland (70°N)	600–650 above timberline	MAAT 0.0–2.0°C annual total of precipitation < 450 mm, < 50% as snow	SE slopes with permafrost, slope inclination 7–25°	frost sorting	sorted streams	J. Piirola (1969)

Patterned grounds are most widespread and most diverse groups of periglacial forms. They are developed on flattenings, which are wet enough, and are covered with a layer of loose material. According to textural curves presented by Ch. Harris (1982), Scandinavian till consists mainly of a frost susceptible clay and silt matrix (up to 70%) containing variable amounts of larger clasts. Patterned grounds occur in valley bottoms and in fjells as well. In the Tarfala valley they are found in the valley floor, on summit of Kebnetjakka and on the pass south of Tarfalapakte. Forms located on mountain passes or ridges are not vegetated and are smaller than those in the valley bottom. Their sizes are usually about 1 m in diameters, but range from a few decimetres up to approximately 3 m. Bare-soil on their surface suggests that they are active. Most often they are sorted and non-sorted circle and polygons. In Abisko mountains similar forms were found in rocky hollows between two roches-moutonnľes on Jiepren summit. Very often such forms exists in front of large snow-patches, as it was observed on Njulla Mt. (Rączkowska 1991). Patterned grounds observed in the valley floors are larger, 1.5–3.0 m in diameter. Most of them are non-sorted polygons. Their surfaces are flat and are covered with mosses and grasses. Vegetation and lichens found on these forms indicate that they were developed under different climatic conditions than present ones (Nyberg and Lindh 1990). Only the polygons near the outflow from Tarfala lake have bare-soil on their surfaces. The largest, relict polygons, with flat surface covered with vegetation, are found on a higher level of the valley floor. They are similar to the tundra polygons described by A. Rapp (1986) or M. Jossefson (1988). Table 2 presents the sites where patterned grounds are found. The most complete description of the sorted circles and polygons in northern Sweden mountains and the mechanism of their recent formation is presented by J. Kling (1996). According to his studies, the upper 15 cm of soil in these forms is moving in all directions 0 to 50 cm/year. The particles are uplifted and lowered by frost heaving (with intensity 7 cm/year) and sorted (Table 3).

When slope gradients increase to 2°, the patterned ground change to elongated forms, and then strips or steps develop, as it is the case on the western side of the Tarfala valley, near the scientific station. These forms are usually up to 1.5 m wide (perpendicular to the slope) and up to few decimetres high. Most of them are sorted strips, with bare-soil on their surfaces. On the same fragments of the slope, non-sorted steps occur at altitude 1,300–1,400 m a.s.l., which is a lower limit of discontinuous permafrost (King 1986). Steps surface is inclined 20° and bare-soil is on it. The inclined non-sorted steps are, according to A. Rapp (1986), indicative of permafrost. The non-sorted strips, which are common forms in northern Sweden mountains, have not been mapped in the study area, but they are found in many others places, as in the Njulla massif for example (Rączkowska 1991). Such forms are usually banked by vegetation. Forms of sorted and non-sorted strips are developed on the convex part of the slope, on those fragments where snow is removed by wind, even in winter. They occur on the slopes with inclination up to 25°. Frost heaving and creeping

Table 3

Rates of present-day intensity of selected periglacial processes

Process and Form	Rates	Location	Author
Frost heaving Sorted circles	7 cm/year	Latnjajaure	J. Kling (1997)
Solifluction Solifluction lobe	1.3–6.2 cm/year	Kärkevegge	A. Rapp, L. Strömquist (1979)
Solifluction Solifluction slopes	0.8–2.4 cm/year	Kärkevegge	A. Rapp, L. Strömquist (1979)
Solifluction Solifluction sheets	up to 7.5 cm/year	Tarfala valley	A. Jahn (1991)
Frost creeping Gelifluction lobes	0–2,5 cm/year	Tarfala valley	A. Jahn (1991)
Frost creeping Debris strips	0.2–1.6 cm/year	Mt. Dalaive, Tarna Mt. Låkktajåkka	S. Rudberg (1962)
Talus creeping Talus slopes	1–4 cm/year	Kärkevegge	A. Rapp (1960)

are the main processes responsible for their development. Creeping rates are 0.2–1.6 cm/year (Tab. 3).

Solifluction is the most widespread process resulting in variable geomorphologic forms such as lobes, terracettes or sheets differentiating in size significantly. The forms mentioned above are observed in a different part of the valley. On the valley slopes occurs stone banked lobes or sheets, with bare-soil on their surface. Ice has been observed in crevasses between stones. The solifluction forms in the valley bottom are larger and covered with vegetation. Intensity of solifluction processes is diversified as it is presented in Table 3. Development of solifluction forms is very often stimulated by meltwater. In front of melting snow patches usually solifluction lobes are developed. Recently active solifluction is observed in a tundra zone, i.e. above 600 m a.s.l. (Rapp and Rudberg 1960; Melander 1977). According to M. Josefsson (1988) solifluction and cryoturbation are active even in a subalpine heath zone, at 340–440 m a.s.l. Distribution of solifluction forms in the Tarfala valley is typical, because the solifluction activity in mountains of northern Sweden concentrates in the lower parts of the slopes where zone of superimposed solifluction forms, especially lobes or sheets occurs. Such zones are wider on the slopes of eastern aspect. In the Tarfala valley this zone is split by forelands of glaciers with glacial landforms.

Nivation niches and ridges occur in the valley as well. On northern rocky slopes of Södra Klipperberget the nivation niches are developed just below the ridge. Their upper part is on rocky slopes with inclination of 40° to 60°. The presence of snow patches inside the niches indicates that nivation is responsible for

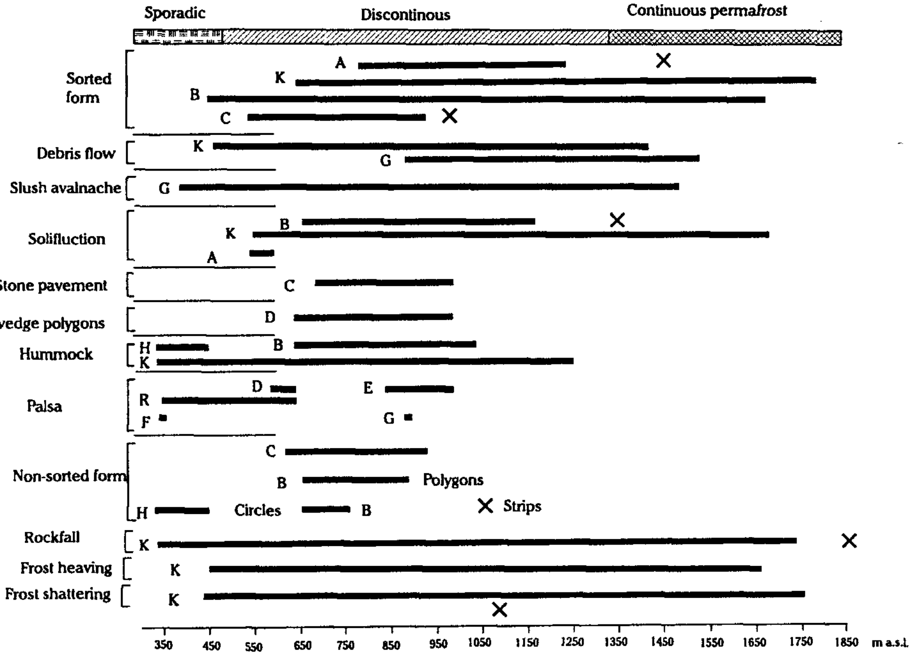

Fig. 3. Altitudinal zonation of periglacial landforms in northen Scandinavian mountains (after Niessen et al. 1992, modified). Permafrost limits after L. King (1986). The letters refers to the following studies: A — S. Rudberg (1962, 1972), B — Ch. Harris (182), C — G. Söderman (1980), D — A. Rapp (1983), E — J. Åkerman and Malmström (1986), F — T. Rosswall et al. (1975), G — R. Nyberg (1985), H — Josefsson (1988), K — A. Niessen et al. (1992), X — Tarfala valley (by author)

their development. The material eroded from the niches accumulates on the talus cones below. Those cones are remodelled by solifluction as evidenced by stone banked lobes developed at their bases. Large longitudinal nivation hollows are developed on the western slope of the Tarfala valley down of Stor glacier and many smaller forms not marked on the maps have been found in many places. The transverse nivation niches, which are common in northern Sweden mountains, are not found in the valley. Most often they develop on the fjells, some of them along the cryoplanation terraces edges (Rączkowska 1991). Location on the east-facing slopes is a distinctive feature of the nivation niches, especially those larger ones, being a few hundred meters in size. Their location is conditioned by snow accumulation on leeward sides of mountain ridges or summits.

OTHERS LANDFORMS

Other landforms develop here due to processes being more characteristic of mountains of alpine type than of subarctic zone. Although those processes are regular element of morphogenetic system of study area.

Rockwalls and rocky slopes are dissected by relatively dense net of chutes and gullies, modelled by erosion of water and of avalanche. Large, well developed avalanche cones formed on both banks of Tarfala lake are evidences of a great importance of avalanche activity in recent relief evolution (R a p p 1986).

Talus cones and slopes develop below rockwalls especially in the upper parts of glacial cirques in the uppermost part of the Tarfala valley. They are dissected by gullies of debris/mud flows. The latter are also significant in the present-day modelling of the Tarfala valley and the whole area of northern Sweden mountains (N y b e r g 1985). In some areas, activity of non-periglacial processes is more important in present day relief modelling than periglacial one.

ZONATION OF PERIGLACIAL LANDFORMS

On the slopes of the Tarfala valley some geomorphologic zones could be distinguished. Their pattern is very typical of all northern Sweden mountains.

The zones are as follows (from the summit area downward):

A. Summits surfaces –fjells where following processes are active nowadays: weathering, frost sorting and creeping, solifluction, nivation, but their intensity depends strongly on environmental conditions and permafrost presence. Periglacial landforms such as blockfields, sorted and non-sorted polygons and circles, sorted and non-sorted strips, solifluction lobes and terracettes, nivation niches evidence them.

B. Slopes of glacial troughs with steep rockwalls and rocky slopes dissected by chutes or gullies in upper part and with taluses or debris slopes below modelled by gravitational processes. The lower parts of debris/talus slopes are modelled by solifluction. Both parts of zone B are interrelated by avalanche and debris flow activity, which can transport loose material from zone A to valley bottoms. The proportions between the lower and upper pars of zone B (i.e. their extents) can differ significantly. Sometimes, from the valley bottom to the summits maturated, smoothed slope occur where only effects of solifluction, frost action and nivation activity are visible.

C. Valley bottom where glacial drift deposits are remodelled by periglacial processes, and patterned ground or solifluction lobes or sheets occur.

The altitudinal extent of periglacial processes in the Tarfala valley is presented in Figure 3 on the background of the data from other parts of northern Scandinavian mountains compiled by N i e s s e n et al. (1992). The majority of geomorphologic processes and forms occurs in altitude 600–1,100 m a.s.l. Some periglacial processes, like frost shattering, frost heave and sorting, and solifluction, act in all range of altitudes taken into consideration, while others, palsa for example, are limited to lowermost altitude.

CONCLUSIONS

1. Distribution of periglacial landforms in the Tarfala valley seems to be much more connected with permafrost extent then with the presence of glaciers. Therefore, the processes responsible for their formation should be called cold climate process not periglacial.
2. Climatic conditions favour periglacial processes, but their role in recent relief evolution is rather small. These processes result in small scale landforms, and only contribute to refreshing of main features of the relief, which are of glacial onset.
3. Distribution of periglacial landforms strongly depends on environmental features, which are additionally controlled and differentiated with altitude, slope aspect and main morphological elements.
4. Patterned grounds and solifluction forms seem to be indicative elements of periglacial landforms of northern Sweden mountains.

Department of Geomorphology
and Hydrology of Mountains and Uplands
Polish Academy of Sciences
ul. św. Jana 22,
31-018 Kraków, Poland
e-mail: raczk@zg.pan.krakow.pl

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STRESZCZENIE

Z. Rączkowska

RZEŹBA PERYGLACJALNA GÓR PÓŁNOCNEJ SZWECJI NA PRZYKŁADZIE DOLINY TARFALA

W pracy przedstawiono charakterystykę rzeźby górnej części doliny Tarfali, położonej w masywie Kebnekaise (68°N). Podstawą analizy rzeźby było kartowanie i wykonana na jego podstawie mapa geomorfologiczna w skali 1 : 10 000. Szczególną uwagę zwrócono na formy i procesy peryglacjalne. Przedstawiono środowiskowe uwarunkowania rozwoju rzeźby peryglacjalnej w górach strefy subarktycznej. Prawidłowości rozmieszczenia i wykształcenia oraz piętrowego zróżnicowania rzeźby peryglacjalnej w dolinie Tarfala przedstawiono w powiązaniu z ich charakterystyką dla gór północnej Szwecji. Stwierdzono, że rozmieszczenie form peryglacjalnych jest związane z obecnością permafrostu. Grunty strukturalne oraz formy soliflukcyjne należą do najpowszechniej występujących form peryglacjalnych. Udział procesów peryglacjalnych we współczesnym przekształcaniu rzeźby jest dominujący, ale ich efekty ograniczone są do przemodelowywania rzeźby glacjalnej.