ACTA UNIVERSITATIS CAROLINAE
2004 GEOGRAPHICA, No. 1, PAG. 59-72

Late pleistocene evolution of periglacial and glacial relief in the Karkonosze Mountains.
New hypotheses and research perspectives

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Abstract

The occurrence of perigiacial landforms in the most elevated part of the Karkonosze has been recognized within glacial cirques and on slopes of residual hills. Some of these landforms have not been previously documented. The inventory of perigiacial landforms includes protalus ramparts, rock glaciers, nivation hollows, cryoplanation terraces and solifluction lobes. Their position in relation to other landscape facets, and to cirques and moraine ridges in particular, allows one to identify phases of geomorphic development at the turn of the Pleistocene and to correlate these tentatively with stratigraphic units of the late Pleistocene. The presented hypothesis of landscape evolution calls for detailed geomorphological research, in which quantitative techniques, GIS-based modelling and dating would be widely implemented.

Key words: landscape evolution, perigiacial, Late Pleistocene, Karkonosze

1. Introduction

Geomorphology of the Karkonosze Mountains has been the subject of research since the mid-19th century. Initially, glacial relief inheritance was in focus and the first synthesis of glacial landforms appeared as early as in 1894 (Partsch, 1894). More recent studies carried out in the 1980s on the northern slope of the massif, in which radiocarbon and thermoluminescence dating has been applied for the first time, have confirmed in principle the model elaborated by Partsch (Chmal, Traczyk, 1999).

Comprehensive reviews of the history of research on the number and age of glacial episodes in the Karkonosze, and on the influence of local geomorphology on the extent of glaciation (Králík, Sekyra, 1969; Engel, 1997; Migoń, 1999), indicate a general view that the Karkonosze were glaciated at least two times. Moreover, glaciers were largely confined to cirques and major valleys.

Another line of research in the Karkonosze has followed pioneering studies on block fields carried out by Łoziński in the beginning of the 20th century (Jahn, 1954). Further studies of block fields include those by Schott (1931), who presented the evidence from the Karkonosze in the wider context of European Mid-mountains, but other local Perigiacial phenomena remained poorly known. In the post-war period the discussion ensued on the present-day status of perigiacial landforms above the timberline, mainly of block fields and stone circles, whether they continue to evolve or, rather, are fossil

Pleistocene phenomena (e.g. Walczak, 1948; Jahn, 1963). It has been found that certain frost-related processes such as frost sorting and patterned ground development may occur today in specific environmental circumstances, modified by human activity (Pelíšek, 1974). Subsequent studies have demonstrated that the efficacy of frost-related phenomena on the summit plateau of the Karkonosze is high enough not only to maintain inherited periglacial landforms, but to create periglacial surface microrelief (Traczyk, 1992; Soukupová et al, 1995).

In the 1960/1970s periglacial research in the Karkonosze flourished and several tens of new publications appeared in print, by both Czech and Polish authors. Besides providing details about geomorphology of cold-climate landforms, they also attempted to establish temporal framework for periglacial geomorphic history. A commonly accepted view has been that about Late Pleistocene (= Würmian) age of periglacial relief (Jahn, 1960), although chronostratigraphical evidence has been missing. Nevertheless, it seems that this position is largely correct. Still, there exists an opportunity to constrain the timing of landform evolution through establishing relative chronologies based on spatial relationships of periglacial, glacial, glacifluvial and fluvial landforms.

Periglacial research in the Karkonosze has subscribed to the conceptual framework of climatic geomorphology, and therefore the issue of rock control has remained neglected, although exceptions are present in the literature (Dumanowski, 1961; Sekyra, 1964; Bartošíková, 1973; Traczyk, 1995). This biased approach has been partly redressed recently (Traczyk, Engel, 2002) and it has been shown that both distribution and geomorphic features of many periglacial landforms in the most elevated part of the Karkonosze are much influenced by lithology, local relief and topoclimatic conditions.

Despite a long history of investigations, there is still a gap as far as detailed geomorphology of cold climate landforms, including micromorphology and lithology of deposits, is concerned. As long as these characteristics remain poorly known, palaeoclimatic context of periglacial landscape facets is difficult to establish. This is particularly important in the light of paucity of chronostratigraphic data and it is assumed that the recognition of relationships between periglacial and glacial relief is the only viable alternative to decipher the timing of geomorphic evolution towards the end of the Pleistocene.

Field mapping of periglacial landforms in the summit part of the Karkonosze enabled for the erection of new hypotheses concerning the course and nature of events affecting the massif in the Late Pleistocene. During this period local glaciers and permafrost steadily decayed, whereas the forest cover expanded, ultimately causing fossilization of most periglacial landforms. The paper also aims to highlight new research opportunities, which may eventually lead to the more precise identification of phases of geomorphic development of the Karkonosze in the Pleistocene.

2. Problems of reconstructions of Pleistocene mountain environments

One of the major problems faced by mountain glacial and periglacial geomorphology is the scarcity of data which can be used to establish ages and timing of formation of individual landforms and cover deposits. Mountain environments are dominated by erosional processes and their relief energy precludes deposition of thick

series of correlative clastic and organic sediments, therefore sedimentary record of geomorphic processes is usually insufficient. Survival of organic deposits which can be analysed by means of palinological and radiocarbon dating methods is a very rare phenomenon. In this respect, the Karkonosze Mountains are no exception and do not significantly differ from other, less elevated mid-European mountain massifs. Biogenic sediments occur only in closed hollows within moraine fields and as infill of former glacial lakes.

Insofar, there have been found only three profiles of young mineral and organic deposits, whose age could have been determined using radiometric dating. These are located in the intra-moraine hollows in the forefield of the Śnieżne Kotły twin cirque (Chmal, Traczyk, 1999), in the former lakes in the vicinity of Hunter's Lodge in the Lomnica valley (Chmal, Traczyk, 1998), and in the bottom of the Labský důl in the headwater of the Labe valley (Jankovská, 2004). Radiocarbon dating of bottom parts of these sediments has revealed that the deposition began at the Pleistocene/Holocene transition. The age obtained are identical with the age of fine-grained lacustrine deposits in the Mały Staw lake in the Łomnica valley (Wicik, 1986). The results of absolute dating indicate that local glaciers were in the state of advanced decay as early as 10 ka ago and relict ice patches may only have survived attached to cirque back walls. Consequently, youngest moraine ridges surrounding the lakes or sedimentary flats developed at their expense need to be older than 10 ka. Unfortunately, the precise age of distal moraine ridges is unknown.

Two other dating methods applied to glacial landforms and deposits in the Karkonosze in the last 15 years have been thermoluminescence (Chmal, Traczyk, 1999) and cosmogenic isotope using ^{10}Be (Bourlès et al., 2004). However, any interpretation of the results obtained in this way requires particular care. For example, the reliability of surface exposure dating is limited by post-exposure weathering changes within boulders and rock outcrops. Detachment of exfoliation spalls may result in apparently younger exposure ages than they are in reality.

Dating methods considered above cannot be applied to periglacial landforms. They lack organic material, but more importantly, their development on slopes and summit flats has been continuous through time, hence they have a history of cyclical growth and degradation in alternating cold conditions of glacial periods and warmer interglacials. We may assume that their structural and textural characteristics, as well as their surface microrelief, are indicators of development and decay of periglacial and permafrost environments. In addition, some cold climate landforms may have evolved until the present-day under the recent climatic regime and in the presence of seasonally frozen ground. This phenomenon of ongoing development has been noticed in previous studies, but still awaits comprehensive explanation based on detailed field monitoring. A notable exception is the study of frost creep by Jahn (1989) in the subalpine belt of the Karkonosze.

It seems that two complementary approaches ought to be followed in order to infer ages and development stages of periglacial landforms in the Karkonosze. One would involve identification of spatial relationships between periglacial landforms, such as protalus ramparts, rock glaciers, nivation hollows, cryoplanation terraces and solifluction lobes, and landforms genetically related to other processes. Specifically, the relationship to glacial landforms needs to be established. Remote sensing techniques and interpretation of small-scale, multispectral aerial photographs and satellite images is particularly promising.

Simultaneously, one should focus on the characteristics of the weathered material itself using both qualitative and quantitative methods of description and assessment of the degree of weathering. The chief objective is to determine whether any given assemblage of landforms and deposits has been shaped during one, or possibly more perigiacial periods. In this way, the possibility opens to distinguish separate weathering facies of different ages among the entire inventory of perigiacial landforms. Such an approach is widely used in studies of coarse, weathering-derived perigiacial deposits in mountain terrains of the subpolar zone (Birkeland and Noller, 2000; Whalley et al., 1997). Field work includes determination of surface microrelief (rounding of block margins, surface roughness, depth of surface pitting, relative elevation of more resistant rock components) and of rock strength using the Schmidt hammer (McCarrol, 1991), and is complemented, if appropriate, by mineralogical analysis of clayey matrix collected from blockfields. It is worth emphasizing that these are relatively low-cost methods, at least if compared with radiometric dating. Moreover, sophisticated measurement instruments are not necessary, but on the other hand, field work can be time consuming and subsequent analysis requires extensive use of statistical methods.

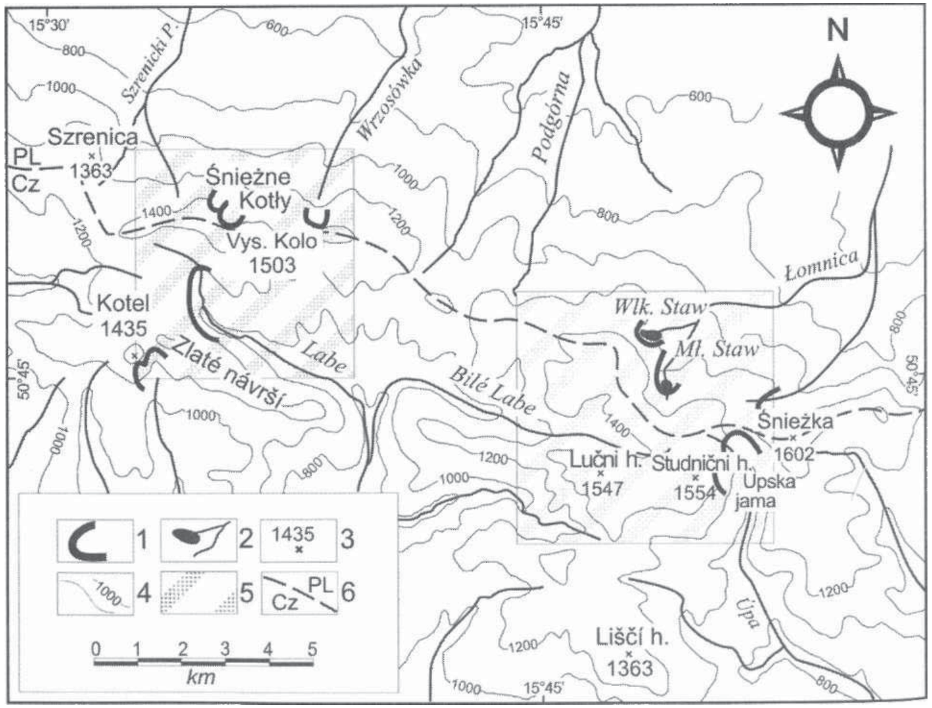

Fig. 1 Area of investigations within local topography of the Karkonosze Mts. Explanations.: **1** - cirques, **2** - rivers and lakes, **3** - selected top of mountains, **4** - contours (200 m interval), **5** - area described in the article, **6** - state border

On the northern slope of the Karkonosze, the best developed moraines occur in the forefield of the Śnieżne Kotły twin cirque and in the Łomnica valley, down the cirques of Wielki Staw and Mały Staw (Fig. 1). In this part of the range glaciers spread over the slope surface and were not confined to incised valleys. Detailed geomorphological studies carried out in both abovementioned areas (Traczyk, 1989; Chmal and Traczyk, 1999) have revealed that the maximum extent of local glaciers during the last glacial period was probably achieved in the early Weichselian. Two frontal moraine ridges are correlated with the glaciation phases Melisey 1 and Melisey II as identified in the Grande Pile profiles in the Vosges, hence with Marine Oxygene Isotope Stages 5d and 5b (Chmal, Traczyk, 1999).

In the late Weichselian, c. 20 ka ago (= Brandenburg or Leszno stage in the Polish Lowland (Sokolowski, 1984)), glaciers of the northern slope terminated with frontal moraines located near the outlet of the cirques. Inside this extent four to five parallel ridges of recessional moraines typically occur. Following radiocarbon dating of lake sediments deposited in between the moraines (Chmal, Traczyk, 1998), one may tentatively correlate phases of recession with the Older and Younger Dryas periods. The youngest recessional ridges encircle topographic hollows which have become lake basins in the Holocene. Rock debris from cirque walls, transported downslope by gravity, is superimposed onto the more distal of the recessional ridges.

Moraine ridges originated during the waning phases of the last glacial period are built of large angular blocks accompanied by small amount of granite grus. The predominance of big blocks may indicate increasing efficacy of frost weathering during this period.

Lateglacial moraine ridges are from a few to more than 30 m high. Such impressive heights are likely to be associated with the steep slope of ice surface and the proximity of cirque walls subjected to intense mechanical disintegration. These moraines have been shaped by gravitational processes rather than by ablation of debris material from ice, hence they are genetically similar to nival moraines (sensu Klimaszewski, 1981: 215, 693) built of material moved across the snow surface. The youngest ridge in the Wielki Śnieżny Kocioł cirque, located in the immediate proximity of the rock wall, may serve as an example. It is up to 12 m high and is composed of loose big granite boulders. Fine material infilling the blocky accumulation is lacking. An origin of this ridge is a nival moraine. In the rear of the ridge there extends a gently sloping accumulation flat devoid of boulder cover, which has probably been formed after the complete wastage of ice and firn. Fine mineral to fill the topographic hollow has been supplied by surface wash from rock walls and debris cones. It is suspected that the youngest moraine ridge was formed in the terminal phase of the last glaciation, during the Older or Younger Dryas cooling, when small local glaciers filled again the inner cirques.

In the Śnieżne Kotły area, on the slope segment located west of the cirque margin, a rock glacier has been recognized within the extensive blocky cover (Chmal, Traczyk, 1993). The entire block field merges in the lower slope with the debris cover which builds a recessional moraine in the front of the Mały Śnieżny Kocioł cirque,

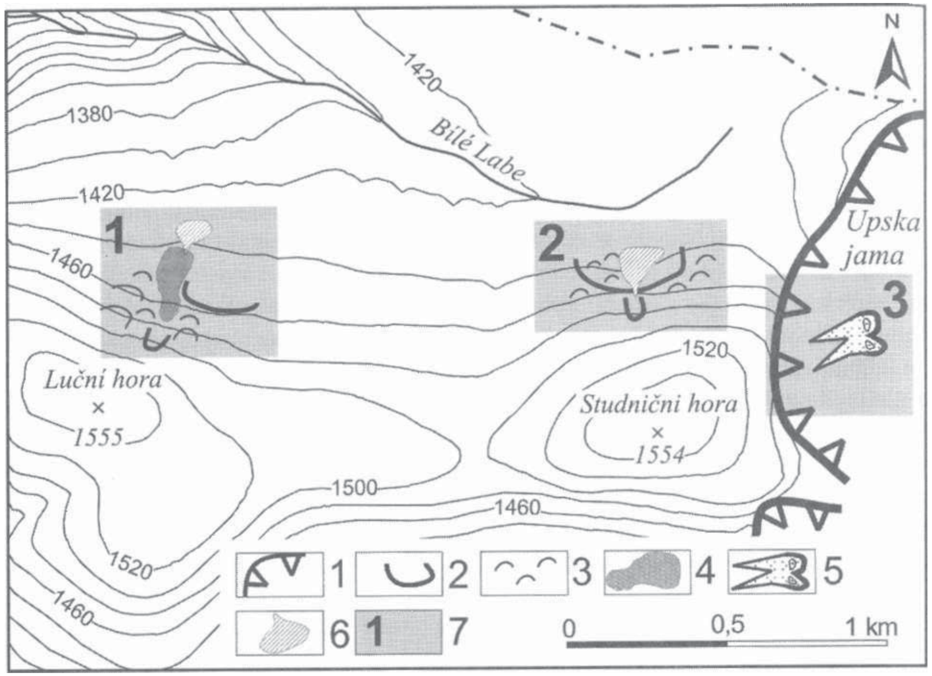

Fig. 2 Schematic sketch of the Luční - Studniční hora - Úpská jáma region in the East Karkonosze Mts. Explanations: **1** - edges of cirques, **2** - edges of nivation hollows, **3** - soliflucion lobes, **4** - rock glacier, **5** - talus with protalus ramparts, **6** - torrential fans, **7** - zones described in the article

and no clear morphological or sedimentary boundary exists between the two. In addition, no significant differences in the degree of weathering between the moraine and the block field has been observed. From an environmental point of view, snow accumulation would need to have been small, to allow cementation ice to develop within the block mantle. All these circumstance point to a latest Pleistocene age of the rock glacier.

One has to acknowledge that the rock glacier west of the Śnieżne Kotły lacks certain geomorphic features deemed to be typical for rock glaciers by Barsch (Żurawek, 1999). However, this does not contradict the interpretation forwarded by Chmal and Traczyk (1993). The most significant observation is that the geomorphic setting of the form in question rules out any other mechanism of downslope movement of the blocky mass than the cryogenic one related to ice cementation and deformation. Moreover, the rock glacier discussed here is not a unique feature. A similar landform has been reported from the northern slope of Śnieżka - Czarny Grzbiet ridge (Traczyk, 1995).

Recent field mapping on the summit plain of the Karkonosze indicates that fossil rock glaciers occur there too, mainly on the northern slope of Luční hora (no 1 - Fig. 2). One of these forms is described here in more detail. It is located at the altitude of 1440 m a.s.l. and has a tongue-like shape. Its basic dimensions are c. 160 m long, 6-10 m high and 25-35 m wide. The upper surface is uneven, consisting of small (up to 1.5 m high) steps and low ridges. The outer slopes in turn are steep (26-32°) and locally

covered by debris talus. In the distal part of the tongue earthwork for military purposes was executed during the World War II and the ditches reveal the internal structure of the form down to the depth of 1.5 m. It is invariably composed of loose angular debris and small boulders, and lacks fine matrix.

An intriguing feature of the surficial geomorphology of the tongue is a 0.5-1 m deep erosional trench which dissects its upper surface. At the outlet of the incision an alluvial fan has formed, well visible in the front of the rock glacier (Fig. 3). The presence of the cut and the alluvial fan are significant for genetic interpretation, as they indirectly confirm cryogenic origin of the block stream. The slope of Luční hora under present-day conditions is dry. Meteoric waters easily infiltrate into the slope cover built mainly of loose debris and no perennial streams flow on the surface. However, in the footslope zone, within the gently inclined summit planation surface, dry channels occur. These are used during the spring melting season, when the deeper parts of the blocky-debris cover are fully saturated or remain frozen. Hence, the erosional incision and the fan mentioned above must have originated in the conditions of ground ice existence within the tongue, therefore in the final stages of the last glaciation. Holocene age seems improbable because permafrost has been no longer present probably and no obstacles to restrict access of rain and melt water to the debris mass existed. During the Lateglacial, however, shallow thawing of permafrost should have favoured surface flow over the frozen debris cover. The subsequent decay of permafrost has led to the fossilization of rock glaciers.

Fig. 3 General view of the rock glacier located on the northern side of the Luční hora (no **1** on the Fig. 2). Note occurrences of the torrential fan at the foot of the rock glacier frontal slope

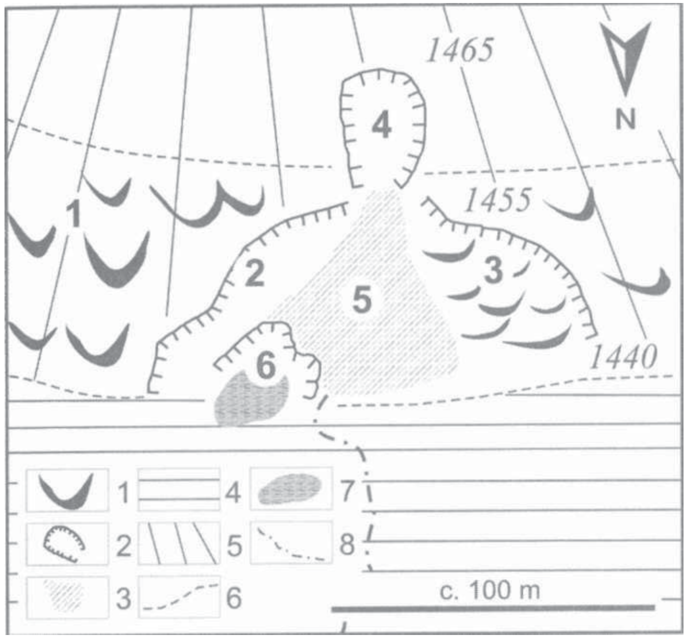

Fig. 4 Geomorphic sketch of the perigiacial forms on the northern side of the Studnicni hora. Explanations: **1** - solifluctuion lobes, **2** - nivation niches, **3** - torrentail fan, **4** - planation surface, **5** - slopes, **6** - break of slopes, **7** - peat bog, **8** - brook; bold numbers indicates probable sequence of form development (for detail see the text)

Another assemblage of perigiacial landforms has been recognized within the slope covers on the northern slope of Studnicni hora (no 2 - Fig. 2, 4). Two nivation hollows are present here, arranged one above the other. The floor of the lower hollow is moulded into small steps, probably solifluction terracettes. In its middle part an extensive torrential fan occurs, whose apex is located just below the upper margin of the hollow and at the outlet of the upper concavity. A small secondary hollow, in turn, has developed in the eastern part of the fan and is now occupied by a peat bog subjected to degradation by nival and frost-related processes. The upper hollow is much smaller than the lower one, but has very distinctive upper margins 4-5 m high. It is located within an evident topographic step built of slope debris. Still higher up, the step grades into a narrow bench 15-30 m wide that terminates against another steeper slope segment. Large solifluction lobes with 2-4 m high toes occur next to the upper hollow.

The spatial pattern of all these landforms indicates the following relationships. Terracettes and solifluction lobes (3 on the Fig. 4) developed after the decay of snow patch in the lower hollow (2). Later on, an upper hollow (4) originated, possibly related to a debris slide, and the torrential fan filling the lower hollow is roughly of the same age (5). Finally, a younger and smaller hollow (6) developed at the expense of the fan.

Such a sequence of events points to two phases of solifluction activity separated by a phase of enhancement of nival phenomena. Subsequenly, gravitational mass movement occurred, to be replaced in the most recent period by another phase of nivation, which probably typifies the contemporary environment too. This suggests that in the Lateglacial, possibly even in the early Holocene, at least two times there existed conditions favourable to solifluction, i.e. snow cover was of insufficient thickness to prevent frost heaving and frost creep. A correlation of these two periods with the Older and Younger Dryas is thus tempting. In the warmer phases of the last glaciation, snow fall probably increased, leading to the development of snow patches and nivation.

Renewal of frost-related processes of creep and solifluction in the Lateglacial is probably indicated by the occurrence of two landforms resembling protalus ramparts at the foot of cirque wall in the southern part of Úpská jáma (no 3 - Fig. 2, 5). These are low (2-3 m) topographic steps in the distal segments of scree cones which evolved beneath a rock wall undercutting the steep eastern slope of Studniční hora. Shallow closed depressions are visible behind the steps, and their origin by melting of ground ice and fan surface collapse is likely. The steps themselves may have been shaped in response to the increase of plasticity of lower fan sections and related solifluction, caused by the development of interstitial ice.

Fig. 5 Protalus ramparts (indicated by the white line) at the foot of the rock-wall in the south part of the Úpská jáma cirque (no **3** on the Fig. 2) (Photo by Z. Engel, 2000)

The period during which protalus ramparts developed ought to have been cold and dry. In addition, it must have postdated glacier ice decay in the Úpská jáma cirque. Again, Older and Younger Dryas are good candidates, but correlation with the events on the higher slope of Studniční hora remains uncertain.

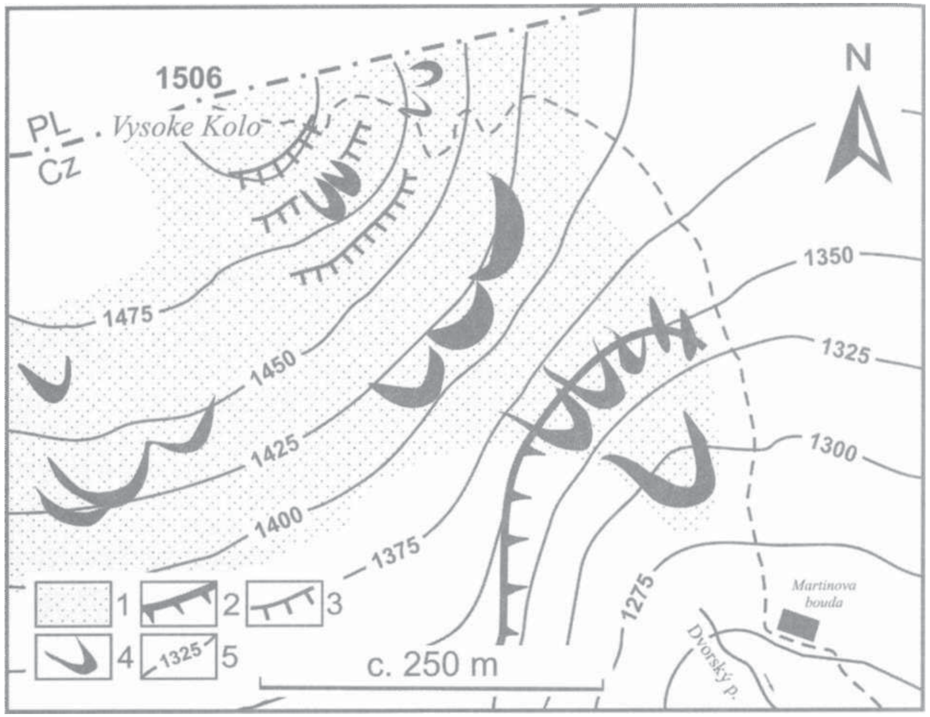

Fig. 6 Geomorphic sketch of the Vysoké Kolo - Dvorský potok river region in the West Karkonosze Mts. Explanations: **1** - block-debris slope cover, 2 - edge of the nivation hollow at the head of the Dvorský potok valley, **3** - frost cliffs, **4** - solifluction lobes, **5** - contours (25 m interval)

Possibly Lateglacial solifluction forms have also been found in the western part of the Karkonosze, in the Wielki Szyszak area (Fig. 6). Southern and eastern slopes of Wielki Szyszak bear an extensive, continuous block cover terminating at the altitude of 1400 m a.s.l. Within this cover a number of steps may be distinguished, which are in fact block covered frost-riven cliffs. Below the steps, in the 1400-1425 m a.s.l. belt, big solifluction tongues occur with their toes as much as 5-6 m high. The second belt of smaller solifluction lobes is located below, between 1330 and 1375 m a.s.l. The lobes and tongues have evidently moved into an extensive slope hollow in the upper part of Dvorský potok catchment, in the vicinity of Martinova bouda. The hollow is probably of nivation origin as suggested by its distinctive upper margin, especially on the western side.

Spatial and temporal relationships between these forms allow one to assume that movement of solifluction lobes occurred after snow patches in the Dvorský potok valley head had disappeared. As the lobes are built of coarse blocky material, their mobility was only possible under conditions of ice cementation. Following the previous interpretations for Luční and Studniční hora sites, they should have evolved in a dry and cold phase of the Lateglacial. Any greater precision in establishing their ages is not possible though.

The presence of at least one such cold and dry phase in the Lateglacial is further indicated by the evidence from the block field on the Zlaté návrší (Fig. 1, 7). A blocky-debris cover is spread over the slope above the road and shows two zones with contrasting degrees of weathering. Its lower part is built of rounded medium- and large-size boulders, whereas the upper one, immediately below the crest, is predominantly composed of angular debris and small blocks. Two separate phases of frost weathering may be assumed here, the younger of these being tentatively associated with the Older or Younger Dryas.

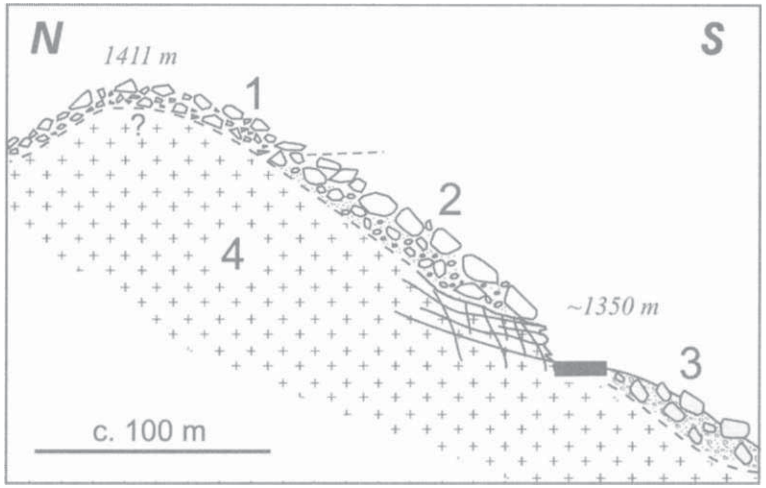

Fig. 7 Slope cross section of the Zlaté návrší ridge (for location see Fig. 1). Explanations: blocky-debris cover built of: **1** - angular debris and small blocks, **2** - rounded medium- and large-size boulders, **3** - solifluction cover (debris with rounded blocky material and sandy-loam matrix), **4** - granite, **5** - metamorphic schist

4. Late Pleistocene evolution of the mountain environment of the Karkonosze

The review of glacial and periglacial landforms recognized in the most elevated parts of the Karkonosze Mountains allows for the following generalization about the evolution of local environment in the Lateglacial. Phases of climate deterioration during the terminal Pleistocene did not cause a re-advance of local glaciers, but their recession continued at slower pace. This was because dry and cold climate at that time did not favour snow accumulation within cirques.

By contrast, frost-related processes within cirque walls could have occurred with Particular efficacy. Their geomorphic impact is revealed by the structure of moraine ridges in the rear sections of cirques. The ridges are composed of angular, unweathered blocks with very small admixture of grus derived from granular disintegration of granite.

Progressive ice wastage in the cirques was accompanied by the development of scree cones and scree slopes, itself influenced by two major factors. Structure of bedrock was important, mainly fracture density and orientation, as well as overall decrease of slope stability consequent to permafrost decay. During the Holocene and towards recent times gravity-driven mass movement of rock fall type has become less frequent, and the magnitude of events has diminished accordingly. Scree cones have not been fossilized though, but are being reshaped by debris flows (Parzóch and Dunajski, 2002).

Climate changes during the Lateglacial have also significantly affected processes moulding the periglacial environment of the Karkonosze. During the cold phases summer thawing reached only shallow depths, whereas segregation and cementation ice could have developed in relation to site-specific textural characteristics of cover deposits. Episodes of warming must have resulted in deeper thawing and rapid melting of ground ice. These conditions combined, have apparently facilitated the development of various phenomena of frost weathering, sorting, denudation and deposition which occurred on the summit plain and on steep slopes in its vicinity. It is likely that some of the periglacial landforms in the Karkonosze such as rock glaciers, solifluction lobes and protalus ramparst evolved in this time.

Except for scree cones, periglacial landforms have become fossilized at the Late Pleistocene/Holocene transition. Climate amelioration has caused disappearance of ground ice and movement of ice-cemented debris could not have occurred any longer. Frost heave and sorting, however, has continued to act owing to the scarcity of vegetation cover.

5. Conclusions

(1) In the latest Pleistocene, thanks to the short-term environmental changes, there existed suitable conditions for enhancement of frost weathering and development of solifluction and mass movement. The geomorphic legacy of these conditions includes the presence of fossil rock glaciers, solifluction lobes and rock fall-derived talus. During warmer and wetter periods the activity of nivation processes was significant.

(2) Spatial and temporal relationships of glacial and periglacial landforms due to degradation and deposition indicates that some cold-climate geomorphic features originated during the Lateglacial, perhaps during the Older and Younger Dryas.

(3) Detailed geomorphological research of periglacial landforms is required in the Karkonosze and dating attempts are indispensable. In this way, phases of glacier recession in the valleys might be correlated with main phases of development of periglacial landforms and cover deposits.

Acknowledgements

The author would like thank to dr Zbyněk Engel (Dept. of the Physical Geography and Geoecology, Charles University, Prague) for filed assistance and discussions carried out in the Karkonosze, and Prof. dr Piotr Migoń (Dept. of Geomorphology, Univ. of Wrocław) for the English translation and some useful comments made on the manuscript.

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PERIGLAC1ÁLNÍ A LEDOVCOVÁ MODELACE RELIÉFU KRKONOŠ VE SVRCHNÍM PLEISTOCÉNU. NOVÉ HYPOTÉZY A PERSPEKTIVY VÝZKUMU

Résumé

Práce se zabývá problematikou vývoje reliéfu hřbetové oblasti Krkonoš v období pozdního glaciálu. Ledovcové a periglaciální tvary reliéfu byly studovány v karech Małego Stawu a Úpské jámy, resp. na hřbetech Studniční hory, Luční hory, Vysokého Kola a Krkonoše. Na základě terénního výzkumu je popsán vztah periglaciálních jevů (pasivní morény, kamenné ledovce, nivační deprese, kryoplanační terasy, soliflukční laloky) k ostatním tvarům reliéfu, především ledovcovým (kary a morény), a fáze jejich vývoje jsou korelovány se stratigrafickými jednotkami svrchního pleistocénu.

Výsledky lze shrnout takto: 1) Morfologie a dynamika změn přírodního prostředí Krkonoš v období svrchního pleistocénu odpovídá podmínkám zvýšené intenzity mrazového zvětrávání, soliflukce (kamenné ledovce) a svahových procesů (kamenné proudy, pasivní morény). Během teplých a vlhkých výkyvů klimatu docházelo v Krkonoších k nárůstu úhrnu sněhových srážek a k následnému rozvoji nivačních procesu. 2) Sled erozních a akumulačních periglaciálních tvarů v hřbetové oblasti Krkonoš a jejich vztah k morénám svědčí o jejich vzniku v průběhu pozdního glaciálu (zřejmě v období staršího a mladšího dryasu). 3) Dalšího pokroku v řešení uvedené problematiky lze dosáhnout uskutečněním podrobných geomorfologických výzkumů (mapování, radiometrické a relativní datování), které by umožnily korelovat fáze ústupu horských ledovců s etapami rozvoje periglaciálních jevů.