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Cold-climate landform patterns in the Sudetes. Effects of lithology, relief and glacial history

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ABSTRACT

The Sudetes have the whole range of landforms and deposits, traditionally described as periglacial. These include blockfields and blockslopes, frost-riven cliffs, tors and cryoplanation terraces, solifluction mantles, rock glaciers, talus slopes and patterned ground and loess covers. This paper examines the influence, which lithology and structure, inherited relief and time may have had on their development. It appears that different rock types support different associations of cold climate landforms. Rock glaciers, blockfields and blockstreams develop on massive, well-jointed rocks. Cryogenic terraces, rock steps, patterned ground and heterogenic solifluction mantles are typical for most metamorphic rocks. No distinctive landforms occur on rocks breaking down through microgelivation. The variety of slope form is largely inherited from pre-Pleistocene times and includes convex-concave, stepped, pediment-like, gravitational rectilinear and concave free face-talus slopes. In spite of ubiquitous solifluction and permafrost creep no uniform characteristic 'periglacial' slope profile has been created. Mid-Pleistocene trimline has been identified on nunataks in the formerly glaciated part of the Sudetes and in their foreland. Hence it is proposed that rock-cut periglacial relief of the Sudetes is the cumulative effect of many successive cold periods during the Pleistocene and the last glacial period alone was of relatively minor importance. By contrast, slope cover deposits are usually of the Last Glacial age.

Key words: cold-climate landforms, the Sudetes

1. Introduction

The mountain massif of the Sudetes (for location see Fig. 1) has a long history of geomorphological evolution, which dates back to at least the beginning of the Cainozoic (Scupin 1937; Jahn 1980; Migoń 1999). Although planation may have been characteristic for the early part of the Cainozoic, long-term increase in relief due to differential tectonics and erosion dominated in the Neogene, producing horst-and-graben or lithologically-controlled topography at the onset of the Quaternary. Superimposed on these older landform elements are various mesoscale features, the origin of which is commonly attributed to the presence of frost and snow in the Pleistocene. These include landforms, such as tors and cryoplanation flats, blockfields and blockstreams, nivation hollows, patterned grounds, and sedimentary mantles of weathering, mass movement or aeolian origin. Since the pioneer work by Łoziński (1909), these features have been considered as witnesses of Pleistocene periglacial (or cryogenic) environment and, owing to contributions particularly by T. Czudek, J. Demek and A. Jahn, figure prominently in the world literature on periglaciation.

However, many issues related to the Pleistocene landscape development of the Sudetes remain unresolved or need re-examination in the light of recent progress in our understanding of 'periglacial' processes (cf. Thorn 1992; French 1996). The two fundamental ones, and in fact closely related to one another, are the actual contribution of cold-climate morphogenesis to the long-term landscape development and the effects on the origin and development of Pleistocene landforms. Until now, the majority of studies on the Pleistocene landforms of the Sudetes has followed the climatic approach and regional climatic conditions have been assumed the primary significance. Other factors, such as lithology, local relief, or time, have apparently been considered less important, although exceptions are present throughout the literature.

This paper attempts to re-address the issue of significance of cold-climate landforms and sediments for the geomorphology of the Sudetes through the critical examination of the available information about selected 'periglacial' landforms and new interpretations of spatial patterns in their distribution. It focuses on blockfields, frost-riven cliffs, cryoplanation terraces, rock glaciers, patterned ground, talus slopes, solifluction and loess mantles. However, features which are very rare, such as involutions and ice wedge casts, or of much uncertain origin, such as 'nivation hollows' are excluded. In particular, we hope to highlight the role of varied lithology, local relief as inherited from previous landforming events, and different time scales for different parts of the Sudetes. Less elevated parts of the mountains, and the entire foreland, were subjected to inland glaciations in the Middle Pleistocene. Hence, the possibility exists to recognise Pleistocene trimlines and to obtain some insights into temporal relationships between 'periglacial' landforms.

2. The Study Area

2.1. Geology

The Sudetes constitute the north-eastern part of the Bohemian Massif, which itself belongs to the 'Hercynian Europe' and consists of the crystalline basement of Proterozoic and Early Palaeozoic age, ultimately consolidated during the Hercynian orogeny in the Devonian and Carboniferous, and younger cover rocks of various ages, from the Carboniferous to the Cretaceous (Don, Żelaźniewicz 1990). In addition, Carboniferous and Permian intrusive and volcanic rocks occupy large areas. Tertiary clastic sediments are widespread in the foreland of the Sudetes (Sudetic Foreland), but in the mountainous area only isolated patches of usually unspecified age have been recognised. Neogene to Early Pleistocene volcanic activity has resulted in the occurrence of numerous volcanic plugs, thin veins, or more extensive lava plateaux.

The crystalline basement of the Sudetes is composed largely of meso-metamorphic rocks, chiefly of gneiss and schist, with subordinate amphibolite and marble, but greenstone facies, chlorite schist and phyllite are also widespread in specific areas. Metamorphic rocks are intruded by igneous rocks of various ages and composition, granites and allied intrusives being most typical. Locally, gabbro and serpentinite are present. Granitoid intrusions are usually fairly heterogeneous and consist of several subtypes of different structure, mineralogy, chemistry, and jointing patterns. Late Palaeozoic extrusive rocks include massive ryolites, basalt, and porous tuff.

Most of the sedimentary rocks in the Sudetes are of terrestrial origin and reflect rapid deposition in intramontane basins or on piedmont surfaces. These are represented by coarse conglomerates, sandstones and mudstones. Short-term marine incursions have resulted in the origin of thin layers of dolomite and limestone, typical for the Late Permian. Late Cretaceous sediments, in turn, are dominated by shallow marine quartz sandstones, mudstones and marls.

From this brief review it follows clearly that the range of lithologies in the Sudetes is extremely wide, and the rocks present differ significantly in terms of their physico-chemical properties and, by inference, in resistance to various exogenic processes. Consequently, the possibility of dominant lithological and structural effect on landform development also during the cold Pleistocene cannot be ignored.

2.2. General geomorphology

The Sudetes in their present-day form provide a typical example of faulted mountains and consist of numerous morphotectonic units which experienced differential uplift or subsidence in the Neogene and, although with diminishing intensity, in the Quaternary (Oberc 1972). The most important fault has been the Sudetic Marginal Fault (Fig. 1), which is responsible for the general uplift of the SW part and the subsidence of the NE part of the Sudetes area, and the origin of the prominent mountain front in the north-east (Krzyszkowski et al. 1995). The downthrown part of the basement area is called the Sudetic Foreland. Superimposed on this macro division are areas of more localised relative uplift or subsidence, hence the range of altitudes in the Sudetes comes up to 1200 m, and up to 200 m in the foreland, locally even 500–600 m. Slope gradients are locally very high, up to 40°; long steep slopes are thus not uncommon.

The interplay of protracted lithologically-controlled selective denudation, local tendencies for planation in homogeneous bedrock, differential uplift and associated erosional dissection resulted in varied ‘preglacial’ morphology, then exposed to the influence of cold environments of the Pleistocene (Fig. 2). Its principal units were local watershed and mid-slope flats, often referred to as remnants of Tertiary planation surfaces (cf. Klimaszewski 1958), extensive gently rolling surfaces, monadnocks and structural escarpments on apparently more resistant rocks such as basalt, gabbro, ryolite, quartzite, siliceous sandstone and certain types of granite, pediment-like surfaces, deeply incised valleys, and fault-generated marginal escarpments of mountain massifs.

3. Cold-climate landforms – critical reappraisal

3.1. Blockfields and block streams

Block covers belong to the most distinctive and characteristic vestiges of cold-climate conditions (cf. Łoziński 1909, Schott 1931, Flohr 1934, Dumanowski 1961a). They occur at different altitudes, from 300–400 m a.s.l. in the Kaczawa Upland and the

Ślęża Massif to 1500–1600 m a.s.l. in the Karkonosze (Giant Mts.), usually in the upper slopes. Various rocks appear to support blockfields, including fine grained granite, quartz sandstone, basalt, gabro, quartzite, hornfels (Fig. 3). All of these are resistant against liberation of fine debris in the course of physical weathering and usually possess regular jointing patterns, best pronounced in granites and thermally jointed basalt. By contrast, blockfields on gneiss, mica schist, greenstone and porphyritic granite are relatively rare.

The size of constituent blocks is determined by lithology and joint density. Massive granite and gabbro produce largest blocks, often >1 m long. Hornfels and quartzite blockfields consist predominantly of coarse debris (0.3–0.6 m), whilst basalt and most metamorphic rocks disintegrates into finer debris (<0.3 m). However, in most cases a variety of sizes is represented. A few available outcrops allow us to infer the maximum thickness of block covers between 2–3 m to 6 m (Fig. 4); this is present in the lower slope sections and only sporadically on the upper convex slope.

Some of the blockfields are clearly autochthonous and have developed on flattish mountain tops through *in situ* weathering (Fig. 2). The majority, however, is of blockslope type, often associated with bedrock outcrops located higher up on the slope. They are elongated along the slope, the blockfields on valley sides in the Śnieżnik Massif being a good example (Martini 1979, Traczyk 1996b). Blockfields developed across the slope, as on the convex break of slope within the summit dome of Mt. Śnieżnik (1425 m a.s.l.), are a rare variety. In the Karkonosze they are probably related to the zones of intersection of sub-horizontal sheeting joints with the slope (Dumanowski 1961). Laterally most extensive are blockfields developed on straight slopes of inclination above 25°, such as those present on granite monadnocks and hornfels ridges in the Karkonosze.

Most blockfields have an open work texture and their morphology consists of distinctive small-scale features such as stripes and furrows, tongues, block steps, and occasionally closed hollows. Their presence and orientation of individual clasts are indicative of solifluidal transport of ice-cemented debris (Traczyk 1995, Leśniewicz 1996). Block tongues are the most distinct manifestations of movement of blockfields through gelifluction. However, in specific relief circumstances, they occur independently of block mantles and take the form of blockstreams or boulder lobes, known from the Nizký Jesenik (Fencl, Svatoš 1962), Ślęża Massif (Traczyk, Żurawek 1999) and the Stołowe Mts. (Traczyk, unpubl.). The favourite setting for blockstreams is the network of small erosional valley cuts in the lower sections of slopes, which have a block cover mantle in their upper parts; on smooth slopes blockstreams are very rare. The movement of block cover is then channelised and accelerated within the valleys; the resultant blockstreams may extend in the front of the block field up to 700 m (NW slope of Mt. Ślęża in the Ślęża Massif). They terminate in distinct lobate toes 3–6 m high. More than one generation of blockstreams occurs in the Ślęża Massif. The movement of blockstreams was accomplished, similarly to the majority of block covers, by slow creep of debris cemented by ground ice as suggested by frequent voids and a chaotic arrangement of clasts (Traczyk, Żurawek 1999). The creep may have been enhanced by concentration of meltwater and more efficient development of ground ice within the valleys.

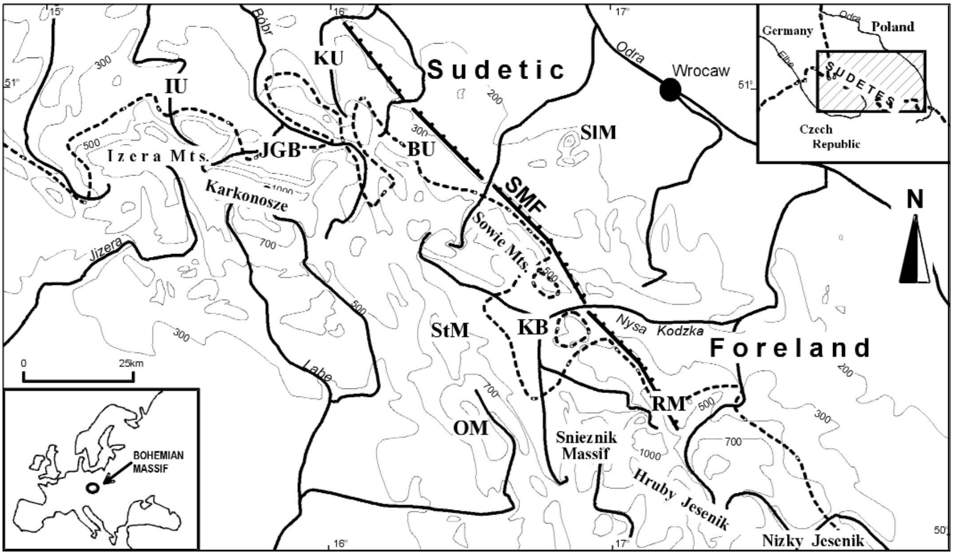

Figure 1: Location of the areas mentioned in the paper. Dashed line indicates the maximum extent of the Scandinavian ice-sheet in the Sudetes; serrated line shows the course of the Sudetic Marginal Fault (SMF). [BU – Bolków Upland, IU – Izera Upland, JGB – Jelenia Góra Basin, KB – Kłodzko Basin, KU – Kaczawa Upland, OM – Orlicke Mts., RM – Rychlebskie Mts., SlM – Ślęża Massif, StM – Stołowe Mts.]

Figure 2: General view of the eastern part of the Karkonosze showing the close co-existence of flattened watersheds and steep slopes. They support different suites of cold-climate landforms. Autochthonous blockfields, residual tors and patterned ground occur on flat surfaces, while blockslopes have developed on steep terrain. Stone stripes and hollows within the blockslope are emphasised by an elongated pattern of dwarf pine vegetation.

Figure 3: Close-up of a blockslope developed on hornfels of Mt. Śnieżka, Karkonosze.

Figure 4: Structure of a blockslope on the rectilinear slope of Mt. Śnieżka (Karkonosze). Concentration of debris in the near-surface part demonstrates the role of frost sorting in the development of cover deposits. In the lower part jointed bedrock is visible.

The majority of blockfields and boulder lobes in their present-day form probably dates back to the last ice age; however some heavily weathered granite blocks in the Karkonosze may be remnants of an older generation of blockfields (Leśniewicz 1996).

3.2. Frost-riven cliffs and tors

Rock outcrops in the form of either isolated residuals rising above flat and gently sloping surfaces (tors) or bedrock steps extending across the slope are common in many Sudetic massifs. They are usually a few metres high, although tors up to 25 m high and steps in excess of 20 m high and 1 km long have also been reported (Jahn 1962; Czudek 1964, 1997; Demek 1964). Particularly the latter are invariably referred to as frost-riven cliffs or scarps (Czudek 1964, 1997; Demek 1964; Martini 1969, 1979; Vitek 1975, 1986, 1995), hence their causal link with periglacial environment is apparently assumed. Mechanical (frost) weathering, enhanced by the presence long-lived snow patches, is invoked as the dominant mechanism responsible for cliff origin and development (Czudek 1997).

A range of lithologies is involved in frost-riven cliffs and tors. They appear to be very common in gneissic-schistose complexes (Czudek 1964; Demek 1964; Sekyra, 1964; Vitek 1975, 1986, 1995), and can also be found in abundance in greenstone (Martini 1969), quartzite (Martini 1979) and gabbro (Żurawek, Migoń 2000). Less frequent are rock steps in basalt (Zygmunt 2000) and serpentinite. Tors in granite are numerous, but these have been excavated from deep weathering profiles (Jahn 1962) whilst landforms resembling frost-riven cliffs are extremely rare (Bartošíková 1973). Rock outcrops in sandstone and conglomerate are also very common, but their occurrence within steep edges of structural escarpments and cuesta faces points to a different mode of origin.

3.3. Cryoplanation terraces and summit flats

The issue of cryoplanation terraces is closely related to the problem of frost-riven cliffs as, according to the model, cliffs and intervening terraces occur in pairs and are genetically inter-related (Demek 1969; Czudek 1995; French 1996). In fact, most detailed studies from the Sudetes report both cliffs and separating benches, considering the latter as features of frost planation (cf. Czudek 1964; Sekyra 1964; Ivan 1965; Martini 1969). V. Panoš (1961) was the first to describe in detail watershed flats cut across schist and marble in the Rychlebské Mountains, Eastern Sudetes, whilst an extensive survey of cryoplanation terraces has been provided recently by Czudek (1997). These mid-slope benches are typically a few tens of metres wide and extend up to a few hundreds of meters across the slope; their inclination does not exceed 7°. Significantly, they again appear to be preferentially associated with gneiss and schist bedrock, whilst only locally with basalt (Zygmunt 2000), granite (Sekyra 1964) or gabbro (Żurawek, Migoń 2000). As pointed out by Czudek (1997), stepped profiles tend to occur in upper sections of slopes.

Summit flats are one of the most conspicuous relief features in the Sudetes, being particularly well developed in metamorphic massifs (Orlické Mts, Śnieżnik Massif, Hrubý Jesenik; Fig. 2). Locally, more than one flat is present and then low rock steps separate the adjoining ones. These summit flats could be as much as 500 m long; low tors resembling Siberian ‘tumps’ occasionally rise above them but are generally rare. A regolith mantle on the flats is generally thin (up to 2 m; Czudek 1997) and usually composed of stony loam; autochthonous blockfields sporadically occur. These characteristics have promoted thinking that the flattened summit parts are Pleistocene ‘cryo-plains’ (Demek 1985; Vítek 1995), and not necessarily remnants of Tertiary surfaces of planation. However, observations in the Ślęża Massif (Sudetic Foreland) suggest that extensive mid-slope benches are pre-Pleistocene features, subsequently only subjected to some reshaping under cold climate conditions (Szczepankiewicz 1958; Migoń 1997b; Żurawek, Migoń 2000).

3.4. Rock glaciers

The first report about relict rock glaciers in the Sudetes was by Petránek (1953), who described a single landform of this kind in one of the valleys on the eastern slope of the Hrubý Jesenik ridge. According to the description provided, the rock glacier is 1.9 km long and 0.35-0.7 km wide, occupying the entire width of the valley; transversal ridges and ogives are also reported. It terminates in a distinct toe 20–30 m high at 820 m a.s.l. Further examples have been provided from the Karkonosze. Two rock glaciers are located in the vicinity of the glacial cirques of Śnieżne Kotły (Chmal, Traczyk 1993), a third one has been recognised on the northern slope of Mt. Śnieżka (Traczyk 1995). They are built of overlapping steps and transversal ridges 2–4 m high and terminate in 10–15 m high frontal ridges; enclosed hollows 2–3 m deep are common. Since all these forms exist within blockslopes, they are regarded as ‘kurum-glaciers’, as distinguished by Romanovski et al. (1989) in Siberia. Hence, they represent a specific, more streamlined mode of permafrost creep within a blockslope. More recently, Żurawek (1999a, 1999b) has re-examined big depositional landforms on the gabbro slopes of Mt. Ślęża, previously interpreted as witnesses of catastrophic mass movements, and recognised them as complex rock glaciers. There are eight individual landforms, up to 1 km long, 0.6 km wide and 18 m high in the frontal parts.

Rock glaciers were supplied by debris originated from frost-riven cliffs at the convex slope break below the summit flat of the Karkonosze (Chmal, Traczyk 1993), from the blockslope (Traczyk 1995), or from extensive blockfields in the upper slope (Żurawek 1999b). In all these settings there must have been a surplus of water percolating down the slope.

Recent re-examination of rock glaciers in the Sudetes (Żurawek 1999a) has indicated that the landforms in the Karkonosze and Hrubý Jesenik do not fully conform to the definition of a rock glacier, as offered by Barsch (1996), but the role of cementation ice in their development is not disputed. The absence of typical rock glaciers (sensu Barsch 1996) in the Sudetes is probably consequent upon the scarcity of rock walls which might have generated abundant debris to be cemented by ice and transformed into large rock glaciers. Relatively infrequent and small rock outcrops on slope breaks were insufficient sources of rock material. Rock glaciers on Mt. Ślęża do, however, fulfil the criteria proposed by Barsch (Żurawek 1999b).

Relationships to local relief clearly show that the Sudetic rock glaciers belong to the type of periglacial-derived features. They probably originated close to the end of the Last Ice Age (Chmal, Traczyk 1993, Żurawek 1999b), in the cold and dry conditions, but unequivocal dating is not yet available.

3.5. Solifluction sheets and stratified slope deposits

Solifluction was probably the most important non-glacial morphogenetic process to modify the relief of the Sudetes in the cold environment of the Pleistocene, and relict solifluction mantles are most widespread among all cold-climate landforms and deposits (Büdel 1937, Arnold 1938, Jahn 1968). They can be found irrespective of bedrock lithology and slope aspect, being known to occur on slopes as gentle as 2–4°. A clear testimony of the high efficacy of solifluction is the extension of individual 'wandering blocks' and coherent sheets well across lithological boundaries. Figures in the order of 500–900 m are not uncommon, and on the long NW slopes of the Ślęża Massif gabbro blocks can be found overlying granite more than 1.5 km downslope from the contact (Szczepankiewicz 1958, Traczyk 1996b, Żurawek, Migoń 2000; Fig. 5). Persistent snow cover and intense aeolian accumulation appear as the only factors capable of having retarded the progress of solifluction.

The characteristics of solifluction mantles differ according to inherited slope morphology. Long slopes of moderate inclination (5–20°) supported solifluction sheets, the thickness of which increased downslope, up to 1.5–2.5 m, and exceptionally even more than 4 m (Wroński 1969; Fig. 6, 7). Lobate forms with debris-banked risers were typical for midslope flats and slightly inclined watershed surfaces. They are best preserved in the summit parts of the Karkonosze, where the risers are 0.5–1.5 m high (Prosová 1963, Sekyra 1964, Traczyk 1995; Fig. 8). It may be expected that similar lobate forms existed at lower elevations as well, but have largely been destroyed in the course of Holocene morpho- and pedogenesis.

Two types of solifluction sheets can be distinguished on the basis of their internal structure and grain-size parameters. The former includes heterogenic covers consisting of blocks, coarse debris and fine matrix, i.e. stony-loamy and debris-silty/sandy covers. The latter type embraces homogenic fine-grained sediments (silt, sand, exceptionally fine debris). It appears that this division is primarily related to bedrock properties, the degree of jointing and susceptibility to macro- and microgelivation.

Heterogenic covers include variants displaying the effects of frost sorting in the vertical profile. It is particularly frequent in stony-loamy mantles and shows up as the concentration of larger clasts in the near-surface part, their downslope alignment and upward tilting. Lower down, fine lamination is often visible. Sorting is largely absent in debris-silty sediments.

Fine-grained homogenic sediments appear in the stratigraphic column either above or below the stony- and debris-rich units. In the first case, they are structureless sandy-silty mantles with small admixture of fine debris, hence fairly similar to the subrecent deluvial (slopewash) sediments. However, they evidently lack artefacts and charcoal, typical for Holocene deposits. Similar deposits have been described by Dylik (1953) from central

Figure 5: In Kowary (East Karkonosze) solifluction loamy mantle derived from gneiss overlies weathered granite c. 1 km downslope from the gneiss/granite boundary.

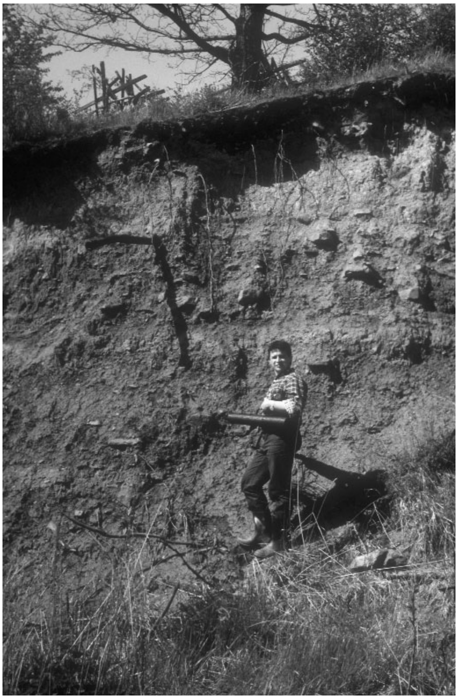

Figure 6: Cut through the thick sequence of solifluction deposits on the lower slope in Ścinawka, W part of the Kłodzko Basin (bedrock is sedimentary). Massive heterogeneous units are separated by thinner units dominated by fine material. Note downslope arrangement of larger clasts.

Figure 7: Solifluction heterogeneous mantle with abundant coarse basalt debris overlying tuff on the slope of Wilcza Góra monadnock, Kaczawa Upland. The uppermost part is enriched in silt, which often forms a separate unit in the top part of the sequence.

Figure 8: Distinct frontal ridge of a solifluction tongue (eastern part of the Karkonosze).

Poland and attributed to unbound congelifluction at the end of the Pleistocene. They may have developed at the expense of older aeolian covers or through selective denudation of coarser slope deposits (Baran 1990).

Fine-grained deposits below the coarse horizon are usually stratified, resembling the grèzes litées (Traczyk 1996b) and consist of alternating layers (laminae) of silt or sand and loose fine debris with an open-work texture. They overlie solid bedrock or lowermost heterogenic mantles, never cropping out at the surface. There appears to be an upper altitudinal limit of their occurrence at c. 600–750 m a.s.l. Stratified slope deposits are known from a variety of lithologies, including schist, gneiss, basalt, coarse granite, greywacke, sandstone and conglomerate (Traczyk 1996b). In accordance with the recent interpretation of stratified deposits (Francou 1989), these deposits are considered as resulting from shallow sheet solifluction in the middle part of the Vistulian (Pleniglacial) (Traczyk 1996b).

Slope solifluction mantles usually occur in a layered manner and consists of two to four separate units (Fig. 6). Threefold division into the lower stony-loamy cover, the middle stratified unit, and the upper debris loam enriched in silt or silty loam (Jahn 1968) is common. In the foothills altitudinal belt a loessic cover forms the near-surface horizon (Traczyk 1996b). In the upper slopes the cover is often reduced to a single blocky-debris loam horizon overlying bedrock.

3.6. Talus slopes

Talus slopes, i.e. steep slopes formed by accumulation of debris at the foot of rockwalls, are relatively rare in the Sudetes, the main reason for this being the scarcity of sufficient relief. Most prominent talus slopes, in the form of distinct cones, occur in the former glacial cirques on the northern slope of the Karkonosze (Stankowski, Wiśniewski 1973). Further examples can be found in deeply incised gorges of Middle Pleistocene age (Traczyk 1996b, Krzyszkowski 1998). Various rocks give rise to talus, including granite, ryolite, and greenstone.

It may be disputed to what extent the development of talus slopes is controlled by cold climate conditions as opposed to climate-independent stress boundary conditions. Unfortunately, no definitive answers can be provided so far since no dating of talus slopes is available.

3.7. Patterned ground

Relict patterned ground has only been recognised in the highest parts of the Sudetes, elevated above 1300–1400 m a.s.l. (Karkonosze, Śnieżnik Massif, Hrubý Jesenik) (Gellert, Schüller 1929, Walczak 1948, Kunský, Záruba 1950, Jahn 1963, Prosová 1963). Sorted patterns located on flattened watershed ridges are found above the reconstructed Pleistocene snowline. Patterned ground is typically developed as oval stone circles of various diameters, up to 1.5-3.5 m, with a debris island in the middle part (Prosová 1963, Czudek 1997).

Most regular is patterned ground supported by metamorphic rocks, gneiss and schist (Prosová 1963, Traczyk 1995, Klementowski 1998). It often occupies extensive terrains and consists of interconnected sorted circles with vegetated cells. Individual cells do not exceed 1.5 m in diameter and debris within the circles shows clear signs of frost sorting, including vertical arrangements of platy clasts. Stone circles developed on granite in the Karkonosze are larger than those on schist and may occasionally be as much as 6 m across (Sekyra 1964); however, they are less regular, poorly sorted, and lack a central debris island.

Differences between sorted patterns are attributed to contrasts in grain-size characteristics of regolith developed on granite and gneiss or schist and consequent susceptibility to frost heave. The former is predominantly sandy whereas the latter contains grus, silt and clay. Traczyk (1995) suggests that deflation of snow may have enhanced the development of patterned ground on mountain-top surfaces. Exposed surfaces lacking the insulating cover of snow drift would have been subjected to more frequent and efficient freezing and frost heave.

Most patterned ground in the Sudetes is considered to be inherited from the Late Glacial but the debate continues as to their contemporaneous activity. Klementowski (1998) maintains that frost sorting is active on Mt. Śnieżnik nowadays, and measurements of recent cryogenic processes in the summit part of the Karkonosze suggest the same (Soukopová et al. 1995). Specific geoecological circumstances and destruction of vegetation cover may also contribute to the present-day development of small sorted patterns (Pelíšek 1974, Traczyk 1992). In addition to sorted patterns, non-sorted patterned ground is occasionally present, taking the form of earth hummocks (thufur). Earth hummocks occur in the same localities as sorted patterns do.

3.8. Loess and loess-like deposits

Loess and loess-like cover deposits are ubiquitous in the foreland of the Middle and East Sudetes, yet in the mountains their extent is restricted to isolated patches in low-elevated parts. Most frequent are loessic deposits in the upland areas of the West Sudetes (Izera, Kaczawa and Bolków Upland), where they often occur close to basalt outcrops. Their thickness is usually less than 2 m and only locally exceeds 4 m. No characteristic erosional landscapes developed in loess are present anywhere in the Sudetes, except individual gullies along valley-sides. In the intramontane basins sizeable loess covers have been mapped only in the northern part of the Kłodzko Basin. The upper altitudinal limit of loess occurrence appears to be at elevation of 400–450 m a.s.l.

Patterns of regional distribution of loess point to two major controls on loess occurrence, i.e. local relief and altitude, and bedrock, chiefly its susceptibility to microgelivation. Loess covers seem to be preferentially associated with rock outcrops which release substantial amounts of silt if subjected to mechanical weathering, such as basalt and low-grade metamorphic schist. Most silt and fine sand constituted loess are thus likely to be winnowed from local regolith and alluvium, hence the deposits would be largely autochthonous. In the absence of abundant local sources, far-travelled aeolian silt particles were incorporated into slope solifluction covers as suggested by silt-rich (30–40%) solifluction deposits in the granite area of the Jelenia Góra Basin where loess-like deposits are absent.

Loess and loess-like deposits usually overlie solifluction diamictites, forming the superficial sedimentary unit, hence their age is inferred to be Late Pleistocene. Subtle layering and admixture of sand and fine debris are quite common in their lower horizons, demonstrating the role of slope mass wasting in the initial phase of the origin of silty deposits. Towards the end of the Pleistocene the role of aeolian deposition became dominant.

4. Lithological control on cold climate landform distribution

In the light of the evidence reviewed above lithology emerges as an important factor controlling both the range of occurrences of cold-climate landforms in the Sudetes as well as their characteristics. It appears as if no landforms exist that would occur in all lithologies present in the area. The only exception is talus slopes, but it can be doubted if these are periglacial *sensu stricto*; stress release after fluvial incision and paraglacial conditions in former glacial cirques are viable alternatives of their origin.

Some landforms tend to be preferentially supported by certain rock types only. Rock glaciers and blockstreams are clearly associated with massive, well-jointed rocks such as fine grained granite, hornfels, quartzite and gabbro. Blockfields have a wider range of occurrences but they are apparently absent on low-grade metamorphic schist and most sedimentary rocks which do not produce coarse debris or blocks in sufficient quantities. Supposedly cryogenic terraces and summit flats in the Karkonosze are apparent on metamorphic rocks, sporadic on fine-grained granite, and apparently absent on coarse-grained granite. A tempting hypothesis that the terraces are in fact structural features is yet to be tested. Furthermore, characteristics of landforms of the same origin markedly differ according to the lithology involved as illustrated by patterned ground. Stone circles in gneiss and schist do not exceed 1–1.5 m in diameter and are fairly well sorted whilst granite gives rise to much larger cells, up to 3 m. Individual blocks can be over 1 m long.

Special attention ought to be paid to frost-riven cliffs and associated cryoplanation benches. These have been considered as the most characteristic Pleistocene landforms in the upland and mountain terrain of the Sudetes and in many accounts bedrock projections have been almost uncritically referred to as frost-riven cliffs. However, detailed examination shows that they are influenced by structure and lithology to a much higher degree than assumed. First, strong lithological control on their distribution becomes immediately apparent. Rock steps and tors appear to be common in gneissic-schistose complexes and greenstone, less so in gabbro, serpentinite and basalt, and are virtually unknown from low-grade metamorphic or sedimentary rocks other than Upper Cretaceous quartz sandstones. Tors in granite have a different origin as these have been excavated from deep weathering profiles rather than owe their existence to periglacial frost weathering and altiplanation. In turn, in sandstone and conglomerate they occur within structural escarpments and are hardly ever associated with terraces. Second, some of the risers simply reflect a local occurrence of more resistant rock, for instance quartzite lenses amidst gneiss or schist (cf. Martini 1979). Third, it is largely unknown to what extent joint density controls the location of tors and cliffs, but in most outcrops the bedrock is massive, with primary joints spaced apart by at least 0.5 m, often following a rectangular pattern. Fourth, no instances have been reported of 'frost-riven cliffs' which would cut diagonally lithological boundaries, thereby showing unequivocally the primacy of climatic factors over local controls.

Given the evidence above and realising that the utmost importance of frost wedging in the development of rock steps is only inferred from the presence of angular debris below the steps and has never been actually proved, it is difficult to sustain the assertion of Czudek (1993: 73) that '*[geological structure] by itself is not decisive*.'

Slope cover deposits are developed on a variety of lithologies, yet their characteristics and subdivisions show again the importance of bedrock properties. Grain size parameters of weathered bedrock control the structure and texture of cover deposits and determine the rheology of the active layer, and hence the infiltration, depth of summer thaw, susceptibility to frost heave and ground ice volume. Coarse blocky regolith produced by quartzite or fine-grained granite, with a negligible amount of fine fraction, did not provide an effective barrier to infiltration, frost heave and ground ice development were limited and the thickness of active layer

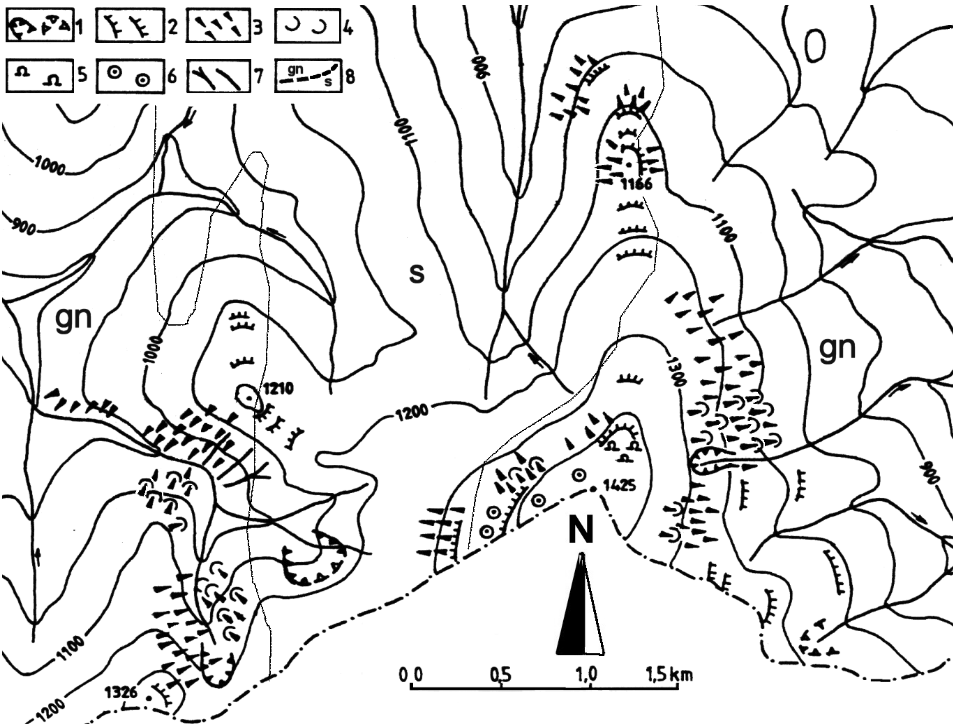

Figure 9: Cold-climate landforms in the summit part of the Śnieżnik Massif (after Traczyk 1996a, modified). 1 – possible nivation hollows, 2 – frost-riven cliffs, 3 – block-debris covers, 4 – solifluction tongues within the block-debris covers, 5 – earth hummocks (thufurs), 6 – sorted circles, 7 – corrasion chutes. Dashed lines denote lithological boundaries (gn – gneiss, s – metamorphic schist).

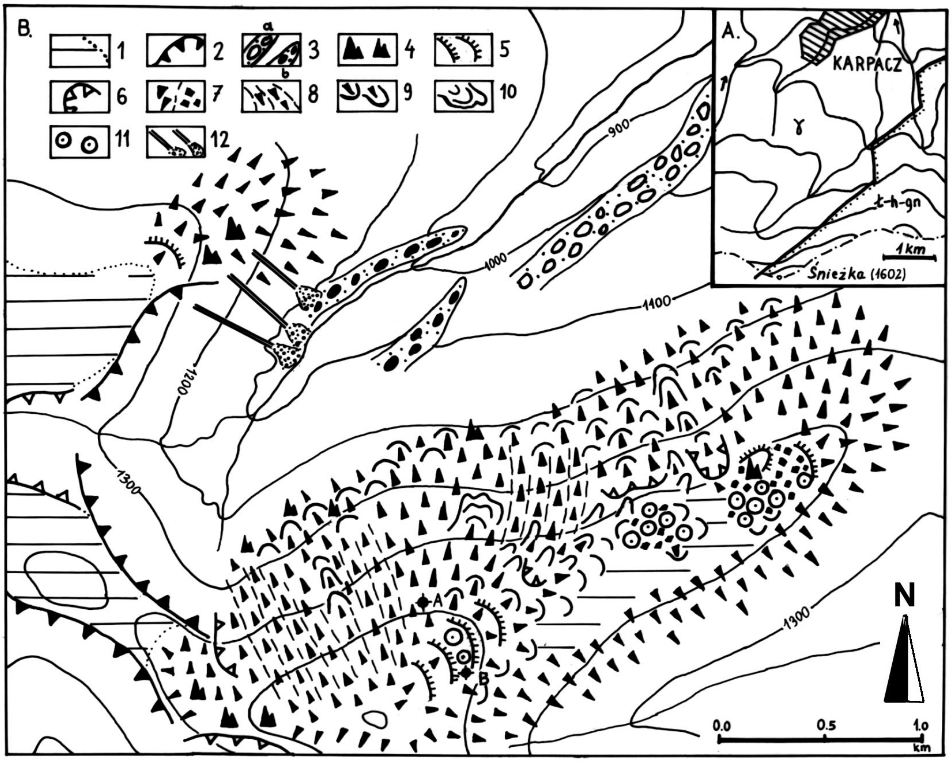

Figure10: Cold-climate landforms in the eastern part of the Karkonosze, including Mt. Śnieżka (1602 m). Inset shows the course of geological boundaries between granite (g) and schist (ł-h-gn) (after Traczyk 1995). 1 – summit planation surface, 2 – glacial cirques, 3 – moraine ridges, older (Riss?) (a) and younger (Würm) (b), 4 – tors, 5 – frost-riven cliffs, 6 – nivation hollows, 7 – blockslopes and blockfields, 8 – block-debris covers with stone stripes, 9 – streamlined forms within blockslope, 10 – incipient rock glacier, 11 – patterned ground, 12 – debris flow tracks and cones.

was in order of a few meters. The resultant slope cover was a blocky mantle transported through permafrost or talus creep. Typical solifluction mantles derived from transport of heterogenic regolith, produced by most Sudetic rocks. Fine-grained stratified deposits were associated with rocks disintegrating into predominantly fine material and supporting a thin active layer; hence shallow sheet solifluction was favoured.

The aforementioned examples of lithological control on the distribution and attributes of Pleistocene landforms and deposits in the Sudetes are summarised in the table below that attempts to relate rock type, predominant type of breakdown and characteristic landforms. It should be noted that it intends to give a general picture; the actual relationships in specific places may be modified by local relief and available time scales (Fig. 9, 10).

The issue of lithological and structural control on periglacial phenomena has long been relatively neglected in comparison to that of climatic control, although distinct rock–landform relationships could have been inferred from many reports, for example in Szekely (1982). Recent re-assessment of some fundamental tenets of periglacial geomorphology (cf. Thorn 1992) has contributed to a revival of interest. French (1996) asserts that periglacial slope morphology is primarily controlled by the underlying bedrock, whereas an extensive survey of periglacial phenomena in Great Britain led Ballantyne and Harris (1994: 187) to conclude that '*Lithology is the dominant influence on the range of periglacial phenomena present on any mountain*'. This statement is evidently confirmed in the Sudetes, although inherited local relief and specific events in the Quaternary history may have altered the Pleistocene evolution of different slopes resulting in various landform and deposit assemblages.

Table 1: Range of features according to jointing and predominant type of breakdown

Jointing	Predominant type of breakdown	Rocks	Landforms and deposits
wide spacing	macrogelivation	some granites	mountain-top blockfields, tors, locally openwork blockslopes & rock glaciers
wide spacing	macrogelivation and granular desintegration	coarse granite, granitogneiss, gabbro, some sandstone	diamictic blockfields, rock glaciers, tors and rock steps, large sorted circles; coarse stony diamictons on slopes
wide spacing	macrogelivation and microgelivation	ryolite, some basalt	locally blockslopes on very step slopes, heterogeneous mountain-top diamictons, steps and terraces, talus slopes; heterogeneous slope diamictons (clasts big)
dense spacing	macrogelivation	some basalt, quartzite, hornfels	blockfields, but blocks smaller than if joint spacing is wide, openwork blockslopes and blockstreams
dense spacing	macrogelivation and granular disintegration	some sandstone	sandy regoliths (clasts small)
dense spacing	macrogelivation and microgelivation	gneiss, limestone, greenstone, serpentinitecircles;	cliffs and terraces, heterogeneous mountain-top diamictons, small sorted heterogeneous slope diamictons (clasts small)
dense spacing	microgelivation	marls, mudstones	no obvious landforms; fine-grained solifluction sheets
schistosity	macrogelivation and microgelivation	mica schist	cliffs and terraces, heterogeneous mountain-top diamictons, small sorted circles; heterogeneous slope diamictons (clasts small)
schistosity	microgelivation	low-grade metamorphic schists, shales	no obvious landforms; fine-grained solifluction sheets

5. Slope morphological system of cold climate landforms

Regularities in the slope evolution in the Sudetes under periglacial conditions have been sought by a few authors, including Jahn's (1980) early claim that slopes developed a characteristic convex-concave longitudinal profile. Reservations to the above generalisation arise for two reasons. First, as has been pointed out by French (1996: 172), convex-concave slopes seem rare in the present-day periglacial zone. Hence, their existence in the former periglacial zone might partially be the effect of Tertiary inheritance. Second, Sudetic slopes display a whole variety of long profiles, acquired in the course of long-term denudational history influenced by complex lithology, tectonics, depth and intensity of erosional downcutting, and changing climates. Simple convex-concave slopes do occur, yet in other places they consist of several individual convex-concave segments. Moreover, other slope types such as rectilinear, stepped, pediment-like and concave can all be found in the Sudetes.

This slope form variety undoubtedly has its origin in the extremely diverse bedrock and complex geomorphic history of the Sudetes. Steep rectilinear slopes have developed upon resistant bedrock and tend to occur in the highest parts of the Sudetes; the regular pyramid of Mt. Śnieżka might serve as an example. Convex-concave slopes include worn-down scarps of tectonic origin, such as along the Sudetic Marginal Fault, and most slopes in moderately dissected mountain ranges. Very often, however, a few successive convex-concave segments can be distinguished and related to either lithological differences or stages in erosional downcutting. Stepped slopes, consisting of alternating short steep segments and benches, are most characteristic for the elevated parts of crystalline massifs and considered as classic periglacial altiplanation slopes (Czudek 1964). Stepped profiles are also common along valley spurs. The influence of unequal bedrock resistance on their form, whether related to lithology or jointing/foliation, seems considerable. It is not yet known if extensive planar surfaces, such as summit flats, might have formed through cryoplanation if no 'preglacial' mountain-top surface existed prior to the Pleistocene. Observations from the Ślęża Massif (Sudetic Foreland) suggest that extensive mid-slope benches are pre-Pleistocene features, subsequently subjected only to some reshaping under cold climate conditions (Szczepankiewicz 1958, Migoń 1997a, Żurawek, Migoń 2000).

Another category includes smooth pediment-like slopes inclined less than 5–8° surrounding more elevated blocks. Czudek (1988, 1997) refers to them as cryopediments, although he also admits that they are best developed in weakly consolidated sedimentary rocks and their evolution as footslope surfaces began in the Pliocene. Finally, concave slopes consisting of a free face, or more often closely spaced rock outcrops, in the upper part and talus or scree below, occur in the Sudetes, though these are relatively rare. They are restricted to former glacial cirques, valley-sides of deep fluvial incisions, most prominent monadnocks and selected cuesta faces. Whilst the history of the latter two can be traced back to pre-Pleistocene times, some of the former are undoubtedly of Pleistocene age, as the incisions are genetically connected with the advance and decay of the Scandinavian ice-sheets. Cirques are obviously Pleistocene landforms as well.

From the above it follows that periglacial slope processes were operating within the landscape, the principal features of which had already been established. Their effects were different according to differences in inherited relief and aspect. Slope inclination appears as the most important factor to have controlled slope evolution in the Pleistocene because it determined the mode and intensity of mass wasting. Its efficacy was modified by aspect which exerted control on the depth of summer thaw and hence availability of water.

The general morphogenetic subdivision of slopes involves two broad categories (Fig. 11). The ‘A’ category denotes slopes which were dominated by slow mass movement, solifluction, supplemented by slope wash in the lower part, and includes convex-concave, stepped and pediment-like slopes. Gravitational rectilinear and concave slopes form the ‘B’ category. The ‘B’-slopes are invariably steeper (30–40°) than the ‘A’-ones (<20–30°).

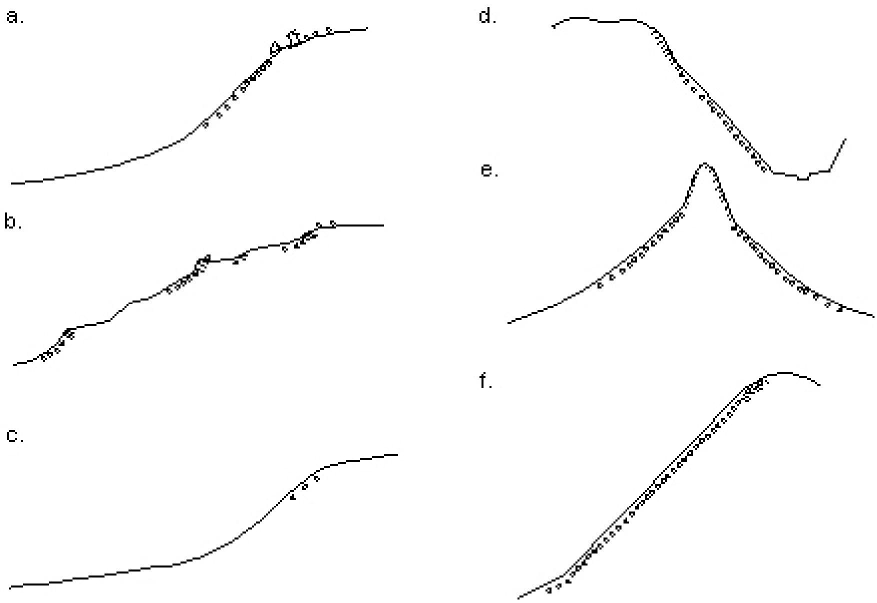

Figure 11: A cartoon to show the variety of slope forms and associated cover sediments in the Sudetes (not to scale).
a – convex-concave, b – stepped, c – pediment-like, d – ‘free face’–gravitational slope on valley sides, e – ‘free face’–gravitational slope of monadnocks, f – rectilinear.

Solifluction was the dominant mass transport process on the ‘A’-slopes, affecting their entire length. It may have been slowed down on local mid-slope flattenings, but these did not act as areas of deposition as suggested by the absence of thick solifluction mantles. Textural variation can be recognised in cover deposits which are dominated by blocks and debris in the upper slope, blocks or debris and heterogeneous loam in the middle slope, and sandy/silty loam with an admixture of debris in the lower slope. This change along the slope may be repetitive if there occur extensive planar surfaces interrupting the long profile. Rock outcrops and sporadic blockfields tend to occur in the upper slopes and along convex slope breaks.

Slope wash may have prevailed over gelifluction in the lower slopes, where the availability of water increased in the period of summer melt of permafrost and snow patches (Jahn 1970). As a result, solifluction mantles became depleted of fines which were progressively washed downslope and were moving more slowly than higher up the slope. Fine material, in turn, was either deposited at the footslope as slope-wash sediments or carried away by rivers. Given the general scarcity of fine material in the regolith developed from crystalline rocks and the secondary depletion due to slope wash, the absence of thick solifluction mantles on the lower slope and the piedmont angle, so characteristic for the Sudetes, becomes more understandable. Even in the front of the fault-generated NE escarpment of the Sudetes, Pleistocene slope-derived sediments are thin, between 0.5 and 2 m (Dumanowski 1961b), although their cover is laterally extensive.

In summary, Pleistocene denudation was most effective in the upper slope sections where the combined effects of mechanical weathering and mass movement accentuated lithological and structural variations in bedrock, resulting in the common assemblage of tors, sinuous rock steps, blockfields and local flats; it is however debatable if these processes were decisive. In the lower slopes the tendency to diversify the relief was replaced by the trend to smooth it through accumulation of solifluction and slope wash deposits, locally aided by sedimentation of loess, as has already been emphasised by Jahn (1980).

The 'B'-type slopes consist of two diverse morphogenetic zones. The upper one is the zone of degradation and abounds in rock outcrops shedding debris to the slope below, although laterally extensive free faces are almost absent in the Sudetes, except some sandstone escarpments. The lower zone is depositional and may include gravitational rectilinear talus slope segment and/or blockslope segment, often with distinctive relief of blockstreams, solifluction terracettes and rock glaciers (='kurum slope'), and characteristic open-work textures indicative of the former presence of cementation ice. However, blockslopes may also occur along the entire slope length.

Although geological structure and inherited relief have clearly played the dominant part in the Pleistocene slope evolution, in the northern part of the mountains glaciation was an additional factor. Ice-sheets could either cover and abrade the whole length of slopes or buttress them to certain height, in both cases interfering with the course of their periglacial evolution. This point is addressed in the next part of the paper.

6. Saalian trimlines and nunatak morphology

It has long been recognised that two Scandinavian ice sheets, the Elsterian and Saalian, covered the Sudetic Foreland and reached their maximum extent on the northern slopes of the Sudetes (Schwarzbach 1942; Badura et al. 1992; Badura, Przybylski 1998; Nývlt 1998); at least one of these invaded intramontane basins leaving till, varved clay and various outwash deposits. Much effort has been spent to identify the maximum vertical extent of the ice sheet surface using the erratics and till patches (Schwarzbach 1942; Szczepankiewicz 1958; Gaba 1972), but surprisingly the possible differences in the course of landform evolution between ice-free and ice-covered slopes, especially on nunataks, have long escaped closer attention.

Martini (1969: 366) was probably the first who recognised the problem working on former nunataks in the Bolków Upland and stated that the well developed tor and altiplanation terrace morphology *'(...) may be considered as the cumulative effect of several periglacial periods'*. Distinctive rock outcrop morphology on Elsterian nunataks in Lausitzer Bergland (West Sudetes) has been interpreted in a similar way (Präger 1987).

The consequences of nunatak history for long-term landform evolution have recently been more extensively considered on the example of Mt. Ślęża (718 m a.s.l.) (Żurawek, Migoń 2000). It has been concluded that a distinct trimline exists at c. 500–550 m a.s.l., which separates the hill top from lower slopes. The former bears the evidence of effective denudation during the Pleistocene and the Tertiary, in the form of numerous tors and rock steps, mid-slope benches, talus and block fields; the latter are generally smooth and covered by block streams solifluction sheets and loess, except for a few rock glaciers. Benches and tors are very rare, as are autochthonous block fields. It has been hypothesised that slopes below 500 m a.s.l. were trimmed by the Saalian ice sheet and during the last glaciation acted as the zone of sediment transfer; the time span after the decay of the Saalian ice sheet has been too short to allow for redevelopment of 'periglacial' hillslope morphology. If this is correct, there are important implications for the assessment of the efficacy of periglacial denudation. It appears that hundreds of thousand of years are required to produce landform assemblages considered as characteristic for periglacial environment. This statement is in accord with recent understanding of time constraints for a well developed high latitude cold climate bedrock morphology (French, Harry 1992; Ballantyne, Harris 1994; French 1996).

The evidence from Mt. Ślęża suggests that remnants of Saalian trimlines ought to occur in other parts of the Sudetes as well. The two highest basalt elevations in the Kaczawa Upland (West Sudetes), Mt. Ostrzyca (501 m a.s.l.) and Muchowskie Hills (475 m a.s.l.), stand 100–150 m above the surrounding plains and both bear the rich assemblage of rock outcrops, rock-cut benches, block fields and block streams in their upper parts (Maciejak 1988; Zygmunt 2000). Since adjacent but lower basalt hills do not possess comparable morphology, having smooth summits and gentle slopes instead, the trimline could be inferred as occurring at an elevation of c. 420–450 m a.s.l. A comparable feature may be expected in the Eastern Sudetes, but no research has been carried out yet.

It appears that Pleistocene continental glaciations in the Sudetes, although being rather brief geological episodes, have played an important part in determining the evolution of cold climate non-glacial landforms. In the foreland and marginal uplands ice sheets were capable of obliterating the evidence of older periglacial morphology, if such existed, and left behind smooth slopes covered by glacigenic sediments. Inselberg-like hills in the Sudetic Foreland were overridden by ice-sheets more than once and they lack any distinctive 'periglacial' morphology, except their most elevated parts above 500 m a.s.l. (Migoń 1997a). Post-Saalian morphogenesis appears to have been of insufficient duration to have re-created 'periglacial' denudational rock slope morphology and the glacially trimmed slopes acted as zones of transport and deposition. In contrast, the development of cold climate landforms on the former nunataks and in the extraglacial zone continued undisturbed and resulted in distinctive morphology by the end of the Pleistocene. Hence it is unreasonable to emphasise only the morphogenetic role of the last glacial period, although generally thin covers of slope sediments can hardly be considered as the cumulative result of periglacial accumulation throughout the Pleistocene.

7. Conclusions

The Sudetes have the whole range of landforms and deposits, traditionally regarded as the evidence of powerful periglacial morphogenesis in the Pleistocene. Most prominent of these are blockfields and blockslopes, frost-riven cliffs, tors and cryoplanation terraces, solifluction mantles and loess covers at lower altitudes. Rock glaciers, talus slopes and patterned ground are also present, although less widespread.

The influence of lithology and structure on the development of cold climate morphology is profound. Diverse response of rocks to weathering resulted in the production of different types of regolith, which in turn showed different susceptibility to frost sorting, heave and development of ground ice. Therefore, specific suites of landforms and deposits have developed according to lithology.

Variability in the geological structure and inherited pre-Pleistocene relief were responsible for the variety of slope form in the Sudetes and influenced the course of periglacial slope development. The majority of slopes were dominated by solifluction, supplemented by slope wash in the lower part, and these include convex-concave, stepped and pediment-like slopes, with a slope gradient less of than 20–30°. Less widespread were steep (30–40°) gravitational rectilinear and concave slopes, interspersed with rock outcrops or a free face above. Notwithstanding these differences, in both cases cold-climate processes were acting towards smoothing the lower slopes through accumulation and enhancing lithological and structural contrasts in the upper slopes through selective physical weathering, but no uniform characteristic 'periglacial' slope profile has been created.

Inland glaciation of the Sudetes had a strong impact on the evolution of periglacial erosional landscapes which appear to have two contrasting 'ages'. Notwithstanding lithological differences, best developed associations of tor-like features, terraces, blockfields and blockstreams occur outside the limit of continental glaciation, i.e. in the extraglacial zone. In the formerly glaciated low-elevated part of the Sudetes and their foreland respective landforms are very rare and never as impressive. The slopes are mantled by glacial deposits, solifluction sheets derived from them, and by loess and loess-like sediments. On the former nunataks a trimline can be quite accurately mapped. It is thus suggested that periglacial relief of the upper Sudetes is the cumulative effect of many successive cold periods during the Pleistocene and the last glacial period alone was not long enough to produce comparable morphology on glacially trimmed slopes. This relatively limited efficacy of periglacial processes seems to reflect the resistance of crystalline rocks in the Sudetes and stands in contrast to the nearby Flysh Carpathians, where the effects of periglacial denudation recorded in the thickness of slope covers are much more impressive.

This systematic review shows that in areas which have a long history of geomorphic evolution and are so diverse lithologically, such as the Sudetes, non-climatic factors of lithology and structure, inherited relief and available time exert crucial control on the development of landforms traditionally regarded as primarily climate-dependent. Each landscape facet was following its own way of development, often contrasting each other, and a purely climatic approach to the Pleistocene morphogenesis evidently oversimplifies the geomorphological reality.

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SOUBOR POVRCHOVÝCH TVARŮ CHLADNÉHO KLIMATU V SUDETECH. VLIVY LITOLOGIE, RELIÉFU A HISTORIE ZALEDNĚNÍ

Résumé

V Sudetech je vyvinut rozsáhlý soubor povrchových tvarů a sedimentů, tradičně popisovaných jako periglaciální: kamenná moře a sutě na svazích, mrazové sruby, tory a kryoplanační terasy, soliflukční pláště, kamenné ledovce, strukturní půdy a sprašové pokryvy. Tato práce zkoumá vliv, který může mít na jejich vývoj

litologie, geologická stavba, zděděný reliéf a čas. Je ukázáno, že různé typy hornin vedou k různým asociacím povrchových tvarů chladného klimatu. Kamenné ledovce, suťová pole a proudy vznikají na masivních horninách s dobrými lomovými vlastnostmi, zatímco kryogenní terasy, skalní stupně, strukturní půdy a heterogenní soliflukční pláště jsou typické převážně pro metamorfované horniny. Nápadné povrchové tvary se nevyskytují na horninách rozpadajících se mikrogelivací. Vliv litologie a stavby na vývoj tvarů reliéfu v chladném klimatu je podstatný. Rozmanitá reakce hornin na zvětrávání vedla ke vzniku různých typů regolitu, což se projevilo v různé citlivosti na mrazové třídění, načechrání a vznik půdního ledu.

Rozmanitost svahových forem je převážně zděděná z předpleistocenního období a zahrnuje konvexně-konkávní, stupňovité, pedimentové a další typy svahů. Značný vliv na vývoj periglaciálních erozních tvarů mělo horské zalednění Sudet, které jeví rysy dvou odlišných „stáří“. Je ukázáno, že skalní periglaciální reliéf Sudet vznikal kumulativním působením řady chladných období v pleistocénu a poslední glaciál byl pouze málo významný. Na rozdíl od toho rozsáhlé svahové sedimenty jsou převážně z období posledního glaciálu. Poměrně malá účinnost periglaciálních procesů v Sudetech odráží resistenci krystalických hornin vůči zvětrávání v chladných podmínkách. Nápadné jsou v tomto smyslu rozdíly při porovnání s blízkými flyšovými Karpaty, kde jsou účinky periglaciální denudace, dokumentované mocností zvětralin na svazích, podstatně výraznější. Systematický výzkum ukazuje, že v oblastech s dlouhou historií geomorfologického vývoje, které se velmi liší litologicky, jsou neklimatické faktory litologie, geologické stavby, zděděného reliéfu a času pro vývoj povrchových tvarů, pokládaných tradičně za primárně klimatického původu, rozhodující.