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GEOMORPHIC DIVERSITY OF THE SUDETES – EFFECTS OF STRUCTURE AND GLOBAL CHANGE SUPERIMPOSED

PIOTR MIGOŃ
Department of Geography and Regional Development, University of Wrocław,
Plac Uniwersytecki 1, 50-137 Wrocław, Poland;
E-mail: piotr.migon@ uni.wroc.pl

Abstract: The Sudetes are mountains of outstanding geomorphic diversity. Reasons reside in lithological and structural variability of bedrock and protracted history of landscape evolution spanning at least the entire Cenozoic. Over this time span, global changes have exerted a key control on the geomorphic evolution of the Sudetes. Late Cenozoic mountain building in the Alpine-Carpathian region induced differential uplift of the Sudetes and radically changed its geomorphic environment, from one typified by a landscape of low relief to one of increasing relief energy and accelerated erosion. Environmental changes were equally profound but their geomorphic effect is less obvious, except for the widespread presence of periglacial landforms of Pleistocene age and localized occurrence of glacial cirques and moraines in the Karkonosze Mts. At the same time, rock control on the location and shape of individual landforms is evident and large tracts of the Sudetes may be described as having structural morphology. Therefore, unequivocal recognition of relief generations in the Sudetes is problematic.

Key words: geomorphology, geodiversity, global change, rock control, the Sudetes

INTRODUCTION

Geodiversity is defined as the natural range of geological, geomorphological and soil features and includes their assemblages, relationships, properties, interpretations and systems (Gray, 2004). In this understanding, geodiversity of the Sudetes is outstanding and its most visible evidence is the variety of landforms in the region. Not only are they diverse morphologically (Fig. 1), which to a large extent reflects the structural and lithological complexity of the Sudetes, but also genetically, being related to different processes operating with different intensities. If one also considers that the physical landscape of the Sudetes has a long geomorphic history whose onset is usually linked with the withdrawal of Cretaceous sea (Jahn 1980) and hence, spans at least the entire Cenozoic, i.e. 65 million years, then it becomes clear that the issue of global change and its consequences is inseparable from an analysis of geomorphological diversity of this mountain range.

The extended timeframe of landscape evolution of the Sudetes has been realized since at least the work by Scupin (1937) and accepted by subsequent researchers who attempted to identify different relief generations in the area (Klimaszewski 1948, Jahn 1953, Walczak 1968). However, their approaches emphasized stage, following the classical thinking by Davis (1899) or King (1953), rather than environmental controls. It was A. Jahn (1980) to explicitly link the geomorphic evolution of the Sudetes with changing global environments for the first

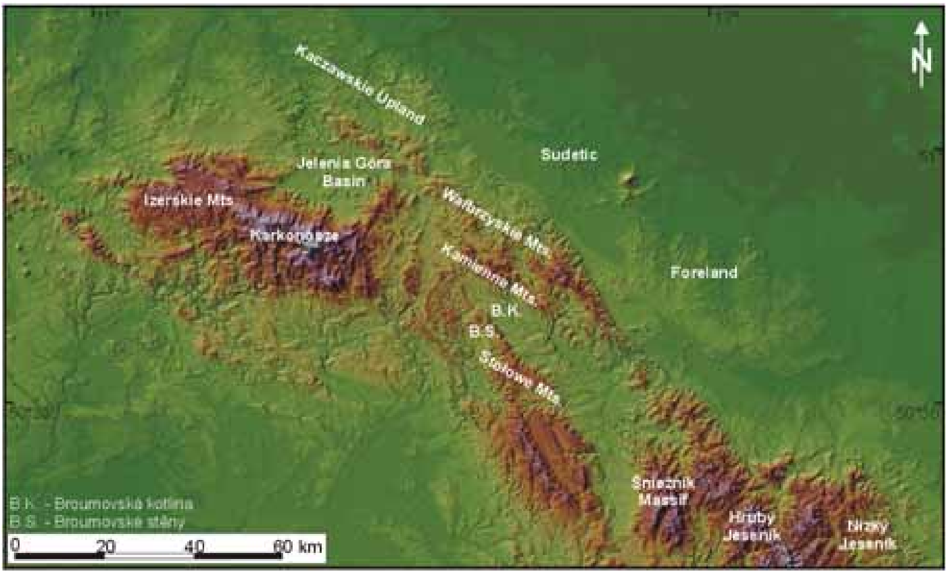

Figure 1. Morphological features of the Sudetes and location of individual mountain massifs.Terrain model generated using Microdem 12.0 software.

time. He reasoned that more than 50 million years of tropical conditions in the present-day central Europe must have left an impact on the morphogenesis strong enough to be still identified today, despite subsequent change towards aridity, temperate climate, and finally, the Pleistocene cold. Indeed, Jahn (1980) focused on the alleged tropical legacy in the Sudetes, being less concerned with landforms of dry or cold climates. In a similar convention, Starkel (1987) looked upon the geomorphic diversity of the Carpathians, but paid equal attention to pre-Quaternary, Pleistocene and recently formed landforms.

The aim of this paper is to show that fundamental controls on the long-term evolution of the Sudetes are related to both rocks and geological structures, largely inherited and conveniently considered as 'passive' controls, as well as major (global) environmental changes experienced by the Sudetes in the Cenozoic. Global change is taken in a broad sense and includes changing tectonic setting of the Sudetes, itself related to global tectonics, in addition to environmental (climatic) changes. Indeed, the latter are often the consequence of continental drift. The focus will be on landforms and geomorphic record rather than Cenozoic deposits in and around the Sudetes, although these will not be neglected. The sources of data used for this paper are mostly published materials, but newly evaluated and interpreted.

GEOMORPHIC DIVERSITY

The immense geomorphic diversity of the Sudetes is revealed at a variety of spatial scales, from regional landscapes to minor landforms. At the regional scale, Sudetes are an assemblage of elevated terrains (massifs), rising to different altitudes from c. 700 m to 1603 m a.s.l., interspersed with intermontane basins of different shape and size (Jahn, 1980; Migoń, 2008a). In contrast to many other mountain ranges, including the Carpathians, the elevated massifs of the Sudetes often have rectangular or rhomboidal outlines (Migoń et al., 2009). Basins are particularly abundant in the western part of the range, whereas in the eastern one highly dissected massifs and extensive uplands dominate (Fig. 1).

Looking more closely, one can recognize that both elevated terrains and basins vary morphologically. Among the former, there are high-altitude tracts of level and gently rolling terrain (e.g. Karkonosze, Izerskie Mts.), highly dissected terrains with abundant steep slopes (e.g. Hrubý Jeseník, Śnieżnik Massif, Kamienne Mts.), uplands with occasional residual ridges and hills (e.g. Nizký Jeseník, Kaczawskie Upland), and inselberg-like massifs, rising by 200–300 m above the surrounding hilly surfaces

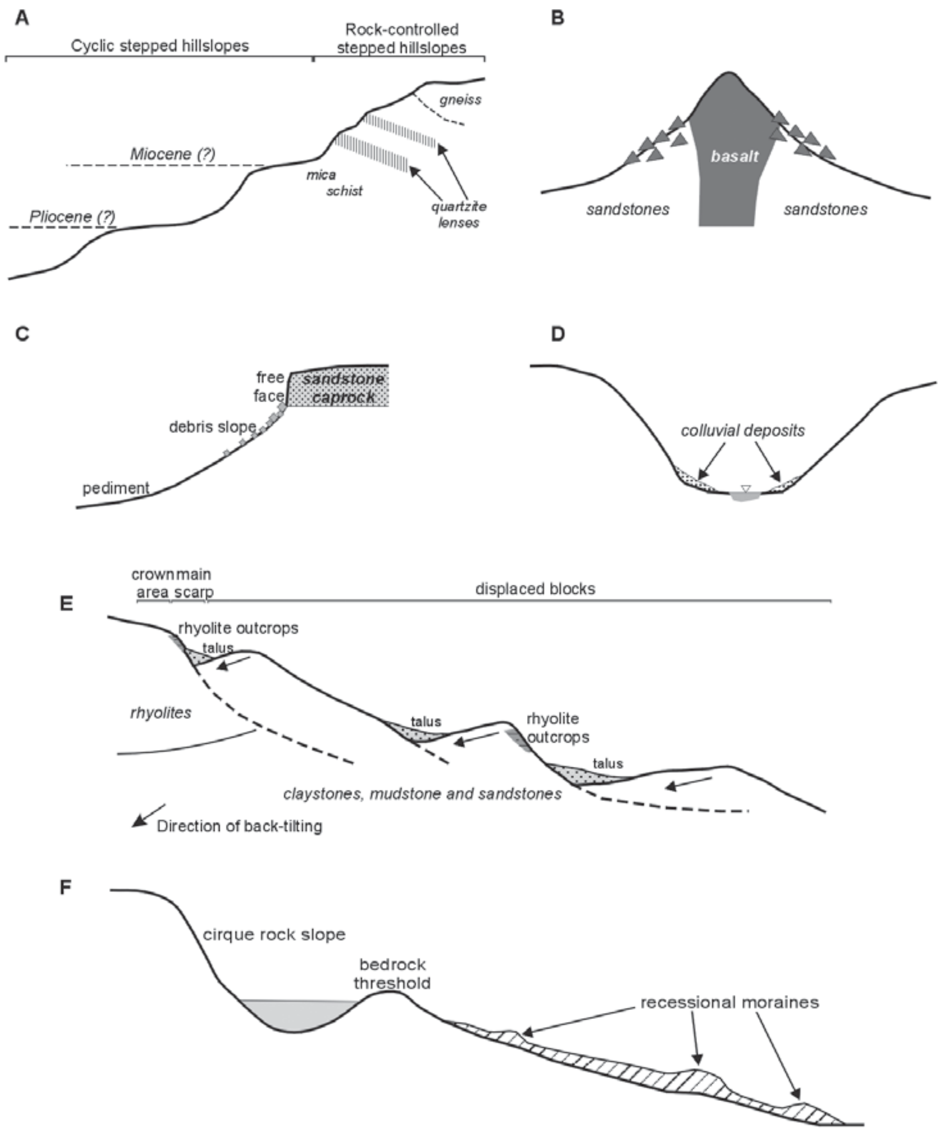

Figure 2. Hillslope diversity in the Sudetes (not to scale).

A – stepped slopes of different origin, B – concave slopes of in ancient volcanic terrain, C – tripartite slope morphology in tablelands and cuesta landscapes, D – straight and convex slopes in river gorges, E – landslide-affected slopes, F – composite slopes in formerly glaciated terrain.

(e.g. Wałbrzyskie Mts.). A very special case is provided by the Stołowe (Table) Mts. in the central part of the Sudetes, which are a vast structural plateau (tableland), developed upon nearly flat-lying sedimentary rocks. To the north-west, the plateau turns into a prolonged escarpment of Broumovské stěny, a classic example of a cuesta. Likewise, basins are morphologically diverse. Some have nearly flat, featureless floors, whereas others host a hilly relief. An example of the latter is the Jelenia Góra Basin, with its abundance of granite inselbergs.

At a smaller scale of inquiry one should notice that hillslopes occur in a variety of shapes (Traczyk and Migoń, 2003) and there is no one 'typical' slope for the Sudetes (Fig. 2). Perhaps most common are stepped hillslopes, within which sloping benches alternate with steeper segments. The latter may have rock cliffs and partly vegetated debris veneers superimposed on them. Reasons for stepped profiles are probably variable and in many cases attributable to changes in lithology or jointing pattern (e.g. Dumanowski, 1964; Martini, 1979). However, very long stepped profiles have also been interpreted in terms of cyclic relief evolution, uplift and slope retreat (Walczak, 1968). Individual pointed peaks, especially those built of Cenozoic volcanic rocks from the basalt family, have their slopes concave, with a steep rock unit in the upper part, grading into less inclined debris slope and finally into a low-angle pediment. In the tableland of the Stołowe Mts. and along many cuesta ridges another variant of concave slope is common (Dumanowski, 1961). It is capped by a thick, resistant bed, usually of quartz sandstone, which forms a rock face up to 40 m high. Talus-covered segment occurs downslope from the free face. Straight and convex slopes line deeply incised river valleys, especially gorges, and these may also have numerous rock cliffs superimposed. Finally, two special cases need mentioning, although neither is very widespread. In the formerly glaciated parts of the Karkonosze hillslopes have highly composite profiles, related to the thickness of moraine accumulation and the history of glaciations (Traczyk, 2009). In the Kamienne Mts landslides are abundant (Synowiec 2003, Migoń et al. 2010) and slopes show complex morphology, with scarps, trenches, benches, hollows, and toe convexities.

As far as minor landforms are concerned, their diversity in the Sudetes is spectacular. Tors are not only abundant, particularly in granite and sandstone terrains, but show a variety of shapes and are of more than one origin (Jahn, 1962; Walczak, 1963; Demek, 1964; Martini, 1969). Exposed rock surfaces are dotted by small-scale features due to selective weathering, such as weathering pits, karren, tafoni, alveoles, and polygonal cracks. In the high-altitude parts of the Sudetes periglacial landforms and structures are widespread, including patterned ground, sorted stripes, earth hummocks, solifluction lobes, and blockfields (e.g. Traczyk and Migoń, 2003; Křížek et al., 2010). Additionally, geomorphic diversity of the Sudetes is enhanced by the presence of bedrock channels, karst landforms, erratic boulders, peat bogs and many other minor features.

GLOBAL CHANGES IN THE CENOZOIC AND THEIR SIGNIFICANCE FOR THE SUDETES

The Cenozoic era was a period of profound environmental changes at the global scale. The key driver of these changes was continental drift, the implications of which for central Europe, hence the Sudetes, were twofold. First, plate movement away from the equator northward was responsible for progressive climatic cooling. Second, continental collision of Africa and Europe resulted in crustal shortening and the origin of the Alps and the Carpathians (Reicherter et al., 2008). Thickening of the crust under the newly created mountain chains generated isostatic response in the forebulge zone. An ancient Variscan orogen of the Sudetes responded in widespread brittle deformation, faulting and differential uplift which continued since probably the late Oligocene until the present-day (Zuchiewicz et al., 2006). As a result, much of the contemporary pattern of mountain massifs and separating basins was directly created through up- and downfaulting, with fault activity continuing to the present-day (e.g. Štěpančíková et al., 2008), whereas enhanced erosion due to increasing relief energy contributed to further relief differentiation and the origin of a range of structural landforms (Placek, 2011). Thus, global tectonic change, not considered explicitly in the past, appears as the fundamental factor to explain the observed geomorphic diversity of the Sudetes.

Jahn (1980) paid considerable attention to the presence of landforms which record geomorphic evolution under tropical conditions. Intermontane basins, planation surfaces, residual granite hills, certain river gorges have all been cited as the legacy of 'tropical Earth'. The process invoked to explain basins and hilly relief was deep weathering acting selectively, supposed to be particularly active in the warm and humid environments of the Palaeogene. Indeed, there is now abundant evidence from central and western Europe that deep weathering was widespread during this period (Migoń and Lidmar-Bergström, 2001) and that climate was predominantly warm and humid, although not fully tropical (Mosbrugger et al., 2005). In the specific context of the Sudetes, thick weathered mantles have survived in the Sudetic Foreland, under the protective cover of Neogene and Quaternary deposits. They are locally as much as 60–80 m thick and spatially co-existent with residual relief with inselbergs, rock-controlled ridges, uplands, and basins. Following Thomas (1989), these residual landscapes were considered as different types of inherited etchsurfaces (Migoń 1999). Residual landscapes in the Sudetes proper listed by Jahn (1980) may be considered as morphological equivalents of the buried Palaeogene landscapes of the Sudetic Foreland. However, it needs emphasizing that the relevance of global changes to the early Cenozoic morphogenesis of the Sudetes is not limited to climatic control. Equally important was the contemporaneous intraplate setting of the Sudetes, predating continental collision in the Mediterranean realm. Thus, deep weathering and occasional stripping shaped a landscape typified by a low rate of geomorphic change, working slowly towards an origin of rock-controlled, low-relief scenery. Seeking analogues in the tropical savannas is not without reasons (Jahn, 1980).

The impact of subsequent shift towards cooler climate in the Oligocene and return to warmer conditions in the Miocene, especially the Middle Miocene (Mosbrugger et al. 2005), has not been discussed for the Sudetes. However, deeply weathered basalt flows of Early Miocene age, buried by Late Miocene deposits (Stoch et al., 1977), point to efficient weathering environments continuing in the Miocene and a causal relationship with the Middle Miocene warming is likely. On the other hand, Jahn (1980) drew attention to the necessity of periodical stripping of weathering products to make the long-term lowering of weathering profiles feasible. Tectonically-driven shifts in the morphogenetic regimes were suggested but the Oligocene cooling may have contributed to the widespread development of stripped etchsurfaces as well.

The Sudetes proper have retained very little of their weathered mantles which existed in the Palaeogene and their interpretation is not straightforward (Jahn et al., 2000). They may represent roots of truncated saprolites of early Cenozoic age, but there are good reasons to presume that some saprolites, for instance widespread grus in granite terrains, are younger and have formed within established hilly etchsurfaces in the late Cenozoic. The paucity of thicker weathered mantles in the Sudetes is typically seen as a result of accelerated erosion in the late Cenozoic, itself a response to regional uplift and differential faulting. A corollary is the widespread occurrence of thick saprolites in the downfaulted block of the Sudetic Foreland, buried by late Cenozoic deposits derived from the elevated block of the Sudetes (Migoń, 1999).

A disputable issue is the impact, or indeed the very presence, of late Miocene aridity. Jahn (1980) assumed that the long period of humid tropical conditions was followed by a period of aridity which lasted c. 10 per cent of the Cenozoic, but this seems unlikely in the light of more recent findings on palaeoenvironments (Mosbrugger et al., 2005). Later, Głazek and Szynkiewicz (1987) emphasized the significance of the Messinian Crisis which occurred in the latest Miocene, c. 5.5 Ma ago, peaking in the desiccation of the Mediterranean Sea (Hsü et al., 1973; Ryan, 2009). They acknowledged short duration of this episode, but considered it rather severe. They went on to suggest that morphology of the tableland of the Stołowe Mts. may have been largely shaped under the conditions of aridity and hence, similarities with classic tableland relief of dry areas are not only visual. Migoń (1992) reckoned that the apparent transformation of structure-controlled granite domes in the Jelenia Góra Basin into talus-covered hills may have occurred during this geologically brief dry spell. However, no unequivocal evidence has ever been provided and palaeobotanical record for the Miocene/Pliocene transition indicates semihumid environments at most (Sadowska, 1987; Stuchlik, 1987).

By contrast, the legacy of global Quaternary cooling is evident in the Sudetes (Fig. 3), although the chronology of events is far from being established. Three separate issues emerge in this context. First, the northern parts of the Sudetes were reached at least once by the Scandinavian ice sheet, most likely during the Marine Oxygen Isotope Stage 12 (San 2 glaciation). The erosional impact of the ice was limited (Hall and Migoń, 2010) and tracts of pre-existing hilly relief in the marginal uplands have been covered by glacial and outwash deposits, but in other places deeply incised epigenetic gorges were formed. Second, in the most elevated belt of the Karkonosze local glaciers developed, leaving behind cirques and moraines. The longest glacier tongues were up to 5 km long on the southern slope (Engel et al., 2010) and 3.5 km long on the northern slope (Traczyk, 1989). Third, and perhaps most importantly, the non-glaciated parts of the Sudetes represented a periglacial environment. Controlled primarily by lithology and available relief, a whole suite of cold-climate landforms, structures and deposits developed (Traczyk and Migoń,2003).

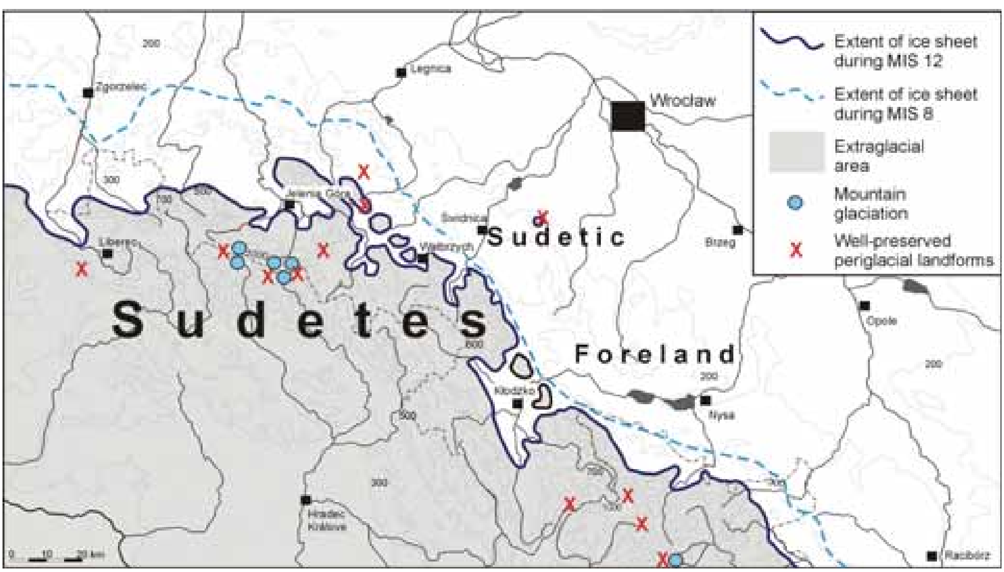

Figure 3. Pleistocene cold-climate legacy in the Sudetes. Probable extents of continental ice sheets after Badura and Przybylski (1998), locations of periglacial landforms after Traczyk and Migoń (2003)

Today, they are best seen above the timberline in the Karkonosze and Hrubý Jeseník (Křížek et al., 2010).

STRUCTURE VERSUS MORPHOLOGY IN THE SUDETES

Given the huge lithological and structural variability in the Sudetes it is rather surprising that, until recently, the issue of rock control in landscape evolution received scant attention. Local studies and observations have not been integrated into a coherent, range-wide picture and the rather outdated hillslope study by Dumanowski (1967) was the only one addressing rock – landform relationships explicitly. Jahn (1980), in his attempt to explain the main geomorphic features of the Sudetes, relegated rock control to a factor of minor importance.

A recent study by Placek (2011, also Placek and Migoń, 2007) contributed significantly to filling the gap. Using GIS tools and an extensive database about rock strength she evaluated relationships between altitude, slope gradients, relief energy and rock resistance at the regional and local scale. The gross morphological features of the Sudetes show limited correlation with rock strength, confirming that they primarily reflect differential faulting. However, even at this scale certain major landforms appear as rock controlled. Mountain ranges of Kamienne Mts. and Wałbrzyskie Mts. owe their existence to very high strength of Permian volcanic rocks and considerable strength differences between volcanic and adjacent sedimentary rocks. Another example is the prominent cuesta of Broumovské stěny, built of mechanically strong Cretaceous sandstones. The huge basin of Broumovská kotlina, sandwiched between the volcanic range of the Kamienne Mts. and the sandstone cuesta and underlain by rather weak Permian deposits, is thus a feature of differential erosion. Hence, it is doubtful if its origin required a phase of tropical morphogenesis as implied by Jahn (1980).

At the scale of medium-size landforms (smaller massifs, isolated hills, escarpments, river gorges), rock strength control is even more evident and has been demonstrated on examples of basalt hills, cuesta landscapes, granite inselbergs, alternating valley morphology, and variable degree of erosional dissection of uplands (Placek, 2011). Surfaces of subdued relief (‘planation surfaces’) are associated with both very strong and rather weak rocks, but required little variation in rock strength and structure to evolve. In lithologically complex terrains planation surfaces could hardly have formed (Placek et al., 2007). In granite massifs it was possible to demonstrate that location and shape of residual hills (inselbergs) reflect either minor lithological differences within an intrusion (coarse versus fine-grained granite) or specific jointing patterns (Migoń, 1997). Domes, conical hills, and boulder inselbergs are examples how form adjusts to the geometry of jointing rather than they are the legacy of changing environmental conditions. Likewise, there is no evidence to sustain the view (Pulina, 1977) that karst landforms in the Sudetes have anything in common with tropical conditions (Migoń, 2009).

DO WE HAVE RELIEF GENERATIONS IN THE SUDETES? – A DISCUSSION

The notion of relief generations comes from the German geomorphological school and was once commonly used as a general framework to carry out morphological analysis of an area (Büdel, 1977; Bremer, 2004). A relief generation in the classical sense denotes a suite of landforms formed under a certain morphoclimatic regime, where a characteristic set of surface processes operates and reflects the contemporaneous environmental conditions. Processes and landforms are therefore in equilibrium with the environment. A change in these conditions brings about a change in morphoclimatic regime and a new assemblage of landforms and surface deposits begins to form. Previous landforms may survive as relicts of the past, or they become erased. However, certain landforms may continue to exist despite the change (Germ. *Weiterbildung*). In an orthodox view, transition from one generation to another is related to major environmental, implicitly global, change. However, rapid uplift of a mountain chain that alters patterns of atmospheric circulation may also result in drastic change in morphoclimatic regime in leeward regions.

Considering the history of global environmental change one might expect at least two distinctive, inherited relief generations in the Sudetes (Fig. 4). These would be an older, tropical (*sensu lato*) relief generation of Palaeogene to Miocene age and a younger generation of Pleistocene age. The lifetimes of their active evolution were vastly different, much longer for the tropical generation, but the relatively recent occurrence of cold climate environment may mean that its geomorphic legacy is more evident. Indeed, despite assertions by Jahn (1980), very few landforms or their assemblages, if any, can be safely shown to be products of tropical morphogenesis, in disequilibrium with subsequent environments. The presence of arid landforms in the Sudetes is even more problematic. Periglacial landforms, although evident at the small scale, are of rather minor importance for the morphology of the Sudetes as a whole.

However, the problem of relief generations in the Sudetes in relation to global change can be also approached in a different way (Fig. 4). As demonstrated earlier in this paper, the fundamental change of global importance was late Cenozoic mountain building in the Alpine-Carpathian region and the resultant uplift of the Sudetes. It changed radically the geomorphic environment, from one typified by a landscape of low relief, with efficient deep weathering and slow, rock-controlled denudation, to one of increasing relief energy, accelerated erosion, and stripping of weathered mantles. Hence, two distinctive relief generations can be potentially identified. The more recent one is

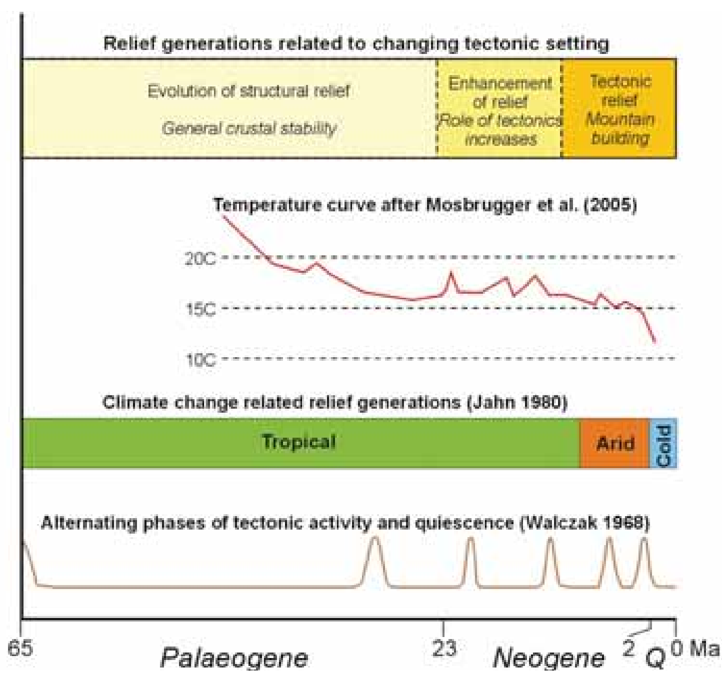

Figure 4. Different conceptual frameworks to identify relief generations in the Sudetes. Temperature curve simplified after Mosbrugger et al. (2005). Mean values from the palaeoclimatic reconstruction from Lusatia (east Germany) were used.

the mountain morphology observed today, developed through differential uplift and associated erosion. An older generation would consist of any landscape units that can be shown to predate the uplift and subsidence in the Neogene, whether they are planation surfaces or not. But such a demonstration is not without problems. The partially buried residual landscape of the Sudetic Foreland, downfaulted in the late Cenozoic, is clearly a component of this older generation (Migoń, 1999). On the other hand, unequivocal demonstration that high-altitude levelled surfaces are early Cenozoic features (see e.g. Walczak, 1968; Demek, 1975; Jahn, 1980) is problematic, since they do not bear any sediments or weathering residuals which can be dated back to the Palaeogene. However, as with climate-controlled relief generations, continuous evolution of certain landforms is possible, especially far from mountain fronts and other core areas of uplift. In the Sudetes, these would include tablelands and cuestas in sedimentary terrains which may have become enhanced in the late Cenozoic but are likely to have much longer geomorphic history.

CONTEMPORARY LANDSCAPE EVOLUTION AND GLOBAL CHANGE SCENARIOS

In recent years, the issue of current global environmental change has entered the research agenda of geomorphologists more evidently than ever before. Attempts are made to define the relevance of geomorphology to the global change debate, to identify the relationships between cause and geomorphic effect, and to predict geomorphic changes to occur in the future (Slaymaker et al., 2009). Moreover, Slaymaker et al. (2009) argue that globally important land use changes have stronger impact on geomorphic systems, especially in short and medium timescales, than disputed climatic change. In Poland, Mojski (2005) urged geomorphologists to be more involved in predicting landform change under global change scenarios.

It is very difficult to predict how, or if, geomorphic evolution of the Sudetes will be affected by currently experienced global environmental change. The contemporary geomorphic system appears to be one of low dynamics and general stability, with more substantial landform changes restricted to rare extreme precipitation events (floods, debris flows) and specific localities in the most elevated parts of the Karkonosze (Migoń, 2008b). On one hand, an increase in frequency of high rainfall events, predicted by many climate change models (e.g. Semmler and Jakob, 2004; Frei et al., 2006), might result in an increasing frequency of flash floods and debris flows. On the other one, temperature rise will result in upslope migration of treeline in the Karkonosze and Hrubý Jeseník, towards glacial cirques and treeless watershed plains, stabilizing their surfaces and limiting scope for debris flows and frost action. Land use changes occur very rapidly in the Sudetes, but their current trend is towards afforestation and grasslands, hence surface stability is generally increasing (Latocha, 2009) Perhaps the most important research question in this context regards the status of relict landslides in the Kamienne Mts. (Migoń et al., 2010). They are features of considerable size, morphologically very clear, yet with no record of historical activity. They are suspected to be of early to mid-Holocene age, but triggering factors remain unknown. If they were related to higher input of water into slope hydrological systems, then an increasing frequency of high rainfall events might affect the threshold of stability and trigger landslide reactivation. If these occur, we will deal with a major change in the geomorphic system of the Sudetes.

CONCLUSIONS

The currently observed geodiversity of the Sudetes, outstanding among other central European mountain ranges, is the combined outcome of profound structural control and major environmental changes. The former is responsible for the origin of a multitude of structural landforms. The latter can be considered as regional manifestations of changes of global dimension. Among them, a shift from general tectonic stability in the early Cenozoic to differential faulting and the origin of horst-and-graben topography in the late Cenozoic, itself related to continental collision in the Mediterranean realm, appears as the most important factor. Consequently, two landform generations may be distinguished. The younger one is the mountain morphology observed today. An older generation consists of those landscape facets which predate differential uplift and subsidence in the Sudetes. They include remnants of planation surfaces, but more varied relief, with inselbergs, uplands and basins as well. Climatic changes experienced in the region during the Cenozoic were profound, but corresponding relief generations, despite previous assertions, are hard to demonstrate unequivocally. In particular, the existence of landforms arising from distinctive tropical morphogenesis is doubtful, as is the presence of morphological indicators of arid conditions. By contrast, cold-climate landforms and structures are evident, but they occur at a rather small scale and are of minor importance for the morphology of the Sudetes as a whole.

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