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Steep slopes in the Sudetes and their morphotectonic interpretation

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The Sudetes is a block-faulted mountain range in Central Europe, at the NE margin of the Bohemian Massif. In the late Cenozoic it has been subject to differential uplift and subsidence and currently represents a horst-and-graben structure, superimposed on older relief due to rock-controlled denudation and erosion. In this paper, the distribution of steep slopes (>15° and >25°) is analyzed using a Digital Elevation Model (DEM) of 50 m spatial resolution, and their morphotectonic significance is discussed. Steep slopes occur in four major settings: heavily dissected and most elevated highlands, straight mountain fronts, narrow sinuous escarpments, and deeply incised river valleys. The former in particular may indicate areas subject to recent uplift, which is followed by efficient fluvial incision, so that little pre-uplift topography has survived. The image of many mountain fronts on the slope map is rather poor, which may be explained by the mechanical weakness of the rock building the footwall. At the same time, the association of the majority of tectonically-induced steep slopes with the most resistant rocks suggests that the intensity of recent uplift is generally low compared with the long-term rates of denudation and erosion.

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INTRODUCTION

One of the very basic tenets of geomorphology holds that the topography of the Earth's surface reflects an interplay of endogenic and exogenic factors and forces, operating at different time scales. Endogenic forces, whether through uplift or subsidence, create relief which is then modified by externally-driven processes of weathering, mass movement and erosion. In particular, high relief is typically taken as a geomorphological proxy of the mean uplift rate exceeding the mean denudation rate. Likewise, a range of specific landforms such as straight escarpments and faceted spurs along mountain fronts, as well as drainage basin parameters, are used to decipher the recent tectonic history of different areas and to indicate spatial differences in the intensity of tectonic deformation (e.g., Bull and McFadden, 1977; Wallace, 1978; Zuchiewicz and McCalpin, 2000; Badura *et al*., 2003, 2007; Pánek, 2004).

This line of research, that is using geomorphology and geomorphometry in particular, to provide an insight into tectonic patterns and processes has been applied at the Sudetes since the mid-1990's (Krzyszkowski *et al*., 1995; Migoń, 1996; Sroka, 1997; Ranoszek, 2001; Badura *et al*., 2003, 2007). However, in the majority of these papers the focus has been on specific mountain fronts rather than being aimed at obtaining a regional picture. In this contribution, we analyze one of the most simple characteristics of the topographic surface, the mean slope gradient, but extend the analysis over the entire Sudetes. Assuming that zones of active tectonics should be associated with higher gradients, we focus on steep slopes, understood as surfaces inclined by more than 15°. The distribution of the steep slopes in the Sudetes is shown, as is the settings in which they occur, whether they can be used as indicators of active tectonic, and, for the Polish part, how their occurrence is controlled by lithology and structure.

STUDY AREA

The Sudetes is a mountain range in Central Europe, which forms the northeastern rim of the Bohemian Massif. It is shared by the Czech Republic, Poland and Germany, and is almost 300 km long and up to 100 km wide (Fig. 1). Reaching a maximum altitude of 1602 m a.s.l. (Mt. Śnieżka), it is the highest range in the Bohemian Massif and is also the most elevated mountain area north of the Alps and the Carpathians.

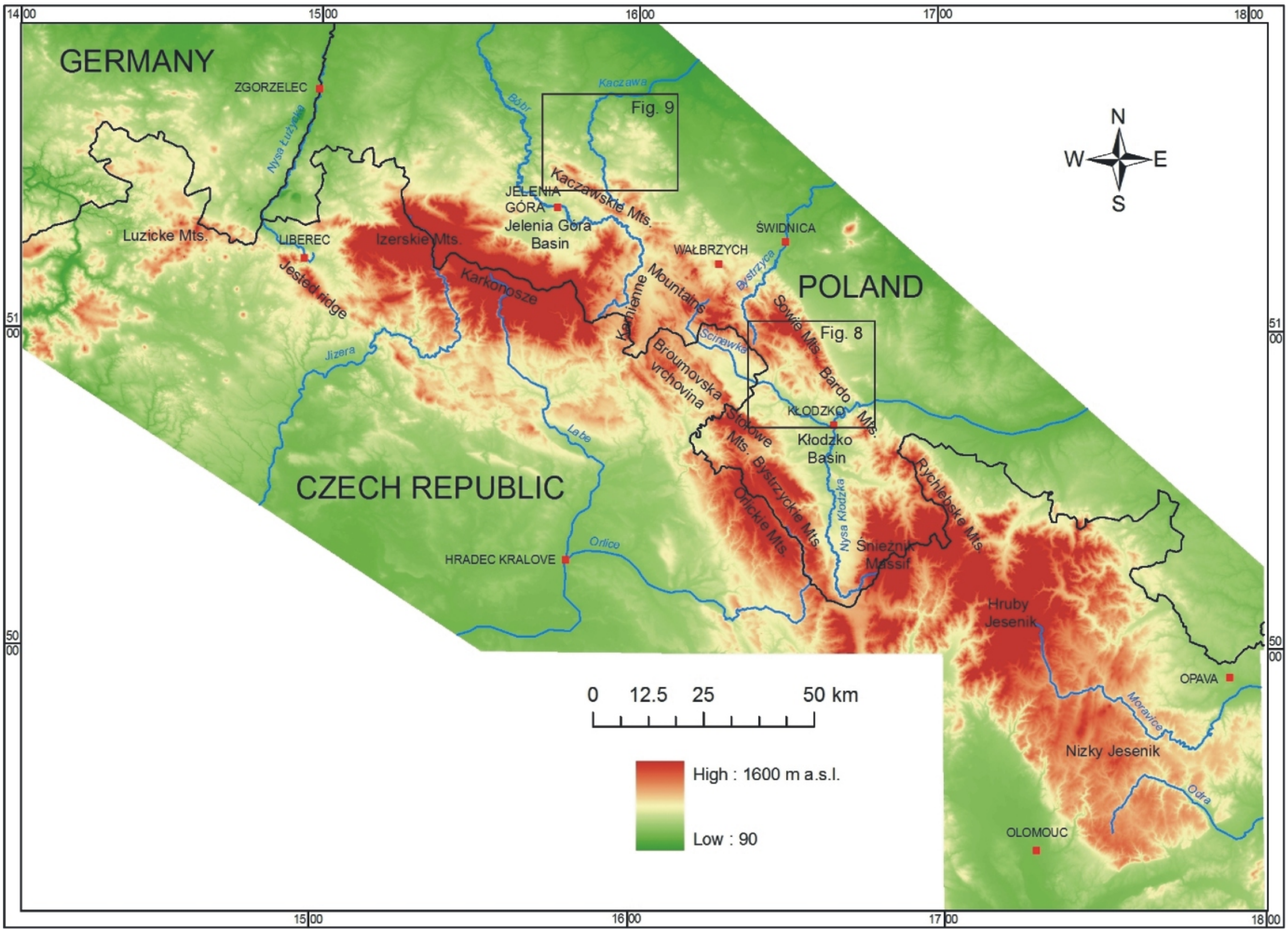

Fig. 1. Location and altitude map of the study area

The geological history of the Sudetes is highly complex and involves many stages of magmatism, sedimentation and deformation, spanning parts of the Precambrian and the entire Phanerozoic (see recent reviews by Aleksandrowski and Mazur, 2002; Żelaźniewicz, 2005; Mazur *et al*., 2006). The ultimate consolidation of the structure took place during the Variscan orogeny in the Devonian and Carboniferous, accompanied by numerous granite intrusions, and was followed by long-lasting, although intermittent terrestrial and marine deposition until the end of the Cretaceous. As a result of this long-term evolution, the Sudetes have become a structural and lithological mosaic, with tens of lithologies occurring side by side (Fig. 2). More importantly in the context of this study, these various lithologies considerably differ in terms of rock strength and resistance against exogenic processes which is reflected in the dissimilar landforms they support (Placek and Migoń, 2007).

In the last 20 million years or so, the Sudetes have been subject to neotectonic uplift and subsidence (Zuchiewicz *et al*., 2006), the effects of which are superimposed onto the residual relief due to differential denudation. The most evident landforms of tectonic origin are straight mountain fronts, among which the one associated with the Sudetic Marginal Fault has already been extensively investigated (Oberc and Dyjor, 1969; Krzyszkowski *et al*., 1995; Krzyszkowski and Olejnik, 1998; Badura *et al*., 2003, 2007). However, a number of critical questions concerning the origin of this mountainous topography have not yet been satisfactorily answered. The broader spatial pattern of neotectonic movements is still insufficiently known, nor is the age of uplift/subsidence well constrained. Furthermore, many fault zones of different ages have been mapped in the Sudetes, but it is unclear which ones have been reactivated in the Neogene. As far as evident mountain fronts are concerned, it was usually assumed that differences in slope steepness between adjacent fault sectors may indicate different rates or ages of surface uplift (e.g., Krzyszkowski *et al*., 1995; Migoń, 1999; Ranoszek, 1999), but the influence of rock resistance has been considered only superficially.

METHODS

The study involved three major steps. In the first one, a digital elevation model has been constructed and used to derive a slope map of the Sudetes. The second step consisted of a field-based assessment of rock strength for the most important lithologies present in the Polish part of the study area and the construction of a rock strength map. The last stage involved spatial analysis of both cartographic images and their comparison.

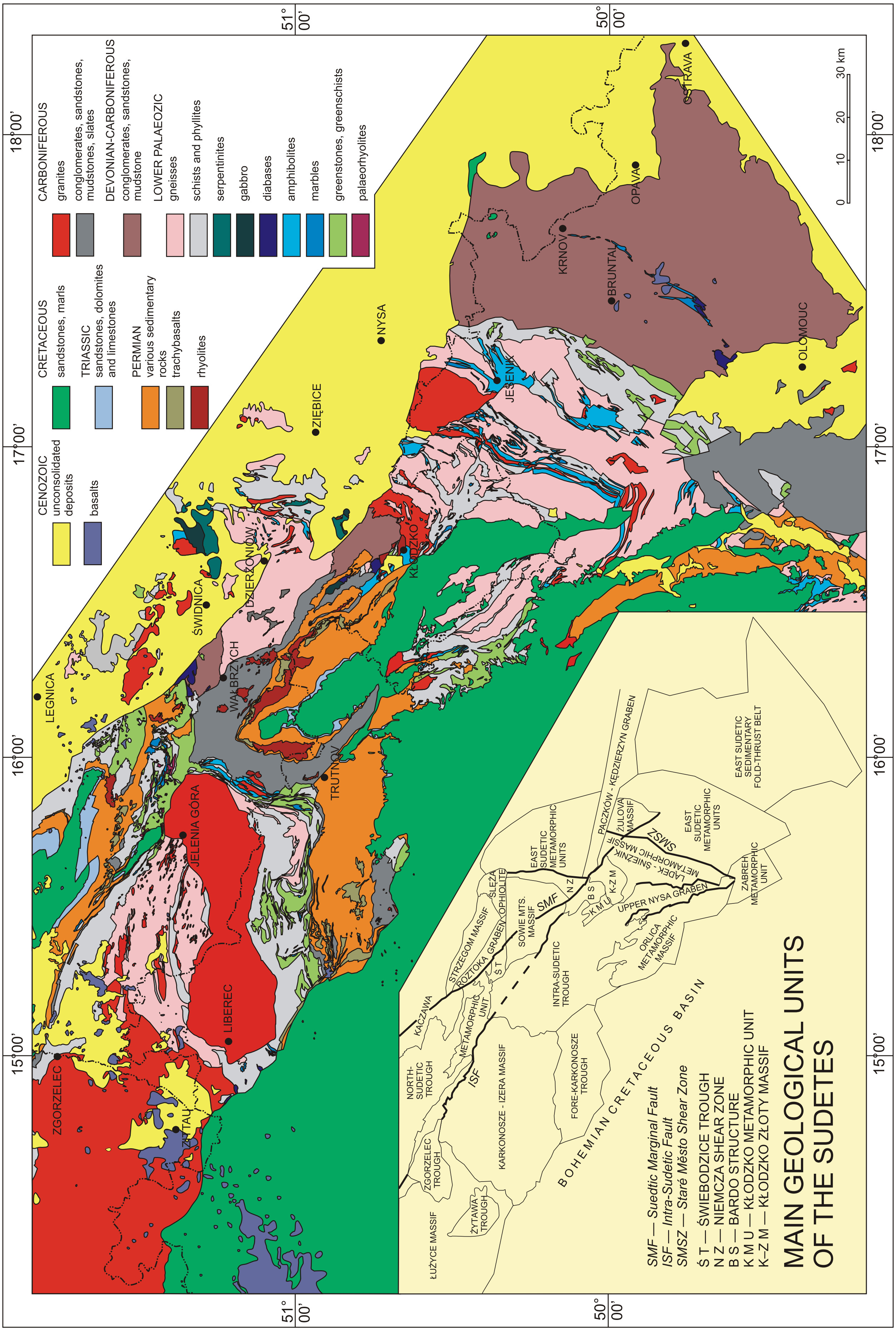

Fig. 2. Geology of the Sudetes (after Żelaźniewicz, 2005, simplified)

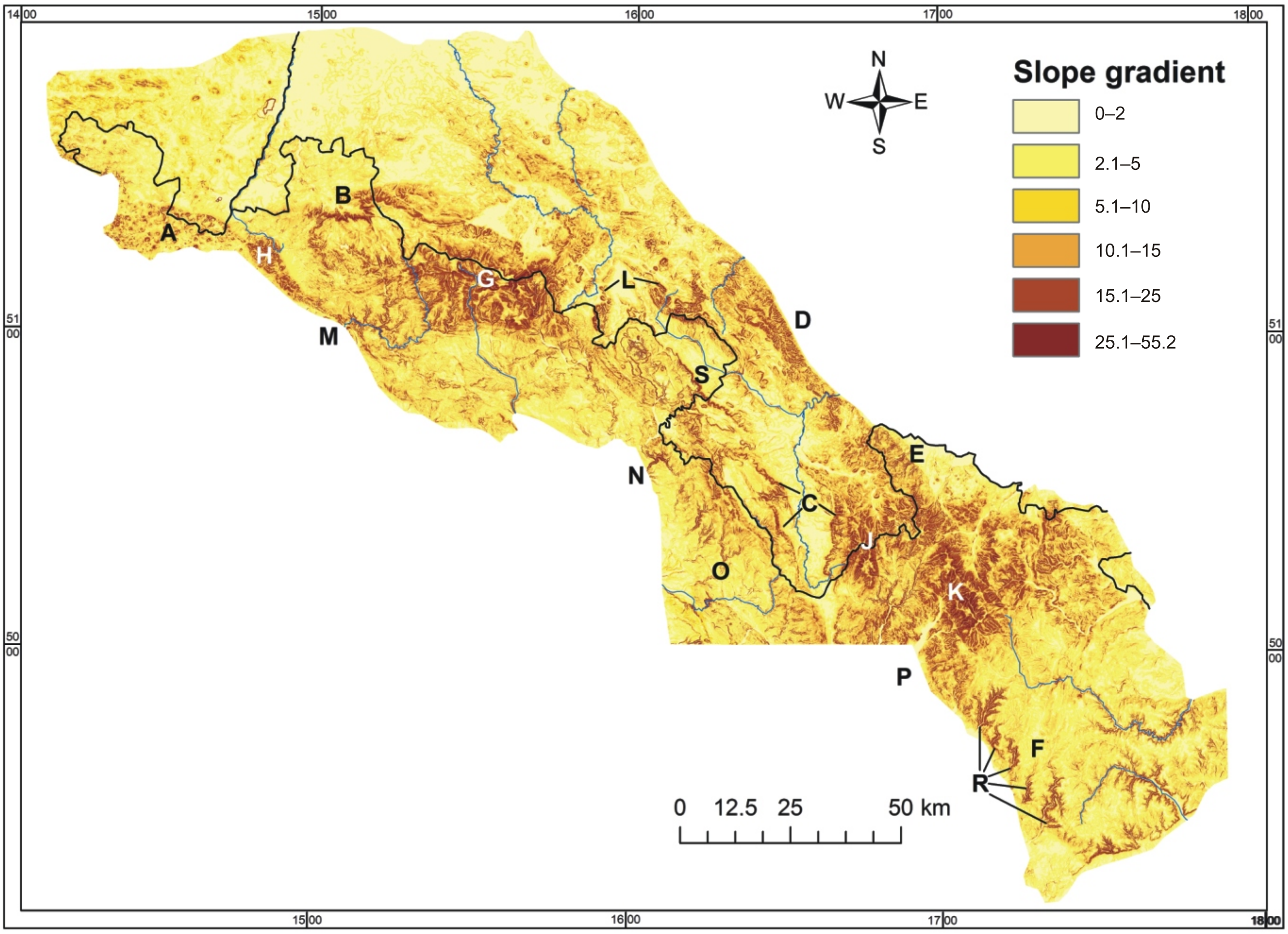

Fig. 3. Slope gradient map for the Sudetes and specific features of the geomorphology of the area (letter codes explained in the text)

Gradients are given in degrees

CONSTRUCTION OF DIGITAL ELEVATION MODEL

The Digital Elevation Model was generated in several steps. First, a DEM for the Polish part of the Sudetes was generated using *ArcMap* software, from analogue maps at 1:25 000 scale using the manual vectorization method. The contour lines, at 25 m spacing, important elevation points and all drainage lines have been digitized. These vectors were then interpolated by the *Topo-to-Raster* tool to create a 50 m resolution raster. Then, the model has been supplemented by data from the DTED (Digital Terrain Elevation Data) available at 30 m resolution. The resolution and geographic coordinate system have been standardized and both models have been merged. The 50 m resolution and 25 m contour line spacing may seem coarse, but have been chosen as sufficient and appropriate for further analysis at a regional scale, in which major features of relief have been sought. For subsequent calculations and analysis the model has been clipped to the geographical borders of the study area. A slope map (Fig. 3) was created automatically by *Spatial Analyst* procedure (*Surface Analysis* tool in *ArcGIS*) and derivative maps showing the distribution of required slope gradients have been extracted.

ROCK STRENGTH ASSESSMENT

To examine the degree of control exerted on topography by rock resistance, a generalized rock strength map for the Polish part of the Sudetes was constructed. Mechanical rock hardness, which is considered one of the most important properties bearing on rock resistance to erosion and slope steepness (e.g., Selby, 1980), was determined in the field using an N-type Schmidt hammer. Schmidt hammer readings on the nominal scale 1–100 correlate well with uniaxial compressive strength of rock, its dry density and Young modulus (Aydin and Basu, 2005). In geomorphology the Schmidt hammer is now routinely used as a reliable and efficient tool to acquire extensive, statistically significant datasets about rock strength (Goudie, 2006). Following the procedure outlined in the literature (Day and Goudie, 1977; Selby, 1980; McCarroll, 1989), readings were taken on planar, vertical, unweathered rock surfaces at sufficient distance from edges and cracks. If possible, quarries were preferred as test sites, otherwise tests were carried out on natural exposures, mainly tors and rocky valley sides. At each test site, forty readings were taken, and the lowest five readings were omitted in calculating the mean values and the standard deviation for each site.

Twenty-nine rock types have been tested and for each type tests were carried out at a few to a few tens of individual sites, depending on exposure availability (Placek and Migoń, 2007). Altogether, more than 600 test sites were used to build the database. The results obtained have been grouped according to the rock type, structural unit, and type of tested surface (natural or quarried), and then subjected to statistical analysis. The calculated mean values have been subsequently used to rank the tested lithologies/structural units using the nominal scale 1÷5 and intervals suggested by Selby (1980). The ranks assigned were adequate to prevailing means for each specific lithology, assuming that test results from fresh quarry surfaces are more reliable than those from natural exposures, which may have suffered from pre-weathering. In a few cases, the same rock type tested in different structural units indicated different levels of resistance, which was accounted for in ranking by giving two different ranks for these units. Next, generalisation of the complicated regional picture of rock resistance variability was performed by merging the extreme intervals proposed by Selby (1980). As a result, three main classes of weak (Schmidt hammer rebound value $R < 40$), moderately strong ($40 \leq R \leq 50$), and strong rocks ($R > 50$) have been distinguished.

The construction of a synthetic picture of rock resistance variability for the Polish Sudetes involved digitizing boundaries of individual geological units in *ArcInfo* and building topology for created polygons by establishing their rank of resistance. If two adjacent units belonged to the same rank, they were merged. There were a few lithological units lacking test sites, usually because of the absence of suitable exposures on which to carry out tests. These were assigned a rank established for the same lithology elsewhere in the Sudetes. As no sites in the Czech part of the Sudetes were investigated, no attempt has been made to provide a similar rock resistance map for the Czech Sudetes. However, there is little reason to assume that the strength of identical lithologies would have been significantly different.

OCCURRENCE OF STEEP SLOPES IN THE SUDETES

Slopes showing a mean gradient in excess of 15° occupy *ca*. 12 per cent of the area within the geographical limits of the Sudetes. However, their distribution is highly irregular, with the steep relief concentrated in the western and east-central part of the Sudetes (Fig. 4). Two main distribution patterns may be distinguished. These are fairly compact areas and more linear features, extending for 10–50 km.

The most extensive, compact areas of steep relief are the rectangular massif of the Karkonosze in the West Sudetes, particularly its southern part, and the massif of Hrubý Jeseník in

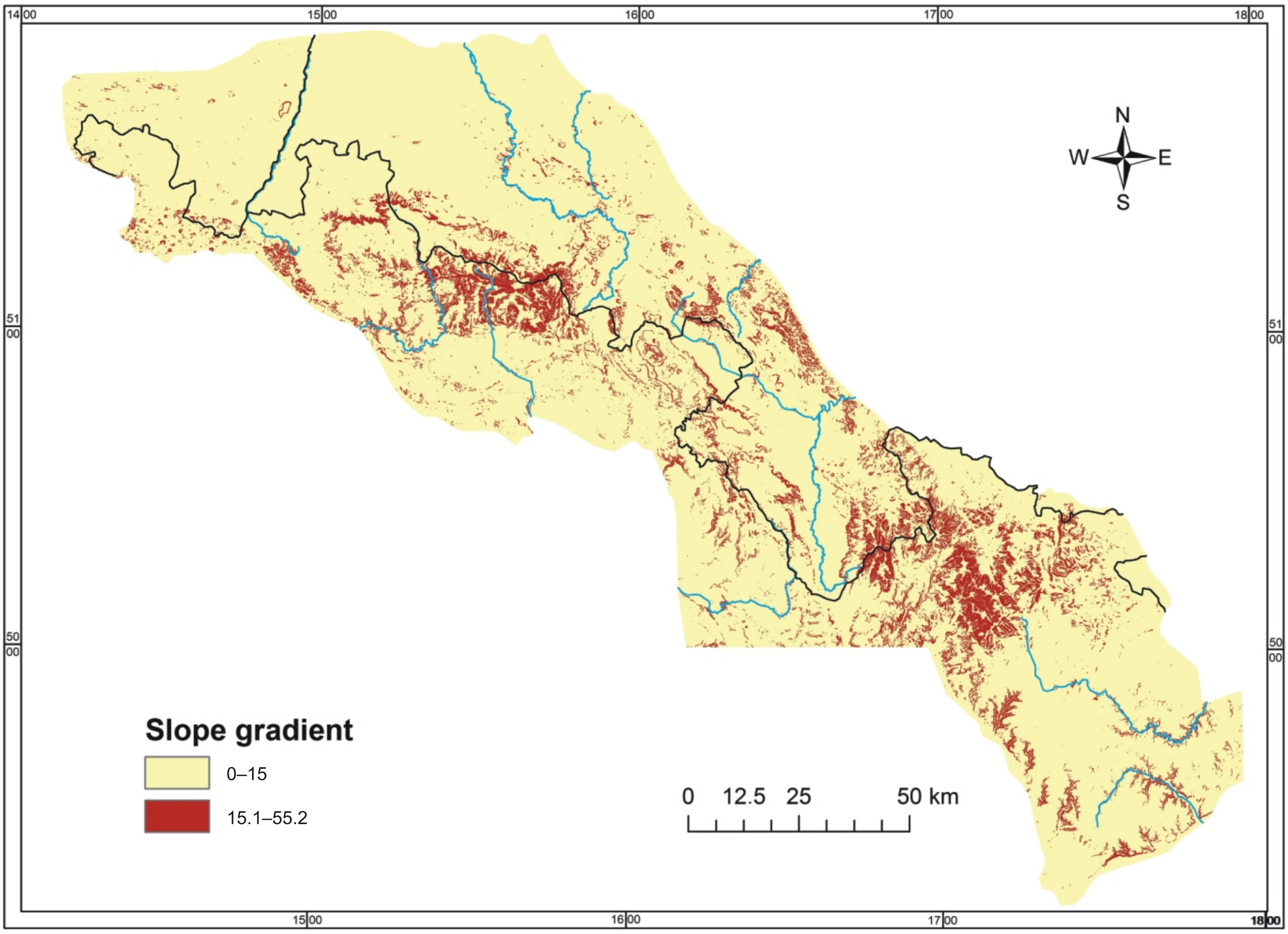

Fig. 4. Spatial distribution of terrain with mean gradient in excess of 15°

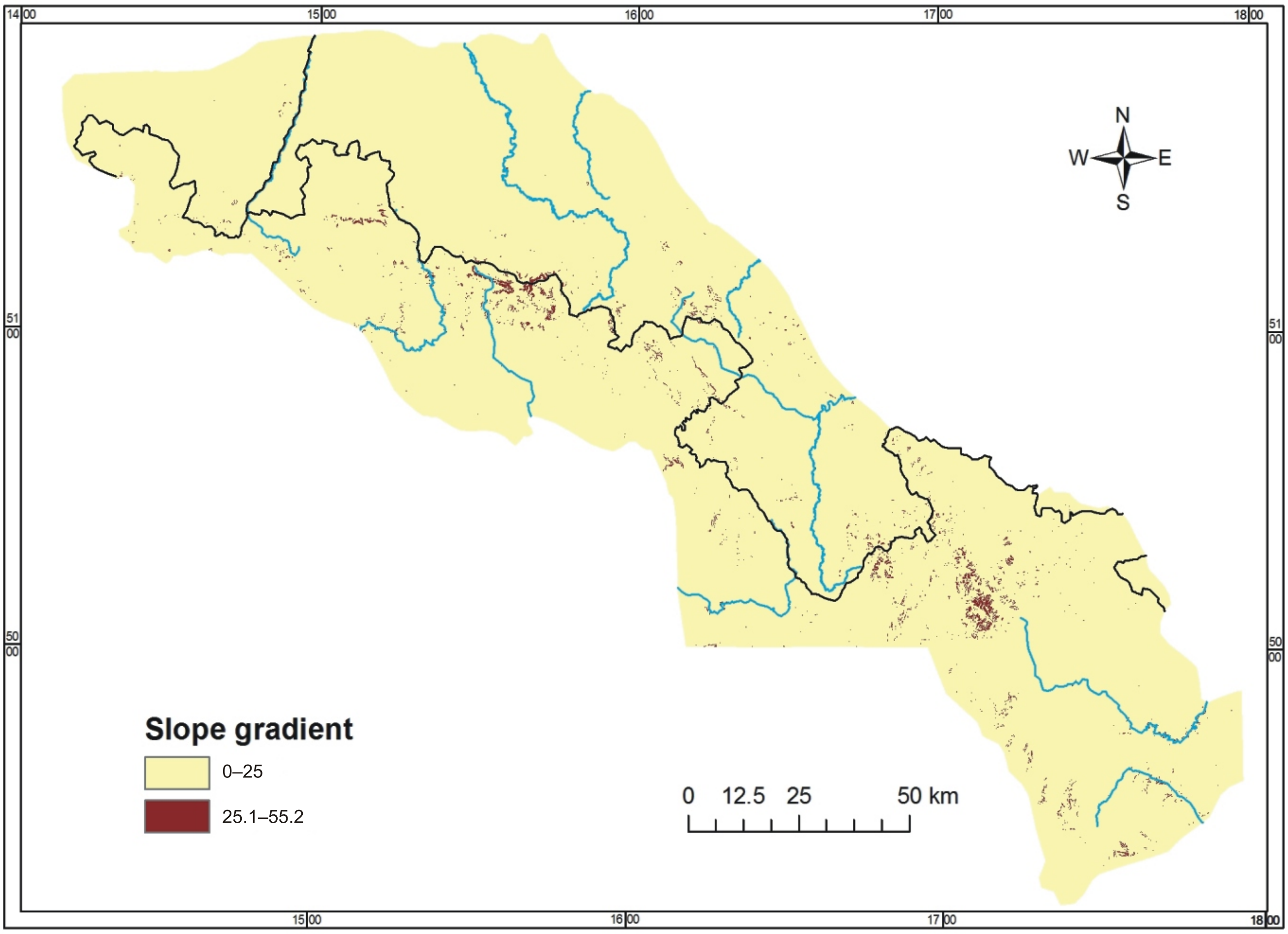

Fig. 5. Spatial distribution of terrain with mean gradient in excess of 25°

the East Sudetes. The Śnieżnik Massif and the southern part of the Złote/Rychlebské Mts., located adjacent to the Hrubý Jeseník, are further terrain units with slopes >15° being widely present. All four areas belong to the highest parts of the Sudetes in terms of altitude (Karkonosze — 1602 m a.s.l.; Hrubý Jeseník — 1491 m a.s.l.; Śnieżnik — 1425 m a.s.l.; Złote/Rychlebské Mts. — 1125 m a.s.l.), thus the steepest relief corresponds with the highest altitude. Less extensive but similarly compact areas of steep terrain are the Ještěd ridge (1012 m), the southeastern part of the Kamienne Mts. (936 m), and the Sowie Mts. (1015 m). In all these areas the extent of low gradient slopes on the most elevated terrain is highly restricted, although at lower altitudes such gentler slopes do occur, e.g. in the northern part of the Karkonosze and along the western boundary of the Śnieżnik Massif.

Among the linear features, long and narrow ribbons of steep slope, sinuous in close-up and parallel to each other, dominate in the Middle Sudetes, to the south of the Kamienne Mts. Geographically, they are associated with the Stołowe Mts. (919 m) and the Broumovská Upland (786 m). Wider linear zones of steep terrain can be recognized along the northern margin of the Izerskie/Jizerské Mts. (West Sudetes), in the Orlické Mts. and around the Bystrzyckie Mts. in the Middle Sudetes.

Two further specific patterns of steep slope occurrence are deeply incised valleys, cut into surfaces of low relief, particularly common in the easternmost part of the Sudetes (Nizký Jeseník) and occasionally as much as 20–25 km long, and isolated spots, which typify the Lužické Mts. in the westernmost part of the range. The latter are in fact steep-sided conical hills built of volcanic rocks of Neogene age, the height of which reaches 300 m.

Notable absences of steep relief are noted in the northwestern part of the Sudetes, along a broad zone transecting the Middle Sudetes along the Nysa Kłodzka and Ścinawka rivers, and in the vast area of Nizký Jeseník. Most of these areas are associated with low altitudes, below 500 m a.s.l. However, in the Bystrzyckie Mts. a large area of low mean slope occurs at an altitude above 700 m a.s.l. Interestingly, the prominent NE-facing mountain front of the Sudetes does not show at all in its NW segment.

The occurrence of the steepest slopes, in excess of 25°, is restricted to certain specific regions and many features identified on Figure 4 do not show any longer (Fig. 5). Leaving aside very small patches of steep terrain, usually sections of river gorges, the following areas appear rather clearly. In the West Sudetes it is the NW sector of the margin of the Izerskie/Jizerské Mts. and the valley sides in the most elevated part of the Karkonosze. In the East Sudetes, the extent of steep surfaces in the Śnieżnik Massif is much smaller, whereas in the Hrubý Jeseník they are still widely represented and certain topographic features become highlighted. Steep valley sides are easily visible to the south of the main ridge, but a clear NW–SE trending zone extends to the NE of the main ridge. Altogether, the >25° surfaces occupy only 1 per cent of the geographical realm of the Sudetes.

MORPHOTECTONIC INTERPRETATION AND SIGNIFICANCE

The initial assumption that increasing slope gradients mean more intense tectonic differentiation of the study area needs now a re-assessment. Different spatial patterns of steep slopes, along with their irregular distribution throughout the area (Fig. 3) indicate that the relationships between topography and tectonics are complex. Moreover, there may be reasons other than the high rate of uplift as to why steep slopes have formed and persist. An obvious example of the latter is the widespread presence of volcanic cones (necks) in the Lužické Mts. which are features of rock-controlled denudation, without a direct relevance to tectonics — Figure 3(A). Other areas of considerable steepness occur as the following surface features: mountain fronts, dissected highlands, deeply incised valleys, and sinuous escarpments.

MOUNTAIN FRONTS

Straight mountain fronts belong to “classic” tectonic landforms and their geomorphology has generated considerable interest both in the Sudetes and elsewhere. The first comprehensive study of twelve major mountain fronts was carried out by Ranoszek (2001), who pointed out their diversity in terms of general relief and morphometric indices. Detailed studies have been subsequently carried out along the front related to the Sudetic Marginal Fault (SMF) and involved an analysis of three-dimensional images derived from digital elevation models and computation of a range of morphometric parameters for individual small catchments located within the mountain front (Badura *et al*., 2003, 2007). The mountain front associated with the SMF shows clear segmentation along strike, a tiered pattern of faceted spurs, and considerable variability of catchment parameters, the reasons of which are likely to be complex.

The mountain fronts analyzed by Ranoszek (2001) and others show on the steep slope map with varying clarity. The northern front of the Izerskie/Jizerské Mts. is most evident, but only in its northwestern (Czech) sector, whereas the northeastern sector, east of the Kwisa River, is barely revealed — Figure 3(B). Both mountain fronts bordering the Upper Nysa Graben show rather clearly on the >15° slope map, although the *en échelon* arrangement of the fronts on the western side is not immediately visible — Figure 3(C). The northern margin of the Karkonosze is shown as a discontinuous, fuzzy feature, even though its Pleistocene reactivation is evident in truncated river terraces (Sroka, 1991). Interestingly, the geomorphologically prominent mountain front associated with the SMF cannot be readily identified and it is only in the Sowie Mts. sector where it shows as a clear linear feature — Figure 3(D). In the Złote/Rychlebské Mts. the image is less evident, as spurs show significantly lower mean gradients than do steep valley sides — Figure 3(E). Further to the east, interfluve sectors of the mountain fronts in the SE Sudetes, bordering the Nizký Jeseník, are poorly or even hardly visible as such — Figure 3(F), but deep fluvial incisions within the front faces are of utmost clarity.

Mapped fault zones without evident topographic expression merit attention too, because their disassociation with steep relief may indicate little or no activity in the “neotectonic”, Neogene–Quaternary period. One such example is the Intra-Sudetic Fault (ISF) along most of its western section. According to Aleksandrowski *et al*. (1997), the ISF is one of the major Variscan structures in the Sudetes and marks the boundary of different terranes, but its subsequent history remains elusive. The absence of steep relief along the ISF supports the proposal that its significance in the late Cenozoic was marginal and contradicts views such as those presented by Dyjor (1995) on his maps of neotectonic structures. A few cases where the ISF does show some relief coincide with strong lithological contrasts (granite/greenschist boundary north of the Jelenia Góra Basin, gneiss/sedimentary rocks boundary south of the Sowie Mts. block, see below). In the eastern part of the Sudetes, the major tectonic boundary of the Stare Město Shear Zone, which separates the West and East Sudetic terranes, fails to be revealed as a distinctive topographic unit. Again, this indicates that regionally important Variscan strike-slip structures played a minor role in the shaping of the mountainous relief of the Sudetes in the Neogene/Quaternary. Apparently, the spatial pattern of normal faulting in the Neogene has developed without any clear influence of antecedent, strike-slip zones.

HIGHLY DISSECTED TERRAINS

In faulted mountain ranges such as the Sudetes, dissected highlands are interpreted as the most uplifted and consequently, the most dissected parts of the terrain. Indeed, the most elevated parts of the Sudetes, which broadly correspond to the steepest parts, have been typically considered as crustal blocks subject to uplift of the highest amplitude (Klimaszewski, 1958; Walczak, 1972; Demek, 1975). This interpretation would receive stronger basis if the boundaries of such an elevated and dissected block can be drawn along roughly straight lines, consistent with normal faulting.

A few steep dissected terrains in the Sudetes meet the above criterion if the slope map rather than a hypsometric map is analyzed. In the West Sudetes, the Karkonosze form an almost rectangular block — Figure 3(G) and the Ještěd ridge, although much narrower, is also bordered by straight lines — Figure 3(H). In the Sowie Mts. there occurs a clear change of slope gradient on the NE side, associated with the front of the Sudetes, but the SW boundary, coincident with the extension of the Intra-Sudetic Fault (Aleksandrowski *et al*., 1997), is also evident. In the East Sudetes the Śnieżnik Massif is a good case, forming a N–S elongated rectangle — Figure 3(J), whereas the western part of the Hrubý Jeseník is another example, extending from NW to SE — Figure 3(K).

In addition, in the East Sudetes there is a group of less dissected highlands, distinguished by a somewhat larger extent of watershed surfaces of low relief. Examples include the NE part of the Hrubý Jeseník (Orlík block) and the southern part of the Złote/Rychlebské Mts. Significantly, they rise to 1000–1200 m a.s.l., hence 200–300 m less than the most dissected massifs. Thus, there is a broad correlation between altitude and the degree of dissection.

Two further areas in the Middle Sudetes stand out on the slope map, rising island-like from an extensive gentle terrain — Figure 3(L). Geographically, they correspond to the Kamienne Mts. However, in both cases the borders of steep terrain do not follow straight lines but are either arcuate, or follow a tortuous line. It will be shown below that lithological rather than tectonic control is responsible in both these instances.

DEEPLY INCISED VALLEYS

The presence of deeply incised valleys, far from other places of steep terrain, is most evident in the southern, Czech/Moravian part of the Sudetes. The valleys typically follow sinuous courses and may join with similarly deeply incised tributaries. Going from the West Sudetes eastwards, the following gorges can be easily identified: the Izera/Jizera valley with its several tributaries — Figure 3(M), Metuje with Olešenka — Figure 3(N), and Zdobnice at the foot of the Orlické Mts. — Figure 3(O), Morava with Branná and Krupá south of the Śnieżnik Massif — Figure 3(P), and numerous valleys in the outer parts of the Nizký Jeseník — Figure 3(R). Practically no analogues exist in the Polish part of the Sudetes, where only short gorges occur.

The origin of the gorges has been variously explained and some interpretation proposals are site-specific. For example, the gorge of Metuje south of Náchod has probably formed due to superposition from the Cretaceous sedimentary cover, still partially preserved above the gorge (Prosová, 1974). In the Nizký Jeseník the setting of the gorges may indicate the progress of valley rejuvenation away from mountain fronts, which themselves are now sufficiently subdued not to appear on the slope map.

In sum, river gorges may be indicators of general uplift and enhanced erosion but are less useful to locate linear zones of active tectonics. Furthermore, the vast majority of gorges are associated with rivers of considerable length and high discharge. Hence, the absence of gorges does not necessarily mean little tectonic activity but may reflect limited capability of the rivers to incise.

SINUOUS ESCARPMENTS

Narrow, sinuous escarpments which abound in the Middle Sudetes are associated with sedimentary rock terrain, mainly with the innermost part of the Intrasudetic Trough built of flat-lying or gently tilted Cretaceous sandstones, mudstones and marls. Steep slope segments are carved out of massive sandstone units which act as caprock to the weaker strata below. The most distinct is the outer scarp which runs NW–SE and turns round near the NW corner of the Cretaceous outcrop area — Figure 3(S). Clear embayments seen in the SE sector of the scarp are huge, amphitheatre-like valley heads formed due to the combination of spring sapping and mass movement (Pulinowa, 1989; Migoń and Zwiernik, 2006). A few isolated plateaux are also revealed.

Interestingly, no similar features are evident in the NW part of the Sudetes, despite similar geological structure. It has been hypothesized that the subdued relief in NW Sudetes may be due to the passage of the Scandinavian ice sheet in the Pleistocene (Migoń, 2005), but the presence or absence of steep scarps in the sedimentary terrain may also be a function of available relief, in turn related to the intensity of uplift and subsidence.

LITHOLOGY AND ROCK STRENGTH AS MODIFYING FACTORS

ROCK STRENGTH VARIABILITY

Rock complexes in the Sudetes vary hugely in their strength, by a factor of three according to the Schmidt hammer scale. Average scores for individual test sites ranged from 21.5 R (Schmidt hammer rebound value) for claystones, 21.9 R for feldspatic sandstones, and 26.8 R for sericite schists to as much as 67.3 R for trachybasalts, 68.9 R for gneiss, 69.6 R for granite, and 70 R for basalts. The complete database for rock strength determination in the Sudetes is presented in Placek and Migoń (2007). The spatial distribution of lithological units of different strength shows considerable irregularity, even despite advanced generalization and reduction of rock strength classification to three classes only (Fig. 6). However, certain areas of rock occurrence of similar strength may be distinguished.

Strong rocks are present in various parts of the Sudetes. In their distribution pattern, extensive and fairly compact areas in the western and the east-central part of the mountain range show up clearly. These are associated with granitoid intrusions, including their metamorphic cover (Karkonosze-Izera Massif, Kłodzko–Złoty Stok Massif), and with large gneissic massifs (Orlica–Śnieżnik Metamorphic Massif, Izera Metamorphic Block, Sowie Mts. Block). Highly lithified Devonian to Carboniferous mudstones, slates and greywackes of the Bardo Structure also belong to this group. Weak rocks dominate in the North-Sudetic Trough in the northwestern part of the Polish Sudetes, in the Upper Nysa Graben in the east, and in certain specific areas in the Middle Sudetes, within the Intra-Sudetic Trough. The majority of mechanically weak rocks is of sedimentary origin and Carboniferous to Cretaceous age, although in the north-west there are extensive outcrops of low grade metamorphic rocks, schist and phyllite, belonging to the same class.

In other parts of the Sudetes strong, moderately strong and weak rocks occur next to each other, alternating over very short distances. The former are revealed as narrow stripes, clusters, and isolated spots, depending on the geological form of occurrence. For example, strong rhyolites and trachybasalts of Permian age occur widely amidst relatively weak sandstones and conglomerates of the same age, whereas elongated stripes or rounded patches within the area built of clayey and siliceous marls of Upper Cretaceous age indicate the presence of moderately strong and strong quartz sandstones. The juxtaposition of somewhat larger areas of contrasting strength, such as that west of the Upper Nysa Graben, often indicates the close occurrence of crystalline basement and sedimentary cover. In the West Sudetes, mainly in the North-Sudetic Trough, scattered spots of strong rocks are associated with Neogene volcanics.

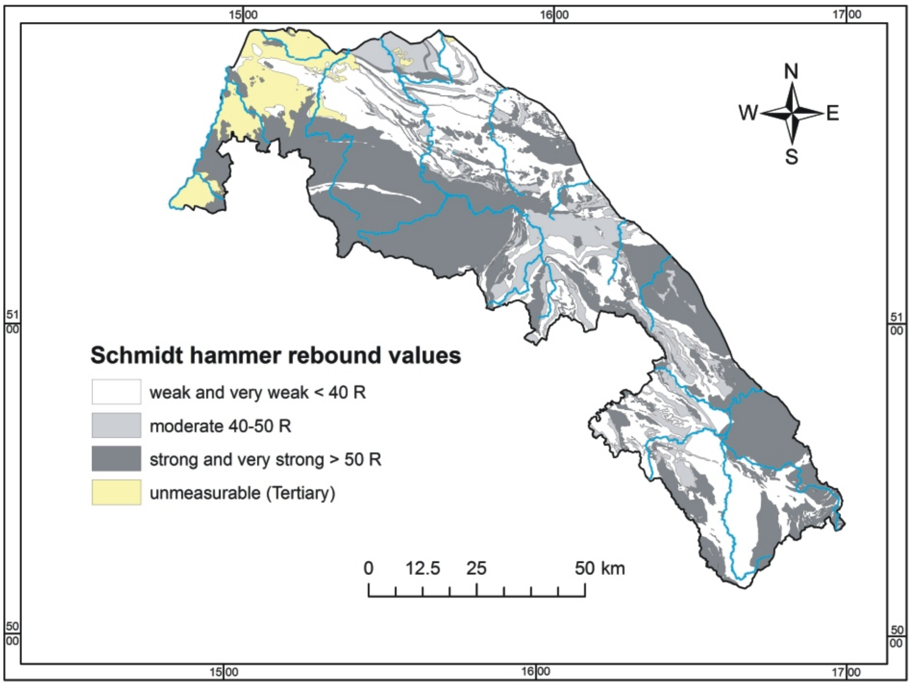

Fig. 6. Spatial distribution of rock strength classes in the Polish part of the Sudetes

ROCK STRENGTH–STEEP SLOPES RELATIONSHIPS

The spatial relationships between the distribution of rock complexes of different strengths and the pattern of high-gradient slopes are not as straightforward as might be expected (Fig. 7).

Steep slopes tend to occur in the highest parts of the Polish Sudetes and are associated with the strongest rocks, i.e. granites and gneisses. However, within the very same rock complexes extensive surfaces of subdued relief exist at low altitude, such as in the Jelenia Góra Basin and the Izera Foreland, both below 500 m a.s.l., and it is only the rock-controlled inselbergs in certain parts of granitic basement which break the topographical monotony of the terrain. Strong rocks support also the less elevated but spatially compact areas of steep slopes mentioned in the previous section, which represent dissected highlands built of various plutonic, volcanic and metamorphic rocks. The most evident straight belts of high-gradient surfaces are associated with strong igneous rocks too. These occur within the Izerskie/Jizerské Mts. and constitute the western rim of the Rudawy Janowickie ridge and the margins of metamorphic massifs on both sides of the Upper Nysa Graben.

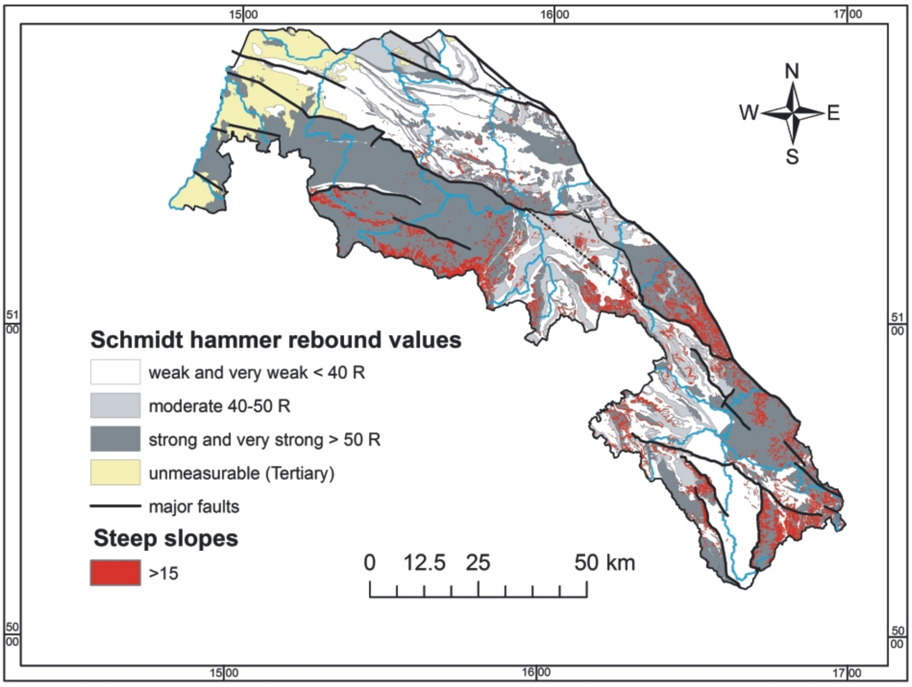

Fig. 7. Rock strength *versus* the distribution of high-gradient areas and major neotectonic faults in the Polish part of the Sudetes

As far as the less extensive patches of steep terrain are concerned, they clearly reflect the shape of the respective geological bodies built of strong rocks. These relationships are most evident in volcanic terrains of both end-Palaeozoic and Neogene age, where a few characteristic patterns may be distinguished:

— isolated spots, indicative of the presence of steep-sided basalt cones (necks);
— rounded patches associated with large rhyolitic and trachybasaltic domes;
— ribbon-like features, typical of marginal slopes of lava flows and ignimbrite plateaux.

A similar picture is characteristic for areas built of metamorphosed limestone in the Kaczawskie Mountains and in the Krowiarki range in the East Sudetes, which are significantly stronger than the surrounding low-grade metamorphic rocks.

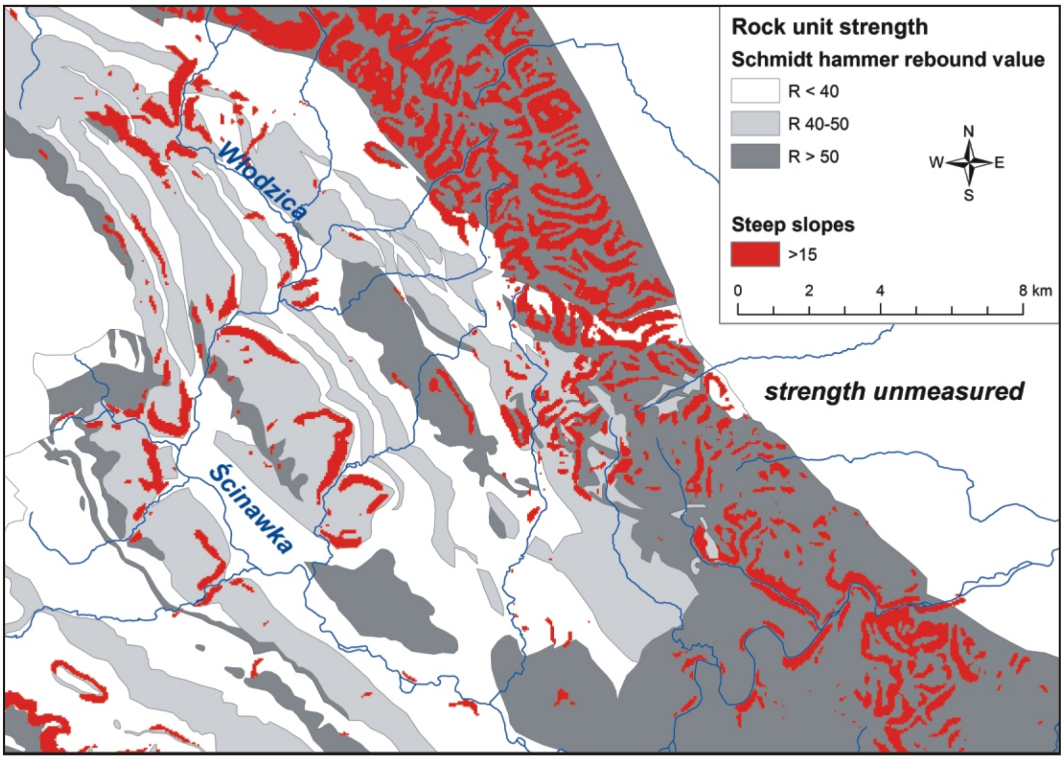

Fig. 8. Rock strength *versus* slope steepness relationships in the northeastern part of the Middle Sudetes

For quartz sandstones of Cretaceous age, lying horizontally or tilted at low angles, narrow sinuous or straight escarpments are characteristic. Among these, the most prominent example is the NE escarpment of the Stołowe Mts., which continues northwards supporting the outer scarp of Broumovské stěny (on the territory of the Czech Republic), Mieroszowskie Ściany and Zawory. Escarpments in the North-Sudetic Trough are, however, much less distinct, except for places where basaltic necks intrude the sandstones. Sedimentary rocks of moderate strength, mainly conglomerates and sandstones ranging in age from Devonian to Permian, support steep slopes only occasionally, e.g. towards the NW end of the Intra-Sudetic Trough, but it needs emphasising that these rocks vary considerably in strength and are generally known as very heterogeneous.

Within deeply incised valleys the relationships between strength and gradient are less obvious and rock complexes of variable strength support steep valley sides. For example, gorges located near the mountain front of the Sudetes north of Wałbrzych are cut into rather weak sandstones and conglomerates of Devonian/Carboniferous age. In the northeastern part of the Intrasudetic Trough, in the vicinity of Nowa Ruda, steep slopes are connected with faces of monoclinal ridges built of moderately strong Permian sedimentary rocks and subject to river undercutting, for example along the Ścinawka and Włodzica valleys (Fig. 8). Likewise, some of their tributaries are steeply incised into outcrops of sandstone and conglomerate, which otherwise support rather gentle slopes. However, locally steep slopes exist away from the current drainage lines which might indicate past drainage pattern changes, but might also be explained by the influence of structure (anti-dip slopes) rather than of lithology. Along the Bóbr gorge in the West Sudetes both very strong (granite-gneiss) and rather weak rock complexes (phyllite, schist) crop out, suggesting the primary role of fluvial incision. However, in the Kaczawa valley within the Kaczawa Upland steep valley sides are almost exclusively associated with the strongest rocks of volcanic origin (Fig. 9).

Steep slopes in weak rocks occur rarely, mainly in two situations. They can be found within valleys subjected to particularly intense fluvial erosion, and within large elevated blocks built of strong metamorphic rocks, but with weak schists sandwiched in between, as in the Śnieżnik Massif.

ROCK STRENGTH CONTROL ON FAULT-GENERATED ESCARPMENTS

Variable geomorphological expression of fault-generated escarpments may have two reasons. First, it may be related to different intensities and rates of uplift, or to different time spans since the major phase of uplift. Generally speaking, lower rates and older ages should result in more subdued morphology, and lower slope gradients would be expected (e.g., Anderson, 1977). An alternative explanation would emphasize unequal rock resistance as a passive factor controlling long-term lowering of a fault scarp. Differences in rock strength would result in varying mean rates of denudation, which are likely to be higher in mechanically weaker bedrock. Therefore, gentle fault-generated scarps do not necessarily mean lower uplift rates but higher denudation rates. In this paper we do not intend to discuss rates of tectonic processes, but wish to emphasize the possible role of the rock strength factor.

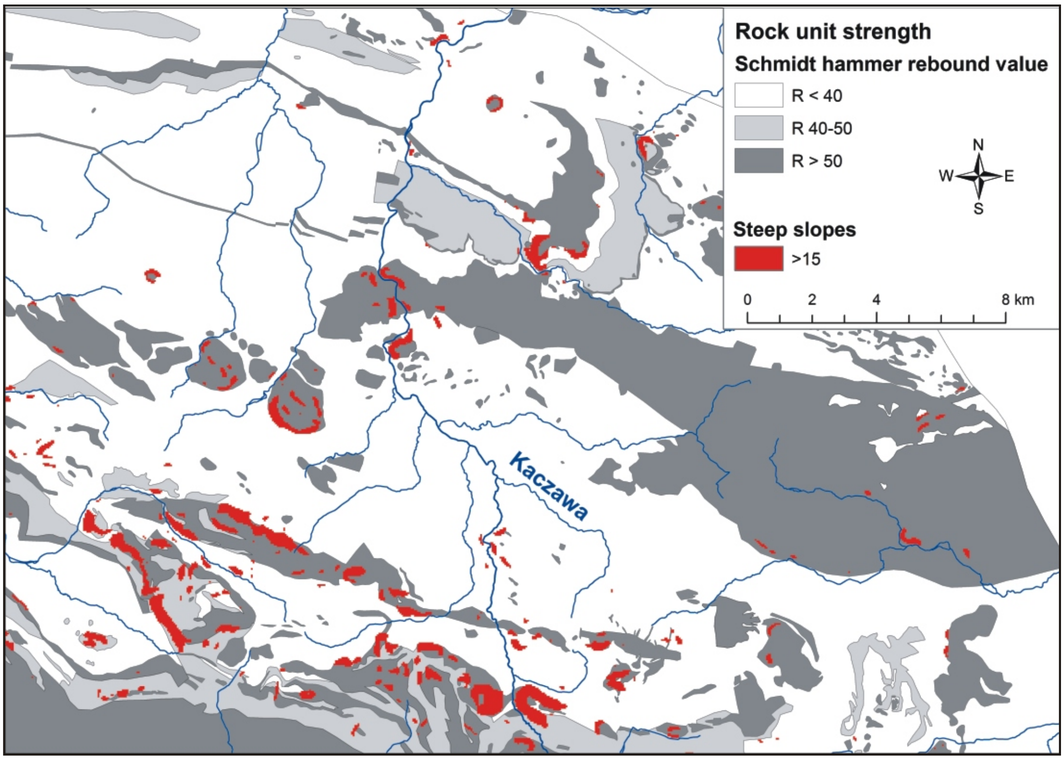

Fig. 9. Rock strength *versus* slope steepness relationships in the eastern part of the Kaczawa Mountains and Kaczawa Upland (West Sudetes)

It is clear (Fig. 7) that all prominent mountain fronts in the Polish Sudetes are supported by rocks invariably classified as strong. Examples include the western escarpment of the Śnieżnik Massif (Ranoszek, 1998, 2001), the northern escarpment of the Karkonosze (Sroka, 1991), and the central sector of the mountain front related to the Sudetic Marginal Fault, in the Sowie Mountains (Krzyszkowski *et al*., 1995; Badura *et al*., 2003).

By contrast, wherever tectonic lines cross terrain built of rocks belonging to the category of "moderately strong" or "weak", the geomorphic expression of mountain fronts is poor. This is particularly evident in the northwestern sector of the Sudetic Marginal Fault, where mean gradients above 15° are uncommon, but the strength of rock is low. A single steep slope spot occurs in association with the basalt plug of Górzec (445 m a.s.l.). Somewhat similar is the situation along the western margin of the Upper Nysa Graben, which follows two *en échelon* faulted escarpments (Ranoszek, 1998). Within the escarpment face three main rock complexes are exposed. These are gneisses classified as strong rocks, Cretaceous sandstones belonging to the "moderately strong" class, and weak schists, mudstones and marls. Steep slopes are distinctly related to the gneissic bedrock, whereas the other rocks build more subdued sections of the escarpment.

Recourse to the rock strength factor may help to explain the peculiar situation at the Intra-Sudetic Fault, where the variability of topographic expression along its length is considerable. It has been commented before that the section of the ISF south of the Sowie Mts. Block is associated with steep relief on the northeastern side. Figure 8 indicates significant rock strength contrast along this section of the fault and hence, the importance of rock-controlled long-term denudation.

DISCUSSION

Various morphometric parameters, derived from different basic materials, have been employed in morphotectonic research. In recent years, with the growing computational capacity of computers, a trend is observed towards the use of increasingly complex indices and sophisticated pictures and images. However, their interpretation is also increasingly difficult. In contrast, slope gradient maps are rather simple tools but if analyzed in a consistent manner over sufficiently wide areas, they may provide useful information.

In the Sudetes, the slope gradient maps reveal the existence of areas characterized by the dominance of significantly steeper gradients than their surroundings. Moreover, these areas cluster in certain specific sub-regions of the Sudetes, particularly in the southwestern and east-central part, coinciding with the highest altitudes recorded in the range. In addition, the maps show clearly that watershed surfaces of low relief, however impressive they may seem to the field observer, can hardly be considered as the first-order landforms in the mountain range of the Sudetes. Their presence is an exception rather than a rule.

Steep slopes occur in different settings and not all of them are directly related to active tectonics. Sinuous escarpments in sedimentary terrain in particular are chiefly due to structure- and rock-controlled scarp retreat, during which steep slope form is maintained. However, their absence from the NW part of the Sudetes, where rock and structure do favour the development of scarpland terrain, may indicate the lack of available initial relief, and hence insufficient uplift or perhaps long-term subsidence. The relationship of other steep slope patterns to active tectonics appears more evident. The hypothesis that the most elevated highlands are the loci of surface uplift receives confirmation. Two points can be made here. First, there is a correlation between altitude and the degree of dissection, which is consistent with the general rule that more uplift (in terms of both amplitude and rate) enhances erosion, which, followed by mass movement, leads to a steady-state mountainous landscape with little previous topography preserved (e.g., Adams, 1985). Second, in the spatial distribution pattern of steep slopes large rectangular structures are seen, which strengthens their interpretation as uplifted blocks delimited by fault zones. However, not all dissected highlands are necessarily associated with increasing uplift. Considerable lithological and rock strength contrasts, such as those between Permian volcanic and sedimentary rocks in the Middle Sudetes, may produce a similar picture.

Interestingly, the picture of mountain fronts is not as clear as expected, and many fail to show altogether. This is despite the evidence of Quaternary tectonics along many of them (e.g., Sroka, 1991; Krzyszkowski *et al*., 1995) and in apparent contradiction with low values of mountain front sinuosity indices, typical of active uplift (Krzyszkowski *et al*., 1995; Ranoszek 2001; Badura *et al*., 2003, 2007). A single interpretation of this situation may not exist, but low rock strength is likely responsible in at least some instances, coinciding with very subdued sectors of fault-generated escarpments. In a few other places, however, the height of mountain fronts is too low (*ca*. 50–70 m) to be revealed clearly on the slope map constructed from 25 m-spaced contour lines. Major Variscan strike-slip zones are revealed poorly on the slope gradient maps and have played a minor role in the most recent geodynamic history of the Sudetes.

The interpretation of isolated deep gorges is ambiguous and their relationships to active tectonics may be various. Some gorges are probably indicators of headward erosion, now rather far away from fault lines (Nizký Jeseník). Others, such as those at the foot of the Orlické Mts., have formed on the ramp of a large tilted block. Overall, their presence is helpful to detect regional differences in the intensity of uplift, but less useful to locate specific lines of ongoing deformation. Clear examples of antecedence across possible up-warped structures are not evident.

CONCLUSIONS

The study presented in this paper, although based on a simple geomorphometric technique, allows us to offer the following conclusions.

1. A slope gradient map proves a useful tool to characterize the diversity of mountain relief and offers an opportunity to provide the quantitative dimension to DEM analysis.

2. The meaning of high gradient areas in the Sudetes varies. Surface uplift, elevated rock strength, and active fluvial erosion are among the factors contributing to the steepness of the terrain.

3. The most elevated mountain massifs in the Sudetes are associated with the highest mean gradients, and are evident on slope maps. They are likely to be tectonic horst structures. By contrast, mountain fronts show up rather poorly on the slope map despite their straight courses.

4. The poor expression of many tectonic lines, suspected to be active in the "neotectonic" period, may be explained by the mechanical weakness of the rock building the footwall. At the same time, the association of the majority of tectonically-induced steep slopes with the most resistant rocks suggests that the intensity of recent uplift — compared with the rate of denudation — is rather low.

5. Certain regionally important tectonic zones of Palaeozoic age, crucial for the amalgamation of the Sudetes during the Variscan orogeny, are very poorly revealed in the contemporary relief. This suggests that little tectonic activity took place specifically along these zones during the "neotectonic period", apparently dominated by normal faulting.

The study has been carried out in the specific geographical context of the Sudetes. However, the technique and the interpretation procedure can be easily applied to other block-faulted ranges, and a comparative analysis of relief versus rock strength relationships between many mountain terrains would be a most useful exercise.

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