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TECTONIC GEOMORPHOLOGY OF THE SUDETES MOUNTAINS (CENTRAL EUROPE) – A REVIEW AND RE-APPRAISAL

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Abstract: The Sudetes are a mountain range in Central Europe, which owes its emergence to the Cenozoic rejuvenation of an old Variscan orogen, subject to stresses from the Alps and the Carpathians. The gross morphological features of the Sudetes are typically explained as reflecting the superposition of the effects of long-term, rock-controlled denudation and Late Cenozoic differential uplift and subsidence. In this paper, early conceptual models, developed in the 1950s and 1960s and emphasizing alternating uplift and planation phases, are presented first. A review of more recent work focused on tectonic landforms and geomorphic indicators of tectonic movements follows, with special attention to fault-generated escarpments, valley morphology, stream longitudinal profiles, terraces and fans, drainage basin characteristics and regional geomorphometric studies. Attempts to provide a timeframe of tectonic relief differentiation are also summarized. In the closing part of the paper, the existing approaches and findings are re-evaluated in order to identify challenges and perspectives for future work. The availability of high-resolution digital terrain models creates a unique opportunity to quantify relief features and detect even the subtle topographic signatures of recent tectonics. A need to reconcile the results of geomorphological analysis with those emerging from other studies focused on faults is highlighted.

Key words: Morphotectonics, tectonic activity, mountain front, fluvial system, morphometric indices, Sudetes.

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INTRODUCTION

Tectonic geomorphology, the subject matter of which is at the interface of tectonics, structural geology and geomorphology, explores linkages and causal relationships between crustal movements, rates of surface processes and the development of landforms. Once understood as a simple description of landforms originating from uplift and subsidence, mainly horst-and-graben structures bounded by fault-scarp fronts, with the role of strike-slip movements considered as minor (Cotton, 1968), it has evolved into a complex field of study, conducted on a variety of spatial and temporal scales, from global and long-term to local and pertinent to events of very short duration, such as earthquakes (Burbank and Anderson, 2011). Bull (2007) put a strong emphasis on processes, arguing that the domain of tectonic geomorphology comprises the influences of vertical and horizontal crust deformation on fluvial, coastal, and glacial processes and the resulting landscapes. However, he also noted that landforms and their evolution histories can be used to recognize active tectonic structures and to decipher the kinematics of faults and folds.

Since landforms are shaped by concurrent action of endogenous and surface processes and reflect various internal and external controls, the major challenge in tectonic geomorphology studies is to extract signals indicative of crustal movements and to avoid over-interpretation. One such area, the morphology of which reflects both uplift and subsidence, as well as the protracted activity of various surface processes, is the Sudetes mountain range that straddles the Czech/Polish border and also includes a part of Germany. Alternating phases of uplift and planation underpinned early conceptual models of long-term landform evolution deemed applicable to the entire range (e.g., Klimaszewski, 1958; Walczak, 1968; Demek, 1975), whereas later research was more focused on individual morphotectonic structures, such as mountain fronts (Krzyszkowski *et al.*, 1995; Ranoszek, 1999; Badura *et al.*, 2003, 2007b; Štěpančíková *et al.*, 2008) or fluvial and terrace systems in zones suspected to be tectonically active (Krzyszkowski and Stachura, 1998a, b; Przybylski, 1998; Krzyszkowski *et al.*, 1998, 2000). Most recently, the advent of digital terrain models has allowed a new, more objective look at the topography (e.g., Badura *et al.*, 2007b; Migoń *et al.*, 2009; Sobczyk and Kasprzak, 2014) and hence opens up new perspectives for tectonic geomorphology studies in the Sudetes, yet to be fully explored. In the meantime, methods of rapid field quantification of rock strength have developed and these provide a basis for deciphering the role of variable rock resistance in the long-term evolution of regional relief, thus facilitating the identification of tectonic signals (Placek, 2011).

The present account is primarily a review paper, in which contributions to the tectonic geomorphology of the Sudetes are recalled and re-assessed. Despite numerous specific studies, no such attempt has yet been offered, especially one that would bring together findings from various parts of the Sudetes. The structure of the paper highlights the type of evidence used to infer tectonic activity instead of following a region-by-region presentation. The focus is on landforms at various spatial scales, starting from the most obvious fault-generated escarpments through fluvial morphological features to basin-scale morphometry. The authors discuss which tectonic geomorphology concepts have stood the test of time, how they changed through the years, and what sources of information and research approaches were used, including their limitations. At the end, the authors identify gaps in our understanding of the tectonic geomorphology of the Sudetes and outline research perspectives and challenges for the future. It is necessary to emphasize that tectonic geomorphology studies were largely decoupled from other approaches to the subject and are yet to be integrated. This particularly applies to the results of short-term geodetic and crustal stress measurements on the one hand and the longer-term landform and sedimentary record on the other. Likewise, there is an obvious shortage of geochronological data that would allow for reliable calculations of uplift and erosion rates. Finally, in a very few publications attempts were made to link the tectonic geomorphology of the Sudetes with the broader geodynamic context of Central Europe.

STUDY AREA

The Sudetes constitute the northeastern, marginal part of the Bohemian Massif, which is a tectonic mega-unit in Central Europe, characterized by large tracts of terrain with exposed basement rocks. While sharing much of the post-Variscan geological record with other parts of the Bohemian Massif, the Sudetes are exceptional in terms of relief diversity (Fig. 1) and preservation of a Permo-Mesozoic sedimentary cover (Fig. 2), which is hardly represented in other marginal elevations, such as the Ore Mountains, Bohemian Forest or the Czech-Moravian Highlands. The Neogene and the Quaternary were characterized by uplift, subsidence and deformation of the entire Bohemian Massif, with alternating periods of compression and extension, in response to the progressive build-up of compressional stresses that were transmitted from the East Alpine-Carpathian orogenic belt (Ziegler and Dèzes, 2007).

General geology

In the most general terms, two principal structural units may be distinguished in the Sudetes. These are the basement, which includes rock series ultimately deformed and metamorphosed during the Variscan orogeny, and the cover rocks represented by sedimentary series, spanning the period from the Late Carboniferous to the Late Cretaceous, and unconsolidated Cenozoic deposits (Fig. 2). In addition, post-orogenic granite intrusions occur in various parts of the Sudetes. The Variscan basement is usually interpreted as a result of the amalgamation of different terranes, which brought crustal blocks of very different origins, lithology and history into close contact (Aleksandrowski and Mazur, 2002). Boundaries are tectonic and major fault zones separate major terranes. The most common basement lithologies include gneiss and mica schist, followed by greenschists, phyllites and amphibolites. Proterozoic granites occupy large parts of the West Sudetes, whereas evidence of mild metamorphism is also recorded in Devonian and Early Carboniferous sedimentary series in the Middle and especially East Sudetes. Post-Variscan cover rocks are predominantly clastic, although the lithology varies from conglomerates to shales, particularly within the Upper Carboniferous and Permian successions. Carbonate rocks are less widespread and no extensive tracts of exposed limestone terrain occur in the Sudetes. The youngest sedimentary solid rocks are Upper Cretaceous sandstones and mudstones, which support tableland and cuesta landscapes in the central and northwestern part of the Sudetes.

Relief and landforms

Within the Bohemian Massif, the Sudetes show extreme diversity of relief (Migoń, 2011; Fig. 1). The most elevated spot in the entire Bohemian Massif is located in the West Sudetes (Śnieżka, 1603 m a.s.l.), whereas altitudes in the East Sudetes approach 1500 m a.s.l. (Praděd, 1491 m). The floors of some intramontane basins lie at 300–400 m a.s.l. and marginal uplands are at less than 300 m a.s.l., resulting in total relief of more than 1300 m. Furthermore, the spatial patterns of elevations and depressions are very complex. The Sudetes lack an axial ridge or any repetitive landform pattern (Jahn, 1980). Instead, they consist of a large number of distinctive geomorphic units, broadly classified as ranges (elongated), massifs (more rectangular in plan), plateaus, uplands and intramontane basins. The ranges, massifs and plateaus may be considerably dissected, but there are also numerous examples of poorly dissected tracts of elevated terrain, especially in the East Sudetes. Consequently, high-altitude surfaces of low relief (formerly referred to as planation surfaces) occur in various parts of the Sudetes, including those in the Karkonosze Mountains at 1300–1500 m a.s.l. (Placek *et al.*, 2007).

Escarpments are common in the Sudetes and vary in terms of height, distinctiveness, relation to geological structure and, apparently, origin (Migoń *et al.*, 2009). Some may be described as outer mountain fronts, separating the Sudetes from the foreland, whereas others are inner mountain fronts bounding intramontane depressions. Certain escarpments follow mapped faults, offset sedimentary series or juxtapose rocks of contrasting origin and age (Fig. 2). In these cases, a solid basis exists for arguing that they are of tectonic origin. However, other major belts of increasing altitude do not show such a relationship and their genesis cannot be deciphered using conventional geological approaches.

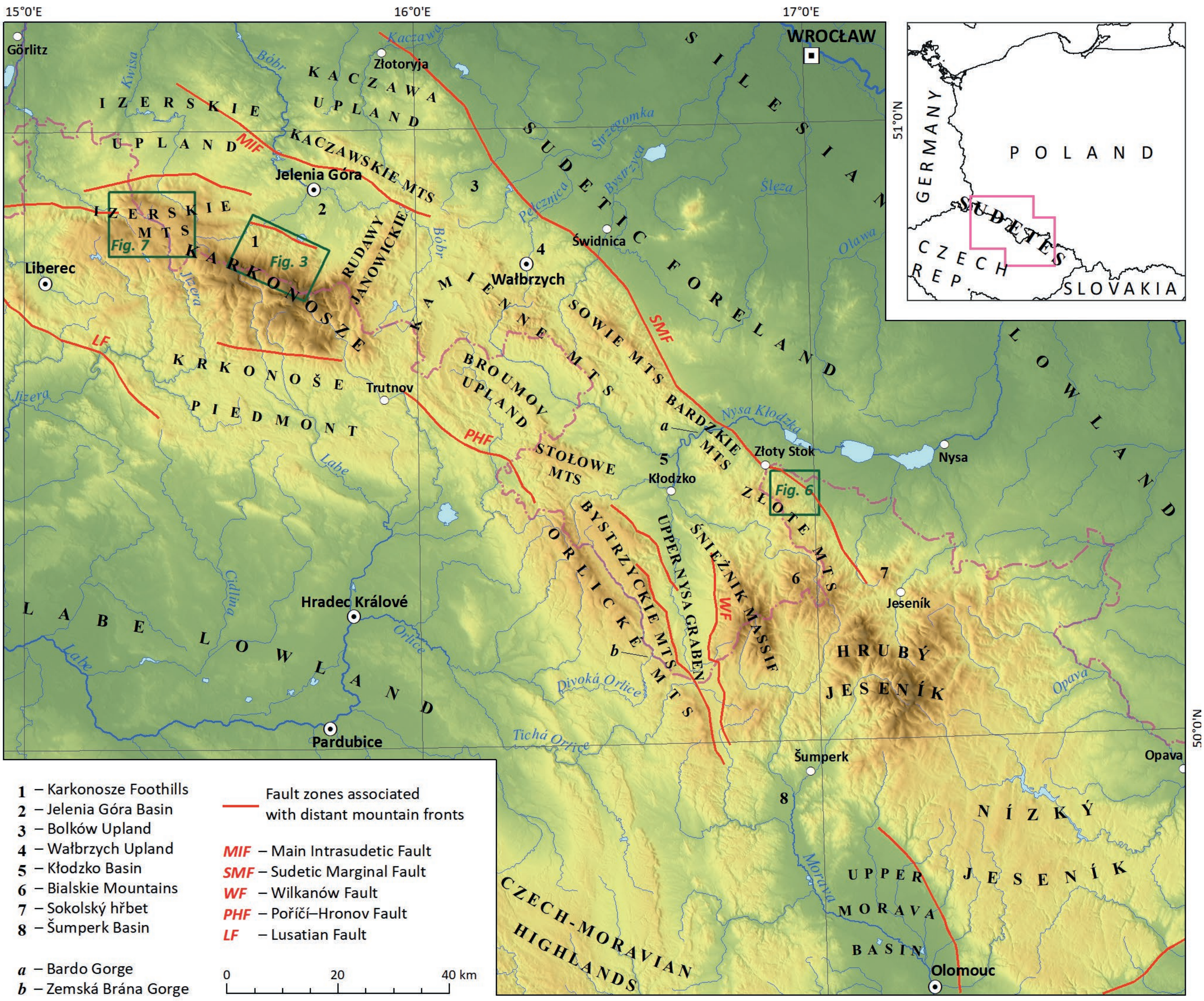

Fig. 1. Location map.

The picture is further complicated by the fact that some important fault lines (or their sections) inherited from the Variscan mountain building, such as the Main Intrasudetic Fault, do not have clear morphological expression, indicating very little activity, if any, during the Late Cenozoic. Finally, some escarpments owe their origin to contrasting rock resistance, for example, at the contact of Permian volcanic and sedimentary rocks, or to the presence of a resistant caprock.

EARLY CONCEPTUAL MODELS

The beginnings

Before the 1950s, the tectonic origin of the main characteristics of the geomorphology of the Sudetes was seldom addressed in detail, although each conceptual model developed later had its predecessors. One of the first to use landforms as evidence of Cenozoic tectonic history was Berg (1927) with respect to the Karkonosze Mountains (Fig. 3A). He interpreted the tiered structure of the northern slopes of the massif as resulting from differential uplift and subsidence along two parallel WNW–ESE-striking faults. The northern one was supposed to coincide with the morphological boundary of the Karkonosze massif against the Jelenia Góra Basin, whereas the geomorphic expression of the southern one was seen in the linear arrangement of passes and range-parallel valley reaches inside the mountain block. Berg (1927) reasoned that prior to tectonic differentiation a regional surface of low relief had existed, subsequently broken along faults and displaced, whereas enhanced erosion contributed to the fragmentation of the pre-uplift surface. Very similar was the interpretation of the morphology of the East Sudetes, offered by Anders (1939). He invoked the mid-Cenozoic activity of numerous faults, including the Sudetic Marginal Fault, which led to the differential displacement of the pre-Neogene surface. Significant altitude changes over short distances, along with peculiarities of drainage patterns (deflections, straight sections), supported his morphotectonic interpretation. He also considered that the pre-uplift surface locally may

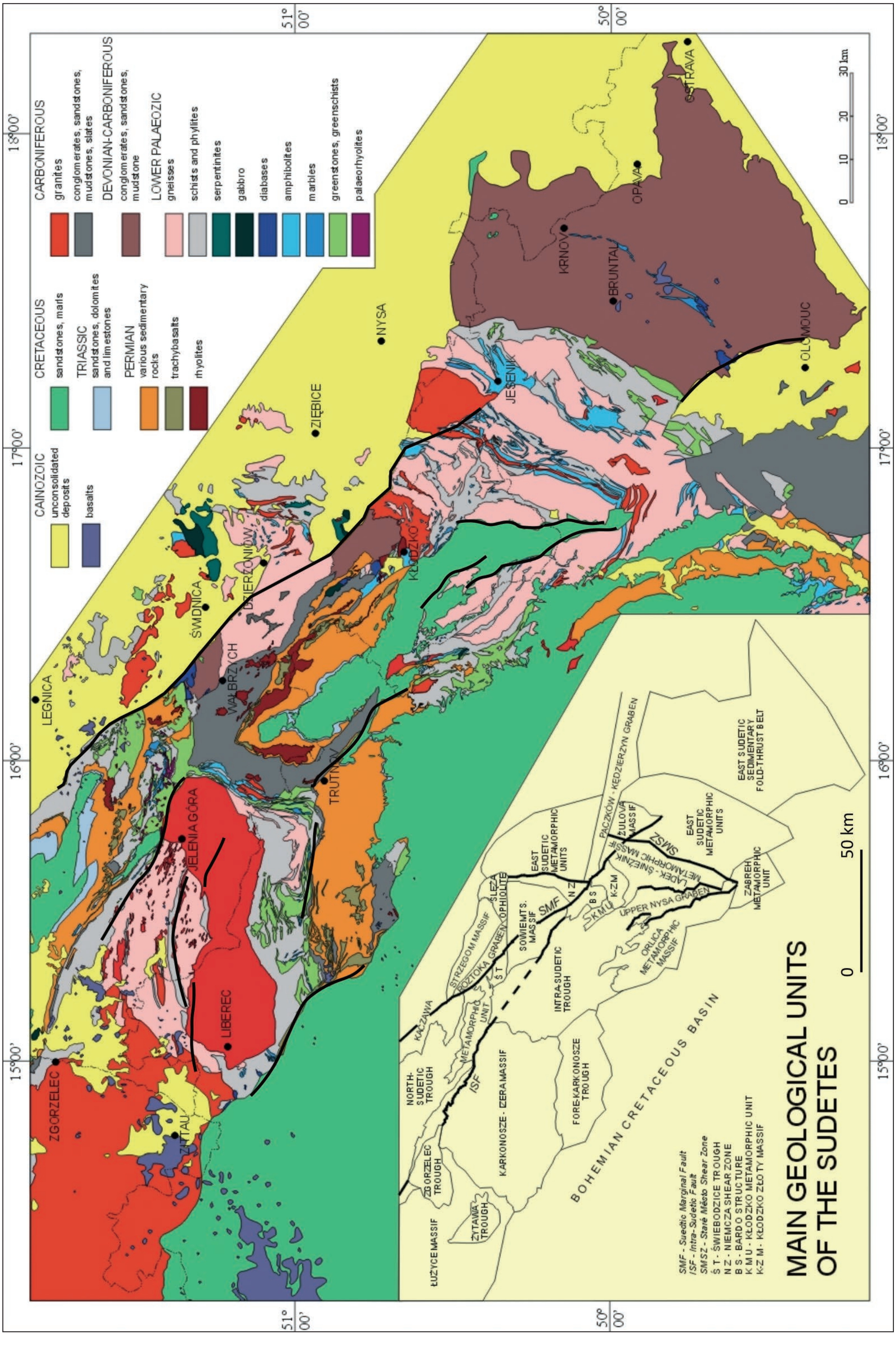

Fig. 2. Geological map of the Sudetes (Placek, 2011, modified). Black solid lines indicate fault zones associated with distinct mountain fronts; see Fig. 1 for explanation.

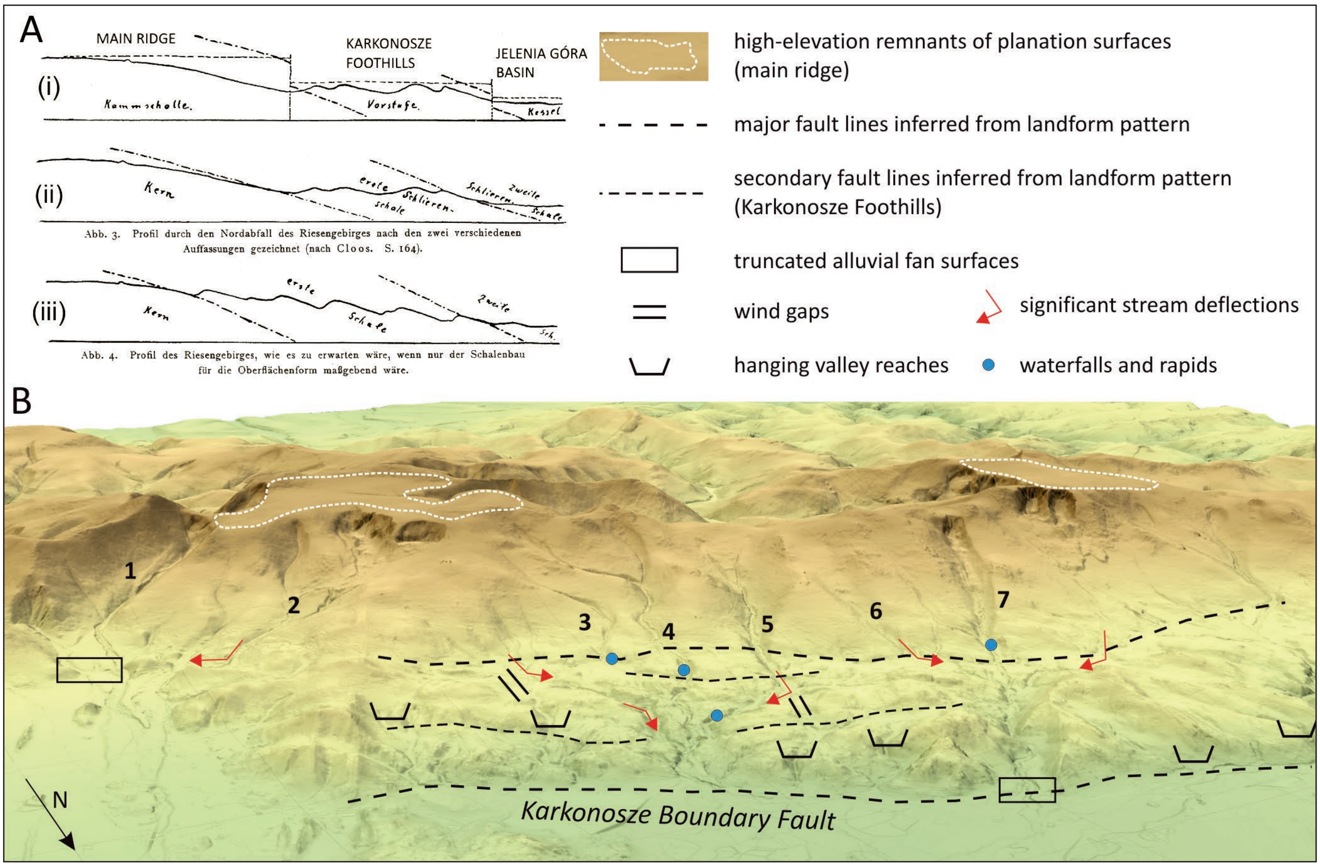

Fig. 3. Morphotectonic features of the northern part of the Karkonosze Mountains (3D visualization of LiDAR-based DEM). **A**. Contrasting interpretations of topography presented in the 1920s. (Berg, 1927) (i) – non-uniform uplift interpretation by G. Berg; (ii) – structural interpretation by H. Cloos; (iii) – topography expected to develop if Cloos' concept were correct. **B**. Selected geomorphic features interpreted as indicative of Late Cenozoic displacements along fault lines (after Sroka, 1991; Migoń, 1992). Main rivers: 1 – Łomniczka, 2 – Łomnica, 3 – Myja, 4 – Podgórna, 5 – Czerwień, 6 – Sopot, 7 – Wrzosówka. Note straight courses of rivers no. 5 and 7 which were interpreted as aligned along prominent SSW–NNE lineaments. See Fig. 1 for location.

have had relief of up to 500 m. Flexural bending was inferred in regions lacking clear, straight escarpments. These two examples show that any larger altitude contrasts were seen as the consequence of differential crustal movements. A different view was presented by Ouvrier (1933), whose conceptual model was clearly influenced by the Penckian model of long-term rise of terrain elevations and planation in the marginal parts of the uplifted block. In his analysis of the Karkonosze block, as many as 16 levels of incomplete planation were distinguished, arranged concentrically around the mountain core. Besides giving attention to planation surfaces, Ouvrier (1933) analyzed drainage patterns and interpreted abrupt deflections, underfit streams and wind gaps in terms of tectonic perturbations. All these publications are entirely descriptive and based on the qualitative analysis of maps and terrain.

Cyclic model involving alternating planation and uplift

The very first concept of relief development for the Polish Sudetes as a whole dates back to the 1950s and 1960s (Klimaszewski, 1958; Walczak, 1968). The model, referred to as "cyclic", underlined the existence of alternating phases of tectonic uplift and tectonic quiescence, the latter favouring planation processes. Being in this regard consistent with the Davisian scheme of landscape evolution (Davis, 1899), it implied, however, an origin for planation surfaces other than peneplanation. Degradation of the topography built by tectonic processes was to be achieved through the parallel retreat of valley sides and enlargement of pediments.

Three levels of planation surfaces of different ages (Palaeogene, Early Miocene and Early Pliocene) were distinguished in the Sudetes (Klimaszewski, 1958; Walczak, 1968; Fig. 4). It was claimed that the oldest occupy watershed positions, whereas the younger ones occur at lower altitudes. According to this model, their development was determined by two factors: (1) long periods of tectonic stability and (2) favourable climatic conditions, understood as a warm and humid climate, which facilitated surface downwearing through efficient chemical weathering of the rocks.

According to the model (Klimaszewski, 1958; Walczak, 1968), the formation of low-relief areas (called as "relief horizons") was interrupted by phases of increased tectonic activity in the Middle Oligocene, Middle Miocene and Late Pliocene, leading to the relative lowering of the base level

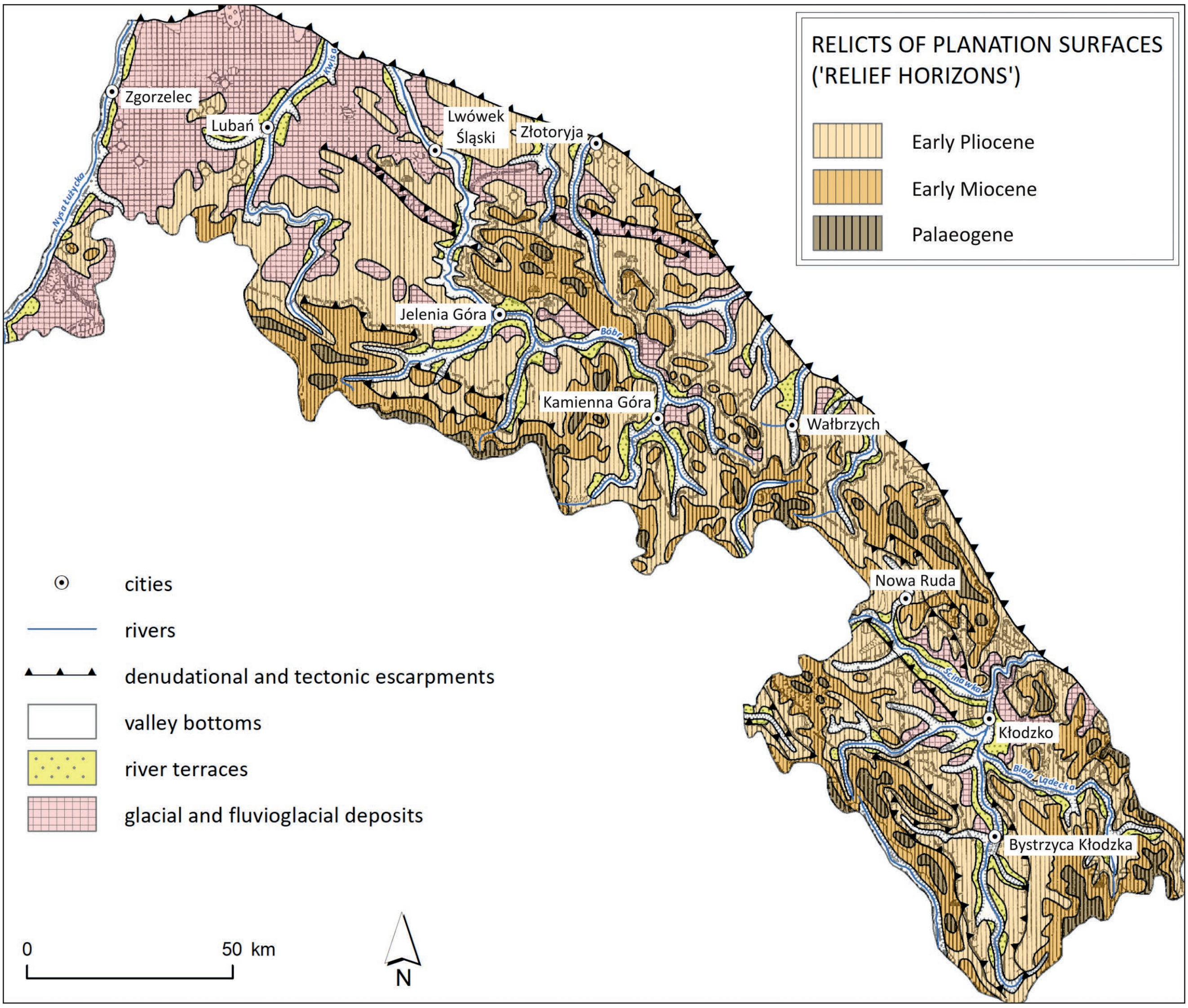

Fig. 4. Spatial distribution of planation surfaces in the Polish part of the Sudetes, according to Walczak (1972).

and the enhancement of river erosion. River incision proceeded concurrently with tectonic uplift, but was terminated by the advent of tectonic quiescence. The consequent crustal stability enabled the rivers to widen their valleys through lateral erosion, which eventually contributed to the formation of a new planation surface at the cost of the older. In this interpretation, the slopes that separate planation surfaces of different ages were supposed to be of denudational origin.

The presence of relicts of planation surfaces was evoked for all geomorphological units of the Polish Sudetes (Klimaszewski, 1958; Walczak, 1968). In most cases, relicts of the Palaeogene planation surface (the oldest "relief horizon") were supposed to occur at 800–1000 m a.s.l. Higher positions were presumed for the Karkonosze Mountains (1320–1420 m a.s.l.) and the Śnieżnik Massif (1100–1200 m a.s.l.). Early Miocene and Early Pliocene horizons were to develop at altitudes of 600–800 m and 400–500 m, respectively, whereas lower altitudes of 400 m and 300–360 m were evoked for the marginal uplands.

The differences in altitudes between particular "relief horizons" were used as a proxy for the total vertical displacement for each tectonic phase. Tectonic uplift of 200–400 m was estimated for the Oligocene (in places up to 600 m), 200–300 m in the Middle Miocene and 200-250 m in the Late Pliocene. These values were lower for the marginal uplands; for example, uplift of approximately 100 m was inferred for the Styrian tectonic phase (Middle Miocene) in this area. A similar total value of displacement was also adopted for the Sudetic Foreland, which as a tectonic unit (Fore-Sudetic Block) was subject to uplift of lower intensity by comparison with the Sudetes. Albeit no direct distinction between surface uplift and rock uplift in the sense of Molnar and England (1990) was introduced in the "cyclic" model of relief evolution of the Sudetes, Walczak (1968) stressed that the relicts of planation surfaces cannot be considered as intact landscape features inherited from the distant past and their subsequent downwearing has to be taken into account. However, he did not try to define the scale or intensity of this process.

The ”cyclic” model, although almost entirely conceptual and hardly tested against the geomorphic evidence (e.g., the actual distribution of level surfaces in different parts of the Sudetes), proved very influential and was used well into the 1980s as a framework to explain the morphological complexity of the Sudetes. However, although tectonic uplift of varying magnitude was assumed for different parts of the Sudetes, neither the detailed pattern of areas subject to uplift and subsidence nor the location of boundary faults inherent to the model were presented cartographically, hence the morphotectonic sub-division of the Sudetes also was not attempted.

Endogenous – exogenous interactions more in focus

The concept of tiered surfaces of low relief, portrayed in the ”cyclic” model as particularly distinctive for the Sudetes, appears to have been borrowed from a previous paper by Jahn (1953). Referring to the cyclic evolution of the relief of the West Sudetes, he had introduced the concept of so-called “morphologies”. Contrary to “relief horizons” (= planation surfaces), “morphologies” were represented by areas of higher relief, far from the old stage of development. Interestingly, no direct explanation of the factors enhancing erosion and responsible for the formation of consecutive “morphologies” were provided. This gap was partially filled nearly 30 years later, when Jahn (1980) strongly emphasized the role of changing climatic conditions in the formation of generations of relief in the Sudetes. Major importance was assigned to the generation of tropical landforms, inherited from a long time span of a warm and humid climate lasting until the Middle Miocene. The legacy of this morphoclimatic regime, under which the chemical weathering of rocks played a dominant role, was sought in the development of intermountain basins, planation surfaces, tors, shield inselbergs, stepped river profiles linked to the tropical *sulas* and general relief inversion on a regional scale. Among them, basins were considered to be the most characteristic elements of the regional landscape and their development was believed to have occurred mainly through the enhanced deep weathering and removal of weathering products.

Although the role of tectonic processes was not entirely neglected in Jahn’s (1980) model, the contribution of endogenic factors and forces to landscape evolution was clearly seen as subordinate and limited to increasing the rates of erosion (stripping) of products of rock disintegration. Apparently, this was due to increasing local relief and decreasing rates of chemical weathering within the areas subject to tectonic uplift, since these were characterized by a lower ground water level. Contrary to this view, Demek (1975) and Dyjor (1975) considered tectonic processes to be the most important morphogenetic factors in the evolution of the regional relief. In their concepts, the role of differential uplift and subsidence of individual tectonic blocks in the Late Cenozoic was crucial, although they tried to determine the time and scale of tectonic processes in different ways. Although the usefulness of planation surfaces in morphostructural analysis was noted by Demek (1975), Dyjor (1975) largely neglected geomorphological evidence and based his reasoning mainly on the geological record.

The vision of the geomorphological development of the Bohemian Massif introduced by Demek (1975) reconciled to some extent the models emphasizing the role of pedimentation (Klimaszewski, 1958; Walczak, 1968), etchplanation (Czudek and Demek, 1970) and differential uplift (Dyjor, 1975; Oberc, 1975) in relief evolution. Accordingly, the Palaeogene planation surface, which developed mainly through the parallel retreat of valley sides, was subject to differential tectonic uplift in the Oligocene. As a result, different crustal blocks were elevated to various altitudes, contemporaneously with removal of the products of tropical weathering. Further remodelling of the exposed, basal surface of weathering (etchplain) by exogenous geomorphic agents led to the formation of a new, Neogene planation surface. The remnants of the Neogene surface were supposed to occur in various positions a.s.l. within the different tectonic blocks. The resumption of tectonic activity in the Pliocene was responsible for subsequent fragmentation of the Neogene etchplain.

Diminishing interest in planation surfaces and alternative approaches

The utility of planation surfaces in morphostructural analysis was criticized by Dyjor (1975), who indicated that interpretation of their distribution may be ambiguous, when the multiphase tectonic movements that disturbed their spatial occurrence are taken into consideration. He also stressed that only one extended phase of tectonic quiescence favouring planation processes could be identified in the Sudetes in the Neogene, in the Late Miocene, the evidence being the presence of the so-called Poznań series, dominated by clay material, thus indicating little relief in the source area. For this reason, he tried to decipher the spatial pattern of Late Cenozoic tectonic deformations, their timing and amplitude on the basis of geological data, that is facies differentiation and geographical extent of the Miocene and Pliocene sedimentary series.

The analysis was carried out mostly within the Sudetic Foreland (Fig. 1), which as a tectonic unit (known as Fore-Sudetic Block) consists of several tectonic grabens infilled with Cenozoic deposits (Dyjor, 1975). The amplitudes of tectonic movements in this area were estimated to have been smaller than 100 m. However, they might occasionally exceed 350 m, a value comparable to some of the vertical displacement inferred for the Sudetes (Kopecký, 1972; Walczak, 1972). It should be emphasized that the analysis on the basis of geological data was of limited usefulness in the Sudetes themselves because of the lack of widespread pre-Quaternary cover deposits. Consequently, only a very crude attempt to identify morphostructural units within the Polish part of the Sudetes was offered.

Although the dominant role of faulting in the morphological evolution of the Sudetes and their foreland was underscored by Dyjor (1975, 1981), he distinctly emphasised the contribution of other types of tectonic movement to landscape development. On his neotectonic map of the Sudetes and Sudetic Foreland extensive areas were identified as subject to “large-radius uplift”. These movements, with an amplitude of 500–1000 m, were not linked to any recognized tectonic fault zones and were supposed to affect large geomorphological units of the Sudetes, such as the Karkonosze, Izerskie, Rudawy Janowickie, Bialskie, Złote and Bystrzyckie mountains. The existence of similar fold-like deformation on the territory of Czechoslovakia was invoked also by Kopecký (1972). The occurrence of mega-folds in the Bohemian Massif, including the mega-anticlinal ridge of the Orlické Mountains in the Sudetes, was indicated by Demek *et al.* (2007, 2009) as well. However, none of these authors analysed the assumed long-wavelength crustal deformations in a more insightful way and it remains unclear what were the specific mechanisms involved and whether the contemporary term ”lithospheric folding” might be applicable.

Conceptual models of relief evolution elaborated for the Sudetes as a whole were subsequently applied to selected smaller areas within the mountain range. For example, the morphological evolution of the Izerskie Mountains was presented by Oberc (1975), who argued for the break-up and differential uplift of the so-called pre-Late Miocene planation surface, which was an equivalent of the Palaeogene surface in the ”cyclic” model by Klimaszewski (1958) and Walczak (1968). Likewise, the genesis of the gross geomorphological feature of the Śnieżnik Massif was explained by differential uplift (Migoń, 1997), although it clearly stood at odds with the previous concept of relief evolution in this area presented by Don (1989), who distinguished six levels of planation surfaces of different ages, spanning from the Paleocene to the Pliocene, consistently with the “cyclic” conceptual model of regional relief development (Klimaszewski, 1958; Walczak, 1968).

THE RECORD OF TECTONIC ACTIVITY IN LANDFORMS, SEDIMENTS AND ELEMENTS OF A FLUVIAL SYSTEM

Fault-generated escarpments

General geomorphic characteristics

Since the majority of large-scale studies on the relief evolution of the Sudetes were based on planation surfaces, believed to be the most useful geomorphic features for morphotectonic reconstruction, until 1990s little attention was paid to the escarpments of tectonic origin themselves. This neglect may be to some extent explained by their problematic identification (Migoń, 1993a, b, 1995), with the consequence that no discrimination was made between the main tectonic and denudational escarpments on the geomorphological map of the Sudetes (Fig. 4; Walczak, 1968). An interest in the morphological expression of fault lines began in 1990s and was mostly concentrated on the northern part of the Karkonosze Mountains (Migoń, 1991, 1992; Sroka, 1991), on the marginal part of the Sudetes along the Sudetic Marginal Fault (Krzyszkowski *et al.,* 1995, 2000; Ivan, 1997; Migoń *et al.*, 1998; Migoń, 1999; Badura *et al.,* 2003, 2007b) and on the escarpments bounding the Upper Nysa Graben (Fig. 1; Sroka, 1997; Ranoszek, 1998, 1999).

Fault-generated escarpments in the Sudetes are represented by both rectilinear mountain fronts and scarps in the interior of the massifs, some of them up to 500 m high (Fig. 5). Their spatial arrangement is often parallel, accounting for the step-like morphology of some mountain ranges. They are developed along faults trending WNW–ESE in the West Sudetes and NW–SE to N–S in the East Sudetes. The total amounts of vertical displacement along these zones were estimated to be 200–500 m (Dyjor, 1975), whereas higher amplitudes of up to 1000 m were seen as unrelated to faults, but instead produced by poorly defined “large-radius uplift” (Kopecký, 1972; Dyjor, 1975, 1981). Individual escarpments differ in terms of lithology and the age of the bedrock involved. They are built of metamorphic, sedimentary and igneous rocks, outcropping, in some cases, next to each other for shorter distances within the footwalls. However, not all straight escarpments were necessarily considered to be a result of faulting. Migoń (1993a, b, 1995) suggested that the contrasting resistance of rocks of various types was a factor contributing to the development of fault-line scarps in the Sudetes, resulting from erosional exposure of older Variscan faults along lithological boundaries, and offered criteria for distinguishing between fault and fault-line escarpments.

Karkonosze and Izerskie Mountains

Although the tectonic nature of some escarpments within the Karkonosze Mountains was inferred as early as in the 1920s and 1930s (Berg, 1927; Ouvrier, 1933), they were subject to more detailed study only in the 1990s. Their straightness, the low degree of erosional dissection, the presence of granite on both sides of the topographic scarp, and the character of river valley morphology, including the presence of hanging valleys and wind gaps, were all considered as indicators of young tectonic movements (Fig. 3; Migoń, 1991, 1992). Some second-order escarpments, for which a tectonic origin was suggested, were identified within the Karkonosze Foothills and a morphotectonic subdivision of this area was also proposed (Migoń, 1992). Likewise, the southern margin of the Karkonosze Mountains is a prominent mountain front, in sections more than 500 m high, which coincides with distinct lineaments identified by means of remote sensing (Lysenko, 2007).

It was assumed that the northern margin of the Karkonosze Mountains developed along a splintered fault with a dominantly vertical displacement, although some contribution of horizontal (strike-slip) movements to the evolution of the escarpment, most likely in the pre-neotectonic (i.e., older than Neogene) stage, was also inferred (Sroka, 1991). The morphological expression of splintering was seen in the occurrence of minor ridges, oblique to the mountain front. Similar landforms were identified in the northern part of the Izerskie Mountains and in the northeastern sector of the Sudetic Marginal Fault (the Kaczawa Upland), although alternative explanations, not only related to splintering, were also presented (Migoń, 1993a, 1995).

The primary role played by differential uplift in the evolution of the escarpments in the Izerskie Mountains (Fig. 5A), including that comprising the western prolongation of the northern escarpment of the Karkonosze Mountains, was underscored by Migoń and Potocki (1996).

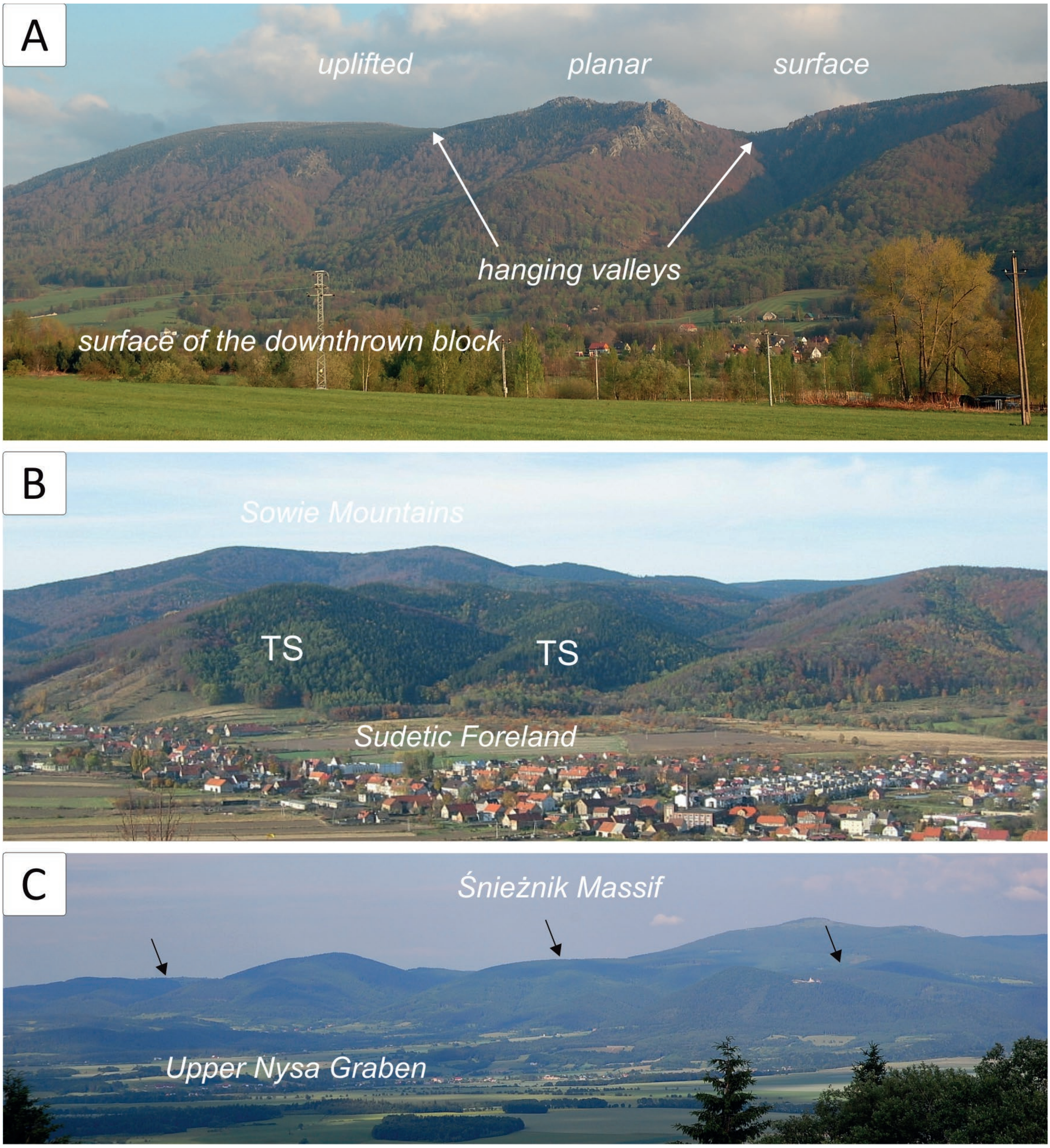

Fig. 5. Examples of mountain fronts in the Sudetes. **A.** Dissected northern escarpment of the Izerskie Mountains. The height of the scarp is 400–500 m. **B.** Boundary mountain front related to the Sudetic Marginal Fault near the town of Bielawa. The height of the marginal scarp is ca. 250 m. Note V-shaped valleys crossing the front and triangular spurs (TS) in between. **C.** Western escarpment of the Śnieżnik Massif related to the Wilkanów Fault. The height of the marginal scarp is 200–300 m, while benches above it (arrows) at c. 800 m a.s.l. were interpreted in different ways: as cyclic surfaces of incomplete planation (Don, 1989) or pre-faulting level surfaces (Migoń, 1997).

They noted some morphological features supporting the idea of the dominant influence of endogenic factors on landscape evolution. Paramount importance was given to the hanging valleys. Their occurrence in relatively homogenous granite bedrock was considered to be an unequivocal indicator of tectonic origin of the escarpments. Except for the presence of hanging valleys, the floors of which are up to 300 m above the surface of the downthrown blocks, the tectonic contribution to the development of the area was believed to be reflected in a sharp asymmetry across the mountain range as a consequence of the tilting of individual blocks.

Sudetic Marginal Fault

The escarpment related to the Sudetic Marginal Fault (SMF), which is one of the main tectonic structures in the region (Oberc and Dyjor, 1969), has received most attention in the neotectonic studies carried out in the Sudetes and their foreland. This polyphase fault zone, trending in a NW–SE direction from Bolesławiec to Jeseník, a distance of approximately 150 km, separates the Sudetes Mountains (Sudetic Block, 400–1000 m a.s.l.) from the Sudetic Foreland (Fore-Sudetic Block, 200–300 m a.s.l.). Its geomorphological expression varies in sharpness and the most prominent scarps occur in the central and southeastern sectors, corresponding to the Sowie and Złote Mountains, respectively (Fig. 5B). In turn, the northwesternmost part of the structure remains buried under the Neogene and Quaternary deposits, thus no related scarp can be observed. It is not entirely clear whether this indicates inactivity in the time span given or efficient deposition, which outpaced vertical tectonic differentiation. The height of the marginal escarpment of the Sudetes varies from 50 to more than 500 m.

Although the greatest amplitude of vertical tectonic displacement along the SMF was assumed for the Neogene (Oberc and Dyjor, 1969; Dyjor, 1975; Krzyszkowski *et al.*, 1995; Migoń, 1995), it was the youngest, Middle and Late Pleistocene movements that attracted most attention. This resulted from the absence of older river terraces and alluvial fans, which could be used as geomorphic markers *sensu* Burbank and Anderson (2011) for tracing tectonic disturbances in longer-term perspective, as well as from the lack of sediments, older than Pliocene and suitable for neotectonic correlation.

Despite the abundance of papers, in which the neotectonic development of the areas adjacent to the SMF is discussed (Krzyszkowski and Pijet, 1993a, b; Krzyszkowski and Stachura, 1993, 1998a, b; Mastalerz and Wojewoda, 1993; Pijet and Krzyszkowski, 1994; Krzyszkowski *et al.*, 1995; Ivan, 1997; Krzyszkowski and Biernat, 1998; Krzyszkowski and Olejnik, 1998; Krzyszkowski *et al.*, 1998, 2000; Migoń and Łach, 1998; Migoń *et al.,* 1998; Migoń, 1999; Štěpančíková, 2007; Štěpančíková *et al.*, 2008), little attention was paid to the morphological expression

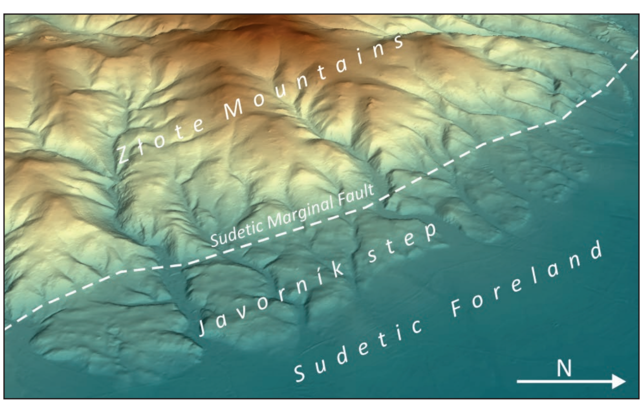

Fig. 6. Range-bounding escarpment of the Sudetes in the Złote Mountains sector of the Sudetic Marginal Fault. A few generations of triangular facets were interpreted as a record of repetitive phases of uplift along the fault. See Fig. 1 for location.

of the fault-generated escarpment itself. Its morphotectonic evolution and the activity of the fault were examined mostly through the analysis of the elements of fluvial systems (i.e., river terraces, alluvial fans, stream longitudinal profiles, river valley morphology, etc.), discussed later in this paper. The splintering of the main fault was evoked for the marginal part of the Złote Mountains (Ivan, 1997). In this case, its morphological consequences were seen in the occurrence of a relatively wide tectonic step parallel to the fault line, named the Javorník step (Fig. 6), rather than elongated range-parallel ridges.

Topographic profiles across the most elevated part of the footwall corresponding to the Sowie Mountains revealed its stepped topography and the occurrence of secondary escarpments, parallel to the one related to the SMF and interpreted as developed along subsidiary faults (Krzyszkowski and Pijet, 1993a, b; Krzyszkowski and Olejnik, 1998). Otherwise, a single escarpment is present, especially in the least elevated (< 450 m a.s.l.), northwestern sector of the SMF (Migoń and Łach, 1998; Migoń *et al.,* 1998), indicating a simple pattern of uplift relative to the foreland.

Attempts also have been made to infer the uplift history from the morphology of the escarpment. Its bipartite morphology, recognized in the Złote (Rychlebské) Mountains sector of the SMF and consisting of a gentler upper and a steeper lower part (8–10° and 14–21°, respectively), was interpreted as a record of at least two different uplift stages (Ivan, 1997). Repetitive phases of uplift along the SMF subsequently were inferred also on the basis of the tiered pattern of triangular and trapezoidal facets (Fig. 6), recognized from the digital elevation model (Badura *et al.*, 2003, 2007b). At least five episodes of uplift were presumed for the most elevated mountain ranges along the SMF, namely for the Złote and Sowie Mountains. The formation of the facets would postdate 31 Ma ago (Oligocene), which is the age of the basalts of the Sichów Hills area, displaced by the fault. In addition to the Złote Mountains sector of the SMF, vertical segmentation of the range front was noted in the Sowie Mountains, where the lowest, steeply inclined part of the slope (up to 29°) was interpreted as a basal scarplet (Krzyszkowski and Olejnik, 1998).

In order to assess the degree of tectonic activity of the SMF in the Quaternary, several morphometric indices were applied (Sroka, 1992; Krzyszkowski *et al.*, 1995; Krzyszkowski and Olejnik, 1998; Badura *et al.*, 2003, 2007b). Most of them were calculated with respect to the elements of fluvial systems; the only one directly related to the morphology of the range front itself was the mountain front sinuosity index (S_{mf}; Bull and McFadden, 1977).

The average value of the index, calculated for 11 segments of the Polish part of the escarpment between Złotoryja and Złoty Stok, was equal to 1.36 (Sroka, 1992; Krzyszkowski *et al.*, 1995), with all sectors falling into the category of “active mountain fronts”, according to the classification by Bull and McFadden (1977). Higher values of the index, indicating less activity, typified the northwestern segment of the scarp and a progressive decrease in them was observed towards the southeast, with the minimum value corresponding to the Sowie Mountains sector of the mountain front. Badura *et al.* (2003) calculated a S_{mf} value of 1.054 for a shorter section of the scarp between Dobromierz and Złoty Stok, with the exclusion of its northwesternmost segment. The value of 1.051 was then obtained for the whole mountain front from Złotoryja to Jeseník (Badura *et al.*, 2007b), although no values for individual segments were presented in either of these papers. Initial morphometric analyses were conducted on topographic maps at a scale of 1 : 100,000 (Sroka, 1992), followed by the application of a DEM (digital elevation model), constructed on the basis of cartographic materials at a 1:10,000 scale (Badura *et al.*, 2003, 2007b). However, it is not clear how the actual piedmont junction – the crucial variable in the calculation – was traced.

Although the footwall of the SMF varies considerably in terms of lithology – comprising metamorphic (phyllites, greenschists, diabases, gneisses, amphibolites), sedimentary (conglomerates, sandstones, mudstones) and igneous (granitoids) rocks – no detailed studies of their strength and resistance to erosion were carried out until the 2000s (Placek, 2011). Thus, differences in the morphological expression of the escarpment, including the results obtained through the application of the S_{mf} index, were interpreted mostly in terms of non-uniform fault activity, whereas the influence of varied rock resistance was considered minor (Sroka, 1992; Krzyszkowski *et al.,* 1995; Migoń, 1995). In these interpretations, the Sowie Mountains segment was seen as a sector of the most intensive Quaternary uplift, whereas diminishing tectonic activity was evoked towards the northwest. This remains consistent with the height of the escarpments as well as with the amount of vertical displacement, estimated for the SMF from comparison of the altitude of low-relief surfaces within the footwall and buried bedrock surfaces in the hanging wall (Oberc and Dyjor, 1969).

Upper Nysa Graben

The problem of separating tectonic and lithological controls on the development of the escarpments is minimized, when the mountain fronts that cut across relatively homogenous rocks are taken into account. The morphology of the gneissic scarp, bounding the Śnieżnik Massif from the west (Figs 1, 5C), was described qualitatively by Ranoszek (1998) and then complemented by more objective morphometric studies (Ranoszek, 1999). Although they were mostly focused on the elements of fluvial systems (river valley morphology, stream longitudinal profiles, river basin asymmetry), the significance of scarp height, inclination, the degree of erosional dissection and the occurrence of trapezoidal facets as well as hanging valleys was also discussed in a morphotectonic context. The bipartite morphology of the escarpment, with a gentler upper slope and a more inclined lower part, separated from each other by a bench up to 300 m wide, was supposed to reflect repetitive phases of tectonic uplift along the fault and the retreat of an older scarp from the fault line, in accordance with the model presented by Hamblin (1976). Analysis of the spatial distribution and size of benches (surfaces of low inclination within the mountain front) led the author to distinguish between the effects of scarp retreat and differential uplift. Erosional retreat of the scarp was considered responsible for the formation of the stepped morphology on a minor scale, as reflected in relatively small differences in altitude between successive benches (up to 100 m). Much greater differences (up to 300 m) were to indicate the occurrence of a separate fault inside the footwall block, parallel to the marginal one. The presence of such a pattern of tectonic deformation was postulated earlier by Migoń (1997) and Sroka (1997). In subsequent publications about the area, the geomorphological characteristics of the range-bounding escarpment were not explored further (Don and Gotowała, 2008; Jamroz *et al.*, 2014; Sobczyk and Kasprzak, 2014) and the validity of bench analysis based on relative height is yet to be critically re-assessed there and also for other locations within the Sudetes.

In contrast, relatively little attention was paid to the morphological expression of the escarpments bounding the Upper Nysa Graben to the west (Sroka, 1997; Ranoszek, 1998; Badura and Rauch, 2014), albeit the occurrence of Upper Cretaceous sediments, both in the tectonic graben (c. 400 m a.s.l.) and in the watershed position in the Bystrzyckie Mountains (700–800 m a.s.l.), unequivocally proves their tectonic origin.

River valley morphology

Studies of river valley morphology were mostly based on cross-profile analysis (Krzyszkowski and Pijet, 1993a, b, 1994; Migoń and Potocki, 1996; Migoń and Łach, 1998; Štěpančíková *et al.*, 2008), supported by the application of morphometric indices (Sroka, 1992; Krzyszkowski *et al.*, 1995; Krzyszkowski and Olejnik, 1998; Ranoszek, 1999; Badura *et al.*, 2003, 2007b), for which topographic maps were the primary source of information.

The alternation of valley reaches of different morphology was recorded, *inter alia*, in the Karkonosze Mountains, where the bedrock is generally uniform (granite; Migoń, 1991, 1992). Deeply incised sections, each with steep rocky sides and a narrow floor with a bedrock channel, in which waterfalls and rapids occur, were correlated with fault zones. They are separated by wider valley sections, with gentler slopes and the presence of alluvial fill. This morphological diversity accounted for hourglass-like planform of some valleys (Sroka, 1991), observed also in the Śnieżnik Massif (Ranoszek, 1998). In the Wałbrzych Upland (Fig. 1), the area adjacent to the SMF, wide valley segments with a thick alluvial cover and distinct terraces, referred to as ”depressions”, were attributed to the subsidiary grabens within the footwall (Krzyszkowski and Stachura, 1993, 1998a, b), although the presence of terrace flights indicates minor uplift with respect to the surroundings, rather than absolute subsidence. A sharp contrast between shallow trough valleys, frequently occupied by peat bogs, in the uppermost sections of the rivers and their V-shaped/gorge-like prolongations corresponding to tectonic escarpments was described from the northern part of the Izerskie Mountains (Migoń and Potocki, 1996). In the northeastern part of the Złote Mountains and the adjacent area of the Žulovská Hilly Land the analysis of river valley morphology enabled the identification of segments showing enhanced erosion and hence, likely subject to recent rejuvenation (Štěpančíková *et al.*, 2008).

In the Izerskie Mountains, non-uniform uplift and tilting of particular tectonic blocks contributed to the pronounced asymmetry of the cross-profiles of some valleys trending from NW to SE, with the NE-facing sides characterised by greater inclination (Migoń and Potocki, 1996). The prevalence of steeper south-facing valley slopes in the northern part of the Śnieżnik Massif was explained in a similar way (Ranoszek, 1998, 1999).

In order to assess the relative tectonic activity of fault zones, the valley floor width – valley height ratio (V_f; Bull and McFadden, 1977) was implemented in the analysis of river valley morphology. A lower degree of river downcutting, corresponding with the higher values of the V_f index, was inferred for the northwestern sector of the SMF, whereas stronger river incision in the southeastern section of the fault was reflected in index minima (Krzyszkowski *et al.*, 1995). The average values calculated for these two segments were equal to 2.4 and 0.6, respectively. The picture of variable degree of tectonic activity along the SMF was basically consistent with the results obtained through the application of S_{mf} index (see part on Fault-generated escarpments).

A similar pattern in the spatial distribution of the V_f index along the SMF was presented by Badura *et al.* (2003, 2007b), who calculated mean values for 15 different segments of the fault zone, with the minimum corresponding to the Sowie and Bardzkie Mountains (0.4) and the maximum to its northwesternmost part (2.0). The similarity of the results was obtained in spite of a different source of data for the morphometric analysis and calculation method. Whereas measurements were at first performed on topographic maps with a 1:10,000 scale, 1 km upstream from the mountain front base (Krzyszkowski *et al.*, 1995), the advent of digital topography enabled computation of the V_f index values with the use of a DEM (Badura *et al.*, 2003, 2007b). They were calculated for valley cross-sections situated upstream from the mountain front, at a distance of 10% of the total length of the stream, measured from the front/piedmont junction.

Low values of the index (< 1), corresponding with strong tectonic activity (Bull and McFadden, 1977), were obtained for the Sowie Mountains sector or the SMF (Krzyszkowski and Olejnik, 1998). Their spatial distribution confirmed the general tendency to unequal uplift of the mountain range, decreasing in the NW direction.

In the Śnieżnik Massif, cross-profiles were located exactly at the line of the range-bounding front (Ranoszek, 1999), which is not recommended for at least two reasons (Bull, 2007). Firstly, the mountain-piedmont junction is an area of tectonically induced bedrock fracturing and weakening and, thus, higher sensitivity to degradation, which might result in enhanced widening of the valley. Secondly, these segments are the most likely sites for climate-driven aggradation.

Stream longitudinal profiles

The changes in river valley morphology were often discussed concurrently with changes in stream longitudinal profiles; the latter usually were derived from 1:25,000 topographic maps, as most studies were performed prior to the advent of detailed DEMs. Most of the rivers crossing fault zones in the Karkonosze Mountains (Migoń, 1991, 1992; Sroka, 1991), Sowie Mountains (Krzyszkowski and Pijet, 1993a, b; Pijet and Krzyszkowski, 1994; Krzyszkowski and Olejnik, 1998), Wałbrzych Upland (Krzyszkowski and Stachura, 1993, 1998a, b) and the Izerskie Mountains (Migoń and Potocki, 1996) are characterised by highly irregular longitudinal profiles, with numerous breaks deemed unrelated to lithological boundaries. As these steeper reaches were usually not present strictly at the presumed fault lines, whether range-bounding or inside the massif, their upstream migration due to headward erosion was inferred. Knickpoint retreat of 200–400 m from the range front was evoked for the Karkonosze Mountains (Sroka, 1991), whereas in the Wałbrzych Upland breaks in longitudinal profiles occasionally were found as much as 2–3 km upward from the nearest fault zones (Krzyszkowski and Stachura, 1993). Different amounts of knickpoint retreat from the marginal parts of the Sokolský Ridge (Złote Mountains) in the East Sudetes were interpreted as one of indicators of differential uplift of the area, with longer distances correlated with a higher degree of tectonic activity (Štěpančíková *et al.*, 2008).

The most prominent steepening of river channels was presented for the central sector of the SMF, corresponding to the Sowie Mountains (Krzyszkowski and Pijet, 1993a, b; Krzyszkowski and Olejnik, 1998). The occurrence of other knickpoints further upstream was correlated with the subsidiary faults. Contrary to this picture, no distinct breaks were recorded in the longitudinal profiles of rivers crossing the SMF in its northwestern part (Migoń and Łach, 1998; Migoń *et al.*, 1998; Migoń, 1999). This underpinned the notion of relatively weak recent tectonic activity in this area (Krzyszkowski *et al.*, 1995). In a few cases the break of slope was observed in the upper section of a river, 3–4 km from the SMF, upstream of which the river valleys were not subject to rejuvenation (Migoń and Łach, 1998). In the Śnieżnik Massif, rejuvenated parts of river valleys were distinguished solely on the basis of the presence of distinct breaks of the valley sides, with no direct reference to the possibly co-existent knickpoints in longitudinal river profiles (Ranoszek, 1999). No detailed studies have yet been undertaken in the Sudetes to distinguish between knickpoints that would indicate the concurrent activity of parallel (subsidiary) faults and those created by the rejuvenation of a single main fault and successive phases of headward erosion.

The absence of evident profile breaks, corresponding with the Wilkanów Fault bounding the Śnieżnik Massif from the west, as well as to tectonic zones supposed to exist in its interior, was underscored (Migoń, 1997; Ranoszek, 1998). The reason was seen in sustained uplift of lower intensity, which enabled rivers to cut down in equilibrium with the lowering of local base level. The application of the stream length – gradient index (SL index; Hack, 1973), however, demonstrated the presence of channel segments abnormally steep with respect to the adjacent ones in the aforementioned zones of tectonic deformation (Ranoszek, 1999).

Besides the Śnieżnik Massif, studies of longitudinal stream profiles based on the SL index were conducted in the Złote Mountains. In their northeastern part, in the Sokolský Ridge, knickpoints in longitudinal profiles and accompanying increased values of the SL index displayed a linear arrangement corresponding with the northwestern edge of the ridge, for which a tectonic origin was inferred (Štěpančíková, 2007; Štěpančíková *et al.*, 2008). In the northwestern part of the Złote Mountains, four different zones of higher SL index values were distinguished and correlated with differently oriented, active faults (Štěpančíková and Stemberk, 2016).

Stream deflections

Although deflections of streams are commonly interpreted as indicators of strike-slip movements along the faults (Wesson *et al.*, 1975), they were occasionally identified in the Sudetes, for which the prevalent occurrence of normal faulting in the Late Cenozoic is assumed (Zuchiewicz *et al.*, 2007). Sroka (1991) noticed that almost all streams crossing the northern margin of the Karkonosze Foothills experience minor deflection towards the west, whereas departures from this rule were explained by the occurrence of both so-called ”lithological barriers” and subsidiary, transverse, tectonic zones. Similar phenomena were recorded in the central sector of the SMF corresponding with the Sowie Mountains, where the opposite sense of deflection of adjacent streams was emphasized (Migoń, 1993a). Whereas changes of river courses in the Karkonosze Mountains were mostly seen as reflecting splintering of the boundary fault, the opposite sense of stream deflections in the Sowie Mountains was presumed to mirror differential tilting of individual tectonic blocks within the footwall, rather than strike-slip displacements, for which a consistent deflection is expected.

The quantitative analysis of deflected streams at the SMF line revealed that most of them are deflected to the north and northeast, with the angle of deflection reaching 90° (Migoń, 1994). This was consistent with the presumed asymmetric tilting of the Sowie Mountains block towards the NW, inferred from the decreasing altitudes of the remnants of Cenozoic planation surfaces and the amount of river incision in this direction (Krzyszkowski and Pijet, 1993a). Some changes in river courses related to tectonic tilting were noticed in the Złote Mountains sector of the SMF as well, although no further description of the phenomenon was offered (Ivan, 1997).

Drainage pattern and its changes

Significant tectonic control of the development of drainage patterns was claimed in many papers, especially with regard to the rivers flowing along secondary faults, perpendicular or oblique to the main fault-generated escarpments (Migoń, 1992; Krzyszkowski and Pijet, 1993a, b; Pijet and Krzyszkowski, 1994; Krzyszkowski and Biernat, 1998; Krzyszkowski and Olejnik, 1998; Migoń and Łach, 1998; Ranoszek, 1998). There is a scarcity of approaches, however, in which any attempt was made to determine this causal relationship in a more objective way. The analysis of the orientation of river valleys juxtaposed with the spatial arrangement of the main fault zones in the area of the Śnieżnik Massif revealed an ambiguous relationship, particularly in its northeastern part (Sroka, 1997). Conversely, a strong correlation between valley and fault orientation was observed in the northeastern part of the Złote Mountains and the adjacent part of the Sudetic Foreland (Štěpančíková *et al.*, 2008), although it should be emphasized that along with river valleys, other morpholineaments, such as rectilinear escarpments, were taken into account in this study.

The spatial pattern of the river network was little studied in the Sudetes. The only example of a more detailed analysis was presented by Sroka (1997) for the vicinity of the Kłodzko Basin (Fig. 1). The author compared the geometric arrangement of fluvial systems with the model patterns of drainage networks presented in the literature. Underrepresentation of the dendritic pattern in its pure form was supposed to result from the high lithological diversity of the area, as well as from the complicated spatial pattern of areas subject to uplift and subsidence. In the immediate vicinity of fault-generated escarpments, a shift from a dendritic to a rectangular pattern was observed. The rectangular drainage pattern in the northeastern part of the Złote Mountains and the adjacent area was taken to reflect the spatial arrangement of joint and fault systems (Štěpančíková *et al.*, 2008). Their influence on spatial pattern of the river valleys was examined also with respect to individual landforms, such as the Zemská Brána Gorge in the Orlické Mountains (Vaničkova, 2007a, b), with the conclusion that the zig-zag course of the gorge reflects the presence of variously striking fault and master joint lines.

Likewise, little attention was paid to the quantitative characteristics of drainage patterns. Drainage density, expressed as a ratio of the total length of the streams over the area under investigation (Neumann 1900, *fide* Horton 1932), was calculated for the Kłodzko Basin and the surrounding mountain ranges (Sroka, 1997). Higher drainage density index values were ascribed to the areas immediately below the escarpments, developed along the SMF and the faults bounding the Upper Nysa Graben.

Tectonically-induced changes in the river network arrangement were described from the Karkonosze (Ouvrier, 1933; Migoń, 1992), Izerskie (Migoń and Potocki, 1996) and Złote Mountains (Štěpančíková, 2007; Štěpančíková *et al.*, 2008), as well as from the intramontane tectonic depression of the Upper Nysa Graben (Sroka, 1997). Consequent flow of rivers draining the northern slope of the main ridge of the Karkonosze Mountains was disturbed, owing to differential uplift of individual tectonic blocks within the area of the Karkonosze Foothills. As a result, subsequent valley segments along less elevated/subsided areas started to form, whereas wind gaps and abandoned valleys in waterdivide position, in the downstream prolongation of consequent streams, mark the trace of the former flow (Fig. 3B).

Contrasting directions of river courses within drainage basins (barbed patterns) were locally interpreted as indicative of a major reorganization of the drainage pattern. Drainage reversal was inferred in the central part of the Izerskie Mountains, where a discrepancy between the overall drainage of the area through the Izera River towards the southeast and generally westward flow of its tributaries was observed (Fig. 7; Migoń and Potocki, 1996). Similar reorganisation of

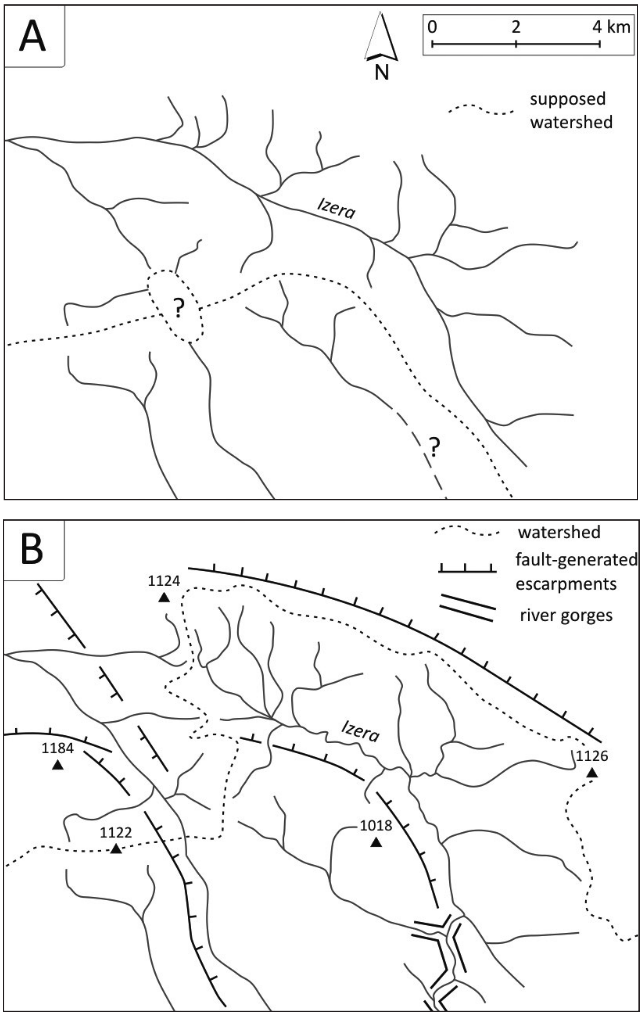

Fig. 7. Drainage reversal in the central part of the Izerskie Mountains according to Migoń and Potocki (1996); see Fig. 1 for location. **A.** Hypothetic original drainage. **B.** Present-day situation.

the river network was presumed in the Upper Nysa Graben (Sroka, 1997). In its southern part, an increased occurrence of river segments with a southerly flow was recorded, which was at odds with the contemporary drainage of the whole area towards the north. Differential uplift of the Sokolský Ridge in the Złote Mountains was seen as a factor disturbing the original drainage of the area to the northeast, forcing a shift towards the northwest (Štěpančíková, 2007; Štěpančíková *et al.*, 2008). The young stage of drainage network development in the uplifted area of the Sokolský Ridge was inferred from the analysis of river valley morphology and stream longitudinal profiles.

In addition to the changes in the river network, assumed to have occurred at some time in the Neogene (e.g., Migoń, 1992; Migoń and Potocki, 1996; Sroka, 1997), those post-dating continental glaciation of the marginal parts of the Sudetes in the Middle Pleistocene were also addressed. In some publications, drainage pattern changes and the formation of deeply incised river gorges (up to 100 m) were attributed to the relatively strong, but short-lived, glacio-isostatic rebound that occurred after the last glaciation in the region (Saalian = Odranian; probably an early part of marine oxygen isotope stage – MOIS 6; Krzyszkowski and Biernat, 1998; Migoń *et al.*, 1998) and in some places also the Elsterian glaciation (MOIS 12; Krzyszkowski and Stachura, 1993, 1998a, b; Krzyszkowski *et al.*, 1998, 2000). The magnitude of the post-Saalian uplift, inferred from the position of hanging valley floors partially filled with glacial deposits and the depth of contemporary incisions, was considered to vary in space, from 20–30 m to nearly 100 m (Krzyszkowski and Biernat, 1998; Krzyszkowski and Stachura, 1998a). It was assumed that these externally driven uplift stages were superimposed on endogenic movements of the Earth's crust in the marginal part of the Sudetes, along the Sudetic Marginal Fault.

Drainage basin characteristics

Morphotectonic studies of river basins were exclusively based on morphometric indices, although the source data for their calculation changed over time. As studies were initially conducted with the use of topographic maps at a 1:10,000 (Sroka, 1992, 1997; Krzyszkowski *et al.*, 1995) or 1:25,000 scale (Krzyszkowski and Olejnik, 1998; Ranoszek, 1999), they were replaced later by DEMs (Badura *et al.*, 2003, 2007b; Sobczyk and Kasprzak, 2014). The advent of digital topography and the development of Geographic Information Systems (GIS) made it possible to extend the number of research objects from a dozen or so to several hundred (Badura *et al.*, 2007b).

Besides the mountain front sinuosity index (S_{mf}) and the valley floor width – valley height ratio (V_f), discussed earlier in this paper, tectonic activity of the SMF was assessed in the light of the basin elongation ratio R_e (Schumm, 1956). Lower values of this index (< 0.5) correspond to more elongated basins, which are likely to have developed in the areas subject to more intensive uplift, whereas more circular ones (> 0.75) are associated with areas of lower tectonic activity (Bull and McFadden, 1977). The mean value of 0.53 was obtained for drainage basins within the footwall of the SMF in the Polish part (Sroka, 1992; Krzyszkowski *et al.*, 1995). Decreasing values of the index towards the southeast, indicating an increase of tectonic activity in this direction, were consistent with the picture obtained through the application of other indices (S_{mf}, V_f). Notwithstanding, their ambiguous relationship was noted in the marginal part of the Sowie Mountains (Krzyszkowski and Olejnik, 1998). In this area, fault segments considered to be the most active in the light of low V_f index values were characterized by the highest values of basin elongation ratio. Such a discrepancy also emerged from data presented by Badura *et al.* (2003). The SMF segments corresponding to the Bardzkie and Sowie Mountains are characterized by the lowest mean values of V_f index and, simultaneously, by the maximal mean values of basin elongation ratio. No explanation of this apparently anomalous relationship was offered in any case and this opens the discussion about the significance and reliability of morphometric indices, especially when lithological diversity of the area and its possible influence on the values obtained are not taken into account.

Along with the basin elongation ratio, other morphometric indices to describe basin shape, such as form ratio, circularity ratio, lemniscate ratio (see Tab. 2), were calculated (Sroka, 1997; Badura *et al.*, 2003, 2007b; Sobczyk and Kasprzak, 2014). Scant attention, however, was paid to their interpretation and this can be to some extent explained by the ambiguity of the results obtained. In the Polish part of the SMF (Badura *et al.*, 2003), for example, the values of circularity ratio indicate the presence of the most circular basins in the Sowie Mountains and the most elongated ones in the northwestern sector of the structure, which is at odds with the general pattern of tectonic activity along the fault, inferred from other indicators (Krzyszkowski *et al.*, 1995). On the other hand, in the light of the form ratio these two segments are not different from each other, as they are characterized by the same mean value of the index, equal to 0.32. As concluded by Sroka (1997), the shape of the basin can designate some tectonic tendencies only in combination with other morphometric indices.

Studies on basin asymmetry, as a potential indicator of block titling, were restricted to the SMF zone (Badura *et al.*, 2003, 2007b) and to the Śnieżnik Massif and adjacent area (Ranoszek, 1999; Sobczyk and Kasprzak, 2014) and were all based on the analysis of the asymmetry factor (AF; Hare and Gardner, 1985) or its modification (Pérez-Peña *et al.*, 2010). In the original index version, values close to 50 correspond with symmetrical basins, whereas much lower/higher values characterize basins, the left/right side of which occupies a wider area. An opposite direction of titling was evoked for the basins developed within the footwall of the SMF, with values ranging from 3.9 to 80.8 (Badura *et al.*, 2003, 2007b). The overall picture, however, is not easy to interpret, as only the average index values were presented for individual fault segments, whereas the calculation of directional data should not be based on a simple mean.

Non-uniform uplift of the Śnieżnik Massif was presumed, especially in its northern and southern parts, adjacent to the range-bounding front associated with the Wilkanów Fault, where AF values (< 50) pointed to the generally northward tilting of individual blocks (Ranoszek, 1999). The occurrence of steeper south-facing valley sides in the northern part of the massif seemed to underpin this notion. The tendency to northward tilting in the southern part of the mountain range was confirmed by Sobczyk and Kasprzak (2014), who extended the area under investigation to the Czech part of the massif as well. However, asymmetric uplift of the area north of Szklary, emphasized by Ranoszek (1999), was not so distinctly revealed. The very likely reason is that different methods for basin delimitation were applied. Ranoszek (1999) located basin outlets along the fault-generated escarpment, so that only the area within the footwall was considered. However, the basins delimited by Sroka (1997) and Sobczyk and Kasprzak (2014) were not restricted to the uplifted part of the mountain range, but extended into the foreland, despite the fact that the development of two different basin parts, separated by fault-generated escarpments, proceeded in different ways. Footwall and hanging wall of a fault represent different domains for geomorphological processes, especially for the fluvial ones (Bull, 2007; Burbank and Anderson, 2011). These differences were recorded in the convex-concave and graded shape of hypsometric curves (Strahler, 1952), elaborated for drainage basins in the vicinity of Kłodzko (Sroka, 1997). The curve shape was recognized as a better indicator of uplift-induced rejuvenation than a single value of the hypsometric integral. In the Śnieżnik Massif and the adjacent areas, these values were juxtaposed with the mean basin slope in order to distinguish terrains subject to the most intensive uplift. They were identified in the eastern (Czech) part of the massif and the Bialskie Mountains, although it should be stressed that the highest values of the hypsometric integral in these parts of the study area were at least partly related to the absence of foreland plains within the basin boundaries.

The simplified version of the hypsometric integral in the assessment of basin rejuvenation owing to tectonic processes was applied by Ranoszek (1999), who calculated the ratio of the rejuvenated part of the basin (the area below a distinct break in valley slope) to its overall area. Besides the hypsometric integral, some simple measures related to basin elevations, such as relief ratio (Schumm, 1956) and relative relief (Melton, 1958), were also calculated (Badura *et al.*, 2003, 2007b; Sroka, 1997), although their role in the assessment of tectonic activity was seen as subordinate.

River terraces and alluvial fans

Much attention was paid to tectonically-induced deformations and the chronostratigraphy of river terraces and alluvial fans in the SMF zone (Zeuner, 1928; Krzyszkowski and Pijet, 1993a, b; Krzyszkowski and Stachura, 1993, 1998a, b; Mastalerz and Wojewoda, 1993; Pijet and Krzyszkowski, 1994; Krzyszkowski *et al.*, 1995, 1998, 2000; Krzyszkowski and Biernat, 1998; Krzyszkowski and Olejnik, 1998; Migoń and Łach, 1998; Migoń *et al.*, 1998; Migoń, 1999). Three terraces of undoubtedly fluvial origin, referred to as the Lower (late Weichselian/Holocene), the Middle (Middle Weichselian) and the Upper (late Saalian/Eemian), were recognized and correlated. Higher upslope, the occurrence of benches with a gravel veneer covered by the Odranian till and slope deposits was also observed and a fluvial origin for these veneers, designated the Main Terrace, was inferred. In the lowermost position of some river valleys, the presence of a late Holocene/medieval terrace was also recognized (Krzyszkowski and Stachura, 1993, 1998a, b; Krzyszkowski and Biernat, 1998; Migoń *et al.*, 1998), whereas in the Nysa Kłodzka valley the uppermost position was occupied by so-called Glaciofluvial Terrace of presumably pre-Elsterian age (Krzyszkowski *et al.*, 1998, 2000). As no terraces older than Middle Pleistocene were unequivocally recognized in the valleys crossing the SMF, their role as markers of tectonics was restricted to the time span from the Middle Pleistocene until now. The Quaternary tectonic activity of the SMF was inferred from truncation of the terraces at the fault line, their divergence and convergence as well as from the changing thickness of alluvial deposits along the river courses (Krzyszkowski and Stachura, 1993; Krzyszkowski *et al.*, 1998).

The vertical offset of the Upper Terrace, the one formed right after the latest glaciation of the region (Odranian), was observed in many valleys near the SMF all along its Polish part. The height of the corresponding fault scarps varied, reaching up to 25 m in the Bystrzyca valley (Krzyszkowski and Biernat, 1998). Less prominent forms (5–10 m high) were identified in the northwestern sector of the SMF (Migoń *et al.*, 1998; Migoń, 1999). The residual character of the fault scarps in the Sudetes was reflected by their relatively gentle slope, not exceeding 15° (Krzyszkowski and Olejnik, 1998).

In some places, with the exception of the Kaczawa Upland, the truncation of the Middle Terrace was also noticed, although geomorphological evidence of this offset was poorly preserved. The most distinct fault scarps are those described from the Pieszycki Potok valley (Krzyszkowski and Olejnik, 1998) and from the Nysa Kłodzka valley (Krzyszkowski *et al.*, 1998, 2000). They are 7 and 10 m in height, respectively. No vertical offset of the younger terraces was recorded.

In the SMF zone, downstream divergence of the terraces was also observed. Almost all terraces in the Nysa Kłodzka valley show a downstream increase in relative height above the channel (Krzyszkowski *et al.*, 1998, 2000), which was also the case for the terraces examined in the Wałbrzych Upland (Krzyszkowski and Stachura, 1998a, b). In other regions, only divergence of the Upper Terrace and occasionally of the Middle Terrace was described (Krzyszkowski and Pijet, 1993a; Krzyszkowski and Biernat, 1998; Krzyszkowski and Olejnik, 1998; Migoń *et al.*, 1998). The convergence of terraces within the widest valley segments in the Wałbrzych Upland was supposed to indicate local zones of subsidence (Krzyszkowski and Stachura, 1998a, b). In the Sowie Mountains sector of the SMF, the southeastward increase in the height of the Upper Terrace in the adjacent valleys (from 8 to 16 m) was seen as reflecting non-uniform uplift of the mountain range (Pijet and Krzyszkowski, 1994). In the Wałbrzych Upland, variable thickness of alluvial deposits of the Lower Terrace along the Strzegomka and Pełcznica rivers was reported (Krzyszkowski and Stachura, 1998a, b). Their abrupt, two-fold increase right below the fault lines was correlated with the occurrence of secondary, downfaulted blocks within the SMF footwall. No detailed studies of terraces as markers of recent tectonics were undertaken beyond the SMF zone in the Sudetes. However, the +10 m offset of the Pleistocene terrace in the Wrzosówka valley at the line of the range-bounding front of the Karkonosze Mountains was mentioned by Sroka (1991).

Concurrently with the studies of river terraces, the record of tectonic deformation was sought in alluvial fan morphology, although fans in the Sudetes are rather poorly developed and not distinct (Krzyszkowski *et al.*, 1995). A similar pattern of evolution was endorsed for alluvial fans in the foreland of the Sowie Mountains (Krzyszkowski *et al.*, 1995; Krzyszkowski and Olejnik, 1998) and the transitional area between the Wałbrzych Upland and the Kaczawa Upland (Migoń *et al.*, 1998). At least three phases of accumulation were recognized as corresponding with the formation of the Upper, Middle and Lower terraces in the mountainous area, separated by enhanced erosion. The main accumulation phase was correlated with the development of the "upper fan", the deposits of which were laid down close to the mountain margin and directly on the top of the Odranian till, with no phase of preceding erosion. Following the general model of alluvial fan evolution within tectonically active mountain fronts (Bull, 1977), the subsequent entrenchment of the fan surfaces and the shift of the apexes of younger fans downstream were taken to indicate diminishing tectonic activity along the SMF in the Late Pleistocene (Krzyszkowski *et al.*, 1995). The asymmetric position of the "middle fan" deposits with respect to the channels within the neighbouring fans of Nysa Mała, Nysa Szalona and Strzegomka was attributed to the tectonic factor, but of a rather minor influence, as no similar asymmetry was displayed by the "lower fan" deposits of these rivers (Migoń *et al.*, 1998). In turn, further to the north-west the contribution of strike-slip faulting to the evolution of the Kaczawa alluvial fan was considered significant and inferred from the alleged northwestward displacement of the fan apex with respect to the present river outlet (Mastalerz and Wojewoda, 1990, 1993), although Krzyszkowski and Migoń (1991) indicated that the evidence for the 2-km scale of the horizontal displacement was far from conclusive.

The influence of Quaternary tectonics on the development of alluvial fans beyond the SMF zone was scarcely addressed. In the Karkonosze Mountains, tectonically induced deformations of alluvial sequences were evoked by Sroka (1991), Chmal and Kasprzak (2009) and Kasprzak (2009) for some of the streams crossing the mountain front and entering the Jelenia Góra Basin.

Sedimentary record of faulting

Comparatively little attention was paid to Quaternary deposits in the proximity of tectonic landforms and the deformation structures within them, as possible indicators of recent faulting. The relatively few efforts to infer neotectonic history from sedimentary records were concentrated along the SMF.

The earliest attempt to link tectonics with the depositional record was undertaken by Mastalerz and Wojewoda (1993), who analysed the sediments exposed in a large gravel pit near Złotoryja, in the northern sector of the SMF, and documented structures indicative of seismicity and normal faulting. Deformation structures in the form of gently dipping normal faults and flexures, interpreted as resulting from fault reactivation triggered by post-glacial glacioisostatic rebound after the Saalian glaciation, were described from several gravel pits near Świdnica, in the middle sector of the SMF (Krzyszkowski and Bowman, 1997). Quaternary tectonics was also documented by means of analysis of *in situ* broken clasts and small-scale faults in gravel deposits at Janowiec, next to the outlet of the Nysa Kłodzka River from the Sudetes, where an additional, minor right-lateral component of movement was inferred (Badura *et al.*, 2007a).

Palaeoseismological analysis of trenches so far has been applied in one sector of the SMF only, in the Złote Mountains segment, at two different locations across the basal part of the marginal escarpment, where the slope and the piedmont meet (Vlčice and Bilá Voda; Štěpančíková *et al.*, 2010, 2011; Štěpančíková and Stemberk, 2016). Sediment analysis revealed a complex deformation history, with episodes of both normal, reverse and strike-slip faulting, which occurred in post-Middle Miocene times. The latter was found to be left-lateral and thus inconsistent with that inferred from broken clasts at Janowiec. Dating of younger colluvial units allowed the constraint of timing of some of these displacement to the latest Pleistocene. The thickness of colluvial deposits at Bilá Voda reaches 3.6 m, indicating multiple faulting events along this segment of the SMF.

Regional morphometric studies

In regional studies, both simple and more complex parameters were used, the primary data being derived from either topographic maps or digital terrain models. Assuming that zones of increased gradients may reflect more intense uplift, the distribution of steep slopes in the Sudetes were examined on the basis of maps derived from a DEM with a spatial resolution of 50 m (Migoń *et al.*, 2009). Two different spatial patterns of steep slopes were recognized, namely extensive, heavily dissected areas and more linear features. The interpretation of the former as the most uplifted blocks was reinforced by their rectangular shape, most likely delimited by faults, and correspondence with the highest altitudes within the range (e.g., Karkonosze Mountains, Hruby Jesenik, Śnieżnik Massif, Złote Mountains).

Linear patterns of steep slopes were related to mountain fronts and deeply incised valleys. Surprisingly, the morphological expression of many fault-generated escarpments on the slope map was rather poor and the reason was seen in the mechanical weakness of the footwalls. Mountain fronts, built of rocks classified as ”strong” (granite, gneiss), showed as more distinctive features, including the western escarpment of the Śnieżnik Massif, the northern margin of the Karkonosze Mountains and the northeastern termination of the Sowie Mountains.

It is noteworthy that prior to DEM-based morphometric studies areas of higher gradients were identified by means of maps of condensed contours (Badura and Przybylski, 1995; Badura, 1996; Migoń, 1996; Migoń and Łach, 1998). In the Western Sudetes, these maps appeared as a useful tool for the identification of lineaments, such as straight escarpments, contributing to the subdivision of this area into morphostructural units of different orders (Migoń, 1996).

As indicated by Pánek (2004, p. 166), the difference between the highest and the lowest altitudes ”is the first rough look in the arrangement of neotectonic movements in the area”. This difference, referred to as ”relief energy”, usually was computed for drainage basins as a reference unit (Sroka, 1997; Badura *et al.*, 2003, 2007b). More often, however, it was used in the calculation of other morphometric indices, such as the hypsometric integral, discussed earlier in this paper (see Drainage basin characteristics).

Maps of relative relief ($H_{max} – H_{min}$, the difference between maximum and minimum elevation) most frequently were juxtaposed against those of relief beyond the reach of headstream erosion (Sroka, 1997; Krzyszkowski and Olejnik, 1998; Krzyszkowski and Stachura, 1998a, b). The latter, referred to as the belt of no erosion *sensu* Horton (1945), was calculated as the difference between the maximum height (H_{max}) and the highest altitude reached by streams eroding headward (E_{max}). The highest values of both measures were interpreted as indicators of more intensive uplift. In the Sowie Mountains, the analysis of their spatial distribution, combined with other geomorphic and morphometric indicators, allowed the inference of subsidiary fault zones, transverse to the SMF and the delineation of minor horsts and grabens within the footwall (Krzyszkowski and Olejnik, 1998). In an area of more diversified lithology, such as the Kłodzko Basin and the adjacent mountain ranges, the influence of rock resistance and permeability on the values of relief above headstream erosion was discussed (Sroka, 1997).

In the vicinity of the Kłodzko Basin, the spatial distribution of H_{max} and H_{min} values was also analysed independently, on the basis of the maps of isobases and summit surface, respectively (Sroka, 1997). These maps allowed the recognition of morphological escarpments of the first and second order. The former were correlated with tectonic zones, but a denudational origin was suggested for the latter, which occurred within the limits of tectonic blocks. The statistical analysis by Sroka (1997) of “relief horizons”, separated by escarpments of different orders, did not support the occurrence of three different planation surfaces evoked by Klimaszewski (1958) and Walczak (1968).

TIMEFRAME OF THE EVOLUTION OF TECTONIC RELIEF

Although the present-day landform pattern of the Sudetes reflects many controls, differential uplift and subsidence in the Late Cenozoic appear to explain best the gross geomorphological features of the area (Demek, 1975; Dyjor, 1975; Sroka, 1997; Zuchiewicz *et al.*, 2007; Migoń, 2008; Migoń and Placek, 2014). However, the elaboration of a precise and reliable timeframe for the neotectonic evolution of the Sudetes encounters considerable difficulties. They result from the lack of widespread deposits, younger than Upper Cretaceous in age, which could be used as correlative horizons documenting breakup and displacement of previously continuous surfaces. The variable hypsometric position of the Turonian deposits in the Bystrzyckie Mountains and the adjacent Upper Nysa Graben, coincident with the distinct topographic escarpments, is the only direct geological proof for vertical offset of an originally continuous stratigraphic horizon in the Sudetes. This, however, permits the determination of the age of faulting during the Alpine tectonic epoch only roughly as post-Upper Cretaceous. Structural analysis may help to decipher the multiphase history of particular fault zones (e.g., Coubal *et al*., 2015), but does not offer direct clues on the age of deformations, although extrapolation of such data beyond the fault zone is even more problematic.

Attempts were made to decipher the neotectonic evolution of the Sudetes, including the timing of tectonic deformations, mostly on the basis of the Neogene sedimentary series infilling tectonic grabens in the Sudetic Foreland, adjacent to the SMF (Oberc and Dyjor, 1969; Oberc, 1972, Dyjor, 1975, 1981; Dyjor and Oberc, 1981). The occurrence of coarse-grained deposits in sedimentary successions was seen as an indicator of enhanced river incision related to stronger tectonic uplift, although the possible influence of climatic factors was not ruled out entirely (Walczak, 1968, 1972). It was assumed that a few phases of stronger uplift contributed to the development of tectonic landforms and they were referred to the Early Miocene (Savian phase), Middle Miocene (Styrian phase), and Pliocene and Early Pleistocene (Vallachian phase). Tectonic activity in the Late Pliocene was considered to be the most important factor in the evolution of the SMF, along which the entire Sudetic Block was uplifted, and was correlated with sedimentation of the coarse-grained syntectonic deposits of the so-called Gozdnica Series. However, the precise dating of this series is problematic and diverging views were presented, with Dyjor (1987) shifting back the onset of deposition to the Miocene/Pliocene transition and Badura and Przybylski (2004) maintaining that it should be placed within the later part of the Pliocene. Likewise, opinions on the age of the main phase of tectonic activity along the SMF varied, ranging from Miocene (Dumanowski, 1961) to Early Pleistocene (Krzyszkowski *et al.*, 1998, 2000).

Beyond the SMF zone, in the area with a scarcity of Neogene deposits, the relicts of planation surfaces, found at different altitudes and believed to be Palaeogene in age, were used as a correlative horizon for determining the time and amplitude of tectonic movements (Klimaszewski, 1958; Walczak, 1968; Demek, 1975). No datable material was found on these surfaces for more precise time constraints; nor did the confined occurrence of these supposed relicts of Palaeogene morphology facilitate the spatial correlation of them. These considerations led to the conclusion that the role of planation surfaces as markers of tectonics is restricted considerably in the Sudetes (Dyjor, 1975; Migoń, 1993b), followed by more general doubts based on more recent low-temperature thermochronology studies, as to whether these surfaces can represent Palaeogene remnants at all (Danišík *et al.*, 2010, 2012; Sobczyk *et al.*, 2015).

Although the Quaternary tectonic activity of the SMF was postulated as early as 1928 by Zeuner, who described divergence of Pleistocene river terraces in the antecedent Bardo Gorge, the youngest tectonic movements were not considered as significant for a long time (Oberc and Dyjor, 1969; Klimaszewski, 1958; Walczak, 1972; Dyjor, 1981). It was even asserted that they had vanished completely, at least before the Middle Pleistocene (Dumanowski, 1961). This notion was challenged by the results of morphotectonic studies carried out in the 1990s, which concentrated mostly on fluvial systems (Krzyszkowski and Pijet, 1993a, b; Mastalerz and Wojewoda, 1993; Krzyszkowski and Stachura, 1993, 1998a, b; Pijet and Krzyszkowski, 1994; Krzyszkowski *et al.*, 1995, 1998, 2000; Krzyszkowski and Biernat, 1998; Krzyszkowski and Olejnik, 1998; Migoń *et al.*, 1998). These contributed to the recognition of the Middle and Late Quaternary tectonic movements, with the amount of throw estimated as a few tens of metres, possibly as much as 80–100 m locally. The role of the glacioisostatic rebound component in Quaternary faulting, mentioned previously by Dyjor and Oberc (1981), was addressed in more detail (Krzyszkowski and Stachura, 1998b). However, the timing of Quaternary tectonic movements that affected the morphology of river terraces and alluvial fans was based entirely on their tentative chronostratigraphy (see the part on River terraces and alluvial fans). This, in turn, was elaborated without the availability of any datable material, which makes all time-correlations very speculative, not only within the SMF zone (see also Sroka, 1991; Chmal and Kasprzak, 2009; Kasprzak, 2009).

MORPHOTECTONIC EVOLUTION OF THE SUDETES – RE-APPRAISAL

Problems of insufficient evidence and lack of transboundary research integration

In the early conceptual models that explained the origin of the gross geomorphological features of the Sudetes, the role of Late Cenozoic tectonics as a contributing factor was seen as either primary or subordinate (see part on Early conceptual models). The significance of alternating phases of tectonic uplift and planation processes (Klimaszewski, 1958; Walczak, 1968), chemical weathering in warm and humid climates (Czudek and Demek, 1970; Jahn, 1980) and differential uplift and subsidence as well as ”large-radius uplift”, unrelated to faults (Kopecký, 1972; Demek, 1975; Dyjor, 1975), were emphasized in these models, which in general were based on assumptions, rather than the provision of clear and objective evidence.

The primacy of concept over evidence was noticeable in many cases, confirmed by the scarcity of illustrative materials. Neither the spatial distribution of planation surfaces of different ages evoked by Klimaszewski (1958), nor the relicts of the Neogene planation surface, supposed to occur at various altitudes within individual tectonic blocks were shown cartographically by Demek (1975). Although the former was eventually elaborated by Walczak (1972), it is clear that the spatial extent of Palaeogene, Miocene and Pliocene ”relief horizons” was delineated subjectively, as no support was given to the occurrence of tiered levels of planation surfaces in the Sudetes in subsequent studies (Sroka, 1997; Placek *et al.*, 2007; Migoń, 2008).

Contrary to Walczak (1972), who did not distinguish between tectonic and denudational escarpments on the geomorphological map of the Sudetes, faults demarcated as “the youngest, NW-SE oriented and forming morphological margins” were presented by Dyjor (1975, p. 124) on a simplified sketch of the neotectonic deformation pattern in the Sudetes and their foreland. Although the tectonic history of these faults was inferred from the analysis of the sedimentary series filling the adjacent grabens, mostly within the Fore-Sudetic Block, neither their geological profile logs, nor the exact location of the study sites were presented and described. The basis for estimating the amplitude of tectonic movements in the interior of the Sudetes (e.g., Karkonosze and Izerskie Mountains) is even less clear, bearing in mind the fact that no widespread covers of sediments younger than Cretaceous in age were preserved in this area and that no solid basis exists for dating the denudation surfaces at water divides. Last but not least, the occurrence of coarse-grained deposits in tectonic depressions, seen as an indicator of accelerated uplift of the footwalls, may have not been exclusively related to tectonics, but also to changing climatic conditions.

The political division of the Sudetes into three parts (Polish, Czech and German) is the likely reason why this mountain range was rarely considered as a unity. Early conceptual models were elaborated mostly for areas located on just one side of the border and cooperation of researchers from different countries was very limited, if indeed any ever had existed. This issue of apparent neglect was addressed by Migoń (2008), who pointed out some weaknesses arising from such a unilateral approach. The analysis of the DEM of 50 m spatial resolution, constructed for the whole transboundary area, revealed, for example, that the morphological axis of the Sudetes postulated by Jahn (1980), which was to consist of intramontane depressions aligned NW–SE, was recognisable only west of the Wilkanów Fault, bounding the Śnieżnik Massif. No similar spatial pattern was observed in the eastern part of the mountain range, which largely belongs to the Czech Republic. The lack of distinct intramontane basins east from the Upper Nysa Graben as well as the limited extent of low-altitude terrains, both abundant on the opposite (western) side of the graben, contributes to the first-order geomorphological division of the Sudetes and the identification of two different major geomorphological units. However, no clear explanation of these fundamental differences was offered. Furthermore, these differences, although identified on the basis of DEM were not described in a more objective, quantitative way.

Table 1

Morphotectonic studies carried out in the Sudetes

Regions		References
Adjacent to the Sudetic Marginal Fault	Kaczawa and Bolków Upland	Mastalerz and Wojewoda, 1993; Migoń and Łach, 1998; Migoń *et al.*, 1998; Migoń, 1999
	Wałbrzych Upland	Krzyszkowski and Stachura, 1993, 1998a, b
	Sowie Mountains	Krzyszkowski and Pijet, 1993a, b; Migoń, 1994; Pijet and Krzyszkowski, 1994; Krzyszkowski and Biernat, 1998; Krzyszkowski and Olejnik, 1998
	Bardzkie Mountains	Sroka, 1997; Krzyszkowski *et al.*, 1998, 2000
	Złote Mountains	Ivan, 1997; Sroka, 1997; Štěpančíková *et al.*, 2008; Sobczyk and Kasprzak, 2014; Štěpančíková and Stemberk, 2016
	Whole segment of the SMF	Oberc and Dyjor, 1969; Sroka, 1992; Krzyszkowski *et al.*, 1995; Badura *et al.*, 2003, 2007
Karkonosze Mountains		Migoń, 1991, 1992, 1996; Sroka, 1991
Izerskie Mountains		Migoń, 1996; Migoń and Potocki, 1996
Śnieżnik Massif		Sroka, 1997; Ranoszek, 1998, 1999; Sobczyk and Kasprzak, 2014
Bystrzyckie Mountains		Sroka, 1997; Ranoszek, 1998; Badura and Rauch, 2014
Upper Nysa Graben		Sroka, 1997; Badura and Rauch, 2014; Jamroz *et al.*, 2014

Limited spatial coverage

An interest in the morphological expression of Late Cenozoic uplift and subsidence was renewed in the 1990s, when there was a shift from large-scale studies encompassing the whole Sudetes to ones focused on smaller areas (Migoń, 1991, 1992; Migoń and Potocki, 1996; Sroka, 1997; Štěpančíková *et al.*, 2008) or even individual landforms (Sroka, 1991; Mastalerz and Wojewoda, 1993; Krzyszkowski *et al.*, 1995; Ivan, 1997; Ranoszek, 1998). Many researches also concentrated on the small-scale indicators of Pleistocene tectonic movements (Krzyszkowski and Pijet, 1993a; Krzyszkowski and Biernat, 1998; Krzyszkowski and Stachura, 1998a, b; Krzyszkowski *et al.,* 1998, 2000; Migoń *et al.*, 1998), previously considered as insignificant (see the part on Timeframe of the evolution of tectonic relief). Contrary to the early conceptual models of regional landscape evolution, these studies were based on explicit field observations or cartographic evidence, although the accuracy of the source materials (e.g., topographic maps) may be doubted. Morphotectonic interpretations were supported by topographic and geological profiles (e.g., Pijet and Krzyszkowski, 1994; Migoń and Potocki, 1996; Krzyszkowski and Stachura, 1998a, b; Ranoszek, 1999) with clearly defined spatial references.

The recognition of the neotectonic history of the Sudetes was restricted to a few specific areas and tectonic structures, whereas others apparently were neglected (Tab. 1). The overall picture of the areas subject to uplift and subsidence is therefore still poorly known. Morphostructural divisions were proposed for the Karkonosze Foothills (Migoń, 1992), the central part of the Izerskie Mountains (Migoń and Potocki, 1996), the central part of the West Sudetes (Migoń, 1996), the Żytawa – Zgorzelec Trough (Badura, 1996), the vicinity of the Kłodzko Basin with the adjacent mountain ranges (Sroka, 1997) and, most recently, for the Upper Nysa Graben and its shoulders (Badura and Rauch, 2014). They show a rather general spatial pattern of tectonic deformations and thus should be considered as a framework for further, more detailed studies, rather than definitive solutions of the problem.

The contribution of diversified lithology to the morphological expression of tectonic landforms was considered rather minor, as no detailed studies of rock resistance were carried out until the 2000s (Placek, 2011). In consequence, the results of morphotectonic studies were often interpreted one-sidedly as reflecting different degrees of tectonic activity, in both amplitude and rate.

Geomorphometry and the quality of source data

The quantitative approach to morphotectonic research in the Sudetes was reflected in the application of morphometric indices, mainly those referring to the elements of fluvial systems (Tab. 2). Among indices related to mountain

Table 2

Morphometric indices of tectonic activity and their application in morphotectonic studies carried out in the Sudetes

Morphometric indices	Original source	Application in the Sudetes
Mountain front morphology		
Mountain front sinuosity index	Bull and McFadden, 1977	Sroka, 1992; Krzyszkowski *et al.*, 1995; Badura *et al.*, 2003, 2007a, b; Valenta *et al.*, 2008
Spacing ratio	Wallace, 1978	–
Facet index	Wells *et al.*, 1988	
River valley morphology		
Valley floor width – valley height ratio	Bull and McFadden, 1977	Sroka, 1992; Krzyszkowski *et al.*, 1995; Krzyszkowski and Olejnik, 1998; Ranoszek, 1999; Badura *et al.*, 2003, 2007a, b
V ratio	Mayer, 1986	
River basin shape		
Form factor	Horton, 1932	Badura *et al.*, 2003, 2007a, b; Sobczyk and Kasprzak, 2014
Circularity ratio	Miller, 1953	Sroka, 1997; Badura *et al.*, 2003, 2007a, b; Sobczyk and Kasprzak, 2014
Basin elongation ratio	Schumm, 1956	Sroka, 1992, 1997; Krzyszkowski *et al.*, 1995; Krzyszkowski and Olejnik, 1998; Badura *et al.*, 2003, 2007a, b; Sobczyk and Kasprzak, 2014
Lemniscate ratio	Chorley *et al.*, 1957	Badura *et al.*, 2003, 2007a, b; Sobczyk and Kasprzak, 2014
Shape factor	Singh, 1988	
Drainage basin compactness	Engstrom, 1989	
Drainage basin shape ratio	Ramírez-Herrera, 1998	
River basin asymmetry		
Asymmetry factor	Hare and Gardner, 1985	Ranoszek, 1999; Badura *et al.*, 2003, 2007a, b; Sobczyk and Kasprzak, 2014
Transverse topographic symmetry factor	Cox, 1994	
River basin hypsometry		
Hypsometric integral (simplification)	Strahler, 1952	Sroka, 1997; Sobczyk and Kasprzak, 2014
Relief ratio	Schumm, 1956	Sroka, 1997; Badura *et al.*, 2003, 2007a, b
Relative relief	Melton, 1958	Badura *et al.*, 2003, 2007a, b
River network pattern		
Drainage density	Neumann, 1900 after Horton, 1932	Sroka, 1997
Bifurcation ratio	Horton, 1932	
Stream frequency	Horton, 1932	
First-order stream frequency	Zuchiewicz, 1980, 2010	Sroka, 1997
Stream longitudinal profiles		
Stream length – gradient index	Hack, 1973	Ranoszek, 1999; Štěpančíková *et al.*, 2008; Štěpančíková and Stemberk, 2016
Steepness index	Snyder *et al.*, 2000	

front morphology, only the S_{mf} index was calculated (see Tab. 2 for references). The morphology of river valleys was quantified exclusively by means of the V_f ratio, calculated only in valley cross-sections located next to the mountain–piedmont junctions, whereas no attempts were made to obtain its values along whole river courses (e.g., Zuchiewicz, 2010; Antón *et al.*, 2014), which might have been useful for the detection of other zones of tectonic deformation. Scarce attention was paid to the qualitative description and quantification of river network patterns and it was only Sroka (1997) who calculated drainage density and first-order stream frequency for the surroundings of the Kłodzko Basin. Stream longitudinal profile analysis was restricted to the occasional application of the stream length – gradient index, calculated for streams crossing the range-bounding front of the Śnieżnik Massif (Ranoszek, 1999) and the Złote Mountains (Štěpančíková *et al.*, 2008; Štěpančíková and Stemberk, 2016). In contrast, other studies contain large quantitative datasets with information about drainage basin characteristics, left essentially unexplained.

In only a few cases, the spatial distribution of morphometric indices of tectonic activity (Tab. 2) was illustrated on maps. More frequently, they were presented by means of tables and graphs, which did not facilitate a perception of the overall picture of tectonic activity, especially when the variables for a great number of reference units were calculated.

Last but not least, there is a problem of accuracy of the data. Until the advent of high-resolution LiDAR data (2011––2013) morphometric studies were based on topographic maps or DEMs, constructed from the digitized contour lines of the very same maps. Prior to the early 2000s, non-automatic measurements and calculations were time-consuming, whereas demarcation of some features for further analysis, such as river basins or the mountain-piedmont junctions, was to some degree subjective. Likewise, the recognition and exact location of small-scale features, such as minor slope breaks, knickpoints and terrace risers, was problematic. The advent of digital topography saw an increase in the number of calculated indices, especially of those referring to the drainage basins. In morphotectonic studies of the Sudetes, the digital elevation model built on the basis of 1:10,000-scale topographic maps was for the first time applied by Badura *et al.* (2003) in morphometric characteristics of the escarpment related to the SMF. However, although computational capabilities and visualization opportunities expanded, problems with data quality remained.

New research opportunities

New research opportunities emerged simultaneously with the availability of LiDAR data derived from airborne laser scanning, which enables the construction of elevation models of very high spatial resolution (up to 1x1 m). However, the application of this dataset in morphotectonic studies of the Sudetes has been very limited up to now (Sobczyk and Kasprzak, 2014; Štěpančíková and Stemberk, 2016) and it is fair to say that many previous studies based on morphometry should now be re-evaluated using LiDAR data.

More importantly, fault zones in the Sudetes and the Cenozoic tectonic history of the area are of interest to other groups. In recent years, palaeostress analysis has become the subject of research, helping to decipher the complex history of the Lusatian Fault zone (Coubal *et al.*, 2015) and the easternmost sector of the Sudetic Marginal Fault (Nováková, 2016). Insights into fault zone architecture are offered by detailed bedrock outcrop analysis (Wojewoda, 2009; Prouza *et al.*, 2012, 2014). Present-day crustal movements are investigated through various types of geodetic measurements, in some cases targeted at known fault zones suspected of being active in the Cenozoic (Kontny, 2004; Grzempowski *et al.*, 2012; Jamroz *et al.*, 2014). Špaček *et al.* (2015) proposed a model for the long-term behaviour of the Upper Morava Basin System, based mainly on the sedimentary architecture of the basin fill, geophysical data and present-day seismicity patterns. The results of low-temperature geochronological studies (Danišík *et al.*, 2010, 2012; Sobczyk *et al.*, 2015) are also relevant to tectonic geomorphology, as they provide information about the depth of erosion and hence indirectly, about the pattern of uplift. However, except for a few cases, all these studies are yet to be integrated with geomorphology. For example, the kinematic model for the easternmost sector of SMF, based on palaeostress studies (Nováková, 2016), should be compared with the changes in river courses, previously highlighted by Ivan (1997). Particular challenges emerge in situations, in which results are inconsistent, for example, subsidence trends are revealed for areas typified by geomorphic indicators of relative uplift (e.g., Jamroz *et al.*, 2014). Likewise, it is argued that any morphotectonic interpretations derived from landform analysis or geophysical proxies should not be in conflict with classic field geology based on outcrop mapping, but these two sources of information should be reconciled. However, this call is valid in the opposite direction, too. Lessons from tectonically active regions show that it is unlikely significant fault zones presumed to be active in the Late Cenozoic do not have geomorphic expression or that expression is very weak (Burbank and Anderson, 2011). A discussion focused on the Upper Nysa Graben provides an example of how opinions on the origin of certain geomorphic features may differ, if different background data are used (Don, 2003; Don and Wojewoda, 2004, 2005; Badura *et al.*, 2005).

The imprint of Variscan tectonic structures on the contemporary morphology of the Sudetes is worthy of further research too. Some inherited tectonic features appear as distinct controls of relief (e.g., Šumperk Basin – Špaček *et al.*, 2015), whereas others do not. Finally, the timing of tectonic differentiation of relief remains a major field of uncertainty, but the development of new dating methods, such as low-temperature thermochronology, may help to offset at least some of these difficulties. Owing to the new data sources and advances in related fields of geoscience, it is now possible to test and verify the state of the art of tectonic geomorphology of the Sudetes and hopefully to better separate the lithological, structural and tectonic controls of relief development and recognize the pattern of long-term endogenous-exogenous interactions.

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