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THE SUDETIC MARGINAL FAULT: A YOUNG MORPHOPHOTECTONIC FEATURE AT THE NE MARGIN OF THE BOHEMIAN MASSIF, CENTRAL EUROPE

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ABSTRACT

We analysed a nearly 133-km-long portion of the Sudetic Marginal Fault (SMF) in Poland (99.7 km) and the Czech Republic (33.8 km), comprised between Złotoryja in the NW and Jesenik in the SE. The fault trace has been subdivided into fifteen segments showing different orientation (N29°W to N56°W, and even N111°W SE of Złoty Stok), geological setting, length (8.8-22.9 km in Poland and 1.4-7.5 km in the Czech Republic), and height of the fault- and fault-line scarps (5-75 m to 200-360 m). Orientation of the entire fault trace approaches N41°W, and the mountain front sinuosity amounts to 1.051. Individual fault segments bear a flight of two to five tiers of triangular facets, showing differentiated state of preservation and degree of erosional remodelling. The highest triangular facets are confined to Rychlebské (Złote) and Sowie Mts. This tiering points to at least five episodes of uplift of the SMF footwall, starting shortly after 31 Ma, i.e. after basalts of the Sichów Hills area were displaced by the fault, and most probably postdating 7-5 Ma time interval, during which rapid cooling and exhumation of the Sowie Góry Mts. massif took place. Morphometric parameters of 244 small catchment areas of streams that dissect the fault scarp include, i.a. elongation, relief, and average slope of individual catchment areas, together with values of the valley floor width to valley height ratios. These figures point to moderate tectonic activity of the SMF and allow us to conclude about Quaternary uplift, particularly important in the Sowie and Rychlebské (Złote) segments.

KEYWORDS: morphotectonics, digital elevation models, drainage basin parameters, Sudetic Marginal Fault, SW Poland, NE Czech Republic

INTRODUCTION

The Sudetic Marginal Fault (SMF; Fig. 1) is one of clearly marked fault zones of Central Europe. It is more than 200-km-long and 133 km of this is represented by a well-pronounced morphotectonic scarp. Despite its morphological distinctness, the evolutionary history of this fault has not been fully recognised. Based on indirect evidence, one can infer that this structure originated during Variscan orogenesis, and became reactivated during the Alpine cycle (Oberc and Dyjor, 1969; Grocholski, 1977; Skácel, 1989, 2004; Aleksandrowski et al., 1997). The age of correlative sediments indicates that the fault was already active in Late Oligocene times, although many researchers suggested either the Middle Miocene or Pliocene as the onset of faulting (cf. Dyjor, 1983, 1993).

The objectives of this paper are threefold:

- to characterize a fragment of the Sudetic Marginal Fault in Poland and the Czech Republic, by means of several morphometric techniques, including digital elevation models and a set of physiographic parameters of small drainage basins of streams that dissect the base of the scarp;
- to check whether morphometric characteristics reflect fault segmentation, and whether the latter is controlled by bedrock lithology or differentiated neotectonic activity; and
- to determine, by means of both geomorphic and geodetic techniques, the sense of recent displacement along the fault.

STATE OF RESEARCH

The neotectonic history of the SMF structure was dealt with by numerous authors, and a summary of this research was already presented by us in a previous paper (Badura et al., 2003 a,b; and references within). Recent crustal movements are geodetically

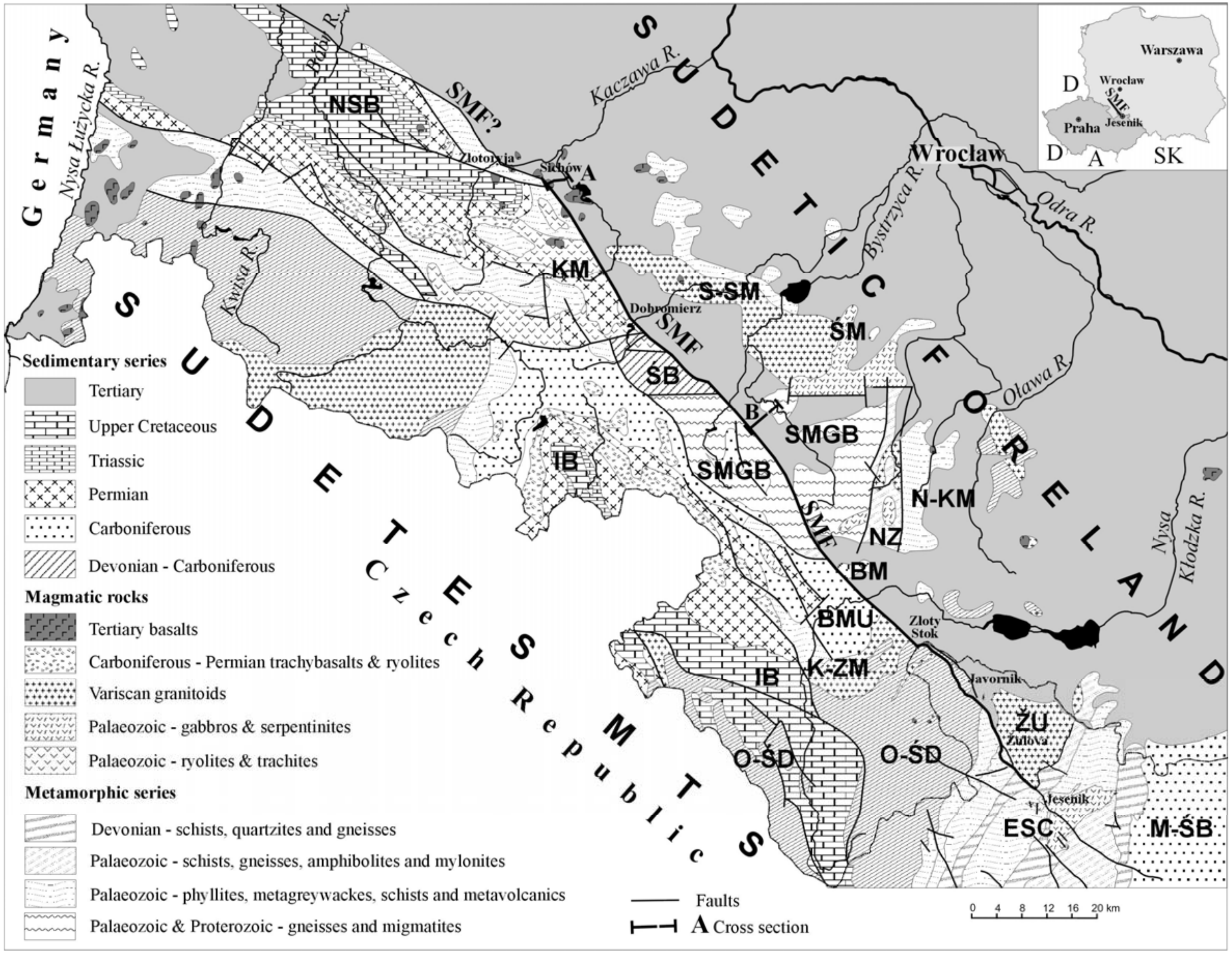

Fig. 1 Geological setting of the Sudetic Marginal Fault (SMF), based Cymerman (2004): BM - Brzeźnica Massif, BMU - Bardo Mts. Unit, ESC – East Sudetes Complex, IB - Intra-Sudetic Basin, KM - Kaczawa Metamorphic Unit, K-ZM - Kłodzko - Złoty Stok Massif, M-ŚB – Moravo-Silesian Basin, N-KM - Niemcza - Kamieniec Metamorphic Unit, NSB - North-Sudetic Basin, NZ- Niemcza Zone, O-ŚD – Orlica – Śnieżnik Dome, SMGB - Sowie Mts. gneissic block, S-SM - Strzegom - Sobótka Massif, ŚB - Świebodzice Basin, ŚM - Ślęża Massif, ŽU – Žulova Massif; SMF - Sudetic Marginal Fault.

monitored in the region at selected geodynamic test areas (Cacoń and Dyjor, 1995, 2002; Cacoń, 1998; Schenk et al., 1998, 2002a; Kontny, 2003; and references therein). The results of studies of recent vertical crustal movements are inconclusive (Wyrzykowski, 1985; Kowalczyk, 2006), pointing generally to rapid subsidence within the grabens that are filled with Neogene and Quaternary sediments on the NE side of the SMF (cf. also Dyjor and Oberc, 1983; Dyjor, 1993, 1995; Cacoń and Dyjor, 1995, 2002). A map by Cacoń and Dyjor (1995) indicates Złoty Stok portion of the fault to be uplifted at >+0.5 mm/yr, while the eastern part of the Paczków Graben (Nysa region) reveals fast subsidence of up to -3.5 mm/yr. The newest map by Kowalczyk (2006) marks subsidence of -1 to -2 mm/yr in the Sowie, Bardo, and Rychlebské Mts. area, while the surrounding regions display rates between -2 and -3 mm/yr. On the other hand, Czech geodetic surveys (Vyskočil, 2001) point to minor uplift of the SE segment of the SMF (0 to +1 mm/yr). Repeated GPS campaigns (1997-2001) appear to suggest a minor left-lateral component of motion along the SMF (Kontny, 2003), although geodetic and geophysical data coming from the southeasternmost part of this zone indicate an opposite trend (cf. Schenk et al., 2002a; Havíř and Špaček, 2004), as do geomorphic studies reported by Grygar and Jelínek (2000, 2003), in-situ stress measurements in the SMF footwall in the Rychlebské Mts., indicative of recent dextral transpression (Štěpančiková and Stemberk, 2002; Štěpančiková et al., 2004, 2007), and recently initiated studies of fractured Pleistocene fluvial pebbles (Tokarski et al., 2005; Badura et al., 2007). It is worth to note that finite element modeling of recent stress in Poland, based on breakout analysis and hydrofracturing tests (Jarosiński, 2006; Jarosiński et al., 2006), also suggests that in the current tectonic regime dextral reactivation of the SMF along with the Teisseyre-Tornquist Zone may have occurred.

GEOLOGICAL SETTING

The geological and geomorphic settings of the SMF were described, i.a., by Teisseyre et al. (1960), Dumanowski (1961), Oberc and Dyjor (1969), Walczak (1972), Grocholski (1977), Jahn (1980), Skácel (1989, 2004), and shown on 1: 25.000 geological maps published by the Polish Geological Institute and the Czech Geological Survey. Recent overview of regional geology of the area was presented by Aleksandrowski et al. (1997), Cymerman (2004), Aramowicz et al. (2006), Mazur et al. (2006), and Štěpančiková (2007).

The NE portion of the Bohemian Massif, cut by the SMF, witnessed Late Palaeozoic uplift, Mesozoic subsidence, and Late Cretaceous-Palaeogene inversion (cf. Aramowicz et al., 2006). The last event resulted in uplift of the Sudetes as a large basement block along the Odra and Elbe fault zones. Fission track apatite ages of gneisses of the Sowie Góry Mts. block revealed two episodes of rapid cooling: 57-43 Ma, postdating Cretaceous-Palaeogene denudation of the order of 4-8 km, and 7-5 Ma due to either decrease in geothermal gradient and/or increased tectonic activity, followed by removal of at least 2 km of overburden (Aramowicz et al., 2006). These ages are comparable on either side of the SMF.

The footwall of the SMF comprises Late Cambrian?-Ordovician through Upper Cretaceous sedimentary rocks in the NW portion and mostly Palaeozoic metamorphic and magmatic rocks in the medial and SE portions. In the hanging wall, in turn, Neogene strata dominate the map picture, overlying the Early Palaeozoic substratum (Figs. 1, 2). Both the Sudetic and Fore-Sudetic blocks, separated by the SMF, bear numerous exposures of Oligocene-Miocene basaltoids (Birkenmajer et al., 1977, 2002a, 2002b, 2004; see also Badura et al., 2005), some of them being located on the fault zone (Figs. 2, 3).

The SMF trends generally NW-SE, although it is accompanied by subsidiary faults of different orientations: N-S, N40-50°W, rarely W-E and N45°E (Fig. 3). At the NW tip of the fault zone, several NW-SE, WNW-ESE and E-W trending faults occur. All of these are accompanied by Oligocene-Neogene volcanic necks, that near Sichów (dated to ca. 31 Ma) being displaced by the SMF (Figs. 1, 2).

GEOMORPHIC SETTING

The SMF separates two units with different morphologies: the Sudetes to the SW, represented by mountain ranges with broad ridges and deeply dissected uplands, with average altitudes 400-800 m a.s.l. near the fault; and the Sudetic Foreland to the NE which displays gently undulate relief (approximately 200-300 m a.s.l.), except for the Ślęża Mt., and is composed of scattered groups of hills or slightly dissected uplands.

The Sudetic mountain front, accompanying the SMF, is generally higher in the south-eastern part (120-300 m) and less elevated in the north-western sector (50-180 m), although large differences among particular local sectors are noticeable. In the south-easternmost stretch the height of the scarp reaches 250-300 m, but farther to the NW it diminishes to 120 m. In the Bardo Mts. sector, the height rises up to 250 m, attaining the highest values in the Sowie Mts. segment (locally exceeding 350 m). In the north-western segments, the height decreases to 60 m, then rises to 120 m, becoming insignificant near Złotoryja.

Differentiated heights of the Sudetic mountain front correlate to some extent with the lithology of the footwall; the highest sectors of the scarp correspond to geological units that are built mainly of gneisses (Sowie Mts., Rychlebské /Złote Mts.), whereas the lowest sectors are composed of poorly consolidated Permian clastics. The height of the front developed on gneisses of the Sowie Mts. diminishes from 250-350

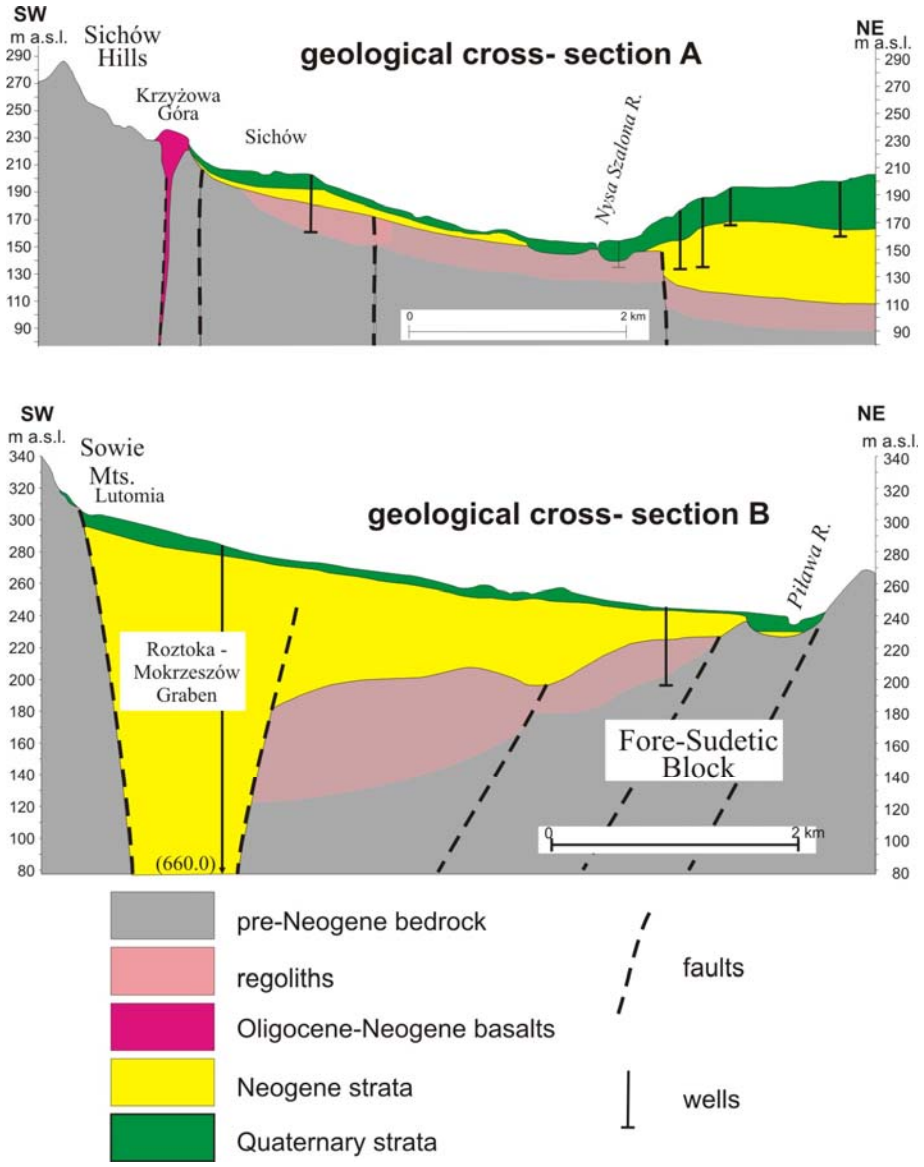

Fig. 2 Geological cross-sections through the SMF zone. See Figure 1 for location.

in the SE to 100-150 m in the NW. In addition, the scarp in the Bardo Mts. Unit segment (greywackes and mudstones) is higher (200-250 m) than that in the Kłodzko-Złoty Stok granitoid segment (100-150 m).

MATERIAL

We analysed a nearly 133-km-long portion of the Sudetic Marginal Fault (SMF) in Poland (99.7 km) and the Czech Republic (33.8 km), comprised between Złotoryja in the NW and Jesenik in the SE. The fault trace has been subdivided into fifteen segments showing different orientation (N29°W to N56°W, and even N111°W SE of Złoty Stok), geological setting, length (8.8-22.9 km in Poland and 1.4-7.5 km in the Czech Republic), and height of the fault- and fault-line scarps (5-75 m to 200-360 m). At the foot of the Sudetic mountain front cut by the SMF, two large (Dobromierz, Javornik) and two minor (Sichów, Świebodzice) fault steps occur. Orientation of the entire fault trace approaches N41°W (Fig. 4). Detailed description of individual segments within the Polish portion of the SMF was presented by Badura et al. (2003a,b). Below, we provide a short overview of the Czech portion of the SMF comprised between Bílá Voda village and Jeseník town. Basing on changeable orientation of the mountain front and of thalwegs of valleys dissecting the scarp, the studied fragment was subdivided into eight segments.

Segment 8, 1.9-km-long, striking N111°W, is related to a transversal Bílá Voda fault, which is younger than the SMF and controls the sinistral offset of the latter (Skácel and Vosyka, 1969). According to the quoted paper, the fault was still active during the Pleistocene. The described segment consists of two

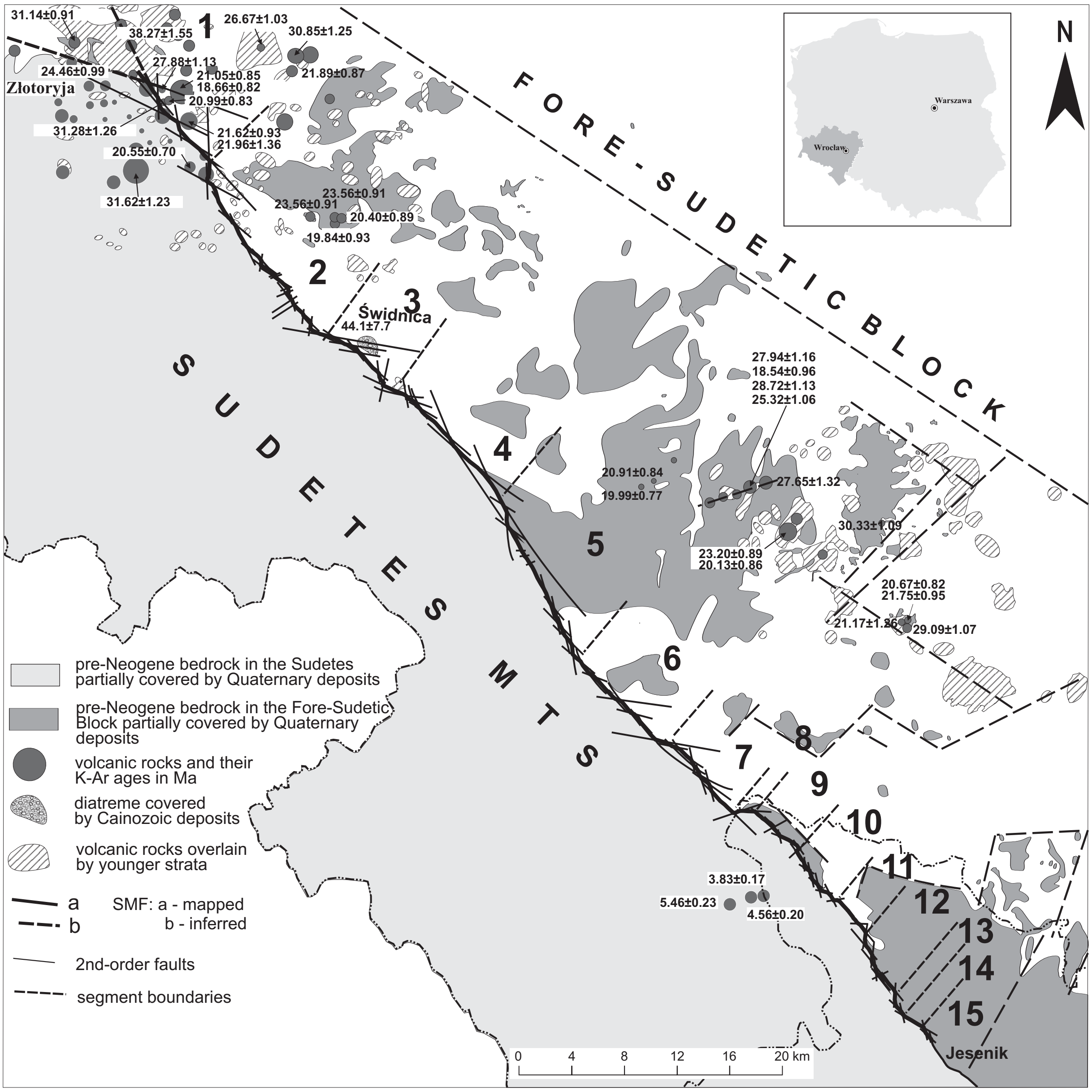

Fig. 3 Simplified geological sketch-map of the Sudetes and Fore-Sudetic Block showing location of Oligocene-Miocene basaltoids and their radiometric ages (based on different sources; cf. also Badura et al., 2005), and segmentation of the SMF.

basins, which bear thalwegs of different orientation. The 100-130-m-high fault scarp is built up of mica shists, phyllonites and gneisses of the Stronie Unit.

Segment 9, 5.5 km long and oriented N53°W, extends between Bílá Voda and the Huštický Brook valley. The step-like relief of the marginal slope of the Rychlebské Mts. is typical of this segment. Individual steps are related to fault scarps controlled by faults parallel to the SMF (Ivan, 1966). The hanging wall of the SMF in this segment is occupied by the fault-controlled Javorník step (Ivan 1966, 1972). The height of the fault scarp is lower in the NW part, composed of mica shists and granodiorites (60-90 m), whereas the SE portion built up of gneisses of the Sněžník Unit rises to 70-110 m.

Segment 10, 7.5 km long and oriented N38°W, cuts alternately gneisses of the footwall, and mica shists and phyllonites of the hanging wall. The fault scarp of this segment belongs to the highest within the Czech portion of the studied fault zone. It is 70-90 m up to 110-230 m high, regardless of bedrock lithology.

The most rectilinear *segment 11,* 4.2 km long and striking N39°W, extends from Červený Brook valley near Uhelná village to Bergov village. The

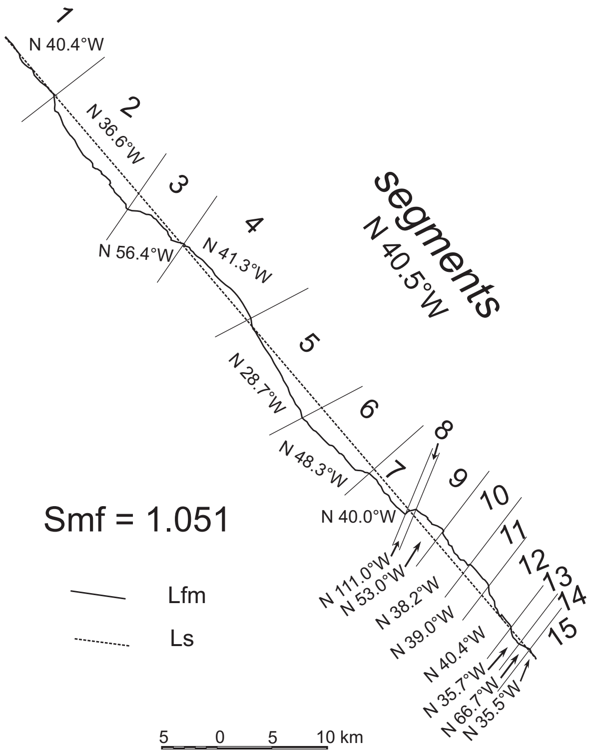

Fig. 4 Orientation of segments of the SMF. Smf - mountain front sinuosity, Lfm - actual trace of the mountain front, Ls - straight line length of the mountain front.

hanging wall comprises a Neogene basin filled with lacustrine deposits up to 400 m thick (Frejková, 1968; Ondra, 1968). The fault scarp is built up of gneisses, paragneisses, granodiorites, amphibolites and granulites, and is 90-130 m high. Up to five levels of triangular facets occur in this segment.

Geological setting of *segment 12*, 7.8 km long and oriented N40°W, is the most complicated one. Whereas the hanging wall comprises partially Neogene deposits and mainly granitoids of the Žulová pluton, the footwall is built up of migmatic gneisses, amphibolites and metagabbro, mica shists, phyllonites, blastomylonites, phyllites, and marbles. Also, the trace of the segment is far from rectilinear (Skácel, 1989; Ivan, 1997). The height of the fault scarp ranges between 60 and 130 m, and in front of the NW portion of this segment the Vojtovice step occurs.

The shortest *segment 13* is 1.4 km long and strikes N36°W. The fault scarp built up of marbles, phyllites and gneisses bears a flight of one to four tiers of triangular facets, up to 100-120 m high.

Segment 14, 3.5 km long and oriented N67°W, cuts amphibolites, gabbro-amphibolites, gneisses, phyllites, marbles, and quartzites. The segment belongs to the most elevated ones, and its base is situated at 450-550 m a.s.l. Some 6 km SW of the SMF, the highest peak of the Rychlebské Mts., Smrk (1125 m a.s.l.), is situated. According to Ivan (1997), this portion of the Rychlebské Mts. could have been uplifted en block. The fault scarp is 95 to 210 m high, and bears well-marked triangular and trapezoidal facets.

Segment 15, 1.85 km long and striking N36°W, extends from the saddle Na Pomezí (579 m a.s.l.) to Jeseník town. The fault scarp consists of several triangular and trapezoidal facets, and is 50 to 185 m high. It is built up of metadacites, phyllites, mica schists, gneisses, and mylonites.

METHODS

Our cartometric study consisted of the construction of digital elevation models for different portions of the SMF. The digital elevation model has been processed from 1:10,000 equal-area topographic maps digitized in the GIS ArcInfo, using the shaded relief map option of the SURFER programme (Fig. 5). Contour lines have been digitized every 20 m in the mountainous area, and every 5.0, 2.5, and even 1.25 m in the Sudetic Foreland. Topographic maps transformed into a raster format helped to determine, owing to the DIDGER programme, drainage basin parameters of 244 small basins that are located at the base of the Sudetic mountain front (Table 1). Unlike previous authors dealing mainly with selected physiographic parameters of large drainage basins of rivers truncating the Sudetic mountain front (cf. Krzyszkowski et al., 1995), we decided to focus on small-scale catchment areas of minor streams that dissect the SMF scarp. Details concerning calculation of individual parameters will be given in a separate chapter.

Geodetic observations on the local network with reference to selected permanent IGS/EPN stations allowed for the velocity calculation within the ITRF and their reduction to local velocities with a geo-kinematic model APKIM2000 (Drewes and Angermann, 2001). The GPS data of daily sessions were processed using the BERNESE software (Hugentobler et al., 2001). Estimation of point velocity components and the satellite antenna phase centre corrections have been made, and the linear model of point velocities and the M-estimation method, unaffected by gross errors, with the “logistic” weighting function, has been applied (Kontny, 2003).

FACETED SPURS

Fault scarps (Fig. 6) degrade from gravity-controlled (10^2 yrs), through debris-controlled (10^3 yrs), to wash-controlled (10^5yrs) slope (Wallace, 1977) due to either: decline, replacement, retreat, or rounding (Mayer, 1986). The scarps are modelled either due to fluvial erosion concurrent with uplift (Hamblin, 1976; Wallace, 1978), or gradual scarp retreat due to mass movements (Anderson, 1977). Due to repeated episodes of faulting, bedrock fault escarpments, several hundred metres high, and fault-

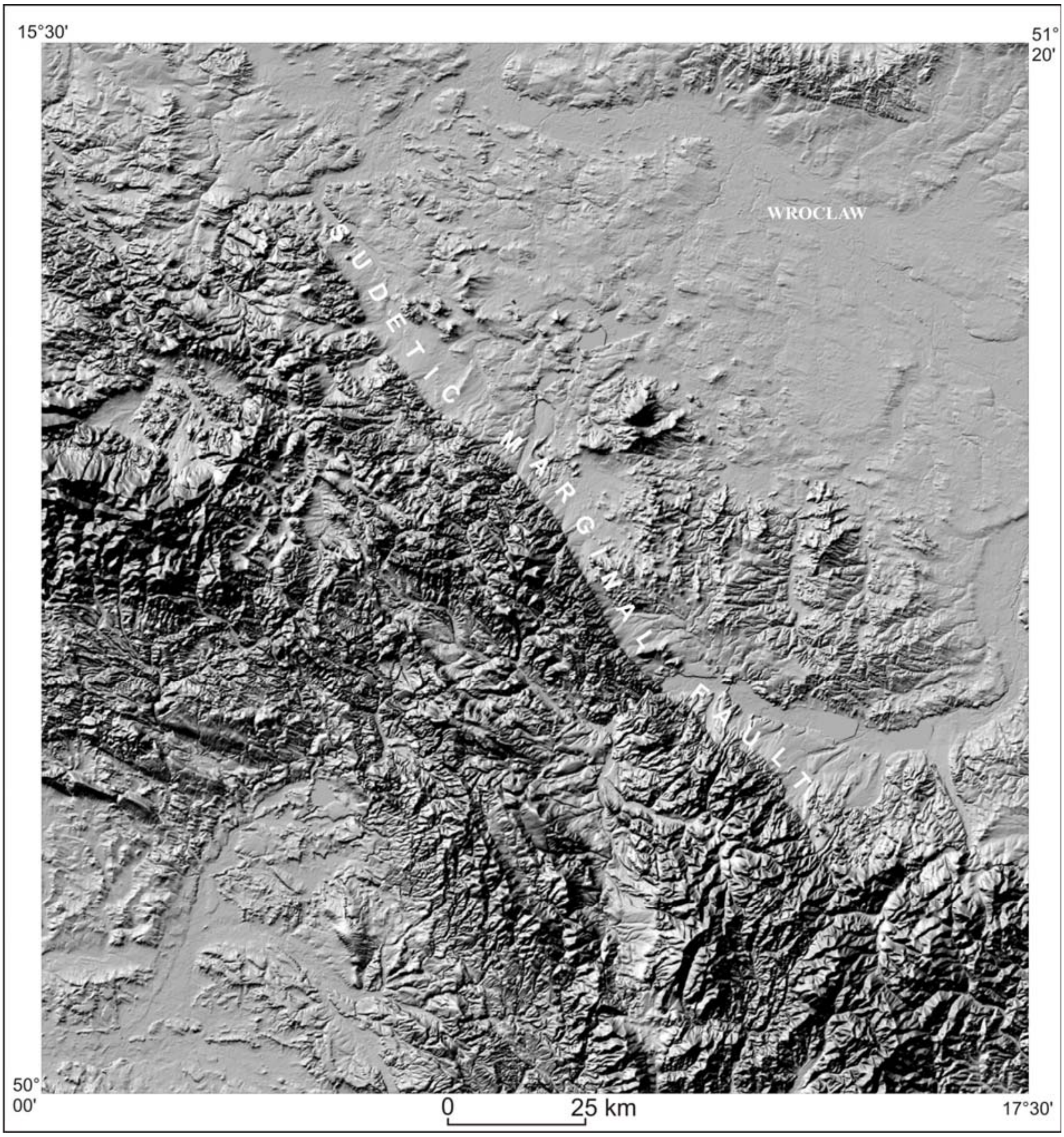

Fig. 5 Digital elevation model of the Sudetic mountain front (based on SRTM, level 2 data).

generated range fronts, several hundred of kilometres long and up to 1 km high, can form (Stewart and Hancock, 1994).

Active fault-generated mountain fronts frequently display triangular or trapezoidal facets (faceted spurs, flatirons) that form due to uplift and dissection of a normal scarp by gullies and whose bases are parallel to the fault trace (Cotton, 1958; Bloom, 1978; Stewart and Hancock, 1990). The triangular facet occurs only where the spur is sharp-crested. If the spur were flat-topped, the facet would be trapezoidal. The slope of the facets range 25-35°, whereas the fault plane dips at 50-90° (Wallace, 1978). In fractured bedrock, slope angles of 25-30° remain stable for hundreds of thousands of years in semi-arid climate (Wallace, 1977; Bloom, 1978). The spacing of facets along range fronts depends on the evolution of drainage basins within the footwall block. Flights of faceted spurs have been interpreted as a result of either episodic uplift (Hamblin, 1976; Anderson, 1977), or distributed faulting within the range-bounding fault (Menges, 1988; Zuchiewicz and McCalpin, 2000). Some authors claim that facets with uniform slopes are active geomorphic features resulting from landsliding (Ellis et al., 1999).

The range front morphology is determined by the ratio of uplift to erosion (Bull, 1984). Fast uplift is considered to produce straight mountain-piedmont

Table 1 Parameters describing small catchment areas along the Sudetic Marginal Fault.

Parameter	Symbol	Formula	References
total area	**A**		Horton (1945)
area of the basin to the right (facing downstream) of the trunk stream	**AR**		
asymmetry factor	**Af**	100(AR/A)	Hare and Gardner (1985)
maximum basin length	**L**		Horton (1945), Schumm (1954)
basin perimeter	**P**		Smith (1950)
mean width of the basin	**W**	A/L	
maximum relief	**H**	Hmax-Hmin	Strahler (1954), Schumm (1954)
basin elongation ratio	**Re**	$2(A/\pi)^{0.5}/L$	Schumm (1956)
form ratio	**Rf**	A/L^2	Horton (1945)
circulatory ratio	**Rk**	$(4\pi A)/P^2$	Miller (1953), Gregory and Walling (1973)
relief ratio	**Rh**	H/L	Schumm (1954, 1956)
relative relief	**Rhp**	H/P	Melton (1957, 1958)

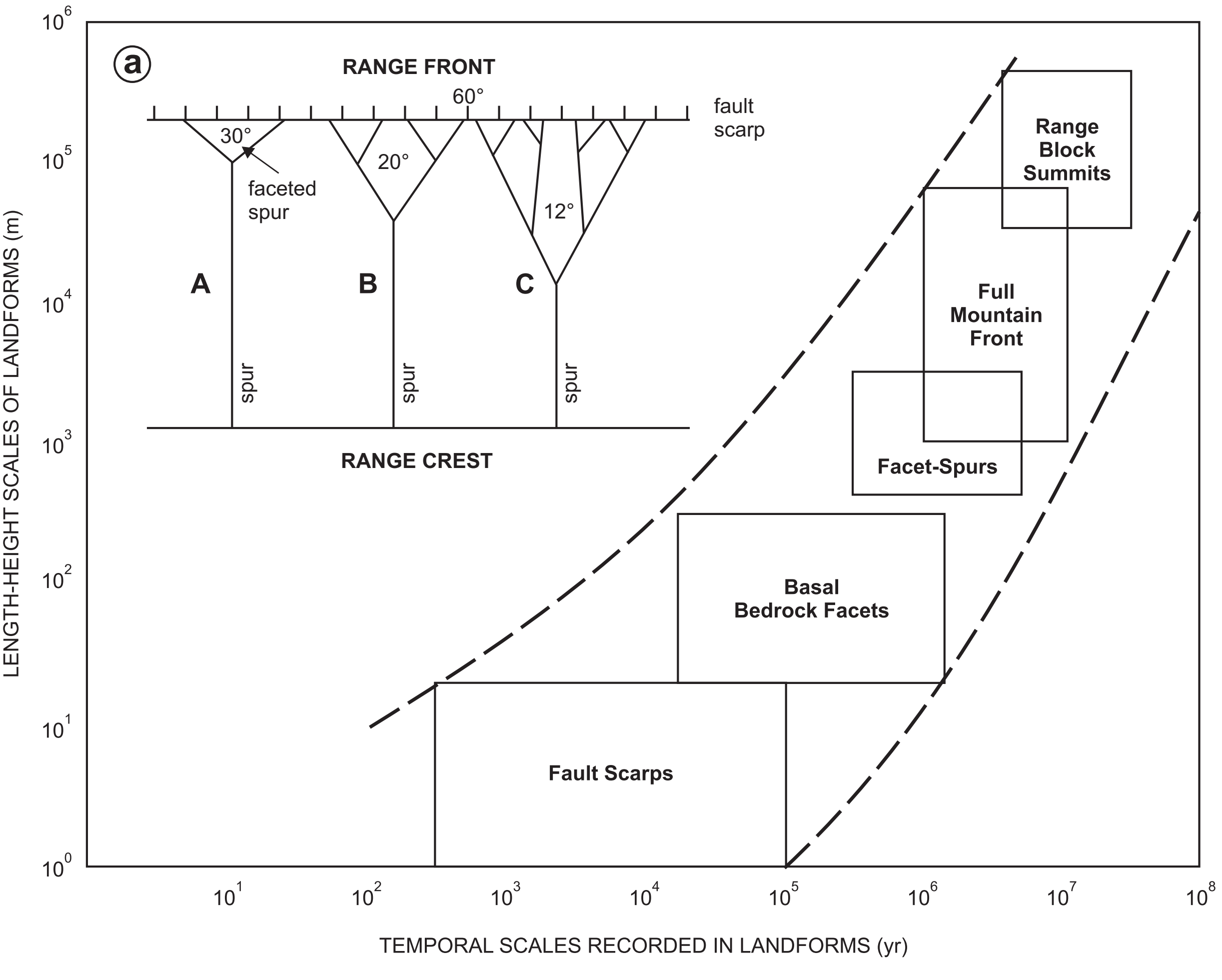

Fig. 6 Temporal and dimension scales of tectonic landforms (adapted from Menges, 1988): a – development of a faceted spur with time (based on Wallace, 1977, 1978).

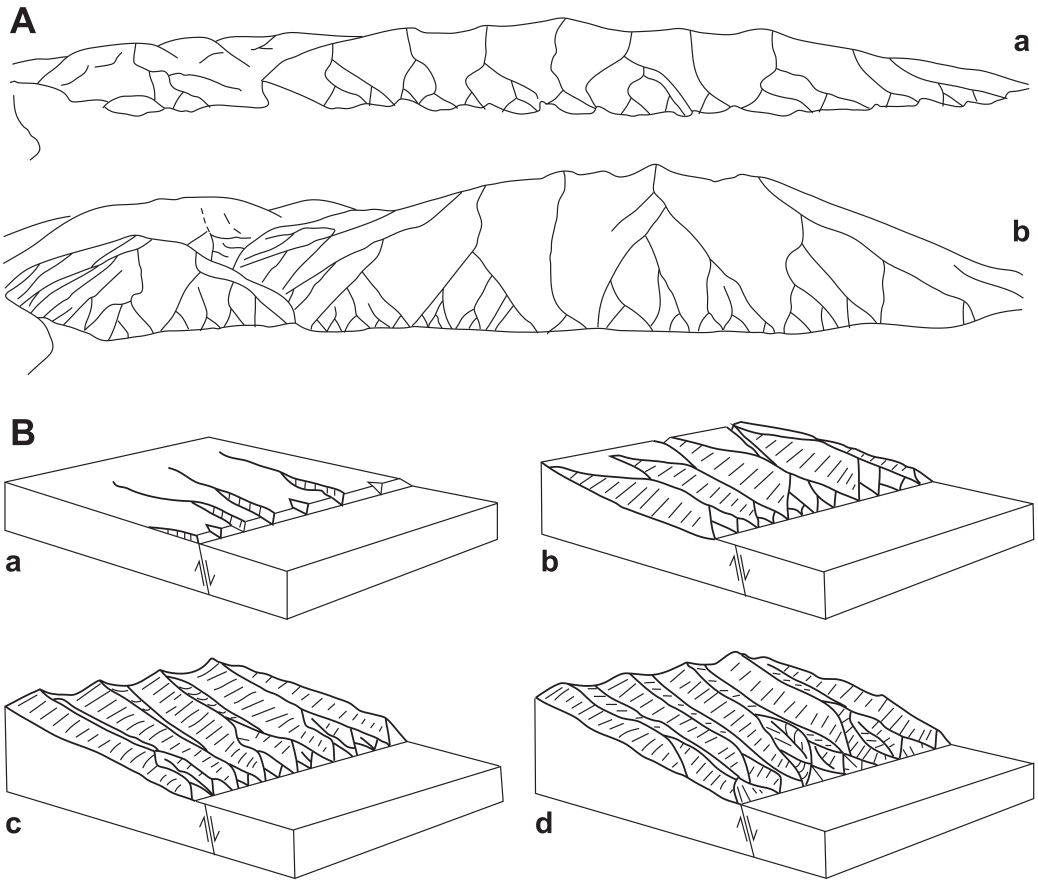

Fig. 7 Development of faceted spurs along a mountain front (based on Anderson, 1977): A - Spanish Fork segment of the Wasatch fault: a - Palaeogene and Neogene planation, b - present; B - evolutionary stages (a through d) of compound faceted spurs.

junctions, narrow valleys with steep long profiles and faceted spur ridges, whereas slow uplift results in embayed mountain-piedmont junctions, broad valleys with gentle long profiles and strongly degraded spurs (Bull, 1987).

The shaping of faceted spurs is thought to result mostly from fluvial erosion concurrent with uplift of the mountain front (Hamblin, 1976; Wallace, 1978) or from gradual backwearing, aided by gravitational mass movements (cf. Anderson, 1977 and discussion therein). Some authors point to the importance of subsidiary faults and fracture zones that run parallel to the main range front fault in modelling fault scarps (cf. Stewart and Hancock, 1988, 1990). The size of a faceted spur is a function of the distance between major canyons incised into the mountain front and of the spur's height (Fig. 7). The steepness of canyon walls exerts control upon main apical angles of faceted spurs. One would expect that on relatively homogeneous bedrock these angles would tend to decrease with facet's age. Departures from this trend imply lithological control. The height of faceted spurs, in turn, is a function of uplift, whereas average inclination may be controlled by a variety of factors. One of them is the age of the spur: on homogeneous bedrock (cf. Wallace, 1977, 1978) the younger facets are steepest.

The geometry of faceted spurs developed on differentiated bedrock, although controlled primarily by the rate of seismotectonic uplift, is frequently modified by resistance to erosion and structure of the bedrock (cf. Zuchiewicz and McCalpin, 2000; Zuchiewicz, 2004).

Digital elevation model of the SMF clearly shows variable orientation and changeable morphotectonic properties of fifteen segments of the fault between Złotoryja and Jesenik. Of particular importance is the presence of clearly visible triangular and trapezoidal facets (Figs. 8-10), located at the foot of the fault scarp.

Individual fault segments bear a flight of two (segment 8) to five tiers (segments 3-5, 9-11) of triangular facets, showing differentiated state of preservation and degree of erosional remodelling (Figs. 8-10). Average heights of these facets in the Czech portion of the fault are: 28 m, 60 m, 111 m, 173 m and 275 m for successively older generations, whereas their equivalents in the Polish segments are, respectively, 23-54 m, 56-120 m, 92-125 m, 147-232 m and 200 m (Fig. 11).

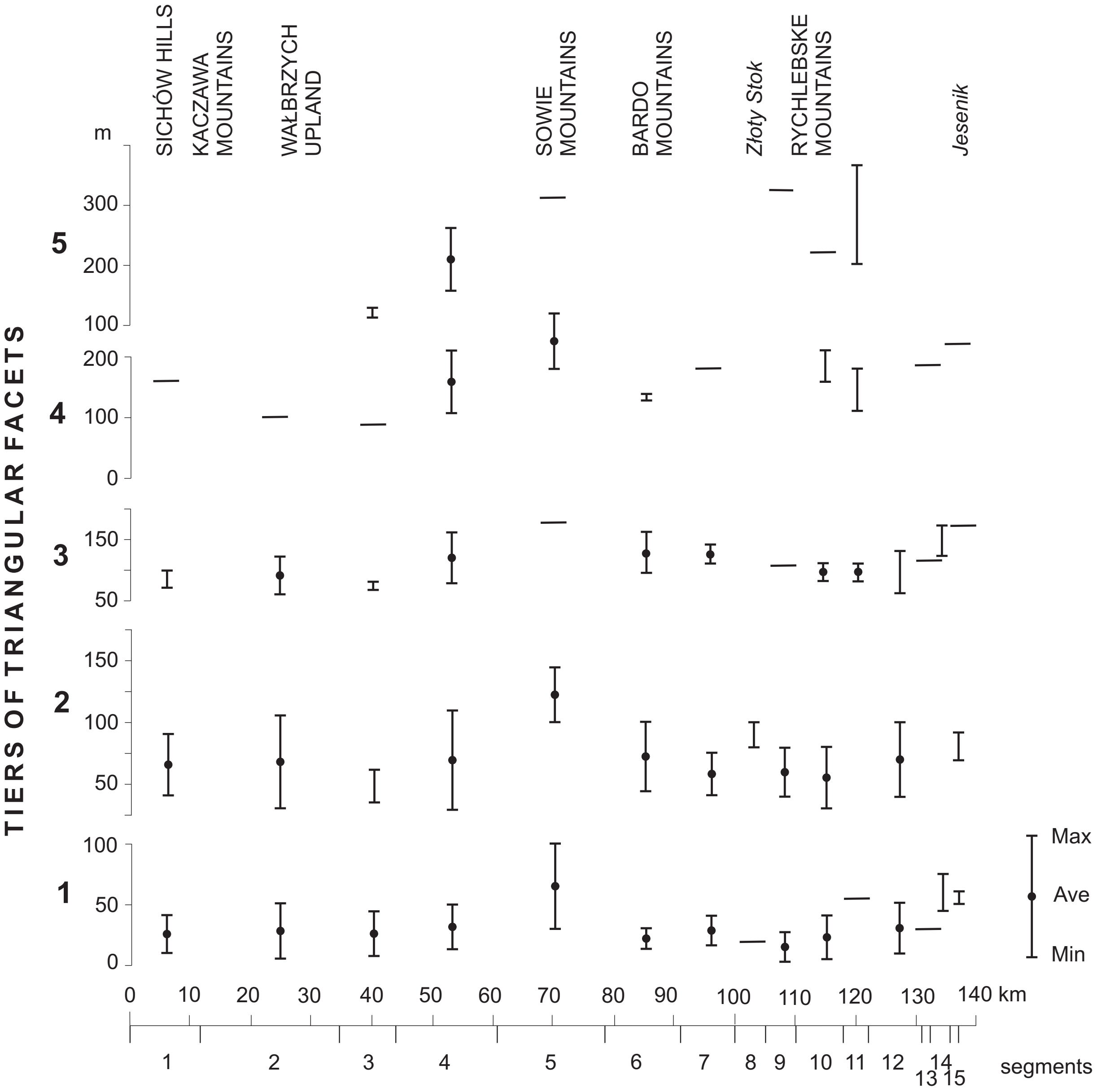

Fig. 11 Heights of faceted spurs along the SMF.

Discrete values are highly scattered: from 5 to 100 m in case of the youngest facets to 200-360 m within the oldest ones. The highest triangular facets are confined to the Sowie Mts. (segment 5) and Rychlebské Mts. (segment 11; Fig. 11).

This tiering points to at least five episodes of uplift of the SMF footwall, probably starting shortly after 31 Ma, i.e. postdating basalts of the Sichów Hills area that are displaced by the fault. More detailed age constraints are provided by the results of apatite fission-track dating of the Sowie Mts. gneisses, pointing to rapid cooling and uplift after 7-5 Ma on either side of the fault (Aramowicz et al., 2006). These data suggest Pliocene and younger ages of the highest triangular facets that accompany the Sudetic mountain front. The ages of younger uplift episodes are difficult to constrain due to the lack of datable marker sediments.

MORPHOTECTONIC PROPERTIES

Morphotectonic indicators of predominantly normal slip along the Sudetic Marginal Fault (SMF) include: well-developed triangular and trapezoidal facets, ubiquitous occurrence of hanging wine-glass (hour-glass) valleys, and rectilinear fault scarps at the foot of the mountain front. The most spectacular example of such features is provided by a fragment of the SMF near Srebrna Góra and Bielawa (segments 6 and 5). However, one should take notice of the fact that the pattern of small-scale faults, particularly in segments 7 through 4, may point to a left-lateral component of motion. This conjecture is compatible

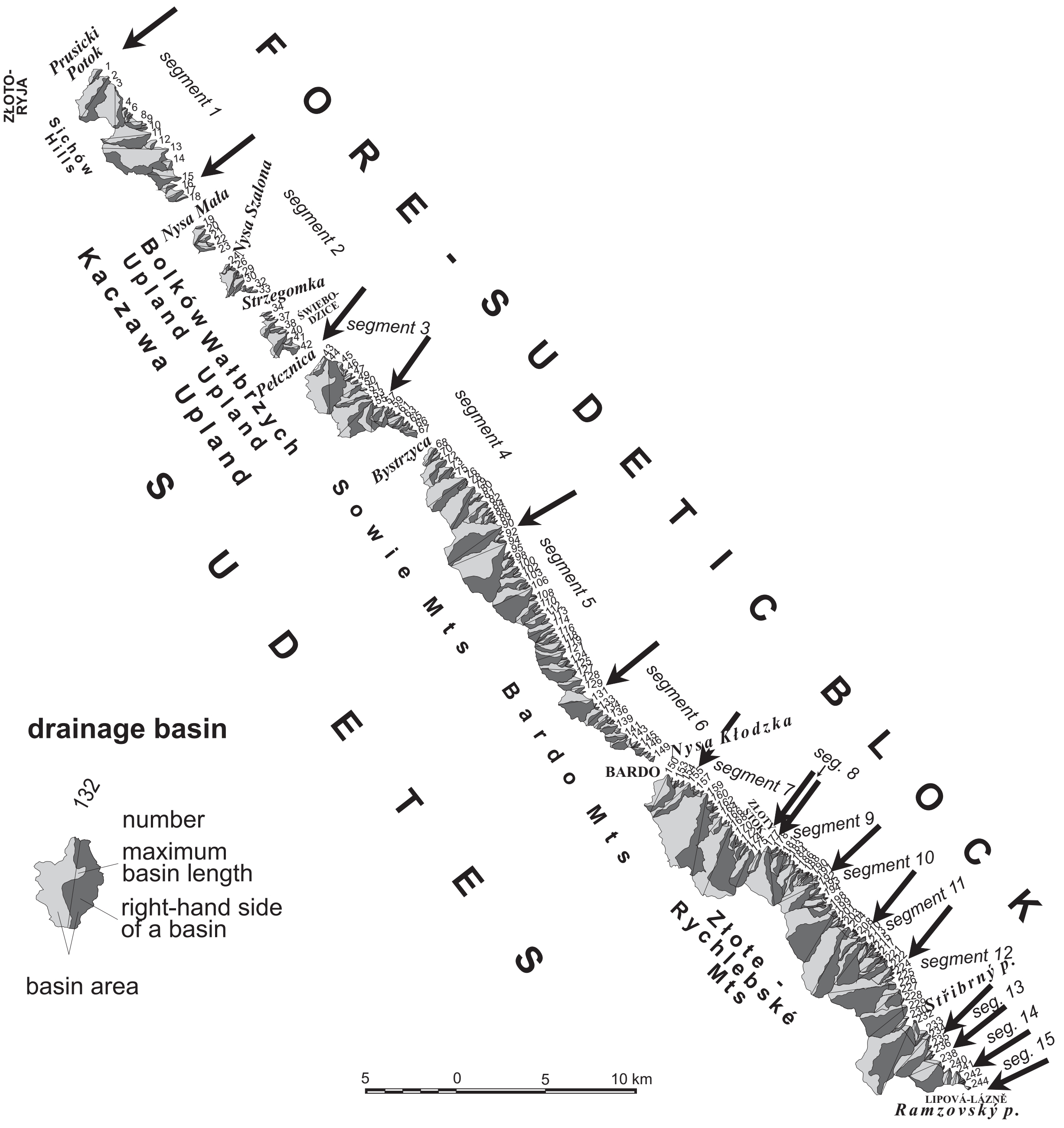

Fig. 12 Distribution of small catchment areas at the foot of the studied portion of the Sudetic mountain front. Note that interbasin areas at the base of the scarp represent the youngest triangular facets.

with conclusions by Mastalerz and Wojewoda (1993) obtained from the NW portion of the SMF, and with recent GPS observations performed on either side of the fault (cf. Schenk et al., 2002b; Kontny, 2003).

The ridge-crest long profile is not uniform, dropping by some 100-150 m in the highest elevated part, probably due to bedrock-controlled erosion. In the middle part of the mountain front, a few breaks of slope are clearly marked at elevations diminishing towards the NW. These breaks coincide at places with secondary faults parallel to the SMF which cut the mountain front on the north-east (cf. also Krzyszkowski and Pijet, 1993). Along the latter, a basal scarp of variable height (80-100 m in the NW to 250 m in the SW) is present. The scarp attains the highest relief in the SE segments of the studied fault portion.

The investigated segments of the Sudetic mountain front are dissected by V-shaped valleys and broad-floored gullies of height differences ranging between 45 and 695 m. These valleys form a dendritic pattern and are associated with 244 small drainage basins (Fig. 12).

Table 2 Average, maximum and minimum values of physiographic parameters of small catchment areas along the Sudetic Marginal Fault.

Parameter (n = 244)	**average**	**max**	**min**
L [km]	1.656	7.708	0.294
A [km^2]	1.614	24.820	0.026
AR [km^2]	0.782	10.223	0.015
Af [%]	48.53	80.77	15.42
P [km]	4.415	26.863	0.749
W [km]	0.520	3.220	0.082
Hmax [m a.s.l.]	554.9	1125.0	302.5
Hmin [m a.s.l.]	355.5	550.0	207.0
H [m]	201.5	695.0	44.5
Re	0.61	0.90	0.43
Rf	0.30	0.63	0.15
Rk	0.58	0.90	0.32
Rh	0.15	0.64	0.04
Rhp	0.06	0.27	0.01
Vfw [m]	29	240	5
Esc [m a.s.l.]	367.4	560.0	217.5
Eld [m a.s.l.]	419.8	765.0	223.8
Erd [m a.s.l.]	418.9	730.0	230.0
Vf	0.83	9.45	0.04

MORPHOMETRIC INDICES

Morphometric indices, particularly those that characterize fault scarps and drainage basins are useful in estimating the recent tectonic activity of a region (Chorley, 1962; Strahler, 1964; Morisawa, 1972; Bull, 1978; Rockwell et al., 1984; Keller and Pinter, 1996; Silva et al., 2003). As far as neotectonic research in Poland is concerned, such studies have hitherto been conducted in the Carpathians, Sudetes, and Roztocze regions (see review in Badura et al., 2003a, b).

PARAMETERS DESCRIBING THE FAULT SCARP

The *mountain front sinuosity index* (Smf; Bull, 1977, 1978) is calculated as a ratio of Lmf to Ls, where Lmf is the length of the mountain front measured along the foot of the mountains at the pronounced break of slope, and Ls is the straight-line length of the mountain front:

$$Smf = Lmf/Ls$$

Mountain fronts associated with active uplift are relatively straight, with low values of Smf which - in arid areas of the Basin and Range Province - range between 1.0 and 1.6. For slightly active and inactive regions, the Smf values tend to be between 1.4-3.0 and 1.8 to >5, respectively (Bull, 1977, 1978; Bull and McFadden, 1977). Generally, the Smf values less than 1.4 indicate tectonically active fronts (Rockwell et al., 1984; Wells et al., 1988), whereas those greater than 3.0 are related to inactive fronts in which the initial range-front fault may be more than 1 km away from the present erosional scarp (Bull and McFadden, 1977). Recent studies conducted along 17 different fault-generated mountain fronts in SE Spain indicated that uplift rates of 0.15-0.08 mm/yr are sufficient to keep low Smf values of active (class 1) fronts, whereas those of 0.07-0.03 mm/yr and below 0.03 mm/yr are characteristic for classes 2 and 3, respectively (cf. Silva et al., 2003). The fault scarp retreat rates, in turn, obtained from talus flatirons in a semi-arid region of NE Spain, cluster around 1 mm/yr (Gutierréz et al., 1998).

The Smf value calculated for the Sudetic mountain front along the SMF is 1.05 (Fig. 4). This figure, even corrected for high resistance contrast of bedrock rocks on either side of the SMF, points to relatively high activity of young uplift. Analogous values calculated by Krzyszkowski et al. (1995) for the entire length of the Polish segment of SMF change from 1.55 in the NW, through 1.15 in the SE, to 1.30-1.35 in the southeasternmost part, and average 1.36. The lowest figures have been found to characterise gneisses (1.2), the highest ones - slates and greenstones (1.5; *op. cit.*).

The same conclusion comes from an analysis of other morphometric indices, including the *valley floor width - valley height ratios* (Bull, 1977, 1978; Bull and McFadden, 1977), showing abnormally low values (Table 2, Fig. 13) for valleys that truncate the Sudetic mountain front. This parameter is calculated as:

$$Vf = 2Vfw/[(Eld - Esc) + (Erd - Esc)];$$

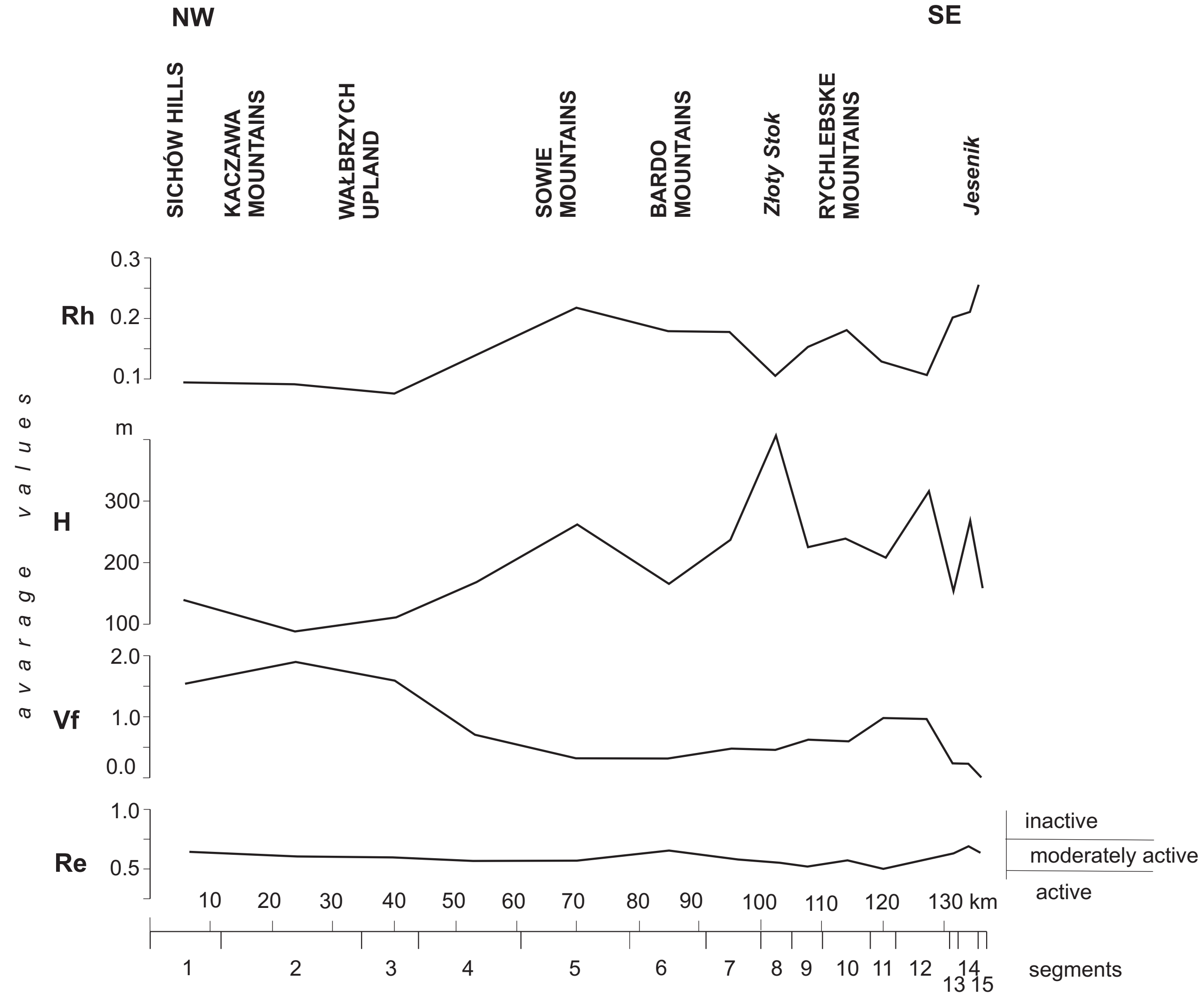

Fig. 13 Variability of average values of physiographic parameters indicative of young uplift (Rh, H, Vf, Re) along the SMF. See text and Table 1 for explanation.

where Vfw is the width of the valley floor, Eld and Erd are elevations of the left and right valley divides, respectively, and Esc is the elevation of the valley floor. This index differentiates between broad-floored valleys (U-shaped), with relatively high values of Vf , and V-shaped canyons with relatively low values. Low values of Vf (<1.0) reflect deep valleys of actively incising streams, commonly associated with uplift; high Vf values (>1.0) are typical of broad-floored valleys with major lateral erosion resulting from relative base-level stability or tectonic quiescence (Rockwell et al., 1984; Keller and Pinter, 1996). The figures quoted by Bull and McFadden (1977) for the Basin and Range Province range between 0.05-47, averaging 1.3-11.0.

Valleys dissecting the Sudetes mountain front studied display Vf values (calculated for valley cross-sections located at a set distance equaling to 10% of the total length upstream of the mountain front) that range between 0.04 and 9.45, average 0.06 (segment 15) to 1.91 (segment 2), and usually do not exceed 0.7 throughout segments 4-10 and 0.25 in segments 13 through 15, being higher than 1.5 in the north-western segments (1-3) (Fig. 13). Vf values quoted by Krzyszkowski et al. (1995) for the entire Polish portion of SMF average at 1.43, ranging from 2.4 to 0.6 in the NW and SE sectors, respectively.

DRAINAGE BASIN PARAMETERS

The drainage basins in question range in *area* between 0.03 and 24.8 km^2, averaging at 0.14 km^2 (segment 15) to 5.31 km^2 (segment 8) per segment. The largest basins occur in segment 7 (Table 2, Fig. 14).

The *asymmetry factor* Af (Kaitanen, 1975; Hare and Gardner, 1985), which is sensitive to tilting perpendicular to the main channel in a basin (Af >50 or Af<50; cf. Table 1, Fig. 14), averages 43 (segment 3 and 14) to 57 (segment 15), although for individual basins this factor changes from 15.4 (segment 7) to

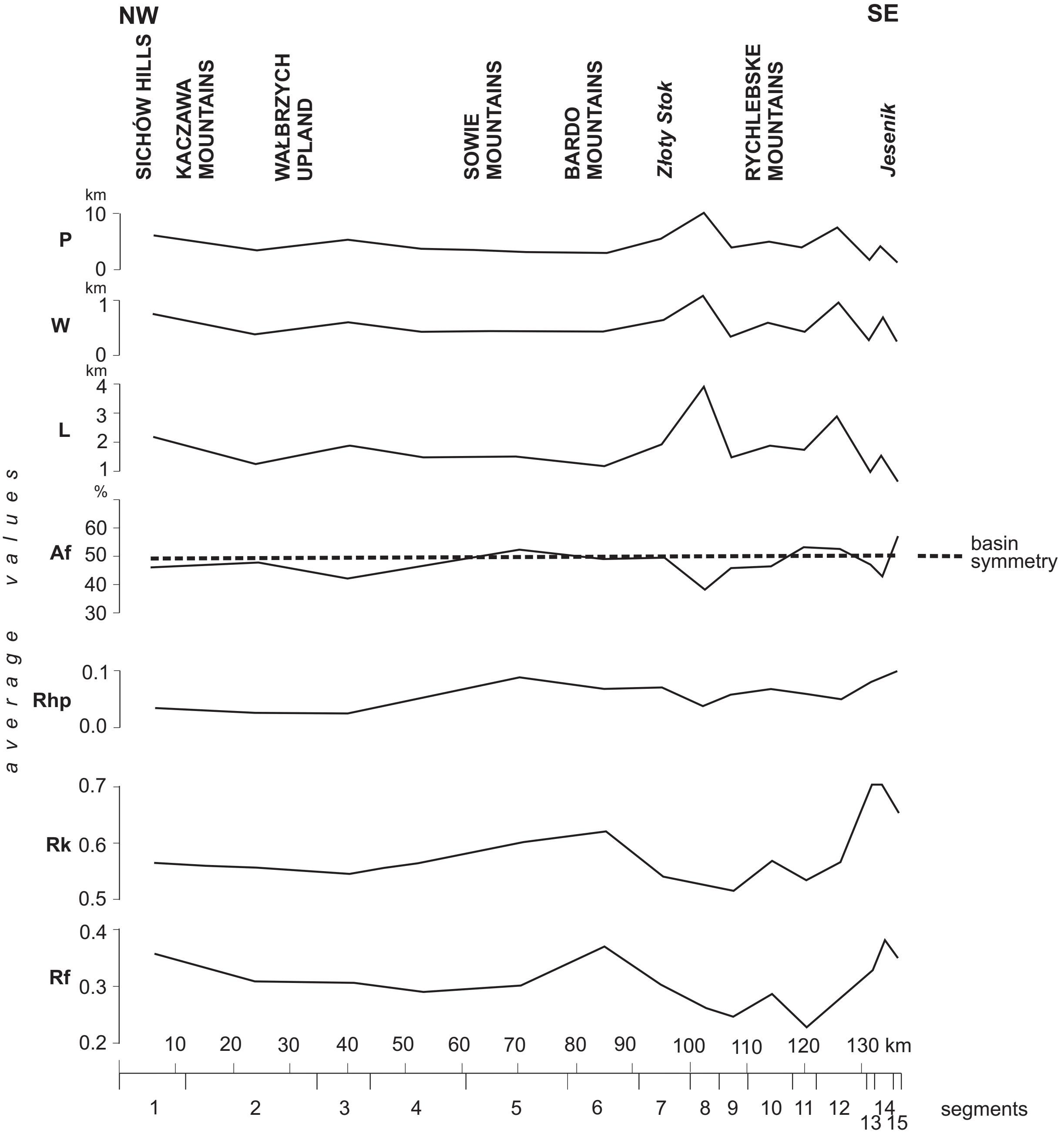

Fig. 14 Variability of average values of physiographic parameters (P, W, L, Af, Rhp, Rk, Rf) along the SMF. See Table 1 for parameter definitions.

80.8 (segment 12), showing that some basins could have been slightly tilted either to the SE (segments 1-4, 8-10, and 13-14) and NW (segment 15), or showed no tilt at all (segments 5-7 and 11-12). Tectonic control of the basin asymmetry is, however, highly problematic in this case.

The *maximum basin length* (L; Horton, 1945; Schumm, 1954) is the distance between the two most distant points in the basin and characterizes best the absolute size of the latter. These figures range from 0.29 to 7.71 km, and average 0.61 km (segment 15) to 3.98 km (segment 8; Fig. 14). The *basin perimeter* values (P) range between 0.75 and 26.86 km, attaining averages of 1.58 km (segment 15) to 10.21 km (segment 8) per segment (Fig. 14). Similarly, the related values of the *mean basin width* (W) are comprised in the interval of 0.08 and 3.22 km for individual basins, and average 0.22 km (segment 15) to 1.10 (segment 8; Fig. 14).

The *form ratio* (Rf; Horton, 1945) compares the basin shape to a rectangle. Low figures characterize elongated basins, whereas those equal to or greater than 1.0 are typical for broad, square-like basins. The Rf values diminish with an increase in the basin area (Eagleson, 1970; Gregory and Walling, 1973). Drainage basins associated with the SMF zone show

Rf values ranging between 0.15 and 0.63, whereas the average figures are between 0.23 (segment 11) and 0.38 (segment 14; Fig. 14). The *circulatory ratio* (Rk; Miller, 1953; Gregory and Walling, 1973) is a ratio of the basin area to the area of a circle of the same perimeter as the basin. Figures lower than 1.0 characterize elongated basins. As far as the SMF basins are concerned, the Rk values range between 0.32 (segments 7 and 2) to 0.90 (segment 3); averaging 0.53 (segment 8) to 0.70 (segments 13, 14; Fig. 14).

The *maximum basin relief* (H; Strahler, 1954; Schumm, 1954), calculated as the difference between the maximum and minimum absolute heights, provides information on the relative rejuvenation of an area. Along the SMF, these values change from 45 m (segments 2 and 1) to 695 m (segment 12) for individual basins, and average 96 m (segment 2) to 417 m (segment 8; Fig. 13). The *relief ratio* (Rh; cf. Schumm, 1954, 1956), representing the mean slope of a basin, is particularly useful for elongated basins (Morisawa, 1962). An increase in bedrock resistance and basin order lead to a decrease of this parameter, as does tectonic uplift of the area. Basins located at the foot of the SMF display Rh values ranging from 0.04 to 0.64, averaging 0.08 (segment 3) and 0.26 (segment 15; Fig. 13). The *relative relief ratio* (Rhp; Melton, 1957, 1958) portrays a ratio of the maximum basin relief to the basin perimeter. These figures change along the SMF from between 0.01 and 0.27, and average 0.03 to 0.10 (Fig. 14).

The *basin elongation ratio* (Bull and McFadden, 1977) is a proxy for indicating recent tectonic activity. This parameter (Re) is calculated as a ratio of the diameter of a circle, whose surface is equal to the drainage basin area, to the maximum basin length (Schumm, 1956; Eagleson, 1970; cf. Table 1). According to Strahler (1964) and Eagleson (1970), values approaching 1.0 characterize poorly dissected basins, whereas those ranging between 0.6-0.8 are typical for areas of steep slopes and differentiated topography. Drainage basins in arid and semiarid climates tend to show Re values ranging from <0.50, through 0.50-0.75 to >0.75 for tectonically active, slightly active and inactive settings, respectively (Bull and McFadden, 1977). The Re values calculated for the Sudetic mountain front (Fig. 13) range from 0.43 to 0.90, averaging for individual segments 0.53 (segment 11) and 0.56-0.57 (segments 9 and 8) to 0.68 (segment 14), and point to moderately active uplift of the footwall of the SMF. The Re values quoted by Krzyszkowski et al. (1995) for the entire SMF change from 0.59 in the NW sector, through 0.53-0.54 in the medial sectors, to 0.48-0.50 in the SE; averaging 0.53.

All these morphometric data (Table 2, Figs. 13, 14) enable us to consider the SMF scarp as one belonging to the 2nd class of relative tectonic activity (sensu Bull, 1977, 1978; Bull and McFadden, 1977), i.e. intermediate between active and inactive faults.

RESULTS OF GEODETIC OBSERVATIONS

The results of repeated measurements of the 1st-order national levelling network and geodetic investigations performed up to the 1990's in the local geodynamic research areas in Lower Silesia show the presence of recent crustal movements, both horizontal and vertical ones, whose rates amount to several millimetres per year (Wyrzykowski, 1985; Cacoń et al., 1998; Cacoń and Dyjor, 1999; Kowalczyk, 2006). Geodynamic geodetic investigations, using an annual GPS epoch measurement technique in a special research network, were initiated in 1996. The network GEOSUD, covering initially the Eastern Sudetes and the Fore-Sudetic area, was extended to the entire region in 2000 (Kontny, 2003). An accuracy analysis of the observations performed in the network ensured determination of the movement parameters of individual points close to the level of 1 mm/year. The velocity vectors of the GEOSUD network point linear movements with their 95% confidence ellipses are presented in Figure 15.

The activity of the investigated tectonic structures (major faults and tectonic grabens) was analysed on the basis of parameters of changeable relative extension and the rotation of the vectors located in the research profiles (Table 3).

Relative extension rates for all the vectors crossing the SMF, except BARD-PRZY (Table 3, bold type), turned out to show negative and comparable values, indicating contraction. Significant and anticlockwise rotation rate of the vectors ZLOT-KOZO and BARD-PRZY point to a possible sinistral component of motion. Compressive and sinistral character of local movements in the SMF zone is visible on the picture of relative (reduced to the southern side of the fault by fixing the northern part) velocity vectors of points situated on either side of the main fault.

Our results appear to show that the area of the Polish Sudetes and the Fore-Sudetic Block undergoes contraction, the axis of which is aligned NE-SW. The contact zone between the two blocks, covering the area of the Sudetic Marginal Fault and the Fore-Sudetic grabens, is subject to the greatest deformation. The results of GPS measurements point to the fastest horizontal movements along the faults situated in the western part of the region. However, a short period of observations in the western part of the network does not allow for far-reaching conclusions. For the time being, the most plausible explanation of recent mobility of the studied area is contemporaneous uplift of the Sudetic block.

FINAL REMARKS

The Sudetic Marginal Fault (SMF) is one of important faults in Central Europe. Between Złotoryja in the NW and Žulova in the SE, the fault is expressed in morphology as a distinct scarp which is about 150 km long and 50 to 400 m high. Orientation of the

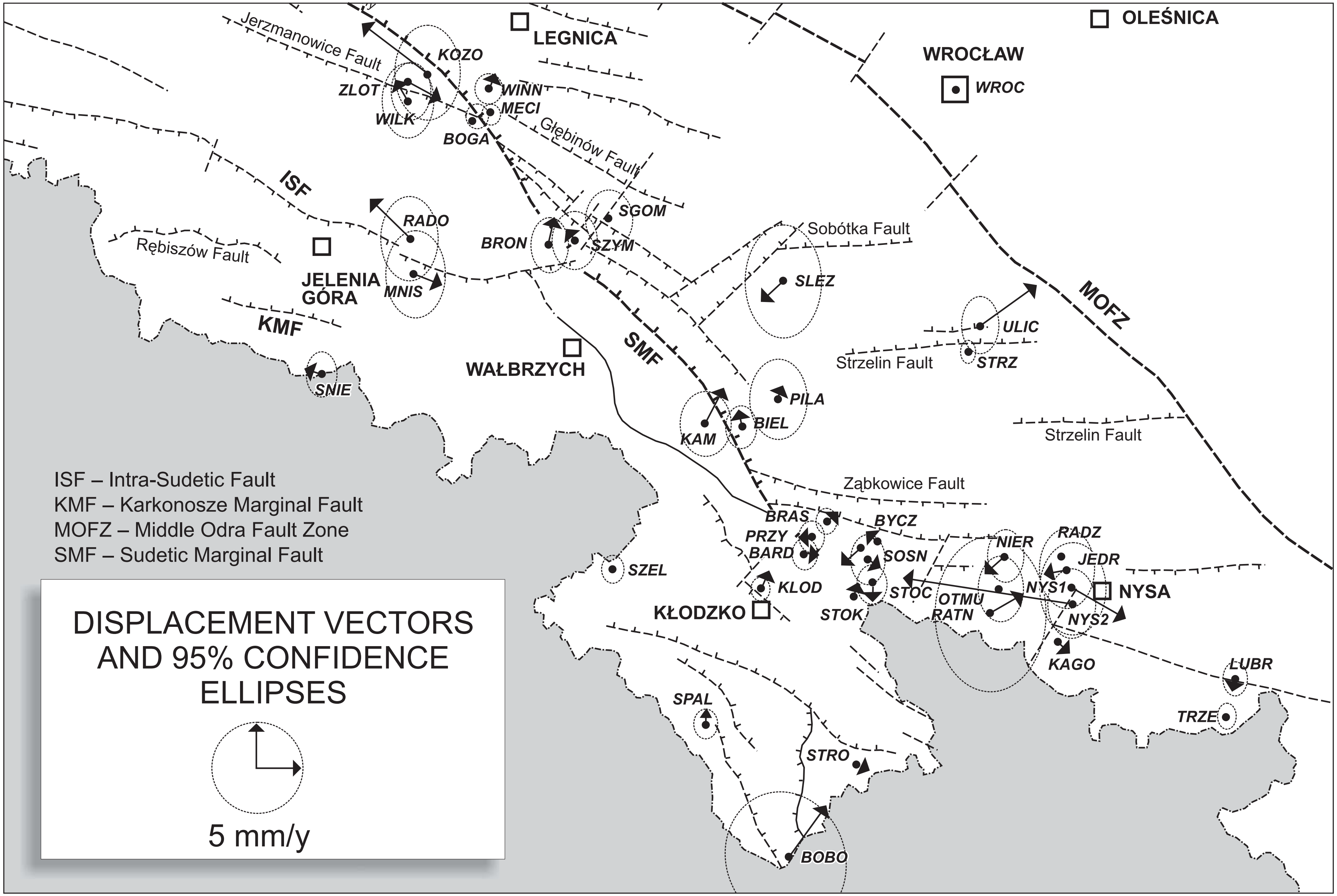

Fig. 15 Horizontal velocity vectors of the GEOSUD network points and their confidence ellipses (based on Kontny, 2003)

Table 3 Rates of vector relative elongation and rotation on the geodetic profiles.

PROFILE	FROM	TO	ε_{AB} (mm/10km/yr)	$\sigma_{\varepsilon_{AB}}$ (mm/10km/yr)	RATIO	$\widehat{\varpi}_{AB}$ (rad/year)	$\sigma_{\widehat{\varpi}_{AB}}$ (rad/year)	RATIO
A	**ZLOT**	**KOZO**	**-4.65**	**8.04**	**-0.6**	**-3.56E-06**	**7.54E-07**	**-4.7**
A	WILK	ZLOT	-7.18	21.14	-0.3	4.35E-06	1.65E-06	2.6
B	**BOGA**	**MECI**	**-4.72**	**4.14**	**-1.1**	**3.04E-08**	**4.78E-07**	**0.1**
B	MECI	WINN	5.81	3.13	1.9	2.80E-07	2.95E-07	0.9
C	**BRON**	**SZYM**	**-4.11**	**5.14**	**-0.8**	**4.85E-07**	**6.33E-07**	**0.8**
C	SZYM	SGOM	0.48	3.59	0.1	3.24E-07	3.69E-07	0.9
D	**KAMI**	**BIEL**	**-4.03**	**3.33**	**-1.2**	**3.65E-07**	**4.11E-07**	**0.9**
D	BIEL	PILA	0.57	3.17	0.2	1.19E-07	3.38E-07	0.4
E	**BARD**	**PRZY**	**1.05**	**7.83**	**0.1**	**-1.33E-06**	**6.71E-07**	**-2.0**
E	KLOD	BARD	-1.26	0.92	-1.4	1.68E-07	9.09E-08	1.9
E	PRZY	BRAS	4.00	2.86	1.4	1.82E-07	2.85E-07	0.6
F	**STOK**	**STOO**	**-4.08**	**4.80**	**-0.9**	**6.96E-07**	**5.41E-07**	**1.3**
F	STOO	SOSN	1.25	4.01	0.3	2.83E-07	3.15E-07	0.9
F	SOSN	BYCZ	1.89	5.14	0.4	-8.41E-07	4.40E-07	-1.9

ε_{AB} - vector relative elongation, $\widehat{\varpi}_{AB}$ - average angle of rotation

entire SMF fault trace approaches N41°W, and the mountain front sinuosity amounts to 1.051.

Individual fault segments of the SMF bear a flight of two to five tiers of triangular facets, showing differentiated state of preservation and degree of erosional remodelling. The highest triangular facets are confined to the Sowie and Rychlebské (Złote) mountains. This staircase arrangements of faceted spurs points to at least five episodes of uplift of the SMF footwall, probably starting shortly after 31 Ma, i.e. after basalts of the Sichów Hills were displaced by the fault, and most probably postdating 7-5 Ma time interval, during which rapid cooling and exhumation of the Sowie Góry Mts. massif took place. The age of younger uplift episodes is difficult to constrain due to the lack of datable marker sediments.

Morphometric parameters of 244 small catchment areas of streams that dissect the fault scarp include, i.a., elongation, relief, and average slope of individual catchment areas, together with values of the valley floor width to valley height ratios. The relief energy values range between 45 m and 695 m, averaging 202 m, basin elongation ratios are between 0.43 and 0.90 (av. 0.61), and valley floor width-valley height ratios change between 0.04 and 9.45, averaging 0.83. All these figures point to moderate tectonic activity of the SMF and do not differ much from those typical for young, moderately active normal fault scarps described from elsewhere (cf. Bull, 1977, 1978; Silva et al., 2003). Quaternary uplift was particularly important in the Sowie and Rychlebské (Złote) Mts. segments.

These observations appear to confirm earlier views on the normal character of faulting along the SMF, supported as well by the results of repeated GPS campaigns. It is worth to note, however, that recent studies of fractured pebbles in Late Pleistocene fluvial gravels in the Bardo Mts. segment of the SMF indicate a dextral component of motion, as do focal solutions of minor earthquakes in the Czech part of the fault. Hence, the sense of motion along the SMF requires further detail studies, including trenching, throughout the entire length of this zone.

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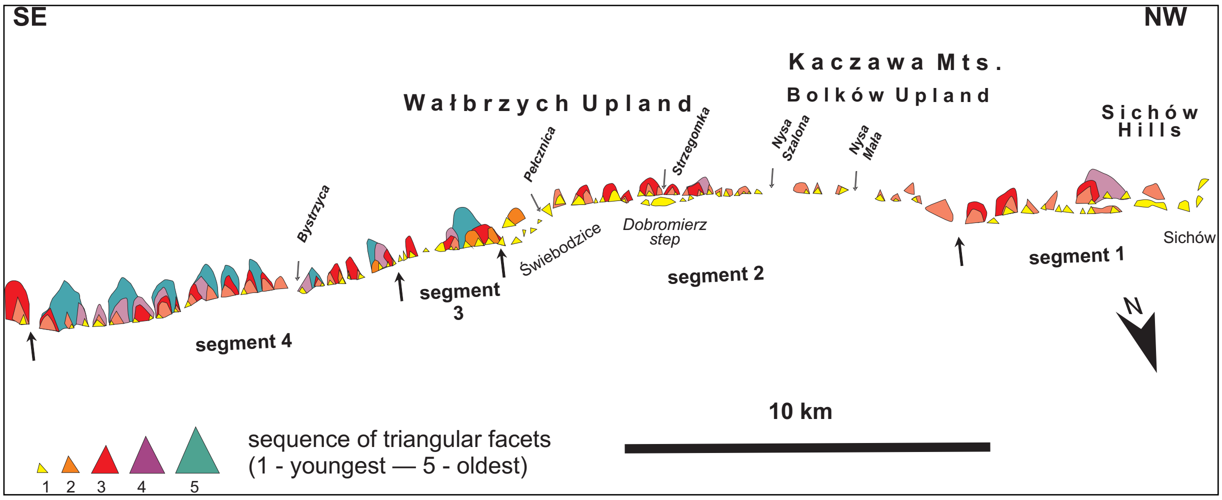

Fig. 8 Perspective drawing of staircase-like arranged faceted spurs along segments 1 through 4 (drawing from DEM).

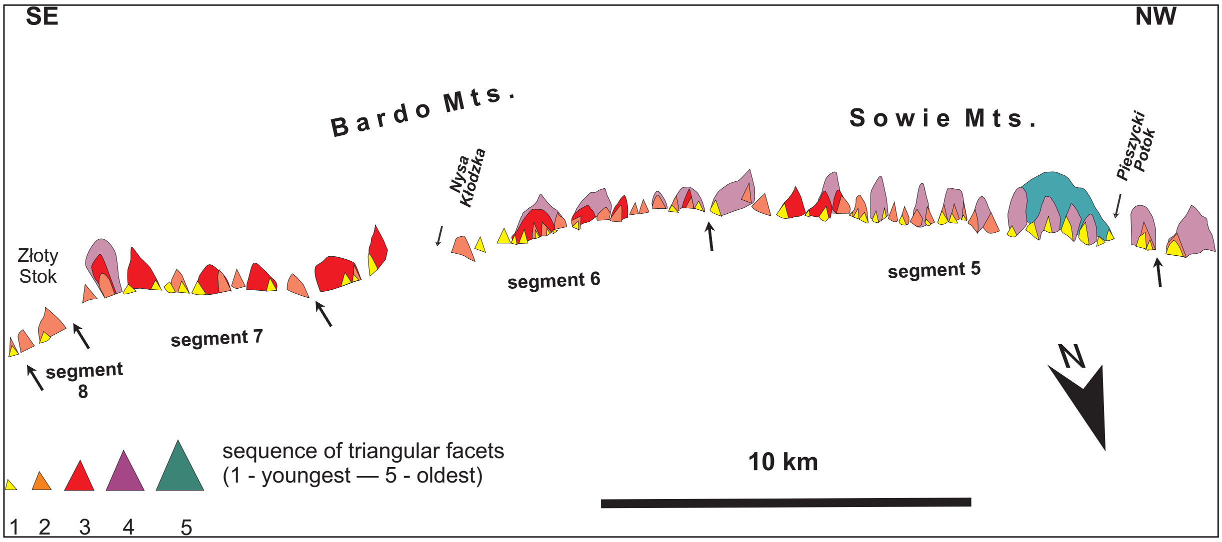

Fig. 9 Perspective drawing of staircase-like arranged faceted spurs along segments 5 through 8 (drawing from DEM).

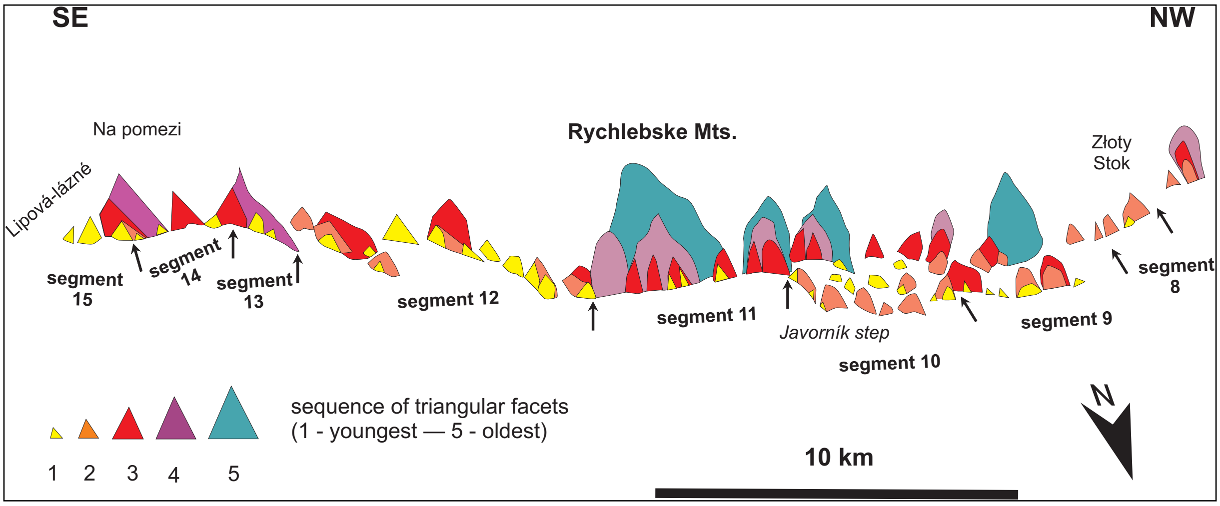

Fig. 10 Perspective drawing of staircase-like arranged faceted spurs along segments 9 through 15 (drawing from DEM).