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LATE CENOZOIC TECTONIC ACTIVITY OF THE ŚNIEŻNIK MASSIF AREA (THE SUDETES, SW POLAND) IN THE LIGHT OF LIDAR DEM MORPHOMETRIC ANALYSIS

Abstract: The Śnieżnik Massif represents a prominent morphological feature in the East Sudetes, which is bounded by a system of faults controlling its differential uplift. Vertical movements originated at least during the Oligocene times, with culmination phase in the Pliocene times, whereas estimated total uplift was in the range of 500–1000 meters. This study presents a qualitative (geomorphometric) and quantitative (morphotectonic) approach that combines the Late Cenozoic tectonic uplift model with landscape evolution theories. Application of basin asymmetry factor (AF) and hypsometric integral (H_i) analyses allowed recognizing a NW trending, presumably tilted, fault blocks. They originated as a result of the Palaeogene planation surface braking and differential uplift. Uplift and later fault-block tilting in the Śnieżnik Massif morphotectonic unit, were generally realized along NE-SW striking the Wilkanów fault to the west and WNW-ESE striking southern fault zone, as expressed here e.g. by Potoczek-Branna, Heřmanice and Pisary faults.

Keywords: Śnieżnik Massif, Sudetes, tectonic geomorphology, tilted blocks, relief evolution

INTRODUCTION

High-resolution digital elevation models based on LiDAR data and recently developed GIS software allow performing more objective and sophisticated morphotectonic analyses for the Sudetes area then previous ones (e.g. Sroka 1997; Ranoszek 1999; Badura et al. 2003a). Recently observed technological advances in hypsometry imaging give an opportunity for the landscape evolution scenarios re-examination, being especially helpful in case of the Late Cenozoic reconstructions. We characterise eastern sector of the Sudetes using general geomorphometric tools as well as morphotectonic indices calculated for 43 basins from the Śnieżnik Massif area and its proximate neighbourhood. Moreover, we combine morphometric results (e.g. hypsometric integral, asymmetry factor) with geological data, represented by structural observations. Due to relatively poor knowledge about the Śnieżnik Massif Pre-Pleistocene development, we aim to add new data to some long-standing geological and geomorphological assumptions and correlations made for the study area (see Walczak 1968; Don

1989; Migoń 1997; and references therein), emphasizing important role of fault block tectonics in topographic evolution.

OUTLINE OF GEOMORPHOLOGY

Study area is located in the East Sudetes (in geographical sense), which going from the south is subdivided into several mountain ranges: the Śnieżnik Massif, the Krowiarki range, the Bialskie and the Złote Mts., terminating to the north in the Bardzkie Mts. and the Fore-Sudetic Block to the north-east (Fig. 1). Formed at the end of the Turonian (Don 1996), longitudinally elongated the Upper Nysa Kłodzka Graben (UNKG), builts western flank of the research area (Fig. 2).

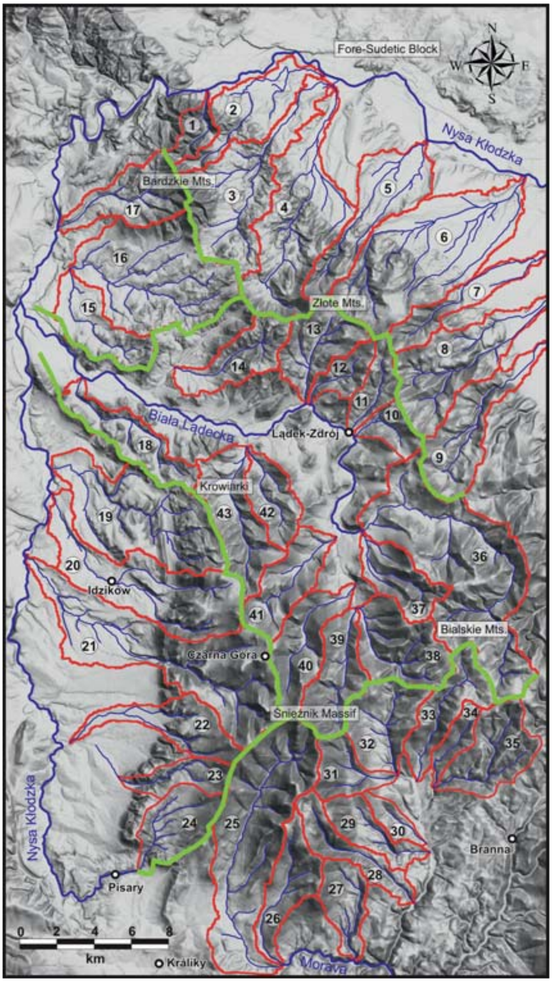

Fig. 1. LiDAR (Poland) and DTED-2 (Czech) based digital elevation model with drainage network and 43 basins used for morphometric analysis superimposed. Green line reflects main water divide. See table 1 for basins' names

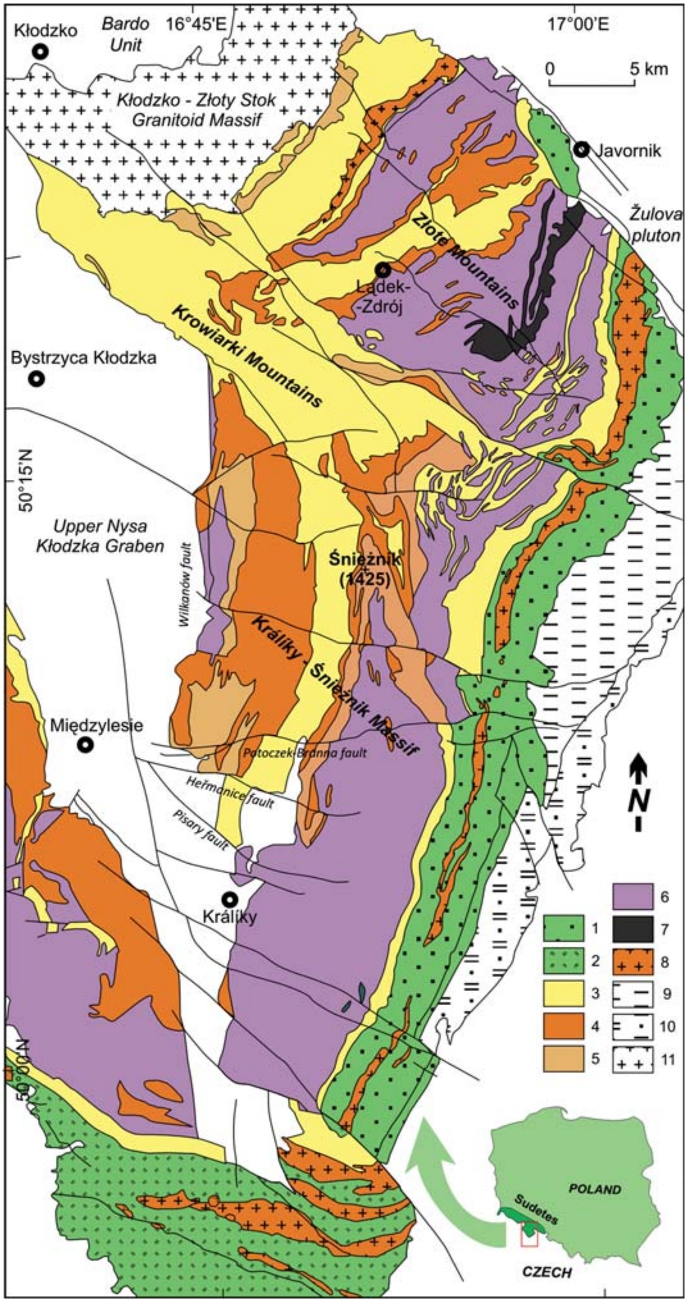

Fig. 2. Geology of the study area (modified after Don et al. 2003; Chopin et al. 2012). 1 — Stare Mesto unit: metabasites and migmatites; 2 — Zabreh unit: metasedimentary & metavolcanic rocks; 3 — Stronie Formation: mica schists and paragneisses; 4 — Śnieżnik Gneisses: augen gneisses; 5 — Gierałtów Gneisses with Śnieżnik Gneisses, mylonites; 6 — Gierałtów Gneisses: gneisses and migmatites; 7 — granulites and eclogites; 8 — granitoids; 9 — Branne unit: metasedimentary & metavolcanic rocks; 10 — Velké Vbrno unit: metasedimentary & metavolcanic rocks; 11 — Variscan granites

The Śnieżnik Massif represents third highest mountain range (after the Karkonosze and the Hrubý Jesenik) in the Sudetes, with centrally located Mt. Śnieżnik (1425 m a.s.l.) forming a topographical junction for spatially dispersed mountain ridges. Protruding to the NW Czarna Góra ridge (1205 m a.s.l.) is bounded by 200–300 high morphological scarp extending southward along the line of Idzików — Marianówka — Nowa Wieś — Gaworów — Pisary — Červený Brook (western front), Vojtiškov — Hynčice — Stříbrnice scarp to the east, and Dziczy ridge — Kamienica and Morawka valleys to the north (Fig. 3b, inset A).

The most prominent geomorphological features refer to wide valleys of the Biała Lądecka and Nysa Kłodzka rivers, sourced with the local material. The Śnieżnik Massif landscape evolution has been described by many authors, thoroughly summarized by P. Migoń (1997). W. Walczak (1968) tended to explain high-elevated flat surfaces across the Sudetes as the morphological features survived as residuum of so-called Palaeogene planation surface. He argued that this gently undulated landscape has been created during the 40 million years long period of tectonic stability (e.g. Klimaszewski 1958). He postulated in the Śnieżnik Massif area a several planation surfaces manifesting from ca.1100–1200 m a.s.l. (upper horizon) to about 700–800 m a.s.l. (lower horizon), which should be formed during the Oligocene tectonic movements (Walczak 1968). In a different manner, A. Jahn (1980) likely inspired by O. Jessen (1938), suggested post-Cretaceous climatically driven morphological evolution of the Sudetes, with three levels of planar units: Upper Palaeogene (highest summits), Oligocene and Lower Miocene. Nevertheless he linked Oligocene-Neogene fluvial processes intensification with active tectonics recorded by thick sedimentary profiles in the Fore-Sudetic Block. Otherwise J. Don (1989) distinguished in the Upper Nysa Kłodzka Graben six planation levels (Palaeocene to Pleistocene in age), suggesting strongly correlation with the tectonic activity phases across the Bohemian Massif (Don, Opletal 1997). P. Migoń (1997) advocated Palaeogene origin of the Śnieżnik Massif relief, pointing out existence of at least two coeval (not younger than the Miocene) planation levels (upper level 1000–1300 m a.s.l.; lower level 820–994 m a.s.l.), which were tectonically dislocated resulting in observed hypsometric discordance. Furthermore, he linked younger foot slope planation surface development with the final phase of enhanced Neogene fluvial erosion. General geomorphological setting of the study area is even more complicated due to dense pattern of faults, many of which (i.e. the Wilkanów fault, Ranoszek 1998; Badura et al. 2003b, 2005b; the Sudetic Marginal Fault, Badura et al. 2003a) might be correlated with inherency of significant morphological features (Oberc 1972). Last but not least, bedrock structural properties (i.e. bedding, foliation, rock mass strength) were likewise indicated as possible driving factors for the landscape evolution (Oberc 1955; Lorenc 1987).

GEOLOGICAL SETTING

Geologically research area is located in the central-east part of the Sudetic Block (Żelaźniewicz, Aleksandrowski 2008) with centrally-located the Orlica — Śnieżnik Dome (OSD).This structural unit is built of Cambrian (granitic protolith age ca. 490–520 Ma; Turniak et al. 2000) orthogneisses (the Gierałtów and Śnieżnik Formation) intercalated with small lenses of ultra-high pressure rocks (granulites and eclogites). Crystalline basement is mantled with supracrustal low-medium and high-grade metamorphic rocks (Kasza 1964; Don 1989; Chopin et al. 2012). Metasedimentary and metavolcanic rocks comprise two separate units represented by Stronie (greywackes, paragneisses) and Młynowiec varieties (mica schists, marbles, amphibolites, paragneisses), dated back to Neoproterozoic and Late Cambrian-Ordovician times, respectively (Jastrzębski et al. 2010; Mazur et al. 2012). Crystalline basement is included in several alternating synforms and antiforms, exposed e.g. in the Biała Lądecka basin headwater (Fig. 2 and Fig. 5).

To the northwest, metamorphic rocks abut upon the Carboniferous Kłodzko — Złoty Stok Granitoid Massif and the Bardo Unit. The latter consists of Upper Devonian limestones and Early Carboniferous flysch greywackes and siltstones overlain by wildflysch deposits (Wajsprych 1978). Also to the northeast, the OSD is limited by Variscan granites, cropping out as the Žulova pluton. To the southeast, the OSD is bounded by the Staré Město Unit, built mostly of high-grade metasedimentary rocks, amphibolites and metagabbros, which contact through system of thrusts sheets with the East Sudetic structural units.

The OSD crystalline basement is covered locally by the Late Cretaceous succession of shallow marine marls, siltstones and sandstones that fill the Upper Nysa Kłodzka Graben (Wojewoda 1997) to the west of the Śnieżnik Massif. Post-Mesozoic sediments are rather sparse and include, among others, spot-like occurrences of Pliocene fluvial sediments (e.g. Jahn et al. 1984) and alkaline basaltoid extrusions, whose origin is ascribed to Miocene-Pliocene to Quaternary tectonic uplift of the Bohemian Massif (Scheck et al. 2002) and well constrained with geochronological methods (K-Ar: Birkenmajer et al. 2002a, b; Badura et al. 2005a, 2006). During the Pleistocene Scandinavian ice-sheet advanced into the Eastern Sudetes, a deposition of glacial and glaciofluvial sediments took place (Badura, Przybylski 1998), remnants of which are preserved in the Bardzkie Mts. and the Upper Nysa Kłodzka Graben. Quaternary vertical displacements in the range of tens of meters have been recorded within the UNKG (Badura, Rauch 2014) and the Sudetic Marginal Fault (Badura et al. 2003a), which are the tectonic features best expressed in the present-day topography. The latter one was reported to be active ca. 11 ka BP acting as the reverse fault, reactivated next as a normal fault during the early Holocene (Štěpančíková et al. 2010).

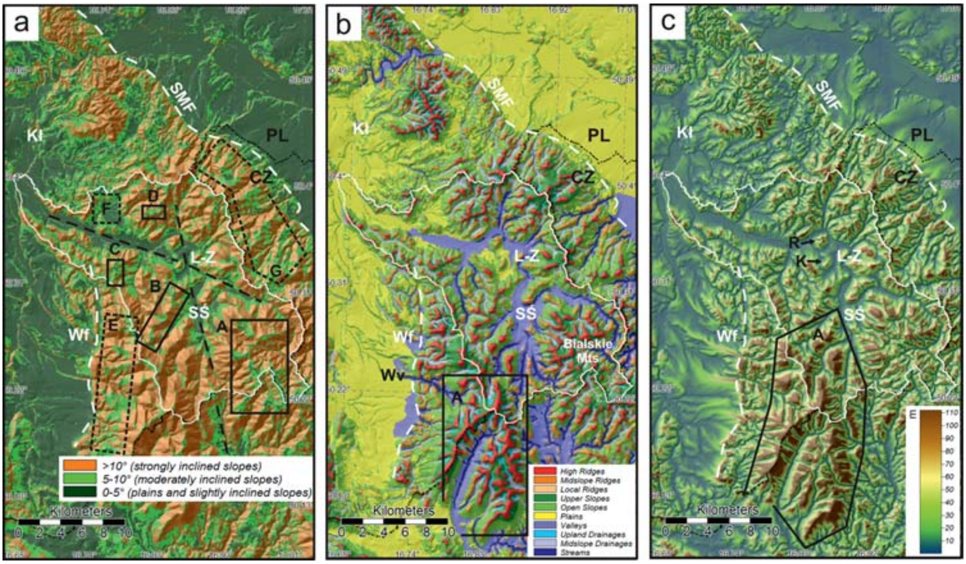

Fig. 3. Geomorphometry of the Śnieżnik Massif: (a) slope, (b) landforms, (c) slope height, Abbreviations used on maps: K — Mt. Kierznia, Kł — Kłodzko, L-Z — Lądek-Zdrój, R — Mt. Radoszka, SMF — Sudetic Marginal Fault, SŚ — Stronie Śląskie, Wf — Wilkanów fault, Wv — Wilczka valley. White line is mimicking the Biała Lądecka basin

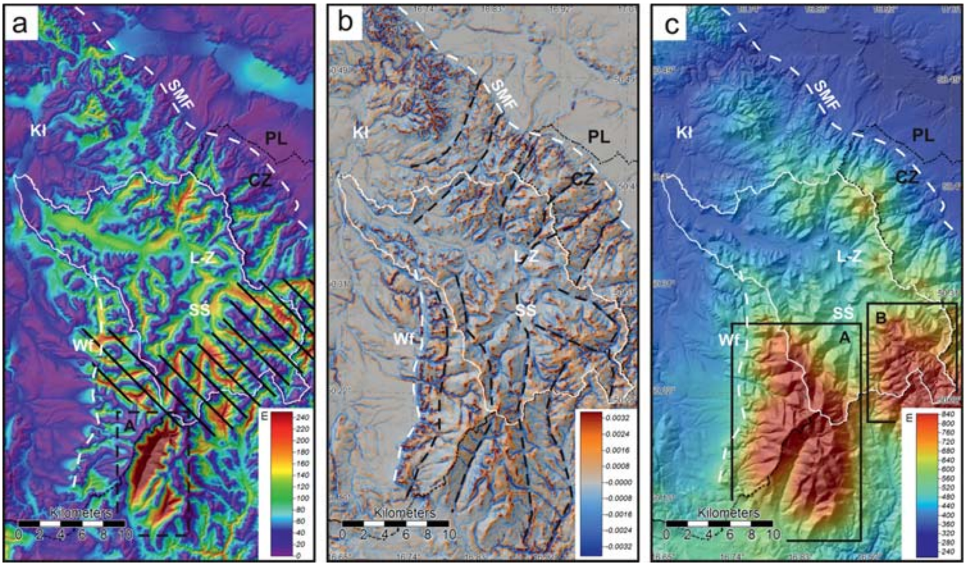

Fig. 4. Geomorphometry of the Śnieżnik Massif: (a) valley depth, (b) longitudinal curvature, (c) channel network base level. Abbreviations used on maps: Kł — Kłodzko, L-Z — Lądek-Zdrój, SMF — Sudetic Marginal Fault, SŚ — Stronie Śląskie, Wf — Wilkanów fault. White line is mimicking the Biała Lądecka basin

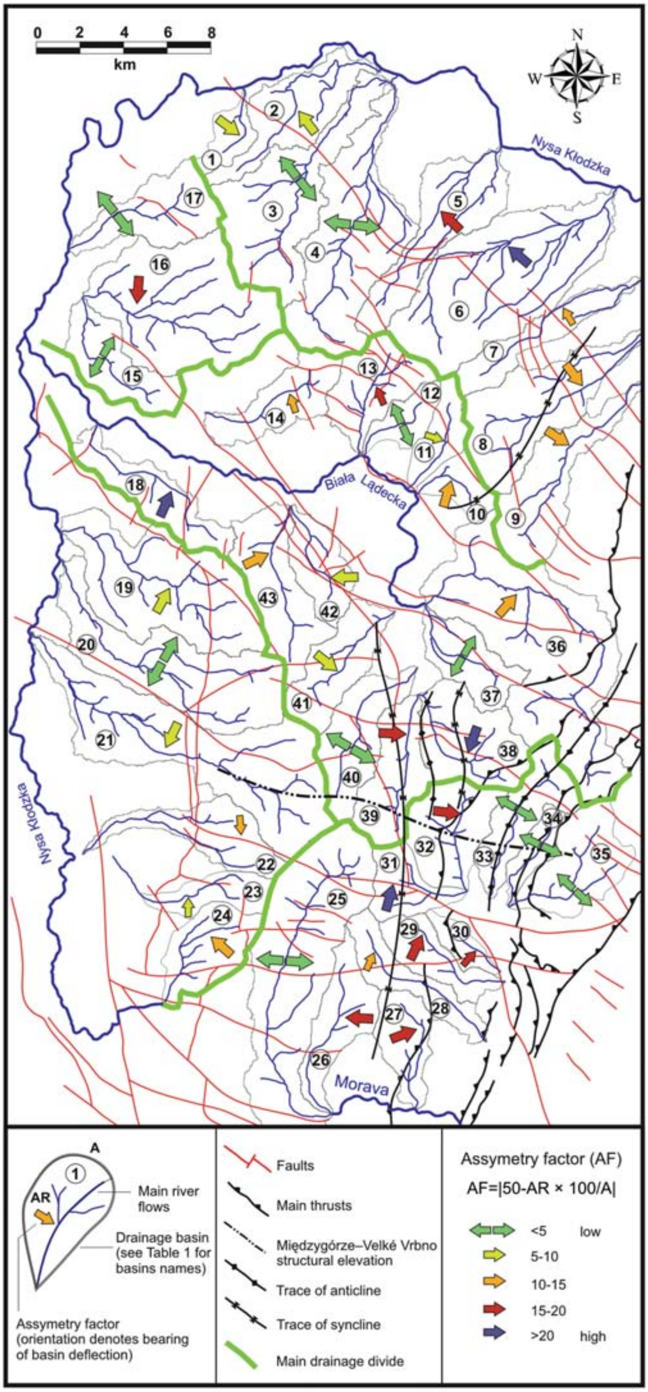

Fig. 5. Distribution of asymmetry factor (AF) parameter and main structural data (faults, folds and thrusts) superimposed

MATERIALS AND METHODS

In this work, we applied a GIS-based analysis of digital elevation model (DEM) for study both Polish and Czech part of the East Sudetes. 1-m resolution (bare ground type) LiDAR DEM data originating from airborne laser scanning (ASL) are available only for the Polish Sudetes. To overcome this problem we have re-interpolated LiDAR data to 30-m resolution sections, which next were combined with 30-m DTED-2 DEM data available for the Czech Sudetes. In the beginning drainage network and watershed boundaries were extracted from DEM by applying D-8 pour flow algorithm (O'Callaghan, Mark 1984) with 10-m sampling resolution. We distinguished 43 basins representing key geomorphological sites across study area. Next, using classic geomorphometric tools available in SAGA GIS software we characterized topography of the East Sudetes. Moreover, application of morphotectonic parameters allowed analysing topographic expressions of recent tectonic movements, which significantly affected relief evolution during the Late Cenozoic.

DEM-based automatic parameterization of the relief helps to better elucidate and emphasize characteristic morphological patterns describing local landscape properties. We analysed DEM data by applying following primary and secondary land-surface parameters in SAGA GIS software (see 'results' for each parameter description): slope, landforms, slope height, valley depth, longitudinal curvature and channel network base level (Cimmery 2007; Olaya 2009; Olaya, Conrad 2009).

Morphotectonic properties of the river basins (i.e. Zuchiewicz 1980) were examined by DEM data analysis in GIS environment. For 43 selected basins (see Table 1) we performed calculation for each basin a following geomorphometry parameters: basin area, right-side basin area, total basin length, elevation and slope characteristics. Next morphometric derivatives were calculated, which are useful tools in identification areas of active tectonics (i.e. Badura et al. 2003a; Pérez-Peña et al. 2010; Matoš et al. 2014): basin elongation ratio (Re); form ratio (Rf); circulatory ratio (Rk); lemniscate coefficient (k); hypsometric integral (HI); asymmetry factor (AF). Furthermore to discriminate possible interactions between fault-block tectonics and/or bedrock structural properties controlling basin evolution, we constrained basins asymmetry factor with field data extracted from geological maps (e.g. Don et al. 2003; Cymerman 2004).

RESULTS AND DISCUSSION

GEOMORPHIC INDICES

SLOPE

Slope inclination values were calculated with nine parameters second order polynomial method described by L. W. Zevenberger and C. R. Thorne (1987) resulting in 3 classes: 0–5°, 5–10° and over 10° (Fig. 3a). Relatively least

Table 1

Drainage basins geomorphometric parameters from the East Sudetes. L — maximum basin length; LR — local relief; Re — basin elongation ratio; Rf — form ratio; Rk — circulatory ratio; k — lemniscate coefficient; HI — hypsometric integral; AF — asymmetry factor; see text for parameters' details. Abbreviations used: (p.) *potok* — brook, (gr) *górny* — upper part, (bn) *bez nazwy* — no name.

No.	Drainage basin	Area [km^2]	L [km]	Elevation [m]		Slope [°]		LR [m]	Re	Rf	Rk	k	HI	AF
				min.	max.	max.	avg.							
1	bn1-Bardo	4.97	16.40	259.0	669.0	35.90	19.69	449.0	0.15	0.02	0.46	42.48	0.46	6.54
2	Jasioniec	16.68	9.40	239.0	748.0	35.96	6.39	321.0	0.49	0.19	0.17	4.16	0.16	7.13
3	Gruda	30.41	11.45	240.0	765.0	35.89	8.65	419.0	0.54	0.23	0.15	3.38	0.34	4.92
4	Mąkolna	35.20	12.55	240.0	871.0	34.51	8.52	432.0	0.53	0.22	0.17	3.51	0.30	3.24
5	Złoty p.	20.50	10.60	228.0	871.0	49.59	7.03	363.0	0.48	0.18	0.20	4.30	0.21	16.34
6	bn2-Cz	45.02	11.85	218.0	900.0	33.87	6.81	401.0	0.64	0.32	0.31	2.45	0.27	20.46
7	Hostický p.	10.86	9.81	240.0	875.0	32.62	8.45	464.0	0.38	0.11	0.15	6.96	0.35	12.71
8	Javornik	24.97	10.12	253.0	848.0	34.20	10.49	512.0	0.56	0.24	0.26	3.22	0.44	12.23
9	Rači p.	18.86	10.15	266.0	851.0	41.10	11.03	566.0	0.48	0.18	0.21	4.29	0.51	10.83
10	Karpowski p.	5.73	3.73	437.0	849.0	41.70	11.61	635.0	0.72	0.41	0.61	1.91	0.48	11.95
11	Lutynia	7.10	5.75	431.0	899.0	35.96	12.18	634.0	0.52	0.21	0.49	3.66	0.43	6.90
12	Borówkowy	5.94	4.98	409.0	887.0	27.60	13.35	616.0	0.55	0.24	0.48	3.28	0.43	3.20
13	Orliczka	13.73	4.98	405.0	872.0	31.02	12.64	405.0	0.84	0.55	0.30	1.42	0.42	15.11
14	Skrzynczana	12.54	6.64	371.0	730.0	32.38	10.55	541.0	0.60	0.28	0.23	2.76	0.47	13.00
15	bn3-Kł. 1	13.56	6.77	297.0	550.0	24.56	5.63	369.0	0.61	0.30	0.26	2.65	0.28	3.24
16	bn4-Kł. 2	39.16	39.74	297.0	747.0	30.78	7.37	419.0	0.77	0.46	0.31	1.70	0.27	15.37
17	Jodłownik	15.20	7.30	286.0	760.0	35.83	11.46	465.0	0.60	0.29	0.27	2.75	0.38	2.50
18	Piotrówka	14.10	8.68	324.0	649.0	35.23	10.00	466.0	0.49	0.19	0.17	4.19	0.44	20.92
19	Równica	36.12	4.15	324.0	964.0	35.37	9.21	502.0	0.63	0.31	0.27	2.55	0.28	7.67
20	Pławna	32.50	11.92	330.0	1203.0	38.82	8.82	585.0	0.54	0.23	0.20	3.43	0.29	0.83
21	Wilczka	46.91	16.47	345.0	1369.0	40.90	10.48	700.0	0.47	0.17	0.18	4.54	0.35	8.77
22	Nowinka	13.95	5.63	406.0	1319.0	43.91	9.86	729.0	0.75	0.44	0.90	1.78	0.35	10.57
23	Goworówka	7.77	6.27	481.0	1215.0	35.38	12.55	804.0	0.50	0.20	0.42	3.97	0.44	6.37
24	Nysa Kł. (gr)	13.24	6.30	545.0	1151.0	38.26	10.79	765.0	0.65	0.33	0.62	2.35	0.36	11.18
25	Morava	45.53	13.46	517.0	1423.0	39.11	13.46	863.0	0.57	0.25	0.25	3.12	0.38	1.97
26	Malá Morava	13.00	8.57	517.0	1304.0	33.92	12.46	863.0	0.47	0.18	0.22	4.43	0.44	15.62
27	Zelený	9.71	5.54	438.0	1094.0	35.04	12.91	722.0	0.63	0.32	0.35	2.48	0.43	16.01
28	Prudký	10.92	8.37	437.0	1305.0	39.17	13.13	873.0	0.45	0.16	0.18	5.04	0.50	11.08
29	Chrastický	9.45	6.32	491.0	1242.0	29.98	12.18	750.0	0.55	0.24	0.26	3.32	0.34	18.25
30	Štěpánovský	3.91	4.33	496.0	861.0	18.25	9.61	616.0	0.52	0.21	0.49	3.76	0.33	18.80
31	Střibnik	8.56	4.96	566.0	1319.0	36.38	16.85	919.0	0.70	0.39	0.55	2.02	0.47	23.36
32	Krupá (gr)	15.39	5.11	566.0	975.00	31.30	11.41	765.0	0.87	0.59	0.70	1.33	0.49	17.32
33	Kuncicky	13.48	7.95	547.0	1106.0	32.60	12.16	875.0	0.52	0.21	0.20	3.68	0.59	4.15
34	Bistřina	4.93	5.04	552.0	1033.0	27.14	13.29	814.0	0.50	0.19	0.42	4.04	0.54	3.75
35	Vrberský	16.12	6.74	549.0	1121.0	33.81	13.84	811.0	0.67	0.35	0.59	2.21	0.46	2.85
36	Biała Lądecka	54.23	12.14	500.0	1122.0	36.73	12.90	806.0	0.68	0.37	0.19	2.13	0.49	13.93
37	Młynowiec	11.20	5.64	502.0	1072.0	33.12	14.44	789.0	0.55	0.24	0.29	3.31	0.50	0.36
38	Morawka	17.88	6.26	558.0	1067.0	35.73	14.88	823.0	0.76	0.46	0.46	1.72	0.52	20.81
39	Kamienica	14.50	7.18	558.0	1418.0	34.87	16.09	881.0	0.60	0.28	0.32	2.79	0.38	16.41
40	Kleśnica	15.10	7.95	532.0	1423.0	43.83	16.21	881.0	0.55	0.24	0.27	3.29	0.39	0.33
41	Sienna Woda	13.89	5.08	492.0	1203.0	40.62	12.60	760.0	0.83	0.54	0.28	1.46	0.38	7.67
42	Rudy p.	9.89	5.90	390.0	793.0	26.37	11.66	563.0	0.60	0.28	0.34	2.76	0.43	5.11
43	Konradka	18.50	8.67	389.0	1087.0	38.59	12.30	619.0	0.56	0.25	0.23	3.19	0.33	10.81

steep areas were classified as flat ones in valleyside, slope, pass and summit position respectively. Prevailing valleyside flat areas (dashed line, Fig. 4a) are observed along the Biała Lądecka river as well as the NNW-SSE trending valleys of Orliczka (the Biała Lądecka right tributary) and Morawka (the Biała Lądecka left tributary), extending further to the south within the Morava valley. Also, valleyside flat surface double-junction point is located nearby river gorge of Lądek-Zdrój. Dominant summit flat surface might be delineated in the Bialskie Mts. range ca.1000 m a.s.l. (Fig. 3a — A), along the Wapniarka hill ca. 530 m a.s.l. (Fig. 3a — B), the Bielica massif ca. 530 m a.s.l. (Fig. 3a — C) and the Sosina hill 550 m a.s.l. (Fig. 3a — D). Flat slope surface areas are typical for the Wilkanów fault (E) morphological scarp to the E from the axial part of the Upper Nysa Kłodzka Graben (Fig. 3a — E), to the north from the Ołdrzychowice site and the Bukówka summit (Fig. 3a — F), and from the hanging wall of the Sudetic Marginal Fault (Fig. 3a — G).

LANDFORMS

Topography Position Index (TPI) based on landforms classification within SAGA GIS software for automatic recognition of landscape evolution trends (Guisan et al. 1999) by analyzing two models of surface curvature. There is considerable difference between wide flat-floored downstream valleys (e.g. the Biała Lądecka mouth, Stronie Śląskie area) and colluvial moderately steep V-shaped valleys in the headwater area of the Śnieżnik Massif. In the region of the Wilkanów Fault (W) and the Sudetic Marginal Fault (NE) intensively dissected relief might be observed. Long-wave highly-elevated ridges are almost solely typical for the Śnieżnik summit vicinity (Fig. 3b), being represented by N trending Żmijowiec-Czarna Góra ridgeline, W trending Mały Śnieżnik and S trending Králický Sněžník ridgelines.

SLOPE HEIGHT

This parameter is based on the relative difference between valley floor and hillslope position, with a drainage network necessary for statistics (Boehner, Conrad 2008; Boehner, Antonić 2009). Most remarkable relief contrasts, in some part over 100 m, are typical for the central part of the Orlica-Śnieżnik Dome, as well as in the Wilkanów fault and the Sudetic Marginal Fault areas. Lowermost parameter results are observed in the wide segment of the Biała Lądecka basin and culminations of the Radoszka (565 m a.s.l.) and the Kierzna hills (570 m a.s.l.).

VALLEY DEPTH

Value used for calculation a total valley incision (Fig. 4a) set up for discrimination areas characterized by over deepened topography. Dashed lines on fig. 3d roughly visualize its lateral extent, cumulating almost entirely in the northern slopes (Poland). From the southern slopes (Czech) the Morava and the Malá Morava basins are the only exceptions, with a valley depth exceeding 240 m.

LONGITUDINAL CURVATURE

This index depicts lineaments manifesting in the relief; however it must be admitted that high-resolution DEM image might be a matter of debate in this case due to unknown error source. On the map (Fig. 4b) high values of curvature correlate with ridgelines strike, lowermost with valleys axis respectively. In the central part of the Biała Lądecka river values tend to reach 0, which reflects no topography change. Some of the most important valley-elongated features in watershed transgressive positions are highlighted with dashed lines on figure 4b.

CHANNEL NETWORK BASE LEVEL

Parameter known also as 'altitude above channel network' or 'vertical distance to channel network', is the difference between the DEM and a surface interpolated from the channel network (C o n r a d 2005). In this meaning it reflects absolute altitude and compactness of the relief. In the study area two individual blocks emerged, namely, the Śnieżnik Massif (A on Fig. 4c) and the Bialskie Mts. (B), constitute local centres of high relief.

MORPHOTECTONIC DATA

To identify areas of increased tectonic activity within the Śnieżnik Massif area we propose combined approach linking geological data with DEM-based morphotectonic study. This approach brings out considering possible interactions between geological factors and local slopes variability controlling basin morphology. Morphometric results are presented in table 1.

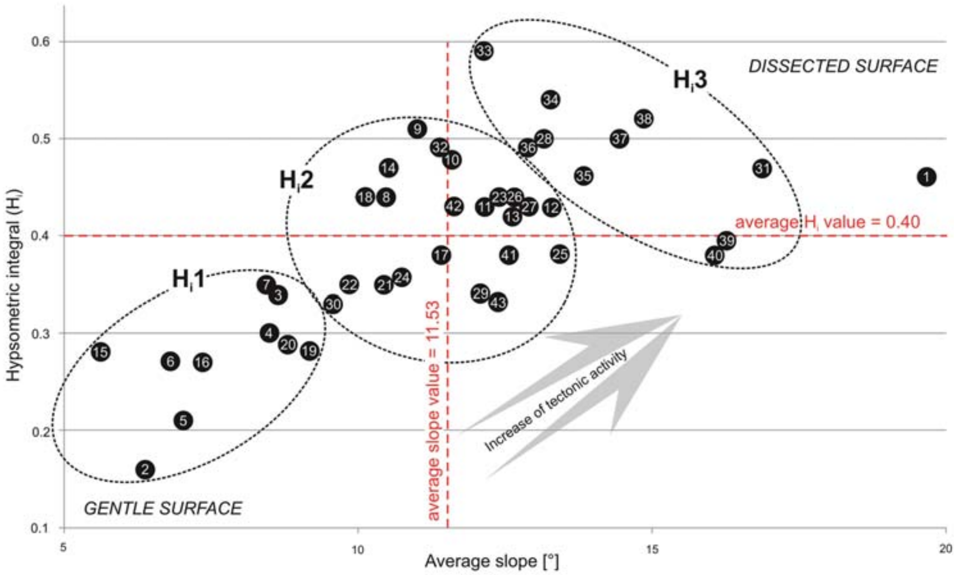

Fig. 6. Scatter plot of hypsometric integral (H_i) vs. average slope

BASIN MORPHOLOGY

Average slope angles analysed for the 43 basins varied between 5.63° and 19.69° respectively, with a mean value of 11.53°. Steepest slopes are observed within a rock complexes built of crystalline rocks, e.g. gneisses from the Gierałtów Formation (Kleśnica, Karpowski Potok) and in the fault strike perpendicularly oriented basins e.g. the Wilkanów fault — Wilczka, Nowinka, the Sudetic Marginal Fault — Złoty Potok. There are observed rapid slope brakes toward the Upper Nysa Kłodzka Graben, the Biała Lądecka valley and the Fore-Sudetic Block (Fig. 1).

HYPSOMETRIC INTEGRAL

Hypsometric integral parameter (Fig. 6) with values close to the 0 depicts tectonically inactive areas typical for matured landscapes, whereas 1 trending values are believed to express actively uplifted terrains (see Strahler 1952; Pérez-Peña et al. 2010; Matoš et al. 2014).We computed basins H_i values with following methodology:

$$H_i = (H_{mean} - H_{min}) / (H_{max} - H_{min})$$

where: H_{mean} — average height values in the drainage area; H_{min} and H_{max} — minimum and maximum elevation in the drainage area.

Hypsometric integral analysis was performed according to methodology proposed by Z. Ruszkiczay-Rüdiger et al. (2009), and final H_i values are summarized on figure 6. Above mentioned authors concluded, that hypsometric integral (H_i) values plotted against average slope result in recognition of subsided and uplifted areas. Hence, we distinguished three groups of H_i values resembling similar properties; nevertheless not all basins might be straightforward classified, which is for example the case of basin no. 1 (Bardo Unit). H_i results are in the range of 0.16 to 0.59 (arithmetic mean 0.40), whereas slope values in the range of 5.69 to 19.69 (arithmetic mean 11.53) respectively.

First group (H_i1) should contain basins characterized with gently undulated topography, which is generally true in case of streams no. 15, 16, 19 and 20, located in within the Upper Nysa Kłodzka Graben. On the other hand, to this group belong also basins from no. 2 to 7, however they developed perpendicularly to morphological scarp of the Sudetic Marginal Fault, for which Pleistocene/Holocene activity has been documented (Štěpančiková et al. 2010). In this case, obtained dataset might be explained with hypsometric data distribution, which expresses low-angled areas widespread in the hanging wall of the SMF.

The largest number of basins belong to group H_i2, thus representing moderate H_i and slope values (ca. 0.3–0.5 and 9.5–13.5, respectively), being a transient and/or mixed type basins. Streams no. 8 and 9 represent fluvial systems draining to the NE of the Sudetic Marginal Fault, however far less influenced than H_i1 by hanging wall topography and of linear, elongated water divides. To H_i2 group belong also streams no. 21 to 24 draining through the Wilkanów fault (e.g. Wilczka, Nowinka) in the UNKG area. Basins no. 8 to 14 highlight existence of the Złote Mts. fault block, bounded to the northeast by the Sudetic Marginal Fault and to the south by WNW-ESE trending Lądek-Zdrój — Gierałtów fault zone system. It brings us to the conclusion that both, fault-related morphological scarps as well as wide depression of the Biała Lądecka valley represent the Late Cenozoic tectonically active areas controlling basins' evolution. Additionally, what makes this interpretation even stronger, all streams described above flow consequently, parallel to dip direction (foliation) and/or bedding within sedimentary rocks, passing perpendicularly through bedrock structural boundaries. Last special case within H_i2 group is represented by basin no. 25 (Morava), wherein long V-shaped valley ended with fault-related headwater zone results in low $H_i = 0.39$. Obtained H_i value contrasts with definitely higher average slope value (13.46), being more typical for H_i3 type river basins. We interpret this unusual situation as a consequence of the central Śnieżnik Massif uplift along south-located fault zone. We come back later to this issue discussing asymmetry factor results.

Data set values for H_i3 vary from 0.38 to 0.59 and from 12.16 to 16.85 for H_i and average slope respectively. This group represents basins located in the central part of the Śnieżnik Massif and the Bialskie Mts. Structural data analysis (Don et al. 2003) exposed, that basins no. 33, 38, 39 reflect fold-axis (syn- or antiform) elongated orientation, controlling their evolution. However, it cannot be unequivocally precluded, that tectonic stress states have been relaxed along Palaeozoic folds, acting during Cenozoic times as local weakness zones.

BASIN ASYMMETRY

Already R. E. Cox (1998), who introduced transverse topographic symmetry factor, observed that basin morphology might be a useful diagnostic tool in the analysis of tilted tectonic blocks. To indentify this component in uplift and tectonic exhumation, we applied a basin asymmetry factor following the methodology proposed by Pérez-Peña et al. (2010):

$$AF = AR/A \times 100$$

Where: AF — asymmetry factor; AR — right side area of the drainage basin; A — total drainage basin area. Results over or below 50 allow to recognize basin asymmetry.

Next, we standardized AF parameter (Pérez-Peña et al. 2010) following the procedure:

$$AF = |50 - AR \times 100/A|.$$

According to AF results, basins are quantified (Table 1 and Fig. 5) as symmetrical (<5), gently asymmetric (5–10), moderate asymmetric (10–15), strongly asymmetric (15–20) and extreme asymmetric (>20). The latter interval is our modification from the original proposition, to emphasize the most deflated watersheds. AF

results range from 0.33 to 23.36, with mean arithmetic value of 10.25, which reveals that most of the basins are moderately asymmetric. Colour-coded arrows (Fig. 5) for asymmetry factor replicate strike (vector axis) perpendicularly toward average azimuth of basin orientation, which improve large-scale data analysis.

Basin asymmetry analysis in the southern termination of the Śnieżnik Massif suggests occurrence of the northward tilted fault block. It is best expressed by consequent basin asymmetry distribution toward N-NE sectors and strongly deepened Morava valley (Fig. 5, basin no. 25), with 8-km long V-shaped valley floor end up with NW-SE fault-controlled steep and small source area. Neighbourhood valleys of the Malá Morava and the Zelený brook are mimicking same patter. Gradually uplift sloping to the NW might be observed, as confirmed by local *AF* variability within basins no. 23, 24 and 25. We interpret NE-SW striking the Wilkanów fault and horizontally to sub-horizontally (WNW-ESE) striking the Potoczek-Branna, the Heřmanice and the Pisary faults as the important zones controlling fault-block uplift and tilting. Method efficiency is confirmed also in case of basin no. 18 (Piotrówka), which is controlled by young (Pliocene-Pleistocene) uplift and watershed divide migration, interpreted from allochthonous sediments found in the Przy Torach cave (Rogala et al. 1998). AF analysis in the central and northern sectors revealed existence of an antecedent valley gorge nearby Lądek-Zdrój. It was formed by braking through the local syn- and anticline ridges (e.g. the Dzielec hill), uplifted alongside NE-SW striking Lądek-Zdrój fault and NW-SE striking Lądek-Zdrój — Gierałtów fault zone. We conclude that the Złote Mts. represent a second important fault block, which is separated from the Śnieżnik Massif to the south, by fault system of Lądek-Zdrój area.

CONCLUSIONS

Intensification of tectonic processes during the Cenozoic times (Reichert-er et al. 2008) as expressed by volcanic activity in the Bohemian Massif (Ulrych et al. 2011) with local centres within study area (vicinity of the Lądek-Zdrój), suggest that modern landscape morphology might have originated in Miocene times (20–25 Ma). As mentioned by S. Dyjor (1975), tectonic uplift of the Śnieżnik Massif reached amplitude of 500–1000 m and started as early as during the Oligocene, with its climax in the Pliocene. Presented here morphotectonic analyses suggest, that the Śnieżnik Massif relief originated by braking and uplift of the Palaeogene planation surface realized through tilted fault blocks. Proposed approach, which combines traditional DEM-based morphometrical analysis with structural geology data, allows characterizing the Late Cenozoic fault-block tectonics, which controlled present-day topography evolution. Basin asymmetry factor analysis juxtaposed with faults orientation, strike and dip of bedding and foliation as well as folds axis, resulted in the identification of dominant driving forces in neotectonic regime. However in case of the East Sudetes, which present a mosaic of geological setting, tectonic processes and erosional history superimposed, above mentioned analyses tend to be at least complicated. We emphasize that proposed methodology of H_i vs. slope analysis might be of ambiguous meaning if done unequivocally and without referring to structural geology, especially dealing with apparently incoherent environments.

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REFERENCES

Badura J., Przybylski B., 1998. *Zasięg lądolodów plejstoceńskich i deglacjacja obszaru między Sudetami a Wałem Śląskim*. Biuletyn Państwowego Instytutu Geologicznego 385, 9–28.

Badura J., Zuchiewicz W., Górecki A., Sroka W., Przybylski B., 2003a. *Morfometria strefy sudeckiego uskoku brzeżnego między Złotym Stokiem a Dobromierzem*. Przegląd Geologiczny 51, 12, 1048–1057.

Badura J., Jamroz O., Zuchiewicz W., 2003b. *Recent crustal mobility of the Upper Nysa Kłodzka graben, SW Poland*. Acta Montana, ser. A 24, 65–71.

Badura J., Pécskay Z., Koszowska E., Wolska A., Zuchiewicz W., Przybylski B., 2005a. *New age and petrological constraints on Lower Silesian basaltoids, SW Poland*. Acta Geodynamica et Geomaterialia 2, 3, 7–15.

Badura J., Przybylski B., Zuchiewicz W., Farbisz J., Sroka W., Jamroz O., 2005b. *Tektonika rowu górnej Nysy Kłodzkiej — sporne problem — dyskusja*. Przegląd Geologiczny 53, 3, 206–211.

Badura J., Pécskay Z., Koszowska E., Wolska A., Zuchiewicz W., Przybylski B., 2006. *Nowe dane o wieku i petrologii kenozoicznych bazaltoidów dolnośląskich*. Przegląd Geologiczny 54, 2, 145–153.

Badura J., Rauch M., 2014. *Tectonics of the Upper Nysa Kłodzka Graben, the Sudetes*. Geologia Sudetica 42, 137–148.

Birkenmajer K., Pécskay Z., Grabowski J., Lorenc M.W., Zagożdżon P.P., 2002a. *Radiometric dating of the tertiary volcanics in Lower Silesia, Poland. II. K-Ar and palaeomagnetic data from Neogene basanites near Lądek Zdrój, Sudetes Mts*. Annales Societatis Geologorum Poloniae 72, 119–129.

Birkenmajer K., Pécskay Z., Grabowski J., Lorenc M.W., Zagożdżon P.P., 2002b. Radiometric dating of the tertiary volcanics in Lower Silesia, Poland. V. K-ar and palaeomagnetic data from late Oligocene to early Miocene basaltic rocks of the North-Sudetic depression, Annales Societatis Geologorum Poloniae 77, 1–16.

Böhner J., Antonić O., 2009. *Land surface parameters specific to topo-climatology*. [in:] *Geomorphometry. Concepts, Software, Applications*. T. Hengl, H.I. Reuter (eds.), Developments in Soil Science 33, 195–226.

Böhner J., Conrad O., 2008. Relative Heights and Slope Positions, SAGA help, ftp://ftp.polito.it/people/fiermonte/PLUGINS/OLD_0/sextante/saga/help/RelativeHeightsandSlopePositions.html

Cimmery V., 2007. *User guide for SAGA* (version 2.0), 380 pp.

Chopin F., Schulmann K., Skrzypek E., Lehmann J., Dujardin J.R., Martelat J.E., Lexa O., Corsini M., Edel J.B., Štipska P., Pitra P., 2012. *Crustal influx, indentation, ductile thinning and gravity redistribution in a continental wedge: Building a Moldanubian mantled gneiss dome with underthrust Saxothuringian material (European Variscan belt)*. Tectonics, doi:10.1029/2011TC002951.

Conrad O., 2005. *Module Basic Terrain Analysis, SAGA-GIS Module Library Documentation (v2.1.3)*. http://www.saga-gis.org/saga_module_doc/2.1.3/ta_compound_0.html.

Cox R.E., 1998. *Analysis of drainage-basin symmetry as a rapid technique to identify areas of possible Quaternary tilt-block tectonics: An example from the Mississippi Embayment*. Geological Society of America Bulletin 106, 5, 571–581.

Cymerman Z., 2004. *Tectonic map of the Sudetes and the Fore-Sudetic Block, 1:200 000*. Państwowy Instytut Geologiczny, Warszawa.

Don J., 1989. *Jaskinia na tle ewolucji geologicznej Masywu Śnieżnika*. [in:] *Jaskinia Niedźwiedzia w Kletnie. Badania i udostępnianie*. A. Jahn, S. Kozłowski, T. Wiszniowska (eds.), Ossolineum, Wrocław, 58–79.

Don J., 1996. *The Late Cretaceous Nysa Graben: implications for Mesozoic-Cenozoic fault-block tectonics of the Sudetes*. Zeitschrift für geologische Wissenschaften 24, 317–324.

Don J., Opletal M., 1997. *Budowa i ewolucja geologiczna Masywu Śnieżnika*. [in:] *Masyw Śnieżnika — zmiany w środowisku przyrodniczym*. A. Jahn, S. Kozłowski (eds.), Polska Agencja Ekologiczna SA, Warszawa, 13–26.

Don J., Skácel J., Gotowała R., 2003. *The boundary zone of the East and West Sudetes on the 1:50 000 scale geological map of the Velké Vrbno, Staré Město and Śnieżnik Metamorphic Units*. Geologia Sudetica 35, 1, 25–59.

Dyjor S., 1975. *Młodotrzeciorzędowe ruchy tektoniczne w Sudetach i na bloku przedsudeckim*. [in:] *Współczesne i neotektoniczne ruchy skorupy ziemskiej w Polsce*. Tom 1, J. Liszkowski, J. Stochlak (eds.), Wydawnictwa Geologiczne, Warszawa, 121–132.

Guisan A., Weiss S.B., Weiss A.D., 1999. *GLM versus CCA spatial modeling of plant species distribution*. Plant Ecology 143, 107–122.

Jahn A., 1980. *Główne cechy i wiek rzeźby Sudetów*. Czasopismo Geograficzne 51, 2, 129–154.

Jahn A., Łańcucka-Środoniowa M., Sadowska A., 1984. *Stanowisko utworów plioceńskich w Kotlinie Kłodzkiej*. Geologia Sudetica 18, 2, 7–44.

Jastrzębski M., Żelaźniewicz A., Nowak I., Murtezi M., Larionov A., 2010. *Protolith age and provenance of metasedimentary rocks in Variscan allochthon units: U–Pb SHRIMP zircon data from the Orlica-Śnieżnik Dome, West Sudetes*. Geological Magazine 147, 416–433.

Jessen O., 1938. *Tertiärklima und Mittelgebirgsmorphologie*. Zeitschrift der Gesellschaft für Erdkunde zu Berlin 1–2, 36–48.

Kasza L., 1964. *Budowa geologiczna górnego dorzecza Białej Lądeckiej*. Geologia Sudetica 1, 119–162.

Klimaszewski M., 1958. *Rozwój geomorfologiczny terytorium Polski w okresie przedczwartorzędowym*. Przegląd Geograficzny 30, 1, 3–43.

Lorenc M., 1987. *Struktury koliste wokół hercyńskich masywów granitodoidowych (Strzelin, Kłodzko-Złoty Stok, Žulova) — interpretacja zdjęcia lotniczego Landsat*. Annales Societatis Geologorum Poloniae 57, 107–124.

Matoš B., Tomljenović B., Trenc N., 2014. *Identification of tectonically active areas using DEM: a quantitative morphometric analysis of Mt. Medvednica, NW Croatia*. Geological Quarterly 58, 1, 51–70.

Mazur S., Szczepański J., Turniak K., McNaughton N. J., 2012. *Location of the Rheic suture in the eastern Bohemian Massif: evidence from detrital zircon data*. Terra Nova 24, 199–206.

Migoń, P., 1997. *Zarys rozwoju geomorfologicznego Masywu Śnieżnika*. [in:] *Masyw Śnieżnika — zmiany w środowisku przyrodniczym*. A. Jahn, S. Kozłowski, M. Pulina (eds.), Wyd. PAE, 35–45.

Oberc J., 1955. *Wpływ budowy geologicznej na morfologię w regionie bardzkim*. Geologia Sudetica 26, 4, 339–362.

Oberc J., 1972. *Sudety i obszary przyległe*. [in:] *Budowa geologiczna Polski. Tektonika — Część,* Wyd. Geologiczne, Warszawa, 307 pp.

O'Callaghan J.F., Mark D.M., 1984. *The extraction of drainage networks from digital elevation data*. Computer Vision, Graphics, and Image Processing 28, 323–344.

Olaya V., 2009. *Basic Land-Surface Parameters*. [in:] *Geomorphometry. Concepts, Software, Applications.* T. Hengl, H.I. Reuter (eds.), Developments in Soil Science, 33, 144–169.

Olaya V., Conrad O., 2009. *Geomorphometry in SAGA*. [in:] *Geomorphometry. Concepts, Software, Applications*. T. Hengl, H.I. Reuter (eds.), Developments in Soil Science 33, 293–308.

Pérez-Peña J.V., Azor A., Azañón J.M., Keller E.A., 2010. *Active tectonics in the Sierra Nevada (Betic Cordillera, SE Spain): Insights from geomorphic indexes and drainage pattern analysis*. Geomorphology 119, 74–87.

Ranoszek W., 1998. *Morfologia progów tektonicznych obramowujących rów Górnej Nysy*. Acta Universitatis Wratislaviensis 2061, Prace Instytutu Geograficznego, Ser. A, Geografia Fizyczna 9, Wrocław, 23–35.

Ranoszek W., 1999. *Zastosowanie różnych metod morfometrycznych w analizie morfologii progu tektonicznego na przykładzie zachodniej krawędzi Masywu Śnieżnika*. Przegląd Geologiczny 47, 1027–1031.

Reicherter K., Froitzheim N., Jarosiński M., Badura J., Franzke H.-J., Hansen M., Hübscher H. Müller R., Poprawa P., Reinecker J., Stackebrandt W., Voigt T., Von Eynetten H., Zuchiewicz W., 2008. *Alpine tectonics north of the Alps*. [in:] *The Geology of Central Europe*. Volume 2: *Mesozoic and Cenozoic*. T. McCann (ed.), Geological Society, London, 1233–1285.

Rogala W., Placek W., Wojtoń A., 1998. *Nowe dane o krasie podziemnym Krowiarek, Sudety Wschodnie*. Acta Univ.Wratislaviensis 2061, Prace Instytutu Geograficznego A9, 13–22.

Ruszkiczay-Rüdiger Z., Fodor L., Horváth E., Telbisz T., 2009. *Discrimination of fluvial, eolian and neotectonic features in a low hilly landscape: a DEM-based morphotectonic analysis in the Central Pannonian Basin, Hungary*. Geomorphology 104, 203–217.

Scheck M., Bayer U., Otto V., Lamarche J., Banka D., Pharaoh T., 2002. *The Elbe Fault System in North Central Europe–a basement controlled zone of crustal weakness*. Tectonophysics 360, 281–299.

Sroka W., 1997. *Ewolucja morfotektoniczna Sudetów w rejonie Kotliny Kłodzkiej w świetle analizy morfometryczno-statystycznej*. Acta Universitatis Wratislaviensis, Prace Geologiczno-Mineralogiczne 1939 (53), 97 pp.

Strahler A., 1952. *Hypsometric (area-altitude) analysis of erosional topography*. Geological Society of America Bulletin 63, 1117–1142.

Štěpančíková P., Hók J., Nývlt D., Dohnal J., Sýkorová I., Stemberk J., 2010. *Active tectonics research using trenching technique on the south-eastern section of the Sudetic Marginal Fault (NE Bohemian Massif, central Europe)*. Tectonics 485, 269–282.

Turniak K., Mazur S., Wysoczański R., 2000. *SHRIMP zircon geochronology and geochemistry of the Orlica-Śnieżnik gneisses (Variscan belt of Central Europe) and their tectonic implications*. Geodinamica Acta 13, 1–20.

Ulrych J., Dostal J., Adamovič J., Jelonek E., Špaček P., Wegner E., Balogh K., 2011. *Recurrent Cenozoic volcanic activity in the Bohemian Massif (Czech Republic)*. Lithos 123, 133–144.

Wajsprych B., 1978. *Allochtoniczne skały paleozoiczne w osadach wizeńskich Gór Bardzkich (Sudety)*. Annales Societatis Geologorum Poloniae 48, 99–127.

Walczak W., 1968. *Dolny Śląsk*. [in:] *Sudety* Część 1, PWN, Warszawa, 384 pp.

Wojewoda J., 1997. *Upper Cretaceous littoral-to-shelf succession in the Intra-Sudetic Basin and Nysa Trough, Sudety Mts.* [in:] *Obszary źródłowe: zapis w osadach*. J. Wojewoda (ed.), Wind, Wrocław 1, 81–96.

Zevenbergen L.W., Thorne C.R., 1987. *Quantitative analysis of land surface topography*. Earth Surface Processes and Landforms 12, 47–56.

Zuchiewicz W., 1980. *Analiza morfometryczno-statystyczna małych zlewni w obszarach mobilnych tektonicznie*. Czasopismo Geograficzne 51, 2, 171–185.

Żelaźniewicz A., Aleksandrowski P., 2008. *Regionalizacja tektoniczna Polski — Polska południowo-zachodnia*. Przegląd Geologiczny 56, 10, 904–911.