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NEOTECTONIC ASPECT OF THE INTRASUDETIC SHEAR ZONE

Jurand WOJEWODA

University of Wrocław, Institute of Geological Sciences, pl. M. Borna 9, 50-204 Wrocław, Poland
**Corresponding author's e-mail*: juwo@ing.uni.wroc.pl

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ABSTRACT

For estimation of recent dynamics of morphology of the Sudetes, satellite radar images of 90-meter resolution have been used. Basing on the Digital Elevation Model, trend surfaces and deviation maps of the morphology were made. The analyzed area ranges over 23000 sq. km and is bordered by the following coordinates: N51°05'32", N49°56'26", E15°02'42" and E17°37'57".

The 8th-order trend surface records four distinct regional morphological domains These are two elevations with their centres located at N50°46'24" - E15°29'24" and N50°07'24" - E17°13'07", as well as two depressions with centers located at N50°05'41" - E15°46'58" and at N50°29'39"- E17°28'30", respectively. The elevations and depressions extend both over the crystalline massifs and sedimentary basins and are highly lithologically differentiated. On the deviation map, the elevations display the highest positive values which suggests a local disequilibrium of morphogenic processes during the formation of recent topography. Today's landscape have been being shaped since the beginning of the Neogene. As the climatic and hydrological conditions have been rather uniform for the whole area, a tectonic uplift must be accounted for the reason of the indicated anomalies occurrence.

There is only one unique profile across the elevations and depressions that reflects the smallest amplitude of relative height (black-white dashed-line). It is parallel to the dominant "Sudetic strike", i.e. 115°, and it follows the Intrasudetic Shear Zone (**ISZ**) that played an important role in the post-Variscan evolution of the Sudetes. Along and inside the ISZ small, mostly pull-apart basins occur (the Krkonoše Piedmont Basin (**KPB**), the Nachod Basin (**NB**), the Upper Nysa Kłodzka Trough (**UNKT**)) – the South Sudetic Basins Suite (**SSBS**) – which are filled with Permian, Triassic and Neogene-to-Recent sediments. The author postulates right lateral regional displacement along and beneath the ISZ as an important factor controlling long time evolution of topography in the analyzed area.

KEYWORDS: Sudetes, Intrasudetic Shear Zone, neotectonics, DEM, trend surface

MAJOR FEATURES AND STAGES OF DEVELOPMENT OF THE GEOLOGICAL FRAMEWORK OF THE SUDETES

The Sudetes constitute a peripheral area of the Bohemian Massif that is concordantly regarded as a part of the Variscan orogeny (see Aleksandrowski, 1995; Żelaźniewicz, 1997; Franke and Żelaźniewicz, 2000; Aleksandrowski and Mazur, 2002). Three groups of phenomena and processes reflect distinct relationship with recent geodynamics of the Sudetes – their geological structure, geomorphology and modern kinematics of the basement.

The geological structure of the Sudetes has formed in three stages. The first of them comprises the time span before the Late Devonian, when protoliths of rocks constituting major portion of so called supracrustal series in the Sudetes have formed – various metamorphic rocks of greenschist to amphibolite facies. Extremely variable geotectonic and geochemical record of this stage has been currently under reconstruction (see review by Żelaźniewicz, 2003).

The second stage, most crucial for recent spatial structure of the Sudetes, corresponds to Variscan orgeny formation between the late Devonian and early Carboniferous. Major regional structural units were formed in the Sudetes, first depositional areas containing local, synorogenic lithological infill developed (Świebodzice and Bardo basins and initial Intra-Sudetic basin), as well as most significant magmatic intrusions in the region occurred. Carboniferous magmatism in the Sudetes is synchronous with the development and consolidation of the Variscan orogeny structure. The apogee of the granitic magmatism dates back to the turn of the Visenian and Namurian (340 – 300 Ma; see compilation by Kröner et al., 1994; Duthou et al., 1991), however its beginning is dated for the turn of the Famienian and Tournaisian, when the oldest synorogenic intrusion had been emplaced (Żelaźniewicz, 1977), among others the Kudowa and Čermna intrusions (380 – 350 Ma; Domečka and Opletal, 1974) and the Kłodzko intrusion regarded as the oldest in the region (Żelaźniewicz, 2003).

The third stage comprises post-consolidational rearrangement of the Variscides. It started in the Westphalian and, with varying intensity, continues up to recent. In response to the post-Variscan rearrangement, supracrustal series, pre- Variscan and Variscan basement became exhumed and sediment

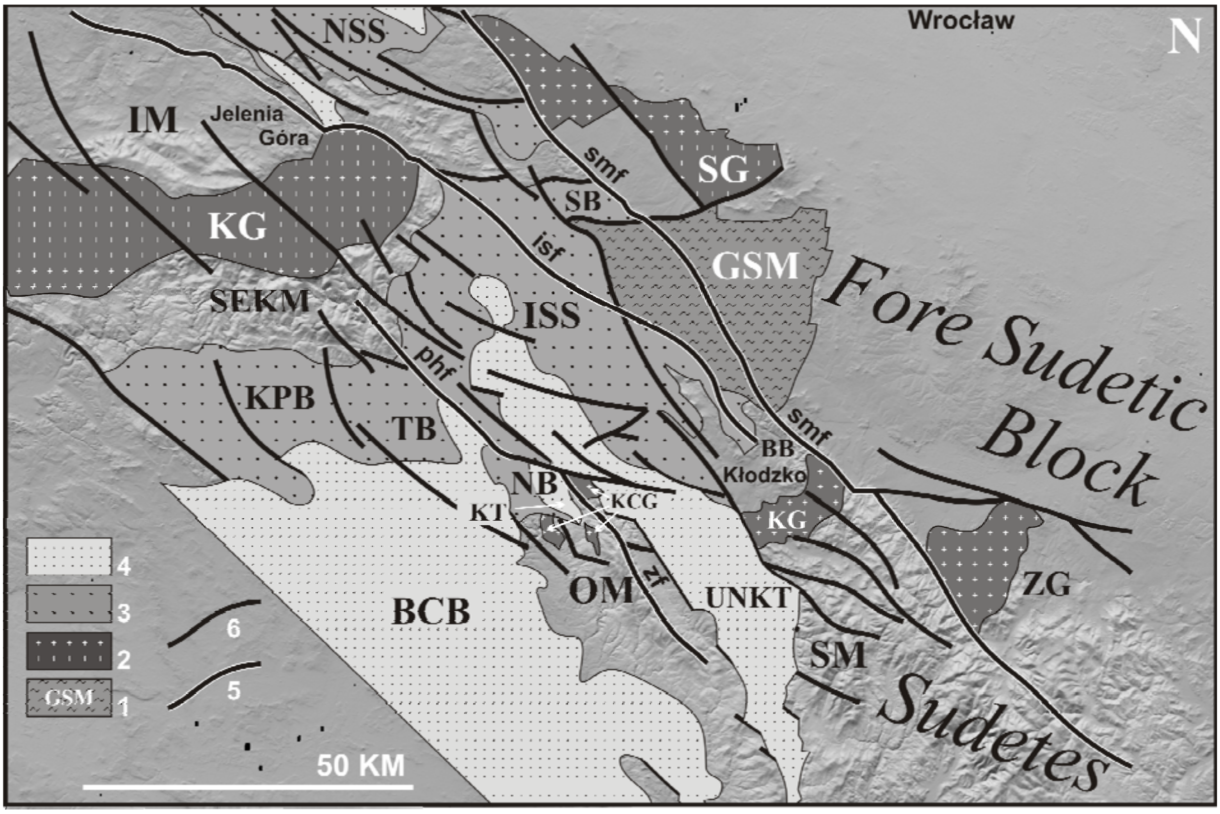

Fig. 1 Major elements of the geological structure of the Sudetes and the Fore-Sudetic Block outlined on the Digital Elevation Model (DEM 90 m).

Explanations: 1 – gneisses of the Góry Sowie Massif; 2 – Variscan granitoid massifs (KG – Karkonosze Granite, KCG –Čermna-Kudowa Granite, SG – Strzegom Granite, KG – Kłodzko Granite, ZG – Žulova Granite); 3 – Sudetic basinal areas (NSS – North-Sudetic Synclinorium, ISS – Intrasudetic Synclinorium, KPB – Krkonoše Piedmont Basin, TB – Trutnov Basin, NB – Nachod Basin, KT – Kudowa Trough, SB – Świebodzice Basin, BB – Bardo Basin, UNKT – Upper Nysa Kłodzka Trough, BCB – Bohemian Cretaceous Basin); 4 – Sudetic Massifs (IM – Izerskie Mts. Massif, SEKM – South-Eastern Krkonoše Massif, OM – Orlickie Mts. Massif, SM – Śnieżnik Massif); 5 – dislocations active since the Permian; 6 – major boundary dislocations of the Sudetes (smf – Sudetic Marginal Fault, isf – Intra-Sudetic Fault, PHF – Pořiči-Hronov Fault Zone, zf – Zieleniec Fault

accumulation begun to develop within Sudetic basins. Epi-Variscan cover in the Sudetes is not uniform – it is made up of local diachronous infills of tectonic troughs. Volcanic-sedimentary successions indicate frequent reactivation of older depositional areas and, successively, formation of new ones. The extent of sedimentary cover and their distinct link to major tectonic lineaments in the Sudetes, as well as the shape of the Sudetic basins indicate for a consequent extensional rearrangement of the Variscan orogeny under regional shear conditions.

One of the most distinct tectonic zones in the Sudetes is the Intrasudetic Shear Zone (ISZ) (*Lužice-Sudetic Fault Zone sensu* Uličný et al., 2002 & 2003; Martínek et al., 2006), being 30 km wide and trending ca.115˚-295˚. It extends between the southern termination of the Karkonosze Massif in the West, over the southern part of the Intrasudetic Synclinorium (ISS), down to Kłodzko-Złoty Stok (KM) and Kłodzko Granite (KG) in the East (Fig. 1.). Rhombohedral troughs filled with Carboniferous to Neogene formations and numerous parallel subordinary faults occur in the ISSZ. Most significant Sudetic dislocations – the Sudetic Marginal Fault (smf), the Intra-Sudetic Fault (isf) and Pořiči-Hronov Faults (phf) are partly parallel, partly oblique to this zone. Additionally, granitoid massifs of Čermna, Kudowa-Olešnice, Kłodzko and Žulova are located in it.

Geomoprphology of the Sudetes dominantly reflects geology of that mountain range, in particular, its lithological and structural variation. It is most clearly evidenced at tectonic boundaries between geological units and in areas where selective weathering of variable lithological formations resulted in development of morphological escarpments. Apart from that, morphology reveals locally relics of ancient reliefs. In the Fore-Sudetic Block, morphology of Paleogene etchplain have been exhumed in many places, whereas in the Sudetes, relics of Palaeogene (?) morphological levelling are common. These features have formed during tectonic stagnation, under influence of local hydrogeological-climatic conditions, often independently of the geological structure of the rock mass.

MODERN KINEMATICS OF THE GEOLOGICAL BASEMENT OF THE SUDETES

Modern kinematics of the Sudetic basement has been estimated directly by geodetic measurements or by morphometric and sedimentological methods. Geodetic methods allow for the assessment of absolute displacement vectors relative to regional reference base (e.g. Cacoń and Deeb, 1996; Cacoń and Dyjor, 2000 and 2002) and for the assessment of relative displacements on local geodetic profiles (e.g. Kontny, 2001). In individual cases, if installation of mechanical or optical measuring devices is possible, direct measurements of relative displacements of rock blocks can be carried out (e.g. Cacoń and Kontny, 1993; Cacoń et al., 2003). Geodetic methods have, however, some disadvantages – they can image relatively short period of geodynamic activity over the studied area, which can reflect both a long-term trend and a short-term anomaly.

Morphometric investigations applied so far in the Sudetes comprised analyses of basic morphological parameters over selected areas using available topographic data (Sroka, 1991 and 1997; Badura and Przybylski, 1993 and 1995; Migoń, 1996; Badura et al., 2003). These interpretations were based on traditional schemes of slope evolution of retrograding morphological escarpments (Migoń, 1995) or on evolution of local river systems (Migoń, 1994). They provided approximate image of relative variation in denudation rate over analysed areas, and, as a consequence, they allow to make hypotheses on relative variation in vertical displacements. The morphometric analyses of tectonic scarp areas in the Sudetes are methodologically more elaborated and justified (e.g. Sroka, 1991; Krzyszkowski and Pijet, 1993; Krzyszkowski et al., 1998; Badura et al., 2002). They were applied, however, exclusively to most spectacular escarpments – smf, marginal fault of the Upper Nysa Kłodzka Trough. These areas do not contribute significantly to overall kinematics of the Sudetes but they rather result from that. Recent attempts on the assessment of horizontal displacements of the basement in selected areas of the Sudetes were based on morphometric analyses of Sudetic river valley anomalies (Migoń, 1994; Wojewoda, 2004, 2005a and 2007a and e). This method enables to assess displacements that took place in a time span determined by the existence of an individual river system, therefore in the Sudetic scheme at least for the Holocene. Maximum displacement that was assessed along WNW-ESE trending faults by this method equalled to almost 400 m (!) in the Ścinawa River valley (dextral; area of the ISS; Wojewoda, 2007e) and about 150 m in the Nysa Kłodzka River valley (sinistral, area of the Upper Nysa Kłodzka Trough; Wojewoda, 2004 and 2005a).

Also sedimentological and structural methods allowed to assess in some cases modern displacements in morphotectonic zones. Sedimentological analysis of the Kaczawa River sediments enabled to locate apexes of successive alluvial fans at the river's Sudetic outlet (Mastalerz and Wojewoda, 1990 and 1993). The oldest evidenced fan apex is located about 1000 m away from the recent river outlet, which indicates for at least that distant sinistral horizontal displacement along the smf in the pre-glacial period.

The most spectacular manifestation of modern dynamics of the Sudetic basement is provided by damages of civil engineering constructions located above active tectonic zones. Works aimed at location, description and classification of such damages have been currently carried in several regions of the Sudetes (cf. Cacoń and Dyjor, 1995; Cacoń et al., 1991; Wojewoda, 2005 b).

MORPHOMETRIC ANALYSIS OF THE SUDETES BASED ON DEM

Digital Elevation Models (DEM) appeared to be an extremely valuable device for morphometric analyses. Initial base for constructing DEM is built on digitalized topographic maps, lidar images or radar, aerial or satellite images. In recent years analysis of DEM images has been increasingly used for the assessment of kinematics of geotectonically active areas (e.g. Carrizo et al., 2005; Ganas et al., 2005; Jordan et al., 2005; Kervyn et al., 2005; Grohmann et al., 2006). Both geodetic and radar DEM were also successfully applied in morphometric analysis of some areas of the Sudetes (Grygar and Jelínek, 2003; Wojewoda, 2004, 2005a, 2006a and b and 2007a, c and e).

For the morphometric analysis of the Sudetes an area of about 23000 sq. km, limited by coordinates of N51°05'32", N49°56'26", E15°02'42" and E17°37'57" was selected. This area does not comprise the Sudetes as defined by H. Teisseyre (1957) but their significant portion. The analysis was made with use of standard procedures provided by MICRODEM 2006.12.1.2. software (Guth, 2003 and 2006).

The 8^{th} order elevation trend surface for the area of the Bohemian Massif determined with use of SRTM 90 m images depicts typical shape for stable litospheric plates undergoing long-lasting denudation (see Bense et al., 1998) and does not show any particular features in the area of the Sudetes (Fig. 2A). However, determining 1^{st} and 8^{th} order trend surfaces separately for the Sudetes in the area limited by above listed coordinates, regional trends become visible (Figs. 2B and C). The surface of the 1^{st} order trend is inclined towards NNE. The 8^{th} order trend surface outlines 2 elevations of elliptical shape located in the north-western part of the analysed area (the Karkonosze-Izerskie Mts. elevation) and in the south-eastern part (the Śnieżnik-Orlickie Mts. elevation). The centres of these elevations are located at N50°46'24" - E15°29'24" and N50°07'24" -

E17°13'07", respectively. Additionally two distinct depressions are visible – one in the south-western part, another one in north-eastern part of the studied area, with their centres located at N50°05'41" - E15°46'58" and N50°29'39"- E17°28'30".

An attempt to determine a vertical plane that intersects with 8th order trend surface defines a profile line with the smallest amplitude of relative height variation was made. For the area tested, there is only one such a plane. It strikes app. 115°-295° (Fig. 2C). The maximum deviation along this profile line does not exceed 60 m over a 180 km distance (!) and the average height for it equals to 418 m a.s.l., which also corresponds to average height a.s.l. of the Sudetes in the area studied. This line is referred as a neutral line of the 8th order trend surface. The elevations and depressions described in the above paragraph locate in pairs on both sides of that neutral line.

A deviation surface of the 8th order was additionally determined for the analysed area (Fig. 2D). Comparing this surface with the shape of elevations and depressions on the 8th order trend surface, a distinct trend of positive anomalies concentration in the elevations and negative anomalies concentration in the depressions becomes remarkable. It indicates that the trend surface in elevated areas outlines upward migration (rise) and downward migration in the depressions (sinking). Such a distinctive differentiation of the surfaces implies high dynamics of processes and their modern nature. However, the actual reason of such behaviour can be different, thus, the implications for its determination must be independent of geometric speculations.

GEOLOGICAL STRUCTURE AND THE TRENDS OF GROUND SURFACE EVOLUTION

Compilation of the main geological structures and the 8th order trend surface of the Sudetes suggests direct link between the elevations, depressions, neutral line and the Intrasudetic Shear Zone (Fig. 3.). Inside this zone, a rhombohedral tectonic troughs occur, that are typical for strike-slip regime (Fig. 3A.).

Both elevations and depressions in the 8th order trend surface comprise lithologically differentiated rocks, including crystalline rocks, supracrustal series and Carboniferous-Cretaceous sedimentary formations. They are situated next to each other, thus, it is difficult to consider climatic phenomena as a factor significantly influencing weathering and erosional variation in the past. Selective denudation is therefore a very unlikely process for development of the elevations and depressions visualized by elevation trend surfaces of the Sudetes.

The tectonic troughs located in the western segment of the ISZ (the Krkonoše Piedmont Basin (**KPB**), the Trutnov Basin (TB), Nachod Basin (**NB**)) are filled with Permo-Triassic, Cretaceous and Neogene-to-Recent sediments. The shape of these basins indicates dextral strike-slip displacement. The Permian and Neogene-to-Recent formations show boundary controlled facies distribution in these troughs (see Martinek, 2007; Wojewoda, 2006a and 2007 b). The tectonic troughs in the eastern segment of the ISZ are located in the area of the Upper Nysa Kłodzka Trough, they are filled with Cretaceous and Neogene-to-Recent sediments and their shapes indicate for sinistral strike-slip displacement (Wojewoda, 2005a). The sinistral displacement is confirmed by modern anomalies of river valley shape of the Nysa Kłodzka River above evidenced fault zones (Wojewoda, 2004 and 2005a).

Strike-slip characteristics of the ISZ is also evidenced by various tectonic structures of varying order. In the axial zone of the ISZ, a parallel boundary fault of the Kudowa Trough (**KT**) is located – the Žďarky-Jakubowice fault – that constitutes an extent of the Poříči-Hronov Fault Zone. Small tectonic structures recently documented in this fault zone univocally indicate for dextral displacement on the fault and for direct link of the Pstrążna Dome and Čermna-Kudowa Granite with the Čermna-Kudowa Granite fault (Fig. 3B; Wojewoda, 2007c).

Nearly the whole massif of the Góry Stołowe Mts. is located inside the ISZ. The above mentioned boundary fault of the Kudowa Trough continues eastwards and in the area of the Góry Stołowe Mts. it determines the southern boundary of a tectonic trough with axis being parallel to t he ISZ (Wojewoda, 2007 d). This trough is reflected by an elongated depression, situated centrally along the watershed axis of the Góry Stołowe Mts. (!), which corresponds to Czerwona Woda Creek valley. Inside the Czerwona Woda Trough, a characteristic rhombohedral areas of increased accommodation of Neogene sediments occur. One of them is represented by Wielkie Torfowisko Batorowskie Bog in which continuous phitogenic sedimentation have taken place after the Pleistocene (Marek, 1998). The shape of the troughs, damages in road pavements above presently active faults and kinematic indicators in the rock formations indicate for strike-slip displacement along the boundary faults of the Czerwona Woda Trough – dextral in its western segment and sinistral in the eastern one. Such an apparent kinematic contradiction within an individual fault zone can be satisfactorily explained by the presence of a diagonal extensional zone in the central part of the Czerwona Woda Trough (Wojewoda, 2007a).

SUMMARY

Implications and facts presented above enable to combine areas of relatively high trend of uprise or sinking of the ground surface in the Sudetes and the ISZ into one coherent kinematic model (Fig. 4). Sedimentological record and indicators of modern kinematics of the basement provide altogether a set of features typical of thin-skin tectonic supra strike-slip zones, characteristics of which was defined by numerous works, including experimental ones (cf. Christie-Blick and Biddle, 1985; Naylor et al., 1986;

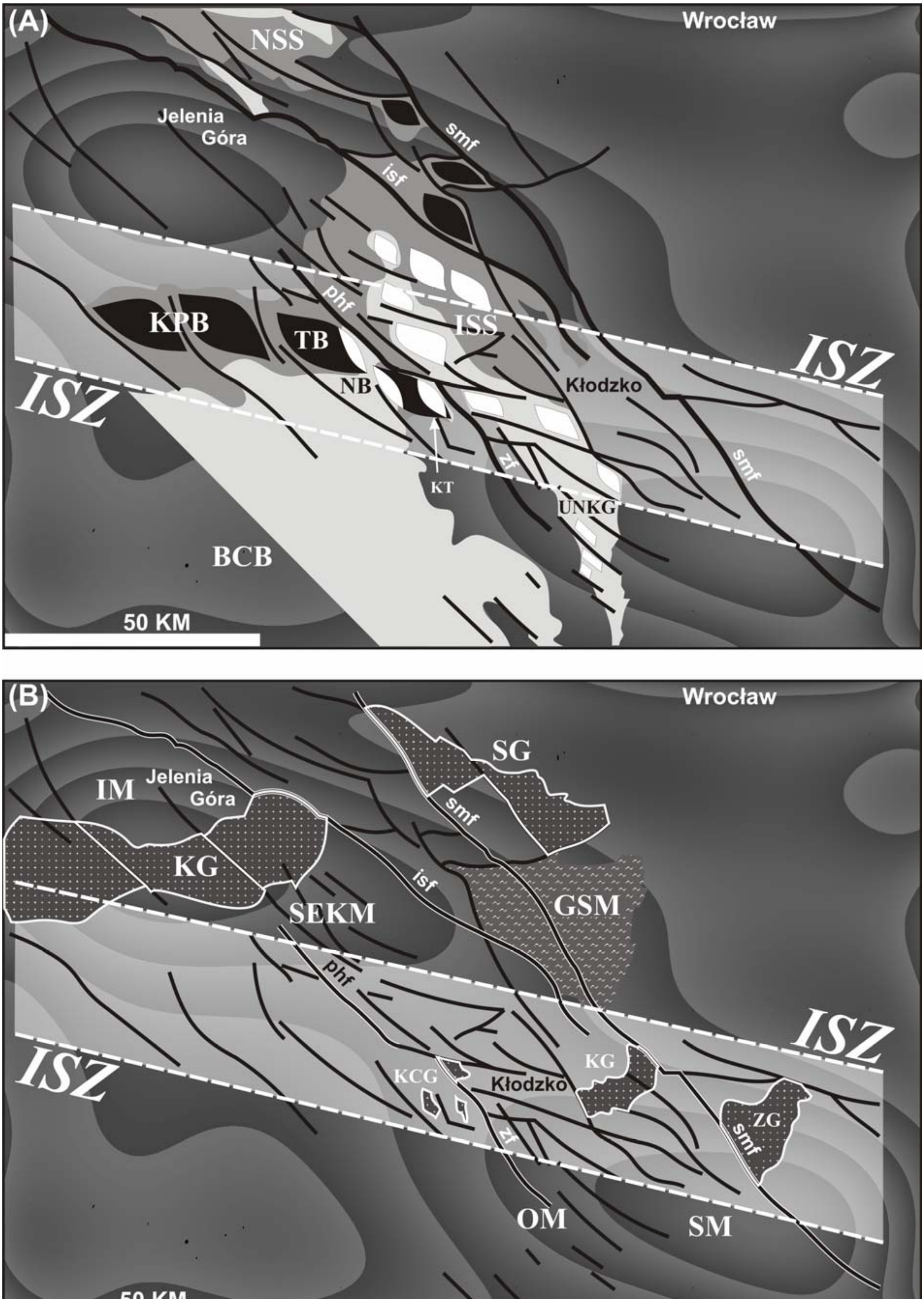

Fig. 3 Major elements of the geological structure of the Sudetes visualized on the 8th order elevation trend surface and the Intra-Sudetic Shear Zone (ISZ).

Explanations: A – rhombohedral Permo-Triassic basins (black colour) and rhombohedral tectonic troughs filled with Cretaceous and Neogene-to-Recent sediments (white colour); B – Variscan granitoid massifs and sudetic massifs (explanations as in Fig. 1.); black lines – active faults and fault zones.

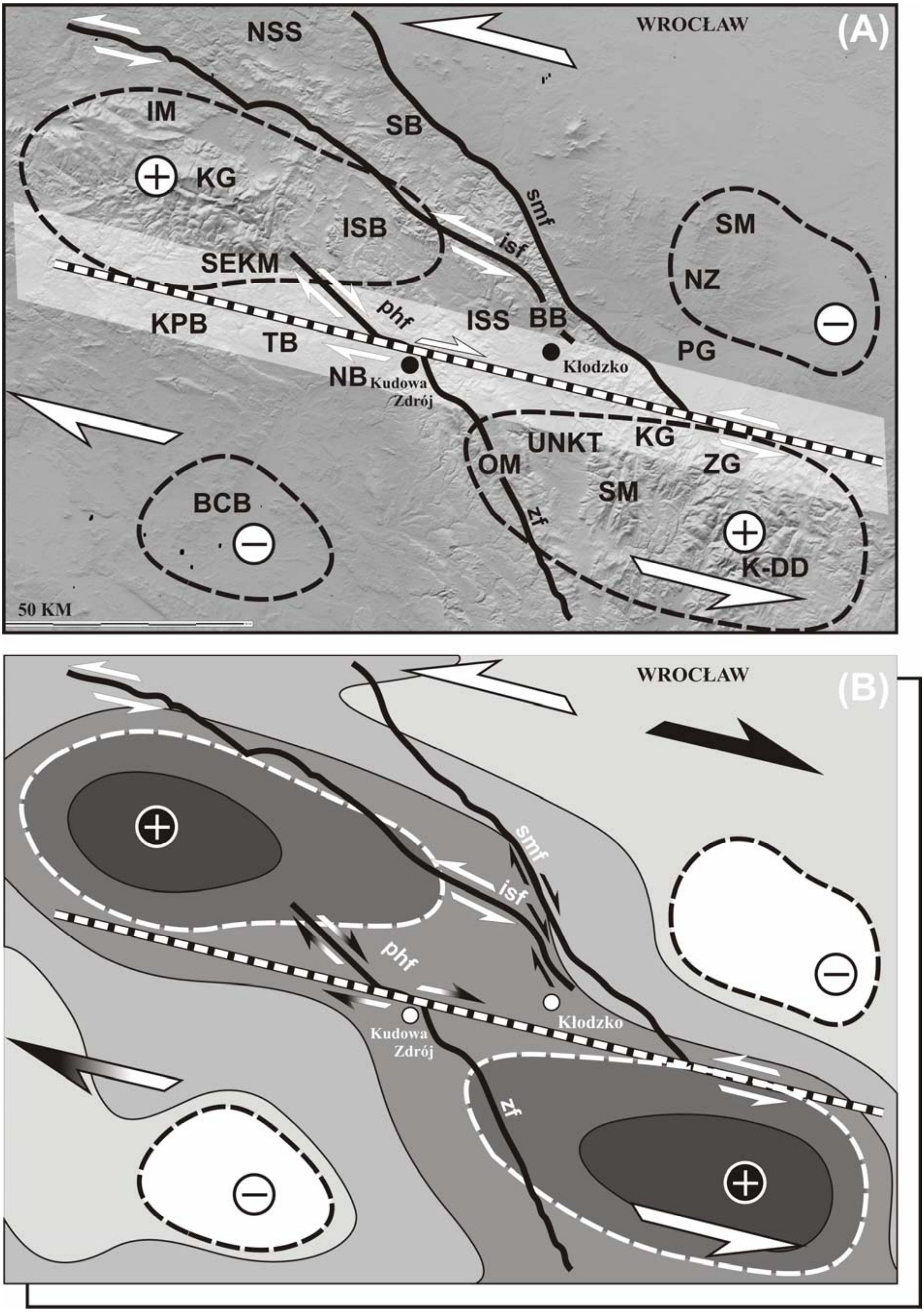

Fig. 4 Presumed kinematic schemes for the Sudetes in the period of their post-variscan rearrangement.

Explanations: A – modern kinematic scheme initiated in the Neogene marked on digital elevation model (DEM 90 m); B – kinematic scheme for an early stage of rearrangement in the Carboniferos and Permian (black arrows) and for the initial stage of the kinematic inversion in the late Cretaceous (white arrows).

Allen and Allen, 1990; Gölke et al., 1994; Neugebauer, 1995; Bertoluzza and Perotti, 1997; Sims et al., 1999). The ISZ most probably represents shallow continuation of a deep strike-slip zone, which had significant influence on the rearrangement of the epivariscan cover in the Sudetes.

The fundamental scheme of the post-Variscan evolution of the Sudetes was formed in the late Carboniferous and it consequently indicates for dextral displacements. It is worth mentioning that it constitutes, in a sense, a continuation of the variscan evolution of that area (Aleksandrowski, 1995). The major dislocations in the Sudetes, as **msf**, **isf** and **phf** either follow the dominant shear direction or they are oblique, which explains varying kinematics evidenced in various segments of these faults, ranging from dip-slip to strike-slip transpressional (cf. Aleksandrowski et al., 1993). Significant change of the regional style of deformation into sinistral took place relatively recently, most probably in the Neogene, however older symptoms of this kinematic inversion are recorded already in Cretaceous sediments as synsedimentary deformational structures (see Burliga and Wojewoda, 2003). The development of pull-apart basins constituting the South Sudetic Basins Suite (**SSBS**) can be related to the older kinematic stage (Wojewoda, 2006a and 2007d). To the Neogene stage, the development of the Upper Nysa Kłodzka Trough (that continues up to recent), as well as the extension recorded in the IS area and modern kinematic trends in the Sudetes can be related among others.

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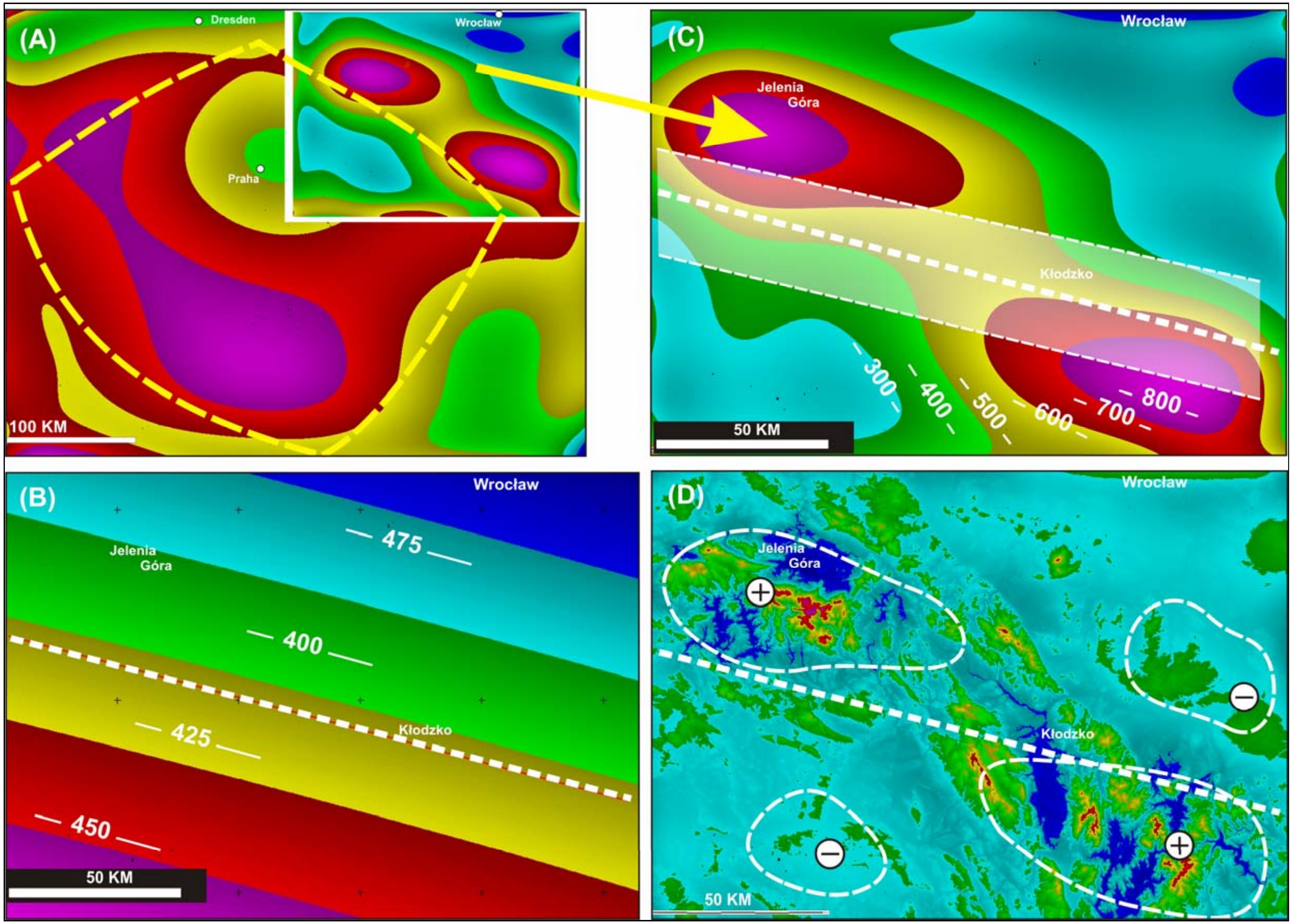

Fig. 2 Elevation model surfaces for the Bohemian Massif and the Sudetes based on DEM (90 m)
Explanations: A – the 8th order elevation trend for the area of the Bohemian Massif (dashed-line) with the selected Sudetes area marked; B – the 1st order elevation trend in the area of the Sudetes (dashed-line – strike of the trend plane at the 418 m a.s.l. trending 115˚-295˚); C – the 8th order elevation trend in the Sudetes (dashed-line – neutral line trending 115˚-295˚, paler area corresponds to Intrasudetic Shear Zone (ISZ)); D – elevation differential surface of the 8th order in the Sudetes ("plus" – central point of an elevation, "minus" – central points of a depression, thin dashed-line – extent of the elevations and depressions in the 8th order elevation trend surface, thick dashed-line – neutral line and ISZ axis)