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Discussions

Late Cretaceous – Early Palaeogene inversion-related tectonic structures at the NE margin of the Bohemian Massif (SW Poland and northern Czechia)

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Abstract. A brief, regional-scale review of the Late Cretaceous – Early Palaeogene inversion-related tectonic structures affecting the Sudetes and their foreland at the NE margin of the Bohemian Massif is presented and complemented with results of new seismic studies. The Sudetes expose Variscan-deformed basement, partly overlain by post-orogenic Permo-Mesozoic cover, containing a wide spectrum of tectonic structures, both brittle and ductile, in the past in this area referred to as young Saxonian or Laramide. We have used newly reprocessed legacy seismics to study these structures at the two main post-Variscan structural units of the area, the North-Sudetic and Intra-Sudetic synclinoria, and discuss the results together with regionally-distributed examples coming from quarries and underground mines as well as those from the literature. The Late Cretaceous –Early Palaeogene tectonic structures in consecutively reviewed Sudetic tectonic units, from the north to south, typically include gentle to moderate buckle folds of detachment type or fault-related, high-angle reverse and normal faults, as well as low-angle thrusts – often rooted in the crystalline basement. The structures hitherto described as grabens, are frequently believed to be bounded by reverse faults (hence we use the term ‘reverse grabens’) and typically reveal strongly synclinal pattern of their sedimentary fill. The crystalline basement top, as imaged by seismic sections in the North Sudetic Synclinorium below the detachment-folded cover, is synformally down-warped with a wavelength of up to 30 km, whereas on the elevated areas, where the basement top is exposed at the surface, it is up-warped (i.e. tectonically buckled). The reviewed compressional structures typically show an orientation fitting the regionally-known Late Cretaceous – Early Palaeogene tectonic shortening direction of NE-SW to NNE-SSW The same applies to the regional joint pattern, typically comprising an orthogonal system of steep joints of c. NW-SE and NE-SW strikes. All the reviewed structures are considered as due to the Late Cretaceous – Early Palaeogene tectonic shortening episode, although some of the discussed faults with a strike-slip component of motion may have been modified, or even produced, by later, Late Cenozoic, tectonism.

1 Introduction

During Late Cretaceous to Early Palaeogene times, compressional tectonic structures developed over vast areas of western and north-central Europe (e.g. Kley and Voigt, 2008; Navabpour et al., 2017; Kley, 2018; Nádaskay et al., 2019; Malz et al., 2020; Voigt et al., 2021). They are currently interpreted as due to collisional interaction of the Iberian mass with continental Europe and the resultant propagation of far-field compressional stress (Kley & Voigt 2008), which brought about widespread inversion of Permo-Mesozoic basins. In Poland and easternmost Germany (e.g. Krzywiec, 2002, 2006; Mazur et al., 2005; Krzywiec and Stachowska, 2016; Kley 2018) the resultant map-scale tectonic structures are mostly NW-SE-trending, large-scale (crustal-scale?), gentle folds up to 1000 km long, 150-250 km wide and up to at least 3 km high (e.g. Pożaryski, 1979). The Mid-Polish Swell (or Anticlinorium), spanning the entire breadth of Poland's NW-SE diagonal from the Baltic Sea to westernmost Ukraine, is the most spectacular example of such structures. To the SW of the Mid-Polish Swell there is the Szczecin-Łódź Trough (Synclinorium), which occurs next to the successive elevated structural element, occurring at the NE margin of the Bohemian Massif, in the borderland between Poland and Czechia. This is the Sudetic area - the principal object to be presented in this paper, whose goal is to briefly overview the wide spectrum of structural effects produced by the Late Cretaceous to Early Cenozoic trans-European compressional event at the NE margin of the Bohemian Massif, in the Sudety Mts and in their northern foreland with a similar geology. An important part of the review is based on new data derived by us from recently reprocessed legacy seismic materials coming from the central areas of the Sudetic region. The other presented examples supply the wide regional context for the seismic results and come either from our own collection or from descriptions made by other authors, though sometimes interpreted by us in a different way. Although the tectonic structures that formed at the turn of Cretaceous and Palaeogene times obviously must have developed also in the Variscan basement, they are – in general - difficult to distinguish from the older ones. Therefore, the scope of this paper is mostly limited to the the tectonic phenomena that occur in the post-orogenic Permo-Mesozoic strata, though, in places also in the late-orogenic Upper Carboniferous.

Below, following the sections on outline geology and methods, an overview of the Late Cretaceous – Early Palaeogene deformation structures in the Sudetes is presented, mostly in a regional context and order, in reference to particular structural units of the Sudetes, moving from the north to south across the area.

2 Outline geology

The Sudetes, low-topography mountains located on the northeastern margin of the Bohemian Massif, together with the southern part of the Silesian-Lusatian Plain share the same pre-Cenozoic geological composition and structure and – in the geological sense – are usually considered collectively as the Sudetic region, or simply, the Sudetes (e.g. Aleksandrowski and Mazur, 2002; Mazur et al., 2006, Kroner et al., 2008). The differences in the topography – mountainous versus lowland - are due to splitting of the Sudetic area into two tectonic blocks: the currently downthrown Fore-Sudetic block in the north and the elevated Sudetic one in the south. The Sudetes constitute the northeasternmost segment of the Central European Variscan internides, exposing crystalline basement of strongly deformed and metamorphosed Late Neoproterozoic to Carboniferous rocks abundantly intruded by Carboniferous granites (e.g. Mazur et al., 2006, 2007, 2020). In the Sudetes, the main tectonostratigraphic domains of the European Variscides: the Moldanubian, Tepla-Barrandian and – particularly – Saxothuringian find their continuation (e.g. Martinez-Catalan et al., 2021).

The Sudety Mountains acquired their present-day mountainous relief due to Neogene uplift of the Sudetic Block in front of the then actively growing Alps and Carpathians (e.g. Żelaźniewicz and Aleksandrowski, 2008; Jarosiński et al., 2009; Żelaźniewicz et al., 2011). This uplift affected the area mostly planated during the Palaeogene and early Miocene times, following the earlier, Late Cretaceous – Early Palaeogene more prominent uplift, which at that time had occurred over a broader area, including also the Fore-Sudetic Block to the north (Fig. 1), which at present is downthrown along the Sudetic Boundary Fault (e.g. Cloos, 1922;Teisseyre, 1957; Oberc 1972).

The Late Cretaceous – Early Palaeogene uplift exhumed the Variscan basement from below the post-Variscan, uppermost Carboniferous through Permo-Mesozoic cover and left the Sudetes tectonically elevated with respect to the adjoining depressed areas: the Fore-Sudetic Homocline to the north and the North Bohemian Cretaceous Basin to the south, which managed to preserve much more of their Permo-Mesozoic post-Variscan sedimentary fill. For over a century, the Sudetes have been considered a part of the classical area in Central Europe, in which the term "Saxonische Tektonik" (cf. Kley, 2013) was applied to deformation structures, mostly fault-related, observed in the Permo-Mesozoic sedimentary basins. In the Sudetes, in the older literature these contractional structures were most often ascribed specifically to the young Saxonian (Closs, 1922; Beyer, 1939; Oberc, 1972, 1977) or Laramide tectonism (Oberc 1972, 1977).

3 Data and methods

The concise regional, though not fully systematic, review of the tectonic structures of likely Late Cretaceous – Early Palaeogene age presented in this paper is based (1) on authors' own analysis and structural interpretation of the newly reprocessed reflection seismic data coming from the two key areas in the Sudetes with the most complete post-Variscan sedimentary record and (2) on structural field data of the present authors or (3) coming from critically assessed literature descriptions. The analysed seismic data were acquired by mining companies in the end 1970s (1976-1980) in the North Sudetic Synclinorium and in the early 1990s (1991-1993) in the Intra-Sudetic Synclinorium (Fig. 2). We received them as raw seismic data (field data, partly pre-processed, reloaded to discs from original magnetic tapes) and the accompanying. paper prints. These seismic data are unique at the scale of the entire Sudetes as the source of valuable information on the structural geology of the Permo-Mesozoic succession in the both main Sudetic synclinorial units.

The reprocessing of, in total, c. 650 km of the seismic profiles was carried out in 2019, using an up-to-date oil-industry software (Głuszyński and Smajdor, 2020). The new processing included post stack time migration (PostSTM), while to some of the profiles also the pre stack time migration stage (PreSTM) procedure was applied. No time-depth conversion was, however, attempted because of too scarce coverage of the area with appropriate drillhole data. As complementary material we used also an analogue/paper print version of a seismic profile from the vicinities of Broumov in Czechia and also some seismic profiles coming from the Fore-Sudetic Homocline. A significant part of the structurally interpreted seismic profiles are presented in this paper. Our structural interpretation of these profiles provides an entirely new material showing the tectonic style and geometry of the compressional tectonic structures affecting the post-Variscan sedimentary cover on the NE margin of the Bohemian massif and allows for inferences as to the mechanics of their formation. An equally important part of the paper, aimed at giving its readers an overall information on the distribution and genetic and geometrical diversity of the tectonic structures that formed or evolved under the Late Cretaceous –Early Palaeogene compressional regime, are depiction and short description of a selection of such structures exposed in natural outcrops and in active mines and quarries throughout the entire Sudetic area or its direct vicinities. This material is either our own or is based on critically evaluated other authors' accounts.

4. Products of Late Cretaceous – Early Palaeogene tectonic shortening: examples from particular structural domains

4.1.The north-eastern margin of the Sudetes: transition to the Fore-Sudetic Homocline

Directly to the northeast of the Sudetic Block, separated by the Middle Odra Fault Zone, the Fore-Sudetic Homocline extends (e.g. Kłapciński et al., 1984; Kroner at al., 2008; Żelaźniewicz et al. 2011). It is defined by shallowly (1-5˚) NE-dipping Permian to Mesozoic strata (Figs. 2 and 3) on top of Variscan-folded Carboniferous (Mazur et al., 2006, 2010), representing the SW limb of the Szczecin-Miechów Synclinorium of the Polish-German Basin. The Permian-Mesozoic succession constitutes the fill of the extensive Polish-German Basin and unconformably overlies the Carboniferous fold-and-thrust flysch belt of the Varican externides (e.g. Mazur at al., 2010, 2020).

The Permo-Mesozoic strata in the southern part of the the Fore-Sudetic Homocline are very gently folded and in few places affected by steep to low-angle reverse faults (Fig. 4). In the close vicinity of the NW-SE-trending Middle Odra Fault system, however, in galleries of c. 0.5-1.2 km-deep mines of the Legnica-Głogów Copper District, a rich inventory of contractional and, also, extensional tectonic structures occur in the base Zechstein/top Rotliegend ore-bearing formation, containing clayey shale, carbonates, anhydrite and rock-salt, apart from sandstones. These structures typically include thrust faults, accompanied by bedding-parallel décollements, as well as detachment folds of origin easily explainable by NE-SW directed tectonic shortening. The meso-scale structures can be studied directly on the galleries' walls (Fig. 5) and were described for decades by e.g. Salski (1965, 1968), Oberc and Salski (1968), Dumicz and Don (1977, 1990), Markiewicz and Szarowski (1990), Żelaźniewicz and Markiewicz (1991). Larger structures appear on mining maps as a complex network of faults, whose pattern reflects reactivation of a few major and numerous minor NW-SE trending fractures propagating upwards from the Variscan basement, which are accompanied by a number of relatively large WSW-ENE en-echelon events (cf. Markiewicz, 2007), the latter most probably formed due to a Late Cretaceous – Early Palaeogene (or Late Cenozoic?) sinistral strike-slip activity of the major NW-SE faults.

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4.2. The Fore-Sudetic Block

At the base Cenozoic level, the Fore-Sudetic Block (Figs. 2 and 3) exposes Variscan basement rocks of various metamorphic grades, varying in age from the Neoproterozoic to probable Devonian (Pożaryski, 1979; Kotański, 1997; Cwojdziński and Żelaźniewicz, 1995; Cymerman, 2010), and, variable igneous plutonic rocks, mostly of basic to ultrabasic Silurian/Early Devonian ophiolitic suite and Carboniferous to Early Permian, granitoids (e.g. Mazur et al., 2006, 2007; Kroner et al., 2008). As the Fore-Sudetic Block is (except at its easternmost perphery) devoid of Permo-Mesozoic deposits and its crystalline basement is eroded deeper than that in the mountainous Sudetes, an idea was conceived long ago (Cloos, 1922; Teisseyre, 1957) that the Block was uplifted with respect to the present-day Sudetes across the Sudetic Boundary Fault, following the Late Cretaceous – Early Palaeogene inversion. This situation was subsequently reversed in the Late Miocene, when the Sudetes were uplifted and the Fore-Sudetic Block downthrown when the Carpathian-Alpine forebulge was formed (e.g. Żelaźniewicz et a., 2011). The lack of Permo-Mesozoic sedimentary cover hampers the direct recognition of the effects of the Late Cretaceous – Early Palaeogene tectonism on the Fore-Sudetic Block, which, nevertheless, can be partly assessed thanks to the presence of the so called Żary Pericline (Fig. 2) in the geological map intersection pattern. This pericline consists in map-view enveloping of the NW-projecting basement "peninsula" with the Permo-Triassic outcrop zone, which continues to the south, onto the Block, from the area of the Fore-Sudetic Homocline. This basement/cover intersection pattern illustrates the likely up-warping (updoming) effect of the Late Cretaceous – Early Palaeogene compression, which seems to have undulated the roof surface of the crystalline basement, producing a very gentle NW-SE trending antiform. This antiform is analogous – but of reverse polarity - to the large, gentle synform that occurs to the south of it and is legible in seismic sections– in the floor of the North-Sudetic Synclinorium (see below). The uplift related to the formation of the antiform in question, must have been one of the important factors facilitating the erosion of the original Permo-Mezosoic cover over the most part of the Fore-Sudetic Block.

4.3. The North Sudetic Synclinorium

The North Sudetic Synclinorium (Figs. 2, 3 and 6) is a fault-bounded, NE-SE elongated tectonic structure, c. 60 km long and up to 24 km wide (Beyer, 1939; Oberc, 1972, 1977; Solecki, 1994; Śliwiński et al., 2003; Kiersnowski *in* McCann et al., 2008a; Żelaźniewicz and Aleksandrowski, 2008; Żelaźniewicz et al., 2011). It is filled with post-Variscan, end Carboniferous-Permian-Triassic and Upper Cretaceous (Cenomanian to Coniacian) continental and shallow marine sedimentary rocks, including also a Lower Permian volcanic member. The succession overlies a subsided top surface of the Variscan epimetamorphic basement the Kaczawa Slate Belt (e.g. Aleksandrowski and Mazur, 2002; Mazur et al., 2006; Żelaźniewicz and Aleksandrowski, 2008). The synclinorium achieved its quasi-basinal structure due to the Santonian-early Campanian to late Maastrichtian-Palaeocene (Walaszczyk *in* Voigt et al., 2008) tectonism. The North Sudetic Synclinorium in its western and central parts defines, in general, a single synclinal structure, while at its eastern and southern extremities it splits into several NW-SE elongated second-order synclinal elements, grabens and half-grabens, some of them separated by basement horsts (Figs. 2 and 7; Beyer, 1939; Śliwiński et al., 2003).

The end Mesozoic – early Cenozoic compressional deformation affected both the crystalline basement and post-Variscan cover. The cover must have once been relatively thick and must have extended over much wider areas of the Lower Silesia Block at that time than it does today (cf. e.g. Migoń and Danišik, 2012; Sobczyk et al., 2015, 2020). It was subsequently eroded from the most uplifted areas, but became preserved in places, where the basement/cover interface had undergone compression-driven down-warping. According to Beyer (1939), this compression in the North Sudetic basin brought about inversion of some of the earlier normal faults, which were then transformed into reverse ones (Fig. 7a). The Variscan basement at the upthrown sides of the former inverted faults was believed by this author to have acted like rigid jaws of a vice, which horizontally squeezed the Permo-Mesozoic succession in the process of a “frame-controlled folding”(German *Rahmenfaltung*, Fig. 7b).

The structural geometry of the Late Cretaceous – Early Palaeogene folds and related thrusts in the North Sudetic Synclinorium was known so far mostly from geological map intersection patterns combined with drilling results (Beyer, 1939; Oberc, 1972, 1977; Leśniak, 1979; Solecki, 1986, 1994; Cymerman, 1998) and from likely smaller-scale analogues occurring in active quarries (Fig. 8a-c). A reflection seismic survey made in 1976-1980 made it possible to better constrain the structure of the post-Variscan cover, which was attempted by Bałazinska and Bossowski (1979; their Fig. 3), applying an assumption of a dominance of nearly vertical faults.

A much closer insight into the geometry and structural style of the Late Cretaceous-deformed Permo-Mesozoic succession was recently enabled by the reprocessing of the same, legacy seismic raw data in 2019. The structural interpretation results of these data are presented in Figures 9 and 10 which depict the along-strike changing geometry of the Permo-Mesozoic succession of the North-Sudetic Synclinorium. This geometry, in general, seems to show products of detachment folding (cf. McClay, 1992) likely formed by buckling mechanism above the metamorphic basement. The structures are complicated by local thrusting/reverse faulting, but, nevertheless do not resemble typical fault-folds. The metamorphic basement seem to have been shortened by down-warping that resulted in the formation of a single synform below the detached Permo-Mesozoic cover. The down-warping may have been associated with development of low-angle thrusts within the basement (not shown in Figs. 9 and 10), where some of the thrusts affecting the Permo-Mesozoic are likely rooted. The *Rahmenfaltung* at the synclinorium edges, invoked by Beyer (1939) and understood here as upthrowing the metamorphic basement on reverse (inverted?) faults, seems to also have its impact on the deformation process as the local source of horizontal shortening forces. The folds interpreted from both the reprocessed seismic sections and from map intersection patterns, show, in general, near-parallel geometry, and shallow WNW-plunging (Solecki, 1986, 1994, 2011) axes. As already mentioned, they are locally affected by high- to medium-angle reverse/thrust faults, sometimes following their axial planes.

Our analysis of newly reprocessed seismic profiles made possible a subsurface mapping of a number of high-angle fault zones. They are, as a rule, trending NW-SE and often continue at distances of tens of kilometres. Other identified major faults represent low-angle thrusts, continuing into the Variscan basement. The thrusting polarity in the Permo-Mesozoic sucession of the North-Sudetic Synclinorium is bimodal and directed both to the NE and SW. This seems typical of a detachment folding. The interpreted fault zones cut across the Permo-Mesozoic strata from the Zechstein at the bottom to the Upper Cretaceous at the top, which confirms their activity continued until at least the Late Cretaceous.

The structural analysis of the reprocessed seismics, made clear the necessity for reinterpretation of the hitherto widely held concept of the internal structure for the North-Sudetic Synclinorium, assuming the dominance of high-angle block tectonics. In a new concept, the significance of low-angle thrust faults, of compressional down-warping of the top basement surface, and of the well-developed detachment folding pattern should be taken into account.

A recent mapping and structural study by Kowalski (2020) of one of the already mentioned second-order synclinal/graben elements branching off from the SE rim of the North Sudetic Synclinorium, the Wleń Graben (Figs. 2 and 7) offers an opportunity to have a closer look on another example of a Late-Cretaceous – Early Palaeogene macro-scale tectonic structure in the NW part of the Sudetes. TheWleń Graben is a narrow structure, c. 17.5 km long and up to 3.5 km wide, downthrown into the low-grade metamorphics of the Kaczawa Slate Belt, filled with Permian, Triassic and Upper Cretaceous (up to lower Coniacian) mostly sedimentary, shallow marine or continental deposits and "bounded by steep, NW−SE-oriented, normal and reverse faults" (Kowalski, 2020; Fig. 11). The graben was earlier studied by Gorczyca-Skała (1977) and discussed by Solecki (1994, 2011), who stressed the particular significance of NNE-SSW to NE-SW directed compression in its formation. Kowalski (2020) advocates a multistage evolution of the graben, from Late Cretaceous times (post-Santonian?) onwards, including the first, extensional stage of its formation with active NW-SE striking normal faults, followed by compressional event of "probably latest Cretaceous to early Palaeogene(?)" age, re-activating and inverting the latter discontinuities and producing new reverse faults and overthrusts, particularly in the central and southern parts of the graben. This was postdated by minor sinistral displacements of the graben fragments along cross-cutting faults of NE-SE trend, and the evolution is believed by this author to have ended with an extensional episode of limited significance, presumably already during the mid- to late Cenozoic.

The cross-sections of the Wleń Graben prepared by Kowalski (2020) and based on his mapping fieldwork and scarce borehole data (Fig. 11) show a rather regular syncline, only slightly modified by the graben's boundary faults and locally complicated by faults striking obliquely to the syncline's axis (Fig. 11). The metamorphic basement top is depicted as concordantly draped around the overlying, synclinally bent base Rotliegend surface. The latter solution may prove problematic and the cited author suggests a seismic survey to be made in order to better understand the structural geometry of the graben.

4.4. The Intra-Sudetic Synclinorium

The Intra-Sudetic Synclinorium is another, apart from the North Sudetic one, extensive Late Cretaceous – Early Palaeogene tectonic structure of NW-SE trend in the Sudetes (Figs. 2, 3 and 11). It has a comparable, though somewhat larger size of c. 80 km in length and up to 30 km in width. It, similarly, affects the post-Variscan continental to shallow marine Permo-

Mesozoic succession, which represents the upper structural level of the Intra-Sudetic Basin (Żelaźniewicz and Aleksandrowski, 2008; Żelaźniewicz et al., 2011), unconformably deposited on top of a thick succession of intramontane Carboniferous syn- to late-orogenic clastics deformed by Variscan tectonism, corresponding to the lower structural level of the Intra-Sudetic Basin (see also: Nemec at al., 1982; Dziedzic and Teisseyre, 1990; Bossowski et al., 1995; McCann, 2008b). The Carboniferous deposits of the Intra-Sudetic Basin restn the Variscan-deformed, mostly crystalline basement of the Sudetic Block. To the SE, the axial zone of the Intra-Sudetic Synclinorium, composed of Late Cretaceous deposits, merges the Upper Nysa-Králiky Graben (Figs. 2 and 12). Another similarity of the Intra-Sudetic to the North Sudetic Synclinorium, is its generally simple, open structure of a single syncline in its NW and central parts, which is replaced by a number of (partly reverse) synclinal grabens separated by basement horsts on its north-eastern flank (Figs. 2 and 12).

The Late Cretaceous to Early Palaeogene tectonic structures of the Intra-Sudetic Synclinorium studied by us on recently reprocessed legacy seismic sections, come only from the NE limb of the synclinorium, located between Mieroszów in the NW and Ścinawka in the SE. In that area it is the Permian rocks that are exposed at the surface, while the Cretaceous succession of the Intra-Sudetic Synclinorium axial zone occurs to the SW and is not covered by the seismics. The seismic sections (location in Fig. 12) are mostly trending SW-NE, that is roughly perpendicular to the synclinorium's axis. They are consecutively presented, from NW to SE, in figures 13 and 14, in order to illustrate in a systematic way the tectonic deformation structures affecting the Permian and Carboniferous strata.

In the NW part of the area covered with seismic data (Figs. 12 and 13), three consecutive profiles show a bunch of faults in Carboniferous clastics, which does not continue upwards into the Permian, although in some profiles (Figs. 13 b and c) these faults manifest themselves also in the Permian strata as gentle ductile folds above the faults. These folds are geometrically entirely consistent with fault-related folds in the Carboniferous. The most likely interpretation of this case seems to be a post-Early Permian reverse-slip activity of faults in the Carboniferous succession (probably representing a reactivated Carboniferous flower structure), associated with gentle folding that locally affected also the overlying Permian strata, though locally were fully accomodated still at the level below the Permian (Fig. 13a). The fault zone in the Carboniferous succession can be followed on seismics at a distance of 7 km, but probably continues further on both to the NW and SE beyond the seismically explored area.

Further to the SE, near Broumov in Czechia (Figs. 12 and 14a,b), a low-angle, NE-vergent thrust zone (which may represent a much evolved continuation of the fault zone from Fig. 13) rooted in the crystalline basement, produces a reverse-slip displacement of the Carboniferous strata by at least 2 km with respect to the footwall, associated with the formation of fault-bend folds. The thrust seems to continue to the NE as a décollement within the Permian strata, overlain by a pair of anticline-syncline, which can be recognized in the surficial geological map outcrop pattern.

Moving further to the SE along the NE flank of the Intra-Sudetic Synclinorium axial zone, in the area of Radków, on the successive seismic profiles one can follow along-strike geometrical changes of a conspicuous low-angle, NE-vergent thrust fault, responsible for an up to 2.5 km magnitude of displacement of the crystalline basement and the overlying Carboniferous

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and Permian over their footwall. The overthrust is related – similarly as in the case at Broumov – with an anticline-syncline pair of the fault-bend or fault-propagation(?) folds.

The conspicuous thrust fault identified at depth in the area of Radków – Ścinawka (Figs. 14 c-f) and – most probably – continuing into the vicinities of Broumov (Fig. 14 a,b), seems to correspond to the major NW-SE trending Ścinawka-Krosnowice Fault (Fig. 12) exposed at the surface. The latter fault has been, however, so far consistently interpreted as a NE-throwing normal (Grocholski and Augustyniak, 1971) or vertical fault (Bossowski and Ihnatowicz, 2006). Therefore, our interpretation of the reprocessed seismic data requires a thoroughgoing change in understanding the nature of this well-known mapped fault at least in its NW, Ścinawka segment, as a low angle Late Cretaceous – Early Palaeogene thrust. In the light of the geological and tectonic context, there can be little doubt about the latter timing of the tectonic structures identified by us on the seismic sections. This is corroborated by their occurrence near to the axial zone of the Intra-Sudetic Synclinorium with abundant presence of the preserved Upper Cretaceous deposits. This is also confirmed by the SE-ward surficial extension of the Ścinawka-Krosnowice Fault, which at its Krosnowice segment defines a tectonic boundary between the Permo-Mesozoic succession of the Intra-Sudetic Basin and Nysa-Králiky Graben on one side and the Śnieżnik – Krowiarki crystalline Massif on the other side.

An interesting Late Cretaceous – Early Palaeogene structure at the NE periphery of the Intra-Sudetic Synclinorium is the NW-SE trending Czerwieńczyce Reverse Graben (Figs. 12 and 15). According to Oberc (1972, 1977), it is bounded by high-angle reverse faults (and, hence, we apply to it the term "reverse graben") and filled with Rotliegend and Upper Carboniferous sedimentary rocks (Oberc, 1972, 1977). On approaching the graben's boundary faults, the strata are strongly dragged upwards, which renders a synclinal geometry to the graben's fill. This 'synclinal' structural characteristics of the Czerwieńczyce Reverse Graben – if correct, being based on surficial geological mapping and involving much extrapolation at depth – is, nevertheless, quite symptomatic of a number of Sudetic grabens and to some degree it resembles cross-sections of e.g. the Wleń Graben by Kowalski (2020; Fig. 11) and – still more – that by Gorczyca-Skała (1977, not reproduced here), or of the Upper Nysa – Králiky Graben by e.g. Jerzykiewicz (1970) and Don and Gotowała (2008) – partly with reverse boundary faults.

4.5. The Upper Nysa - Králiky Graben

The Upper Nysa Nysa – Králiky Graben (Fig. 16) is a distinctive tectonic and topographic, fault-bounded feature of nearly N-S trend, c.45 km long and from 3 to 12 km wide, merging to the north with the Intra-Sudetic Synclinorium, and filled with shallow marine sedimentary rocks, including a time span from the early Cenomanian, through Turonian to Coniacian and Santonian (e.g. Don and Don, 1960; Jerzykiewicz, 1970, 1971; Radwański, 1975; Don and Gotowała, 2008; Badura and Rauch, 2014). Most of the earlier authors (except Jerzykiewicz, 1970, 1971; Radwański, 1975 and Oberc 1972) explained the origin of the Upper Nysa – Králiky Graben as a result of a Late Cretaceous rifting modified later by Cenozoic subsidence (e.g. Don and Don, 1960; Don, 1996; Wojewoda, 1997; Don and Gotowała, 2008). The early rifting was inferred to have occurred on stratigraphic and sedimentological premises – not convincing in our opinion – and most often explained as due to compression- or extension-driven updoming of the Orlica-Śnieżnik Massif during the Cretaceous or, still, by pull-apart graben formation due to strike-slip displacements on NW-SE trending structural discontinuities in the crystalline basement. In contrast, we, in this paper, interpret the mostly N-S trending Upper Nysa – Králiky Graben to represent a Late Cenozoic feature, whose boundary faults cut out and downthrown a strip of the Cretaceous (Cenomanian, Turonian, Coniacian through to Santonian) shallow marine succession previously much more widespread over the area. The Cretaceous is now preserved within the graben due to its being downthrown against the uplifted crystalline basement around. The uniqueness of the Cretaceous deposits in the Upper Nysa – Králiky Graben consists only in the preservation of the thick Coniacian to Santonian succession, absent from the uplifted areas nearby, from where it must have clearly been eroded. The Upper Nysa – Králiky Graben is imposed on and cuts across earlier, Late Cretaceous –Early Palaeogene, tectonic structures of stable NW-SE strike, which are in most places oblique to and cross-cut by the graben's boundaries (Fig. 16). These structures are represented by differentially dip-slip displaced fault blocks, often bounded by reverse faults, and by gentle folds (Badura & Rauch, 2014; Don and Gotowała, 2008).

Locally, shallow-dipping thrust faults, most probably of Late Cretaceous-Early Palaeogene age were mapped, drilled or directly observed in outcrops within or in direct vicinities of the Upper Nysa – Králiky Graben. A relatively extensive, at least 25 km-long, NW-SE trending trace of the Zieleniec Thrust Fault was mapped by Cymerman (1990) and extrapolated on maps by other authors within the SW flank of the Upper Nysa –Králiky Graben. On this c. 40-50˚ SW-dipping fault a 500 Ma orthogneiss mass from the Góry Bystrzyckie Mts was overthrust, displaced by at least 5300 m toward the NE (Cymerman, 1990) and emplaced on top of the Turonian clastics, equivalent to those from the lower part of the Upper Nysa - Králiky Graben fill (Fig. 17) and resting themselves on analogous orthogneiss basement. Cymerman (1990) has interpreted this thrust as produced by Late Alpine (Miocene) compression. The Zieleniec Thrust was later confirmed by drilling, as reported by Kozdrój (2014), who interpreted the thrusting as the result of a Cenozoic gigantic, gravity-driven landslide, at the same time referring to inversion of an original normal fault into a reverse one. One of most important arguments for this judgement was finding a subhorizontal position of the Cretaceous/gneiss contact in the drillcore. In our opinion, taking into account its significant extent,and the involvement in the major NW-SE trending fault system (Fig. 12), termed the South-Sudetic Shear Zone by Wojewoda (e.g. in Wojewoda and Kowalski, 2016), involving the major Pořici-Hronov Fault (see below), there cannot be much doubt that the Zieleniec thrust represents a Late Cretaceous – Early Palaeogene thrust, similar to that of the Łużyce Thrust (see below), though of an opposite vergence.

To the NW the Zieleniec Thrust merges the SE-extension of the Pořici-Hronov major fault system (Fig. 12), partly representing the SW boundary to the Intra-Sudetic Synclinorium. It was active, as well, in the Late Cretaceous - Early Palaeogene as a high-angle reverse fault of complex structure, but of the opposite, SW, polarity (Prouza et al., 2014), which – according to some authors - is combined with the strike-slip component of motion (Wojewoda, 2007, 2009; Nováková, 2014) (Fig. 18a). To the SE, the Pořici-Hronov fault continues into that of Duszniki-Gorzanów/Krosnowice, at the northern end of the Upper Nysa – Králiky Graben.

A presumable splay fault, branching off from the Zieleniec Thrust (Figs. 12 and 18b) was described directly in a c. 1 km-long chain of outcrops along a road cut between Duszniki Zdrój and Lewin Kłodzki near the pass of Polskie Wrota on the same SW flank of the Upper Nysa - Králiky Graben (Wojewoda et al., 2010; Aleksandrowski and Wojewoda, 2010). A c. 20˚ NW-dipping detachment can be seen to occur there roughly along the bedding in Middle Turonian mudstones and calcareous claystone. On a closer inspection, the detachment was found to represent a shear zone, attaining 7 to 25 cm in thickness and composed of interconnected, kinematically linked surfaces, confined between two distinct boundaries of mostly intact rock (Fig. 18b). The shear zone shows internal flaser bedding and is composed of cataclastic flow products of host-rock composition, which coexist with crush breccia and calcite veins. On evidence from the orientation of the accompanying joints, the detachment was then interpreted as SE-vergent and probably genetically related to a supposed strike slip motion on the nearby major NW-SE-trending Duszniki-Gorzanów Fault, being a SE continuation of the Poříči-Hronov fault system (cf. Petrascheck, 1933; Prouza et al., 2014). It seems likely, however, that the joints can represent the youngest, Miocene, deformation and episode of motion on the detachment in question, whereas, the very origin of it and principal displacement was related to that on the Zieleniec Thrust.

4.6. The south-western margin of the Sudetes: transition to the North Bohemian Cretaceous Basin

The NW segment of the Sudetic Block, represented by the Karkonosze-Izera Massif, to the SW adjoins the North Bohemian Cretaceous Basin (Fig. 2). At its Sudetic margin, the basin is composed of deltaic to shallow-marine and hemipelagic Cenomanian to Santonian clastic deposits, not exceeding 600 to 700 m in thickness that rest subhorizontally on scarce subcrops of Permian and Carboniferous, but mostly on the crystalline Variscan basement of the Bohemian Massif (e.g. Klein and Soukup, 1966; Malkovský, 1987; Uličny et al., 2009; Wilmsen et al., 2014). Its interior is only little affected by the Late Cretaceous –Early Palaeogene tectonism, however at its boundary with the Sudetic block the deformation is concentrated at the spectacular and at places well exposed Lusatian Thrust (Fig. 2 and 19 a-c), which continues NW up to the vicinities of Dresden (e.g. Wagenbreth, 1967), whereas to the east it continues to the western Karkonosze Piedmont area (Prouza et al., 2013). The Lusatian Thrust has been excellently described and analysed in detail by Coubal et al. (2014).

The Lusatian Thrust (e.g. Malkovský, 1976), similarly to other main NW-SE trending fault zones of the Sudetic area at the Bohemian NE margin (the Intra-Sudetic Fault, the Sudetic Boundary Fault, the Odra Fault Zone) derives its origin from a major Variscan fracture, rooted deeply in the basement and likely having a primary strike-slip characteristics (cf. Aleksandrowski et al., 1997). It must have been reactivated during the Late Cretaceous – Early Palaeogene compressional episode and propagated into the Permo-Mesozoic cover. The Lusatian Thrust emplaces the Variscan crystalline complexes of Lusatia and of the West Sudetes on top of the Mesozoic strata of the North Bohemian Cretaceous Basin. This fault zone reveals significant along-strike changes in the dip angle of its displacement surface, between low-angle or subhorizontal in the northwest (Figs. 2 and 19a) through medium-angle (Figs. 2 and 19b) and high-angle attitude (Figs. 2 and 19c). The angle made by the displacement zone/fault core with respect to the – supposedly generally subhorizontal - tectonic shortening direction had serious influence on the structural style and complexity of the brittle structures developed around the fault core and on the width of the damage zone (Coubal et al., 2014). The smaller the angle between the two, the more smoothly the displacement occurred (Fig. 17a). An increase of the fault plane dip angle made the displacement more difficult to be achieved, which resulted in widening a zone of damage and of fault drag and favoured splitting the displacement into several slip surfaces (Fig. 19b and c).

5 Regional jointing pattern: a likely product of Late Cretaceous – Early Palaeogene deformation

The regional pattern of tectonic joints over the area of the Sudetes or of SW Poland can be inferred from a number of local studies on jointing, most of which were conducted decades ago. Not attempting to make a systematic review of such studies, for the needs of a brief review made in this paper, several stereograms or rose diagrams of the dominant joint sets coming from various sources (Jerzykiewicz et al., 1974; Aleksandrowski, 1976; Solecki, 2011; Selerowicz et al., 2014) and various locations in the Polish Sudetes have been mounted on the geological map (Fig. 20). The data come mostly from the Permo-Mesozoic strata exposed in outcrops in the both Sudetic synclinoria, in underground galleries of the deep copper mines at the Fore-Sudetic Homocline and in the Opole Cretaceous Basin. Two stereograms, show, additionally the joint pattern in the crystalline basement rocks of the Karkonosze Massif.

All the presented diagrams show most steep joints to be concentrated in two mutually perpendicular maxima, in which the joint planes are approximately paralallel and perpendicular, respectively, to the inferred Late Cretaceous-Early Palaeogene shortening direction (cf. e.g. Solecki, 2011, Nováková, 2014). As, moreover, they occur in the Permo-Mesozoic strata, a conclusion that they are genetically related to that shortening event seems reasonable. Actually, we believe that the formation of dominant jointing pattern in the post-Variscan (but also partly in the Variscan) Sudetes and the SW part of Poland resulted from the Late Cretaceous-Early Palaeogene compressional event.

6 Conclusion

In our brief review of the Late Cretaceous – Early Palaeogene tectonic structures affecting the NE margin of the Bohemian Massif we have shown their common and widespread occurrence all over the region and, to some degree, shortly discussed their style and mechanisms of formation. These structures are easily recognizable in the Permo-Mesozoic post-Variscan cover as devoid of other, earlier formed contractional deformations, but, though present, they are much less obvious in the Varican basement that was heavily tectonized before. Those developed in the post-Variscan cover, particularly the fault-displacement effects – and, among them, the strike-slip related ones - can still be difficult to be separated from the structures that might have resulted from the younger Cenozoic events.

Our structural analysis of newly reprocessed legacy seismic profiles, complemented with outcrop, drillhole data, have revealed an important contribution of thin-skinned fold-and-thrust type contractional deformation in the Permo-Mesozoic (partly also in the Carboniferous) strata of the two main Sudetic synclinoria. Such deformation includes also gentle buckling of the basement/cover interface and decoupling/decollement of the Permo-Mesozoic cover along weak, clayey horizons in Zechstein strata. The low-angle thrust faults identified in the Permo-Mesozoic in the seismic record are often rooted in the top parts of the Variscan basement, so some elements of the thick-skinned style of shortening can be also involved (and, actually, are to be expected in the deep crystalline basement). It is, therefore, likely that also outside the areas covered with Permo-Mesozoic sedimentary sequences, over the crystalline basement exposure areas, some (even major) faults interpreted from surficial geological maps and outcrop relationships as vertical or high-angle structures, may have at depth a geometry of low-angle thrusts. This may have important practical implications on e.g. geothermal prospecting in the Sudetes, where the deep underground waters in the crystalline basement circulate, almost exclusively, along structural discontinuities, such as fault zones and fracture corridors (e.g. Dowgiałło, 2002).

The Late Cretaceous – Early Palaeogene compressional event seems to be also responsible for the formation of the regionally dominant tectonic joints pattern in both Permo-Mesozoic and older rocks of the Sudetic area, characterized by an ortogonal joint system with two sub-vertical sets of c. NW-SE and NE-SW strikes, as is shown by a comparison of results from a few local studies.

Data availability

The seismic data from Poland are available at the National Geological Archive and the seismic profile from Broumov area is available at the Czech Geological Survey Archive.

Author contributions

PA and AG wrote the text, prepared the figures, and compiled the paper.

Competing interests

The authors declare they have no conflict of interest.

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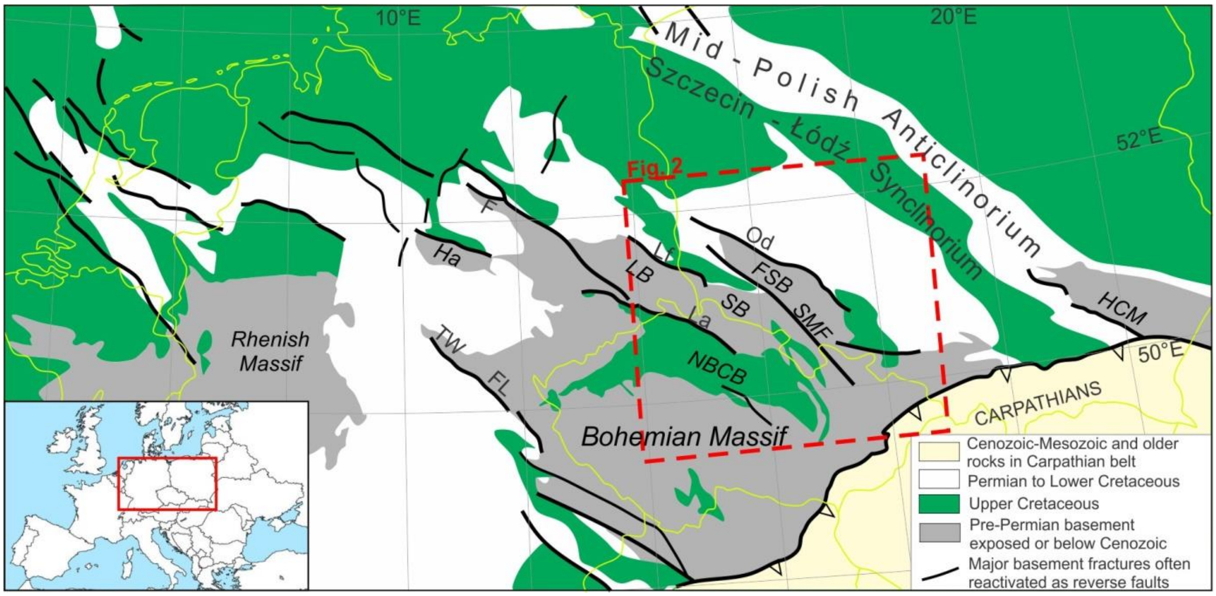


Figure 1: The main Late Cretaceous – Early Palaeogene tectonic structures in Central Europe. Modified after Kley and Voigt 2008.. Abbreviations: Lf - Lusatian Main Fault, Od - Odra Fault, Ha-Harz Block, F – Flechtingen High, TW - Thuringian Forest, FL – Franconian Line, LB - Lusatian Block, SB - Sudetic Block, FSB - Fore-Sudetic Block, NBCB - North Bohemian Cretaceous Basin, HCM - Holy Cross Mountains

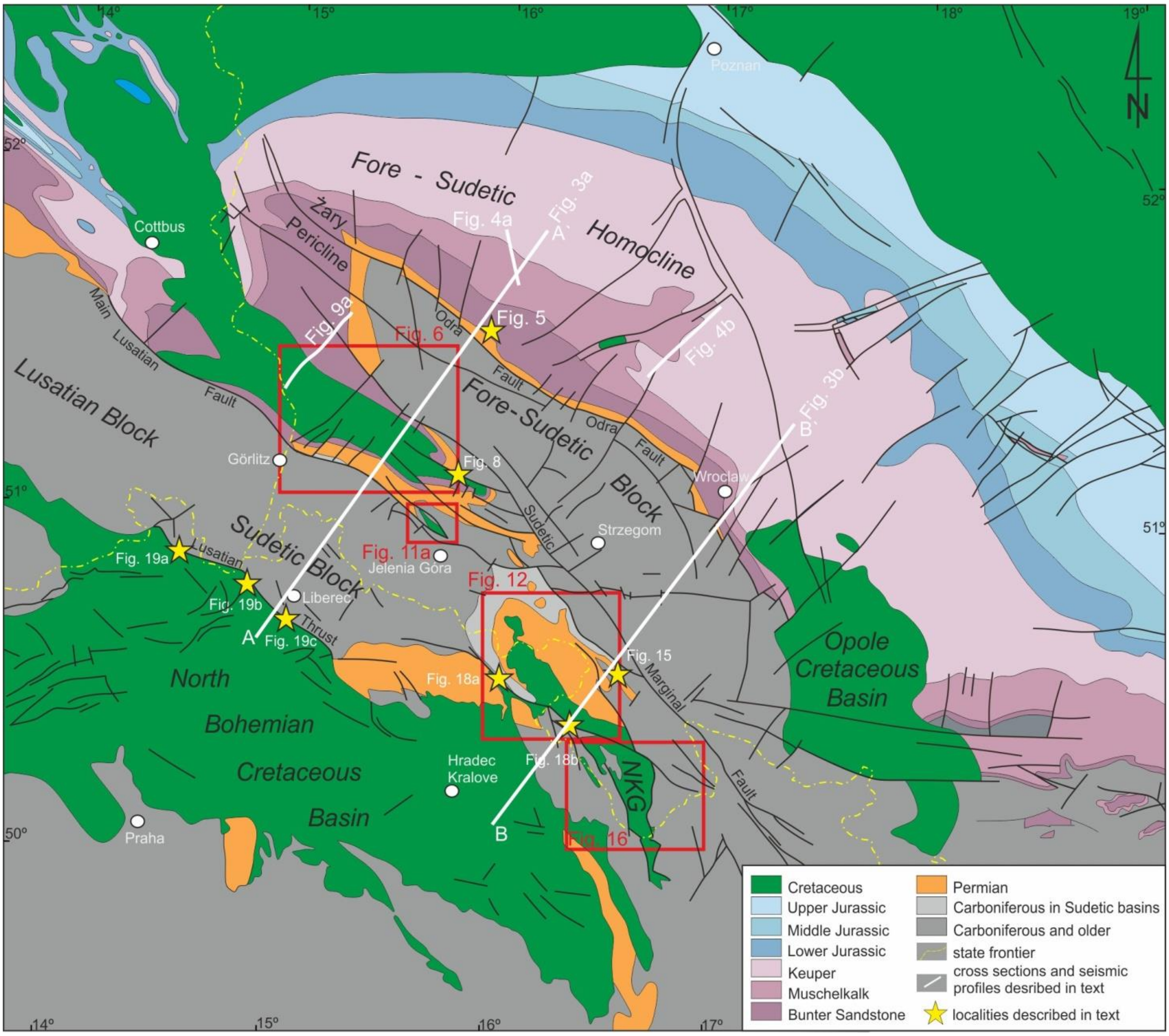


Figure 2: Outline geology of the Bohemian Massif NE margin (SW Poland and northern Czechia). Simplified from Dadlez (2000). NKG – Nysa-Králiky Graben. Red boxes show location of Figs. 6, 11a, 12 and 16.

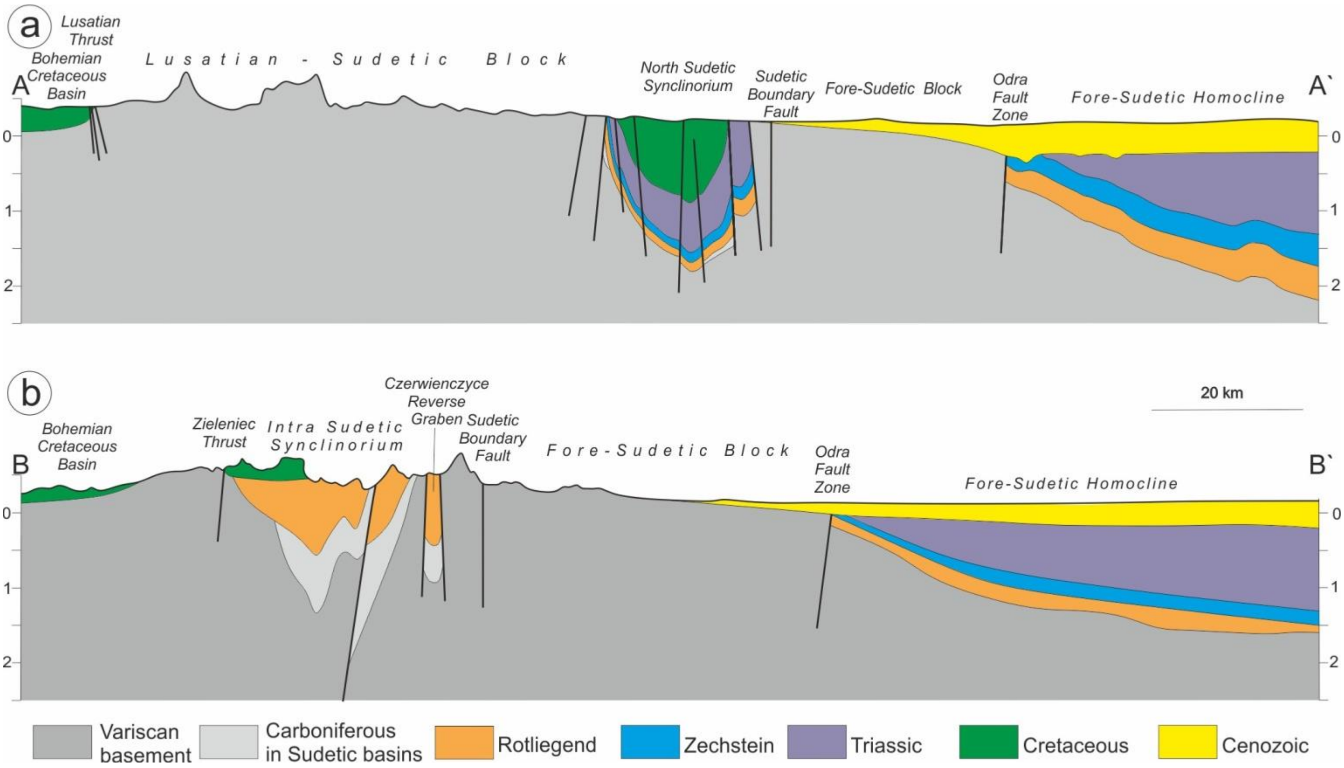
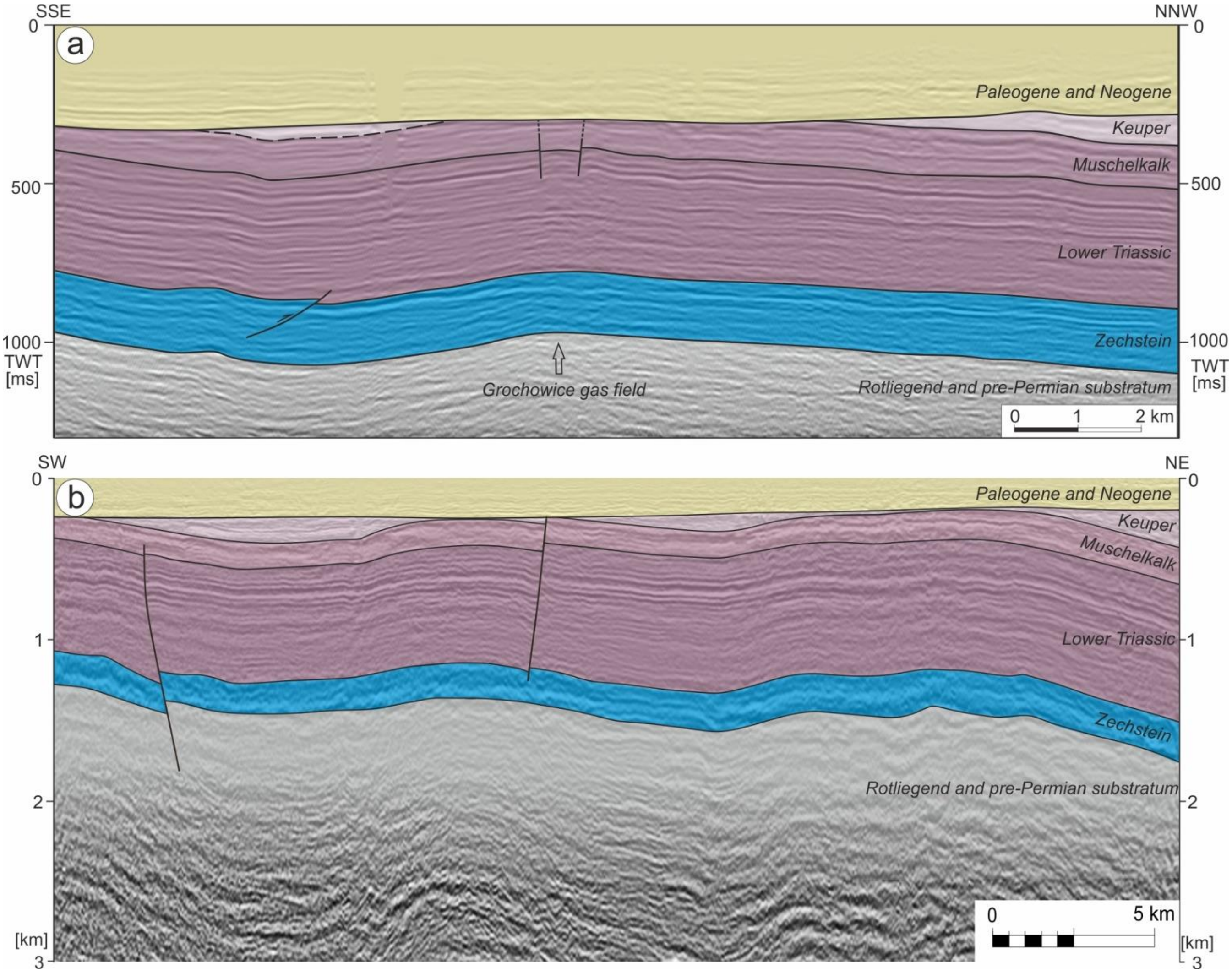


Figure 3: Schematic regional cross sections across the Bohemian Massif NE margin (highly vertically exaggerated). Location in Figure 2.



685 **Figure 4: Two seismic profiles from the Fore-Sudetic Homocline (location in Figure 2) showing very gentle folds in Triassic and Permian (Rotliegend not marked). Note steep to low-angle mainly reverse faults. The anticlines are structural traps for hydrocarbons, with gas fields known in Rotliegend strata (e.g. Grochowice gas field in Figure 4a). Please note the different scales of the two profiles.**

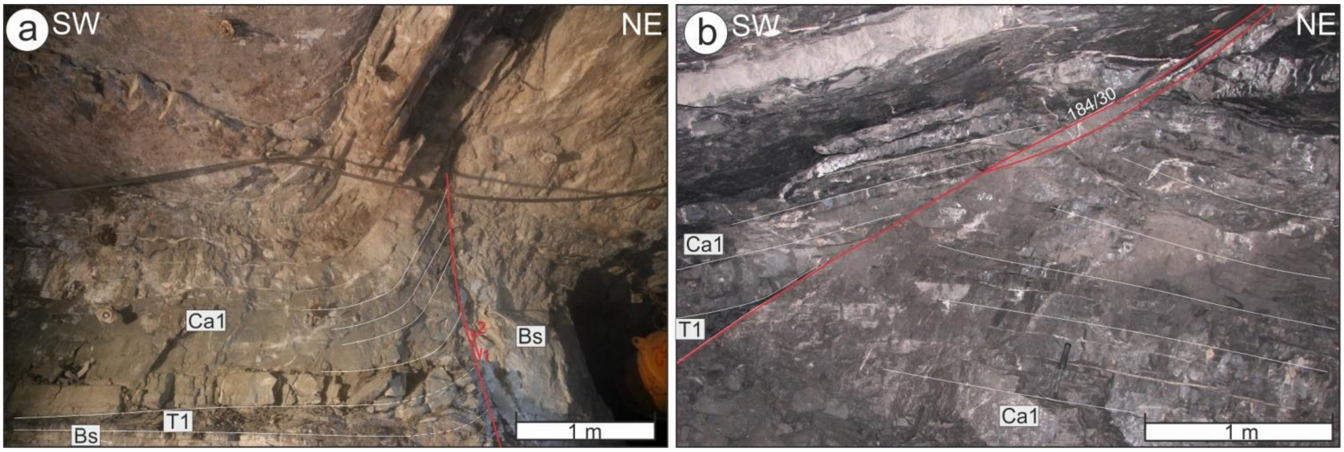


Figure 5: Examples of tectonic structures observed on galleries` walls in copper and silver mines on the Fore-Sudetic Homocline at the base Zechstein ore-bearing formation (location in Figure 2). (a) Inverted steep fault, originally normal. The inversion caused fault-drag of Ca1 Zechstein Limestone. (b) Thrust fault in carbonate rock. Abbreviations: Bs- Weissliegend Sandstone, T1-Kuppferschiefer Shale, Ca1-Zechstein Limestone.

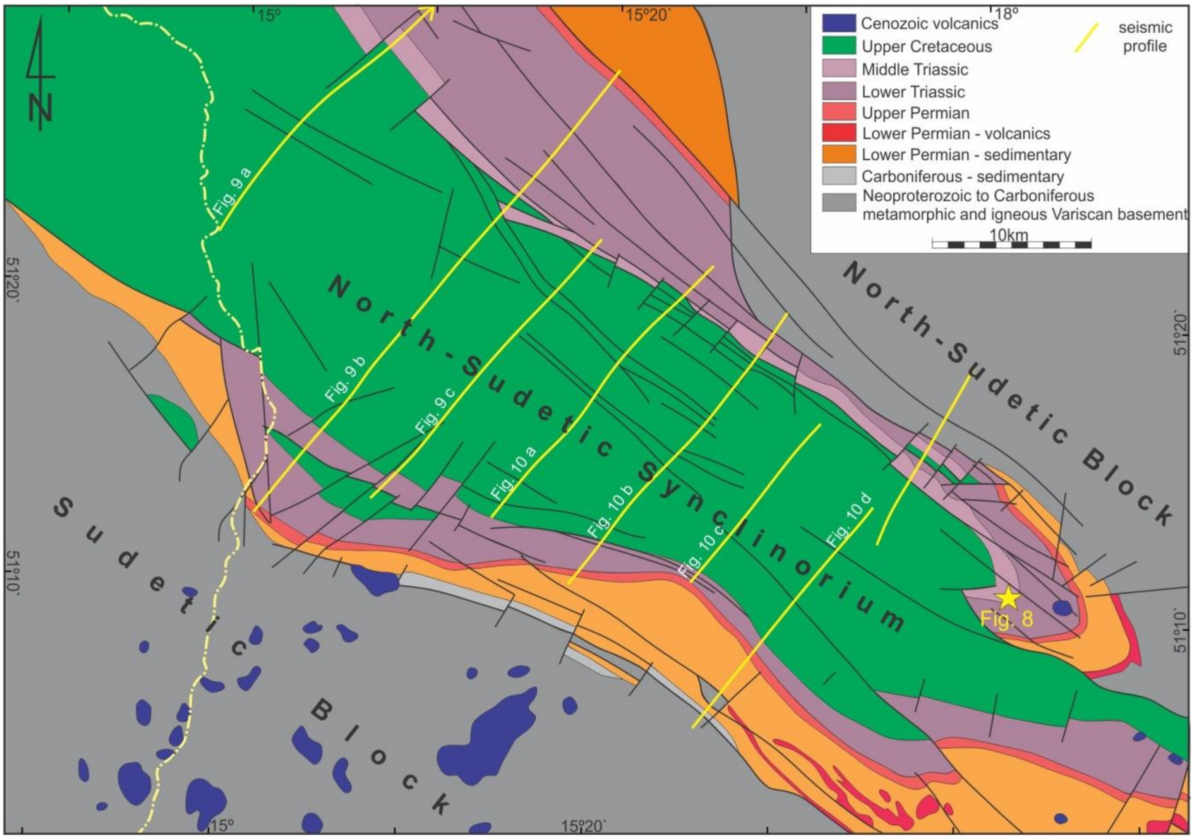


Figure 6: Geological map of the North Sudetic Synclinorium (based on Bałazińska and Bossowski, 1979; Krentz et al., 2001 and Cymerman, 2010). Locations of interpreted seismic profiles are shown. For full-length location of seismic profile of Figure 8a - see Figure 2. The map is based on Solecki (1994) and Cymerman (2010).

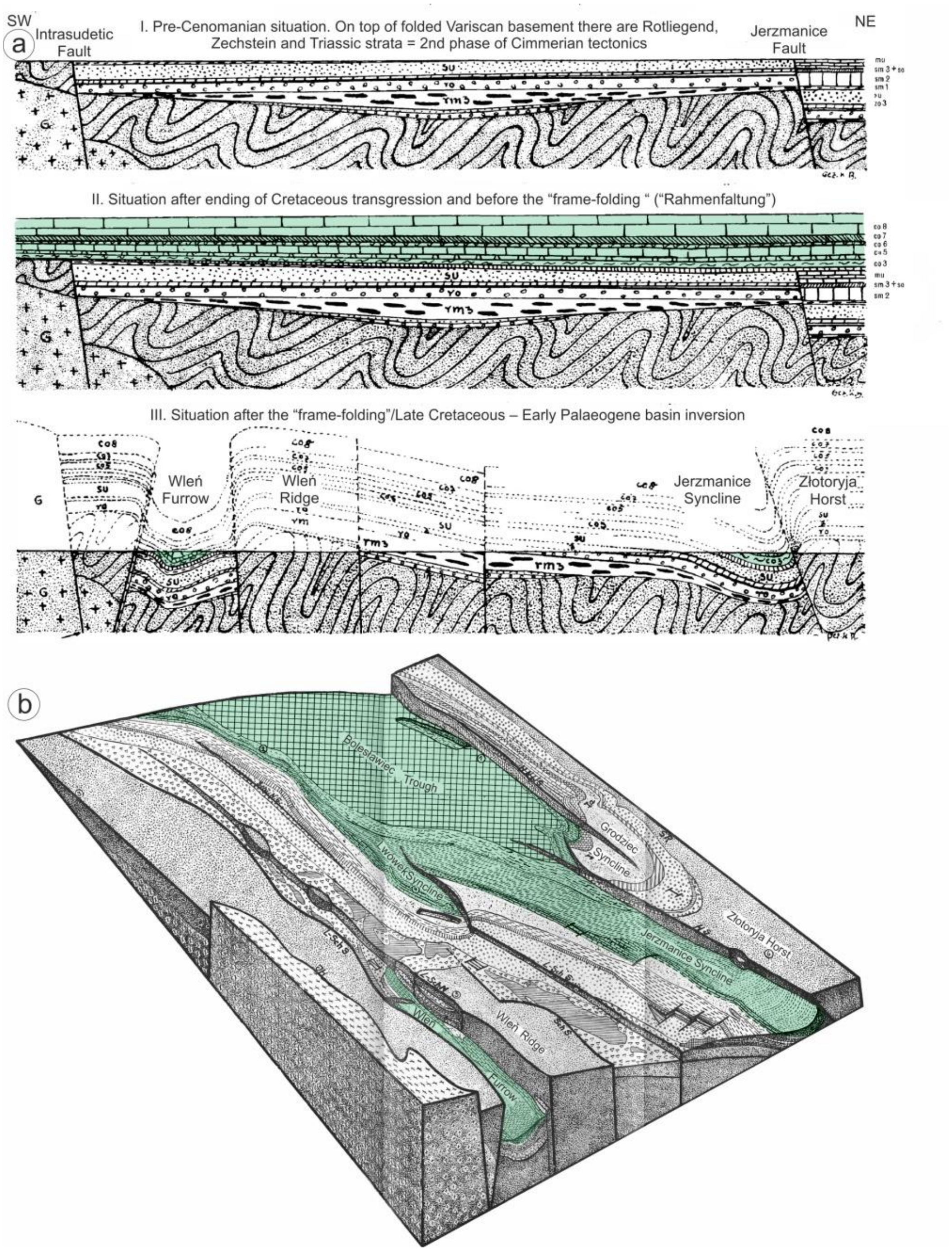


Figure 7: Kurt Beyer's (1939) interpretation of the "young Saxonian" tectonics in the North Sudetic Synclinorium (Basin).

700 (a) Main tectonic deformation stages in the North Sudetic Basin. (b) Block-diagram showing simple open structure of the western part of the North Sudetic Synclinorium and complex pattern of blocks and synclinal grabens in its eastern part.

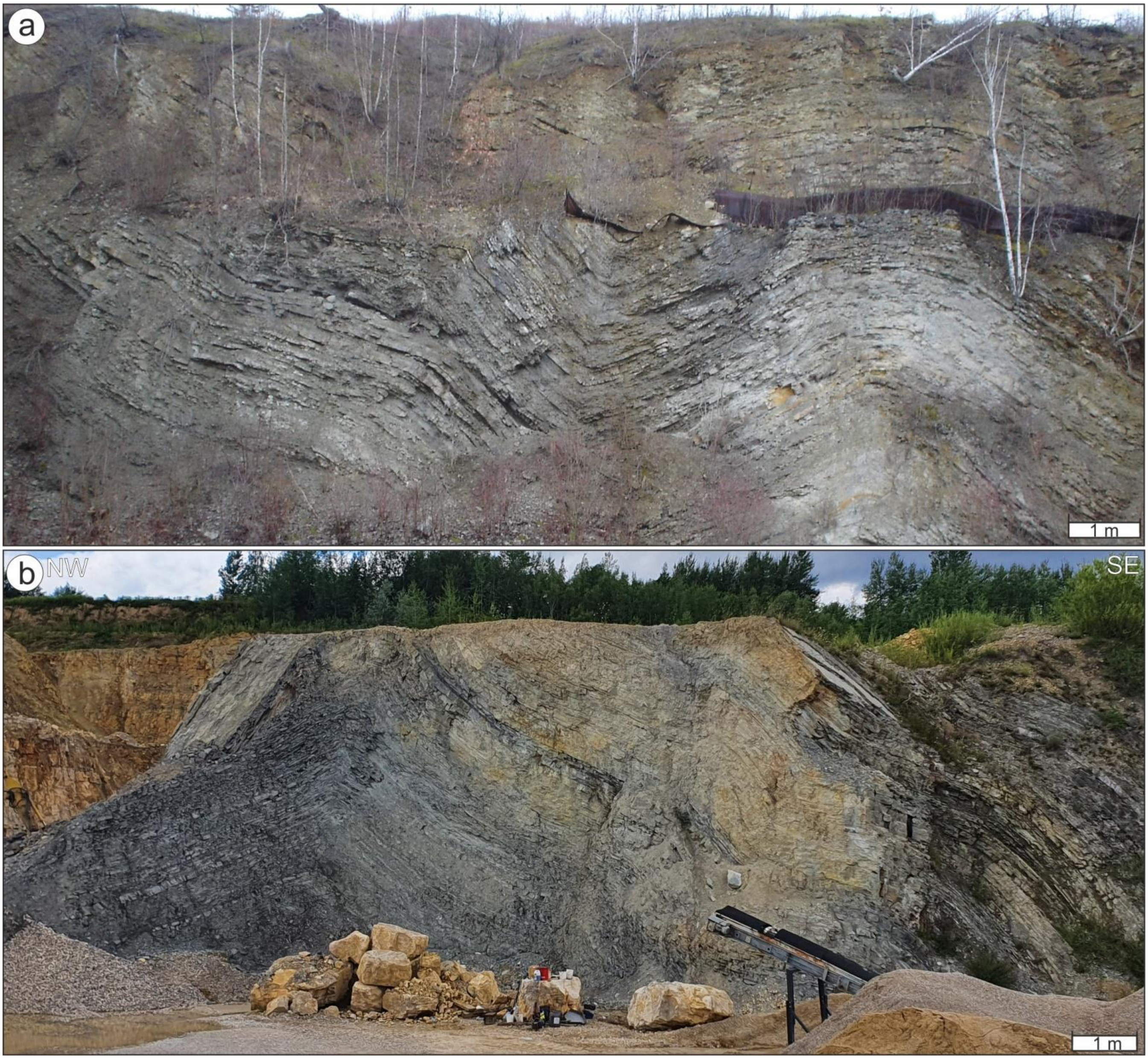


Figure 8: Folds in Muschelkalk in a quarry at Raciborowice (location given in Figure 6). (a) photo courtesy of Andrzej Solecki.

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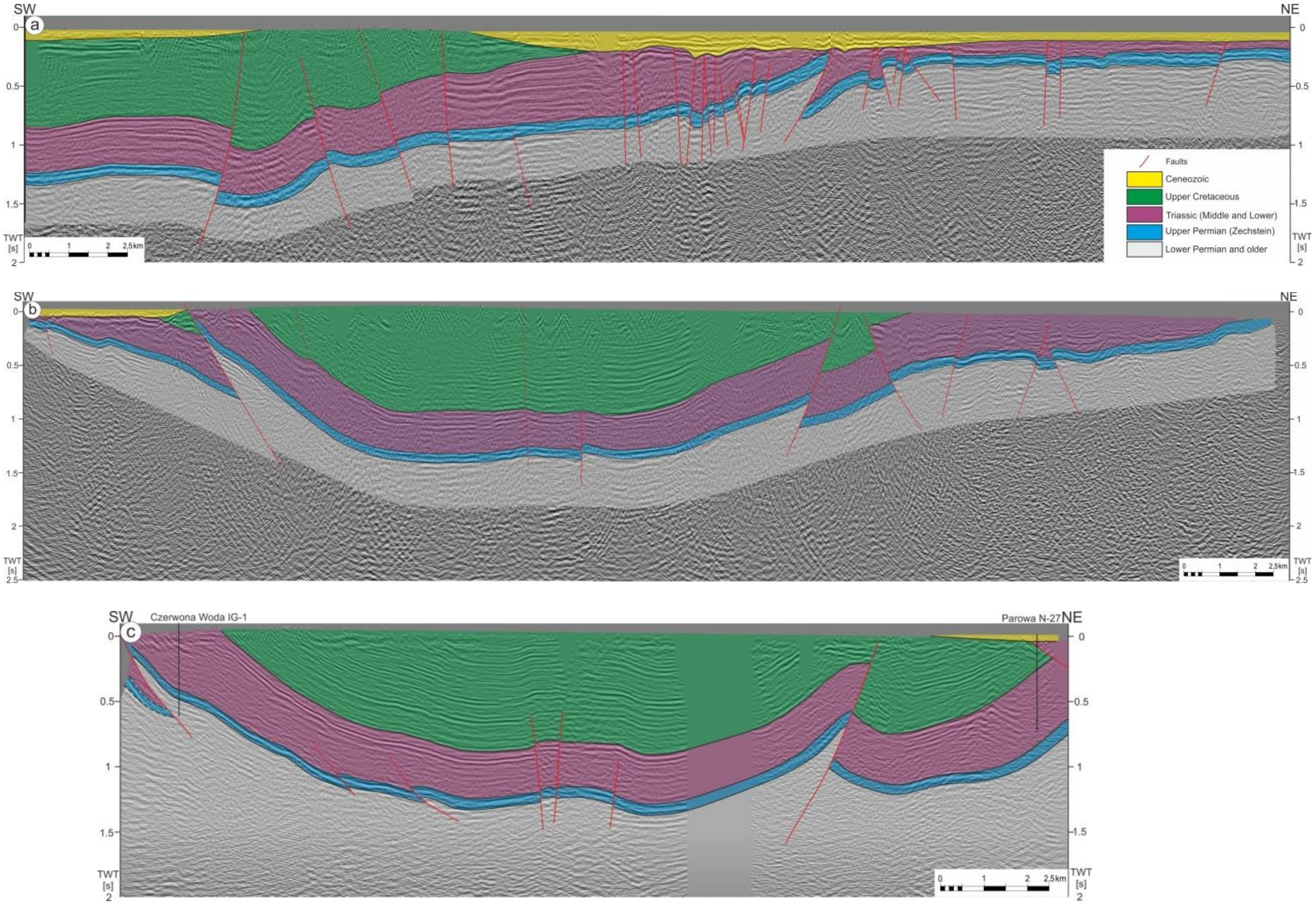

Figure 9 a-c: Interpreted seismic profiles from the North-Sudetic Synclinorium (location in Figure 6).

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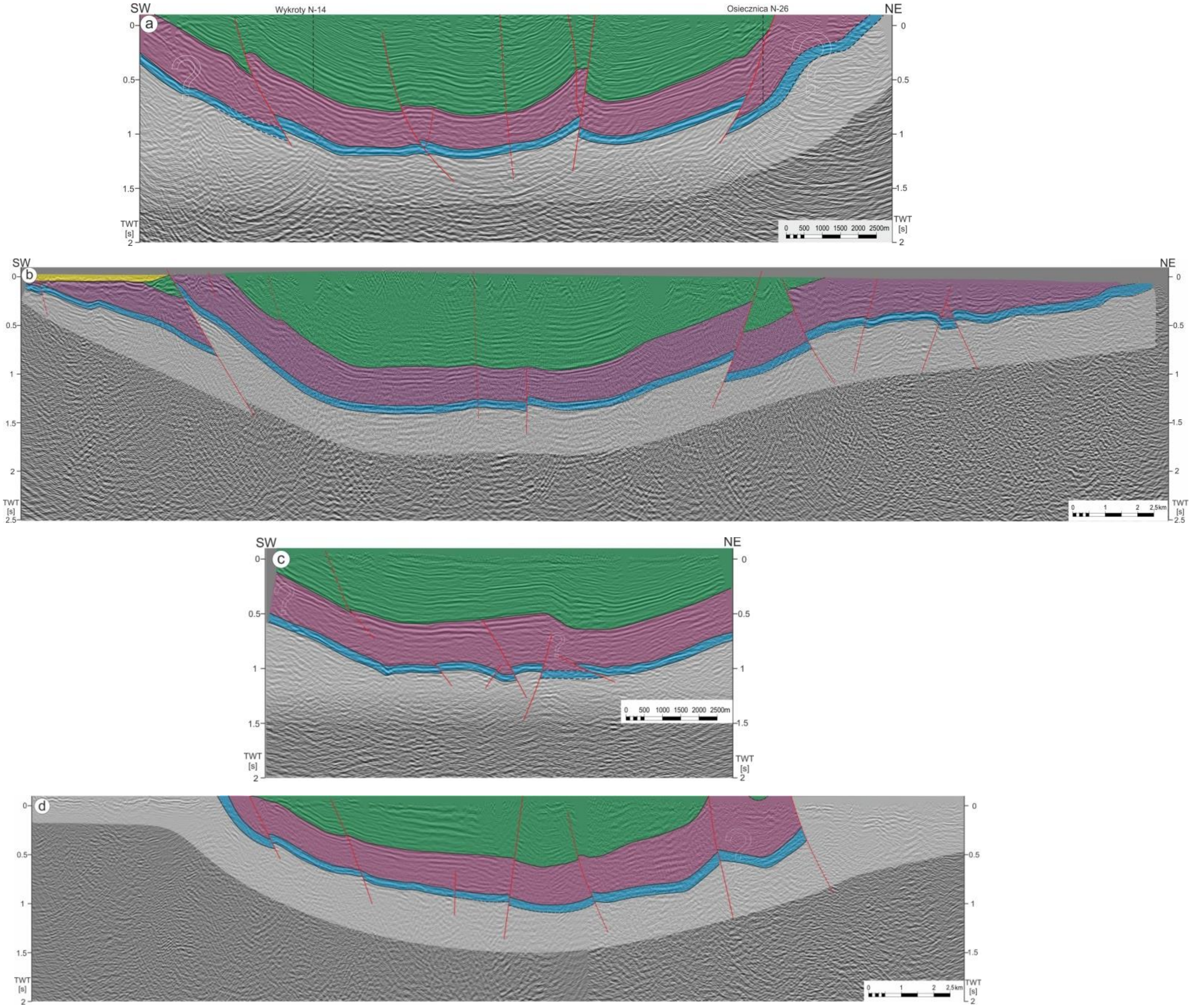

Figure 10 a-d: Interpreted seismic profiles from the North-Sudetic Synclinorium (location in Figure 6).

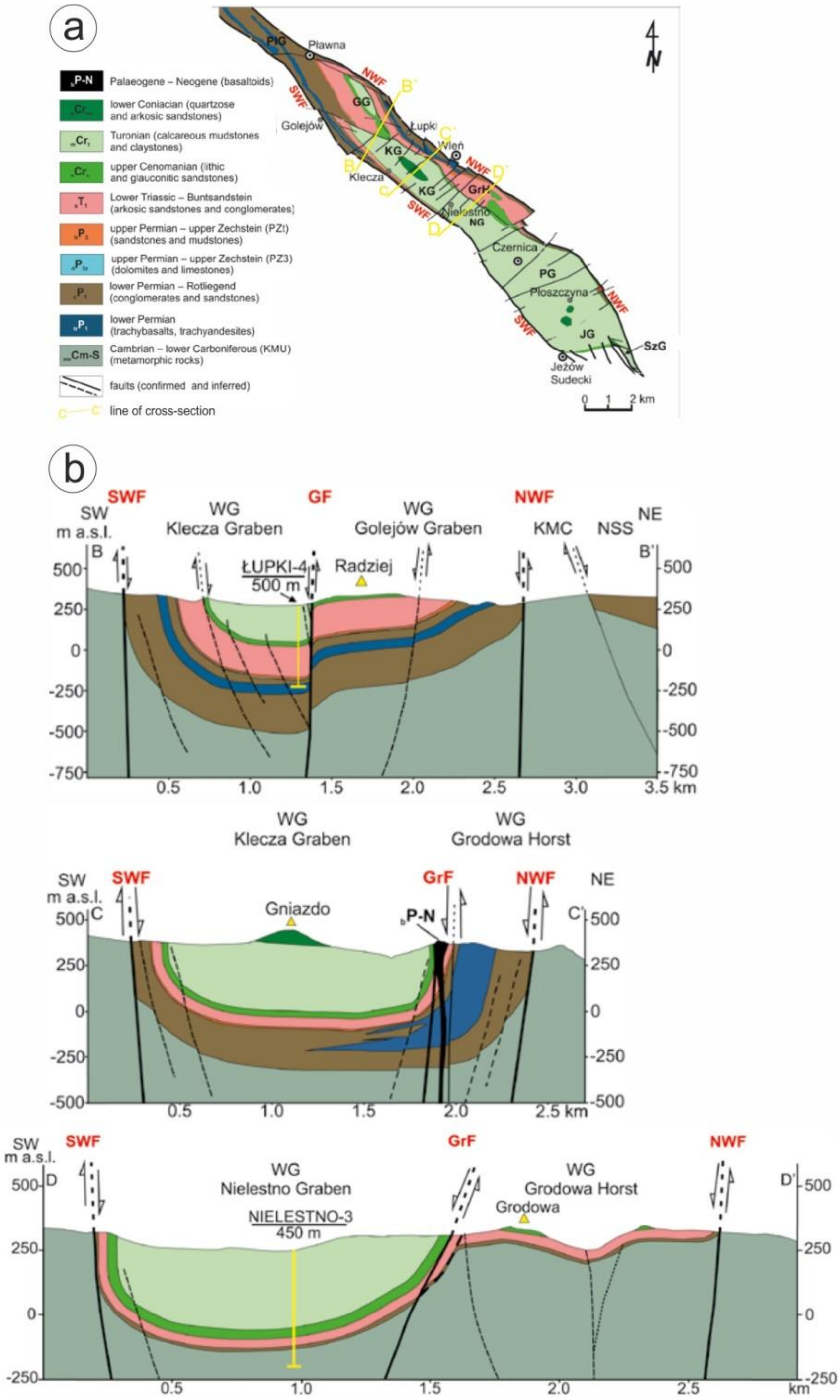

Figure 11: Simplified geological map and cross-sections of the Wleń Graben according to Kowalski (2020)

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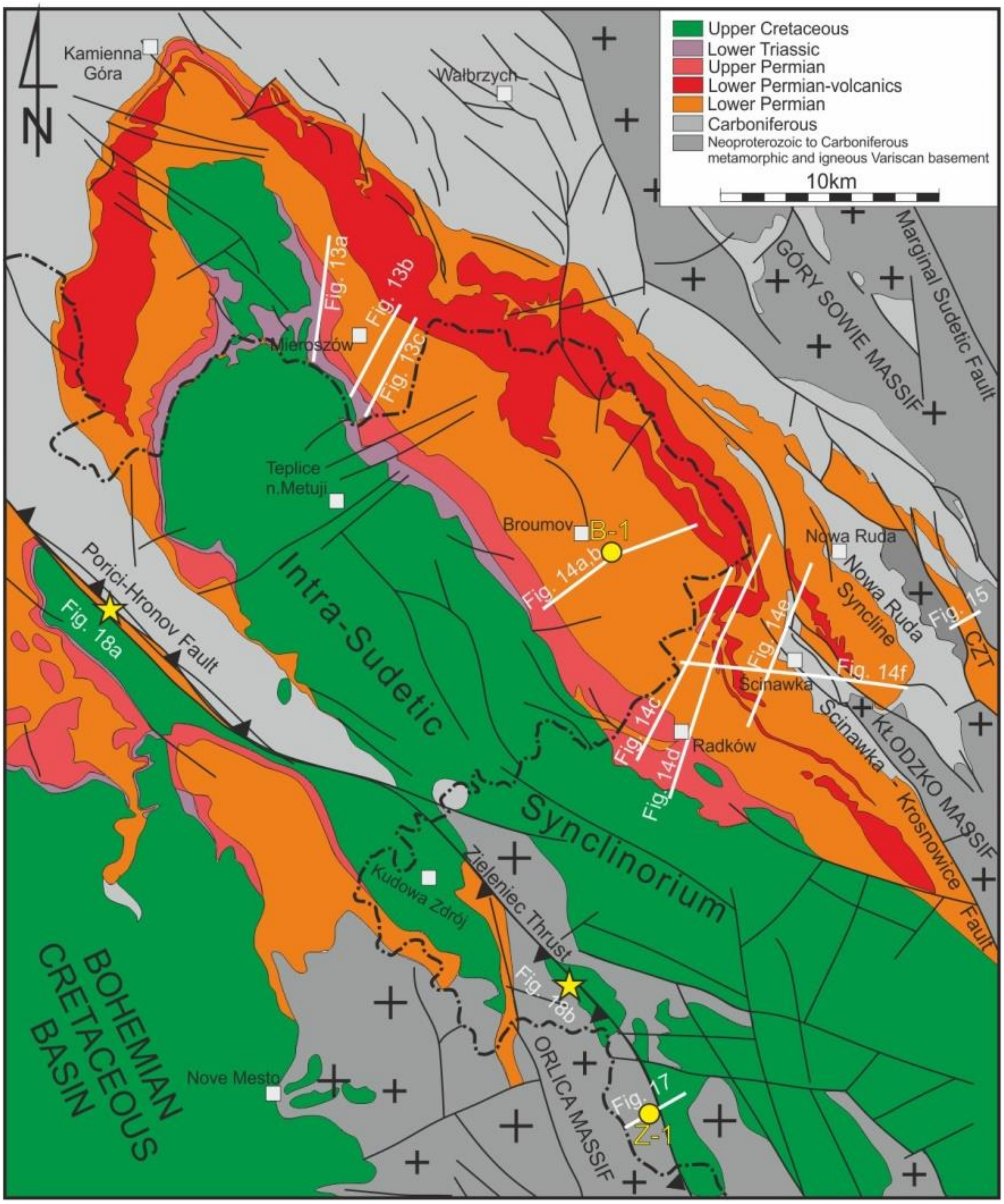

Figure 12: Geological map of the Intra-Sudetic Synclinorium (based on Grocholski and Augustyniak, 1971, Bossowski and Ihnatowicz, 2006, and Cymerman, 2010). Location of the interpreted seismic profiles and described localities is shown. CZT – Czerwieńczyce Trough (inverted graben).

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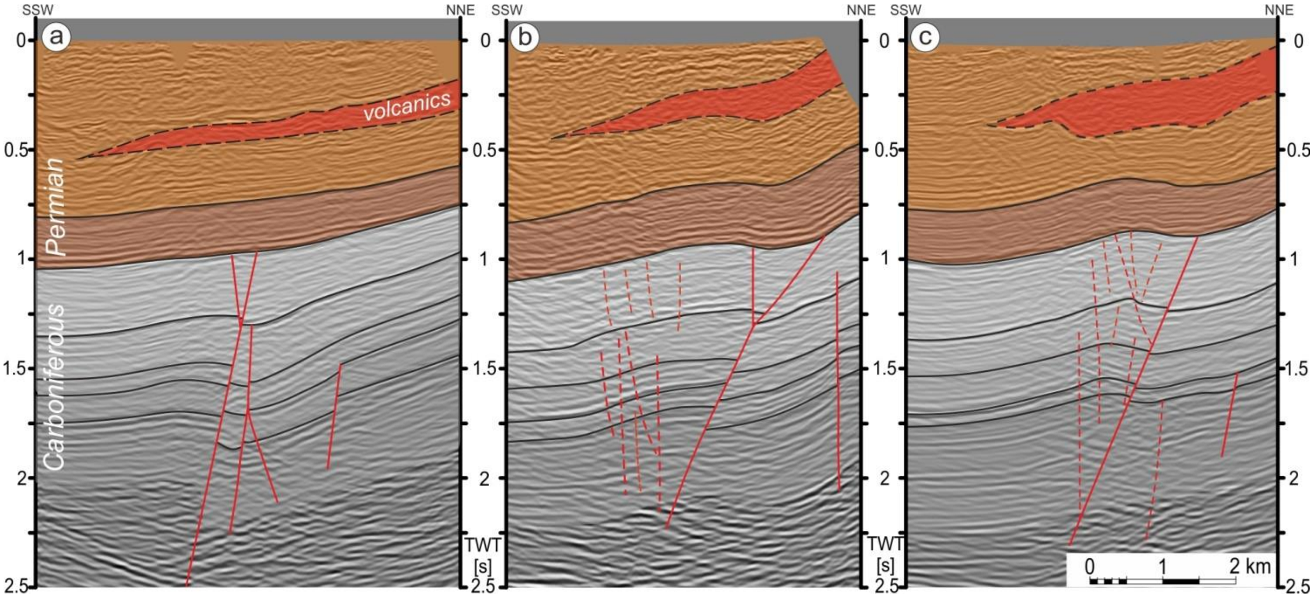

730 **Figure 13: Seismic profiles from Mieroszów vicinities showing probable effects of Late Cretaceous – Early Palaeogene reactivation of a Carboniferous flower structure. The Permian volcanic member(red) continues to the NNE to outcrop massively in the Suche Mountains. Location is given in Figure 12.**

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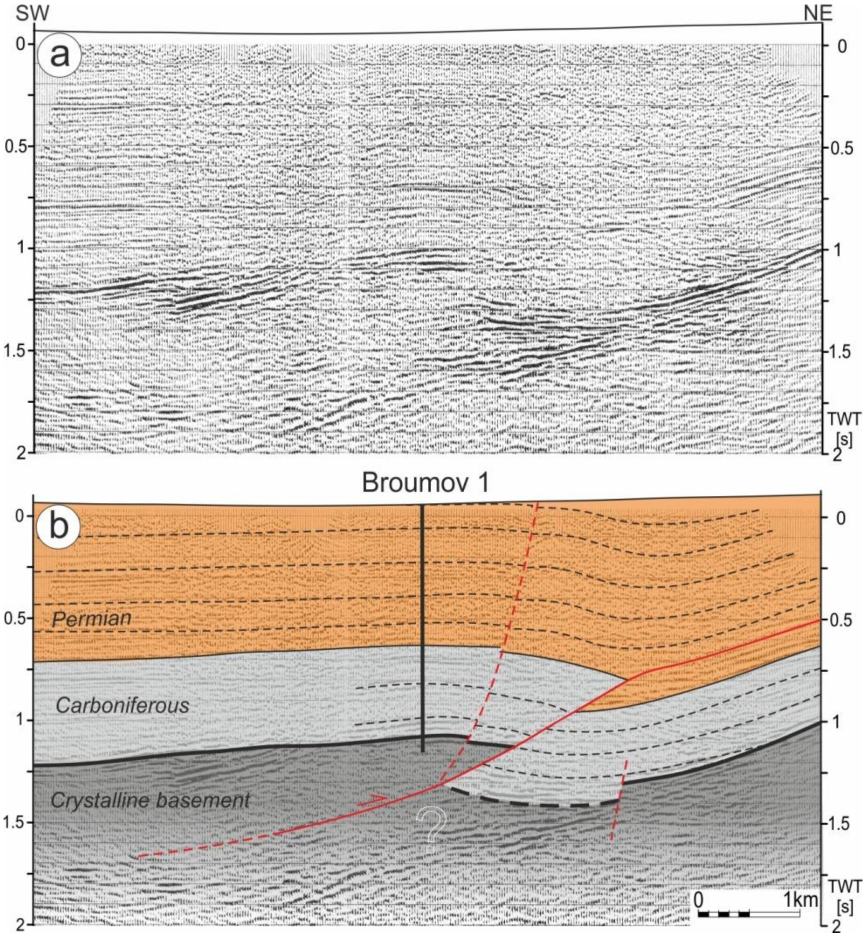

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Figure 14 a,b: (a) Seismic profile from vicinities of Broumov and its interpretation (made on printed paper version – Brada et al., 1982).Location in Fig. 12. The section shows that the Broumov well was drilled in the hanging-wall of a thrust fault and, hence, the Carboniferous in the neigbourhood may occur deeper than found in the well. The thrust continues to the NE parallel to the bedding – most probably along the Permian Anthracosia Shale member.

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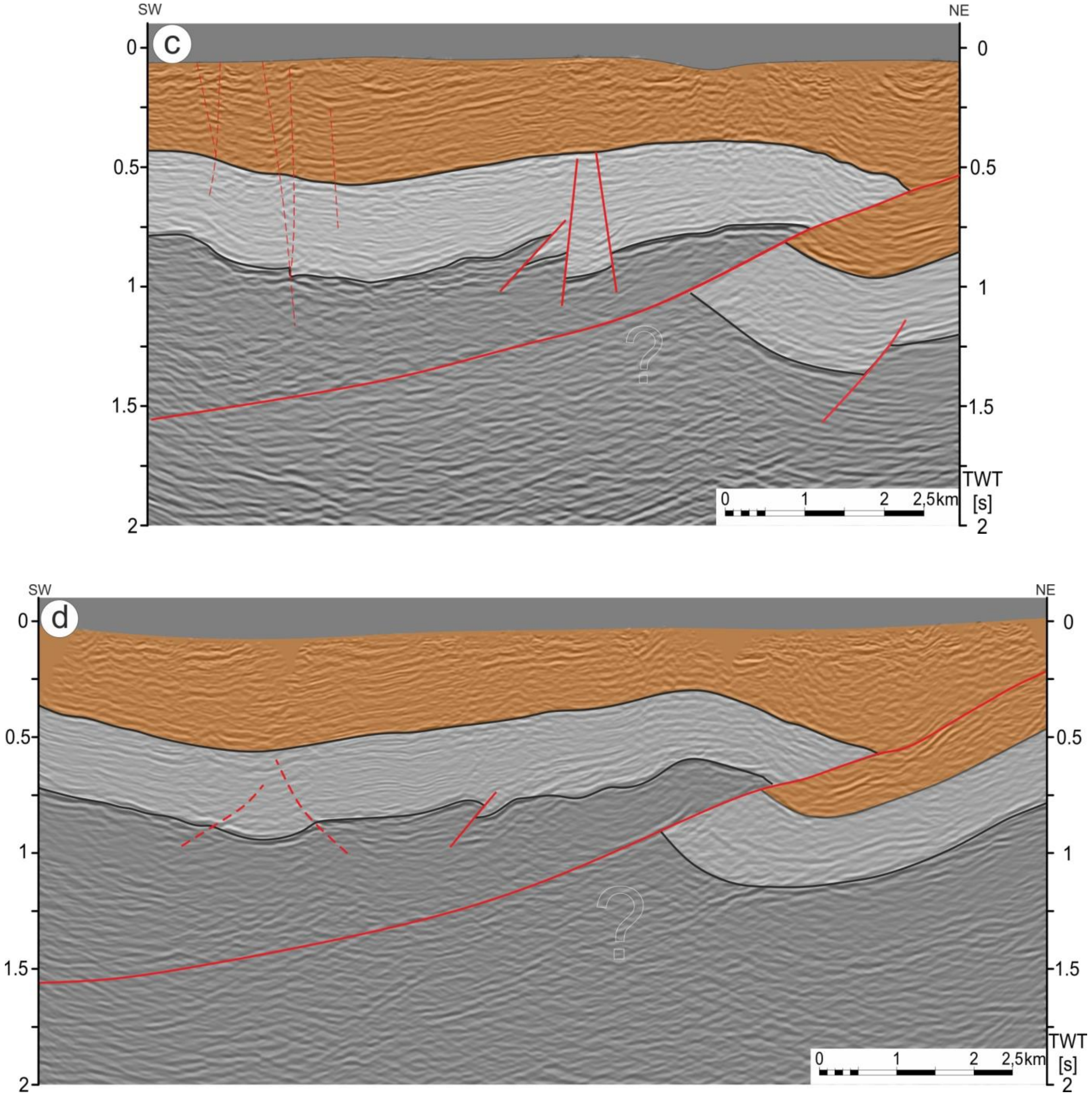
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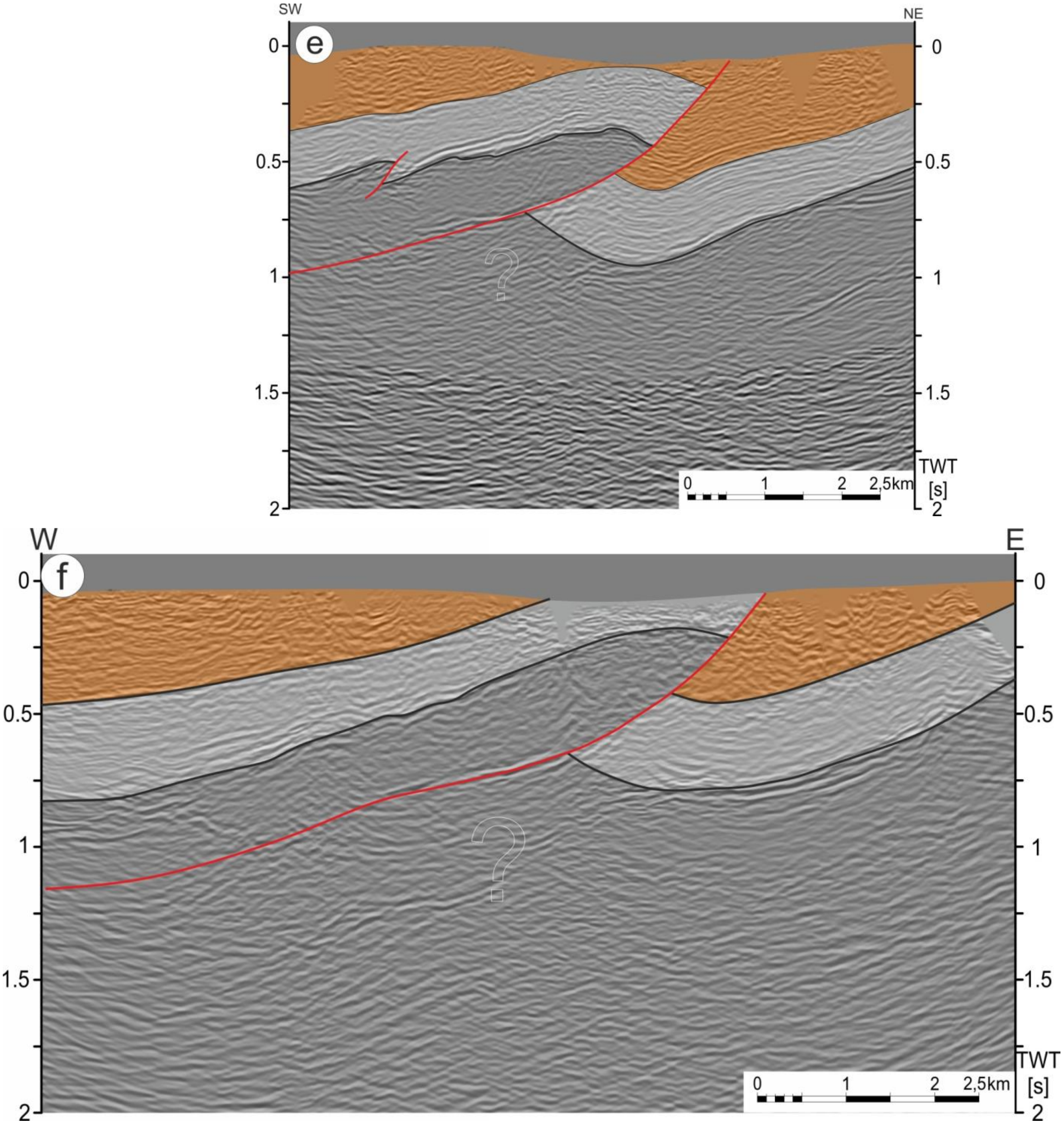


Figure 14 c-f: Seismic profiles from vicinities of Radków. Location in Fig. 12.

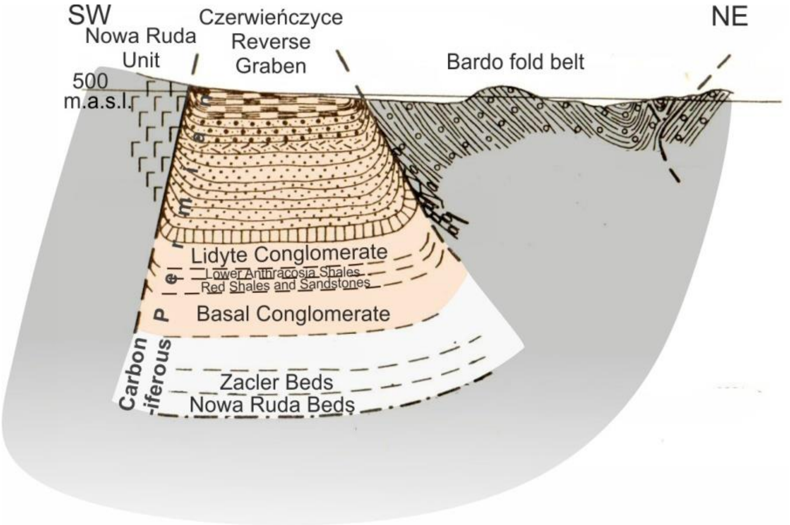


Figure 15: Geological cross- section of the Czerwieńczyce Reverse Graben after Oberc (1972). Location in Fig. 12.

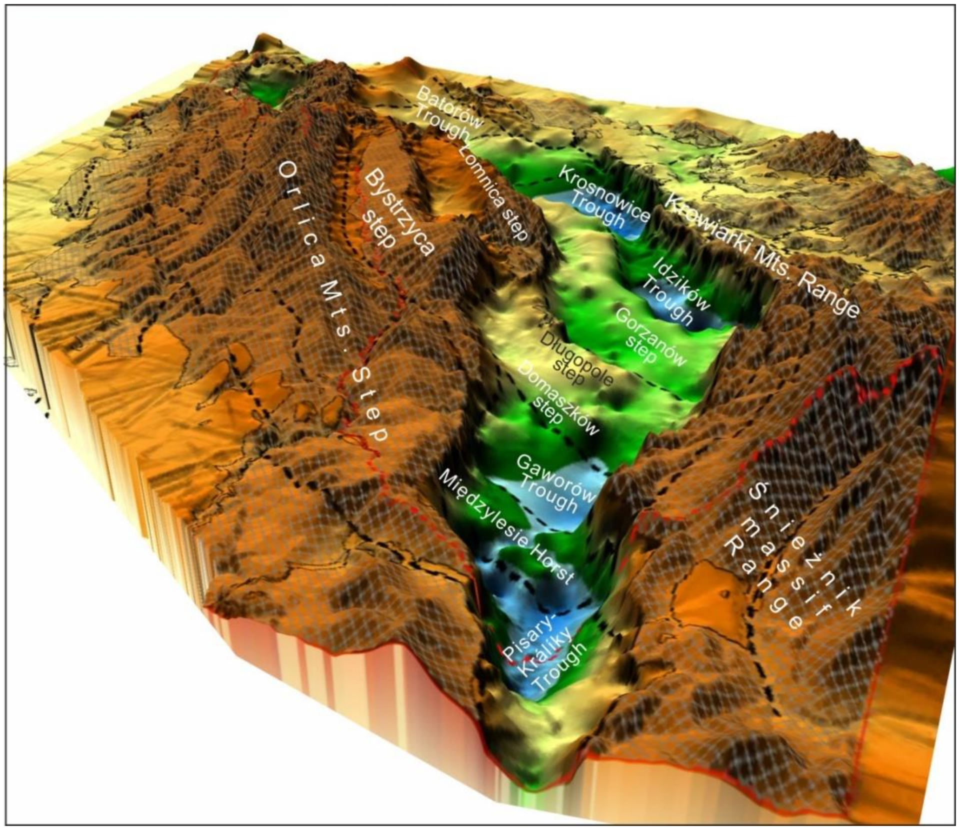


Figure 16: Perspective view towards the north onto the base Cretaceous relief (known from boreholes) in the Upper Nysa-Králiky Graben (from Badura and Rauch, 2014). The oblique-striking blocks reflect NW-SE trending Late-Cretaceous – Early Palaeogene inverted blocks on the Cretaceous graben floor and folds in its fill (removed from the picture), once continuing laterally, before the graben formed in Miocene times. Location given in Fig. 2.

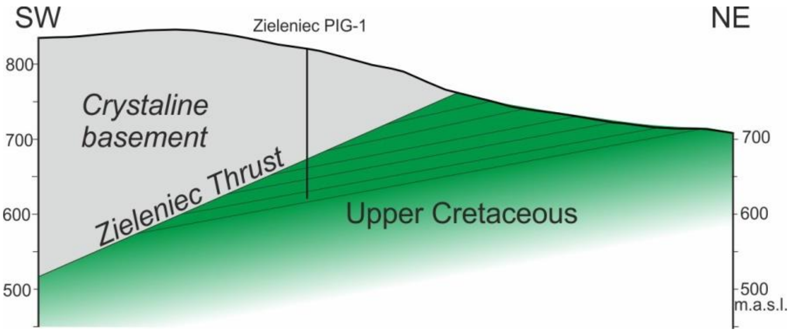


Figure 17: Schematic section across the Zieleniec Thrust (based on data from Cymerman, 1990, and Kozdrój, 2014). Location in Fig. 12.

Figure 18: Examples of outcrop-scale brittle structures related to major faults at the SW boundary of the Intra-Sudetic Synclinorium.

(a) The Pořiči-Hronov Fault, interpreted as high-angle reverse one, near the village of Malé Svatoňovice: tectonic contact between nearly vertically dipping Upper Cretaceous sandstones in the SW and the Permian sandstone in the NE.

(b) Shallow NW-dipping detachment along the bedding of Middle Turonian mudstones and calcareous claystones in a road cut near the village of Lewin Kłodzki, probably related to the NW continuation of the Zieleniec Thrust. Location given in Fig. 12.

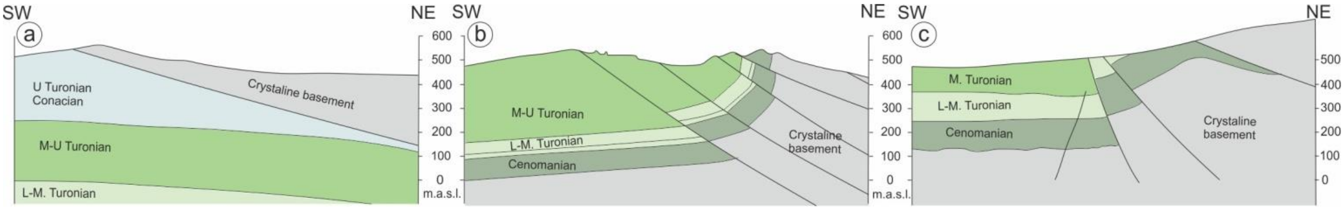
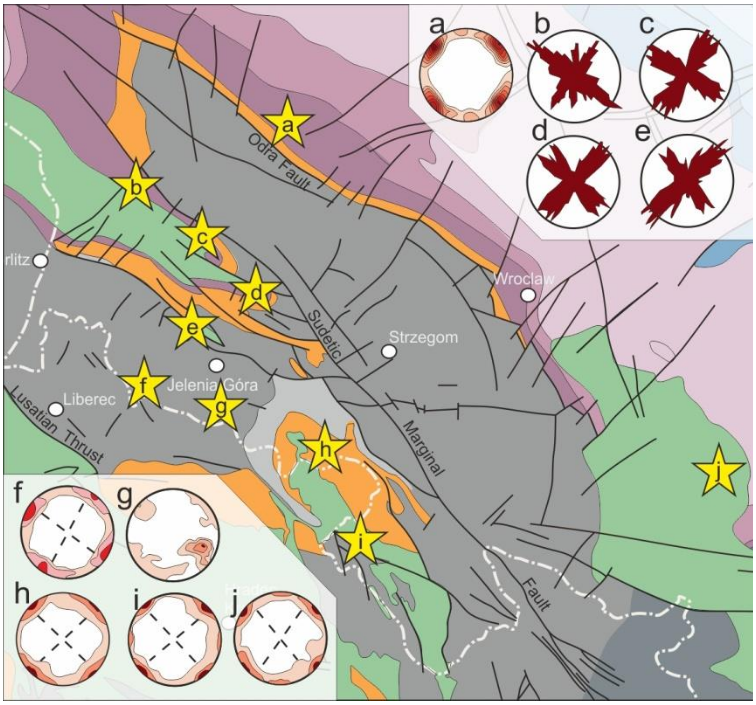


Figure 19: Schematic sections across the Lusatian Thrust in three localities, showing along-strike stucture changes (based on Coubal et al., 2014). Location in Fig. 2.



770 **Figure 20: Comparison of stereograms and rose diagrams of the dominant steep joint sets coming from several local studies (by Jerzykiewicz et al., 1974, Aleksandrowski, 1976, Solecki, 2011, Selerowicz et al., 2014) made at various locations in the Polish Sudetes. Background: the geological map of Figure 2.**