



Late Cretaceous–early Palaeogene inversion-related tectonic structures at the northeastern margin of the Bohemian Massif (southwestern 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 Sudety Mountains 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 in the two main post-Variscan structural units of the area: the North Sudetic and Intra-Sudetic synclinoria. The results were discussed together with regionally distributed examples of tectonic structures from quarries and underground mines as well as those known from the literature. The Late Cretaceous–early Palaeogene tectonic structures in consecutively reviewed Sudetic tectonic units, from the north to the south, typically include gentle to moderately tight buckle folds, locally of detachment type or fault-related and high-angle reverse and normal faults, as well as low-angle thrusts – often rooted in the crystalline basement. The structures termed grabens in the local literature are at the same time frequently interpreted as bounded by reverse faults (hence we use here the term “reverse grabens”) and typically reveal a strongly synclinal pattern of their sedimentary fill. The top of the crystalline basement, as imaged by seismic data in the North Sudetic Synclinorium below the faulted and 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 tectonically up-warped

(i.e. antiformally buckled). The compressional structures typically show an orientation that fits the regionally known Late Cretaceous–early Palaeogene tectonic shortening direction of NE–SW to NNE–SSW. The same applies to the regional jointing pattern, typically comprising an orthogonal system of steep joints of ca. NW–SE and NE–SW strikes. All the reviewed structures are regarded as being 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 late Cenozoic tectonism.

1 Introduction

During Late Cretaceous to early Palaeogene times, compressional tectonic structures developed over vast areas of western and the northern part of central Europe (e.g. Ziegler, 1987; Ziegler et al., 1995; Navabpour et al., 2017; Kley, 2018; Nádaskay et al., 2019; Malz et al., 2020; Voigt et al., 2021). They are currently interpreted as being due to collisional interaction of the Iberian mass with continental Europe and the resultant propagation of far-field compressional stress (Kley and 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 (Fig. 1) are mostly NW–SE-trending, large-scale, gentle folds up to 1000 km long, ca. 150 km wide and up to at least 3 km high

(e.g. Pożaryski, 1979). The Mid-Polish Swell (or Anticlinorium), spanning the entire length of Poland's NW–SE diagonal from the Baltic Sea to westernmost Ukraine, is the most spectacular example of such a structure. To the SW of the Mid-Polish Swell there is the Szczecin–Łódź Trough (Synclinorium) and a successive elevated structural element, occurring at the NE margin of the Bohemian Massif, in the borderland between Poland and Czechia. This complex element combines the Fore-Sudetic Homocline and the Sudetic area, composed of the Fore-Sudetic and Sudetic blocks (Fig. 1). The latter tectonic units are the principal object to be presented in this paper, the goal of which is to give a brief overview of 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.

An important part of this review is based on recently reprocessed legacy seismic data from the central areas of the Sudetic region. The other presented examples of tectonic structures supply the wide regional context for the seismic results and come either from our own field work 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 in the Permo-Mesozoic strata obviously must have developed also in the Variscan basement, they are – in general – difficult to distinguish from the older structures. Therefore, the scope of this paper is mostly limited to the tectonic phenomena that occur in the post-orogenic (post-Variscan) Permo-Mesozoic strata, though, in places also in the late-orogenic upper Carboniferous. An overview of the Late Cretaceous–early Palaeogene deformation structures in the Sudetic area is presented in this paper, mostly in their regional context and in reference to particular structural units of the Sudetes, moving from the north to the south across the area.

2 Geological outline

The Sudetes (Polish and Czech name: *Sudety*), 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 – have for decades usually been considered collectively as the Sudetic area or region or simply as the Sudetes (e.g. Aleksandrowski and Mazur, 2002; Mazur et al., 2006; Kroner et al., 2008). The differences in topography – mountainous versus lowland – are due to the splitting of the Sudetic area into two tectonic blocks: the currently downthrown and mostly flat or hilly Fore-Sudetic Block in the northeast and the elevated, mountainous Sudetic Block in the southwest (Fig. 1). The Sudetes constitute the northeasternmost segment of the Central European Variscan internides, exposing crystalline basement of strongly deformed and meta-

morphosed late Neoproterozoic to Carboniferous rocks abundantly intruded by Carboniferous granites (e.g. Mazur et al., 2006, 2007, 2020). The Variscan Orogenic Belt formed in Europe in approximately Middle Devonian to late Carboniferous times and currently extends from Portugal and Spain across Britain, France and Germany to Czechia and Poland. It continues further to the southeast to Romania and Anatolia and is also represented by numerous dismembered internal massifs within the Alpine–Carpathian orogenic system. Its formation was contemporaneous with the Acadian and Alleghenian orogenies in the Appalachians, whose particular major tectonostratigraphic zones define links to those of the European Variscan Belt across the Atlantic (e.g. Matte, 2001; Martínez Catalán et al., 2002; Kroner et al., 2008). In the Sudetes, the main tectonostratigraphic domains of the European Variscides (the Moldanubian, Teplá–Barrandian and – particularly – Saxothuringian) find their continuation (e.g. Martínez-Catalán et al., 2020).

The Variscan basement rocks are partly overlain by syn- to late-orogenic Carboniferous intramontane basins and remnants of the now much eroded post-orogenic Permo-Mesozoic sedimentary-volcanic cover. To the north, in the North Sudetic Synclinorium, there occur lower Permian red beds with volcanics and upper Permian Zechstein facies carbonates, sulfates and clastics, averaging ca. 1000 m in thickness. The Lower Triassic Buntsandstein of variegated sandstones, totalling ca. 600 m in thickness, is capped by Röt dolomites and later Keuper evaporites and Muschelkalk limestones (e.g. Baranowski et al., 1990; Chrzastek and Wojewoda, 2011). To the south, in the Intra-Sudetic Synclinorium, lower Permian red beds and shales with volcanics up to 1250 m thick are followed by upper Permian, mostly fluvatile sedimentary rocks. The Lower Triassic is represented by the Buntsandstein facies, which does not exceed a few tens of metres in thickness (e.g. Dziedzic and Teisseyre, 1990). The Sudetic area is described in the literature to have been emergent in its most part during the Triassic (e.g. Feist-Burkhardt et al., 2008). In the Jurassic and Lower Cretaceous times the Sudetes must have also remained emergent, as no Jurassic and Lower Cretaceous strata are known from the area. In the Late Cretaceous, however a system of sedimentary basins formed along reactivated Variscan, mostly NW–SE-trending shear and fault zones over the northern Bohemian Massif, accumulating an at least 1000 m thick succession of shallow marine sediments (e.g. Wojewoda, 1997; Scheck et al., 2002; Uličný et al., 2009). The Intra- and North Sudetic Synclinoria were filled with Cenomanian, Turonian, Coniacian and Santonian sandstones, marls and siltstones (Wojewoda, 1997).

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 an area mostly planated during Palaeogene and early Miocene times, following the earlier, Late Cretaceous–early Palaeo-

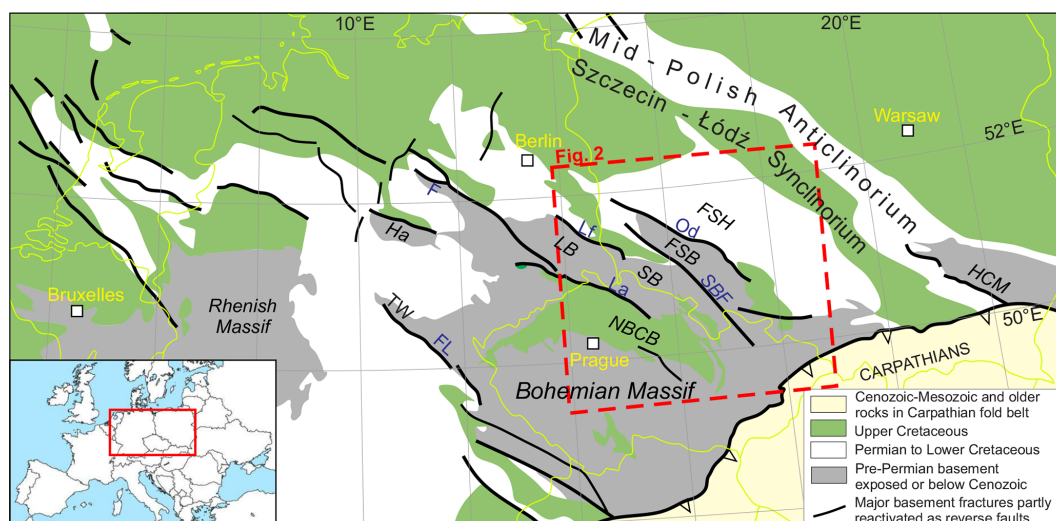


Figure 1. The main Late Cretaceous–early Palaeogene tectonic structures in central Europe. Modified after Kley and Voigt (2008). Abbreviations: F – Flechtingen High; FL – Franconian Line; FSB – Fore-Sudetic Block; FSH – Fore-Sudetic Homocline; Ha – Harz Block; HCM – Holy Cross Mountains; La – Lusatian Thrust; LB – Lusatian Block; Lf – Lusatian Main Fault; NBCB – North Bohemian Cretaceous Basin; Od – Odra Fault; TW – Thuringian Forest; SB – Sudetic Block; SBF – Sudetic Boundary Fault.

gene more prominent uplift, which at that time had occurred over a broader area, including also the Fore-Sudetic Block (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 that occurred concurrently with or slightly postdated the trans-European compressional event related to the Africa–Iberia and western to north-central Europe convergence at ca. 86–70 Ma (Kley and Voigt, 2008) exhumed the Variscan basement from below the post-Variscan, uppermost Carboniferous through Permo-Mesozoic cover and left the entire Sudetic area tectonically elevated with respect to the adjoining depressed areas: the Fore-Sudetic Homocline to the northeast and the North Bohemian Cretaceous Basin to the southwest. Within both these tectonic units much of the deformed Permo-Mesozoic post-Variscan sedimentary fill has been preserved. Among the Late Cretaceous–early Palaeogene contractional structures in the Sudetes that have escaped erosion, are the North and Intra-Sudetic synclinoria, representing the largest objects of that kind (Fig. 2). For over a century, the Sudetes have been considered a part of the classical area in central Europe, in which the term “Saxonische Tektonik” (compare to Kley, 2013) was applied to deformation structures, mostly fault-related, observed in the Permo-Mesozoic sedimentary basins. 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 the authors’ own analysis and structural interpretation of the newly reprocessed seismic reflection data located in the two key areas in the Sudetes containing the most complete post-Variscan sedimentary record and (2) on structural field data of the present authors or (3) on data coming from critically assessed literature descriptions. We have also used data from exploration boreholes drilled in the last 5 decades, prospecting for copper and coal deposits in the North Sudetic and Intra-Sudetic synclinoria, respectively.

The analysed seismic data were acquired by mining and oil companies in the late 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 printouts. These seismic data are unique at the scale of the entire Sudetes and the source of valuable information on the structural geology of the Permo-Mesozoic succession in both main Sudetic synclinorial units.

The reprocessing of, in total, ca. 650 km of 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 the pre-stack time migration stage (PreSTM) procedure was also applied to some of the profiles. No time–depth conversion was, however, attempted because of too scarce a coverage of the area with appropriate drill hole data. As complementary

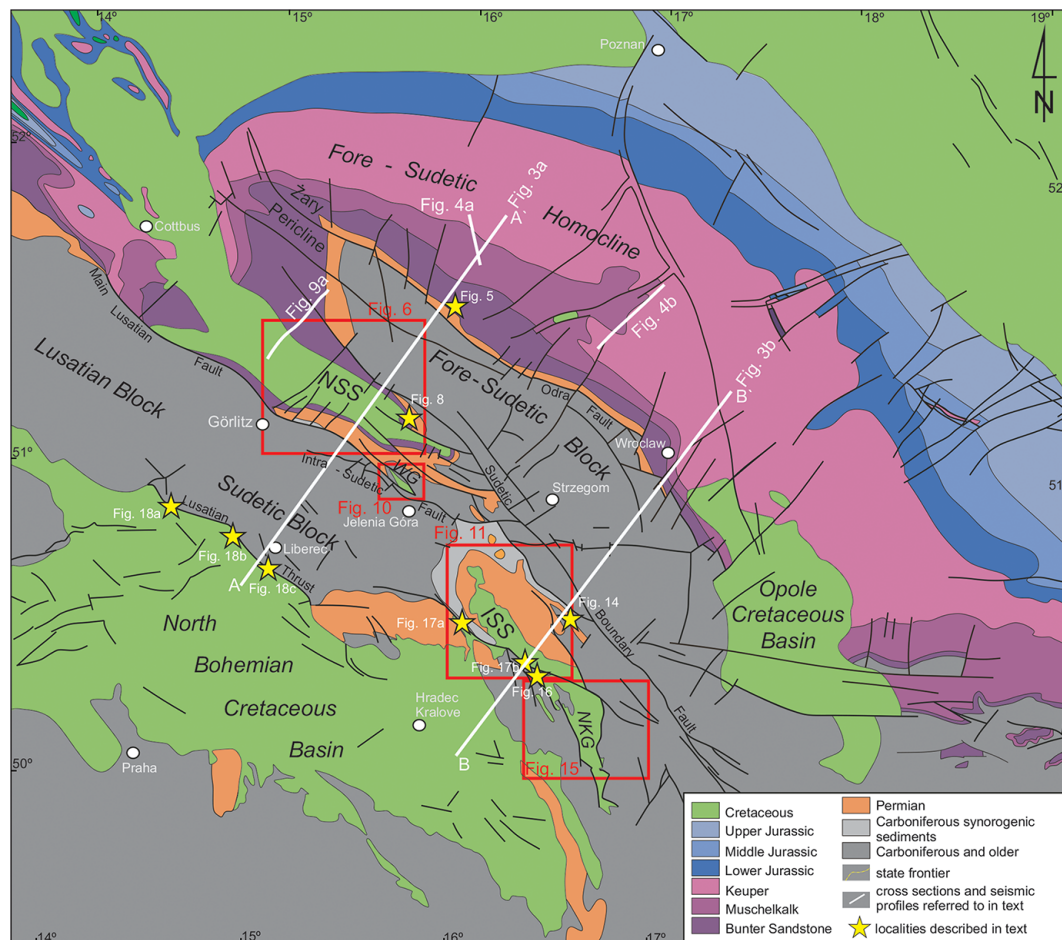


Figure 2. Geological map without Cenozoic of NE margin of the Bohemian Massif and its surroundings in SW Poland and N Czechia (simplified after Dadlez et al., 2000). ISS – Intra-Sudetic Synclinorium; NKG – Nysa–Králíky Graben; NSS – North Sudetic Synclinorium; WG – Wleń Graben. Red boxes show location of Figs. 6, 10a, 11 and 14.

material we also used an analogue paper print version of a seismic profile from the vicinity of Broumov in Czechia and also some seismic profiles from the Fore-Sudetic Homocline. The largest part of the structurally interpreted seismic profiles is presented in this paper. Our structural interpretation of these profiles provides entirely new material showing the tectonic style and geometry of the compressional tectonic structures affecting the post-Variscan sedimentary cover along the NE margin of the Bohemian Massif and allows for some inferences as to the mechanics of their formation. An equally important part of the paper, aimed at giving its readers 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, is 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 vicinity. This material is either our own or is based on critically evaluated literature accounts.

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

4.1 The northeastern margin of the Sudetes: transition to the Fore-Sudetic Homocline

Directly northeast of the Sudetic area, separated by the Middle Odra Fault Zone, the Fore-Sudetic Homocline extends (e.g. Kłapciński et al., 1984; Kroner et al., 2008; Żelaźniewicz et al., 2011). It is defined by gently (1–5°) NE-dipping Permian to Mesozoic strata (Figs. 2 and 3) on top of Variscan-folded Carboniferous (e.g. 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 Variscan externalides (e.g. Mazur et al., 2010, 2020).

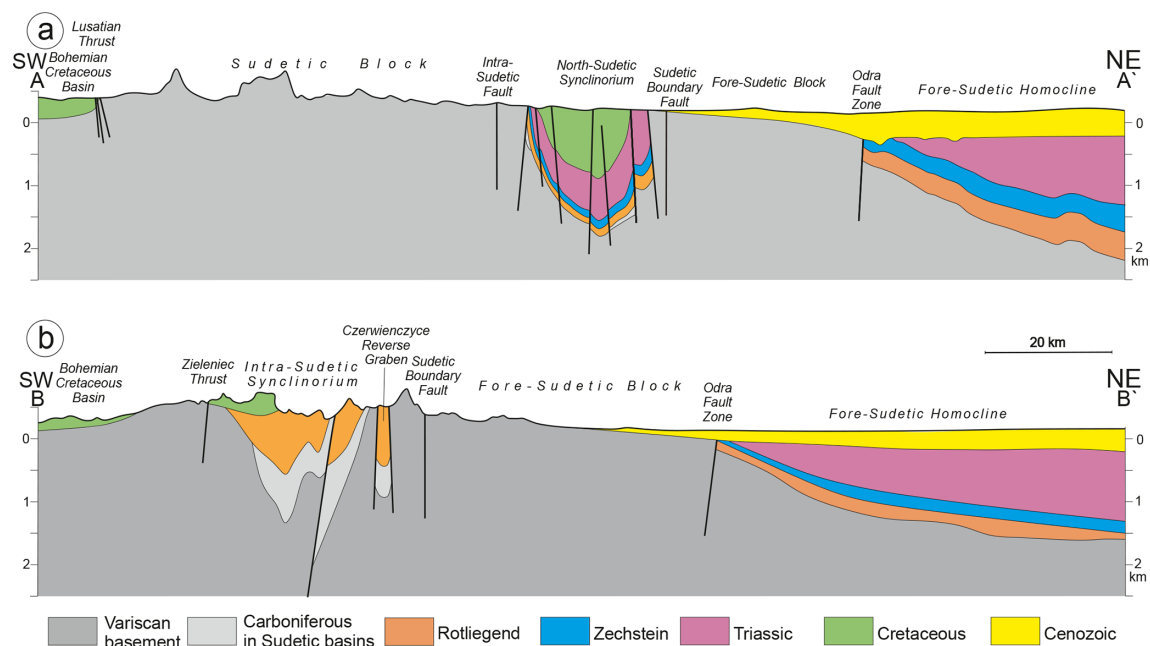


Figure 3. Schematic regional cross-sections across the Bohemian Massif NE margin (highly vertically exaggerated). Location in Fig. 2.

The Permo-Mesozoic strata in the southern part of the Fore-Sudetic Homocline are very gently folded and in a 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 ca. 0.5–1.2 km deep mines of the Legnica–Głogów Copper District, a rich inventory of contractional and, also, extensional tectonic structures occurs 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 decollements, as well as folds, all indicative of NE–SW-directed tectonic shortening. The meso-scale structures can be studied directly on the galleries’ walls (Fig. 5; see 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, accompanied by a number of relatively large WSW–ENE en echelon fractures (compare to 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.

The southwestern margin of the Fore-Sudetic Homocline is the only area in the scope of interest of this paper, in which, due to the presence of rock salt in the Zechstein strata, the formation of Late Cretaceous–early Palaeogene structures may have been locally affected by salt tectonics.

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; Kortański, 1997; Cwojdzński and Żelaźniewicz, 1995; Cymerman, 2010), and variable igneous plutonic rocks, mostly representing elements of a 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 and westernmost peripheries) devoid of Permo-Mesozoic deposits and its crystalline basement is eroded deeper than that on the mountainous Sudetic Block, an idea was conceived long ago (Cloos, 1922; Teisseyre, 1957) that the former block had been uplifted with respect to the present-day Sudety Mountains (Sudetic Block) across the Sudetic Boundary Fault, following the Late Cretaceous–early Palaeogene inversion. This situation was subsequently reversed in the late Miocene, when the Sudety Mountains were uplifted, whereas the Fore-Sudetic Block was downthrown simultaneously with the formation of the Carpathian–Alpine forebulge (e.g. Żelaźniewicz et al., 2011). The relatively small extent of the Permo-Mesozoic sedimentary cover on the Fore-Sudetic Block hampers direct recognition of the effects of the Late Cretaceous–early Palaeogene tectonism on the block. Nevertheless, these can be partly assessed thanks to the presence of the so-called Żary Pericline (Fig. 2) in the geological map intersection pattern. In map view, this pericline consists in the enveloping of the NW-projecting basement “peninsula” of

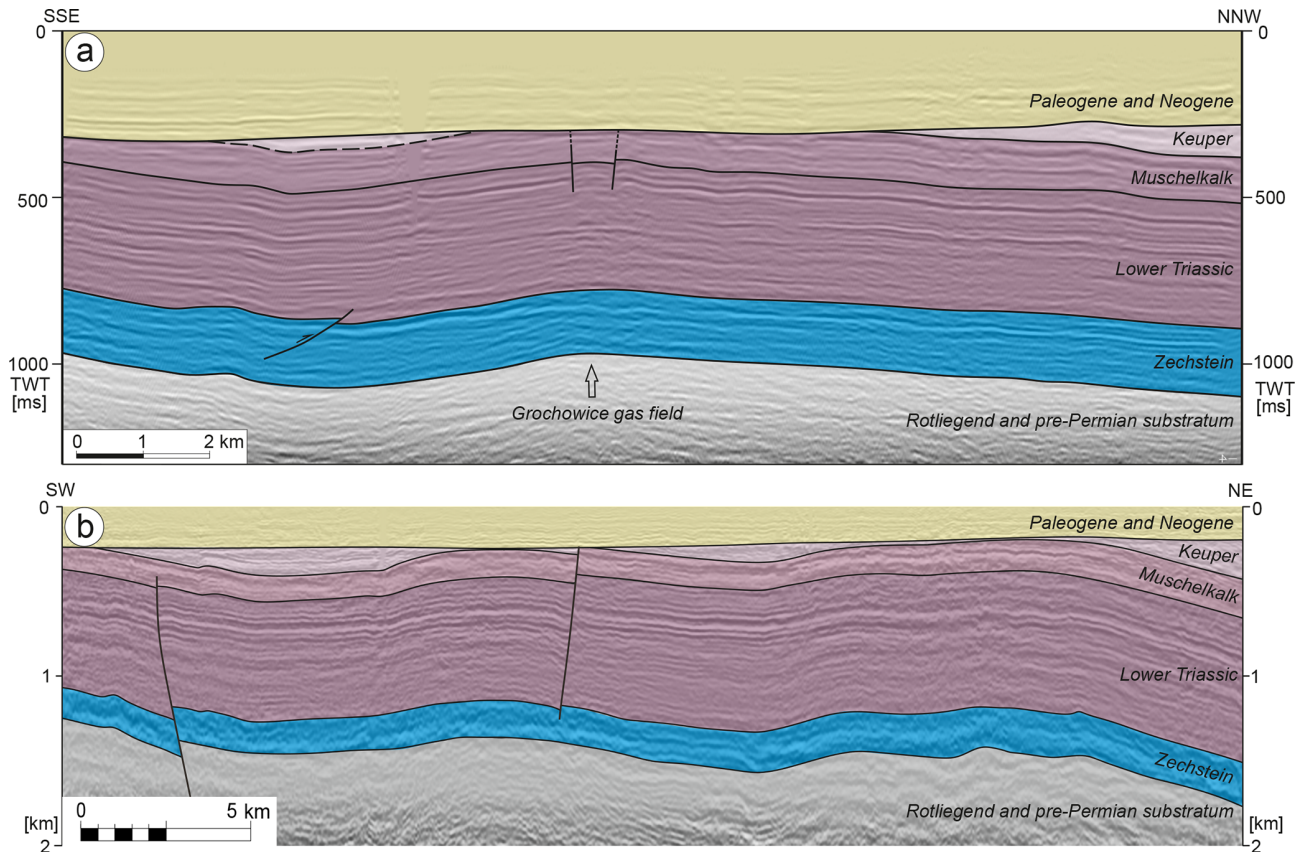


Figure 4. Two seismic profiles from the Fore-Sudetic Homocline (location in Fig. 2) showing very gentle folds in Triassic and Permian (Rotliegend not marked). Note steep to low-angle mainly reverse faults. The anticlines are structural traps for hydrocarbons, with gas fields known in Rotliegend strata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

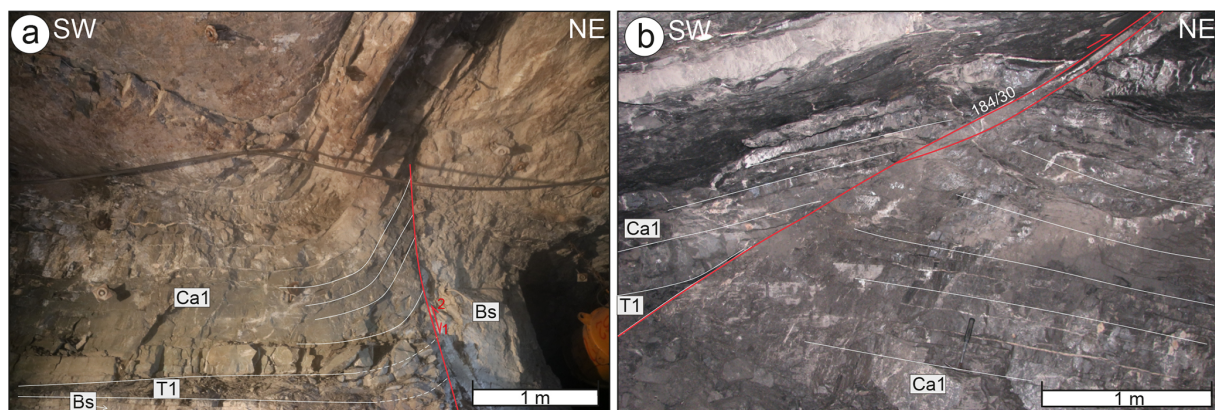


Figure 5. Examples of tectonic structures observed on gallery walls in copper and silver mines on the Fore-Sudetic Homocline at the base Zechstein (upper Permian) ore-bearing formation at the contact with the Rotliegend (lower Permian) strata (location in Fig. 2). (a) Inverted steep fault, originally normal. The inversion caused fault drag of Ca1 Zechstein Limestone. (b) Thrust fault in carbonate rock (orientation recorded as dip direction/dip angle). Abbreviations: Bs – Weissliegend Sandstone (lower Permian); T1 – Kupferschiefer shale (upper Permian); Ca1 – Zechstein Limestone (upper Permian).

the Fore-Sudetic Block by the Permo-Triassic outcrop zone, which continues to the southwest from 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 seems to be analogous to the large, gentle synform that occurs to the south of it and is observable on seismic profiles – 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 leading to the erosion of the original Permo-Mesozoic cover over the largest 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, NW–SE-elongated tectonic structure, ca. 60 km long and up to 24 km wide (Beyer, 1939; Oberc, 1972, 1977; Solecki, 1994; 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 (e.g. Milewicz, 1997; Śliwiński et al., 2003; Chrzastek and Wojewoda, 2011). The succession overlies a subsided top surface of the Variscan epi-metamorphic basement, termed the Kaczawa Slate Belt in this region (e.g. Aleksandrowski and Mazur, 2002; Mazur et al., 2006; Żelaźniewicz and Aleksandrowski, 2008). The synclinorium acquired its geometry due to the Santonian–early Campanian to late Maastrichtian–Paleocene (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, 3, 6 and 7; Beyer, 1939; Śliwiński et al., 2003).

The late 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 Sudetic area than it does today (compare e.g. Migoń and Danišik, 2012; Sobczyk et al., 2015, 2020). It was subsequently eroded from the most uplifted areas but preserved in places where the basement–cover interface had undergone compression-driven down-warping. According to Beyer (1939), this compression in the North Sudetic Synclinorium 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 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. 7a and b).

The structural geometry of the Late Cretaceous–early Palaeogene folds and related thrusts in the North Sudetic Synclinorium has been 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 supposed smaller-scale analogues occurring in active quarries (Fig. 8). The seismic data acquired 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), who assumed a dominance of nearly vertical faults.

A much better insight into the geometry and structural style of the deformed Permo-Mesozoic succession was recently enabled by the reprocessing of the same legacy seismic data (Głuszyński and Smajdor, 2020). The structural interpretation results of these data are presented on seismic sections in Fig. 9. The sections depict the along-strike changing geometry of the Permo-Mesozoic succession of the North Sudetic Synclinorium. This geometry, in general, seems to have resulted from gentle buckle downfolding of the basement–cover interface, producing a single syncline, up to ca. 20 km wide, in the Permo-Mesozoic strata. The syncline is locally complicated by reverse faults (or their clusters), cutting across the Cretaceous, Triassic and Zechstein strata and hard to follow in the Rotliegend clastics and volcanics, though in some cases probably penetrating the epi-metamorphic basement while shallowing their dips. The reverse faults are often related to folds, some of them likely having been initiated as fault-propagation folds. In places, decoupling or decollement phenomena occur along weak, clayey horizons in the Zechstein and Muschelkalk strata affected by local thrusting, accompanied by spectacular but rather infrequent zones, where meso-scale detachment folds have developed (Fig. 8), apparently due to locally increased horizontal shortening in the footwall of steep reverse faults (Fig. 9g).

The down-warping of the metamorphic basement below the Permo-Mesozoic cover may have facilitated the development of local low-angle thrusts in the basement (not visible in Fig. 9), where some of the thrusts affecting the Permo-Mesozoic are likely rooted. The *Rahmenfaltung* at the synclinorium edges (Fig. 7), invoked by Beyer (1939) and understood as upthrowing the relatively rigid metamorphic basement on reverse (inverted?) faults, may have also had its effect on the deformation process through exerting a horizontal-component tectonic force on the adjacent horizontal sedimentary strata. The local folds in the synclinorium interpreted from both the reprocessed seismic sections and from map intersection patterns show, in general, near-parallel geometry and shallow WNW-plunging axes (Solecki, 1986, 1994, 2011). Our analysis of the reprocessed seismic profiles made possible a subsurface mapping of a number of high-angle fault zones. They are, as a rule, trending NW–SE

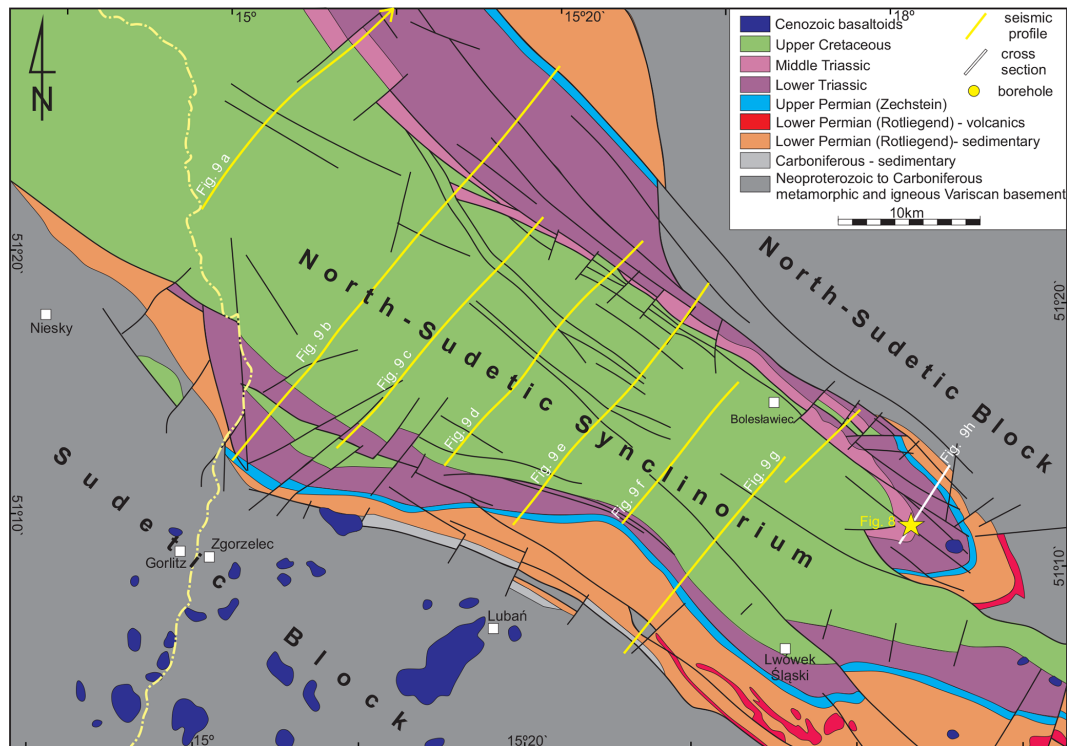


Figure 6. Geological map (without Cenozoic) of the North Sudetic Synclinorium (based on Bałazińska and Bossowski, 1979; Solecki, 1994; Krentz et al., 2000; Cymerman, 2010), showing locations of the interpreted seismic profiles. For full-length location of the seismic profile of Fig. 9a, see Fig. 2.

and often continue over distances of tens of kilometres (up to at least 40 km). Other identified major faults represent low-angle thrusts, continuing into the Variscan basement. The polarity of the local thrusts in the Permo-Mesozoic succession of the North Sudetic Synclinorium is bimodal and directed both to the NE and SW. This seems typical of folding affecting a detached succession (the Permo-Mesozoic sedimentary rocks detached from the underlying low-grade metamorphic rocks). 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. On neither of the seismic profiles studied by us were any structures modified by salt tectonics identified, in spite of a single rock salt intercalation in boreholes relatively close the profile shown in Fig. 9a. Our structural analysis of the reprocessed seismics makes it possible to reinterpret the hitherto widely held concept of the internal structure for the North Sudetic Synclinorium that assumed the dominance of high-angle fault block tectonics (e.g. Milewicz, 1968; Bałazińska and Bossowski, 1979), although Solecki (1986, 1994) already postulated earlier that the main factor controlling the formation of the North Sudetic Synclinorium might have been a compressive inversion of hypothetical normal listric faults in the basement. In our opinion, effects of compressional downwarping of the top basement surface due to buckling of the

basement–cover interface are of primary significance in this structure and those related to both high-angle and low-angle thrust faulting and to local detachment folding (Fig. 8) affecting the Permo-Mesozoic cover are of lesser significance.

A recent mapping and structural study by Kowalski (2021) of one of the already mentioned second-order synclinal or 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 at another example of a Late Cretaceous–early Palaeogene macro-scale tectonic structure in the NW part of the Sudetes. The Wleń Graben is a narrow structure, ca. 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 (Fig. 10; Kowalski, 2021). 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 (2021) 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 a compressional event of “probably latest Cretaceous to early Palaeogene(?)” age, re-

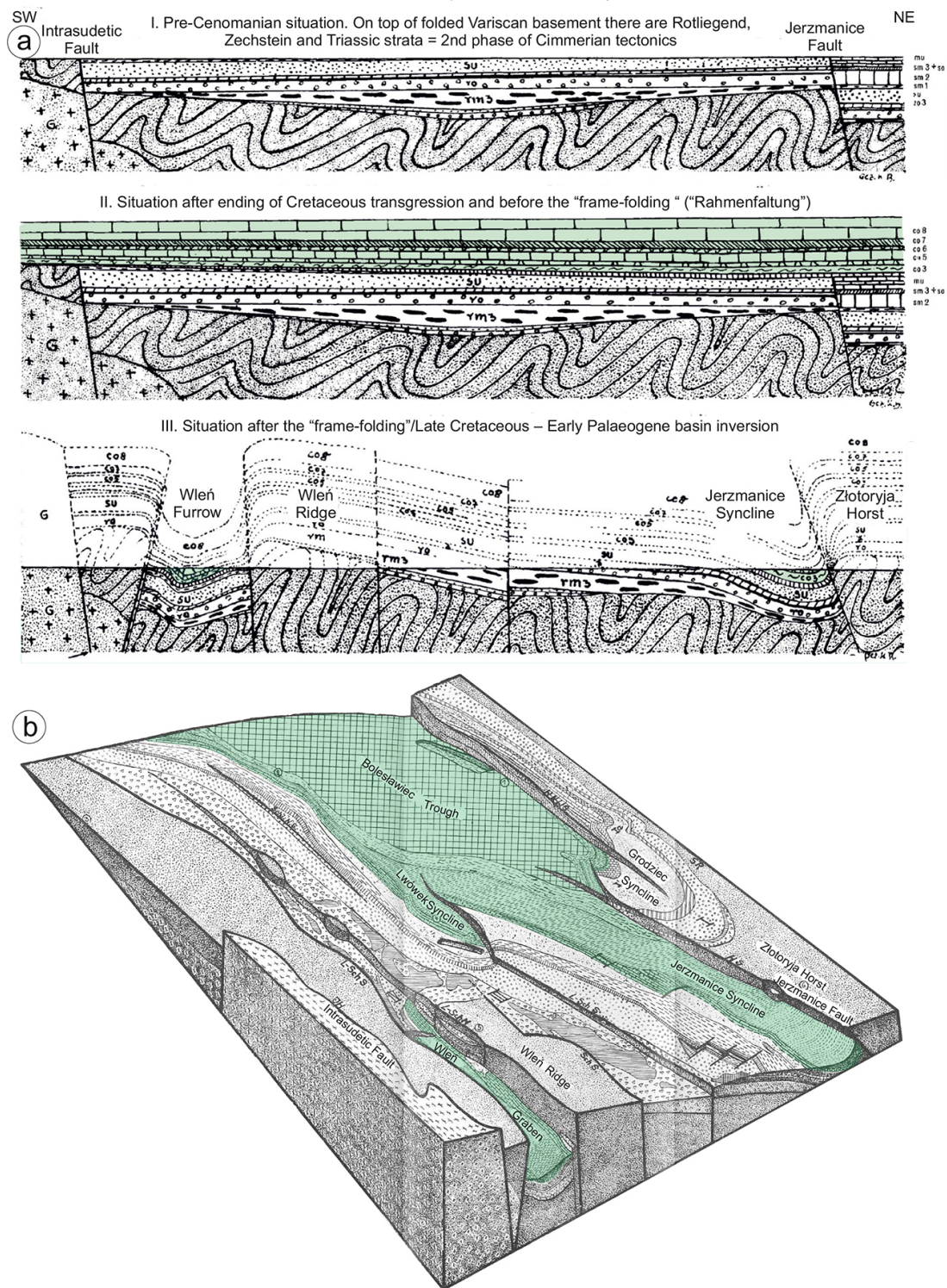


Figure 7. The interpretation of Kurt Beyer (1939) of the “young Saxonian” tectonics in the North Sudetic Synclinorium (Basin). **(a)** Main tectonic deformation stages in the North Sudetic Basin. **(b)** Block-diagram showing simple open structure of the western part of the North Sudetic Synclinorium (Bolesławiec Trough) and complex pattern of blocks and synclinal grabens (Jerzmanice Syncline and Wleń Trough) in its eastern part (compare Figs. 2 and 6).

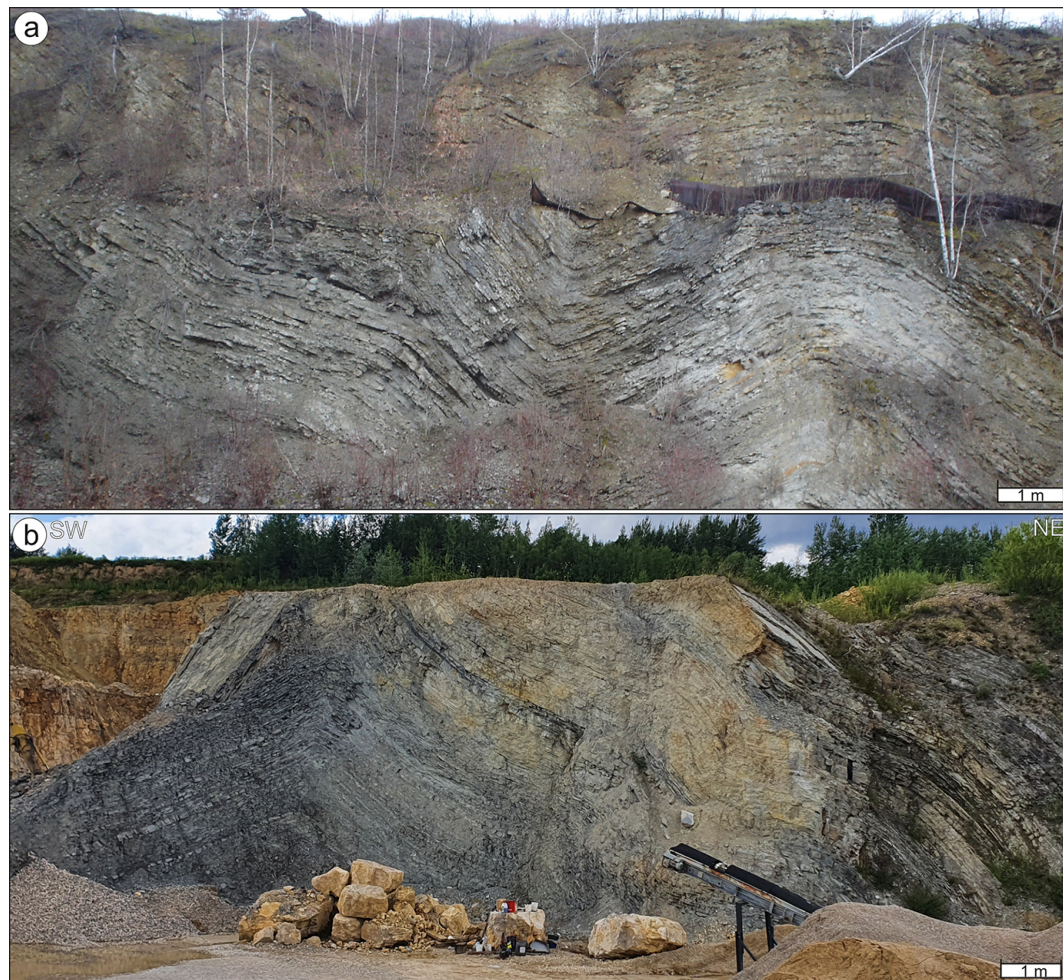


Figure 8. Folds in Muschelkalk in a quarry at Raciborowice (location in Fig. 6; photo in **a** – courtesy of Andrzej Solecki).

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 elaborated by Kowalski (2021) on the basis on his mapping fieldwork and scarce borehole data (Fig. 10) 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. The metamorphic basement top is depicted as concordantly adherent to the overlying, synclinally bent base Rotliegend surface. The concordant folding of the basement and cover, together with the above-mentioned apparent lack of a dip-slip displacement on the boundary faults of the Wleń Graben, suggests that the “graben's” origin may instead have been due to downfolding (buckling) rather than downthrow-

ing on reverse faults. The cited author (Kowalski, 2021) suggests a seismic survey to be made in order to better understand the structural geometry of the graben.

4.4 The Intra-Sudetic Synclinorium

In addition to the North Sudetic Synclinorium, the Intra-Sudetic Synclinorium is another 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 ca. 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 Synclinorium (Żelaźniewicz and Aleksandrowski, 2008; Żelaźniewicz et al., 2011), 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 Synclinorium (see also Nemec et al., 1982; Dziedzic and Teisseyre, 1990; Bossowski et al., 1995; McCann, 2008b). The Carbonifer-

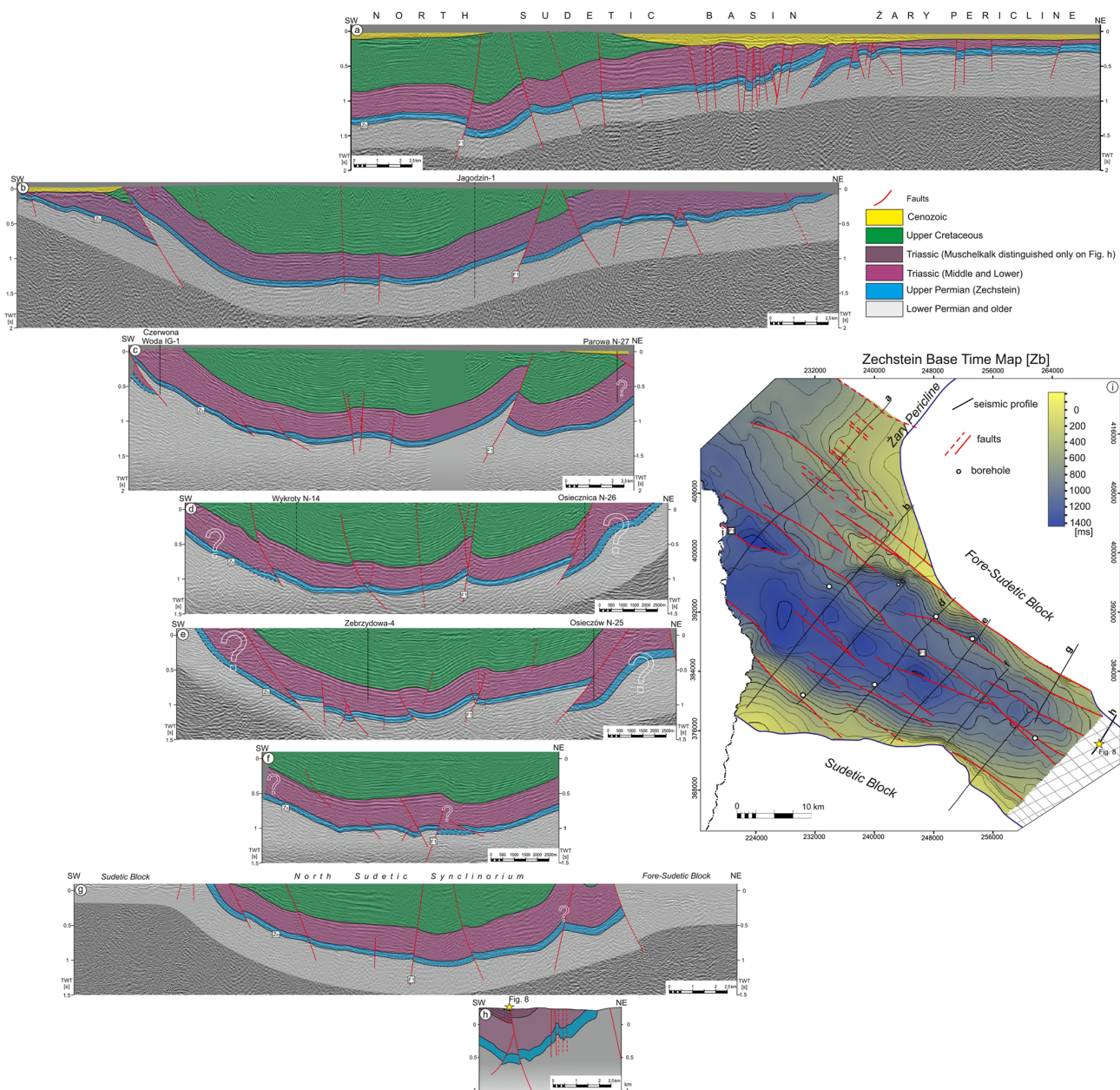


Figure 9. Interpreted seismic profiles from the North Sudetic Synclinorium (location in Fig. 6). Explanations in the text.

ous deposits of the Intra-Sudetic Synclinorium rest on the Variscan-deformed, mostly crystalline basement of the Sudetic Block. To the SE, the axial zone of the Intra-Sudetic Synclinorium, composed of Upper Cretaceous deposits, merges with the Upper Nysa–Králíky Graben (Figs. 2 and 11). Another similarity of the Intra-Sudetic to the North Sudetic Synclinorium is its generally simple, open structure of a single syncline in its northwestern and central parts, which is replaced by a number of synclinal grabens separated by basement horsts on its eastern flank (Figs. 2 and 11). Some of the synclinal grabens are bounded by reverse faults.

The Late Cretaceous to early Palaeogene tectonic structures of the Intra-Sudetic Synclinorium imaged by reprocessed seismic data can be only studied in 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 has not been imaged by seismic data. The seismic profiles (location in Fig. 11) are mostly trending SW–NE, i.e. roughly perpendicular to the synclinorium's axis. They are consecutively presented, from NW to SE, in Figs. 12 and 13,

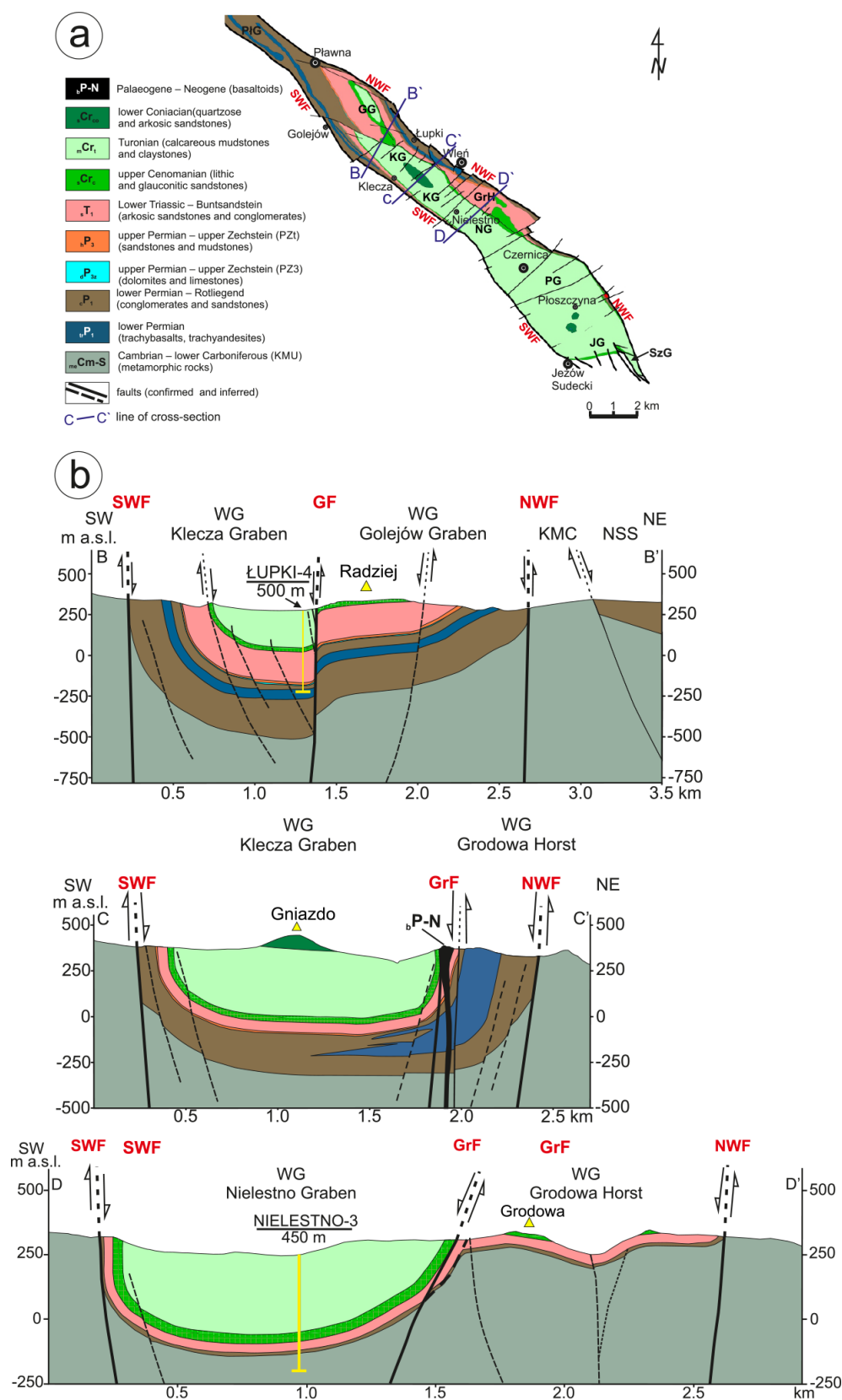


Figure 10. Simplified geological map and three selected cross-sections of the Wleń Graben according to Kowalski (2021).

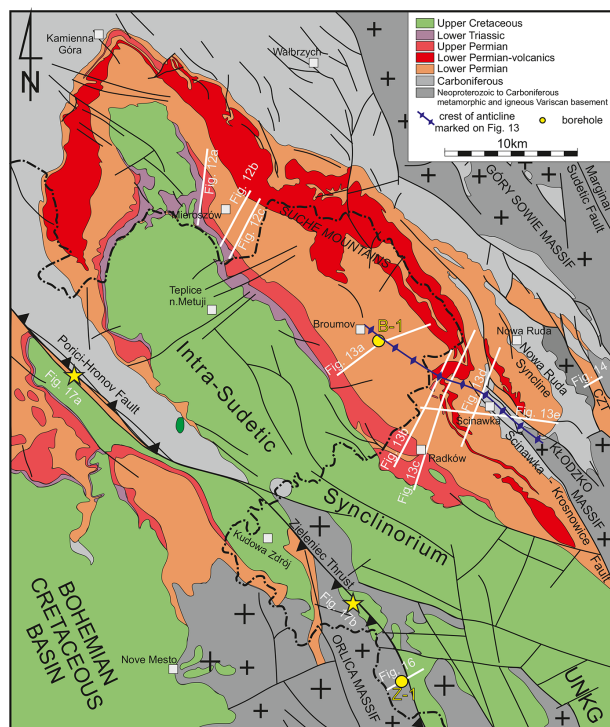


Figure 11. Geological map of the Intra-Sudetic Synclinorium (based on Grocholski and Augustyniak, 1971; Bossowski and Bałazińska, 1982; Bossowski and Ihnatowicz, 2006; Cymerman, 2010). Location of the interpreted seismic profiles and described localities is shown. CZT – Czerwieńczyce Trough (reverse graben); UNKG – Upper Nysa - Králiky Graben.

in order to illustrate in a systematic way the tectonic structures affecting the Permian and Carboniferous strata.

In the NW part of the area covered by seismic data (Figs. 11 and 12), three consecutive profiles show a group of planar faults in Carboniferous clastics, which do not continue upwards into the Permian, although in some profiles (Fig. 12b and c) these faults manifest themselves also in the Permian strata as gentle 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, associated with gentle folding that locally affected also the overlying Permian strata, though in places the displacement on them entirely ceases still at a level below the Permian (Fig. 12a). The fault zone in the Carboniferous succession can be followed on seismic profiles over a distance of 7 km along-strike, 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. 11 and 13a), a low-angle, NE-verging thrust zone (which may represent a more developed continuation of the fault zone from Fig. 12) rooted in the crystalline basement produces a

reverse-slip displacement of the Carboniferous strata by at least 2 km, associated with the formation of fault-bend folds. The thrust seems to continue to the NE as a decollement within the Permian strata, overlain by an anticline–syncline pair, which can be recognised 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 (Fig. 13b–e) one can follow along-strike geometrical changes in a conspicuous low-angle, NE-verging thrust fault, responsible for up to 2.5 km of displacement of the crystalline basement and the overlying Carboniferous and Permian strata over their footwall. Similar to the case at Broumov, the overthrust is related to an anticline–syncline pair of fault-bend or fault-propagation(?) folds.

The conspicuous thrust fault identified at depth in the area of Radków–Ścinawka (Fig. 13b–e) and – most probably – continuing into the vicinity of Broumov (Fig. 13a) seems to correspond to the major NW–SE-trending Ścinawka–Krosnowice Fault (Fig. 11) 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 implies an important change in understanding the geometry and kinematics of this well-known mapped fault, so far regarded as a steep fracture at least in its NW, Ścinawka segment as a low-angle Late Cretaceous–early Palaeogene thrust. In the light of their geological context, there can be little doubt about the timing of the tectonic structures identified in the seismic profiles. Our interpretation is corroborated by their occurrence near the axial zone of the Intra-Sudetic Synclinorium, characterised by thick preserved Upper Cretaceous deposits. It is also confirmed by the southeastward 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. 11 and 14). 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 lower Permian Rotliegend and Upper Carboniferous sedimentary rocks. 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 characteristic 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 (2021;

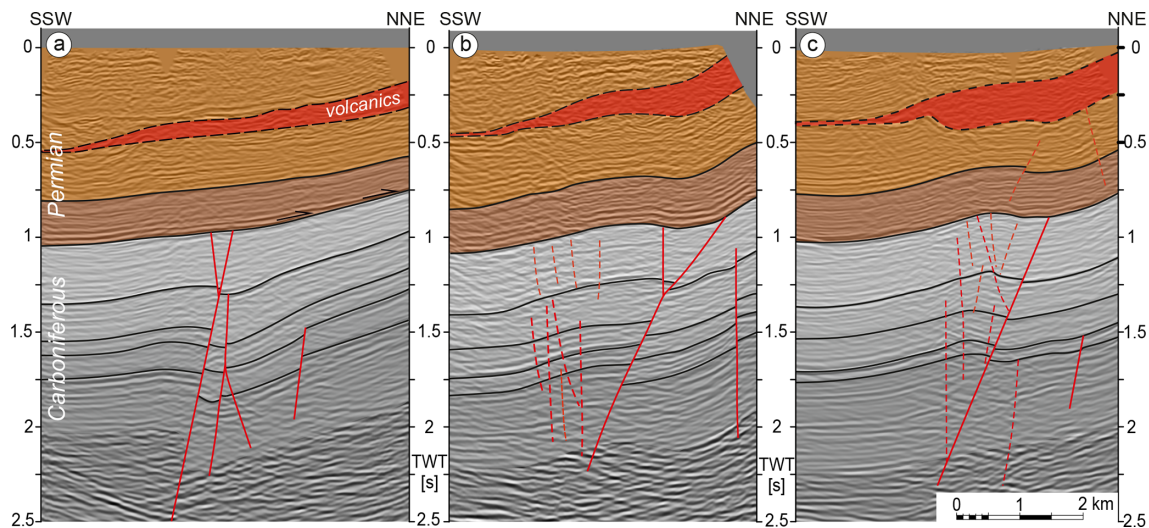


Figure 12. Seismic profiles from the vicinity of Mioszów arranged successively along-strike of the structures from NW to SE, showing probable effects of Late Cretaceous–early Palaeogene reactivation of originally Carboniferous faults. The Permian volcanic member (in red) continues to the NNE to outcrop massively in the nearby Suche Mountains. Location in Fig. 11. The faults in (a) do not show effects of post-Carboniferous reactivation, but further to SE the motion on faults resulted in very gentle folding of the overlying Permian strata in (b) and (c).

Fig. 10) and – still more – by Gorczyca-Skała (1977, not reproduced here) or of the Upper Nysa–Králíky Graben by, e.g., Jerzykiewicz (1970) and Don and Gotowała (2008), partly with reverse boundary faults.

4.5 The Upper Nysa–Králíky Graben

The Upper Nysa–Králíky Graben (Figs. 2 and 15) is a distinctive tectonic and topographic fault-bounded feature of approximate N–S trend, ca. 45 km long and from 3 to 12 km wide, merging to the north with the Intra-Sudetic Synclinoorium. It is composed of shallow marine sedimentary rocks, including a time span from the early Cenomanian through to the Turonian to Coniacian and Santonian (e.g. Don and Don, 1960; Jerzykiewicz, 1970, 1971; Radwański, 1975; Don and Gotowała, 2008; Badura and Rauch, 2014), downthrown with respect to the medium-grade metamorphic rocks of the Orlica-Śnieżnik Massif of the graben's shoulders. Most of the earlier authors (except Jerzykiewicz, 1970, 1971; Radwański, 1975 and Oberc, 1972) explained the origin of the Upper Nysa–Králíky Graben as a result of a Late Cretaceous rifting, subsequently modified 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, as they ignored the striking resemblance of the lower parts of the Cretaceous stratigraphic columns from within the graben and from the Góry Stołowe (Table Mountains) on one of its shoulders (Don and Gotowała, 2008) and the probable absence of fault-controlled coarse-grained deposits along the graben's edges. The as-

sumed rifting was explained by most authors as being due to compression or, by contrast, as due to extension-driven updoming of the Orlica-Śnieżnik Massif during the Cretaceous or by pull-apart graben formation due to strike-slip displacements on NW–SE-trending structural discontinuities in the crystalline basement. In contrast, we interpret the mostly N–S-trending Upper Nysa–Králíky Graben as representing 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 uniqueness of the Cretaceous deposits in the Upper Nysa–Králíky Graben consists only in the preservation of the thick Coniacian to Santonian succession in it, absent from the uplifted areas nearby (Don and Gotowała, 2008), from where it must have been eroded. The Upper Nysa–Králíky Graben is imposed on and cuts across earlier, Late Cretaceous–early Palaeogene tectonic structures of consistent NW–SE strike, which are in most places oblique to and cross-cut by the graben's boundaries (Fig. 15). These structures are represented by differentially dip-slip-displaced fault blocks, often bounded by reverse faults, and by gentle folds (Badura and 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 the direct vicinity of the Upper Nysa–Králíky Graben. A relatively extensive, at least 25 km long, NW–SE-trending trace of the Zieloniec Thrust Fault (Fig. 11) was mapped by Cymerman (1990) and extrapolated on maps by other authors within the SW flank of the Upper Nysa–Králíky Graben. On this ca. 40–

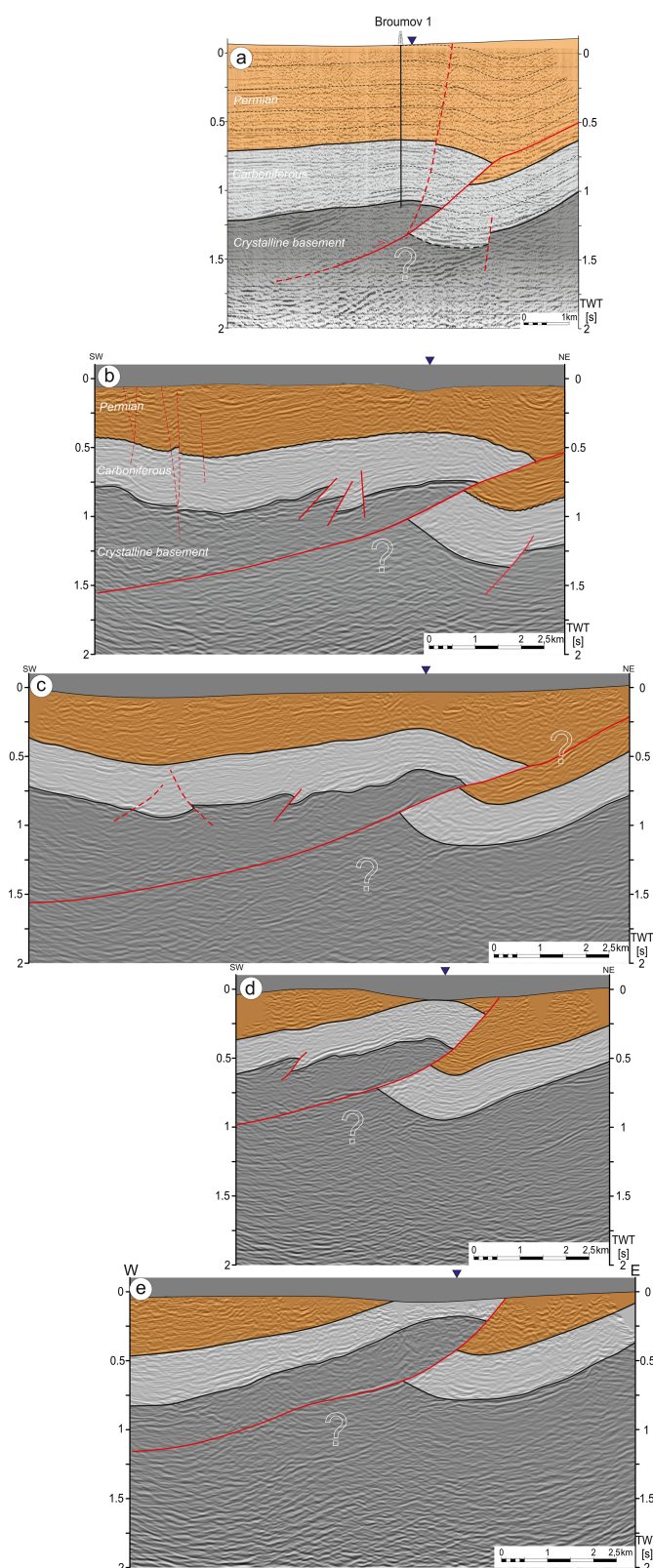


Figure 13. Seismic profiles from the vicinity of Broumov (paper print version – Brada et al., 1982) (a) and from the vicinity of Radków, all arranged consecutively from NW to SE (b–e). Location in Fig. 11. The section in (a) shows that the Broumov well was drilled in the hanging wall of a thrust fault, and, hence, the Carboniferous in the neighbourhood may occur deeper than found in the well. The thrust continues to the NE parallel to the bedding – most probably as a decollement or detachment along the lower Permian Anthracosia Shale member.

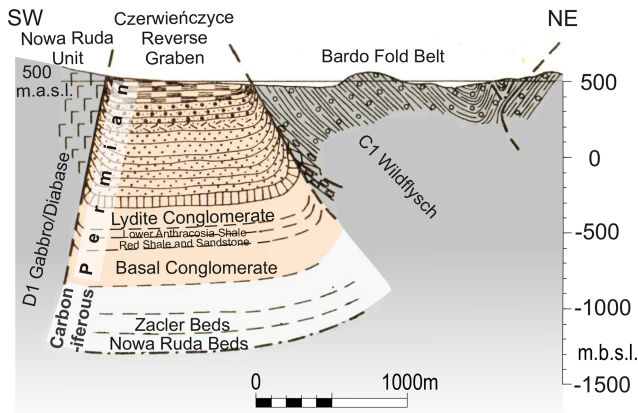


Figure 14. Geological cross-section of the Czerwieńczyce Reverse Graben after Oberc (1972). Location in Figs. 2 and 11.

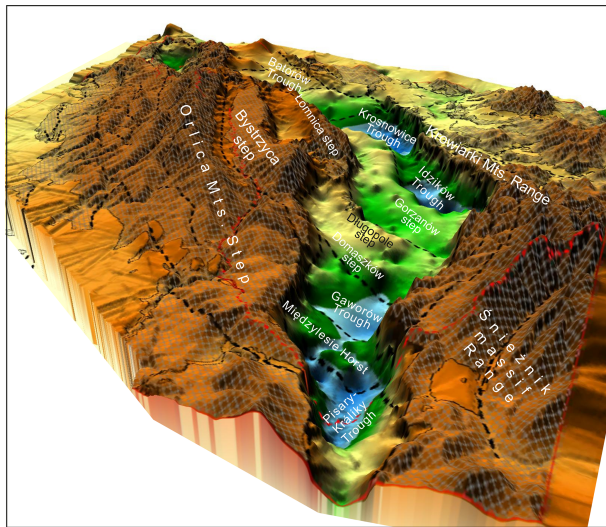


Figure 15. Perspective view towards the north onto the base Cretaceous relief (known from boreholes) in the Upper Nysa–Králíky Graben (from Badura and Rauch, 2014). The oblique-striking troughs, steps and horsts reflect NW–SE-trending Late Cretaceous–early Palaeogene structural grain defined by inverted blocks underlying the Cretaceous graben floor and folds in its fill (removed from the picture), once continuing laterally, before the graben formation in Miocene times. Location given in Fig. 2.

50° SW-dipping fault (Fig. 16) a 500 Ma orthogneiss mass of the Góry Bystrzyckie Mountains was overthrust, displaced by at least 5300 m toward the NE (Cymerman, 1990) and emplaced on top of the gently dipping Turonian clastics, equivalent to those from the lower part of the Upper Nysa–Králíky Graben fill and resting on analogous orthogneiss basement. Cymerman (1990) interpreted this thrust as produced by late Alpine (Miocene) compression. The Zieloniec 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

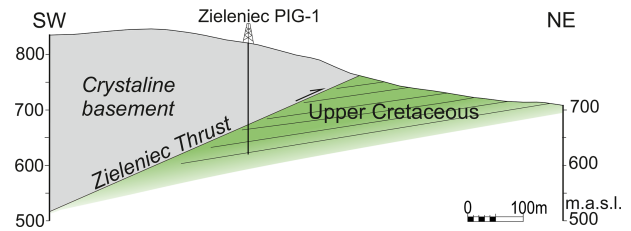


Figure 16. Schematic section across the Zieloniec Thrust (based on data from Cymerman, 1990, and Kozdrój, 2014). Location in Figs. 2 and 11.

to the inversion of an original normal fault into a reverse one. One of the most important arguments for this interpretation was finding a subhorizontal position of the Cretaceous–gneiss contact in the drill core. In our opinion, taking into account the significant extent of the Zieloniec Thrust and its involvement in the major NW–SE-trending fault system (Fig. 11), termed the South Sudetic Shear Zone by Wojewoda (e.g. in Wojewoda and Kowalski, 2016), which also comprises the major Poříčí–Hronov Fault (see below), there cannot be much doubt that the Zieloniec Thrust represents a Late Cretaceous–early Palaeogene structure similar to that of the Łużyce Thrust (see below), though of an opposite vergence.

To the NW the Zieloniec Thrust merges with the south-eastern extension of the Poříčí–Hronov major fault system (Fig. 11), 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 an opposite, SW, polarity (Prouza et al., 2014), which – according to some authors – was combined with a strike-slip component of motion (Wojewoda, 2007, 2009; Nováková, 2014) (Fig. 17a). To the SE, the Poříčí–Hronov Fault continues into the Duszniki–Gorzanów (or Krosnowice) Fault, at the northern end of the Upper Nysa–Králíky Graben (compare Petrascheck, 1933; Prouza et al., 2014).

A presumable NW extension of the Zieloniec Thrust (Figs. 11 and 17b) was described directly in a ca. 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–Králíky Graben (Wojewoda et al., 2010; Aleksandrowski and Wojewoda, 2010). A ca. 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. 17b). 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. Based on evidence from

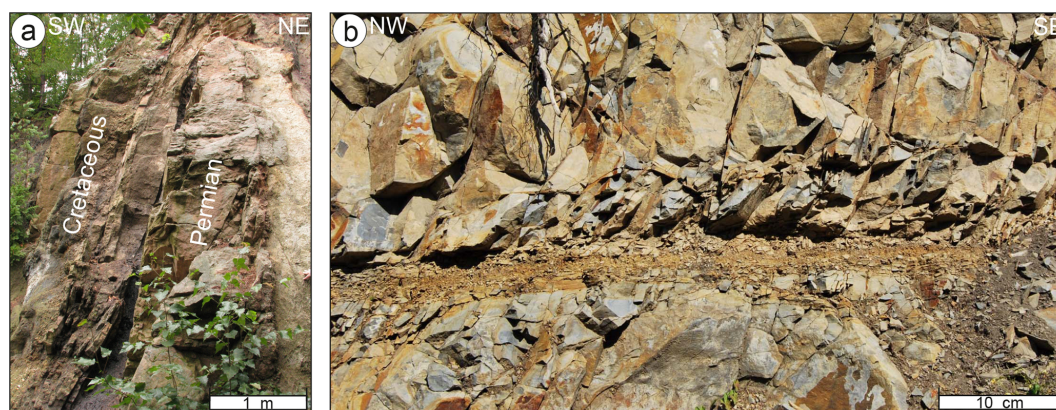


Figure 17. Examples of outcrop-scale brittle structures related to major faults at the SW boundary of the Intra-Sudetic Synclinorium. **(a)** The Poříčí–Hronov Fault, interpreted as a high-angle reverse structure, near the village of Malé Svatoňovice: tectonic contact between nearly vertically dipping 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 in Figs. 2 and 11.

the orientation of the accompanying joints, the detachment was originally interpreted as SE-verging 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 Poříčí–Hronov Fault system (compare 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 its very origin and principal displacement were related to the Zieleniec Thrust.

4.6 The southwestern margin of the Sudetes: transition to the North Bohemian Cretaceous Basin

The NW segment of the Sudetic Block, represented by the Karkonosze–Iżera 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 sub-crops of Permian and Carboniferous but mostly on the crystalline Variscan basement of the Bohemian Massif (e.g. Klein and Soukup, 1966; Malkovský, 1987; Uličný et al., 2009; Wilmsen et al., 2014). The basin's 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 in places well-exposed Lusatian Thrust (Figs. 2 and 18a–c), which continues NW up to the vicinity of Dresden (e.g. Wagenbreth, 1967), whereas to the east it continues to the western Karkonosze Piedmont Basin area (Prouza et al., 2014). The Lusatian Thrust has been excellently described and analysed in detail by Coubal et al. (2014, 2015).

The Lusatian Thrust (e.g. Malkovský, 1976, 1977), similarly to other main NW–SE-trending fault zones of the Sude-

tic 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 primary strike-slip characteristics (compare to 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 Western 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, which is between low angle or subhorizontal in the northwest (Figs. 2 and 18a) through to medium-angle (Figs. 2 and 18b) and high-angle attitudes (Figs. 2 and 18c). The angle made by the displacement zone (or fault) core, apparently representing a reactivated fracture, with respect to the – supposedly generally subhorizontal – tectonic shortening direction had a serious influence on the structural style and complexity of the brittle structures that developed around the fault core and across the width of the damage zone (Coubal et al., 2014). The smaller the angle between the two, the more smoothly the displacement occurred (Fig. 18a–c). An increase in 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. 18b and c).

5 Regional jointing pattern and deformation bands – likely products of Late Cretaceous–early Palaeogene deformation

The regional pattern of tectonic joints over the Sudetic area or that of SW Poland can be inferred from a number of local

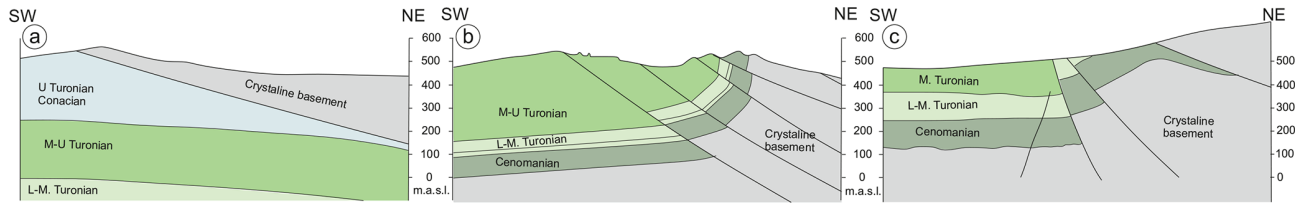


Figure 18. Schematic sections across the Lusatian Thrust at three localities, showing along-strike structure changes (based on Coubal et al., 2014). Location in Fig. 2.

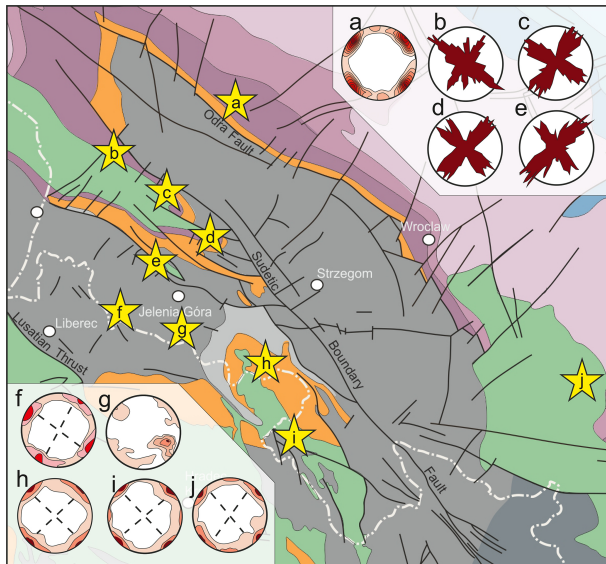


Figure 19. Comparison of stereograms and rose diagrams of the dominant steep joint sets coming from several local studies (by Jerzykiewicz et al., 1974; Aleksandrowski, 1976; Solecki, 2011; Selerowicz et al., 2014) made at various locations in the Polish Sudetes. Background: the geological map of Fig. 2.

studies on jointing, most of which were conducted decades ago. Not attempting to make a systematic review of such studies, for the needs of the brief review made in this paper, several stereograms and 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 are shown on the geological map (Fig. 19). The data come mostly from the Permo-Mesozoic strata exposed at 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 (Fig. 2).

Two stereograms (Fig. 19f, g) show, additionally the jointing pattern in the Carboniferous granitic rocks of the Karkonosze Massif. From recent low-temperature geochronology studies (Migoń and Danišík, 2012; Sobczyk et al., 2015) it follows that the present-day exposure level of at least some parts of the Karkonosze pluton was still at a depth of a few kilometres at the end of Cretaceous,

and hence the joints we observe recently in granites on the earth's surface may, indeed, be Late Cretaceous–Cenozoic, in respect of their initiation and opening (compare e.g. Price, 1966; Jaroszewski, 1984; Suppe, 1985; Engelder, 1985, 1987, 1993; Price and Cosgrove, 1994), similarly to the joints in the Mesozoic sedimentary rocks. We suppose that the initiation of the dominant regional tectonic joints pattern in the Sudetic rock complexes may have occurred at a depth of a few kilometres, under a significant overburden, due to the Late Cretaceous–early Palaeogene compression. The initiation involved processes of subcritical crack growth under directional stress (e.g. Atkinson, 1982; Atkinson and Meredith, 1987), leading to the formation of anisotropy defined by systematically oriented microfractures. The latter mechanical anisotropy acquired by the rocks on compression may have subsequently controlled the massive joint opening during the Cenozoic regional uplift and concomitant unloading and extension.

All the diagrams presented in Fig. 19 show most steep joints to be concentrated in two mutually perpendicular maxima, in which the joint planes are approximately parallel and perpendicular to the inferred Late Cretaceous–early Palaeogene shortening direction (compare e.g. Solecki, 1995, 2011; Nováková, 2014). As, moreover, they occur in the Permo-Mesozoic strata, a conclusion that they are genetically related to that shortening event seems plausible. We suppose that the formation of the dominant jointing pattern in the post-Variscan (but also partly in the Variscan) Sudetes and, in general, in the SW part of Poland resulted from the Late Cretaceous–early Palaeogene compressional event.

A more direct record of the Late Cretaceous–early Palaeogene compressional event is contained in the well-developed systems of silicified complementary deformation bands (compare Aydin and Johnson, 1983; Fossen et al., 2007), described by Solecki (1988, 1994, 1995, 2011) as cataclastic bands from the Buntsandstein and Coniacian sandstones of the North Sudetic Synclinorium (see also Kowalski, 2021). The bisectors of the acute angle between the best-developed two complementary sets of the deformation bands, dipping at moderate angles to the NE and SW, respectively, correspond to the maximum principal compressive stress axis during their formation and, as a rule, show a subhorizontal, NE–SW-oriented position.

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 recognisable in the Permo-Mesozoic post-Variscan cover, which is devoid of other, earlier formed contractional deformations, but, though undoubtedly present, they are much less obvious in the Variscan basement that was heavily tectonised before. The structures developed in the post-Variscan cover particularly those due to fault displacements – and, among them, the strike-slip-related ones – can still be difficult to separate from the structures that might have resulted from the younger, Cenozoic events.

Our structural analysis of newly reprocessed legacy seismic profiles, complemented with outcrop and drill hole data, has revealed the structural geometry and some interesting details of the tectonic structures produced by contractional deformation in the Permo-Mesozoic (partly also in the Carboniferous) strata of the two main Sudetic synclinoria. The deformation included gentle buckling of the basement–cover interface in the North Sudetic Synclinorium, with local complications of thus produced wide synclinal folds by relatively minor thrusts, often rooted in the Variscan metamorphic basement and accompanied by thrust-related folds. Locally, rather infrequent decoupling or decollement of some packages within the Permo-Mesozoic succession along weak, clayey horizons in, e.g., Triassic Muschelkalk strata was also recorded. As the low- or medium-angle thrust faults identified in the Permo-Mesozoic strata are often rooted in the top parts of the Variscan basement, particularly in the Intra-Sudetic Synclinorium, some elements of the thick-skinned style of shortening can 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 for, e.g., geothermal prospecting in the Sudetes, where the deep groundwaters 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, characterised by an orthogonal joint system with two sub-vertical sets of ca. 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, Polish Geological Institute in Warsaw, and the seismic profile from the Broumov area is available at the Czech Geological Survey Archive in Prague.

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

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