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The Variscan Orogen in Poland

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The structure and evolution of the Polish part of the Variscan Orogenic Belt is reviewed, based on published data and interpretations. The Sudetic segment of the Variscides, together with adjacent areas, experienced multi-stage accretion during successive collisional events that followed the closure of different segments of the Rheic Ocean. In SW Poland, Variscan tectono-stratigraphic units are tectonically juxtaposed and often bear record of contrasting exhumation/cooling paths, constrained by palaeontological and geochronological data. This points to the collage-type tectonics of this area. A three-partite subdivision of the Sudetes is proposed that reflects timing differences in deformation and exhumation of the respective segments. The Central, West and East Sudetes were deformed and amalgamated during the Middle/Late Devonian, at the turn from the Devonian to Carboniferous and during Early Carboniferous times, respectively. Problems in extending the classical tectono-stratigraphic zonation of the Variscides into the Sudetes are discussed and attributed to activity along Late Palaeozoic strike-slip faults and shear zones, disrupting and dispersing the initially more simply distributed tectono-stratigraphic units into the present-day structural mosaic. Relationships between the Variscan Externides and the foreland basin are explored. Sediments of the foreland basin locally onlap the external fold-and-thrust belt that had undergone an earliest Carboniferous partial tectono-thermal overprint. During the Late Carboniferous, the SW part of the foreland basin was heavily affected by thrusting and folding and incorporated into the Externides. During Westphalian C to Early Permian times, localized folding and thrusting affected the distal parts of the foreland basin, probably in response to dextral transpressional movements along NW–SE trending basement faults.

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INTRODUCTION

The Variscan Belt of Europe, as defined by Suess (1888) and Bertrand (1887), extends from Spain and Portugal through France and Germany to Czechia and Poland (Fig. 1). The largest exposures of the Variscan basement define the European "Mittelgebirge", an extensive belt of uplifts and highs that were variably elevated during the latest Cretaceous and Cenozoic in response to the build-up of collision-related intraplate compressional stresses, rifting and mantle plume activity (e.g. Ziegler, 1987, 1990; Dèzes *et al*., 2004; Ziegler and Dèzes, 2005). Comparably to many other orogens, the European Variscides reveal a roughly bi-lateral symmetry. Their axial parts contain medium- to high-grade rocks of the Variscan internides, injected by voluminous granite intrusions and affected by widespread late orogenic migmatization. The metamorphic internides continue from the Ossa-Morena Zone in Spain, through the Massif Central, via the Vosges and Black Forest, to the Bohemian Massif in the NE. The metamorphic axial zone is flanked to the NW by the external fold-and-thrust belt that extends from southern Portugal through Cornwall, the Ardennes and Rhenish Massif, to Central Poland and is usually referred to as the Rhenohercynian Zone. Its counterpart on the SW flank of the orogen is represented by the non- to weakly metamorphic belt of SW Sardinia and the French Montagne Noire that plunges northeastward beneath the Alpine thrust front (von Raumer and Neubauer, 1993). In some interpretations (not shared by the present authors), it reappears as the Moravo-Silesian Zone within the Bohemian Massif (e.g. Matte *et al*., 1990).

The Central European part of the Variscan Orogen is commonly subdivided into the Moldanubian, Saxothuringian and Rhenohercynian zones, following the classical scheme of Kossmat (1927) (Fig. 2). In Central Europe this scheme is completed by the additional Moravo-Silesian and Teplá-Barrandian zones, as well as by the Lugian domain. The latter term, introduced by Suess (1926) as Lugicum, covers the West and Central Sudetes and has recently been re-defined as Lugo-Sudeticum by Narębski (1992), owing to difficulties encountered in extending Kossmat's scheme into the Sudetes. These difficulties are re-

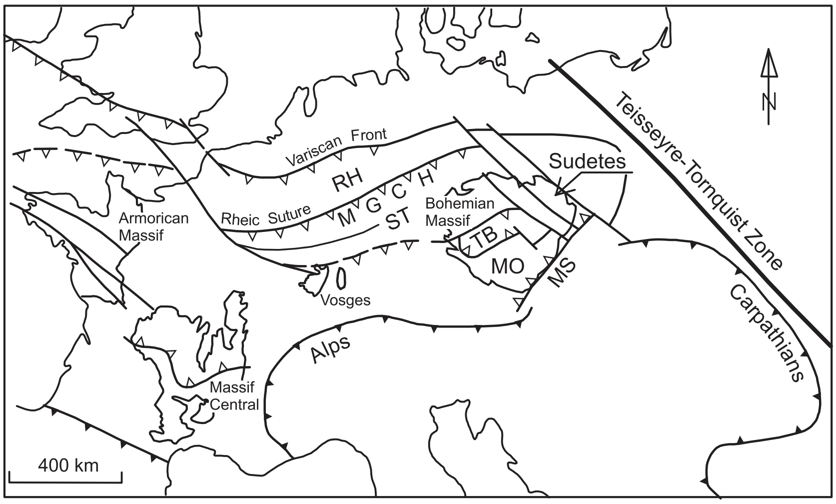

Fig. 1. Tectonic setting of Sudetes in the Variscan Belt

MGCH — Mid-German Crystalline High; MO — Moldanubian; MS — Moravo-Silesian; RH — Rhenohercynian; ST — Saxothuringian; TB — Teplá-Barrandian

flected in contrasting interpretations of the location, extent and correlations of the main tectono-stratigraphic zones in the Sudetic area (e.g. Cymerman *et al*., 1997; Aleksandrowski and Mazur, 2002; Franke and Żelaźniewicz, 2002).

A characteristic feature of the NE termination of the European Variscides are changes in the orientation of their structural grain from NE–SW in Germany, to NW–SE and, then, abruptly, to NNE–SSW, in the southwesternmost part of Poland, corresponding to the Sudetic area. The geometry of this part of the Variscan Belt is explained by two alternative hypotheses, which assume either oroclinal closure of the orogen towards the NE (see e.g. Walter, 1992; Don, 1995), or an imprint of distinctly oriented deformation fabrics on the Sudetic portion of the belt by regional-scale

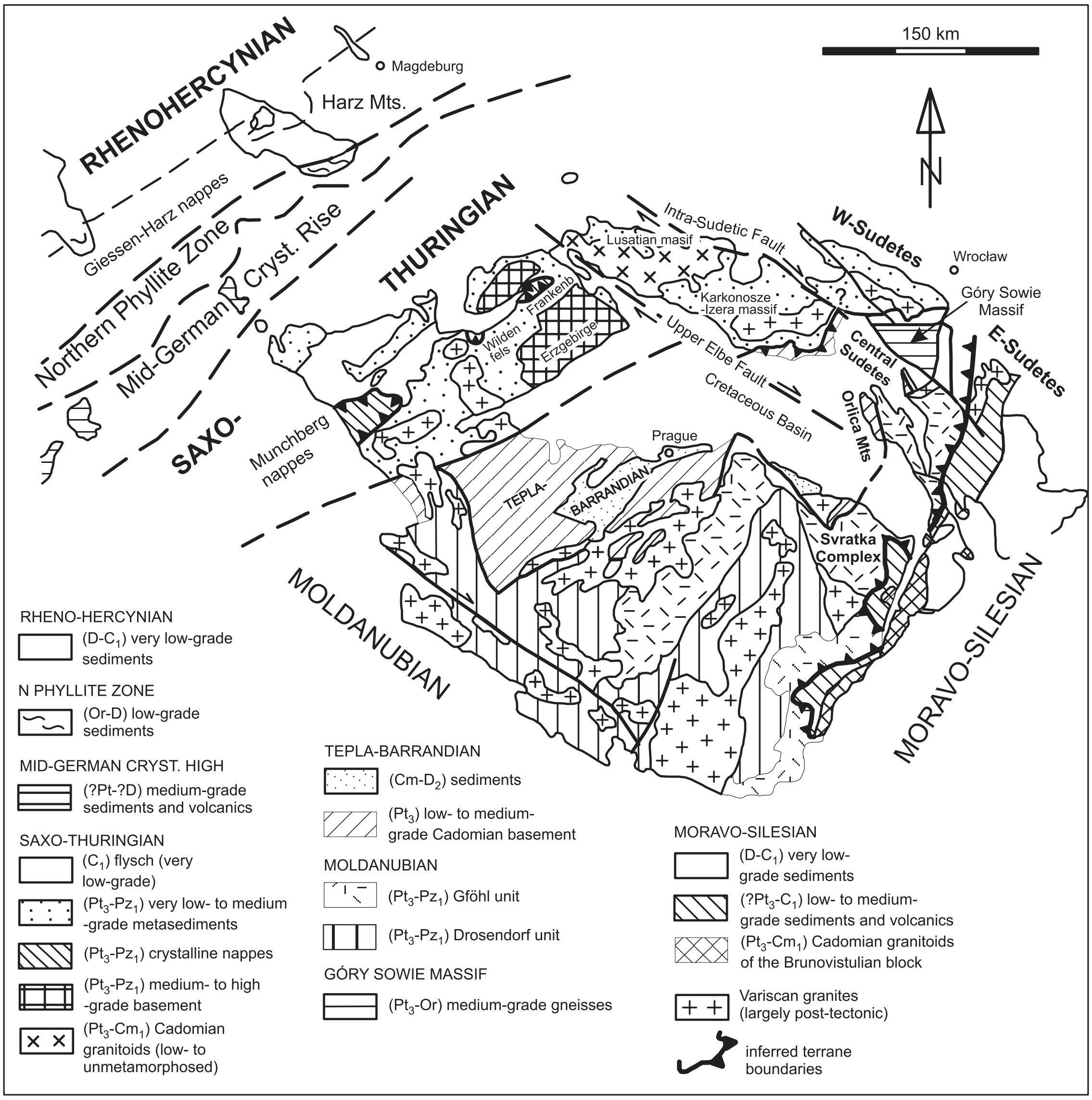

Fig. 2. Tectonostratigraphic division of the Bohemian Massif (modified from Matte *et al*., 1990)

Age assignments: Pt — Proterozoic; Pz — Palaeozoic; Cm — Cambrian; Or — Ordovician; D — Devonian; C — Carboniferous shearing, which was particularly intense in this area and which occurred along major strike-slip shear zones and faults roughly parallel and perpendicular to the nearby Teisseyre-Tornquist Lineament (Fig. 1; Arthaud and Matte, 1977; Aleksandrowski, 1995; Aleksandrowski *et al*., 1997).

The present paper provides a comprehensive up-to-date geological overview of the Polish part of the Variscan Belt, represented by the Sudetes and their foreland. The need for consistency of presented arguments and ideas, required, however, including in this review also the parts of the Sudetes that are located in the Czech Republic. This paper is based on a compilation of published data and interpretations and attempts at arriving at a synthesis of currently available evidence. At the same time, however, the scope of this contribution and the need for conciseness restrict the presentation of local details and nuances of numerous local to regional hypotheses.

TECTONIC SETTING OF THE POLISH VARISCIDES

The Variscides of Poland comprise metamorphic internides that crop out in the area of the Sudetes and an external fold-and-thrust belt, which is deeply buried in Central-West Poland beneath thick Permo-Mesozoic strata. A wide foreland basin flanks the Variscan external belt and extends towards the NE across the Teisseyre-Tornquist Zone.

The Sudetes represent the NE-most exposed part of the Variscan crystalline basement in Europe. They straddle the boundary between Poland and the Czech Republic and constitute the NE margin of the Bohemian Massif (Figs. 2 and 3). The Sudetes contain variously metamorphosed volcano-sedimentary successions and igneous suites of pre-Carboniferous age. Metamorphic rocks are onlapped by sediments contained in Late Devonian to Carboniferous intramontane troughs and are intruded by voluminous late- to post-orogenic Carboniferous granites. The Sudetic Internides are juxtaposed along major faults against the Variscan external fold-and-thrust belt that subcrops at the base of the Permo-Mesozoic succession of the Fore-Sudetic Monocline*. Pre-orogenic, weakly metamorphosed Late Devonian sediments of the external belt have been penetrated only by few wells on the Leszno-Wolsztyn High. The bulk of rocks traditionally ascribed to the Variscan external zone of Central-West Poland is formed by Carboniferous syn-orogenic turbidite successions that, in our interpretation, were deposited in the proximal parts of the foreland basin, probably on top of earlier tectonised Late Devonian sediments. As the SW parts of the foreland basin successions are folded and thrust-faulted, they are here included in the external part of the orogen. However, the transition between the fold-thrust belt and the largely undeformed foreland is rather gradual and, hence, a discrete Variscan thrust front probably cannot be defined in Poland, although it has been to date a subject of various interpretations (e.g. Jubitz *et al*., 1986; Pożaryski *et al*., 1992). On the other hand, Variscan intraplate deformations are well developed even far beyond the traditionally assumed confines of the Variscan Belt, e.g. in Carboniferous of the Lublin Trough and of the Holy Cross Mountains in East and Central Poland.

The geologically coherent Sudetic area is divided into two domains of contrasting topography: the low-mountainous ridge of the Sudetes Mountains to the SW and the largely peneplained lowland of the Fore-Sudetic Block to the NE, separated by the Sudetic Boundary Fault. The latter is a late Variscan fracture zone (e.g. Aleksandrowski *et al*., 1997) that was rejuvenated during the latest Cretaceous-Paleocene and Neogene uplift stages affecting the Bohemian Massif (Ziegler and Dèzes, 2006). The Sudetic area extends between the WNW–ESE trending Middle Odra Fault Zone in the NE and the parallel Upper Elbe Fault Zone in the SW (Fig. 3). To the SE, the Variscan basement of the Sudetes plunges beneath the Miocene Carpathian Foreland Basin and to the NW it merges with the Lusatian Massif.

The Sudetes consist of a mosaic of structurally distinct, fault-bounded pre-Permian units (Fig. 3), affected by mostly Devonian to Carboniferous deformation and characterized by frequent changes in the dominant structural trends. Variations in the geological evolution of most Sudetic units, combined with the occurrence of ophiolitic bodies and/or meta-igneous rocks with a MORB-like geochemical signature along some of their boundaries and the preservation of HP to UHP metamorphic rocks (blueschists, eclogites, granulites), suggest that the area comprises fragments of distinct tectonostratigraphic terranes that are separated by tectonic sutures and major faults/shear zones. A possible terrane pattern for this region has recently been a matter of lively debate (Matte *et al*., 1990; Aleksandrowski, 1990, 1995; Oliver *et al*., 1993; Franke *et al*., 1995; Cymerman *et al*., 1997; Franke and Żelaźniewicz, 2000, 2002; Aleksandrowski and Mazur, 2002). The Sudetic terranes appear to form the continuation of the Armorican Terrane Assemblage known from the western parts of the Variscan Orogen (Franke *et al*., 1995; Pharaoh, 1999; Aleksandrowski and Mazur, 2002; Winchester *et al*., 2002). These are the Saxothuringian, Teplá-Barrandian and Moldanubian terranes, whereas the Moravo-Silesian and Brunovistulian terranes may represent the peri-Baltica terranes of the Trans-European Suture Zone (Belka *et al*., 2002).

The Sudetes are generally divided into the western, central and eastern parts on account of important differences in their lithostratigraphy, structure and geological evolution (Fig. 4). Furthermore, the Sudetic area is split into halves by the major strike-slip Intra-Sudetic Fault that parallels the Middle Odra and Upper Elbe faults (Fig. 3).

GEOLOGICAL UNITS OF SUDETES

Below, moving from the NW to the SE, the essential features of successive Sudetic structural units are reviewed. These units are more thoroughly described where specific geological aspects are important to palaeotectonic reconstructions and the understanding of the sequence of tectono-metamorphic events, or where up-to-date descriptions are only briefly summarized in the available literature.

* The traditional term “Fore-Sudetic Monocline” is retained here on Editors’ request, although according to the authors the correct English translation of the original Polish name for this regional feature should read “Fore-Sudetic Homocline”.

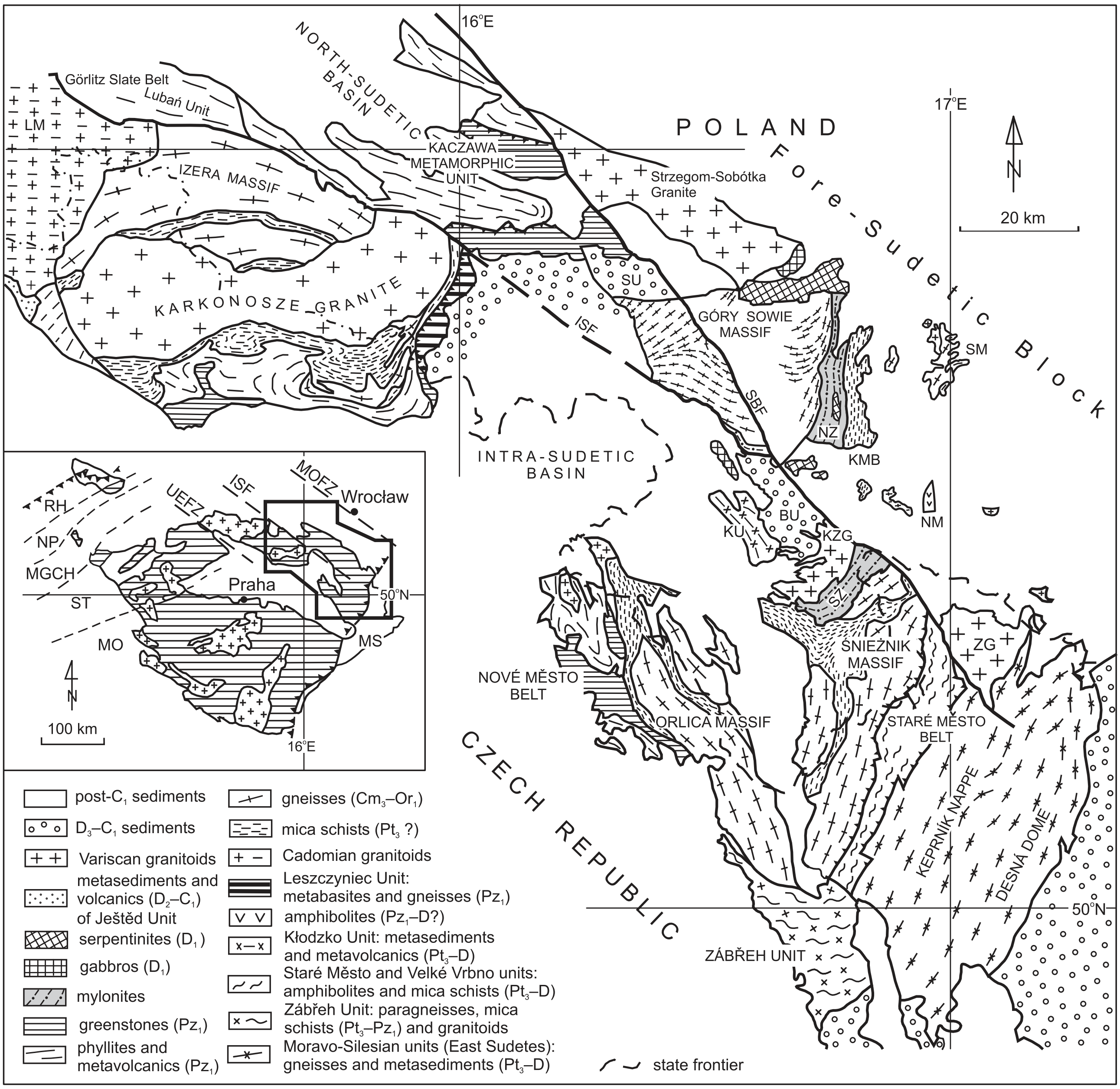

Fig. 3. Geological sketch map of the Sudetes (after Aleksandrowski *et al*., 1997)

BU — Bardo Sedimentary Unit; ISF — Intra-Sudetic Fault; KMB — Kamieniec Metamorphic Belt; KU — Kłodzko Metamorphic Unit; KZG — Kłodzko-Złoty Stok Granite; LM — Lusatian Massif; MGCH — Mid-German Crystalline High; MO — Moldanubian Zone; MOFZ — Middle Odra Fault Zone; MS — Moravo-Silesian Zone; NM — Niedźwiedź Massif; NP — Northern Phyllite Zone; NZ — Niemcza Shear Zone; RH — Rhenohercynian Zone; SU — Świebodzice Sedimentary Unit; SBF — Sudetic Boundary Fault; SM — Strzelin Massif; ST — Saxothuringian Zone; SZ — Skrzynka Shear Zone; ; UEFZ — Upper Elbe Fault Zone; ZG — Žulová Granite; other explanations as on Figure 2

WEST SUDETES

The West Sudetes comprise the Karkonosze-Izera Massif, the Kaczawa Metamorphic Unit and the Görlitz Slate Belt, as well as the eastern part of the Lusatian Massif (Fig. 3), all of them deformed between the Late Devonian and Late Carboniferous. The deformation climax, accompanied by orogenic uplift, took place there during the Early Carboniferous and was followed by sedimentation in the intramontane North-Sudetic Permo-Mesozoic Basin from the latest Carboniferous onward.

LUSATIAN MASSIF AND GÖRLITZ SLATE BELT

The Lusatian Massif comprises mostly Neoproterozoic to Early Cambrian granitoids (540–530 Ma; Kröner *et al*., 1994; Linnemann *et al*., 2000; Tikhomirova, 2002; Żelaźniewicz *et al*., 2004), with a weak or missing deformation fabric. They were emplaced during the final phases of the Cadomian Orogeny (Linnemann *et al*., 2000). These granitoids intruded non- to low-grade metamorphic Neoproterozoic turbiditic greywackes (Linnemann *et al*., 1998), containing intercalations of felsic

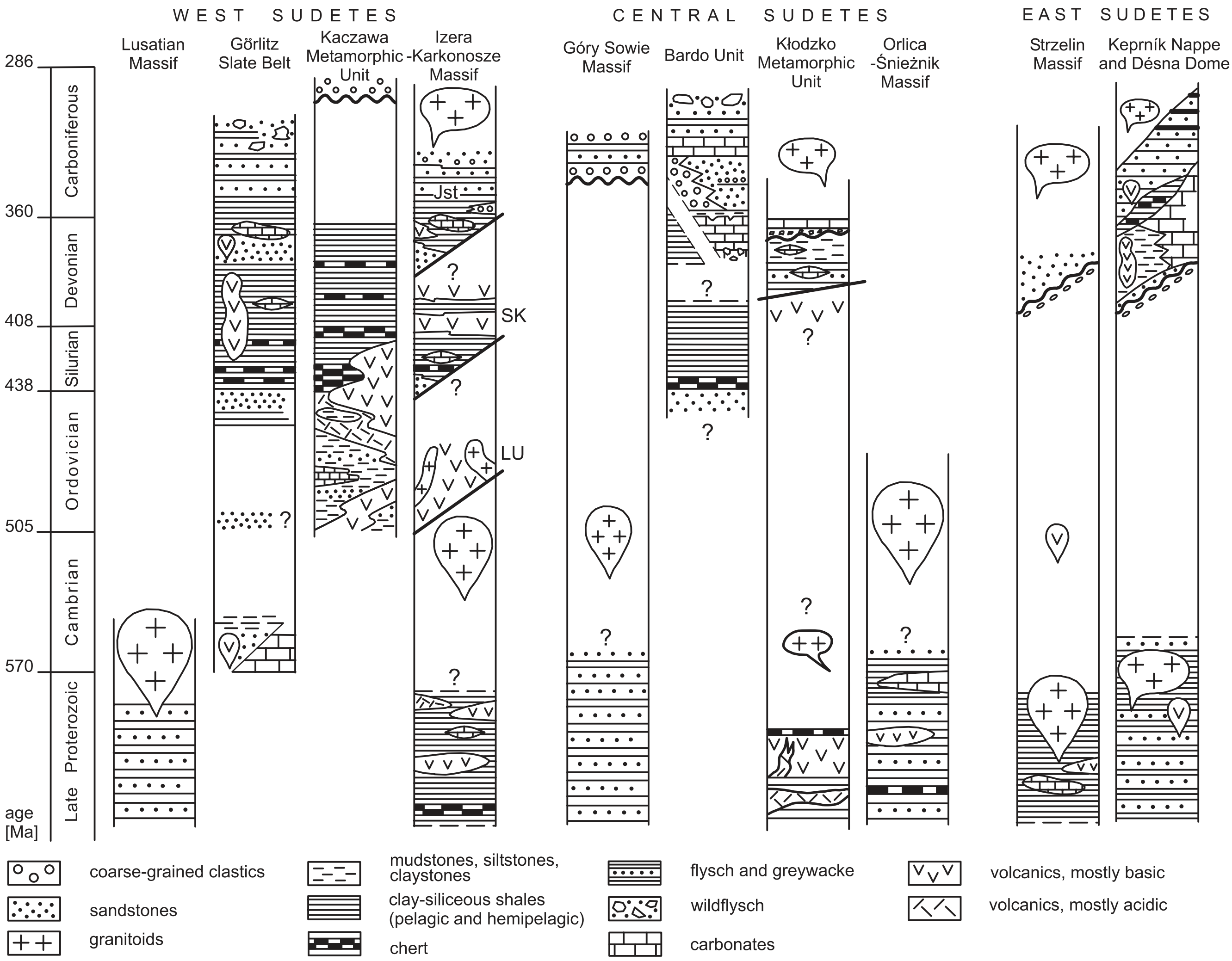

Fig. 4. Simplified stratigraphic columns of the main structural units of the Sudetes (modified from Aleksandrowski and Mazur, 2002)

Metamorphic rocks are represented by their sedimentary and igneous protoliths; LU — Leszczyniec Unit, SK — South Karkonosze Unit, Jst — Ještěd Unit

volcaniclastic rocks dated on zircons as *c*. 575 Ma by the U-Pb SHRIMP method (Buschmann *et al*., 2001). The Görlitz Slate Belt (e.g. Urbanek *et al*., 1995), sometimes inappropriately referred to as the "Görlitz Syncline", flanks the Lusatian Massif to the NE and contains fragments of dismembered Early Cambrian to Early Carboniferous sedimentary successions, partly embedded in Early Carboniferous flysch (*cf*. Linnemann and Buschmann, 1995).

The Görlitz succession (Fig. 4) begins with Early Cambrian carbonates, sandstones and scarce volcanics, capped by trilobite-bearing shales (Freyer, 1977; Urbanek *et al*., 1995). The scarce Ordovician rocks are generally siliciclastics. The Silurian section is comparable to that of the Thuringian facies of the Saxothuringian Zone (Hirschmann, 1966), and is composed of siliceous and "alum shales", intercalated at the top with tuffs, quartzites, greywacke and rare limestone (Urbanek *et al*., 1995). The Devonian is represented by a monotonous series of alternating quartzites, pelites and greywackes with rare limestones and basic volcanic rocks. The Lower Carboniferous consists of flysch, accompanied towards the top by chert, limestone and significant conglomerate intercalations (Urbanek *et al*., 1995) and also of wildflysch containing olistoliths of Ordovician through Lower Carboniferous rocks (Thomas, 1990). Linnemann and Buschmann (1995) and Linnemann *et al*. (1998), interpreted the entire Görlitz Slate Belt as an Early Carboniferous wildflysch, comprising variable size olistolithic fragments of dismembered older strata. The development of the south-verging tight folds and steeply dipping "schuppen" structure of the Görlitz Slate Belt is dated at the middle to late Viséan (Hirschmann, 1966; Brause and Hirschmann, 1969).

KACZAWA METAMORPHIC UNIT

The Kaczawa Metamorphic Unit comprises several folded thrust sheets, composed of numerous slices and significant mélange bodies. These involve various fragments of a volcano-sedimentary succession of proven Ordovician through Late Devonian (Famennian) age (Baranowski *et al*., 1987, 1990). The Wojcieszów Limestone, originally thought to be Late Cambrian in age, was recently re-interpreted as Ordovician-Silurian, based on palaeontological findings (Skowronek and Steffahn, 2000). The lower part of the Kaczawa succession, comprising Ordovician shallow marine sedimentary rocks and bimodal within-plate volcanics, is interpreted as deposited in an intra-continental rift

(Baranowski *et al*., 1990; Kryza and Muszyński, 1992; Kryza, 1993; Furnes *et al*., 1994; Seston *et al*., 2000). These rocks are overlain by a thick monotonous sequence of tholeitic E-MORB to N-MORB pillowed basalts accompanied by Silurian black graptolitic shales and by Devonian siliceous and clayey slates and cherts, believed to have accumulated in an evolved, probably oceanic rift environment (Furnes *et al*., 1994). The upper part of the Kaczawa succession, interpreted as an end Devonian/Early Carboniferous accretionary prism, is made up of low-grade metamorphosed (in blueschist overprinted by greenschist facies) siliciclastics, volcaniclastics, carbonates, basic and acidic volcanics, pelagic clayey and siliceous shales and flysch (Baranowski *et al.*, 1987, 1990; Kryza and Muszyński, 1992; Collins *et al*., 2000; Seston *et al*., 2000).

The high-pressure metamorphism is thought to have taken place by *c*. 360 Ma, by analogy to that dated in the East Karkonosze Suture by Maluski and Patočka (1997). The Kaczawa thrust sheets were emplaced during the latest Devonian-earliest Carboniferous in a top-to-NW to WNW shearing regime, synchronous with greenschist facies metamorphism. Subsequently, they were affected by a top-to-ESE extensional collapse and 2–3 times folded and refolded in progressively more brittle and cool conditions (Kryza *et al*., 1998; Seston *et al*., 2000; Cymerman, 2002), probably contemporaneously with recurrent strike-slip motions on the adjacent Intra-Sudetic Fault (Aleksandrowski, 1995; Aleksandrowski *et al*., 1997).

The Kaczawa Metamorphic Unit has been considered to continue westward into the Görlitz Slate Belt (e.g. Jaeger, 1964; Hirschmann, 1966; Brause and Hirschmann, 1969; Urbanek *et al*., 1995). This view, however, though widely held due to geographic proximity of both units (Fig. 3), does not explain the important differences in stratigraphy, age of deformation and variation of metamorphic grade between them. The Görlitz Palaeozoic succession is unmetamorphosed or very slightly metamorphosed, whereas the Kaczawa Unit, over its entire extensive outcrop area, shows a greenschist facies metamorphism, obliterating relicts of an earlier HP/LP event. The Lower Cambrian known from the Görlitz Slate Belt is missing in the Kaczawa Unit. Furthermore, products of the Ordovician volcanism widespread in the Kaczawa succession are absent in the Görlitz Slate Belt. The latter does not contain extensive bodies of Silurian mafic MORB-type volcanics, and its Devonian deposits represent shallower water facies than those of the Kaczawa Mountains. Lower Carboniferous rocks have as yet not been unequivocally recognized in the central and eastern part of the Kaczawa Unit. Early Carboniferous ages, are, nevertheless, suspected for some of the mélange bodies in that region (Baranowski *et al*., 1987, 1990; Collins *et al*., 2000). At the same time, however, greenschist facies Kaczawa rock fragments are abundantly present as pebbles in middle Viséan conglomerates of the northern rim of the Intra-Sudetic Basin (A. K. Teisseyre, 1971, 1975). Therefore, the metamorphism, deformation and exhumation of at least part of the Kaczawa Unit must have taken place by early Viséan times.

On the other hand, Early Carboniferous deposits in the westernmost part of the Kaczawa Metamorphic Unit near Gryfów Śląski and Lubań, extend upward into the lower part of the upper Viséan, as documented by conodont stratigraphy (Chorowska, 1978). In this area, Palaeozoic rocks crop out in an elongated narrow belt adjacent to the Intra-Sudetic Fault. Further west, this belt merges into the Görlitz Slate Belt. According to Milewicz *et al*. (1989) and Cymerman (2002), NE of Gryfów Śląski, this belt of Palaeozoic rocks is tectonically divided into two segments with differing metamorphic grades. The eastern segment shows greenschist facies metamorphism, typical of the Kaczawa rocks, and is included into the Pilchowice Unit of the Kaczawa succession that extends eastward into the vicinity of Jelenia Góra. The western segment, however, distinguished as the Lubań Unit (Fig. 3), shows only a very weak metamorphic imprint and contains Viséan limestone fragments occurring within a chaotic deposit at Rząsiny (Chorowska, 1978). The timing of tectonic deformation inferred from this finding does not match that of the eastern Kaczawa Unit, but corresponds to that of the Görlitz Slate Belt. Consequently, the Lubań Unit probably represents the easternmost part of the Görlitz Slate Belt that was extended and sheared along the northern wall of the Intra-Sudetic Fault Zone.

KARKONOSZE-IZERA MASSIF

The Karkonosze-Izera Massif includes the Karkonosze Granite Pluton, dated at 329±17 Ma (Rb-Sr whole rock isochrone; Duthou *et al*., 1991) and its metamorphic envelope (Fig. 5). The latter comprises four structural units (Fig. 6). From base to top these are: (1) the Izera-Kowary, (2) Ještěd, (3) South Karkonosze and (4) Leszczyniec units, the latter two units containing a tectonic suture (Mazur and Aleksandrowski, 2001).

The Izera-Kowary Unit consists mainly of the Late Cambrian/Early Ordovician Izera (Rumburk) Granite (Borkowska *et al*., 1980; Oliver *et al*., 1993; Korytowski *et al*., 1993), most of which was transformed into the Izera/Kowary Gneiss during its Late Devonian to Early Carboniferous deformation. This gneiss extends into Czechia where it is referred to as the Krkonoše Gneiss that has been dated at ±500 Ma (Kröner *et al*., 2001). The other significant component of the Izera-Kowary Unit are mica schists that represent the remains of the Neoproterozoic(?) envelope of the Izera Granite. These rocks underwent medium pressure metamorphism under upper greenschist-lower amphibolite facies conditions (Żaba, 1984; Oberc-Dziedzic, 1988; Kryza and Mazur, 1995). Towards the west, the Izera-Kowary Granite and Gneiss reveal intrusive contacts with the Neoproterozoic-Early Cambrian granitoids of the Lusatian Massif (Ebert, 1943; Domečka, 1970).

The Ještěd Unit, a small fault-bounded block, exposed at the SW margin of the Karkonosze-Izera Massif, comprises Middle to Late Devonian shallow marine to hemipelagic sediments with minor volcanics (Jítrava Group of Chaloupský, 1989) that were subjected to a very weak, low temperature-medium pressure metamorphism. These pre-orogenic deposits pass upwards into Tournaisian to lower Viséan Culm-facies greywackes and conglomerates (Chlupáč and Hladil, 1992; Chlupáč, 1993).

The South Karkonosze Unit comprises a several hundred metres thick succession of metamorphosed Ordovician to Devonian sedimentary rocks (Chlupáč, 1993, 1997), containing bimodal, mostly basic volcanics. The latter represent a differentiated magmatic suite, ranging from predominantly felsic rocks with a within-plate geochemical signature, dated at 501±8 Ma

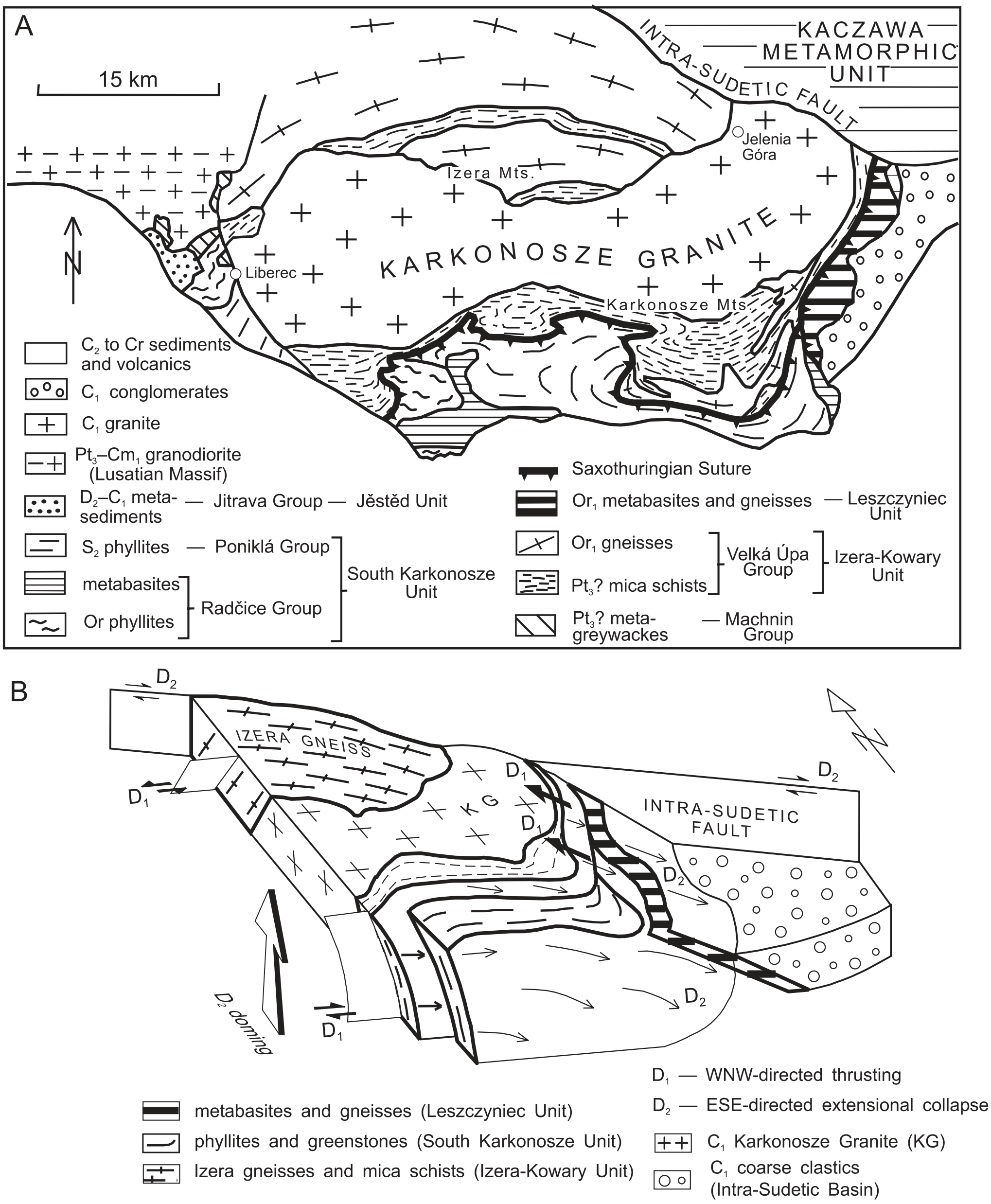

Fig. 5. Geology of the Karkonosze-Izera Massif

A — sketch map, **B** — block diagram showing deformation partitioning and sense of tectonic transport during deformation events D_1 and D_2 (modified from Mazur, 1995); other explanations as on Figure 2

(Rb-Sr whole rock method; Bendl and Patočka, 1995) to basic lavas and pyroclastics of P-type MORB affinities (Bendl *et al.*, 1997; Patočka and Smulikowski, 2000). The basic metavolcanics preserve the record of an early blueschist facies metamorphism (e.g. Cháb and Vrána, 1979; Kryza and Mazur, 1995; Smulikowski, 1995; Patočka *et al.*, 1996), dated at *c.* 360 Ma, which was followed by a greenschist overprint at *c.* 340 Ma (^{40}Ar-^{39}Ar method; Maluski and Patočka, 1997). The South Karkonosze Unit probably represents a tectonically dismembered, once continuous and laterally diversified sedimentary succession that was deposited in a large marine basin (Mazur and Aleksandrowski, 2001).

The Leszczyniec Unit consists of a differentiated suite of mafic and felsic intrusive and extrusive rocks (Teisseyre, 1973; Kryza and Mazur, 1995) dated at *c.* 500 Ma (U-Pb zircon method; Oliver *et al*., 1993) and showing N-MORB affinities (Kryza *et al*., 1995; Wichester *et al*., 1995). The Leszczyniec unit wedges out to the south and does not continue into Czechia (Mazur, 1995, Mazur and Aleksandrowski, 2001).

Since the beginning of the 1990's, a new nappe model was developed for the Karkonosze-Izera Massif (Mazur, 1995; Mazur and Kryza, 1996; Seston *et al*., 2000; Mazur and Aleksandrowski, 2001), mainly on the basis of contrasting metamorphic paths (Kryza and Mazur, 1995) and the record of

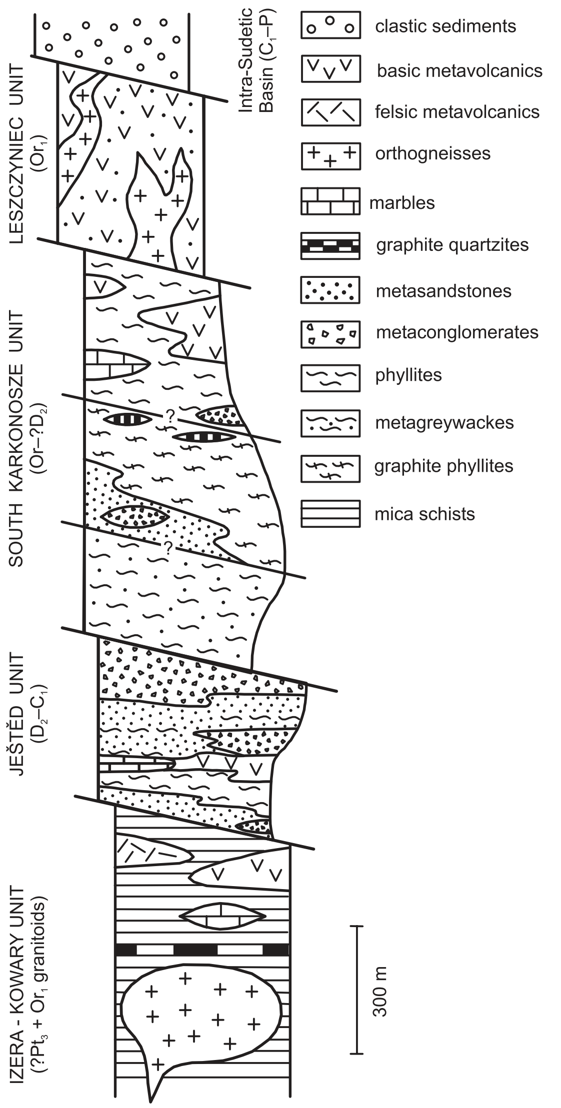

Fig. 6. Simplified tectonostratigraphic division of rock complexes composing the Karkonosze-Izera Massif (after Mazur and Aleksandrowski, 2001)

Age assignments as on Figure 2

different tectonic settings (Mazur and Aleksandrowski, 2001) of its four constituent units. The gneisses and mica schists of the Izera-Kowary Unit are considered to represent the Early Palaeozoic continental crust of the Saxothuringian Basin (Franke and Żelaźniewicz, 2000; Mazur and Aleksandrowski, 2001) that was subjected to Variscan deformation in the collision zone, which extended along the southern and eastern rims of the Karkonosze-Izera Massif. A small fragment of the sedimentary succession that was deposited on the NE passive margin of the Saxothuringian Terrane, probably parautochthonous or representing the lowermost nappe, is the Ještěd Unit of the Karkonosze-Izera Massif, tectonically sandwiched between the overlying South Karkonosze Unit and the underlying Izera-Kowary Unit.

The South Karkonosze Unit occupies a structurally higher position in the Karkonosze-Izera Massif and is probably composed of lower order thrust sheets or slices with mutually similar structural and metamorphic histories derived from the volcano-sedimentary fill of an Early Palaeozoic rifted passive margin. The Leszczyniec Unit, which forms the structurally highest element of this nappe pile, is characterized by a NNE–SSW structural grain, that differs entirely from the WNW–ESE structural trend of the remaining part of the Karkonosze-Izera Massif and is interpreted to represent an obducted sea floor fragment (Mazur and Aleksandrowski, 2001). The South Karkonosze and Leszczyniec nappes, comprising blueschist facies rocks and MORB-type magmatic complexes, were tectonically emplaced on top of the continental basement parautochthonous Izera-Kowary Unit. The entire NW-ward displaced nappe stack shows metamorphic inversion (Mazur and Kryza, 1996; Mazur and Aleksandrowski, 2001) and must have formed at the turn of the Late Devonian and the Early Carboniferous. It was subsequently modified by Early Carboniferous, SE-directed extensional unroofing and, eventually, by the late Viséan intrusion of the Karkonosze Granite (Fig. 5; Mazur, 1995; Mazur and Aleksandrowski, 2001).

CENTRAL SUDETES

The Central Sudetes comprise the structural units that occur (1) to the E of the Karkonosze-Izera Massif and of the Kaczawa Metamorphic Unit, (2) to the W of the Velké Vrbno and Branná units of the East Sudetes, as well as (3) to the W of the Strzelin Massif in the eastern part of the Fore-Sudetic Block (Fig. 3). Thus, the Central Sudetes include the Góry Sowie Massif, together with the surrounding mafic and ultramafic bodies of the Central Sudetic Ophiolite, the Kłodzko Unit, the Orlica-Śnieżnik Massif, the Nové Město, Staré Město and Kamieniec Metamorphic belts, and the Niemcza and Skrzynka Shear zones, as well as the Niedźwiedź Amphibolite Massif. These are partly covered by the tectonized sedimentary fill of the Bardo and Świebodzice successor basins, which were initiated during the Late Devonian, and by that of the Intra-Sudetic Basin that began to subside during the middle Viséan (Turnau *et al*., 2002). The main deformation in this area occurred at the turn of the Middle to the Late Devonian, to be soon followed by regional uplift, and a succession of overprinting Carboniferous tectonic pulses.

GÓRY SOWIE MASSIF

The Góry Sowie Massif is composed of amphibolite facies paragneisses thought to have been derived from Neoproterozoic to Early Cambrian protoliths (Fig. 4; Gunia, 1985, 1999). They are accompanied by migmatites and orthogneisses that contain small ultramafic and granulitic bodies (Grocholski, 1967; Kryza, 1981; Żelaźniewicz, 1990), recording pressure and temperature conditions typical of mantle and lower crustal levels. Granulite formation at pressures of 16–20 kbars and temperatures above 900°C (Kryza *et al*., 1996) was dated, using the U-Pb zircon method, at *c*. 400 Ma (O'Brien *et al*., 1997) and 395 Ma (Kryza and Fanning, 2004). These ages correspond closely with the Sm-Nd age of the associated, mantle-derived peridotites (Brueckner *et al*., 1996). This granulite-grade metamorphic event was followed by relatively rapid uplift of the massif, associated with contemporaneous decompression under amphibolite facies conditions. The time interval for this MP/HT metamorphism is estimated at *c*. 385–370 Ma on the basis of U-Pb monazite, xenotime and zircon ages and Rb-Sr data (van Breemen *et al*., 1988; Bröcker *et al*., 1998; Timmermann *et al*., 2000). Gneiss pebbles in the latest Devonian-earliest Carboniferous conglomerates of the Świebodzice Sedimentary Unit record the final exhumation of the Góry Sowie Massif (Porębski, 1981, 1990). The minor orthogneisses forming scattered bodies, mostly occurring in the SW part of the Góry Sowie Massif, were dated at *c*. 500 Ma with the U-Pb evaporation method on zircons (Kröner and Hegner, 1998) and seem to be equivalents of Early Palaeozoic granite intrusions of this age, well known from other parts of the Sudetes.

Thermobarometric data and radiometric age constraints (Brueckner *et al*., 1996; Kryza *et al*., 1996; O'Brien *et al*., 1997; Kryza and Fanning, 2004) indicate that the Góry Sowie granulites represent "type I granulites" of Pin and Vielzeuf (1983), that were derived from a continental crust subducted in the Variscan belt to mantle depths at around 430–400 Ma (Vielzeuf and Pin, 1989). Subsequently, at *c*. 385–370 Ma (Bröcker *et al*., 1998) these granulites experienced a distinct decompressional event (4–10 kbar) under continuing high temperatures (600–700°C) that coincided with peak metamorphism and anatexis in the surrounding gneisses and migmatites (Kryza *et al*., 1996). Consequently, the Góry Sowie Massif can be considered a piece of the Neoproterozoic continental crust that was subducted to mantle depths during the Late Silurian/Early Devonian and was exhumed during the Late Devonian. The associated metamorphism mostly ceased before the latest Devonian i.e. prior to the deposition of the Świebodzice Sedimentary Unit.

ŚWIEBODZICE SEDIMENTARY UNIT

The Late Devonian (upper Frasnian-Famennian) to lowermost Carboniferous Świebodzice Sedimentary Unit ("Depression"), up to 4000 m thick, occurs in a small, rhomboidal, fault-bounded block and consists mainly of polymict conglomerates. In their lower part, the conglomerates are interbedded with thick fossiliferous mudstones containing sandstone turbidites and rare limestone lenses. According to Porębski (1981, 1990), these deposits reflect mostly gravity-flow sedimentation in a marine slope-type fan-delta complex of a rapidly subsiding basin, bounded to the SW and S by active fault systems with a probable strike-slip displacement component.

BARDO SEDIMENTARY UNIT

The sedimentary succession of the Bardo Unit comprises unmetamorphosed Upper Devonian limestones and Early Carboniferous flysch that is capped by wildflysch deposits (Wajsprych, 1978, 1986). The wildflysch contains large olistoliths of Lower Palaeozoic (Ordovician and Silurian) and Devonian deep marine sediments (Haydukiewicz, 1990). The Bardo succession was folded at the turn of Early/Late Carboniferous into E–W trending folds and intruded by the Kłodzko-Złoty Stok Granitoid Pluton. Late Carboniferous refolding produced NE–SW to N–S trending folds, superposed onto the older E–W structures (Oberc, 1972).

CENTRAL SUDETIC OPHIOLITE

The Central Sudetic Ophiolite comprises several mafic and ultramafic bodies that crop out along the northern (Ślęża Ophiolite), eastern (Szklary and Braszowice Serpentinite massifs) and southwestern (Nowa Ruda Gabbro-Diabase Massif) rims of the Góry Sowie Massif. The Devonian exhumation of the Central Sudetic Ophiolite is constrained by the occurrence of a pre-Late Devonian erosional surface cutting the Nowa Ruda Massif. This situation refers directly only to the Nowa Ruda Ophiolite, but may concern also the other Circum-Góry Sowie ophiolites, as all these ophiolite bodies show similar geochemical characteristics (Pin *et al*., 1988; Gunia, 1997) and probably represent parts of one and the same dismembered ophiolitic suite.

For several years the inferred Devonian obduction and exhumation age of the Central Sudetic Ophiolite was contradicted by the first isotopic dating of its protolith. Whole-rock Sm-Nd analysis of six samples of the Ślęża Gabbro, indicated an age of 353±21 Ma, and ten samples of gabbro from the Nowa Ruda Massif yielded an age of 351±16 Ma (Pin *et al*., 1988). However, Oliver *et al*. (1993) determined a Silurian igneous age (420+20/–2 Ma) for the Ślęża Gabbro on the basis of conventional U-Pb zircon method. A recent U-Pb age of 400+4/–3 Ma (Dubińska *et al*., 2004), obtained on abraded low-temperature zircons from rodingitized plagiogranite of the Ślęża Ophiolite, was interpreted as corresponding to the age of serpentinization/rodingitization, and considered as a minimum age of their igneous protolith. This suggests a Late Silurian to Early Devonian age for this ophiolite. Consequently, the previous Sm-Nd ages may reflect subsequent thermal overprints during tectonic emplacement and cooling of the Central Sudetic Ophiolite.

The spatial interrelationship between the Central Sudetic Ophiolite and the Góry Sowie Massif is not clear, since their contact is not exposed. From Viséan times onward, the Góry Sowie Massif supplied the marginal parts of the Bardo Basin with abundant gneissic pebbles that accumulated in a system of coarse clastic fans along the SW margin of the Góry Sowie Massif (Wajsprych, 1978, 1986; Haydukiewicz, 1990). The mapped relationships show that the Bardo Sedimentary Unit is partly floored by the Kłodzko metamorphic rocks and partly by the Nowa Ruda Ophiolite. However, the only borehole that drilled through the entire Bardo succession was stopped after penetrating several tens of metres into typical Góry Sowie Gneiss (Chorowska *et al*., 1986). Therefore, it seems likely that the Góry Sowie Gneiss, together with rocks of the Kłodzko Metamorphic Unit and of the Nowa Ruda Ophiolite form the pre-Carboniferous basement, on which the Bardo sedimentary succession was laid down.

KŁODZKO METAMORPHIC UNIT

The Kłodzko Metamorphic Unit consists of six smaller tectonic units (Fig. 7). These are, from base to top: (1) the Mały Bożków Unit, comprising a Middle Devonian (Givetian) progradational shelf sequence (Hladil *et al*., 1999), (2) a mélange

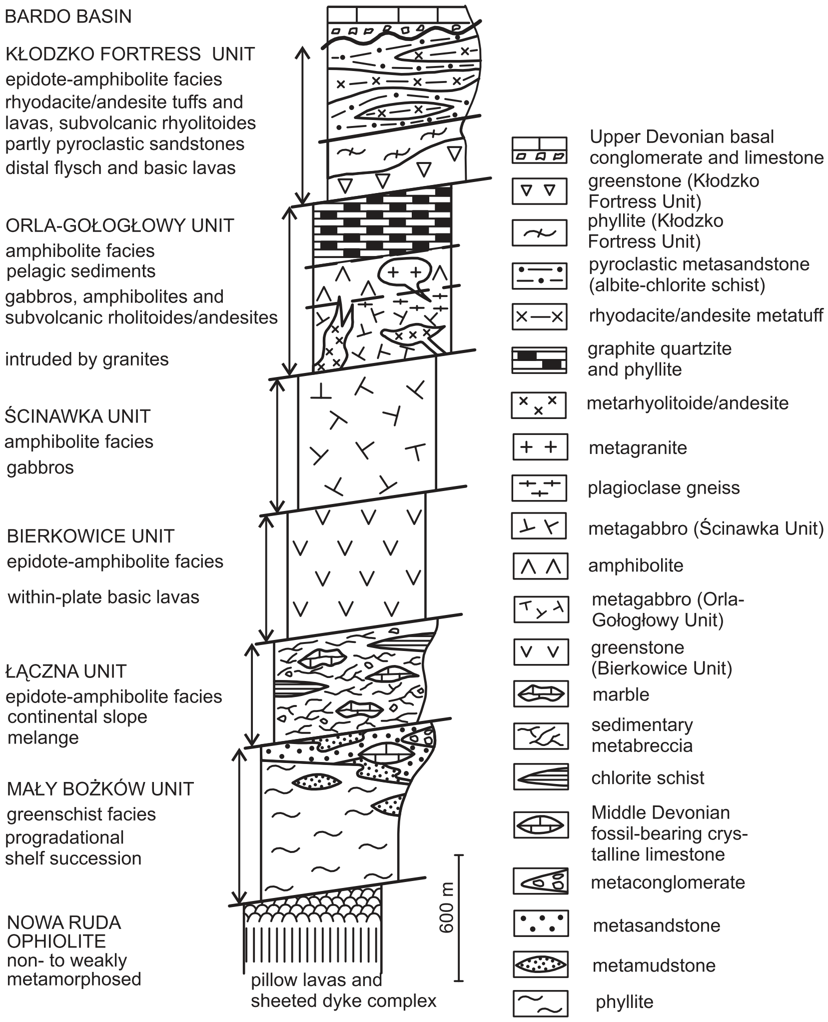

Fig. 7. Lithotectonic profile of the Kłodzko Metamorphic Unit (after Mazur, 2003)

body of unknown age referred to as the Łączna Unit (Mazur, 2003), (3) the Bierkowice Unit, composed of a Palaeozoic (?) monotonous sequence of mafic volcanics with intraplate basalt geochemical signature (Kryza *et al*., 2003), (4) the MORB-type gabbro of the Ścinawka Unit (Kryza *et al*., 2003) that shows affinities to (5) the Orla-Gołogłowy Unit, being composed of Neoproterozoic MORB-type gabbro and mafic volcanics (Kryza *et al*., 2003; Mazur *et al*., 2004), associated with some felsic subvolcanic rocks and locally accompanied by graphite bearing black schists (latter intruded by a minor Early Palaeozoic granite body, subsequently transformed into the Ścinawka Gneiss), (6) the Kłodzko Fortress Unit, consisting of distal flysch deposits that contain basaltic lavas, pyroclastic sandstones and dacitic/andesitic tuffs, which yielded a Neoproterozoic-Early Cambrian age (Mazur *et al*., 2004; Turniak *et al*., 2005). The metamorphic grade increases upwards from greenschist to amphibolite facies, except for the highest unit that shows an epidote-amphibolite facies metamorphism.

Zircons dating yielded an age of 590.1±7.2 Ma for the protolith of a gabbro-plagioclase gneiss suite comprised in the Orla-Gołogłowy Unit and a rather imprecise estimate of 590–600 Ma, constraining the maximum deposition age of the volcano-sedimentary succession from the Kłodzko Fortress Unit (Mazur *et al*., 2004). Later SHRIMP analyses on zircons from the latter unit (Turniak *et al*., 2005) yielded two groups of $^{238}U/^{206}Pb$ ages, interpreted to indicate the time of protolith formation (528.4±5.2 Ma) and the age of an inherited component (543.3±5 Ma). These new results indicate that the volcano-sedimentary succession of the Kłodzko Fortress Unit either represents an age interval of *c*. 528–590 Ma, or that the previously reported multigrain age of *c*. 590–600 Ma reflects mixing of grains with different ages. Samples of the Ścinawka Gneiss invariably yielded ages in the range of 490–500 Ma, regardless of the dating method applied (Mazur *et al*., 2004; Turniak *et al*., 2005).

The tectonic nature of contacts between the different units of the Kłodzko Unit was inferred from their contrasting metamorphic paths and differences in their lithostratigraphy and palaeoenvironmental affinities (Mazur, 2003). They form a nappe stack assembled due to a top-to-the WNW thrusting and emplaced on the essentially unmetamorphosed Nowa Ruda Ophiolite. The structurally lower Mały Bożków, Łączna and Bierkowice units of the NE part of the Kłodzko Unit consist, at least partly, of Middle Devonian sediments and volcanics derived from a passive continental margin. The upper Ścinawka, Orla-Gołogłowy and Kłodzko Fortress units of the SW part of the Massif are represented by Neoproterozoic successions that were thrust within a Variscan nappe pile as three separate tectonic elements over Palaeozoic rocks (Mazur, 2003). Bulk compositional and Nd-isotope results show that the Neoproterozoic sequence is characterized by the association of calc-alkaline felsic metavolcanics with metagabbros and cumulates of variable trace-element features, partly resembling N-MORB, and suggest a subduction-related environment of their emplacement (Kryza *et al*., 2003). Following Nance and Murphy (1996), the presence of a Neoproterozoic subduction-related magmatism in the Kłodzko Unit can be interpreted as indicating subduction of an oceanic-type domain beneath the active Gondwana margin prior to the Cadomian collision.

The Middle/Late Devonian termination of folding and metamorphism in the Kłodzko Unit and the adjacent Nowa Ruda Ophiolite Massif is constrained by an unconformity at the base of non-metamorphosed late Frasnian or earliest Famennian sediments resting on crystalline basement rocks of these massifs, first described by Bederke (1924) and more recently confirmed by Kryza *et al*. (1999). The most complete profile of this Upper Devonian succession is exposed at Mt. Wapnica in Dzikowiec, adjacent to the Nowa Ruda Massif (e.g. Bederke, 1924; Mazur, 1987). The unconformity that truncates the metamorphic rocks of the Kłodzko Unit and the ophiolites of the Nowa Ruda Massif, presumably developed during a relatively short time interval of about 10 Ma between the early Givetian and late Frasnian. This is suggested by the late Frasnian/Famennian age of limestones which directly overlie the basal conglomerates (Gürich, 1902; Bederke, 1929; Gunia, 1977) and by the early Givetian age of a coralline fauna from the greenschist facies crystalline limestone of the Kłodzko Unit at Mały Bożków (Hladil *et al*., 1999), previously interpreted as Late Silurian (Gunia and Wojciechowska, 1971). The presence of this unconformity implies that at the turn from the Middle to the Late Devonian, freshly deformed and metamorphosed rocks had been exposed and onlapped by deposits of the Bardo Sedimentary Unit, that eventually were folded during latest Viséan/Namurian times (Oberc, 1972). Bederke (1929) considered this unconformity as evidence for an imprint of the Caledonian Orogeny on the Sudetes. In a modified form, Bederke's conclusions have been revived in many recent publications (e.g. Don, 1984, 1990; Oliver *et al*., 1993; Johnston *et al*., 1994; Kröner and Hegner, 1998; Kröner *et al*., 2000). However, many lines of evidence suggest that the main tectono-thermal events of the Sudetes are related to multi-stage Late Devonian and Early Carboniferous collisional events (e.g. Aleksandrowski, 1994; Franke and Żelaźniewicz, 2000; Aleksandrowski *et al*., 2000).

INTRA-SUDETIC BASIN

The Intra-Sudetic Basin is a syn- to post-orogenic, relatively large (60 × 25 km) autochthonous basin that was initiated during the middle Viséan (Turnau *et al*., 2002). The basin remained active throughout Carboniferous and Permian times and contains up to 10 km of clastic sediments (Nemec *et al*., 1982; Dziedzic and Teisseyre, 1990). Its Early Carboniferous deposits reflected rapid late-orogenic uplift of surrounding areas, accompanied by extensional exhumation of the newly deformed and metamorphosed Sudetic crystalline complexes. The Early Carboniferous sediments consist mainly of coarse alluvial fan deposits accumulated in a continental environment along active fault scarps (Teisseyre, 1975). During the latest Viséan, the basin was progressively filled with deltaic deposits that graded upwards into shallow marine sediments. The Late Carboniferous series consists mostly of coal-bearing molasse that is succeeded by Early Permian continental clastics deposited under arid conditions (Wojewoda and Mastalerz, 1989). Several pulses of volcanism, reaching a climax in the Early Permian, accompanied the development of the Intra-Sudetic Basin (Awdankiewicz, 1999*a*, 2004). Large volumes of basaltic to rhyolitic lavas and subvolcanic intrusions reveal geochemical signatures evolving from a typical supra-subduction setting during the Early Carboniferous to an intra-plate environment during the Late Carboniferous and Early Permian (Awdankiewicz, 1999*b*). In the Intra-Sudetic Basin, volcanism and sedimentation ceased prior to and during the early Late Permian, respectively. Along the western basin margin, the upper Viséan conglomerates are involved in a regional-size NNE–SSW trending monocline together with the adjacent metamorphic complex of the Karkonosze-Izera Massif.

ORLICA-ŚNIEŻNIK MASSIF

The Orlica-Śnieżnik Massif (Fig. 3) is composed mostly of amphibolite-grade orthogneisses, with eclogite and granulite inliers, and subordinate staurolite-grade variegated supracrustal series (e.g. Don *et al*., 1990). The emplacement age of a magmatic precursor to all textural varieties of the orthogneisses was dated at *c*. 500 Ma, using various U-Pb and Pb-Pb methods on zircons (Oliver *et al*., 1993; Turniak *et al*., 2000; Kröner *et al*., 2001). Supracrustal rocks intruded by the protoliths of these orthogneisses are believed to be mostly Neoproterozoic in age, although available micropalaeontological and radiometric data reveal Early Cambrian ages (Fig. 4; Gunia, 1984, 1990; Kröner *et al*., 2001). Variscan tectonothermal phenomena include medium- to high-grade metamorphism and intense synmetamorphic deformation, accompanied by exhumation of high-grade rocks. The high pressure and temperature metamorphism was dated at *c*. 360–369 Ma, using the U-Pb method on zircons (Klemd and Bröcker, 1999), whereas the Lu-Hf geochronology yielded a considerably older age of *c*. 386 Ma (Szczepański *et al*., 2004). On the other hand, Sm-Nd whole rock ages for eclogites range from 350 to 330 Ma (Brueckner *et al*., 1991) and seem to reflect rather progressive cooling and decompression increments than peak metamorphism conditions. An age of *c*. 342 Ma was determined by SHRIMP dating of metamorphic rims on zircons from an orthogneiss (Turniak *et al*., 2000) and interpreted as reflecting a later HT/L-MP metamorphic event, which resulted in partial migmatisation of Orlica-Śnieżnik rock complexes. Ar-Ar cooling ages for the Orlica-Śnieżnik Massif are in the range of 340–330 Ma (Steltenpohl *et al*., 1993; Maluski *et al*., 1995; Marheine *et al*., 2002).

The structure of the Orlica-Śnieżnik Massif is not sufficiently understood despite numerous studies carried out since the 1960's (e.g. Don, 1964; Dumicz, 1990, Don *et al*., 1990). The common view is that this massif represents a gneissic "dome", with the gneisses cropping out in antiforms and mantling schists preserved in synforms (e.g. Don, 1982; for an alternative interpretation see Dumicz, 1979). There is some evidence, however, that the Orlica-Śnieżnik Massif consists of a number of folded thrust sheets, as is the case with the East Sudetic units adjacent to the SE. For the Orlica-Śnieżnik Massif, the nappe model originally proposed by Pauk (1953) has recently been supported by petrological data on contrasting P-T paths of HP rocks (eclogites and granulites) coming from different parts of the massif (Bröcker and Klemd, 1996). Tectonic transport directions within the Orlica-Śnieżnik Massif are still under discussion. A map view, combined with some structural evidence, supports the early concept of Suess (1912) contending that the Orlica-Śnieżnik rock complexes show an E to SE directed tectonic polarity (Żelaźniewicz, 1988; Dumicz, 1993). On the other hand, analysis of mesoscale kinematic indicators inspired Cymerman (1992, 1997) to assume a N- to NE-directed sense of shear under a transpressional regime, in agreement with the tectonic models of Matte *et al*. (1990) and of Schulmann *et al*. (1991).

NOVÉ MĚSTO BELT

The Nové Město Belt is located in the western Orlica Mountains on the SW flank the Orlica-Śnieżnik Massif

(Fig. 3), with only its NW-most part stretching into Poland. It is composed mostly of phyllites, greenstones and amphibolites of unknown age that are traditionally regarded as Late Proterozoic by comparison to the Teplá-Barrandian domain of the Bohemian Massif (Chaloupský *et al*., 1995). The amphibolites crop out in a more or less continuous, 1.5–5 km wide zone that is separated from the Orlica-Śnieżnik Massif by an up to 2 km wide mica schist belt. According to the geochemical results of Opletal *et al*. (1990) and Floyd *et al*. (1996), these amphibolites show MORB-type affinities. In the contact zone between the Nové Město Belt and the Orlica-Śnieżnik Massif, there occur two late-tectonic granitoid intrusions, the Olešnice and Kudowa plutons. The third late-tectonic intrusion is that of the Nový Hrádek Granodiorite, entirely surrounded by phyllites in map view. Small granitoid bodies are also common in the contact zone further to the south. Rb-Sr dating based on a whole rock isochron yielded an age of *c*. 330 Ma for the Kudowa Granite (Bachliński, 2000). In the Nové Město Belt, the metamorphic grade increases from greenschist facies in the west, to amphibolite facies along its boundary with the Orlica-Śnieżnik Massif. Metamorphic isograds roughly parallel the contacts with the granitoid intrusions and the boundary with the Orlica-Śnieżnik Massif.

An important structural discontinuity along the contact between the Nové Město Belt and the Orlica-Śnieżnik Massif was suggested by Fajst (1976), who documented two divergent structural trends on both sides of the contact. The Orlica-Śnieżnik Massif is characterized by an approximately N–S structural grain whereas the Nové Město Belt shows NW–SE structural trends (Mazur *et al*., 2005). The fabric of the Nové Město Belt bears record of D_1 top-to-ESE ductile thrusting. The D_2 kinematics are NNW–SSE-directed dextral strike-slip at the contact of the Nové Město Belt with the Orlica-Śnieżnik Massif mica schists and gneisses, changing gradually into a top-to-NNE shearing in the core of the massif. The foliation in the whole area was deformed into E–W trending and S-verging F_3 folds.

The entire Nové Město Belt was tectonically emplaced on top of the Orlica-Śnieżnik Massif along a top-to-ESE thrust plane, which corresponded to their primary contact. At the same time, the phyllites and amphibolites of the Nové Město Belt were juxtaposed (Mazur *et al*., 2005). The timing of this event is provisionally constrained by Sm-Nd dating of garnets from the mica schists of the contact zone at *c*. 380 Ma (R. Anczkiewicz, pers. com.). This original contact zone was subsequently folded and reactivated as a major dextral shear zone, resulting in the present-day direct juxtaposition of the Nové Město and the Orlica-Śnieżnik units (Mazur *et al*., 2005).

NIEMCZA AND SKRZYNKA SHEAR ZONES

The Niemcza Shear Zone extends along the eastern edge of the Góry Sowie Massif (Fig. 8) and was interpreted by Scheumann (1937) to contain mylonitised gneisses. Based on microstructural study, Mazur and Puziewicz (1995*a*) showed that the Niemcza Zone represented a 5 km wide, left-lateral strike-slip ductile shear belt, separating the Góry Sowie Massif from the Kamieniec Metamorphic Belt. According to Scheumann (1937) and Mazur and Puziewicz (1995*a*), the Niemcza mylonites were derived from the Góry Sowie Gneiss.

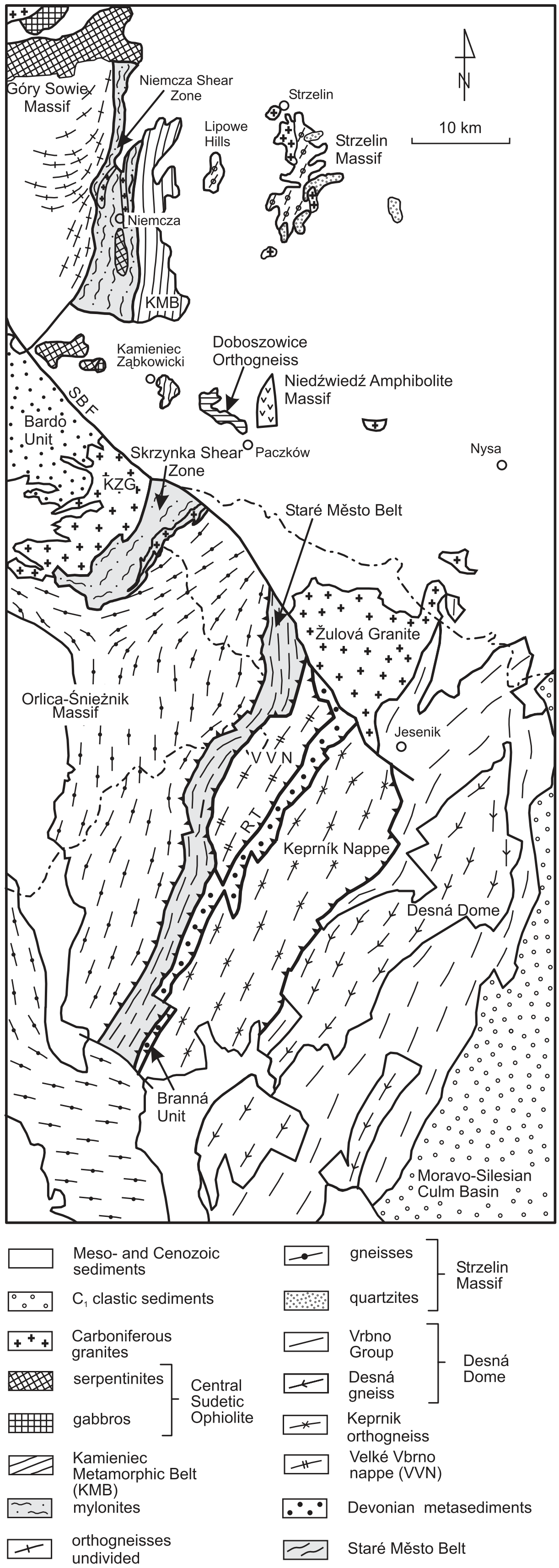

Fig. 8. Geological sketch map of the East Sudetes (modified from Aleksandrowski and Mazur, 2002)

KZG — Kłodzko-Złoty Stok Granite; SBF — Sudetic Boundary Fault; RT — Ramzová Thrust; VVN — Velké Vrbno Nappe

However, Franke and Żelaźniewicz (2000) preferred an alternative interpretation of the Niemcza Zone rocks as metagreywackes, following early concepts of Finckh (1925), Bederke (1929) and Meister (1932). The Niemcza Zone includes minor lenses of non-mylonitic gneisses, amphibolites and quartz-graphite schists. The mylonites occur as high- and low-temperature varieties, formed under amphibolite and greenschist facies conditions, respectively (Mazur and Puziewicz, 1995*a*). The Niemcza Zone contains numerous small bodies of undeformed to little deformed granitoids and syenites/diorites. One late kinematic granodiorite was dated, using the U-Pb method on zircons, at *c*. 340 Ma (Oliver *et al*., 1993; Kröner and Hegner, 1998). As earlier fabrics are completely obliterated in the mylonites, there is no record of superposed structures. However, a continuous fabric transition from non-mylonitized gneiss to mylonite can be observed along the boundary of the Niemcza Zone and the Góry Sowie Massif (e.g. Piekiełko Gorge west of Niemcza) and at the contacts of non-mylonitized gneissic pods included in the Niemcza Zone. In the southern part of the adjoining Kamieniec Metamorphic Belt, older structures, showing a top-to-NE sense of shear on a shallow westerly dipping foliation, are locally preserved and overprinted by a common top-to-SW or sinistral fabric. Hence, by analogy, the left-lateral motion in the Niemcza Zone (or the top-to-S motion where the foliation displays a shallow-dip) seems to be younger and superimposed on the earlier regional fabric that may be related to top-to-NE thrusting and dextral shearing along the SE margin of the Bohemian Massif (Rajlich, 1987; Schulmann *et al*., 1991; Fritz and Neubauer, 1993).

The Skrzynka (or Złoty Stok-Skrzynka) Shear Zone, trending NNE–SSW to NE–SW, is approximately 12 km long and 4 km wide and constitutes the boundary between the sedimentary rocks of the Bardo Sedimentary Unit and the Kłodzko-Złoty Stok Granitoid Massif to the NW and the Śnieżnik Massif to the SE (Fig. 8; e.g. Don *et al*., 1990). The Skrzynka Shear Zone exposes various blastomylonites, mylonites, cataclasites, gneisses and schists. The regional amphibolite-facies metamorphism is thermally overprinted along the contact with the Kłodzko-Złoty Stok Granitoid Massif. The penetrative, steeply dipping foliation of the Skrzynka Zone parallels its boundaries and contains sub-horizontal to shallow SW-plunging mineral stretching lineation. The main deformation in the Skrzynka Zone was a left-lateral, ductile strike-slip non-coaxial shear (e.g. Cymerman, 1992, 1996). The latest stages of the shearing seem to postdate the emplacement of the Kłodzko-Złoty Stok Pluton and the small Jawornik Granitoid body near to the SE boundary of the Skrzynka Zone, since the margins of both the igneous bodies underwent mylonitization.

It is likely that the Niemcza and Skrzynka shear zones were once linked in a single kinematic system and that their present-day sinistral offset by about 10–15 km resulted from late displacements along the Intra-Sudetic Fault (Fig. 3).

KAMIENIEC METAMORPHIC BELT

The Kamieniec Metamorphic Belt crops out as a N–S elongated schist belt to the E of the Niemcza Shear Zone. It comprises mica schists with intercalations of quartz-feldspar schists and marbles, and subordinate lenses of quartz-graphite and amphibolitic schists and eclogites. The Kamieniec Belt consists of two tectonic units with different metamorphic grades. Whereas the first unit comprises mica schists containing kyanite, garnet, staurolite and late andalusite porphyroblasts, the second is composed of mica schists with albite porphyroblasts (Mazur and Józefiak, 1999). The eclogite inclusion in the higher-grade mica schist unit preserves the record of an early high-pressure metamorphic event that was experienced also by part of the surrounding mica schists (Achramowicz *et al*., 1997). Both units of the Kamieniec Belt were juxtaposed during E-directed thrusting under peak metamorphic conditions (Mazur and Józefiak, 1999; for an alternative interpretation see Nowak, 1998). Effects of this first deformation were overprinted and mostly obliterated by folding and non- to coaxial shearing that produced the NE–SW oriented structural grain under lower amphibolite facies conditions. The structural evolution of the Kamieniec Belt ended with its WSW- to SW-directed extensional unroofing, associated with LP/HT metamorphism within the andalusite stability field (Mazur and Józefiak, 1999). The timing of these tectono-thermal events is still poorly constrained. The terminating extensional event appears to be roughly contemporaneous with the sinistral shearing along the Niemcza Zone, estimated at *c*. 340 Ma. On the other hand, the Doboszowice Orthogneiss (Fig. 8), interpreted as a syn-kinematic granite intrusion into the Kamieniec Belt (Mazur and Puziewicz, 1995*b*), is dated as old as *c*. 380 Ma (Kröner and Mazur, 2003) and already bears the NE–SW oriented fabric.

THE STARÉ MĚSTO BELT

The Staré Město Belt is a tectonic boundary that separates the Central from the East Sudetes (or the Lugian from the Moravo-Silesian domain) and is entirely located in the Czech Republic. It consists of a stack of thrust sheets that flank the Orlica-Śnieżnik Massif to the SE (Fig. 3). The NNE–SSW trending, *c*. 40 km long and 4–5 km wide Staré Město Belt (Fig. 8) comprises high-grade metasediments, banded felsic/amphibolite rocks with lenses of spinel peridotites at their base, sheared gabbros, and a syntectonic tonalite intrusion (Parry *et al*., 1997; Schulmann and Gayer, 2000). The peridotite bodies are considered as mantle-derived tectonic slices (Parry *et al*., 1997; Schulmann and Gayer, 2000). U-Pb zircon dating of the banded amphibolites and metagabbros yielded Late Cambrian ages of 510–500 Ma (Kröner *et al*., 2000). Similar ages have been obtained from the Orlica-Śnieżnik Massif and from many igneous rock suites of the Central and West Sudetes (Oliver *et al*., 1993; Turniak *et al*., 2000; Kröner *et al*., 2001). East of the Staré Město Belt, however, basement orthogneisses and paragneisses have yielded mainly Neoproterozoic protolith ages of 684–546 Ma (van Breemen *et al*., 1982; Kröner *et al*., 2000). Hence, the Staré Město Belt is the easternmost unit of the Central Sudetes, and marks the contact between two major crustal domains of different affinities. The Staré Město rocks have been interpreted as products of a Cambro-Ordovician continental rifting (Parry *et al*., 1997; Štípská *et al*., 2001; Kröner *et al*., 2000). This is corroborated by crustal contamination of MORB-type amphibolites (Floyd *et al*., 1996). Moreover, the MP/HT granulite facies metamorphism, synchronous with the intrusion of a Cambrian magmatic suite and associated with pressures of 7–10 kbars and temperatures of 800–850°C (Štípská *et al*., 2001), must have been accompanied by an exceptionally high heat flow, typical of thinned continental crust (Parry *et al*., 1997; Štípská *et al*., 2001). The age of crustal thinning and associated extensional tectonics has been determined on metamorphic zircons from a high-grade migmatitic metapelite at 507±7 Ma (Kröner *et al*., 2000). The Variscan deformation and metamorphism in the Staré Město Belt, as well as its thrusting over the East Sudetes, is believed to have been roughly contemporaneous with the intrusion of a syntectonic tonalite dyke dated at 339±7 Ma (intra-Viséan), using the Pb-Pb method on zircons (Parry *et al*., 1997).

The Staré Město Belt shows the typical features of a suture zone. Suturing of the dissimilar crustal domains of the East and Central Sudetes across the Staré Město Thrust Belt was apparently accompanied by exhumation of earlier subducted crustal fragments. The timing and polarity of subduction of the oceanic domain that separated the East and Central Sudetes are still poorly constrained and the present-day position of the Staré Město Belt does not necessarily mirror the original geometry of the colliding terrane margins. According to Schulmann and Gayer (2000), however, the Staré Město Suture involved Early Carboniferous westward subduction of the East Sudetic domain beneath the active margin of the Central Sudetes. The possible N-ward continuation of the Staré Město Belt across the Sudetic Boundary Fault into the Fore-Sudetic area (e.g. into the Niedźwiedź Amphibolite Massif) remains problematic, owing to the scarcity of outcrops emerging from beneath a thick Cenozoic cover.

NIEDŹWIEDŹ AMPHIBOLITE MASSIF

Despite rare outcrops, the Niedźwiedź Massif is relatively well known from borehole data (Cymerman and Jerzmański, 1987, Jerzmański, 1992). It comprises a 1.5 km-thick succession of mostly MORB-type amphibolites and metagabbros (Awdankiewicz, 2001). These rocks were subjected to medium- to high-grade metamorphism, leading in places to partial melting of the metabasites and the production of tonalite melts (Puziewicz and Koepke, 2001). The Niedźwiedź Massif appears to be overridden from the W by a medium- to high-grade association of paragneisses, amphibolites and hornblende gneisses of unknown age, referred to as the Chałupki Unit (Puziewicz *et al*., 1999; Mazur and Józefiak, 1999).

EAST SUDETES

The East Sudetes form part of a collision-related belt of deformation and metamorphism, nearly 50 km wide and 300 km long, that occupies the eastern margin of the Bohemian Massif, from Lower Austria, through Moravia, to Silesia (Fig. 2). This belt is composed of nappe piles that crop out in three tectonic half-windows (of the Thaya, Svratka and East Sudetes) from below the upper plate Moldanubian in the S and the Central Sudetic rock complexes in the N. The nappes exposed in the Thaya and Svratka windows are referred to as Moravian units, whereas those outcropping in the East Sudetes are termed Silesian units (Suess, 1912, 1926; Dudek, 1980). The entire eastern Bohemian collisional belt is commonly referred to as the Moravo-Silesian Zone (e.g. Dallmeyer *et al*., 1995; Franke and Żelaźniewicz, 2000; Hartley and Ottava, 2001) or as the Moravian Terrane (Matte *et al*., 1990; Matte, 1991).

The Sudetic segment of this belt consists of the East Sudetic stack of nappes that is overridden from the W by the Central Sudetic Orlica-Śnieżnik Massif and the Staré Město Belt (Fig. 3). From top to bottom, or in map view from W to E, the East Sudetic nappe stack consists of the Velké Vrbno Nappe (upper allochthon' of Schulmann and Gayer, 2000) and the Keprník Nappe ("lower allochthon"), separated by the detached Branná Unit (Fig. 8). The Keprník Nappe rests on parautochthonous gneisses of the Desná Unit and their Devonian volcano-sedimentary cover, formed by the probably allochthonous Vrbno Group (Cháb *et al*., 1994; Schulmann and Gayer, 2000). Towards the east, they adjoin the thrust-folded Early Carboniferous fill of the Upper Silesian Foreland Basin that is underlain by Devonian platform carbonates.

VELKÉ VRBNO NAPPE

The Velké Vrbno Nappe is located eastward of the adjacent Staré Město Belt and comprises orthogneisses and metasediments (banded amphibolite rocks, kyanite-staurolite mica schists, graphite schists and quartzites, dolomitic marbles and biotite paragneisses), which were metamorphosed under upper-amphibolite facies conditions. The gneisses were dated at *c.* 574 Ma (Kröner *et al*., 2000). The presence of relict eclogites (Žáček, 1996) points to an older stage of HP/LT metamorphism. The protolith of the supracrustal series must have been a variegated, volcano-sedimentary sequence of unknown age, traditionally considered to be Early Palaeozoic (e.g. Květoň, 1951).

BRANNÁ UNIT AND KEPRNÍK NAPPE

In the Czech Republic, the Velké Vrbno Nappe overrides a narrow belt of highly sheared Devonian metasediments of the Branná Unit, metamorphosed under greenschist facies conditions. These are mostly shallow water polymict metaconglomerates, quartzites, crystalline limestones, sericite and sericite-graphite phyllites, porphyroids and calc-silicate schists. A major thrust plane at the top of the Branná Unit, known as the Ramzová Thrust Fault, was for many decades considered the tectonic boundary between the East and Central Sudetes (Suess, 1912). This concept assumed the orthogneisses of the Velké Vrbno Nappe to be equivalent to those of the Orlica-Śnieżnik Massif and had to be abandoned because of new isotope protolith datings proving different ages for these two orthogneiss groups (see above). The low-grade Branná Unit is thrust over the crystalline Keprník Nappe that is made up of a large granitic orthogneiss body (U-Pb zircon-dated at *c.* 546 Ma, van Breemen *et al*., 1982; 584±8 Ma, Kröner *et al*., 2000) with subordinate staurolite-bearing metapelites, calc-silicate rocks and quartzites (Cháb *et al*., 1994).

DESNÁ DOME

The easternmost tectonic unit of the Silesian domain, known as the Desná Dome, consists of the relatively monotonous metasedimentary succession of the Devonian Vrbno Group, resting on the Desná gneisses and mylonites that yielded U-Pb and Pb-Pb zircon ages of 570–650 Ma (Kröner *et al*., 2000). The Vrbno Group comprises a succession of predominantly deep-water siliciclastic, siliceous and calcareous slates, up to 3000 m thick, associated with abundant metavolcanics (Svoboda *et al*., 1966) that was metamorphosed under greenschist facies conditions. The facies development of the Vrbno Group differs from that of the shallow-water Devonian of the Branná Unit, of the Devonian platform rocks of the Brno Massif, and of the substrate to the Upper Carboniferous Silesian Coal Basin and the Miocene Carpathian Foredeep. The Vrbno Group was presumably thrust over the Brunovistulian gneissic basement, now exposed in the core of the Desná Dome. The metavolcanic rocks of the Vrbno Group are interpreted as having been deposited in an extensional basin. The supra-subduction geochemical signature of some of its metavolcanic rocks presumably indicate a back-arc setting that may have been initiated as intracontinental rift (Patočka and Valenta, 1996). Palaeontologic dating of crystalline limestones suggests that much of the Vrbno volcano-sedimentary succession was deposited between end Givetian and latest Frasnian times (Hladil, 1986).

STRZELIN MASSIF

Towards the north, the East Sudetic nappe pile is covered by Cenozoic sediments. Crystalline rocks emerge at the surface mostly within the Strzelin Massif (including the area of the Strzelin and Lipowe Hills, *c*. 40 km south of Wrocław; Fig. 8), composed of two metamorphic rock complexes (Oberc-Dziedzic *et al*., 2005). The structurally lower Strzelin Complex crops out predominatly in the central and eastern parts of the Strzelin Massif, whereas the upper Stachów Complex is mostly exposed in its western parts, the Lipowe Hills. These metamorphic complexes are intruded by abundant granitoids that range in age between *c*. 350 and 330 Ma (dated with the Rb-Sr whole rock method; Oberc-Dziedzic *et al*., 1996).

The Strzelin Complex consists of a core unit, an inner envelope of older schists, and an outer envelope of younger schists, the latter referred to as the Jegłowa Beds (Oberc-Dziedzic *et al*., 2005). The core unit comprises several varieties of Neoproterozoic gneisses, including: (1) the Strzelin Gneiss, typical of the northern part of the massif, with SHRIMP zircon ages of 600±7 Ma and 568±7 Ma (Oberc-Dziedzic *et al*., 2003) and (2) the sillimanite-bearing and migmatitic Nowolesie Gneiss, widespread in the southern part of the Strzelin Massif, which yielded a mean $^{207}Pb/^{206}Pb$ age of 1020±1 Ma, obtained with the single zircon evaporation method (Kröner and Mazur, 2003). The Strzelin Gneiss contains centimetre- to several metre-thick foliation-parallel amphibolite inliers of within-plate geochemical signature (Szczepański and Oberc-Dziedzic, 1998), whereas the Nowolesie Gneiss is rich in pegmatite bodies. The inner envelope of the gneisses is composed of amphibolites of within-plate geochemical signature (Szczepański and Oberc-Dziedzic, 1998), mica schists, calc-silicate rocks and marbles. The outer envelope (Jegłowa Beds) consists of quartzites, quartz-sericite schists and metaconglomerates, whose protoliths were deposited on a continental margin during Early- to Mid-Devonian times (Patočka and Szczepański, 1997). Bederke (1931) and Oberc (1966) compared these rocks with the fossiliferous Lower Devonian quartzites of the East Sudetes. The Jegłowa Beds represent a thin veneer of sediments on top of the Strzelin and Nowolesie gneisses. Their nearly horizontal tectonic contacts with the gneisses are oblique to the regional foliation (Oberc-Dziedzic, 1995).

The Stachów Complex comprises two varieties of orthogneisses: (1) the Gościęcice Augen Gneiss and (2) the Stachów Gneiss, both of Cambrian age. The magmatic protolith of the Gościęcice Gneiss is dated on zircons at 504±3 Ma (Oliver *et al*., 1993) and 513±1 Ma (Kröner and Mazur, 2003), using conventional and single grain evaporation methods, respectively. The SHRIMP zircon age of the Stachów Gneiss with the mean value of 500±5 Ma, is interpreted to date the emplacement of its magmatic precursor (Oberc-Dziedzic *et al*., 2005).

Although the Strzelin and Stachów orthogneisses correspond to peraluminous S-type granites, they differ in age and trace element characteristics, indicating a different derivation and petrogenetic history. The Neoproterozoic Strzelin Gneiss seems to be equivalent to the Keprník Gneiss of Brunovistulian affinity (Oberc-Dziedzic *et al*., 2005). On the other hand, the Late Cambrian/Early Ordovician ages of the Gościęcice and Stachów gneisses are comparable to those of the widespread orthogneisses of the West and Central Sudetes, e.g. in the Orlica-Śnieżnik Massif (Oliver *et al*., 1993; Turniak *et al*., 2000; Kröner *et al*., 2001). Consequently, the Stachów Complex is interpreted as being thrust over that of Strzelin along the Strzelin Thrust Fault at the Central/East Sudetes boundary zone (Oberc-Dziedzic and Madej, 2002; Oberc-Dziedzic *et al*., 2005).

MORAVO-SILESIAN FOLD-THRUST BELT

The East Sudetic nappe stack is flanked to the SE by the external Moravo-Silesian Fold-Thrust Belt that involves the up to 7.5 km thick syn-orogenic Early Carboniferous Culm facies succession and minor pre-orogenic Devonian sediments of the Moravo-Silesian Basin, that represents a fragment of the Variscan foreland basin system (Figs. 2 and 8). To the N and NE, the heavily deformed Moravo-Silesian Fold-Thrust Belt grades into the less deformed, large foreland basin of SW Poland and to the SE it is buried beneath the Neogene Carpathian foredeep and nappes. The Moravo-Silesian Fold-Thrust Belt is exposed in the Drahany Uplands and the Nizký Jesenik Mountains, both being separated by the Olomouc depression (Fig. 9).

The Moravo-Silesian Basin developed on top of the Neoproterozoic crystalline basement and of the erosionally truncated Lower Palaeozoic sediments of the Brunovistulian Terrane (Belka *et al*., 2002). In this basin, sedimentation commenced with transgressive Pragian basal conglomerates and sandstones (Chlupáč, 1989). The overlying Devonian succession, locally exposed in the fold-thrust belt, is developed in three facies associations (Chlupáč, 1964, 1988): (1) the Moravian Karst platform carbonates, (2) the transitional platform to slope facies and (3) the open marine basinal facies. The carbonate platform was established on top of continental and shallow marine Emsian siliciclastics during the late Emsian. It persisted until end-Frasnian times (Hladil, 1986), attaining a thickness of up to 1600 m (e.g. Kalvoda *et al*., 2002). During Famennian to late Viséan times, this carbonate platform broke gradually down along flexure-induced extensional faults, re-

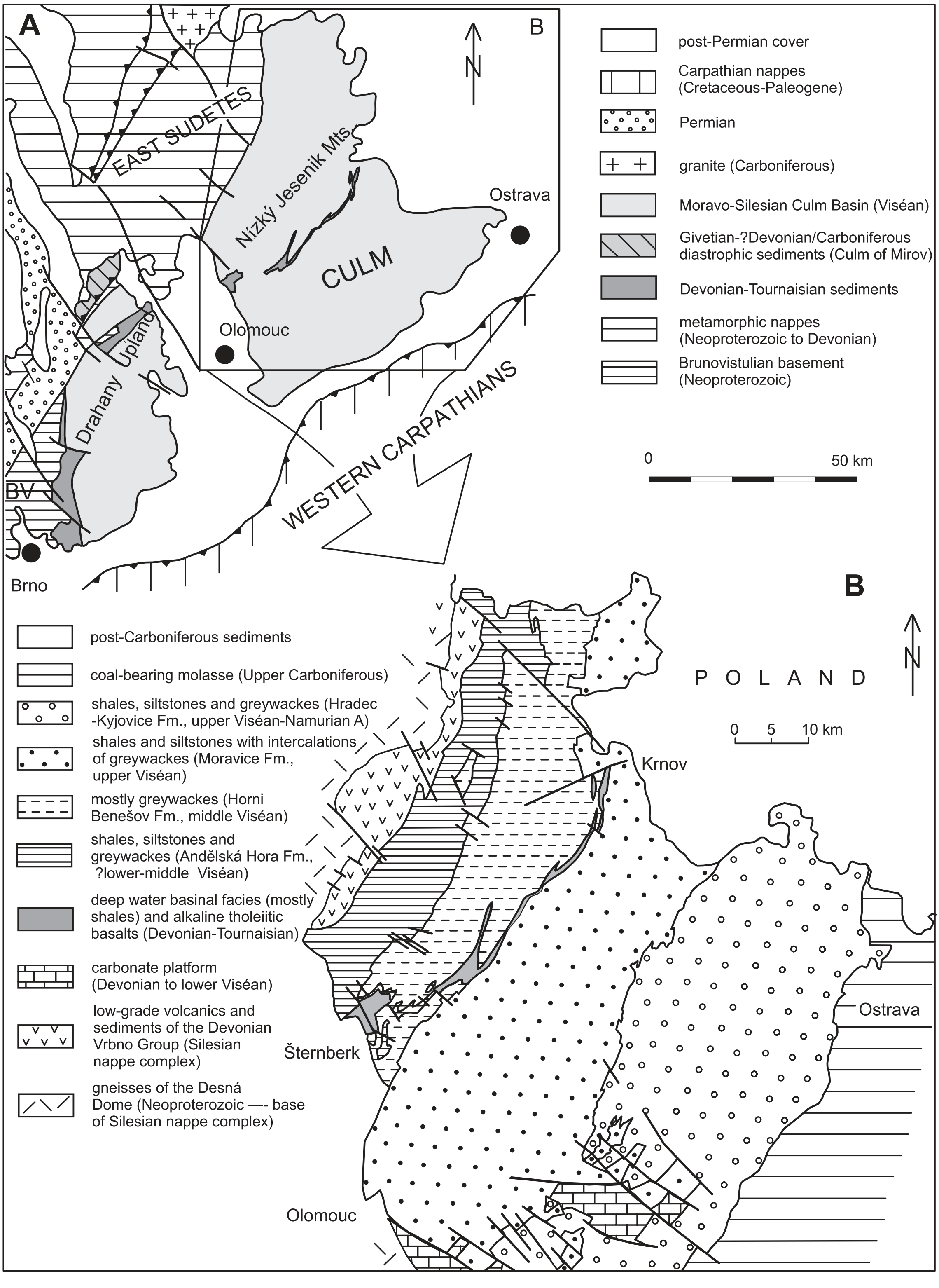

Fig. 9. A — Moravo-Silesian Fold-Thrust Belt: its location at the eastern margin of the Bohemian Massif; BV — Neoproterozoic crystalline basement of the Brno Massif (Brunovistulian Block); B — simplified geological map of the northern part of Moravo-Silesian Thrust-Fold Belt (Carpathian nappes and foredeep not shown; based on Dvořák, 1992)

lated to thrust-loaded flexural subsidence of this platform (model of e.g. the Austrian Molasse Basin; Ziegler *et al.*, 2002). In the area of the platform/slope transition, the carbonate platform commenced to step back during the Givetian (Bábek, 1999) and was gradually replaced by pelagic Fammennian to Tournaisian basinal shales. The basinal facies succession consists of Pragian to Tournaisian reefal limestones, calciturbidites and pelagic carbonates, as well as radiolarian shales deposited on the slopes of volcanic seamounts (Galle *et al.*, 1995). These are closely associated with a volcanic suite that ranges in age from the Emsian to Tournaisian (Kalvoda *et al*., 2002) and comprises alkali basalts and tholeiites showing the geochemical signature of within-plate and MORB magma types. This points to the emplacement of these volcanics under a tensional regime on strongly thinned continental and/or on oceanic crust (Souček, 1981, Přichystal, 1990), as seen also in the Rhenohercynian Basin of Germany (e.g. Ziegler, 1990).

In the Moravo-Silesian Basin, deposition of the syn-orogenic clastic Culm flysch commenced during the early to middle Viséan and lasted until early Namurian times (Klominský, 1994; Hartley and Otava, 2001). The Culm succession has been traditionally divided into several major formations based on litho- and biostratigraphical criteria (Fig. 9; e.g. Dvořák, 1973). The contact between the Culm flysch and its basal siliceous shales and the Devonian carbonates was presumably concordant, although it was associated with a hiatus spanning a minimum of 20 Ma (Dvořák, 1992). At present, this contact is known only from boreholes located close to the western border of the basin. Within the fold-thrust belt, this mechanically weak contact was employed by thrusts that were activated during the inversion of the basin (Hartley and Otava, 2001). The turbiditic Culm succession of the Moravo-Silesian Basin grades upward into paralic coal measures that span late Namurian A to Westphalian D times (Unrug and Dembowski, 1971; Klominský, 1994) and are preserved in the little deformed external parts of the basin, where they are of major economic importance (Fig. 9).

During the Carboniferous, the Moravo-Silesian Basin was supplied with sediments from the S and SW. These were transported N-ward, approximately parallel to the basin axis (Unrug and Dembowski, 1971, Hartley and Otava, 2001). During most of the Viséan, the main clastic sources were low-grade metamorphic massifs and intrabasinal Viséan limestones, as evidenced by the composition of clasts and heavy minerals. During the latest Viséan, these sources were partly replaced by high-grade metamorphic terrains. This change reflects progressive stacking and erosional exhumation of the Moldanubian and Central and East Sudetic nappe piles along the eastern margin of the Bohemian Massif. These nappes, undergoing intense erosion during their uplift, supplied abundant detritus to the basin, starting at the transition to the Namurian around 330 Ma (Hartley and Otava, 2001).

The Moravo-Silesian Basin succession underwent diachronous deformation after the early Namurian, which resulted in a gradual eastward decrease in the age and intensity of deformation (Kumpera and Martinec, 1995). The deformation of the eastern part of the basin involved the development of an imbricate thrust system with eastern polarity, including numerous duplex structures and E-vergent folds (Synek *et al.*, 1990; Rajlich, 1990). On the other hand, the western part of the basin underwent westward backthrusting onto the metamorphosed Devonian succession of the east-vergent East Sudetic nappe complex (Cháb, 1990; Čižek and Tomek, 1991). In this way, inversion of the basin resulted in the bivergent geometry of the Moravo-Silesian Fold-Thrust Belt, whose axial part is characterized by subvertical major faults and dominant cleavages. In the axial zone of this belt, basinal-facies Devonian rocks are up-thrown along high-angle regional (strike-slip?) shear zones as a major pop-up structure (Kumpera and Martinec, 1995; Grygar and Vavro, 1995; Schulmann and Gayer, 2000). An alternative hypothesis assumes that these slices of the Devonian rocks represent a folded thrust sheet that separates two Culm-bearing nappes, all being thrust towards the east (Cháb, 1986; Chadima and Melichar, 1998). Although the structural style of the Moravo-Silesian Fold-Thrust Belt is still variably interpreted, it is fairly well established that its western margin was involved in the Variscan nappe pile of the East Sudetes and is tectonically overlain by crystalline thrust sheets. As a result of tectonic loading, the Carboniferous succession of the western part the basin suffered greenschist facies metamorphism (Cháb, 1990) and acquired a structural pattern analogous to that of the adjacent allochthonous Devonian Vrbno Group. The metamorphosed Culm rocks bear a NNE–SSW trending, steeply dipping foliation and a stretching lineation that plunges to the NE to N at shallow angles. The age of this deformation presumably corresponds to the cooling of Devonian rocks in this area, determined at *c*. 300 Ma by the Ar-Ar method (Maluski *et al*., 1995).

The overall tectonics of the Moravo-Silesian Fold-Thrust Belt resulted from the collisional interaction of the Bruno-Vistulian Neoproterozoic basement block with the Variscan collage of the Bohemian Massif (see e.g. Matte *et al*., 1990, Aleksandrowski and Mazur, 2002) and is likely to contain a significant NNE–SSW-directed strike-slip component. These strike-slip displacements may have resulted from recurrent sinistral and dextral shearing events (*cf.* Rajlich, 1987, 1990), the effects of which are still poorly constrained.

CONSTRAINTS ON THE GEODYNAMIC EVOLUTION OF THE SUDETES

ROCK COMPLEXES

The Sudetes expose a variety of metamorphic complexes with Neoproterozoic and Early Palaeozoic to Devonian protoliths (Fig. 4). The Neoproterozoic complexes represent splinters derived from an active margin of Gondwana and bear record of magmatism and metamorphism related to the Cadomian (Panafrican) Orogeny that occurred at *c*. 530–620 Ma (Kröner *et al*., 1994; Buschmann *et al*., 2001; Oberc-Dziedzic *et al*., 2003; Mazur *et al*., 2004). The Neoproterozoic complexes consist of (1) plutonic and volcano-sedimentary rocks with magmatic arc and back-arc basin affinities (in the Kłodzko Metamorphic Unit), (2) late orogenic granitoids intruded into greywackes (in the Lusatian Massif and the East Sudetes) and, most probably, also (3) pelitic series enveloping Early Palaeozoic granitoid intrusions (in the Izera-Karkonosze and Orlica-Śnieżnik massifs) of hitherto poorly constrained age (Gunia, 1984, 1990; Kröner *et al*., 2001).

Late Cambrian-Early Ordovician granitic intrusions are widespread in the Sudetes, similarly to several other regions of the Variscan belt. These granites, which are mostly deformed into gneisses due to Variscan tectonism are believed to have been intruded during continental rifting (e.g. Pin *et al*., 2006) and detachment of crustal blocks from the margin of Gondwana. Locally they have preserved a record of Ordovician LP–HT metamorphism, that reflects thinning of the continental crust (Kröner *et al*., 2000; Štipska *et al*., 2001).

The Ordovician to Devonian volcano-sedimentary basinal sequences of the Kaczawa Metamorphic Unit and of the southern Karkonosze-Izera Massif were deposited during the Ordovician in a continental rift that evolved during the Silurian-Devonian into an oceanic basin (Furnes *et al*., 1994; Patočka and Smulikowski, 2000). They contain Ordovician rift-related intraplate bimodal volcanics, Silurian metabasalts of MORB-type geochemical signature, and Silurian-Devonian deep marine deposits (cherts). In the eastern part of the Izera-Karkonosze Massif the Leszczyniec Meta-Igneous Unit is composed of Ordovician mafic, mostly MORB-type, rocks (of basalt/gabbro protolith composition), associated with plagiogranite and tonalite gneisses, defining a system of plutonic and subvolcanic intrusions.

The little metamorphosed Circum-Góry Sowie (Central Sudetic) Ophiolite has yielded a Late Silurian (?)-Early Devonian age (420–400 Ma; Oliver *et al*., 1993; Dubińska *et al*., 2004) and displays almost all the layers of a typical oceanic crust: serpentinized ultramafics, massive gabbros and cumulates, sheeted dykes, pillow lavas and deep marine radiolarian cherts (Majerowicz 1981).

Early/Middle Devonian to Early Carboniferous sedimentary sequences that were deposited on actively extending continental margins occur in the Görlitz Slate Belt, in the Ještěd Unit of the Izera-Karkonosze Massif and in the Vrbno Unit of the East Sudetes. In the former two units these sequences are typified by a transition from Devonian, mostly carbonate, shelf deposits to Carboniferous turbidites and/or mélanges, whereas the rocks of the Vrbno Group are interpreted as a volcano-sedimentary fill of a Middle to Late Devonian back-arc basin (Patočka and Valenta, 1996).

Sedimentation in evolving intermontane basin began during the Late Devonian (in the Bardo and Świebodzice basins) or the Early Carboniferous (in the Intra-Sudetic Basin) on top of the metamorphosed and exhumed Sudetic crystalline complexes.

TECTONICS

The Sudetes developed, together with the entire Variscan Belt, during Devonian and Early Carboniferous times in response to closure of at least two marine basins floored by oceanic crust, concomitant amalgamation of the Armorican terranes, and their subsequent accretion to the collage of the Trans-European Suture Zone on the SW flank the East European Platform (*cf.* Matte *et al*., 1990, Cymerman *et al*., 1997; Pharaoh, 1999; Belka *et al*., 2002; Franke and Żelaźniewicz, 2000; Aleksandrowski and Mazur, 2002; Winchester and PACE, 2002). The vestiges of these oceanic basins are the allochthonous volcano-sedimentary complexes of the Kaczawa Unit and of the southern and eastern Izera-Karkonosze Massif. They are involved in nappe piles that are thrust towards the NW (Mazur and Kryza, 1996; Seston *et al*., 2000; Collins *et al*., 2000; Mazur and Aleksandrowski, 2001), and represent tectonic sutures, as evidenced by meta-igneous rocks of MORB-type geochemical features associated with deep marine sediments (Furnes *et al*., 1994; Winchester *et al*., 1995; Kryza *et al*., 1995; Patočka and Smulikowski, 2000) and a record of HP, blueschist-facies metamorphism (Cháb and Vrana, 1979; Kryza *et al*., 1990; Smulikowski, 1995; Kryza and Mazur, 1995). The latter was overprinted by greenschist facies alteration. In these nappe piles, MORB-type rocks override thrust units that contain intraplate volcanics. In the Kaczawa Unit, mélange bodies, often less metamorphosed than the embedding rocks, form an important part of the nappe pile (Baranowski *et al*., 1990; Collins *et al*., 2000; Kryza and Muszyński, 2003).

The metamorphic nappes of the Karkonosze-Izera Massif and of the Kaczawa Unit were tectonically emplaced on top of continental crust considered as a part of the pre-Variscan passive margin of Saxothuringia (e.g. Mazur and Aleksandrowski, 2001; Franke and Żelaźniewicz, 2002; Aleksandrowski and Mazur, 2002). This continental crust consists of Neoproterozoic to Early Cambrian Lusatian granitoids (540–530 Ma; Kröner *et al*., 1994; Tikhomirova, 2002) and greywackes that were deposited on the Cadomian active margin of Gondwana (Kemnitz and Budzinski, 1994; Gehmlich *et al*., 1997; Buschmann *et al*., 2001).

To the east, within the Karkonosze-Izera Massif, the Neoproterozoic rocks were massively intruded by Early Ordovician granitoids, later deformed into orthogneisses by Variscan tectonism. These granitoids were emplaced due to rifting at the eastern margin of Saxothuringia. The syn- and post-rift sedimentary-volcanic cover of this passive margin is only fragmentarily preserved, comprising the Ještěd Unit in the Karkonosze-Izera Massif, the Torgau-Doberlug "Syncline" and the Görlitz Slate Belt in the direct neighbourhood of the Lusatian Massif. The Görlitz Slate Belt itself constitutes a parautochthonous basement that was overridden by the allochthonous units of the Kaczawa nappe stack (Aleksandrowski and Mazur, 2002).

The tectonic sutures, which rest on the allochthonous units of the Kaczawa nappes and of the southern and eastern parts of the Karkonosze-Izera Massif, are in contact with Late Palaeozoic sedimentary basins to the east. The floor of these basins comprises metamorphic complexes that tectonically override the sutures zones. The Intra-Sudetic Basin, to the east of the Karkonosze-Izera Massif, developed during the late middle Viséan (Turnau *et al*., 2002) in response to a top-to-ESE directed gravitational collapse (Mazur, 1995; Mazur and Aleksandrowski, 2001). The Świebodzice Sedimentary Unit, east of the Kaczawa nappe complex, was initiated in the latest Devonian as a piggy-back basin.

The Central Sudetic tectonic units located east of the Intra-Sudetic Basin and Świebodzice Unit, are mostly, if not entirely, allochthonous. These are the metamorphic massifs of the Góry Sowie, of Kłodzko, of the Orlica-Śnieżnik and of Nové Město, as well as the Central Sudetic Ophiolite. The latter is the vestige of the second generation of oceanic basins, whose closure resulted in the formation of the Sudetic segment of the Variscan Belt. The Central Sudetic Ophiolite is little and selectively metamorphosed, whilst the Góry Sowie and Orlica-Śnieżnik Massifs contain (U)HP granulites (Kryza *et al*., 1996), indicating that these units were derived from subducted continental crust. Granulites from the Orlica-Śnieżnik Massif contain a record of an early UHP metamorphism (Szczepański *et al*., 2004) and are associated with HP eclogites. The spatial relationships between the Góry Sowie Massif and the Central Sudetic Ophiolite remain unclear (see discussion in Aleksandrowski and Mazur, 2002), whereas the Kłodzko Unit and, probably, also that of the Orlica-Śnieżnik are located in a tectonically higher position than the ophiolite. The Central Sudetic tectonic units were presumably thrust to the NW, although this conclusion is based exclusively on the data from the Kłodzko Metamorphic Unit (Mazur, 2003; Mazur *et al*., 2004). At the boundary of the Orlica-Śnieżnik and Nové Město units, an opposite, top-to-SE, polarity of thrusting has been recorded (Mazur *et al*., 2005); the lack of metamorphic grade inversion leads, however, to the conclusion that the contact between these two units can be of a back-thrust type. In general, the Central Sudetes comprise structural units that represent Neoproterozoic to Cambrian volcano-sedimentary sequences of an active Gondwana margin (the Kłodzko Metamorphic Unit: Mazur *et al*., 2004; the Góry Sowie Massif: Gunia, 1985), as well as units dominated by Early Ordovician granitoid bodies (Orlica-Śnieżnik Massif: e.g. Oliver *et al*., 1993; Turniak *et al*., 2000; Kröner *et al*., 2001). In contrast to the West Sudetes, the Central Sudetes do not contain Early Palaeozoic volcano-sedimentary sequences that were deposited in open marine basins, except for scarce olistoliths in the sedimentary succession the Bardo Unit.

East of the Orlica-Śnieżnik Massif, separated by a suture zone referred to as the Staré Město Belt, the East Sudetic nappe complex occurs. The Staré Město belt is mostly composed of rocks derived from an Early Ordovician initial rift that recorded a rift-related HT-LP metamorphism (Kröner *et al*., 2000; Štipská *et al*., 2001). These rocks are intruded by synorogenic tonalites of *c*. 340 Ma age (Parry *et al*., 1997). The East Sudetic nappe complex forms part of the NE–SW striking Moravo-Silesian Zone, located along the eastern margin of the Bohemian Massif. It traces the suture zone between the Armorican Terrane Assemblage, represented here by the Central Sudetes, and the adjacent continental Brunovistulian microplate. The latter extends from the vicinities of Brno into Upper Silesia and plunges SE-ward beneath the frontal Carpathian thrust. The crystalline basement of the Brunovistulian Terrane is composed of Neoproterozoic metamorphic and intrusive rocks that are covered by Palaeozoic sedimentary strata. On the western margin of the Brunovistulian Terrane, this sedimentary succession commences with Early Devonian basal conglomerates and quartzites, which grade upward into Middle-Late Devonian platform carbonates and Early Carboniferous, syn-orogenic turbidites of the Moravo-Silesian Foreland Basin.

The East Sudetic nappe system contains detached fragments of the Neoproterozoic Bruno-Vistulian basement and metamorphosed sediments of its cover (Schulmann and Gayer, 2000). The tectonically lowermost element is a 3000 m thick allochthonous sequence of Middle Devonian shales and volcanics (Vrbno Group, Cháb *et al*., 1994), representing the fill of a back-arc basin (Patočka and Valenta, 1996). The East Sudetic nappes were thrust NE-ward under a dextral transpressional regime (Matte *et al*., 1990; Schulmann and Gayer, 2000). The structural plan is dominated by NE–SW to NNE–SSW trending lineations, characteristic not only for the East Sudetic nappe complex, but also for the adjacent part of the Central Sudetes, particularly of the Orlica-Śnieżnik Massif. In the boundary zone between the latter and the Nové Město Unit, the NNE–SSW lineation overprints an older, NW–SE structural grain (Mazur *et al*., 2005).

Two important WNW–ESE striking wrench fault/shear zones, the Elbe and the Intra-Sudetic fault zones, hamper correlations between the Sudetes and the remaining parts of the Bohemian Massif, as well as of particular Sudetic units with one another. Although the magnitude of displacement along these fault zones is still a matter of dispute and controversy (Aleksandrowski, 1990, 1995; Matte *et al*., 1990; Oliver *et al*., 1993; Aleksandrowski *et al*., 1997), they delimit all adjacent structural units and, thus, render it difficult to establish reliable transregional correlations. Tectonic activity along both of these major fault zones terminated essentially after the Late Carboniferous sinistral displacement that may have locally attained up to 15–20 km, and which was preceded by more important Late Devonian(?)-Early Carboniferous dextral displacements (Aleksandrowski *et al*., 1997; Mattern, 2001).

TERRANES

Transregional correlations of particular units of the Sudetic mosaic with their possible counterparts in other areas of the European Variscan Belt have since long been difficult and controversial. This is exemplified by Suess's (1926) concept to include much of the Sudetes into a distinct Lugian domain, incompatible with the remaining Variscan units, though Kossmat (1927) suggested that the same area formed part of his Saxothuringian Zone. Little progress was made in resolving these problems until the late 1980's, when it became apparent that the terrane concept could be successfully applied to the Sudetes. These presented a rewarding object, taking into account differences in the evolutionary histories of most of their units and the occurrence of ophiolites and igneous bodies with MORB affinities, as well as of HP metamorphic complexes, including blueschist and eclogite facies, along some of their contacts. This suggested the presence of several discrete tectonostratigraphic terranes, bounded by sutures and major fault and shear zones.

Since the early 1990's, several working models were advanced for the evolution of the NE Bohemian Massif, suggesting different terrane configurations. These models can be divided into two groups. Those of the first group are based on the assumption that the tectonics of the Sudetes was shaped mainly by the Variscan Orogeny during Devonian-Carboniferous times and that all major tectonostratigraphic units of the Central European Variscan Belt, mostly as defined by Kossmat (1927), continue into the Sudetes (e.g. Matte *et al*., 1990; Franke and Żelaźniewicz, 2000, 2002; Aleksandrowski and Mazur, 2002). Models of the second group assume a significant or even predominant role of Caledonian orogenic events during Ordovician through Early-Middle Devonian times and introduce into the Sudetes exotic terranes that have no affinities to the major Variscan tectonostratigraphic units (e.g. Oliver *et al*., 1993; Johnston *et al*., 1994; Cymerman *et al*., 1997; Kröner and Hegner, 1998).

The terrane model developed by Aleksandrowski and Mazur (2002) for the Variscan Sudetes is given in Figure 10. It is based on the assumption that all major units ("zones") of the Central European Variscan Belt established in the Bohemian Massif continue into the Sudetic area. This model rejects some and modifies other previous terrane concepts and gives a possible accretion scenario for the Sudetic terranes. Taking into account the geological history of the different Sudetic units, and particularly their palaeotectonic interpretation, a relatively simple division of the Sudetes into the following distinct tectonostratigraphic terranes of different provenance and evolution is suggested (Fig. 10).

1. The Lusatia-Izera Terrane comprises the Lusatian Massif and the Kowary-Izera Unit of the Karkonosze-Izera Massif, both being formed by the crystalline basement of the passive margin of the continental Saxothuringian domain. The Görlitz Slate Belt and the Ještěd Unit are made up of Variscan-deformed sedimentary successions deposited on this passive margin (Mazur and Aleksandrowski, 2001).

2. The South-East Karkonosze Terrane was thrust over the Lusatia-Izera Terrane and comprises the South Karkonosze and Leszczyniec units of the Karkonosze-Izera Massif. These units contain the (meta)sedimentary-volcanic succession of the oceanic Saxothuringian Basin and parts of its oceanic crust, respectively. The latter was thrust over the imbricated basin fill during Late Devonian-Early Carboniferous times. Correspondingly, this terrane contains parts of the Saxothuringian Suture (Mazur and Aleksandrowski, 2001).

3. The Kaczawa Terrane is separated from the Lusatia-Izera Terrane by the strike-slip Intra-Sudetic Fault Zone and from the Góry Sowie-Kłodzko Terrane by an inferred thrust contact (see Seston *et al*., 2000). It contains a Palaeozoic rift-to-oceanic volcano-sedimentary succession involved in a Variscan accretionary prism, which formed during latest Devonian-earliest Carboniferous (?) times. The affinity of the Kaczawa succession is still unclear (oceanic Saxothuringian or Rhenohercynian basin?).

4. The composite Góry Sowie-Kłodzko Terrane includes, apart from the Góry Sowie Massif and the NE part of the Kłodzko Unit, also the Świebodzice and Bardo sedimentary units, the Central Sudetic ophiolites, the Niemcza Shear Zone, as well as the basement of the NE part of the Intra-Sudetic Basin. These units represent a variety of palaeotectonic environments, including subducted continental crust (Góry Sowie), Middle Devonian passive margin sequences (NE Kłodzko Unit), oceanic crust (Central Sudetic Ophiolite), and the synorogenic Świebodzice and Bardo basins. The principal common feature of the units forming part of this terrane is their Eo-Variscan, pre-Late Devonian deformation, metamorphism and exhumation that are significantly older than the main tectonic paroxysms that affected the other Sudetic terranes. The Góry Sowie-Kłodzko Terrane shows some affinities with parts of the NE Massif Central and Armorican Massif in France, as well as with the Teplá-Barrandian domain in the Bohemian Massif.

5. The Teplá-Barrandian Terrane is interpreted to include, in its Sudetic segment, the Nové Město Belt, Zábřeh Unit and the basement underlying the SW part of the Intra-Sudetic Basin (*cf*. Mazur and Aleksandrowski, 2001), which crops out in the SW part of the Kłodzko Unit. It cannot be excluded, however, that also the Góry Sowie-Kłodzko Terrane forms part of the Teplá-Barrandian, and/or, alternatively, that the Góry Sowie Massif represents still another separate terrane fragment (e.g. Mid-German Crystalline High at the northern rim of the Saxothuringian Terrane).

6. In its Sudetic part, the Moldanubian Terrane seems to comprise the Orlica-Śnieżnik Massif and the Kamieniec and the Staré Město metamorphic belts, although the affinity of this area to the Saxothuringian Terrane cannot be excluded (e.g. Franke and Żelaźniewicz, 2002). Its western boundary against the Góry Sowie-Kłodzko Terrane is probably located along the sinistral Niemcza and Skrzynka shear zones, that against the Teplá-Barrandian Terrane presumably follows a former thrust in the Orlica Mountains that was later converted into a dextral ductile fault, and the eastern contact with the Moravian Terrane is represented by the East Sudetic thrust belt.

7. The Moravian Terrane is inferred to occur in the East Sudetes between the Moldanubian and Brunovistulian Terranes by analogy with the situation further south in Moravia. This narrow terrane corresponds to the Velké Vrbno and Branná thrust units.

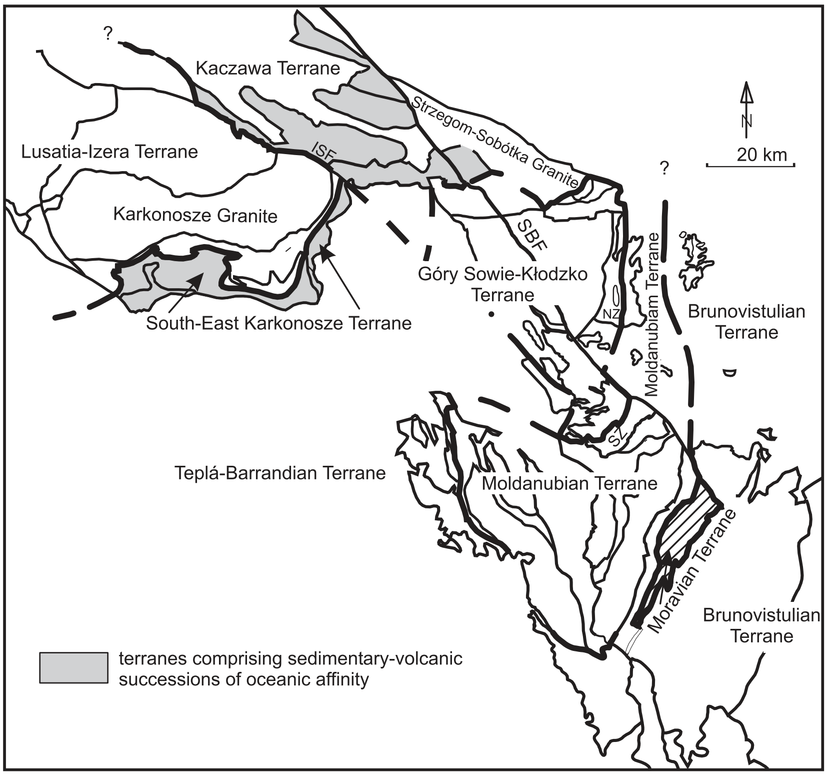

Fig. 10. Tectonostratigraphic terranes in the Sudetes (after Aleksandrowski and Mazur, 2002)

ISF — Intra-Sudetic Fault; SBF — Sudetic Boundary Fault; NZ — Niemcza Shear Zone; SZ — Skrzynka Shear Zone

8. The Brunovistulian Terrane comprises the Keprník Nappe and Desná Dome and the more easterly located successive units of the East Sudetes, including the folded and thrust-faulted Culm Basin and the little tectonised coal-bearing Silesian molasse basin at the East-Sudetic foreland. Both basins rest on Brunovistulian basement of hypothetical Avalonian affinity (Friedl *et al*., 2000). Within the Fore-Sudetic Block, the Brunovistulian Terrane includes also the Strzelin Massif of similar characteristics. The latter two terranes are equivalent to the traditionally distinguished Moravo-Silesian Zone of the Variscides.

Incorporating the Góry Sowie Massif and the Kłodzko Metamorphic Unit into one single terrane (Aleksandrowski and Mazur, 2002) is based on their adjacent location and the same age of pre-Late Devonian exhumation, as well as on the record of preceding Eo-Variscan convergence in the both units, though not necessarily contemporaneous and involving different palaeotectonic environments. This model differs significantly from the earlier hypothesis of Aleksandrowski (1990, 1995) that postulated Late Devonian(?)-Early Carboniferous long-distance strike-slip displacements along the Intra-Sudetic Fault Zone, thought to continue SE-ward beneath the Intra-Sudetic Basin and along the SW margin of the Góry Sowie Massif, and thus to separate it from the Kłodzko Unit. In their current terrane model, Aleksandrowski and Mazur (2002) refrain from presenting alternative hypotheses and advance the simplest possible solutions. Future research is needed to address the questions of a possible SE-ward continuation of the Intra-Sudetic Fault Zone beyond the Intra-Sudetic Basin, and, if so, whether it follows the boundary of the Góry Sowie Massif and the Kłodzko Unit (Aleksandrowski 1990, 1995; Aleksandrowski *et al*., 1997) or continues somewhere south of the Kłodzko Unit. On the other hand, it cannot be excluded that the Góry Sowie Massif, partly with a similar geological history, but involving a lithostratigraphic and palaeotectonic environment that strikingly differs from that of the Kłodzko Unit, may have fortuitously been juxtaposed with the latter by horizontal displacement along the Intra-Sudetic Fault, which resulted in unrelated crustal fragments with an accidentally similar record of Eo-Variscan uplift and cooling (probably widespread in the Variscan realm) to be now located adjacent to each other.

TIME CONSTRAINTS

The accretion of the Sudetic segment of the Variscides was a multi-stage process. The oldest recorded tectono-metamorphic events took place at the Silurian/Devonian turn. The 400–395 Ma (O'Brien *et al*., 1997; Kryza and Fanning, 2004) and 386 Ma (Szczepański *et al*., 2004) old granulites of the Góry Sowie and the Orlica-Śnieżnik massifs, respectively, testify to the subduction of continental crust, shortly after the Central Sudetic Ophiolite rocks had crystallized (420–400 Ma; Oliver *et al*., 1993; Dubińska *et al*., 2004). During the subsequent emplacement of nappes, including ophiolites and metamorphic complexes, fragments of the subducted continental crust were exhumed. The early Givetian fauna coming from metamorphosed sediments of the Kłodzko Unit, constrains the lower time limit of nappe emplacement (Hladil *et al*., 1999). Its upper age limit is provided by a the pre-Late Devonian unconformity on top of the ophiolites and of the nearby Kłodzko Metamorphic Unit, that is overlain by unmetamorphosed Late Frasnian to Famennian limestones (Bederke, 1924, 1929; Kryza *et al*., 1999). These Late Devonian carbonates grade upward into the Early Carboniferous clastic sequence of the Bardo Sedimentary Unit (Haydukiewicz, 1990, Wajsprych, 1986). Consequently, the emplacement and exhumation of the Central Sudetic nappes must have taken place within a narrow time span between c. 390 and 380 Ma.

In the more westerly located Kaczawa Basin of the West-Sudetes, deep-water sedimentation lasted, however, until the end of Devonian times, suggesting that the Kaczawa successions were incorporated into an accretionary prism at least as late as end-Devonian times. This is compatible with the occurrence of blueschist facies rocks in the adjacent Karkonosze-Izera Massif that yielded a metamorphic age of *c*. 360 Ma (Maluski and Patočka, 1997). The final thrusting of the nappes in the Kaczawa Unit and in the S and E parts of the Karkonosze Massif over the eastern margin of Saxothuringia (Lusatia-Izera Terrane) occurred not earlier than during the Viséan, as indicated by the age of sediments underlying these allochthonous units in the Ještěd unit (Chlupač, 1993) and the western part of the Kaczawa nappe pile (Chorowska, 1978).

The collision of the Central Sudetic orogenic wedge with the continental Brunovistulian Terrane is thought to have commenced during the earliest Carboniferous and to last until the turn from the Early to the Late Carboniferous (Schulmann and Gayer, 2000), although no conclusive time constraints are as yet available. In the West and much of the Central Sudetes tectonic activity was dominated at these times by strike-slip movements along major faults/shear zones, exhumation of core complexes and an intense granitic plutonism. A 340 Ma extensional collapse with a top-to-SE sense of motion was documented from the eastern margin of the Karkonosze-Izera Massif (Mazur, 1995; Mazur and Aleksandrowski, 2001). Dextral strike-slip displacements occurred at that time not only along the WNW–ESE trending Upper Elbe and Intra-Sudetic Fault Zones (Aleksandrowski *et al*., 1997; Mattern, 2001), but also along the boundary between the Nové Město Unit and the Orlica-Śnieżnik Massif (Mazur *et al*., 2005). At the same time, sinistral displacements occurred on regional, NNE–SSW striking Niemcza Shear Zone (Mazur and Puziewicz, 1995a) and the NE–SW trending Złoty Stok-Skrzynka Shear Zone of (e.g. Cymerman, 1996). Plutonic processes climaxed at 340–310 Ma (*cf.* e.g. Aleksandrowski *et al*., 2000), resulting in the emplacement of several large granitic bodies, such as those of Karkonosze, Strzegom-Sobótka, Kłodzko-Złoty Stok and Žulová (Fig. 3).

Assembly of the Sudetes involved the closure of at least two oceanic basins, from which the allochthonous complexes of the Kaczawa and S and E Karkonosze, and the Sudetic ophiolites were derived. It cannot be excluded either, that a further oceanic basin separated the Central Sudetes from the Brunovistulian Terrane, vestiges of which may be represented by metamorphosed MORB-type mafic rocks contained in the Staré Město Belt (Přichistal, 1990). Closure of these basins involved three collisional events that took place (1) at the turn from the Middle to the Late Devonian, resulting in the amalgamation of the Central Sudetes, (2) at the turn from the Devonian to the Carboniferous due to collision of the Lusatia-Izera Terrane with the terranes of Teplá-Barrandian and of Góry Sowie-Kłodzko in the West Sudetes and (3) during the Early

Carboniferous collision of the East Sudetic orogenic wedge with the continental Brunovistulian Terrane.

VARISCAN EXTERNAL ZONE IN SW POLAND

In western Poland, the fold-and-thrust belt of the Variscan Externides and their associated foreland basin are almost entirely buried beneath the up to 8 km thick Permian to Cenozoic sediments of the North German-Polish Basin. The SW and central parts of this belt cover the area of southern Wielkopolska and involve a more than 2 km thick late Viséan to Westphalian syn- to post-orogenic clastic turbidite succession that was deposited on top of a mostly unknown basement. The latter reveals seismic properties typical of Variscan crust and extends up to the Dolsk Fault in the NE (Fig. 11; Dadlez, 2006; Guterch and Grad, 2006). Only at the Leszno-Wolsztyn High, immediately south of the Dolsk Fault, the entire late Viséan-Namurian A turbidite sequence have been penetrated by boreholes, which terminated in Upper Devonian phyllites (Haydukiewicz *et al*., 1999) of early Viséan cooling signature (*c*. 340 Ma; Żelaźniewicz *et al*., 2003). These phyllites are presumably involved in nappes that were thrust northward onto the northern foreland of the Variscan Orogen, corresponding to the Rhenohercynian Shelf of the Old Red Continent (Ziegler, 1989, 1990).

In the northern Wielkopolska, Kuiavia, northern Małopolska and Upper Silesia regions of Poland, the Variscan foreland basin developed on top of a collage of presumable Neoproterozoic terranes that were accreted to the East European Craton during Early Palaeozoic times, now forming the Trans-European Suture Zone (TESZ) (e.g. Pharaoh, 1999, Winchester and PACE 2002; Nawrocki and Poprawa, 2006). In this area, Late Carboniferous clastic successions (Namurian to Westphalian) rest on Early Carboniferous and Devonian carbonates, shales and sands. During the late stages of the Variscan Orogeny, these were locally deformed, uplifted and erosionally truncated. During the latest Carboniferous and Early Permian, the Variscan foreland basin was affected by important wrenching along fault systems paralleling the Teisseyre-Tornquist and Sorgenfrei-Tornquist zones, leading to deformation of its sedimentary fill. The trace of the Variscan deformation front is ill-defined in western Poland (Jubitz *et al*., 1986; Pożaryski *et al*., 1992), owing to local intensity of latest Carboniferous-Early Permian deformations and the scarcity of borehole data.

During Middle and Late Devonian times, a vast carbonate platform occupied the Rhenohercynian Shelf and extended via Pommerania in the NW, through the Holy Cross Mountains into Upper Silesia and the Moravo-Silesian domain in the S. Intermittent back-arc extension, punctuated by bimodal magmatic activity, caused modification of this carbonate platform, which persisted in its distal parts into the Viséan, whilst in the deeper parts of the basin, pelagic shales and flysch-type Culm sediments were deposited. During the end-Viséan/early Namurian, the Polish equivalents of the Rhenohercynian Shelf subsided rapidly in response to thrust-loading that directly postdated the Late Devonian to Viséan collision-related events in the Sudetic segment of the Variscan Internides, involving nappe stacking, crustal thickening, widespread granitic plutonism and thermal metamorphism, as well as orogenic uplift and extensional unroofing. In the proximal parts of the evolving flexural foreland basin, thick late Viséan to Namurian turbiditic sequences were deposited. They are now involved in the fold-and-thrust belt of the Variscan Externides. Subsidence of the Variscan foreland basin in front of the evolving orogen, commencing in the late Viséan and Namurian A, was accompanied by a rapid N- and NE-ward advance of late-orogenic clastic systems across Wielkopolska and Upper Silesia and Małopolska, to reach the Lublin Trough in the east and Pomerania in the north (Fig. 11). Rapid subsidence of this foreland basin was locally interrupted during the late Namurian and earliest Westphalian by a period of non-deposition, with sedimentation resuming during the Westphalian A to B. Development of such a hiatus, e.g. in northern Pommerania, is thought to be related to intraplate compressional deformations, reflecting increas-

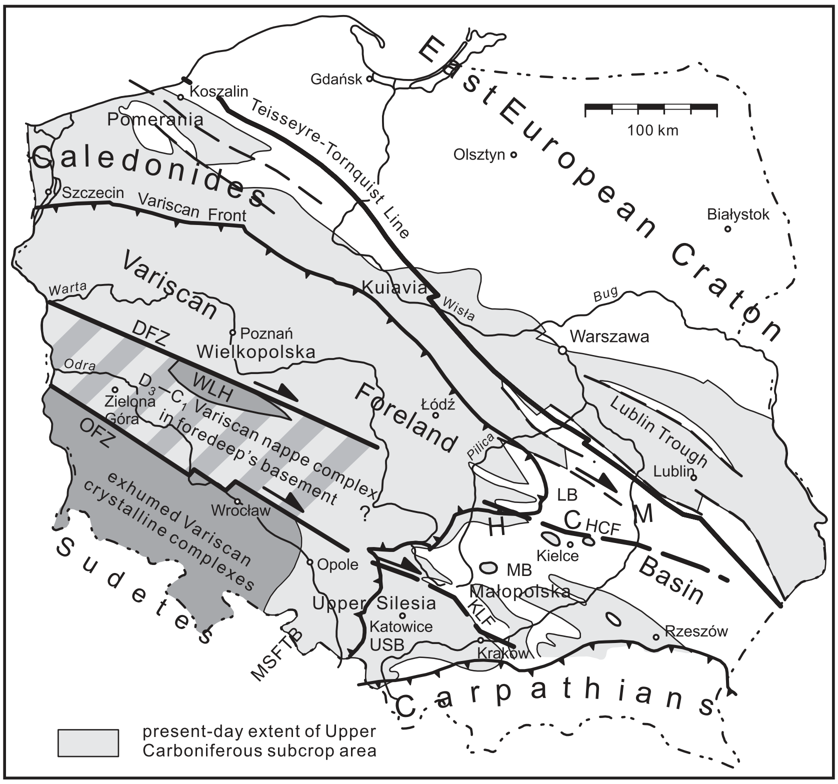

Fig. 11. Variscan external zone of Poland

Location of the Variscan front according to Pożaryski *et al*. (1992) is indicated; DFZ — Dolsk Fault Zone; HCF — Holy Cross Fault; HCM — Holy Cross Mts.; KLF — Kraków-Lubliniec Fault; LB — Łysogóry Block; MB — Małopolska Block; MSFTB — Moravo-Silesian Fold-and-Thrust Belt; OFZ — Odra Fault Zone; USB — Upper Silesian Block; WLH — Wolsztyn-Leszno High ing collisional coupling between the Variscan orogenic wedge and its foreland (Ziegler, 1990; Ziegler *et al*., 2002).

^{40}Ar-^{39}Ar analyses of detritial white mica from Carboniferous sandstones of the Variscan Externides of SW Poland yielded plateau-like ages in the range of *c*. 370–355 Ma (Mazur *et al*., 2006). A comparable plateau-like age of *c*. 360 Ma was obtained from neocrystalline white mica of a phyllite of the Wolsztyn-Leszno High, underlying the Carboniferous foreland sequences. These ages indicate that the Variscan foreland basin was supplied with clastics derived from rocks that were exhumed and cooled during the Late Devonian. Such rocks may have once constituted a stack of early Variscan nappes that occupied the structurally highest position in the internal orogenic zone, representing equivalents of such phyllite units as the Wolsztyn-Leszno High that floored the southern part of the Carboniferous foreland basin.

In SW Poland, deformation of the Variscan external thrust-and-fold belt climaxed in the Westphalian C, leading to localized, moderate to intense folding and thrusting (Mazur *et al*., 2003), probably under an overall dextral transpressional regime that, at least partly involved activity along major NW–SE trending strike-slip fault zones in the basement (e.g. the Teisseyre-Tornquist Zone, Dolsk Fault, Kraków-Lubliniec and Middle Odra faults). This deformation must have been contemporaneous with the late folding of the Holy Cross Mts. that is known to have occurred between the Namurian A and Permian. In the Lublin Trough, which is superimposed onto the East European cratonic basement, sedimentation terminated at the end of the Westphalian. Following basin inversion, up to a few hundred metres thick successions of Westphalian D to Stephanian continental clastic sediments were deposited in local transtensional grabens in SW and central Poland, as well as in parts of Pomerania and Upper Silesia.

CONCLUSION

Our present state of knowledge on the structure and evolution of the Polish Variscides allows highlighting a few key problems that are critical for the understanding of this part of the European Variscan Belt. The available data point towards multi-stage accretion of the Variscan Belt, comprising a number of spatially and temporally different collisional events that are related to successive closure stages of certain segments of the Rheic Ocean (Fig. 12). Specifically, structural units that are now juxtaposed, often bear record of contrasting exhumation/cooling paths, constrained by palaeontological and geochronological evidence. This fact, together with the tectonic and/or suture-type characteristics of their boundaries, supports a terrane approach to the tectonics of the Sudetes, despite complexities and controversies related to particular interpretations. There is gradually increasing evidence, emerging from recently acquired structural and geochronological data for a three-partite subdivision of the Sudetes into central, western and eastern segments that were deformed and accreted during the Middle/Late Devonian, at the turn from the Devonian to the Carboniferous, and during the Early Carboniferous, respectively (Fig. 12). The end-Devonian/earliest Carboniferous main compressional stage, crucial for the tectonic development of the West Sudetes, was contemporaneous with extensional unroofing of the Central Sudetes, manifested by uplift of the Góry Sowie and Kłodzko massifs and the onset of subsidence of the Świebodzice and Bardo basins. Similarly, the contractional tectonics in the East Sudetes was associated with significant strike-slip movements in the West and Central Sudetes and their extensional unroofing. An exception is the Orlica-Śnieżnik Massif bearing a vestige of Late Devonian deformation that was intensely overprinted by Early Carboniferous compressional deformation and metamorphism at the contact of the Central and East Sudetes. In this context, the first tectono-thermal events that affected the phyllites from the Leszno-Wolsztyn High, now occurring beneath the Carboniferous foreland basin of SW Poland, can be tentatively correlated with Devonian tectonic events in the Sudetes, despite limited geochronological evidence. The Leszno-Wolsztyn rocks were subsequently overstepped by thick upper Viséan to Namurian sedimentary successions, whose deposition was controlled by orogenic uplift and erosion of the Sudetes. The Late Carboniferous inversion of the Polish Variscan Foreland Basin was apparently associated with a considerable N- and E-ward transport of the Variscan orogenic wedge and its interaction with the foreland lithosphere. These processes were apparently mostly controlled by strike-slip displacements along such major fault zones as Teisseyre-Tornquist, Dolsk or Middle Odra zones, operating under an overall dextral transpressional regime (e.g. Arthaud and Matte, 1977; Ziegler, 1990).

The structural evolution of the Variscan Externides of SW Poland comprised three main stages: (1) thermal overprint and deformation of Devonian pre-orogenic sediments during the latest Devonian/earliest Carboniferous, (2) rapid subsidence of the foreland basin and sediment accumulation in the time span from the Viséan to Westphalian and (3) localised thrusting and folding, partly under a transpressional regime, of the Carboniferous syn-orogenic sediments during the Westphalian C. The geological and structural continuity is clearly traceable within the foreland basin system, fringing the northern flank of the Variscan Belt from England to Poland. It cannot be excluded, however, that in SW Poland the foreland basin succession onlapped and buried the northern frontal thrust zone of the Variscan metamorphic nappes.

The growing amount of new data on the evolution and structure of the Polish Variscides demonstrate the difficulties and pitfalls inevitably related to attempts to extend the classical tectonostratigraphic zonation of the Variscides into SW Poland. The scheme, conceived by Kossmat (1927) for type localities in Germany and Bohemia, is not fully applicable to the Sudetes and their northern foreland. Mutually exclusive, alternative terrane models proposed during the last fifteen years for SW Poland reflect the particular complexity of the Variscan geology of this area. This is in part due to the fact that Late Palaeozoic strike-slip faults and shear zones, which appear to be increasingly frequent on approaching the Teisseyre-Tornquist Line, have dissected initially continuous tectonostratigraphic units and dispersed their fragments into a geologists' puzzle. Moreover, certain fragments are either buried below younger sediments or were differentially uplifted and eroded down to various structural levels. All this does not help to correlate and compare particular structural units with one an-

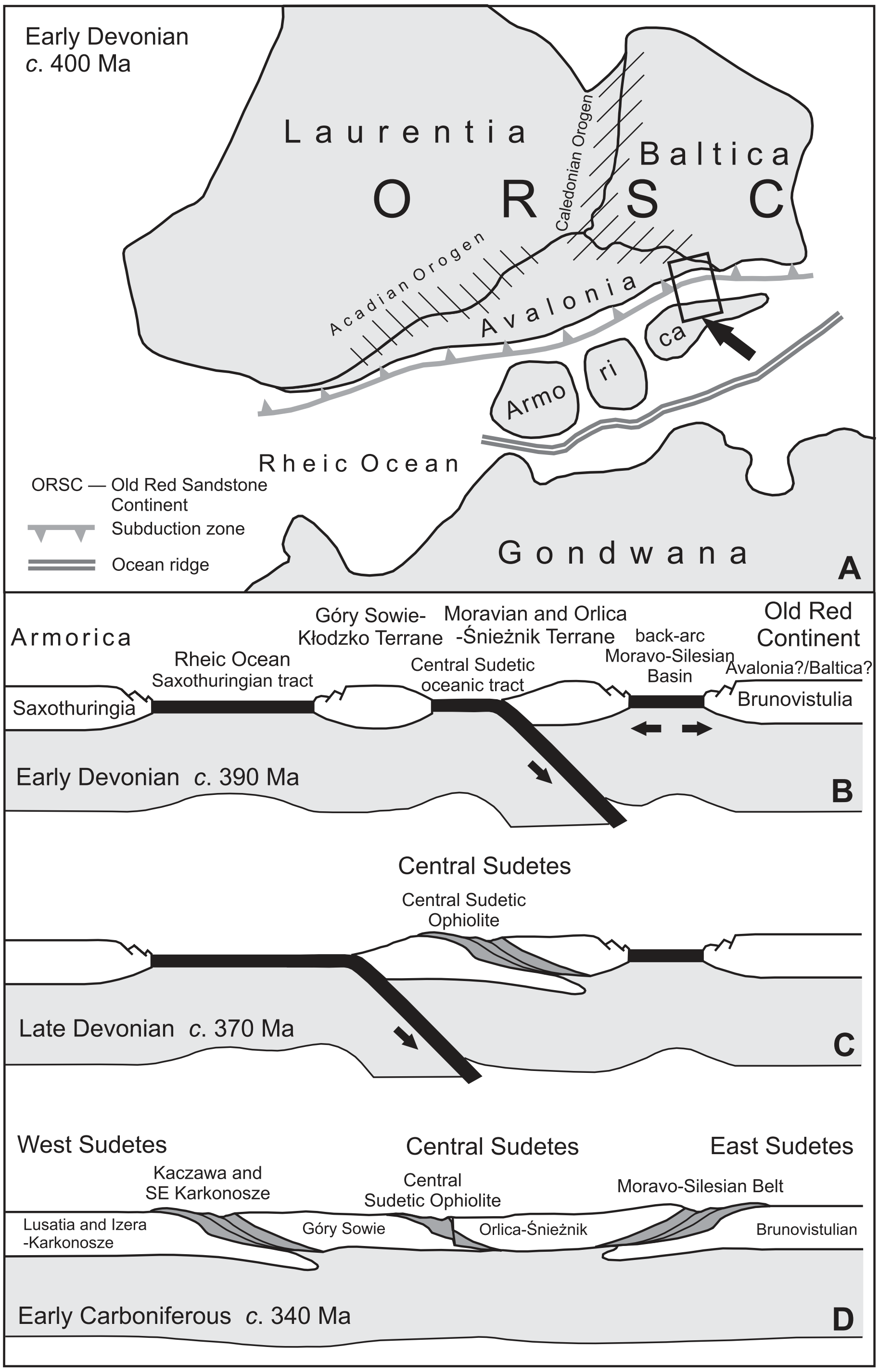

Fig. 12. Hypothetical geodynamic scenario of evolution of the Sudetes area in the Late Palaeozoic (much simplified)

The palaeogeographic sketch map (**A**) is inspired by plate tectonic reconstructions by Ron Blakey (Northern Arizona University); arrowed box indicates area shown on schematic cross-sections (**B**–**D**); major strike-slip motions are not taken into account in the restorations; **B** — Góry Sowie-Kłodzko Terrane is approaching Moravian and Orlica-Śnieżnik Terrane due to closure of the Central-Sudetic oceanic area; Moravo-Silesian back-arc Basin is formed in the Early Devonian; **C** — Central Sudetes are accreted due to continental collision between Góry Sowie-Kłodzko and Moravian terranes; (U)HP rocks in Orlica-Śnieżnik and Góry Sowie massifs are formed by subduction to mantle depths and, subsequently, exhumation as a nappe pile including Central Sudetic Ophiolite; **D** — accretion of the Sudetes is completed by closing of the Saxothuringian Oceanic Tract and the Moravo-Slesian Basin; Kaczawa and South Karkonosze/Leszczyniec units (W) and Moravo-Silesian Belt (E) include remnants of tectonic sutures

other and to their possible counterparts elsewhere. Of course, SW Poland must contain an extension of most major Variscan tectonostratigraphic units (terranes), though probably fragmented and reshuffled by strike-slip displacements. Furthermore, it seems unlikely that the basement of the Sudetes is mostly exotic with respect to the remaining part of the Variscan Belt, as implied by some interpretations, following the early concept of a separate Lugian domain in the West Sudetes (Suess, 1926). Unfortunately, interpretations are hampered by the generally poor preservation of tectonic sutures, crucial for defining the extent of the different terranes of the Sudetes. This is largely due to the intensity of the Variscan tectonism that fragmented, displaced and unrooted the sutures with respect to the original terrane boundaries (e.g. Aleksandrowski and Mazur, 2002).

Since the suspected terranes of SW Poland are probably derived from an ancient margin of Gondwana, they are expected to share a common Neoproterozoic basement as well as common effects of Ordovician rifting and break-up. Taking into account all the above circumstances, it is clear that still much more work is needed in order to identify and assess the significance of all possible tectonic sutures and the effects of large-scale strike-slip displacements in the Sudetes and entire SW Poland before the puzzle of the distribution, provenance and evolution of the Variscan terranes/tectonostratigraphic zones can be solved convincingly.

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