The Sudetic geological mosaic: Insights into the root of the Variscan orogen

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A b s t r a c t: The Sudetes in the NE part of the Bohemian Massif stretch between the NW–SE-trending Odra Fault Zone and Elbe Fault Zone and represent a structural mosaic which was shaped, predominantly, during the Variscan orogeny. They are composed of various geological units, including basement units in which Neoproterozoic to Carboniferous rocks are exposed, and a post-orogenic cover of younger deposits. During the long history of geological research, the Sudetes have become a "type locality" for a range of important geological phenomena, such as granites and orthogneisses, ophiolites and (meta)volcanic sequences, granulites, eclogites and blueschists, nappe tectonics and terrane concepts. In spite of significant recent achievements, many key problems need further study, and a selection of them is proposed in this paper: (a) the presence of older, Neoproterozoic (Cadomian) rocks and their position within the Variscan collage, (b) the character and emplacement setting of Palaeozoic, pre-Variscan sedimentary successions and magmatic complexes (including ophiolites), (c) structural evolution, metamorphism (in particular HP/T grades) and exhumation of deeper crustal blocks during the Variscan orogeny, and (d) post-orogenic development. Future investigations would require an interdisciplinary approach, combining various geological disciplines: structural geology, petrology, geochemistry, geophysics and geochronology, and, also, multilateral interlaboratory cooperation.

Key words: *Variscan Belt, Sudetes, Cadomian orogeny, Variscan orogeny, (meta)granitoids, (meta)volcanics, ophiolites, granulites, eclogites, blueschists, nappe tectonics, terranes*

The Variscan orogen of Europe, one of the classically defined, global-scale orogenic systems (Suess, 1926; Kossmat, 1927; Stille, 1951) separates the Caledonides in the north from the Alpides in the south of Europe, all three Phanerozoic orogenic belts located west and southwest of the Precambrian East European Craton. The major Variscan orogenic processes, including metamorphism, deformation, exhumation and intense granite plutonism, echoed by syn- and post-orogenic volcanic activity and sedimentation at the surface level, culminated through Late Devonian to Permian times, ca. 380 to 280 Ma.

The Variscan orogen, moderately rejuvenated due to compressional stress field induced by Alpine collisional events, is strongly eroded and largely covered by younger deposits. The original, continuous mountain belt is exposed only locally across the west and central Europe, showing various levels and parts of the orogenic system, often presenting a puzzle of not easily interpretable pieces of geological information. Among the largest outcrops of the Variscan orogen is the Bohemian Massif and, in turn, one of its most intriguing parts is the Sudetes Mountains area, along the Polish–Czech border.

The Sudetes form the NE part of the Bohemian Massif situated between two major NW–SE-trending fault systems, parallel to the SW margin of the East European Craton (i.e., to the Tornquist-Teisseyre Line or Trans-European Suture Zone): the Odra Fault Zone in the NE, and the Elbe Fault Zone in the SW (Fig. 1). To the NW, the Sudetes adjoin the Lusatian Block in Germany whereas to the SE they are buried under the Carboniferous, Silesian coal basin and the Carpathian nappe system.

The geologically consistent area of the Sudetes is divided into two morphological domains by the NW–SE-trending Sudetic Boundary Fault. This Tertiary feature separates the mountainous part of the Sudetes to the SW from the Fore-Sudetic Block to the NE. The latter is much more flat, compared to the Sudetic mountain range, and largely covered by Cenozoic deposits.

The Sudetes area is a complex structural mosaic, composed of various types of geological units:

a) basement units, including fragments of the older (Cadomian) basement, Palaeozoic variously metamorphosed successions and (meta)igneous complexes, all sealed by extensive Variscan granitoid bodies, and

b) late- to post-orogenic (post-Variscan) cover, ranging from the Lower Carboniferous up to Cenozoic deposits.

The long and complex geological history makes the area a very attractive field for geological studies. The region is relatively well exposed and thus often providing unique possibilities for investigations, particularly of selected "hot" topics of basement geology.

More systematic geological investigations in the area started already in the 19th century, contributing significantly to the history of sciences at the Wrocław *Alma Mater*, which recently celebrated its 300th anniversary (Grodzicki, 2003). These early studies were continued, e.g., as detailed geological mapping, in the first half of the 20th century. The studies covered many aspects of geological sciences, including basic mineralogy and petrology (see Mierzejewski et al., 2003, and refs. therein), stratigraphy (Bederke, 1924), tectonics (Cloos, 1927), large-scale structural interpretations (Suess, 1926; Kossmat, 1927). The classical achievements were followed by more detailed studies during later decades of the 20th century (summarized, e.g., in Kodym & Svoboda, 1948; Oberc, 1972; Teisseyre, 1980) that contributed much to the knowledge of basic issues encountered in the geology of Central Europe. Specific problems, such as those concerning the petrogenesis of eclogites, were intensely studied in the region (Smulikowski, 1967) which became a sort of their "type area".

In spite of the evident progress in geological studies in that unique area, many basic questions remain still unsolved and attract interest of international geological community in various fields of Earth sciences. Consequently, since the 1990s, the Sudetes have been investigated by a number of joint multi-national research projects such as Europrobe or PACE (e.g., Winchester et al., 2002) and bilateral cooperative research between the Université Blaise

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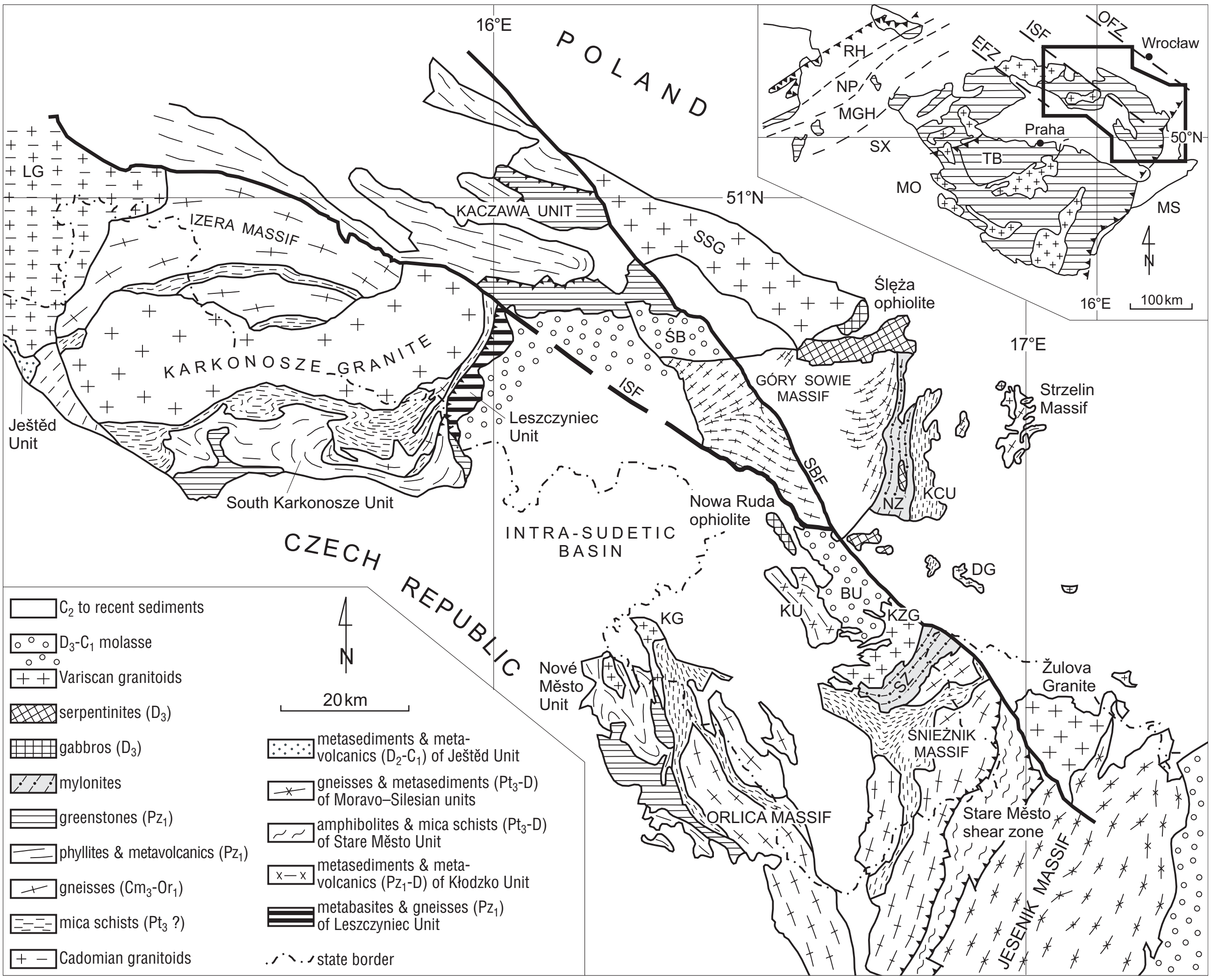

Fig. 1. Geological sketch of the Sudetes (after Aleksandrowski et al., 1997); BU — Bardo Unit, DG — Doboszowice gneiss, ISF — Intra-Sudetic Fault, KCU — Kamieniec Unit, KG — Kudowa granite, KU — Kłodzko Metamorphic Unit (Complex), KZG — Kłodzko–Złoty Stok granitoids, NZ — Niemcza Zone, LG — Lusatian granitoids, SBF — Sudetic Boundary Fault, SSG — Strzegom-Sobótka granitoids. Inset map: EFZ — Elbe Fault Zone, ISF — Intra-Sudetic Fault, MGH — Mid-German High, MO — Moldanubian Zone, MS — Moravo–Silesian Zone, NP — Northern Phyllite Zone, OFZ — Odra Fault Zone, RH — Rhenohercynian Zone, SX — Saxothuringian Zone, TB — Teplá–Barrandian Zone

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In this paper, we intend to outline selected important problems of basement geology of the Sudetes area which attract wide international attention, to discuss shortly some important controversies, and point to more intriguing targets for possible future investigations.

Outline of the geology of the Sudetes

The tectonic picture of the Sudetes (Fig. 1) reflects their complex geological evolution which is, in a simplified way, outlined in the following paragraphs describing (a) locally preserved/defined fragments of the Cadomian basement, (b) widely distributed pre-Variscan Palaeozoic successions and igneous complexes, (c) Variscan structural, metamorphic and magmatic evolution, and (d) post-Variscan development.

Cadomian basement. The rocks of confirmed Neoproterozoic age, largely formed or emplaced prior to or during the Cadomian orogeny, occur in the Lusatian Block, in the Strzelin Massif and equivalent Silesian domain of the East Sudetes (in the Czech territory), and in the Kłodzko Metamorphic Complex. It is likely that also other metasedimentary-metavolcanic complexes in the Sudetes, in particular those intruded by Lower Palaeozoic granitoids, are of Neoproterozoic age.

In the Lusatian Block, the Cadomian basement rocks are represented by the Lusatian greywackes and granodiorites. The greywakes cover small area near the western Polish border, on the NE periphery of the Lusatian Granodiorite Massif. They consist of a succession of anchimetamorphic medium- to coarse-grained greywackes, intercalated with slates and interpreted as hemipelagic turbidites. The composition of detrital clasts and the whole rock geochemical signature suggest that material of the greywackes derived from a magmatic arc with maximum of the magmatism at about 575 Ma and deposited on an active continental margin. The Lusatian greywacke succession was subjected to very low grade regional metamorphism and folded into open E–W to SE–NW-trending folds during the Cadomian orogeny. After folding, the greywackes were intruded and thermally metamorphosed by the

Lusatian granodiorites. The latter rocks cropping out on the Polish territory near Zgorzelec were dated at ca. 540–530 Ma by the single zircon evaporation technique and SHRIMP method (Tikhomirova, 2002, and refs. therein).

In the Strzelin Massif (Fig. 1), in its northern part, the Cadomian basement consists of the fine- to medium-grained porphyritic biotite-muscovite Strzelin gneiss with conformable, several centimetre to several metre thick, intercalations of amphibolites interpreted as former mafic dykes (Szczepański & Oberc-Dziedzic, 1998). In the southern part of the massif, the Neoproterozoic rocks are represented by the Nowolesie migmatitic sillimanite gneiss. The granitic protolith of the Strzelin gneiss is dated at 600–568 Ma by the U–Pb zircon SHRIMP analysis (Oberc-Dziedzic et al., 2003a). The age of 1020 Ma was obtained with the single grain evaporation method for the Nowolesie gneiss (Kröner & Mazur, 2003). The Neoproterozoic dates strongly indicate a Moravo–Silesian affinity for the Strzelin and Nowolesie gneisses and prove that the fragment of the Brunovistulian basement can be traced beyond the mountainous part of the East Sudetes.

The gneisses of the Strzelin Massif are predominantly peraluminous rocks corresponding to medium to highly potassic granites or granodiorites. Their compositions and proportions of major and trace elements point to greywacke as a magma source for the granitic protolith. The peraluminousity of the gneisses, their monotonous, fine- to medium-grained, porphyritic fabric, and the lack of mafic enclaves also suggest an S–type granite as a precursor of the gneisses (Oberc-Dziedzic et al., 2003a, and refs. therein).

The Neopretorozoic succession of the Kłodzko Metamorphic Complex (KU in Fig. 1) is comprised within three separate tectonic elements, thrust over the Palaeozoic rocks within a Variscan nappe pile (Mazur, 2003b). The Neoproterozoic components of this tectonic stack consist of two distinct lithological associations: (1) an amphibolite-grade mostly meta-igneous suite composed of metagabbros and amphibolites accompanied by felsic metavolcanics and (2) an epidote-amphibolite grade volcano sedimentary succession. Zircons from a plagioclase gneiss which occurs intimately associated with metagabbros yielded an age of 590±10 Ma which is interpreted as the time of igneous crystallization for the whole plutonic suite. Furthermore, a fraction of euhedral zircons with magmatic zonation, derived from a rhyodacite/andesite tuffaceous rock, revealed the age of 590–600 Ma which constrains a maximum deposition age of the volcano-sedimentary succession, probably corresponding to the time of volcanic activity (Mazur et al., 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. The metagabbros range from slightly enriched to depleted rocks, and their E Nd_{560} varies from +2.2 to +8.6 (Kryza et al., 2003). The intermediate and acidic rocks are peraluminous to metaluminous rhyolites, rhyodacites/dacites and andesites, with trace-element patterns generally rather flat to slightly enriched in most-incompatible elements. Their E Nd_{560} values, between +2.9 to +8.6, within the same range as in the metagabbros, together with the lack of alkaline rocks, suggest a subduction-related environment (Kryza et al., 2003).

The recognition of Neoproterozoic subduction-related magmatism in the KU provides new evidence for the presence in the Sudetes of rock assemblages representing a Pan-African active margin. They can be interpreted as indication for the subduction of an oceanic-type domain beneath the Gondwana active margin prior to the Cadomian collision (Mazur, 2003b, and refs. therein). Consequently, the plutonic crustal fragment may correspond to the floor of a back-arc basin while the volcano-sedimentary succession represents its surface equivalent deposited in a magmatic arc setting.

Pre-Variscan successions and igneous complexes. Most of the metamorphosed volcano-sedimentary successions exposed in the West Sudetes show geochemical signatures indicating an origin in an initial rift or mature oceanic setting (Narębski, 1992; Furnes et al., 1994; Kryza & Pin, 1997; Floyd et al., 2000). These magmatic suites represent the record of Early Palaeozoic rifting that led to the break-up of the northern Gondwana margin (e.g., Pin, 1990) and the separation of crustal fragments (considered in some models as terranes) now assembled in the Variscan Belt (Tait et al., 2000). Magmatic complexes with such characteristics are widespread throughout the European Variscides (Pin, 1990; Floyd et al., 2000). In the Sudetes, they are mainly represented by the volcano-sedimentary successions of the Kaczawa and South Karkonosze metamorphic units (Furnes et al., 1994, and refs. therein), non- to weakly metamorphosed sediments of the Bardo Basin, and by the Sudetic ophiolites (Pin et al., 1988). These occurrences are interpreted as representing Cambrian–Ordovician continental rifts, as well as Silurian and Devonian successions of oceanic basins.

The Kaczawa Complex is among the best documented Palaeozoic pre-Variscan sequences in the Sudetes. It is exposed in a few fault-bounded units, each containing different parts of the stratigraphic successions and sedimentary/tectonic mélange bodies. The stratigraphic successions comprise metasedimentary and metavolcanic rocks ranging in age from the Cambrian–Ordovician to Upper Devonian–Lower Carboniferous. The biostratigraphic control is rather scarce, with many parts of the successions, in particular metavolcanogenic, of unknown ages. The lower part of the Kaczawa sequence, exposed mainly in the SW part of the area (e.g., Świerzawa and Bolków units), is represented by composite metavolcanic suites (alkaline and transitional to tholeiitic basalts, trachytes and rhyodacites) and associated metasedimentary rocks, all interpreted to have been emplaced in a continental initial rift setting during Cambrian–Ordovician times (Furnes et al., 1994; Fig. 2). The higher part of the sequence, exposed predominantly in the northern and eastern part of the area (Jakuszowa and Dobromierz units) and including Silurian graptolitic black slates and cherts, conodont-bearing Devonian slates, as well as thick, often pillowed MOR–type metabasalts, are considered to represent subsequent, more evolved rift setting and deep-basin environment, possibly developed on an oceanic-type crust (Fig. 2). The Kaczawa mélanges, assigned mostly to the Upper Devonian and Lower Carboniferous, are interpreted as polygenetic rocks, products of overlapping rapid sedi-

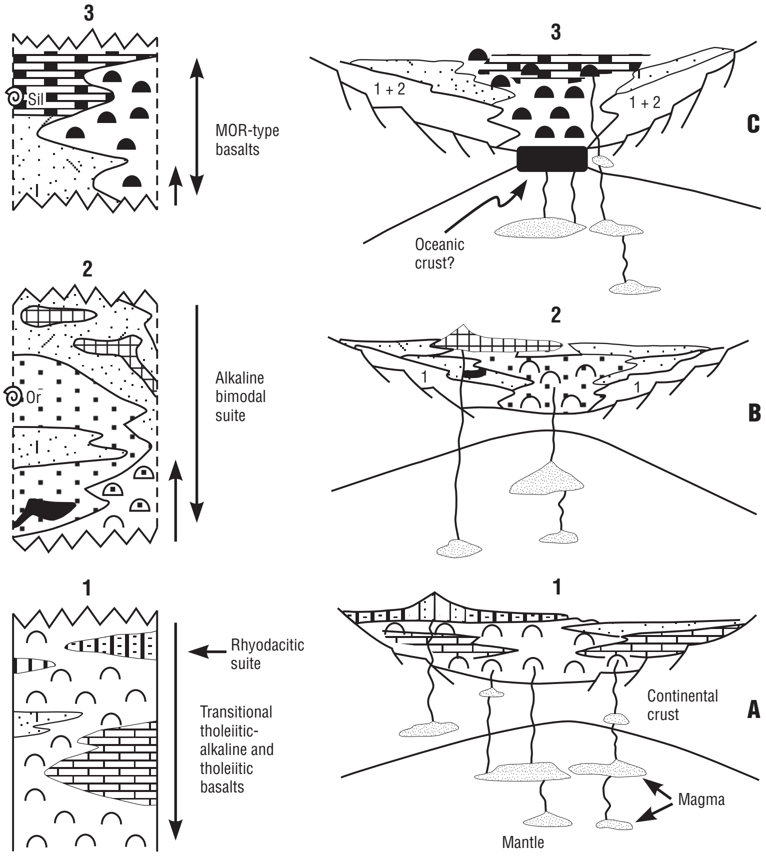

Fig. 2. Development of palaeotectonic settings prior to the Variscan orogeny, based on interpretation of metavolcanic-metasedimentary successions of the Kaczawa Complex (after Furnes et al., 1994). A — Cambrian?–Ordovician: at this stage, mantle-generated, basaltic magma might have become contaminated at different crustal levels, and rhyodacitic magma was produced by crustal melting; B — development of alkaline bimodal suite of mantle-generated melts; at that stage, the continental crust suffered continued attenuation; C — during Silurian time the predominance of basaltic melts were generated from a depleted mantle, and at this stage a true oceanic crust was probably developed

mentary and tectonic processes at the early stages of the Variscan orogeny (Baranowski et al., 1990; Collins et al., 2000).

The rocks of various tectonic units of the Kaczawa Complex bear well preserved records of HP–LT metamorphism of blueschist facies type, and of subsequent greenschist facies overprint. However, part of the tectonic units, in particular mélange bodies, experienced significantly lower-grade metamorphism (anchizone to very-low-grade conditions; Kryza & Muszyński, 2003, and refs. therein). The lithological contents and specific structural and metamorphic patterns allow to interpret the Kaczawa Complex to comprise fragments of a Variscan accretionary prism (Baranowski et al., 1990; Kryza & Muszyński, 2003).

Palaeozoic successions are well recognized in practically non- to very weakly metamorphosed sequences of the Bardo Basin. The Bardo succession is formed of Upper Devonian limestones and Lower Carboniferous flysch overlain by thick wildflysch sediments, the latter containing olistoliths of Ordovician, Silurian and Devonian deep marine sediments (Wajsprych, 1978; Haydukiewicz, 1990). The succession was folded at the turn of Early/Late Carboniferous and intruded by the Variscan Kłodzko–Złoty Stok Pluton (Oberc, 1972).

Early Palaeozoic volcano-sedimentary successions of the Sudetes are accompanied by widespread orthogneisses yielding ca. 500 Ma U–Pb zircon protolith ages (Oliver et al., 1993; Kröner et al., 2001). Granitoid magmatism of this age is widespread not only in the Sudetes (Oliver et al., 1993) but also in the entire Variscan Belt (cf. Aleksandrowski et al., 2000). No consensus has been reached so far concerning the origin of this magmatic activity, which has been related either to subduction zone processes (Oliver et al., 1993; Kröner & Hegner, 1998) or to rift-related settings (e.g., Kryza & Pin, 1997). Early Palaeozoic orthogneisses are found mostly within mid- to higher grade schists and gneisses of unknown or uncertain Precambrian–Early Palaeozoic ages. In some higher-grade metamorphic complexes, e.g., in the Góry Sowie Block, there is evidence (problematic fossils, isotopic ages) that they may contain Lower Palaeozoic successions (Gunia, 2000), however in other units, e.g., in the Orlica–Śnieżnik Dome (Don, 1990) and Izera–Karkonosze Massif (Oberc-Dziedzic, 2003), there are arguments that Cambrian/Ordovician granites intruded into already deformed and metamorphosed schists and gneisses.

Lower Palaeozoic successions are documented also in several other tectonic units of the Sudetes, e.g., in the Kłodzko Metamorphic Complex and SE metamorphic envelope of the Karkonosze Pluton, however, due to the sparse biostratigraphic and geochronological control, the position of many lithological units and primary relationships between them are mostly uncertain.

Variscan orogeny. The Sudetes represent a part of the Variscan Belt assembled during Late Devonian to Early Carboniferous terrane collisions (e.g., Matte et al., 1990, Cymerman et al., 1997; Aleksandrowski & Mazur, 2002). The remnants of tectonic sutures which provide testimony of these events can still be found in the Sudetes as the dismembered ophiolite suite (e.g., Majerowicz, 1979; Pin et al., 1988; Floyd et al., 2002), extensive MORB-type metaigneous complexes (Furnes et al., 1994; Winchester et al., 1995; Kryza et al., 2003), occurrences of rocks subjected to high pressure metamorphism (e.g., Kryza et al., 1990). The presence of Variscan suture zones have been so far confirmed along the southern and eastern margins of the Karkonosze–Izera Massif (Mazur & Kryza, 1996; Seston et al., 2000; Mazur & Aleksandrowski, 2001a), in the Kłodzko Metamorphic Complex (Mazur, 2003a) and the Stare Město Belt (Schulmann & Gayer, 2000). Furthermore, a tectonic position of the Kaczawa Complex, the Sudetic Ophiolite and the Nové Město Unit suggests their close relationship to still not precisely defined tectonic sutures (Baranowski et al., 1990; Seston et al., 2000; Collins et al., 2000; Pin et al., 1988; Mazur & Aleksandrowski, 2001b).

An important hint in resolving a complex structure of the Sudetes, partly concealed beneath a sedimentary cover, is provided by metamorphic record revealed by the rock complexes of the crystalline basement, which went through various P–T–t (pressure–temperature–time) paths. The metamorphic grade differs between neighbouring geological units and, in several cases, also within particular larger tectonic assemblages juxtaposing a number of individual thrust sheets. Records of polymetamorphism and/or changing T, P conditions during metamorphism are common, confirming structural complexities of the basement. The main metamorphic events were connected with the Variscan orogeny, however, in several cases, there are arguments for earlier (Cadomian?) metamorphism: e.g., the ca. 500 Ma Izera granites intruded into already metamorphosed gneisses and schists of the Cadomian(?) basement (Oberc-Dziedzic, 2003). Particularly intriguing are the high-P and high-T granulites of the Góry Sowie Massif, dated at ca. 400 Ma (O'Brien et al., 1997) and interpreted to represent the early, Eo-Variscan stages of the orogenic evolution (Aleksandrowski et al., 2000). The high-P (and ultra-high-P) granulites and eclogites of the Śnieżnik area, apparently significantly younger (ca. 355–325 Ma, Brueckner et al., 1991; 369–360 Ma, Klemd & Bröcker, 1999; 342–341 Ma, Štipska et al., 2004) seem to have gone through different P–T–t paths. In each case, these very-high-grade metamorphic rocks are hosted by considerably lower-grade (in particular lower-P) rocks, but the mutual relationships between them are uncertain.

Medium- to low-grade metamorphic units, e.g., the Kłodzko Metamorphic Complex, display complex metamorphic patterns, reflecting changing T, P conditions in time and, additionally, tectonic juxtapositions (Wojciechowska, 1990; Kryza & Mazur, 2001; Mazur, 2003b). Two rock complexes, i.e., the E and S cover of the Karkonosze Pluton, and the Kaczawa Complex, bear evidence of high-P/T metamorphism, with earlier blueschist-facies parageneses overprinted by greenschist-facies mineral assemblages. The Kaczawa Complex, with its metasedimentary and tectonic mélanges is considered to comprise fragments of the Variscan accretionary prism (Baranowski et al., 1990; Collins et al., 2000). A few basement units of the Sudetes, e.g., the Bardo Unit and the W part of the Kaczawa Mts, display only very low-grade metamorphism, which proves their shallow tectonic burial during the orogeny. In general, temperature-dominated Late Variscan metamorphic imprint was stronger in the eastern part of the Sudetes region (Oberc-Dziedzic, 1989).

Despite its mosaic structure and imperfect exposure, the Sudetes bear records of all tectonic phases which characterize the development of a collisional orogen. The occurrences of ultra-high-P granulites and eclogites provide evidence for a crustal thickening or continental subduction at preliminary stages of collision (Kryza et al., 1996). An advanced convergence combined with a simultaneous syn-collisional uplift resulted in the development of crystalline nappe piles showing inversion of metamorphic grade (Fig. 3) and stratigraphic succession (Kryza & Mazur, 1995; Mazur & Kryza, 1996; Mazur & Aleksandrowski, 2001a; Mazur 2003b). Gravitational instability of the upper crust induced by the emplacement of nappe complexes led to the localized extensional collapse and the onset of sedimentation in intramontane sedimentary basins (Mazur & Aleksandrowski, 2001a). Furthermore, large but still not quantified strike-slip displacements along the NW–SE and N–S oriented regional-scale shear zones additionally contributed to the overall structural pattern of the Sudetes (Aleksandrowski et al., 1997). Complex interactions between accreted crustal elements gave rise to the twofold orientation of the structural grain in the Sudetes comprising the NW–SE "West Sudetic" direction and the NNE–SSW "East Sudetic" one (e.g., Aleksandrowski et al., 2000).

Folding and metamorphism were soon followed by intense granite plutonism and a subsequent uplift and volcanism. In the Sudetes, as elsewhere in the Bohemian Massif, a large number of late to post-orogenic, Variscan granitoid bodies are found, including the large massifs of Karkonosze and the Strzegom–Sobótka, and a range of smaller bodies, including those found subsurface within the NW-trending Odra Fault Zone (Majerowicz, 1972; Oberc-Dziedzic et al., 1999, and refs. therein).

There are distinct differences between the Variscan granitoids in the western part of the Sudetes and those in the central and eastern part of the area, including the Odra Fault Zone. The granitoids of the first group form large plutons (Karkonosze and Strzegom–Sobótka) composed of granites or granodiorites without or with only minor contribution (in the Strzegom–Sobótka Massif) of more basic members, such as tonalite. These granitoids are practically devoid of distinct magmatic foliation. The granitoids in the central and eastern part of the area form relatively small bodies composed not only of granites but also of tonalites and quartz diorites. The coarse-grained granodiorites of that area are characterized by the presence of pronounced magmatic or subsolidus foliations resulted from syn-intrusive shearing.

The Rb–Sr ages of the Variscan granitoids range within more than 60 Ma, from 347 Ma (biotite granite in the Strzelin Massif, Oberc-Dziedzic et al., 1996), to 280 Ma (granodiorite in the Strzegom–Sobótka Massif, Pin et al., 1989); distinctly older, ca. 380 Ma, is the Doboszowice gneiss

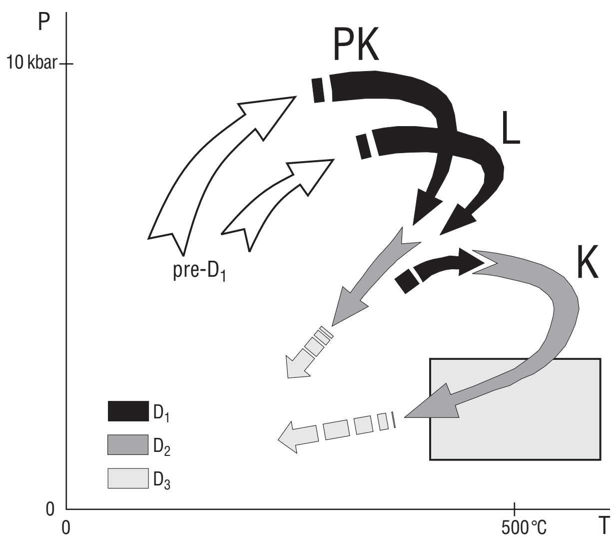

Fig. 3. Simplified P–T paths for tectonic units of the E metamorphic cover of the Karkonosze Pluton (from Kryza & Mazur, 1995). PK — South Karkonosze unit, L — Leszczyniec unit, K — Kowary unit; the shaded box — approximate extent of LP–HT metamorphism

(Kröner & Mazur, 2003). Most ages cluster around 330 Ma. Apparently similar range of ages reveal the Variscan volcanic suites in the Intra- and North Sudetic Basins (Awdankiewicz, 1999).

A post-metamorphic uplift of the Sudetes took place in a wide time span between the Late Devonian and Late Carboniferous, as documented by the stratigraphic record (Bederke, 1924; Porębski 1981) and $^{40}Ar/^{39}Ar$ cooling ages (Steltenpohl et al., 1993; Maluski et al., 1995; Marhaine et al., 2002). Its temporal and spatial diversity points to a multi-stage tectonic evolution of the Sudetes and their composite internal structure. Furthermore, the uplift history is partly mirrored by the onset and expansion of the Sudetic foreland basin which stretches out north of the Odra Fault Zone beneath thick Permo–Mesozoic sediments of the Polish Basin. The extensive sequence of the Carboniferous flysch documented by boreholes in that area reveals rapid subsidence and fast sediment accumulation from the Visean until the tectonic inversion in the Late Westphalian. Eventually, the deposition of the Stephanian to Lower Rotliegendes molasse marked the end of the Variscan orogeny.

Post-Variscan evolution. Variscan tectonic activity was eventually terminated by the overall uplift and associated widespread magmatism at the turn of the Carboniferous and Permian. A several thousand metres thick succession of the Variscan, mostly post-orogenic molasse onlapped wide areas of the Sudetes in a response to intense, deeply incised erosion. A Zechstein marine transgression that flooded the margins of the Sudetes heralded an advanced peneplanation of the former mountain range. During a major part of the Mesozoic era, the entire Sudetes remained an area of relative tectonic quiescence, elevated with respect to the neighbouring Polish Basin. This is evidenced by sedimentary gaps in the Mesozoic within the Sudetes. Tectonic activity was resumed in the Late Cretaceous, as manifested by the subsidence of pre-existing intramontane basins, formation of new tectonic graben and, consequently, deposition of a thick (up to 900 m in the Nysa Graben) Upper Cretaceous clastic and marl succession. As a result of Late Cretaceous–Paleogene inversion, the Sudetes were uplifted as a large basement block along the Odra and Elbe fault zones forming their NE and SW boundaries, respectively.

In the Paleogene, very little sediments were accumulated in the Sudetes and their surroundings as they were probably still elevated and being subject to denudation. Only in the Miocene, a thicker succession of shallow marine sands and clays containing brown coal seams partly onlapped the Sudetic basement. At the same time, narrow NW–SE elongated tectonic grabens developed along the Sudetic Boundary Fault (SBF), marking a principal period of its activity (Dyjor, 1995). Contemporaneously, basaltic volcanism was widespread throughout the area. The final uplift of the monotonous SW segment of the Sudetes, along the SBF, took place in the Pliocene and was recorded in the Sudetic foreland by sedimentation of gravels.

Important issues and achievements

The Sudetes offer research opportunities to investigate vestiges of the old Precambrian basement incorporated into Palaeozoic orogenic structures and Palaeozoic successions providing records of sedimentary and magmatic development prior to the Variscan orogeny. These issues contribute to the understanding of palaeogeographic and palaeotectonic scenarios of plates and crustal blocks (terranes?) rearrangement preceding the formation of the Variscan Belt. The posterior Variscan accretion most importantly influenced the final structure of the Sudetes and left a collage of basement units which had gone trough various P–T paths and, subsequently, become tectonically juxtaposed. Finally, late and post-orogenic evolution is well documented in the discordantly overlying cover units.

Here, we outline a selection of important current topics of geology, in particular of the basement units, where significant achievements have already been made, but where we still find research topics important for basic geological disciplines and for wide-scale tectonic models.

Pre-Variscan (meta)igneous complexes, ophiolites and palaeotectonic settings. The "bimodal volcanic suites" of Early Palaeozoic age are found in several tectonic units of the Sudetes. They display wide geochemical variations, from basites of recent within-plate type characteristics, alkaline basic and acidic rocks and, subordinately, felsic rocks of crustal geochemical imprint. The most "complete" associations of these rocks occur, e.g., in the Kaczawa Complex but members of similar suites are found also in several other units: the Kłodzko Metamorphic Complex, S and E cover of the Karkonosze Pluton, and in a poorly stratigraphically constrained position also in higher-grade metamorphic complexes (the Góry Sowie Block, Fore-Sudetic Block, Orlica–Śnieżnik Dome). The overall geochemical characteristics and Sm–Nd isotope data, together with other geological arguments, lead to a widely accepted model of extensional, most likely initial rift setting of that magmatic activity, apparently along the northern periphery of Gondwana, in Cambrian–Ordovician times.

The "initial-rift" type of metaigneous successions in a few basement units are juxtaposed with predominantly mafic metaigneous rocks displaying transitional- to N–MORB characteristics, including high E–Nd values, typical of recent ocean-floor basalts. They are thought to represent younger (mostly Silurian or Devonian?) magmatism, but their age is, in most cases, poorly constrained. The best examples are known from the Kaczawa Complex and E metamorphic envelope of the Karkonosze Pluton. In both areas, they are interpreted to have been emplaced in a mature rift setting, and to form higher thrust/nappe units. The regional distribution of these rocks is considered by some authors to trace major tectonic sutures (Seston et al., 2000; Mazur & Aleksandrowski, 2001a, b).

The Sudetic ophiolite assemblages are among best preserved and complete ophiolitic suites in the Variscan Belt. The fairly large ultramafic-mafic complexes along the NE, E and S margins of the Góry Sowie Block were first recognized as ophiolites in the late 1970s (Majerowicz, 1979) based on general petrographic features, while later reported geochemical data indicated their MORB affinity. More recent geochemical studies revealed some internal complexities of the suites, e.g., significant geochemical contrast between the plutonic and subvolcanic/volcanic members (Fig. 4), but overall confirmed their MOR–type

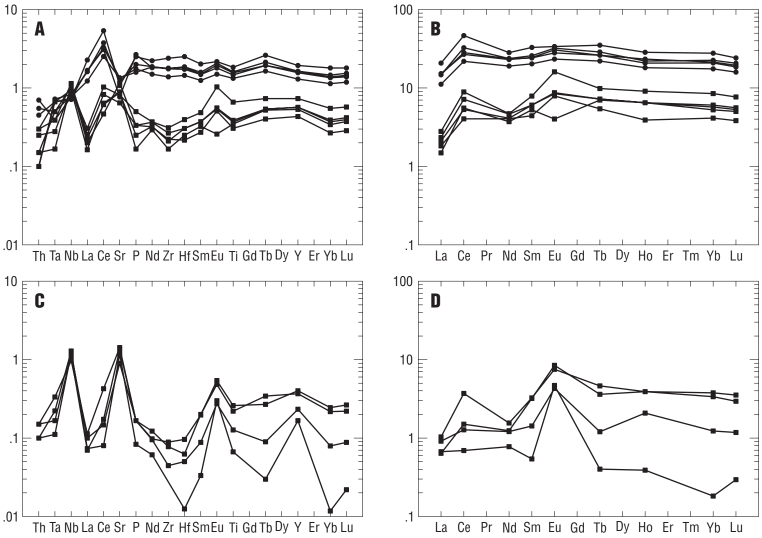

Fig. 4. Mafic rocks of Mt. Ślęża plotted on multi-element variation diagrams. Squares — plutonic group, circles — subvolcanic/volcanic group. Left-hand column — incompatible trace-elements normalised to MORB; right-hand side column — REE normalised according to Sun (1980); A & B — metabasalts and metadiabases (higher plots) and metagabbros of the upper part of the plutonic assemblage (lower plots), C & D — mafic cumulates (based on Kryza & Abdel Wahed, 2000 — *vide* Floyd et al., 2002)

characteristics (Pin et al., 1988; Majerowicz & Pin, 1994; Floyd et al., 2002, and refs. therein). The magmatic emplacement age of the ophiolites was previously determined at ca. 353 Ma using the Sm–Nd isochrone method (Pin et al., 1988) but afterward reinterpreted to ca. 420 Ma based on U–Pb multigrain zircon method (Oliver et al., 1993). The latest ages of 400 +4/–3 Ma on zircons from rodingites have been interpreted as corresponding to serpentinization processes (Dubińska et al., 2004). The mafic rocks of the ophiolites are usually weakly and locally deformed and display only partial metamorphic alteration. The provenance of the ophiolitic suites, their age and relationships to other igneous complexes, as well as their tectonic position are key problems of this part of the Variscan orogen. Mierzejewski (1993) suggested that the Ślęża ophiolite lies on top of a westward overthrust pile of tectonic units.

Granulites, eclogites and blueschists. The Variscan tectonic movements exhumed rocks from deep crustal levels which experienced high-P and, some of them also high-T metamorphism. These rocks are themselves of particular interest for petrologists, as natural samples of the deep crust and extreme metamorphic conditions. The information recorded in their P–T–t paths is also important for tectonic models, giving evidence of subduction and subsequent large-scale exhumation of continental crust.

The well known granulites (and associated ultramafics) of the Góry Sowie Block experienced granulite-facies peak conditions of ca. 15–20 kbar [1.5–2.0 GPa] at up to 1000°C (Kryza et al., 1996) that correspond to a depth of around 50 km below the Earth surface. That HP–HT metamorphic event was timed at ca. 400 Ma using U–Pb zircon method (O'Brien et al., 1997). These deep-crustal rocks seem to represent considerably higher P–T conditions compared with those of the surrounding gneisses and migmatites, although recent studies indicated also relatively high P and T for the latter rocks (Kryza & Pin, 2002; Fig. 5). A tectonic position of the granulites inliers still remains uncertain and requires further studies.

The eclogites of the Śnieżnik Massif became a classical example of these intriguing metamorphic rocks after the detailed petrographic studies by Smulikowski (1967). They comprise typical eclogites and transitional eclogite-granulites (locality Stary Gierałtów), the latter having thermobarometric evidence of ultrahigh-P and high-T conditions estimated at more than 20–30 kbar [2–3 GPa] at around 900–1000°C (Bakun-Czubarow, 1998; Kryza et al., 1996). The age of the eclogite-facies metamorphism is still debatable (ca. 325–355 Ma Sm–Nd isochron by Brückner et al., 1991), as is the geological position of the UHP rocks in relation to the surrounding gneisses (Don, 1990; Szczepański & Anczkiewicz, 2002). More recently, relics of eclogite facies rocks were also found in the Fore-Sudetic Block (Achramowicz et al., 1997), thus demonstrating a wider distribution of eclogites in the Sudetes than was previously known.

Similarly important both for petrologic considerations and for large-scale tectonic interpretations are blueschist facies rocks of the West Sudetes: in the Kaczawa Complex and in the S and E metamorphic cover of the Karkonosze Pluton. In the Kaczawa Complex, the evidence of an early high P/T metamorphic event is evidenced by relict jadeite in felsic lavas, zoned metamorphic amphiboles, with earlier glaucophane rimmed by subsequent actinolite, and zoned white micas, with Si-rich grain cores. The P–T conditions for that early metamorphic stage were estimated at more than ca. 10 kb [1 GPa] and 350 °C, and for the later greenschist facies overprint at below 6–8 kb [0.6–0.8 GPa] and ca. 400 °C (Kryza et al., 1990). The high-P/T conditions were confirmed by white mica XRD studies in apparently weaker metamorphosed mélanges where b_0 and IC parameters correspond to micas from accretionary and Alpine-orogenic settings (Kryza & Muszyński, 2003, and refs. therein).

The blueschist facies rocks of the S and E envelop of the Karkonosze Pluton represent possibly a somewhat higher metamorphic grade (garnet in the paragenesis; Fig. 3). The sequence of the blueschist- and subsequent greenschist facies events in that area was dated at 360 and 340 Ma, respectively, using the $^{40}Ar/^{39}Ar$ method (Maluski & Patočka, 1997). The presence of the HP–LT rocks support the hypothesis that in the Sudetes we are dealing with rock

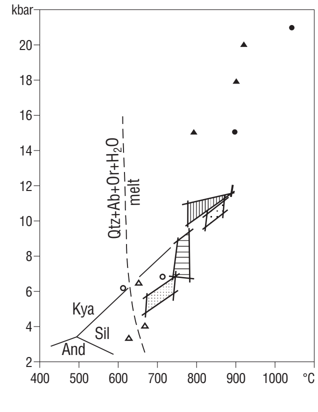

Fig. 5. P–T paths for the Góry Sowie granulites, migmatites and metagabbro-norites (from Kryza & Pin, 2002). Felsic granulites — triangles, CPx — bearing granulites — circles (closed symbols — cores, open symbols — rims); migmatites: coarse dots — core compositions, fine dots — rim compositions; metagabbro-norites: vertical hatching — massive center of intrusion, horizontal hatching — foliated margin of intrusion

assemblages of fossil accretionary margins presently preserved within collisional tectonic sutures.

Nappe tectonics and terrane concepts in the Sudetes. A nappe structure, representing one of key features of orogenic belts, was recognized practically within all segments of the European Varscides (e.g., Matte et al., 1990). Likewise in the Sudetes, the earliest concepts of nappe tectonics date back to the beginning of the 20th century. A nappe structure of the East Sudetes, together with the entire eastern margin of the Bohemian Massif, has not been questioned since the pioneering work of Suess (1912). In the West Sudetes, their mosaic structure partly obscured features characteristic of crystalline nappe complexes, the presence of which was more slowly emerging from geological literature (e.g., Kodym & Svoboda, 1948; Teisseyre, 1963; Oberc, 1972). Therefore, despite the early development, nappe concepts remained mostly abandoned in the West Sudetes until the mid-1990s. A new chapter of structural studies on the nappe tectonics of the Sudetes has been commenced since then, which resulted in qualitatively original interpretations for the Karkonosze–Izera Massif (Mazur, 1995; Mazur & Kryza, 1996; Mazur & Aleksandrowski, 2001a, b), Kaczawa Complex (Collins et al., 2000; Seston et al., 2000), East Sudetes (Schulmann & Gayer, 2000) and Kłodzko Metamorphic Complex (Mazur, 2003b).

The southern and eastern Karkonosze–Izera Massif exposes blueschist facies rocks and MORB–type magmatic complexes. During the Late Devonian to Early Carboniferous times, these were overthrust within a nappe pile toward the NW onto the pre-Variscan Saxothuringian basement of the Izera–Kowary metagranitoids and their envelope (Fig. 6). The lowermost nappe (or parautochthonous?) unit of the pile is the low grade metamorphosed Ještěd complex, a Devonian to Early Carboniferous sedimentary succession of the Saxothuringian passive margin. This is tectonically overlain by the South Karkonosze complex, which represents Ordovician–Silurian volcano-sedimentary infill of the Saxothuringian Basin, affected by Late Devonian HP/T metamorphism. The uppermost nappe is the Early Palaeozoic epidote-amphibolite grade Leszczyniec MORB-like complex, cropping out on the eastern margin of the Karkonosze–Izera Massif. It probably represents a fragment of obducted Saxothuringian basin floor. The nappe pile was stacked beneath the overriding upper plate margin, now concealed below the Intra-Sudetic Basin and hypothesized to represent a fragment of the Teplá–Barrandian Terrane. The final stages of the NW-ward nappe stacking were accompanied and followed by SE-directed Early Carboniferous extensional collapse

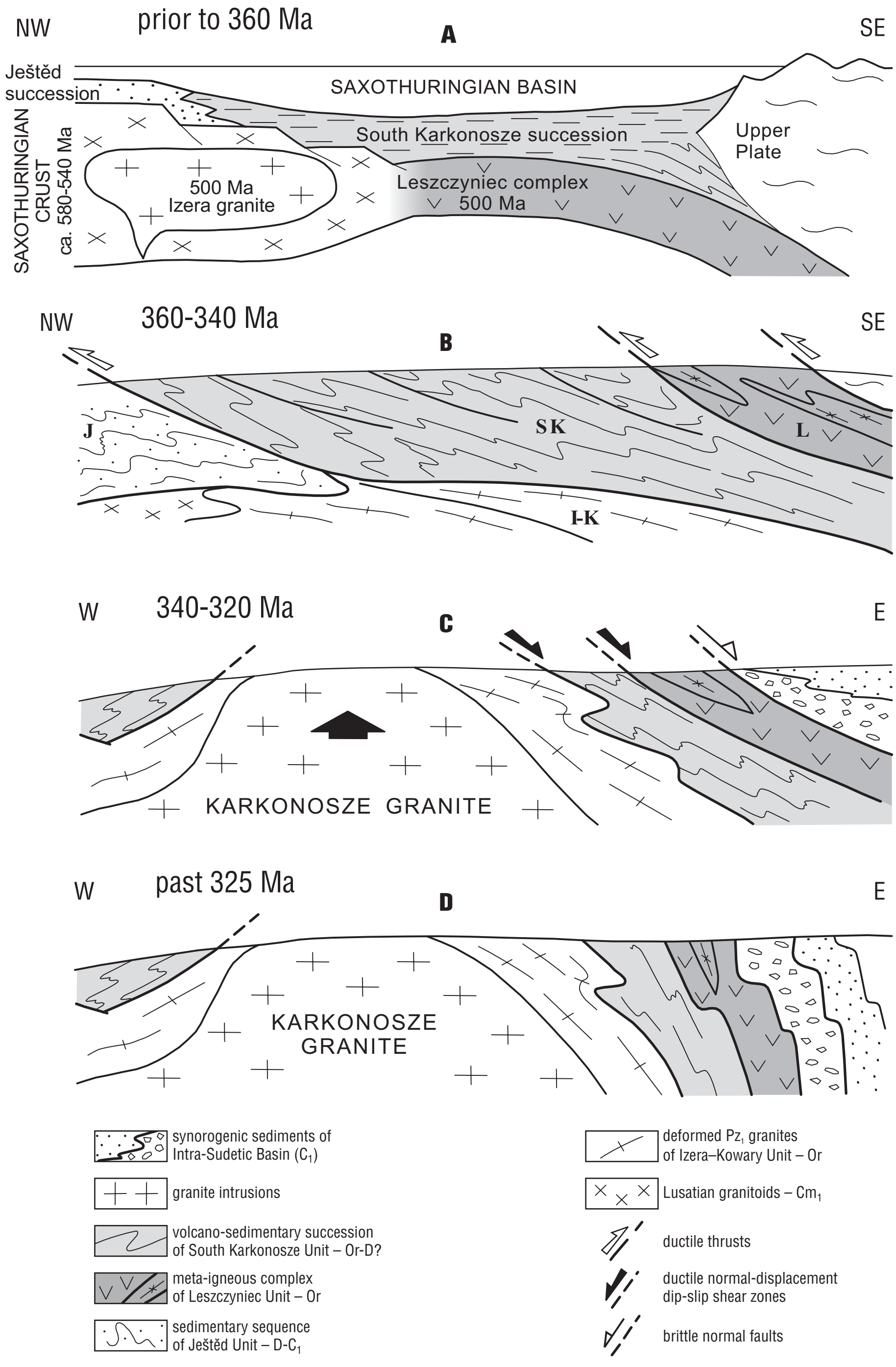

Fig. 6. Late Devonian to Carboniferous structural evolution of the Karkonosze–Izera Massif leading to the formation of a suture zone and nappe structure (vertically exaggerated schematic model). A — schematic palinspastic restoration of the S and E Karkonosze tectonic units prior to the overthrusting event (inspired by W. Franke's reconstructions of the Saxothuringian Zone); B — NW-ward overthrusting event. C — top-to-ESE extensional collapse followed by intrusion of the Karkonosze granite; D — development of the East Karkonosze flexure (after Mazur,

(Fig. 6). The lower plate of the suture zone was uplifted at that time and intruded by the ca. 330 Ma old, nearly undeformed Karkonosze granite pluton. As a result of the collapse, the Teplá–Barrandian(?) upper plate was downthrown on shear zones and brittle faults and buried under the several km-thick syn-orogenic Visean through Namurian and post-orogenic Late Carboniferous–Early Permian succession of the Intra-Sudetic Basin.

The Kłodzko Metamorphic Complex (KMC = KU in Fig. 1) is generally divided into two parts with different lithology and metamorphic grade. The NE part mostly comprises metasedimentary and metavolcanic rocks, which are ascribed to three individual tectonic units metamorphosed under greenschist to epidote–amphibolite facies conditions. Their protoliths comprised various rock associations emplaced in different palaeogeographic settings, including shelf, initial rift, and continental slope environments. Although only the lowermost unit is palaeontologically dated as Middle Devonian (Hladil et al., 1999), a Palaeozoic age is tentatively assumed for the whole NE part of the KMC. The latter is overlain by another three tectonic elements containing geochronologically dated amphibolite-grade fragments of the Neoproterozoic crust (Mazur et al., 2003) that form the SW part of the KMC. The tectonic units comprised in the KMC are interpreted as thrust sheets within a nappe pile assembled at the turn of the Middle and Late Devonian due to the WNW-directed tectonic transport. A nappe structure of the KMC is characterized by the occurrence of increasingly higher tectonic units from the west to east (Mazur, 2003b) and by a tectonic inversion of the metamorphic P–T conditions (Kryza & Mazur, 2001). The whole KMC rests upon the Nowa Ruda Massif considered a part of the dismembered Sudetic Ophiolite, and is transgressively onlapped by the non-metamorphosed upper Frasnian to Fammenian limestones (Bederke, 1924; Kryza et al., 1999) forming the base of the Upper Devonian–Carboniferous succession of the Bardo Basin (Haydukiewicz, 1990).

The KMC exemplifies the complex evolution of the different terranes presently comprised in the Variscan Belt. Its Neopretorozoic succession was originally developed by Cadomian subduction beneath the northern Gondwana margin (Kryza et al., 2003). The Neoproterozoic crust was subsequently onlapped by the Early Palaeozoic to Devonian volcano-sedimentary succession, which developed on a passive continental margin. The latter is probably represented by tectonic units comprised in the NE part of the KMC. At the turn of the Middle and Late Devonian times, the protoliths of the KMC, including both the Neoproterozoic, mostly igneous suites and their Palaeozoic volcano-sedimentary cover, must have been tectonically juxtaposed. By the end of the Late Devonian, the tectonic units were exhumed as a nappe pile and, finally, thrust over the adjacent Nowa Ruda ophiolite (Mazur, 2003b).

Rapidly growing amount of structural, petrological and geochronological data highlighted important contrasts between the provenance and evolution of different parts of the Sudetes. These dissimilarities can be readily explained on the ground of terrane interpretations which have been initiated by the innovative paper of Matte et al. (1990). A continuing discussion on the terrane subdivision of the Sudetes soon resulted in a number of partly alternative solutions (e.g., Narebski, 1992; Cymerman et al., 1997; Franke & Żelaźniewicz, 2002; Aleksandrowski & Mazur, 2002), the systematic presentation of which far exceeds the scope of this paper. Therefore, only one recent terrane model is presented below (Aleksandrowski & Mazur, 2002) to illustrate the complexity of a tectonic collage cropping out in the Sudetes. This interpretation grows up from the original proposal of Matte et al. (1990) and fits well though not perfectly to available geological data (Fig. 7).

The Sudetic segment of the Variscan Belt is interpreted by Aleksandrowski and Mazur (2002) as having formed by the accretion of five major and two or three minor terranes (Fig. 7). From west to east, the major terranes are: (1) Lusatia–Izera Terrane exposing Armorican continental basement reworked by Ordovician plutonism and Late Devonian–Carboniferous collision, showing Saxothuringian affinities; (2) composite Góry Sowie–Kłodzko Terrane characterized by polycyclic evolution (Silurian

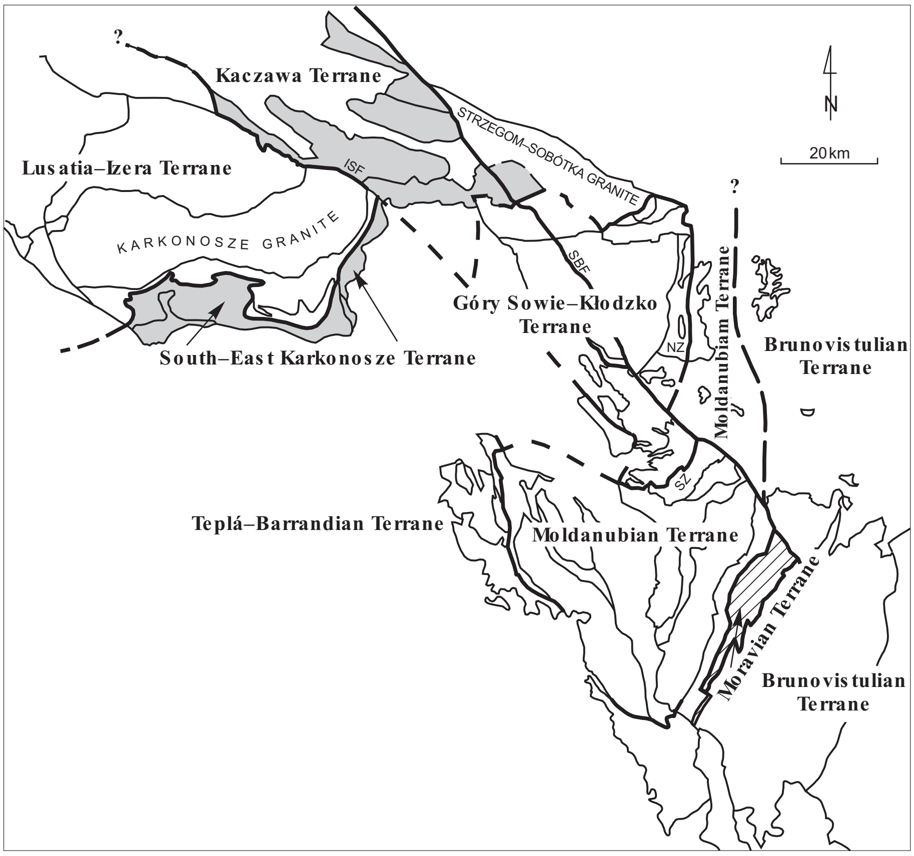

Fig. 7. Tectonostratigraphic terranes in the Sudetes (after Aleksandrowski & Mazur, 2002). ISF — Intra-Sudetic Fault, NZ — Niemcza Shear Zone, SBF — Sudetic Boundary Fault, SZ — Skrzynka Shear Zone.

subduction, Mid- to Late Devonian collision, exhumation and extension, Carboniferous deformational overprint), with analogues in the NE Massif Central and Armorica; (3) Teplá–Barrandian Terrane distinguished to incorporate in its Sudetic segment the Nové Město Unit and the SW part of the basement of the Intra-Sudetic Basin; (4) Moldanubian (Gföhl) Terrane comprising Orlica–Śnieżnik and Kamieniec massifs, affected by Early Carboniferous high-grade metamorphism and exhumation and (5) Brunovistulian Terrane in the East Sudetes, set up on Avalonian crust and affected by Devonian to Late Carboniferous sedimentation, magmatism and tectonism. The major terranes are separated by two smaller ones squeezed along their boundaries: (1) Moravian Terrane, between the Moldanubian and Brunovistulian, deformed during Early Carboniferous collision, and (2) South–East Karkonosze Terrane of affinities to the Saxothuringian oceanic realm, sandwiched between the Lusatia–Izera and Góry Sowie–Kłodzko (together with Teplá–Barrandian) terranes, subjected to HP-metamorphism and tectonised due to Late Devonian–Early Carboniferous convergence. The Kaczawa Terrane in the NW, of oceanic accretionary prism features, metamorphosed and deformed during the latest Devonian–Early Carboniferous (?) times, may either be a distinct unit unrelated to closure of the Saxothuringian Ocean or represents a continuation of the South-East Karkonosze Terrane.

Timing of events and selected geochronological problems. Two research topics involving intense geochronological investigations have recently focused wide scientific interest: (a) Neoproterozoic basement units, comprising old granitoids usually transformed into orthogneisses, mylonites and less commonly migmatites, usually yielding inheritance of older materials (e.g., inherited zircons), and usually showing rather obscure relationships to the widespread products of Cambro–Ordovician granitoid plutonism; (b) metamorphic events and other deep crustal processes culminated in the exhumation of basement units during the Variscan orogeny.

Neoproterozoic, Cambro–Ordovician and Variscan granitoids. The group of Neoproterozoic granitoids is represented by the Lusatian granodiorites (ca. 540–530 Ma; Tikhomirova, 2002) exposed in the western part of the Sudetes, and often correlated with the Saxothuringian Terrane (Franke & Żelaźniewicz, 2002; Aleksandrowski & Mazur, 2002). The Lusatian granodiorites were derived from greywackes with a minor contribution from the mantle (Tikhomirova, 2002, and refs. therein). They are only weakly affected by Variscan deformation.

Neoproterozoic granites were also the protolith of the Strzelin gneiss considered a part of the Brunovistulian Terrane (Oberc-Dziedzic et al., 2003a; Aleksandrowski & Mazur, 2002). The Strzelin gneiss yields two distinct mean ages of ca. 600 Ma and ca. 568 Ma (Oberc-Dziedzic et al., 2003a) interpreted as the age of magmatic protolith and subsequent metamorphic dissolution and/or anatectic resorption. The Strzelin gneiss is an equivalent of the Keprnik gneiss (ca. 584 Ma, Oberc-Dziedzic et al., 2003a, and refs. therein) from the East Sudetes on the Czech territory. Both gneisses show not only comparable ages but they are also geochemically similar, representing K-rich granitoids.

Another group of gneisses and migmatites cropping out in the Sudetes was derived from Cambro–Ordovician granitoids. Two large exposures of these rocks, in the Karkonosze Izera Massif and in the Orlica–Śnieżnik Dome, were geochronologically studied, and the age of ca. 500 Ma of main rock varieties was confirmed using various methods (Borkowska et al., 1980, 1990; van Breemen et al., 1982; Oliver et al., 1993; Kröner et al., 2000, 2001; Turniak et al., 2000).

The Izera granites intruded the Neoproterozoic Lusatian granodiorites. Furthermore, the age of zircon xenocrysts and Nd mean crustal residence ages from the Lusatian granodiorites (2795–620 Ma) and the Izera gneisses (granites) (2070–546 Ma, 1.34 and 1.87 Ga; Tikhomirova, 2002) are different, indicating probably different magma sources. The relatively high $^{87}Sr/^{86}Sr$ initial ratio of 0.7090 ±0.0013 (Borkowska et al., 1980), the presence of magmatic cordierite and relict garnet and sillimanite, the lack of mafic enclaves in the granites and the lack of coexistening tonalites and diorites within the Izera granites support their crustal origin; this is in contrast with the biotite Lusatian granodiorites, with $^{87}Sr/^{86}Sr$ initial ratio 0.704–0.706 (Tikhomirova, 2002, and refs. therein), interpreted to have derived from mixed crustal-mantle source.

In the Strzelin Massif, the ca. 500 Ma gneisses are represented by the augen Gościęcice gneiss (ca. 504 Ma; Oliver et al., 1993) and the light Stachów gneiss (ca. 500 Ma; Oberc-Dziedzic et al., 2003b), similar to the Izera or Śnieżnik gneisses. The age of inherited zircon cores (between ca. 1916, 636, and 560 Ma) in the light Stachów gneiss is different from that revealed by cores of inherited zircons (1230–1870 Ma) in the Strzelin gneiss. It suggests that the Neoproterozoic gneiss could not be the source material for the ca. 500 Ma gneiss. The contact between the two gneisses is tectonic. The ca. 500 Ma gneisses were thrust onto the Neoproterozoic gneiss and on its metamorphic envelope along the so-called Strzelin Thrust which could be a part of the boundary between the East and West Sudetes (Oberc-Dziedzic & Madej, 2002). If this supposition is correct, the ca. 500 Ma gneisses in the Strzelin Massif represent a part of the Saxothuringian Terrane tectonically juxtaposed against the Brunovistulian Terrane.

The third, youngest, Variscan group of granitoids (ca. 347–280 Ma) intruded various parts of the Sudetes. Despite being metaluminous or peraluminous, they are characterised by relatively low initial ratio of $^{87}Sr/^{86}Sr = 0.705–706$ (Duthou et al., 1991; Pin et al., 1989; Oberc-Dziedzic et al., 1996) suggesting that they evolved from low $^{87}Sr/^{86}Sr$ precursors and escaped significant crustal contamination (Oberc-Dziedzic et al., 1996). It may mean that none of them resulted from the reworking and melting of any of the gneisses exposed in the region (Kennan et al., 1999). More basic granitoids: tonalite, granodiorite and quartz diorite, show different values of initial ratio $^{87}Sr/^{86}Sr$. It could be caused by contamination of the juvenile magma by an older crustal material (Oberc-Dziedzic et al., 1996).

The reported results suggest that the three age groups of the Sudetic granitoids, inspite of their recent spatial links, are genetically unrelated and derived from different sources. Better verification of that hypothesis requires further investigations.

Timing of metamorphism and exhumation. The stratigraphic evidence acquired over the past decades suggested a multi-stage metamorphic and uplift history of the Sudetes in Variscan times (cf. Aleksandrowski et al., 2000). It is enough to mention that the occurrence of non-metamorphosed Upper Devonian strata, uncomformably overlying the metamorphic basement of the Kłodzko Metamorphic

Complex (Bederke 1924), was considered for a long time one of key arguments in favour of Caledonian tectonism in the Sudetes (e.g., Teisseyre, 1963). Although the recent palaeontological data of Hladil et al. (1999) demonstrated that the Kłodzko Complex must have been tectonized after the early Givetian, the pre-Upper Devonian unconformity still documented its early uplift (Kryza et al., 1999, and refs. therein) ascribed by Aleksandrowski et al. (2000) to the initial Eo-Variscan convergence. This concept is essentially consistent with numerous geochronological data obtained over the past twenty years in the adjacent Góry Sowie Massif. The granulite-facies metamorphism dated at 401.5 ±0.9 Ma (O'Brien et al., 1997) was soon followed in that area by a rapid decompression to amphibolite facies conditions. The latter temperature dominated metamorphism took place between ca. 400 and 370 Ma (Timmerman et al., 2000; Żelaźniewicz, 2003) and was eventually terminated by the exhumation of the Góry Sowie gneisses. The gneisses must have been at the surface by the end of Devonian since they already supplied detritus to the neighbouring Świebodzice Basin (Porębski, 1981). Nevertheless, at the present erosional level, the Góry Sowie gneisses bear also a mark of a younger Early Carboniferous thermal event mostly related to the widespread mylonitization, especially in the adjacent Niemcza Zone (D. Schneider — pers. com. to S.M., 2004; Steltenpohl et al., 1993). Indeed, this Early Carboniferous post-metamorphic cooling in the range of 340–320 Ma appears to be the characteristic feature of the entire West Sudetes (e.g., Marhaine et al., 2002). In the metamorphic nappes of the SE Karkonosze–Izera Massif, it was preceded by the HP blueschists facies metamorphic event dated at minimum at 360 Ma (Maluski & Patočka, 1997). Interestingly, post-metamorphic cooling ages become considerably younger towards the East Sudetes, where they indicate mostly Late Carboniferous uplift (e.g., Maluski et al., 1995; Szczepański, 2002). At the present state of knowledge, the Orlica–Śnieżnik Dome remains the most puzzling element of the Sudetic mosaic in terms of timing of its thermal evolution. During the last 15 years, a vast majority of authors have pointed out not only to the Early Carboniferous cooling of the Orlica–Śnieżnik Dome between ca. 340 and 330 Ma (e.g., Steltenpohl et al., 1993; Maluski et al., 1995; Marhaine et al., 2002) but also to its almost synchronous HT metamorphism (Turniak et al., 2000; D. Schneider — pers. com. to S.M., 2004) or even eclogite- and granulite-grade metamorphism (Brückner et al., 1991; Štipska et al., 2004). On the other hand, an increasing number of data seems to reveal an isotopic signature of a much older thermal event tentatively estimated at ca. 380 Ma (Borkowska et al., 1990; Klemd & Bröcker, 1999; R. Anczkiewicz, M. Bröcker, D. Schneider — pers. com. to S.M., 2004). If these preliminary data are confirmed, they will shed a new light on the tectonic position of the UHP rocks in the Orlica–Śnieżnik Dome.

Conclusion: Selected research problems for further study

Summing up our review of the history and selected problems of geology in the Sudetes, we list a range of issues worth future studies and important for better understanding the geological evolution of that area, within the context of the Central European Variscides. The key research targets can be grouped into the following topics:

❑ Cadomian basement: distribution of Neoproterozoic basement units and their position in the Variscan collage.

❑ Pre-Variscan Palaeozoic scenario: sedimentary and magmatic suites, their ages and emplacement settings (combining sedimentological, stratigraphic, petrological and geochemical studies).

❑ Variscan orogeny: location of major tectonic units and sutures (e.g., position of ophiolites and HP rocks), structural and metamorphic evolution of the basement units, exhumation of deep-crustal rocks.

❑ Late- and post-orogenic evolution: late-orogenic tectonics, magmatism and sedimentation, platform-stage development.

Evidently, effective progress of the studies would require an interdisciplinary approach and collaboration of specialists from various fields of geological sciences, applying modern research methods, e.g., of structural geology, petrology, geophysics and geochronology. This could be achieved through the further development of inter-laboratory cooperation and undertaking joint multilateral projects.

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