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Collage tectonics in the northeasternmost part of the Variscan Belt: the Sudetes, Bohemian Massif

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Abstract: A synthesis of published and new data is used to interpret the Sudetic segment of the Variscan belt as having formed by the accretion of four major and two or three minor terranes. 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 multistage evolution (Silurian subduction, mid- to late Devonian collision, exhumation and extension, Carboniferous deformational overprint), with analogues elsewhere in the Bohemian Massif, Massif Central and Armorica; (3) Moldanubian (Gföhl) Terrane comprising the Orlica-Śnieżnik and Kamieniec massifs, affected by Early Carboniferous high-grade metamorphism and exhumation and (4) Brunovistulian Terrane in the East Sudetes, set up on Avalonian crust and affected by Devonian to late Carboniferous sedimentation, magmatism and tectonism. The main 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) SE 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 high pressure-metamorphism and tectonized during Late Devonian–Early Carboniferous convergence. The Kaczawa Terrane in the NW, of oceanic accretionary prism features, metamorphosed and deformed during latest Devonian–Early Carboniferous times, may either be a distinct unit unrelated to closure of the Saxothuringian Ocean or represent a continuation of the SE Karkonosze Terrane.

The Variscan Belt of central Europe, together with the adjoining fragment of the Trans-European Suture Zone defines a composite tectonic collage finally assembled during the Carboniferous. It comprises units derived from Avalonia, from the Armorican Terrane Assemblage and others of uncertain (northern Gondwana?, Baltica?) provenance (e.g. Pharaoh 1999; Belka *et al.* 2000; Franke 2000; Tait *et al.* 2000, Aleksandrowski *et al.* 2000; Winchester & PACE 2002). One of its key fragments, of as yet poorly constrained geological structure and evolution, is the northeasternmost segment of the Variscides: the Sudetes area in southwestern Poland and northern Bohemia. Geologically, the area is located on the NE margin of the Bohemian Massif; it shows a complex structure consisting of a mosaic of geologically distinct, fault-bounded pre-Permian units affected by contractional, strike-slip and extensional tectonics and characterized by abrupt changes in the dominant structural trends. The apparently independent geological evolution of most geological units in the Sudetes, combined with the occurrence of ophiolitic bodies along some of their boundaries, or of igneous rocks with MORB-type geochemical signature, as well as of high pressure (HP) metamorphic rocks (blueschists and eclogites) strongly suggests that the area comprises a number of distinct tectonostratigraphic terranes, separated by tectonic sutures and major faults/shear zones. A possible terrane arrangement in this region was a matter of a lively discussion during the last decade (Matte *et al.* 1990; Aleksandrowski 1990, 1995; Oliver *et al.* 1993; Cymerman & Piasecki 1994; Franke *et al.* 1995*a*; Cymerman *et al.* 1997; Franke & Żelaźniewicz 2000). We reassess the evidence published to date and combine it with our new data from several Sudetic units. An updated terrane model of the Sudetes is proposed, based on the assumption that most of the main tectonic units known from elsewhere in the Variscan Belt continue into this area. It rejects some and modifies other previous terrane concepts. In conclusion, a possible setting for accretion of the Sudetic terranes is given. We identify and discuss many unsolved problems of Sudetic/Variscan geology, the answers to which may significantly improve knowledge of the tectonic structure and evolution of the Variscan Belt of central Europe.

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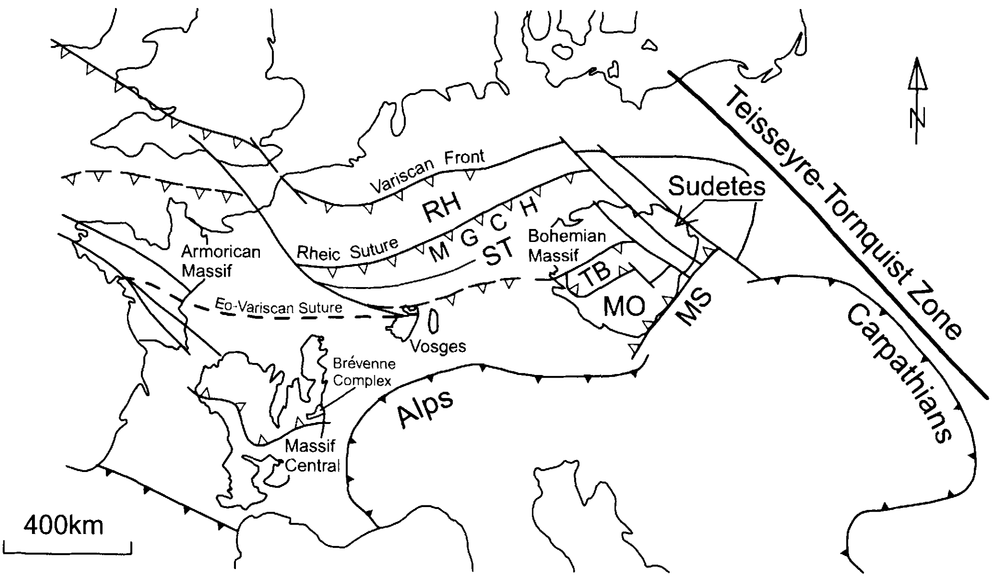


Fig. 1. Tectonic setting of Sudetes in the Variscan Belt. MGCH, Mid-German Crystalline High; MO, Moldanubian; MS, Moravo-Silesian; RH, Rhenohercynian; ST, Saxothuringian; TB, Tepla-Barrandian.

Tectonic setting

The Sudetes, a mountainous area on the northern margin of the Bohemian Massif, together with the southern part of the Silesian-Lusatian Plain (in the geological sense collectively termed here the Sudetic region or, simply, the Sudetes), represents the northeasternmost outcropping segment of the Central European Variscan Belt (Figs 1 and 2) and exposes strongly deformed and metamorphosed complexes of the Variscan internides. To the NE, across the Middle Odra Fault Zone, these complexes adjoin Carboniferous unmetamorphosed flysch and molasse succession of the Variscan externides, buried below the thick Permo-Mesozoic sequence of the German–Polish Basin and underlain by a poorly documented Devonian and low-grade metamorphosed Lower Palaeozoic basement (Grad *et al.* 2002). The Variscan externides and their basement merge into the Trans-European Suture Zone, a broad and complex zone of Palaeozoic terrane accretion separating the Phanerozoic lithosphere of central and eastern Europe from the Precambrian East European Platform (Pharaoh 1999).

The Sudetic region extends between the WNW–ESE trending Middle Odra Fault Zone in the NE and the parallel Elbe Fault Zone in the SW (Fig. 2). To the SE, it approaches the Miocene Carpathian Front and to the NW it merges with the Lusatian Massif. The area is usually divided into the West Sudetic domain or Lugicum (Suess 1926), with prevailing NW–SE structural trends and a smaller, East Sudetic domain (partly equivalent to Suess's Silesicum) with predominantly NNE–SSW structures. The West Sudetic, Lugian domain reveals complex geology, consisting of a variety of distinct, fault-bounded Palaeozoic tectonic units with usually unclear mutual geometrical and genetic interrelationships. It is bisected by a prominent WNW–ESE to NW–SE fault zone, the Intra-Sudetic Fault, parallel to the Middle Odra and Elbe Faults. In this paper, we concur with some workers (e.g. Teisseyre *et al.* 1957) and distinguish the eastern part of the Lugian domain as the Central Sudetes, to account for its distinct geological features. The East Sudetes, located further to the SE and east, show a generally regular, zonal geological structure with dominant trends roughly at right angles to those prevailing in the West and Central Sudetes.

The NW–SE trending Sudetic Boundary Fault divides the Sudetes into the Sudetic mountains in the south and the Sudetic foreland in the north; this topographically based distinction is the result of Late Tertiary (Alpine) uplift of the southern side of the fault. The depositional, magmatic and deformational evolution of the main structural units of the Sudetes is summarized diagrammatically in Figure 3 and the distribution of these units is shown in Figure 2.

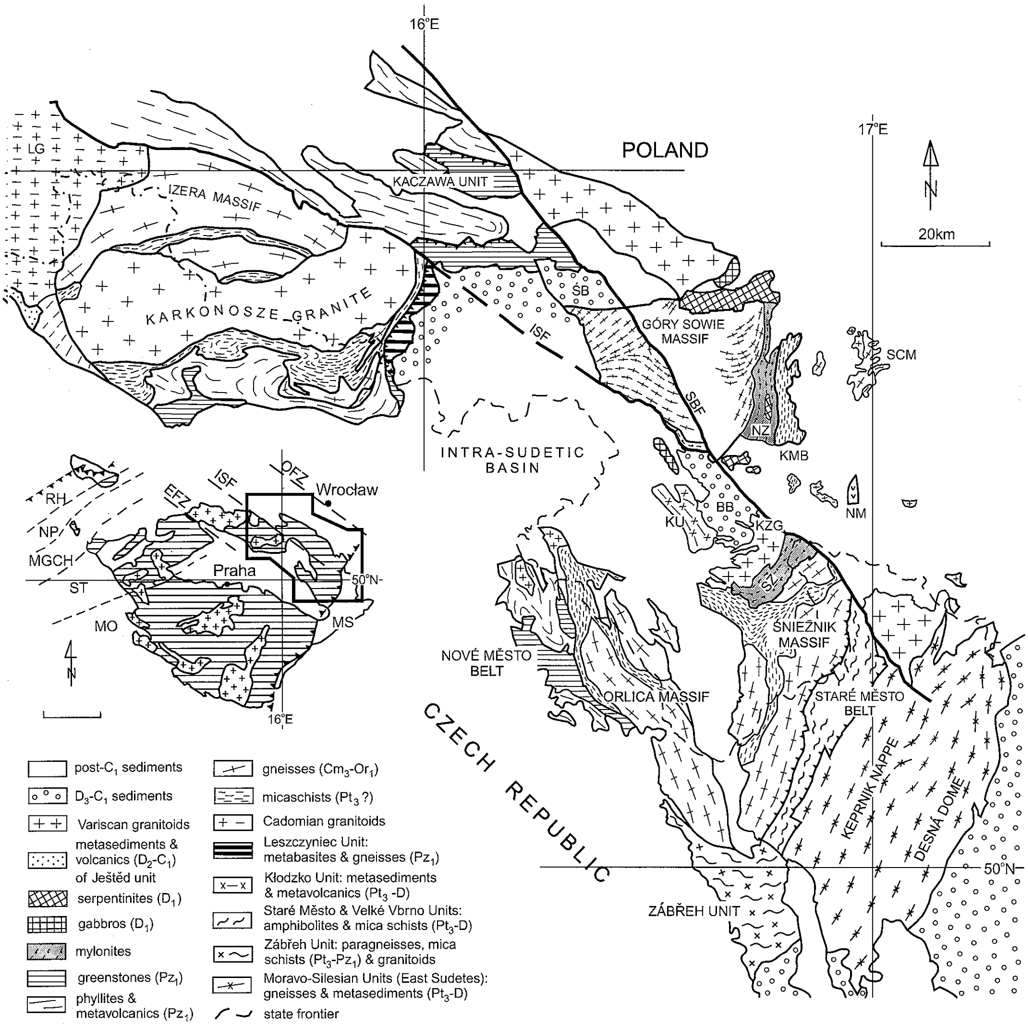


Fig. 2. Geological sketch map of the Sudetes. BB, Bardo Basin; EFZ, Elbe Fault Zone; ISF, Intra-Sudetic Fault; KMB, Kamieniec Metamorphic Belt; KU, Kłodzko Metamorphic Unit; KZG, Kłodzko, Złoty Stok Granite; LG, Lustian Granitoid Massif; MGCH, Mid-German Crystalline High; MO, Moldanubian Zone; NM, Niedźwiedź Massif; NP, Northern Phyllite Zone; NZ, Niemcza Shear Zone; OFZ, Odra Fault Zone; RH, Rhenohercynian Zone; RT, Ramzová Thrust; ŚB, Świebodzice Basin; SBF, Sudetic Boundary Fault; SCM, Strzelin Crystalline Massif; ST, Saxothuringian Zone; SZ, Skrzynka Shear Zone. *Age assignments*: Pt, Proterozoic; Pz,Palaeozoic; Cm, Cambrian; Or, Ordovician; D, Devonian; C, Carboniferous; $_1$, early; $_2$, middle; $_3$, late.

A controversy has persisted since the 1920s as to whether the West and Central Sudetes are an extension of the Saxothuringian Zone of the German Variscides (Kossmat 1927) or pertain to a distinct crustal domain, referred to as Lugicum (Suess 1926; Stille 1951). The East Sudetes have been included in the Moravo-Silesian Zone of the Variscides (Suess 1912, 1926), which is often believed either to continue into the Rhenohercynian Zone in Germany (e.g. Engel & Franke 1983; Franke 1989) or to represent a fragment of a separate, SE branch of the Variscan Belt (e.g. Dvořák & Paproth 1969; Matte 1986, 1991). The Moravo-Silesian Zone is underlain by crystalline Cadomian basement of the Brunovistulian Block (Dudek 1980; Schulmann & Gayer 2000; Friedl *et al.* 2000).

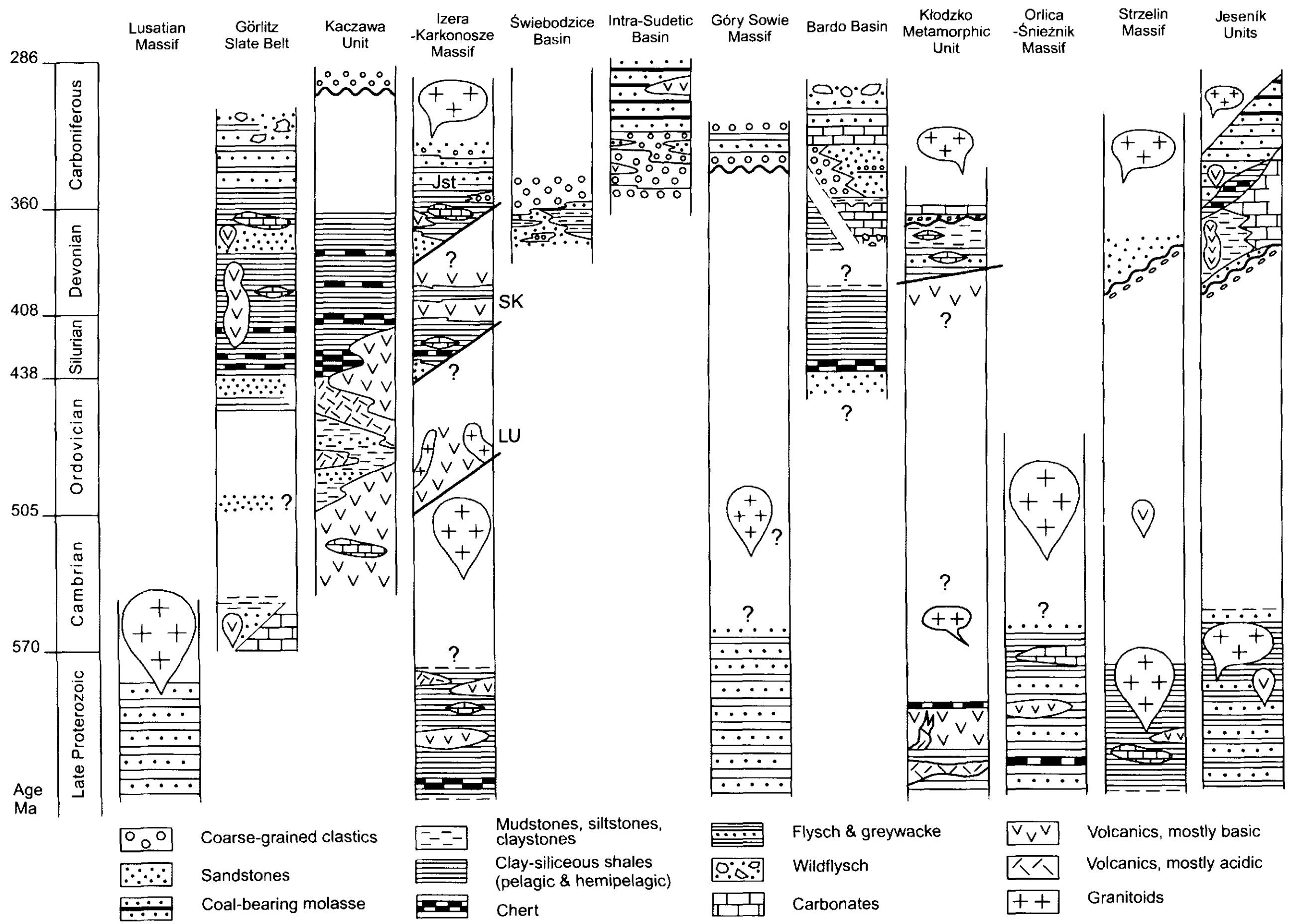


Fig. 3. Simplified stratigraphic columns of the main structural units of the Sudetes (modified from Aleksandrowski *et al.* 2000). Metamorphic rocks are represented by their sedimentary and igneous protoliths. LU, Leszczyniec Unit; SK, South Karkonosze Unit; Jst, Ještěd Unit.

Geology of the Sudetes: an overview

Below, we review the basic geological features of particular Sudetic structural units from NW to SE. Units are more comprehensively described where their specific geological aspects are significant for possible palaeotectonic reconstructions and understanding the sequence of terrane accretion, or where up-to date descriptions in the existing literature are lacking.

West Sudetes

The West Sudetes extend from the Lusatian Massif in the NW to the eastern rims of the Karkonosze-Izera Massif and the Kaczawa Unit (Figs 1 and 2).

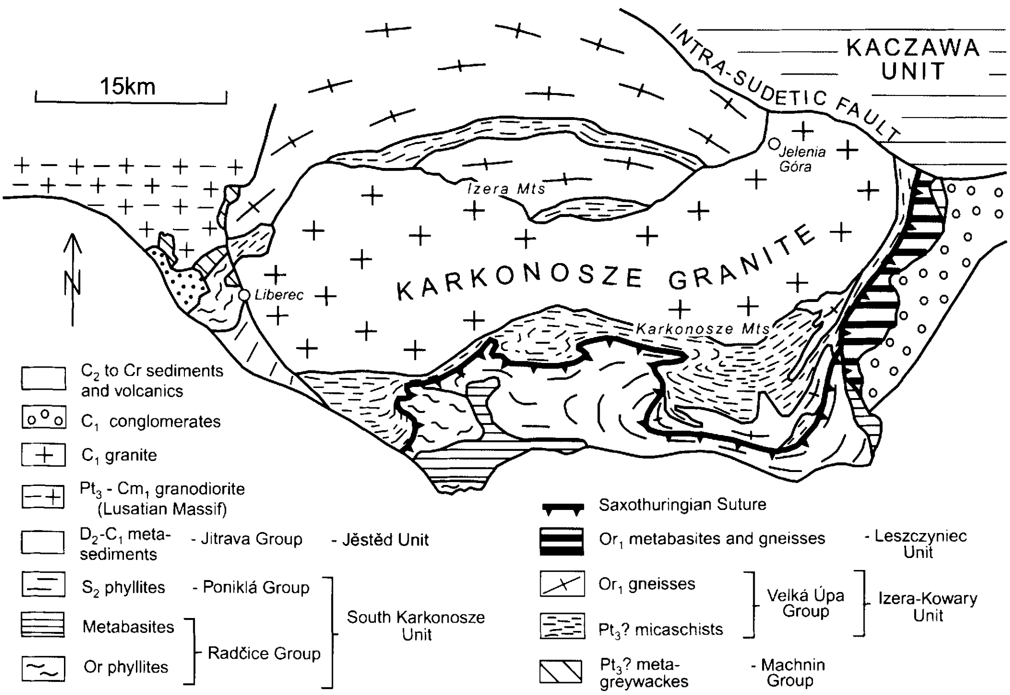
Lusatian Massif and Görlitz Slate Belt. The Lusatian Massif comprises Cadomian, Neoproterozoic to Early Cambrian granitoids within non- to low-grade metamorphic Neoproterozoic turbiditic greywackes (e.g. Kröner *et al.*1994; Linnemann *et al.*1998). The Görlitz Slate Belt (e.g. Urbanek *et al.*1995), sometimes inappropriately referred to as the 'Görlitz Syncline', adjoins the Lusatian Massif in the NE and contains fragments of dismembered Lower Cambrian to Lower Carboniferous sequences partly embedded in Lower Carboniferous flysch (cf. Linnemann & Buschmann 1995). Its tectonic fabric seems to be analogous to that of the Kaczawa Unit.

Kaczawa Unit. The Kaczawa Unit comprises several folded thrust-sheets composed of numerous thrust slices and significant mélange bodies. The thrust sheets and mélanges involve various fragments of a sedimentary–volcanic succession of Late Cambrian/Ordovician through Late Devonian (Famennian) age (Baranowski *et al.* 1987, 1990). The Kaczawa succession is made up of low-grade metamorphosed (in blueschist overprinted by greenschist facies) siliciclastics, volcaniclastics, carbonates, basic and acid volcanics, pelagic clay and siliceous shales and flysch, and is interpreted as an end Devonian/Early Carboniferous accretionary prism complex (Baranowski *et al.* 1987, 1990; Kryza & Muszyński 1992; Collins *et al.* 2000; Seston *et. al.* 2000). The lower part of the Kaczawa succession, comprising Cambrian?–Ordovician shallow marine sedimentary rocks and bimodal volcanics of within-plate geochemical signature, is interpreted to have accumulated in an initial rift underlain by continental crust (Baranowski *et al.* 1990; Kryza & Muszyński 1992; Kryza 1993; Furnes *et al.* 1994; Seston *et al.* 2000). The upper part of the succession is dominated by a thick monotonous sequence of tholeiitic E-MORB to N-MORB pillowed basalts accompanied by black graptolitic shales in the Silurian and by siliceous and clayey slates and cherts in the Devonian parts of the profile. It was probably emplaced in an oceanic rift environment (Furnes *et al.* 1994).

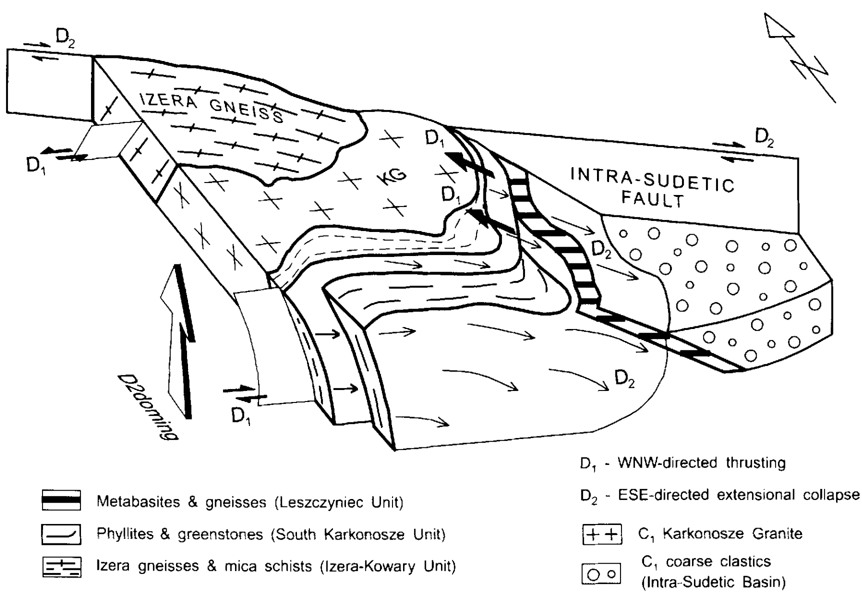
The high pressure metamorphism is thought to have taken place by about 360 Ma, by analogy with rocks dated in the east Karkonosze suture by Maluski & Patočka (1997). The Kaczawa thrust sheets were emplaced during latest Devonian(?)-earliest Carboniferous(?) times in a top-to-NW to WNW shearing regime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

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

The Izera-Kowary Unit is composed mainly of the Upper Cambrian/Lower Ordovician (Borkowska *et al.* 1980; Oliver *et al.* 1993; Korytowski *et al.* 1993) Izera (Rumburk) Granite, in most part transformed by a subsequent, Late Devonian to Early Carboniferous deformation into the Izera/Kowary Granite Gneiss and Gneiss (equivalent to the Krkonoše Gneiss on the Czech side of the massif, dated at around 500 Ma by Oliver *et al.* 1993 and Kröner *et al.* 2001). Its other significant component is mica schist representing remains of its Neoproterozoic(?) envelope (Velká Úpa Group on the Czech side and Czarnów Formation on the Polish side; Chaloupský 1965; Teisseyre 1973). These rocks underwent medium pressure metamorphism under upper greenschist – lower amphibolite facies conditions (Żaba 1984; Oberc-Dziedzic 1987; Kryza & Mazur 1995). To the east and south, the Izera-Kowary rocks plunge below



A



B

Fig. 4. 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 Aleksandrowski *et al.* 1997). *Age assignments* as in Figure 2.

metamorphic complexes of the South Karkonosze and the Leszczyniec units affected by HP metamorphism. Towards the west, the Izera-Kowary granite and gneiss reveal intrusive contacts with Cadomian granitoids of the Lusatian Massif (Ebert 1943; Domečka 1970).

The Ještěd Unit, a small fault-bounded block exposed at the SW edge of the Karkonosze-Izera Massif, comprises Middle to Upper Devonian shallow marine to hemipelagic sediments with minor volcanics (Jítrava Group of Chaloupský 1989), subjected to very weak, low temperature–medium pressure metamorphism, passing upwards into greywackes and conglomerates of probably Tournaisian to (?)Early Viséan Culm facies rocks (Chlupáč & Hladil 1992; Chlupáč 1993).

The South Karkonosze Unit comprises several hundred metres of metamorphosed Ordovician to (?)Devonian sedimentary rocks (Chlupáč 1993, 1997) accompanied by bimodal, mostly basic volcanics (Figs 3 and 4). Described as the Poniklá and Radčice groups on the Czech side (Chaloupský 1989) and as the Niedamirów Formation on the Polish side (Kryza & Mazur 1995), the sequence contains highly differentiated marine sedimentary rocks and is characterized by close proximity of various facies assemblages typical of a neritic through hemipelagic to pelagic environment. The metavolcanic rocks of the Radčice Group, including the Železný Brod Complex and the Rýchory Mountains metavolcanic succession, and those of the Poniklá Group, represent a differentiated magmatic suite, ranging from predominantly felsic rocks (dated at 501 +/–8 Ma using Rb–Sr whole rock method; Bendl & Patočka 1995) of within-plate geochemical signature to basic lavas and pyroclastics of P-type MORB affinities (Bendl *et al.* 1997; Patočka & Smulikowski 1998, 2000). The basic metavolcanics of the Radčice Group in the Železný Brod and Rýchory Mountains preserve a record of early blueschist facies metamorphism (Wieser 1978; Cháb & Vrána 1979; Guiraud & Burg 1984; Kryza & Mazur 1995; Smulikowski 1995; Patočka *et al.* 1996) dated at about 360 Ma, followed by a greenschist overprint of about 340 Ma ($^{40}Ar/^{39}Ar$ method; Maluski & Patočka 1997). The South Karkonosze Unit probably represents a tectonically dismembered, once vertically continuous and laterally diversified sedimentary succession of an extensive marine basin (Mazur & Aleksandrowski 2001*a*).

The Leszczyniec Unit is represented by a differentiated suite of mafic and felsic rocks of volcanic and plutonic origin (Teisseyre 1973; Kryza *et al.* 1995; Mazur & Kryza 1995*b*), dated at *c.* 500 Ma (U–Pb zircon method; Oliver *et al.* 1993) and showing N-MORB affinities (Kryza *et al.* 1995; Winchester *et al.* 1995). The Leszczyniec Unit tapers out to the south and does not continue into the Rýchory Mountains (Mazur 1995; Mazur & Aleksandrowski 2001*a*).

The concept of a nappe structure for the Karkonosze-Izera Massif was introduced by Kodym & Svoboda (1948) and partly accepted by Oberc (1961, 1972). A new nappe model for the massif was proposed in several recent papers (Mazur 1995; Mazur & Kryza 1996; Seston *et al.* 2000; Mazur & Aleksandrowski 2001*a*). The nappe structure is inferred from contrasting metamorphic paths (Kryza & Mazur 1995) and the record of different tectonic settings (Mazur & Aleksandrowski 2001*a*) shown by the four constituent units of the Karkonosze-Izera Massif. The Izera-Kowary Unit (together with the adjacent Lusatian Massif) represents pre-Variscan continental crust of Saxothuringian affinity. A small fragment of its original sedimentary cover, probably parautochthonous (or representing the lowermost nappe?) is the Ještěd Unit, tectonically sandwiched between the overlying South Karkonosze Unit and the underlying Izera-Kowary rocks. A structurally higher position is occupied by the South Karkonosze Unit, probably composed of lower order thrust sheets or slices with mutually similar structural and metamorphic histories. The uppermost position in the pile is held by the Leszczyniec Unit, characterized by the NNE–SSW structural grain, entirely different from the WNW–ESE structural trend in the remaining part of the Karkonosze-Izera Massif (Mazur & Aleksandrowski 2001*a*).

The South Karkonosze and Leszczyniec nappes, comprising blueschist facies rocks and MORB-type magmatic complexes, are tectonically emplaced on top of the parautochthonous Izera-Kowary unit of continental basement features. The nappe pile was formed at the turn of Late Devonian/Early Carboniferous time due to northwestward thrusting and in general, shows metamorphic inversion (Mazur & Aleksandrowski 2001*a*). It was subsequently modified by Early Carboniferous, southeasterly-directed extensional collapse and, eventually, intruded by the Karkonosze Granite (Mazur 1995; Mazur & Aleksandrowski 2001*a*).

Central Sudetes

The Central Sudetes comprise structural units that occur east of the Karkonosze-Izera Massif and the Kaczawa Unit and west of the Velké

Vrbno and Branná units of the East Sudetes as well as west of the Strzelin Crystalline Massif in the eastern part of the Fore-Sudetic Block.

Góry Sowie Massif. The Góry Sowie Massif is made up of amphibolite facies paragneisses thought to have been derived from uppermost Proterozoic protoliths (Gunia 1985; but see Moczydłowska 1995, who questions the fossil determinations of Gunia). They are accompanied by migmatites and orthogneisses and contain small ultramafic and granulitic bodies (Kryza 1981; Żelaźniewicz 1990) recording pressure and temperature conditions typical of mantle and lower crustal levels. Granulite formation at pressures of 18–20 kbar and temperatures above 900 °C (Kryza *et al.* 1996) was dated, using the U–Pb zircon method, at about 400 Ma (O'Brien *et al.* 1997), corresponding closely with a Sm–Nd age of the associated, mantle-derived ultramafics (Brueckner *et al.* 1996). This high 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 medium pressure–high temperature metamorphism is estimated at around 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). The final exhumation of the Góry Sowie Massif is recorded by gneissic pebbles in uppermost Devonian–lowermost Carboniferous conglomerates of the Świebodzice Basin (Porębski 1981, 1990).

Świebodzice Basin. The Upper Devonian (upper Frasnian–Famennian) to lowermost Carboniferous Świebodzice Basin ('Depression') succession, up to 4000 m thick, occurs in a small, rhomboidal, fault-bounded block, consisting mainly of polymict conglomerates. In the lower part, they are interbedded with thick fossiliferous mudstones containing sandstone turbidites and rare limestone lenses. These deposits reflect mostly gravity-flow sedimentation within a slope-type fan-delta complex which invaded a rapidly subsiding basin, bounded to the SW and south by an active fault system, of probable strike-slip displacement component (Porębski 1981, 1990).

Bardo Basin. The Bardo Basin succession comprises unmetamorphosed Upper Devonian limestone and Lower Carboniferous flysch strata, capped by wildflysch deposits (Wajsprych 1978, 1986). The wildflysch contains large olistoliths of Lower Palaeozoic and Devonian deep marine sediments (Haydukiewicz 1990). The Bardo Basin succession was folded at the turn of Early/Late Carboniferous into east–west trending folds and intruded by the Kłodzko-Złoty Stok Granitoid Pluton. Late Carboniferous refolding produced NE–SW to north–south trending folds superimposed on the older east–west structures (Oberc 1972).

Central Sudetic Ophiolite. The Central Sudetic Ophiolite comprises several mafic/ultramafic bodies that crop out along the northern (Ślęża Ophiolite), eastern (Szklary and Braszowice ultramafic bodies) 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-Upper 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 are probably related.

For several years an inferred Devonian age of obduction and exhumation of the Ślęża Ophiolite contradicted the first isotopic dating of its protolith. Whole-rock Sm–Nd analysis of six samples of the ophiolitic gabbro indicated an age of 353 +/– 21 Ma, and ten samples of gabbro from the Nowa Ruda Gabbro-Diabase Massif, on the SW side of the Góry Sowie 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 ophiolite on the basis of U–Pb zircon measurements on a gabbro sample. A recent U–Pb age of 400 + 4/–3 Ma (Żelaźniewicz *et al.* 1998) was obtained on abraded zircons from rodingitized plagiogranite of the Ślęża Massif. The latter date seems to be the most reliable approximation of the age of ophiolite igneous crystallization, whereas the Sm–Nd ages may reflect subsequent overprints of tectonic emplacement and cooling.

Kłodzko Metamorphic Unit. The Kłodzko Metamorphic Unit (Kłodzko Massif) comprises six tectonic subunits (Figs 5 and 6), representing (from base to top):

(1) the Mały Bożków Subunit comprising Middle Devonian (Givetian) progradational shelf sequence (Hladil *et al.* 1999);
(2) a mélange body of unknown age, defining the Łączna Subunit (Mazur & Kryza 1999);
(3) the Bierkowice Subunit, composed of Palaeozoic(?) mafic volcanics with intraplate basalt geochemical signature (Kryza *et al.* 2000);

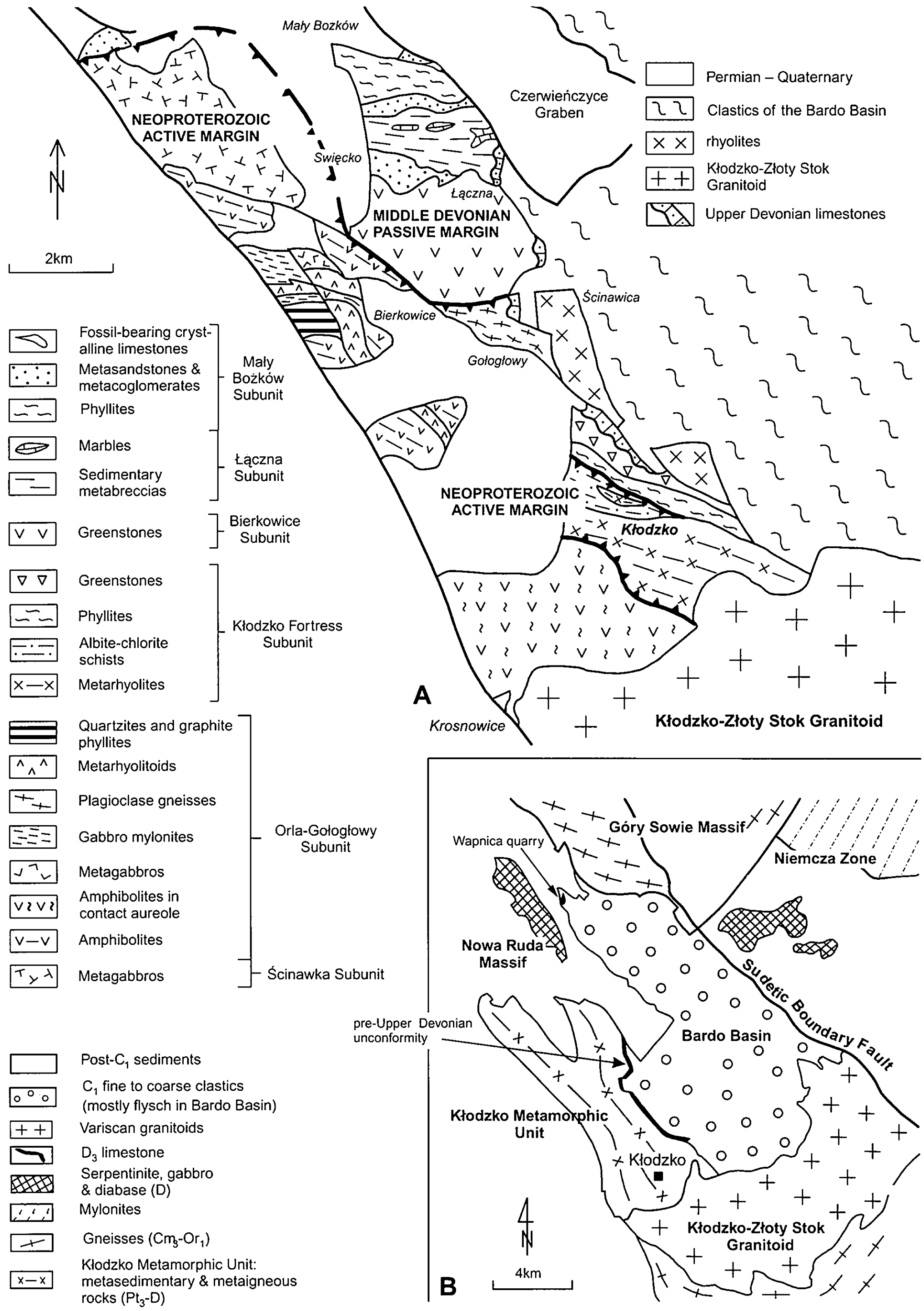
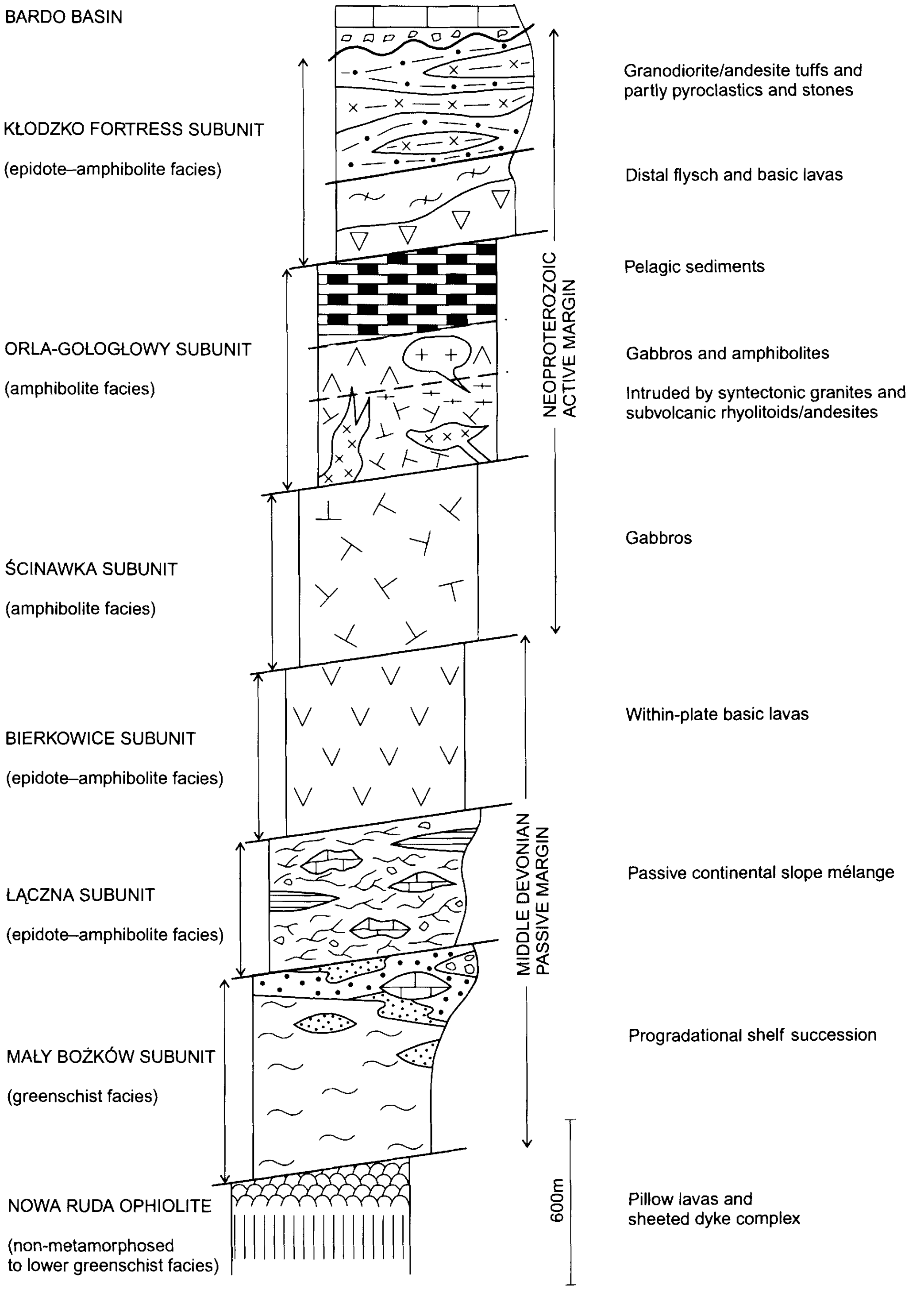


Fig. 5. Sketch geological map showing palaeotectonic interpretation of the Kłodzko Metamorphic Unit (after Mazur, unpublished data). *Inset*: geological setting within the Góry Sowie–Kłodzko domain of Central Sudetes.


BARDO BASIN
KŁODZKO FORTRESS SUBUNIT
(epidote–amphibolite facies)
ORLA-GOŁOGŁOWY SUBUNIT
(amphibolite facies)
ŚCINAWKA SUBUNIT
(amphibolite facies)
BIERKOWICE SUBUNIT
(epidote–amphibolite facies)
ŁĄCZNA SUBUNIT
(epidote–amphibolite facies)
MAŁY BOŻKÓW SUBUNIT
(greenschist facies)
NOWA RUDA OPHIOLITE
(non-metamorphosed
to lower greenschist facies)
NEOPROTEROZOIC ACTIVE MARGIN
MIDDLE DEVONIAN PASSIVE MARGIN
600m
Granodiorite/andesite tuffs and partly pyroclastics and stones
Distal flysch and basic lavas
Pelagic sediments
Gabbros and amphibolites
Intruded by syntectonic granites and subvolcanic rhyolitoids/andesites
Gabbros
Within-plate basic lavas
Passive continental slope mélange
Progradational shelf succession
Pillow lavas and
sheeted dyke complex

(4) MORB-type gabbro of the Ścinawka Subunit (Kryza *et al.* 2000), showing affinities to
(5) the Orla-Gołogłowy Subunit, composed of gabbro and MORB-type mafic volcanics (Kryza *et al.* 2000), intruded by granitoids and accompanied by deep marine sediments; some subvolcanic felsic rocks being preliminarily dated as Neoproterozoic (U-Pb method on zircons; K. Turniak 2001, pers. com.), and
(6) distal flysch with basaltic lavas, accompanied by pyroclastic sandstones and dacitic/andesitic tuffs, the latter of Neoproterozoic age (K. Turniak 2001, pers. com.), composing the Kłodzko Fortress Subunit.

Thus, the lower three subunits of the Kłodzko Metamorphic Unit comprise rocks which are, at least in part, of Middle Devonian age, whereas the remaining upper three subunits include Neoproterozoic plutonic and volcanic rocks. The tectonic contacts between the subunits were inferred mostly from their contrasting metamorphic paths (Kryza *et al.* 2000), different lithostratigraphic contents and palaeoenvironmental affinities. The metamorphic grade increases up-profile, from greenschist to amphibolite facies, except for the highest subunit that shows epidote–amphibolite facies metamorphism. All the subunits of the Kłodzko Metamorphic Unit record the same sequence of deformation, in part shared with the Bardo Basin succession: (1) WNW-directed ductile thrusting; (2) folding into east–west-trending folds; and (3) dextral strike-slip shearing along WNW–ESE direction, associated with exhumation in a transpressive regime. These three deformation events were recorded only in the metamorphic rocks of the Kłodzko Unit. The following two events also affected the sedimentary succession of the Bardo Basin: (4) WNW–ESE-directed sinistral strike-slip synchronous with the emplacement of the Kłodzko-Złoty Stok Granitoid intrusion; (5) intense folding of the Bardo Basin and the adjacent part of the Kłodzko Metamorphic Unit due to north–south compression. The first deformation event, the top-to-WNW thrusting, resulted in nappe formation in the Kłodzko Metamorphic Unit. The entire nappe pile rests on top of the essentially unmetamorphosed Nowa Ruda Ophiolite and is unconformably covered by the younger sedimentary sequence of the Bardo Basin.

Intra-Sudetic Basin. The Intra-Sudetic Basin is a syn- to post-orogenic, relatively large (60 × 25 km) intramontane basin, initiated during Tournaisian time. The basin remained active throughout the Carboniferous and Permian periods, accumulating molasse up to 11 000 m (Nemec *et al.* 1982; Dziedzic & Teisseyre 1990). The Early Carboniferous sedimentation reflected rapid orogenic uplift of the basin's surroundings, accompanied by extensional collapse and exhumation of the freshly deformed Sudetic crystalline complexes.

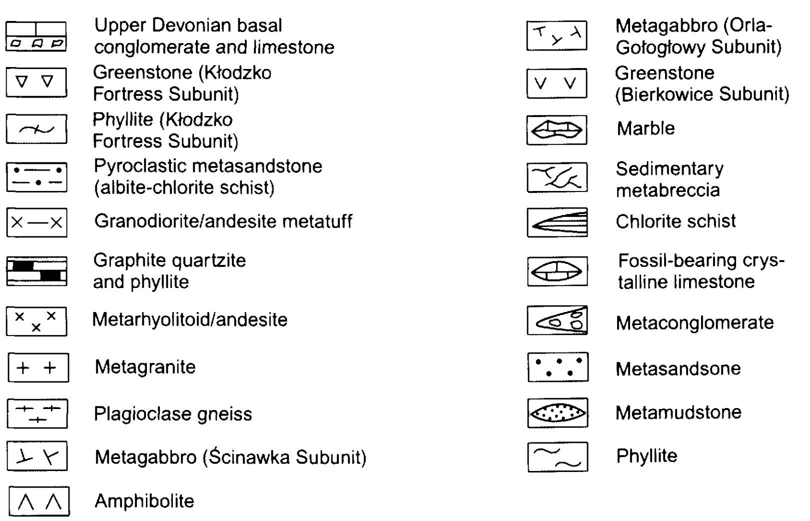


Fig. 6. Lithotectonic log of the Kłodzko Metamorphic Unit (after Mazur, unpublished data).

Orlica-Śnieżnik Massif. The Orlica-Śnieżnik Massif is composed mostly of amphibolite-grade orthogneisses and subordinate staurolite-grade variegated schists of presumably Neoproterozoic protoliths with eclogite and granulite lenses (e.g. Don *et al.* 1990). Emplacement of the magmatic precursor to all textural varieties of orthogneisses was dated at approximately 500 Ma, using various U–Pb and Pb/Pb methods (Oliver *et al.* 1993; Turniak *et al.* 2000; Kröner *et al.* 2001). The Carboniferous tectonothermal phenomena included medium- to high-grade metamorphism and intense synmetamorphic deformation, accompanied by exhumation of high-grade rocks. High pressure and temperature granulite facies metamorphism is dated at around 360–369 Ma, using the U–Pb method on zircons (Klemd & Bröcker 1999), and Sm–Nd whole rock ages for eclogites range from 350 to 330 Ma (Brueckner *et al.* 1991). The age of a later high temperature–medium or low pressure phase of metamorphism, which resulted in partial migmatization of Orlica-Śnieżnik rock complexes has been determined by SHRIMP dating of metamorphic rims on zircons at about 342 Ma (Turniak *et al.* 2000). 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.* 2000). The structure of the Orlica-Śnieżnik Massif is poorly understood. The common view is that the massif represents a gneissic dome, in which the gneisses crop out in antiforms, whereas 'mantling' schists are preserved in synforms. There is a little evidence, however, that the Orlica-Śnieżnik Massif is composed of a number of folded thrust sheets, as are the East Sudetic units adjacent to the SE. This question awaits further research.

Nové Město Belt. The Nové Město Belt is located in the western Góry Orlickie (Orlica Mts) and adjoins the Orlica-Śnieżnik Massif to the NE (Fig. 2). It is composed mostly of phyllites, greenstones and amphibolites, whose ages remain unknown, but which are traditionally viewed as Late Proterozoic by comparison to the Teplá-Barrandian domain of the Bohemian Massif (Chaloupský *et al.* 1995). The amphibolites crop out in an approximately continuous belt, 1.5 to 5 km wide, that follows the contact with the Orlica-Śnieżnik Massif (Fig. 7). According to the geochemical results of Opletal *et al.* (1990) and Floyd *et al.* (1996), they show MORB-type affinities. On the eastern side, the contact is mostly accompanied by a mica schist belt up to 2 km wide. Two late-tectonic granitoid intrusions, the Olešnice and Kudowa plutons, are emplaced in the contact zone. A third late-tectonic intrusion, the Nový Hrádek Granodiorite, is entirely surrounded by phyllites in plan view. Small granitoid bodies are also common in the contact zone further to the south. Metamorphic grade increases in the Nové Město Belt from greenschist facies in the west, to amphibolite facies along the boundary with the Orlica-Śnieżnik Massif. Metamorphic isograds are roughly parallel to the boundary with the Orlica-Śnieżnik Massif and the contacts with the granitoid intrusions.

An important structural discontinuity along the contact between the Nové Město Belt and the Orlica-Śnieżnik Massif is suggested by the structural study by Fajst (1976), who documented divergent structural trends on both sides of the contact. The Orlica-Śnieżnik Massif is characterized by approximately north–south structural grain whereas the Nové Město Belt shows NW–SE structural trends. The two structural patterns are locally superimposed within the contact zone. Across the entire NW part of the Orlica-Śnieżnik Massif and the Nové Město Belt, they are uniformly overprinted by younger east–west trending folds.

The fabric of the Nové Město Belt bears a 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 (the Uhřinov Shear Zone), changing gradually into top-to-NNE shearing in the core of the Massif. The foliation in the whole area is refolded by east–west trending south-vergent F_3 folds.

A primary contact between the Nové Město Belt and the Orlica-Śnieżnik Massif was probably represented by a thrust characterized by top-to-ESE kinematics (Mazur & Aleksandrowski 2001*b*), which juxtaposed phyllites and amphibolites of the Nové Město Belt, differing in their metamorphic grade. The original contact was subsequently folded and reactivated as a major dextral shear zone. Dextral displacements resulted in the subsequent juxtaposition of the Nové Město and the Orlica-Śnieżnik units. A similar deformation sequence including top-to-ESE thrusting and succeeding dextral shear was described by Přikryl *et al.* (1996) further to the east in the Orlica-Śnieżnik Massif. The Nové Město Belt partly continues to the SE into the Zábřeh metamorphic belt (Opletal *et al.* 1980).

Niemcza and Skrzynka Shear Zones. The Niemcza Shear Zone, extending along the eastern edge of the Góry Sowie Massif (see Fig. 8), was interpreted by Scheumann (1937) to contain mylonitized gneisses. Based on detailed

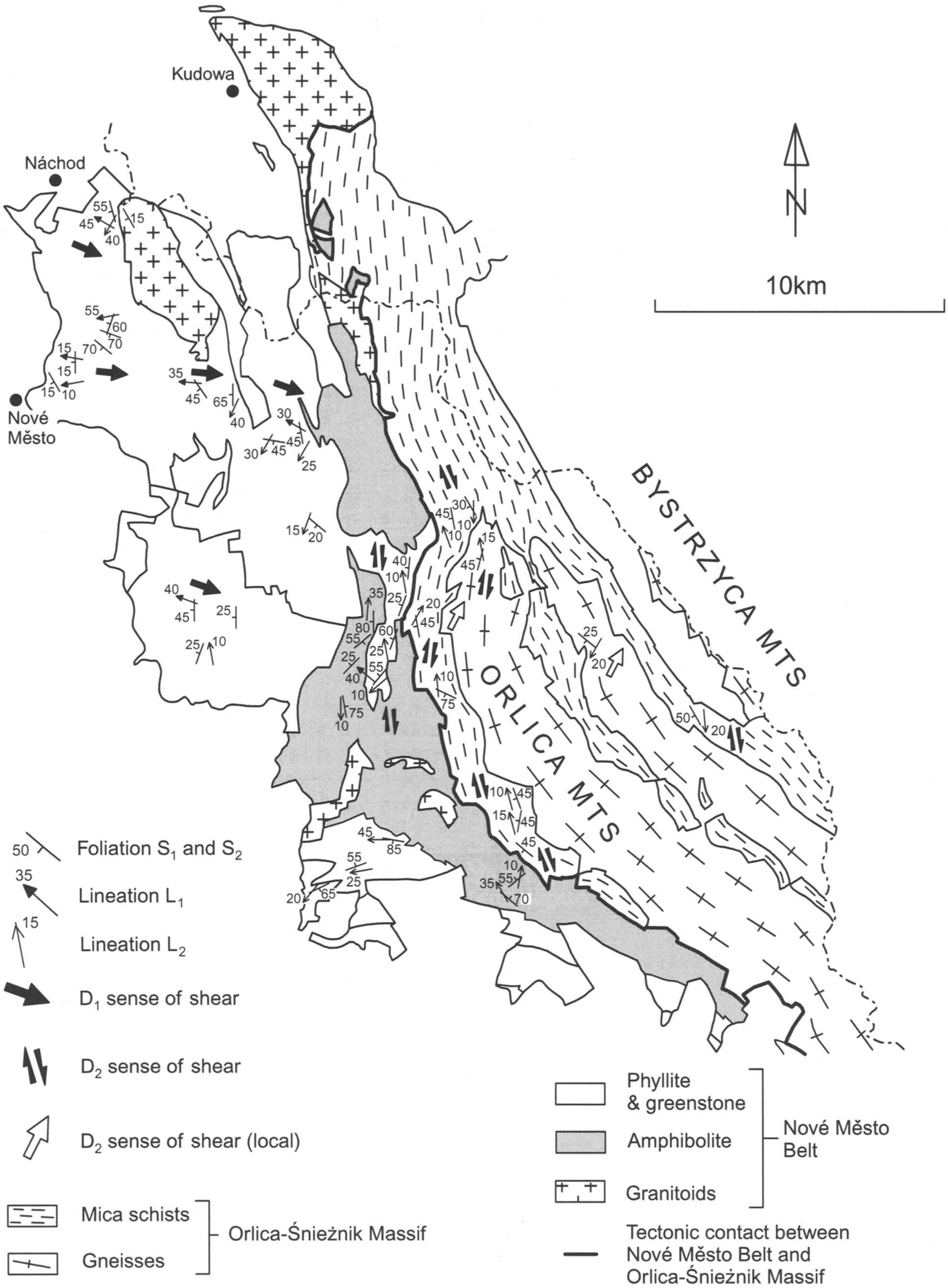


Fig. 7. Schematic geological and tectonic map of the Nové Město Belt (after Aleksandrowski & Mazur, unpublished data).

study, Mazur & Puziewicz (1995) 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. The Niemcza mylonites were derived from the Góry Sowie Gneiss (Scheumann 1937; Mazur & Puziewicz 1995; but see e.g. Franke & Żelaźniewicz 2000, for an

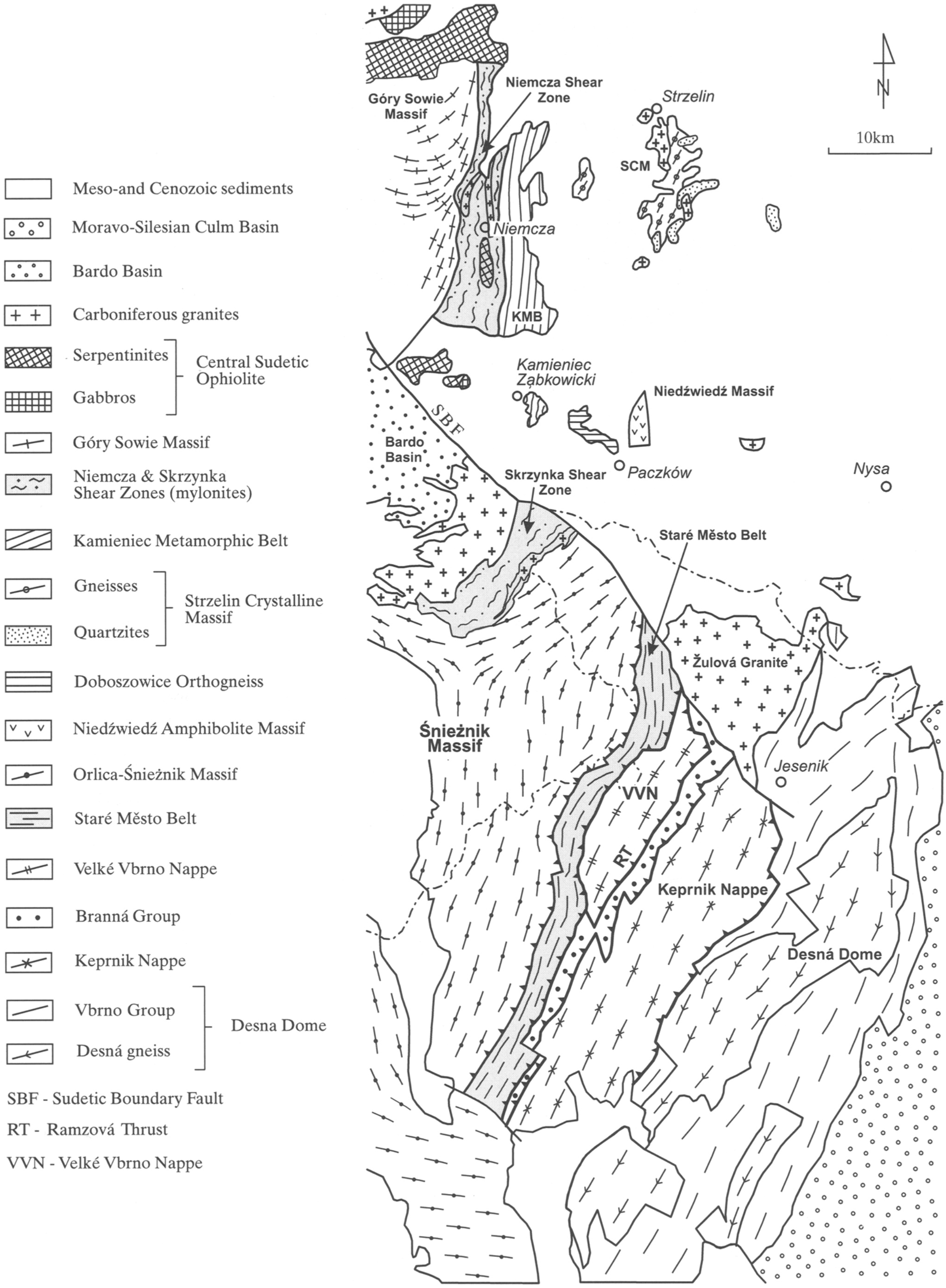


Fig. 8. Geological sketch map of the East Sudetes.

alternative interpretation of the Niemcza Zone rocks as metagreywackes, following Bederke 1929) and include minor lenses of non-mylonitic gneisses, amphibolites and quartzo-graphitic schists. The mylonites occur as high- and low-temperature varieties, formed in amphibolite and greenschist facies conditions respectively (Mazur & Puziewicz 1995). The Niemcza Shear 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 about 340 Ma (Oliver *et al.* 1993; Kröner & Hegner 1998). Earlier fabric is completely obliterated in the mylonites, so that no superposition of structures can be recorded. However, in the southern part of the adjoining Kamieniec Metamorphic Belt, older structures showing a top-to-the-NE sense of shear on a shallow westerly dipping foliation are locally preserved and overprinted by a common top-to-the-SW or sinistral fabric. Hence, by analogy, the left-lateral motion in the Niemcza Zone (or top-to-the-south motion in places where the foliation is shallow-dipping) seems to be younger and superimposed on the earlier fabric of regional extent, related to the Early Carboniferous top-to-the NE thrusting and dextral shearing on the SE edge of the Bohemian Massif (Rajlich, 1987; Schulmann *et al.* 1991; Fritz & Neubauer, 1993).

The Skrzynka (or Złoty Stok-Skrzynka) Shear Zone, trending NNE–SSW to NE–SW (Fig. 8), is approximately 12 km long and 4 km wide and constitutes the boundary between the sedimentary rocks of the Bardo Basin and the Kłodzko-Złoty Stok Granitoid Massif to the NW and the Śnieżnik Massif to the SE (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 within the Skrzynka Zone parallels its boundaries and contains a subhorizontal to shallow SW plunging mineral stretching lineation. Cymerman (1992, 1996) showed that the main deformation in the Skrzynka Zone was a left-lateral, ductile strike-slip non-coaxial shear. The latest stages of the shearing seem to have postdated the emplacement of both the Kłodzko-Złoty Stok pluton and another small granitoid body near to the SE boundary of the Skrzynka Zone (the Jawornik Granitoid), since the margins of the two plutons underwent mylonitization.

Kamieniec Metamorphic Belt. The Kamieniec Metamorphic Belt crops out as a north–south elongated schist belt east of the Góry Sowie Massif and of the Niemcza Shear Zone (Fig. 8). It comprises mica schists containing intercalations of quartzo-feldspathic schists and marbles and subordinate lenses of quartzo-graphitic and amphibolitic schists and eclogites. The Kamieniec Belt consists of two tectonic units with different metamorphic grades. The first unit comprises mica schists containing kyanite, garnet, staurolite and late andalusite porphyroblasts, whereas the second one is composed of mica schists with albite porphyroblasts (Mazur & Józefiak 1999).

Staré Město Belt. The Staré Město Belt forms a tectonic boundary separating the Central from the East Sudetes (or the Lugian domain from the Moravo-Silesian domain). It is a stack of thrust sheets adjacent in the SE to the Orlica-Śnieżnik Massif (Fig. 8). Occupying a NNE–SSW elongated outcrop zone about 40 km long and 4–5 km wide, the Staré Město Belt 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 & Gayer 2000). The peridotite bodies are considered to be tectonic slices extracted from the mantle by thick-skinned thrusting (Parry *et al.* 1997; Schulmann & Gayer 2000). U–Pb zircon dating of the banded amphibolites and metagabbros yielded Cambrian ages (510–500 Ma, Kröner *et al.* 2000). Analogous ages are widespread, as well, in the Orlica-Śnieżnik Massif and in 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, Neoproterozoic protolith ages (from 684–546 Ma) of the basement orthogneisses and of the paragneisses have been recorded (van Breemen *et al.* 1982; Kröner *et al.* 2000). Thus the Staré Město Belt is the easternmost unit of the Central Sudetes; east of it units of different affinities occur. The Staré Město rocks have been interpreted as products of a Cambro-Ordovician initial rift (Parry *et al.* 1997; Štípská *et al.* 2001; Kröner *et al.* 2000), based on their igneous association. This conclusion is corroborated by crustal contamination of MORB-type amphibolites, suggesting the emplacement of their protoliths in an ensialic rift zone (Floyd *et al.* 1996). At the same time, medium pressure–high temperature granulite facies metamorphism, synchronous with the intrusion of Cambro-Ordovician magmatic suite and associated with pressures of 7–10 kbar 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 the crustal thinning and the associated extensional tectonics has been determined on metamorphic zircons from 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 the thrusting of the belt over the East Sudetes, was roughly contemporaneous with the intrusion of a syntectonic tonalite dyke dated at 339 ± 7 Ma, using the Pb/Pb method on zircons (Parry *et al.* 1997).

The Staré Město Belt shows features typical of a suture zone. The juxtaposition of dissimilar crustal domains of the East and Central Sudetes along the Staré Město thrust belt must have been triggered by exhumation of plate fragments, that, earlier, had been subducted westwards, below the active margin of the West Sudetes during Early Carboniferous times (Schulmann & Gayer 2000). The possible continuation of the Staré Město Belt northward, across the Sudetic Boundary Fault, into the Fore-Sudetic area, remains problematic. The scarcity of outcrops emerging from beneath a thick Cenozoic cover prevents any definite correlations, but the Staré Město Belt probably continues into the Niedźwiedź Amphibolite Massif.

Niedźwiedź Amphibolite Massif. Despite the rare outcrops, the Niedźwiedź Massif is relatively well known from borehole data (Cymerman & Jerzmański 1987, Jerzmański 1992). It comprises a 1.5 km-thick succession of MORB-type amphibolites and metagabbros (Awdankiewicz 2001) that were subjected to high-grade metamorphism, locally leading to partial melting of the metabasites (Puziewicz & Koepke 2001). The Niedźwiedź Massif is apparently overthrust from the west by a medium- to high-grade association of paragneisses, amphibolites and hornblende gneisses (Mazur & 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. The belt is composed of nappe piles that crop out from below the upper plate of the collision zone (represented in the south by Moldanubian and in the north by Central Sudetic rock complexes) in three tectonic half-windows: of Thaya (Czech: Dyje), of Svratka (German: Schwarzawa) and of the East Sudetes. The nappes exposed in the two former windows were distinguished as Moravian units, whereas those cropping out in the East Sudetes were termed Silesian units (Suess 1912, 1926; Dudek 1980). Recently, the eastern Bohemian collisional belt, together with an extensive Devonian–Carboniferous sedimentary basin to the east, are usually described under the general name of the Moravo-Silesian Zone, Belt or domain (e.g. Dallmeyer *et al.* 1995; Franke & Żelaźniewicz 2000) or as the Moravian Terrane (Matte *et al.* 1990; Matte 1991). Significant differences between the structure of the collision zone in Moravia and that in Silesia, have been reported, however, in a number of recent papers (e.g. Schulmann *et al.* 1991; Schulmann & Gayer 2000).

In its Sudetic segment, the collision zone is represented by the East Sudetic pile of nappes (Fig. 8), overridden from the west by the Central Sudetic Orlica-Śnieżnik Massif and the Staré Město Belt. From top to bottom, or in plan view from the west to the east, the East Sudetic nappe pile comprises the highest Velké Vbrno Nappe ('upper allochthon' of Schulmann & Gayer 2000) and the Keprník Nappe ('lower allochthon'), separated from each other by the detached Branná Unit. The Keprník Nappe rests in turn on parautochthonous gneisses of the Desná Dome (Schulmann & Gayer 2000) covered by the probably allochthonous Devonian metasedimentary Vrbno Group.

Velké Vrbno Nappe. Directly east of the Staré Město Belt, there occurs the Velké Vbrno Nappe, composed of orthogneisses and metasediments (banded amphibolite rocks, kyanite–staurolite mica schists, graphite schists and quartzites, dolomitic marbles and biotite paragneisses) metamorphosed under upper-amphibolite facies conditions. The gneisses were dated at about 574 Ma (Kröner *et al.* 2000). The presence of relict eclogites (Žáček 1996; Schulmann & Gayer 2000) points to an older stage of high pressure–low temperature metamorphism. A protolith of the supracrustal series must have been a variegated, volcanosedimentary sequence of unknown age, traditionally considered to be Early Palaeozoic (e.g. Květoň 1951).

Branná Unit and Keprník Nappe. The Velké Vbrno Nappe overrides a narrow belt of highly sheared Devonian metasediments named the

Branná Unit, metamorphosed under greenschist facies conditions. It mostly comprises shallow water polymict metaconglomerates, quartzites, crystalline limestones, sericite and sericite–graphite phyllites, porphyroids and calcsilicate schists. The Branná Unit is overthrust on the crystalline Keprník Nappe, made up of a large granitic orthogneiss body (U–Pb zircon-dated at around 546 Ma; van Breemen *et al.* 1982) with subordinate staurolite-bearing metapelites, calcsilicate rocks and quartzites (Schulmann & Gayer 2000).

Desná Dome. The easternmost tectonic unit of the Silesian domain, known as the Desná Dome, contains the relatively monotonous metasedimentary Devonian succession of the Vrbno Group (Fig. 8), overlying Desná gneisses and mylonites with U–Pb zircon ages of 570–650 Ma (Kröner and colleagues data reported by Schulmann & Gayer 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), metamorphosed under greenschist facies conditions and markedly different from the shallow-water Devonian of the Branná Unit and from platform Devonian rocks of the Brno Massif and the basement underlying the Upper Carboniferous Silesian Coal Basin and the Miocene Carpathian nappes. The Vrbno Group was presumably overthrust on the Brunovistulian gneissic basement now exposed within the Desná Dome. The metavolcanic rocks of the Vrbno Group are interpreted as originally deposited in an extensional basin related to crustal thinning. The supra-subduction geochemical signature of some metavolcanic rocks may indicate arc and back-arc (the latter initiated as intracontinental rift) tectonic settings (Patočka & Valenta 1996). Palaeontological dating of crystalline limestones suggests that much of the Vrbno volcano-sedimentary succession was formed between end Givetian and latest Frasnian times (Hladil 1986).

Strzelin Crystalline Massif. Towards the north, the East Sudetic nappe pile plunges below a cover of Cenozoic sediments. The crystalline rocks emerge at the surface only within the Strzelin Crystalline Massif, 40 km south of Wrocław. The massif mainly consists of gneisses accompanied by minor mica schists and amphibolites with a within-plate geochemical signature (Szczepański & Oberc-Dziedzic 1998). These rocks are tectonically interleaved with quartzites similar to those known from the Desna Dome and Branná Unit, which are therefore also assumed to be of Early to Middle Devonian age. Varied gneisses are derived from different protoliths, dated at 504 ± 3 Ma (Oliver *et al.* 1993) and at about 570 to 600 Ma (Oberc-Dziedzic *et al.* 2001). The metamorphic rocks of the Strzelin Massif are intruded by abundant granitoids ranging in age from around 350 to 330 Ma (dated by the Rb–Sr whole rock method, Oberc-Dziedzic *et al.* 1996).

Interpretation and discussion

The structural units of the Sudetes described above represent various palaeotectonic environments, geological evolutionary paths and various, often unclear, affinities. Here, we present and, where necessary, discuss the interpretation of particular units, as adopted in the recent literature, or proposed by us.

West Sudetes

Lusatian and Karkonosze-Izera massifs and Görlitz Slate Belt: the Saxothuringian passive margin. The Lusatian Massif represents the Neoproterozoic parautochthonous continental basement of the epicontinental part of the Saxothuringian Basin (Linnemann *et al.* 1998, 2000; Franke & Żelaźniewicz 2000; Mazur & Aleksandrowski 2001*a*). Similarly, the adjacent gneisses and mica schists of the Izera-Kowary Unit in the Karkonosze-Izera Massif, are interpreted as the pre-Variscan (Early Palaeozoic) continental crust partly underlying the Saxothuringian Basin (Franke & Żelaźniewicz 2000; Mazur & Aleksandrowski 2001*a*), subsequently involved in Variscan deformation near to a collision zone extending along the Saxothuringian Suture (see below). This continental crust must have once underlain the passive margin of the Saxothuringian epicontinental area (Mazur & Aleksandrowski 2001*a*). The Izera gneisses are Early Ordovician intrusions into an older basement of Cadomian Lusatian granitoids (Domečka 1970) dated at between *c.* 590–545 Ma (Kröner *et al.* 1994). Structurally, therefore, the NW part of the Karkonosze-Izera Massif constitutes one common element together with the Lusatian Massif. The intensity of deformation and metamorphism gradually increases eastwards, i.e. towards the suture zone, starting from practically undeformed Cadomian granitoids of Lusatia (Ebert 1943).

The sedimentary succession of the NE passive margin of the epicontinental part of Saxothuringia is represented by the rocks of the

Ještěd Unit (Karkonosze-Izera Massif; Figs 2 and 4; Mazur & Aleksandrowski 2001*a*) and of the thrust-folded and strike-slip sheared Görlitz Slate Belt (cf. Hirschmann 1966; Brause & Hirschmann 1969; Urbanek *et al.* 1995), together with its eastward continuation up to the vicinities of Gryfów Śląski (the Lubań subunit, previously considered as the western part of the Kaczawa Unit; see discussion below).

Saxothuringian Suture in the southern and eastern Karkonosze Mountains. The suture of the SE Karkonosze Mountains is probably a fragment of the Saxothuringian Suture (equivalent names: the Münchberg-Teplá Suture (Matte *et al.* 1990); or Teplá/Saxothuringian (Mazur & Aleksandrowski 2001*a*)), defining a boundary between the Saxothuringian domain to the NW and the Teplá-Barrandian domain to the SE (e.g. Matte *et al.* 1990; Matte 1991, 1998; Franke *et al.* 1995*a*). The Saxothuringian Suture is known from exposures near to Mariánské Lázně and in the Münchberg nappe pile in the western part of the Bohemian Massif. In that area the suture is defined by eclogites derived from *c.* 500 Ma MOR-type magmatic rocks and accreted continental slope sediments of the Saxothuringian Bavarian facies (Beard *et al.* 1995; Franke *et al.* 1998). The suture continues to the NE, below the cover of Mesozoic–Cenozoic rocks of the Cheb (Eger) Graben, up to the upper Elbe Valley, where it is presumably displaced to the SE on the dextral Elbe Fault Zone together with the entire Teplá-Barrandian domain (cf. Rajlich 1987; Pin *et al.* 1988; Matte *et al.* 1990; Aleksandrowski 1990, 1995), to crop out in the southern and eastern Karkonosze Mountains. Further to the NE, the Saxothuringian Suture is cut by the dextral strike-slip Intra-Sudetic Fault Zone (see Aleksandrowski 1990, 1995; Aleksandrowski *et al.* 1997) so that no direct continuation of it can be identified.

An age equivalent of the Mariánské Lázně Complex in the eastern Karkonosze-Izera Massif is the Leszczyniec Unit (Figs 2 and 4), metamorphosed under relatively high pressure epidote–amphibolite facies (Kryza & Mazur 1995) and showing *c.* 500 Ma protolith age (Oliver *et al.* 1993). It is interpreted as an obducted fragment of the Saxothuringian sea floor (Mazur & Aleksandrowski 2001*a*). The underlying South Karkonosze Unit comprises a volcanosedimentary basin infill metamorphosed under blueschist facies conditions. The rocks bear record of changing tectonic environments from initial rifting during the Ordovician to a mature oceanic basin during the Silurian (Patočka & Smulikowski 1998; 2000). Both the Leszczyniec and South Karkonosze units are derived from a hypothetical root zone of the SE Karkonosze nappe pile, currently buried below the Carboniferous and Permian deposits of the Intra-Sudetic and Fore-Karkonosze basins. These units can be considered together as a separate 'oceanic' South Karkonosze Terrane composed of fragments of the floor and sedimentary succession of the Saxothuringian Sea (Mazur & Aleksandrowski 2001*a*).

Kaczawa Unit: a rift to oceanic succession involved in an accretionary prism. The Kaczawa Unit exposes a volcanic–sedimentary succession that records a transition from an initial rift in the Ordovician, to a mature ocean in Silurian times (Furnes *et al.* 1994). As an accretionary prism (Baranowski *et al.* 1990) with a significant proportion of rocks of oceanic affinities, the Kaczawa Unit is, in a way, analogous to a tectonic suture: it separates distinct continental domains of different provenance (the Lusatian Massif together with the Görlitz Slate Belt in the west and the Góry Sowie Massif in the east). A suture zone proper, related to the Kaczawa thrust stack, might be expected to occur within a hypothetical root zone that must be concealed somewhere to the east, probably below the Świebodzice Basin and/or the Góry Sowie Massif.

No direct relationship between the Görlitz and Kaczawa successions. Traditionally, the Kaczawa Unit has been considered to continue westward into the Görlitz Slate Belt (e.g. Jaeger 1964; Hirschmann 1966; Brause & Hirschmann 1969; Urbanek *et al.* 1995). This view, however, though widely held due to geographical proximity of both units, does not seem to be correct, as indicated by important differences in stratigraphy, age of deformation and variation of metamorphic grade between rock complexes of the two units.

The Görlitz Palaeozoic succession is unmetamorphosed or very slightly metamorphosed, in contrast to that of the Kaczawa Unit, which, over its entire extensive outcrop area shows greenschist facies metamorphism, obliterating relicts of an earlier high pressure–low temperature event. The Görlitz succession begins with Lower Cambrian carbonates, sandstones and scarce volcanics capped by trilobite-bearing shales (Freyer 1977; Urbanek *et al.* 1995), whereas rocks of such age are not known in the Kaczawa Mountains. Although abundant in the Kaczawa Unit, no Upper Cambrian(?)–Lower Ordovician volcanics are known from the

Görlitz Slate Belt; the scarce Ordovician rocks there are siliciclastics. The Silurian section in the Görlitz succession, comparable to that of the Thuringian facies of the Saxothuringian Zone (Hirschmann 1966), is composed of siliceous and 'alum shales', intercalated at the top with tuffs, quartzites, greywacke and rare limestone (Urbanek *et al.* 1995): the latter intercalations are not present in Silurian rocks in the Kaczawa Unit, which instead contains significant amounts of mafic MORB-type volcanics. The Devonian section in the Görlitz succession is more terrigenous than that in the Kaczawa Mountains, and is represented by a monotonous series of alternating quartzites, pelites and greywackes with rare limestones and basic volcanic rocks (Urbanek *et al.* 1995), whereas the latter are not yet described from the Devonian of the Kaczawa Unit.

The Lower Carboniferous of the Görlitz Slate Belt is composed of normal flysch, accompanied towards the top by chert, limestone and significant conglomerate intercalations (Urbanek *et al.* 1995) and, also of wildflysch deposits containg fragments of Ordovician through Lower Carboniferous rocks as olistoliths (Thomas 1990). Linnemann & Buschmann (1995) and Linnemann *et al.* (1998) even interpreted the entire Görlitz Slate Belt as a Lower Carboniferous flysch embedding various sized fragments of dismembered Lower Cambrian to Lower Carboniferous sequences. The south-verging tight folds and steep schuppen structure formation in the Görlitz Slate Belt is dated at middle Viséan and its final stage considered as late Viséan (Hirschmann 1966; Brause & Hirschmann 1969).

Lower Carboniferous rocks have not yet been recognized unequivocally 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, considered to be of tectonic origin (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 Late Tournaisian(?)–Early Viséan conglomerates of the northern rim of the Intra-Sudetic Basin (A. K. Teisseyre 1968, 1971, 1975) and, less abundantly, in the Świebodzice Basin (H. Teisseyre 1968). Therefore, the metamorphism, deformation and exhumation of at least part of the Kaczawa Unit must have taken place by Early Viséan times.

At the same time, conodont-proven Lower Carboniferous deposits, reaching up to the lower part of the upper Viséan, have been documented by Chorowska (1978) from the far-western part of the Kaczawa Unit, near Gryfów Śląski and Lubań. Palaeozoic rocks crop out there along an elongated narrow belt adjacent to the Intra-Sudetic Fault to the south. Further west, this belt merges into the Görlitz Slate Belt. According to Milewicz *et al.* (1989, see also Cymerman in press), this belt of Palaeozoic rocks is tectonically divided NE of Gryfów Śląski, into two segments with differing metamorphic grades. The eastern segment shows greenschist facies metamorphism, typical of the Kaczawa rocks and is included in the Pilchowice Subunit, extending east to near Jelenia Góra. The western segment, however, distinguished as the Lubań Subunit (Fig. 9), shows only a very weak metamorphic imprint. The Viséan limestone in Rząsiny, occurring as fragments within a chaotic deposit (olistostrome; Chorowska 1978), comes from the Lubań Subunit. The timing of tectonic deformation inferred from this finding does not match the relationships known from the Kaczawa Unit further east; instead it corresponds well with those determined for the Görlitz Slate Belt (see above). We therefore suggest, that the Lubań Subunit probably represents the easternmost part of the Görlitz Slate Belt, extended and sheared along the northern wall of the Intra-Sudetic Fault Zone. Thus, the discovery of upper Viséan sediments there should not directly affect conclusions about the timing of deformation and metamorphism within the Kaczawa Unit.

Central Sudetes

Based on contrasting geological histories, the Central Sudetes can be subdivided into two domains. The northwestern domain, includes the Góry Sowie Massif and the Kłodzko Metamorphic Unit, together with the surrounding Central Sudetic ophiolitic bodies and the Bardo and Świebodzice sedimentary basins and, probably much of the NE part of the basement to the Intra-Sudetic Basin. The southeastern domain corresponds to the Orlica-Śnieżnik Massif and the Staré Město Belt in the Sudetic Mountains and the Kamieniec Metamorphic Belt in the Fore-Sudetic Block. The two domains are separated by the major strike-slip Skrzynka and Niemcza shear zones.

Kłodzko Metamorphic Unit: contrasting palaeotectonic elements juxtaposed in a nappe pile. The Kłodzko Metamorphic Unit juxtaposes rocks that have formed at various times in two contrasting tectonic environments: a passive continental margin of (at least partly) Middle Devonian age and a Neoproterozoic(?) active

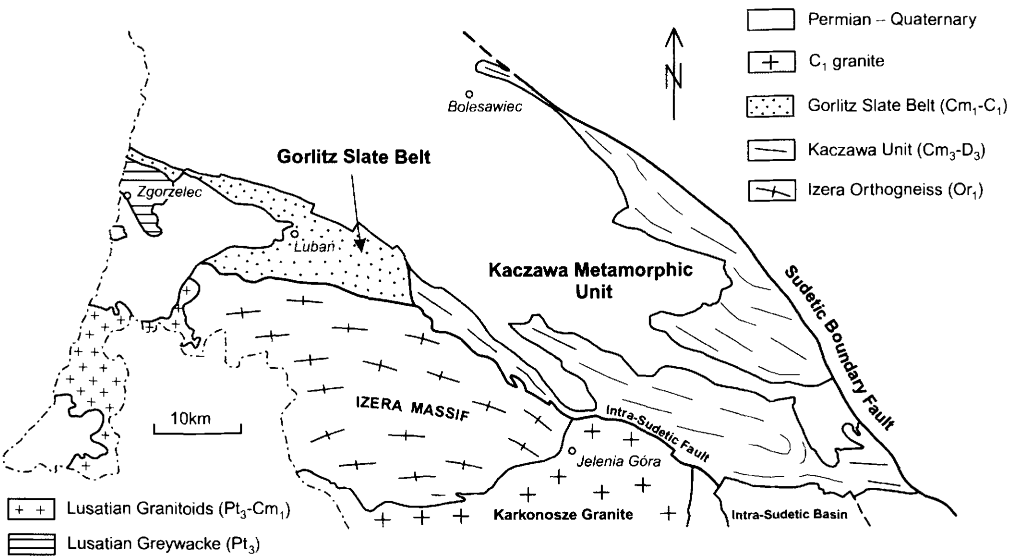


Fig. 9. Schematic map showing the suggested extent of the Kaczawa Unit and the Görlitz Slate Belt in the West Sudetes. *Age assignments* as in Figure 2.

continental margin (Figs 5 and 6). The structurally lower NE part of the Kłodzko Unit is, thus, represented by passive margin Middle Devonian sediments and volcanics (the Mały Bożków, Łączna and Bierkowice subunits). The upper SW part comprises rocks yielding Neoproterozoic ages and representing fragments of a supracrustal magmatic arc sequence interlayered with distal flysch sediments (the Kłodzko Fortress Subunit) and relics of a plutonic–volcanic complex associated with deep marine sedimentary rocks, possibly of back-arc origin (the Orla-Gołogłowy and Ścinawka subunits). Further to the NW, the Nowa Ruda Ophiolite is overridden by the Kłodzko Unit nappe pile. The stacking of nappes must have taken place in Middle to Late Devonian times, i.e. approximately synchronously with the obduction of the Nowa Ruda Ophiolite. Subsequently, the entire nappe pile was buried below the clastic deposits of the Bardo Basin. Sedimentation continued there from Upper Devonian to the beginning of Late Carboniferous times, i.e. until the folding of the sedimentary sequence and emplacement of the Kłodzko-Złoty Stok Granitoid Pluton.

Góry Sowie Massif: Cadomian continental crust subducted to mantle depths in Late Silurian/Early Devonian and exhumed in Late Devonian times. The thermobarometric data and radiometric age constraints on relict granulitic and eclogitic rocks (Kryza *et al.* 1996; O'Brien *et al.* 1997; Brueckner *et al.*1991, 1996) accompanying widespread paragneisses and migmatites, indicate that the Góry Sowie granulites represent 'type I granulites' of Pin & Vielzeuf (1983), probably derived from continental crust subducted in the Variscan Belt to mantle depths at around 430–400 Ma (Vielzeuf & Pin 1989). Subsequently, the granulites experienced a distinct decompressive event (4–10 kbar), under continuing high temperatures (600°–700 °C), probably coinciding with the peak of metamorphism and anatexis in the surrounding gneisses (Kryza *et al.* 1996). The cooling ages of about 385–370 Ma (van Breemen *et al.* 1988; Bröcker *et al.* 1998) represent the end of metamorphism in the Góry Sowie Massif prior to the Late Devonian. Gneissic clasts in the Late Devonian strata of the Świebodzice Basin show that Góry Sowie gneisses were exhumed during the Famennian (Porębski 1981, 1990).

Position of Kłodzko Metamorphic Unit and of Central Sudetic Ophiolites relative to Góry Sowie Massif. The spatial interrelationships between the Góry Sowie Massif on one side and the Kłodzko Metamorphic Unit and the Central Sudetic Ophiolite on the other side are not clear, since their contacts are not exposed. From Viséan times, the Góry Sowie Massif abundantly supplied the marginal parts of the Bardo Basin with gneissic pebbles which accumulated in a system of coarse clastic fans that developed along the SW edge of the Góry Sowie Massif (Wajsprych 1978, 1986; Haydukiewicz 1990).

The mapped relationships show that the Bardo Basin is in part floored by the Kłodzko Metamorphic and the Nowa Ruda Ophiolite rocks. However the only borehole believed to have penetrated through the Bardo Basin fill, was stopped after drilling several tens of metres in typical Góry Sowie gneiss (Chorowska *et al.* 1986). Therefore, it cannot be excluded that all three: the Kłodzko Metamorphic Massif, the Nowa Ruda Ophiolite and the Góry Sowie gneisses constituted a pre-Carboniferous basement on which the Bardo Basin succession was laid down.

Based on gravimetric data, the Central Sudetic ophiolites have been thought to extend below the Góry Sowie Massif (Znosko 1981). However, on recent gravimetric maps (e.g. Królikowski & Petecki 1995) as well as on the gravimetric and magnetic data referred to by Znosko (1981), the maximum values of positive Bouguer anomalies or positive magnetic anomalies roughly coincide with the ophiolite outcrops at the northern, eastern and southern margins of the Góry Sowie Massif. The massif itself coincides with high unidirectional negative gradients in gravimetric and magnetic fields, with no positive anomalies below the gneisses. Therefore, a more reasonable conclusion is that the Góry Sowie Massif is not underlain by dense and highly magnetic ophiolitic rocks. Moreover, the Góry Sowie Massif has been uplifted since the beginning of the Carboniferous, bounded by high-angle faults. Thus, any ophiolites that underlie the Góry Sowie Massif would have been buried more deeply in the areas adjacent to the massif than below the massif itself. However, the ophiolite may have been thrust over the gneisses. The spatial relationship of the Góry Sowie gneisses and the Sudetic ophiolites remains unsolved and requires further study.

Nové Město Belt: the sheared NE margin of Teplá-Barrandian domain? Rocks of the Teplá-Barrandian domain are believed by some workers to continue northeastwards into the basement of the North Bohemian Cretaceous Basin (Malkovský 1979; see also Chaloupský 1989; Pin *et al.* 1988; and Matte *et al.* 1990). This implies that the Nové Město Belt may be the northeasternmost fragment of the Teplá-Barrandian (Chaloupský 1989) emerging from below the deposits of the North Bohemian Basin. The NE edge of the Nové Město Belt, defined by the dextral Uhřinov Shear Zone (Mazur & Aleksandrowski 2001*b*), is an important tectonic boundary that separates low-grade phyllites, greenstones and amphibolites, from geologically different amphibolite-grade gneisses and mica schists of the Orlica-Śnieżnik Massif. The Nové Město rocks show similarities in lithology and metamorphic grade to the Teplá Complex in the interior of the Bohemian Massif (Chaloupský *et al.* 1995), whereas the Orlica-Śnieżnik rocks have affinities to the Gföhl Unit of the Moldanubian Zone of the Bohemian Massif (discussed in some detail below). The structural characteristics of this tectonic contact between the Nové Město Belt, and the Orlica-Śnieżnik Massif are roughly similar to those of the contact between the Teplá-Barrandian and Moldanubian domains exposed in the Železné Hory Mountains. A primary thrust contact in the latter area was extensively modified by a normal top-to-NW ductile shear zone (Pitra *et al.* 1994). The orientation of the stretching lineation at Železné Hory is analogous to that in the Orlica Mountains and suggestive of a strike-slip dextral shearing component. The prevailing strike-slip and down-dip sense of displacement in the Orlica and Železné Hory mountains, respectively, is determined from the present-day attitude of foliation. This has been strongly reorientated by late domal uplift, which is particularly distinct in the footwall of the Nové Město Belt. The lithological and geochemical characteristics of the amphibolite belt along the NE flank of the Nové Město Belt may indicate a tectonic suture (Opletal *et al.* 1990; Floyd *et al.* 1996).

Góry Sowie–Kłodzko domain of Central Sudetes: an area of pre-Upper Devonian subduction, collision and exhumation

The Kłodzko Metamorphic Massif, together with the Góry Sowie Massif, the Świebodzice and Bardo basins, the Central Sudetic Ophiolite massifs as well as the basement of the NE part of the Intra-Sudetic Basin, represent the large Central Sudetic domain that contains a record of pre-Late Devonian Eo-Variscan deformation and exhumation. This area is collectively termed here the Góry Sowie–Kłodzko domain (and below is distinguished as a terrane). The effects of the pre-Late Devonian tectonism were subsequently overprinted there by Early Carboniferous deformation, so widespread in the Sudetes and the entire Bohemian Massif. One of the most typical features of the Góry Sowie–Kłodzko domain is the widespread pre-upper Devonian unconformity.

Pre-Upper Devonian unconformity. The pre-Upper Devonian erosional surface that planes the top of the Nowa Ruda Ophiolite Massif and of the Kłodzko Metamorphic Unit is characteristic of the NW part of Central Sudetes. The crystalline metamorphic or igneous basement is overlain by unmetamorphosed upper Devonian basal conglomerates and limestones. This relationship was considered by Bederke (1924, 1929) as a record of the Caledonian Orogeny in the Sudetes. In modified form, Bederke's conclusions can be found in many recent publications (e.g. Don 1984, 1990; Oliver *et al.* 1993; Johnston *et al.* 1994; Kröner & Hegner 1998; Kröner *et al.* 2000). However, many lines of evidence suggest that the main tectonic and thermal events occurred in the Sudetes during end-Devonian and Early Carboniferous times (e.g. Aleksandrowski 1994; Żelaźniewicz & Franke 1994; Aleksandrowski *et al.* 2000). These include: (1) continuous Palaeozoic basinal sedimentation of the Kaczawa succession, lasting until the end of the Devonian; (2) Carboniferous metamorphic ages in the Karkonosze-Izera and Orlica-Śnieżnik complexes; and (3) widespread Carboniferous granitoid plutonism.

The type localities of the pre-Upper Devonian unconformity in the Sudetes are outcrops exposing the contact of Upper Devonian strata of the Bardo Basin with the underlying metamorphics of the Kłodzko Massif and mafic plutonic rocks of the Nowa Ruda Ophiolite Massif. The crystalline basement rocks of the Kłodzko Metamorphic Unit and of the Nowa Ruda Massif were described by Bederke (1924) to be in sedimentary contact with unmetamorphosed Upper Devonian and Tournaisian thin basal conglomerates, calcareous breccias and limestones up to 60 m thick. The most complete profile of the Upper Devonian succession is exposed at Mt Wapnica in Dzikowiec, adjacent to the Nowa Ruda Massif (Fig. 5), a part of the circum-Góry Sowie, Central Sudetic Ophiolite belt. At its base is a calcareous sedimentary breccia comprising large boulders of gabbro (e.g. Gürich 1900; Mazur 1987), which are believed to have been derived from the crystalline basement of the Nowa Ruda Massif (Gürich 1900, 1902; Dathe 1900). The sedimentary contact of the basal breccia with the gabbroic basement was documented by Gürich (1900) in the Dzikowiec (Ebersdorf) quarry, which is no longer exposed. The age of the breccia was provisionally estimated as upper Frasnian, based on problematic macrofauna (Gürich 1902; Bederke 1929). The size and quantity of the gabbro pebbles decreases rapidly upwards as the sedimentary breccia grades into the Basal Limestone and, then, into the partly nodular Main Limestone (Mazur 1987). The age of the latter is palaeontologically well constrained by conodonts as Famennian (Freyer 1968; Chorowska 1974). The Main Limestone passes upwards into the upper Famennian *Clymenia* Limestone (Weyer 1965; Freyer 1968; Chorowska 1974). The uppermost part of the calcareous succession forms the Lower Tournaisian limestone representing the ammonoid zone *Gattendorfia crassa* (Schindewolf 1937; Weyer 1965), consistent with the conodont fauna (Freyer 1968; Chorowska 1974; Dzik 1997). In most places, the limestones are discordantly overlain by a thick sequence of Culm sandstones (Dathe 1900; Bederke 1924) considered to be latest Tournaisian in age (Głuszak & Tomaś 1993). This contact probably represents a local erosional discordance (Mazur 1987) rather than a significant thrust plane (the Kłodzko Thrust of Bederke 1924). The base of the sandstones is usually marked by a thin layer of black shales, which are dated by conodonts as Tournaisian (Haydukiewicz 1981). The fragmentary outcrops of Upper Devonian strata at the boundary of the Kłodzko Metamorphic Unit and the Bardo Basin are comparable to those exposed at Mt Wapnica (Bederke 1924; Gunia 1977). The specific feature of the Mt Wapnica profile is the unconformable contact of Upper Devonian rocks with gabbro of the Nowa Ruda Massif: in all other localities the Upper Devonian is in contact with the metamorphic basement of the Kłodzko Unit. Bederke (1924) described eight localities of Devonian sedimentary rocks along the western edge of the Bardo Basin. However, except in the Mt Wapnica section, the angular unconformity has not been exposed since the 1950s. The unconformity was recently excavated in two of Bederke's localities around Kłodzko (Kryza *et al.* 1999). At each site, the metamorphic rocks were found to be in unconformable contact with the overlying basal sedimentary breccias and conglomerates with no evidence of tectonic disturbance. Near the Gołogłowy quarry the Upper Devonian rocks overlying the unconformity, show an upward transition into the Bardo Basin succession (Haydukiewicz 1981).

The angular unconformity cutting the Kłodzko Metamorphic Unit and the Nowa Ruda Ophiolite Massif must have formed during a relatively narrow time interval of about 10 Ma between the early Givetian and late Frasnian. This timing is constrained by the late Frasnian/Famennian age of the limestones directly overlying the basal conglomerates (Gürich 1902; Bederke 1929; Gunia 1977) and by the early Givetian age of a coralline fauna from the greenschist facies crystalline limestones of the Kłodzko Metamorphic

Unit (underlying the unconformity) at Maly Bożków (Hladil *et al.* 1999), previously interpreted as Late Silurian (Gunia & Wojciechowska 1971). The existence of this unconformity implies that at the turn of Middle and Late Devonian times, freshly deformed and metamorphosed rocks were exposed and onlapped by deposits of the Bardo sequence, which were folded during latest Viséan/Namurian times (Oberc 1972). Apart from the Kłodzko/Nowa Ruda/Bardo units, the pre-Upper Devonian unconformity most probably defines the floor of the Świebodzice Basin, although no details are known about its basement.

Multistage evolution of the Góry Sowie–Kłodzko domain. The geological data from the Góry Sowie–Kłodzko domain of the Central Sudetes indicate multistage evolution defined by three stages of convergence and two stages of extension. The first, Late Silurian/Early Devonian convergence was recorded in the high pressure–high temperature metamorphism of the Góry Sowie Massif. The resulting granulites, about 400 Ma old (O'Brien *et al.* 1997) are evidence for a continental subduction, which was presumably due to late Silurian/Early Devonian collision. However, the tectonically isolated position of the Góry Sowie Massif within younger metamorphic complexes does not allow a reconstruction of Silurian/Early Devonian accretion in the Central Sudetes.

The Late Silurian/Early Devonian convergence was followed by a relatively long period of extension, resulting in the opening of an oceanic basin (whose floor supplied the protolith for the Central Sudetic ophiolites). The 400 Ma age of these rocks (Żelaźniewicz *et al.* 1998), seems to be the most probable from among the several determinations (Pin *et al.* 1988; Oliver *et al.* 1993), and shows that extension took place in earliest Devonian times, contemporaneously with the uplift and exhumation of the Góry Sowie Massif. A wide range of cooling ages for the Góry Sowie gneisses (van Breemen *et al.* 1988; Bröcker *et al.* 1998; Timmermann *et al.* 2000) reflects their gradual exhumation during the Early and Middle Devonian. The extension lasted until the late Middle Devonian, as documented by the early Givetian age of the Mały Bożków succession in the Kłodzko Metamorphic Unit (Hladil *et al.* 1999).

A successive compressional stage took place between the early Givetian and Famennian. It resulted in obduction of the Central Sudetic ophiolites and in deformation and metamorphism of the Kłodzko Unit, which was finally thrust upon the Nowa Ruda Ophiolite.

The termination of the Middle/Late Devonian stage of accretion in the Central Sudetes is constrained by the late Frasnian or earliest Famennian age of the pre-upper Devonian unconformity. The unconformity defines the beginning of the successive extensional stage, leading to the formation of the Bardo Basin. Its subsidence and the accompanying sedimentation lasted until the turn of the Early/Late Carboniferous, when inversion took place and folding affected the basin fill, probably synchronously with the intrusion of the Kłodzko- Złoty Stok Granitoid Pluton. The latter compressional stage did not result in any metamorphic or thick-skinned tectonic effects in the Bardo Basin or in the other units of the Góry Sowie–Kłodzko domain; however, it had a significant influence on the adjacent Orlica-Śnieżnik Massif (see below).

Transregional correlations. A record of pre-Late Devonian deformation and exhumation, typical of the Góry Sowie–Kłodzko domain, is present also in few other areas of the Bohemian Massif, such as the basement of the North Bohemian Basin and the Münchberg Massif. In the North Bohemian Cretaceous Basin, whose basement is often interpreted to lie within the Teplá-Barrandian domain (Malkovsky 1979; Chaloupsky *et al.* 1995), boreholes east of Hradec Kralove reveal unmetamorphosed Upper Devonian to Lower Carboniferous succession resting transgressively on low-grade schists of uncertain, Lower Palaeozoic(?) age (Chlupač & Zikmundová 1976; Čech *et al.* 1989). At the same time, within the allochthonous units of the Münchberg Massif, there occur approximately 395 Ma eclogites (Stosch & Lugmair 1990), previously dated at *c.* 425–410 Ma (Gebauer & Grünenfelder 1979). They underwent cooling and exhumation by Famennian (*c.* 365 Ma) times, i.e. before the final stacking of the Münchberg nappe pile. This exhumation is believed to have taken place in a relatively narrow zone between the colliding Teplá-Barrandian domain to the SE and the Saxothuringian passive margin, resulting in the sedimentation of Givetian clastics on top of the Barrandian sedimentary succession and of Famennian greywackes at the southern flank of the Fichtelgebirge (Franke *et al.*1995*b*; Franke *et al.*1998; Franke 2000; Franke & Stein 2000).

However, the Central Sudetic Góry Sowie–Kłodzko domain seem to be the only area in the Bohemian Massif known to have recorded effects of Palaeozoic tectonic evolution in which early collision was followed by later rifting and opening of a basin underlain by oceanic crust. A record of polycyclic tectonic evolution similar to that from the Góry Sowie–Kłodzko domain of the Central Sudetes is known in areas of the Variscan Belt outside the Bohemian Massif. Close analogues occur in France, where a belt of Upper Silurian to Early Devonian high-grade metamorphic rocks extends from the southern part of the Armorican massif to the NE Massif Central and the Vosges (e.g. Faure *et al.* 1997; Shelley & Bossière 2000 and references therein). It defines the Massif Central suture (Matte 1991, 1998), also called Eo-Variscan Suture (e.g. Faure *et al.* 1997), which is interpreted to have originated due to Late Silurian continental subduction, which was also responsible for the high pressure metamorphism (e.g. Pin & Vielzeuf 1988; Pin 1990). This was followed by crustal extension from Mid-Devonian time, leading to the formation of Brévenne Rift in the NE part of the Massif Central and similar smaller structures in the Armorican Massif and the southern Vosges. This 'mid-Variscan' stage of the orogenic evolution was terminated by Late Variscan compression ('the Hercynian Event'; e.g. Faure *et al.* 1997). These geological relationships in the 'Moldanubian Zone' of France led Ziegler (1986), Eisbacher *et al.* (1989) and Pin (1990) to assume a succession of two orogenic cycles during formation of that part of the Variscan Belt.

High pressure metamorphic rocks of the French Variscides known as the 'Leptyno-Amphibolite Complex' (e.g. Pin & Vielzeuf 1983; Ledru *et al.* 1989) yield ages ranging from 440 to 400 Ma (Pin & Peucat 1986; Paquette *et al.* 1995). During exhumation, the Silurian high pressure metamorphosed rocks underwent almost isothermal decompression, leading to partial melting and migmatization (Santallier *et al.* 1994), an event dated by various methods at 385–380 Ma (Pin & Peucat 1986; Costa & Maluski 1988; Boutin *et al.* 1995). The migmatization ages point indirectly to rapid uplift and correspond well to stratigraphic data. The latter suggest the Eo-Variscan complexes were already exposed at the surface in Middle Devonian times. They are unconformably covered by Givetian unmetamorphosed sandstones and limestones that occur in a zone extending from the Armorican Massif through the northern Massif Central to the Vosges (cf. Faure *et al.* 1997).

The development of the Devonian Brévenne-Violay-Beaujolais rift in the NE part of the Massif Central (Sider & Ohnenstetter 1986; Sider *et al.* 1986; Ohnenstetter & Sider 1988; Leloix *et al.* 1999) is evidence for Devonian extension of the Eo-Variscan complexes. The Devonian rocks exposed in the rift comprise mafic and acidic volcanic rocks, gabbro, diabase, trondhjemite, serpentinized ultramafic rocks, siltstones, cherts greywackes and sandstones with gabbro clasts (cf. Leloix *et al.* 1999). They form several tectonic units and reveal variable metamorphic grade, from greenchist to amphibolite facies. The tectonic units are thrust to the NW, over gneissic basement (Affoux Gneiss). The entire nappe pile shows tectonic inversion of metamorphic grade, with metamorphism increasing from greenschist to amphibolite facies from the base to top of the profile and from the NW to the SE in plan view.

The deformed and metamorphosed Devonian rocks are covered by Late Tournaisian–Early Viséan volcanosedimentary formations, which are in part unmetamorphosed and undeformed, but locally underwent deformation and weak greenschist facies metamorphism due to post-thrusting dextral wrenching. They are, in turn, unconformably overlain by entirely undeformed and unmetamorphosed mid- and upper Viséan formations.

The evolution of the the Brévenne-Violay-Beaujolais Complex shows a number of similarities with the Central Sudetes and, in particular, with the Kłodzko Metamorphic Unit together with the Nowa Ruda Ophiolite. In this comparison the position of the Góry Sowie Massif can be hypothetically compared to that of the pre-Early Devonian Affoux Gneiss in the Brévenne rift basement. The Devonian rocks of the Brévenne rift sedimentary infill record extension that followed the Eo-Variscan convergence, although the age of deformation is a little different in both areas. In the Kłodzko Metamorphic Unit these processes took place during the Frasnian, whereas in the Brévenne-Violay-Beaujolais Complex they occurred at the Famennian/Tournaisian boundary (Pin & Paquette 1998). A common feature of both areas is early Carboniferous subsidence with the development of sedimentary basins above freshly deformed and metamorphosed complexes. However, the NE Massif Central recorded an intra-Viséan tectonic event, whereas in the Central Sudetes the folding of the Bardo Basin infill took place at the turn of Early and Late Carboniferous times.

East Sudetes: fragment of a Variscan collisional belt along the eastern margin of the Bohemian Massif

The East Sudetes lie within a Variscan collision zone at the eastern margin of the Bohemian Massif, that separates the Brunovistulian (or Brunosilesian) domain in the east and the units comprised in the Moldanubian and West and Central Sudetic (Lugicum) domains in the west (Matte *et al.* 1990; Schulmann *et al.* 1991; Fritz & Neubauer 1993; Schulmann & Gayer 2000). The Early Carboniferous collision followed westward subduction of the Brunovistulian passive margin, below the Moldanubian and Central Sudetic domains. The collision resulted in large-scale eastward overthrusting of the latter domains onto nappe complexes of the underthrust lower plate (e.g. Suess 1912; Matte *et al.* 1990; Schulmann & Gayer 2000). The Moravian, more southerly segment of this collision zone has been considered in the literature as different and distinct from that of the East Sudetes. However, a question arises if, indeed, there are no close analogies between the contents, structure and development of both segments of the Moravo-Silesian Zone.

Southern Moravian equivalent? In Moravia, the collision zone comprises three main elements thrust towards the east. The uppermost position in the thrust stack is occupied by the Moldanubian 'upper plate', exposed in the west, which overrides the Moravian Nappes and the parautochthonous Brunovistulian 'lower plate' extending far to the east. The Moravian supracrustal thrust sheets appear exotic with respect to the Brunovistulian basement and its sedimentary cover. They contain variegated metasediments, in early papers named the Inner and Outer Phyllites, separated from each other by the Biteš Orthogneiss (Suess 1912, 1926). The Inner Phyllites are greenchist facies metapelites with intercalations of crystalline limestones, quartzites, graphitic schists, metagreywackes and metabasites. The Outer Phyllite comprises amphibolite facies biotite- and two-mica paragneisses with abundant mica schists, crystalline limestones, amphibolites, quartzites, graphite schists and calc-silicate rocks. The age of this sequence is not exactly known; it is usually referred to as Neoproterozoic or Early Palaeozoic.

The adjacent sedimentary cover of the Brunovistulian domain, exposed within the Brno Massif and in the central part of the Svratka Window, overthrust by the Moravian Nappes, is represented by Middle Devonian to Tournaisian shallow water limestones resting directly on basal clastics and the crystalline basement (Dvorak 1995). The 586 Ma (Friedl *et al.* 1998) age of the Biteš Gneiss is contemporary with that of the Neoproterozoic granitoids from the Brunovistulian basement dated at 560–590 Ma (van Breemen *et al.* 1982; Friedl *et al.* 1998). However, as the geochemical characteristics of the Biteš Gneiss do not conform exactly to those of the Brno Massif granitoids (Hanžl 1994), the Moravian units may be a distinct, narrow domain, squeezed in between the Moldanubian and Brunovistulian elements (the upper and lower plates) and not detached and overthrust fragments of the subducted Brunovistulian margin.

Possible affinities between the East Sudetes and Moravia. The structure of the metamorphic ('Silesian') domain in the East Sudetes, seems to differ significantly from that in Moravia. Schulmann & Gayer (2000) contend that in the boundary zone of our Central Sudetes and the East Sudetes, the Central Sudetic 'upper plate' (Lugicum) is juxtaposed across the Staré Město Suture with a nappe complex derived directly from the subducted Brunovistulian passive margin. No additional tectonic elements between the Central Sudetes and the Brunovistulian-derived units are distinguished that could be correlated with the Moravian Nappes further south. Hence all of the metamorphic nappe units of the East Sudetes (Silesian units) are considered to be derived from the Brunovistulian domain.

Independently of its uncertain age, the lithological content of the supracrustal series in the high-grade metamorphic Velké Vrbno Nappe, occurring directly east of the Staré Město Suture, differs from that of the Devonian sequences exposed further east. Therefore, we follow earlier interpretations (e.g. Zapletal 1932, 1950; Mísař *et al.* 1983; Mísař & Urban 1995), in suggesting that the Velké Vbrno Nappe, as a likely northward continuation and/or structural equivalent of the Moravian Nappes, may represent a distinct terrane located between the Central Sudetes and the Brunovistulian domain.

Further east, the Branná succession has been considered as an original sedimentary cover of the Keprník Nappe (e.g. Schulmann & Gayer 2000), despite being completely detached from its basement. However, the different facies in the presumed Devonian metasediments in the Branná Group and those of the basinal Devonian Vrbno Group in the Desná Dome, and the contrastingly low grade of metamorphism in the Branná rocks compared to the amphibolite-grade metamorphism in both the adjacent Velké Vrbno and Keprník units, suggest that the Branná succession belongs to the 'exotic' Moravian domain between the Brunovistulian and Central Sudetic/Moldanubian domains. In such a model, the Velké Vrbno Nappe will be the upper member and the Branná Unit the lower member of a northern extension of the Moravian nappe pile, showing inverted metamorphic gradient. The Keprník Nappe, adjacent to the east, will thus represent the uppermost member in the separate stack of nappes that involve the reactivated Brunovistulian basement. Hence, the basal thrust of the Branná Unit will mask a cryptic suture between the Moravian and Brunovistulian domains.

The basin in which the Vrbno Group sediments were deposited can hardly be correlated with the Staré Město Suture zone. The latter comprises exclusively Cambrian–Ordovician mafic igneous rocks, as well as older paragneisses of unknown age and synorogenic Carboniferous tonalites. Also, clastic rocks at the base of the Vrbno Group indicate that it must have been deposited in an open basin in Early/Middle Devonian time. Therefore the Vrbno Group may represent sediments of a marine basin which separated the Brunovistulian and Moravian domains. By contrast, the Staré Město Belt corresponds to a separate oceanic basin delimiting the Central Sudetic and Moravian units.

Terranes in the Sudetes

Previous terrane models

Models suggesting several terrane configurations proposed since the early 1990s for the NE Bohemian Massif, can be differentiated into two groups. Some of the models are based on the assumption that the tectonics of the Sudetic area were shaped mainly by the Variscan tectonism during Devonian–Carboniferous times and that the main tectonostratigraphic units of the central European Variscan Belt, mostly as defined by Kossmat (1927), continue into the Sudetes. The other models assume a significant or even predominant role of Caledonian orogenic events during Ordovician through Early–Middle Devonian times and introduce exotic terranes into the Sudetes, that do not show affinities to the main Variscan tectonostratigraphic units.

The idea of a direct continuation of the main Variscan units (though not necessarily understood as mutually significantly diplaced tectonostratigraphic terranes) into the Sudetes has been presented systematically by Franke and co-authors (e.g. Behr *et al.* 1984; Franke 1989; Franke *et al.* 1993, 1995a; Franke & Żelaźniewicz 2000). They consider the West and Central Sudetes to be an easterly continuation of the Saxothuringian Zone, and the East Sudetes an extension of the Rhenohercynian Zone of the Variscides.

The terrane model of Matte *et al.* (1990, repeated in Matte 1991 and 1998 and mostly accepted by Pharaoh 1999), has also suggested a direct continuation into the Sudetes, along a roughly SW–NE trend, of the main Variscan terranes/tectonostratigraphic zones from the western and central Bohemian Massif, as well as from Germany and France. The Saxothuringian Zone of the German Variscides has, thus, been extended into the Lusatian Massif, most of the Karkonosze-Izera Massif, Kaczawa Unit and the tectonic substrate of the Góry Sowie Massif, including the Niemcza Shear Zone. The southern and eastern margins of the Karkonosze-Izera Massif, the eastern Kaczawa Unit and the Góry Sowie Massif, together with the surrounding ophiolites, have been incorporated into the Münchberg-Teplá Terrane. The basement of the Intra-Sudetic Basin, as well as the Nové Město and Kłodzko metamorphic units have been ascribed to the Barrandian Terrane of the central Bohemian Massif. The Gföhl Terrane of the Moldanubian domain of the SE Bohemian Massif has been extrapolated into the Orlica-Śnieżnik Massif of the Sudetes, whereas the East Sudetes (Jeseník metamorphic area and the Carboniferous basin to the east) have been included in the Moravian Terrane. Matte *et al.* (1990) considered that terrane assembly occurred during the Variscan orogeny at 390 to 300 Ma.

Another terrane configuration is implicit in the strike-slip tectonic model of the Sudetes by Aleksandrowski (1990, 1995). The eastern extension of the Saxothuringian domain, located in the part of the West and Central Sudetes south of the Intra-Sudetic Fault was assumed to continue into the Orlica-Śnieżnik Massif. The Kaczawa Unit and the Góry Sowie Massif may have been displaced on the latter fault from the Northern Phyllite Zone at the southern rim of the Rhenohercynian domain in Germany and from the area of the Mid-German Crystalline High, respectively. A combination of the effects of Devonian–Carboniferous strike-slip tectonics with the ideas of Matte *et al.* (1990) about the general NE–SW structural grain of the Sudetic collage was suggested by Aleksandrowski (1998) and Aleksandrowski *et al.* (2000, fig. 1).

Among hypotheses ascribing the formation of the Sudetes to the Caledonian orogeny, early concepts (Don 1984, 1990), though not conceived in terms of tectonostratigraphic terranes or mobilistic tectonic solutions, assumed nevertheless, that the portion of the West Sudetes located north of the Intra-Sudetic Fault had undergone the 'Hercynian' orogenic cycle, whereas that located south of the fault had showed an entirely different geological evolution, being consolidated by the Caledonian orogeny.

Ideas that, unlike in the Variscan belt proper, the Caledonian orogeny played a predominant role in the Sudetes during Ordovician through Early-Mid Devonian times (Oliver *et al.* 1993; Johnson *et al.* 1994), led these authors to place a Gondwana-Baltica, Caledonian Tornquist Suture along the Intra-Sudetic Fault zone and to recognize a number of (exotic?) pre-Variscan terranes in the West Sudetes, apparently unrelated to the well-established major Variscan tectonostratigraphic zones. The terranes included a central, 'Sudetic Batholith Terrane', comprising all the *c.* 500 Ma metagranites, surrounded and, partly, cross-cut by the adjacent Rudawy Janowickie, Kłodzko, Góry Sowie and Kaczawa terranes. A partly similar proposal (Cymerman & Piasecki 1994; Cymerman *et al.* 1997), incorporating also some elements from the concept of Matte *et al.* (1990), explained the evolution of the Sudetes in terms of superposition of successive orogenic cycles. Cymerman *et al.* (1997) distinguished a late Proterozoic, Lusatian Terrane from a Caledonian, Saxothuringian one, comprising the Karkonosze-Izera Massif and the western Kaczawa Unit. The Saxothuringian Terrane was believed to be separated by a Caledonian suture along the Rudawy Janowickie and the 'Kaczawa Line' from the mostly Silurian Central Sudetic Terrane, including the eastern Kaczawa Unit and the basement to the Intra-Sudetic and Świebodzice basins, the Kłodzko Metamorphic Unit and the circum-Góry Sowie ophiolites together with the Niemcza Shear Zone and the tectonic substrate to the Góry Sowie. The Central Sudetic Terrane, tectonically overlain by a high-grade Góry Sowie Terrane, was interpreted as having accreted in Early Carboniferous times to the Moldanubian Terrane, represented in the Sudetes by the Orlica-Śnieżnik Massif.

A distinct view on the Variscan tectonics of central Europe, including the Sudetes, has been held by Krohe (1996). He argued that the original Armorica- and Avalonia-derived terranes in this area were assembled during Late Ordovician to Early Devonian times and were later intensely sheared, displaced and reshuffled along numerous strike-slip faults by Late Devonian–Early Carboniferous intracontinental tectonism. As a result, the recent puzzle of small fault-bounded crustal blocks comprising the central European Variscides define an assemblage of splinters and slivers broken off from original larger terranes, whose fragmentation precludes reconstruction of any consistent primary larger units or zones.

A comprehensive critical assessment of the evidence invoked in support of the Caledonian orogeny in the Sudetes and of the terrane arrangement suggested by Oliver and collaborators (Oliver *et al.* 1993; Johnston *et al.* 1994) has recently been produced by Aleksandrowski *et al.* (2000; see also Aleksandrowski 1994 and Żelaźniewicz & Franke 1994). In the light of available data, most of this evidence and of the conclusions based on it (in particular, the location of the Tornquist Suture in the Sudetes) cannot be sustained. Similar reservations apply to the model of Cymerman & Piasecki (1994) and Cymerman *et al.* (1997). Their terrane distribution also overlooked the significance of the Intra-Sudetic Fault, whereas a number of the inferred terrane boundaries do not seem to follow any real geological lines (e.g. their southern and NW boundaries of the Central Sudetic Terrane and the boundary between their Lusatian and Saxothuringian terranes). The regional kinematic model of of Cymerman & Piasecki (1994) and Cymerman *et al.* (1997), assuming, for example significant southward tectonic transport of the Góry Sowie allochthonous massif does not fit the regional tectonic context. On the other hand, these authors rightly related the Orlica-Śnieżnik Massif to the Gföhl Unit of the Moldanubian Zone (after Matte *et al.* 1990) and assembled several units into their Central Sudetic Terrane.

Among the terrane models published to date, that of Matte *et al.* (1990) most closely fits the available geological data. Our criticisms concern a few particular, relatively detailed solutions adopted in it. The Münchberg-Teplá Terrane of these authors has already been discussed critically (Mazur & Aleksandrowski 2001*a*). This terrane does not appear to continue, as assumed by Matte *et al.* (1990), north of the Intra-Sudetic Fault into the eastern Kaczawa Unit, the Góry Sowie Massif and, in particular, the Central Sudetic Ophiolites, as the latter show a different age from that of the mafic rocks in the Münchberg-Teplá (or South Karkonosze; Mazur & Aleksandrowski 2001*a*) Terrane. The Niemcza Shear Zone, included by Matte *et al.* (1990) in the Saxothuringian Terrane, in our opinion does not seem to fit there. Matte *et al.* (1990) did not extend their model onto the NE Fore-Sudetic Block.

Terrane boundaries: tectonic sutures and strike-slip shear zones

Rock associations typical of tectonic suture zones occur in the Sudetes, generally, within at least three areas/zones. The first one extends along the southern and eastern margins of the Karkonosze-Izera Massif. It is typified by Cambrian/Ordovician protolith ages of MORB-type basalt complexes and by blueschist facies metamorphism in late Devonian time. It resulted from the closure of the Saxothuringian oceanic basin. The second suture zone comprises the Central Sudetic ophiolitic bodies, which show Late Silurian(?) to Mid-Devonian protolith ages and have experienced pre-Famennian deformation and metamorphism. To which Variscan suture this ophiolite belt corresponds is, as yet, unclear. The third suture zone is the Staré Město Belt with Cambrian/Ordovician ages of igneous protoliths, metamorphosed and deformed during Carboniferous collision. This suture zone can be either correlated with the Rheic (Rheno-Hercynian) Suture, bounding the Rheno-Hercynian domain of the Variscides (i.e. Finger *et al.* 1998), considered a part of a suture related to the SE branch of the Variscan orogen (cf. Matte 1986, 1991; Matte *et al.* 1990) or can constitute a separate, local suture between the Central Sudetic domain and the Brunovistulian Block. One candidate for a suture zone is the boundary between the Nové Město Belt and the Orlica-Śnieżnik Massif. A hypothetical and cryptic suture, may be concealed below the Świebodzice Basin and/or the Góry Sowie Gneiss Massif and related to the Kaczawa thrust stack. Another candidate for a cryptic suture is the basal thrust of the Branná Unit in the East Sudetes. The above sutures almost always follow thrust zones/belts (sometimes, as is the case with the East Karkonosze or the NE boundary of the Nové Město Belt, the original thrusts were later reactivated in normal or strike-slip regime), corresponding to terrane boundaries. The remaining terrane boundaries in the Sudetes are main strike-slip ductile shear or fault zones, notably the Intra-Sudetic Fault zone and the Niemcza and Skrzynka shear zones (Aleksandrowski *et al.* 1997) or a combination of thrust with strike-slip tectonics, as in the case of the Kłodzko Metamorphic Unit.

Terranes

From the preceding overview of the particular structural units and discussion of various aspects of their geology, the Sudetes may be divided into distinct tectonostratigraphic terranes of different provenance and evolution. From NW to SE, we propose the following tectonostratigraphic terranes to be distinguished on the NE margin of the Bohemian Massif (Fig. 10).

(1) The Lusatia-Izera Terrane comprises the Lusatian Massif and the Kowary-Izera Unit of the Karkonosze-Izera Massif, which both correspond to crystalline basement of the passive margin of Saxothuringian epicontinental area. The Görlitz Slate Belt and the Ještěd Unit are made up of Variscan-deformed sedimentary successions deposited on this passive margin.

(2) The South-East Karkonosze Terrane is 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 Saxothuringian oceanic basin and the adjacent oceanic basin floor, with the latter overthrust upon the basin infill during Late Devonian–Early Carboniferous times. This terrane contains a fragment of the Saxothuringian Suture.

(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 (Seston *et al.* 2000). It contains a Palaeozoic rift-to-oceanic volcanosedimentary succession involved in a Variscan accretionary prism, which formed during the latest Devonian-earliest Carboniferous(?). The affinities of the Kaczawa succession are still unclear (Saxothuringian or Rheic oceanic basin infill?).

(4) The composite Góry Sowie–Kłodzko Terrane includes the Góry Sowie Massif and the NE part of the Kłodzko Metamorphic Unit, the Świebodzice and Bardo basins, the Central Sudetic ophiolites, the Niemcza Shear Zone, and NE part of the basement to the Intra-Sudetic Basin. These units represent a variety of palaeotectonic environments, including subducted continental crust (Góry Sowie), Middle Devonian passive margin (Kłodzko Metamorphic Unit), oceanic crust (Central Sudetic ophiolites) and synorogenic basins (Świebodzice and Bardo). The principal common feature for the units of this terrane is Eo-Variscan, pre-Upper Devonian deformation, metamorphism and exhumation, which took place significantly earlier than in other Sudetic terranes. This terrane shows some affinities with parts of the NE Massif Central and Armorican Massif in France as well as with the Teplá-Barrandian Terrane that extends well beyond the Sudetes into the central Bohemian Massif.

(5) The Teplá-Barrandian Terrane, in its Sudetic segment, is interpreted here to

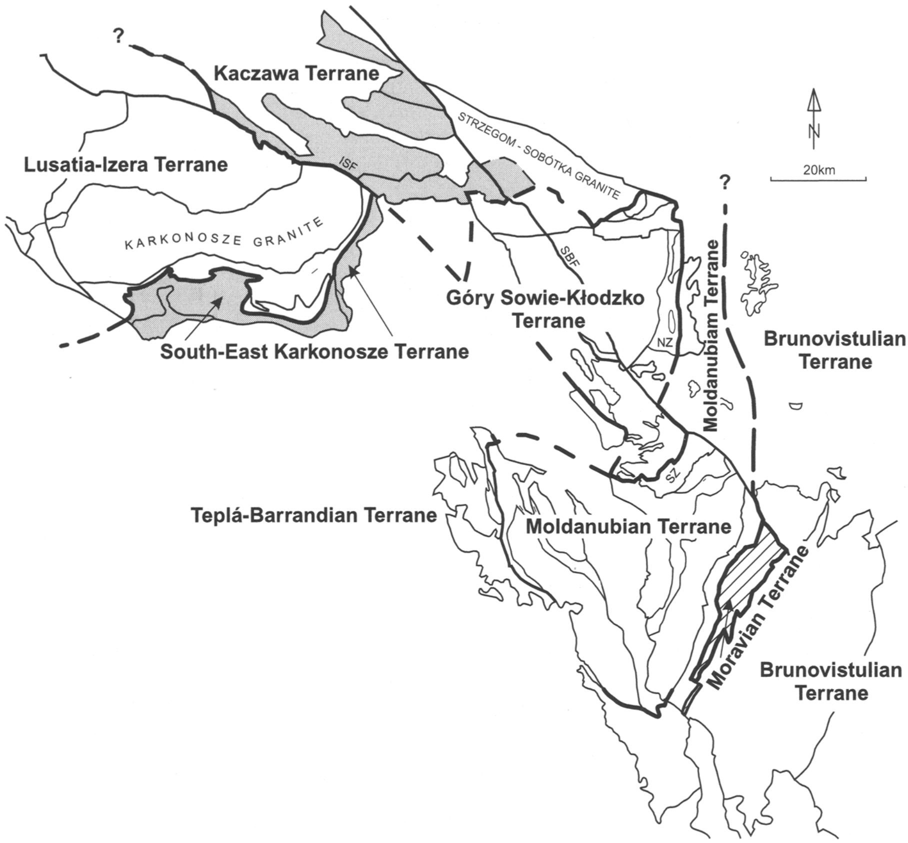


Fig. 10. Tectonostratigraphic terranes in the Sudetes.

incorporate the Nové Město Belt, Zábřeh Unit and the SW part of the basement of the Intra-Sudetic Basin (cf. Mazur & Aleksandrowski 2001*b*), which crops out in the SW part of the Kłodzko Metamorphic Unit. It cannot be excluded that the Góry Sowie-Kłodzko Terrane is part of the Teplá-Barrandian.

(6) The Moldanubian (Gföhl) Terrane in the Sudetes comprises the Orlica-Śnieżnik Massif, the Kamieniec Metamorphic Belt and the Staré Město Belt. Its western boundary with the Góry Sowie-Kłodzko Terrane bounds the sinistral Niemcza and Skrzynka shear zones; with the Teplá-Barrandian Terrane it is a primary thrust, later converted into a dextral ductile fault, and with the Moravian Terrane it is a thrust belt. The rock complexes of the terrane display prominent Early Carboniferous collision-related medium- to high-grade (high pressure-high temperature and high temperature-medium to low pressure) metamorphism and deformation, analogous to that of the Gföhl Terrane of the Moldanubian domain in the Bohemian Massif further south.

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

(8) The Brunovistulian Terrane comprises the Keprník Nappe and Desná Dome and the successive, easterly located units of the East Sudetes, including the Culm basin and the coal-bearing molasse basin at the East-Sudetic foreland, both basins established on Brunovistulian basement of Avalonian affinities (Friedl *et al.* 2000; Finger *et al.* 2000). Within the Fore-Sudetic Block, the Brunovistulian Terrane includes also the Strzelin Crystalline Massif of similar characteristics.

The proposed terrane distribution is in many respects similar to those earlier suggested by

Matte *et al.* (1990), Cymerman & Piasecki (1994) and Cymerman *et al.* (1997). However, certain solutions incorporate new field and laboratory data and use different criteria to distinguish the tectonostratigraphic terranes.

Discussion

'Oceanic' Kaczawa Terrane and the Central Sudetic ophiolites: Saxothuringian or Rheic realm? Similar geological characteristics of the Kaczawa and South Karkonosze Terranes suggest that they may represent a common 'oceanic' terrane derived from the Saxothuringian ocean. On the other hand, the correlation between them is hampered by the still fairly incomplete knowledge of the stratigraphy of both areas and by the fact that they are separated by a major strike-slip shear zone of the Intra-Sudetic Fault. Large-scale dextral displacement up to about 300 km during Late Devonian-Carboniferous times was proposed for this fault zone (Aleksandrowski 1990, 1995). The displacement was believed to have moved the Kaczawa Unit and Góry Sowie Massif from their original locations thought to be the Northern Phyllite Zone and Mid-German Crystalline High, respectively, of the German Variscides (Figs 1 and 2) and to have emplaced them in their present position, adjacent to units of different provenance SW of the Intra-Sudetic Fault (Aleksandrowski 1990, 1995; Aleksandrowski *et al.* 1997). Indeed, there is a general resemblance between the south Karkonosze unit and that of the Kaczawa terrane. Likewise, correlation of the Kaczawa and Góry Sowie with the Northern Phyllite and Mid-German Crystalline High, still cannot be rejected, and if correct, would imply a possible linkage between the Central Sudetic ophiolites and similar bodies of the Lizard-Rhenish suture (see discussion below).

Góry Sowie–Kłodzko Terrane: deformed, exhumed and subsequently rifted prior to the main collision. The Central Sudetes within the Góry Sowie–Kłodzko Terrane are typified by certain features that make this area different from all other segments of the Bohemian Massif. Unlike the Teplá-Barrandian domain or Münchberg Massif, the Central Sudetes contain Late Silurian/Early Devonian high pressure granulites in the Góry Sowie Massif, comparable to the type I granulites of Pin & Vielzeuf (1988) considered as typical of Eo-Variscan complexes. The Central Sudetes also record late Silurian(?)-Devonian rifting (up to the oceanic stage), documented by approximately 400 Ma ages of the circum-Góry Sowie ophiolites (Żelaźniewicz *et al.* 1998). Similarly, no pre-Famennian angular unconformity on top of the obducted ophiolites and mid-Devonian metasediments is known from other places in the Bohemian Massif.

Is the Góry Sowie–Kłodzko Terrane in the Central Sudetes an exotic element in the Bohemian Massif, as tacitly assumed by Cymerman & Piasecki (1994) and Cymerman *et al.* (1997)? In our opinion, a better solution is to attempt to correlate this area with appropriate Variscan segments outside the Sudetes. On the basis of numerous mutual similarities, the Góry Sowie–Kłodzko Terrane can be compared to the basement of the North Bohemian Basin within the Teplá-Barrandian Terrane, to the Münchberg Massif and, in particular, to the 'Moldanubian Zone' in the NE part of the French Massif Central and southern Armorican Massif. If such a parallel were correct, the Central Sudetic Ophiolite could be expected to represent an obducted relict of closure of a local basin underlain by oceanic crust, probably of back-arc origin. The formation of this basin would reflect Early Devonian extension and rifting, otherwise relatively widespread in the Variscan belt. The main difficulty, however, in trying to correlate the Central Sudetes with the NE Massif Central is the lack of a direct spatial link between the two areas.

An alternative interpretation for the Central Sudetic Ophiolite, based on its protolith age, is to locate it in the Rheno-Hercynian (Rheic) suture (cf. Finger *et al.* 1998). The recent dating of the Lizard Ophiolite (Clark *et al.* 1998; 397 ± 2 Ma, U–Pb zircon) yielded almost identical results to those obtained from the Central Sudetic Ślęża Ophiolite. The Rheic suture may continue into the Sudetes either due to oroclinal bending of the Variscan belt (e.g. Engel & Franke 1983; Franke 1989) or as the result of dextral displacement on large-scale strike-slip faults (Aleksandrowski 1990, 1995).

Irrespective of the assumed interpretation, the Early Devonian high-grade metamorphism in the Góry Sowie must have been the effect of continental crust subduction due to the collision of Avalonia and Armorica from Silurian to Devonian times. However, as no similar ages of high-grade metamorphism have so far been reported from the Rheno-Hercynian or Mid-German Crystalline zones, it is not possible to correlate them with the Sudetes.

Niemcza and Skrzynka strike-slip shear zones: an intra-Central Sudetic terrane boundary. The Central Sudetes are cut by the Niemcza and Skrzynka late-orogenic sinistral shear zones

(Mazur & Puziewicz 1995; Cymerman 1996; Aleksandrowski *et al.* 1997). In separating the Góry Sowie–Kłodzko Terrane to the west and north, from the Orlica-Śnieżnik Massif and the Kamieniec Metamorphic Belt, i.e. the Gföhl Terrane to the east and south, they separate the NW domain with features similar to those of the NE Massif Central and Teplá-Barrandian from the SE domain which is analogous in many respects to the Moldanubian zone in the Moravia and Austria. The Niemcza and Skrzynka shear zones can be considered together as a sinistral shear belt that splits the Central Sudetes into terranes of dissimilar deformation, metamorphism and exhumation ages. The sinistral displacements along the Niemcza and Skrzynka shear zones presumably accommodated much strain and protected the area west of them from intense tectonism caused by the collision of the Moldanubian and Moravian terranes to the east.

In contrast to other Central Sudetic units, which had already undergone tectonism and exhumation prior to the Late Devonian, the Orlica-Śnieżnik Massif mainly records the effects of the Carboniferous convergent stage. This may have resulted from possible obliteration of any intra-Devonian tectonic events by high-grade metamorphism that affected the Orlica-Śnieżnik rocks during Late Devonian–Early Carboniferous times. Possible intra-Devonian exhumation of some subunits of the Orlica-Śnieżnik Massif is consistent with the largely neglected discovery by Kasza (1964) of unmetamorphosed conglomerates of unknown age wedged between thrust slices involving the Śnieżnik crystalline rocks.

Affinities of the Orlica-Śnieżnik Massif and Kamieniec Metamorphic Belt with the Moldanubian domain of the SE Bohemian Massif. The analogies between the Orlica-Śnieżnik Massif and the Gföhl Nappe in the Czech and Austrian parts of the Moldanubian Zone were described by Matte *et al.* (1990). Further evidence that the two areas are equivalent is provided by new zircon SHRIMP dating of gneisses from the Orlica-Śnieżnik and from the Gföhl units (Friedl *et al.* 2000; Turniak *et al.* 2000). The gneissic protoliths in both areas show nearly identical ages of around 500 Ma, and the high temperature and moderate to low pressure metamorphism, resulting in migmatization, has been determined, again in both areas, at 340 Ma. The rocks of the Kamieniec Metamorphic Belt on the Fore-Sudetic Block also show numerous similarities to Gföhl rocks exposed further south. The higher-grade Kamieniec metamorphic complex is in many respects analogous to the mica schist zone at the sole of the Moldanubian nappes.

The prolongation of the collision zone from the East Sudetes into the Fore-Sudetic Block. Both terrane boundaries from the East Sudetes (i.e. that separating the Moldanubian and Moravian, as well as that between the Moravian and Brunovistulian terranes) presumably continue to the north, over the Fore-Sudetic Block. The Moldanubian/Moravian boundary follows the eastern limit of the Niedźwiedź Massif, whereas the Moravian/Brunovistulian one is presumably buried below Cenozoic deposits further to the east. The largest outcrop zone of crystalline basement in the eastern part of the Fore-Sudetic Block is the Strzelin Crystalline Massif located to the east of that of Niedźwiedź. The Strzelin Massif rocks show an overall similarity to the basement of the Desná Dome, in containing both Devonian quartzites of imprecise age and Neoproterozoic orthogneisses dated at 600–570 Ma (Oberc-Dziedzic *et al.* 2001). Inherited zircons from these gneisses yielded ages of around 1230 and 1880 Ma (Oberc-Dziedzic *et al.* 2001), pointing to their possible Avalonian affinities.

Possible provenance of the Brunovistulian Terrane. Currently, a lively discussion continues about the problem whether the Brunovistulian microcontinent represents an easternmost Avalonian fragment (Moczydłowska 1997; Friedl *et al.* 2000, Finger *et al.* 2000), or a distinct Gondwana-derived terrane, which docked to Baltica during Early Cambrian times (Belka *et al.* 2000; Valverde-Vaquero *et al.* 2000). The two alternative solutions are based on different interpretation of palaeontological, geochronological and palaeomagnetic data. Both of these solutions imply the existence of an extensive ocean between the Moldanubian and Brunovistulian domains during Early Palaeozoic and Devonian times. If such an extensive oceanic domain existed between the Moldanubian and Brunovistulian terranes during the Early Palaeozoic, which of the two basins that later closed along the eastern edge of the Bohemian Massif could have been this ocean? Most probably, it was not the basin that separated the Moravian and Brunovistulian terranes, since this one opened only as late as the Devonian. Therefore, the remnant of the postulated ocean should be the Staré Město Suture.

Rotation of the Brunovistulian Terrane? The terrane model proposed here does not take into account the clockwise rotation by 90° to 135° of the Brunovistulian basement with respect to the German segments of the Variscan belt, postulated by Krs *et al.* (1994) and Tait *et al.* (1996) to have occurred since the Late Devonian. This rotation was used by Tait *et al.* (1996) to support the oroclinal model of the eastern termination of the belt. However, the Devonian limestones used for magnetic measurements have undergone significant tectonic strain associated with ductile thrusting and intense folding (Kettner 1949; Kalvoda & Melichar 1999), and we believe this has not been sufficiently accounted for in both the interpretations assuming significant rotation. Hence, the problem of possible rotation requires further study.

Conclusion: the accretionary setting of the Sudetic terranes

The Sudetic segment of the Variscan Orogenic Belt formed by accretion of the following terranes: the Moldanubian (Gföhl), Góry Sowie–Kłodzko and NE Teplá-Barrandian, making up the Central Sudetes and the Lusatia-Izera and Brunovistulian terranes located in the West and East Sudetes, respectively. Between these large units are smaller terranes compressed along their boundaries, namely the Moravian Terrane between the Moldanubian and Brunovistulian, and the SE Karkonosze and Kaczawa terranes between the Lusatia-Izera and Teplá on one side and the Góry Sowie–Kłodzko on the other side. The Moravian Terrane in the East Sudetes is inferred to be an extension of the likewise named terrane known from the tectonic windows in southern Moravia, whereas the SE Karkonosze and Kaczawa terranes probably represent the Saxothuringian oceanic realm.

Amalgamation of the Sudetic segment of the Variscan Belt continued from Late Silurian to Early Carboniferous times. It was not a continuous process of terrane convergence, but rather a sequence of several distinct orogenic events separated by stages of extension and rifting. In the Late Silurian an amalgamation of the composite Góry Sowie–Kłodzko Terrane began (as inferred by analogy with the situation in the Massif Central and Armorica) during the Eo-Variscan orogenic cycle. The Góry Sowie Massif represents a fragment of continental crust that had been deeply subducted. By analogy with the geological relationships in the Massif Central and Brittany, there may have been NW-directed (?) subduction of a small oceanic domain together with a fragment of a Gondwana-derived continental crust below the southern, active margin of Armorica (Faure *et al.* 1997).

Following Eo-Variscan compression, Devonian extension took place in various segments of the Variscan Belt. In the Sudetes it resulted in opening of two basins: the Central Sudetic oceanic basin floored by oceanic crust, now preserved as the Central Sudetic Ophiolite, and the Vrbno Group basin, separating the Moravian and Brunovistulian terranes. In Middle to Late Devonian times, the Central Sudetic oceanic basin was closed and its floor partly obducted as the Central Sudetic Ophiolite. At the same time the Kłodzko Metamorphic Unit underwent deformation and metamorphism. Soon afterwards, during the Late Devonian, a new sedimentary cycle commenced in the NW Central Sudetes, recorded by deposition in the Bardo Basin. Simultaneously, in the western part of the Sudetes a SE-directed subduction of the Saxothuringian Ocean continued below the active margin of the already amalgamated Teplá-Barrandian and Góry Sowie-Kłodzko terranes. In the east, the subduction of the oceanic basin separating the Moldanubian and Moravian terranes, probably commenced in Late Devonian times.

At the turn of Devonian/Carboniferous times a collision started between the Saxothuringian epicontinental domain, represented in the Sudetes by the Lusatia-Izera Terrane, and the already amalgamated Teplá-Barrandian and Góry Sowie–Kłodzko terranes, which brought about the Saxothuringian Suture zone. In the West Sudetes this also led to northwestward thrusting in the Karkonosze-Izera Massif, including the overthrusting of the SE Karkonosze Terrane. The accretion of the Sudetic area was completed by early/mid Carboniferous times, when collision between the Moldanubian Terrane (at that time already amalgamated with the West and Central Sudetes) and the Moravian and Brunovistulian terranes occurred. The Staré Město Suture zone developed at that time, together with the nappe structure of the East Sudetes.

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