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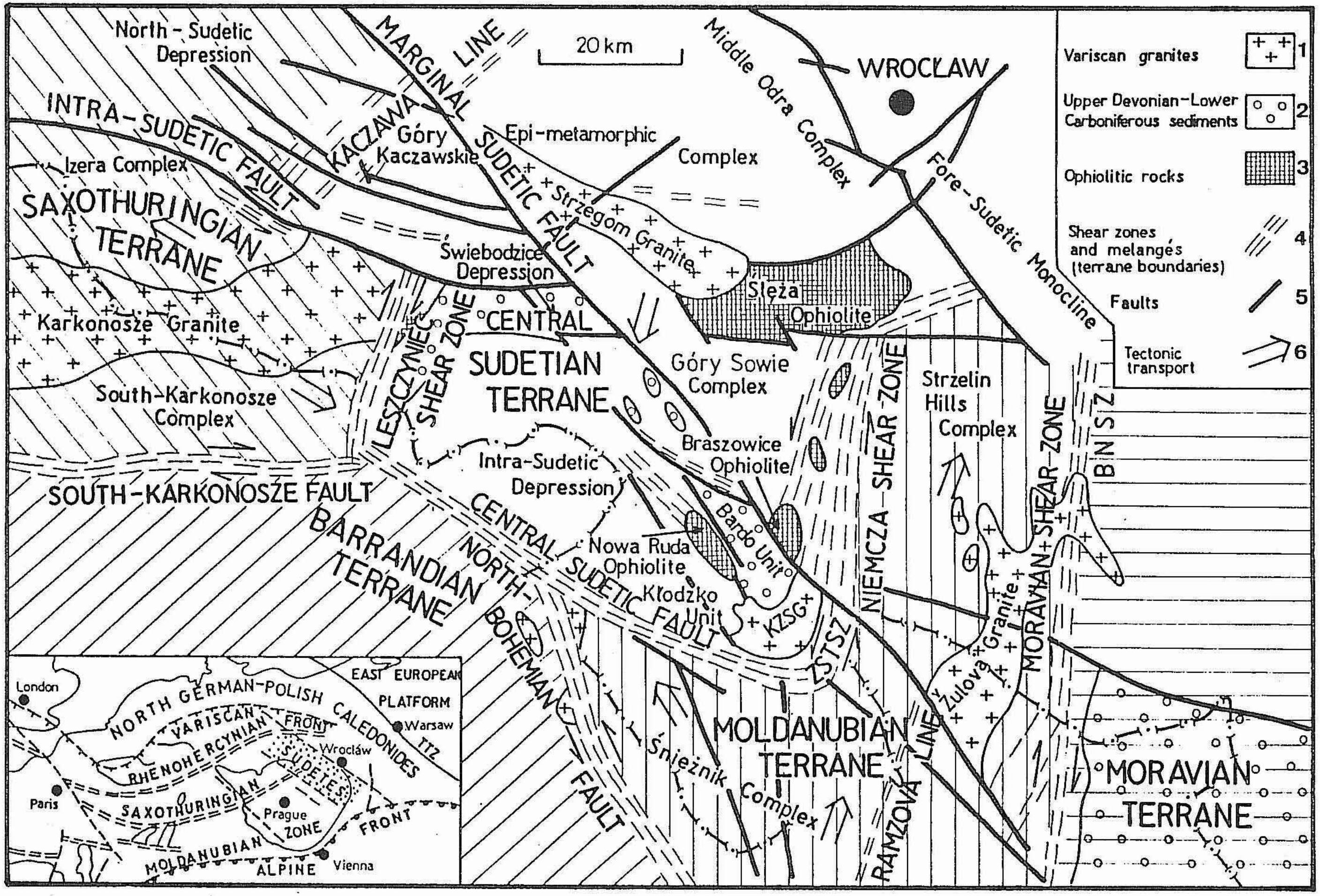
The terrane concept in the Sudetes, Bohemian Massif

We present a new division of the pre-Permian rocks of the Sudetes into five distinct terranes, differing from those previously described from the Bohemian Massif and the Sudetes. These are: a newly redefined, composite Central Sudetian Terrane, surrounded, from northwest to southeast, by the Saxothuringian, Barrandian, Moldanubian and Moravian Terranes. The terrane boundaries are dominantly large-scale ductile shear zones. From northwest to southeast, these are the Kaczawa line, the Intra-Sudetic Fault, the Leszczyniec shear zone, the South Karkonosze fault system, the North Bohemian fault zone, and the ductile shear zones of Złoty Stok – Trzebieszowice, Niemcza, Brzeg – Nysa and Moravian. The present disposition of the terranes and their boundaries reflect earlier Caledonian plate boundaries strongly reworked and modified by later Variscan (or Silurian?) plate interaction.

INTRODUCTION

Many orogenic belts preserve a record of various and complex combinations of compressional, extensional, and wrenching tectonics affecting one or another part of the orogen at different times during its evolution. In the last decade, there has been a growing acceptance that some orogenic belts are composed of suspect terranes that have originated far from their present location (P. J. Coney *et al.*, 1980; Z. Ben-Avraham *et al.*, 1981; D. L. Jones *et al.*, 1982; A. Nur, 1983; J. D. Keppie, 1989; D. G. Howell, 1989). Two major implications follow from the displaced terrane concept. Through much of geological time, terrane accretion may have been the common cause of orogeny (A. Nur, 1983; J. D. Keppie, 1989). All orogenic belts are therefore likely to contain cryptic strike-slip faults with very large displacements, which means that where displaced terrane boundaries exist it is not possible to infer original spatial relationships from present day cross-strike sections. The terrane concept has greatly modified our ideas of continental accretion and may be considered one of the major modifications of plate tectonics models. The more recent definition of a terrane is as "...an area characterized by an internal continuity of geology that is bounded by faults, melanges representing a trench complex, or cryptic suture zones


North-Sudetic Depression
MARGINAL LINE
20 km
Middle Odra Complex
WROCŁAW
INTRA-SUDETIC FAULT
KACZAWA
Góry Kaczawskie
SUDETIC FAULT
Epi-metamorphic Complex
Izera Complex
SAXOTHURINGIAN TERRANE
Strzegom Granite
Fore-Sudetic Monocline
Świebodzice Depression
Ślęża Ophiolite
Karkonosze Granite
CENTRAL
LESZCZYNIEC SHEAR ZONE
SUDETIAN TERRANE
Góry Sowie Complex
South-Karkonosze Complex
Strzelin Hills Complex
Braszowice Ophiolite
Intra-Sudetic Depression
NIEMCZA-SHEAR ZONE
MORAVIAN SHEAR ZONE
BNSZ
SOUTH-KARKONOSZE FAULT
BARRANDIAN TERRANE
CENTRAL SUDETIC FAULT
NORTH-BOHEMIAN FAULT
Nowa Ruda Ophiolite
Bardo Unit
Kłodzko Unit
KZSG
ZSTSZ
Żulova Granite
MOLDANUBIAN TERRANE
RAMZOVA LINE
Śnieżnik Complex
MORAVIAN TERRANE
Variscan granites 1
Upper Devonian-Lower Carboniferous sediments 2
Ophiolitic rocks 3
Shear zones and melangés (terrane boundaries) 4
Faults 5
Tectonic transport 6
London
Paris
NORTH GERMAN-POLISH CALEDONIDES
EAST EUROPEAN PLATFORM
Warsaw
TTZ
VARISCAN FRONT
RHENOHERCYNIAN
SUDETES
Wrocław
SAXOTHURINGIAN
Prague
ZONE
MOLDANUBIAN
ALPINE FRONT
Vienna

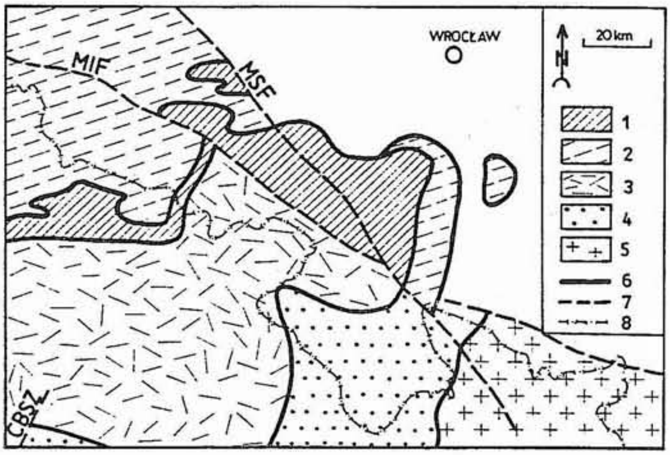


Fig. 2. Terranes in the NE part of the Bohemian Massif by P. H. Matte *et al.* (1990; modified)
1 — Münchberg - Tepla Terrane; 2 — Saxothuringian Terrane; 3 — Barrandian Terrane; 4 — Gföhl Terrane; 5 — Moravian Terrane; 6 — terrane boundary; 7 — main faults; 8 — state boundary; CBSZ — Central Bohemian shear zone; MIF — Main Intra-Sudetic Fault; MSF — Marginal Sudetic Fault
Terrany w NE części masywu czeskiego według P. H. Matte'a i in. (1990; zmodyfikowane)
1 — terran Münchbergu - Tepli; 2 — terran saksoturyngski; 3 — terran Barrandianu; 4 — terran Gföhl; 5 — terran morawski; 6 — granica terranu; 7 — główne uskoki; 8 — granica państwowa; CBSZ — środkowoczeska strefa ścinań; MIF — główny uskok śródsudecki; MSF — brzeżny uskok sudecki

across which neighbouring terranes may have a distinct geologic record not explicable by facies changes (i.e. exotic terranes), or may have a similar geological record (i.e. proximal terranes) that may only be distinguished by the presence of a terrane boundary representing telescoped oceanic lithosphere..." (J. D. Keppie, 1989). Terranes are fault-bounded entities and have all scale from small seamounts and oceanic arcs to oceanic plateaus or microcontinents (J. F. Dewey *et al.*, 1986). In short, adjacent displaced terranes must either have incompatible geology, or show evidence of having once been separated by an ocean.

In applying the terrane concept to the Variscan belt, a number of difficulties are encountered (W. Franke, 1989; P. H. Matte *et al.*, 1990; P. H. Matte, 1991). One of these is deciphering boundaries of suspect terranes. A major problem associated with the infusion of the terrane concept into current thinking on the European Variscan Belt continues to be the simple definition of exactly what and where are the terrane boundaries. Reactivation of primary terrane boundaries during later deformational events has obscured original accre-

Fig. 1. Map of tectonostratigraphic terranes from the Sudetes, and their tectonic boundaries
BNSZ — Brzeg - Nysa shear zone; ZSTSZ — Złoty Stok - Trzebieszowice shear zone; KZSG — Kłodzko - Złoty Stok granitoids
Mapa terranów tektonostratygraficznych z obszaru Sudetów i ich granice
BNSZ — strefa ścinań Brzegu - Nysy; ZSTST — strefa ścinań Złotego Stoku - Trzebieszowic; KZSG — granitoidy kłodzko-złotostockie; 1 — granity waryscyjskie; 2 — osady górnego dewonu-dolnego karbonu; 3 — ofiolity; 4 — strefy ścinań, melanże (granice terranu); 5 — uskoki; 6 — transport tektoniczny

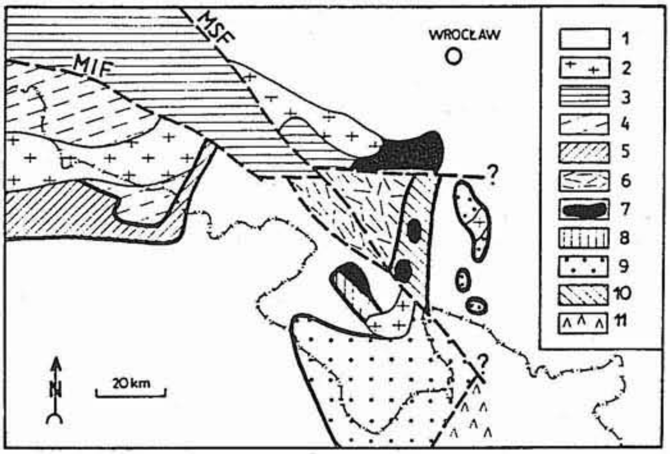


Fig. 3. A terrane map of the Sudetes according to G. J. H. Oliver *et al.* (1993; modified)
1 — Carboniferous and younger sediments; 2 — Variscan granitoids; 3 — Kaczawa Terrane; 4 — Izera complex (western part of the Sudeten batholithic terrane); 5 — Rudawy Janowickie Terrane; 6 — Góry Sowie Terrane; 7 — Ślęża and Nowa Ruda ophiolites; 8 — Kłodzko Terrane; 9 — Śnieżnik complex (eastern part of the Sudeten batholithic terrane); 10 — Niemcza Zone; 11 — Moravian Terrane; other explonations as in Fig. 2
Mapa terranów sudeckich według G. J. H. Olivera i in. (1993; zmieniona)
1 — skały osadowe karbonu i młodsze; 2 — granitoidy waryscyjskie; 3 — terran kaczawski; 4 — kompleks izerski (zachodnia część batolitowego terranu sudeckiego); 5 — terran Rudaw Janowickich; 6 — terran sowiogórski; 7 — ofiolity Ślęży i Nowej Rudy; 8 — terran kłodzki; 9 — kompleks śnieżnicki (wschodnia część batolitowego terranu sudeckiego); 10 — strefa Niemczy; 11 — terran morawski; pozostałe objaśnienia jak na fig. 2

tionary relationships. Terrane boundaries, especially in the ductile lower crust, are usually overprinted by magmatic and deformational processes that take place in the post-orogenic, post-docking phase of orogenic collapse (J. B. Platt, 1986; J. F. Dewey, 1988). As a result, signs of docking and fault zones are found in the rigid upper crust only, while the ductile lower crust shows "lamellae" (R. Meissner, 1989), interpreted as a consequence of strong deformational patterns.

In the northeastern part of the Bohemian Massif (inset in Fig. 1), the Sudetian orogenic belt abounds in small but fundamentally different tectonostratigraphic domains (suspect terranes). Some boundaries between these domains have been reworked during later orogenic events to such an extent, that for many years there has been no consensus on whether they were tectonic or stratigraphic. Until a few years ago, few ductile shear zones have been recognized and fabrics indicating the sense of shear (other than fold vergence) have been seldom recorded from any boundary. In recent years, the terrane concept has been applied to the Sudetes (P. H. Matte *et al.*, 1990; Z. Cymerman, 1991*a*; G. J. H. Oliver *et al.*, 1993), where it now poses the problem of what terrane boundaries are and where they are (Figs. 1, 2, 3). Most recent workers interpret the Palaeozoic orogenic evolution of the Bohemian Massif and the Sudetes using the concept of terrane accretion during the Variscan orogeny (A. Grocholski, 1987; P. H. Matte *et al.*, 1990; P. H. Matte, 1991; W. Franke, O.

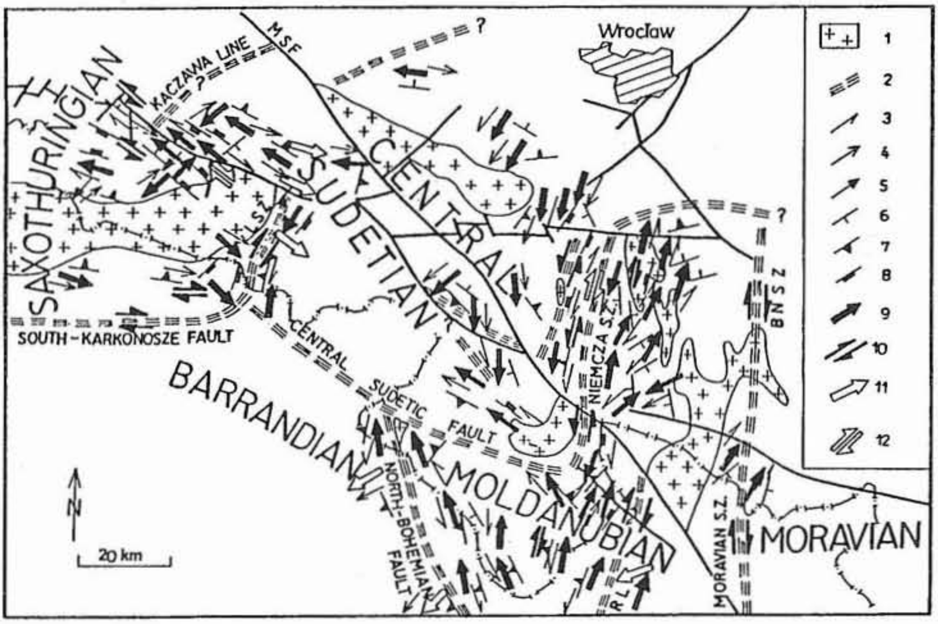


Fig. 4. Structural-kinematic sketch-map of all Sudetian terranes, and their boundaries
1 — late- and post-tectonic Variscan granitoids; 2 — main tectonic zones (ductile shear zones, melanges, and brittle fault zones); stretching lineation with plunge angle up: 3 — to 35°, 4 — to 65°, 5 — to 90°; penetrative foliation with dip angle: 6 — to 35°, 7 — to 65°, 8 — to 90° ; 9–10 — sense of shear: penetrative, older on gently (9) to steeply (10) dipping shear zones; 11–12 — younger, extensional and moderately (11) to steeply (12) dipping shear zones; LSZ — Leszczyniec shear zone; RL — Ramzova tectonic line; other explanations as in Figs. 1 and 2
Uproszczona mapa strukturalno-kinematyczna wszystkich terranów sudeckich i ich granic
1 — granitoidy waryscyjskie późno- i post-tektoniczne; 2 — główne strefy tektoniczne (podatne strefy ścinań, melanże, strefy uskokowe); lineacje ekstensyjne o kącie nachylenia: 3 — do 35°, 4 — do 65°, 5 — do 90°; penetratywna foliacja o kącie upadu: 6 — do 35°, 7 — do 65°, 8 — do 90°; 9–10 — zwroty ścinań penetratywne, starsze — na łagodnie (9) i stromo (10) zapadających strefach ścinań; 11–12 — młodsze, ekstensyjne: łagodnie (11) i stromo (12) zapadające strefy ścinań; LSZ — strefa ścinań Leszczyńca; RL — linia ramzowska; pozostałe objaśnienia jak na fig. 1 i 2

Onken, 1990; W. Franke, 1989; Z. Cymerman, 1991*a*), but G. J. H. Oliver *et al.* (1993) has proposed accretion during the Caledonian orogenesis followed by Variscan reworking.

Ongoing investigations by the authors focus on the identification of terrane boundaries and their correlation. To delineate terranes in the Sudetes we have to search for main tectonic boundaries. These show that the studied domain boundaries are often ductile shear zones. The mylonitic rocks along these boundaries abound in stretching lineations (e.g. Z. Cymerman, 1989*a*, 1991*a*, 1992) defined by the alignment of elongate minerals, rodded quartz veins, and trials of monomineralic aggregates derived from granulated and dynamically recrystallized porphyroclasts. Characteristic of all these ductile shear zones are abundant asymmetric fabrics that can be used to derive the apparent sense of tectonic transport in the shear zones (C. Simpson, S. M. Schmid, 1983; Z. Cymerman, 1989*b*, 1992). These include S–C foliations (D. Berthe *et al.*, 1979) an extensional shear bands (S. H.

White *et al.*, 1980; D. Gapais, S. H. White, 1982), rotated porphyroclasts with and without "tails" (C. Simpson, S. M. Schmid, 1983; C. W. Passchier, C. Simpson, 1986) and asymmetric, curvilinear, and sheath-type syn-shearing folds (P. R. Cobbold, H. Quinquis, 1980).

Recognition of mylonite zones is further aided by new criteria for identifying the products of shear-induced metamorphism, such as muscovitised matrices in mylonites, the presence of syn-shearing porphyroblasts and of vein systems. Amongst the most useful field criteria is the presence of swarms of concordant and subconcordant quartz veinlets developed on all scales in the mylonitic rocks. Many of these products can be used as kinematic indicators. They have been outlined and depicted from Newfoundland and Scandinavia (M. A. J. Piasecki, 1988; M. A. J. Piasecki, R. A. Cliff, 1988), and from Scotland, where they were shown by structural work (S. Temperley, 1991) and geochemical study (E. K. Hyslop, 1992) to have formed continuously during ductile shearing.

This paper reviews the geological framework of the Sudetes, and, using the preliminary results of our own structural and kinematic studies (Fig. 4), proposes a new demarcation of Sudetian suspect terranes and a new working model for Palaeozoic terrane accretion.

SUDETIAN TERRANES

The well known classical systems of zones in the Bohemian Massif (F. Kossmat, 1927) have been redefined by P. M. Matte *et al.* (1990), who separated the Sudetes into five terranes: the Saxothuringian, Münchberg, Barrandian, Gföhl and Moravian (Fig. 2). On the other hand, G. J. H. Oliver *et al.* (1993) recognized seven terranes in the Sudetes: the Sudetian batholith terrane, Rudawy Janowickie, Kaczawa, Góry Sowie, Kłodzko, Ślęża – Nowa Ruda ophiolite and the Moravian (Fig. 3). The present authors modify Z. Cymerman's (1991*a*) subdivision of the Sudetes into five terranes, within which a newly redefined Central Sudetian Terrane occupies a central and key position, surrounded by the Saxothuringian, Barrandian, Moldanubian and Moravian terranes (Fig. 1).

BARRANDIAN TERRANE (CENTRAL BOHEMIAN REGION OR BOHEMICUM)

The Barrandian Terrane is largely confined to the central and northern part of the Bohemian Massif (the Tepla – Barrandian and Żelezne Hory regions), and to the south-western fragment of the Sudetes in Czech Republic. It consists of weakly metamorphosed, very thick Upper Proterozoic(?) volcano-sedimentary sequences deposited on a thinned (continental or oceanic?) crust (Z. Misař *et al.*, 1983; J. Chaloupsky, 1989). Geochemical data suggest that some volcanics have affinity with an oceanic setting, others with island arc-continental margin (F. Fiala, 1978). These rocks are unconformably overlain by clastics and other shallow-water deposits ranging in age from the Cambrian to Devonian, the "Barrandian Series" (*sensu stricto*). It is separated from the easternmost part of Saxothuringian, Central Sudetian and Moldanubian terranes, by the complex South Karkonosze Fault (J. Chaloupsky, 1989), the Central Sudetic Fault and the North Bohemian Fault, respectively (Fig. 1). The North Bohemian fault zone (identical with the Orlice structural discordance of M. Fajst (1990) is only exposed in the Orlickie Mts., but the other boundaries

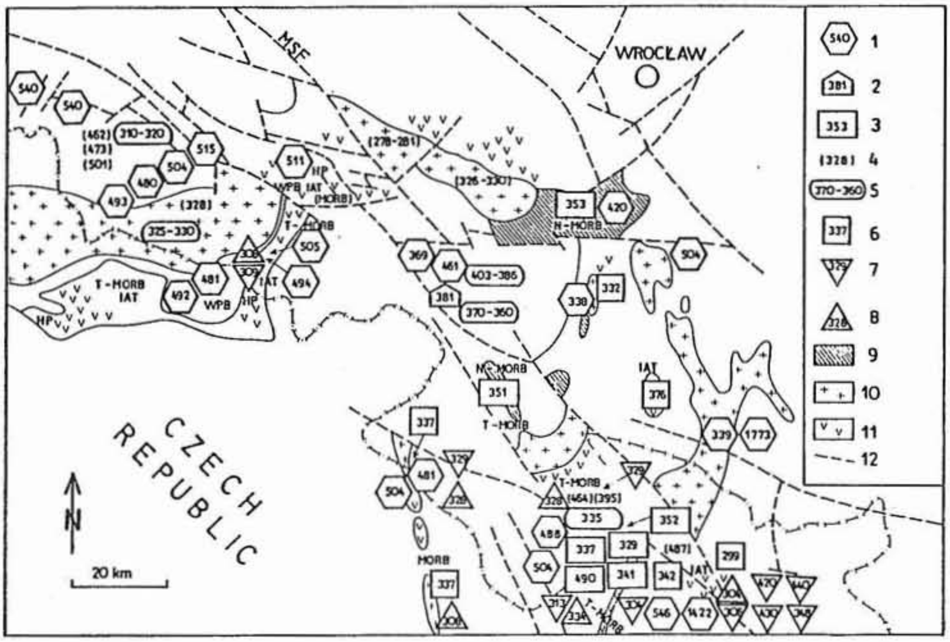


Fig. 5. Compiled map of new and the most important isotopic, and geochemical data from the Sudetes (after various authors; cited references and personal information from: M. G. Steltenpohl in 1993 and H. Maluski in 1993)
Radiometric data: 1 — U-Pb (zircon), 2 — U-Pb (monazite), 3 — Sm-Nd, 4 — Rb-Sr (whole rock), 5 — Rb-Sr (muscovite and biotite), 6 — Ar-Ar (hornblende), 7 — Ar-Ar (muscovite), 8 — Ar-Ar (biotite); 9 — dismembered ophiolitic sequence; 10 — late- and post-tectonic Variscan granitoids; 11 — metabasites and bimodal rock series; 12 — main brittle faults; HP — indicators of high-pressure-low-temperature regional metamorphism; WPB — within plate basalts; MORB — mid-ocean ridge basalts; N-MORB — normal mid-ocean ridge basalts; T-MORB — transitional mid-ocean ridge basalts; IAT — island arc tholleites; other explanations as in Fig. 2
Mapa zestawienia najważniejszych, nowych danych izotopowych i geochemicznych dla terranów sudeckich na podstawie danych różnych autorów; literatura cytowana i informacje ustne: M. G. Steltenpohl, 1993 r. i H. Maluski, 1993 r.
Dane radiometryczne: 1 — U-Pb (cyrkon), 2 — U-Pb (monacyt), 3 — Sm-Nd, 4 — Rb-Sr (cała skała), 5 — Rb-Sr (muskowit i biotyt), 6 — Ar-Ar (hornblenda), 7 — Ar-Ar (muskowit), 8 — Ar-Ar (biotyt); 9 — rozczłonkowana tektonicznie sekwencja ofiolitowa; 10 — późno- i post-tektoniczne granitoidy waryscyjskie; 11 — metabazyty i serie skał bimodalnych; 12 — główne uskoki kruche; HP — wskaźniki metamorfizmu wysokociśnieniowego-niskotemperaturowego; WPB — bazalty śródpłytowe; MORB — bazalty grzbietów śródoceanicznych; N-MORB — bazalty normalne grzbietów śródoceanicznych; T-MORB — bazalty przejściowe grzbietów śródoceanicznych; IAT — toleity łuków wyspowych; pozostałe objaśnienia jak na fig. 2

are largely obscured by Permo-Carboniferous and Mesozoic cover, and are known only from steep gravity gradients and numerous boreholes (M. Suk *at al.*, 1984).

The southeastern boundary of the Barrandian Terrane is marked by the Central Bohemian shear zone in the Central Bohemian region. This large-scale shear zone trends north–northeast, has a dextral transcurrent sense of shearing (P. Rajlich, 1987), and may represent a continuation of the dextral transcurrent Leszczyniec shear zone from the Rudawy Janowickie Mts.

SAXOTHURINGIAN TERRANE (WESTERN LUGICUM)

The Saxothuringian Terrane forms the Western Sudetes (Western Lugicum), and may continue towards the British Isles as the Channel-Saxothuringian Terrane (P. H. Matte *et al.*, 1990). It is bounded in the south by the South Karkonosze fault zone and in the east by the Leszczyniec shear zone and its northern continuation in the Góry Kaczawskie region, the Kaczawa line. The latter is marked by occurrences of melange belts (Z. Baranowski *et al.*, 1990), and also by a jump in metamorphic grade from very low to the northwest of the line, to high-grade greenschist facies to the southeast (S. Maciejewski, T. Morawski, 1979), still preserving a high-pressure paragenesis represented by relicts of jadeite and glaucophane (R. Kryza *et al.*, 1990), as in the Rudawy Janowickie region (T. Wieser, 1978). This eastern boundary of the Saxothuringian Terrane is displaced by some 25 km by sinistral Intra-Sudetic Fault, a complex ductile-brittle shear zone.

In the Sudetes, the Saxothuringian Terrane comprises, from south to north, the South Karkonosze metamorphic complex, the Karkonosze granite batholith, the Izera metamorphic complex, and the western part of the Kaczawa epimetamorphic complex, west of the Kaczawa line (Fig. 1).

The Izera metamorphic complex consists largely of mylonitic augen and layered gneisses with granites (Rumburk granites), granodiorites (Zawidów granodiorites), and leucogranites. It contains three belts of mica schists, of which the central one, richly mineralized in tin, marks a wide zone of ductile mylonite. Kinematic fabrics in mylonitic Izera gneisses indicate penetrative ductile oblique thrusting (top-to-southwest) predominating in the southern part of the complex, and transcurrent sinistral to oblique shearing movements (in general, top-to-northwest) in the eastern and northeastern part of the Izera mylonitic gneisses (Fig. 4). Whether this tectonic pattern represents the products of one continuous deformation or of distinct events, it was accompanied by amphibolite facies metamorphism. A later, more localized deformational event of dextral transcurrent shearing associated with greenschist metamorphism overprints the pervasive sinistral mylonitic fabric. Recent U-Pb dating in the Izera complex yielded (Fig. 5). Cambro-Lower Ordovician ages of ca. 540 Ma from granodiorites within the gneiss, and ca. 515 Ma for weakly foliated Izera granite-gneiss (A. Korytkowski *et al.*, 1993), compatible with G. J. H. Oliver's *et al.* (1993) U-Pb zircon age of 493 Ma from unfoliated Rumburk granite which intrudes the gneisses, and with a Rb-Sr whole rock isochron age for the same granite of 501±32 Ma (M. Borkowska *et al.*, 1980). Analyses of zircon populations from the Izera gneisses (G. J. H. Oliver *et al.*, 1993) show abundant evidence of zircon inheritance and later Pb loss, indicating ages of crystallization between ca. 505 and 480 Ma. Clearly the Cambro-Ordovician plutonic rocks of the Izera complex represent an Early Palaeozoic basement of the Central European Caledonides (E. Bederke, 1924; J. Znosko, 1981; J. Chaloupsky, 1989; D. R. Bowes, M. Aftalion, 1991; G. J. H. Oliver *et al.*, 1993).

The Izera metamorphic complex and the South Karkonosze metamorphic complexes are intruded by a post-tectonic, S-type Karkonosze granites of batholithic proportion (W. Narębski *et al.*, 1986; C. Pin *et al.*, 1987), which has yielded a Variscan Rb-Sr whole rock isochron age of ca. 328±12 Ma (C. Pin *et al.*, 1987). Concordant biotite and muscovite mineral ages from the Izera gneisses (310–320 Ma, M. Borkowska *et al.*, 1980) represent either a thermal event related to the emplacement of the batholith, or cooling ages following Variscan metamorphism, ductile shearing and reworking of the old gneiss complex.

To the west of the Saxothuringian Terrane, in Saxony (Germany), lies the Lusatian pluton comprising granodiorites intruding a thick Late Proterozoic greywacke-pelite succession of low metamorphic grade. Its tectonic relationship to the Saxothuringian Terrane remains to be established. E. Hegener *et al.* (1993) obtained Cadomian U-Pb zircon ages of 587–542 Ma from its granitoid rocks, and speculated that this complex may have been part of a Proterozoic of the East European Platform, or may represent a displaced terrane.

The Intra-Sudetic Fault (J. Oberc, 1972; J. Don, 1984, 1990) forms a very complex zone of shearing, locally 10 to 15 km wide, in which movements extended from ductile to brittle stages of deformation. Late Variscan sinistral transtensional shearing along the fault zone is evidenced by belts of ductile-brittle fault rocks along the northern margin of the Karkonosze granite (328±12 Ma, C. Pin *et al.*, 1987). These displace the dextral Leszczyniec shear zone — Kaczawa line terrane boundary sinistrally by 25 to 30 km (Fig. 1). Yet to the west of this terrane boundary, the Intra-Sudetic Fault may itself represent an Ordovician suture (G. J. H. Oliver *et al.*, 1993), separating the Izera complex from the epimetamorphic rocks of the western part of the Góry Kaczawskie region. The implications are that the Intra-Sudetic Fault may have a very complex polyorogenic history.

CENTRAL SUDETIAN TERRANE (CENTRAL LUGICUM)

The Central Sudetian Terrane, certainly a composite terrane, is bounded from the west by the Leszczyniec shear zone and the Kaczawa line (Fig. 1). Its southern boundary, the Central Sudetic Fault (new term) is documented by a geophysical anomaly under the Intra-Sudetic Depression. This is continuous southeastwards with a wide belt of Złoty Stok – Trzebieszowice (Skrzynka) mylonites with older(?) dextral and younger dominantly sinistral sense of transtensional shearing between the Śnieżnik complex (*sensu stricto)* and Złoty Stok granitoids (Fig. 4). At the latter locality, this large-scale shear zone swings to the north where it is well known as the Niemcza shear zone, the eastern boundary of the composite Central Sudetian Terrane. Other boundaries are hidden under thick Carboniferous and Permian sediments of the North Sudetic Depression and the Permian, Triassic, Cretaceous and Cenozoic deposits of the eastern part of the Fore-Sudetic Block (Fig. 1).

The Central Sudetian Terrane includes the Sudetic parts of the Barrandian and Münchberg terranes (Fig. 2) of P. H. Matte's subdivision (P. H. Matte *et al.*, 1990), and almost five terranes (Fig. 3) invoked by G. J. H. Oliver *et al.* (1993). It comprises the Góry Sowie migmatites, gneisses, amphibolites and rare lenses of granulites and eclogites, polydeformed and retrogressed (A. Żelaźniewicz, 1987; Z. Cymerman, 1989*c*, 1990). The age of the Góry Sowie migmatites and gneisses is still controversial: O. van Breemen *et al.* (1988) interpreted a U-Pb zircon (unabraided) age of 369±15 Ma as the age of metamorphism, but G. J. H. Oliver *et al.* (1993) obtained an age of 460+50/-2 Ma for a syntectonic granite (Fig. 5), indicating that the Góry Sowie complex may have undergone both Ordovician and Devonian tectonometamorphic events. The Góry Sowie complex are underlain by a major dismembered ophiolite (Ślęża, Braszowice, Nowa Ruda and Leszczyniec(?) ophiolites in Fig. 1). However, the present sequence of the Ślęża ophiolite is inverted, the ophiolite pieces having been emplaced (underthrusted) below the Góry Sowie complex (Z. Cymerman, 1987, 1989*c*, 1990). The uppermost part of the Ślęża ophiolite (sheeted dykes) rest structurally above the epimetamorphic Góry Kaczawskie complex, itself structurally above the higher metamorphic grade Middle Odra complex, southwest of Wrocław (Fig. 1). The Ślęża and Braszowice ophiolites have a trace element geochemistry of MORB affinity (C. Pin *et al.*, 1988) interpreted as products of normal oceanic spreading, but without excluding a possible subduction-related marginal basin setting. Their age is controversial. It was thought to be Early Carboniferous, with a Sm-Nd whole rock age of 353±21 Ma (C. Pin *et al.*, 1988), in apparent agreement with the sedimentary history of the Bardo Unit, claimed to display a pelagic facies from the Frasnian to Tournasian times (J. Haydukiewicz, 1981), a view challenged by B. Wajsprych (1978) who suggested that the pelagic rocks were olistoliths. A new U-Pb zircon age between 416 and 422 Ma for the Ślęża gabbroic ophiolite (G. J. H. Oliver *et al.*, 1993) suggest a Silurian age for crystallization of the gabbro (Fig. 5). This is supported by the presence of ophiolite(?) detritus in Upper Devonian, fossiliferous conglomerates overlying the Nowa Ruda ophiolite. Thus, the 353±21 Ma age may perhaps be related to the accretion of the Central Sudetian Terrane to the Moldanubian one.

The north-northeast trending Leszczyniec shear zone is ca. 4 km wide, southeast to east moderately dipping belt of anastomosing belts of ductile shearing developed under upper greenschist facies conditions. It is probably the northern continuity of the dextral Central Bohemian shear zone (P. Rajlich, 1987). It separates mylonitic Kowary orthogneisses and Czarnów schists (similar to the Izera complex) that mantle the Saxothuringian Terrane, from the Leszczyniec Unit (ophiolite?) — J. Szałamacha, M. Szałamacha (1968, 1991). The Rudawy Janowickie metamorphic complex comprises several north-northeast trending belts of metasediments separating belts of volcanics (Leszczyniec Unit) some of the volcanic belts comprising island-arc tholeites (W. Narębski *et al.*, 1986), others MORBS-type basalts (J. Szałamacha, M. Szałamacha, 1991; G. J. H. Oliver *et al.*, 1993). The Leszczyniec shear zone appears to represent relicts of a convergent plate-margin, a conclusion substantiated by local occurrences of rocks bearing a glaucophane-crossite-Mn-rich garnet-phengite assemblage overprinted by a greenschist paragenesis (T. Wieser, 1978). Apparently similar lithologies with relict jadeite and glaucophane overprinted by amphibolite facies mineralogies occur in the eastern part of the Góry Kaczawskie complex (R. Kryza *et al.*, 1990). In the Rudawy Janowickie metamorphic complex, a hornblende gabbro member of a disrupted ophiolite suite, and a felsic volcanic boudin within sheared island arc basalt, yielded U-Pb ages of respectively 505±5 and 494±2 Ma (G. J. H. Oliver *et al.*, 1993). This age is taken to indicate either Ordovician interaction between oceanic crust and continent or island arc (Saxothuringian), or Ordovician rifting with the development of a plutonic arc on the Saxothuringian margin, facing IAT and MORB volcanicity of the Leszczyniec Unit.

The kinematic and structural histories of the Leszczyniec shear zone is complex and polygenetic (Fig. 3). The Early Ordovician regime may be represented in some metagabbroic rocks by rare almost north-south trending sub-horizontal stretching lineation with dextral sense of shearing. A parallel case is documented from the "Central Mobile Belt" of the Newfoundland Appalachians (H. Williams, M. A. J. Piasecki, 1990; S. P. Colman-Sadd *et al.*, 1992), where the rock fabrics of the earliest (Ordovician) interaction between terranes (marked by ophiolites and melanges) was all but obliterated by ductile shearing during later (Silurian) terrane interaction. In the Leszczyniec shear zone, these relict fabrics are overprinted by widespread transtensional ductile to brittle fabrics with normal faulting (Fig. 4). It may indicate an earliest transpressive regime, probably related to the main amalgamation of the Central Sudetian Terrane (including the Leszczyniec Unit) with the Saxothuringian Terrane above a subduction zone with associated HP metamorphism. These earliest movements were followed by large-scale extensional shearing, indicated by east-dipping mylonitic foliation, steeply plunging extensional lineations and down-dip (east-side down, or normal) sense of shear movements throughout all the units within the Rudawy Janowickie metamorphic complex (Z. Cymerman, M. G. Steltenpohl, 1992). This Late Variscan extension can be well correlated with the emplacement of the Karkonosze granite (ca. 328±12 Ma; C. Pin *et al.*, 1987). It was probably contemporaneous with, or slightly preceded an extensional collapse of the thickened crust directed to the east and southeast, which initiated regional normal faulting (Z. Cymerman, M. G. Steltenpohl, 1992) and the formation of the Intra-Sudetic Depression (basin). This basin, filled with Lower Carboniferous molasse deposits up to 6.5 km thick (K. Dziedzic, A. K. Teisseyre, 1990) formed along the hanging-walls of these normal brittle faults from Visean to Namurian time. Its oldest rocks and greatest thicknesses occur in the western and northern part of the basin. Accumulation of the molasse was accompanied by intensive uplift of an easternmost part of the Saxothuringian Terrane (the so-called Sudetic phase) which tilted the whole of the Rudawy Janowickie metamorphic complex and the Dinantian deposits towards the east and southeast (K. Dziedzic, A. K. Teisseyre, 1990).

On the opposite side of the Central Sudetian Terrane is located the Niemcza shear zone (Fig. 1) and its southern continuation, the Złoty Stok – Trzebieszowice shear zone (Z. Cymerman, 1992). The Niemcza shear zone form a belt up to 10 km wide of ductile mylonites derived from the Góry Sowie protolith (S. Cwojdziński, M. Walczak-Augustyniak, 1986). In the northern part of the shear zone stretching lineations plunge gently to the north-northeast, but in the southern part to the south-southeast (Fig. 4). The dominant sense of shearing is sinistral, but dextral (younger?) kinematic fabrics are locally present, as in some of the Niemcza syn- to late-kinematic granodiorites (Fig. 4). Foliation dips east along the western flank of the shear zone and west along the eastern flank, which has always been interpreted as a synformal structure (e.g. H. Dziedzic, 1985; J. Oberc, 1972). However, the same sense of shear on opposite-dipping foliation planes indicate that shear planes anastomose a round mega-boudins of dismembered ophiolite suite (serpentinised peridotites, gabbros and amphibolites).

A weakly foliated, late-tectonic granodiorite which intrudes the Niemcza zone mylonites has yielded a U-Pb zircon age of 338±4 Ma (Fig. 5), providing a minimum Upper Visean age for the shearing processes (G. J. H. Oliver *et al.*, 1993). Since a synkinematic granodiorite in the shear zone has yielded an Ar-Ar plateau age of 332 Ma (M. G. Steltenpohl *et al.*, 1993) then the age of the ductile shearing in the Niemcza shear zone should not be younger than Upper Visean.

MOLDANUBIAN TERRANE (EASTERN LUGICUM)

The Moldanubian Terrane in the Sudetes comprises the Śnieżnik metamorphic complex (J. Don *et al.*, 1990; Z. Cymerman, 1992) and its northern continuation, the Strzelin Hills complex (*sensu lato*), and the original Silesicum of F. E. Suess (1912), Z. Misař *et al.* (1983), J. Chab *et al.* (1990). The Sudetian part of the Moldanubian Terrane is located between the

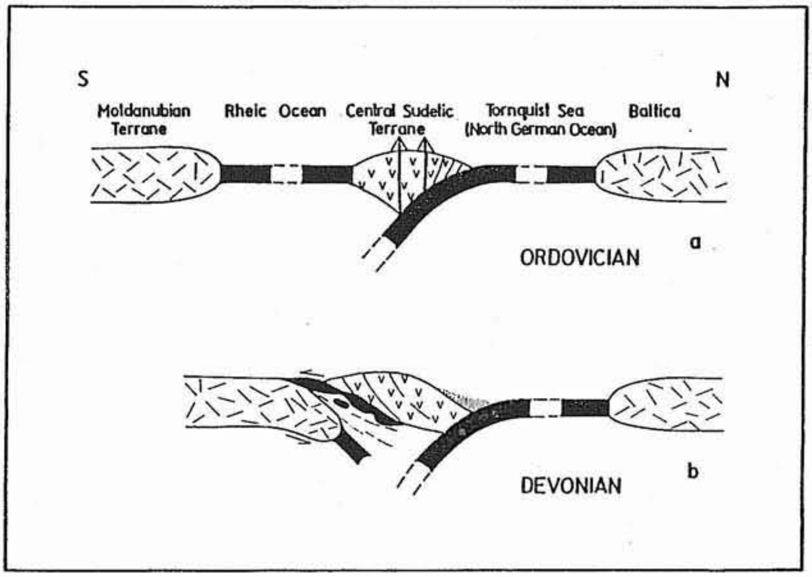


Fig. 6. Schematic plate tectonic interpretation of the Lower to Middle Palaeozoic convergance in the terms of arc-continent oblique collision; the final stage of Variscan collision and later (Carboniferous) regional extension are not shown

a — subducted oceanic crust and passive margin with bimodal magmatism of Early Palaeozoic age, with concomitant high-pressure metamorphism (e.g. eclogites and granulites of the Moldanubian Terrane); b — obducted oceanic crust (e.g. Ślęża, Nowa Ruda ophiolites) with island arc assemblages (Góry Sowie complex), devoid of high-pressure metamorphic overprinting

Schematyczna interpretacja według modelu tektoniki płyt konwergencji podczas skośnej kolizji łuk–kontynent w dolnym i środkowym paleozoiku; końcowy etap waryscyjskiej kolizji i późniejszej (karbońskiej) regionalnej ekstensji nie został przedstawiony

a — subdukowana skorupa oceaniczna i pasywny brzeg z wczesnopaleozoicznym magmatyzmem bimodalnym i z towarzyszącym metamorfizmem wysokociśnieniowym (np. eklogity i granulity terranu moldanubskiego); b — obdukowana skorupa oceaniczna (np.: ofiolity Ślęży i Nowej Rudy) z zespołami łuku wyspowego (metamorfik sowiogórski), bez nałożonego metamorfizmu wysokociśnieniowego

North Bohemian Fault and Moravian shear zone (Moravosilesian tectonic zone of Z. Misař *et al.*, 1983).

The Śnieżnik complex consists of two informal lithostratigraphic units (group): the Gneiss Group, composed of migmatic gneisses with eclogite pods, orthogneisses and the Stronie Group, formed of mica schists and plagioclase paragneisses with intercalations of marbles, amphibolites, quartzites and graphitic schists. A coarse-grained Śnieżnik augen gneiss and a fine-grained mylonitic derivative gave Rb-Sr whole-rock ages of 395±35 and 464±18 Ma, respectively (M. Borkowska *et al.*, 1990). O. van Breemen *et al.* (1988) and G. J. H. Oliver *et al.* (1993) obtained ages of 487±13 and ca. 488–504 Ma, by respectively Rb-Sr and U-Pb zircon methods on foliated granite gneiss (Fig. 5). A whole-rock biotite and muscovite Rb-Sr age of 335±5 Ma (M. Borkowska *et al.*, 1990) probably dated the last

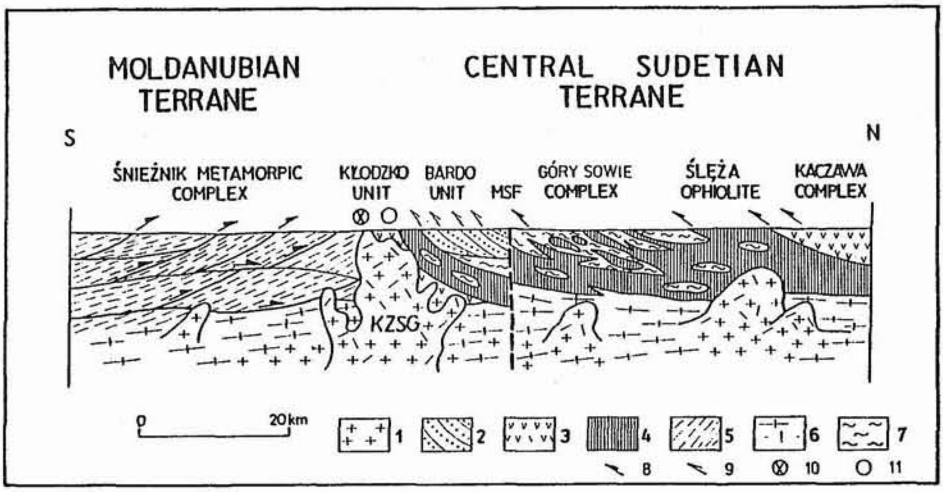


Fig. 7. Cross-section through the central part of the Sudetes

1 — Variscan granitoids; 2 — Upper Devonian and Lower Carboniferous sediments; 3 — Lower Palaeozoic including Devonian; 4 — ophiolitic units; 5 — gneisses and migmatites (high-temperature-low-pressure metamorphism); 6 — gneisses and schists with eclogite and granulite lenses (middle-temperature-middle-pressure to high-pressure metamorphism); 7 — gneisses and migmatites; 8 — ductile thrusting; 9 — brittle thrusting; 10 — strike-slip fault with displacement from viewer; 11 — strike-slip fault with displacement toward viewer; other explanations as in Figs. 1 and 2

Przekrój geologiczny przez centralną część Sudetów

1 — granitoidy waryscyjskie; 2 — osady dewonu górnego i karbonu dolnego; 3 — skały dolnopaleozoiczne i dewońskie; 4 — ofiolity; 5 — gnejsy i migmaty (wysokotemperaturowy-niskociśnieniowy metamorfizm regionalny); 6 — gnejsy i łupki z soczewami eklogitów i granulitów (metamorfizm regionalny średniotemperaturowy-średniociśnieniowy aż do wysokociśnieniowego); 7 — gnejsy i migmatyty; 8 — nasunięcia typu podatnego; 9 — nasunięcia typu kruchego; 10 — uskok przesuwczy z przemieszczeniem od strony patrzącego; 11 — uskok przesuwczy z przemieszczeniem w kierunku patrzącego; pozostałe objaśnienia jak na fig. 1 i 2

(Variscan) metamorphism; and Sm-Nd analysis of an eclogite yielded an age of 352–357 Ma (H. K. Brueckner *et al.*, 1991).

Samples analysed by G. J. H. Oliver *et al.* (1993) from Kamienna Góra (not Kamienica!) are not from the Moravian Terrane, but from the south-eastern part of the Strzelin Hills complex, Fore-Sudetic fragment of the Moldanubian Terrane (Fig. 3). His 339±4 Ma ages from late-tectonic granites may be related to the latest stages of accretion of the Moldanubian and Moravian terranes (stitching pluton). At this time the Moldanubian Terrane began to uplift rapidly (G. M. Steltenpohl *et al.*, 1993), and the Moravian one started to collapse, with deposition of Visean to Namurian molasses in a Carboniferous basin interpreted as a syntectonic foredeep basin controlled by large scale strike-slip faulting (J. Dvorak, 1980; P. Rajlich, 1990).

MORAVIAN TERRANE (BRUNOVISTULICUM)

The Moravian Terrane comprises an Upper Proterozoic, Pan-African-type basement which yielded U-Pb ages of ca. 570 Ma (O. van Breemen, S. Vrana, 1982), overlain unconformably by a thin cover of epicontinental Middle Devonian sediments and volcanics, and Late Devonian to Early Carboniferous carbonates (Z. Misař *et al.*, 1983). Towards the northeast, the Devonian carbonates become laterally replaced by a "paired belt" of flysch and coal-bearing molasse (M. Suk *et al.*, 1984), that grades upwards into a foredeep filled with Namurian limnic deposits.

It may be accepted that the Moravian (or Brunovistulian) and the eastern part of the Moldanubian (Moravosilesicum) terranes are separated by a major, complex, westerly dipping zone of shearing, the Moravian shear zone (Fig. 1) (P. H. Matte *et al.*, 1990; P. Rajlich, 1987, 1990), which is identical to some extent with the Moldanubian Overthrust (F. E. Suess, 1912) or the Moravosilesian tectonic zone (Z. Misař *et al.*, 1983; J. Dvorak, 1980). This zone is commonly marked by well developed near-horizontal stretching lineation (P. Rajlich, 1990) with a dextral sense of shear, displacing top-to-northeast (Fig. 4). This kinematic pattern probably indicate a Variscan transpressive regime; a view supported by the presence in the adjacent Carboniferous foredeep of upright folds trending northeast with steep fan-like cleavage and a subhorizontal stretching lineation (P. Rajlich, 1987).

The Moravian shear zone continues southwards (the Boskovice – Diendorf Fault), probably as far as Krems in Lower Austria. A likely northern continuation of the Moravian shear zone has been recently identified in deep boreholes within the Fore-Sudetic Block (Z. Cymerman, 1991*b*). Named the Brzeg – Nysa shear zone, it takes the form of more than 5 km wide zone of mylonitic gneisses and quartzites under a thick cover of Permo-Triassic and younger deposits. It is thought to be of similar age as the Niemcza shear zone (Z. Cymerman, 1991*b*). Its northerly course is followed by a graben filled with up to 2 km of Lower Permian red beds.

DISCUSSION

Our conclusion is that the Sudetes are a collage of variably displaced terranes, the products of more than one Palaeozoic orogeny, and that their present disposition resulting mainly from the accretion of a composite Central Sudetian Terrane, differs from previous tectonic models for this northeasternmost part of the Central European Variscan Belt. It does not fully support Oliver's plate tectonic model with Caledonian accretion of six terranes along the Intra-Sudetic Fault (G. J. H. Oliver *et al.*, 1993). We recognize that the Intra-Sudetic Fault zone has a complex history, probably beginning as a Caledonian, southwards dipping, zone of subduction of oceanic crust below an island arc/continental region which produced batholithic granitoids now recorded in the Saxothuringian and Moldanubian terranes. We suggest that the present disposition of terranes reflects a modification of earlier formed (Early Caledonian) terranes and their boundaries by Variscan (and probably also Silurian) orogenic events. For example, we see the Intra-Sudetic Fault as an older terrane boundary strongly modified by later tectonic events.

Our model relates the present disposition of Sudetian terranes to Palaeozoic tectonothermal activity in the hanging-wall of a southward dipping, probably Silurian subduction zone of the Rheic Ocean. This is thought to be marked by a major magnetic anomaly in the Central Sudetian Terrane (C. Królikowski, A. Grobelny, 1991). We interpret the rocks of the Central

Sudetian Terrane as a volcanic arc (Góry Sowie complex, possibly rooted in the Middle Odra complex) with oceanic crust (ophiolites) all thrust southwards, in between the volcanic arc or continental Moldanubian and Saxothuringian terranes (Fig. 6), modifying an earlier configuration of terranes and earlier units represented by the Rudawy Janowickie and Góry Kaczawskie regions. The crustal thickening consequent of this thrusting resulted in the formation of migmatites and post-tectonic granites within the Central Sudetian Terrane (Fig. 7). The model implies that southward oceanic subduction beneath the northern margin of the Bohemian Massif was succeeded by diachronous underthrusting of the northern parts of the Moldanubian and Saxothuringian terranes. This transition from B to A-type subduction is likely to have been diachronous along the suture, now situated along the Middle Odra complex (S. Cwojdziński, 1992) and its timing at any point cannot be identified from geological data.

The subduction-related nature of Caledonian plutonism and the existence in the Sudetes of a collage of terranes imply the presence of a major plate boundary in the Sudetes during the Caledonian events. There is however, at present, insufficient evidence to demonstrate unequivocally the precise nature and the geometry of this boundary. At this stage we present only the so far identified tectonic lines, mainly ductile shear zones related to these terranes amalgamation and accretion during Palaeozoic time.

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MODEL TERRANOWY W SUDETACH (MASYW CZESKI)

Streszczenie

Przedstawiono podział skał przedpermskich w Sudetach na pięć terranów. Złożony terran środkowosudecki *(Central Sudetian)* jest otoczony od NW ku SE przez następujące terrany: saksoturyngski, Barrandianu, moldanubski i morawski. Granice terranów są na ogół regionalnymi strefami ścinań podatnych. Od NW po SE rozpoznano prawdopodobne granice terranów: linię Kaczawy, uskok śródsudecki, strefę ścinań Leszczyńca,

system uskokowy południowych Karkonoszy, strefę dyslokacyjną północnoczeską oraz strefę ścinań podatnych: Złotego Stoku – Trzebieszowic, Niemczy, Nysy – Brzegu i morawską.

Ewolucja zespołu różnorodnych terranów w Sudetach związana jest z aktywnością tektonotermiczną płyty górnej, prawdopodobnej sylurskiej strefy subdukcji oceanu reickiego. Skały terranu środkowosudeckiego interpretujemy jako łuk wulkaniczny (jednostka sowiogórska zakorzeniona w metamorfiku środkowej Odry?) ze skorupą oceaniczną (fragmenty ofiolitów środkowosudeckich). Terran środkowosudecki został nasunięty (obdukowany?) ku południowi na terran moldanubski i saksoturyngski, modyfikując wcześniejszą konfigurację terranów i jednostek tektonicznych na północnych peryferiach masywu czeskiego. Skierowana ku południowi subdukcja skorupy oceanicznej pod północny brzeg masywu czeskiego była najprawdopodobniej zastąpiona przez diachroniczne, późniejsze podsuwanie się terranów moldanubskiego i saksoturyngskiego. Przejście subdukcji od typu B do A mogło być diachroniczne wzdłuż strefy szwu, położonej obecnie wzdłuż granic metamorfiku środkowej Odry (S. Cwojdziński, 1992).

Magmatyzm kaledoński, związany z procesami subdukcji, a także wielce prawdopodobna możliwość istnienia w Sudetach zespołu kilku terranów, wskazują na istnienie granicy płyt litosfery na północnych peryferiach masywu czeskiego w starszym paleozoiku. Jednak brak obecnie wystarczających dowodów (np. geofizycznych) do wyznaczenia charakteru i geometrii tej granicy płyt. Na obecnym etapie rozpoznania przedstawiono jedynie regionalne linie tektoniczne, wyznaczone głównie przez strefy ścinań podatnych, które mogły być związane z akrecją terranów podczas orogenez paleozoicznych w Sudetach.