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Palaeozoic orogeneses in the Sudetes: a geodynamic model

Zbigniew CYMERMAN

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The Palaeozoic geodynamic evolution of the Sudetes resulted from two successive orogenic events: (1) Ordovician-Silurian geotectonic processes (pre-Variscan stages), and (2) the Variscan orogeny. Early Palaeozoic rifting of Cadomian crustal segments and opening of the Ligerian (Galicia–Massif Central) and/or Saxothuringian Ocean occurred in Ordovician-Silurian times on the northern (peri-Gondwana) periphery of the Bohemian Massif. At the same time, the Góry Sowie terrane with a magmatic arc affinity quite probably developed on the SW margin of Baltica due to subduction of the Tornquist Ocean. Two major structural events characterised the Variscan evolution of the Sudetes: (1) regional-scale ductile thrusting of Late Devonian-Early Carboniferous age, and (2) Early Carboniferous-Early Permian regional extension. Ductile thrusting is characterised by: (I) a general NNE-directed, dextral transpressional stacking of ductile nappes due to oblique collision of the Moldanubian and Moravian microplates in the Eastern Sudetes, and (II) SW- to NW-directed, sinistral transpressional stacking of ductile nappes due to westward lateral extrusion of continental crust in the Central and Western Sudetes, itself a result of oblique indentation of the Central Sudetic oceanic lithosphere. The first Variscan deformation in the Sudetes might reflect a purely convergent setting that evolved into a transpressive setting during oblique convergence. Special attention is given to the geometry and kinematics of intraplate tectonic escape and a model of indentation processes in the Sudetes. The presented new geotectonic model for the Variscan evolution of the Sudetes is consistent with lateral escape of the Saxothuringian terrane as an important way of accommodating Variscan strain in the NE part of the Bohemian Massif. This model explains the lateral expulsion (escape) process as due to the indentation of the Central Sudetic terrane along with the Góry Sowie terrane and by the oblique subduction of the Ligerian/Saxothuringian Ocean(s) (now tectonically dismembered ophiolitic rocks of the Central Sudetic terrane).

Zbigniew Cymerman, Lower Silesian Branch, Polish Geological Institute, Jaworowa 19, PL-53-122 Wrocław, Poland *(received: March 18, 1999; accepted: November 11, 1999).*

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INTRODUCTION

The definition of "orogeny" within most orogenic belts was originally based on the presence of unconformities (Stille, 1945, 1951; Harland, 1969; Trumpy, 1971; Rodgers, 1982). Traditional thinking of "orogenic events" and "tectonic phases" was based on a definition of orogeny as occurring in sharply delimited pulses with orogenic belt evolution considered as a series of such events, phases, or episodes (Stille, 1945, 1951; Rodgers, 1971). However, orogenic concepts have changed because of the plate-tectonic paradigm, which assumes that initiation of orogenic processes is associated with reorganisation of crustal plate motions and poles of rotation, and that deformation on a plate-scale is continuous and gradual, involving generally slow rates of deformation. Rodgers (1971) attacked the dogma that orogenies are sharp, discrete events punctuating the geological record and he showed that the Taconic orogeny of the North Appalachians included three long-lived and partly overlapping events.

Many orogenic events have now been redefined over longer periods and do not represent brief, singular events (< 10 Ma duration) but more prolonged episodes or sequences of events that lasted over a geological period or more (Rodgers, 1971; Williams, 1993). Orogeny may exhibit its signature in the rock record in the form of episodic pulses with time-scales of a few Ma simply because of changes in accommodation mechanisms on an orogenic and plate scale (Harrison *et al.*, 1992; Gray and Foster, 1997). More recently, arguments for more "continuous" deformation, associated with the gradual and approximately linear displacements of lithospheric plates in the plate-tectonic paradigm (Hsü, 1989), led to the concept of "megascale" orogeny with > 100 Ma duration (Gray and Foster, 1997).

In the modern context, orogeny should be defined by a combination of recognised unconformities, rock deformation with the development of penetrative fabrics, metamorphism, magmatism, sedimentation, and syn- and/or post-orogenic

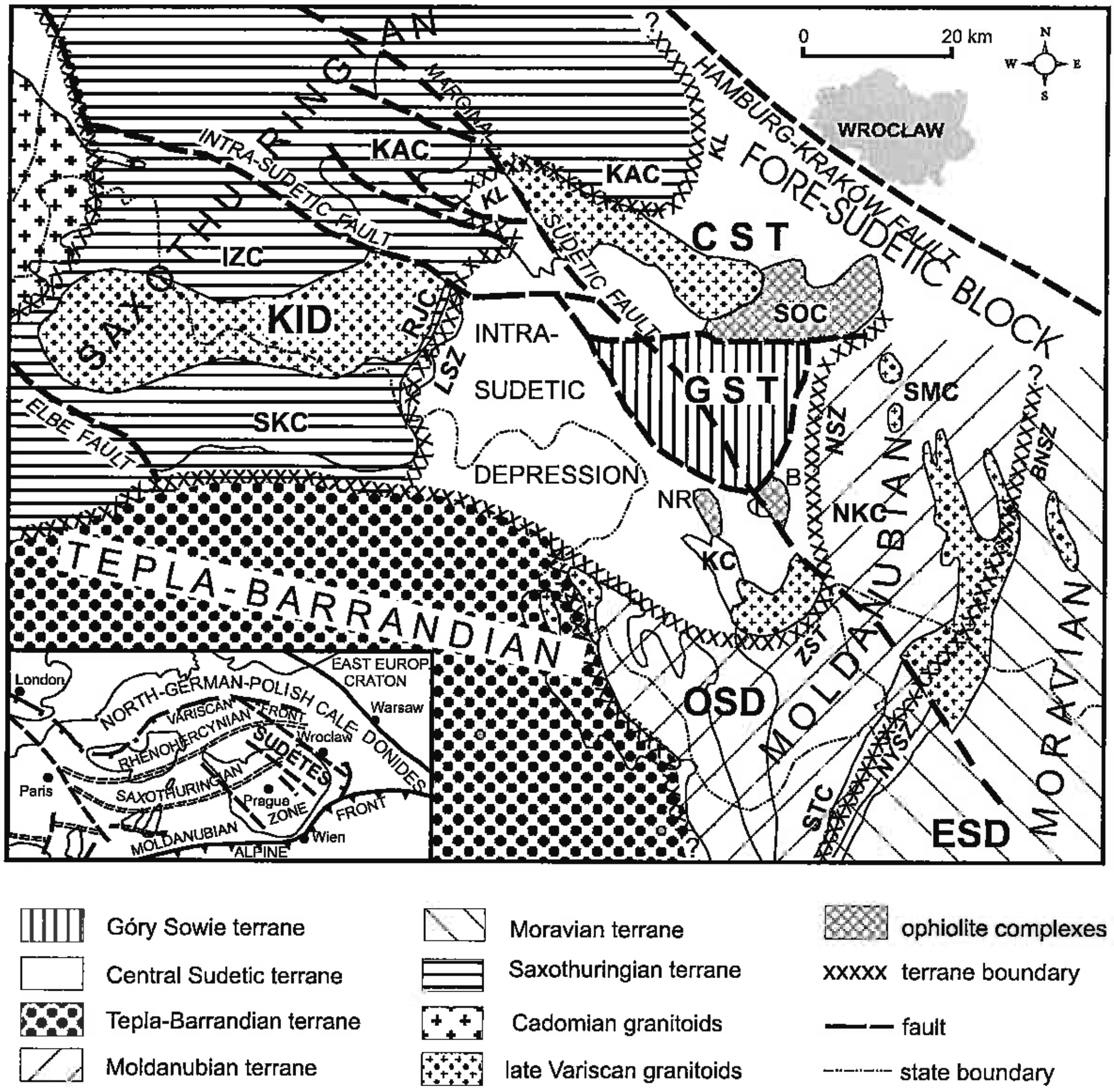

Fig. 1. Sketch-map of Sudetic terrranes (modified after Cymerman *et al.*, 1997)

Terranes: CST — Central Sudetic, GST — Góry Sowie; **terrane boundaries**: BNSZ — Brzeg–Nysa shear zone, KL — Kaczawa tectonic line, LSZ — Leszczyniec shear zone, NSZ — Niemcza shear zone, NYSZ — Nyznerov shear zone, ZST — Złoty Stok–Trzebieszowice shear zone; **metamorphic core complexes**: ESD — East Sudetes domes, KID — Karkonosze–Izera dome, OSD — Orlica–Śnieżnik dome; **ophiolitic complexes**: B — Braszowice, NR — Nowa Ruda, SOC — Ślęża; **geological units**: IZC — Izera metamorphic complex, KAC — Kaczawa metamorphic complex, KC — Kłodzko metamorphic complex, NKC — Niemcza–Kamieniec Ząbkowicki metamorphic complex, SMC — Strzelin metamorphic complex, SKC — South Karkonosze metamorphic complex, STC — Staré Město metamorphic complex

exhumation. Observations from many different parts of the Earth show that orogenic belts evolved along stages of subduction, followed by collision, intracontinental deformation and post-collisional thinning of a thickened crust (Wilson, 1990; Sengör, 1990; Vauchez and Nicolas, 1991; Beaumount *et al.*, 1994; Ellis, 1996; McCaffrey and Nabelek, 1998). Changes from dominant continental collision to shortening on major ductile thrusts appear episodic in terms of data obtained from studies of uplift, sedimentation, and geochronology. However, on the scale of the entire orogenic system, convergence is seen to take place at a relatively constant rate (Harrison *et al.*, 1992).

The Variscides of Europe form an orogenic belt extending for *ca.* 8,000 km from Portugal to Poland. In Central Europe, a division of the Variscides into three major zones (Rhenohercynian, Saxothuringian, and Moldanubian) (Fig. 1) was established by Suess (1926), Kossmat (1927) and Stille (1951); and modern reviews regard these classical Variscan domains as parts of peri-Gondwana crustal blocks which collided with Laurussia during the Late Palaeozoic collision (Ziegler, 1986; Franke *et al.*, 1993, 1995; Edel and Weber, 1995). With the advent of plate tectonics these zones were reinterpreted as independent microplates or terranes (Matte *et al.*, 1990; Oczlon, 1992; Edel and Weber, 1995), and the Palaeozoic evolution of Central Europe was seen as controlled by subduction of oceanic domains separating Laurussia and Gondwana, and by the accretion of Gondwana-derived fragments to Laurussia (Ziegler, 1986; Paris and Robardet, 1990; Pin, 1990; Oczlon, 1992). Although many aspects of the geotectonic evolution of the Variscan belt in Central Europe are still poorly understood and controversial, and expressed in a number of geodynamic models incorporating different concepts (Behr, 1978; Ziegler, 1986; Matte *et al.*, 1990; Oczlon, 1992; Edel and Weber, 1995; Franke *et al.*, 1995), there is general agreement among these authors and others that this orogenic belt resulted from Late Devonian-Early Carboniferous collisional processes (Franke, 1989; Matte, 1991; Franke *et al.*, 1995; Oncken, 1997; Oncken *et al.*, 1999).

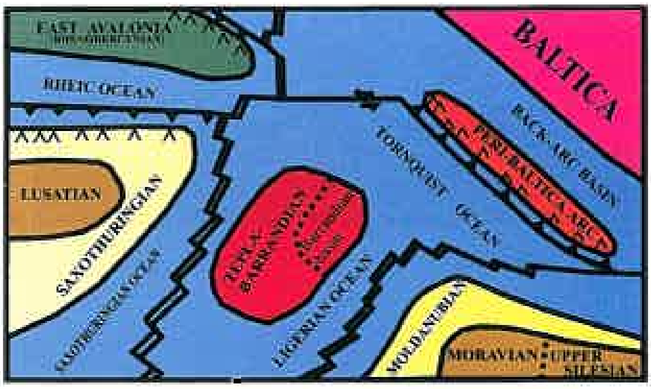

Fig. 2. Schematic map showing the relative position of exotic terranes in Central Europe during the Early Palaeozoic that were accreted to Baltica during the Silurian and Devonian and the names of the oceans and/or seas formed by the breakup of Rodinia. This map does not represent the palaeogeography at any specific Early Palaeozoic time. Not to scale

Uncertainties relating to orogenic evolution are particularly acute in the Sudetes, where the Variscan orogenic belt forms a complex mosaic-like structure (Teisseyre, 1980; Cymerman *et al.*, 1997). The oroclinal bend of the Variscides in SW Poland further complicates tectonic interpretations. Numerous plate tectonic and non-plate tectonic models have been proposed for the origin of the Sudetes (*cf.* Matte *et al.*, 1990; Matte, 1991; Oliver *et al.*, 1993; Cymerman and Piasecki, 1994; Cymerman *et al.*, 1997; Żelaźniewicz, 1997).

The aim of this paper is to establish the orogenic framework for the tectonic evolution of the Sudetes during Palaeozoic deformations, because the knowledge gained from the Sudetes area may lead to a better understanding of the geotectonic evolution of the entire Bohemian Massif. In this study, recent structural, kinematic, geochemical and isotopic data are used to assess the tectonometamorphic history of different parts of the Sudetes during Variscan and Caledonian orogenic processes. The geometry and kinematics of the Variscan intraplate tectonic escape are described and a model of indentation processes in the Central Sudetes is proposed.

GENERAL SETTING

The Sudetes, located at the NE margin of the Bohemian Massif, in between the NW-trending Hamburg–Kraków fault zone and Elbe fault zone (Fig. 1), represent the principal exposure of the Variscan Orogenic Belt in SW Poland and the northern Czech Republic with relics of a Neoproterozoic basement in the Lusatian and Brno Massifs (Linnemann *et al.*, 1997; Hanžl and Melichar, 1997). The Sudetes mosaic-like features may be explained in terms of a complex of accreted terranes (Matte *et al.*, 1990; Matte, 1991; Oliver *et al.*, 1993; Cymerman and Piasecki, 1994; Cymerman *et al.*, 1997). In the Sudetes, seven distinct terranes exhibit an almost symmetrical distribution (Cymerman *et al.*, 1997). A central terrane of magmatic arc affinity termed the Góry Sowie terrane, together with surrounding marginal/oceanic and ophiolitic rocks of the Central Sudetic terrane, are bordered, respectively to the NW and SE, by continental crusts of the Saxothuringian terrane and Moldanubian terrane (Fig. 1). These are, in turn, bordered (again respectively to the NW and SE) by the Lusatian terrane and Moravian terrane, which are also of continental crust, though contain Cadomian granitoids and represent rifted and disrupted fragments of Gondwana affinity (Havlíček *et al.*, 1994; Linnemann, 1995; Cymerman *et al.*, 1997; Hanžl and Melichar, 1997; Linnemann *et al.*, 1997).

In the Sudetes, these terranes take the form of crustal blocks showing contrasts in stratigraphy and metamorphic grade (Oberc-Dziedzic, 1989; Don, 1990; Kryza, 1995). Their boundaries, where exposed, are generally major ductile shear zones, such as the Niemcza shear zone and the Leszczyniec shear zone (Fig. 1). However, poor exposure, stratigraphic uncertainties and a paucity of isotopic data have led to contrasting interpretations of the tectonometamorphic evolution and palaeotectonic position of the Sudetic metamorphic terranes (*cf.* Mierzejewski, 1993; Cymerman *et al.*, 1997; Żelaźniewicz, 1997).

In the Sudetes, the main Variscan deformation commenced in Late Devonian times, locally concurrent with a phase of high-pressure (HP) metamorphism (Brueckner *et al.*, 1991; Steltenpohl *et al.*, 1993; Patočka and Smulikowski, 1995; Kryza and Mazur, 1995; Kryza *et al.*, 1996; O'Brien *et al.*, 1997), and continued into Early Carboniferous time under widespread retrogressive greenschist to amphibolite facies conditions (Kryza, 1995; Kryza and Mazur, 1995). Extensive high-temperature (HT) — low-pressure (LP) recrystallization and associated widespread Late Variscan granitoid intrusions have almost completely obliterated the evidence for earlier HP metamorphism (Maluski and Patočka, 1997)

Over three decades, structural studies in the Sudetes have shown that the different metamorphic complexes have undergone complicated, polyphase deformation (Wojciechowska, 1972; Teisseyre, 1980; Don, 1982; Cymerman, 1989; Dumicz, 1989). However, the relationships between the various types of recorded deformation structures and their significance for regional tectonics remain largely unconstrained. Moreover, the short-lived, "deformational" events in the Sudetes that previously assigned orogeny status are better viewed as parts of a continuous, progressive "Variscan orogeny" (Cymerman, 1997).

The Sudetes show evidence for subduction-related diachronous deformation. The apparent complexity of deformation patterns in the Sudetes probably reflects the interaction of a number of terranes and subduction systems in a relatively complex oceanic setting during the Early Palaeozoic time to Middle Devonian. Metamorphic rocks of the Central Sudetic and Góry Sowie terranes probably relate to pre-Variscan (Caledonian) deformation in an arc and fore-arc position, whereas metamorphic complexes in the western and eastern parts of the Sudetes

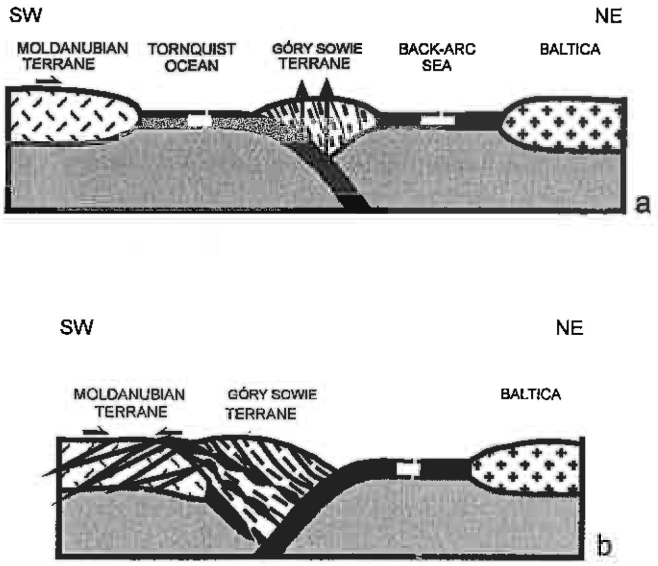

Fig. 3. Schematic cross-sections of evolution of the Góry Sowie terrane and Ślęża ophiolite complex in Ordovician-Silurian (**a**) and Late Devonian-Early Carboniferous times (**b**)

may be related to accretionary-complex style deformation in small marginal ocean basins and/or back-arc basins. In this light, the orogenic framework of the Sudetes requires a large revision.

GEODYNAMIC EVOLUTION

A compilation of geological data from different parts of the Sudetes indicates that the geodynamic evolution of this segment of Central European Variscides involved an earlier orogenic event during the Ordovician-Silurian, separated by a Silurian to Middle Devonian stage of rifting from a later orogenic process in Late Devonian-Early Carboniferous times. Here, I propose that the orogenic cycles (i.e. the Variscan and, locally, pre-Variscan [Caledonian]) in the Sudetes be expanded to comprise evolving deformational, metamorphic, sedimentary and magmatic events from Early to Late Palaeozoic times.

PRE-VARISCAN (CALEDONIAN) STAGE

EARLY PALAEOZOIC RIFTING OF PERI-GONDWANA AND OPENING OF OCEANIC BASINS

During the Cambrian to Ordovician, the latest Proterozoic (*ca.* 800–550 Ma) Pan-African crust (Küster and Harms, 1998; Paquette and Nédélec, 1998; Ferré *et al.*, 1998) of Gondwana was split into several microcontinents (Van der Voo, 1988; Dalziel *et al.*, 1994; Torsvik *et al.*, 1996). Avalonia and a probably composite Armorica were the main continental masses that drifted away from the northern margin of Gondwana (*op. cit.*). The North Armorican Massif is the typical locality of the Late Precambrian Cadomian orogeny (Balé and Brun, 1989). The Cadomian orogeny of the Armorican Massif started around 570–580 Ma and ended at *ca.* 540 Ma (Dallmeyer *et al.*, 1991; Hébert, 1995). From south to north, the Massif Central, which remained a part of Gondwana, became separated by the Galicia–Massif Central Ocean (Matte, 1986) also called as the Ligerian Ocean (Oczlon, 1992) or the South Armorican Ocean (Paris and Robardet, 1990), from Armorica; and the opening up of the Rheic Sea separated the latter from Avalonia (McKerrow and Cocks, 1986; Paris and Robardet, 1990). At least three and perhaps four oceanic basins existed during the Early Palaeozoic in Europe: the Iapetus Ocean, the Tornquist Ocean, the Rheic Ocean and the Ligerian Ocean (Fig. 2).

Bimodal magmatic rocks of the so-called "leptynite-amphibolite suite" (Pl. I, Figs. 1, 2) are inferred to suggest crustal extension and ocean crust formation (Pin, 1990). These types of magmatic rocks are well documented from zones now identified as forming the tectonic boundaries of terranes in different parts of the Sudetes (Fig. 1), such as the Leszczyniec shear zone, the Złoty Stok–Trzebieszowice shear zone (Pl. I, Figs. 3, 4), the Niemcza shear zone, and the Nyznerov shear zone (Cymerman and Piasecki, 1994; Cymerman *et al.*, 1997). However, it is unclear whether all the "leptynite-amphibolite" complexes represent the opening up of one ocean or of several small scale oceanic basins.

The "leptynite-amphibolite" complexes are found associated with HT or HP granulites (Pl. II, Figs. 1, 2) and eclogites, respectively. These complexes consists of an association of acidic ortho- or paragneisses and amphibolites. They may represent the transition of oceanic and continental crust as these were was affected by the final stage of subduction with later overthrusting due to collisional processes (Pin and Vielzeuf, 1988). The Staré Město complex located at the boundary area (the Nyznerov shear zone) between the Moldanubian and Moravian terranes (Fig. 1) is composed mainly of spinel peridotites, leptyno-amphibolites, metagabbros (*ca.* 514 Ma) and migmatites. Kröner *et al.* (in press) interpreted the Staré Město complex as originating in a Cambro-Ordovician passive margin with the formation of oceanic crust in a back-arc setting. The leptyno-amphibolites underwent Cambro-Ordovician (*ca.* 500 Ma) LP granulite facies metamorphism and anatexis. However, if the HT granulites and HP eclogites of the Orlica–Śnieżnik dome are considered as pre-orogenic syn-rift metamorphics their emplacement (also in the Staré Město complex and in the Złoty Stok–Trzebieszowice shear zone) is much easier to explain by ductile Variscan transpression of lower crust transitional to oceanic crust. This process would not require syn-collisional subduction of continental crust (Chemenda *et al.*, 1995) to explain the granulite belt formation and the emplacement of elongated eclogitic lenses in the Orlica–Śnieżnik dome.

The Lusatian, Tepla–Barrandian and Moravian (Moravo-Silesian) terranes represent Proto-Gondwana derived microplates which were separated by rifting during Cambro-Ordovician times. This rifting resulted in the formation of the basinal/oceanic crust of the Central Sudetic terrane and the thinning of the continental crust of the Saxothuringian and Moldanubian terranes. Variscan tectonothermal activity was generally penetrative and intensive, and only in some localised

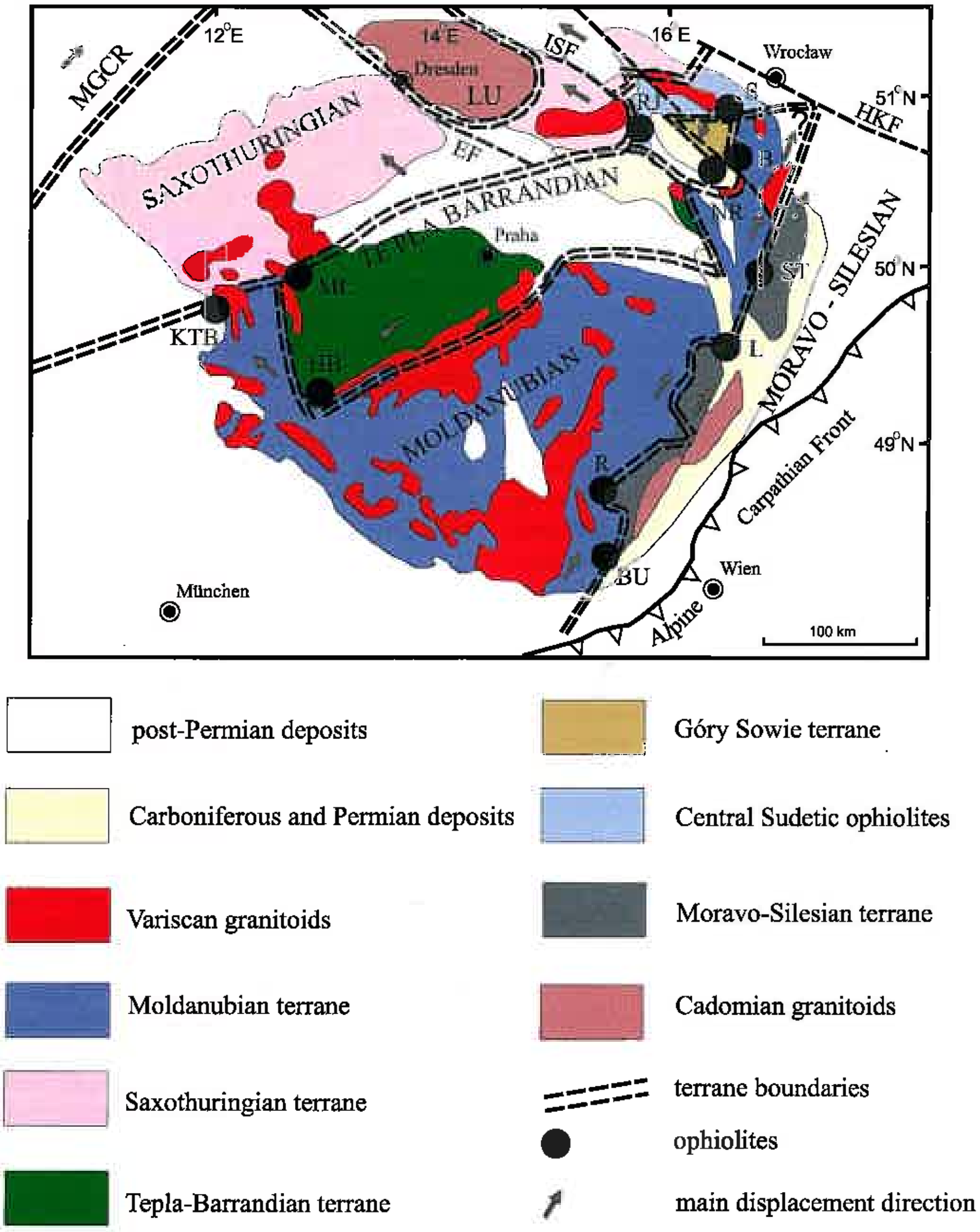

Fig. 4. Geological sketch-map of the Bohemian Massif with plate boundaries and ophiolite occurrences

Tectonostratigraphic units: MGCR — Middle German crystalline rise, LU — Lusatian terrane; **faults**: EF — Elbe fault zone, ISF — Intra-Sudetic fault, HKF — Hamburg-Kraków (Cracow) fault zone; **ophiolites**: B — Braszowice, BU — Buschandlwand, HB — Hoher Bogen, KTB — KTB well MOR-metabasalts, ML — Mariánské Lázně, L — Letovice, NR — Nowa Ruda, RJ — Rudawy Janowickie, R — Raabs, S — Ślęża, ST — Staré Město

areas there is a record of pre-Variscan events. These areas are represented by the Tepla–Barrandian terrane, the Góry Sowie terrane and the Staré Město metamorphic complex. These terranes were subsequently affected by episodes of subduction/obduction, perhaps as early as in the Ordovician (Oliver *et al.*, 1993; Johnson *et al.*, 1994; Kröner *et al.*, in press) or Silurian (Kröner and Hegner, 1998).

However, the most important event in the structural development of the Sudetes was the Silurian and Variscan oblique accretion of the Góry Sowie terrane on to the northeastern periphery of the Bohemian Massif (the Moldanubian and Moravian terranes). The amalgamation of two terranes is indicated when synchronous deformation occurs across the intervening suture. The continuous Silurian and Early Variscan accretion and intentation (wedging) of the Góry Sowie terrane at a subduction zone (Fig. 3) overprinted and strongly obscured the less widespread Cambro-Ordovician structures associated with incipient rifting (Furnes *et al.*, 1994; Winchester *et al.*, 1995) and transposed the margins of the Moldanubian and Saxothuringian terranes. Additionally, more than one subduction zone may have operated concurrently on probably irregular and complex northeastern periphery of the Bohemian Massif. Thus, the Early Palaeozoic-Devonian terrane accretion and the evolution of terrane-bounding tectonic zones in the Sudetes is probably more complex than a simple convergence model.

Żelaźniewicz (1997) considered that the Góry Sowie metamorphic complex, like all the geological units in the Sudetes, developed upon Neoproterozoic (Cadomian) continental crust. However, a lack of Neoproterozoic detrital and xenocrystic zircons in the Góry Sowie metamorphic rocks does not confirm this view (Kröner and Hegner, 1998). Isotopic dating of detrital zircons from the Góry Sowie metamorphic complex points to much older (Palaeoproterozoic and even Archaean) origin of the rock material. The results of detrital zircon studies from the Góry Sowie metamorphic complex show that sediments transported into the Góry Sowie basin were highly heterogenous and much older (*ca.* 2215, 2395, 2416, 2620 and 2923 Ma) than those originating from supracrustal series of other Sudetic metamorphic complexes, such as the Stronie Formation of the Orlica–Śnieżnik dome. O'Brien *et al.* (1997) have, also, described detrital zircon grains of ages about 450 Ma from a pelitic protolith of the Góry Sowie granulites. The lack of zircon ages reflecting the Cadomian (Pan-African) orogeny indicates that Cadomian metamorphism may not have affected the Góry Sowie metamorphic complex. Kröner and Hegner (1998) interpreted the ages of these xenocrystic zircons as indicating a possible derivation from as far as the Guiana Shield. On the other hand, Cymerman (1998) considered that the Góry Sowie metamorphic complex was a part of the peri-Baltica magmatic arc.

SILURO-DEVONIAN CONVERGENCE: CLOSE OF THE TORNQUIST OCEAN

In the Sudetes, dismembered ophiolite sequences of the Central Sudetes area and "leptynite-amphibolite" complexes of the marginal parts of the Central Sudetic terrane provide evidence for subduction/obduction related deformation. The "leptynite-amphibolite" complexes experienced a HP metamorphism from blueschist facies to eclogite facies in the South Karkonosze metamorphic complex and in the Moldanubian terrane, respectively (Pin, 1990; Brueckner *et al.*, 1991; Kryza *et al.*, 1996; Maluski and Patočka, 1997).

The HP metamorphism in the Góry Sowie terrane dated at *ca.* 405–402 Ma (Brueckner *et al.*, 1996; O'Brien *et al.*, 1997) is consistent with subduction that involved Tornquist oceanic crust (Fig. 3a). In this hypothesis of Siluro-Devonian closure of the Tornquist Ocean on the northeastern periphery of the Bohemian Massif, the HP metamorphism (Kryza and Mazur, 1995; Maluski and Patočka, 1997) is restricted to the Leszczyniec shear zone (Cymerman and Piasecki, 1994) which continues northwards along the Kaczawa tectonic line and to the Niemcza shear zone and its southern continuation — the Złoty Stok–Trzebieszowice shear zone (Cymerman, 1996*b*, 1997). These zones appears as the overthrusted relicts of a palaeo-suture zone between the peri-Gondwana Moldanubian terrane and a peri-Baltica magmatic arc (Cymerman, 1998).

In the Góry Sowie metamorphic complex, Sm-Nd isotopic ages from a garnet-peridotite gave a range from *ca.* 402 Ma in the core of the garnet to about 386 Ma in its outer zone (Brueckner *et al.*, 1996). The Góry Sowie peridotites are characterised by a very quick growth of garnet, and by rapid decompression and cooling. This process was interpreted by Brueckner *et al.* (1996) as indicating rifting at the time when the peridotites were isobarically cooled during tectonic displacement. Similar ages (*ca.* 400 Ma) have been obtained using the U-Pb method on HP metamorphic zircons from the Góry Sowie granulites (O'Brien *et al.*, 1997). H. Timmermann *et al.* (1999) have obtained 400–394 Ma dates from monazites from a post-deformational granite dyke. These radiometric ages apparent the time of S-type granite mobilisation during high grade metamorphism and anatexis of the Góry Sowie metamorphic rocks (Pl. II, Figs. 3, 4). On the other hand, Roberts and Finger (1997) have recently assumed, basing on examples from the Austrian part of the Bohemian Massif, that growth of zircons was related to their exhumation into a shallower crust level, where medium-pressure conditions dominated. They suggested that isotopic dating of zircons from granulites, which is based on the growth of zircon, does not automatically reflect peak pressure and temperature of regional metamorphism. This implies that the peak temperature and pressure conditions may have been much older, as in the case of granulites and peridotites from the Góry Sowie metamorphic complex.

In the Central Sudetic terrane, gabbros from an ophiolitic sequence yielded a Sm-Nd isochron age of *ca.* 357 Ma, interpreted as the time of magmatic crystallization (Pin *et al.*, 1988). However, this age is more likely to represent the time when the ophiolitic rocks passed through the closure temperatures of the Sm-Nd system during their exhumation, rather than reflecting the age of their crystallization. In addition, it is difficult to reconcile this Late Famennian isotopic age of the gabbro with the fact that the ophiolitic sequence is overlain by Famennian rocks of the Bardo unit (Narębski *et al.*, 1982). A more credible age of the formation of the Central Sudetic ophiolites has been given by U-Pb zircon dating which indicates a Silurian formation age of *ca.* 420 Ma (Oliver *et al.*, 1993). Similar isotopic ages have been obtained from the Góry Sowie peridotite, using the Sm-Nd method (Brueckner *et al.*, 1996). The peridotite is characterised by both a very quick growth of garnets, and followed by rapid decompression and cooling. These metamorphic processes have been interpreted as rifting indicators when hot Góry Sowie peridotites were isobarically cooled due to their tectonic displacement (Brueckner *et al.*, 1996).

Two main problems are still pending, namely:

1. The sense of pre-Variscan subduction (i.e. NE- or SW-ward) is not documented by microstructural evidence since HP minerals from the Sudetic metamorphic complexes are mostly erased by younger, widespread Variscan tectonometamorphic events.
2. The geodynamic setting of Early Palaeozoic convergence in the Sudetes is still unclear, in contrast to the geochemical evidence of extensional processes.

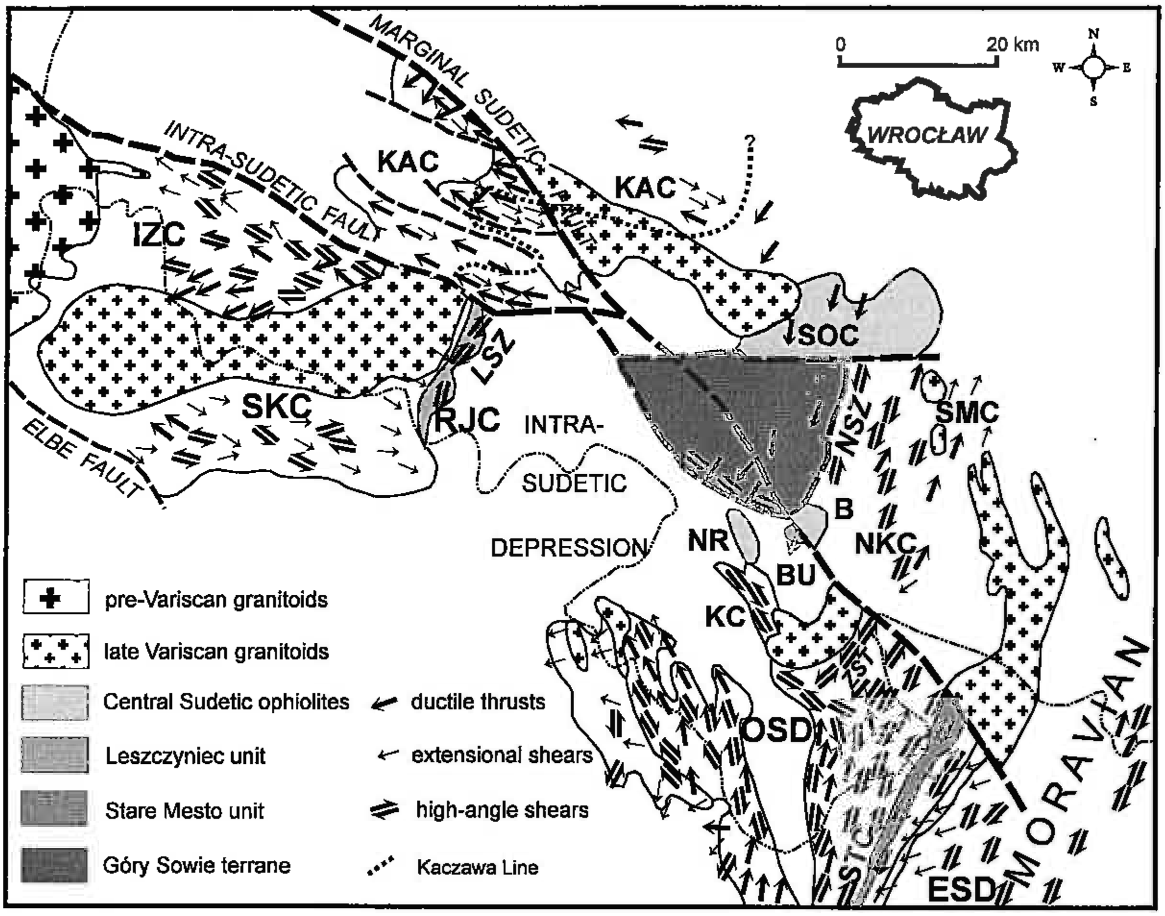

Fig. 5. Schematic structural-kinematic map of the Sudetes

B — Braszowice ophiolites; BU — Bardo unit; IZC — Izera metamorphic complex; KAC — Kaczawa metamorphic complex; LSZ — Leszczyniec shear zone; NR — Nowa Ruda ophiolites; NSZ — Niemcza shear zone; OSD — Orlica–Śnieżnik dome; RJC — Rudawy Janowickie metamorphic complex; SKC — South Karkonosze metamorphic complex; SOC — Ślęża ophiolite complex; SMC — Strzelin metamorphic complex; STC — Staré Město metamorphic complex; ZST — Złoty Stok–Trzebieszowice shear zone; ESD — East Sudetic metamorphic complex; KC — Kłodzko metamorphic complex; NKC — Niemcza–Kamieniec Ząbkowicki metamorphic complex

VARISCAN OROGENY

CLOSURE OF THE OCEANIC CRUSTS AND OBLIQUE COLLISION

The existence of numerous occurrences of mafic and ultramafic rocks of ophiolitic character in the Central Europe might correspond to the remnants of limited oceanic or sea areas which may have separated the different crustal blocks (terranes) (Figs. 2, 4). Complete closure of the Rheic Ocean led to collision between the Armorican microcontinents and East Avalonia, the latter having been accreted to Baltica since the Late Fammenian, in Central Europe (Ziegler, 1986; McKerrow and Cocks, 1986; Paris and Robardet, 1990; Robardet *et al.*, 1990). On the other hand, since the Late Devonian, closure of the Saxothuringian Ocean (Franke, 1989; Franke *et al.*, 1995) also called the Galicia–Massif Central Ocean (Matte, 1991) or the Ligerian Ocean (Oczlon, 1992) led to collision between the combined peri-Gondwanian plates (Armorican terrane complex) and the peri-Baltica arc (Fig. 2). The ophiolite remnants within the Bohemian Massif (Fig. 4) are a product of obduction, detachment and thrust imbrication within the different parts of the former oceanic crust (Figs. 2, 3). Obduction processes must be associated with simultaneous shortening; otherwise the ocean/mantle slab will not climb up (Balé and Brun, 1989).

In the Sudetes, the closure of the Saxothuringian Ocean and Ligerian Ocean (Fig. 2) is characterised by localised ductile shearing directed top-to-the-SW or to S, as seen in a large variety of asymmetric mylonitic structures that indicate the sense of shear (Fig. 5; Pl. III, Figs. 1, 2). Many examples of these mylonitic fabrics have been recorded within the southern part of the Góry Sowie complex and the surrounding rocks of the Central Sudetic terrane (Cymerman, 1993*a*; Cymerman and Piasecki, 1994; Mazur and Puziewicz, 1995; Aleksandrowski *et al.*, 1997).

The S- top SW-directed shearing took place under greenschist and lower amphibolite facies in the mafic and ultramafic rocks of the Central Sudetic terrane. Dismembered tectonic blocks of mafic and ultramafic rocks are concentrated along regional-scale shear zones (the Niemcza, Złoty Stok–Trzebieszowice and Leszczyniec shear zones). The tectonic blocks are out of petrologic equilibrium with their host mylonitic schists and mylonitic, retrogressed gneisses within which they are boudinaged (tectonically dismembered) as relatively rigid bodies. The presence of these "exotic" blocks suggests that the mylonitic (Pl. I, Fig. 3; Pl. III, Figs. 1, 2) and cataclastic rocks (Pl. III, Figs. 3, 4) define fundamental tectonic boundaries in the Sudetes (Figs. 1, 4).

The subduction model implies that the western and central parts of the Kaczawa metamorphic complex has the form of a Variscan accretionary prism. This is supported by the strong development of bedding-parallel fabrics, including mylonitic fabrics in many horizons of metavolcanic and metasedimentary rocks (Pl. IV, Figs. 1, 2), as well as a zone of melange/broken formation locally up to 2-km thick (Baranowski *et al.*, 1990).

VARISCAN TRANSPRESSION

In general, structural and kinematic data support the fact that the first part of the Variscan deformation in the Sudetes reflects a purely convergent setting that evolved into a transpressive setting during progressive oblique convergence. The main structures in the Sudetes resulted from a single kinematic event, combining a compressional and a wrenching regime of deformation, i.e. transpressional deformation (Holdswoth, 1994; Kirkwood, 1995; Fossen and Tikoff, 1998). Many regions of transpression exhibit tectonic structures such as stretching mineral lineations, folds, foliations, and shear zones, with orientations that vary within these areas. In general, these have been interpreted as recording partitioning of strain in order to accommodate contraction, extension, and transcurrent motion either sequentially or simultaneously (Fossen and Tikoff, 1993; Boronkay and Doutsos, 1994; Krantz, 1995; Liu, 1996).

In zones of oblique convergence, deformation in the overriding plate commonly evolves into a partitioned system with orogen-parallel strike-slip faults and orogen-orthogonal thrusting (Pinet and Cobbold, 1992; Fossen *et al.*, 1994). There is a strong analogy to the structures of the Izera metamorphic complex and Orlica–Śnieżnik dome, in which structural relationships were recognised that suggest vertical partitioning of strain into kinematic domains with different directions of tectonic transport (Cymerman, 1994, 1996*a*, *b*, 1997, 1999).

I here report the development of structures in different part of the Sudetes, related to a heterogeneous distribution of strain across the transpression zones. The Sudetes were affected by two major, composite, Variscan (Late Devonian–Early Carboniferous) structural episodes: D_1 and D_2.

The majority of the Sudetes is dominated by D_1 structures, which are the most common and most penetrative. They appear to have resulted from a single kinematic event during the high-grade transpressional episode, in which non-coaxial deformation (simple shear) has been heterogeneously and irregularly partitioned into zones of high and low strain (Pl. IV, Figs. 3, 4). Both high- and low-strain D_1 zones are characterised by L_1 mineral extensional lineation preserved on S_1 foliation planes (Pl. V, Fig. 1). The L_1 lineation is typically subparallel to the fold axes of isoclinal and tight folds (Pl. V, Fig. 2). Within D_1 low-strain zones, complex fold interference geometries (Pl. V, Fig. 3) are preserved, with fold axes co-linear with the L_1 lineation. The D_1 low-strain zones are transposed into zones of D_1 high strain, which preserve a relatively planar to tightly folded S_1 mylonitic foliation (Pl. V, Fig. 4). Kinematic and structural analyses suggest that the D_1 Variscan structures developed in response to transpressional deformation in the Sudetes, except the Góry Sowie metamorphic complex (Cymerman, 1999).

In the Góry Sowie metamorphic complex development of extensive migmatites and folds (Pl. II, Figs. 3, 4; Pl. VI, Fig. 1) appear not to have occurred during the D_1 Variscan transpressional event, but much earlier, probably during the Caledonian deformation. The emplacement of pegmatites along with the intrusion of a number of syn-kinematic granites and granodiorites (Pl. VI, Fig. 2), as for example in the Niemcza shear zone (Steltenpohl *et al.*, 1993; Mazur and Puziewicz, 1995), occurred during the D_2 extensional, Variscan regime.

In general, Late Devonian-Early Carboniferous D_1 regional-scale ductile thrusting in the Sudetes is characterised by:

1. In the western part of the Sudetes, by SW- to NW-directed (Fig. 5), sinistral transpressional stacking of nappes, interpreted as reflecting westward-directed lateral extrusion (escape) of the Saxothuringian continental crust (Fig. 6).
2. In the eastern part of the Sudetes, a general NNE-directed (Fig. 5), dextral transpressional stacking of ductile sheets (nappes) (Fig. 6).

WESTERN PART OF THE SUDETES

The Karkonosze–Izera dome is located in the western part of the Sudetes and comprises the Karkonosze granite pluton along with three metamorphic complexes (Mierzejewski and Oberc-Dziedzic, 1990). These are: (1) the Izera metamorphic complex, (2) the South Karkonosze metamorphic complex, and (3) the Rudawy Janowickie metamorphic complex. The Karkonosze–Izera dome is separated from the Kaczawa metamorphic complex by the brittle Intra-Sudetic fault (Fig. 1).

The Izera metamorphic complex and the northern part of the South Karkonosze metamorphic complex are composed mainly of Late Cambrian-Early Ordovician orthogneisses (Oliver *et al.*, 1993) and of mica schist belts (Mierzejewski and Oberc-Dziedzic, 1990). During Variscan deformation, the Izera metamorphic complex has undergone heterogeneous deformation (Pl. V, Fig. 2; Pl. VII, Fig. 1). The main deformation D_1 is characterised by localised ductile shear zones surrounding lenses of weakly deformed Izera granite (Pl. VI, Figs. 3, 4). Within the Izera metamorphic complex, lithological boundaries are generally parallel to the dominant fabric, a mylonitic foliation (dominantly $S > L$), with a main stretching lineation L_1 (Pl. V, Fig. 1). Local variations in strain intensity between fabrics that are parallel suggest that the fabrics commonly represent the combined effects of pure shear (flattening) and simple shear (Pl. VII, Fig. 1), a regime of deformation sometimes referred to as a "general shear" (Hanmer and Passchier, 1991; Weijermars, 1992; Jiang, 1994; Robin and Cruden, 1994). The regional patterns of the distribution of shear zone in the Izera metamorphic complex reveals the kinematics of the main ductile deformation phase D_1 on a large, regional scale (Cymerman, 1999).

Based on micro- and meso-structural methods and kinematic indicator analysis, a tectonic model of evolution of the Izera metamorphic complex with two deformation phases is proposed: (1) an earlier phase of movement with top-to-the-SW, correlated with the D_1 event of ductile nappe stacking, and (2) a later, syn- to post-collisional ductile NW-directed extension (D_2) that created important shear zones leading to a bulk displacement with top-to-the-NW (Pl. VI, Fig. 4). In general, the Izera metamorphic rocks show heterogeneously localised deformation fabrics with moderately to steeply NE-dipping main foliation (S_1 and/or S_2) and subhorizontal stretching lineations (L_1 and/or L_2). However, the effects of D_1 ductile, sinistral transpressional shearing with top-to-the-SW (Pl. VI, Fig. 3) are mainly recorded in the southern part of the Izera metamorphic complex and the South Karkonosze metamorphic complex, but are absent from the northern part of the Izera metamorphic complex.

The South Karkonosze metamorphic complex is located in the Czech Republic and is composed of three lithostratigraphic units: (I) the South Karkonosze unit, (II) the Ponikla unit, and (III) the Železny Brod–Rýchory unit (Chaloupský, 1989; Kachlik and Patočka, 1998). The South Karkonosze metamorphic complex is the southern continuity of the Izera metamorphic complex and is composed of orthogneisses and mica schists (Mierzejewski and Oberc-Dziedzic, 1990). The Ponikła unit comprises a wide range of metasedimentary and metavolcanic rocks, whereas the Železny Brod–Rýchory unit is composed mainly of metabasites with mafic blueschists (Maluski and Patočka, 1997; Kachlik and Patočka, 1998).

Two ductile deformation events (D_1 and D_2) have been recognised in the South Karkonosze metamorphic complex. The main S_1 foliation is almost parallel to the southern margin of the Karkonosze granites and trends dominantly W–E, except in the central part of the South Karkonosze metamorphic complex, where it defines an antiform-like structure. The dip of the generally steep S_1 foliation decreases towards the southern boundary of the Karkonosze granite. The L_1 stretching lineation plunges to the ESE, except near the vicinity of Železny Brod where it plunges to the W or NW. Shear sense indicators show a dextral sense of shearing, except in the western part of the South Karkonosze metamorphic complex, where the displacement is top-to-the-W or NW (Fig. 5). The D_1 deformation involved both W- and ESE-directed thrusting strongly combined with non-rotational shortening (flattening) in an approximately N–S direction. Such changes in the transport direction of nappes through time are not surprising, given the complicated structural evolution of the Sudetes. Nappe translation paths that include large changes in directions of relative movements have been described from several orogenic belts (Merle and Brun, 1984; Northrup and Burchfield, 1996).

Interestingly, the structural development of the South Karkonosze metamorphic complex provides an example in which different parts of individual thrust sheets or fold nappes are interpreted to have moved in different directions at essentially the same time. This pattern of deformation underscores the potential geometric complexity of nappe emplacement kinematics in environments with partitioned deformation and in which rocks complexes are evolving rheologically. Interpretation of the deformational history in such an environment is made difficult by the seemingly contradictory or incompatible kinematic characteristics of contemporaneous deformation at different locations and/or structural levels. On the other hand, the finite strain produced by a system of partitioned deformation can strongly resemble the results of a series of temporally distinct deformational episodes, and one could easily assign contemporaneous structures to temporally distinct episodes of deformation because of their apparently disparate kinematic characteristics.

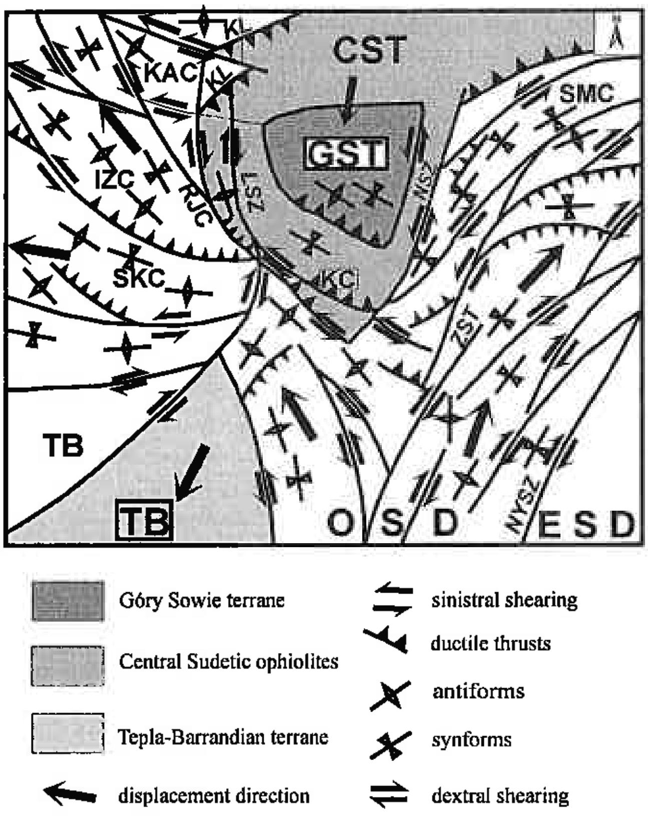

Fig. 6. Speculative model of the oblique accretion of the Middle Sudetian indenter, composed of the Góry Sowie terrane and the Central Sudetic terrane into the northernmost part of the Bohemian Massif. Contemporaneous or pene-contemporaneous development of localised ductile shear zones and deformation partitioned into domains of sinistral and dextral transpression in the western and eastern parts of the Sudetes, respectively

GST — Góry Sowie terrane; CST — Central Sudetic terrane; ESD — East Sudetic domes; IZC — Izera metamorphic complex; KAC — Kaczawa metamorphic complex; KC — Kłodzko metamorphic complex; KL — Kaczawa tectonic line; LSZ — Leszczyniec shear zone; NSZ — Niemcza shear zone; OSD — Orlica–Śnieżnik dome; NYSZ — Nyznerov shear zone; RJC — Rudawy Janowickie metamorphic complex; SKC — South Karkonosze metamorphic complex; SMC — Strzelin metamorphic complex; TB — Tepla–Barrandian terrane; ZST — Złoty Stok–Trzebieszowice shear zone

The Rudawy Janowickie metamorphic complex contains varied metabasic and metasedimentary rocks (Pl. I, Figs. 1, 2; Pl. III, Fig. 3), very similar to those in the South Karkonosze metamorphic complex. The Rudawy Janowickie metamorphic complex is divided into three geochemical provinces (Winchester *et al.*, 1995). The western province contains both alkali basaltic and transitional tholeiitic metabasites, associated with varied metasediments, whereas the central and eastern provinces contain voluminous tholeiitic metabasites of MORB-like composition. The latter are separated from the western province by the dextral, heterogeneous, and anastomosing Leszczyniec shear zone (Cymerman and Piasecki, 1994). The mylonitic rocks of the Leszczyniec shear zone have been modified by ductile-brittle extensional shear zones of Early Carboniferous age (Pl. III, Fig. 3). Magma generation dated at 505±5 and 494±2 Ma (U-Pb zircon) from felsic and metabasic rocks in the central province (Oliver *et al.*, 1993) was followed by early blueschist and later greenschist facies metamorphism (Kryza and Mazur, 1995). $^{40}Ar/^{39}Ar$ dating of phengites indicated ages of *ca.* 360 Ma for the blueschist facies metamorphic event, and *ca.* 340 Ma for the greenschist facies overprint (Maluski and Patočka, 1997).

The Rudawy Janowickie metamorphic complex is characterised by two tectonic events: a D_1 transpressional event and a D_2 extensional deformation, each exhibiting a different kinematic and metamorphic evolution (Cymerman, 1996*a*). The older oblique emplacement (D_1) of the Leszczyniec unit over the Ponikla unit under HP–MT metamorphic conditions probably occurred prior to the Visean. A regional, subhorizontal NNE–SSW stretching lineation (L_1) on steeply to almost vertical S_1 foliation planes and rare shear criteria observed in the Leszczyniec unit indicate a displacement of this unit towards the SSW during the D_1 deformation. However, locally some domains in the Leszczyniec unit show more complicated L_1 mineral lineation trajectories probably related to early lateral dextral ramping and strain partitioning.

The Kaczawa metamorphic complex comprises varied lithologies (Pl. IV, Figs. 1, 2) of Cambrian(?) to Late Devonian age, and locally Early Carboniferous rocks in the NW part. Voluminous metavolcanic rocks include metabasites of alkali basaltic, transitional tholeiitic and MORB-like tholeiitic compositions, affected by greenschist facies metamorphism overprinting an earlier blueschist facies metamorphism (Baranowski *et al.*, 1990; Kryza, 1995). The Kaczawa metabasalts were interpreted to have been extruded in an evolving rift basin (Furnes *et al.*, 1994). There is a clear division between alkali metabasalts-dominated volcanic rocks and metasediments in the western part of the Kaczawa metamorphic complex and MORB-like metabasalts found in the eastern part of the Kaczawa metamorphic complex (Furnes *et al.*, 1994). An important structural zone, termed the Kaczawa line (Fig. 1), was proposed to divide these different rock associations in the Kaczawa metamorphic complex (Cymerman *et al.*, 1997). Field data indicate that the Kaczawa line contains heterogeneous, locally highly strained mylonitic rocks. Together the strained rocks form a complex, anastomosing mylonitic zone separating the structurally lower units containing alkaline and transitional tholeiitic metabasalts from MORB-like metabasites. This high-strain zone, which incorporates lower-strain lenses, is interpreted as a basal ductile thrust, developed during a D_1 sinistral transpressional regime, and as the northern continuation of the Leszczyniec shear zone known from the Rudawy Janowickie metamorphic complex. Differential displacements during D_1 main ductile thrusting and subsequent D_2 extensional deformation modified the Kaczawa tectonic line, resulting in its sinuous course on geological maps (Figs. 1, 5, 6).

EASTERN PART OF THE SUDETES

The D_1 transpressional deformation in the eastern part of the Sudetes is well documented in the Orlica–Śnieżnik dome, the largest tectonic unit, exposing Late Proterozoic to Early Ordovician supracrustal and igneous rocks. It represents the deepest exhumed part of the Variscan orogen in the Sudetes. The northern continuation of the Orlica–Śnieżnik dome rocks in the Fore-Sudetic Block is the Strzelin and Niemcza–Kamieniec metamorphic complexes (Fig. 1). One of the most characteristic features of the eastern part of the Sudetes and the eastern part of the Fore-Sudetic block is the constant kinematics indicating top-to-the-NNE (Pl. VII, Fig. 2) transpressive displacement (Rajlich, 1990; Cymerman, 1997).

The kinematic and structural features of the Orlica–Śnieżnik dome are best interpreted as representing heterogeneous motion over ductile thrusts with a flat-ramp geometry (Cymerman, 1997). Most ductile shear zones trend N–S, dip moderately to steeply, exhibit a dominant dextral senses of shearing and may be interpreted as lateral ramps of ductile thrust sheets. Locally, as in the northern part of the Orlica–Śnieżnik dome, the shear zones strike E–W and may be inferred to be frontal ramps of ductile thrust sheets. The invoked regime of thrusting involving lateral and frontal ramps may also explain the presence of flattening strain geometry, as well as, locally the opposing sense of shear (Pl. I, Figs. 3, 4; Pl. V, Fig. 4). Motion over a steep ramp would be expected to lead first to compression, followed by horizontal stretching as the thrust slice reaches the top of the ramp. Imbrication of lithological units in the Orlica–Śnieżnik dome also appears to indicate the presence of duplex-like structures in the footwall and supports the model of generally NNE-directed ductile thrusting (Cymerman, 1997).

The architecture of the Orlica–Śnieżnik dome comprises a system of deformation belts that accommodated oblique convergence in a transpressional orogen during long-lived, Variscan, progressive deformation (Cymerman, 1997). Transpression was accommodated in two ways, either as a single zone in which shortening is spread over a much greater width than strike slip, or as several non-overlapping zones, separated by undeformed domains. In general, transpression in the Orlica–Śnieżnik dome is partitioned into localised zones of shortening perpendicular to the N–S regional trend of the orogen and zones of mixed shortening and strike-slip. The more local "antithetic" shearing toward the SW, especially in the SW part of the Orlica–Śnieżnik dome (Fig. 5), may be related to backthrusting in connection with the "backfold", or due to flow perturbation during heterogeneous shearing (Cymerman, 1997).

The overall structural evolution of the Orlica–Śnieżnik dome is best interpreted as the result of Variscan transpressional convergence of the Moldanubian and Moravian realms. Such ductile, dextral displacement of thrust sheets towards the N and NE resulting from a dextral transpressive regime are a characteristic feature of the NE part of the Bohemian Massif (Rajlich, 1990). This transpression led to the transport of the Orlica–Śnieżnik dome nappe sheets towards the dismembered packages of ophiolitic and/or arc island sequences in the SE part of the Central Sudetic terrane (Cymerman and Piasecki, 1994). It is important to note that the Variscan deformation history recorded in the Orlica–Śnieżnik dome is not compatible with that of the Moravian foreland. For example, while crustal stacking still occurred in the East Sudetes domes from about 320 to *ca.* 300 Ma, uplift was almost terminated in the Orlica–Śnieżnik dome (Steltenpohl *et al.*, 1993; Maluski *et al.*, 1995).

VARISCAN EXTENSION

In the Sudetes, the D_1 Variscan deformation effects are overprinted by regionally extensive, high-strain D_2 zones, characterised by extensional movement inferred to be parallel to the L_2 mineral extensional lineation. On a regional scale, several late orogenic granites were emplaced during late syn-D_2 deformation, for example the Karkonosze granitoids. The D_2 structures from the Sudetes indicate localised Variscan extension directed *ca.* NW–SE and generally SW–NE in the western and eastern parts of the Sudetes (Pl. VII, Fig. 3), respectively.

$^{40}Ar/^{39}Ar$ data have constrained the late exhumation history of the some parts of the Sudetes (Steltenpohl *et al.*, 1993; Oliver and Kelley, 1993; Maluski *et al.*, 1995). The P–T paths from the Karkonosze–Izera dome, the Góry Sowie metamorphic complex, and the Orlica–Śnieżnik dome record almost isothermal decompression from the deeper part of the continental crust with increased temperatures (*ca.* 800–900°C). This is interpreted to have resulted from an extensional deformation combined with high heat flow. Under such regime, crustal thinning was accompanied by upwelling of astenospheric material and convective heat transfer by the Late Variscan magmatic rocks.

A Late Variscan extensional tectonism in the Sudetes is associated with uplift of the thickened orogenic domains. A progressive evolution from deep ductile to shallow brittle deformation is related to fast exhumation and warping of the thickened domains, promoted by migmatization and anatectic granitoid emplacement. Such late, rapid uplift accompanied by a strong increase in the geotherm has been observed in different parts of the Sudetes, and is usually associated with the development of metamorphic core complexes such as the Karkonosze–Izera dome or the Orlica–Śnieżnik dome (Cymerman, 1994, 1996*a*, *b*, 1997). On the other hand, syn-collisional extensional processes in the Sudetes, such as in the Strzelin metamorphic complex, can result from localised deformation and duplexing with growing subduction-collision complexes.

In the western part of the Sudetes, wide, large-scale D_2 extensional shear zones have been recognised in the NW and E parts of the Karkonosze–Izera dome (Cymerman, 1994, 1996*a*). In the northern part of the Izera metamorphic complex the D_2 extensional event comprised oblique to sinistral strike-slip shearing related to NW-directed extensional collapse (Cymerman, 1994, 1999). The S_2 foliations in the orthogneisses and mica schist belts dip moderately to steeply to the N or NE. The stretching lineations (L_2) mainly plunge gently W or NW. Abundant kinematic indicators show top-to-the-W or NW movement, that is normal to the oblique sense of shear (Pl. VI, Fig. 4).

A zone of D_2 extensional ductile deformation is well documented from the western part of the Rudawy Janowickie metamorphic complex (Cymerman, 1996*a*) and the eastern part of the South Karkonosze metamorphic complex and has a width of at least 4 km. The well developed S_2 mylonitic foliation in the orthogneisses strikes NNE–SSW and dips moderately to the ESE. The regional L_2 stretching lineation trends W–E to NW–SE. The D_2 deformation changes from ductile shearing in the footwall to transitional and brittle displacement in the hangingwall. It was characterised by non-coaxial shearing, during which the hangingwall of the structure moved down and to the east relative to the footwall. The D_2 extensional deformation probably was contemporaneous with, or slightly preceded, the extensional collapse of the crust directed to the east, which initiated the formation of the Intra-Sudetic Depression (Cymerman, 1996*a*).

A Late Variscan extensional tectonism in the central part of the Sudetes was also associated with the uplift of the thickened domains. Belts of mylonitic rocks from the southern part of the Góry Sowie metamorphic complex indicate localised extension with the development of normal and/or sinistral, oblique, high-angle D_2 shear zones (Pl. III, Fig. 1). A progressive evolution from deep ductile to shallow brittle deformation along the southern margin of the Góry Sowie metamorphic complex may be related to fast exhumation and warping of the previously thickened domains. The extensional regime was probably accompanied by upwelling of asthenospheric material and convective heat transfer by late-orogenic magmatic rocks.

In the eastern part of the Sudetes, Late Variscan extensional deformation is closely associated with the uplift of the Keprnik (Pl. VII, Fig. 3) and Desná domes and the gravitational collapse of the previously thickened crust of the Orlica–Śnieżnik dome. The $^{40}Ar/^{39}Ar$ mineral cooling data document rapid exhumation of the Orlica–Śnieżnik dome (Steltenpohl *et al.*, 1993) during delamination and extensional collapse processes similar to those of metamorphic core complexes.

The D_2 extensional event in the Niemcza–Kamieniec metamorphic complex (eastern part of the Fore-Sudetic Block) took place under lower amphibolite to greenschist facies conditions. It was related to localised sinistral transtensional displacements with top-to-the-SW shearing. In the Strzelin metamorphic complex, progressive D_1 shortening event was followed by the development of normal, moderately to low-angle shear zones (D_2) characterised by down-dip (normal) displacement with a sense of top-to-the-NNE (Pl. VII, Fig. 2) (Cymerman, 1993*b*). The D_2 deformation was accompanied by the Strzelin granitoid intrusion emplacements.

GEODYNAMIC IMPLICATIONS

The plate-kinematic framework of the Sudetes is still far from being completely understood. The tectonic setting of the protoliths is largely known only from the geochemistry of metamorphic rocks (Oliver *et al.*, 1993; Furnes *et al.*, 1994; Winchester *et al.*, 1995; Kröner and Hegner, 1998). At this stage of knowledge the model presented here is only the next step in a better understanding of tectonic processes, which may be related to terrane accretion in the Sudetes during Palaeozoic times (Matte *et al.*, 1990; Oliver *et al.*, 1993; Cymerman and Piasecki, 1994; Cymerman *et al.*, 1997).

During the main phase (D_1) of the Variscan orogeny, marked by horizontal compression, mantle-lithosphere delamination took place, so that the more rigid domains (e.g. pieces of uppermost mantle) may have become intertwined with the weaker parts of the crust, creating the crocodile-like patterns as seen in some seismic reflection interpretations. All the deep reflection lines in the Central Variscan internides (e.g. DEKORP, GB-2A) show similar patterns (Behr and Heinrichs, 1987; Cwojdziński *et al.*, 1995). Strongly dipping reflectors which may represent major thrusts along the terrane boundaries concentrate in the rigid upper crust and these are truncated by subhorizontal lamellae of the lower crust, thought to have been emplaced by late-orogenic extensional shearing. Such extensional shearing, probably formed during orogenic collapse with crustal root disappearance, was responsible for the creation of lower crustal reflectivity in the Bohemian Massif. This means, that there is little hope of identifying compressional structures in the once ductile lower crust, especially in the Variscan internides such as the Sudetes, where thermal peaks and the emplacement of syn- and post-orogenic granitoids were pronounced.

Sengör (1990) defined three major types of collisional belts: (1) Alpine-type, (2) Himalayan-type, and (3) Altaid-type. The Alpine- and Himalayan-type belts are characterised by narrow suture zones marking the sites of obliteration of oceanic lithosphere by subduction-accretion and collisional processes. On the other hand, the Altaid-type (Turkic-type) collisional belts possess wide sutures (up to several hundred kilometres) characterised by subduction-accretion complexes and arc-derived granitoids intrusions, similar to the Circum-Pacific accreted terranes. These subduction-accretion complexes are often juxtaposed by thrust faults and disrupted orogen-parallel strike-slip, resulting in bifurcating lithological domains (Sengör and Natal'in, 1996). The Altaid-type of collisional belt is the best model for the Palaeozoic accretionary history of the Sudetes.

The Lusatian, Tepla–Barrandian and Moravian terranes represent Gondwana-derived microplates (Figs. 2, 4) which were separated by rifting processes during Cambrian-Ordovician times or a little later (Silurian ophiolites suggest it happened later). The resultant basinal/oceanic crust of the Central Sudetic terrane and thinned continental crust of the Saxothuringian and Moldanubian terranes were subsequently affected by episodes of subduction/obduction, perhaps as early as in the Ordovician (Oliver *et al.*, 1993) or Silurian (Kröner and Hegner, 1998). However, the development of most important structures in the Sudetes resulted from Devonian oblique accretion of the Góry Sowie terrane of an inferred magmatic arc setting (Kröner and Hegner, 1998). Plate convergence exactly orthogonal to plate boundaries occurs less frequently than oblique movement, so most collisional orogens are transpressional and must, in some manner, accommodate an orogen-parallel component of structural transport (Fossen *et al.*, 1994).

In general, the geotectonic model for the Variscan evolution of the western part of the Sudetes proposed here is consistent with lateral escape of the Saxothuringian terrane as an important way of accommodating the Early Variscan deformation in the NE part of the Bohemian Massif. This model explains lateral expulsion as due to indentation of the Central Sudetic terrane and by the oblique subduction of the Ligerian and/or the Saxothuringian Ocean (now preserved as tectonically dismembered fragments of the Central Sudetic terrane).

CONCLUSIONS

1. The Palaeozoic geodynamic evolution of the Sudetes resulted from two successive orogenic events: (1) the Ordovician-Silurian geotectonic processes (pre-Variscan [Caledonian] stage), and (2) Variscan orogeny.

2. The Early Palaeozoic rifting of the Cadomian crust segments (Lusatian and Moravian terranes) and opening of the Saxothuringian and the Ligerian Oceans occurred during Ordovician-Silurian times on the northern (Gondwana) periphery of the Bohemian Massif. At the same time, the Góry Sowie terrane with a magmatic arc setting probably developed on the SW margin of Baltica (the so-called peri-Baltica arc) due to subduction of the Tornquist Ocean.

3. In the Sudetes, the Variscan orogeny is characterised by two major structural events: (1) Late Devonian-Early Carboniferous regional-scale ductile thrusting, and (2) Early Carboniferous-Early Permian regional extension.

4. The Late Devonian-Early Carboniferous regional-scale ductile thrusting was characterised by: (1) a general NNE-directed, dextral transpressional stacking of ductile sheets due to oblique collision of the Moldanubian and Moravian microplates (terranes) in the eastern part of the Sudetes, and (2) SW- to NW-directed, sinistral transpressional stacking of ductile nappes due to westward lateral extrusion (escape) of the Saxothuringian continental crust in the central and western parts of the Sudetes as a result of almost frontal indentation of the Central Sudetic oceanic lithosphere.

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REFERENCES

ALEKSANDROWSKI P., KRYZA R., MAZUR J. and ŻABA J. (1997) — Kinematic data on major Variscan strike-slip faults and shear zones in the Polish Sudetes, northeast Bohemian Massif. Geol. Mag., **134**: 727–739.

BALÉ P. and BRUN J.-P. (1989) — Late Precambrian thrust and wrench zones in northern Brittany (France). J. Struct. Geol., **1**: 391–405.

BARANOWSKI Z., HAYDUKIEWICZ A., KRYZA R., LORENC S., MUSZYŃSKI A., SOLECKI A. and URBANEK Z. (1990) — Outline of the geology of the Góry Kaczawskie (Sudetes, Poland). N. Jb. Geol. Paläont., Abh., **179**: 223–257.

BEAMOUNT C., FULLSACK P. and HAMILTON J. (1994) — Styles of crustal deformation caused by subduction of the underlying lithosphere. Tectonophysics, **232**: 119–132.

BEHR H.-J. (1978) — Subfluenz-Prozesse im Grundgebirges-stockwerk Mitteleuropas. Z. Dtsch. Geol. Ges., **129**: 283–318.

BEHR H.-J. and HEINRICHS T. (1987) — Geological interpretation of DEKORP 2-S. A deep reflection profile across the Saxothuringian and possible implications for the Late Variscan structural evolution of Central Europe. Tectonophysics, **142**: 173–202.

BORONKAY K. and DOUTSOS T. (1994) — Transpression and transtension within different structural levels in the central Aegean region. J. Struct. Geol., **16**: 1555–1573.

BRUECKNER H. K., BLUNSZTAJN J. and BAKUN-CZUBAROW N. (1996) — Trace element and Sm-Nd age zoning in garnets from peridotites of Caledonian and Variscan mountains and tectonic implications. J. Met. Geol., **14**: 61–73.

BRUECKNER H. K., MEDARIS L. G. and BAKUN-CZUBAROW N. (1991) — Nd and Sr age and isotopic patterns form Variscan eclogites of the eastern Bohemian Massif. N. Jb. Miner., Abh., **163**: 169–196.

CHALOUPSKÝ J. (1989) — Major tectonostratigraphic units of the Bohemian Massif. Geol. Soc. Am., Spec. Paper, **230**: 101–114.

CHEMENDA A., MATTAUER M., MALAVIEILLE J. and BOKUN A. N. (1995) — A mechanism for syncollisional rock exhumation and associated normal faulting. Earth Planet. Sc. Lett., **132**: 225–232.

CWOJDZIŃSKI S., MŁYNARSKI S., DZIEWIŃSKA L., JÓŹWIAK W., ZIENTARA P. and BAZIUK T. (1995) — GB-2A — pierwszy sejsmiczny profil głębokich badań refleksyjnych (GBS) na Dolnym Śląsku. Prz. Geol., **43**: 738–744.

CYMERMAN Z. (1989) — Structural evolution of the Góry Sowie unit in the area of northern part of the Bielawa Hills, Sudetes (in Polish with English summary). Geol. Sudet., **24** (1–2): 191–284.

CYMERMAN Z. (1993*a*) —Tectonic position of Owl Mts unit — remarks to the model of unrooted Variscan nappes of the crystalline basement in Lower Silesia (in Polish only). Prz. Geol., **41** (1): 27–30.

CYMERMAN Z. (1993*b*) — Tectonic units of the Strzelin metamorphic complex (Lower Silesia, SW Poland) in light of a new structural analysis (in Polish only). Prz. Geol., **41** (6): 421–427.

CYMERMAN Z. (1994) — Shearing zones in the Izera metamorphic terrain, Sudeten (SW Poland) (in Polish with English summary). Prz. Geol., **42** (4): 264–270.

CYMERMAN Z. (1996*a*) — Transpression and extension in the Rudawy Janowickie metamorphic complex (Western Sudetes, SW Poland) (in Polish with English summary). Prz. Geol., **44** (12): 1211–1216.

CYMERMAN Z. (1996*b*) — The Złoty Stok–Trzebieszowice regional shear zone: the boundary of terranes in the Góry Złote Mts. (Sudetes). Geol. Quart., **40** (1): 89–118.

CYMERMAN Z. (1997) — Structure, kinematics and an evolution of the Orlica–Śnieżnik Dome, Sudetes. Pr. Państw. Inst. Geol., **156**.

CYMERMAN Z. (1998) — The Góry Sowie terrane: a key to understanding the Palaeozoic evolution of the Sudetes area and beyond. Geol. Quart., **42** (4): 379–400.

CYMERMAN Z. (1999) — Structural and metamorphic evolution of the Izera metamorphic complex. Exkurs.f. u. Veröfftl. GGW, Berlin, **206**: 113–131.

CYMERMAN Z. and PIASECKI M. A. J. (1994) — The terrane concept in the Sudetes, Bohemian Massif. Geol. Quart., **38** (2): 191–210.

CYMERMAN Z., PIASECKI M. A. J. and SESTON R. (1997) — Terrane and terrane boundaries in the Sudetes, northeast Bohemian Massif. Geol. Mag., **134**: 717–725.

DALLMEYER R. D., STRACHAN R. A. and D'LEMOS R. S. (1991) — Chronology of Cadomian tectonothermal activity in the baie de Saint-Brieuc (north Brittany), France: evidence from Ar/Ar mineral ages. Canad. J. Earth Sc., **28**: 762–773.

DALZIEL I. W. D., DALLA-SALDA L. H. and GAHAGAN L. M. (1994) — Paleozoic Laurentia-Gondwana interaction and the origin of the Appalachian-Andean mountain system. Geol. Soc. Amer. Bull., **106**: 243–252.

DON J. (1982) — The Sienna synform and the relationship of gneisses to the deformational stages distinguished in the Śnieżnik metamorphic massif (Sudetes). Geol. Sudet., **17** (1–2): 103–124.

DON J. (1990) — The differences in Palaeozoic facies-structural evolution if the West Sudetes. N. Jb. Geol. Paläont. Abh., **179**: 307–328.

DUMICZ M. (1989) — The Śnieżnik Mts. gneisses sequence in the light of mesostructural analysis of some areas of the Międzygórze and Gierałtów units. Geol. Sudet., **24** (1–2): 139–189.

EDEL J. B. and WEBER K. (1995) — Cadomian terranes, wrench faulting and thrusting in the Central Europe Variscides: geophysical and geological evidence. Geol. Rdsch., **84**: 412–432.

ELLIS S. (1996) — Forces driving continental collision: reconciling indentation and mantle subduction tectonics. Geology, **24**: 699–702.

FERRÉ E. C., CABY R., PEUCAT J. J., CAPDEVILA R. M. and MONIÉ P. (1998) — Pan-African, post-collisional, ferro-potassic granite and quartz-monzonite plutons of eastern Nigeria. Lithos, **45**: 255–279.

FOSSEN H. and TIKOFF B. (1993) — The deformation matrix for simultaneous simple shearing. Pure shearing and volume change and its application to transpression-transtension tectonics. J. Struct. Geol., **15**: 413–422.

FOSSEN H. and TIKOFF B. (1998) — Extended models of transpression and transtension and application to tectonic settings GSL. In: Continental Transpressional and Transtensional Tectonics (eds. R. E. Holdsworth, R. A. Strachan and J. F. Dewey). Geol. Soc. London, Spec. Publ., **135**: 15–33.

FOSSEN H., TIKOFF T. B. and TEYSSIER C. T. (1994) — Strain modelling of transpressional and transtensional deformation. Norsk Geol. Tidsskr., **74**: 134–145.

FRANKE W. (1989) — Tectonostratigraphic units in the Variscan belt of Central Europe. Geol. Soc. Amer., Spec. Publ., **230**: 67–90.

FRANKE W., DALLMEYER W. and WEBER K. (1995) — Geodynamic evolution. In: Pre-Permian Geology of Central and Eastern Europe (eds. R. D. Dallmeyer, W. Franke and K. Weber): 579–593. Springer-Verlag. Berlin.

FRANKE W., ŻELAŹNIEWICZ A., PORĘBSKI S. and WAJSPRYCH B. (1993) — Saxothuringian zone in Germany and Poland: differences and common features. Geol. Rdsch., **82**: 583–599.

FURNES H., KRYZA R., MUSZYŃSKI A., PIN C. M. and GARMANN L. B. (1994) — Geochemical evidence for progressive, rift-related early Palaeozoic volcanism in the Western Sudetes. J. Geol. Soc. London, **151**: 91–109.

GRAY D. R. and FOSTER D. A. (1997) — Orogenic concepts — application and definition: Lochlan Fold Belt, Eastern Australia. Amer. J. Sc., **297**: 859–891.

HANMER S. and PASSCHIER C. (1991) — Shear-sense indicators: a review. Geol. Surv. Canada, Spec. Paper: 90–17.

HANŽL P. and MELICHAR R. (1997) — The Brno Massif: a section through the active continental margin or a composed terrane?. Krystalinikum, **23**: 33–58.

HARLAND W. B. (1969) — Interpretation of stratigraphic ages in belts. In: Time and Place in Orogeny (eds. P. E. Kent, G. E. Satterhwaite and M. A. Spencer). Geol. Soc. London, Spec. Publ., **3**: 115–135.

HARRISON T. M., COPELAND P., KIDD W. S. F. and YIN A. (1992) — Raising Tibet. Science, **255**: 1663–1670.

HAVLIČEK V., VANEK J. and FATKA O. (1994) — Perunica microcontinent in the Ordovician (its position within the Mediterranean province, series division, bentic and pelagic associations). Sbor. Geol. Ved., **46**: 23–56.

HÉBERT R. (1995) — Evidence for multiple high-T metamorphism and regional migmatization within the Cadomian belt of northern Britanny, France. J. Geol. Soc. London, **152**: 213–216.

HOLDSWOTH R. E. (1994) — Structural evolution of the Gander–Avalon terrane boundary: a reactivated transpression zone in the NE Newfoundland Appalachians. J. Geol. Soc. London, **151**: 629–646.

HSÜ K. J. (1989) — Time and place in Alpine orogenesis — the Fermor Lecture. In: Alpine Tectonics (eds. M. P. Coward, D. Dietrich and R. G. Park). Geol. Soc. London, Spec. Publ., **45**: 421–443.

JIANG D. (1994) — Vorticity determination, distribution, partitioning and the heterogeneity and non-steadiness of natural deformations. J. Struct. Geol., **16**: 121–130.

JOHNSTON J. D., TAIT J. A., OLIVER G. J. and MURPHY F. C. (1994) — Evidence for a Caledonian orogeny in Poland. Trans. Royal Soc. Edinburgh, Earth Sc., **85**: 131–142.

KACHLIK V. and PATOČKA F. (1998) — Lithostratigraphy and tectonomagmatic evolution of the Železny Brod crystalline unit: some constraints for the palaeotectonic development of the W Sudetes (NE Bohemian Massif). Geolines, Praha, **6**: 34–35.

KIRKWOOD D. (1995) — Strain partitioning and progressive deformation history in a transpressive belt, northern Appalachians. Tectonophysics, **241**: 15–34.

KOSSMAT F. (1927) — Gliederung des varistischen Gebirgsbaues. Abh. Sächs. Geol. Landesanst, **1**.

KRANTZ R. W. (1995) — The transpressional strain model applied to strike-slip, oblique-convergent and oblique-divergent deformation. J. Struct. Geol., **17**: 1125–1137.

KRÖNER A. and HEGNER E. (1998) — Geochemistry, single zircon ages and Sm-Nd systematics of granitoid rocks from the Góry Sowie (Owl) Mts., Polish West Sudetes: evidence for early Palaeozoic arc-related plutonism. J. Geol. Soc. London, **155**: 711–724.

KRÖNER A., ŠTIPSKA P., SCHULMANN K. and JAECKEL P. (in press) — Chronological constraints on the pre-Variscan evolution of the northeastern margin of the Bohemian Massif, Czech Republic. J. Geol. Soc. London.

KRYZA R. (1995) — Western Sudetes (Lugicum): metamorphic evolution. In: Pre-Permian Geology of Central and Eastern Europe (eds. R. D. Dallmeyer, W. Franke and K. Weber): 351–360. Springer-Verlag. Berlin.

KRYZA R. and MAZUR S. (1995) — Contrasting metamorphic paths in the eastern part of the Karkonosze–Izera Block, SW Poland. N. Jb. Miner. Abh., **169**: 157–192.

KRYZA R., PIN C. and VIELZEUF D. (1996) — High-pressure granulites from the Sudetes (south-west Poland): evidence of crustal subduction and collisional thickening in the Variscan Belt. J. Metam. Geol., **14**: 531–546.

KÜSTER D. and HARMS U. (1998) — Post-collisional potassic granitoids from the southern and northwestern parts of the Late Neoproterozoic East African orogen: a review. Lithos, **45**: 177–195.

LINNEMANN U. (1995) — The Neoproterozoic terranes of Saxony (Germany). Prec. Res., **73**: 235–250.

LINNEMANN U., GEHMLICH M. and TICHOMIROWA M. (1997) — Peri-Gondwanan terranes of the Saxo-Thuringian Zone (central European Variscides, Germany). Terra Nostra, **11**: 73–78.

LIU M. (1996) — Dynamic interactions between crustal shortening, extension, and magmatism in the North American Cordillera. Tectonophysics, **146**: 447–467.

MALUSKI H. and PATOČKA F. (1997) — Geochemistry and ^{40}Ar-^{39}Ar geochronology of the mafic metavolcanic rocks from the Rýchory Mountains complex (West Sudetes, Bohemian Massif): palaeotectonic significance. Geol. Mag., **134**: 703–716.

MALUSKI H., RAJLICH P. and SOUCEK J. (1995) — Pre-Variscan, Variscan and early Alpine thermo-tectonic history of the north-eastern Bohemian Massif: an Ar/Ar study. Geol. Rdsch., **84**: 345–358.

MATTE P. (1986) — Tectonics and plate tectonics model of the Variscan belt of Europe. Tectonophysics, **126**: 329–374.

MATTE P. (1991) — Accretionary history and crustal evolution of the Variscan belt in western Europe. Tectonophysics, **196**: 309–337.

MATTE P., MALUSKI H., RAJLICH P. and FRANKE W. (1990) — Terrane boundaries in the Moldanubian Massif: result of large-scale Variscan shearing. Tectonophysics, **177**: 151–170.

MAZUR S. and PUZIEWICZ J. (1995) — Mylonity strefy Niemczy. Ann. Soc. Geol. Pol., **64** (1–4): 23–52.

MCCAFFREY R. and NABELEK J. (1998) — Role of oblique convergence in the active deformation of the Himalayas and southern Tibet plateau. Geology, **26**: 691–694.

MCKERROW W. S. and COCKS L. R. M. (1986) — Oceans, island arcs and olistostromes: the use of fossils in distinguishing sutures, terranes and environments around the Iapetus Ocean. J. Geol. Soc. London, **143**: 185–191.

MERLE O. and BRUN J. P. (1984) — The curved translation path of the Parpillon Nappe (French Alps). J. Struct. Geol., **6**: 711–719.

MIERZEJEWSKI M. P. (1993) — Przemieszczenia fragmentów litosfery a powstanie i ruchy magm — wybrane przykłady z regionu sudeckiego i przedsudeckiego. Geol. Sudet., **27** (1–2): 97–180.

MIERZEJEWSKI M. P. and OBERC-DZIEDZIC T. (1990) — The Izera-Karkonosze Block and its tectonic development (Sudetes, Poland). N. Jb. Geol. Paläont. Abh., **179**: 197–222.

NARĘBSKI W., WAJSPRYCH B. and BAKUN-CZUBAROW N. (1982) — On the nature, origin and geotectonic significance of ophiolites and related rock suites in the Polish part of the Sudetes. Ofioliti, **2** (3): 407–428.

NORTHRUP C. J. and BURCHFIELD B. C. (1996) — Orogen-parallel transport and vertical partitioning of strain during oblique collision, Efjorden, north Norway. J. Struct. Geol., **18**: 1231–1244.

OBERC-DZIEDZIC T. (1989) — Metamorfizm waryscyjski Sudetów i bloku przedsudeckiego. Pr. Geol.-Miner., **17**, Acta Univ. Wratisl., **1113**: 115–138.

O'BRIEN P. J., KRÖNER A., JACKEL P., HEGENER E., ŻELAŹNIEWICZ A. and KRYZA R. (1997) — Petrological and isotopic studies on Palaeozic high-pressure granulites, Góry Sowie Mts, Polish Sudetes. J. Petrol., **38**: 433–456.

OCZLON M. S. (1992) — Gondwana and Laurussia before and during the Variscan orogeny in Europe and related areas. Heidelberger Geowiss. Abh., **53**: 1–56.

OLIVER G. J. H., CORFU F. and KROGH T. E. (1993) — U-Pb ages from SW Poland: evidence for a Caledonian suture zone between Baltica and Gondwana. J. Geol. Soc. London, **150**: 355–369.

OLIVER G. J. H. and KELLEY S. (1993) — ^{40}Ar-^{39}Ar fusion ages from the Polish Sudetes: Variscan tectonothermal reworking of Caledonian protoliths. N. Jb. Geol. Paläont. Mh., **26**: 321–334.

ONCKEN O. (1997) — Transformation of a magmatic arc and an orogenic root during oblique collision and its consequences for the evolution of the European Variscides (Mid-German crystalline rise). Geol. Rdsch., **86**: 2–20.

ONCKEN O., VON WINTERFELD C. and DITTMAR U. (1999) — Accretion of a rifted passive margin: The Late Paleozoic Rhenohercynian fold and thrust belt (Middle European Variscides). Tectonics, **18**: 75–89.

PAQUETTE J. L. and NÉDÉLEC A. (1998) — A new insight into Pan-African tectonics in the East-West Gondwana collision zone by U-Pb zircon dating of granites from central Madagascar. Earth Planet. Sc. Letters, **155**: 45–56.

PARIS F. and ROBARDET M. (1990) — Early Palaeozoic paleobiogeography of the Variscan regions. Tectonophysics, **177**: 193–213.

PATOČKA F. and SMULIKOWSKI W. (1995) — Petrology and geochemistry of metabasic rocks of the Rýchory Mts–Rudawy Janowickie Mts complex. Pr. Spec. Pol. Tow. Miner., **9**: 146–150.

PIN C. (1990) — Variscan oceans: ages, origins and geodynamic implications inferred from geochemical and radiometric data. Tectonophysics, **177**: 215–227.

PIN C., MAJEROWICZ A. and WOJCIECHOWSKA I. (1988) — Upper Palaeozoic oceanic crust in the Polish Sudetes: Nd-Sr isotope and trace element evidence. Lithos, **21**: 195–209.

PIN C. and VIELZEUF D. (1988) — Les granulites de haute-pression d'Europe moyenne témoins d'une subduction éo-hercynienne. Implications sur l'origine des groupes leptyno-amphiboliques. Bull. Geol. Soc. France, **8**: 13–20.

PINET N. and COBBOLD P. R. (1992) — Experimental insights into the partitioning of motion within zones of oblique subduction. Tectonophysics, **206**: 371–388.

RAJLICH P. (1990) — Strain and tectonic styles related to Variscan transpression and transtension in the Moravo-Silesian basin, Bohemian Massif, Czechoslovakia. Tectonophysics, **174**: 351–367.

ROBARDET M., PARIS F. and RACHEBOEUF P. R. (1990) — Palaeogeographic evolution of southwestern Europe during Early Palaeozoic times. In: Palaeozoic Palaeogeography and Biogeography (eds. W. S. McKerrow and C. R. Scotese). Geol. Soc. Mem., **12**: 411–419.

ROBERTS M. P. and FINGER F. (1997) — Do U-Pb zircon ages from granulites reflect peak metamorphic conditions?. Geology, **25**: 319–322.

ROBIN P.-Y. and CRUDEN A. R. (1994) — Strain and vorticity patterns in ideally ductile transpression zones. J. Struct. Geol., **16**: 447–466.

RODGERS J. (1971) — The Taconic orogeny. Geol. Soc. Amer. Bull., **82**: 1141–1178.

RODGERS J. (1982) — The life history of a mountain range — the Appalachians. In: Mountain Building Processes (ed. K. J. Hsü): 229–241. Academic Press. London.

SENGÖR A. M. C. (1990) — Plate tectonics and orogenic research after 25 years: a Tethyan perspective. Earth Sc. Rev., **27**: 1–201.

SENGÖR A. M. C. and NATAL'IN B. A. (1996) — Turkic-type orogeny and its role in the making of the continental crust. Ann. Rev. Earth Planet. Sc., **24**: 263–337.

STELTENPOHL M. G., CYMERMAN Z., KROGH E. and KUNK M. J. (1993) — Exhumation of eclogitized continental basement during Variscan lithospheric delamination and gravitational collapse, Sudety Mountains, Poland. Geology, **21**: 1111–1114.

STILLE H. (1945) — Betrachtungen zum Werden des europäischen Kontinents. Z. Dtsch. Geol. Ges., **97**: 7–29.

STILLE H. (1951) — Das mitteleuropäische bariszische Grundgebirge im Bilde des gesamteuropäischen. Beth. Geol. Jb., **2**.

SUESS F. E. (1926) —Intrusiontektonik und Wandertektonik im varistischen Grundgebirge. Borntraeger. Berlin.

TEISSEYRE H. (1980) — Precambrian in the South-Western Poland. Geol. Sudet., **15**: 7–40.

TIMMERMANN H., PARRISH R. R., NOBLE S. R. and KRYZA R. (1999) — Single cycle Variscan orogeny inferred from new U-(Th-)Pb data from the Sudetes Mountains in Poland and the Czech Republic. In: EUG 10, Journal Conference Abstracts, **4** (1): 90–95.

TORSVIK T. H., SMETHURST M. A., MEERT J. G., VAN DER VOO R., McKERROW W. S., BRASIER M. D., STURT B. A. and WALDERHAUG H. J. (1996) — Continental break-up and collision in the Neoproterozoic and Palaeozoic: a tale of Baltica and Laurentia. Earth Sc. Rev., **40**: 229–258.

TRUMPY R. (1971) — Stratigraphy in mountain belts. Quaterly J. Geol Soc. London, **126**: 239–318.

VAN DER VOO R. (1988) — Paleozoic paleogeography of North America, Gondwana and intervening displaced terranes: comparisions of paleomagnetism with paleoclimatology and biogeographical patterns. Geol. Soc. Amer. Bull., **100**: 311–324.

VAUCHEZ A. and NICOLAS A. (1991) — Mountain building: strike-parallel motion and mantle anisotropy. Tectonophysics, **185**: 183–201.

WEIJERMARS R. (1992) — Progressive deformation in anisotropic rocks. J. Struct. Geol., **14**: 723–742.

WILLIAMS H. (1993) — Acadian orogeny in Newfoundland. In: The Acadian Orogeny: Recent Studies in New England, Marimtime Canada and the Autochthonous Foreland (eds. D. C. Roy and J. W. Skeehan). Geol. Soc. Amer., Spec. Publ., **275**: 123–133.

WILSON J. T. (1990) — On the building and classification of mountains. J. Geophys. Res., **95** (B5): 6611–6628.

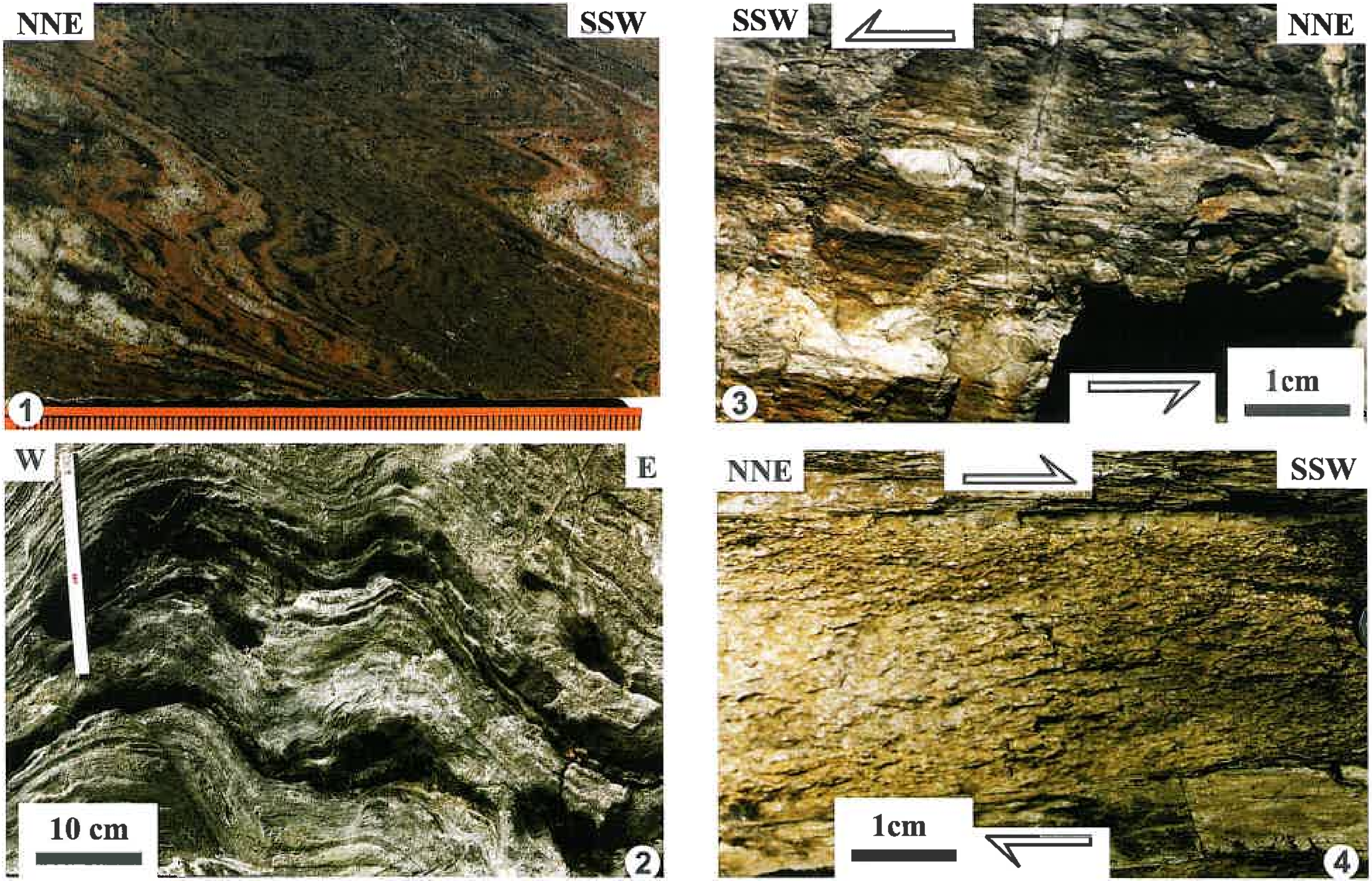
WINCHESTER J. A., FLOYD P. A., CHOCYK M., HORBOWY K. and KOZDRÓJ W. (1995) — Geochemistry and tectonic environment of Ordovician meta-igneous rocks in the Rudawy Janowickie Complex, SW Poland. J. Geol. Soc. London, **152**: 105–115.

WOJCIECHOWSKA I. (1972) — Sequence of deformation in the Stronie complex of Ołdrzychowice (Eastern Sudetes, Lądek–Śnieżnik metamorphic area). Bull. Acad. Pol. Sc. Ser. Sc. Terre, **20**: 279–284.

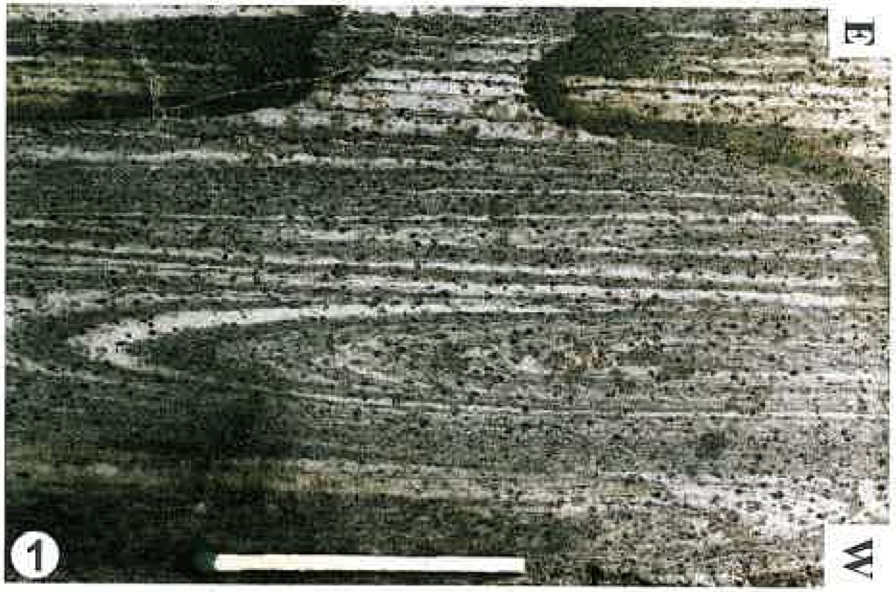
ZIEGLER P. A. (1986) — Geodynamic model for Palaeozoic crustal consolidation of Western and Central Europe. Tectonophysics, **126**: 303–328.

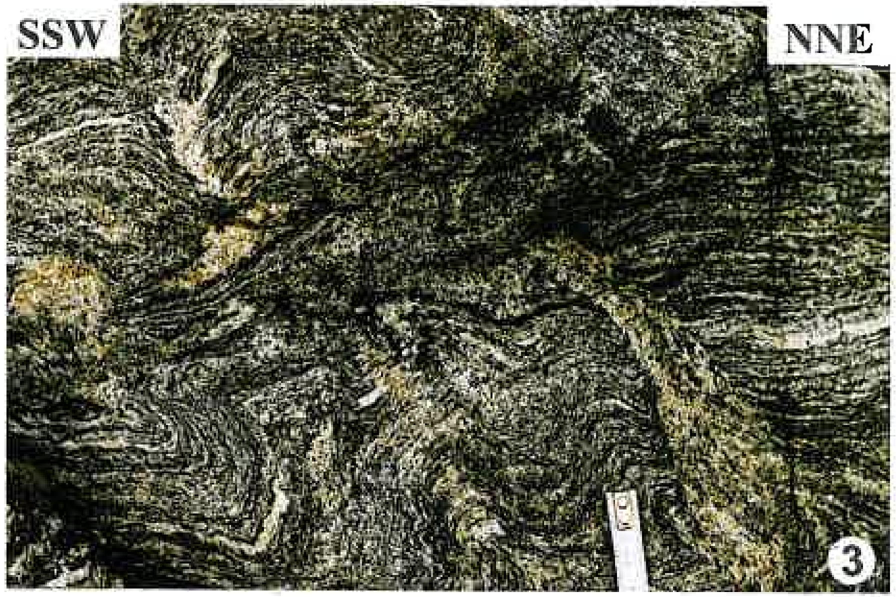
ŻELAŹNIEWICZ A. (1997) — The Sudetes as a Palaeozoic orogen in Central Europe. Geol. Mag., **134**: 691–702.

PLATE I



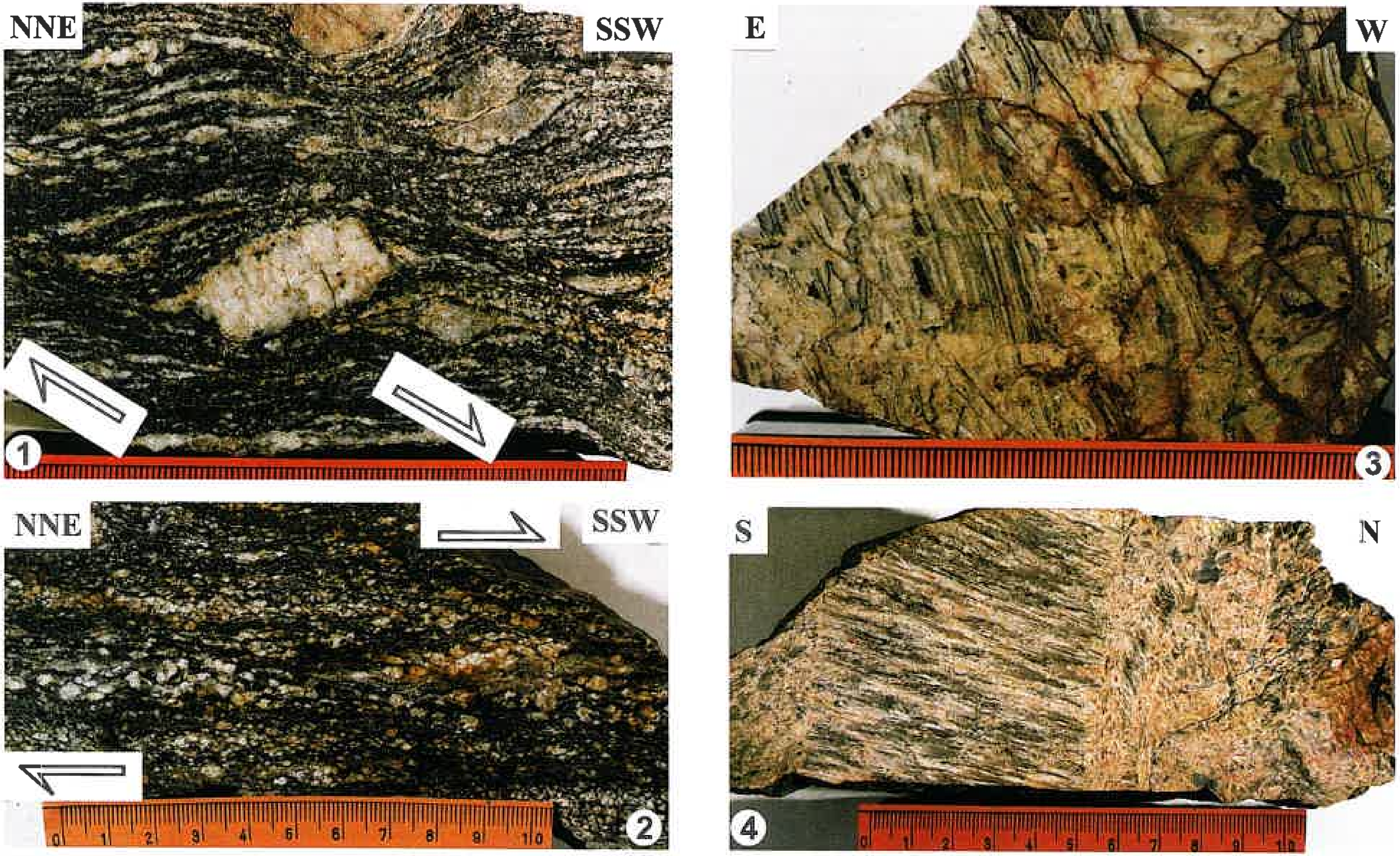
1. Open to tight folds in pure shear domains and layered fabric of leptinites in simple shear domains (strain partitioning) (plane perpendicular to foliation and parallel to mineral extensional lineation). Northern part of the Rudawy Janowickie metamorphic complex; Miedzianka. *2.* Examples of open to tight folds from banded amphibolites. YZ-plane of finite strain (plane perpendicular to foliation and perpendicular to mineral extensional lineation). Northernmost part of the Rudawy Janowickie metamorphic complex; Ciechanowice. *3.* Mylonitic schists with asymmetric leptinitic lenses from the Złoty Stok–Trzebieszowice shear zone. XZ-plane of finite strain (plane perpendicular to foliation and parallel to mineral extensional lineation). Abandoned big quarry; south of Złoty Stok. *4.* Strongly mylonitic leptinites. XZ-plane of finite strain (plane perpendicular to foliation and parallel to mineral extensional lineation). Złoty Stok–Trzebieszowice shear zone; northern slope of the Kikoł Mts.





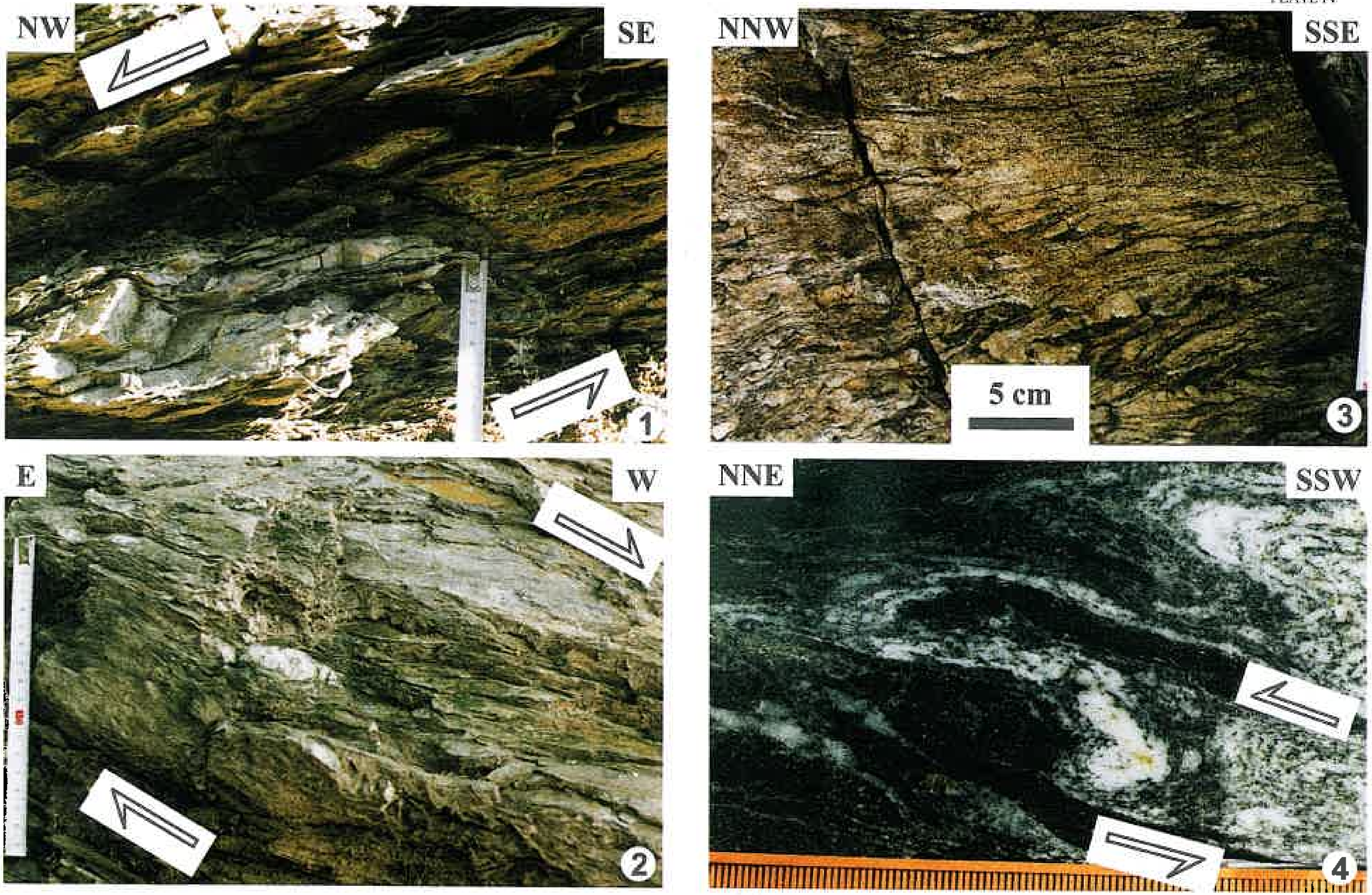
1. Strongly sheared felsic granulite with tight, similar-type fold. XZ-plane of finite strain (plane perpendicular to foliation and parallel to mineral extensional lineation). Orlica–Śnieżnik dome; Stary Gierałtów unit. *2*. Strain partitioning in felsic granulite. Different types of open, asymmetric folds are developed within the pure shear (coaxial) domain, whereas the laminated fabric formed in simple shear domains. Almost YZ-plane of finite strain (plane perpendicular to foliation and almost perpendicular to mineral extensional lineation). Orlica–Śnieżnik dome; Stary Gierałtów unit. *3*. Examples of various fold structures (isoclinal, tight, open, dysharmonic) in migmatites. Note leucosome veins cutting penetrative foliation (diktyonitic texture) parallel to axial planes of open folds (plane perpendicular to fold axes and mineral lineation). Metatexites from the central part of the Góry Sowie metamorphic complex; Bystrzyca Górna. *4*. Diatexites with strong textural modification and destruction of palaeosome and with the development of flow magma structures and melt segregation. Central part of the Góry Sowie metamorphic complex; Rościszów

PLATE III

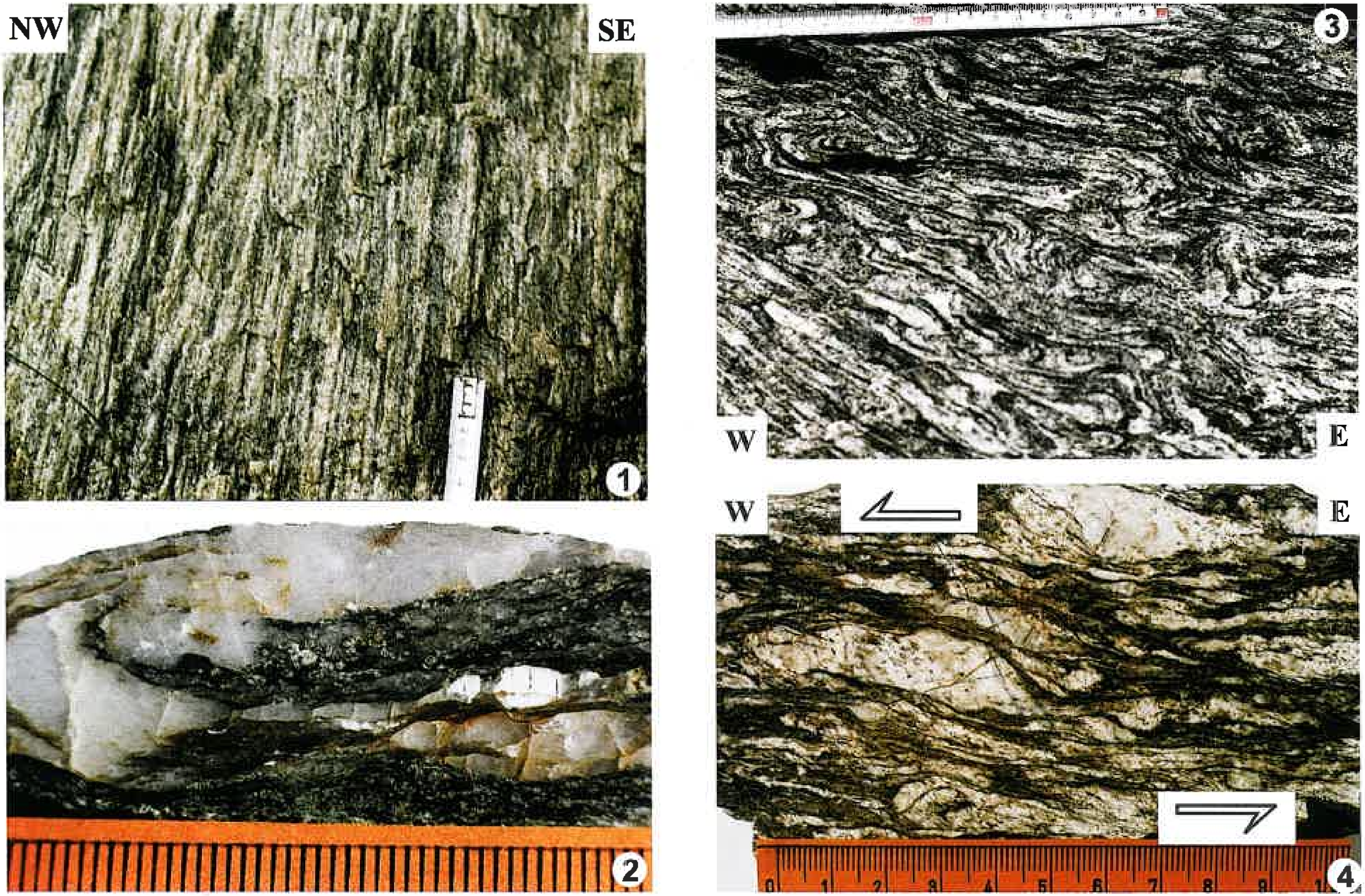


1. Augen orthogneisses from the southeastern part of the Góry Sowie metamorphic complex. Extensional, sinistral sense of shearing with top-to-the-SSW is well defined by σ– and δ-type porphyroclasts and extensional, asymmetric shear bands. XZ-plane of finite strain (plane perpendicular to foliation and parallel to extensional mineral lineation). *2.* Gneissic mylonite dipping at *ca.* 60° towards ESE. Dextral sense of shear with top-to-the-SSW documented by numerous small porphyroclasts of type σ and rare type δ, as well as extensional, asymmetric shear bands (plane perpendicular to foliation and parallel to stretching lineation). Northern part of the Niemcza shear zone; Piekiełko gorge near Gilów. *3.* Tectonic breccias from calc-silicate rocks of the Rudawy Janowickie metamorphic complex. Rędziny active quarry. *4.* Domains of cataclastic rocks cutting ultramylonitic fabric of the Śnieżnik orthogneisses. XZ-plane of strain (plane perpendicular to foliation and parallel to mineral extensional lineation). Orlica–Śnieżnik dome; Duszniki Zdrój

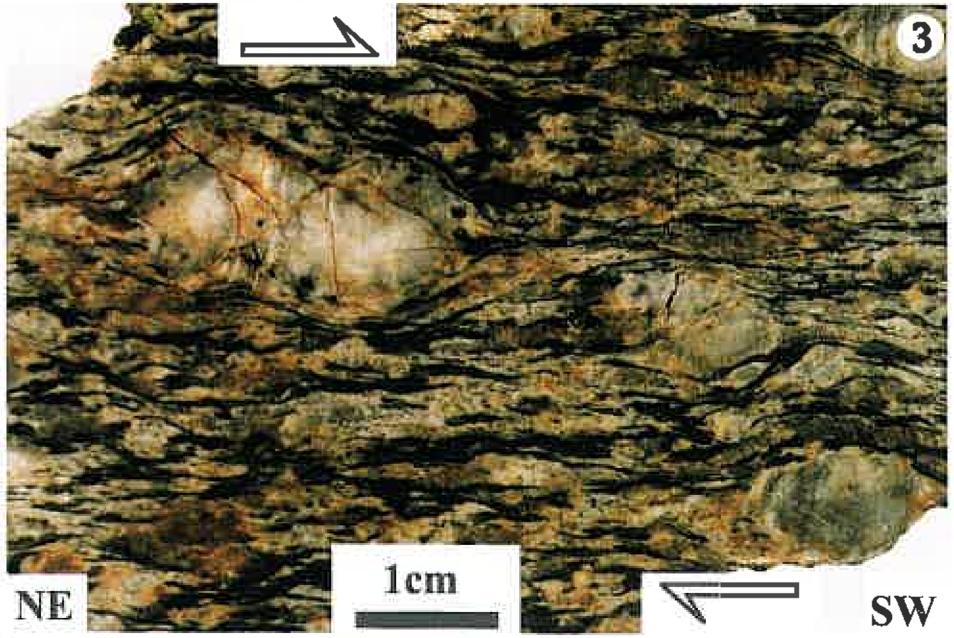
PLATE IV

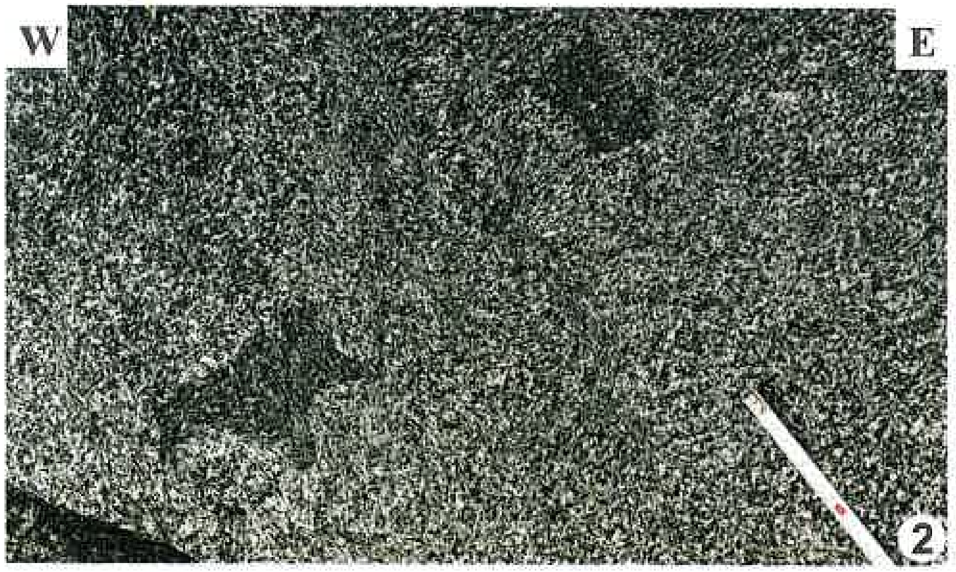


1. Asymmetrical mylonitic fabric in slates. Northern part of the Kaczawa metamorphic complex. XZ-plane of finite strain (plane perpendicular to foliation and parallel to mineral extensional lineation). Road outcrop; east of Złotoryja. *2.* Asymmetric, extensional shear bands in greenschists of the Dobromierz unit. XZ-plane of finite strain (plane perpendicular to foliation and parallel to mineral extensional lineation). Southern part of the Kaczawa metamorphic complex; Kaczorów. *3.* Strain irregularly partitioned into domains of simple and pure shear. Layered orthogneisses from the Orlica–Śnieżnik dome; Międzygórze unit. *4.* Strain partitioning in migmatitic gneisses. Localised ductile domains of simple shear and domains in which pure shear is more dominant, showing the development of folds. Note, that leucosome layers are sinistrally displaced into the melanocratic neosome domains. Almost XZ-plane of strain (plane perpendicular to foliation and almost perpendicular to mineral extensional lineation). Orlica–Śnieżnik dome; Nowy Gierałtów; Łysiec unit

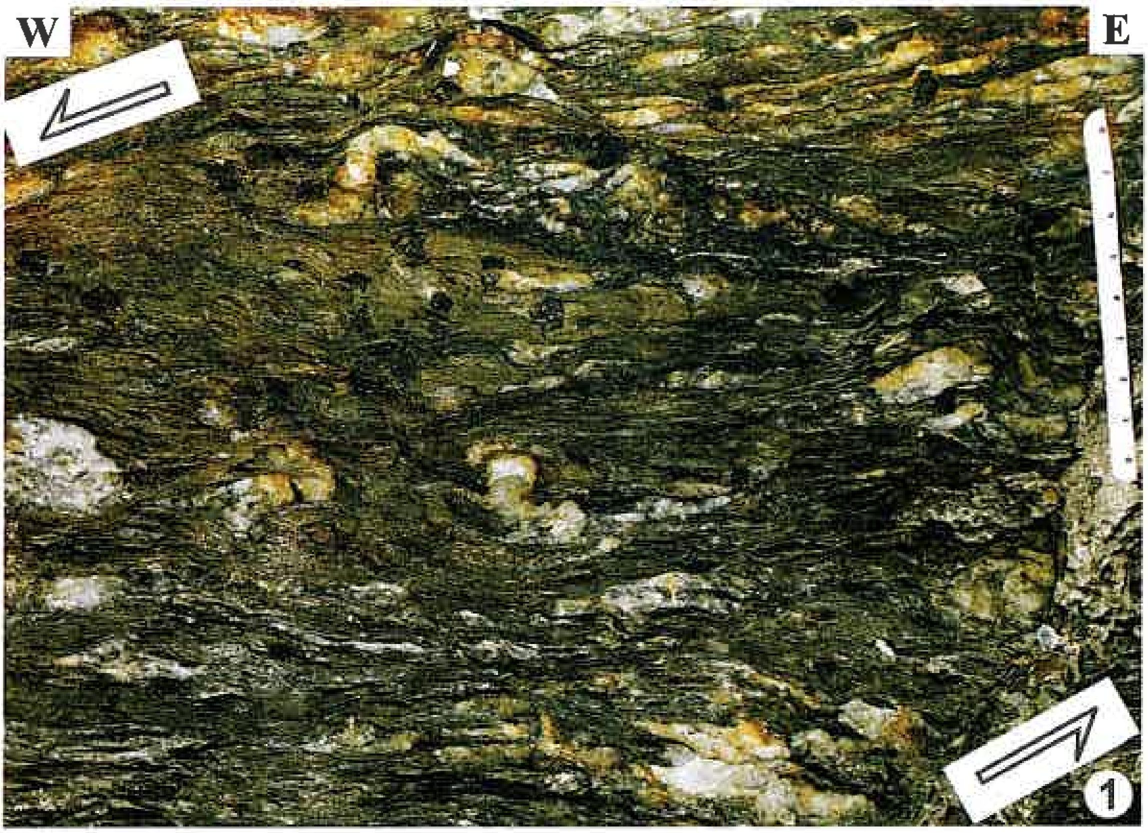


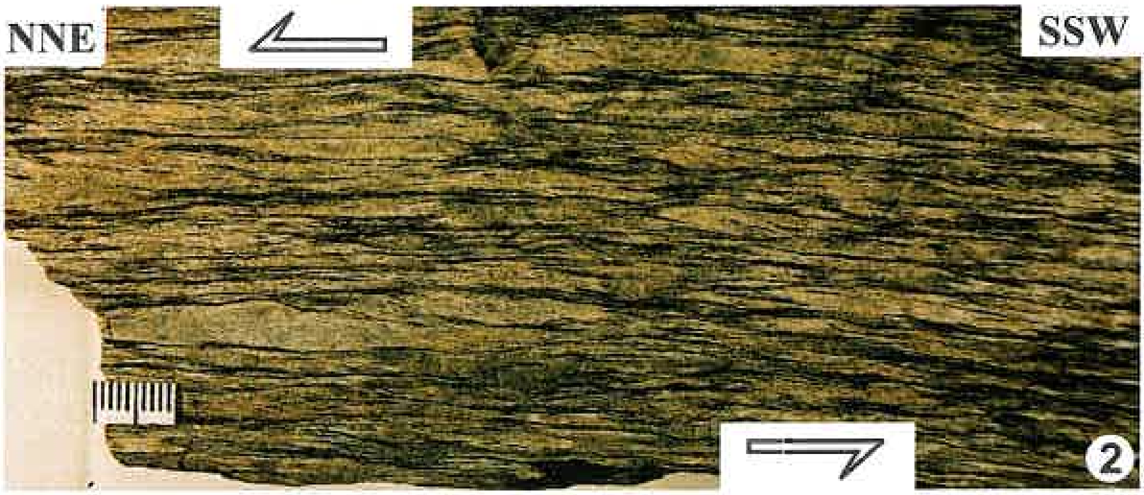
1. Penetrative mineral extensional lineation (L_1) preserved on S_1 foliation planes. Izera orthogneisses. Izera metamorphic complex; Leśna. *2.* Almost rootless isoclinal fold formed by folding of quartzitic laminae. Złotniki Lubańskie schist belt. Almost YZ-plane of strain (plane perpendicular to foliation and almost perpendicular to mineral extensional lineation). Izera metamorphic complex; unoriented sample. *3.* Complex fold interference geometries in the migmatitic gneisses. Orlica–Śnieżnik dome; Międzygórze unit. *4.* Sinistral D_1 high strain domain of mylonitic orthogneisses, which preserved relics of intrafoliational fold hinges. Orlica–Śnieżnik dome; Koleba unit

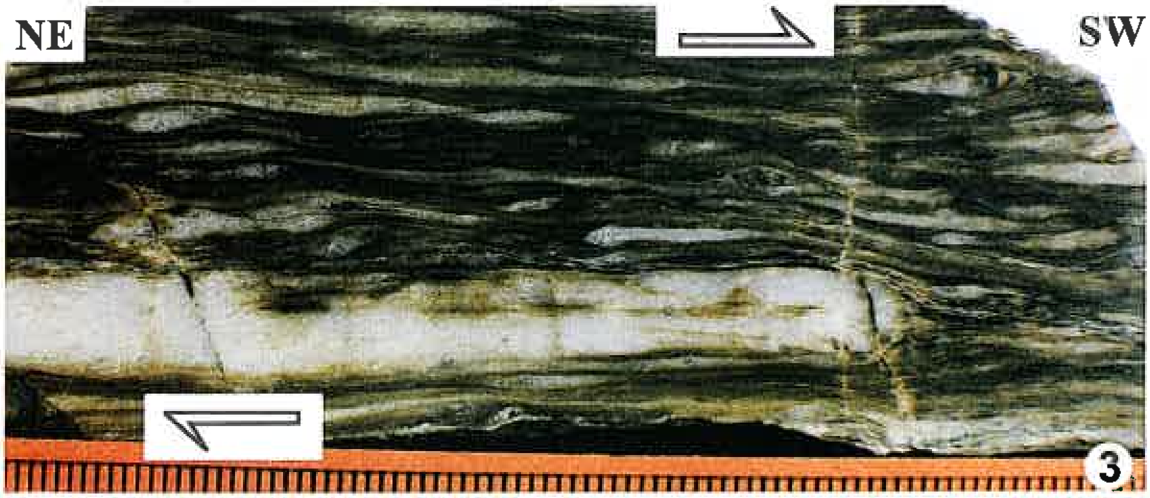




1. Ptygmatic folds with characteristic bowel-like (convolute) folding of leucosome lamina. Góry Sowie metamorphic complex; Fore-Sudetic block; vicinity of Bielawa. *2.* Syn-kinematic granodiorites. Niemcza shear zone; Kośmin; abandoned quarry. *3.* Moderately sheared Izera augen orthogneisses with porphyroclasts of σ-type and δ-type, which indicate clockwise sense of shear (top-to-the-SW). XZ-plane of strain (plane perpendicular to foliation and parallel to mineral extensional lineation). Izera metamorphic complex; vicinity of Świeradów Zdrój. *4.* Strongly sheared Izera orthogneisses with later, asymmetrical, extensional shear bands. Dextral sense of shear (top-to-the-NW). XZ-plane of strain (plane perpendicular to foliation and parallel to mineral extensional lineation). Izera metamorphic complex; Lubomierz







1. Mica schists fabrics commonly represent the combined effects of pure shear (flattening) and simple shear. XZ-plane of strain (plane perpendicular to foliation and parallel to mineral extensional lineation). Izera metamorphic complex; Kamienica schist belt; Krobica active quarry. *2.* Strongly sheared Strzelin orthogneisses with S-C mylonitic structure, σ-type porphyroclasts and asymmetrical extensional shear bands. Sinistral sense of ductile shear (top-to-the-NNE). XZ-plane of strain XZ-plane of strain (plane perpendicular to foliation and parallel to mineral extensional lineation). Strzelin metamorphic complex; Gościęcice. *3.* Asymmetric, extensional shear bands and asymmetric quartz lenses in meta-conglomerates of strain (plane perpendicular to foliation and parallel to mineral extensional lineation). East Sudetes domes; Branna unit; Ramzova