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GEOLOGY OF THE KARKONOSZE-IZERA MASSIF: AN OVERVIEW

Tectonic setting

The Karkonosze-Izera massif occupies the south-central part of the West Sudetes on the NE margin of the Bohemian Massif (Fig. 1). Its tectonic position within the central European Variscides, together with that of the entire West Sudetes, remains disputable. The whole West Sudetic mosaic has most often been considered a part of the Saxothuringian zone (e.g. Behr et al. 1984; Franke et al. 1993) in accordance with the older views of Kossmat (1927). The peculiarities of the geology of that region, however, made some workers distinguish it as a separate Lugian domain of the Variscan belt (Suess 1926, Dallmeyer et al. 1995). More recent interpretations invoke a number of variously defined tectonostratigraphic terranes in the West Sudetes, either showing close affinities to the major tectonic provinces of the Variscan orogen (Matte et al. 1990, Aleksandrowski 1995, Franke et al. 1993) or, at least in part, exotic with respect to the remaining parts of the Variscides (Oliver et al. 1993, Cymerman & Piasecki 1994). From among the various models, the hypothetical terrane interpretation proposed by Matte et al. (1990) and Matte (1991) in many respects seems to fit best (though not perfectly) the field relationships in the West Sudetes, in particular within the Karkonosze-Izera massif. According to the latter interpretation, the extent of the Saxothuringian domain in the West Sudetes is limited to their NW part (the Lusatian massif, Görlitz slate belt and most parts of the Karkonosze-Izera massif). Further to the SE (in the southern and eastern Karkonosze-Izera massif, the most part of the Kaczawa unit, the basement of the Intra-Sudetic basin and the Góry Sowie massif) there is a continuation of the Tepla-Barrandian domain ('Tepla-Münchberg' and 'Barrandian' terranes of Matte). Thus, in this concept, the Karkonosze-Izera massif is crosscut by an important terrane boundary and partitioned into two distinct domains of the central European Variscides.

Lithotectonic units

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

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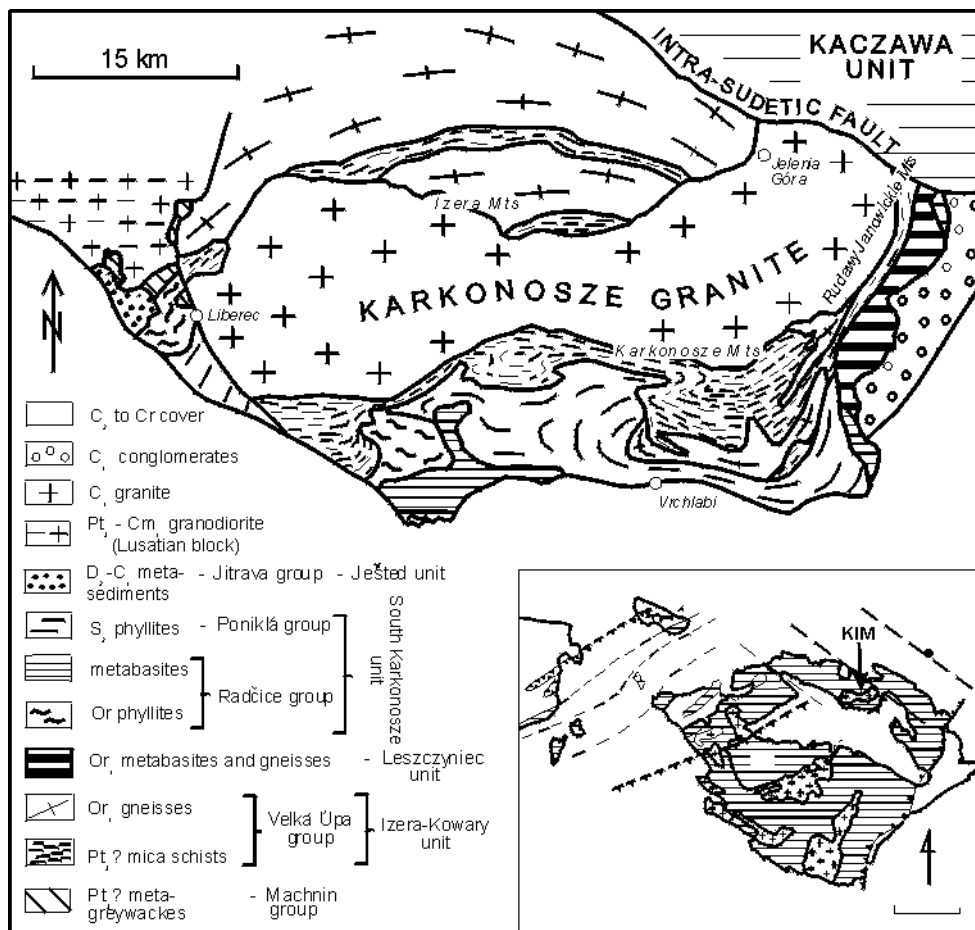


Fig. 1. Geological sketch map of the Karkonosze-Izera massif with inset map to show its tectonic location. *Inset*: hachure - pre-Permian crystalline rocks; highlighted - Tepla-Barrandian domain and Tepla-derived nappes; EFZ - Elbe fault zone; ISF - Intra-Sudetic fault zone; MGH - Mid-German crystalline high; MO - Moldanubian domain; MS - Moravo-Silesian domain; NP - Northern Phyllite zone; OFZ - Odra fault zone; RH - Rhenohercynian domain; SX - Saxothuringian domain; T/S - Tepla/Saxothuringian suture; KIM – Karkonosze-Izera massif.

The Izera-Kowary unit is composed mainly of the Upper Cambrian/Lower Ordovician (Borkowska *et al.* 1980; Oliver *et al.* 1993; Korytowski *et al.* 1993) Izera (Rumburk) granite, in most part transformed by a subsequent, Late Devonian to Early Carboniferous deformation into the Izera/Kowary granite-gneiss and gneiss (equivalent to the Krkonoše gneiss on the Czech side of the massif, dated at c. 500 Ma by Oliver *et al.* 1993 and Kröner *et al.* 2001). Its other significant component are mica schists representing remains of its Neoproterozoic(?) envelope. The mica schist sequence is most abundantly developed on the southern side of the Karkonosze pluton, in the Czech Republic (Fig. 1). It was distinguished

by Chaloupský (1965) as the Velká Úpa group and subdivided into two monotonous members separated by a variegated one. The lower member is composed of grey muscovite-albite mica schists with intercalations of albite-epidote amphibolite and quartzite. The intermediate member comprises variegated mica schists with intercalations of quartzite, erlan, crystalline limestone, striped amphibolite, felsic metavolcanics, chlorite schist and graphite mica schist, whereas the upper member includes greenish-grey chlorite-muscovite-albite mica schists. The intermediate, variegated member continues into the eastern envelope of the Karkonosze granite in the Rudawy Janowickie Mts in Poland and is distinguished in that area as the Czarnów formation (Teisseyre 1973). The variegated metavolcanic rocks of the Czarnów formation predominantly show within-plate geochemical signature (Winchester et al. 1995). To the north of the Karkonosze pluton, mica schists forms three relatively narrow belts embedded into the Izera gneiss. From the north to south these are: Złotniki Lubańskie, Stara Kamienica and Szklarska Poręba belts, the latter mostly transformed into hornfelses within the contact aureole of the Karkonosze intrusion. Mica schists belts trend approximately E-W and comprise minor intercalations of amphibolites, quartzites and calc-silicate rocks. Amphibolites of the Stara Kamienica belt constitute a fairly homogeneous group derived from the protolith of OIB affinity developed within intracontinental rift setting (Ilnicki 2000). Consistently, the intra-plate continental rift setting was also postulated for the majority of metabasic dykes studied by Nowak (2000) in the northern part of the Izera-Karkonosze massif. Stara Kamienica amphibolites experienced three stages of metamorphism (Ilnicki 2001) from greenschist facies through MP/MT epidote-amphibolite facies (560°C, 7.5 kbar) to LP/HT amphibolite facies (600°C, 5 kbar). These results are generally compatible with earlier data pointing to MP/LP metamorphism of the Izera-Kowary unit under upper greenschist-lower amphibolite facies conditions (e.g. Żaba 1984; Oberc-Dziedzic 1987; Kryza & Mazur 1995). To the east and south, the Izera-Kowary rocks plunge below metamorphic complexes of the South Karkonosze and the Leszczyniec units affected by HP metamorphism. Towards the west, the Izera-Kowary granite and gneiss reveal intrusive contacts with Cadomian granitoids of the Lusatian Massif (Ebert 1943; Domečka 1970).

The Ještěd unit, a small fault-bounded element exposed at the SW edge of the Karkonosze-Izera massif, comprises Middle to Upper Devonian shallow marine to hemipelagic sediments with minor volcanics (Jítrava group of Chaloupský 1989), subjected to very weak, LT-MP metamorphism, passing upwards into greywackes and conglomerates of probably Tournaisian to (?)Early Visean Culm facies rocks (Chlupáč 1993).

The South Karkonosze Unit comprises several hundred metres of metamorphosed Ordovician to (?)Devonian sedimentary rocks (Chlupáč 1993) accompanied by bimodal, mostly basic volcanics. Described as the Poniklá and Radčice groups on the Czech side (Chaloupský 1989) and as the Niedamirów Formation on the Polish side (Kryza & Mazur 1995), the sequence contains highly differentiated marine sedimentary rocks and is characterised by close proximity of various facies assemblages typical of a neritic through hemipelagic to pelagic

environment. The metavolcanic rocks of the Radčice Group, including the Železný Brod Complex and the Rýchory Mts metavolcanic succession, and those of the Poniklá Group, represent a differentiated magmatic suite, ranging from predominantly felsic rocks (dated at 501 +/-8 Ma using Rb-Sr whole rock method; Bendl & Patočka 1995) of within-plate geochemical signature to basic lavas and pyroclastics of P-type MORB affinities (Bendl *et al.* 1997; Patočka & Smulikowski 2000). The basic metavolcanics of the Radčice Group in the Železný Brod and Rýchory Mts preserve record of early blueschist facies metamorphism (e.g. Wieser 1978; Cháb & Vrána 1979; Kryza & Mazur 1995; Smulikowski 1995; Patočka *et al.* 1996) dated at c. 360 Ma, followed by a greenschist overprint of c. 340 Ma (^{40}Ar - ^{39}Ar method; Maluski & Patočka 1997). The South Karkonosze Unit probably represents a tectonically dismembered, once vertically continuous and laterally diversified sedimentary succession of an extensive marine basin (Mazur & Aleksandrowski 2001).

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

Structural and metamorphic evolution

The structural study of the eastern margin of the Karkonosze-Izera massif, carried out by Mazur (1995), revealed several types of deformational structures and these were ascribed to three main generations: D₁, D₂ and D₃. Kinematic analysis combined with new petrological evidence, allowed a reassessment of the sequence and regimes of the successive deformation events. The established model was subsequently extended over the entire area of the Karkonosze-Izera massif after having performed reconnaissance studies in selected key areas and completion of our data base with re-interpreted abundant earlier published data on the orientation and morphology of the tectonic structures in the southern (Maška 1954; Oberc 1960; Chaloupský 1989) and northern (Oberc 1967; Oberc-Dziedzic 1974; Žaba 1979) portions of the Karkonosze-Izera massif.

D₁ event: NW-directed ductile thrusting

The D₁ event produced the main foliation S₁ and mostly NW-SE trending stretching lineation L₁ with local relics of top-to-the NW shear indicators. The L₁ stretching lineation in the Leszczyniec unit is NNE-SSW-oriented and, thus, it differs from the general trend of L₁ in the neighbouring units.

The foliation S₁ in the Izera-Kowary orthogneiss is defined by a preferred orientation of micas, K-feldspar megacrysts and alternating mica, quartz and feldspar layers. The predominantly oblate shapes of K-feldspar augens indicate a predominant flattening component of strain during the D₁ event. The L₁ lineation is outlined by elongation of K-feldspar megacrysts, mica aggregates and quartz

ribbons. The gneisses in high strain domains are well-lineated and display distinct shear sense criteria, such as asymmetric tails around K-feldspar grains, asymmetric pressure shadows and extensional shear bands. The gneisses in the volumetrically prevalent less strained domains show a nearly symmetric fabric pointing to approximately coaxial deformation. The low-strain rocks are transitive to varieties showing primary granitic textures. The plagioclase crystals in the Kowary gneiss from the eastern margin of the Kowary-Izera unit are usually composed of albite, whereas the garnet cores from mica schist intercalations are relatively rich in spessartine and poor in almandine component (Kryza and Mazur 1995). This mineral assemblage indicates deformation under upper greenschist facies conditions during the D₁ event.

The metabasites of the South Karkonosze unit contain foliation, S₁, and stretching lineation, L₁, the latter defined mostly by aligned amphibole prisms. In the glaucophane-bearing rocks, the blue amphiboles are involved in the D₁ fabric. Cores of crystals composed of glaucophane or crossite are often rimmed by pale-green actinolite, which is a proof for a gradual decompression during the D₁ event (Mazur & Kryza 1996). A zonation of the amphiboles documents a continuous transition from HP blueschist to MP greenschist facies, contemporaneous with the development of the D₁ structures. The opposite trend is evident in the metabasites of the Leszczyńiec unit. Amphiboles which define the foliation and lineation in these rocks in places exhibit a distinct zonation, ranging from pale-green actinolite in the cores to bluish-green hornblende or actinolitic hornblende in the rims. The presence of albite in equilibrium with hornblende suggests a continuous transition in the Leszczyńiec unit from greenschist (actinolite) to epidote-amphibolite facies conditions at the time of the D₁ event (Kryza & Mazur 1995). An exception from this rule was noted in the hornblende-rich variety of the Paczyn gneiss. The hornblende cores usually display greenish-brown pleochroism and are rimmed by bluish-green actinolite (Kryza & Mazur 1995). Kinematic indicators in the Leszczyńiec unit are of variable asymmetry but most of them suggest, in the present coordinates, a sinistral sense of shear.

D₂ event: top-to-SE extensional collapse

Effects of the D₂ deformation are particularly intense along the east and south margins of the Izera-Kowary unit. In most of the mica schists from this unit, the D₂ event produced a new penetrative foliation, S₂, that overprints and obliterates earlier S₁ structures. Relics of S₁ are often preserved as inclusion trails in plagioclase and garnet. The S₂ foliation in the mica schists bears stretching lineation, L₂, defined by parallel alignment of micas. In the Izera-Kowary gneiss, L₂ is often present on S₁ planes as a lineation of micas and small crenulations. In places, L₁ and L₂ are superposed and cross each other obliquely at an angle of 20-40°. However, in most localities only one lineation is conspicuous. The distinct zonation of plagioclase and garnet porphyroblasts in the mica schists on the eastern margin of the Karkonosze-Izera massif indicates a gradual transition to temperature-dominated metamorphism during their growth (Kryza and Mazur

1995). The same trend, contemporaneous with the D_2 event, is demonstrated in white mica plates parallel to S_2 by the decrease of Si content. This reflects an episode of HT/LP metamorphism, at the end of the D_2 deformation, associated with decompression of the Iżera-Kowary unit and, probably, coeval with the emplacement of the Karkonosze granite.

The L_2 lineation trends most often WNW-ESE throughout the entire Karkonosze-Iżera massif. The discrimination between L_2 and the similarly trending L_1 lineation is mainly based on the contrasting kinematics of the D_1 and D_2 deformations and on the different morphology of both lineations. The differences between the two can be easily observed in outcrops where L_1 and L_2 are superimposed and cross each other. The L_2 lineation plunges steeply on the steep foliation at the eastern margin of the massif; the dip of foliation and the plunge of the lineation gradually decrease westward. In rocks subjected to intense D_2 deformation an asymmetric fabric has developed. Numerous kinematic indicators, such as asymmetric pressure shadows around porphyroblasts and extensional shear bands, consistently show a top-to-the ESE sense of shear. The D_2 shearing was accompanied and followed by extensive folding at different scales. The axes of F_2 folds are approximately parallel to the L_2 lineation.

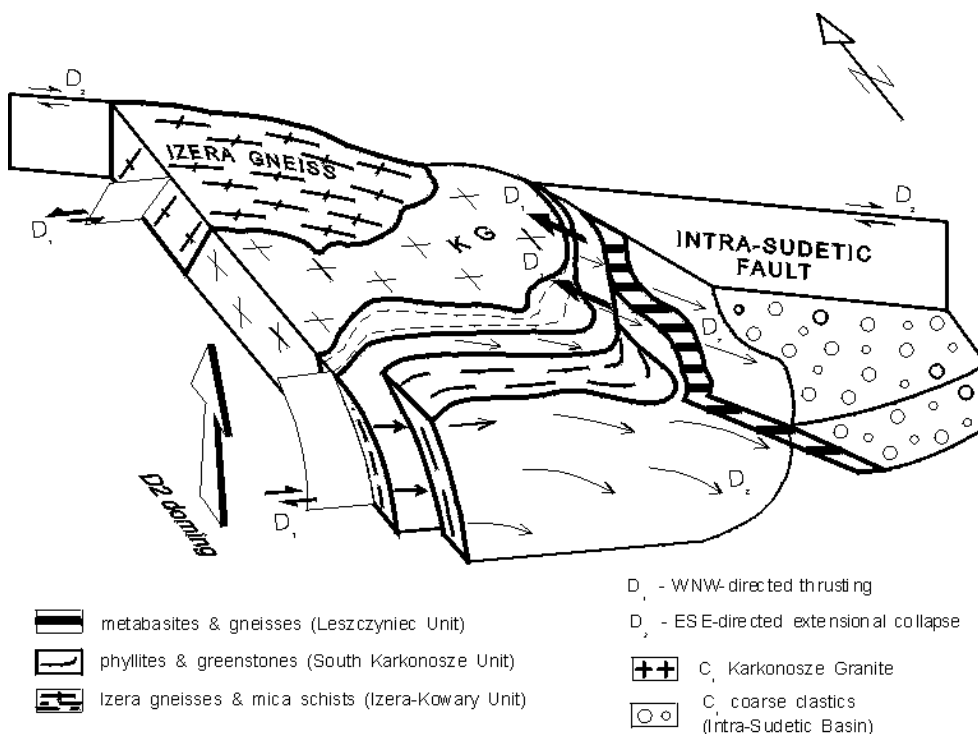


Fig. 2. Block diagram showing deformation partitioning and sense of tectonic transport in the Karkonosze-Iżera massif during deformation events D_1 and D_2 (modified from Mazur 1995).

The emplacement of the Karkonosze granite was immediately preceded and partly accompanied by growing of a regional dome, which eventually imposed its geometry onto the entire Karkonosze-Izera massif (Fig. 2). The doming, coeval with the final phases of the D₂ extensional collapse, resulted in reorientation of earlier D₁ structures on flanks of the dome (Aleksandrowski et al. 1997). The D₁ sense-of-shear indicators were reoriented together with the S₁ foliation and show, in the present coordinates, a sinistral and dextral sense of shear on the north and south flanks of the dome, respectively (Fig. 2). Similarly, the D₂ kinematic indicators, mostly pre-dating the formation of the dome, were rotated, on the northern and southern flanks of the Karkonosze-Izera dome, from their original top-to-the ESE alignment. Consequently, on the northern side of the Karkonosze pluton, deformation associated with the D₂ extensional collapse is manifested as a dextral approximately strike-slip shear.

In general, the Karkonosze granite bears no evidence of a solid-state deformation. Nevertheless, a WNW-ESE trending, sparse lineation, defined by alignment of feldspar megacrysts was recognised in the granite by Cloos (1925). Recent studies on the magnetic fabric (Diot et al. 1995) provide evidence for a WNW-ESE trending magnetic lineation in the Karkonosze granite. This lineation is interpreted to reflect the direction of magmatic flow. The magnetic lineation of the granite roughly parallels both the feldspar lineation of Cloos (1925) and the L₂ stretching lineation in the adjacent metamorphic rocks. The parallelism of the lineations developed in the pluton and within its metamorphic envelope indicates a relationship between the granite emplacement and the final phase of the D₂ event. Furthermore, the granite has recorded evidence of a top-to-the ESE sense of shear, characteristic of the D₂ deformation in the country rocks, indicated by tilting of feldspar megacrysts (Diot et al. 1995).

Late semi-brittle event D₃

From the centre towards the eastern margin of the Karkonosze-Izera massif, the foliation becomes increasingly steeper, with its dip changing from ca 50°E at the southeastern contact with the Karkonosze granite, through an approximately vertical position over the most part of the Rudawy Janowickie Mts, up to 70°-80°W near to the faulted boundary with the Intra-Sudetic basin. This important reorientation of the regional foliation on the eastern margin of the Karkonosze-Izera massif has been attributed to a rotation around a NNE-SSW trending axis of the so called East Karkonosze monocline (Oberc 1960). The reorientation was accompanied by formation of small-scale angular and rounded, relatively open F₃ folds of roughly N-S trending axes. The origin of the monocline must have post-dated the D₂ event and the emplacement of the Karkonosze granite, since the rotation affected, apart from the metamorphic complexes of the Rudawy Janowickie Mts, also the Upper Visean conglomerates of the Szczawno formation in the Intra-Sudetic basin (Dziedzic and Teisseyre 1990). The Szczawno formation is unconformably overlain by the Biały Kamień beds of Westphalian age (Dziedzic and Teisseyre 1990), providing the upper time limit for the development of the East Karkonosze monocline.

Lusatian and Karkonosze-Izera massifs: the Saxothuringian passive margin

The Lusatian massif represents the Neoproterozoic parautochthonous continental basement of the epicontinental part of the Saxothuringian basin (Linnemann *et al.* 2000; Franke & Żelaźniewicz 2000; Mazur & Aleksandrowski 2001). Similarly, the adjacent gneisses and mica schists of the Izera-Kowary unit in the Karkonosze-Izera massif, are interpreted as the pre-Variscan (Early Palaeozoic) continental crust partly underlying the Saxothuringian basin (Franke & Żelaźniewicz 2000; Mazur & Aleksandrowski 2001), subsequently involved in Variscan deformation near to a collision zone extending along the Saxothuringian Suture (see below). This continental crust must have once underlain the passive margin of the Saxothuringian epicontinental area (Mazur & Aleksandrowski 2001). The Izera gneisses are Early Ordovician intrusions into an older basement of Cadomian Lusatian granitoids (Domečka 1970) dated at between c. 590-545 Ma (Kröner *et al.* 1994). Structurally, therefore, the NW part of the Karkonosze-Izera massif constitutes one common element together with the Lusatian massif. The intensity of deformation and metamorphism gradually increases eastwards, i.e. towards the suture zone, starting from practically undeformed Cadomian granitoids of Lusatia (Ebert 1943). The sedimentary succession of the NE passive margin of the epicontinental part of Saxothuringia is represented by the rocks of the Ještěd unit (Mazur & Aleksandrowski 2001) and of the thrust-folded and strike-slip sheared Görlitz Slate Belt (cf. Brause & Hirschmann 1969; Urbanek *et al.* 1995).

Teplá/Saxothuringian Suture

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

The South Karkonosze and Leszczyńiec nappes, comprising blueschist facies rocks and MORB-type magmatic complexes, are tectonically emplaced on top of the parautochthonous Izera-Kowary unit of continental basement features.

Accordingly, they display features typical of a suture zone. The whole nappe pile was formed at the turn of Late Devonian/Early Carboniferous time due to NW-ward thrusting and shows, in general, metamorphic inversion (Mazur & Aleksandrowski 2001). It was subsequently modified by Early Carboniferous, SE-directed extensional collapse and, eventually, intruded by the Karkonosze granite (Mazur 1995; Mazur & Aleksandrowski 2001). The Leszczyniec unit is interpreted as an obducted fragment of the Saxothuringian sea floor (Mazur & Aleksandrowski 2001). The underlying South Karkonosze Unit comprises metamorphosed volcano-sedimentary complex of the basin infill. Its rocks bear record of changing tectonic environments from initial rifting during the Ordovician to a mature oceanic basin during the Silurian (Patočka & Smulikowski 1998). Both the Leszczyniec and South Karkonosze units are derived from a hypothetical root zone of the SE Karkonosze nappe pile, currently buried below the Carboniferous and Permian deposits of the Intra-Sudetic and Fore-Karkonosze basins.

The suture of the SE Karkonosze Mts is probably a fragment of the Teplá/Saxothuringian Suture (equivalent to the Münchberg-Teplá Suture of Matte *et al.* 1990), defining a boundary between the Saxothuringian domain to the NW and the Teplá -Barrandian domain to the SE (e.g. Matte *et al.* 1990; Matte 1991; Franke *et al.* 1995). The Teplá/Saxothuringian Suture is known from exposures near to Mariánské Lázně and in the Münchberg nappe pile in the W part of the Bohemian Massif. In that area the suture is defined by eclogites derived from c. 500 Ma MOR-type magmatic rocks and accreted continental slope sediments of the Saxothuringian Bavarian facies (Beard *et al.* 1995; Franke *et al.* 1995). The suture continues to the NE, below the cover of Mesozoic-Cenozoic rocks of the Cheb (Eger) graben, up to the upper Elbe Valley, where it is presumably displaced to the SE on the dextral Elbe fault zone together with the entire Teplá-Barrandian domain (cf. Rajlich 1987; Pin *et al.* 1988; Matte *et al.* 1990), to crop out in the southern and eastern Karkonosze Mts.

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