Tectonic Position of Eclogites and Blueschists in the Bohemian Massif

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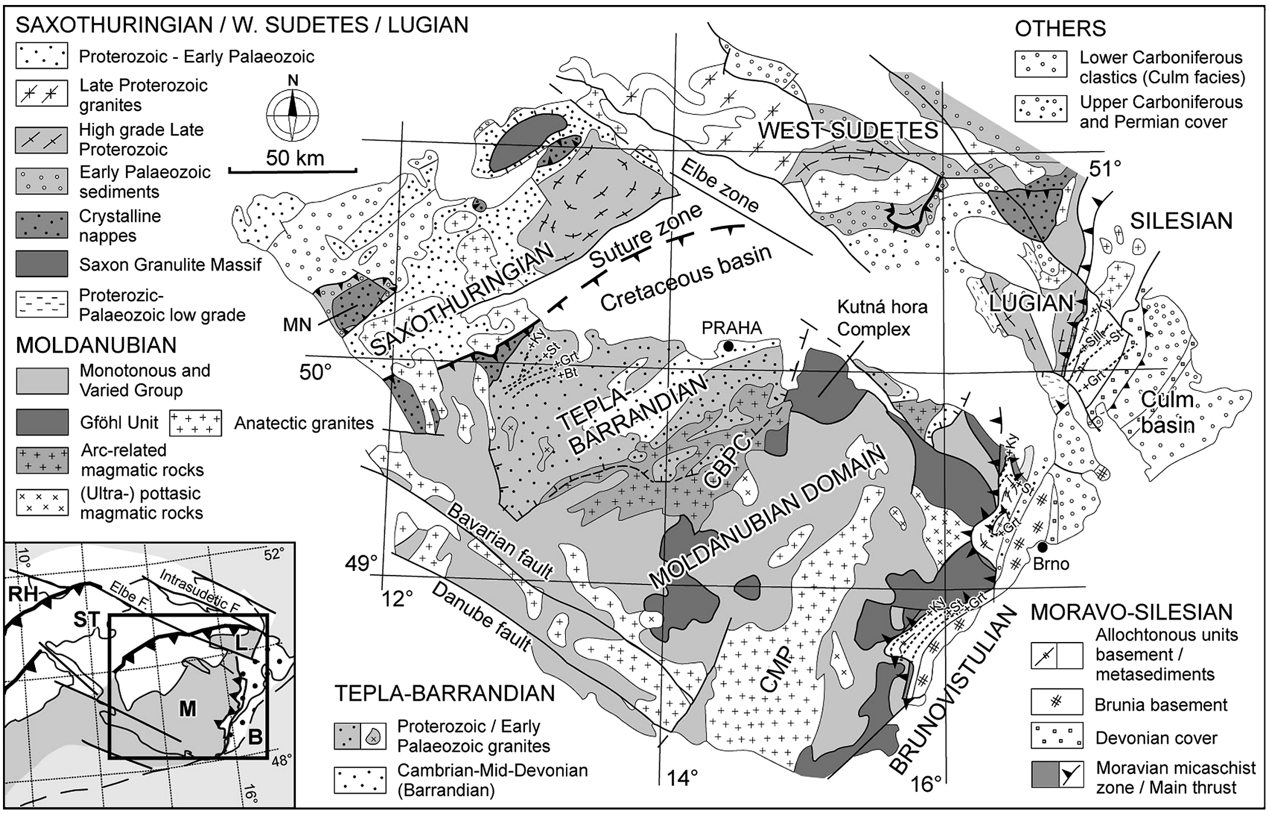
ABSTRACT: This contribution summarizes the data about structural position and age of blueschist– and eclogite–facies rocks exposed in the Bohemian Massif. Published tectonic models explaining the position and exhumation of high-pressure rocks within individual tectonic units of the Bohemian Massif are briefly reviewed and put into context of the large–scale structure of this part of the Varican orogenic belt in Central Europe.

KEY WORDS: eclogites, blueschists, geochronology, tectonics, Bohemian Massif

Introduction

The Bohemian Massif represents a relic of the Variscan orogenic belt in Central Europe (Fig. 1). The present day structure of the Bohemian Massif shows that its tectonic evolution was controlled by the Devonian-Carboniferous subduction of an oceanic crust (so called Saxothuringian Ocean, situated at the southeastern side of the present–day Saxothuringian Domain; Fig. 1) underneath the continental domains representing various tectonic units in the central and eastern Czech Republic, southern Poland and northern Austria (Fig. 1; Franke, 1989; 2000; Schulmann et al., 2009). The subduction lasted at least from c. 400 Ma, which is the oldest record of high-pressure metamorphism at the western margin of the Bohemian Massif, and culminated in the early Carboniferous at c. 340 Ma by a continental collision responsible for the development of a deep orogenic root in the back-arc region of the orogen (Schulmann et al., 2005; 2009). Episodic exhumation of deeply buried rocks and/or middle crustal segments occurred in various parts of this subduction/collisional system, as documented in particular units of the Bohemian Massif. As the metamorphic conditions of high-pressure metamorphism in eclogites will be described elsewhere (see Massonne, this volume), this contribution briefly reviews the published interpretations of the tectonic position of eclogite facies rocks in all major tectonic units of the Bohemian Massif.



■ **Fig. 1.** Outline of geology of the Bohemian Massif with major crustal units indicated. CBPC – Central Bohemian Plutonic Complex; CMP – Central Moldanubian Pluton; MN – Münchberg nappe.

Southern and central Saxothuringian Domain

Two periods of eclogite facies metamorphism are recorded in the southern part of the Saxothuringian Domain in the Bohemian Massif. An early high-pressure event is recognized in mafic eclogites of the Münchberg nappe, and the same tectonic evolution has been inferred also for two other small denudation relics of presumably the same nappe system – the Wildenfels and Frankenberg klippens (Franke, 1984). Eclogite facies metamorphism in the Münchberg nappe has been dated by using conventional U-Pb isotopic analysis of zircons, which provided a concordia lower intercept age of 380 +14/–22 Ma. Dating of zircons from cogenetic metagabbro provided an age of 525 +40/-31 Ma, which was interpreted to be the protolith age for both the metagabbro and the eclogite. Dating of eclogites by the U–Pb, Sm–Nd and Rb–Sr methods gave a metamorphic age of c. 380–395 Ma (Gebauer and Grünenfelder, 1979; Stosch and Lugmair, 1990). K-Ar and Ar-Ar dating of white micas and hornblendes yielded a range of cooling ages clustering around 380 Ma, suggesting that the eclogites were exhumed shortly after their formation. Although the cooling ages suggest Devonian exhumation of the Münchberg eclogites, final emplacement of the nappe system must have occurred during the Lower Carboniferous, because nappe emplacement deformed the underlying unmetamorphosed sediments of this age (Franke, 1984).

The Lower Carboniferous age for final thrusting of the Münchberg nappe system connects this event with emplacement of high-pressure nappes of the central Erzgebirge. According to Rötzler et al. (1998) and Willner et al. (2000), the eclogite facies rocks occur within two tectonic units dominated by high-pressure metasedimentary rocks and associated orthogneisses. Many of these orthogneiss bodies represent relics of Cambro-Ordovician granitoids thrust over a deeply buried cover of the Erzgebirge autochthon (Konopásek et al. 2001) and are often associated with lenses of mafic eclogites and metasedimentary eclogite facies rocks (Konopásek 2001, Gross et al. 2008). U-Pb dating of metamorphic zircons extracted from mafic eclogites provided an age of c. 340 Ma, which was interpreted as the age of high-pressure, subduction-related metamorphism (von Quadt and Günther 1998, von Quadt and Gebauer 1998). This dating is a strong evidence that eclogite facies metamorphism in the central Erzgebirge is diachronous with respect to that present in the Münchberg nappe and also in the Mariánské Lázně Complex (see below).

Konopásek and Schulmann (2005) have recognized that the uppermost allochthonous unit is represented by relics of felsic gneisses metamorphosed at high pressures and high temperatures. Relics of this unit contain felsic high-pressure granulites (Behr et al., 1965; Kotková et al., 1996; Willner et al., 1997), lenses of high-temperature eclogites (Schmädicke et al., 1992), and associated ultra high-pressure gneisses (Nasdala and Massonne, 2000). Dating of the granulite facies metamorphism (Kotková et al., 1996; Kröner and Willner 1998) yielded a similar age (within error) as the age of high-pressure metamorphism in mafic eclogites (see above) and of ultra high-pressure metamorphism in felsic gneisses (Massonne et al., 2007), i.e. ~340 Ma.

There seems to be general agreement that the (ultra) high-pressure rocks exposed in the southern part of the Saxothuringian Domain have formed during subduction of the Saxothuringian ocean below easterly lying tectonic units forming the core of the Bohemian Massif (see summary in Franke, 2000). However, the interpretation of exhumation of the Erzgebirge high-pressure rocks into their present-day position, and thus the interpretation of the post-subduction evolution of the Erzgebirge Complex, varies considerably.

Krohe (1996) and Willner et al. (2000; 2002) have suggested that subduction of the Saxothuringian ocean terminated in the Devonian (at c. 400–390 Ma), and subsequent continental-type collision created an excess crustal thickness that was maintained for approximately 60–50 Ma. In this model, most of the structures related to the crustal stacking were overprinted during fast unroofing during the Carboniferous in the time period between c. 340 and 330 Ma. Thus, the present-day structure of the Erzgebirge Complex is the result of extension-related deformation that was triggered by delamination of the lithospheric root.

Konopásek et al. (2001; 2003) argued against any major role of extension during the tectonic evolution of the Erzgebirge Complex. In the Czech part of the Erzgebirge, they have recognized three stages of deformation in the schists and gneisses. The first two deformation events are compressional and associated with thrust-related emplacement of high-pressure nappes and their subsequent refolding. According to these authors, only the third and final deformation event is associated with sub-vertical principal compression, but the strain achieved during this deformation was negligible. Later, Konopásek and Schulmann (2005) published a tectonic model, in which they interpreted the high-pressure metasedimentary units of the Erzgebirge Complex as a former sedimentary cover of the Saxothuringian basement that was dragged down into the subduction zone and metamorphosed at medium temperatures and pressures of the amphibolite to eclogite facies transition. Overlying slabs of orthogneisses and especially all units with preserved granulite-facies metamorphism were interpreted as crustal rocks that, during the collisional process, occupied a position close to a continental magmatic arc at the base of the overriding Teplá-Barrandian plate. Here, the rocks were subjected to a higher thermal flux, and during the Carboniferous subduction and later collision recorded high-pressure granulite-facies metamorphism, in contrast to the eclogite facies metamorphism of all high-pressure/medium-temperature units of the central Erzgebirge, which were derived from the lower plate, i.e. from the underthrust Saxothuringian crust.

Western flank of the Teplá–Barrandian Domain

The Teplá–Barrandian Domain represents the overriding plate with respect to the Saxothuringian Domain. The western flank of the Teplá–Barrandian Domain is characterized by exhumed metabasic rocks with relics of eclogites and a significant volume of strongly serpentinized peridotite. This rock assemblage is known as the Mariánské Lázně Complex (Kastl and Tonika 1984), and its continuation is hidden beneath Tertiary sediments and volcanics of the Eger Graben (Mlčoch and Konopásek 2010). Eclogite formation in the Mariánské Lázně Complex has been correlated with that in the Münchberg nappe (e.g. Franke 2000) and interpreted as evidence for early subduction of the Saxothuringian ocean. Eclogite facies metamorphism in the

Mariánské Lázně Complex was Devonian in age (367–377 Ma; Beard et al.,, 1995), as was exhumation and cooling of the complex (368-386 Ma; Kreuzer et al., 1992; Dallmeyer and Urban 1998; Bowes et al., 2002; Timmermann et al., 2004). The lack of Carboniferous metamorphic ages along the western flank of the Teplá–Barrandian Domain suggests that the Mariánské Lázně Complex was situated in the upper crust during Lower Carboniferous convergence of the Saxothuringian and the Teplá-Barrandian domains, and that deformation was partitioned into underthrusting Saxothuringian crust (Hafoudh 2009).

Northern Saxothuringian Domain

The northern part of the Saxothuringian Domain (also known as the West Sudetes) is exposed in the northern Czech Republic and southwestern Poland. When compared with the central Saxothuringian Domain, the northern part represents an upper-crustal section consisting of Neo-Proterozoic – Cambrian basement and overlying Proterozoic - Lower Palaeozoic (meta-) sedimentary cover, which now occurs as (par-)autochthonous units or thrust sheets in the Krkonoše-Jizera and Kaczawa complexes (e.g. Franke and Żelaźniewicz 2000 for review). Subduction-related high-pressure metamorphism in mafic volcanics of the Krkonoše Mts. was recognized by Cháb and Vrána (1979) and later studied by several other authors (Guiraud and Burg 1984; Kryza and Mazur 1995; Smulikowski 1995; Patočka et al., 1996). In the Kaczawa Mts., the first detailed description of mafic high-pressure rocks and estimates of metamorphic conditions were made by Kryza et al., (1990).

The tectonic position of high-pressure metabasites and newly recognized blueschist-facies metasediments was interpreted by Seston et al., (2000); Mazur and Aleksandrowski (2001) and Žáčková et al., (2010). The tectonic model proposes the presence of three thrust sheets resting upon (par-)autochthonous basement, which is represented in the Krkonoše-Jizera Complex by the Upper Cambrian Jizera (Izera) orthogneiss (Kröner et al., 2001) and by very-low grade to unmetamorphosed sediments in the Ještěd Mts. (Chlupáč 1993). The lowermost thrust sheet was recognized by Žáčková et al., (2010) in the central and eastern part of the Krkonoše Mts. It consists of relics of garnet-bearing metasedimentary blueschists surrounded by their equivalents reworked under greenschist-facies conditions. Dating of monazites from the blueschist-facies assemblages has suggested an early Carboniferous age of c. 330 Ma for this high-pressure event (Žáčková et al., 2010). The unit containing relics of mafic blueschists represents the middle thrust sheet. It covers most of the Czech part of the Krkonoše-Jizera Complex (Mazur and Aleksandrowski 2001) and the tectonically lowermost part of the Kaczawa Mts. (Seston et al., 2000). Maluski and Patočka (1997) have suggested a Devonian age of c. 360 Ma for metamorphism of the mafic blueschists. However, it should be noted that this suggestion is based on a single Ar-Ar age, which has not been confirmed in other blueschist massifs of the West Sudetes. The uppermost thrust sheet is represented by units with a high proportion of mafic rocks, which do not show signs of high-pressure metamorphism (Kryza and Mazur 1995). The presence of contrasting metamorphic paths and metamorphic ages in the nappe stack of the West Sudetes led Mazur and Aleksandrowski (2001) and Žáčková et al., (2010) to suggest that tectonic evolution of the West Sudetes may by the same as that along the Saxothuringian–Teplá-Barrandian boundary (see above) in the southern part of the Saxothuringian Domain.

The Kutná hora Complex

The Kutná hora Complex is situated at the northern flank of the high-grade core of the Bohemian Massif, and traditionally considered as a separate unit, mainly due to differences in metamorphic evolution with respect to the underlying, southerly exposed Moldanubian Domain. According to Synek and Oliveriová (1993), the Kutná hora Complex is a stack of three nappes that were thrust over the underlying migmatitic gneisses of the Moldanubian Domain. Eclogite facies rocks in the Kutná hora Complex are confined to the uppermost allochthonous unit, which is usually considered to be correlative with the Gföhl unit in the Moldanubian Domain (see below), due to a lithologic assemblage which includes eclogites, peridotites and high-pressure felsic granulites (Synek and Oliveriová 1993). However, exhumation histories of the uppermost allochthon in the Kutná hora Complex and the Moldanubian Gföhl unit suggest that the tectonometamorphic evolution of these two units during the Variscan orogeny might have been different (Vrána et al., 2009).

Machek et al., (2009) have suggested that eclogites and associated peridotites of the Kutná Hora Complex uppermost allochthon were emplaced into the granulitic lower crust in a magmatic arc setting. In their interpretation, the incorporation of mafic eclogites and mantle peridotites into the felsic lower crust is the result of transpressional deformation concentrated in a lithospheric-scale weak zone that developed due to magma ascent from a subducting slab in the magmatic arc region. Medaris et al., (2005) ascribed the origin and exhumation of eclogite facies rocks in the Kutná Hora Complex (and in the Gföhl unit of the Moldanubian Domain in general, see below) to northwesterly subduction (in present-day coordinates) of an oceanic domain, which was originally located between the Teplá-Barrandian and Moldanubian domains.

The Moldanubian Domain

The Moldanubian Domain represents the high-grade core of the Bohemian Massif. Tollmann (1982) subdivided the Moldanubian Domain into two major tectonometamorphic units that are regarded as high-grade nappes (Fuchs, 1986; Franke ,1989; Matte et al., 1990). The lower Drosendorf nappe consists of two sub-units: the Monotonous Group, which consists mostly of migmatitic clastic metasediments, and the Variegated Group, which also contains migmatitic clastic metasediments, but with numerous intercalations of amphibolites, calcsilicates and marbles. The upper Gföhl nappe comprises high-grade migmatitic gneisses with numerous bodies of granulites, high-temperature eclogites and associated mantle rocks. Schulmann et al. (2005) have interpreted the difference in metamorphic grade of these tectonometamorphic units in terms of position in the crust and defined the Gföhl unit as the orogenic lower crust and the Monotonous and Variegated units as the orogenic middle crust.

Eclogite facies rocks occur in both units of the Moldanubian Domain (see summary by Medaris et al., 1995) and samples from particular units show marked differences in metamorphic conditions, which correspond to differences in thermal evolution of the surrounding gneisses (see summary by Medaris et al., 1995 and Schulmann et al., 2005). Sm-Nd dating of Gföhl eclogites and peridotites yields mostly early Carboniferous ages between 354-324 Ma, although Devonian ages between 370 and 377 Ma have been reported for some mantle rocks in the Gföhl unit (Beard et al., 1992; Becker, 1997; Brueckner et al., 1991; Carswell and Jamtveit, 1990).

Schulmann et al. (2005) have proposed that the Moldanubian Domain represents a former back-arc region developed during the Devonian as an extensional response to southeastward subduction of the Saxothuringian ocean (see above). A switch in tectonic regime from extension to compression in such a back-arc region during the early Carboniferous caused its homogeneous thickening, such that the bottom of the thickened crust reached conditions of eclogite facies. Continuous shortening caused large-scale folding of the original "tectonometamorphic" stratification of the continental crust and allowed rapid extrusion of the granulitic orogenic lower crust over the lower-grade orogenic middle crust.

As previously described, an alternative model for the evolution of the Moldanubian Domain proposed a westward subduction of an oceanic domain developed between the Teplá-Barrandian and the present-day Moldanubian domains (Medaris et al., 2005). Such subduction culminated with continental-type collision, and the high-grade Gföhl unit in this model represents a rock assemblage of the deeply buried Moldanubian continental crust with tectonic inclusions of eclogites and peridotites from the overlying mantle wedge.

The Lugian Domain

The Lugian Domain in the northeastern part of the Bohemian Massif shows many similarities with the Moldanubaian Domain, and several authors consider them as tectonically equivalent (e.g. Mazur et al., 2005; Schulmann et al., 2008). High-pressure granulites and eclogites are exposed in the Czech part of the Lugian Domain in an ~15 km-long belt surrounded by medium- to high-grade orthogneisses (Pouba et al., 1985). Exhumation of this high-pressure belt was interpreted by Štípská et al. (2004) to be similar to that of lower crustal rocks in the Moldanubian Domain, as proposed by Schulmann et al. (2005) and described above. The model of Štípská et al. (2004) suggests a crustal-scale folding that triggers extrusion of the lower crustal rocks into the core of a megafold represented by mid-crustal gneisses. The early extrusion rate for this high-pressure belt from depths corresponding to c. 18-20 kbar to mid-crustal levels was estimated by the authors to be 3-15 mm/year.

The Brunovistulian Domain and the Silesian Domain

From the tectonic point of view, the Brunovistulian Domain (Dudek, 1980) and the tectonically lowermost part of the Silesian Domain (Dudek, 1995; Finger et al., 1995) represent the easternmost exposed continental block of the Bohemian Massif. Their uppermost part is represented by nappes of metasediments intercalated with orthogneiss bodies representing metamorphosed and imbricated Brunovistulian-Silesian basement and its sedimentary cover (Schulmann et al., 1991; Štípská and Schulmann, 1995; Schulmann and Gayer, 2000). This rock assemblage is known as the Moravo-Silesian Zone, and its tectonically uppermost part contains metabasites with relics of eclogite facies metamorphism (Žáček, 1996; Konopásek et al., 2002; Štípská et al., 2006).

There are two models for the presence of eclogite-facies metamorphism at the eastern margin of the Bohemian Massif. Finger and Steyrer (1995) and Finger et al. (2007) suggest the presence of an oceanic domain (the Raabs ocean) separating the Moldamubian Domain and the Moravo-Silesian Zone. In their model, this oceanic domain existed until ~345 Ma and then was subducted to the west below the Moldanubian continental crust. In the model of Schulmann et al. (2005), there was no large-scale oceanic domain between the Moldanubian and Moravo-Silesian continental blocks, and their pre-collisional boundary had the character of a failed rift domain (Kröner et al., 2000), which was thermally influenced during Devonian back-arc extension (Štípská et al., 2006; Košuličová and Štípská, 2007). By implication, the formation of eclogites at the eastern margin of the Bohemian Massif would be the result of deep underthrusting of such thinned crust and mafic volcanics below the strongly weakened Moldanubian Domain (Schulmann et al., 2005).

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