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Crustal structure of the western part of the Bohemian Massif, Czech Republic

— *A summary of the project "Geological model of western Bohemia, related to the deep borehole KTB in Germany"*

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A multidisciplinary geoscience project on crustal structure of western Bohemia, Czech Republic, was implemented during the period 1991–1994. It included measurement of 200 km long deep seismic profile across several major units of the Variscan fold belt. Data and interpretations resulting from the project have now been published in English version as vol. 47 (1997) of the Journal of Geological Sciences (series Geology) by the Czech Geological Survey, Prague. The results include information on crustal geology of the internal zones of Variscides in the eastern and NE surrounding of the 9101 m deep KTB scientific borehole in SE Germany.

Introduction

The Bohemian Massif (BM) is the largest domain in the series of uplifted blocks representing exposure of the European Variscan belt that formed after Ordovician rifting of Gondwana subcontinents and their subsequent Devonian and Carboniferous collision/amalgamation. The internal zones were affected by late orogenic collapse and later modifications resulted from localized brittle Alpine tectonic reworking of this foreland domain. The western part of the BM in the Czech Republic comprises several major units of the European Variscan belt, the Saxothuringian Zone, the Moldanubian Zone, and the suture represented by the basic Mariánské Lázně Complex, separating the Saxothuringian Zone from the Teplá-Barrandian unit (Figure 1). Relations of the geological units are partially obscured by Late-Variscan granitoid plutons and the structure of the Earth's crust in this region was unclear.

The geological complexity of the region challenged and inspired the leading specialists of the scientific deep drilling program in Germany to propose a program that resulted in the implementation of the German Continental Drilling Program, KTB. This development stimulated formulation of the Czech project: **"Geological Model of western Bohemia related to the deep borehole KTB in Germany"**. It proceeded in the period 1991–1994, concurrently with the main stage of the German program KTB, which included scientific superdeep borehole, 9101 m deep, in the basement of the Bohemian Massif near Weiden, northern Bavaria, and only 20 km to the boundary with western part of the Czech Republic. The aim of the Czech project was to bring modern geophysical and geological data on geological structures and evolution of the Earth's crust in the region of western Bohemia, and to synthesize and interpret new data sets using also information obtained in the KTB program. The multi-component program coordinated by the Czech Geological Survey, Prague, included cooperation of more than 50 specialists from seven

geoscience institutions in the Czech Republic. The exchange of information between German and Czech geoscientists was supported by bilateral agreement on scientific and technical cooperation.

Western Bohemia was largely covered by relatively dense network of regional geophysical data during the last two decades, including detailed gravimetric survey and airborne magnetometric and radiometric measurements (Šrámek et al., 1997 and Pokorný et al., 1997). However, a ca. 10 km wide belt along boundary with Germany and some other gaps were measured only during the present project. Regional coverage of the area up to the boundary with Germany thus allowed comparative study of units and geological objects on both sides of the international boundary.

The results from the Czech program are now published as Volume 47 of the *Journal of Geological Sciences*, series Geology (240p.), by the Czech Geological Survey, Prague. This contribution to *Episodes* highlights some of the new information on geology of the Variscan orogen in western Bohemia. It aims at informing international geoscience community about the new volume of data, besides those published by German colleagues, e.g., "The KTB Deep Drill Hole", *Journal of Geophysical Research*, Vol. 102, No. B8 (1997). Understandably, it is not possible to introduce here all new results ranging from regional geophysics to isotope studies contained in 21 chapters of the publication, rather, attention is drawn to several interesting topics.

200 km long, deep reflection seismic profile 9HR

The most powerful tool for recognition of the crustal structure is the deep reflection seismics. The newly measured 200 kilometre-long reflection seismic profile 9HR represents a backbone of the project. It started in Klingenthal, in the Saxothuringian Zone, 2.7 km inside Germany, and continued to the SE across the Mariánské Lázně Complex (MLC), the Teplá-Barrandian unit (TBU), and to Prácheň in the Moldanubian Zone in southern Bohemia (Figure 1). In terms of the technique used, it is the first major seismic profile in the interior part of the Bohemian Massif aimed at characterization of the internal crustal structure. The seismic experiment headed by Č. Tomek (Tomek et al., 1997) used dynamite charges 20 kg in weight placed in ca. 20 m deep drillholes, with shotpoint spacing of 200 m. This resulted in higher energy, better reflection definition, and responses from deeper structures. For the first time in the seismic investigation in the European Variscides, several reflections from the mantle (at depths of 35, 42, and 56 km) were registered. Interpretation of the seismic profile was supported by density model section obtained from detailed regional gravity data and a large database on rock densities (Švancara-Chlupáčová, 1997).

Figure 1 Geological map of western Bohemia, Czech Republic, and the adjacent part of northern Bavaria, Germany. The location of the 9HR seismic profile is shown. Geology is based on published maps, simplified. Inset shows position of the area in Central Europe and relative to the Rhenohercynian (RH), Saxothuringian (ST), and Moldanubian (MN) Zones of the Variscan orogen.

The most important information obtained includes (Figure 6):

- Regional position of the Moho boundary shows relatively limited variation: it is at a depth of 33 km below the Krušné hory Mts./Erzgebirge (in the NW of the 9HR line) and 37 to 38 km below the Moldanubian Zone, in the SE part of the line; there is a distinct elevation to a depth of ca. 28 to 30 km at intersection with the Tertiary Ohře rift near Karlovy Vary (corresponding to projection of the Doupov Mts. Tertiary volcanic complex, D = 30 km);
- Reflections in the upper crust at the NW end of the 9HR profile, dipping NW, correspond to weakly metamorphosed Palaeozoic formations, with dip towards the Vogtland megasyncline; the system of subhorizontal reflections at a depth of 10 km in the Saxothuringian Zone (near km 0) continuing up to km 70 of the line and then sloping to the base of the crust (at km 100) is interpreted as the main thrust fault of this part of the Variscan orogen. Overlying this fault are allochthonous units of the Saxothuringian Zone, the ophiolite suture unit MLC, together with the overlying

Teplá-Barrandian unit (TBU). The underlying complex with SE-dipping reflections in the middle and lower crust is interpreted as the "European parautochthon", belonging probably to the East Avalonia (or laterally correlated with the Cadomian crust of the type of the Lusitanian pluton, cropping out in a structural elevation ca. 150 km to the NE);

- In the NW part of the 9HR line, the junction between the crystalline complex of the Saxothuringian Zone and the Mariánské Lázně Complex is masked by intrusion of the Late-Variscan Karlovy Vary pluton, which is nearly 10 km thick;
- Position of the Mariánské Lázně Complex (MLC) and its subsurface continuation to the SE, beneath TBU is indicated; the internal structure of the TBU with prominent subparallel SE-dipping reflecting horizons, showing vertical extension through much of the crustal thickness, can be correlated with the pattern of relatively continuous and coherent lithological layering of low-grade Upper Proterozoic volcano-sedimentary complex; this situation continues to the SE up to the Central Bohemian suture, seen as a

or steeply NW-dipping junction of TBU with the Moldanubian Zone;

- In the Moldanubian crust the reflecting domains are typically short (5 to 10 km) and belong to several sets of apparent orientations: a) shallow-dipping to the NW, b) moderately-dipping to the NW, c) shallow-dipping to the SE, and d) subhorizontal reflections of increasing frequency in the middle and lower crust. In absence of a cross-oriented seismic line, possible sideways dip of some reflecting domains remains unconstrained. The reflections a and b and some horizontal (or shallow NE-dipping ?) reflections can be correlated with late, extension-related shear foliations documented in surface geology (Lobkowicz et al., 1996). The reflection pattern does not suggest presence of large, >5 to 8 km thick, isotropic, Late-Variscan granitoid plutons (transparent in terms of reflection seismics) in the Moldanubian crust along the 9HR line. Felsic granulite bodies up to 20 km long and slices of upper mantle peridotite crop out at the SE end of the 9HR line. The reflection seismics data, even if combined with additional geophysical information, such as detailed gravimetry, do not constrain probable presence of the granulite+peridotite assemblage in the Moldanubian middle and lower crust;
- For the first time, information is obtained on probable emplacement of basaltoid intrusions at the crust/mantle boundary as the abyssal manifestation of the volcanic activity during the Tertiary (Doupov Mts. volcanic complex) (Figures 1 and 6). The intrusions are possibly up to 3 km thick (Tomek et al., 1997). The associated increased geothermal gradient and degassing constitute important factors in the formation of abundant springs of mineralized waters in the west Bohemian spa region (Karlovy Vary, Mariánské Lázně, Františkovy Lázně).

The Mariánské Lázně Complex, a major relic of the intra-Variscan suture

The Mariánské Lázně Complex (MLC), defined recently as an independent unit in between the Saxothuringian Zone and the TBU, represents a segment of an important suture in the geological pattern of western Bohemia. It is a collage of oceanic crust slices, associated with some continental rocks, metamorphosed under high pressures (HP) and reworked by polyphase tectonic processes. Basic rocks thus occur as tectonically imbricated and intersliced with minor bodies of paragneisses and orthogneisses. Peridotites, gabbros, basalts and intermediate members of the oceanic crustal sequence are identified as protolith rocks of metabasites and gneisses. The allochthonous melange segments were subducted to deep levels, metamorphosed during the Palaeo-Variscan stage, and while in middle to upper crustal position, thrust over the SE margin of the Saxothuringian Zone. Environments of these processes span the pressure interval 1.6 to 2.5 MPa and a later relaxed geotherm reaching an episodic granulite grade, followed by exposition to hydration and tectonic processes in shallower crustal levels.

Petrological and geochemical study of eclogites, garnet amphibolites, and metagabbros in the MLC shows their similar chemical composition, corresponding dominantly to MORB-like protoliths, with age of peak metamorphism 370–380 Ma (Beard et al., 1995). Geothermobarometric study of garnet amphibolites (associated with eclogites and partly derived from eclogites) provided the P-T data set from the core and the SW margin of the complex, and from partial segments inserted tectonically in the western part of TBU. The notably variable PT-conditions within upper amphibolite facies (Figure 2) superimposed on the HP and HT events, obtained from the individual domains in the MLC, support rather complex late tectonic evolution and

Figure 2 P-T plot of equilibration of Grt-Hbl-Pl (Qtz) assemblage from metabasic rocks of the MLC. A – core of MLC, B – interior SE margin of MLC, C – metabasites incorporated in the W part of TBU (i. e., largely in allochthonous position), D – amphibolites of the W part of TBU.

apparent mutual allochthonity of segments of the complex (Stědrá, 1997). This indicates a status of thrust slices for the main domains of MLC, which probably evolved in the course of obduction of the metabasic complex.

A protolith zircon age of 496 ± 1 Ma for the MLC metagabbro (Bowes and Aftalion, 1991) corresponds approximately to the ages obtained by the same method for metagabbros in similar units in Germany, i.e., in the Münchberg Massif (Bosbach et al., 1991), and the Erbsdorf-Vohenstrauß unit (KTB samples; Quadrt and Gebauer, 1993). Geochronological data for the main metamorphic events in both units are similar. The geochemical features of basic rocks from the MLC and the Münchberg Massif are also comparable (Patzak et al., 1991; O'Brien, 1991; Quadrt, 1990; Quadrt and Gebauer, 1993). Evolution of the MLC is directly comparable with that of the Erbsdorf-Vohenstrauß Unit in Bavaria (O'Brien et al., 1997).

Figure 3 A schematized section of the upper crust of the Teplá-Barrandian unit (TBU) showing superposition of transgression surfaces of major sedimentary units from the Cambrian to the Upper Cretaceous on the Upper Proterozoic basement. See text for discussion.

Figure 4 A schematized review of the neo-Variscan heterogeneous assemblage of the crustal and upper mantle units represented in the surface exposure of the Moldanubian Zone. The partial units are arranged in reference to the geographic distribution from NW (top left) to SE (bottom right). The allochthonous bodies of upper mantle rocks are shown by cross-ruling pattern.

Relations of some major units: contrasting evolution of the Teplá-Barrandian Unit and the Moldanubian Zone during the Variscan orogenic processes

The joint interpretation of data obtained by geophysical and geological methods resulted in formulation of the following characteristic features and differences between the Moldanubian Zone and the Teplá-Barrandian unit (TBU).

The Teplá-Barrandian unit

The TBU is a segment of pre-Variscan crust which retained notable structural coherency in its inner parts (central Bohemia) during the Variscan. This is expressed in preservation of several unmetamorphosed sedimentary units, including Cambrian, Ordovician to middle Devonian, Westphalian to Lower Permian, and Upper Cretaceous, which successively transgressed the Upper Proterozoic basement of the TBU (Figure 3). The situation indicates recurrent and prolonged episodes of a conservative isostasy which should explain preservation (though largely in erosional relics) of several sedimentary sequences in the uppermost crust through the interval of nearly 500 Ma. However, it is uncertain to which degree a regime of conservative isostasy functioned between upper Devonian and Westphalian.

There is a prograde zoning of regional metamorphism in the Upper Proterozoic of TBU towards NW and SW. The metamorphism at the NW of the TBU was polyphase. Surprisingly, its first stage was a LP one. The second stage, typical Barrovian MP-MT, reached $T > 600^\circ\text{C}$ and P up to 1 GPa; pressure reached its maximum near the outer edge of kyanite zone. The third stage was retrograde and started by crystallization of sillimanite. Cháb and Žáček (1997) assume a Cadomian age for the first and second stage of metamorphism. An important set of

Figure 5 Highly schematic crustal section of the Moldanubian Zone and the neighbouring units carrying mainly record of the Cadomian evolution, i.e., the Teplá-Barrandian Unit at the NW and the Brunovistulian Unit at the SE. Regional variations in grade of the Variscan metamorphism, palaeo-Variscan and neo-Variscan ages of metamorphic crystallisation, and Ar-Ar cooling ages indicate a major upward transport of crustal (and mantle) masses of the Moldanubian Zone relative to the neighbouring units in the course of the neo-Variscan evolution.

Figure 6 Geological model of the crustal and upper mantle structure in western and southwestern Bohemia (based on Tomek et al., 1997, and geological and geophysical data in Vrána and Štědrá, 1997).

radiometric ages confirms the predominance of the Cadomian intrusions, partly transformed to orthogneiss, in the W part of the TBU (Dörr et al., 1995).

The Teplá-Barrandian Unit, localized in a nearly central part of the Bohemian Massif, shows gravity and magnetization properties which make it distinct from the neighbouring units (Šrámek and Mrlina, 1997, and Pokorný et al., 1997). In the region of interest, TBU it is bound by shear (fault) zones with a steep dip — i.e., the Central Bohemian Suture, the West Bohemian Shearzone, and the

Litoměřice fault zone, used for intrusion by a number of the Variscan "stitching" granitoid plutons. In western Bohemia, kinematic indicators in mylonites in the West Bohemian shear zone correspond to uplift of the Moldanubian Zone relative the TBU (Zulauf, 1994, 1997). Along the Central Bohemian Suture, in the segment adjacent to the Klatovy apophysis, kinematic indicators on cleavages in the TBU, steeply dipping toward WNW, also correspond to the relative uplift of the Moldanubian Zone (Zulauf, 1997).

In old classifications of the zonal structure of the Variscan orogen, the Teplá-Barrandian unit used to be included in the Moldanubian Zone, extending thus Moldanubian Zone s.s. (such as used in the present text) to Moldanubian Zone s.l. The present comparison of TBU and the Moldanubian Zone (s.s.) shows clearly that the two units exhibit sharply contrasting and independent history during the Variscan orogen and should be considered separately.

The Moldanubian Zone

The present radiometric database for the Moldanubian Zone, in combination with structural, petrological and geochemical information shows that this unit comprises a number of heterogeneous crustal and upper mantle segments (Figure 4). The crustal partial units range in age from Lower Proterozoic to Lower Palaeozoic (also defined as several distinct terranes — Matte et al., 1988) which were clearly assembled only during the Variscan.

Geochronological data, including cooling ages, indicate a major upward mass flow in the Moldanubian Zone during the neo-Variscan, prior to gravitational collapse (Figure 5). This feature is essential in explaining the proportion of rocks with a Variscan early HP history ($P > 1.5$ GPa) succeeded by HT conditions (700 to 1000°C) under relatively low pressures (0.5 GPa) and the significant proportion of Variscan upper mantle rocks exposed on the Earth's surface. These rocks often closely associate with other HP/HT rocks which crystallized during the palaeo-Variscan and neo-Variscan events from mantle melts in upper mantle levels (part of eclogites, garnet pyroxenites, garnet and spinel peridotites) (Medaris et al., 1995a, b). In contrast, no Variscan HP rocks occur in upper crustal positions in the TBU.

These relations imply that the cumulative effect of several deformation stages affecting the Moldanubian rocks must be a major upward transport of crustal and upper mantle masses. The early and intermediate deformation structures are extensively obliterated by younger deformations, often characterized by high deformation rates, and finally, late extensional deformation modified the anomalously thick pile of crustal masses carrying some upper mantle segments.

Laterally, in the east of the Bohemian Massif, the Moldanubian Zone is translated on the Cadomian Brunovistulian Unit (Dallmeyer et al., 1995) and in the west on the TBU. The model profile (Figures 5 and 6) suggests potential gravity transport of uppermost crustal segments from their "Moldanubian homeland" and their translation on laterally adjacent units, caused by the constriction and uplift of the Moldanubian Zone. In addition to such tectonic erosion (of unknown extent), a high-rate surficial erosion of the Earth's crust took place in pre-Westphalian times, as follows from the analysis of Culm in Moravia (Kumpera and Martinec, 1995).

The observed and interpreted relations indicate probable absence of a continuous layer of Cadomian crust in a lower crustal level (a kind of westward continuation of the Brunovistulian Zone) beneath the Moldanubian Zone. High-pressure granulites and eclogites, at least in part derived from the subducted plate, were obducted and telescoped together with some upper mantle masses into higher crustal levels of the Moldanubian Zone. Also, some exotic allochthonous segments of ancient, pre-Cadomian crust (Světlick orthogneiss, Dobra gneiss) were emplaced into the Moldanubian complex in the course of mass transport on lithospheric scale. This situation is not compatible with preservation of a more or less continuous Cadomian layer in the lower crust under the Moldanubian Zone.

The crustal section of western and southwestern Bohemia

The 9HR seismic profile (Tomek et al. 1997), complemented by gravity model profile (Švancara and Chlupáčová, 1997) in combination with geological information was used for construction of crustal cross-section along the Kraslice-Prachatice line (Figure 6). It shows

the main features of the crustal structure as a model interpretation supported by geophysical and geological data.

The interpretation of the 9HR reflection seismic profile (Tomek et al., 1997) suggests that the TBU and all the geological units occurring more northerly represent a set of high allochthones. Only the SE part of the TBU is preserved in its whole-crustal thickness (Figure 6). The other units, the MLC and the Saxothuringian Zone, rooted under the TBU, are strongly thinned and laminated, forming relatively thin bodies dipping to the SE and tilted to a subhorizontal position only in the upper crust. All these units appear to be under-thrust by a seismically strongly laminated Avalonian(?) type crust. The combination of the tectonic position of the TBU and the subdued effects of the Variscan deformation and metamorphism, which dominate in the surrounding units, constitute the features of the TBU as a unit different from the neighbouring units. The 9HR profile features the Variscan orogen in western Bohemia as a typical example of a thick-skinned tectonics.

Extensive application of geochronological methods to a number of units in western part of the Bohemian Massif brought recognition of Palaeo-Variscan domains (e.g., Münchberg nappe, Erben-dorf-Vohenstrauß unit [with the KTB site], MLC complex) which cooled through the Ar-Ar closing temperatures during upper Devonian, approx. 380 to 390 Ma, and Neo-Variscan domains, including mainly a large part of the Saxothuringian Zone and the Moldanubian Zone, where processes of HP-HT crystallization in crustal and upper mantle rocks culminated by 340 to 350 Ma. This brings forward previously unsuspected complexity in evolution of the Variscan orogen.

The goal of understanding the crustal structure and tectonic evolution of the western part of the Bohemian Massif has not been fully achieved. Even so, some important advances can be listed as follows:

- Several major units, i.e., the Saxothuringian Zone, TBU and the Moldanubian Zone contain a substantial proportion of Cadomian (Pan-African) crust and a variable proportion of Lower Palaeozoic units;
- The styles of tectonic deformations of Palaeozoic and of Variscan metamorphism differ among these units:
 - a) in TBU mediotype deformation, unmetamorphosed; there is progression to amphibolite facies towards the NW and SW marginal faults in the Upper Proterozoic rocks,
 - b) in the Saxothuringian Zone involvement in crustal stacking and a complex polyphase deformation, low-grade to high-grade metamorphism (HP in some domains),
 - c) in the Moldanubian Zone involvement in crustal stacking, high-grade metamorphism, HP-HT in some domains, followed by LP-HT metamorphism. The neo-Variscan extrusion of over-thickened crust with mantle segments is a specific feature of this zone;
- The role of late extensional deformation increases very approximately in the sequence a) to c); some parts of the Moldanubian Zone show >70 vol% overprinting of early structures by late extensional deformation, associated with amphibolite facies to rather cold, brittle deformation conditions;
- The borders of the TBU with the Saxothuringian Zone and Moldanubian Zone are modified by steep faults associated in places with a vertical component of > 10 km, accompanied by brittle-ductile to brittle deformation; the marginal faults bounding the TBU were used for emplacement of a number of Variscan intrusions or plutons dated mainly at 350 to 340 Ma (Zulauf 1997);
- the sets of successive penetrative deformation structures in the major units can not be traced across boundaries of the major units;
- An important Mesozoic-Tertiary crustal stacking, recognized in the KTB borehole in Northern Bavaria near the Franconian line, appears to be confined to certain zones. Some other areas were largely unaffected by such deformation, as indicated by continuous cover of Westphalian to Lower Permian sediments, e.g. in the Plzeň basin.

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