Univerzita Karlova v Praze

Přírodovědecká fakulta

Ústav petrologie a strukturní geologie

STUDIJNÍ PROGRAM: GEOLOGIE

Mgr. Lukáš Vondrovic

MECHANISMY VMÍSTĚNÍ A STAVBY PLUTONŮ VÝCHODNÍ PERIFERIE MOLDANUBIKA; IMPLIKACE PRO GEODYNAMICKÝ VÝVOJ VÝCHODNÍHO OKRAJE ČESKÉHO MASÍVU

EMPLACEMENT AND FABRIC PATTERNS OF PLUTONS IN THE EASTERN PERIPHERY OF THE MOLDANUBIAN ZONE; IMPLICATIONS FOR GEODYNAMIC EVOLUTION OF THE BOHEMIAN MASSIF

Disertační práce/Ph.D Thesis

Vedoucí závěrečné práce/Supervisor:

RNDr. Kryštof Verner, Ph.D

Konzultant/Consultant:

Mgr. David Buriánek, Ph.D

Praha, 2015

PROHLÁŠENÍ

Prohlašuji, že jsem závěrečnou práci zpracoval samostatně a že jsem uvedl všechny použité informační zdroje a literaturu. Tato práce ani její podstatná část nebyla předložena k získání jiného nebo stejného akademického titulu.

DECLARATION

I, Lukáš Vondrovic declare that this thesis, presented for the Ph.D. degree at Charles University in Prague, is a result of my own original research and has not been previously submitted to Charles University in Prague or any other institution. I have clearly indicated, when appropriate, the contributions of colleagues and have made every effort to acknowledge all collaborative work. The copyright to the material within this thesis belongs to the author and any information or quotation taken from it should be acknowledged and published only if prior consent has been given.

V Praze / In Prague 23. 7. 2015

Lukáš Vondrovic

ACKNOWLEDGMENT

I would like to thank my supervisor, Kryštof Verner, who expanded my knowledge in structural geology and introduced me an uncertain world of geological science. He provided me complex scientific support from Bc to Ph.D level with high of scientific support of our research. My second thank is addressed to my consultant David Buriánek for expanding my knowledge in metamorphic petrology. Further, I would like to thank Václav Kachlík, Patricie Týcová, Marta Chlupáčová, Jiři Sláma, Jitka Míková, Jaroslava Pertoldová and all coauthors, editors and reviewers. My special thanks go to Jakub Trubač and Darren von Lansperk who helped me in final phase of thesis completion. The last, but not least thanks go to my wife Lenka son Ignác, daughter Antonie, my parents and church in Korouhev, providing me support during all hard days.

This work was supported by project of Grant Agency of Charles University (No. 81909; GAUK), by the Special Studies, Research Methodology, Doctoral and Diploma Thesis (No. 32300; Czech Geological Survey).

CONTENT

ABSTRAKT

Předkládaná disertační práce se zabývá analýzou strukturního záznamu a krystalizačního stáří vybraných granitoidních plutonů vápenato-alkalického složení, které byly vmístěny do metamorfovaných hornin jednotek periferní oblasti moldanubika v severovýchodní části Českého masivu. Důležitou součástí práce dále bylo zhodnocení tektonického a metamorfního vývoje okolních metamorfovaných hornin poličského a zábřežského krystalinika. Výsledky práce přinášejí širší implikace pro interpretaci raných etap variského geodynamického vývoje severovýchodní části Českého masivu. Metamorfované horniny zábřežského krystalinika prodělaly regionální metamorfózu v podmínkách středních teplot T: 660°C a nižších tlaků P: 0.6 Gpa). Strukturní záznam jednotky je definován superpozicí dvou regionálních staveb, a to strmé foliace v-z. průběhu (S_1), která byla variabilně převrásněna do foliačních ploch subhorizontální orientace (S_2). Do těchto hornin byla v období variských orogenních procesů (354±4 Ma; U/Pb na zirkonech) vmístěna tělesa granitoidů vápenato-alkalického složení se stanovenými podmínkami krystalizace T: 706 až 795 °C a P: 0.3 až 0.4 Gpa. V těsném okolí intruzí byly identifikovány účinky kontaktní metamorfózy za teplot 599 až 663 °C a tlaků 0.4 Gpa). Magmatické foliace v granitoidech mají tranzitní magmatický až submagmatický charakter v paralelní orientaci s regionálními metamorfními foliacemi S_1. Poličské krystalinikum je tvořeno metamorfovanými horninami vulkanosedimentárního původu. P-T podmínky metamorfózy centrální a severní části jednotky byly stanoveny na T: 620°C až 680 °C a P: 0.6 Gpa, resp. 585 ± 80 °C a 0.39 ± 0.22 Gpa. Strukturní záznam v jednotce je definován superpozicí tří odlišných staveb. Mezi nejstarší stavby patří středně ukloněná foliace S_1 sz-jv. průběhu doprovázená mírně ukloněnými lineacemi a indikátory pravostranné kinematiky. Tyto foliace byly v západní části jednotky refoliovány do ploch foliace S_2 průběhu sv-jz. Na tyto dvě foliace jsou pak naloženy mírně ukloněné foliace k severu, místy s indikátory poklesové kinematiky. Do severní a centrální části poličského krystalinika byly vmístěny granitoidy vápenato-alkalického složení. Krystalizační stáří budislavského plutonu bylo stanoveno na 346 ± 6Ma (U/Pb na zirkonech). Teplotní a tlakové podmínky krystalizace byly stanoveny na T: 655 až 730 °C, a P: 0.4 až 0.6 Gpa. Vnitřní stavby plutonu odráží jak procesy spojené s vmístěním magmatu, tak působení regionálního napěťového pole. Těleso miřetínského plutonu bylo datováno na 345.9 ± 5Ma (U/Pb na zirkonech). Pluton byl vmístěn do severní části poličského krystalinika, a to synchronně s tvorbou regionálních foliací S_2 za podmínek krystalizace T: 653 až 681 °C, P: 0.29 až 0.43 GPa. Procesy regionální

metamorfózy hornin poličského a zábřežského krystalinika v podmínkách středních teplot a nižších až středních tlaků souvisejí se vznikem raných metamorfních staveb a byly spojeny s aktivitou pravostranné střižné zóny mezi jednotkami moldanubika a západních Sudet. Vmístění a krystalizace granitoidů vápenato-alkalického složení bylo synchronní s procesy regionální metamorfózy a deformace. Zjištěné krystalizační stáří granitoidů v rozmezí 354 až 346 Ma (U/Pb na zirkonech) tak udává i časový rámec regionálních metamorfních procesů spojených s formováním pravostranné střižné zóny v průběhu zsz(sz)-vjv(jv). Konec aktivity této regionální střižné zóny byl datován intruzí miřetínského plutonu v čase 345.9 Ma. Tyto procesy odráží nejstarší duktilní aktivitu zóny labských deformací, tedy rozsáhlé deformační zóny SZ-JV průběhu v reologicky méně odolných horninách východní části tepelsko-barrandienské jednotky jako odraz regionálního kompresního napěťového pole ve směru SZ-JV. Studované vápenato-alkalické plutony tak datují nejstarší svrchně-variský tektonometamorfní událost v oblasti středně-korových jednotek východního okraje Českého masivu.

ABSTRACT

The Ph.D. thesis focuses on an analysis of the structural record and geochronology of selected calc-alkaline plutons emplaced in the rocks of the eastern periphery of the Moldanubian Zone (eastern margin of the Bohemian Massif). In addition, it includes an analysis of the tectonic and metamorphic record of the host rocks of the Polička and Zábřeh Units. The results revealed a number of important implications regarding the geodynamic evolution of the north-eastern part of the Bohemian Massif. The rocks of the Zábřeh Unit were metamorphosed under middle temperature and lower pressure conditions (T: 660 °C, P: 0.6 Gpa). The structural record is defined by the superposition of regional steep E-W trending metamorphic fabric (S_1) which was variably obliterated by means of intensive folding into S_2 flat-lying foliation. This unit is in the northern part intruded by calc-alkaline rocks of the Zábřeh Intrusive Complex (354±4Ma, U/Pb on zircons) with calculated P-T crystallisation conditions of 706–795 °C and P: 0.3–0.4 Gpa. A contact metamorphic event took place within the host rocks in the proximity of the intrusion (T: 599-663 °C, P: 0.4 Gpa). The internal fabric of the Zábřeh Intrusive Complex exhibits a magmatic to submagmatic gradient and the orientation of the intrusive contacts and magmatic foliation respects the S_1 foliation of the host rocks. The second area studied, the Polička Unit, consists of a metamorphosed volcanosedimentary complex. The P-T conditions of the metamorphism of the central and northern parts of the

unit (which feature calc-alkaline intrusions) have been estimated at T: 620–680 °C and P: 0.6 Gpa and 585 ± 80 °C and 0.39 ± 0.22 Gpa respectively. This unit displays complex structural and metamorphic pattern from greenschist to granulite facies. The structural record of the Polička Unit is defined by the superposition of three distinct fabrics: the oldest NW-SE steeply to moderately dipping S_1 fabric which bears gently plunging lineations and indicators of right-lateral kinematics; the S_2 NE-SW trending foliation of the northern and eastern parts of the unit, and flat-lying S_3 foliation occasionally associated with indicators of normal kinematics. The Budislav Pluton (346±6 Ma, U/Pb on zircons, T: 655-730 °C, P: 0.4–0.6 Gpa) intruding the central part of the Polička Unit reflects internal emplacement processes within its structures and the formation of S_1 regional tectonometamorphic fabric. The final intrusion studied, the Miřetín Pluton (346±6Ma, U/Pb on zircons), intruded the northern part of the Polička Unit during the formation of S_2 foliation within the host rocks. The P-T conditions of magma crystallisation have been estimated at T: 653–681 °C, P: 0.29–0.43G Pa. Subsequent brittle cleavage is connected with normal faulting along the boundary of the Polička and Hlinsko Units. The regional metamorphic processes of the Polička and Zábřeh Units under middle temperature and low to middle pressure conditions were connected with the formation of early-Variscan tectonometamorphic fabrics. The origin of these fabrics was related to right-lateral transpressive shearing that took place in the space between the Moldanubian lower crust and the Western Sudetes. The emplacement of the calc-alkaline plutons studied was synchronous with regional deformation and the formation of S_1 fabric within host rocks. The crystallisation age of 354 to 346 Ma (U/Pb on zircons) limits the time span of the formation of the WNW (NW) – ESE (SE) trending right-lateral shear zone. The end of the shearing process was post-dated by the emplacement of the Miřetín Pluton at 345.9 Ma. The intrusion of calc-alkaline plutons in the mid- to upper-crustal level rocks reflects the initiation of the so-called Elbe Zone of the Bohemian Massif which was active in the mid- to upper-crustal rocks of the Teplá-Barrandian Unit between Moldanubian Zone and Western Sudetes reflecting the regional NW-SE stress field.

Introduction

1. Introduction

The Ph.D. thesis focuses on the reconstruction of the tectonometamorphic and geochronological evolution of the mid- to upper-crustal Polička and Zábřeh Units outcropping along the north-eastern periphery of the Moldanubian Zone (Bohemian Massif). This region is made up of a collage of various crustal-scale segments that were metamorphosed and consolidated during the Variscan orogeny (Schulmann et al 2005; 2008; Verner et al. 2009; Pertoldová et al. 2010). The study is dedicated to the issue of the emplacement and structural evolution of calc-alkaline plutons intruding the Polička and Zábřeh Units. The age and composition of the plutons studied suggest that they were formed as a result of the first Variscan magmatic event in the Bohemian Massif dated at 356 to 346 Ma (e.g. Holub et al. 1997; Franke et al. 2000; Žák et al. 2012). As part of the investigation, extensive field-oriented structural research (the analysis of fabrics in plutons and structures in metamorphic rocks) was conducted at a scale of 1:25.000. In addition, the microstructural analysis of fabrics within the plutons and their host rocks was performed employing a combination of optical microscopy and the EBSD method (e.g. Prior et al. 1999). The field and laboratory analysis of the fabric pattern was complemented by the use of the Anisotropy of Magnetic Susceptibility (AMS) analytical method in plutonic rocks in order to quantify orientation, fabric parameters and gradients (e.g. Hrouda and Tarling 1984). In addition, new radiometric dating (U−Pb dating on zircons) complemented existing information on the crystallization age of the plutons linked to regional tectonics. In co-operation with the co-authors of the attached papers, a study was performed of the regional metamorphic evolution of the areas under investigation. THERMOCALC and Perple_X (e.g. Holland et al. 1998) software together with conventional geobarometry and thermometry was employed for the analysis of P–T evolution and for subsequent thermodynamic modelling based on the bulk chemical compositions of the rocks obtained by means of silicate analysis (e.g. Holland et al. 1998).

The rock of the eastern margin of the Bohemian Massif reflects the complex geological evolution of the whole of the Central European Variscides (the Bohemian Massif) which was formed by the accretion of several Gondwana-derived microplates to the Laurussia continent during the Devonian to Carboniferous closure of the Rheic Ocean and other small oceanic domains (Pharaoh 1999; Winchester 2002; Franke 2006; Linnemann et al. 2000; Kroner and Romer 2013 and references therein) and, according to lithology and tectonic evolution, it can be divided into three principal zones. The Saxothuringian Zone of the Bohemian Massif consists of Neoproterozoic and Lower Palaeozoic volcano-sedimentary series with lower-

Cambrian to late-Devonian metagranitoids (e.g., Linnemann & Romer 2002; Buschmann et al. 2006; Nowak et al. 2011). The upper-crustal Teplá-Barrandian Zone of the Bohemian Massif outcrops in a hanging-wall position with respect to the adjacent more metamorphosed Saxothuringian and Moldanubian Zones and consists of: medium-grade Neoproterozoic sediments, originally part of the Cadomian accretionary wedge (Sláma et al. 2008; Hajná et al. 2010, 2011) which were subsequently intruded by Cambro-Ordovician granitoids and an unmetamorphosed early Cambrian to early Devonian volcano-sedimentary sequence (Chlupáč et al. 1998). In contrast the Moldanubian Zone, the middle to lower crust (known as the "orogenic root domain"), is deeply eroded and was subject to a complex Variscan tectonometamorphic history (e.g. Vrána et al. 1995; Finger et al. 2007; Faryad et al. 2010; Franěk et al. 2011). This unit comprises two major sub-units with contrasting tectonometamorphic evolutions: the mid-crustal Drosendorf Unit and the lower-crustal Gföhl Unit (e.g. Urban and Synek 1995) which were exhumed from different depths.

Variscan tectonometamorphic processes were accompanied by extensive magmatic activity which revealed the following general relations between granitoid petrogenesis and the geodynamic setting (see Finger et al. 1997 for reviews): (1) syn-collisional Late Devonian-Early Carboniferous (~370–34 0Ma) crustal thickening broadly overlaps with the emplacement of metaluminous, calc-alkaline and high-K I-type plutons; (2) the rapid exhumation of the lower- to middle-crust at around ~341-336Ma (e.g. Willner et al. 2002 and references therein) which is associated with the intrusion of ultrapotassic, magnesium-rich plutons (e.g., Holub 1997; Gerdes et al. 2000a; Verner et al. 2006; 2008); (3) during and following subsequent LP-HT regional metamorphism and anatexis in the innermost part of the orogenic belt (the Moldanubian Zone), at ~335–321Ma (e.g., Kalt et al. 1999, 2000; Gerdes et al. 2000b; Tropper et al. 2006; Vrána et al. 1995; Willner et al. 2002) was intruded by large volumes of peraluminous S-type and high-K I-type granitoids; (4) late Variscan strike-slip shearing (Brandmayr et al. 1995; Edel et al. 2003; Finger et al. 2010) which broadly overlaps the emplacement of calc-alkaline, I-type plutons (310–290Ma) and which marked the end of Variscan magmatic activity.

The thesis aims to provide an insight into the first-event syn-collisional calc-alkaline granitoid complexes of the Bohemian Massif including primarily a number of intrusions along the north eastern periphery of the Moldanubian Zone. The results have broad implications in terms of understanding the origin and tectonic evolution of continental magmatic arcs and early-Variscan (~356 to 346 Ma) geodynamic processes.

The key topics discussed in the thesis consist of:

(i) The emplacement, fabric pattern and geochronology of calc-alkaline plutons in the eastern periphery of the Moldanubian Zone – its origin and tectonic significance

The granodiorite to tonalitic plutons intruding the Polička and Zábřeh Units (Miřetín and Budislav plutons, Zábřeh Intrusive complex, Buriánek et al. 2003, Verner et al. 2009, Pitra et al. 1994, Vondrovic et al. 2011, Lehmann et al. 2013) exhibit similar geochemical and geochronological characteristics to other plutons intruding the central and western parts of the Teplá-Barrandian Zone (e.g. Buriánek et al. 2003, Vondrovic et al. 2011, Žák et al. 2014). The tectonic significance of calc-alkaline plutons in the Teplá-Barrandian has been synthesised and discussed in a number of papers (e.g. Žák et al. 2005, 2011, 2014, Janoušek et al. 2004) as a result of the subduction and related transpression of the Saxothuringian domain beneath the Teplá-Barrandian. Existing interpretations of the calc-alkaline plutons studied along the eastern margin of the Bohemian Massif connect the emplacement of the studied plutons with various geodynamic processes such as extensional shearing (e.g. Pitra et al. 1994) or the growth of an orogenic core complex (Lehmann et al. 2013). The data presented in this thesis (Parts 3 and 4 of the thesis) allows the suggestion of an alternative scenario through the synthesisation of an early-Variscan calc-alkaline event in the Bohemian Massif.

(ii) The analysis of tectonic and metamorphic evolution of variscan mid- to upper- crustal continental crust in the peripheral part of orogenic root domain

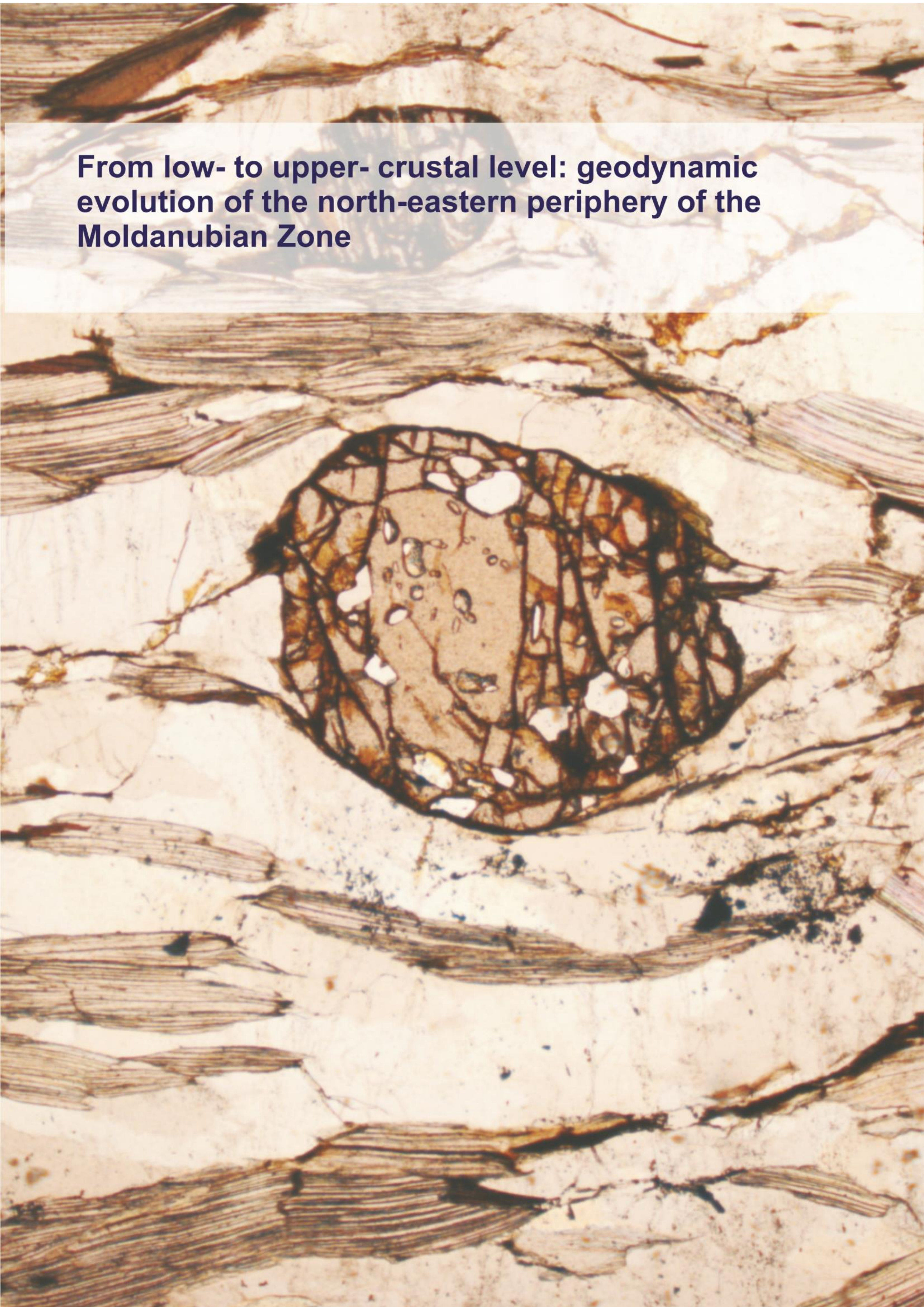
The metamorphic complexes of the Polička Unit were found to be generally metamorphosed in a range from greenschist to granulite facies conditions (Buriánek et al. 2003; Tajčmanová et al. 2010). Previous studies concentrated on different segments of the Polička Unit e.g. Vír granulite (Konopásek et al. 1997; Tajčmanová et al 2010), areas surrounding calc-alkaline plutons (Buriánek et al. 2003) or the northern part of the Polička Unit in the proximity of the Hlinsko Unit (Vondrovic et al. 2011). In this study the author interprets this intriguing metamorphic gradient as one unit which was formed as the result of a complex geological evolution as described in Part 2 of this thesis and in Buriánek et al. in prep. In the case of the Zábřeh Unit petrological research focused on a comparison of the metamorphic gradients in the Polička and Zábřeh Units which, it is supposed, form part of a single geological unit (e.g. Melichar 1995; Verner et al. 2009) as well as on an estimation of the P-T conditions of pluton emplacement (Part 3 of this thesis, Vondrovic et al. in prep.).

(iii) Correlation of structural record of the calc-alkaline plutons and tectonometamorhic evolution of the host rocks

The area of research resulted from the complex structural pattern of the host rocks. In the case of the Polička Unit the complex geotectonic evolution resulted in a complicated structural pattern: (i) the regional transpressional NNW-SSE trending metamorphic fabric (Verner et al. 2009; Pertoldová et al. 2010; this study) in the northern part of the Polička Unit passes into the NNE-SSW trending fabric reflecting a late strain increment in the area (Pitra et al. 1996; Vondrovic et al. 2011), whereas the eastern part reflects the Brunia indentation (Schulmann et al. 2005). The regional transpressional fabric is towards structurally lower units obliterated by the regional fabric of the Moldanubian Unit (e.g. Verner et al. 2009; Schulmann et al. 2005). In the case of the Zábřeh Unit the complex structure reflects at least three events represented by the formation of a steep metamorphic fabric that was later transposed to a flat lying and, subsequently, semi-brittle regime affected by localised kink-band folds. This study attempts to correlate fabric evolution in the mid- to upper-crustal level of the eastern termination of the Variscan orogen, interpreted by means of deciphering the tectonic evolution of calc-alkaline plutons and host rocks (Parts 3 and 4 of this thesis; Vondrovic et al. 2011; Žák et al. 2014) and to provide new insight into the tectonic evolution of the Variscan mid- to upper-crust in the period 354-346Ma.

The thesis is divided into four thematic sections. The first section (Part II) focuses on a description of metamorphic and petrological zonation from the lower- to upper-crustal level in a circa 20km section reaching from the Moldanubian to its peripheral domains. The second section (Part III) reveals tectonic implications based on the structural record and radiometric dating of selected plutonic bodies of calc-alkaline composition. The final section (Part IV) provides important insight into the synthesis of Variscan plutonism in the Central European Variscides. Last section (Part VI) shows the activities in the area of geoscience popularization.

From low- to upper- crustal level: geodynamic evolution of the north-eastern periphery of the Moldanubian Zone



2. From low- to upper- crustal level: geodynamic evolution of the NE periphery of the Moldanubian Zone

This part of the study synthesises the current state of knowledge on the subject and provides new insight into the interpretation of the geodynamic evolution of the main units surrounding the NE periphery of the Moldanubian Zone (Kutná Hora Complex, Svratka Unit, Polička and Zábřeh Units, Strážek Unit). While the protolite of these rocks indicates different sources, the structural record and P-T evolution reveal a strong Variscan imprint. The metamorphic zonation from granulite to upper amphibolite (greenschist) facies metamorphism provides a unique opportunity for the study of processes in the low- to mid-crustal scale.

The first paper summarises structural, petrological and geochronological data from the main units on the NE periphery of the Moldanubian Zone - the Svratka, Polička and Zábřeh Units, the Kutná Hora Complex and the Strážek Unit as part of the Moldanubian Zone (for general characteristics see Vrána et al. 1995; Schulmann et al. 2005, 2008). These lower- and upper-crustal units are characterized by a complex geodynamic evolution strongly dominated by a Variscan tectonometamorphic fabric. The mid- to upper-crustal Svratka, Polička and Zábřeh Units were affected by a ~MP/MT "long-lived" (~350–339Ma) tectonometamorphic event reflecting ~WNW–ESE right-lateral strike-slip shearing. In the Polička and Zábřeh Units these regional fabrics are related to the syn-tectonic emplacement of calc-alkaline plutons (Zábřeh Intrusive Complex, Miřetín nad Budislav plutons) in the time span 354-346Ma. In the lower crustal units – the Kutná Hora Complex and the Strážek Unit the first recognised event is strongly obliterated by high-pressure, high-temperature events followed by the heterogeneous and polyphase exhumation of deep-seated rocks to mid-crustal levels. The geodynamic evolution terminated the intrusion of ultrapotassic rocks in the Strážek Unit at ~339Ma.

The second paper provides an evaluation of tectonometamorphic events and petrochemical and geochronological results with concern to selected rocks types in the north-eastern periphery of the Moldanubian Zone - the Strážek Unit and the Svratka, Kutná Hora, Polička and Orlice-Sněžník Units. The geochemical comparison of the gneisses and migmatites of the Svratka and Strážek Units revealed differences in terms of protolite detrital material. The mica schists of the Svratka Unit underwent two distinct metamorphic events (under conditions of P:~0.8 GPa T: ~670 °C and P: 0.6-0.9 Gpa T: 600-650 °C) similar to those observed in the Kutná Hora Unit. The PT (not P-T??) conditions of the skarns in the Strážek and the Kutná

Hora Units are similar to those in the surrounding metasedimentary rocks. The calc-silicate rocks of the Polička Unit exhibited an interval of 560-650 °C and 0.5-0.7 GPa while the same rocks from the Moldanubian Zone and the Svratka Unit correspond to 640-680 °C and 0.5-0.7 GPa. The peraluminous metagranites, orthogneisses and migmatites studied from both the Svratka and Orlice-Sněžník Units proved to be similar in terms of their composition and geochemical fractionation. The rocks of the units studied on the NE periphery of the MZ recorded complex polymetamorphic and polyphase tectonometamorphic processes during the interval from ~Cadomian to Cambro-Ordovician events to the youngest events of the Variscan orogeny.

The final paper describes the complex geodynamic evolution of the Polička Unit. According to the petrological and structural record, the division of the Polička unit is suggested as follows: (i) The southern part can be interpreted as a structurally lower segment recording regional transpressional shearing and including an allochtonous body of felsic granulite (peak metamorphic conditions 860-1000°C and 1.6 Gpa; Tajčmanová et al. 2010); (ii) The central part consists of a relatively monotonous complex of flysch metasediments (e.g. Kodym and Svoboda 1950; Melichar and Hanžl 1997). Estimated P-T conditions in the range ~ 570-640 °C and 0.5-0.6 Gpa exhibit an increasing trend from NW to SE (parallel to the main tectonometamorphic fabric). The metamorphic conditions (~620-680 °C and ~ 0.6 Gpa) recorded in metapelites in the contact aureoles of calc-alkaline intrusions indicate that peak metamorphism is contemporary with the intrusion of a calc-alkaline magmatic event; (iii) The northern part is lithologically relatively monotonous and very similar to the Hlinsko Unit (Pitra and Guiraud 1996). The metamorphic assemblage limits peak P-T conditions to ~590°C and 0.4 Gpa which is consistent with P-T data for the crystallization of the Miřetín pluton at 653-681 °C and 0.3-0.4 GPa (Vondrovic et al. 2011); (iv) The eastern part consists of micaschists with peak P-T conditions (~0.8 GPa and ~650 °C). Distinct metamorphic record in the partial units in the Polička Unit is interpreted as being result of the different exhumation rate of each unit that was caused by oblique Brunia indentation during the exhumation of the high-grade rocks. The complex geodynamic evolution is described in part III.

Paper No. I.

Verner, K. - Buriánek, D. - Vrána, S. - **Vondrovic, L.** - Pertoldová, J. - Hanžl, P. - Nahodilová, R. (2009a): Tectonometamorphic features of geological units along the northern periphery of the Moldanubian Zone (Bohemian Massif). – Journal of Geosciences 54, 2, 87-100. ISSN 1802-6222. DOI 10.3190/jgeosci.046.

Paper No. II.

Pertoldová, J. - Verner, K. - Vrána, S. - Buriánek, D. - Štědrá, V. - **Vondrovic, L.** (2010): Comparison of lithology and tectonometamorphic evolution of units at northern margin of the Moldanubian Zone: implications for geodynamic evolution in the northeastern part of the Bohemian Massif. – Journal of Geosciences 55, 4, 299-319. ISSN 1802-6222. DOI 10.3190/jgeosci.083.

IF=1.026

Paper No. III.

Buriánek, D. - **Vondrovic, L.** - Verner, K. (2015): Tectonometamorphic evolution and geochronology of the Polička Unit (NE Bohemian Massif): from successive oblique collision to crustal exhumation

Article manuscript

Paper No. I.

VERNER, K. - BURIÁNEK, D. - VRÁNA, S. - VONDROVIC, L. - PERTOLDOVÁ, J. - HANŽL, P. - NAHODILOVÁ, R. (2009A): TECTONOMETAMORPHIC FEATURES OF GEOLOGICAL UNITS ALONG THE NORTHERN PERIPHERY OF THE MOLDANUBIAN ZONE (BOHEMIAN MASSIF). – JOURNAL OF GEOSCIENCES 54, 2, 87-100. ISSN 1802-6222. DOI 10.3190/JGEOSCI.046.

DOI: 10.3190/jgeosci.046

Original paper

Tectonometamorphic features of geological units along the northern periphery of the Moldanubian Zone

KRYŠTOF VERNER[1,3]*, DAVID BURIÁNEK[2], STANISLAV VRÁNA[1], LUKÁŠ VONDROVIC[1,3], JAROSLAVA PERTOLDOVÁ[1], PAVEL HANŽL[2], RADMILA NAHODILOVÁ[1]

[1] *Czech Geological Survey, Klárov 3, 118 21 Prague 1, Czech Republic; krystof.verner@geology.cz*

[2] *Czech Geological Survey, Leitnerova 22, 658 59 Brno , Czech Republic*

[3] *Institute of Petrology and Structural Geology, Charles University, 128 43 Albertov 6, Prague 2, Czech Republic*

* Corresponding author

Keywords: Central European Variscides, Bohemian Massif, Moldanubian Zone, West Sudetes, metamorphic structures, Calc-alkaline plutons

Received: 11 March 2009; accepted 15 June 2009; handling editor: V. Kachlík

Running title: Tectonometamorphic features of the northern periphery of the Moldanubian Zone

Abstract

In this paper are reviewed structural, petrological and geochronological data from the main units at the NE periphery of the Moldanubian Zone, i.e. Kutná Hora Complex, Svratka Unit, Polička and Zábřeh units, Strážek Unit of the Moldanubian Zone. In this domain of the Bohemian Massif, the lower- and upper-crustal units are dominated by metamorphic fabrics produced during the Variscan orogeny.

The mid- to upper-crustal Svratka, Polička and Zábřeh Units are affected by ~MP/MT ”long-lived“ (~350–339 Ma) tectonometamorphic event reflecting ~WNW-ESE right-lateral strike-slip shearing (transpressional to transtensional tectonics). These regional fabrics are in the Polička and Zábřeh Unit related with syn-tectonic emplacement and crystallization calc-alkaline intrusions (Zábřeh Intrusive Complex, Miřetín nad Budislav plutons). In the three structurally high units in the Kutná Hora Complex, Orlice–Sněžník and the Strážek units the strike-slip "long-lived" tectonic is rather localized, the high-pressure, high-temperature events followed by heterogeneous and polyphase exhumation of deep-seated rocks to mid-crustal levels are preserved. Ultrapotassic rocks (durbachites) of the Strážek Unit, dated at ~339 Ma, intruded posttectonicaly.

1. Introduction

The present paper outlines the geological and tectonic setting of the units extending along the NE margin of the Moldanubian Zone (Figs 1–2) from the Strážek Unit in the south through the Kutná Hora Complex, Svratka, Polička and Zábřeh units up to the southern part of the Orlice–Sněžník Unit (West Sudetes) in the NE. The Strážek Unit, as a part of the Moldanubian Zone, corresponds to exhumed high-grade, lower- to mid-crustal rocks that recorded complex with a polyphase Variscan tectonometamorphic record (for a general review, see Urban and Synek 1995; Vrána et al. 1995). The Kutná Hora Complex and the Svratka Unit represent a crustal stack of rocks with different lower- to mid- crustal history (e. g. Synek and Oliveriová 1993; Melichar ed. 2008). The structurally uppermost Polička and Zábřeh units are composed of a less metamorphosed volcanosedimentary sequences, probably with the broad affinity to the Teplá–Barrandian Unit (Bohemicum). The Orlice–Sněžník Unit as part of the West Sudetes (Lugicum) consists of high-grade polymetamorphic migmatites, orthogneisses and metasediments. The protoliths to orthogneisses was dated as Cambro–Ordovician (Kröner et al. 2001), metasediments are probably of Neoproterozoic to

Earlypalaeozoic age. The HP rocks including granulites, eclogites and peridotites reveal both Palaeovariscan and Neovariscan crystallization/equilibration ages. In general, the geological evolution of some rocks in the studied area started during Neoproterozoic to earliest Palaeozoic times (~570–530 Ma). Late Cadomian subduction at the northern periphery of the Gondwana continent was followed by crustal extension and incipient rifting (e.g. Franke 2000; Hegner and Kröner 2000a,b). The Cambro–Ordovician rifting event led to the opening of the Rheic Ocean (for a general review, see Kröner et al. 2000a; Linnemann et al. 2008). The Variscan orogeny was initiated by the Devonian to Early Carboniferous collision of Gondwana-derived crustal segments with the Old Red (Laurussia) continent (see Franke 2000 for an overview). Palaeovariscan orogenic processes, supported by ages near 380–370 Ma, are poorly constrained at present due to an extensive Neovariscan overprint (Mazur et al 2006). The subsequent continental subduction, succeeding in consumption of oceanic domains and accompanied by HP/HT metamorphism at ~340 Ma, was followed by isostatically-driven very fast exhumation of deep-seated rocks (Kröner et al. 2008; Schulmann et al. 2009 and references therein).

The orogenic processes were accompanied by extensive magmatic/plutonic activity (Finger et al. 1997). In the studied area two main stages of Variscan magmatic activity were identified (Buriánek et al. 2003; Janoušek and Holub 2007): (i) The calc-alkaline plutons (dated at ~350 Ma) intruded the Polička and Zábřeh units; (ii) emplacement of the ultrapotassic (durbachite) plutons (~343–335 Ma) in the Moldanubian Zone. The Kutná Hora Complex and the Svratka Unit are free of Variscan plutons.

The accretion of individual blocks/units of the Central European Variscides (Bohemian Massif) led to the juxtaposition of different crustal segments (e.g. Schulmann et al. 2009): (i) the Moldanubian Zone (MZ) built by Variscan and pre-Variscan lower- to mid-crustal rocks (for a general review see e.g. Fiala at al. 1995; Urban and Synek 1995; Schulmann et al. 2008); (ii) the Teplá–Barrandian Unit (TBU) representing the upper-crustal segment composed of Neoproterozoic rocks metamorphosed during the Cadomian event and the overlying deformed volcanosedimentary sequence of Lower Palaeozoic age (e.g., Drost et al. 2004; Dörr and Zulauf, in print); (iii) Lugicum (West Sudetes) and Saxothuringicum including Neoproterozoic to Lower Palaeozoic basement rocks with tectonically implanted slices of the Variscan HP and UHP rocks (Kröner et al. 2001; Mazur et al. 2005; Mazur et al. 2006). The eastern margins the Moldanubian and Lugian domains were thrust over the

Moravo-Silesian Zone nape pile (Schulmann et al. 1991; Schulmann and Gayer 2000). The Moravo-Silesian Zone consists of a pre-Variscan, mostly metaigneous basement with deformed and a tectonically-imbricated metasedimentary sequence of Devonian age (for a review, see Finger et al. 2000; Schulmann and Gayer 2000).

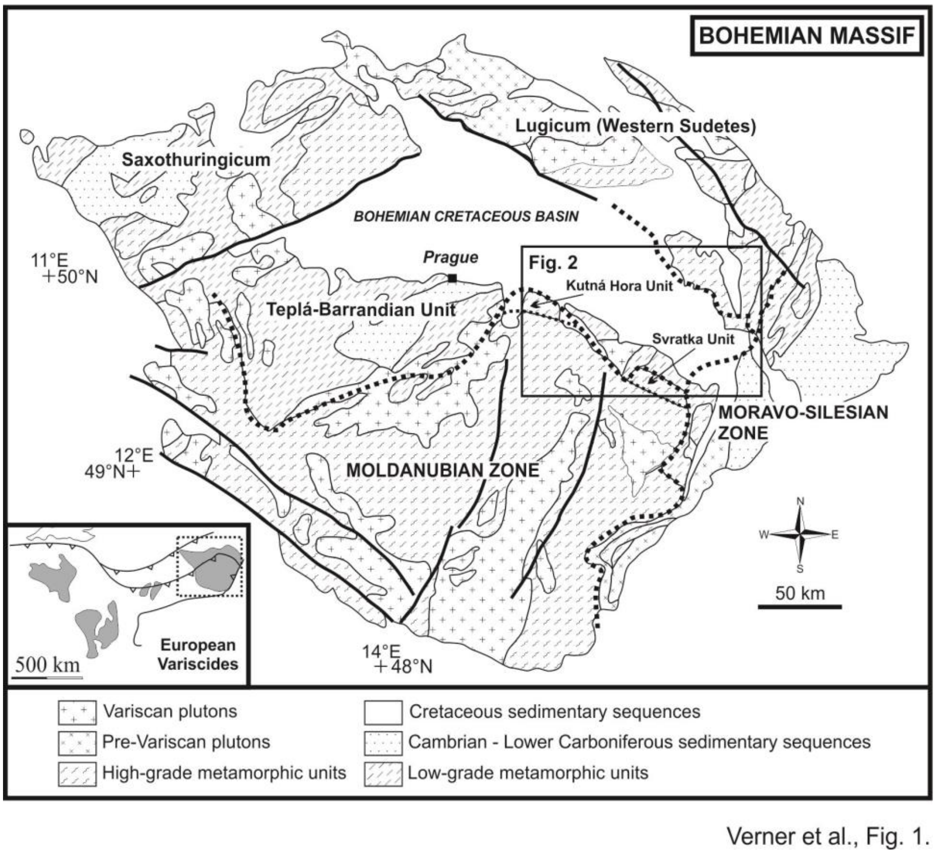


Fig. 1 Geological sketch map of the Bohemian Massif with location of the study area at the NE periphery of the Moldanubian Zone. After Franke et al. (2000).

2. Regional geological setting and structural pattern

2.1 North-eastern part of the Moldanubian Zone

The Moldanubian Zone (MZ) is a super-unit representing a heterogeneous crustal stack number of units and rock types with contrasting lithology, ages and tectonometamorphic evolution. The Monotonous Unit contains a uniform sequence dominated by partly migmatitized paragneisses. The Varied Unit is built by paragneisses with abundant intercalations of marbles, calc-silicate rocks, quartzites, graphitic gneisses and amphibolites. Both the units had sedimentary protoliths mainly of Early Palaeozoic age (Fiala et al. 1995, Drábek and Stein 2003; Janoušek et al. 2008). The Gföhl Unit is composed by lower-crustal components (granulites, migmatitic orthogneisses, with lenses of peridotites and eclogites) derived from heterogeneous sources. The SHRIMP U-Pb dating on zircons indicates a protolith age of 488 ± 6 Ma for Gföhl migmatitic orthogneisses (Friedl et al. 2004). In distant parts of the Moldanubian Zone orthogneisses with Mesoproterozoic and Palaeoproterozoic ages were incorporated in the distant parts of Moldanubian Zone (i.e., Dobra orthogneisses of ~1.38 Ga and Světlík orthogneisses of ~2.08 Ga protolith ages, Wendt et al. 1993; Friedl et al. 2004).

In general, the estimated P-T conditions of regional metamorphism in rocks of the Monotonous and Varied units are in the wide range of T = 630–720 °C and P = 0.4–1.0 GPa (Vrána et al. 1995; Linner 1996; Racek et al. 2006). The P-T conditions of peak metamorphism of granulites and eclogites in the Gföhl Unit were calculated at T = ~850–1000 °C and P = ~1.5–2.0 GPa, with subsequent retrograde metamorphism at T = ~600–800 °C and P = ~0.6–0.8 GPa (for review see Štípská et al. 2004; Tajčmanová et al. 2006).

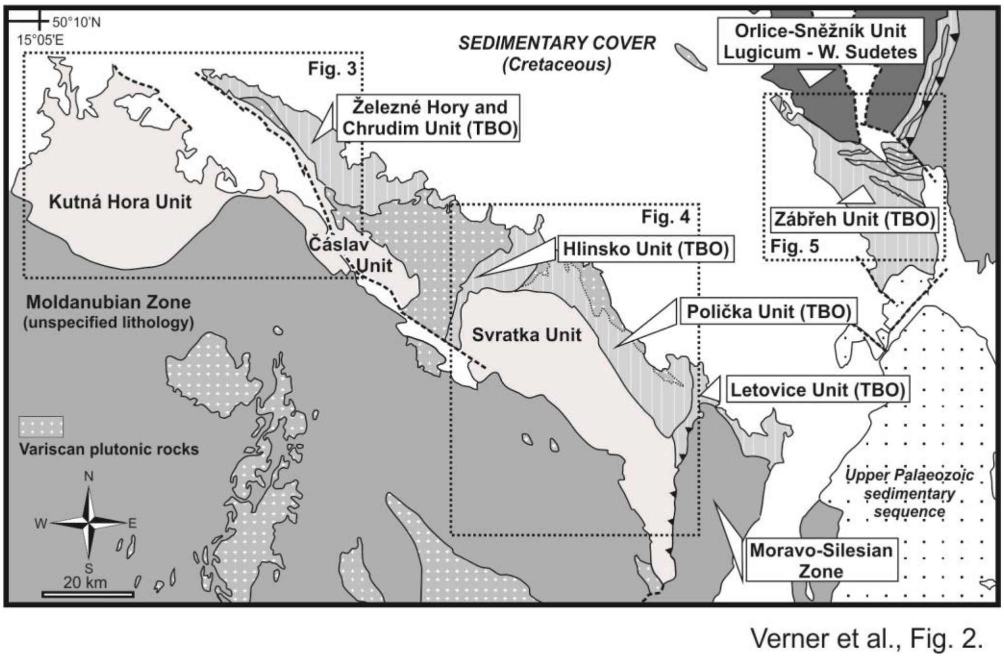


Fig. 2 Simplified geological map of the NE periphery of the Moldanubian Zone showing the positions of detailed structural maps (Figs 3–5). After Cháb et al. (2007).

Given the geodynamic evolution outlined above the structural record of the Moldanubian Zone is complicated and several regional fabrics are observed. On the basis of several petrostructural studies new concepts of tectonic evolution were published. For example, one of the early fabrics are steeply dipping ~NNE–SSW metamorphic foliations, preserved in relicts across the MZ, are interpreted by some authors as originated due to vertical extrusion of lower-crustal rocks (e.g. Tajčmanová et al. 2006). In addition, the Variscan exhumation processes were associated with formation of well-developed, moderately-dipping to “flat-lying” orogenic fabrics. The interpretations of Moldanubian flat-lying fabrics are in part controversial (for the discussion see Verner et al. 2008).

The northeastern part of the Moldanubian Zone (designated as the Strážek Unit) is composed of migmatized paragneisses with calc-silicate intercalations and migmatites with a amphibolite layers (Medaris et al. 1995; Owen and Dostal 1996; Hanžl ed. 2008). Felsic granulites and ultramafic rocks derived from upper mantle (Weiss 1992) are interpreted as allochthonous bodies. Metamorphic evolution in the Strážek Unit is similar to the metamorphic record in other parts of the Moldanubian Zone. High-temperature and high-pressure conditions identified in granulites, eclogites and garnet peridotites were followed by the nearly isothermal decompression at high temperatures (Medaris et al. 1995; Owen and Dostal 1996; Tajčmanová et al. 2006). The structural pattern of the Strážek Unit is defined by two superimposed regional metamorphic foliations with associated mineral lineations: (i) earlier, steeply dipping foliation with regional ~NNE–SSW strike is heterogeneously reworked into (ii) gently to moderately ~NE or ~SW dipping metamorphic foliation, defining the northern boundary of the Moldanubian Zone, bearing a ~NW–SE trending mineral lineation (Fig. 6c). The above structures are truncated in some places by intrusive contacts of the ultrapotassic (durbachite) intrusions dated at 339 Ma, (unpublished geochronological data of A. Gerdes).

2.2 Kutná Hora Complex (KHC)

The Kutná Hora Complex (western part of the Kutná Hora–Svratka Super-unit; Fig. 2) consists of three different structural and lithological sub-units (Fig 3; Synek and Oliveriová 1993; Kachlík 1999). The KHC is composed of several allochthonous slices, including the Malín Plaňany and Běstvina units, which are overlying the Kouřim and Mica Schist units (Fig. 2). The three uppermost units represent volcanosedimentary sequences of unidentified stratigraphy and poorly known metamorphic age. The Běstvina Unit (defined by Losert 1967) is formed by felsic granulites and partly migmatized gneisses with lenses of garnet peridotites, eclogites and rare garnet amphibolites. The Malín Unit (Losert 1956a, b) consists mainly of kyanite-bearing migmatites accompanied by garnet amphibolites, partly serpentinized garnet peridotites/lherzolites, eclogites and several skarn bodies. The Plaňany Unit (Fišera 1977) is represented by various types of migmatites with lenses of amphibolites, serpentinites and pyroxenites. The underlying part of the Kutná Hora Complex is represented by the Kouřim Unit (termed also the Kouřim Orthogneiss Nappe), consisting of granitic orthogneisses and fine-grained leucocratic migmatites. The lowermost Mica Schist Unit represents a sequence of metapelites intercalated with amphibolites and marbles (Synek and Oliveriová 1993; Kachlík 1999). The structural analysis by Synek and Oliveriová (1993) documented a polyphase history including three major tectonometamorphic events. These authors suggested that the thrusting of the three allochthonous units took place after most of their tectonometamorphic evolution was completed. At first, the bodies of HP-HT granulites, eclogites and garnet peridotites/lherzolites were emplaced in the Běstvina and Malín units during the initial ~HT-HP tectonometamorphic event. In addition, the felsic granulites of the Běstvina Unit were equilibrated under eclogite-facies conditions (P = ~1.8–2.1 GPa; Vrána et al. 2005). The early structures are generally rare, corresponding foliation planes dip steeply to the ~NE.

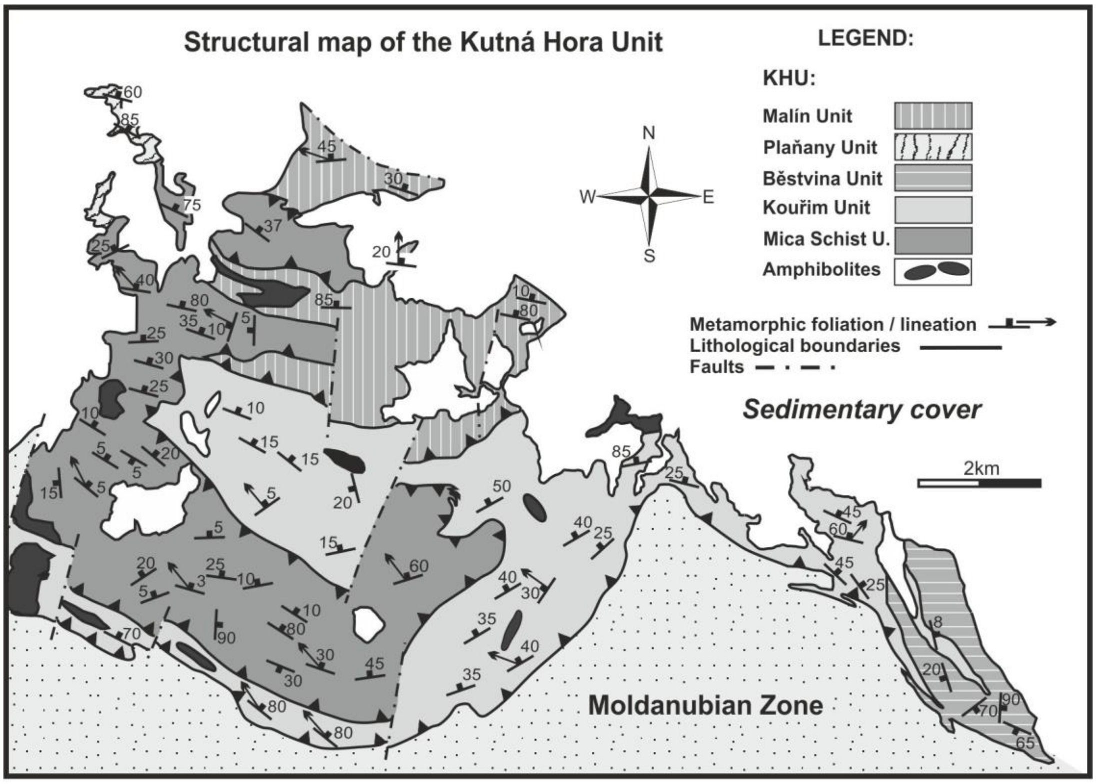


Fig. 3. Structural and geological sketch of the Kutná Hora Unit. After Synek and Oliveriová (1993).

The following tectonometamorphic event was connected with intense migmatization producing kyanite-bearing leucosomes (P = 1.5 GPa). The last event was characterized by superimposed retrograde metamorphism under HP amphibolite-facies conditions (formation of foliation with newly crystallized biotite, muscovite ± garnet and kyanite: Vrána et al. this volume).The structurally uppermost units of the Kutná Hora Complex represent segments of high-pressure, deeper parts of the Palaeovariscan crust, which were not affected by late LP-HT Variscan metamorphic overprint.

2.3 The Svratka Unit

The Svratka Unit (SU), located in the eastern part of the Kutná Hora–Svratka Superunit has a ~NW-SE elongated shape with brachyanticlinally-terminated NW part (Fig 2). The longest dimension is 35 km and the shortest is ~15 km. The Svratka Unit consists of polymetamorphic migmatites, paragneisses and mica schists, with elongated bodies of Cambro–Ordovician metagranites to orthogneisses. Minor lithologies are represented by layers of dolomitic marbles, calc-silicate rocks, amphibolites and skarns (Němec 1998; Melichar ed. 2008; Hanžl ed. 2008). The Svratka metagranites recently dated at 515 ± 9 Ma (U-Pb zircon, Schulmann et al. 2005) were emplaced during the Cambro–Ordovician magmatic event into the older migmatitized rocks. The maximum age of the volcanosedimentary complex is defined by abundant detrital zircons in strata-bound skarns dated at ~540–560 Ma (Pertoldová et al. this volume).

During the Variscan Orogeny, the whole Svratka Unit was affected by penetrative deformation and regional metamorphism, which attained amphibolite-facies conditions (T = ~ 640–670 ºC and P = ~0.7–0.8 GPa; Pitra and Guiraud 1996; D. Buriánek unpublished data). Subsequently, these rocks were subject to a partial decrease in pressure of about ~0.2 GPa and crystallization of new mineral assemblage (Ms + Bt + Grt + St ± Sill) corresponding to T = 580–650 °C and P = ~0.6 GPa (D. Buriánek unpublished data). In the case of skarns, the relicts of the oldest ~HP metamorphism (*c.* ~1.4 GPa) were identified (Pertoldová 1986).

The regional structures are defined by penetrative metamorphic foliation associated with well-developed stretching lineation. This foliation (compositional and deformational layering) dips in the western and central parts of the Svratka Unit under moderate angles to the ~NNW–NE, whereas in the eastern domain dips steeply to moderately to the ~SW. The well-developed metamorphic lineation (elongated quartz and feldspar aggregates, lattice preferred orientation of new micas) has a relatively uniform geometry in the whole unit and dips under low angles to the ~NW or SE. The orientation of the penetrative metamorphic structures described above defines well the regional structural framework of the NE periphery of the Moldanubian Zone. Rarely were encountered relicts of older metamorphic fabric (of an unknown age) in the form of rootless isoclinal folds (Fig. 6b), especially in quartzo-feldspathic rocks, enclosed within the ~NW–SE trending regional fabric. In less deformed parts, especially in metagranite and polymetamorphic migmatite bodies, relicts of magmatic or migmatite textures (e.g. relict magmatic zoning in minerals and incipient stage of recrystallization in metagranites, evidence for primary crystallization textures of leucosomes in migmatites) can be observed. The effect of the Variscan deformation and recrystallization include dynamically recrystallized quartz and feldspar aggregates accompanied by a sub-solidus deformation of primary grains (Zavřelová et al. 2006; Buriánek et al. this volume). On the other hand, the pervasive fabric of the SU is locally modified by brittle–ductile and brittle extensional deformation (e. g., in the form of narrow shear zones and faults, or extensional kink-band folds).

2.4 Eastern part of Teplá–Barrandian Unit (TBU)

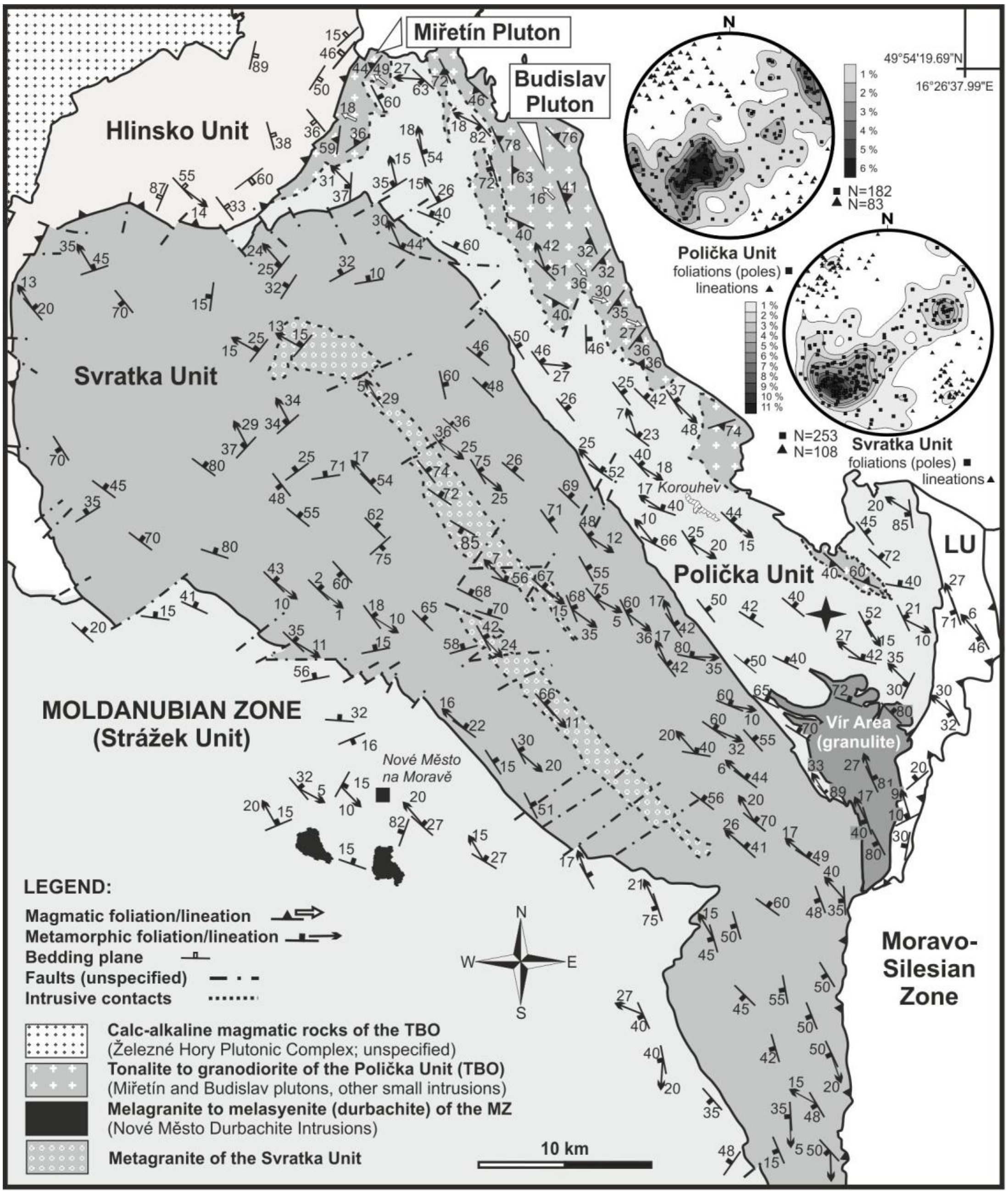
The TBU is an independent upper-crustal segment positioned between the Saxothuringian Zone and exhumed Moldanubian Zone. In general, the Teplá-Barrandian Unit is subdivided into a metamorphosed basement of Neoproterozoic (Cadomian) age, transgressively overlain by Cambrian to Middle Devonian volcanosedimentary sequence of deformed but unmetamorphosed rocks (e.g. Chaloupský et al. 1995; Melichar 2004). The Polička and Zábřeh units are interpreted by some geologists as the easternmost equivalents of the Teplá–Barrandian Unit (see Mísař and Dudek 1993). The Polička and Zábřeh units were affected by a variable degree of Variscan tectonometamorphic overprint under greenschist- and amphibolite-facies conditions. The pre-Variscan structures in these units were extensively obliterated (Pitra et al 1994; Buriánek et al. 2003).

2.4.1 Polička Unit (PU)

As seen in the Fig. 4, the PU is separated from the overlying, less metamorphosed metasediments of the Hlinsko Unit (possibly corresponding to the TBU – Vachtl 1962; Pitra and Guiraud 1996) by localized, ~NNE–SSW trending, normal low-temperature shear zones and faults (Fig. 6d). The protolith to the rocks of the Polička Unit corresponded to a relatively monotonous Neoproterozoic and Lower-Palaeozoic sequence of flysch sediments and volcanic rocks (Kodym and Svoboda 1950). During the Variscan orogenic processes, the volcanosedimentary sequence of the PU was affected by regional metamorphism under lower amphibolite-facies conditions, accompanied by emplacement of calc-alkaline (granodiorite to tonalite) intrusions, Budislav and Miřetín plutons. On the basis of its lithological composition, the PU was subdivided by Melichar (1995) into three main parts: (i) medium-grained biotite and two-mica gneisses with amphibolites, marbles and associated calc-silicate rocks present along the boundary with the overlying Svratka Unit; bodies of leucocratic metagranites are present in the southern part of Polička Unit, (ii) the central part of the Polička Unit, consisting of a monotonous sequence of medium-grained paragneisses with calc-silicate nodules (up to 0.5 m thick), and (iii) the northern part, composed of paragneisses with lenses of mica schists and quartzites and abundant calc-alkaline granitic rocks. The Variscan metamorphic evolution across the Polička Unit shows a slight variation. Relicts of the prograde ~LP–MT metamorphism (T = 560 ºC and P = 0.3 GPa) are preserved only in its western part; the conditions of metamorphic grade increases in intensity from the west to the east, with a maximum at T = ~580–680 °C and P = ~0.5–0.7 GPa. The advective heat input related to granitic intrusions, is at present poorly defined. Finally, retrograde metamorphism took place that was manifested by aggregates of newly formed muscovite (Buriánek et al. 2003).

In the southeast, the Polička Unit is rimmed by a segment of Variscan felsic granulites and associated orthogneisses, (designated Vír Area) The Vír granulites reached peak temperatures of ~850–900°C and pressures of 1.3–1.4 GPa (Tajčmanová et al. 2006), followed by retrograde metamorphic overprint under amphibolite facies conditions (T = ~600°C and P = 0.6–0.8 GPa, Štoudová et al. 1999). The metamorphic evolution including an early high HP/HT stage, followed by HT decompression resembles granulites in the Moldanubian Zone (see above).

The overall structural pattern of the Polička Unit (Fig. 4) is defined by regional metamorphic foliation (pervasive schistosity or compositional banding), which dips moderately to the ~NE in its central and eastern parts. Foliations steeply to moderately dipping to the ~WNW were mapped in the western part of the Polička Unit. Well-developed, gently ~NW–SE plunging stretching lineation, bearing indicators of dextral kinematics, was observed across the Polička Unit.



Verner et al., Fig. 4.

Fig. 4a **–** Structural and geological sketch of the mid- to upper-crustal Svratka and Polička units including the neighbouring metamorphic complexes. **b –** Stereograms (lower hemisphere, equal area projection) of foliations and lineations from the two main units.. Modified after Cháb et. al (2007), Hanžl ed (2008), Melichar ed (2008).

The northern part of PU was intruded by numerous bodies of calc-alkaline composition (i.e. the Mířetín and Budislav plutons; Buriánek et al. 2003; Vondrovic and Verner 2008). The Budislav Pluton was emplaced within the northern part of the Polička Unit (dated at 350 ± 5 Ma; U-Pb method on zircon; Vondrovic and Verner 2008). In the Budislav Pluton, magmatic to HT sub-solidus fabrics defined by shape-preferred orientation of plagioclase, amphibole and biotite aggregates were identified. The corresponding foliations dip under moderate angles to the ~NE/SW and the associated strongly-developed lineations have a sub-horizontal orientation. The overall fabrics in the Budislav Pluton are roughly parallel to the pluton intrusive contacts, as well as to the orientation of the regional metamorphic fabric in the Polička Unit.

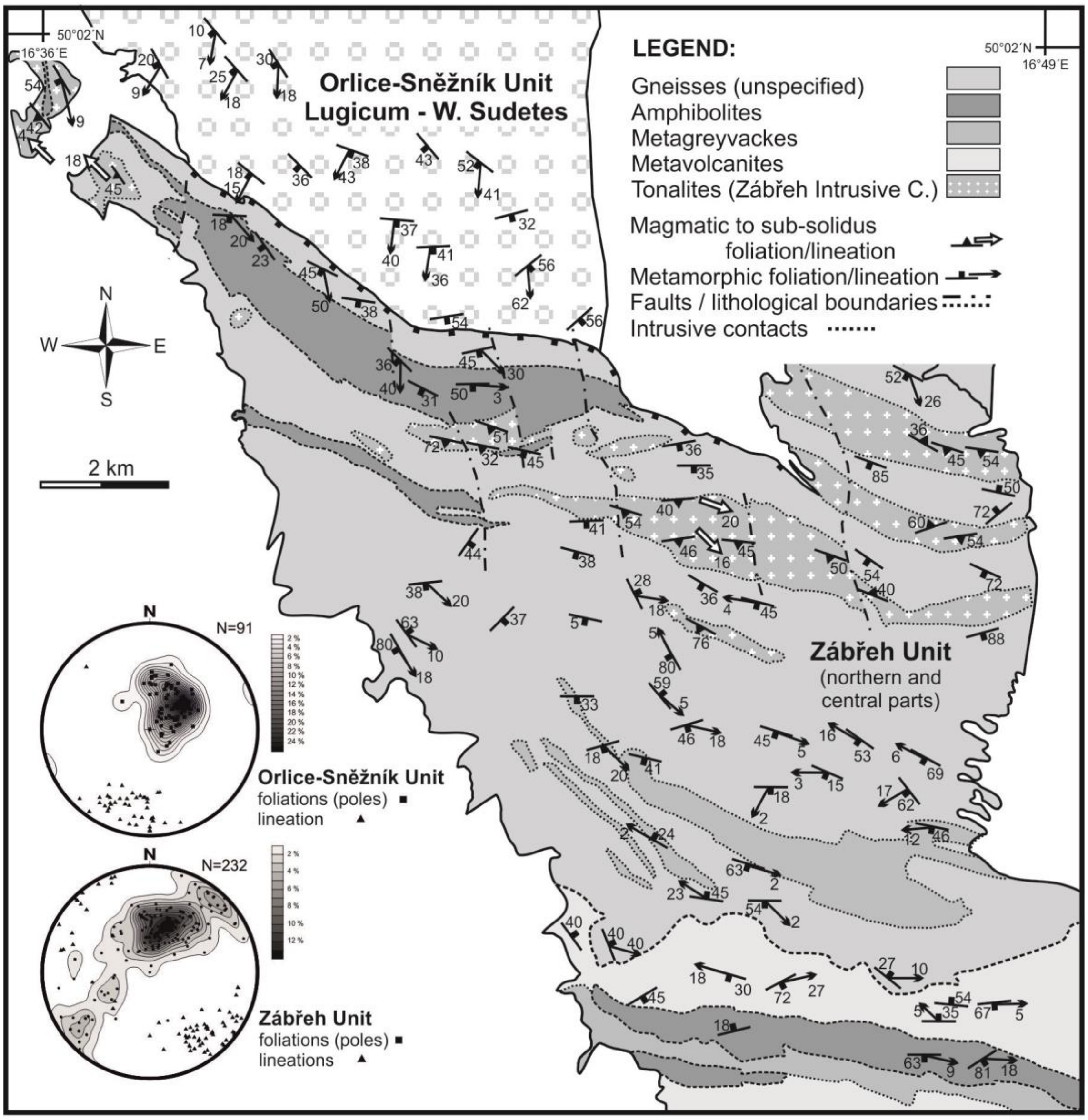
The second intrusive body of the PU, the Miřetín Pluton, is deformed medium-grained, porphyritic biotite tonalite to granodiorite, that intruded the western flank of the Polička Unit, at the border with the Hlinsko and Svratka units. The crystallization age of the Miřetín Pluton was determined at 348 ± 7 Ma (U-Pb zircon; Vondrovic and Verner 2008). The Miřetín Pluton has a ~NNE–SSW elongated shape (Fig. 4). Two distinct solid-state fabrics were recognized in this pluton: (i) Relatively older, pervasive high-temperature solid-state foliation plunges under moderate angles to the ~WNW. These foliation planes are accompanied by well developed stretching lineations dipping to the ~NW and overthrusting kinematic indicators. (ii) Along the western rim of the Miřetín Pluton, the low–temperature cleavage roughly parallel to the boundary between the Polička and Hlinsko units was superimposed on the older fabrics (Fig. 6d).

2.4.2 Zábřeh Unit (ZU)

The Zábřeh Unit is adjacent to the Lugicum (West Sudetes; for a general review see Franke and Żelaźniewicz 2000; Mazur et al. 2006). It is positioned in the hanging wall of the exhumed pre-Variscan and Palaeovariscan deep-crustal rocks of the Orlice–Sněžník Unit (OSU). The Zábřeh Unit is a low-grade volcanosedimentary complex, originally classified as a part of the Lugicum (Mísař and Dudek 1993). In lithological composition it rather corresponds to the Polička and Hlinsko units (i.e., the eastern prolongation of the Teplá–Barrandian Unit; Mísař and Dudek 1993; Buriánek et al. 2003). In detail, the Zábřeh Unit is composed of two lithological parts (Fajst 1976; Hanžl et al. 2000; Buriánek et al. 2003). The southern part is formed by low-grade metapelites and metabasites, while the northern includes paragneisses with intercalations of amphibolites and acid metavolcanites (Fig. 5). The intensity of the Variscan metamorphism increases from the central part to the south and north; the central part exhibits the lowest grade of metamorphism. The P-T conditions estimated from the northern part of the Zábřeh Unit fall in the middle part of the amphibolite facies (P = ~0.6 GPa and T ~ 660 °C; D. Buriánek unpublished data). Rocks of the northern segment of the Zábřeh Unit were intruded by numerous sills and dykes of calc-alkaline rocks of broadly granodioritic composition (called the Zábřeh Intrusive Complex). Geochemical similarities between the calc-alkaline rocks from the Zábřeh and Polička units were demonstrated by Buriánek et al. (2003). The crystallization age of the former intrusive rocks was estimated by the U-Pb method on zircon at ~354 Ma (Kachlík and Sláma unpublished data). Some effects of contact metamorphism and local partial melting (anatexis) were observed in narrow zones along these intrusions. Two distinct metamorphic fabrics occur in the structural framework of the Zábřeh Unit. The dominant metamorphic foliation generally dips under moderate angles to the ~SSW (see the maxima in stereograms and structural map; Fig. 5) and is associated with well-developed mineral and stretching lineation gently plunging to the ~SE. In the northern part of the Zábřeh Unit, folded relicts of planar structures with steeply dipping E–W orientation were observed. Locally, towards the southern part of the Zábřeh Unit, the regional metamorphic foliation was deformed into large open folds with ~E–W oriented axes. The orientation of intrusive contacts and fabrics (magmatic to sub-solidus foliation and well-developed lineation) of the granodiorite intrusions of the Zábřeh Intrusive Complex are roughly parallel to the orientation of the younger regional metamorphic fabric. The boundary between the less metamorphosed rocks of the Zábřeh Unit and the adjacent underlying lower to mid- crustal Orlice-Sněžník Unit (Lugicum) is roughly parallel to the regional metamorphic fabric in the northern part of the Zábřeh Unit. In the southern part of the Orlice-Sněžník Unit, these margin-parallel foliations are superimposed on ”flat-lying“ fabrics (Fig. 5).

2.5. Orlice–Sněžník Unit (OSU)

The OSU occurs in the SE part of the Lugicum (West Sudetes). It consists of high-grade polymetamorphic migmatites, orthogneisses (both originally of Cambro–Ordovician age; Kröner et al. 2001; Bröcker et al. 2009) and schists with inclusions of HP and UHP rocks (eclogites and granulites). For a general review of the lithological composition and geochronology of the Orlice-Sněžník Unit, see Kröner et al. (2001). Rocks of the OSU show high- to medium- grade Variscan tectonometamorphic overprint recorded in several principal phases: (i) the first reflects prograde UHP metamorphic conditions in granulites at around 386 Ma (Anczkiewicz et al. 2007); (ii) the second event (~340 Ma) was associated with the HT retrograde metamorphism of the lower-crustal rocks (Kryza et al. 1996; Anczkiewicz et al. 2007) and (iii) additional retrograde processes under the amphibolite-facies conditions (Jastrzębski 2009).



Verner et al., Fig. 5.

Fig. 5a Structural and geological sketch of the Zábřeh Unit and southern part of the Orlice–Sněžník Unit. **b –** Stereograms (lower hemisphere, equal area projection) of foliations and lineations from the both units. Modified after Cháb et. al (2007).

Compared to the complex metamorphic history of the Orlice-Sněžník Unit, some additional fabrics were described (Fajst 1976; Cymerman et al. 1997). The structural pattern in the southern part of the OSU is dominated by “flat-lying” retrograde mylonitic foliation associated with well-developed ~N–S lineation.

3. Discussion

The units at the NE periphery of the Moldanubian Zone carry a set of structures and metamorphic fabrics reflecting the Variscan geodynamic evolution in a regional cross-section, from the high-grade rocks of the Moldanubian Zone to the mid- and upper-crustal segments of the Svratka Unit as well as the Polička and Zábřeh units. In the northeast, high-grade rocks reappear in the Orlice–Sněžník Unit. At present, there is not sufficient information permitting classification of the individual structural patterns that were defined in the Kutná Hora Unit by Synek and Oliveriová (1993) as belonging to Palaeovariscan or Neovariscan deformation events. With regard to some similarities in lithology and Variscan tectonometamorphic evolution of the Polička and Zábřeh units (e.g., Buriánek et al. 2003; Buriánek et al. this volume), they can be perhaps correlated with some less metamorphosed segments of the Teplá-Barrandian Unit (e.g., the Hlinsko Unit).

The high-grade rocks of the Vír Area (Vír granulite; for specification see Tajčmanová et al. 2006), conventionally classified as the SE part of the Polička Unit, were probably derived from the Moldanubian lower crust and incorporated tectonically in their present position. The Vír segment should be considered as a separate crustal slice independent of the Polička Unit.

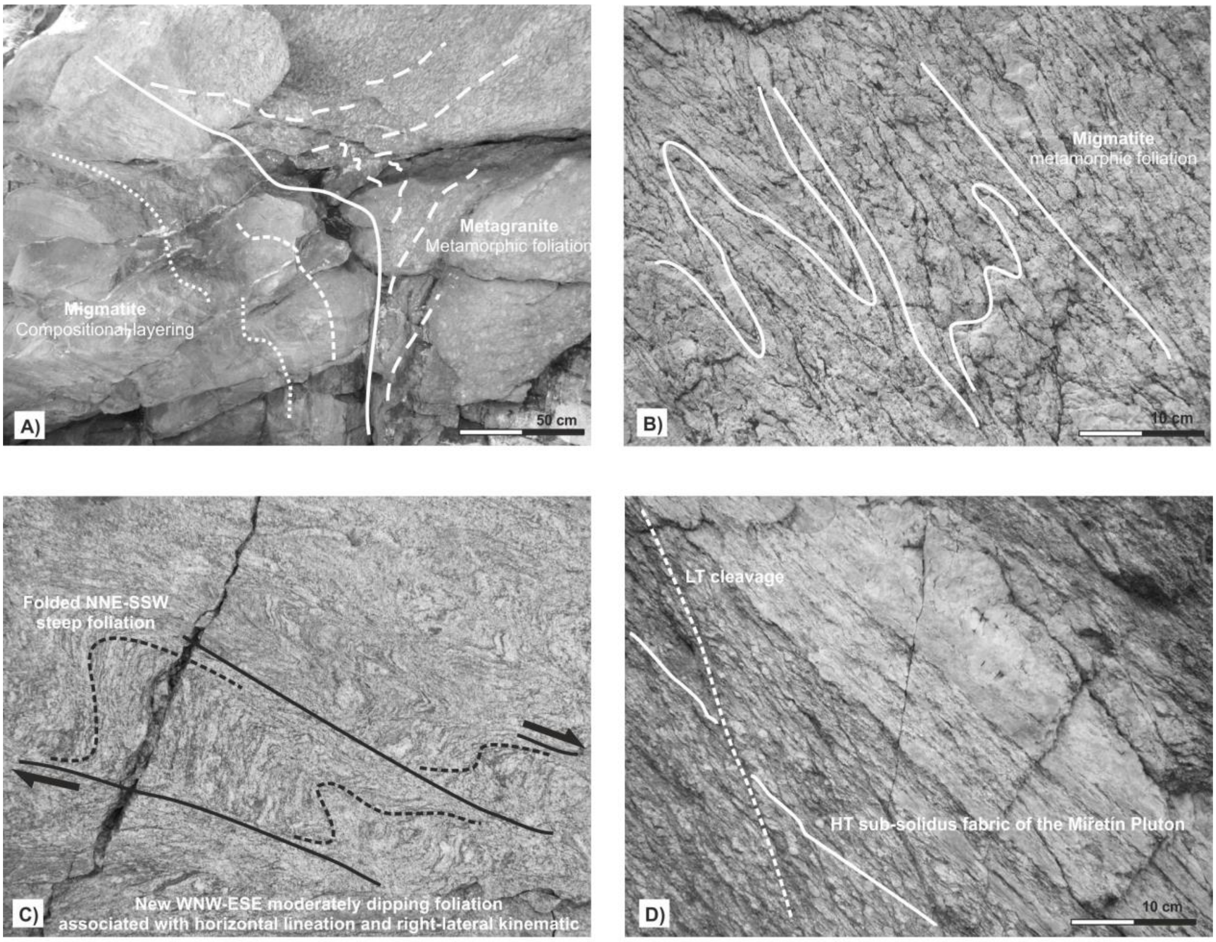
In the case of the Kutná Hora Complex, there are substantial differences in the lithology and Variscan tectonometamorphic evolution between the structurally uppermost members of the KHC (Malín, Běstvina and Plaňany units) and the Svratka Unit. The stratigraphic age of the three allochtonous units in the KHC is unknown but their HP/HT metamorphism is probably Palaeovariscan age as indicated by Sm-Nd dating of garnet peridotites and pyroxenites from the Malín Unit (~378 Ma; Brueckner et al. 1996). On the other hand, the structurally lower Kouřim and Mica Schist units could be probably correlated with similar lithologies in the Svratka Unit.

The structures of pre-Variscan age are rarely preserved in the complex of polymetamorphic migmatites of the Svratka Unit (Fig. 6a). Angular blocks of leucocratic migmatites with well-developed, leucosome textures are enclosed in Cambro–Ordovician metagranites as xenoliths. The Svratka metagranites were emplaced at ~515 Ma (Schulmann et al. 2005). The emplacement of the Svratka metagranite took place most likely during crustal extension, close to early Cambro–Ordovician geodynamic processes (Hegner and Kröner 2000; Kröner et al. 2000a; Buriánek et al. this volume).

In addition, the deformation-resistant skarn bodies retain some relicts of older deformation structures and keep record of the prevariscan prograde metamorphic evolution, with mineral assemblages indicating conditions of ~ 1.4 GPa (Pertoldová et al. this volume).

During the Variscan orogeny, two principal metamorphic fabrics were formed in the studied area. The relatively older fabrics occur in a distant part of the Moldanubian Zone (i.e. in the centre of the Strážek Unit). Some authors interpreted these steep N–E trending foliations as the earliest structures in the Strážek Unit to be associated with early stages of the Moldanubian Zone exhumation (Štípská et al. 2004; Tajčmanová et al. 2006; Schulmann et al. 2008). The relatively younger regional fabrics in the Strážek Unit were imprinted under amphibolite-facies conditions (T ~ 620 °C and P ~ 0.5 GPa; Tajčmanová et al. 2006). In the Svratka and Polička units similar fabrics bear characteristics of penetrative deformation under peak metamorphic conditions. In general, this relatively younger mid- to upper-crustal pervasive metamorphic schistosity dips moderately to the ~NNE–NE or to the ~SSW–SW in the southeastern part of the studied area. These planar fabrics are generally associated with well-developed, subhorizontal stretching lineation and right-lateral kinematic indicators (indicating transpressional to transtensional tectonics). The ages for HP/HT equilibration of Moldanubian granulites, garnet peridotites and associated ultramafic rocks falling into the narrow range of 340–338 Ma (Becker 1997; Kröner et al 2000b; Tajčmanová et al. 2006) and crystallization ages of ultrapotassic intrusions (~339 Ma; Janoušek and Holub 2007) prove that the exhumation of the Moldanubian Zone closely followed this HP/HT event. This means that deformation structures and mineral assemblages in micaceous gneisses at the contact of the Moldanubian Zone with the Svratka Unit and Kutná Hora Complex must have post-dated the exhumation of the Moldanubian Zone.

During the Variscan evolution, the ~350 Ma old calc-alkaline igneous magmas (Budislav Pluton and the Zábřeh Intrusive Complex) were emplaced in the eastern part of the Polička and the Zábřeh units (Vondrovic and Verner 2008). In both plutons, relicts of magmatic fabric were overprinted by regional ~WNW–ESE magmatic to HT solid-state foliation associated with subhorizontal lineation. These relationships indicate that calc-alkaline intrusions bear convincing evidence of syntectonic emplacement and crystallization (following the criteria defined by Paterson et al. 1998). This second event must have terminated before the crystallization of the ultrapotassic (durbachite) intrusions, which were emplaced post-tectonically into the marginal part of the Strážek Unit at ~ 339 Ma.



Verner et al., Fig. 6.

Fig. 6. Field photographs of fabric relationships. **a –** A stoped block of leucocratic migmatite in the metagranite of Cambro–Ordovician age (western part of the Svratka Unit; locality Zkamenělý Zámek near Svratka). **b –** Small isoclinal folds as relicts of older metamorphic fabric (eastern part of the Svratka Unit; locality: Bystřice nad Pernštejnem). **c –** Relationships of two regional metamorphic fabrics in the NE part of Moldanubian Zone (Strážek Unit; locality: Nové Město na Moravě quarry). **d –** The evidence of low-temperature cleavage superimposed on regional high-temperature solid-state fabric (western part of the Miřetín Pluton, Polička Unit; locality: Otradov)

4. Conclusions

The following conclusions concerning the regional tectonometamorphic evolution were reached:

- The HT/HP tectonometamorphic event (~340 Ma) was followed by HT decompression and polyphase exhumation of deep-seated rocks in the NE part of the Moldanubian Zone (Strážek Unit).
- In contrast, in the Kutná Hora Unit exhumation processes probably took place earlier – at ~350 Ma. This unit was not affected by LP/HP Variscan decompressional recrystallization.
- The ”long-lived“ regional tectonometamorphic evolution (~350–339 Ma) in the mid- to upper-crustal part of the Svratka, Polička and Zábřeh units (all interpreted as representing the eastern prolongation of the TBU) reflects right-lateral strike-slip shearing (transpressional to transtensional tectonics) at an approximate depth of ~18 km.
- The calc-alkaline plutons were emplaced syntectonically in upper- to mid- crustal rocks of the Polička and Zábřeh units during the formation of these regional metamorphic fabrics at around 350 Ma. In this context, the calc-alkaline intrusions are excellent time-markers of regional transpressional to transtensional geodynamic events in the mid- to upper-crustal segment of this part of the Variscan belt.
- The latest structural stages were connected with formation of extensive localized brittle–ductile shear zones and faults (e.g., NNE–SSW boundary between the Polička and Hlinsko units).
- The broad relationships of the described structures provide important constraints for the kinematic framework and timing of the geodynamic processes involving the different segments of the Variscan orogenic crust along the NE periphery of the Moldanubian Zone.

Acknowledgements This research was funded by Czech Geological Survey Research Project No. 6352 (to Jaroslava Pertoldová). The thorough reviews and constructive comments by the handling editor Vaclav Kachlík; Fritz Finger and two anonymous reviewers helped to improve the manuscript and are gratefully acknowledged.

References

ANCZKIEWICZ R, SZCZEPAŃSKI J, MAZUR S, STOREY CD, CROWLEY Q, VILLA IM, THIRLWALL MF, JEFFRIES ET (2007) Lu-Hf geochronology and trace element distribution in garnet; implications for uplift and exhumation of ultra-high pressure granulites in the Sudetes, SW Poland. Lithos 95: 363-380

BECKER H (1997) Sm-Nd garnet ages and cooling history of high-temperature garnet peridotite massifs and high-pressure granulites from Lower Austria. Contrib Mineral Petrol 127: 224-236

BRÖCKER M, KLEMD R, COSCA M, BROCK W, LARIONOV A N, RODIONOV N (2009) The timing of eclogite facies metamorphism and migmatization in the Orlica-Snieznik complex, Bohemian Massif: constraints from a multimethod geochronological study. J Metamorph Geol 27: 385-403

BRUECKNER K, BLUSZTAJN J, BAKUN-CZUBAROW N (1996) Trace element and Sm-Nd 'age' zoning in garnets from peridotites of the Caledonian and Variscan mountains and tectonic implications. J Metamorph Geol 14: 61–73

BURIÁNEK D, NĚMEČKOVÁ M, HANŽL P (2003) Petrology and geochemistry of plutonic rocks from the Polička and Zábřeh crystalline units (NE Bohemian Massif). Bull Czech Geol Surv 78: 9–22.

BURIÁNEK D, VERNER K, HANŽL P, KRUMLOVÁ H (2009) Petrochemical and microstructural comparison between Cambro–Ordovician metagranites and migmatites of the Svratka Unit and the Orlice–Sněžník Unit. J Geosci

Cháb J, Stráník Z, Eliáš M, Adamovič J, Babůrek J, Breiter K, Cajz V, Domečka K, Fišera M, Hanžl P, Holub V, Hradecký P, Chlupáč I, Klomínský J, Mašek J, Mlčoch B, Opletal M, Otava J, Pálenský P, Prouza V, Růžička M, Schovánek P, Slabý J, Valečka J, Žáček V (2007) Geological map of Czech Republic 1 : 500 000 (uncovered). Czech Geological Survey Prague ISBN 978-80-7075-699-7

CHALOUPSKÝ J, CHLUPÁČ I, MAŠEK J, WALDHAUSROVÁ J, CHÁB J (1995) VII. C. Teplá Barrandian Zone (Bohemicum): Stratigraphy. In: DALLMEYER RD, FRANKE W, WEBER K (eds) Pre-Permian Geology of Central and Eastern Europe. Springer-Verlag, Berlin, pp 379-392

CYMERMAN Z, PIASECKI A J, SESTON R (1997) Terranes and terrane boundaries in the Sudetes, Northeast Bohemian Massif. Geol Mag 134: 717-725

DÖRR W, ZULAUF G (in print) Elevator tectonics and orogenic collapse of a Tibetan-style plateau in the European Variscides: the role of the Bohemian shear zone. Int J Earth Sci (Geol Rundsch)

DRÁBEK M, STEIN H (2003) The age of formation of a marble in the Moldanubian Varied Group, Bohemian Massif, Czech Republic using Re-Os dating of molybdenite. In: ELIOPOULOS CJ, SPRY P, STEIN H, BEAUDOIN G (eds) Mineral Exploration and Sustainable Development. Millpress, Rotterdam, pp 973-976

DROST K, LINNEMANN U, MCNAUGHTON N, FATKA O, KRAFT P, GEHMLICH M, TONK CH, MAREK J (2004) New data on the Neoproterozoic–Cambrian geotectonic setting of the Teplá–Barrandian volcano-sedimentary successions: geochemistry, U-Pb zircon ages, and provenance (Bohemian Massif, Czech Republic). Int J Earth Sci 93: 742–757

FAJST M (1976) A new unconformity in the Precambrian of the Bohemian Massif. Čas Min Geol 21: 257-275 (in Czech)

FIALA J, FUCHS G, WENDT I (1995): VII. C. Moldanubian Zone, 1. Stratigraphy. In: Dallmeyer RD, FRANKE W, WEBER K (eds) Pre-Permian Geology of Central and Eastern Europe. Springer-Verlag, Berlin, pp 417-428.

FINGER F, ROBERTS MP, HAUNSCHMID B, SCHERMAIER A, STEYRER HP (1997) Variscan granitoids of Central Europe: their typology, potential sources and tectonothermal relations. Mineral Petrol 61: 67–96

FINGER F, HANŽL P, PIN C, VON QUADT A, STEYRER H P (2000) The Brunovistulian: Avalonian Precambrian sequence at the eastern end of the Central European Variscides? In: Franke W, Haak V, Oncken O, Tanner D (eds) Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geological Society Special Publication 179, London, p. 103-112

FIŠERA M (1977) Geology and petrology of the Kutná Hora Unit west of Kolín. Czech Geological Survey Research Papers 16: 19-31 (in Czech)

FRANKE W (2000) The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. In: FRANKE W, HAAK W, ONCKEN O, TANNER D (eds) Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geol Soc London Spec Publ 179: 35–63.

FRANKE W, ŻELAŹNIEWICZ A (2000) The eastern termination of the Variscides; terrane correlation and kinematic evolution. In: FRANKE W, HAAK W, ONCKEN O, TANNER D (eds) Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geol Soc London Spec Publ 179: 63-86.

FRIEDL G, FINGER F, PAQUETTE JL, VON QUADT A, MCNAUGHTON NJ, FLETCHER IR (2004) Pre-Variscan geological events in the Austrian part of the Bohemian Massif deduced from U-Pb zircon ages. Int J Earth Sci 93: 802–823

HANŽL P, BURIÁNKOVÁ K, KABÁTNÍK P, FINGER F (2000) The results of geological mapping of western part of Zábřeh Unit. Geol výzk Mor a Slez v roce 1999, pp 116-119 (in Czech)

Hanžl P, Buriánková K, Bešta J, Blažková Š, Břízová E, Dosbaba M, Fürych V,
Kirchner K, Kryštofová E, Lysenko V, Pertoldová J, Roštínský P, Rýda K, Skácelová D, Skácelová Z, Vít J, Zavřelová A, Žáčková E (2008) Basic geological map ČR 1:25 000 with explanations, 24-113 Nové Město na Moravě. Czech Geological Survey, Prague, pp 1-79 (in Czech)

Hanžl P, Buriánek D, Čurda J, Fürich V, Hrdličková K, Kirchner K, Lysenko V, Mrnková J, Otava J, Pertoldová J, Roštínský P, Rýda K, Skácelová Z, Vít J, Zelenka P (2008) Basic geological map ČR 1:25 000 with explanations, 14-333 Svratka. Czech Geological Survey, Prague, pp 1-72 (in Czech)

HEGNER E, KRÖNER A (2000) Review of Nd isotopic data and xenocryst and detrital zircon ages from the pre-Variscan basement in the eastern Bohemian Massif: speculations on palinspasic reconstructions. In: FRANKE W, HAAK W, ONCKEN O, TANNER D (eds) Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geol Soc London Spec Publ 179: pp 113-129

JANOUŠEK V, HOLUB F V (2007) The causal link between HP-HT metamorphism and ultrapotassic magmatism in collisional orogens: case study from the Moldanubian Zone of the Bohemian Massif. Proc Geol Assoc 118: 75-86

JANOUŠEK V, VRÁNA S, ERBAN V, VOKURKA K, DRÁBEK M (2008) Metabasic rocks in the Varied Group of the Moldanubian Zone, southern Bohemia – their petrology, geochemical character and possible petrogenesis. J Geosci 53: 31–64

JASTRZĘBSKI M (in print) A Variscan continental collision of the West Sudetes and the Brunovistulian Terrane: a contribution from structural and metamorphic records of the Stronie Formation, the Orlica–Śnieżnik Dome, SW Poland. Int J Earth Sci DOI 10.1007/s00531-008-0357-5

KACHLÍK V (1999) Relationship between Moldanubicum, the Kutná Hora crystalline Unit and Bohemicum (central Bohemia, Czech Republic): a result of the polyphase Variscan nappe tectonics. J Czech Geol Soc 44: 201-291

KODYM O, SVOBODA J (1950) The report about geological mapping around Jevíčko, Letovice and Polička. Věst Stát geol úst 25: 109-160 (in Czech)

KRÖNER A, ŠTÍPSKÁ P, SCHULMANN K, JAECKEL P (2000a) Chronological constraints on the pre-Variscan evolution of the northeastern margin of the Bohemian Massif, Czech Republic, In: FRANKE W, HAAK W, ONCKEN O, TANNER D (eds) Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geol Soc London Spec Publ 179: pp 175-198

KRÖNER A, O'BRIEN PJ, NEMCHIN AA, PIDGEON R T (2000b) Zircon ages for high pressure granulites from South Bohemia, Czech Republic, and their connection to Carboniferous high temperature processes. Contrib Mineral Petrol 138: 127-142

KRÖNER A, JAECKEL P, HEGNER E, OPLETAL M (2001) Single zircon ages and whole rock Nd isotopic systematics of early Palaeozoic granitoid gneisses from the Czech and Polish Sudetes (Jizerské hory, Krkonoše Mountains and Orlice–Sněžník Complex). Int J Earth Sci 90: 304–324

Kröner U, Mansy J L, Mazur S, Aleksandrowski P, Hann H P, Huckriede H, Lacquement F, Lamarche J, Ledru P, Pharaoh T C, Zedler H, Zeh A, Zulauf G (2008) Variscan tectonics. In: McCann T (ed) The Geology of Central Europe, Vol 1. Geological Society of London Special Publication, pp 599-665

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

LINNEMANN U, PEREIRA F, JEFFRIES T E, DROST K, GERDES A (2008) The Cadomian Orogeny and the opening of the Rheic Ocean: the diacrony of geotectonic processes constrained by LA-ICP-MS U-Pb zircon dating (Ossa-Morena and Saxo–Thuringian zones, Iberian and Bohemian massifs), Tectonophysics 461: 21-43

LINNER M (1996) Metamorphism and partial melting of paragneisses of the Monotonous Group, SE Moldanubicum (Austria). Mineral Petrol 58: 215-234

LOSERT J (1956a) Report about detailed geological mapping in the nw. part of Kutná Hora ore district. Zpr geol výzk v R 1955: 99-101 (in Czech)

LOSERT J (1956b) Dumortierites from the migmatites and pegmatites in the vicinity of Kutná Hora. Rozpr Čs Akad Věd, ř Mat Přír Věd 66,1: 1-44

LOSERT J (1967) Contribution to the problem of the pre-Assyntian tectogenesis and metamorphism in the Moldanubicum of the Bohemian Massif. Krystalinikum 5: 61-84.

MAZUR S, ALEKSANDROWSKI P, SZCZEPAŃSKI J (2005) The presumed Teplá–Barrandian/ Moldanubian terrane boundary in the Orlica Mountains (Sudetes, Bohemian Massif): structural and petrological characteristics. Lithos 82: 85–112

Mazur S, Aleksandrowski P, kryza P, Oberc-Dziedzic T (2006) The Variscan orogen in Poland. Geol Quart 50: 89-118.

MEDARIS LG JR, JELÍNEK E, MÍSAŘ Z (1995) Czech eclogites: terrane settings and implications for Variscan tectonic evolution of the Bohemian Massif. Eur J Mineral 7: 7–28

MELICHAR R (1995) The structural analysis of the Polička and Svratka units. Unpublished PhD thesis, Charles University, Prague, pp 1–271 (in Czech)

MELICHAR R (2004) Tectonics of the Prague Synform; a hundred years of scientific discussion. Krystalinikum 30: 167-187

Melichar R, Buriánek D, Břízová E, Buriánková K, Čurda J, Fürych V, Hanžl P, Kirchner K, Lysenko V, Mrnková J, Roštínský P, Rýda K, Skácelová Z, Vít J (2008) Explanations to the geological map ČR 1:25 000, 24-111 Sněžné. Czech Geological Survey Prague, pp 1-58 (in Czech)

MÍSAŘ Z, DUDEK A (1993) Some critical events in the geological history of eastern margin of the Bohemian Massif. J Czech Geol Soc 38: 9-20

NĚMEC D (1998) Highly mafic amphibolites in the Moldanubian Zone of the Bohemian–Moravian Heights (Českomoravská vrchovina). Acta Mus Moraviae, Sci Nat 83: 105-25.

OWEN JV, DOSTAL J (1996) Contrasting corona structures in mafic granulite from the Blanský Les complex, Bohemian Massif, Czech Republic. Canad Mineral 34: 959–66

PATERSON SR, FOWLER TK, SCHMIDT KL (1998) Interpreting magmatic fabric patterns in plutons. Lithos 44: 53-82

PERTOLDOVÁ J (1986) Conditions of Genesis of Skarns at Pernštejn , Županovice and Nové Město pod Smrkem Deposits. Unpublished PhD thesis, Charles University, Prague, pp 1–86 (in Czech)

PERTOLDOVÁ J, TÝCOVÁ P, VERNER K, KOŠULIČOVÁ M, PERTOLD Z, KOŠLER J, KONOPÁSEK J, PUDILOVÁ M (2009) Tectonometamorphic history of skarns, origin and age of their protolith and implications for genetic interpretation; an example from the Svratka Unit, the Moldanubian Zone, and the Kutná Hora Unit, Bohemian Massif.

PITRA P, BURG J P, SCHULMANN K, LEDRU P (1994) Late-orogenic extension in the Bohemian Massif: petrostructural evidence in the Hlinsko region. Geodin Acta 6: 15–31

PITRA P, GUIRAUD M (1996) Probable anticlockwise P-T evolution in extending crust: Hlinsko region, Bohemian Massif. J Metamorph Geol 14: 49–60

RACEK M, ŠTÍPSKÁ P, PITRA P, SCHULMANN K, LEXA O (2006) Metamorphic record of burial and exhumation of orogenic lower and middle crust: a new tectonothermal model for the Drosendorf Window (Bohemian Massif, Austria). Mineral Petrol 86: 221–251

SCHULMANN K, LEDRU P, AUTRAN A (1991) Evolution of nappes in the eastern margin of the Bohemian Massif: a kinematic interpretation. Geol Rundsch 80: 73–92

SCHULMANN K, GAYER R (2000) A model for a continental accretionary wedge developed by oblique collision: the NE Bohemian Massif. J Geol Soc, London 157: 401–416.

SCHULMANN K, KRÖNER A, HEGNER E, WENDT I, KONOPÁSEK J, LEXA O, ŠTÍPSKÁ P (2005) Chronological constraints on the pre-orogenic history, burial and exhumation of deep-seated rocks along the eastern margin of the Variscan orogen Bohemian Massif, Czech Republic. Amer J Sci 305: 407-448

SCHULMANN K, LEXA O, ŠTÍPSKÁ P, RACEK M, TAJČMANOVÁ L, KONOPÁSEK J, EDEL JB, PESCHLER A, LEHMANN J (2008) Vertical extrusion and horizontal channel flow of orogenic lower crust: key exhumation mechanisms in large hot orogens? J Metamorph Geol 26: 273-297

SCHULMANN K, KONOPÁSEK J, JANOUŠEK V, LEXA O, LARDEAUX J M, EDEL J B, ŠTÍPSKÁ P, ULRICH S (2009) An Andean type Palaeozoic convergence in the Bohemian Massif. Comptes Rendus Geosciences 341: 266-286

SYNEK J, OLIVERIOVÁ D (1993) Terrane character of the north-east margin of the Moldanubian Zone: the Kutná Hora Crystalline Complex, Bohemian Massif. Geol Rundsch 82: 566-582

ŠTÍPSKÁ P, SCHULMANN K, KRÖNER A (2004) Vertical extrusion and middle crustal spreading of omphacite granulite: a model of syn-convergent exhumation (Bohemian Massif, Czech Republic). J Metamorph Geol 22: 179–198

ŠTOUDOVÁ S, SCHULMANN K, KONOPÁSEK J (1999) The contrast between metamorphic and structural evolution of the Vír Granulite and surrounding metapelites of the Policka Crystalline Unit. Terra Nostra 99: 191-193

TAJČMANOVÁ L, KONOPÁSEK J, SCHULMANN K (2006) Thermal evolution of the orogenic lower crust during exhumation within a thickened Moldanubian root of the Variscan belt of Central Europe. J Metamorph Geol 24: 119–134.

URBAN M, SYNEK J (1995) Moldanubian Zone – Structure (Chapter VII.C.2.) In: DALLMEYER RD, FRANKE W, WEBER K (eds) Tectonostratigraphic Evolution of the Central and East European Orogens. Springer-Verlag, Berlin, pp. 429–443

VACHTL J (1962) The Hlinsko Palaeozoic and its relationship to neighbouring units. Sbor Ústř úst geol 27: 341-359 (in Czech)

VERNER K, ŽÁK J, NAHODILOVÁ R, HOLUB FV (2008) Magmatic fabrics and emplacement of the cone-sheet-bearing Knížecí Stolec durbachitic pluton (Moldanubian Unit, Bohemian Massif): implications for mid-crustal reworking of granulitic lower crust in the Central European Variscides. Int J Earth Sci 97: 19-33

VONDROVIC L, VERNER K (2008) The record of structural evolution and U-Pb zircon dating of the tonalite intrusions (Polička Crystalline Unit, Bohemian Massif). In: POBLET J, MEDINA MG, PEDREIRA D, FERNÁNDEZ CL (eds) International Meeting of Young Researches in Structural Geology and Tectonics – Programme and Extended abstracts, University of Oviedo, Spain, pp 369-373.

VRÁNA S, BLÜMEL P, PETRAKAKIS K (1995) Moldanubian Zone – Metamorphic Evolution (Chapter VII.C.4) In: Dallmeyer RD, Franke W, Weber K, (eds) Pre-Permian Geology of Central and Eastern Europe. Springer-Verlag, Berlin, pp 453–468

VRÁNA S, ŠTĚDRÁ V, MILAN FIŠERA M (2005) Petrology and geochemistry of the Běstvina granulite body metamorphosed at eclogite facies conditions, Bohemian Massif. J Czech Geol Soc 50: 95-106

VRÁNA S, ŠTĚDRÁ V, NAHODILOVÁ R (2009) Geochemistry and petrology of high-pressure albite-K-feldspar kyanite-garnet felsic gneisses and granulites from the Kutná Hora Unit. Variscides.

WEISS J (1992) Oceanic crustal relicts in the continental lithosphere of Czechoslovakia. Krystalinikum 21: 89-100.

WENDT J, KRÖNER A, FIALA J, TODT W (1993) Evidence from zircon dating for existence of approximately 2.1 Ga old crystalline basement in Southern Bohemia, Czech Republic. Geol Rundsch 82: 42–50.

ZAVŘELOVÁ A, MELICHAR R, SOEJONO I, VERNER K, TAJČMANOVÁ L (2006) Tectonometamorphic Evolution of the Svratka Crystalline Complex (NE): Evidence for Wrench-Dominated Transpression along the NE Margin of the Variscan Orogenic Root. Geolines 20: 138

Paper No. II.

PERTOLDOVÁ, J. - VERNER, K. - VRÁNA, S. - BURIÁNEK, D. - ŠTĚDRÁ, V. - VONDROVIC, L. (2010): COMPARISON OF LITHOLOGY AND TECTONOMETAMORPHIC EVOLUTION OF UNITS AT NORTHERN MARGIN OF THE MOLDANUBIAN ZONE: IMPLICATIONS FOR GEODYNAMIC EVOLUTION IN THE NORTHEASTERN PART OF THE BOHEMIAN MASSIF. – JOURNAL OF GEOSCIENCES 55, 4, 299-319. ISSN 1802-6222. DOI 10.3190/JGEOSCI.083.

DOI: 10.3190/jgeosci.083

Comparison of lithology and tectonometamorphic evolution of units at the northern margin of the Moldanubian Zone: implications for geodynamic evolution in the northeastern part of the Bohemian Massif

JAROSLAVA PERTOLDOVÁ[1]*, KRYŠTOF VERNER[1,2], STANISLAV VRÁNA[1], DAVID BURIÁNEK[3], VERONIKA ŠTĚDRÁ[1], LUKÁŠ VONDROVIC[1,2]

[1] *Czech Geological Survey, Klárov 3, 118 21 Prague 1, Czech Republic; jaroslava.pertoldova@geology.cz*

[2] *Institute of Petrology and Structural Geology, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic*

[3] *Czech Geological Survey, Leitnerova 22, 658 59 Brno, Czech Republic*

*Corresponding author

Keywords: Variscides, Bohemian Massif, lithology, structures, metamorphic evolution

Received: 11 October 2010; accepted: 21 December 2010; handling editor: V. Kachlík

The online version of this article (doi: 10.3190/jgeosci.083) contains supplementary electronic material.

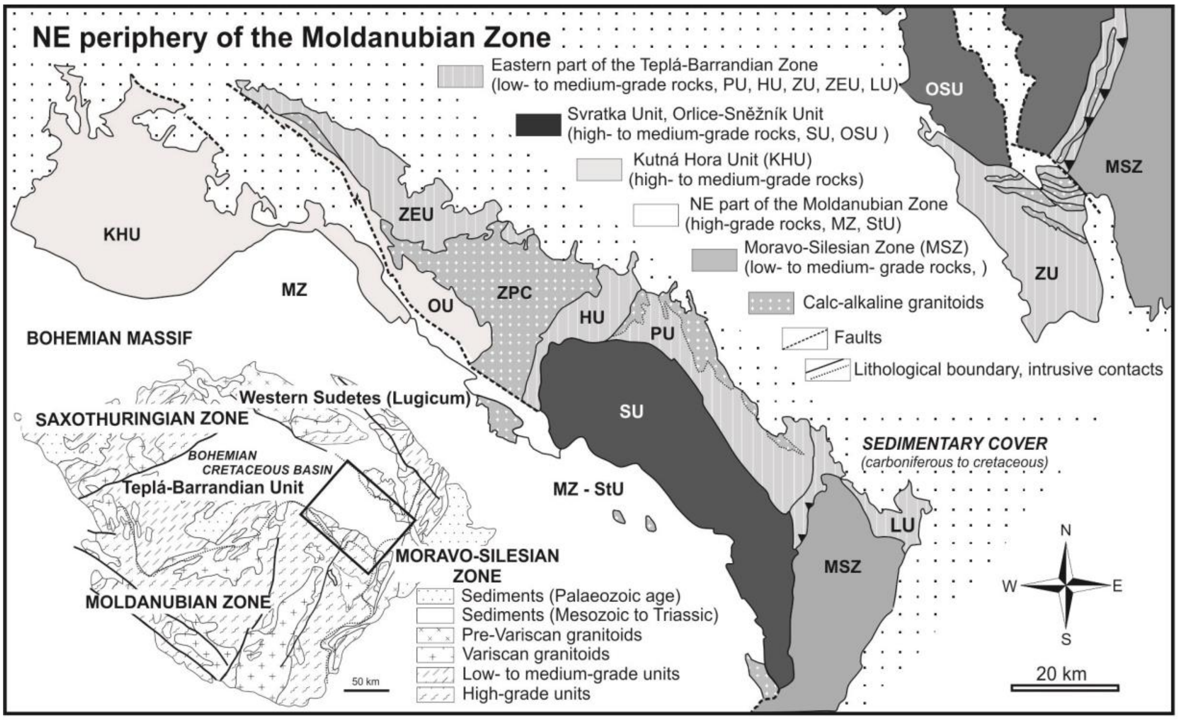
Abstract

Multidisciplinary research evaluates structural, metamorphic and petrochemical data of selected rock types in different units located in the northeastern part of the Bohemian Massif, Czech Republic: (1) the Strážek Unit in the northeastern part of the Moldanubian Zone, (2) the Svratka and Kutná Hora units correlated with the Orlice–Sněžník Unit in Western Sudetes as well as (3) the Polička, Hlinsko and Zábřeh units belonging to the Teplá–Barrandian Zone. Petrochemical data for metasediments of the Polička, Hlinsko and Zábřeh units are mutually comparable and confirm a lithological affinity to the upper-crustal Teplá–Barrandian Zone. The FeOt/MnO ratios in metasediments of the Strážek Unit and the Svratka Unit indicate differences in the origin of sedimentary protolith rocks. Relict pre-Variscan structures, including extensive migmatization, and high-grade mineral assemblages with peak metamorphic pressures of ~1.4 GPa in skarn bodies, are preserved in the Svratka Unit. The

evidence for Palaeo-Variscan (390–355 Ma) HP and UHP events, recorded in the high-grade Kutná Hora and Orlice–Sněžník units, was observed neither in the NE part of the Moldanubian Zone (Strážek Unit) nor the Teplá–Barrandian Zone (Polička and Zábřeh units). The Variscan orogenic event imprinted in the Svratka, Polička and Zábřeh units was the right-lateral slip along WNW–ESE trending shear zones. This deformation was accompanied by metamorphism at ~580–650 °C and ~0.5–0.7 GPa (352–343 Ma) and intrusion of numerous small bodies of syn-deformation calc-alkaline granitoids in the Polička and Zábřeh units. The younger metamorphic fabrics in the northeastern part of the Moldanubian Zone reflect a fast exhumation of deep-seated high-grade complexes at ~340 Ma, which was constrained by post-tectonic emplacement of durbachites at ~339 Ma. Metamorphic development in felsic granulites of the Strážek Unit, metamorphosed c. 340 Ma ago at 850 °C and 1.8 GPa,was followed by decompression to T ≅ 790 °C and P = 1.3 GPa and finally T = 700 °C and P = ~0.4 GPa. In contrast, Běstvina granulite in the Kutná Hora Unit, with the ~360 Ma high-grade metamorphism at 800–920 °C and 1.8–2.1 GPa, is free of such a HT–LP overprint. Thus the data indicate that the Svratka and Kutná Hora units, exhibiting numerous mutual differences, should not be considered as belonging to the Moldanubian Zone as they evolved as independent entities.The geochemical data on garnet–clinopyroxene skarns from the Moldanubian Zone, the Svratka and Kutná Hora units do not provide mutually distinguishing features. This is largely due to a very wide compositional variation in rocks interpreted as metamorphosed exhalite with detrital material admixture. Skarns from the Svratka Unit preserve clinopyroxenes with elevated jadeite component (0.5–24 mol. %) and prograde compositional zoning in garnet – features obliterated in samples from the Moldanubian Zone and the Kutná Hora Unit.

1. Introduction

This paper presents a new interpretation of tectono- metamorphic processes and their time relationships in the units located along the northeastern margin of the Moldanubian Zone, Czech Republic. Information on thispart of the Bohemian Massif plays an important role in elucidation of its geodynamic development in space andtime. Attention is focused on lithological, petrochemical, structural and geochronological data related to the pre-Variscan, as well as Paleo- and Neo-Variscan evolution of the studied units.



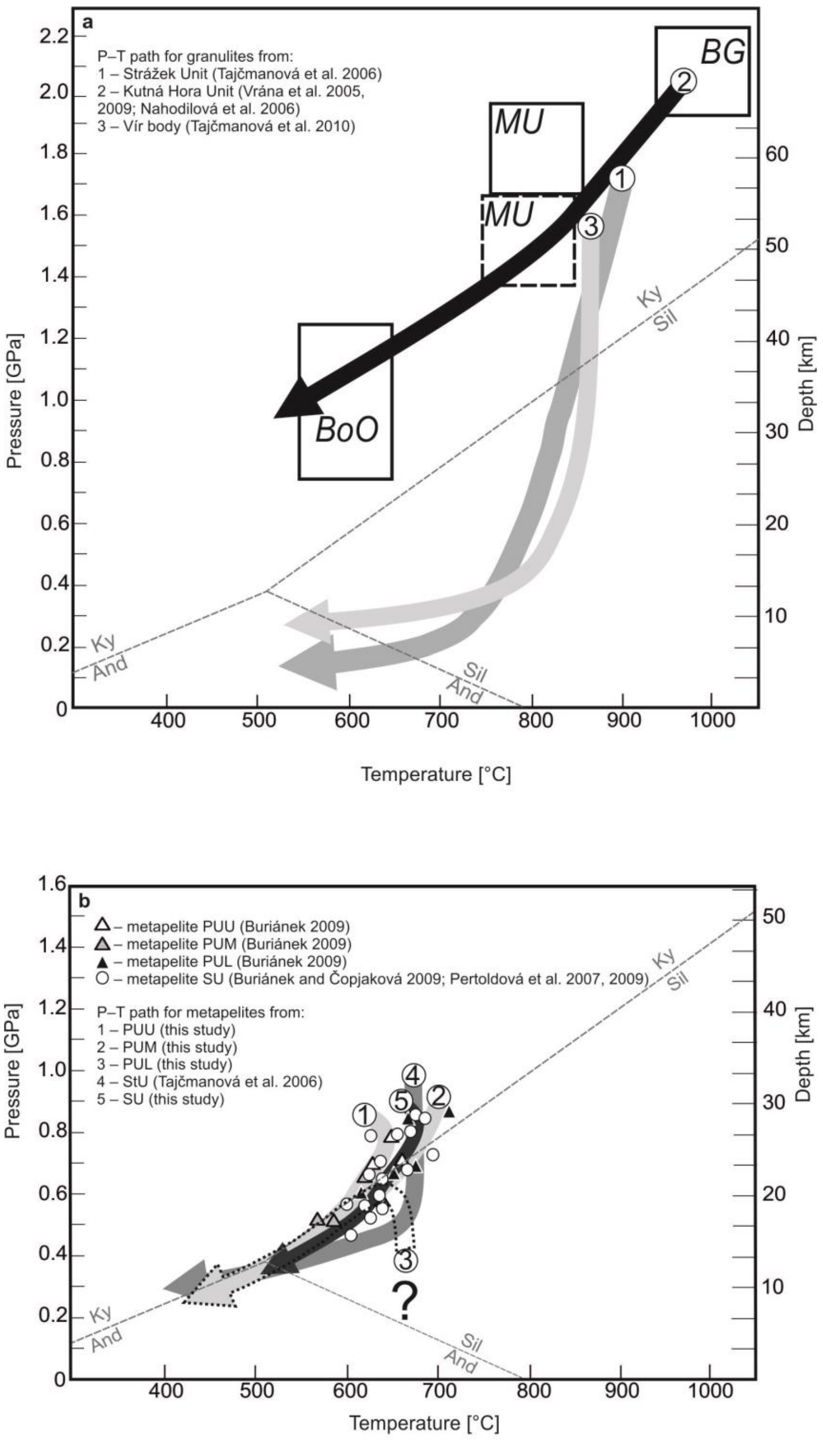
Pertoldová et al. Fig. 1

Fig. 1 A simplified geologic map of units along the NE margin of the Moldanubian Zone. Explanations: HU – Hlinsko Unit; KHU – Kutná Hora Unit; LU – Letovice Unit; MSZ – Moravo-Silesian Zone; MZ – Moldanubian Zone; PU – Polička Unit; OSU – Orlice-Sněžník Unit; OU – Oheb Unit; StU – Strážek Unit; SU – Svratka Unit; ZEU – Železné Hory Unit; ZPC – Železné Hory Plutonic Complex; ZU – Zábřeh Unit.

We evaluate the results of our multidisciplinary re-search performed in different units located in the north-eastern part of the Bohemian Massif: (1) The Strážek Unit representing the north-eastern Moldanubian Zone, (2) the Svratka, Kutná Hora, Polička, Hlinsko, Zábřehand Orlice–Sněžník units (Fig. 1). More focussed papers stemming from individual parts of this research were published in the special volume “Geological development of the region at the NE periphery of the Moldanubian Zone, eastern part of the Bohemian Massif” of the Journal of Geosciences (e. g. Buriánek et al. 2009b; Pertoldová et al. 2009; Štědrá and Nahodilová 2009; Verner et al. 2009; Vrána et al. 2009). We also integrate new geological datasets collected during geological mapping in the region (Project No. 6328 “Geological mapping of the Žďárské Vrchy Protected Landscape Area”). On the basis of new field structural data we characterize regional fabric patterns and tectonic boundaries of the individual units. For lithological and petrochemical correlations were chosen the most telling rock types, i.e., metapelites, migmatites, orthogneisses, metagranites and skarns. Others, such as granulites and eclogites, were compared according to their P–T history and ages. The P–T estimations from metamorphic assemblages with structural, petrochemical and geochronological data in the selected rocks serve as a basis for unique comparison of lithology and geochemical composition, timing and tectonometamorphic evolution and their interpretation, and information published in the literature, we propose a geological model presenting tectonometamorphic processes and their time relationshipsin the units located along the northeastern margin of the Moldanubian Zone.

2. Geological setting

The oldest processes recorded in the studied rocks took place in Neoproterozoic to Early Palaeozoic times (~570–530 Ma), i.e. late during the Cadomian Orogeny, at the periphery of the Gondwana and Avalonia (Hegnerand Kröner 2000). The development culminated by the Cambro–Ordovician magmatic stage (e.g. Linnemann et al. 2008). The subsequent Late Devonian to Early Carboniferous collision of Gondwana-derived crustal segments with the Old Red continent resulted in assembly of heterogeneous units and created a new geological framework for the western and central parts of the European continent (e. g. Franke 2000). This Variscan evolution,i.e. subduction of oceanic crust and crustal thickening associated with high-pressure metamorphism, was datedat ~390–355 Ma (e. g. in the Orlice–Sněžník and KutnáHora units; Mazur et al. 2005; R. Nahodilová, personal comm.) and Neo-Variscan stage at around 340 Ma (Fiala et al. 1995; Finger et al. 2007; Schulmann et al. 2008, 2009). These processes were followed by fast exhumation of deep-seated rocks and wrench tectonic activity (Kröner et al. 2000 and references therein). These events were connected with juxtaposition of various crustal segments: (1) the Moldanubian Zone comprising a heterogeneous complex of high-grade rocks (for a general review see Fiala et al. 1995; Urban and Synek 1995; Vrána et al. 1995; Schulmann et al. 2008). The term is used here as defined by Fiala et al. (1995), except of the Svratka and the Kutná Hora units – below we present evidence indicating that the latter two units evolved as separate entities; (2) the Teplá–Barrandian Zone as the upper-crustal segment including unmetamorphosed to medium-grade Neoproterozoic and Lower Palaeozoic volcanosedimentary sequences (e.g.Chaloupský et al. 1995; Zulauf 1997; Drost et al. 2004); (3) the Saxothuringian Zone and Western Sudetes as Neoproterozoic to Lower Palaeozoic rock complexes with tectonically implanted slices of Variscan HP and UHP rocks (Kröner et al. 2001; Mazur et al. 2005). The units nowadays located at the eastern margin of the Bohemian Massif were thrust over pre-Variscan basement, deformed Late Neoproterozoic granitoids and a tectonically imbricated metasedimentary sequence of Devonian age of the Moravo–Silesian Zone (Schulmann and Gayer 2000). The area of our interest is located in the north-eastern part of the Bohemian Massif, and is built by severalc rustal segments with distinct lithology, composition, tectonometamorphic evolution and age. Proposal of the regional geological division of the Czech Republic published by Chlupáč and Štorch (1992) defined various units discussed in the current paper. These are, from the south to the north (Fig. 1): (1) the Strážek Unit representingthe NE part of the Moldanubian Zone. It consists of Variscan high-grade rocks, such as migmatites and migmatized paragneisses, with bodies of felsic granulites, ultramafic rocks, amphibolites and skarns (Tajčmanová et al.2006; Schulmann et al. 2005, 2008); (2) the Kutná Hora Unit subdivided into four sub-units of high-pressure migmatites, orthogneisses, paragneisses and mica schists, enclosing lenses of felsic granulites, garnet peridotitesand eclogites. The sub-units recorded an early-Variscan HP tectonometamorphic evolution at around 370–360 Ma (Synek and Oliveriová 1993; Kachlík 1999; Vrána et al.2005; Medaris et al. 2005, 2006; Nahodilová et al. 2006;Štědrá and Nahodilová 2009; Vrána et al. 2009; Faryad2009); (3) the Svratka Unit consists of polymetamorphic migmatites, mica schists and paragneisses with amphibolite and skarn intercalations that are cut by bodies of Cambrian metagranites and orthogneisses (Melichar et al. 2008; Verner et al. 2009). The unit exhibits lithologi-cal similarities to the Orlice–Sněžník Unit (basement ofWestern Sudetes; Buriánek et al. 2009b); (4) the structurally overlying Polička, Hlinsko and Zábřeh units arelow- to medium-grade volcanosedimentary sequences of Neoproterozoic to Lower Palaeozoic age, classified by some authors as the more strongly metamorphosed eastern part of the Teplá–Barrandian Zone (Mísař et al.1983; Verner et al. 2009) or viewed as relics of an allochthonous cover of the Orlice–Sněžník Unit (e. g. Mazur et al. 2005; Cháb et al. 2010). The Polička, Hlinsko and Zábřeh units contain abundant Variscan calc-alkaline granitoids (Buriánek et al. 2003; Vondrovic and Verner 2008); (5) the high-grade Orlice–Sněžník Unit resemblesin terms of its P–T development and tectonometamorphic evolution the high-grade Moldanubian Zone. However,the ages of HP–HT metamorphism and the following mid-crustal re-equilibration of the Orlice–Sněžník Unit (dated at c. 360–370 Ma and ~345 Ma, respectively) weresubstantially different (Mazur et al. 2005).



Pertoldová et al. Fig. 2

Fig. 2 Summary of published P-T paths for a) metapelites in the Strážek Unit (StU), Svratka Unit (SU), Upper part of the Polička Unit (PUU), Middle part of the Polička Unit (PUM), Lower part of the Polička Unit (PUL); b) granulites in the Strážek Unit, granulites and other rock types in the Kutná Hora Unit (BG- Běstvina granulite, MU- Malín Unit, BoO - Bohouňovice orthogneiss), and Vír granulite

3. Geological features and metamorphic evolution

3.1. Strážek unit

The Strážek Unit is composed of Variscan high-grade rocks such as migmatized paragneisses and migmatites with lenses of amphibolites, skarns and tectonic slices of high-pressure felsic granulites (Bory and Drahonín massifs) and upper-mantle ultramafic rocks (Medaris et al.1995; Tajčmanová et al. 2006; Hanžl et al. 2008a). The Bory granulite Massif carries numerous boudins of upper mantle peridotite, Grt-pyroxenite and eclogite with P–T conditions of equilibration estimated at 3.8–4.8 GPa and 900–1 000 °C (Medaris et al. 2005, 2009; Ackerman et al. 2009; Naemura et al. 2009). Felsic granulites of the Strážek Unit preserve early mineral assemblages, indicating HP metamorphic evolution of these rocks under T = 850 °C and P = 1.8 GPa at 340 ± 1.1 Ma (U–Pb on zircon) (Schulmann et al. 2005; Tajčmanová et al. 2006). The subsequent metamorphic events recorded in rocks of the Strážek Unit (partial stages of fast exhumation and re-equilibration) were determined at T ≅ 790 °C and P = 1.3 GPa and, finally, at T ≅ 700 °C and P ~ 0.4 GPa (Owen and Dostal 1996; Tajčmanová et al. 2006). The overall metamorphic evolution of felsic granulites from Strážek Unit is shown in Fig. 2a (P–T path No. 1).

3.2. Kutná Hora unit

The Kutná Hora Unit (see Fig. 3 in Verner et al. 2009) consists of four different structural sub-units (Synek andOliveriová 1993; Verner et al. 2009; Štědrá and Nahodilová 2009): (1) polymetamorphic high-pressure Malínmigmatites and granulitic Běstvina sub-unit higher in the structural sequence, (2) the Kouřim Nappe consisting of migmatites,orthogneisses and fine-grained leucocratic et al. Fig.(3) the Mica Schist sub-unit, and (4) the Plaňany sub-unit. The Rataje Mica Schist zone, included by Synek and Oliveriová (1993) in the Kutná Hora Unit, in fact represents a retrogressed marginal part of the Moldanubian Zone (Koutek 1933; Mísař et al. 1983; Kachlík 1999). Several metamorphic phases, based on mineral assemblages and tied to tectonic events, have been defined in the Kutná Hora Unit. The early mineral assemblage evolved under upper mantle conditions in tectonic slices of Grt peridotites, Grt pyroxenites, eclogites and felsic granulites. The Běstvina sub-unit carries numerous boudins of upper mantle garnet peridotite, Grt pyroxenite and eclogiteequilibrated at 3–5 GPa and 850–1 100 °C (Medaris et al. 2006; Faryad 2009). The eclogites in the central part of the Kutná Hora Unit indicate minimum pressures exceeding

2.2–2.3 GPa and temperatures of c. 600–820 °C (Medaris et al. 2006; Štědrá and Nahodilová 2009). In HP/HT granulites of the Běstvina sub-unit equilibration took place at 840–920 °C and 1.8–2.2 GPa (Vrána et al. 2005). Nahodilová et al. (2006) and Faryad (2009) determinedthe conditions of the retrogression at 705 ± 97 °C and 1.4 ± 0.2 GPa. This event can be possibly correlated with the high-pressure migmatization in the Malín sub-unit undereclogite-facies conditions, succeeded by regional high-pressure mylonitic deformation (Synek and Oliveriová 1993; Vrána et al. 2009). The leucogranites intruded in migmatites of the Malín sub-unit were affected by super-imposed HP tectonometamorphic event and transformed to Ky–Grt gneisses under a pressure of 0.9 to 1.2 GPa (Synek and Oliveriová 1993; Vrána et al. 2009). Key stages of P–T evolution of HP metamorphic rocks from the Kutná Hora Unit are summarized in Fig. 2a.

3.3. Svratka unit

This unit consists of pre-Variscan polymetamorphic migmatites with elongated bodies of orthogneisses of Cambrian age, mica schists, paragneisses and small intercalations of dolomitic marbles, amphibolites and skarns (Melichar 1995; Schulmann et al. 2005; Melichar et al. 2008; Hanžl et al. 2008b). The early, pre-Variscan metamorphic stage resulted in extensive migmatization. It is characterized by prograde garnet zoning in skarns, and corresponded to pressures ~1.4 GPa (Pertoldová et al. 2009). The peak metamorphic conditions during the Variscan orogeny were estimated at ~640–670 ºC and 0.6–0.8 GPa (Buriánek and Čopjaková 2009). This metamorphic event was identified in mica schists by a stable Ms + Bt + Grt + St + Ky mineral assemblage. Sillimanite is associated with superimposed deformation at ~580–650 °C and 0.6 GPa (Buriánek and Čopjaková 2009; Tajčmanová et al. 2010). The overall metamorphic development in metapelites of the Svratka Unit is summarized in Fig. 2b (P–T path No. 5). The age of the regional Variscan tectonometamorphic event in the Svratka Unit is unknown as the published results of $^{40}Ar/^{39}Ar$ muscovite dating (from 325 ± 0.4 to 331.6 ± 0.3 Ma; Fritz et al. 1996) most likely reflect cooling during the later stages of exhumation.

3.4. Polička unit

The Polička Unit represents probably Neoproterozoic to Lower Palaeozoic volcanosedimentary sequence penetrated by calc-alkaline plutonic rocks dated at ~346 ± 6 Ma(U–Pb on zircon; Vondrovic and Verner 2008; Vondrovic et al. unpublished data). On the basis of the lithological composition, the Polička Unit can be subdivided into three different parts (Melichar 1995), which are, from south to north: (1) the structurally lowest medium-grained biotite and two-mica paragneisses (± Grt ± Sil) with deformed bodies of metagranites, amphibolites, marbles, calc-silicate rocks and an allochthonous Vír felsic granulite massif; (2) middle part consists of a monotonous complex of medium-grained biotite to two-mica paragneisses (± Grt ± Sil) with abundant calc-silicate nodules and intercalations of metapelites and metaconglomerates; (3) the upper part is composed of mica schist with inter-calations of quartzite and paragneiss. Mica schists of the uppermost Polička Unit exhibit the mineral assemblage Qtz + Ms + Bt ± Pl ± St ± Grt ± Pl (± Ky in the eastern part of the unit), indicating peak metamorphic conditions of T ≅ 650 °C and P ≅ 0.8 GPa and a retrograde overprint at 660 °C and 0.7 GPa (Buriánek 2009) (Fig. 2b, P–T path No. 1). In the metapelites of the middle part of the Polička Unit, the mineral assemblage equilibrated at 570–680 °C and ~0.6 GPa; (Fig. 2b, P–T path No. 2). Relics of sillimanite pseudomorphs after andalusite indicate an older LP metamorphic event (Buriánek et al. 2003). Estimated peak P–T conditions in allochthonous tectonic slices of Vír granulites dated by Tajčmanová et al. (2010) at ~354 ± 7 Ma (U–Pb on zircon) correspond to T = 860–1000 °C and P = 1.6 GPa (Tajčmanová et al. 2010) (Fig. 2a, P–T path No. 3). These granulites are accompanied by predominating retrogressed orthogneisses. Mineral assemblages in the surrounding metapelites indicate metamorphic conditions of c. 700 °C and 0.7 GPa, reflecting exhumation of granulites accompanied by partial melting of the metasediments (Buriánek 2009; Buriánek et al. 2009a; Tajčmanová et al. 2010). The U–Pb zircon ages (339 ± 3 Ma and 336.2 ± 1.2 Ma) from granulites of the Vír area and the surrounding amphibolites reflect exhumation of these rocks into a higher crustal level (Tajčmanová et al. 2010). Monazite (U–Pb) dating at 336± 1 Ma on an orthogneiss-like sample by van Breemen et al. (1982) may indicate a post-peak retrogressive event.

3.5. Zábřeh unit

The Zábřeh Unit is composed of two lithological subunits, low-grade metapelites and metabasites in the south and paragneisses with intercalations of metavolcanites intruded by numerous sheets of calc-alkaline plutonites in the north (Fajst 1976; Hanžl et al. 2000; Buriánek et al. 2003; Verner et al. 2009). The intensity of metamorphism gently increases from the central part to both the south and north. The peak P–T conditions in the northern part were estimated at ~0.6 GPa and ~ 660 °C (D. Buriánek, unpublished data). In addition, effects of local contact metamorphism in narrow zones along the northern intrusive sheets were identified.

3.6. Hlinsko unit

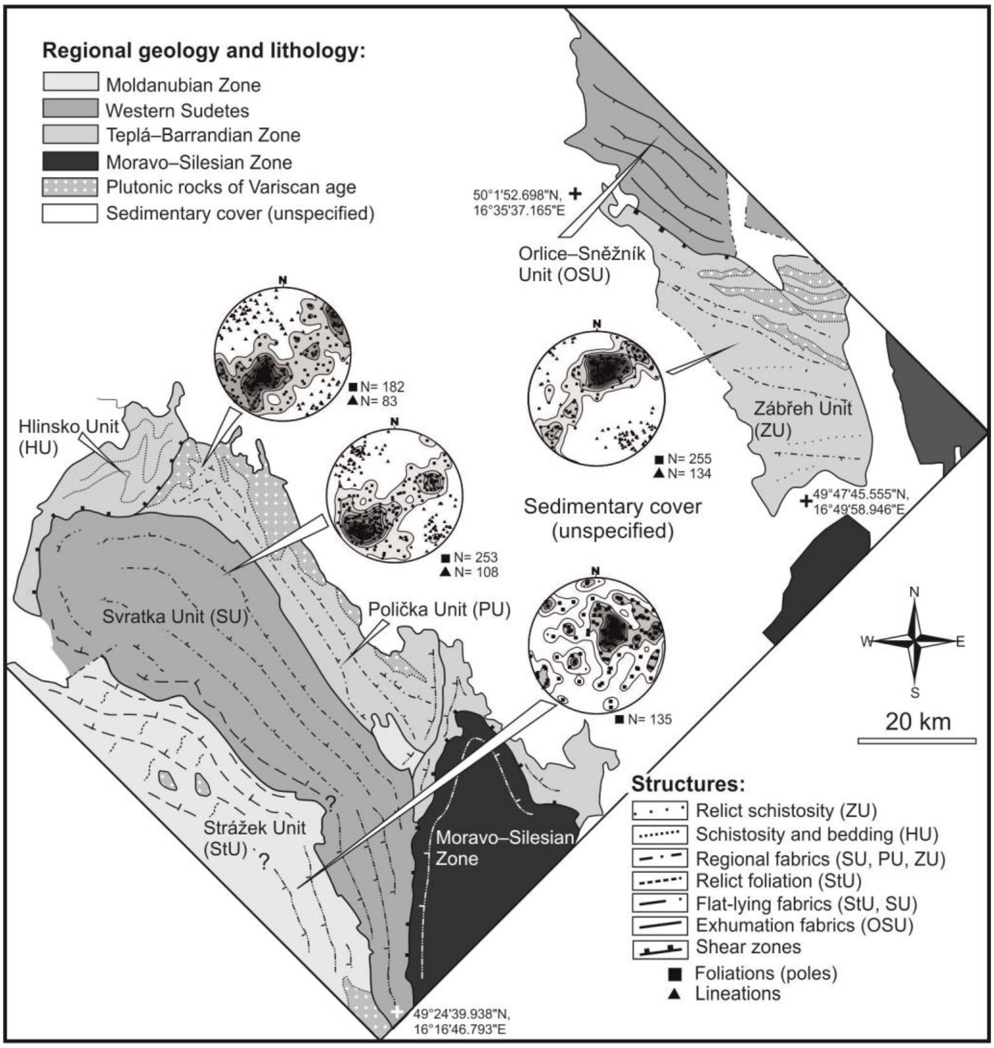
The Hlinsko Unit, separated by a NNE–SSW trending polyphase shear zone, extends along the northwestern margins of the Svratka and Polička units. It consists of three metasedimentary groups folded in a great synform elongated NNE–SSW. Some weakly metamorphosed rocks carry fossils of Silurian and Late Ordovician age (Štorch and Kraft 2009). Greywackes and metapelites, in places with layers of metavolcanites, were classified asthe Hlinsko and Vítanov groups, metapelites with abundant quartzites were assigned to the Mrákotín Series and graywackes to the Rychmburk Series (Vachtl 1962). An anticlockwise P–T path with peak metamorphic conditions of 0.35–0.4 GPa and 600–530 °C was proposed by Pitra and Guiraud (1996) for more strongly metamorphosed parts of this unit.

3.7. Orlice–Sněžník unit

The Orlice–Sněžník Unit occurs in the SE part of the Western Sudetes (Lugicum) (Kryza et al. 1996; Mazur et al. 2005; Anczkiewicz et al. 2007; Jastrzębski 2009). Lithology and tectonometamorphic evolution of units at the northern margin of the Moldanubian Zone. It consists of high- to medium-grade polymetamorphic migmatites and orthogneisses of Cambrian protolith age, with outer envelope of staurolite schists and biotite paragneisses. Migmatites and orthogneisses of the Orlice–Sněžník Unit contain abundant eclogite and granulite bodies (Opletal et al. 1980; Mazur et al. 2005). The latter rocks experienced an Early Variscan HP (UHP) metamorphic evolution followed by a high- to medium-grade (HT/M–LP) regional tectonometamorphic overprint (Mazur et al. 2005).

4. Structural patterns

Rocks of the studied units in the northeastern part of the Bohemian Massif recorded complex and polyphase tectonometamorphic processes, particularly during the Variscan orogeny. The orientation and relationships of regional fabrics briefly described below are shown in Fig. 3. In the high-grade rocks of the Strážek Unit, the HP(MP)–HT metamorphic stage was followed by rapid exhumation of high-grade rocks. This event was associated with isothermal decompression at high temperatures (Tajčmanová et al. 2010). The regional structural pattern in this unit is formed by subvertical, ~NNE–SSW to N–S trending metamorphic foliations,



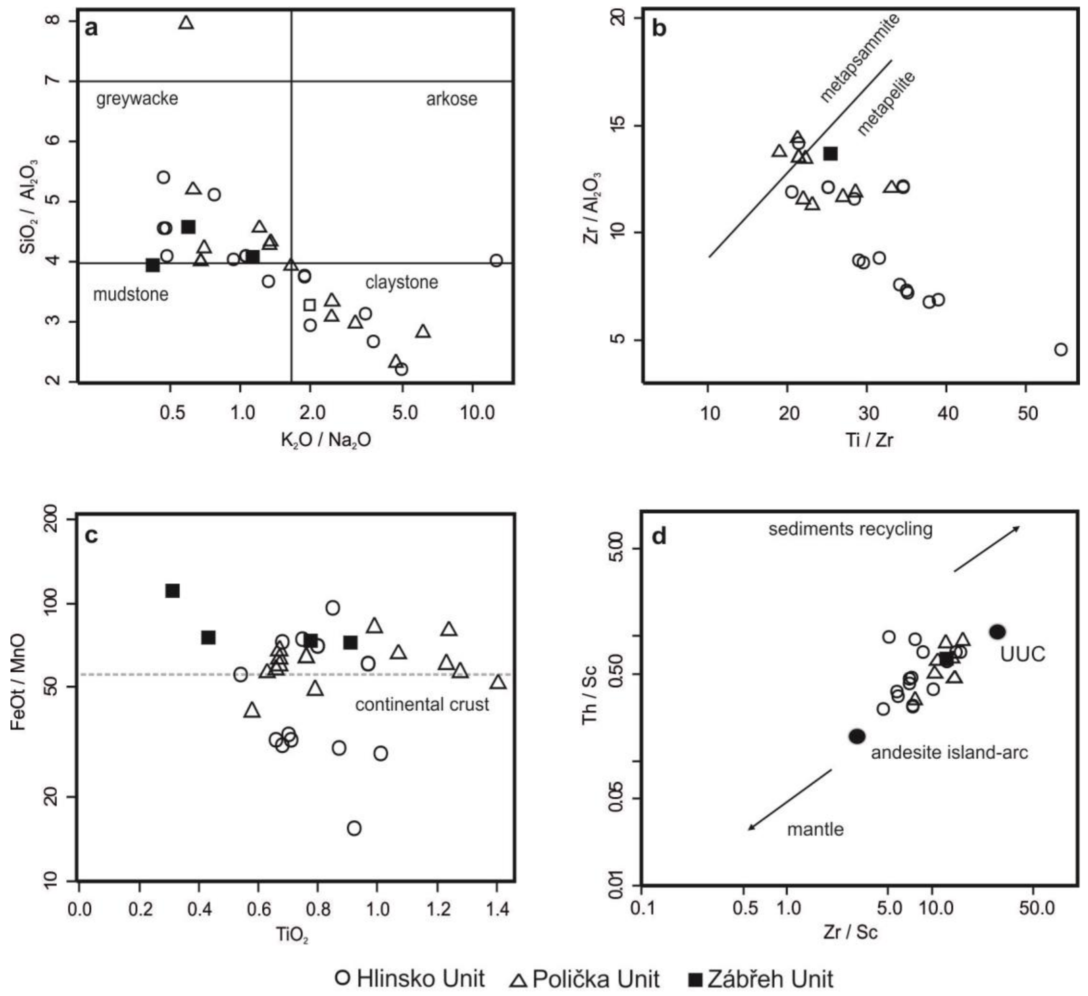
Pertoldová et al. Fig. 3

Fig. 3 Structural scheme of the studied area containing rare relics of high-grade fabrics, especially in form of minor root-less to isoclinal folds (Tajčmanová et al. 2010). These fabrics were heterogeneously reworked to ~NW–SE to WNW–SSE, flat-lying to gently NNE dipping foliations, in places associated with WNW–ESE plunging mineral lineation. In the Strážek Unit, the formation of this second fabrics is constrained by post-tectonic emplacement of ultrapotassic, Mg-rich granitoids (durbachites) dated by U–Pb method on zircon at 339 ± 2 Ma (A. Gerdes, unpublished data; Verner et al. 2009). In general, secondflat-lying fabrics are in northern and north-western parts of the Strážek Unit roughly parallel to the boundary with the adjacent Svratka Unit. In the Kutná Hora Unit, several stages of regional Variscan tectonometamorphic evolution were identified (e. g. Synek and Oliveriová 1993; Štědrá and Nahodilová 2009; Vrána et al. 2009). During an Early Variscan event, the bodies of mantle peridotites and related UHP rocks, with their relict structures, were tectonically incorporated into gneisses and granulites (Synek and Oliveriová1993). Faryad (2009) presented an alternative model ofcrustal and upper-mantle rocks juxtaposition (Machek et al. 2009). Early deformation structures imprinted during the polyphase exhumation of the high-pressure granulites, garnet–kyanite migmatites and other deep-seated rocks of the Kutná Hora Unit are unknown and were at least partly obliterated by younger deformations. To a late generation belong gently to moderately dipping, ~NW to ~NE trending retrograde planar fabrics developed on a regional scale. This event took place in the stability field of biotite and muscovite in the upper Kouřim Nappe, and of garnet + kyanite (± sillimanite) in the Malín and Mica Schist sub-units. This stage was also linked with intensemid-crustal mylonitization and low-angle shearing that resulted in juxtaposition of individual segments of the Kutná Hora Unit and in transformation of alkali-feldspargranite dykes in HP migmatites of the Malín sub-unit into mylonitic garnet–kyanite-bearing orthogneisses (Vrána et al. 2009). Numerous lenses of upper mantle rocks also occur in narrow and steep zones of kyanite–garnet mica schists (Štědrá et al. 2008). Finally, the late tectonic episodes in the Kutná Hora Unit proceeded under the low-temperature brittle–ductile conditions associated with a syntectonic oriented, and later even random, growth of muscovite (Synek and Oliveriová 1993). In the overlying Svratka Unit, relics of pre-Variscan tectonometamorphic record linked with ~HP metamorphic conditions (P = ~1.4 GPa) were identified (Pertoldová et al. 2009). In addition, discordant intrusive contacts between Cambrian granites (515 ± 9 Ma, U–Pb zircon age by Schulmann et al. 2005) and the surrounding migmatites were described by Verner et al. (2009). This finding constrains the upper age limit of pre-Variscan high-pressure metamorphism and migmatization of the Svratka Unit to Cambrian times. The Variscan structural pattern of the Svratka Unit is defined by regional metamorphic foliations dipping steeply to moderately to the~NNW–NE in its western and central, and steeply to the ~SW in its eastern part. These foliations are associated by well-developed stretching lineations (elongated quartz and feldspar aggregates) which plunge under low angles to the ~NW or SE (Verner et al. 2009). Kinematic background of these fabrics suggests a polyphase evolution of right-lateral transtensional to transpressionalwidely-distributed shear zone. In the southern part of the Svratka Unit these regional fabrics were affected by tectonometamorphic overprint associated with minor partial melting and formation of the gently NNE dipping foliation. During the Variscan Orogeny, the Svratka Unit was affected by regional metamorphism reaching only the amphibolite-facies conditions only (Fig. 2b; P–T path 5).   The structural pattern of the overlying Polička Unit is defined by regional metamorphic foliations (pervasive schistosity or compositional banding), which dip steeply to moderately to the NNE–ENE in the central and eastern part, and to the WNW along the western margin of this unit. The foliations bear well-developed, gently plunging NW–SE stretching lineation associated with right-lateral kinematic indicators (Verner et al. 2009). The northern part of The Polička Unit was intruded by numerous bodies of calc-alkaline composition (dated by U–Pb method on zircon at ~352–343 Ma; Vondrovic and Verner 2008; L. Vondrovic unpublished data). The transition of magmatic to HT sub-solidus fabrics in regional orientation, mostly parallel to the intrusive contacts, indicate syntectonic emplacement of these intrusions in relation to the main tectonometamorphic event (Verner et al. 2009). In the northern part of the Zábřeh Unit, the regional metamorphic foliations dip moderately to steeply to the ~SSW and are associated with well-developed stretching lineation which plunges gently to the ~ESE or WNW. The intrusive contacts and magmatic to sub-solidus fabrics of abundant calc-alkaline intrusions are roughly parallel to the orientation of the host metamorphic fabrics. The origin of these fabrics in the Zábřeh Unit as well as in the underlying Polička and Svratka units were broadly related with the activity of a regional WNW–ESE directed transpressional to transtensional zone.   Towards the south, the intensity of the transpressional to transtensional fabrics gradually decreases and relics of older low-grade fabrics with a flat-lying orientation could be observed. Finally, the complex of the Zábřeh Unit was affected by sub-vertical shortening. The low-temperature cleavage as well as the axial planes of open folds dipping gently to the SSW were identified. The boundary between the Zábřeh Unit and the adjacent underlying lower to mid- crustal Orlice–Sněžník Unit (Lugicum) is roughly parallel to the regional metamorphic fabrics, however, strongly modified by the Late Variscan right-lateral “Elbe Zone” fault system. In the upper-crustal Hlinsko Unit several different events in tectonic evolution were identified (Pitra et al. 1994). The bedding planes broadly associated with orientation of low-grade cleavage were affected by folding during polyphase ~E–W shortening and related development of different sets of crenulation cleavages. The last event of ~E–W shortening of metasediments of the Hlinsko Unit resulted in the formation of a regional WNW-vergent synclinal structure. The boundary between the upper-crustal Hlinsko Unit and mid-crustal Polička Unit has a character of moderate- to low-temperature NNE–SSW oriented shear zone. The initial stages of shearingduring compression were related to the syntectonic emplacement and subsequent high-temperature deformation of calc-alkaline granitoids of the Miřetín Pluton, recently dated by Vondrovic and Verner (2008, unpublished data) at 345 ± 5 Ma (U–Pb on zircon). In the southern part of the high-grade Orlice–SněžníkUnit (eastern part of Lugicum), a set of retrograde mid-crustal fabrics was identified (Mazur et al. 2005).On a regional scale, along the southern margin of the Orlice–Sněžník Unit, the medium-grade compositional banding dips under moderate angles to the SW and to S. These planar fabrics are associated with well-developed ~NNW–SSE to N–S plunging stretching lineation and indicators of regional extension.

5. Lithological and petrochemical comparison of selected rocks

5.1. Metapelites and metapsammites

The metasediments of the studied units experienced a complicated history of polyphase metamorphism and migmatization (Buriánková et al. 2008; Hanžl et al. 2008b), which affected the composition of the original sediments with varying intensity. The Polička, Zabřeh and Hlinsko units represent metasedimentary sequences with a predominance of muscovite–biotite to biotite gneisses and lower grade rocks (Buriánek 2010). As these complexes are largely free of migmatization, the main features of sedimentary protoliths are probably widely preserved and thus can be studied by geochemical methods. The primary data used for construction of the whole-rock geochemical diagrams are stored in electronic appendices 1 and 2. In the K_2O/Na_2O vs. SiO_2/Al_2O_3 (wt. %) plot of Wimmenauer (1984), gneisses and other metasediments from the Polička, Zábřeh and Hlinsko units form a roughly linear data array mainly in the fields of greywacke and claystone, less frequently mudstone (Fig. 4a). Overall, the geochemical features of metasediments of the Hlinsko, Zábřeh and Polička units are all mutually comparable. Major- and trace-element data for metasediments from these units present evidence of their affinity to the Bohemicum (Patočka et al. 2003; Drost et al. 2004; Buriánek 2010). Manganese-rich metasediments from the Hlinsko Unit (Fig. 4c) can be interpreted as metapelites and metapsammites deposited around submarine springs (Buriánek and Otava 2007). The chemical composition of Polička Unit metasediments probably resulted from mixing between arc and continental-derived detritus.The elevated La/Th ratio, together with decreased Th/Sc and Zr/Sc ratios, in the Hlinsko Unit sediments indicate a larger input from the volcanic arc source (Fig. 4d). Indeed, tuffitic horizons were indentified in the VítanovFormation of the Hlinsko Unit. Biotite to muscovite–biotite migmatites, gneisses or mica schists are predominant in the Strážek and Svratka units. Because of probable modifications due to migmati zation (e.g., Inger and Harris 1993; Bea 1996), some geochemical features of these rocks are discussed separately. Shortage of modern whole-rock analyses from the Kutná Hora Unit prevents correlation for this unit. In the K2O/Na2O vs. SiO2/Al2O3 (wt. %) plot of Wimmenauer (1984), migmatites and gneisses fall mainly along the greywacke–arkose boundary (Fig. 5a). Mica schists of Svratka Unit almost form a separate field with lower SiO2/Al2O3 and increased K2O/Na2O values, along the boundary between the fields of arkose and claystone. In the TiO2 vs FeOt/MnOt diagram (Fig. 5b), the Strážek Unit samples plot along an approximately horizontal line near the crustal FeOt/MnO value (c. 55 – Quin and Humayun 2008; Lewis 2004). On the other hand, the migmatites and, in particular, mica schists and paragneisses from Svratka Unit exhibit dramatic deviations from the normal crustal FeOt/MnO ratios. Migmatites from Svratka Unit display a wide variation (6–100) and micaschists plot at higher still FeOt/MnO values (c. 100–190).These relations indicate a very high contrast in the geochemistry of the two units. The Zr/Hf ratio in the rocks of the Svratka and Strážekunits is 32 and 42 respectively, as indicated by linear fits. This situation suggests evolved material in the course of deposition of sediments that became protolith to the metamorphic rocks of the Svratka Unit (Dostal and Chatterjee 2000; Linnen and Keppler 2002).



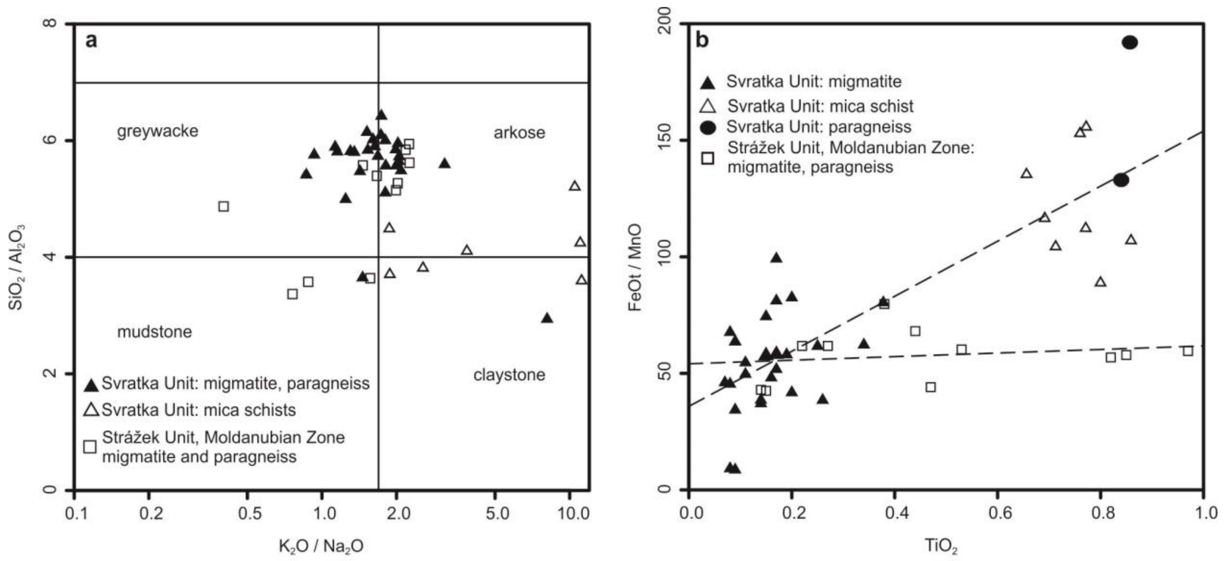
Pertoldová et al. Fig. 4

Fig. 4 Whole-rock geochemistry of paragneisses in the Polička, Hlinsko and Zábřeh units. a – K2O/Na2O vs. SiO2/Al2O3 (Wimmenauer 1984); b – Ti/Zr vs. Zr/Al2O3 (Roser and Nathan 1997); c – TiO2 vs. FeOt/MnO (FeOt/MnO ratio typical for the continental crust according Maynard 2005); d – Zr/Sc vs Th/Sc plot (after McLennan et al. 1990, 1993). UCC – Upper Continental Crust.

5.2. Neoproterozoic and early Paleozoic orthogneisses and metagranites

Orthogneisses to metagranites are relatively common rock-types in the units along the NE margin of the Moldanubian Zone. Data on the lithological composition and geodynamic evolution of rocks in the Svratka and the Orlice–Sněžník units were used and compared. The radiometric dating of metagranites from the Svratka Unit (conventional U–Pb method on zircon) revealed three different stages in the evolution of these rocks (Schulmann et al. 2005): (I) 1932 ± 7 Ma – inherited (upper intercept) age indicates a period of partial melting of the

Palaeoproterozoic basement; (II) the date 515 ± 9 Ma suggests granite intrusion and crystallization; (III) the age of c. 340 Ma reflects a period of the Variscan regional tectonometamorphic overprint. For comparison, granitic protolith geochronology data for the Orlice–Sněžník orthogneisses include single zircon Pb–Pb ages of 515–503 Ma (Kröner et al. 2001) and U–Pb ages of 503–488 Ma (Mazur et al. 2010). In the Svratka and Orlice–Sněžník units, the studiedeta-granitic rocks are very similar in petrology, as well as mineral and whole-rock chemical composition (Buriánek et al. 2009b). Differences in microstructures and textures relate to distinct geodynamic evolution of the individual bodies. In general, primary magmatic minerals are recrystallized into a mosaic of K-feldspar, albitic plagioclase, quartz, biotite and muscovite aggregates.



Pertoldová et al. Fig. 5

Fig. 5 Whole-rock geochemistry of gneisses and migmatites in the SU and StU units. a – K_2O/Na_2O vs SiO_2/Al_2O_3 (Wimmenauer 1984); b –TiO_2 vs FeOt/MnO.

Apatite, zircon, monazite and ilmenite are common accessories. The whole-rock compositions of samples from the Svratka and Orlice–Sněžník units are similar and contain relatively high SiO_2 (~76 wt. %), the A/CNK ratio ranges between 1.0 and 1.3, $K_2O + Na_2O$ values from 7.2 to 8.8 wt. % and K_2O/Na_2O ratios reach 1.4–2.4. These data indicate highly potassic to shoshonitic characteristics of the studied rocks. The rocks are relatively poor in Ba, Nb, Ta, Sr, Hf and Zr, and rich in Cs, Rb, Th, U, K and HREE (Buriánek et al. 2009b). In general, the genesis of the protolith to the orthogneisses to metagranites from the Svratka and Orlice–Sněžník units can be interpreted as being a result of partial melting of a similar continental crust at the time of the Cambrian extensional event. During the ascent and emplacement, these rocks developeby moderate degrees of melt fractionation (Buriánek et al. 2009b).

5.3. Eclogites and metabasites

Most previously published reports on eclogites and other metabasites in the Kutná Hora Unit were focused on a rigid block of the Běstvina granulite (Medaris et al. 2005, 2006; Faryad 2009). The eclogite-bearing inner part of Kutná Hora Unit is an area roughly corresponding to the Inner Mica Schist Zone sensu Synek and Oliveriová (1993) and its tectonic contact with the high-grade Malín Unit (Losert 1967). Eclogites in the inner part of the Kutná Hora Unit, along with associated garnet peridotites, occur in mylonitized biotite–muscovite gneisses and mica schists, indicating the character of a deep-seated shear zone (Paděra 1972; Medaris et al. 2005). The zone played an important role in incorporation of the lower-crustal and mantle-derived rocks to upper crustal levels. Several eclogite and Cpx-bearing intermediate rock occurrences have been newly described in the inner part of Kutná Hora Unit near Roztěž, Bořetice and Miškovice (Štědrá and Nahodilová 2009). The REE patterns indicate a lower crustal rather than a mantle source for these HP rocks. The P–T calculations yielded minimum pressures above 2.15–2.3 GPa and temperatures of c. 600–650 °C, and in some cases 720–820 °C, for the peak of metamorphism (Tab. 1) (Štědrá and Nahodilová 2009). Although partially affected by thermal overprint and retrogression, the eclogite samples from this part of the Kutná Hora Unit clearly record a prograde metamorphic path and can be thus compared in this respect with some eclogites in the Běstvina Unit (Medaris at al. 2006; Faryad 2009). A high-pressure mineral assemblage and peak pres- sures recorded in one sample of eclogite from the Strážek Unit (Moldanubian Zone) compares to the highest pressures found in the studied area along the Kutná Hora Unit–Moldanubian Zone boundary (P > 2.0 GPa, T = 700–750 °C). On the other hand, the Borek eclogite equilibrated under less extreme metamorphic conditions (Medaris et al. 1998).

Unit	Kutná Hora Unit							
Locality	Bořetice blocks	Roztěž	Poličany	Ratboř	Plaňany	Bečváry	Stříbrná Skalice	Žehušice
Rock type	Ky eclogite	Eclogite	Eclogite	Grt peridotite	Grt lherzolite	Grt peridotite	Amphibolite	Grt amphibolite
Crystallization				820–890	1120–1190	845/4.1		
HP stage (min. P)	620/2.0 860/2.3	720–810/2.2–2.3					620–710/0.9–1.2	606/1.3
HT stage		890/1.3						
Retrograde stage			550–600/0.5					
Age determination	338 ± 8 Ma**					377 ± 20 Ma*		
References	SN2009	SN2009	NV1996	M2006	S2007	M2005	K1999	NV1996

Unit	Kutná Hora Unit – Běstvina						Moldanubian Zone	
Locality	Spačice	Spačice	Spačice	Spačice	Úhrov	Úhrov	Bída	Borek
Rock type	Ky eclogite	Qtz eclogite	Grt peridotite	Ky eclogite	Grt peridotite	Ky eclogite	Eclogite	Eclogite
Crystallization					1170/4.4			
HP stage (min. P)	830–920/2.3–2.5	1160–1180/1.7–1.9	950/4.5	960/3.4		930/2.5	660–820/1.9–2.3	650/1.4–1.5
HT stage								
Retrograde stage								
Age determination						344 ± 6 Ma**		
References	SN2009	M1998	WF2009	WF2009	M2005	S2009, M2006	SN2009	M1998, M2005

Geothermobarometry references:
SN2009 – Štědrá and Nahodilová (2009); M1998, M2005, M2006 – Medaris et al. (1998, 2005, 2006); NV1996 – Novák and Vrbová (1994); K1999 – Kachlík (1999); S2007 – Pertoldová et al. (2007); WF2009 – Faryad (2009)
Sm–Nd geochronology references:

Tab. 1 Summary of P-T data (T(°C)/P(GPa)) from eclogites and peridotites

5.4. Skarns

Skarns in the Svratka Unit, in the neighbouring part of the Moldanubian Zone (Strážek Unit) and in the Kutná Hora Unit form competent lenses and layers in gneisses and migmatites and preserve some early deformation struc tures. The major minerals are garnet and clinopyroxene. The garnet composition corresponds predominantly to the grossular–almandine–andradite series (Grs75–21, Alm78–25, Adr65–0, Sps23–0 Prp7–0; XFe = 0.95−1.00), clinopyroxene belongs mostly to the hedenbergite group. The content of the jadeite component is notably increased only in samples from the Svratka Unit (0.5−24 mol. %). Garnets in skarns from the Svratka Unit exhibit well-defined prograde compositional zoning and, together with variation in the jadeite component in pyroxenes and reaction textures, recorded at least three metamorphic episodes, similarly to their host rocks. Garnet compositions indicating peak pressure conditions of metamorphism in skarns in the Strážek Unit are not preserved and the chemical zoning of garnets shows exclusively a retrograde evolution imprint. The oxygen and fluorine fugacities were probably increased in some garnets, but only locally. Although the chemically homogeneous compositions of individual generations of clinopyroxene and epidote do not reflect the prograde and retrograde events in skarns from the Kutná Hora Unit, a prograde compositional zoning in some garnets was observed (Pertoldová et al. 2009). A summary of the petrological data for skarns is presented in Tab. 2. Altogether 59 whole-rock samples were used for major- and trace-element analyses of skarns in the studied units (Pertoldová et al. 2009). Skarns from the Svratka Unit are highly variable in abundances of major and trace elements (35–55 wt. % SiO2, 1–18 % Al2O3, 1–23 % CaO, 2–47 % Fe2O3 and 2–8 % MgO). Seven samples out of 30 have positive Eu anomaly and low total REE contents. Major elements in skarns from the Moldanubian Zone exhibit a wide variation: 20–60 wt. % SiO2, 1–17 % Al2O3, 5–30 % CaO, 1–66 % Fe2O3 and 0.5 –14 % MgO. The Eu/Eu* ratios cover a wide range of 0.5 to 3.5; the majority of samples are characterised by values near 1.0. The highest Eu/Eu* values are characteristic of samples with low ΣREE. Samples from the Kutná Hora Unit represent mainly Grt–Cpx assemblages with variable contents of the major elements: 22–55 wt. % SiO2, 2–14 % Al2O3, 14–31 % CaO, 2–58 % Fe2O3 and 0.5–4 % MgO. The abundances of trace elements are variable, both for the individual localities and for the individual samples.

unit	skarn type	minerals				note
		rock–forming	minor	accesoric	*secondary*	
Svratka Unit	Grt–Cpx, Cpx–Grt, garnetite, Cpx skarn, Grt–Hbl, Gru–Cpx	Grt (Grs_{21-44} Alm_{25-78} Sps_{0-23} Adr_{0-12} $Prp_{0.5-7}$), Cpx	Qtz, Pl, Ep, Mag	Zrn, Ttn, Aln, Ap, Ilm, Ccp, Au, Py, native Bi	Hbl, Pl	Garnets show prograde compositional zoning. Decompression textures: Ttn→Ttn–Plg symplectite, Grt→Hbl–Plg symplectite, Cpx→Cpx–Plg symplectite. The content of jadeite component in Cpx is 0.5–24 mol.%.
Moldanubian Zone	Grt–Cpx, Cpx–Grt, garnetite, Cpx, Mag with Hbl	older Grt (Grs_{74-67} Alm_{9-12} Adr_{15-18}), Cpx, younger Grt (Grs_{34-35} Alm_{6-8} Sps_4 Adr_{53-54})	Qtz, Pl, Ep, Mag, Czo	Ttn, Ap, native Bi, Py, Po	Hbl, Pl	Garnets show weak retrograde zoning. Younger Grt rich in Adr fills fractures in older Grt.
Kutná Hora Complex	Grt–Cpx, Cpx–Grt, garnetite, Cpx with Grt	Grt (Grs_{50-75} Alm_{24-15} Sps_{2-0} Adr_{31-9} Prp_{1-3}), Grt (Grs_{24-65} Alm_{9-0} Sps_{4-0} Adr_{65-33}), Cpx, Ep	Mag, Pl	Ttn, Aln, Ap, cerite, hydrogrossular	Grt, Ep, Hbl	Two types of garnet. Both are characterized by inverse variation in the Grs and And components. Grt and Cpx show weak prograde zoning. Four generations of Ep and three generations of Cpx. Some Ep are enriched in REE.

Tab. 2 The summary of petrological results from skarns in the Svratka Unit, the Moldanubian Zone and the Kutná Hora Unit.

6. Discussion and conclusions

On the basis of the summarized petrological, lithological, geochemical and structural data sets, we present an interpretation of the broadly discussed geodynamic evolution and regional classification of various chrustal units bordering the northeastern part of the Moldanubian Zone (Fig. 6).

6.1. Lithology and geochemistry

6.1.1. Metasediments

Metasediments from Polička, Zábřeh (eastern part) and Strážek units have FeOt/MnO ratios typical of the continental crust (Maynard 2005). The contrast in FeOt/MnO values in metasediments from Svratka and Hlinsko units indicate a role of specific redox conditions at the time of deposition and diagenesis of protolith sediments. Details of the scenario are not well understood yet. In any case, the differences in the FeOt/MnO values indicate a major contrast in deposition conditions of the protolith sediments of the Svratka and Strážek units. Both weakly oxidizing or weakly reducing conditions can induce a lower Mn content in seawater (Maynard 2005). Sample sets for individual units exhibit characteristic pattern in the high-field-strength elements contents. Low Th/Sc and Zr/Sc ratios and LREE contents are typical signatures of metasediments from the Hlinsko Unit and indicate a considerable proportion of igneous-arc material in the sedimentary protolith. Metasediments of the Polička and Zábřeh units probably represent mixing of arc- and continent-derived material and show affinity to the Hlinsko Unit.

6.1.2. Orthogneisses

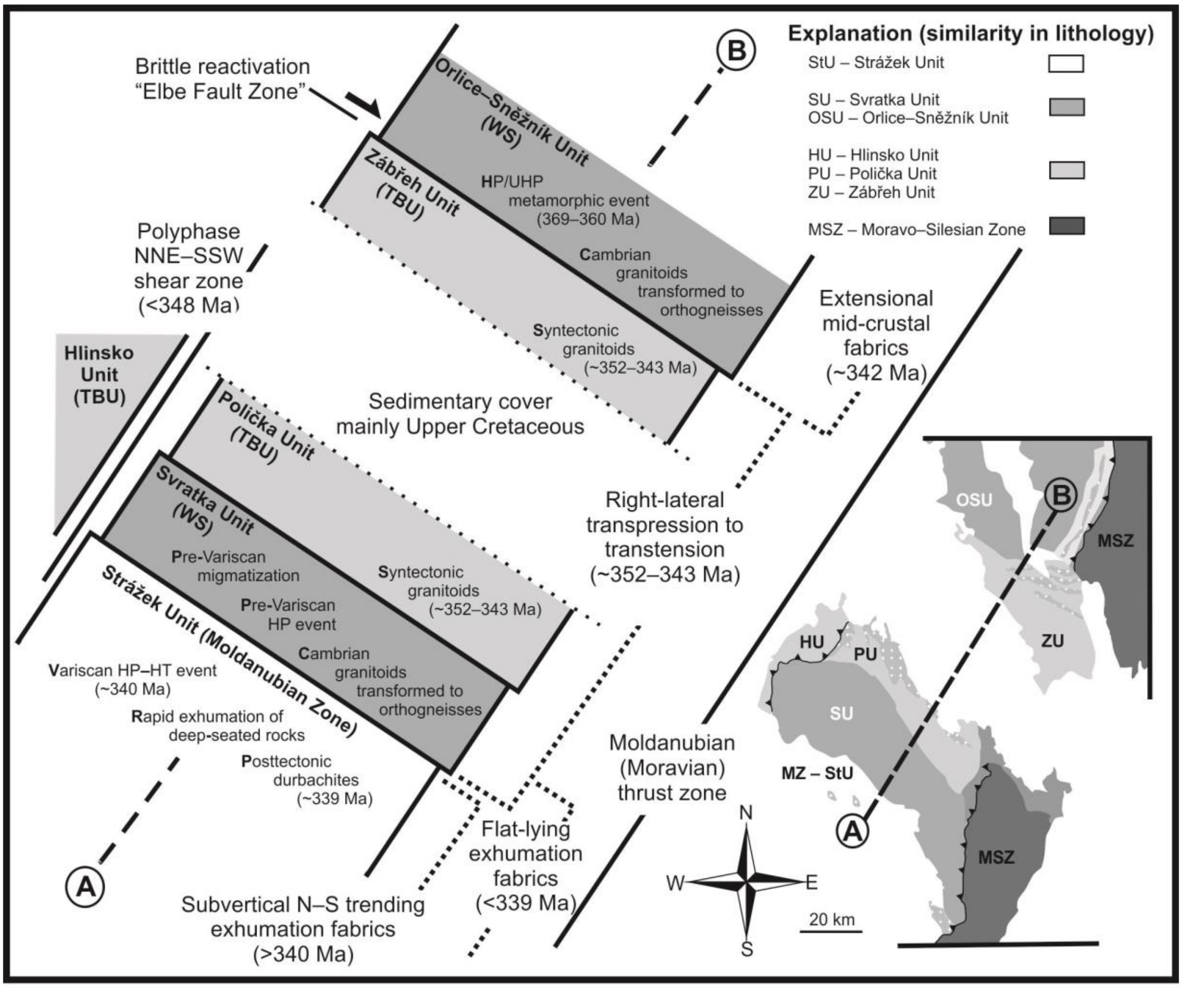
As shown by Buriánek et al. (2009b), protoliths to orthogneisses and metagranites in the Svratka and the Orlice–Sněžník units were likely to have originated by melting of similar crustal rocks and evolved by analogous processes during Cambrian magmatic event 530–515 Ma ago (U–Pb on zircon) (Kröner et al. 2001; Štípská et al. 2004; Schulmann et al. 2005). The rock-forming minerals of the studied rocks were affected by Variscan deformation and metamorphic recrystallization under ~MP−MT conditions at ~350−330 Ma (Buriánek et al. 2009b). Based on published petrochemical data on different types of Cambrian orthogneisses from the Bohemian part of the Moldanubian Zone (e. g. Vrána and Kröner 1995; Breiter et al. 2005), these orthogneisses seem essentially different from the studied metaigneous rocks in the Svratka and Orlice–Sněžník units.

6.1.3. Granulites

Granulites are high-pressure rocks equilibrated in fact under eclogite-facies conditions (P = 1.8–2.2 GPa) at high temperatures (T = 800–1 000 °C). Rock-types with granite composition (Ky–Grt–Pl–Kfs (mesoperthite)–Qtz ± Bt) strongly predominate in all the granulite massifs listed above. However, aberrant compositions are also present; e.g. in the Běstvina body these are rocks of paragneiss composition (rich in Grt, Ky and primary Bt, with greywacke-like chemistry), and rare albite–K-feldspar felsic granulites (Vrána et al. 2005, 2009). Granulites form small bodies up to 10 km long, tectonically incorporated in paragneiss–migmatite host-rocks, the latter carrying mineral assemblages indicating significantly lower pressures and temperatures of equilibration. It is of particular interest that granulites in individual units feature contrasting P–T paths during exhumation-related decompression (Tab. 3). Granulites in the Strážek Unit (Drahonín and Bory massifs) exhibit prominent HT–MP/LP decompression recrystallization (Owen and Dostal 1996; Tajčmanová et al. 2006), which however lacks in the Kutná Hora Unit (Běstvina Massif) (Vrána et al. 2005, 2009). In Běstvina, the composition of the outer zone of garnet in granulites, perfect preservation of kyanite, and the absence of newly formed LP phases all indicate a mild decompression (P ~ 1.4 GPa) in the kyanite field. The major contrast in the P–T path of the two types of granulites (Fig. 2a) excludes any joint evolution as parts of a former coherent unit with the Moldanubian Zone. In addition, the Běstvina granulite in Kutná Hora Unit has age of HP metamorphism by 20 Ma older than Moldanubian granulites (Tab. 3). The third mode of granulite occurrence (Vír) represents a segment directly at the junction of the Svratka and Polička units. These rocks preserve an evidence for decompression recrystallization similar to that in granulites of the Moldanubian Zone (Štoudová et al. 1999; Tajčmanová et al. 2010), but the original source of these thrust-slices remains uncertain.

6.1.4. Skarns

The geochemical features of the studied skarns do not indicate systematic differences among the three studied geological units, although their tectono-metamorphic development was different. The δ18O (SMOW) values for garnet and clinopyroxene from skarn localities in the Moldanubian Zone and the Svratka Unit are low, ranging from -0.1 up to +4.0 (Pertold et al. 1997; Pertoldová et al. 1998, 2009; Drahota et al. 2005). Such low values do not support the idea of contact metamorphic genesis (Pertoldová et al. 2009). Based on the major- and trace-element geochemistry and the geological position, the skarn protoliths are instead interpreted as rocks of mixed detrital–exhalative origin deposited on a sea floor.



Pertoldová et al. Fig. 6

Fig. 6 Schematic relations of units bordering the Moldanubian Zone in NE Bohemia.

The total REE contents and type of Eu anomaly are highly variable and indicate variations in the local temperature and redox conditions among the individual layers at a single locality, as well as various localities (Pertoldová et al. 2009). There is also an indication of a rather conservative character of the metamorphism with limited migration of components within the garnet–clinopyroxene rocks. It is probable that hydrothermal solutions, instrumental in the development of skarn protoliths, debouched on the sea floor along fault zones with the character of local extensional rifts. The deposition of exhalites proceeded along such zones, and they were mixed with detrital material in variable pro ortions. The large variability of the zircon ages in skarn from the Svratka Unit suggests their detrital origin. The fact that most of the data falls between 540 and 580 Ma possibly indicates a source in the rocks of Neoproterozoic age (Pertoldová et al. 2009).

Massif	Dimensions	Geological unit	Peak P–T conditions	Decompression P–T	Age determination*	Main references
Běstvina	9 × 3 km	Kutná Hora Unit	1.8–2.2 GPa, 800–900 °C	1.4 GPa, *c.* 710 °C, decompression in Ky field	U–Pb zircon 360 ± 5.3 Ma**	Vrána et al. (2005), Nahodilová et al. (2006)
Drahonín	4 × 1.5 km	Strážek Unit (MZ)	1.8 GPa, *c.* 850 °C	c. 0.4 GPa, *c.* 700 °C, inversion Ky → Sil	U–Pb zircon 340 ± 1.1 Ma	Schulmann et al. (2005), Tajčmanová et al. (2006)
Bory	10 × 3.5 km	Strážek Unit (MZ)	1.6 GPa, 850–900 °C	widespread inversion Ky → Sil ± hercynite and newly formed Crd	U–Pb zircon 347 + 9/-10 Ma	Kröner et al. (1988), Staňková (1982), Kotková et al. (2003)
Vír	9 × 6 km	junction of Svratka and Polička units	1.6 GPa, 860–1000 °C	0.6–0.8 GPa, 600 °C	U–Pb zircon 354 ± 7 Ma, monazite in orthogneiss 338 ± 3 Ma***	van Breemen et al. (1982), Štoudová et al. (1999), Tajčmanová et al. (2010)

* U–Pb age determinations on zircon are interpreted as dating the HP events

Tab. 3 Main features of granulite massifs in the studied area.

6.2. Geodynamic evolution

6.2.1. Indicators of Pre-variscan tectonometamorphic evolution

Field relationships between different rock-types, presence of relict structures, geochronology and P–T data originating from the Svratka Unit provide an evidence for important role of pre-Variscan geodynamic events.Discordant intrusive contacts between Cambrian granites dated by Schulmann et al. (2005) at 515 ± 9 Ma and the surrounding migmatites, as well as the absence of additional Variscan partial melting and high-grade overprint, lithology and tectonometamorphic evolution of units at the northern margin of the Moldanubian Zone indicate that the previously identified HP–HT event in skarns (Buriánek et al. 2009b; Pertoldová et al. 2009; Verner et al. 2009) must have been of pre-Variscan age. On a regional scale, the HP–HT processes including extensive partial melting and emplacement of calc-alkaline granitoids could be related with crustal exhumation in final stages of the Cadomian orogenic processes, or with continental extension during early Cambrian rifting (Linnemann et al. 2000). In contrast to the published models (e. g. Pitra et al. 1994; Mazur et al. 2005; Schulmann et al. 2005, 2008), the Svratka Unit was affected by Variscan regional metamorphism reaching amphibolite facies conditions only (Fig. 2b; P–T path 5). This is in sharp contrast to the high-grade Kutná Hora Unit and the Moldanubian Zone.

6.2.2. High-grade metamorphic events of the variscan age

Granulites as a typical and ubiquitous rock-type are excellent objects for comparison of tectonometamorphic and geochronological evolution in the high-grade Strážek Unit, Kutná Hora Unit and Vír area. Granulites of the Strážek Unit recorded a rapid, nearly isothermal MP–LP decompression recrystallization at ~340 Ma (Tajčmanová et al. 2006; Verner et al. 2009). In contrast, granulites of the Kutná Hora Unit are characterized by a perfect preservation of kyanite and an absence of newly formed low-pressure mineral assemblages (Synek and Oliveriová 1993; Vrána et al. 2005, 2009) (Tab. 3). The Vír granulite body occurs in a tectonic position between the less metamorphosed Svratka and Polička units; however the estimated P–T path is similar to other Moldanubian granulites (Tajčmanová et al. 2010). In view of the geochronological data of the HP or UHP rocks in the Kutná Hora Unit (the HP crystallization of Běstvina granulite was dated at 360.4 ± 5.3 Ma; U–Pb zircon, R. Nahodilová, personal comm.) and in the Orlice–Sněžník Unit (the UHP/HP metamorphic event is constrained to the age range of 360–369 Ma, Klemd and Bröcker 1999; Mazur et al. 2005 and references therein). We suggest that Kutná Hora Unit can be consid ered as part of the Palaeo-Variscan frame against which rocks of the Moldanubian Zone were exhumed during the Neo-Variscan event (at around 340 Ma; Tajčmanová et al. 2006). This interpretation is an alternative to the earlier accepted opinion of Synek and Oliveriová (1993), who considered the Moldanubian Zone to be a passive paraautochthon unit, upon which the allochthonous partial units of the Kutná Hora Unit were overthrust. Although some geologists refer to the Kutná Hora Unit as belonging to the Gföhl Unit (e.g., Franke 2000; Medaris et al. 2005, 2006, 2009; Faryad 2009; Faryad et al. 2010), it is suggested that use of the latter term should be limited to the Moldanubian Zone. Importantly, the mineral assemblages and mineral chemistry in metasedimentary gneisses and migmatites hosting granulite massifs correspond to metamorphic pressures significantly lower than those of the Variscan granulites. This indicates that individual granulite bodies may mark former major discontinuities, along which granulites were emplaced as allochthonous segments from deeper structures. The role of granulites as tectonic markers is somewhat similar to that of metabasic eclogites and peridotites/lherzolites.

6.2.3. Structural evolution

The structural information for the Palaeo-Variscan (390–355 Ma) HP and UHP events identified on the basis of geochronological data in the Kutná Hora and Orlice–Sněžník Units (R. Nahodilová, unpublished data; Mazurt al. 2005) remains unknown. In the Moldanubian Zone, only a few geochronological data indicate Palaeo-Variscan processes in garnet–pyroxenites and eclogites (Carswell and Jamtveit 1990; Beard et al. 1992), no information is available from metasedimentary complexes. The first well-recorded event of the Variscan geodynamic evolution in the northern part of the studied area (Svratka, Polička and Zábřeh units) were widely distributed WNW–ESE right-lateral, transpressional to transtensional deformations. This event proceeded under T = ~580–650 °C and P = ~0.5–0.7 GPa, in the Polička and Zábřeh units dated by synchronous emplacement of calc-alkaline granitoids at around 352–343 Ma (Vondrovic and Verner 2008, unpublished data; Verner et al. 2009). On a regional scale, a similar kinematic framework was documented along the Teplá–Barrandian/Moldanubian boundary, in this case dated by syntectonic emplacement of the slightly older calc-alkaline Sázava and the high-K calc-alkaline Blatná plutonic suites of the Central Bohemian Plutonic Complex (Janoušek et al. 2004, 2010b; Žák et al. 2005, 2009). In the high-grade Strážek Unit (northeastern part of the Moldanubian Zone), a set of several younger metamorphic fabrics was formed. These reflect partial stages of a very fast exhumation of deep-seated rocks at around 340 Ma: (1) development of relict HP structures in felsic granulites, which correspond to early stages of their lower-crustal evolution dated at 340 ± 1.1 Ma (Schulmann et al. 2005; Tajčmanová et al. 2006); (2) regional, medium-pressure, steeply dipping NNE–SSW foliations reflecting an episode of exhumation (Schulmann et al. 2008); (3) formation of flat-lying fabrics during a sub-vertical shortening of partly exhumed rocks (Verner et al. 2008) and (4) structures of thrusting of Moldanubian rocks over the less metamorhosed or unmetamorphosed rocks of the Moravo–Silesian Zone during lateral indentation of the Brunia continent (Schulmann et al. 2008). In contrast to results of previously published papers (Tajčmannová et al. 2006; Schulmann et al. 2005, 2008), the upper limit for all these events in the NE part of the Moldanubian Zone is age-constrained by the post-tectonic mid- to upper-crustal emplacement of the durbachites (Dosbaba and Sulovský 2006; Verner et al. 2009). Durbachite bodies intruded in the eastern part of the Moldanubian Zone were dated by several authors in the range ~341–323 Ma (Schulmann et al. 2005; Verner et al 2009; Janoušek et al. 2010a; Kotková et al. 2010; Kusiak et al. 2010). However, reliable geochronological data sets from porphyritic Moldanubian durbachites give a clear evidence of emplacement and crystallization of these rocks close to 339 Ma (Verner et al 2008; Janoušek et al. 2010a; Kusiak et al. 2010). On a regional scale, the flat-lying and thrusting fabrics (points 3 and 4 described above) were in the southern part of the overlying Svratka Unit superimposed on older transpressional to transtensional fabrics defined in the Svratka, Polička and Zábřeh units. The initial phase of the extensional tectonics in this part of the Bohemian Massif began somewhat later than ~338–333 Ma, with formation of the NNE–SSW system of HT to LT mylonitized zones (e. g. Přibyslav mylonite Zone; Verner et al. 2006). A good example of the presence of this extensional event is partial low-temperature reworking of the NNE–SSW trending shear zone which separates the less metamorphosed Hlinsko Unit from the Polička and Svratka units (Pitra et al. 1994; Vondrovic and Verner unpublished data). In case of the Orlice–Sněžník Unit (Western Sudetes) a distinct set of various regional fabrics reflecting partial stages of orogenic exhumation by c. ~345 Ma was described (Mazur et al. 2005). However, these exhumation structures have a different character and orientation compared to the presently studied units. Structural relationships between the southern part of the Orlice–Sněžník Unit and the overlying Zábřeh Unit are unclear. The reason could be the spatial occurrence of conspicuous system of right-lateral WNW–ESE fault structures of the “Elbe Zone”, the activity of which is constrained by syntectonic emplacement of the Meissen Massif at 334 Ma and and the intrusion of the Markersbach granite dated at 327 Ma (Hofmann et al. 2008); Linnemann et al. (2008) suggested that the activity started already at around 343 Ma.

References

ANCZKIEWICZ R, SZCZEPANSKI J, MAZUR S, STOREY C, CROWLEY Q, VILLA IM THIRLWALL M, JEFFRIES TE et al. (2007) Lu-Hf geochronology and trace element distribution in garnet: Implications for uplift and exhumation of ultra-high pressure granulites in the Sudetes, SW Poland. Lithos 95: 363-380

BEARD BL, MEDARIS LG JR., JOHNSON CM, BRUECKNER HK, MÍSAŘ Z (1992) Petrogenesis of Variscan high-temperature group A eclogites from the Moldanubian Zone of the Bohemian Massif, Czechoslovakia. Contrib Mineral Petrol 111: 468–483

BECKER H (1997) Sm-Nd garnet ages and cooling history of high-temperature garnet peridotite massifs and high-pressure granulites from Lower Austria. Contrib Mineral Petrol 127: 224-236

BRUECKNER HK, MEDARIS LG, BAKUN-CZUBAROW N (1991) Nd and Sr age and isotope patterns from Variscan eclogites of the eastern Bohemian Massif. Neu Jb Mineral, Abh 163: 169-196

BURIÁNEK D, NĚMEČKOVÁ M, HANŽL P (2003) Petrology and geochemistry of plutonic rocks from the Polička and Zábřeh crystalline units (NE Bohemian Massif). Bulletin of the Czech Geological Survey 78, p. 9–22.

BURIÁNEK D AND PERTOLDOVÁ J (2009) Metamorphism of the calc-silicate rocks in the Moldanubian Zone, Svratka Unit and Polička Unit J Geosci.

BURIÁNEK D, VERNER K, HANŽL P, KRUMLOVÁ H (2009) Petrochemical and microstructural comparison between Cambro-Ordovician metagranites and migmatites of the Svratka Unit and the Orlice-Sněžník Unit. Journal of Geosciences xxx

DRÁBEK M, STEIN H (2003) The age of formation of a marble in the Moldanubian Varied Group, Bohemian Massif, Czech Republic using Re-Os dating of molybdenite. In: Eliopoulos CJ, Spry P, Stein H, Beaudoin G (eds) Mineral Exploration and Sustainable Development. Millpress, Rotterdam, pp 973-976

EDEL JB, SCHULMANN K, HOLUB FV (2003) Anticlockwise and clockwise rotations of the Eastern Variscides accommodated by dextral lithospheric wrenching: palaeomagnetic and structural evidence. Journal of the Geological Society, v. 160, p. 209–218.

FIALA J, FUCHS G, WENDT JI (1995) Moldanubian Zone – Stratigraphy. In: Dallmeyer RD, Franke W, Weber K (eds) Pre-Permian Geology of Central and Eastern Europe. Springer, Berlin, pp 417-428

FRANKE W (2000) The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. In Franke W, Haak W, Oncken O, Tanner D (eds) Orogenic Processes: Quatification and Modelling in the Variscan Belt, Geological Society, London Special Publication 179 pp. 35–63.

GORDON SM, SCHNEIDER DA, MANECKI M, HOLM DK (2005) Exhumation and metamorphism of an ultrahigh-grade terrane: geochronometric investigations of the Sudete Mountains (Bohemia), Poland and Czech Republic. J Geol Soc, London 162: 841-855

HEGNER E, KRÖNER A (2000) Review of Nd isotopic data and xenocryst and detrital zircon ages from the pre-Variscan basement in the eastern Bohemian Massif: speculations on palinspasic reconstructions. In FRANKE W, HAAK W, ONCKEN O, TANNER D (eds) Orogenic Processes: Quatification and Modelling in the Variscan Belt. Geological Society, London Special Publication 179 pp. 113-129

HOLUB FV, MUNSCHI RL (1984) Subsolidus rection rims between the olivine and calcic plagioclase in the Svatý Kříž Massif, eastern Bohemia. Krystalinikum 17: 47–58

HOLUB FV, COCHERIE A, ROSSI P (1997) Radiometric dating of granitic rocks from the CentralBohemian Plutonic Complex (Czech Republic); constraints on geochronology of thermal and tectonic events along the Moldanubian-Barrandian boundary. Comptes Rendus de ‘l Academie des Sciences, Serie II, 325: 19–26

JANOUŠEK V, VRÁNA S, ERBAN V, VOKURKA K, DRÁBEK M (2008) Metabasic rocks in the Varied Group of the Moldanubian Zone, southern Bohemia – their petrology, geochemical character and possible petrogenesis. J Geosci 53: 31-46

KACHLÍK V (1999) Relationship between Moldanubicum, the Kutná Hora Crystalline Unit and Bohemicum (Central Bohemia, Czech Republic): a result of polyphase Variscan nappe tectonics. J Czech Geol Soc 44: 201-291

KRYZA R, PIN C, VIELZEUF D (1996) High-pressure granulites from the Sudetes (South-west Poland); evidence of crustal subduction and collisional thickening in the Variscan Belt. Journal of Metamorphic Geology 14(4):531-546

MAYER A, GERDES A, JANOUŠEK V, ERBAN V, STARIJAS B, FINGER F (2007) The metabasite bodies of the Moldanubian Zone in Lower Austria: geochemistry and zircon ages. In: Venera Z (ed) CzechTec 07. 5th meeting of the Central European Tectonic Studies Group (CETeG) and 12th Meeting of the Czech Tectonic Studies Group (ČTS). Czech Geological Survey, Prague, pp 56-57

MAZUR S, ALEKSANDROWSKI P, SZCZEPANSKI J (2005) The presumed Teplá –Barrandian⁄ Moldanubian terrane boundary in the Orlica Mountains (Sudetes, Bohemian Massif): structural and petrological characteristics. Lithos 82: 85–112

MEDARIS LG, BEARD BL, JOHNSON CM, VALLEY JW, SPICUZZA MJ, JELÍNEK E, MÍSAŘ Z (1995) Garnet pyroxenite and eclogite in the Bohemian Massif: geochemical evidence for Variscan recycling of subducted lithosphere. Geol Rundsch 84: 489–505

MEDARIS G JR., FOURNELLE JH, GHENT ED, JELÍNEK E, MÍSAŘ Z (1998) Prograde eclogite in the Gföhl Nappe, Czech Republic: new eviodence on Variscan high-pressure metamorphism. J Metamorph Geol 16: 563–576

MEDARIS G JR., WANG H, JELÍNEK E, MIHALJEVIČ M, JAKEŠ P (2005) Characteristics and origins of diverse Variscan peridotites in the Gföhl Nappe, Bohemian Massif, Czech Republic. Lithos 82: 1–23

Medaris G, Beard L, Jelinek E (2006**)** Mantle-derived, UHP garnet pyroxenite and eclogite in the Moldanubial Gfohl Nappe, Bohemian Massif; a geochemical review, new P-T determinations, and tectonic interpretation. International Geology Review 48(9):765-777

MELICHAR R, BŘÍZOVÁ E, BURIÁNEK D, ČURDA J, FÜRYCH V, HANŽL P, HRDLIČKOVÁ K, KIRCHNER K, LYSENKO V, MRNKOVÁ J, ROŠTÍNSKÝ P, RÝDA K, SKÁCELOVÁ Z, VÍT J (2008) Basic geological map ČR 1:25 000 with explanation, 24-111 Sněžné. Česká geologická služba, Praha, pp 58 (in Czech)

NAHODILOVÁ R, FARYAD S, PERTOLDOVÁ J, KONOPÁSEK J, ŠTĚDRÁ V (2006) The different metamorphic evolution of HP rocks of the Gföhl unit in Kutná Hora Crystalline Complex against in Moldanubian Zone in Austria. XI. Meeting of the Czech tectonic studies group in Zakopane, Geolines 20: 98-99

NĚMEC D (1980) Fluorine phengites from tin-bearing orthogneisses of the Bohemian-Moravian Heights, Czechoslovakia. Neu. Jb Miner, Abh 139:155-169

NOVÁK JK, VRBOVÁ H (1994) Petrogenesis and geochemistry of mafic rocks from the Kutná Hora Crystalline Complex and the neighbouring part of the Rataje Micaschist Zone. Geolines 4: 1–41

OLIVERIOVA D, SYNEK J, MALUSKI H (1995) Dating middle and late Variscan tectonometamorphic events on the NE rim of the Moldanubian Zone, Kutna Hora crystalline complex; an 39Ar/40Ar study. in Proceedings of the international conference on Thermal and mechanical interactions in deep-seated rocks, Journal of the Czech Geological Society 40(3):35

ONDŘÍK J, HOLUB M, MÍSAŘ M, MOUPIC Z, SCHARMOVÁ M, STEMBERK J, ŠPAČEK J, ZÁLIŠ J (1996) Strážek Unit – south. The final report of exploration on the uranium ore. Geam Dolní Rožínka, DIAMO Stráž pod Ralskem MS-Geofond. Praha (In Czech)

PADĚRA K (1972) Griquaites in the Moldanubicum of the Bohemian Massif. Upper Mantle Project Programme in Czechoslovakia 1962–1970: 51–59

PERTOLDOVÁ J, BURIÁNEK D, HRDLIČKOVÁ K, ČAPEK D, ČOPJAKOVÁ R, SCHULMANNOVÁ B, DUŠEK K, HALODA J, HANŽL P, KONOPÁSEK J, KOPAČKOVÁ V, KOŠULIČOVÁ M, MALEC J, NAHODILOVÁ R, SOEJONO I, SULOVSKÝ P, ŠKODA R, ŠTĚDRÁ V, TÁBORSKÝ Z, TAJČMANOVÁ L, TÝCOVÁ P, VERNER K, VESELOVSKÝ F, VONDROVIC L, VRÁNA S, ZAVŘELOVÁ A, ŽÁČKOVÁ E, ŠRÁMEK J, MELICHAR R (2007) Investigation of litologically contrasting rocks in the crystalline units at the NE margin of the Moldanubian Zone – Continuation of basic geological mapping 1:25000 (in Czech). MS. Archives of the Czech Geological Survey, Prague. (in Czech)

PERTOLDOVÁ J, TÝCOVÁ P. VERNER K, KOŠULIČOVÁ M, PERTOLD Z, KOŠLER J, KONOPÁSEK J, PUDILOVÁ M 2009 Tectonometamorphic history of skarns, origin and age of their protolith and implications for genetic interpretation; an example from the Svratka Unit, the Moldanubian Zone, and the Kutná Hora Unit, Bohemian Massif. J. Geosci

SCHULMANN K, KRÖNER A, HEGNER E, WENDT I, KONOPÁSEK J, LEXA O, ŠTÍPSKÁ P (2005) Chronological constraints on the pre-orogenic history, burial and exhumation of deep-seated rocks along the eastern margin of the Variscan Orogen, Bohemian Massif, Czech Republic. Amer J Sci 305: 407-448

ŠTĚDRÁ V, NAHODILOVÁ R, BURIÁNKOVÁ K (2007) Eclogites and related metabasic rocks. – In: PERTOLDOVÁ J, BURIÁNEK D, HRDLIČKOVÁ K, ČAPEK D, ČOPJAKOVÁ R, SCHULMANNOVÁ, B, DUŠEK K, HALODA J, HANŽL P, KONOPÁSEK J, KOPAČKOVÁ V, KOŠULIČOVÁ M, MALEC J, NAHODILOVÁ R, SOEJONO I, SULOVSKÝ P, ŠKODA R, ŠTĚDRÁ V, TÁBORSKÝ Z, TAJČMANOVÁ L, TÝCOVÁ P, VERNER K, VESELOVSKÝ F, VONDROVIC L, VRÁNA S, ZAVŘELOVÁ A, ŽÁČKOVÁ E, ŠRÁMEK J, MELICHAR R (2007) Investigation of litologically contrasting rocks in the crystalline units at the NE margin of the Moldanubian Zone – Continuation of basic geological mapping 1:25000 (in Czech). MS. Archives of the Czech Geological Survey, Prague. (in Czech)

ŠTĚDRÁ V, NAHODILOVÁ R (2009) High-pressure metabasic rocks from the Kutná Hora Crystalline Unit, Czech Republic: structural position, geochemical characteristics and metamorphic record of exotic lithologies along the segmented Moldanubian margin, Bohemian Massif J Geosci 54 (2): NN

ŠTĚDRÁ V (ed) (2009) Basic geological map ČR 1:25 000 with explanation, 13324 Kutná Hora. Česká geologická služba, Praha, (in Czech).

ŠTOUDOVÁ S, SCHULMANN K, KONOPÁSEK J. (1999) A Contrast between Metamorphic and Structural Evolution of the Vír Granulite and Surrounding Rocks of the Polička Crystalline Unit. Geolines 8: 64

SYNEK J, OLIVERIOVA D (1993) Terrane character of the north-east margin of the Moldanubian Zone: the Kutna Hora Crystalline Complex, Bohemian Massif. Geologische Rundschau 82(3):566-582

TAJČMANOVÁ L, KONOPÁSEK J, SCHULMANN K (2006) Thermal evolution of the orogenic lower crust during exhumation within a thickened Moldanubian root of the Variscan belt of Central Europe. J Metamorph Geol 24: 119–134

VERNER K, ŽÁK J, HROUDA F, HOLUB FV (2006) Magma emplacement during exhumation of the lower- to mid-crustal orogenic root; the Jihlava syenitoid pluton, Moldanubian Unit, Bohemian Massif. Journal of Structural Geology 28(8):1553-1567

VERNER K, ŽÁK J, NAHODILOVÁ R, HOLUB FV (2008) Magmatic fabrics and emplacement of the cone-sheet-bearing Knizeci Stolec durbachitic pluton (Moldanubian Unit, Bohemian Massif); implications for mid-crustal reworking of granulitic lower crust in the Central European Variscides. International Journal of Earth Sciences 97(1):19-33

VERNER K, BURIÁNEK D, VRÁNA S, VONDROVIC L, PERTOLDOVÁ J, HANŽL P, NAHODILOVÁ R (2009) Lithological and structural features of geological units along the northern periphery of the Moldanubian Zone: A review of the geology of the Northeastern Variscides J Geosci…

VONDROVIC L, VERNER K (2008) The record of structural evolution and U-Pb zircon dating of the tonalite intrusions (Polička Crystalline Unit, Bohemian Massif). In Poblet J., Medina M., G., Pedreira D., Fernández, C., L.: Programme and Extended abstracts, International Meeting of Young Researches in Structural Geology and Tectonics. University of Oviedo, Spain p. 369-373

VRÁNA S, ŠTĚDRÁ V, FIŠERA M (2005) Petrology and geochemistry of the Běstvina granulite body metamorphosed at eclogite facies conditions, Bohemian Massif. J Czech Geol Soc 50: 95-106

VRÁNA S, ŠTĚDRÁ V, NAHODILOVÁ R (2009) Geochemistry and petrology of high-pressure albite-K-feldspar kyanite-garnet felsic gneisses and granulites from the Kutná Hora Unit. J Geosci 54 (2): NN

Paper No. III.

BURIÁNEK, D. - VONDROVIC, L. - VERNER, K. (2015) TECTONOMETAMORPHIC EVOLUTION AND GEOCHRONOLOGY OF THE POLIČKA UNIT (NE BOHEMIAN MASSIF): FROM SUCCESSIVE OBLIQUE COLLISION TO CRUSTAL EXHUMATION

Early stage article manuscript

Original paper

Tectonometamorphic evolution of the Polička Unit (NE Bohemian Massif): from successive oblique collision to crustal exhumation

DAVID BURIÁNEK[1*], LUKÁŠ VONDROVIC[2,3] ,KRYŠTOF VERNER[2,3]

[1]*Czech Geological Survey, Leitnerova 22, Brno 65869, Czech Republic; david.burianek@geology.cz*

[2]*Czech Geological Survey, Klárov 3, Prague 1, 11821, Czech Republic;*

[3] *Institute of Petrology and Structural Geology, Charles University, Albertov 6, Prague, 12843, Czech Republic*

* *Corresponding author*

Keywords: European Variscides; Bohemian Massif, Polička Unit; metamorphic evolution; metapelites.

Running title: Tectonometamorphic evolution of the Polička Unit

1. Introduction

The Variscan Late Devonian to Early Carboniferous collision of Gondwana-derived microcontinents with the Old Red continent (for a general review, see Franke 2000; Schulmann et al. 2009; Žák et al. 2014) created the geological framework of the Bohemian Massif (Central European Variscides, Fig. 1a). During this episode the upper- to mid-crustal Neoproterozoic to lower-Palaeozoic? volcanosedimentary sequence of the north eastern flank of the Bohemian Massif (Polička Unit, eastern Teplá-Barrandian Zone) outcrops between two different domains of medium to high-grade rocks – the eastern Saxothuringian Zone (Western Sudetes) and the Moldanubian Zone. During the Variscan orogeny this upper- to mid-crustal segment was affected by three distinct regional geodynamic events related to successive continental collisions followed by the exhumation of deep-seated rocks from both the high-grade domains (e.g. Verner et al. 2009). Initially, polyphase ~NW-SE right-lateral transpressional shearing along the Elbe Shear Zone with the syntectonic emplacement of calc-alkaline granitoids (Pertoldová et al. 2011; Žák et al. 2014) was followed by the oblique ~NNE-SSW underthrusting of the Brunia microcontinent and the roughly synchronous exhumation and unroofing of thickened Moldanubian crust (e.g. Schulmann et al. 2009, 2014). We propose that comprehensive structural analysis and the reconstruction of both the metamorphic pattern and the careful structural analysis lead to a better understanding of the geological processes which created these collisional belts. This study, based on extensive field structural data and the results of thermodynamic P-T modelling concerning the Polička Unit and its surroundings, aims to interpret the Variscan geodynamic evolution of the eastern termination of the Bohemian Massif.

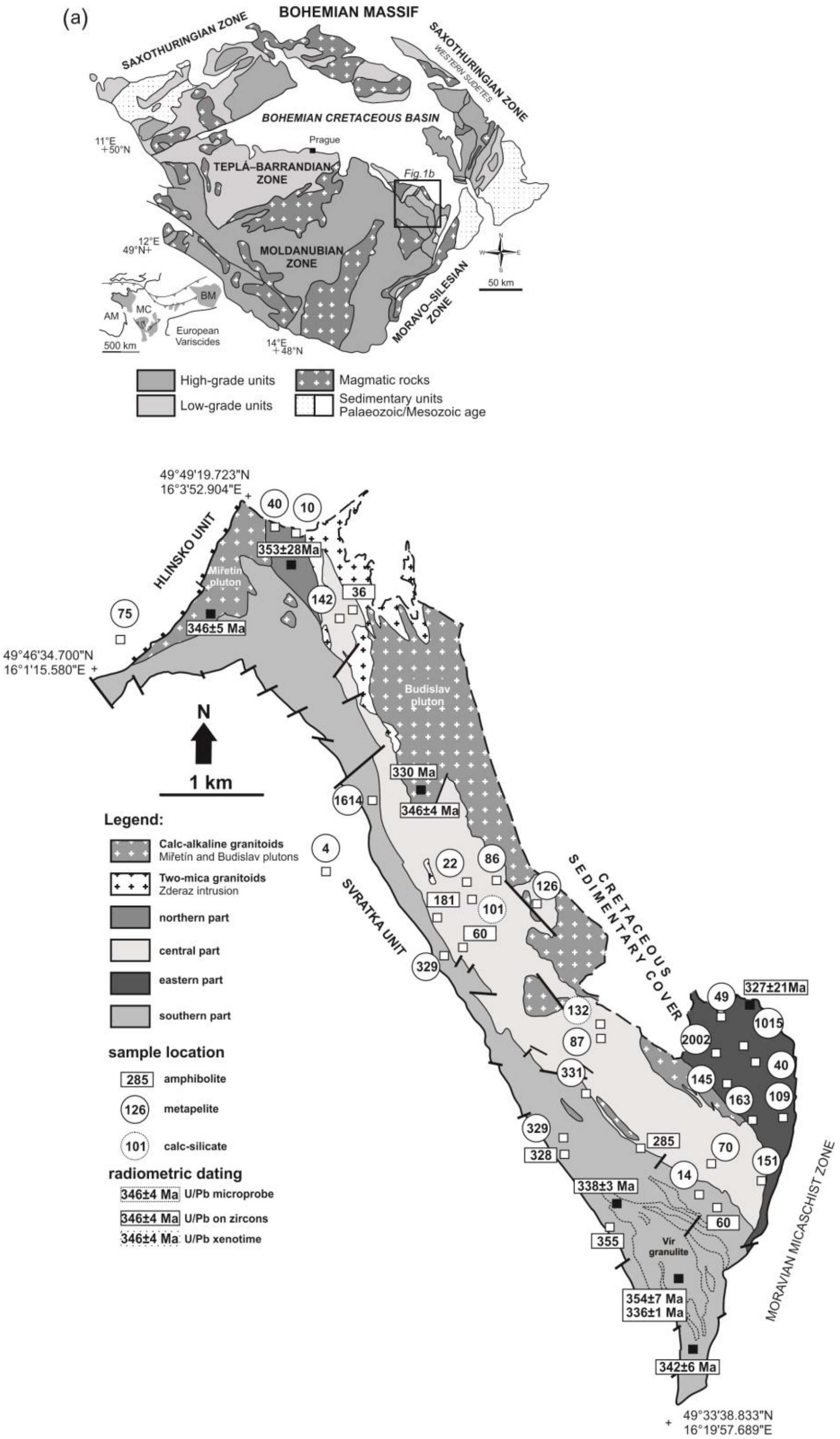


Fig. 1 a) Simplified geological map of the Bohemian massif, b) Simplified geological map of the Polička Unit with sample locations (modified from: Buriánek ed. 2009, Čech ed. 2009, Hanžl ed. 2008, Stárková and Macek 1994).

2. Geological pattern

The low- to medium-grade volcanosedimentary rocks of the Teplá-Barrandian Zone as an assumed relic of the Cadomian orogenic wedge (Hajná et al. 2011) were tectonically incorporated between lower- to mid-crustal units of the eastern Saxothuringian Zone (Western Sudetes) and the Moldanubian Zone during an early Variscan compressional (transpressional) episode (Verner et al. 2009). The Polička Unit (Fig. 1) studied herein makes up part of the eastern section of this segment (Mísař et al. 1983, Melichar 1995; Fig. 1). In contrast to the western Teplá-Barrandian Zone, the eastern part (eg. the Hlinsko, Polička and Zábřeh Units) experienced a relatively higher metamorphic overprint under ~LP to MP / MT conditions and successive deformational events (Schulmann et al. 2005; Pertoldová et al. 2010). Lithologically the Polička Unit is composed predominantly of Neoproterozoic to Lower Palaeozoic metamorphosed flysch sediments locally with elongated bodies of calc-silicate rocks, marbles and prevailing metavolcanic rocks of tholeiitic composition (Kodym and Svoboda 1950; Svoboda 1956; Melichar and Hanžl 1997). This metamorphosed sequence was syntectonically intruded by granodiorites to tonalites of calc-alkaline composition (Buriánek et al. 2003), i.e. the Budislav and Miřetín Plutons dated at ~346Ma (U-Pb on zircons, Vondrovic et al. in rew). Recent investigation work has indicated a significant difference in the lithology and metamorphic history of rocks from various parts of the Polička Unit (Melichar 1995; Buriánek et al. 2003; Buriánek and Pertoldová 2009; Verner et al. 2009; Tajčmanová et al. 2010; Pertoldová et al. 2010) which is divided into four segments (Fig. 1) based principally on differences in lithology and metamorphic pattern (Melichar 1995): (a) medium-grained biotite and two-mica migmatites with bodies of leucocratic metagranites, amphibolites, marbles and associated calc-silicate rocks outcropping along the underlying Svratka Unit (southern part), (b) a sequence of medium-grained paragneisses with calc-silicate rocks, intercalations of metaconglomerates and abundant granitoids (central part), (c) metagreywackes with intercalations of phyllite and fine-grained metaconglomerates (northern part) and (d) a complex of mica schist with quartzite and paragneiss intercalations (eastern part). The presence of amphibolites with MORB signatures (Melichar and Hanžl 1997) in the southern part of the unit suggests the importance of this contact as a possible suture zone flanking the border of the Tepla-Barrandian domain (Mazur et al. 2005, Propach and Pfeiffer, 1998). Put simply, the Polička Unit underwent regional metamorphism at T = ~580–680°C and P = ~0.5-0.7GPa with an increasing degree of metamorphism from the northwest to the southeast as well as from north to south.

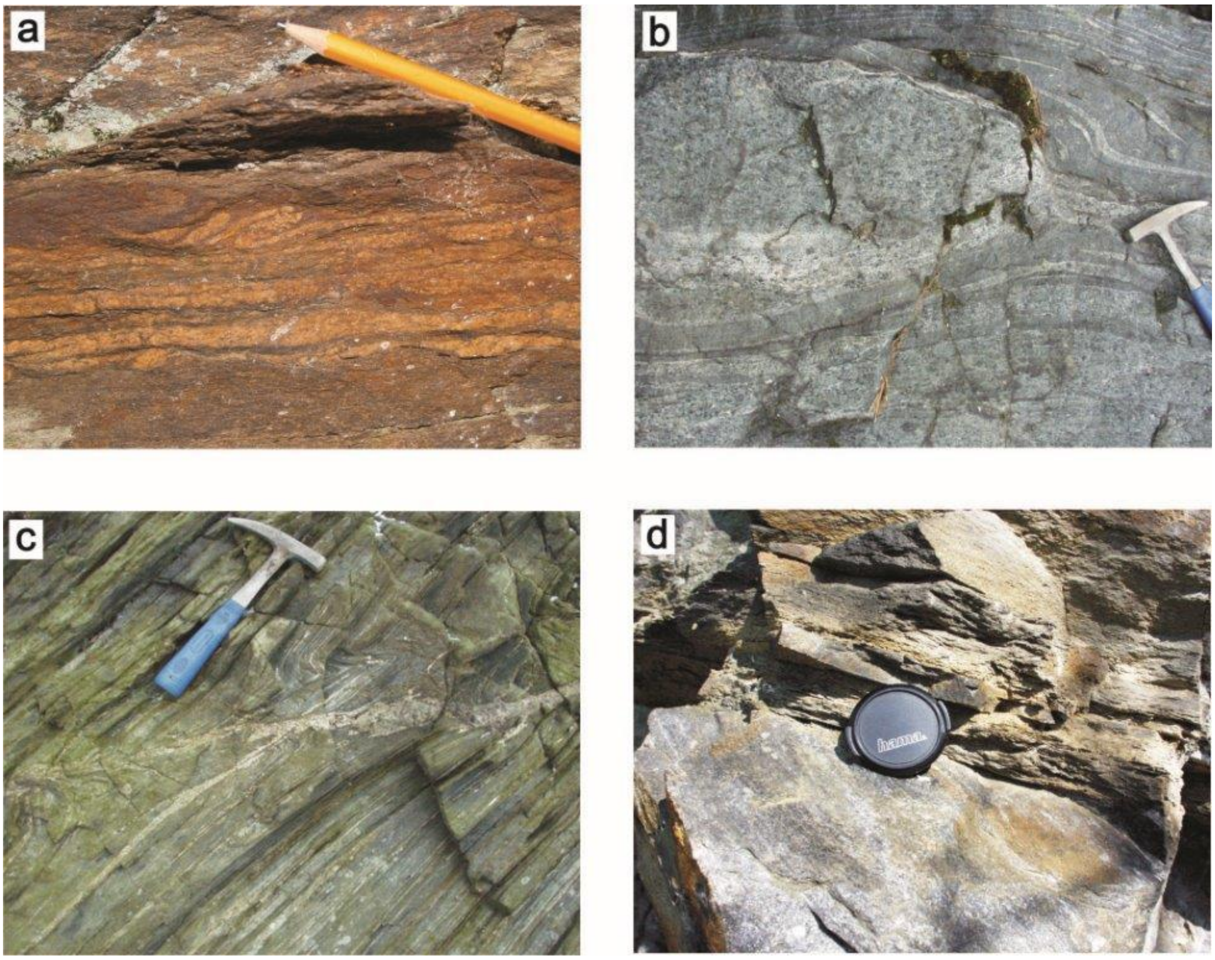


Fig. 2 Field photo: a – relic fabric within regional foliation (393, Hluboké); b – coarse-grained amphibolite boudin from lover amphibolite belt (355, Korouhvice). c – anatectic melt in amphibolite (Nedvězí), d) the relationship between two distinct metamorphic fabric D_1 and D_3

3. Methods

The chemical analysis of the minerals was performed using a Cameca SX-100 electron microprobe at the Joint Microprobe Laboratory of the Masaryk University and the Czech Geological Survey in Brno. Measurements were taken in wave dispersion mode under the following conditions: 15kV acceleration voltage, 5µm electron beam diameter, 30nA current and an integration time of 20 seconds. Augite (Si, Mg), orthoclase (K), jadeite (Na), chromite (Cr), almandine (Al), andradite (Fe, Ca), rhodonite (Mn), and TiO (Ti) were used as standards. The crystallochemical formula of garnet was calculated on the basis of 12 and that of staurolite 46 oxygen atoms. The crystallochemical formulae of feldspar were recalculated to 8 and those of micas to 22 oxygen atoms. The amphibole formulae were calculated assuming 23 O, 2 (OH, F, Cl) and Fe^{3+} and were estimated using the 13 eCNK (Leake et al. 1997) recalculation method; the mineral abbreviations employed are according to Kretz (1983). The THERMOCALC program was used for the calculation of P–T conditions in the metapelites. The THERMOCALC program v. 2.7 was run in average P–T mode using the data set (8 December 1997) and activities from the AX program (Holland and Powell 1998). The pseudosection for a selected metapelite sample (LV40) was calculated using the PERPLEX program (Connolly 1990) and the assemblages were computed using VERTEX (Connolly 1990). The following solid solution models were employed: chlorite (Holland et al. 1998), plagioclase (Newton et al. 1980) and other minerals (Holland and Powell 1998). The temperatures of the amphibolites were computed by means of an amphibole–plagioclase thermometer using amphibole and plagioclase rim compositions (Holland and Blundy 1994). The mineral compositions were restricted to amphiboles which have Na^{A}>0.02pfu, Al^{VI}>1.8pfu, Si in the range 7.0 – 6.0pfu and plagioclases with X_{an} > 0.1 and <0.9. The thermometer was calibrated in the range 400–1000°C and 0.1–1.5GPa.

4. Lithology and petrology

The rocks of the southern part are predominantly exposed along the boundary with the underlying Svratka Unit. This segment is represented by dominant medium-grained biotite to muscovite-biotite gneisses and migmatites (Fig. 2a, Qtz + Bt + Pl ± Kfs ± Ms ± Sil ± Grt ± Tur) with strongly deformed bodies of metagranitoids (Qtz + Ms + Pl + Kfs ± Bt), amphibolites (Amp + Pl ± Qtz), marbles (Cal ± Dol ± Phl ± Tr ± Cpx ± Qtz ± Pl) and calc-silicate rocks (Cpx + Pl + Ttn ± Kfs ± Czo ± Grt ± Qtz ± Amp ± Cal). Amphibolite bodies are situated along the contact between the southern and central part as well as along the contact between the Svratka Unit and the southern part. The dominant rock type consists of medium-grained foliated amphibolite locally with several-centimetre-thick layers and lenses of calc-silicate rock and cummingtonite amphibolites. Several-metre-thick coarse-grained, granoblastic metagabbros boudins parallel to foliation and intercalated within medium-grained nematoblastic amphibolites are common near to contact with granulite bodies (Fig. 2b). Elongated bodies of marbles up to 0.5km long are present along the boundary between the southern and central parts of the eastern part of the Polička Unit (according to Novák 1987).

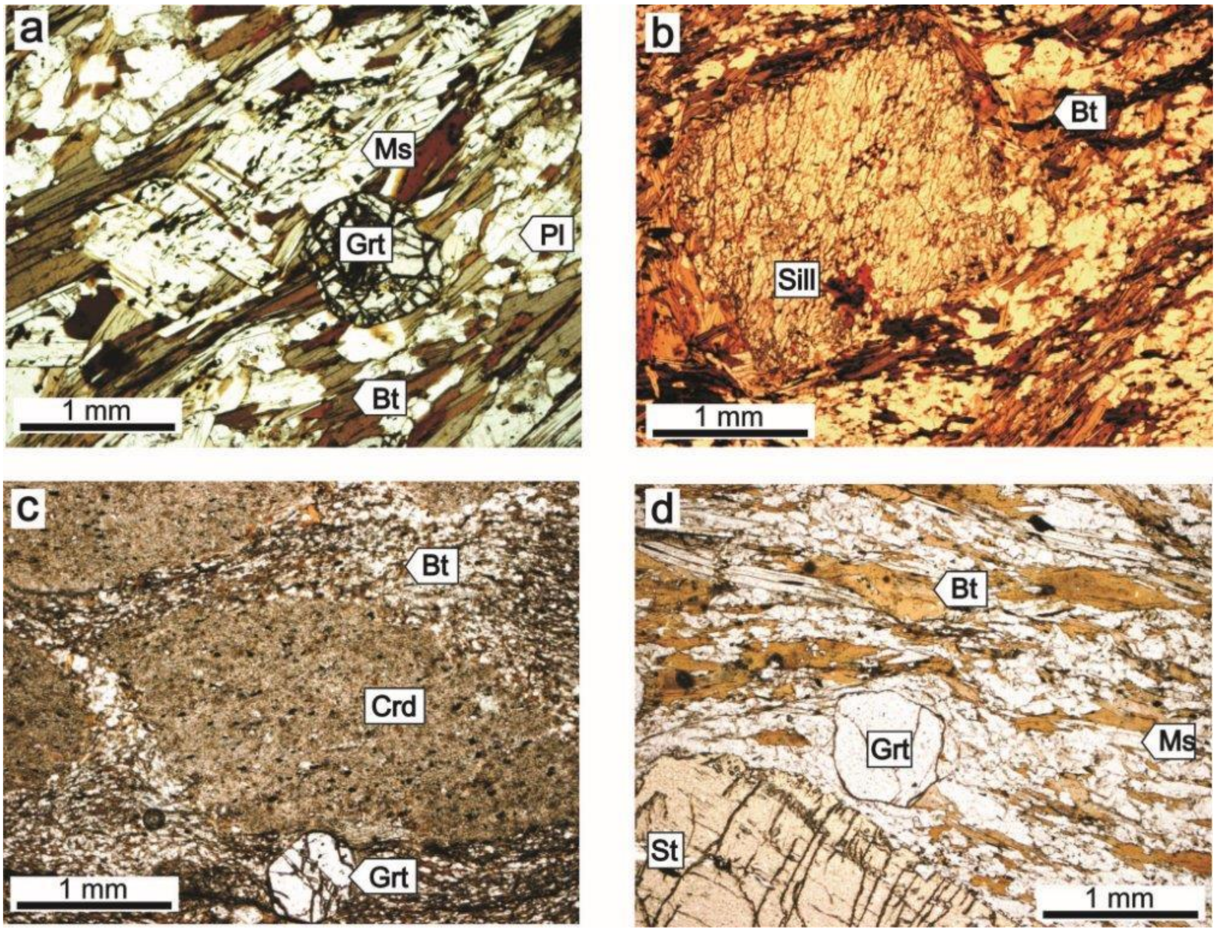


Fig. 3 Microphotographs and back-scattered electron (BSE) images a – Garnet porphyroblast inside foliation (D_1) in the gneiss (DB305, Korouhev), central part; b – pseudomorph sillimanite after andalusite in the muscovite-biotite gneiss, central part (DB092, Oldříš); **c** – Pinitized cordierite poikiloblast from contact hornfels from northern part (40, Peralec); d – Staurolite and garnet porphyroblasts in mica schist from eastern part (188, Stašov). Location of studied samples is in Fig. 1b.

HP felsic granulites of the Vír area (Grt + Bt + Pl + Kfs + Qtz ± Ky ± Sill) outcrop in the SE flank of the Polička Unit with minor domains made up of intermediate granulites (Opx + Grt + Bt + Pl + Kfs + Qtz ± Cpx) (Tajčmanová et al. 2010). The central domain of the Polička Unit is composed of a monotonous complex of medium-grained biotite to muscovite-biotite paragneisses (Fig. 3a) with intercalations of metaconglomerates and locally-abundant calc-silicate nodules (Di + Pl + Qtz ± Cal ± Czo ± Ttn ± Amp ± Grt) up to 0.5m in size as well as rare medium- to fine-grained amphibolites. Sillimanite within the paragneisses occurs as elongated needle aggregates or as pseudomorphosis after andalusite (Fig. 3b).

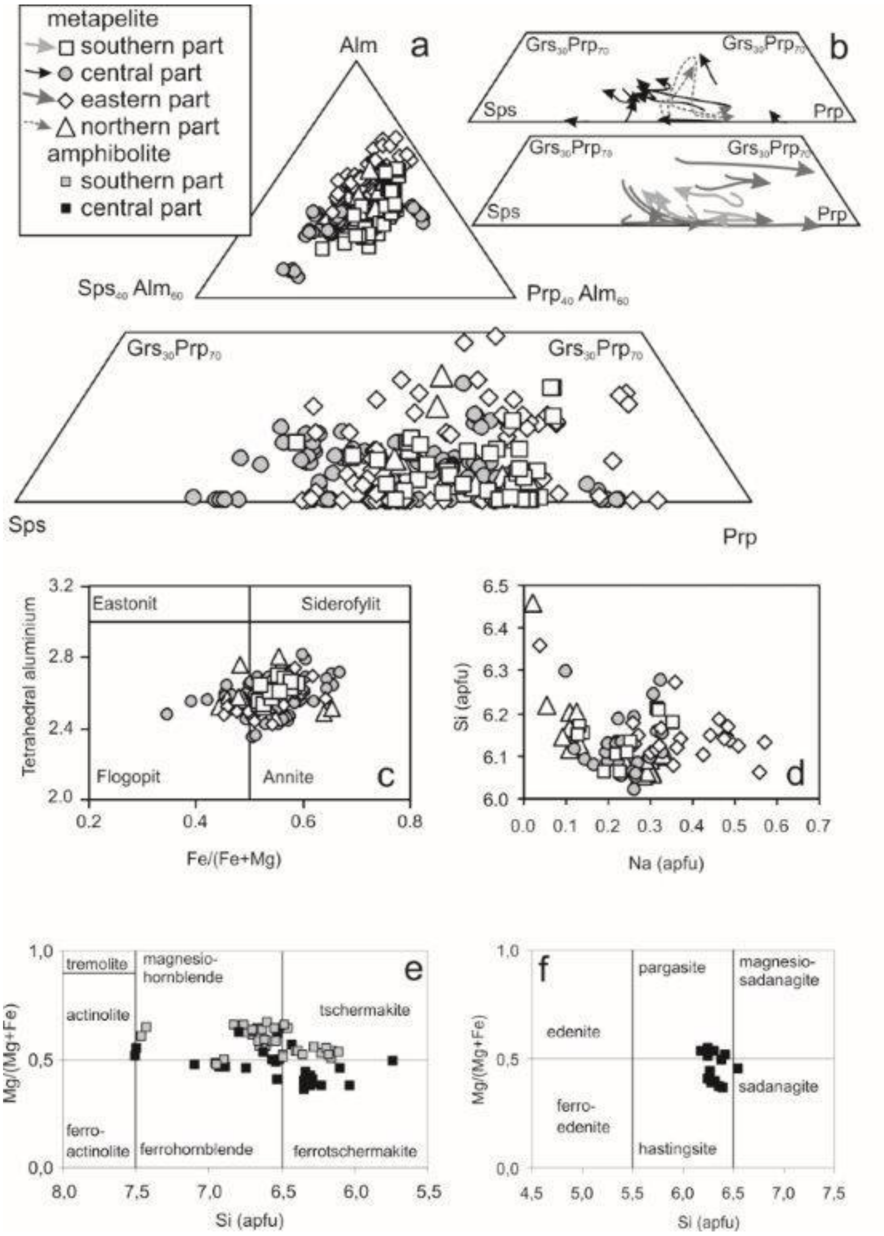


Fig. 4 Classification diagrams for rock forming minerals: a – composition of garnet from metapelites b – Simplified garnet zonation arrow represent direction from rim to core; c – Fe/Fe+Mg and tetrahedral aluminium diagram for biotites from metapelites; c – Fe/Fe+Mg and tetrahedral aluminium diagram for biotites from metapelites; c – Fe/Fe+Mg and tetrahedral aluminium diagram for biotites from metapelites; Na and Si diagram for muscovite from metapelites; d-e – classification of the amphiboles (Leake et al., 1997).

The low-grade metamorphosed northern part is composed of metagreywackes with intercalations of cordierite-andalusite hornfelses and fine-grained conglomerates. The eastern part of the Polička Unit is made up of a metasedimentary sequence consisting of micaschists (Fig. 3d; Qtz + Ms ± Bt ± St ± Grt ± Sill ± Pl ± Ky) with graphitic quartzite and paragneiss intercalations. Abundant graphitic gneisses and quartzites occur along the boundary with the central part (Buriánek 1999).

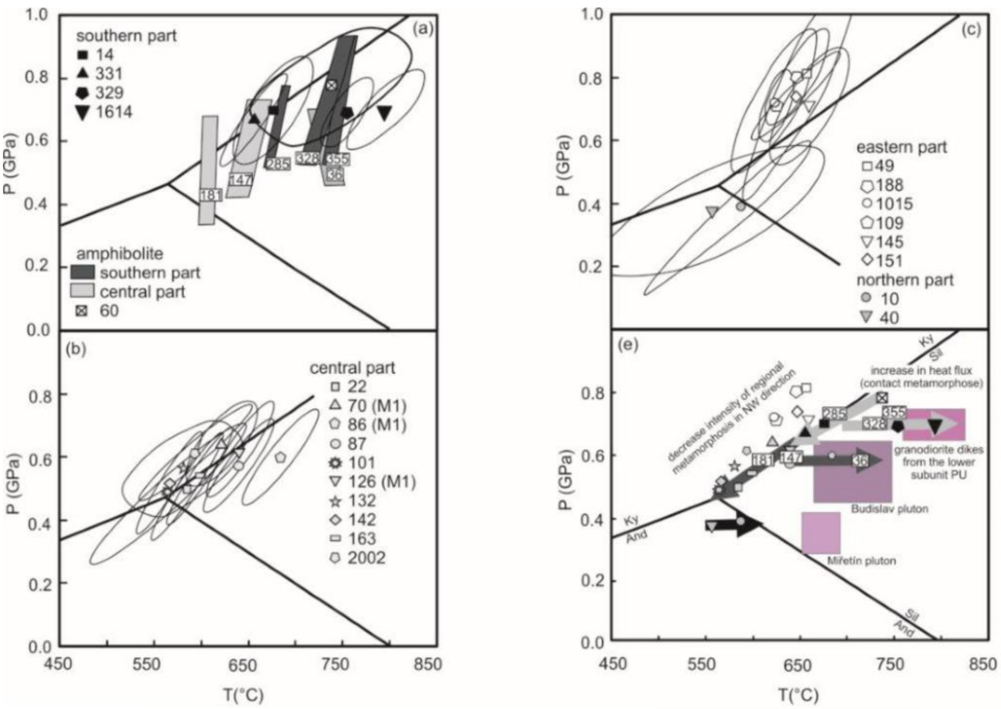


Fig. 5 Selected average thermobarometric data from metapelites, calc-silicate rocks and amphibolites (a-c) calculated using „optimal thermobarometry“ approach of Powell and Holland (1994), average pressure-temperature (P-T) estimates with (symbols) 2σ uncertainties (ovals) and amphibole-plagioclase thermometer (gray-filled field) Holland and Blundy (1994). b – summary of P–T paths for rocks of the different parts of the Polička unit: arrows indicates increase intensity of regional metamorphosis in SE direction and influence of the tonalite intrusions (P-T conditions of crystallization tonalite intrusions according Buriánek et al. (2003) and Vondrovic et al. (2010, 2011). The Al_2SiO_5 univariant curves are according to Holdaway (1971) and Pattison et al. (1992).

5. Mineral chemistry-selected rock forming minerals

Garnet compositional trends are plotted in Fig. 4 where the four groups correspond to different PU segments. Garnet from the migmatite southern part of the Polička Unit is compositionally zoned ($Alm_{60–72}$ $Sps_{11–30}$ $Pyr_{5–17}$ $Grs_{1–5}$) and the central part of the grains is characterised by relatively high Grs and Sps content (Fig. 4a). The transition towards the outer part of the garnet is marked by a continuous decrease in Grs and Sps and the outer zone is characterised by smoothly decreasing Prp content (Fig. 4b). Garnet zonation in the paragneisses of the central part (Fig. 4b) is restricted to a small retrograde rim with slightly higher Sps and X_{Fe} and lower Prp content compared to the core ($Alm_{61–79}$ $Sps_{7–28}$ $Pyr_{8–17}$ $Grs_{0–4}$ $Adr_{3–1}$). Garnet porphyroblasts in andalusite-cordierite hornfels of the northern part exhibit weak zoning (Fig. 4a, b) principally within the almandine and spessartine components ($Alm_{70–78}$ $Prp_{10–14}$ $Sps_{5–12}$ $Grs_{1–7}$ $Adr_{0–5}$). Biotites from all parts of the PU exhibit a similar chemical composition (^{IV}Al = 2.35-2.80apfu; Fe/(Mg + Fe) = 0.35–0.59; Fig. 4c). Younger recrystallised biotite from small shear zones in the gneiss of the central part is characterised by a lower content of Ti (0.15-0.20apfu) than in the dominant biotite (Ti = 0.22-0.40apfu). The muscovite from migmatite in the southern part (Si 6.06–6.13 and Na 0.22–0.25apfu; Fig. 4d), except for younger muscovite after sillimanite (Si 6.15–6.17 and Na 0.13–0.14apfu; Fig. 4d), exhibits a similar chemical composition to that of the muscovite from paragneisses in the central part (Si 6.02–6.00 and Na 0.10–0.33apfu; Fig. 4d). Micaschist in the eastern part contains muscovite with higher contents of Na (Si 6.06–6.27 and Na 0.26–0.57apfu). The primary muscovite from the metagreywacke in the northern part is typically characterised by higher Si (6.12–6.22apfu) and lower Na (0.05–0.13apfu) content than that of secondary muscovite which forms pseudomorph after cordierite (Si 6.05–6.13 and Na 0.24–0.34apfu; Fig. 4d). With concern to the amphibolite of the southern part, magnesiohorblende and tschermakite (Fig. 4e-f; Mg/(Fe+Mg) = 0.36–0.67; Si = 5.74–7.51apfu) dominate as opposed to ferrotschermakite, hastingsite and pargasite (Fig. 4e-f; Mg/(Fe+Mg) = 0.37–0.62; Si = 6.18–6.79apfu) in the amphibolite of the central part.

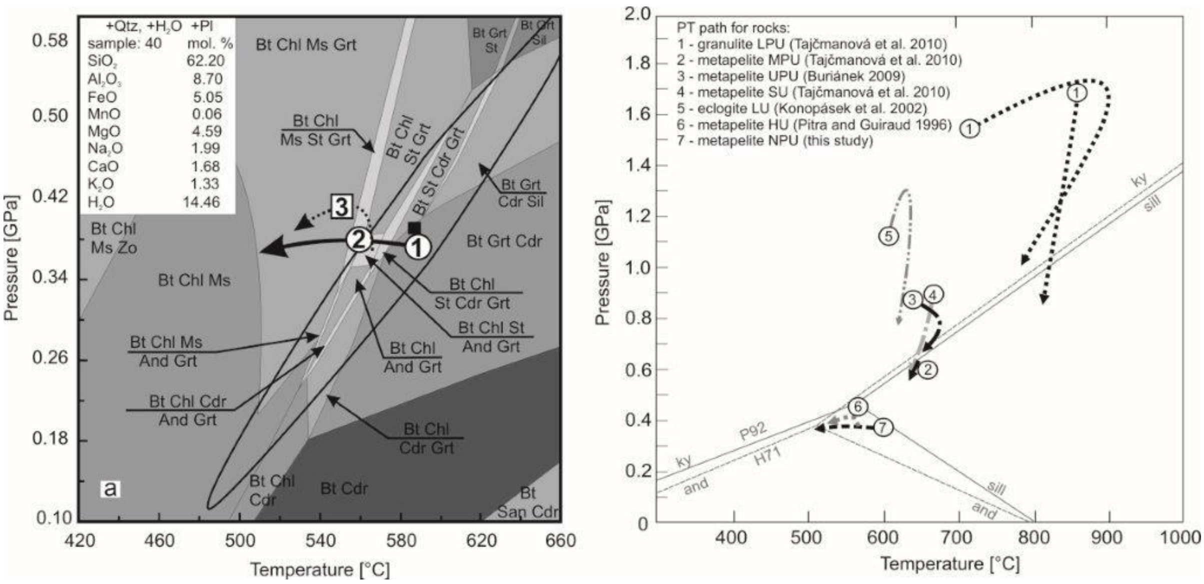


Fig. 6 P-T conditions metamorphosis for rocks from Polička Unit: a – T–P pseudosection for metapelite from the northern termination of the Polička Unit (sample 40) calculated in the MnNCKFMASH system using the PERPLEX software. The bulk-rock composition (in wt. %) used for the calculation is indicated in the bottom part of the plot. The light grey, medium grey and dark grey fields are tri-, quadri- and quintivariant fields, respectively. The dark arrow shows the assumed P-T path for sample 40 and the white circle corresponds to mineral assemblage Crd-Bt-Grt (+Pl, +Qtz) (1) and (2) corresponds to P-T conditions calculated for the matrix mineral assemblage Bt-Ms-Chl-Grt-St (+Pl, +Qtz) using the average P-T mode in THERMOCALC. Arrow 3 indicates PT path for metapelites from Hlinsko Unit (Pitra and Guiraud 1996). The label (dark square) enclosed in oval indicate P-T conditions calculated for matrix mineral assemblages of sample 10 using the average P-T mode in THERMOCALC; b – P- T paths of individual samples from calculated by several authors for different parts of the Polička Unit and surrounding geological units.

6. Field structural pattern

The structural pattern of the Polička Unit and its surroundings is defined by the superposition of regional fabrics reflecting successive stages of Variscan geodynamic evolution in the peripheral part of the Variscan orogenic root (Moldanubian Unit) The oldest pervasive compositional banding, including scarce relics of rootless and isoclinal folds, is well developed primarily in the central and south-eastern part of the Polička Unit. Corresponding steeply to moderately NNE to ENE dipping D_1 foliation bears well-developed, gently plunging NW (SE) to WNW (ESE) stretching or mineral lineation (e.g. the lattice preferred orientation of newly-formed micas, elongated and recrystallised quartz and feldspar aggregates). Associated kinematic indicators such as the asymmetry of isoclinal folds, recrystallised mineral aggregates in pressure shadows and mica-fishes indicate right-lateral shearing parallel to stretching lineation. In the eastern and western parts of the Polička Unit the fabrics described above were transposed into steeply to moderately W to WNW dipping D_2 foliation (Fig. 7). The associated stretching lineation and fold axes plunge predominantly at low angles to the NW to N. The heterogeneous superimposition of retrograde metamorphic D_3 foliation defined as the irregular banding of the partly recrystallised original metamorphic assemblage dipping gently to moderately ~N to ~NNE was observed in certain narrow zones across the Polička Unit (Fig. 7). This foliation often contains mineral and stretching lineation with normal kinematic indicators. The calc-alkaline Budislav Pluton (dated at ~346 Ma, Vondrovic et al. in prep.) exhibits a ~NW to ~SE elongated shape and its intrusive contacts are primarily parallel to well-developed transitional magmatic to solid-state foliations dipping steeply to moderately to the ~NNE or ~SSW. Gently ~NW or SE plunging mineral lineations were identified in a number of locations. In contrast, the Miřetín Pluton (dated at 346Ma; Vondrovic et al. 2011) was emplaced in the less metamorphosed north-western part (southern part) of the Polička Unit (Fig. 7). The preserved transitional submagmatic to subsolidus foliation dipping under moderate angles to the WNW revealed similarities with the orientation of superimposed (second) regional metamorphic fabric, the ~NW contact of which was strongly affected by later normal faulting and LT sub-solidus deformation (Vondrovic et al. 2011).

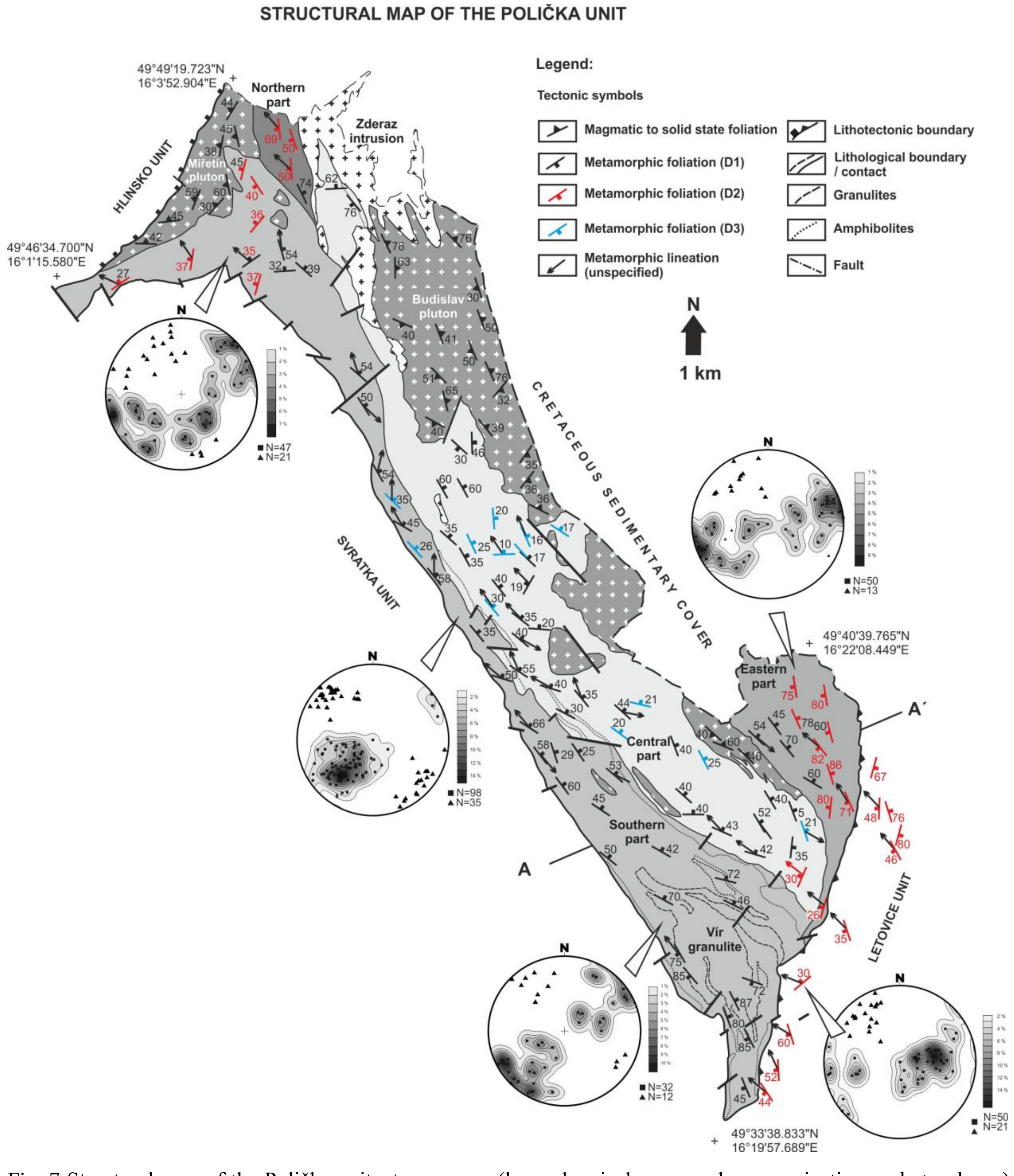


Fig. 7 Structural map of the Polička unit, stereograms (lower hemisphere, equal area projection, pole to planes) of foliations (squares) and lineations (triangles).

7. P-T evolution

Polička Unit

The variability of the lithology of individual parts of the unit exhibits a strong correlation with P-T evolution (Fig 5a-c). The intensity of regional metamorphism in the southern and central parts increases systematically towards the SE; moreover, the rocks of the southern, central and northern parts were affected by contact metamorphism associated with intrusions of calc-alkaline granitoids (Fig 5c). The Miřetín Pluton intruded at a higher crustal level (653–681°C and 0.3–0.4Gpa; Vondrovic et al. 2010, 2011) than the Budislav Pluton (559–750°C and ~ 0.5Gpa; Buriánek et al 2003, Vondrovic et al. 2010).

The average P-T conditions of metamorphism calculated for gneisses and migmatites with the association Pl + Bt + Ms ± Kfs + Qtz + Sil + Grt from the southern part of the PU are: 654–795°C and ~ 0.7Gpa (Buriánek et al. 2009). The garnet amphibolite situated close to the granulite body exhibits average P-T conditions of ~ 740°C and P ~ 0.8Gpa (Fig 5a). Metamorphic conditions of 720°C to 750°C for amphibolite along the contact zone with the Svratka Unit and 678°C to 688°C for amphibolite close to contact with the central part of the PU (both with a pressure of 0.7Gpa) were estimated by means of amphibole–plagioclase thermometers (Holland and Blundy 1994).

The metamorphic assemblage within the metapelites of the central part of the PU equilibrated at 564–684°C and 0.5–0.6GPa (Fig 5b). Metapelites from the southeast section (~ 640°C and P ~ 0.6Gpa) exhibit a higher metamorphic grade than rocks in the northern termination of the central part of the PU (~ 570°C and P ~ 0.5Gpa; Fig 5b). Metapelites near to the contact zone with calc-alkaline intrusions indicate slightly higher temperatures (~ 620–680°C and P ~ 0.6Gpa). Relics of sillimanite pseudomorphs after andalusite point to the occurrence of an older LP metamorphic event (Buriánek et al. 2003). Calculation performed by means of amphibole–plagioclase thermometers (Holland and Blundy 1994) revealed temperatures of 593°C to 673°C at a pressure of 0.5Gpa for the amphibolite belt situated along the contact zone with the southern part of the PU. These calculations also confirmed an increase in temperature towards the SE in the upper amphibolite belt with the sole exception of the sample taken from Proseč (~ 740°C) which was affected by contact metamorphosis. The average P–T peak conditions for phyllite from the northern part of the PU near the village of Perálec were determined at 585 ± 80°C and 0.39 ± 0.22GPa (Fig 5c). The older stable mineral assemblage corresponds to the Crd + BtI + Grt + Pl + Qtz field which was partially replaced by a new mineral assemblage consisting of BtII + Ms + Chl + Grt + St + Pl + Qtz. Average P–T calculations for the metamorphic assemblage in the matrix yielded 561 ± 96°C and 0.37 ± 0.17Gpa which is consistent with the position of the Bt-Ms-Chl-Grt-St field in the P–T pseudosection (Fig. 6a). The eastern part (Fig 5c of the Polička Unit indicates peak metamorphic conditions of T ~ 650°C and P ~ 0.8Gpa (Qtz + Ms + Bt + Pl + St + Grt) followed by a younger overprint at 625–660°C and ~ 0.7GPa (Qtz + Ms + Bt + Pl + Grt + Pl ± Ky ± Sill). The intensity of the MP-MT retrograde metamorphic overprint increases towards the central part of the PU.

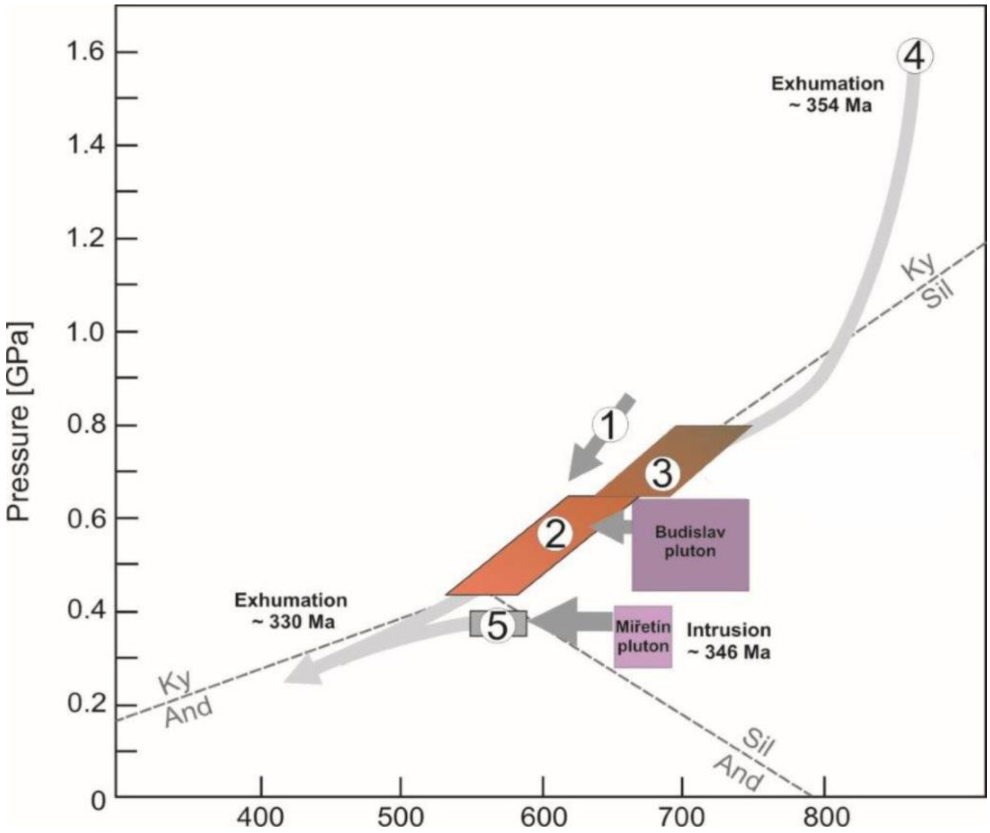


Fig. 8 P–T–t paths for the individual parts of the Polička Unit: 1 – Eastern part (Buriánek 2009), 2 – Central part, 3 – Southern part, 4 – Granulite (Tajčmanová et al 2010), 5 – Northern part. The Al_2SiO_5 univariant curves are according to Holdaway (1971).

8. Discussion

8.1. Metamorphic evolution

According to new petrological and structural data from the Polička Unit and its surroundings we assume a Variscan tectonometamorphic evolution with broad implication for the northeastern part of the Bohemian massif. The Polička Unit was divided into four domains based on differences in lithology, structural pattern and P-T data. The southern part with presence of high-pressure felsic granulites and complex structural pattern can be interpreted as the lowest part of the unit. Peak metamorphic conditions of the granulites were estimated at T: 860–1000 °C and P: 1.6 Gpa in 354 Ma (Tajčmanová et al. 2010). The exhumation of granulites to the mid crustal levels dated at ~338 Ma (Tajčmanová et al. 2010) These processes were broadly associated with partial melting of host metasediments and amphibolites at around 342 Ma (Schulman et al 2005). Stable mineral assemblages in the migmatitised gneisses (Qtz + Pl + Bt + Grt + Sill ± Kfs) and amphibolites (Amp + Pl ± Bt ± Grt) indicate T: 650–800 °C and P: 0.7–0.8 GPa. The comparison of P-T data from adjacent Svratka Unit reveals a similar pressure (~ 0.7 GPa) but higher temperatures of regional metamorphism. For the southern domain is typical an interference an early ~NW-SE trending metamorphic foliation well preserved also in high-pressure granulites (transpressional fabrics) and late gently NNE dipping foliation with normal kinematics resulted in large-scal exhumation of high-grade Moldanubian Zone. The central part of the Polička Unit is built by low- to medium-grade metasediments (e.g. Kodym and Svoboda 1950; Melichar and Hanžl 1997). Syntectonic mineral assemblage metapelites (Qtz + Pl + Ms + Bt + Grt + Sill) recorded temperatures and pressures between ~ 570–640 °C and 0.5–0.6 Gpa. In contrast to the southern domain relatively lower peak metamorphic conditions here suggest that the central part represents shallower parts of the transpressional zone. Estimated metamorphic conditions (T: ~620–680 °C and P: ~ 0.6 Gpa) from metapelites in the contact aureole of the Budislav pluton indicate that peak metamorphism is contemporary with intrusion calc-alkaline granitoids at around 346 Ma.

The northern domain reveals distinct similarities to the Hlinsko Unit (Pitra and Guiraud 1996). Metamorphic assemblage of cordierite hornfels (Grt + Cdr + Bt +Pl ± And) reflects the peak P-T conditions with associated with contemporary contact metamorphism at T: ~590 °C and P: 0.4 Gpa. This assemblage was partially replaced by new chlorite, muscovite and small grains of staurolite in a stability field with Sps-rich rim of garnets. This stage can be interpreted as product of retrograde isobaric cooling at around 560 °C. These all results are constistent to P-T data calculated for crystallization of the Miřetín pluton at 653–681 °C and 0.3–0.4 GPa (Vondrovic et al. 2011). On the other hand metapelites from Hlinsko Unit reflects cooling from ~ 570 °C to 550–530 °C and slight increase of pressure from about 0.36 Gpa to 0.40 Gpa (Pitra and Guiraud 1996). New calculations for metapelites (T = 542 ± 20 °C and P = 0.3 ± 0.12 GPa) in the southeastern termination Hlinsko Unit near contact with

Miřetín pluton validate lower P-T conditions estimated by Pitra and Guiraud (1996). This diference can be explained by NNW-SSE normal faulting between the Polička and overlying Hlinsko Unit (Pitra et al. 1994; Vondrovic et al. 2011). Lithological compositions as well as differences in P-T data from both metamorphic suggest that rocks in the northern part of the Polička and Hlinsko Unit have similar protolith and were followed by comparable P-T path of contact metamorphism related with intrusion of the Miřetín pluton. The Eastern part consists mainly of micaschists with the peak P–T conditions T: ~650 °C and P: ~0.8 GPa which is comparable with P-T record of adjacent Letovice Unit (Konopásek et al. 2002). Differences in P-T paths between the central and southern part indicate different crustal levels of dextral transpressional zone. Syntectonic intrusion of the calc-alkaline melt caused thermally softening surrounding metamorphosed volcanosedimentary complex and allowed strong deformation and migmatization at mid-crustal level deformation zone (~ 650–800 °C and 0.7–0.8 Gpa) represented by southern part. Emplacement of the calc-alkaline granitiods to the central part was synchronous to the formation dominant penetrative foliation at P-T conditions T:~ 570–640 °C and P: 0.5–0.6 Gpa. Contemporaneous rapid exhumation eastern part of the southern part of the Polička Unit is evidenced by the presence of newly formed dehydratation melts in the metasediments and amphibolites along the granulite body dated at the ~ 342 Ma (Schulman et al 2005). The late event of normal in the Polička Unit represents a final stage of geodynamic evolution associated with retrograde metamorphism (reactions silimanite and K-feldspar associated with formation younger muscovite).

8.2 Geodynamic evolution

With respect to new metamorphic, geochronological and structural data from the Polička Unit we propose new sketch of Variscan geodynamic evolution of northeastern Bohemian Massif divided into three distinct phases. The oldest ~NW–SE metamorphic foliation associated with well-developed subhorizontal ~NW–SE stretching lineation mostly bearing right-lateral kinematic indicators (first phase) was made up during oblique transpressional shearing between ~380 and 346 Ma (Fig 9a, Verner et al. 2009; Žák et al. 2005, 2014) reflecting a regional ~NW–SE compression stress field (Edel et al. 2003).

a)

b)

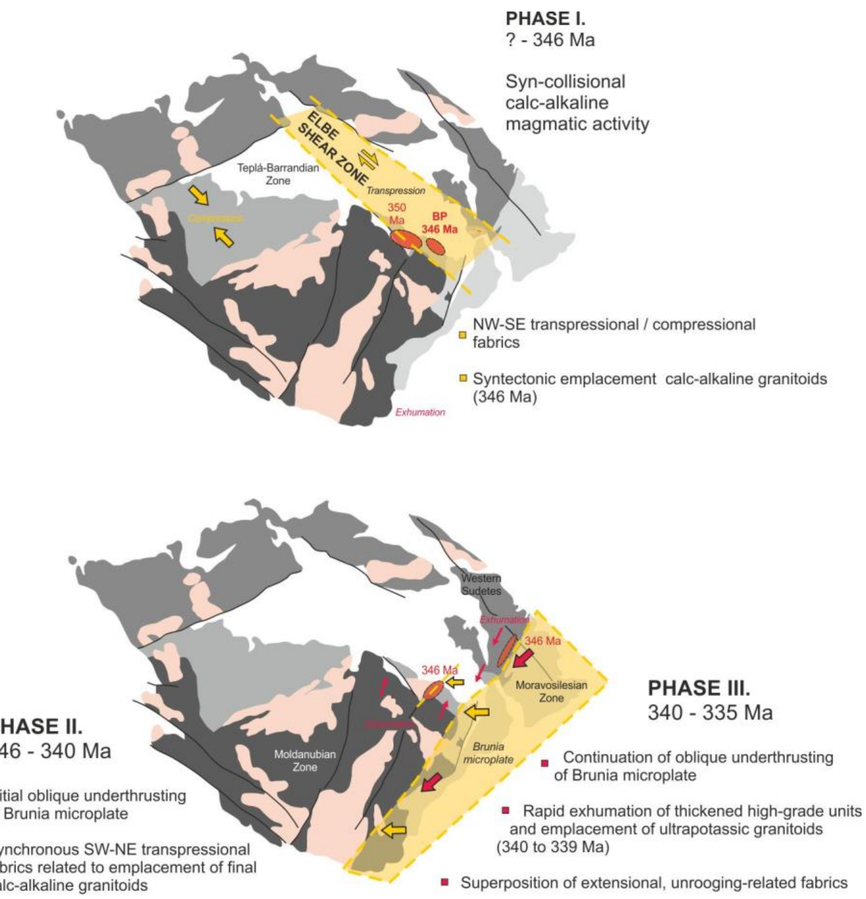


Fig. 9 The sketch of the geological evolution of the area: a) the first phase marked by activity of dextral transpressive Elbe shear zone b) the Brunia underthrusting and exhumation of high-grade complex

This transpressional deformation had been enforced mainly within a ~50–100 km wide ~WNW–ESE trending belt “Elbe Zone” which was thermally weakened zone of mid- to upper-crustal rocks of the Teplá-Barrandian Zone with presence of syntectonic calc-alkaline granitoids in Polčika Unit dated at 346 Ma (e. g. Verner et al. 2009; Vondrovic et al. 2011; Žák et al. 2014, Fig. 9a). Associated ~LP to MP/MT metamorphism increasing southeastward in fabric-parallel direction was dated by U/Pb method on monazites revealing distinct maxima in age at ~346 Ma (F. Finger, unpublished data). This age most likely corresponds to main episode of regional deformation and patial recrystallization of prevailing gneisses supported by heigtened heat flow due to synchronous emplacement of calc-alkaline granitoids dated similarly at ~346 Ma (Verner et al. 2009; Vondrovic et al. 2011; Žák et al. 2014). The origin of high-pressure granulites (Vír granulite) as southeastern part of the Polička Unit dated at 354 Ma (U/Pb on zircons; Tajčmannová et al. 2010) probably reflects the peak P–T conditions attained during early compressional event and crustal thickening of Variscan orogenic root.

According to similar fabric pattern in granulites and host southeastern Polička Unit (Fig 7.) both units had been juxtaposed during the transpressional deformation along the “Elbe Zone”. In the continuation of continental collision during heterogeneous anticlockwise rotation of regional stress–field from ~NW–SE to SW–NE direction (Edel et al. 2003) a successive ~NNE–SSW trending oblique underthrusting of the Brunia microplate caused metamorphic inversion, structural reworking and thickenning of the continental crust along whole eastern termination of the Bohemian massif (e. g. Fritz & Neubauer 1993; Schulmann et al. 2005, 2008; Kalvoda et al. 2008). The termination of oblique underthrusting had to take place before exhumation of migmatite-granite Pelhřimov core complex more southward dated at 329 Ma (Verner et al. 2014). In the Polička Unit and the surroundings this event was associated with heterogeneous superimposition of ~NNE–SSW foliation and gently plunging stretching lineation (second phase, Fig 9b) affected mainly the western and eastern flanks of this region. Assumed response to the growth of crustal thickness and also relative decreasing of compressional strain-rate was relativelly rapid exhumation of the crust associated with formation of heterogeneous gently dipping metamorphic foliation in several places bearing normal kinematic indicators (last phase, Fig. 9b). During the time–span of probably overlaped second and third phase all rocks underwent heterogeneous retrograde metamorphism and partial recrystallization at MP/LP and MT conditions (Tajčmannnová et al. 2010). This event can be timed by the origin of retrograde mineral assemblage in HP granulites at 340 Ma (Schulmann et al 2005) or by partial recrystallization during superimposition of normal fabrics in central and eastern Polička Unit. Relativelly higher grade of retrograde metamorphism and probably also accrual rate of crustal exhumation towards the E or SE of the region where the Brunia continent can explain general increasing of degree of metamorphism in this direction. This event was finished before a posttectonic emplacement of ultrapotassic Mg-rich granitoids (durbachites) along the northeastern edge of the Moldanubian Zone (dated at 338 Ma; Verner et al 2009) and also by sharp superimposition of ~NNE–SSW right-lateral Přibyslav Mylonite Zone at around 336 Ma (Verner et al. 2006).

9. Conclusions

We have drawn the following conclusions:

The Polička Unit is a volcanosedimentary unit that displays a complex geological evolution. The metamorphic fabric exhibits a complex pattern as follows:

(a) The structurally lower southern part is made up of migmatitised gneisses (T: 654–795°C and P: 0.7GPa) and an allochtonous granulite body. (b) The central part consists of a relatively monotonous complex of flysch metasediments with estimated P-T conditions in the range of T: 570-640°C and P: 0.5-0.6Gpa which exhibit an increasing trend from NW to SE (parallel to the main tectonometamorphic fabric). (c) The northern part is lithologically relatively monotonous and very similar to the Hlinsko Unit. The metamorphic assemblage limits peak P-T conditions to 590°C and 0.4Gpa. (d) The eastern part consists of micaschist rocks with lenses of quartzites with estimated peak P-T conditions of T: 650°C and P: 0.8GPa. The distinct metamorphic record in partial units of the Polička Unit has been interpreted as being the result of combination of the activity of “Elbe” dextral transpressive shearing that was coeval with formation of S_1 foliation and with the different exhumation rates of each unit that was caused by oblique Brunia continent indentation and related partial movements along particular tectonic boundaries during the exhumation of high-grade rocks in 346> Ma.

References

ANDERSON JL, SMITH DR (1995) The effects of temperature and fO_2 on the Al–in–hornblende barometer. Amer Miner 80: 549–55

BELL TH, JOHNSON SE, DAVIS B, FORDE A, HAYWARD N, WILKINS C (1992) Porphyroblast inclusion-trail orientation data: eppure non son girate?.- Journal of Metamorphic Geology, 10, 295–307

BURIÁNEK D (2009) Petrography of the Polička crystalline Complex. Acta Musei Moraviae, Scientae geologicae, 94: 3–46 (in Czech)

BURIÁNEK D (ed), BŘÍZOVÁ E, ČECH S, ČURDA J, FÜRYCH V, HANŽL P, KIRCHNER K, LYSENKO V, ROŠTÍNSKÝ P, RÝDA K, SKÁCELOVÁ D, SKÁCELOVÁ Z, VERNER K, VÍT J (2009) Basic geological map ČR 1:25 000 with explanations, 24-112 Jedlová. Czech Geological Survey, Prague, pp 1-76 (in Czech)

BURIÁNEK D, NĚMEČKOVÁ M, HANŽL P (2003) Petrology and geochemistry of plutonic rocks from the Polička and Zábřeh crystalline units (NE Bohemian Massif). Bull Czech Geol Surv 78, p. 9–22.

BURIÁNEK D, PERTOLDOVÁ J (2009) Garnet–forming reactions in calc–silicate rocks from the Polička Unit, Svratka Unit and SE part of the Moldanubian Zone. J Geosci 54 (3): 245 – 268

BURIÁNEK D, HRDLIČKOVÁ K, HANŽL P (2009) Geological position and origin of augen gneisses from the Polička Unit, eastern Bohemian Massif. Journal of Geosciences 54, 2, 201-219. ISSN 1802-6222.

BURIÁNEK D (1999) Metamorphic characteristic Polička crystalline unit. - *MS*, PřF MU, 1-67 (in Czech)

BURIÁNEK D, ČOPJAKOVÁ R (2008): Tourmalines from the mica schists of Svratka crystalline unit. Acta Musei Moraviae, Scientae geologicae 93, 61-79 (in Czech)

ČECH S (ed), BŘÍZOVÁ E, BURIÁNEK D, ČURDA J, FÜRYCH V, KIRCHNER K, LYSENKO V, MRNKOVÁ J, ROŠTÍNSKÝ P, RÝDA K, SKÁCELOVÁ Z, VÍT J (2009) Basic geological map ČR 1:25 000 with explanations 14-334 Polička. Czech Geological Survey, Prague, pp 1-65 (in Czech)

CHÁB J, SUCHÝ V, VEJNAR Z (1995) Moldanubian region; Tepla–Barrandian Zone (Bohemicum); Metamorphic evolution In: Dallmeyer RD, Franke W, Weber K (eds) Pre–Permian Geology of Central and Eastern Europe. Springer–Verlag, Berlin, pp 403–410

CHÁB J, SUK M (1977) Regional metamorphism in Bohemia and Moravia. - *Knihovna Ústř. Úst. Geol.*, 50, 1–156 (in Czech)

CONNOLLY JAD (1990) Multivariable phase diagrams; an algorithm based on generalized thermodynamics. Am J Sci 290: 666–718

FRANKE W (2000) The mid–European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. In: Franke W, Haak W, Oncken O, Tanner D (eds) Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geol Soc London Spec Publ 179: 35–63

HANŽL P (ed), BURIÁNEK D, ČURDA J, FÜRICH V, HRDLIČKOVÁ K, KIRCHNER K, LYSENKO V, MRNKOVÁ J, OTAVA J, PERTOLDOVÁ J, ROŠTÍNSKÝ P, RÝDA K, SKÁCELOVÁ Z, VÍT J, ZELENKA P (2008) Basic geological map ČR 1:25 000 with explanations, 14-333 Svratka. Czech Geological Survey, Prague, pp 1-72 (in Czech)

HANŽL P, MELICHAR R, LEICHMANN J (1999) Excursion guide of 4th meeting of the Czech tectonic studies group. Geolines, 8: 80–96

HOLLAND T, BAKER J, POWELL R (1998) Mixing properties and activity–composition relationships of chlorites in the system MgO–FeO–Al2O3–SiO2–H2O. Europ J Mineral 10: 395–406

HOLLAND T, BLUNDY J (1994) Non–ideal interactions in calcic amphiboles and their bearing on amphibole–plagioclase thermometry. Contrib Mineral Petrol 116, 4: 433–447

HOLLAND T, POWELL R (1998) An internally consistent thermodynamic data set with uncertainties and correlations: the system $Na_2O–K_2O–CaO–MgO–MnO–FeO–Fe_2O_3–Al_2O_3–SiO_2–TiO_2–C–H_2–O_2$. J Metamorph Geol 8: 89–124

JELÍNEK E, PAČESOVÁ M, MÍSAŘ Z, MARTINEC P, WEISS Z (1984) Geochemistry of a dismembered metaophiolite complex, Letovice, Czechoslovakia. Transactions of the Royal Society of Edinburgh, Earth Sciences 75, 37–48.

KODYM O, SVOBODA J (1950) The report about geological mapping around Jevíčko, Letovice and Polička. Věstník Státního geologického ústavu 25. (in Czech)

KONOPÁSEK J, SCHULMANN K, JOHAN V (2002) Eclogite-facies metamorphism at the eastern margin of the Bohemian Massif-subduction prior to continental underthrusting? *Eur. J. Mineral.*, 14, 701-713

KRETZ R (1983) Symbols for rock–forming minerals. Amer Miner 68: 277–279

LEAKE BE, WOOLLEY AR, ARPS CES, BIRCH WD, GILBERT MC, GRICE JD, HAWTHORNE FC, KATO A, KISCH HJ, KRIVOVICHEV VG, LINTHOUT K, LAIRD J, MANDARINO J, MARESCH WV, NICKEL EH, ROCK NMS, SCHUMACHER JC, SMITH DC, STEPHENSON NCN, UNGARETTI L, WHITTAKER EJW, YOUZHI G (1997)

Nomenclature of amphiboles. Report of the Subcommittee on Amphiboles of the International Mineralogical Association Commission on New Minerals and Mineral Names. Eur J Mineral 9: 623–651

MAZUR S A, ALEKSANDROWSKI P, SZCZEPANSKI J (2005) The presumed Teplá-Barrandian/Moldanubian terrane boundary in the Orlica Mountains (Sudetes, Bohemian Massif): structural and petrological characteristics. Lithos, 82(1-2): 85-112

MELICHAR R (1995) The structural analysis of the Polička and Svratka units. Unpublished PhD thesis, Charles University, Prague, pp 1–271 (in Czech)

MELICHAR R, HANŽL P (1997) Lithotectonic correlation of the Polička and Zábřeh crystalline units. J Czech Geol Soc 42: 64

MÍSAŘ Z, DUDEK A, HAVLENA V, WEISS J (1983) Geology of the Bohemian Massif. SPN, Prague, pp 1–334 (in Czech)

NĚMEC D. (1968) Die Metamorphose des NE-Randes des Kernes der Bohemische Masse. *Verh. Geol. Bundesanst.* (Wien), 1968, 1–2, 189–203

NEWTON RC, CHARLU TV, KLEPPA OJ (1980) Thermochemistry of the high structural state plagioclases. Geochim Cosmochim Acta 44: 933–941

NOVÁK M (1987) Metamorphosed carbonate rocks of the northeastern edge of the Moldanubian unit. *Čas. Morav. Muz., Vědy přír.*, 72, 5–28 (in Czech)

NOVÁK M, HOUZAR S, ŠREIN V, (1997) Gahnite-bearing marbeles and their significance for regional classification of the estern part of the Bohemian Massif. - *J. Czech Geol. Soc.*, 42, 1–2, 33–40. Brno.

PATTISON, D.R.M. (1992) Stability of andalusite and sillimanite and the Al_2SiO_5 triple point: Constraints from the Ballachulish aureole, Scotland. Journal of Geology, 100, 423–446

PEARCE JA, CANN JR (1973) Tectonic setting of basic volcanic rocks determined using trace element analyses. Earth Planet Sci Lett 19: 290-300

PEARCE JA, NORRY MJ (1979) Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. Contrib Mineral Petrol 69: 33-47

PERTOLDOVÁ J, VERNER K, VRÁNA S, BURIÁNEK D, ŠTĚDRÁ V, VONDROVIC L (2010) Comparison of lithology and tectonometamorphic evolution of units at northern margin of the Moldanubian Zone: implications for geodynamic evolution in the northeastern part of the Bohemian Massif. J Geosci 55(4): 299–319

PITRA P, GUIRAUD M (1996) Probable anticlockwise P–T evolution in extending crust: Hlinsko region, Bohemian Massif. J Metamorph Geol 14: 49–60

PROPACH G, PFEIFFER T (1998) Ocean floor basalt, not continental gabbro: a reinterpretation of the Hoher Bogen amphibolites, Teplá-Barrandian, Bohemian massif. Geologische Rundschau, 87(3): 303-313

SCHULMANN K, KRÖNER A, HEGNER E, WENDT I, KONOPÁSEK J, LEXA O, ŠTÍPSKÁ P (2005) Chronological constraints on the pre–orogenic history, burial and exhumation of deep–seated rocks along the eastern margin of the Variscan Orogen, Bohemian Massif, Czech Republic. Amer J Sci 305: 407–448

SCHULMANN K, LEXA O, ŠTÍPSKÁ P, RACEK M, TAJČMANOVÁ L, KONOPÁSEK J, EDEL JB, PESCHLER A, LEHMANN J (2008) Vertical extrusion and horizontal channel flow of orogenic lower crust: key exhumation mechanisms in large hot orogens? J Metam Geol 26 (2): 273–297

SLOBODNÍK M, HLADÍKOVÁ J (1994) Sulphidic mineralization in the Polička crystalline complex; a discusion of the sediment-hosted type mineralization. *Věst. Čes. geol. Úst.*, 69, 3,37–45

SOEJONO I, ŽÁČKOVÁ E, JANOUŠEK V, MACHEK M, KOŠLER J (2010) Vestige of an Early Cambrian incipient oceanic crust incorporated in the Variscan Orogen: Letovice Complex, Bohemian Massif. Journal of Geological Society, London 167, 1113-1130

STÁRKOVÁ I, MACEK J (1994) Geological map ČR 1:50 000, 24-13 Bystřice nad Pernštejnem. Czech Geological Survey, Prague

ŠTORCH P, KRAFT P (2009) Graptolite assemblages and stratigraphy of the Lower Silurian Mrakotin Formation, Hlinsko Zone, NE interior of the Bohemian Massif (Czech Republic). Bull Geosci 84(1): 51–74

SUN SS, MCDONOUGH WF (1989) Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders AD, Norry M (eds) Magmatism in Ocean Basins. Geol Soc London Spec Pub 42: pp 313-345

SVOBODA J (1956) Příspěvek ke paleogeografi siluru v českém masivu. Věst. Ústř. Úst. Geol. 31: 120–127 (in Czech)

TAJČMANOVÁ L, SOEJONO I, KONOPÁSEK J, KOŠLER J, KLÖTZLI U (2010) Structural position of high-pressure felsic to intermediate granulites from NE Moldanubian domain (Bohemian Massif). Journal of the Geological Society, 167(2): 329-345

VACHTL J (1962) The Hlinsko Palaeozoic and its relationship to neighbouring units. Sbor Ústř úst geol 27: 341-359 (in Czech)

VERNER K, ŽÁK J, HROUDA F, HOLUB FV (2006) Magma emplacement during exhumation of the lower- to mid-crustal orogenic root: the Jihlava syenitoid pluton, Moldanubian Unit, Bohemian Massif. Journal of Structural Geology 28: 1553–1567.

VERNER K, BURIÁNEK D, VRÁNA S, VONDROVIC L, PERTOLDOVÁ J, HANŽL P, NAHODILOVÁ R (2009) Lithological and structural features of geological units along the northern periphery of the Moldanubian Zone: A review of the geology of the Northeastern Variscides. J Geosci 54: 87–100

VONDROVIC L, VERNER K (2010) The record of structural evolution and U–Pb zircon dating of the tonalite intrusions (Polička Crystalline Unit, Bohemian Massif). Trabajos de Geología 30: 316–321

VONDROVIC L (2008) Record structural evolution of magmatic rocks Polička crystalline unit. - *MS*, Přír. fak. Univ. Karl. Praha., 1-74 (in Czech)

VONDROVIC L, VERNER K, BURIÁNEK D, HALODOVÁ P, KACHLÍK V, MÍKOVÁ J (2011) Emplacement, structural and P–T evolution of the ~346 Ma Miřetín Pluton (eastern Teplá–Barrandian Zone, Bohemian Massif): implications for regional transpressional tectonics. J Geosci 56: 343–357

VONDROVIC, L. - VERNER, K. - BURIÁNEK, D. (2010) Geology, emplacement and structural evolution of the calc-alkaline intrusions in the Polička and Zábřeh Units (eastern part of Bohemian massif). In Miroslav Ludwiniak, Andrzej Konon, Anna Zylinska: 8 th meeting of the Central European Tectonic Group Studies (CETEG), s. 122. – University of Warsaw. Warsaw.

WINCHESTER JA, FLOYD PA (1977) Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chem Geol 20: 325-343

Fabric and emplacement of the calc-alkaline plutons of the NE periphery of the Moldanubian Zone (Bohemian Massif)

3. Fabric and emplacement of the calc-alkaline plutons of the NE periphery of the Moldanubian Zone (Bohemian massif)

This part of the study considers the emplacement mechanisms, related structures and internal fabrics of the calc-alkaline plutons intruding units on the eastern periphery of the Moldanubian Zone of Bohemian Massif and the southern part surrounding the Lugian domain (Polička and Zábřeh Units). The granodiorite to tonalite plutons the (Miřetín and Budislav Plutons, Zábřeh Intrusive Complex, Buriánek et al. 2003; Verner et al. 2009; Vondrovic et al. 2011; Lehmann et al. 2013) exhibit similar geochemical and geochronological characteristics to other plutons intruding the central and western parts of the Teplá-Barrandian Zone (e.g. Buriánek et al. 2003; Vondrovic et al. 2011; Žák et al. 2014). The tectonic significance of calc-alkaline plutons in the Teplá-Barrandian has been synthetised and discussed in a number of papers to date (e.g. Holub et al. 1997; Janoušek et al. 2004; Žák et al. 2005). The structural record is described in this study together with a proposal concerning a new tectonic scenario for the evolution of an early-Variscan calc-alkaline plutonic event in the eastern margin of the Bohemian Massif.

The first paper focuses on the reconstruction of a regional geodynamic event which occurred during, and shortly after, the crystallization of the ~346Ma Miřetín Pluton (Polička Unit). At the regional scale, this event took place before the high-grade metamorphism and exhumation of the deep-seated rocks of the Moldanubian Zone located in the south (e.g. Vrána et al. 1995; Schulmann et al. 2008). The Miřetín Pluton (dated at 345.9 ± 5 Ma; U-Pb on zircons) forms one of a group of calc-alkaline intrusions emplaced in the marginal parts of the eastern Teplá-Barrandian Zone. Its emplacement in the upper- to mid-crustal levels of the Variscan continental crust took place during, or shortly after, peak metamorphism (at c.10km) as described in the host rock. Magma from the Miřetín pluton intruded syntectonically into the NNE-SSW oriented transpressional domain in such a way that the shortest dimension of the Miřetín Pluton was roughly parallel to the direction of principal shortening. During, or closely following, its emplacement the pluton was affected by pervasive submagmatic to high-T solid-state deformation reflecting the final increment of the regional strain-field at circa 580 °C and 0.4 GPa. In addition, the NNE-SSW oriented boundary between the Miřetín Pluton and the structurally overlying Hlinsko Unit bears microstructural evidence of low-T normal faulting which originated during a regional extensional event.

The second and last papers evaluate the emplacement of the calc-alkaline Budislav Pluton and the Zábřeh Intrusive Complex (dated at 346Ma ± 5 Ma; and 354± 6Ma - U-Pb age obtained by means of the laser-ablation ICP MS method on zircons). These plutons make up geochemically and geochronologically comparable intrusions which intrude the mid-crustal rocks of the Polička and Zábřeh Units (eastern margin of the Bohemian Massif). The internal fabric of the plutons and the host rocks indicates synchroneity between magma emplacement and the development of the main tectonometamorphic fabrics in the host rocks. The geochemical composition reveals similarities to other calc-alkaline granitoids in the Bohemian Massif (e.g. the Central Bohemian Plutonic Complex) which have been principally interpreted as magma mixing products, i.e. between basic magmas derived from a mantle wedge above a subduction zone and crustally-derived acid melts. The conditions of the magma crystallization of the Budislav Pluton (T: 655-730 °C and P: 04.-0.6 Gpa) correspond to the peak metamorphic evolution of the host rocks of the north-western part of the Polička Unit (T: 620-680 °C and P: 0.6 Gpa). With regard to the Zábřeh Unit, emplacement conditions (T: 706-795°C and P: ~0.3-0.4Gpa) roughly correspond to the contact metamorphism observed within the host rock (T: ~599-663°C and P: 0.4 Gpa). It is assumed that the plutons studied were emplaced in a zone of dextral transpressive shearing that took place within the Variscan mid- to upper-crustal level in 354-346Ma. This transpressional deformation was enforced primarily within the ~50-70 km wide ~WNW-ESE trending "Elbe Zone" belt which consisted of a thermally weakened zone of mid- to upper-crustal rocks of the Teplá-Barrandian Zone with the presence of syntectonic calc-alkaline granitoids. In this context, these calc-alkaline intrusions provide excellent time-markers of early-variscan geodynamic processes in the mid- to upper-crustal segment of this part of the Variscan belt.

Paper No. I.

Vondrovic, L. - Verner, K. - Buriánek, D. - Halodová, P. - Kachlík, V. - Míková, J. (2011): Emplacement, structural and P-T evolution of the ˜346 Ma Miřetín Pluton (eastern Teplá-Barrandian Zone, Bohemian Massif): implications for regional transpressional tectonics. – Journal of Geosciences 56, 4, 343-357. ISSN 1802-6222. DOI 10.3190/jgeosci.109.
IF=1.279

Paper No. II.

Vondrovic, L. - Verner, K (2010). The record of structural evolution and U-Pb zircon dating of the tonalite intrusions (Polička Crystalline Unit, Bohemian Massif) -Trabajos de Geología, Universidad de Oviedo, 30: 316-321

Paper No. III

Vondrovic L, - Verner, K – Buriánek, D. – Holub, FV – Sláma, J. – Žák, J. – Kachlík, V. - (2015): Emplacement and geochronology of calc-alkaline plutons (Bohemian Massif): Implications for early- variscan magmatic and geodynamic proceses
Article manuscript

Paper No. I.

VONDROVIC, L. - VERNER, K. - BURIÁNEK, D. - HALODOVÁ, P. - KACHLÍK, V. - MÍKOVÁ, J. (2011): EMPLACEMENT, STRUCTURAL AND P-T EVOLUTION OF THE 346 MA MIŘETÍN PLUTON (EASTERN TEPLÁ-BARRANDIAN ZONE, BOHEMIAN MASSIF): IMPLICATIONS FOR REGIONAL TRANSPRESSIONAL TECTONICS. – JOURNAL OF GEOSCIENCES 56, 4, 343-357. ISSN 1802-6222. DOI 10.3190/JGEOSCI.109.

DOI: 10.3190/jgeosci.108

Original paper

Emplacement, structural and P–T evolution of the ~346 Ma Mířetín Pluton (eastern Teplá–Barrandian Zone, Bohemian Massif): implications for regional transpressional tectonics

LUKÁŠ VONDROVIC[1,2*], KRYŠTOF VERNER[1,2], DAVID BURIÁNEK[3], PATRICIE HALODOVÁ[4], VÁCLAV KACHLÍK[5], JITKA MÍKOVÁ[4]

[1]*Czech Geological Survey, Klárov 3, 118 21 Prague 1, Czech Republic; lukas.vondrovic@geology.cz*

[2] *Institute of Petrology and Structural Geology, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic*

[3]*Czech Geological Survey, Leitnerova 22, 658 69 Brno, Czech Republic*

[4]*Czech Geological Survey, Geologická 6, 152 00 Prague 5, Czech Republic*

[5]*Institute of Geology and Palaeontology, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic*

* *Corresponding author*

Received: 27 April 2011; accepted: 17 December 2011; handling editor: J Žák

Keywords: European Variscides, Bohemian Massif, Mířetín Pluton, emplacement, transpression, U–Pb zircon dating

Running title: Syntectonic emplacement of calc-alkaline granitoids from eastern Teplá Barrandian Zone during regional transpression

Abstract

The calc-alkaline Miřetín Pluton (newly dated at 346 Ma ± 5 Ma; an U–Pb age obtained by laser-ablation ICP MS method on zircons) is a NNE–SSW elongated intrusive body emplaced into the upper- to mid- crustal rocks of the Polička Unit (eastern Teplá–Barrandian Zone; Bohemian Massif). Its composition reveals similarities to other calc-alkaline granitoids, which are mostly interpreted as products of magma mixing between the basic magmas derived from mantle wedge above a subduction zone with crustally-derived acid melts. The conditions of magma crystallization estimated at 653–681 °C and 0.29–0.43 GPa roughly correspond to peak metamorphic evolution of the host volcano-sedimentary rocks of the northwestern part of the Polička and Hlinsko units. The Miřetín Pluton was emplaced into a NNE–SSW oriented transpressional domain, well recognized on a regional scale along the eastern margin of the Teplá–Barrandian Zone. During, or shortly after, the magma emplacement, the Miřetín Pluton was affected by pervasive submagmatic to high-T solid-state deformation, reflecting an additional strain increment of regional transpression in a narrow zone of thermal softening. Sharply superimposed low-T solid-state fabric preserved along the western part of the Pluton was connected with normal shearing between the Polička Unit at the bottom and the overlying Hlinsko Unit after 335 Ma.

1. Introduction

Fabrics in granitoid intrusions commonly reflect magma emplacement and/or a record of regional geodynamic processes (e.g. changes in the regional strain field, regional kinematic framework and local exhumation paths), which could have operated during and/or after the magma crystallization (e.g. Paterson et al. 1998). The structural framework of granitoids emplaced during transpression reflects an interplay between local strain field and regional deformation of host rocks, thermo-mechanical effects of the crystallized magma and development of transitional magmatic to subsolidus fabrics (e. g. Tikoff and Greene 1997; Saint Blanquat et al. 1998; Chardon et al. 1999; Brown and Solar 1999; Miller and Paterson 2001; Schmidt and Paterson 2002). Many analogous studies revealing relationships between magmatic and tectonic processes were also recently performed in the Bohemian Massif (e.g. Schulmann et al. 2005; Žák et al. 2005, 2011; Verner et al. 2008, 2009).

This work focuses on reconstruction of a regional geodynamic event which occurred during, and shortly after, the crystallization of the ~346 Ma Miřetín Pluton, emplaced into the mid- to upper-crustal levels of units at the NE periphery of the Moldanubian Zone (Fig. 1a–b). On a regional scale, it took place before the high-grade metamorphism and exhumation of the deep-seated rocks of the Moldanubian Zone located to the S (e. g. Vrána et al. 1995; Schulmann et al. 2008). The genesis of similar plutons of calc-alkaline composition (e.g. ~354 Ma Sázava Pluton of the Central Bohemian Plutonic Complex; Janoušek et al. 2004, 353–346 Ma Zábřeh Intrusive Complex, Budislav and Miřetín plutons; Verner et al. 2009; Vondrovic and Verner 2010) has been interpreted as one of magmatic-arc granites (e.g. Finger et al. 1997; Schulmann et al. 2009; Žák et al. 2011). In a broad sense, most of these intrusions were emplaced in relation to the regional Late Devonian to Early Carboniferous (356–346 Ma) transpressional or compressional tectonic event, which took place along the eastern margin of the upper-crustal Teplá–Barrandian Zone (Žák et al. 2005, 2011; Verner et al. 2009; Pertoldová et al. 2010).

Based on combination of field structural data, microstructural and EBSD analyses, U–Pb zircon dating and estimation of P–T conditions of magma crystallization we provide new insights into emplacement mechanisms and subsequent geodynamic evolution of the Miřetín Pluton and its surrounding units of the easternmost flank of the Teplá–Barrandian Zone.

2. Regional geological setting

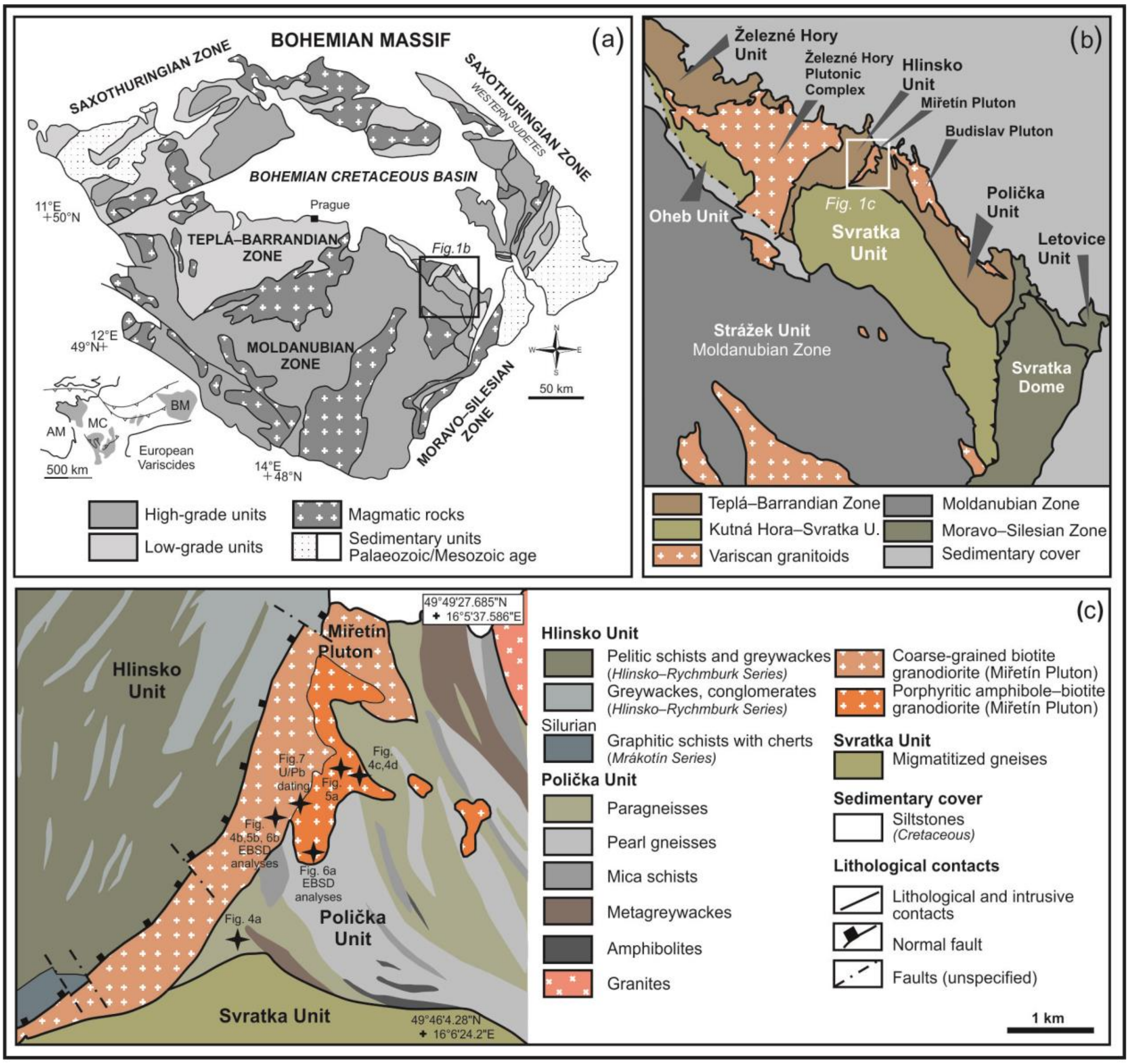
In a broad sense, the studied area (the Miřetín Pluton and its host upper- to mid-crustal Polička and Hlinsko units; Fig. 1a–c) is assumed to belong to the eastern extension of the Teplá–Barrandian Zone (e.g. Mísař et al. 1983; Verner et al. 2009; Pertoldová et al. 2010). However, some authors also pointed out its lithological affinities to the Western Sudetes (e.g. Cháb et al. 2010). The Teplá–Barrandian Zone crops out between the high-grade Moldanubian Zone in the southeast and the Saxothuringian Zone in the west to north. The central part of the Teplá–Barrandian Zone contains Neoproterozoic to Lower Palaeozoic unmetamorphosed volcanic and sedimentary rocks, which did not undergo strong Variscan metamorphism. In contrast, its margins (e.g. Teplá, Domažlice, Železné Hory, Hlinsko and Polička units) were exposed to an amphibolite-facies Variscan overprint (Cháb et al. 1995). The southern and eastern Teplá–Barrandian Zone was intruded by numerous granitoid bodies of calc-alkaline composition (Holub et al. 1997a, b; Hrouda et al. 1999; Janoušek et al. 2000; Žák et al. 2005, 2011; Verner et al. 2009).

The *Hlinsko Unit* (Fig. 1b–c) is bound by the Železné hory Plutonic Complex in the W, mid-crustal Svratka Unit in the S and upper- to mid-crustal Polička Unit in the E. Eastern part of the Hlinsko Unit is separated from the Polička Unit by a NNE–SSW trending normal shear zone (e.g. Pitra et al. 1994). The Hlinsko Unit is composed of two different metasedimentary formations folded into a large, NNE–SSW elongated synform: (i) the prevailing Hlinsko–Rychmburk Formation composed of greywackes and metapelites with minor layers of metavolcanic rocks (e.g. Vachtl 1962) and (ii) the Mrákotín Formation built by dark phyllitic slates to graphitic schists and phyllites with quartzite intercalations, forming the central part of the Hlinsko synform (e.g. Štorch and Kraft 2009). The age of the Hlinsko–Rychmburk Formation is unknown; however it is assumed to be Neoproterozoic to Early Carboniferous (Pitra et al. 1994 and references therein). The Mrákotín Formation was assigned to the Silurian based on paleontological data (Würm 1927; Štorch and Kraft 2009). The Variscan regional metamorphism of the Hlinsko Unit metapelites attained peak pressures of 0.35–0.40 GPa and temperatures of 530–570 °C (Pitra and Guiraud 1996).

The Hlinsko Unit recorded a polyphase Variscan geodynamic evolution. The oldest metamorphic structures are cleavage planes related to non-cylindrical recumbent folding of the primary bedding. These cleavages are accompanied by a subhorizontal ~NW–SE mineral lineation (Pitra et al. 1994). The superimposed deformation stage was connected with ~E–W shortening, which produced various types of folds with W or E moderately to steeply dipping axial planes and also the large-scale synform of whole Hlinsko Unit. This compressional event was connected with a subsequent generation of ~N–S (NNE–SSW) axial cleavages (Pitra et al. 1994).

The *Polička Unit* is composed of metamorphosed volcano-sedimentary sequences of unknown age (Buriánek et al. 2003; Buriánek and Pertoldová 2009; Verner et al. 2009). Its northern part is lithologically monotonous, composed of rhythmically alternating metagreywackes and schists with scarce intercalations of metaconglomerates, fine-grained amphibolites, calc-silicate rocks and marbles. During Variscan orogeny, regional tectonometamorphic processes under greenschist- to amphibolite-facies conditions affected these rocks. Degree of regional metamorphism gently increases towards the E to SE. For the northwestern Polička Unit the P–T conditions were estimated at 559 ± 65 °C and 0.3 ± 0.2 GPa, for the central and eastern parts at 564–640 °C and 0.49–0.64 GPa (Buriánek 2009; Pertoldová et al. 2010).

The overall structural pattern is defined by pervasive schistosity dipping in the central and eastern parts under moderate angles to the ~NE or ~SW. The regional metamorphic fabrics along the western flank of this unit dip under moderate angles to ~WNW or NE. Across the whole Polička Unit, the regional fabrics bear a gently to moderately ~WNW-plunging stretching or mineral lineation and indicators of right-lateral or thrusting kinematics (Verner et al. 2009).



Vondrovic et al. Fig. 1

Fig. 1a – Schematic map of the Bohemian Massif, modified from Franke (2000); **b –**Schematic sketch of the NE part of the Bohemian Massif (NE periphery of the Moldanubian Zone); **c –** Geological outline of the studied area (Miřetín Pluton and its host rocks of the Polička and Hlinsko units) based on geological map 1:50 000, sheet 14-33 Polička (Stárková ed. 1998). Locations of studied samples and photographs are also shown.

Metamorphic rocks of the Polička Unit were intruded by several granitoid bodies, mainly of calc-alkaline composition (e. g. Miřetín and Budislav plutons). The Miřetín Pluton was emplaced into the northwestern part of the Polička Unit (Fig. 1c) and its intrusive contacts are mostly parallel to the regional metamorphic structures. Original contacts with the Hlinsko Unit in the W were later modified by large-scale normal faults (Fig. 1c). The Pluton has an irregular NNE–SSW elongated outline with approximate dimensions of ~8 km (NNE–SSW) and ~1.5 km (WNW–ESE). Granitoids of the Miřetín Pluton (SiO_2 = 59.3–65.0 wt. %) are high-K calc-alkaline (K_2O = 2.4–4.0 wt. %) and subaluminous (A/CNK = 0.9–1.2); the trace-element signature clearly indicates their magmatic-arc origin (e.g. Buriánek et al. 2003).The rocks of Miřetín Pluton (biotite and amphibole–biotite granodiorites) were affected by pervasive deformation and limited recrystallization at relatively high temperatures.

Sample	Locality	Analyses	Rock type	Loc. type	X-coordinate*	Y-coordinate*
404	Pastvisko	petrology	tonalite	outcrop	49°47'23.977"	16°5'52.805"
L23	Kutřín	petrology	medium-grained Bt granodiorite	outcrop	49°49'8.846"	16°3'41.955"
LV13S	Kutřín	petrology	porphyritic Amp–Bt granodiorite	outcrop	49°49'21.380"	16°3'34.622"
L136	Rychnov	EBSD	porphyritic Amp–Bt granodiorite	quarry	49°46'59.270"	16°4'12.429"
L90	Otradov	EBSD	coarse-grained Bt granodiorite	outcrop	49°47'38.193"	16°3'15.751"
LV92	Otradov	U–Pb dating	porphyritic Amp–Bt granodiorite	outcrop	49°47'34.546"	16°3'25.188"
*WGS-84 = World Geodetic System 1984						

Tab. 1 List and localization of studied samples

3. Analytical techniques

Note that the brief description and GPS coordinates of samples studied by individual methods is given in Tab. 1 and shown on Fig. 1c.

3.1. Mineral chemistry

Chemical analyses of the minerals were obtained using a Cameca SX-100 electron microprobe at the Joint Electron Microprobe Laboratory of the Masaryk University and the Czech Geological Survey in the Brno village. The measurements were carried out in a wave dispersion mode using 15 kV of acceleration voltage, 5 µm of beam diameter, 30 nA of current and integration time of 20 s. The crystallochemical formulae of feldspar were recalculated to 8 and those of micas to 22 oxygen atoms. The amphibole formulae were obtained assuming 23 O, 2 (OH, F, Cl) and Fe^{3+}/ Fe^{2+} ratios were estimated based on 13 cations except Ca, Na and K (Leake et al. 1997). The mineral abbreviations are according to Kretz (1983).

The solidus temperatures of the Miřetín Pluton were estimated using the thermometer of Holland and Blundy (1994) from amphibole and plagioclase rim compositions. These thermometers perform well (± 40 °C) in the range 400–1000 °C and 0.1–1.5 GPa over a broad range of bulk compositions. The usable mineral compositions are restricted to amphiboles with Na^{A}>0.02 pfu, ^{VI}Al>1.8 pfu, and Si of 7.0–6.0 pfu and plagioclases with X_{an} of 0.1–0.9. The Al-in-hornblende barometer of Anderson and Smith (1995) is recommended for amphiboles with $Fe/(Mg + Fe) \leq 0.65$.

3.2 Electron back-scatter diffraction (EBSD)

The lattice preferred orientation (LPO) of quartz aggregates was measured using the EBSD method (see Prior et al. 1999 for overview of its principles) on a CamScan 3200 scanning electron microscope at the Czech Geological Survey, Prague. The EBSD patterns were recorded using a HKL Technology Nordlys II camera system and indexed using the Channel5 software (Schmidt and Olensen 1989). Pattern acquisition was carried out using acceleration voltage of 20 kV, beam current of ~5 nA, working distance of 33 mm and sample tilt of 70°. The analyses were performed in the manual mode; each individual grain is represented by one orientation measurement. Crystallographic orientation data given by three Euler angles φ_1, Φ, φ_2 were obtained from interactively indexed EBSD patterns. We used the crystallographic parameters of Bonlen et al. (1980) for quartz indexation. The LPO patterns of quartz are presented in stereonets, lower hemisphere equal area projection.

3.3 U–Pb dating

A Thermo-Finnigan Element 2 sector field ICP-MS coupled to a 213 Nd:YAG laser (New Wave Research UP-213) at Bergen University, Norway was used to measure the Pb/U and Pb isotopic ratios in zircons. Laser-ablation ICP-MS isotopic analysis of zircons followed the technique described in Košler et al. (2002) and Košler and Sylvester (2003). The sample introduction system enabled simultaneous nebulisation of a tracer solution and laser ablation of the solid sample (Horn et al. 2000). Tracer solution containing natural Tl ($^{205}Tl/^{203}Tl$ = 2.3871; Dunstan et al. 1980), ^{209}Bi and enriched ^{233}U and ^{237}Np (> 99 %) was aspirated through an Apex desolvation nebuliser (Elemental Scientific) and mixed with the sample from the laser cell, resulting in a mixture of sample and tracer solution dry aerosol, which entered the plasma. The laser was set up to produce an energy density of *c.* 5 J/cm^2 at a repetition rate of 10 Hz. The sample was placed in the ablation cell, which was moved during ablation at a speed of 10 $\mu m \cdot s^{-1}$ beneath the stationary laser beam to produce a linear grid (*c.* 20 × 100 μm) in the sample. Typical sequence consisted of a 40 s measurement of analytes in the gas blank and aspirated tracer solution, followed by acquisition of the U and Pb signals from zircon, along with the continuous signal from the aspirated tracer solution, for another 160 s. The data were acquired in the time-resolved – peak jumping – pulse counting mode with 1 point measured per peak for masses 202 (flyback), 203 and 205 (Tl), 206 and 207 (Pb), 209 (Bi), 233 (U), 237 (Np), 238 (U), 249 (^{233}U oxide), 253 (^{237}Np oxide) and 254 (^{238}U oxide). Raw data were corrected for dead time of the electron multiplier and processed off-line in the Lamdate spreadsheet-based program (Košler et al. 2002). Data reduction included correction for the gas blank, laser-induced elemental fractionation of Pb and U and instrument mass bias. No common Pb correction was applied to the data. Calculation of mean ages and plotting of a Concordia diagram was performed with the Isoplot program of Ludwig (2003).

4. Petrology and P–T evolution of the Miřetín Pluton

The Miřetín Pluton is composed of two texturally different varieties of calc-alkaline granitoids: (i) coarse- to medium-grained biotite granodiorite and (ii) porphyritic amphibole–biotite granodiorite to tonalite with abundant microgranular enclaves of diorites and gabbros. In both textural varieties of the granodiorites, plagioclase grains have subhedral shapes and reveal oscillatory zoning well visible in optical CL. The anorthite contents continuously decrease rimwards (from $An_{31–36}$ to $An_{2–20}$). K-feldspar ($Ab_{2–7}$) occurs as subhedral crystals (Tab. 2). Biotite has ^{IV}Al = 2.32–2.60 apfu and Fe/(Fe + Mg) = 0.59–0.47 (Fig. 2a; Tab. 3); subhedral to anhedral amphibole corresponds to magnesiohornblende (Mg/(Fe + Mg) = 0.50–0.60, Si = 6.9–7.3 apfu; Fig. 2b, Tab. 4). Anhedral quartz grains form aggregates in interstitial domains. Apatite, monazite, zircon and titanite are common accessory minerals in both textural varieties.

Amphibole-rich mafic microgranular enclaves contain subhedral plagioclase with patchily zoned anorthite-rich cores ($An_{49–82}$) and relative homogenous andesine rim ($An_{30–31}$) and anhedral quartz grains. Amphibole in enclaves corresponds to magnesiohornblende (Mg/(Fe + Mg) = 0.56–0.60, Si = 6.6–7.0 apfu; Fig. 2b) partially replaced by actinolite (Mg/(Fe + Mg) = 0.68–0.69, Si = 7.7–7.8 apfu). Biotite (Fig. 2a, ^{IV}Al = 2.32–2.37 apfu and Fe/(Fe + Mg) = 0.47–0.49) is the most abundant near the boundary with granodiorite Common accessory minerals are apatite, monazite, zircon and ilmenite ± titanite.

Estimated P–T conditions of 653–681 °C and 0.29–0.43 GPa (Fig. 2c, Tab. 5) obtained from the amphibole–plagioclase thermometer (Holland and Blundy 1994) and Al-in-hornblende barometer (Anderson and Smith 1995) reflect the final stages of magma crystallization or the subsequent high-T subsolidus deformation of the Miřetín Pluton granitoids.

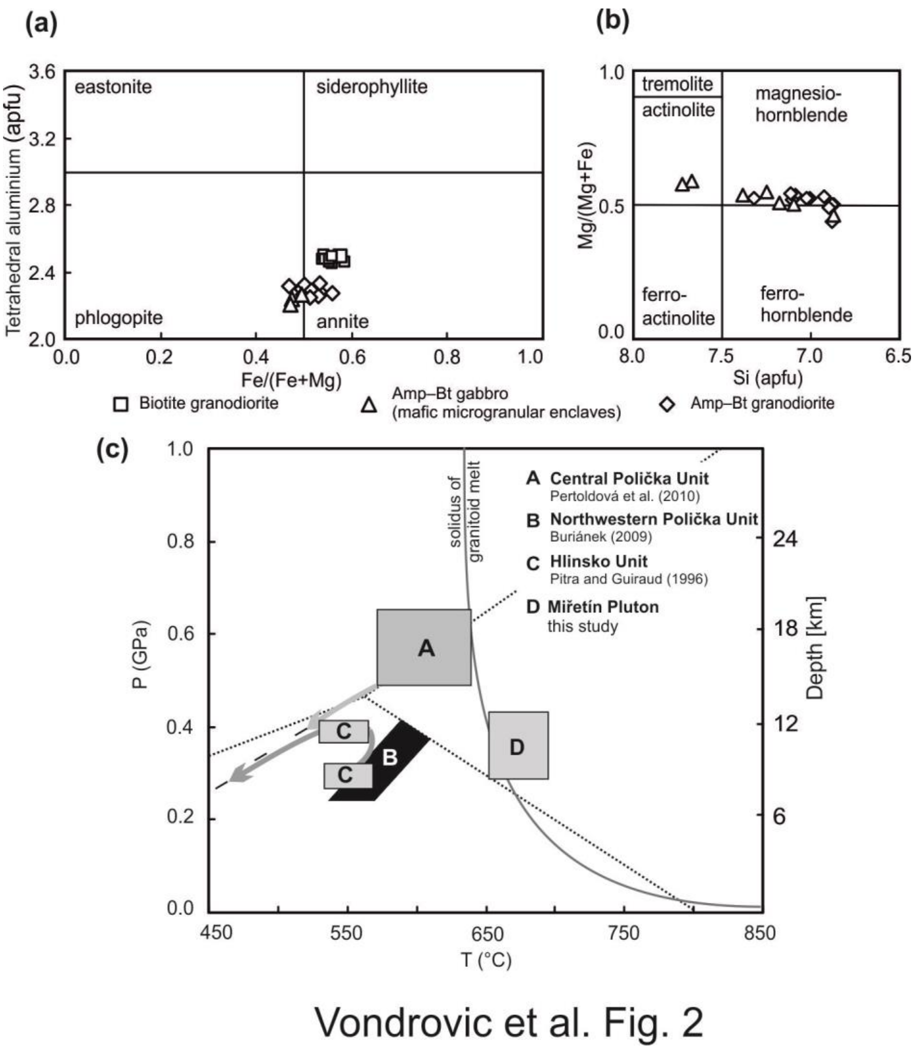


Fig. 2 a Fe/(Fe + Mg) vs. Al^{IV} classification diagram for biotites (Miřetín Pluton); **b –** Mg/(Fe + Mg) vs. Si (apfu) classification diagram for amphiboles (Miřetín Pluton, classification according Leake et al. 1997) **c –** Summary P–T diagram showing inferred paths of regional metamorphic evolution for the Polička and Hlinsko units (taken from literature) as well as crystallization conditions of the Miřetín Pluton (this study).

5. Structural pattern

The eastern flank of the Hlinsko Unit exhibits a relatively simple structural pattern. Relics of bedding or an early subhorizontal spaced cleavage were observed. These fabrics have been intensely folded into moderately to steeply ~WNW or ~ESE dipping planes, mostly parallel to the ~NNE–SSW trending axial cleavages and new low-T schistosity. The axes of these folds have a subhorizontal NNE–SSW or gently NNE plunging orientation (Fig. 3). The overall structural pattern in the central and eastern parts of the Polička Unit is defined by regional metamorphic foliation (pervasive metamorphic schistosity or compositional banding) dipping moderately to steeply to the ~NE or SW (Fig. 3).

Sample	L23	L23	L23	404	404	404	LV13S	LV13S	LV13S
SiO_2	59,20	59,31	57,35	58,55	57,68	59,35	61,74	61,51	65,17
P_2O_5	0,00	0,02	0,00	0,04	0,00	0,00	0,10	0,09	0,00
Al_2O_3	25,93	25,77	26,80	26,05	26,31	25,77	23,93	24,16	18,10
FeO	0,05	0,06	0,04	0,01	0,02	0,33	0,01	0,03	0,01
CaO	7,61	7,81	9,06	8,13	8,80	7,95	5,83	5,92	0,00
Na_2O	7,15	7,00	6,33	6,77	6,58	7,09	8,18	8,20	0,23
K_2O	0,23	0,21	0,22	0,26	0,15	0,20	0,29	0,21	16,22
BaO	0,00	0,00	0,02	0,00	0,00	0,00	0,00	0,02	0,07
SrO	0,08	0,13	0,08	0,11	0,11	0,09	0,04	0,08	0,09
Total	100,18	100,18	99,80	99,81	99,54	100,69	100,08	100,12	99,74
(apfu)									
Si	2,638	2,642	2,576	2,622	2,596	2,632	2,739	2,728	3,013
Al	1,362	1,353	1,419	1,375	1,395	1,347	1,251	1,263	0,987
Fe^{3+}	0,002	0,002	0,001	0,001	0,001	0,012	0,000	0,001	0,001
T-site	4,002	3,997	3,997	3,997	3,992	3,991	3,991	3,992	4,000
K	0,013	0,012	0,013	0,015	0,009	0,011	0,016	0,012	0,957
Na	0,618	0,605	0,552	0,588	0,574	0,609	0,703	0,705	0,020
Ca	0,359	0,368	0,431	0,385	0,419	0,373	0,274	0,278	0,000
Ba	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001
Sr	0,002	0,003	0,002	0,003	0,003	0,002	0,001	0,002	0,002
O-site	0,992	0,988	0,997	0,991	1,005	0,996	0,994	0,997	0,981
Mol %									
An	36,2	37,4	43,3	39,0	41,8	37,5	27,6	27,9	0,0
Ab	62,4	61,4	55,5	59,5	57,3	61,3	70,8	70,9	2,1
Or	1,3	1,2	1,3	1,5	0,9	1,1	1,6	1,2	97,9

Tab. 2 Representative compositions of feldspars (wt. % and apfu)

These regional foliations are associated with well-developed stretching and/or mineral lineation gently plunging to ~NW and indicators of right-lateral transpressional kinematics (e.g. meso- to micro-scale asymmetric folds, localized shear zones and recrystallized quartz and feldspathic aggregates in pressure shadows, as well as asymmetric deformation of porphyroblasts). In the northwestern part of the Polička Unit, the NW–SE trending regional fabrics described above were refolded into the NNE–SSW direction (Fig. 4a). New foliation planes dip steeply to moderately to the WNW and bear ~NW to NNW-plunging stretching lineations with indicators of top-to-the-E (thrusting) kinematics. Contacts between the Miřetín Pluton and host Polička Unit are intrusive. Their orientation is mostly parallel to the second NNE–SSW trending metamorphic fabrics identified in the northwestern part of the Polička Unit. Contacts between the upper-crustal Hlinsko Unit and Miřetín Pluton were modified by NNE–SSW trending normal fault (Fig. 3). According to the criteria defined by Paterson et al. (1998) and Vernon (2000), two distinct solid-state fabrics were identified in the Miřetín Pluton (Figs 4b, 5a–b).

Sample	LV13S	LV13S	LV13S	LV13S	LV13S	L23	L23	L23	404
SiO_2	35,43	35,46	35,67	35,51	35,41	36,91	36,68	36,70	36,60
TiO_2	2,17	2,36	2,36	2,51	2,65	2,15	1,89	1,54	3,02
Al_2O_3	17,89	18,75	18,17	18,90	18,89	15,68	15,90	15,84	15,41
FeO	20,68	20,39	20,41	19,41	19,84	19,80	20,76	20,96	21,41
MnO	0,35	0,33	0,23	0,25	0,32	0,38	0,43	0,38	–
MgO	9,15	8,69	9,22	9,16	8,78	11,13	10,40	10,97	9,47
Na_2O	0,07	0,13	0,12	0,17	0,10	0,07	0,07	0,12	–
K_2O	9,68	9,79	9,79	9,86	9,53	9,36	9,40	9,40	10,03
BaO	0,11	0,20	0,08	0,14	0,09	0,30	0,26	0,29	–
F	0,01	0,00	0,00	0,03	0,08	0,00	0,01	0,07	–
Cl	0,13	0,11	0,11	0,11	0,12	0,07	0,09	0,10	–
H_2O*	3,87	3,91	3,91	3,91	3,87	3,92	3,89	3,87	3,91
O=F,Cl	0,03	0,03	0,03	0,04	0,06	0,02	0,02	0,05	0,00
Total	99,58	100,09	100,06	99,95	99,68	99,76	99,80	100,21	99,86
(apfu)									
Si	5,438	5,404	5,434	5,393	5,395	5,623	5,614	5,600	5,615
Al^{IV}	2,562	2,596	2,566	2,607	2,605	2,377	2,386	2,400	2,385
Al^{VI}	0,675	0,772	0,695	0,777	0,787	0,439	0,482	0,449	0,401
Ti	0,251	0,270	0,270	0,287	0,303	0,246	0,217	0,176	0,348
Fe	2,655	2,599	2,600	2,466	2,528	2,523	2,657	2,675	2,747
Mn	0,045	0,043	0,030	0,032	0,042	0,048	0,056	0,049	–
Mg	2,094	1,974	2,094	2,074	1,993	2,527	2,373	2,496	2,166
Na	0,022	0,040	0,037	0,049	0,030	0,021	0,020	0,037	–
K	1,895	1,903	1,902	1,911	1,852	1,819	1,834	1,830	1,962
Ba	0,007	0,012	0,005	0,008	0,005	0,018	0,015	0,018	–
F	0,005	0,000	0,000	0,014	0,040	0,000	0,002	0,032	–
Cl	0,034	0,029	0,030	0,028	0,031	0,019	0,022	0,025	–
OH*	3,960	3,971	3,970	3,958	3,928	3,981	3,975	3,943	4,000
ΣCAT.	19,643	19,613	19,633	19,604	19,541	19,641	19,655	19,728	19,624

Tab. 3 Selected chemical compositions of biotite (wt. % and apfu)

High-T solid-state fabrics with some relics of submagmatic flow are defined by the ductile deformation and accompanying recrystallization of feldspars, quartz and biotite aggregates. This high-T solid-state foliation dips under moderate angles to the W to NW and bears well-developed stretching lineation plunging to WNW to N (ductile elongation of quartzo–feldspathic and biotite aggregates). The asymmetry of the deformed and recrystallized mineral aggregates and folded leucogranite dikes indicates thrusting kinematics (Fig. 4b–c). This high-T solid-state deformation was in some places localized into narrow zones of mylonites (Fig. 4d).

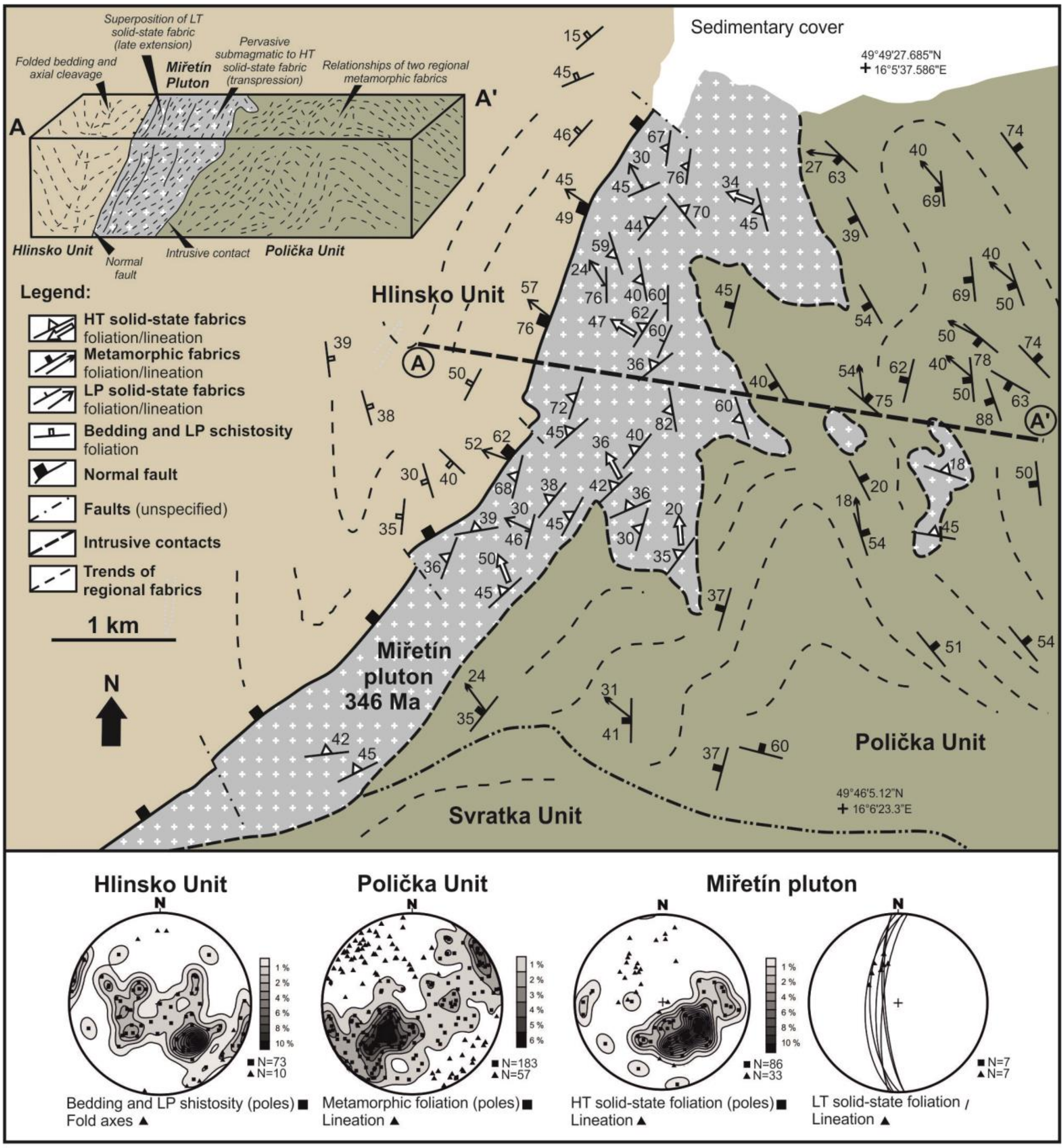
Second, sharply superimposed fabrics have a character of discrete low-T spaced cleavage (Fig. 4b, 5b), marked by localized brittle–ductile to brittle deformation and rare recrystallization. This cleavage dips under a moderate to steep angle to the WNW and is associated with moderately NW plunging stretching lineation (striations) and indicators of W-side-down kinematics. These low-T solid-state fabrics occur only in a narrow zone (up to 0.5 km wide) along the western flank of the Pluton and are parallel to the fault-controlled boundary between the Miřetín Pluton and structurally overlying Hlinsko Unit.

Sample	L23	L23	L23	404
SiO_2	48,15	46,45	46,25	46,27
TiO_2	0,39	0,56	0,55	1,15
Al_2O_3	7,82	9,20	9,11	7,83
Cr_2O_3	0,01	0,02	0,02	0,00
$Fe_2O_3^{calc}$	0,89	1,62	1,70	2,23
FeO^{calc}	14,78	14,96	14,90	15,65
MnO	0,51	0,55	0,55	0,45
MgO	11,56	10,91	10,81	10,78
CaO	12,17	12,11	12,06	12,03
Na_2O	0,91	0,99	0,98	0,88
K_2O	0,57	0,85	0,78	0,92
H_2O	2,05	2,04	2,03	2,03
Cl	0,05	0,06	0,06	0,00
O=Cl	-0,01	-0,01	-0,01	0,00
TOTAL	99,86	100,31	99,78	100,21
(apfu)				
Si	7,097	6,867	6,872	6,889
Al^{IV}	0,903	1,133	1,128	1,111
ΣT	8,000	8,000	8,000	8,000
Al^{VI}	0,455	0,470	0,468	0,262
Ti	0,044	0,062	0,062	0,129
Fe^{3+}	0,098	0,181	0,191	0,249
Cr	0,001	0,002	0,002	0,000
Mg	2,541	2,404	2,394	2,393
Fe^{2+}	1,821	1,850	1,851	1,948
Mn	0,040	0,031	0,032	0,019
ΣC	5,000	5,000	5,000	5,000
Mn	0,024	0,039	0,037	0,038
Ca	1,922	1,917	1,920	1,919
Na	0,053	0,044	0,043	0,043
ΣB	2,000	2,000	2,000	2,000
Na	0,208	0,239	0,239	0,211
K	0,107	0,161	0,147	0,175
ΣA	0,315	0,400	0,386	0,385
Cl	0,012	0,015	0,014	0,000
ΣCAT.	15,315	15,400	15,386	15,385

Tab. 4 Selected chemical compositions of amphibole (wt. % and apfu)

Sample	Locality	Rock	Mineral assemblage	Amp–Pl*	Amp**
404	Pastvisko	tonalite	Pl + Qtz + Kfs + Bt + Amp	659-675	0.29-0.35
L23	Kutřín	granodiorite	Pl + Qtz + Kfs + Bt + Amp	653-681	0.32-0.43
LV13S	Kutřín	granodiorite	Pl + Qtz + Kfs + Bt	–	–
*amphibole–plagioclase thermometer (Holland and Blundy 1994)					
**Al-in-hornblende barometer (Anderson and Smith 1995)					

Tab. 5 The petrologically studied samples of plutonic rocks, their mineral assemblages and estimated P–T conditions

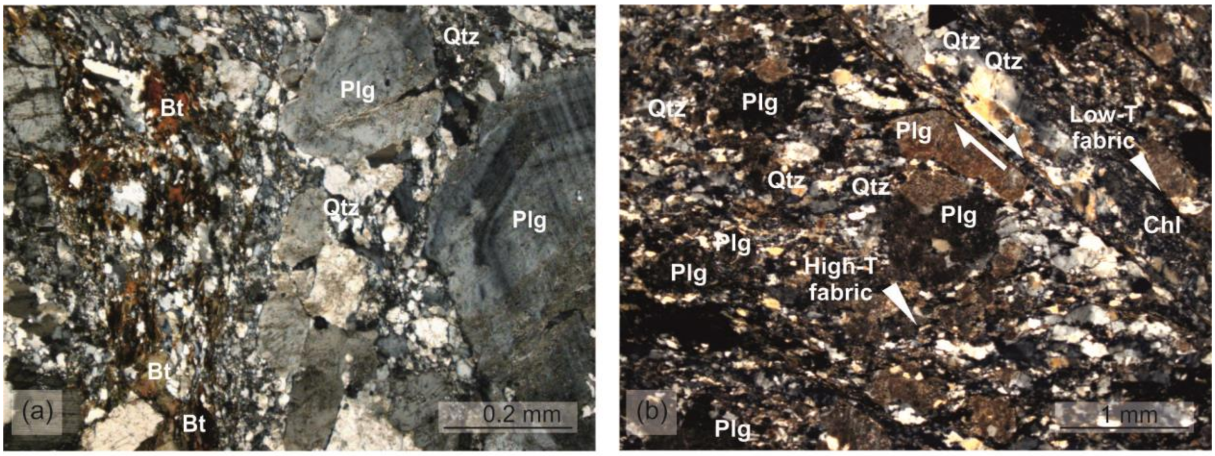


Vondrovic et al. Fig. 3

Fig. 3 Structural map of the Mířetín Pluton and its metamorphic host rocks of Polička and Hlinsko units. Below: orientation stereograms (lower hemisphere, equal area projection) of regional fabrics.

Vondrovic et al. Fig. 4

Fig. 4 Field photographs. **a –** Transpressional metamorphic foliation in paragneisses of the northwestern Polička Unit; **b** – Relationships between the high-T solid-state fabric with an evidence for thrusting kinematics and low-T solid-state fabrics bearing an indicators of west-side-down kinematics (Miřetín Pluton); **c** – Asymmetrically folded leucogranite dikes in a zone of high-T solid-state deformation indicating thrusting kinematics (Miřetín Pluton); **d** – Mylonite zone with folded syntectonic dike of leucogranite composition (Miřetín Pluton).



Vondrovic et al. Fig. 5

Fig. 5 Photomicrographs. **a** – Magmatic grains of plagioclase, K-feldspar, biotite and quartz affected by internal plastic deformation (recrystallization along grain boundaries and formation of deformation lamellae, i.e. “ribbon microstructure”) bearing evidence for grain-boundary migration recrystallization. **b** – Microstructural evidence for superimposition of pervasive high-T solid-state fabrics and low-T solid-state deformation and recrystallization (cataclastic flow). Angular fragments of quartz and plagioclase grains as well as new chlorite aggregates occur in a very fine-grained matrix in discrete cleavage planes (western flank of the Miřetín Pluton).

6. Microstructures and EBSD analyses

Microstructural analysis of Miřetín Pluton fabrics was carried out on the basis of 18 oriented thin-sections. According to the criteria of microstructural classification for deformed magmatic rocks (e.g. Paterson et al. 1989; Vernon 2000; Passchier and Trouw 2005), three distinct events of microstructural evolution were defined in the Miřetín Pluton: (i) fabrics of submagmatic flow which include an evidence for melt-supported intracrystalline deformation and recrystallization identified in relics; (ii) high-T solid-state fabrics involving features of penetrative crystal-plastic deformation and dynamic recrystallization (above ~500 °C); and (iii) low-T solid-state fabrics bearing evidence for superimposed non-penetrative and localized brittle–ductile to brittle deformation. Across the Miřetín Pluton, identified fabrics of submagmatic flow and high-T sub-solidus deformation vary in intensity and exhibit a transitional character.

6.1 Submagmatic flow

Evidence for submagmatic flow is preserved especially in the eastern part of the Miřetín Pluton, as the effects of penetrative high–T solid–state deformation continuously increase towards the west. The textures of the submagmatic stage include relics of magmatic preferred orientation of feldspars and amphiboles, evidence for crystallization of the melt remaining in interstitial domains and magmatic zoning in conjunction with a small amount of crystal-plastic deformation and recrystallization (Fig. 5a). The initial stages of crystal–plastic deformation and recrystallization (predominantly along fractures and crystal boundaries) were heterogeneous and focused into quartz and biotite aggregates. Quartz aggregates are slightly elongated and show undulose extinction, formation of a chessboard-pattern and interlobate shape of subgrains (0.1–0.4 mm in size). These microstructural features indicate activity of high-T grain boundary migration (GBM) recrystallization (Stipp et al. 2002). Some of biotite aggregates were affected by kinking and locally also by pressure dissolution. Feldspars were more resistant at this stage, bearing no evidence for internal crystal-plastic deformation. However, myrmekites and flame perthites can be locally observed.

6.2 High-T solid-state fabrics

Characteristic features of the high-T sub-solidus fabrics are as follows (Fig. 5a–b): (i) the presence of anastomosing foliation defined by folded and dynamically recrystallized biotite (with mica-fish texture) and quartz aggregates, both interconnected into narrow penetrative ribbons which commonly enclose less deformed porphyroblasts of feldspars; (ii) recrystallized aggregates of quartz and feldspar which reveal irregular and lobate shapes of new subgrains. The shape and degree of lattice preferred orientation of these sub-grains clearly indicate the high-T GBM recrystallization; (iii) the presence of mechanical twinning of feldspars, including formation of deformation lamellae, and (iv) abundant myrmekite and perthite textures.

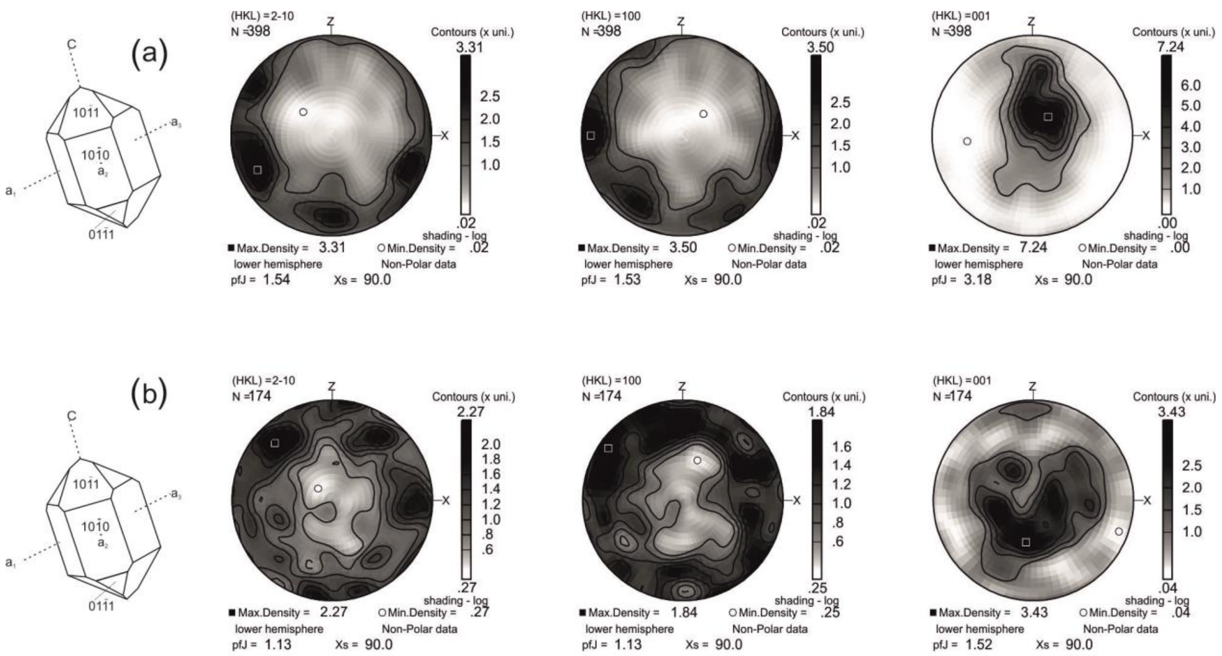
6.3 Low-T solid-state fabrics

Effects of low-T sub-solidus deformation were identified locally in a relatively narrow zone along the western margin of the Pluton (Fig. 5b). Corresponding textures indicate brittle–ductile to brittle deformation. Quartz and feldspar aggregates are deformed by fracturing bearing a record of cataclastic flow (the presence of angular grain fragments in a very fine-grained matrix). Biotite aggregates are occasionally fractured and recrystallized to chlorite subgrains (Fig. 5b).

6.4 Electron back-scatter diffraction (EBSD) analyses

Two samples were studied in order to evaluate the conditions of deformation. The first (LV136; Fig. 6a) exhibits high-T sub-solidus deformation without a subsequent brittle event. The measured quartz grains are anhedral, partly recrystallized. On a orientation diagram (Fig.

6a), the quartz *c* axes (001) show strong maxima near the centre. The *a* axes (100) produced two peaks on the periphery of diagram. According to Passchier and Trouw (2005), such a geometry probably corresponds to the prism <a> slip, which is active at moderate temperatures (*c.* 550 °C). The second sample (L90; Fig. 6b) showed small quartz grains, which were recrystallized in highly strained domains, reflecting the low-T subsolidus overprint. In this case, the EBSD results show maxima of *c* axes (001) in a relatively wide belt of N–S orientation. The *a* axes (100) define several peaks on the periphery of the stereonet. According to Passchier and Trouw (2005), such a geometry corresponds to the basal <a> slip, which is active at lower temperatures (*c.* 350 °C).



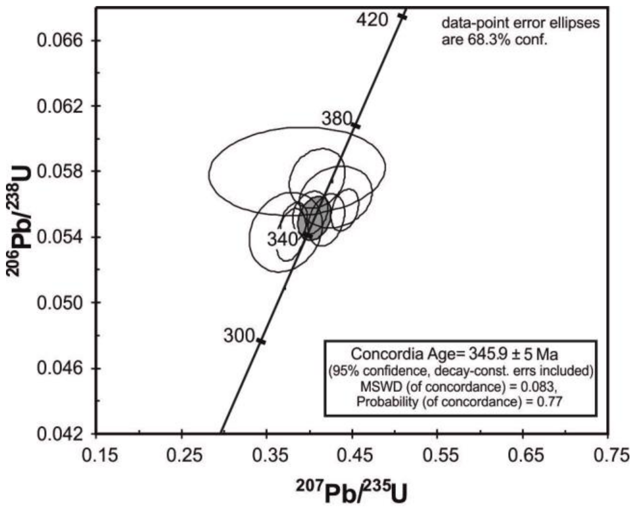
Vondrovic et al. Fig. 7

Fig. 6 Stereographic projection (equal area, lower hemisphere) of quartz *c* axes orientations obtained using the EBSD method shown in XZ section. The LPO patterns of high-T (**a**) and low-T (**b**) solid-state fabrics.

7. U–Pb dating of the Miřetín Pluton

Analysed zircon grains were separated from porphyritic amphibole–biotite granodiorite indicating clear evidence for transitional submagmatic to high-T deformation with no evidence for low-T recrystallization (sample L92; see Fig. 1c and Tab. 1 for its location). Zircon grains are euhedral, oscillatory zoned and prismatic with features pointing to crystallization from a granitoid magma. Rarely, some consist of oscillatory-zoned rims surrounding unzoned xenocrystic cores.

The U–Pb data obtained by laser-ablation ICP-MS dating of fifteen zircon grains are given in Tab. 6 and plotted on Concordia diagram (Fig. 7). Zircon grains yielded concordant U–Pb ages with the mean of 345.9 ± 5 Ma (2σ), which is interpreted as the magmatic (crystallization) age.



Vondrovic et al. Fig. 6

Fig. 7 U–Pb Concordia diagram for zircons of the Miřetín Pluton. The error ellipses are plotted with 1σ uncertainties.

Analysis	Concentrations		Atomic ratios						Apparent ages (Ma)					
	Pb μg/g	U μg/g	$^{207}Pb/^{235}U$	1σ (abs)	$^{206}Pb/^{238}U$	1σ (abs)	$^{207}Pb/^{206}Pb$	1σ (abs)	$^{207}Pb/^{235}U$	1σ (abs)	$^{206}Pb/^{238}U$	1σ (abs)	$^{207}Pb/^{206}Pb$	1σ (abs)
070709JMa10	6	89	0.4185	0.0139	0.0551	0.0010	0.0541	0.0012	323.5	0.0139	328.7	0.001	376.9	51.5
070709JMa16	6	100	0.4299	0.0280	0.0564	0.0012	0.0554	0.0029	330.3	0.0280	363.5	0.0012	429.9	115.3
070709JMa21	11	186	0.4401	0.0108	0.0557	0.0008	0.0568	0.0011	379.0	0.108	327.4	0.0008	484.9	43.8
070709JMa23	9	150	0.4080	0.0216	0.0576	0.0012	0.0520	0.0021	321.3	0.216	328.3	0.0012	284.0	91.0
070709JMa25	7	125	0.3805	0.0104	0.0549	0.0008	0.0503	0.0012	416.3	0.0104	351.9	0.011	208.6	54.2
070709JMa26	6	102	0.3772	0.0112	0.0542	0.0011	0.0507	0.0013	341.5	0.0689	348.1	0.0035	227.3	58.6
070710JMa07	9	157	0.5068	0.0689	0.0561	0.0035	0.0648	0.0052	320.6	0.0136	341.1	0.0009	766.2	167.9
070710JMa14	5	81	0.3999	0.0136	0.0555	0.0009	0.0517	0.0014	381.4	0.0281	346.5	0.0016	271.9	63.8
070710JMa17	4	58	0.3713	0.0281	0.0543	0.0016	0.0505	0.0027	344.3	0.0422	329.4	0.001	217.5	125.6
070710JMa18	8	136	0.4559	0.0422	0.0552	0.0010	0.0631	0.0044	355.0	0.0239	345.6	0.0029	712.2	147.5
070710JMa21	8	139	0.4036	0.0239	0.0524	0.0029	0.0587	0.0044	363.1	0.0354	354.0	0.0019	556.9	163.8
070710JMa30	4	71	0.3752	0.0354	0.0523	0.0019	0.0518	0.0031	370.3	0.0683	349.2	0.0018	275.5	137.9
070710JMa31	5	87	0.3844	0.0683	0.0580	0.0018	0.0484	0.0066	347.4	0.0272	360.9	0.0016	120.1	322.8
070710JMa33	4	67	0.4525	0.0272	0.0521	0.0016	0.0627	0.0030	327.4	0.0329	344.5	0.0027	698.4	101.2
070710JMa37	4	56	0.3722	0.0329	0.0523	0.0027	0.0531	0.0030	325.0	0.00045	340.0	0.0009	333.7	126.9

Tab. 6 Results of U–Pb dating of the Miřetín Pluton (laser ablation ICP-MS)

8. Discussion

8.1 Age and genesis of the Miřetín Pluton

The granitoids of the Miřetín Pluton resemble geochemically other Variscan calc-alkaline intrusions that intruded marginal parts of the Teplá–Barrandian Zone (e. g. Holub 1997b; Janoušek et al. 2000, 2004; Buriánek et al. 2003). For this reason, the genesis of this Pluton was probably also associated with mixing of basic mantle-derived magmas from a suprasubduction environment with crustal melts of tonalite composition (Buriánek et al. 2003; Janoušek et al. 2004).

The newly determined U–Pb zircon age of the Miřetín Pluton (345.9 ± 5 Ma) differs somewhat from previously published geochronological data from the same (Schulmann et al. 2005). The relatively younger age of 327 ± 6 Ma established by the U–Pb zircon dissolution and vapour transfer method was similarly interpreted as timing the magma emplacement (Schulmann et al. 2005). Furthermore, the Pb–Pb evaporation age of 323 ± 1.1 Ma on the same sample was adopted as the time limit for the extensional shearing tectonics (Schulmann et al. 2005). The discrepancy of ~20 M. y. between our new and the previously published geochronological data may be caused by selection of different rock-samples, which could have been variously affected by high- to low-T deformation and recrystallization and use of different geochronological methods.

Our concordant age of 345.9 ± 5 Ma was obtained on sample taken from the least deformed domain of the Miřetín Pluton, which showed no evidence for low-T subsolidus overprint. This new result is consistent with reported ages for other calc-alkaline plutons of Variscan age emplaced into the rocks of the Teplá–Barrandian Unit (357–345 Ma; Holub et al. 1997a; Janoušek et al. 2004, 2010; Vondrovic and Verner 2010).

8.2 P–T conditions of regional metamorphism and magmatic crystallization

The metamorphic assemblage of cordierite hornfelses (Grt + Cdr + Bt + Ms + Pl ± And ± St) from the northwestern Polička Unit constrains the peak P–T conditions with rare evidence for contact metamorphism to 559 ± 65 °C and 0.3 ± 0.2 GPa (Buriánek 2009). These results are roughly consistent with the P–T data newly estimated for the Miřetín Pluton (T = 653–681 °C and P = 0.29–0.43 GPa; Fig. 2c, Tab. 5) which could reflect the conditions of magma crystallization or closely following high-T recrystallization. Based on concordance of these P–T data, the Miřetín Pluton was obviously emplaced during the peak regional metamorphism of the host Polička Unit. On the other hand, metapelites from the Hlinsko Unit reflect cooling from ~600 °C to 530 °C and a slight increase in pressure from *c.* 0.36 GPa to 0.40 GPa (Pitra and Guiraud 1996). The lithological compositions as well as estimated P–T conditions from the Hlinsko and Polička units suggest that these rocks have a similar protolith and were affected by comparable P–T path of the Variscan regional metamorphism. Subtle differences in P–T conditions and structural pattern can be explained by the later NNW–SSE normal faulting between the Polička Unit and the overlying Hlinsko Unit.

8.3 Fabrics and emplacement of the Miřetín Pluton

The ~346 Ma Miřetín Pluton was emplaced into the upper- to mid-crustal rocks of the Polička Unit and probably also into the Hlinsko Unit (at a depth of *c.* 10 km), which were synchronously affected by two distinct stages of transpressional (compressional) deformation (Verner et al. 2009; Pertoldová et al. 2010). Intrusive contacts and internal fabrics of the Miřetín Pluton dip at moderate angles to ~WNW (Fig. 3) and thus are oriented at a high angle to the regional transpressional fabrics well preserved in all units at the NE periphery of the Moldanubian Zone (Verner et al. 2009). Structures in the Miřetín pluton are mostly parallel to the superimposed compressional fabrics in the northwestern Polička Unit. In addition, microstructural and EBSD analyses of the Miřetín Pluton reveal two distinct sub-solidus fabrics: (i) contact subparallel, pervasive transitional submagmatic to high-T foliation (>500 °C) associated with well developed stretching lineation bearing evidence for thrusting kinematics and (ii) low-T (~350 °C), sharply superimposed cleavage planes with an evidence for west-side-down kinematics identified in a narrow NNW–SSE zone along the western part of the Miřetín Pluton. This structural pattern (i.e. the presence of pervasive submagmatic to high-T solid-state fabrics and mostly parallel orientation of the intrusive contacts in relation to the regional metamorphic fabrics) resembles highly asymmetric sheet-like magmatic bodies syntectonically emplaced during regional transpressional (compressional) event (e.g. Brown and Solar 1999). The ascent and emplacement of the Miřetín Pluton into higher crustal levels caused presumably limited softening of the host rocks and synkinematic growth of LP–HT metamorphic assemblages. This thermal anomaly resulted in an increasing ductile deformation in and around the Pluton, with the same orientation as the superimposed metamorphic fabrics in the northwestern Polička Unit. In general, all these fabrics reflected the orientation of the regional strain field (the WNW–ESE shortening and perpendicular stretching). Our interpretation of the emplacement and geodynamic evolution of the Miřetín

Pluton as well as the regional evolution of the host rocks discussed above is at variance with the earlier concepts of Pitra et al. (1994), Pitra and Guiraud (1996) and Schulmann et al. (2005) who interpreted the genesis of the Miřetín Pluton as a synkinematic laccolith within a shallow-dipping normal shear zone between the Hlinsko metasedimentary sequence and high-grade rocks of the Svratka Unit at around 327 Ma.

8.4 Regional tectonic evolution

Age, emplacement and subsequent solid-state deformation of the Miřetín Pluton point to synmagmatic activity of the NNE–SSW trending transpression zone, which also affected the upper- to mid-crustal units outside the E margin of the Teplá–Barrandian Zone (e.g. Žák et al. 2005, 2009). This is also consistent with interpretation of the transition from transpression to large-scale exhumation of the Variscan orogenic root along the Teplá Barrandian/Moldanubian boundary dated at 346 Ma (Žák et al. 2005; Janoušek et al. 2010). Sharply superimposed low-T cleavages are consistent with the NNW–SSE trending normal fault zone located between the Polička Unit and the overlying Hlinsko Unit. On a regional scale, their origin was associated with a ~WNW–ESE extensional event assumed to have occurred after 335 Ma (Verner et al. 2006; Pertoldová et al. 2010).

9. Conclusions

The Miřetín Pluton (dated at 345.9 ± 5 Ma; U–Pb on zircons) belongs to the group of calc-alkaline intrusions emplaced into marginal parts of the eastern Teplá–Barrandian Zone. The Miřetín Pluton intruded the units rimming the northern margin of the high-grade Moldanubian Zone. Its emplacement into the upper- to mid-crustal levels of the Variscan continental crust took place during, or shortly after, their peak metamorphism (at *c.*10 km). Magma was intruded syntectonically into a NNE–SSW oriented transpressional domain, whereby the shortest dimension of the Miřetín Pluton was roughly parallel to the direction of principal shortening. During, or closely after, its emplacement, the Pluton was affected by pervasive submagmatic to high-T solid-state deformation, reflecting the last increment of regional strain-field of this NNE–SSW trending transpressional zone at *c.* 580 °C and 0.4 GPa. The NNE–SSW oriented boundary between the Miřetín Pluton and the structurally overlying Hlinsko Unit bears microstructural evidence of low-T normal faulting, which originated during a regional extensional event, probably later than 335 Ma.

Acknowledgements. Thorough reviews by Eckardt Stein and Carlo Dietl improved greatly this manuscript and are gratefully acknowledged. We would also like to thank František V. Holub for helpful discussion and we appreciate the assistance of Renata Čopjaková at the electron microprobe. We also thank Jiří Žák and Vojtěch Janoušek for careful editorial work. This research was supported by the Grant Agency of Charles University research project No. 81909, the Ministry of Education, Youth and Sports of the Czech Republic through Research Plan No. MSM0021620855 and the Czech Geological Survey research project No. 323000.

References

ANDERSON JL, SMITH DR (1995) The effects of temperature and fO_2 on the Al-in-hornblende barometer. Amer Miner 80: 549–559

BONLEN SR, PEACOR DR, ESSENE EJ (1980) Crystal chemistry of a metamorphic biotite
and its significance in water barometry. Amer Miner 65: 55–62

BROWN M, SOLAR GS (1999) The mechanism of ascent and emplacement of granite magma during transpression: a syntectonic granite paradigm. Tectonophysics 312: 1–33

BURIÁNEK D (2009) Petrography of the Polička crystalline Complex. Acta Mus Moraviae Sci Nat 94: 3–46 (in Czech)

BURIÁNEK D, PERTOLDOVÁ J (2009) Garnet-forming reactions in calc-silicate rocks from the Polička Unit, Svratka Unit and SE part of the Moldanubian Zone. J Geosci 54: 245–268

BURIÁNEK D, NĚMEČKOVÁ M, HANŽL P (2003) Petrology and geochemistry of plutonic rocks from the Polička and Zábřeh crystalline units (NE Bohemian Massif). Bull Czech Geol Surv 78: 9–22

CHÁB J, SUCHÝ V, VEJNAR Z (1995) Moldanubian region; Teplá–Barrandian Zone (Bohemicum) – Metamorphic evolution (Chapter VII.B4). In: DALLMEYER RD, FRANKE W, WEBER K (eds) Pre-Permian Geology of Central and Eastern Europe. Springer-Verlag, Berlin, 403–410

CHÁB J, BREITER K, FATKA O, HLADIL J, KALVODA J, ŠIMŮNEK Z, ŠTORCH P, VAŠÍČEK Z, ZAJÍC J, ZAPLETAL J (2010) Outline of the Geology of the Bohemian Massif: the Basement Rocks and their Carboniferous and Permian Cover. Czech Geological Survey, Prague, pp 1–296

CHARDON D, ANDRONICOS CL, HOLLISTER LS (1999) Large-scale transpressive shear zone patterns and displacements within magmatic arcs: the Coast Plutonic Complex, British Columbia. Tectonics 18: 278–292

DUNSTAN LP, GRAMLICH JW, BARNES IL, PURDY WC (1980) Absolute isotopic abundance and the atomic weight of a reference sample of thallium. J Res Nat Bur Stand 85: 1–10

FINGER F, ROBERTS MP, HAUNSCHMID B, SCHERMAIER A, STEYRER HP (1997) Variscan granitoids of central Europe: their typology, potential sources and tectonothermal relations. Mineral Petrol 61: 67–96

FRANKE W (2000) The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. In: FRANKE W, HAAK W, ONCKEN O, TANNER D (eds) Orogenic Processes: Quantification and Modelling in the Variscan Belt. Geological Society of London Special Publications 179: 35–63

HOLLAND T, BLUNDY J (1994) Non-ideal interactions in calcic amphiboles and their bearing on amphibole–plagioclase thermometry. Contrib Mineral Petrol 116: 433–447

HOLUB FV, COCHERIE A, ROSSI P (1997a) Radiometric dating of granitic rocks from the Central Bohemian Plutonic Complex (Czech Republic): constraints on the chronology of the thermal and tectonic events along the Moldanubian–Barrandian boundary. C R Acad Sci Paris Earth Planet Sci 325: 19–26

HOLUB FV, MACHART J, MANOVÁ M (1997b) The Central Bohemian Plutonic Complex: Geology, chemical composition and genetic interpretation. Sbor geol Věd, Ložisk Geol Mineral 31: 27–50

HORN I, RUDNICK RL, MCDONOUGH WF (2000) Precise elemental and isotope ratio determination by simultaneous solution nebulization and laser ablation ICP-MS: application to U–Pb geochronology. Chem Geol 164: 281–301

HROUDA F, TÁBORSKÁ Š, SCHULMANN K, JEŽEK J, DOLEJŠ D (1999) Magnetic fabric and rheology of co-mingled magmas in the Nasavrky Plutonic Complex (E. Bohemia): implications for intrusive strain regime and emplacement mechanism. Tectonophysics 307: 93–111

JANOUŠEK V, BOWES DR, ROGERS G, FARROW CM, JELÍNEK E (2000) Modelling diverse processes in the petrogenesis of a composite batholith: the Central Bohemian Pluton, Central European Hercynides. J Petrol 41: 511–543

JANOUŠEK V, BRAITHWAITE C, BOWES DR, GERDES A (2004) Magma-mixing in the genesis of Hercynian calc-alkaline granitoids: an integrated petrographic and geochemical study of the Sázava intrusion, Central Bohemian Pluton, Czech Republic. Lithos 78: 67–99

JANOUŠEK V, WIEGAND B, ŽÁK J (2010) Dating the onset of Variscan crustal exhumation in the core of the Bohemian Massif: new U–Pb single zircon ages from the high-K calc-alkaline granodiorites of the Blatná suite, Central Bohemian Plutonic Complex. J Geol Soc, London 167: 347–360

KOŠLER J, SYLVESTER PJ (2003) Present trends and the future of zircon in geochronology: laser ablation ICP-MS. In: HANCHAR JM, HOSKIN PWO (eds) Zircon. Mineralogical Society of America Reviews in Mineralogy and Geochemistry 53: 243–275

KOŠLER J, FONNELAND H, SYLVESTER P, TUBRETT M, PEDERSEN RB (2002) U–Pb dating of detrital zircons for sediment provenance studies – a comparison of laser ablation ICP-MS and SIMS techniques. Chem Geol 182: 605–618

KRETZ R (1983) Symbols for rock-forming minerals. Amer Miner 68: 277–279

Leake BE, Woolley AR, Arps CES, Birch WD, Gilbert MC, Grice JD, Hawthorne FC, Kato A, Kisch HJ, Krivovichev VG, Linthout K, Laird J, Mandarino J, Maresch WV, Nickel EH, Rock NMS, Schumacher JC, Smith DC, Stephenson NCN, Ungaretti L, Whittaker EJW, Youzhi G (1997) Nomenclature of amphiboles. Report of the Subcommittee on Amphiboles of the International Mineralogical Association Commission on New Minerals and Mineral Names. Eur J Mineral 9: 623–651

LUDWIG KR (2003) Isoplot/Ex version 3.00. A Geochronological Toolkit for Microsoft Excel, User's Manual. Berkeley Geochronology Center Special Publications 4: 1–70

MILLER RB, PATERSON SR (2001) Construction of mid-crustal sheeted plutons: examples from the North Cascades, Washington. Geol Soc Am Bull 113: 1423–1442

MÍSAŘ Z, DUDEK A, HAVLENA V, WEISS J (1983) Geology of the Bohemian Massif. SPN, Prague, pp 1–334 (in Czech)

PASSCHIER CW, TROUW RAJ (2005) Microtectonics. Springer-Verlag, Berlin, pp 1–366

PATERSON SR, VERNON RH, TOBISCH OT (1989) A review of criteria for identification of magmatic and tectonic foliations in granitoids. J Struct Geol 11: 349–363

PATERSON SR, FOWLER TK, SCHMIDT KL, YOSHINOBU AS, YUAN ES, MILLER RB (1998) Interpreting magmatic fabric patterns in plutons. Lithos 44: 53–82

PERTOLDOVÁ J, VERNER K, VRÁNA S, BURIÁNEK D, ŠTĚDRÁ V, VONDROVIC L (2010) Comparison of lithology and tectonometamorphic evolution of units at northern margin of the Moldanubian Zone: implications for geodynamic evolution in the northeastern part of the Bohemian Massif. J Geosci 55: 299–319

PITRA P, GUIRAUD M (1996) Probable anticlockwise P–T evolution in extending crust: Hlinsko region, Bohemian Massif. J Metamorph Geol 14: 49–60

PITRA P, BURG JP, SCHULMANN K, LEDRU P (1994) Late-orogenic extension in the Bohemian Massif: petrostructural evidence in the Hlinsko region. Geodin Acta 6: 15–31

PRIOR DJ, BOYLE AP, BRENKER F, CHEADLE MC, DAY A, LOPEZ G, PERUZZO L, POTIS GJ, REDDY S, SPIESS R, TIMMS NE, TRIMBY P, WHEELER J, ZETTRSTROM L (1999) The application of electron backscatter diffraction and orientation contrast imaging in the SEM to textural problems in rocks. Amer Miner 84: 1741–1759

SAINT BLANQUAT M, TIKOFF B, TEYSSIER CH, VIGNERESSE JL (1998) Transpressional kinematics and magmatic arcs. In: HOLDSWORTH RE, STRACHAN RA, DEWEY JE (eds) Continental Transpressional and Transtensional Tectonics. Geological Society of London Special Publications 135: 327–340

SCHMIDT NH, OLENSEN NO (1989) Computer-aided determination of crystal-lattice orientation from electronchannelling patterns in the SEM. Canad Mineral 28: 15–22

SCHMIDT KL, PATERSON SR (2002) A doubly vergent fan structure in the Peninsular Ranges Batholith: transpression or local complex flow around a continental margin buttress? Tectonics 21: 1050–1069

SCHULMANN K, KRÖNER A, HEGNER E, WENDT I, KONOPÁSEK J, LEXA O, ŠTÍPSKÁ P (2005) Chronological constraints on the pre-orogenic history, burial and exhumation of deep-seated rocks along the eastern margin of the Variscan Orogen, Bohemian Massif, Czech Republic. Amer J Sci 305: 407–448

SCHULMANN K, LEXA O, ŠTÍPSKÁ P, RACEK M, TAJČMANOVÁ L, KONOPÁSEK J, EDEL JB, PESCHLER A, LEHMANN J (2008) Vertical extrusion and horizontal channel flow of orogenic lower crust: key exhumation mechanisms in large hot orogens? J Metam Geol 26: 273–297

SCHULMANN K, KONOPÁSEK J, JANOUŠEK V, LEXA O, LARDEAUX JM, EDEL JB, ŠTÍPSKÁ P, ULRICH S (2009) An Andean type Palaeozoic convergence in the Bohemian Massif. C R Geosci 341: 266–286

STÁRKOVÁ I ed. (1998) Basic geological map 1:50 000, sheet 14–33 Polička. Czech Geological Survey, Prague

STIPP M, STUENITZ STÜNITZ H, HEILBRONNER R, SCHMID SM (2002) Dynamic recrystallization of quartz; correlation between natural and experimental conditions. In: MEER DS, DRURY MR, BRESSES JHP, PENNOCK GM (eds) Deformation Mechanisms, Rheology and tectonics; Current Status and Future Perspectives. Geological Society of London Special Publications 200: 171–190

ŠTORCH P, KRAFT P (2009) Graptolite assemblages and stratigraphy of the Lower Silurian Mrákotín Formation, Hlinsko Zone, NE interior of the Bohemian Massif (Czech Republic). Bull Geosci 84: 51–74

TIKOFF B, GREENE D (1997) Stretching lineations in transpressional shear zones: an example from the Sierra Nevada Batholith, California. J Struct Geol 19: 29–39

VACHTL J (1962) The Hlinsko Palaeozoic and its relationship to neighbouring units. Sbor Ústř Úst geol 27: 341–359 (in Czech)

VERNER K, ŽÁK J, HROUDA F, HOLUB FV (2006) Magma emplacement during exhumation of the lower- to mid-crustal orogenic root; the Jihlava syenitoid pluton, Moldanubian Unit, Bohemian Massif. J Struct Geol 28: 1553–1567

VERNER K, ŽÁK J, NAHODILOVÁ R, HOLUB FV (2008) Magmatic fabrics and emplacement of the cone-sheet-bearing Knížecí Stolec durbachitic Pluton (Moldanubian Unit, Bohemian Massif): implications for mid-crustal reworking of granulitic lower crust in the Central European Variscides. Int J Earth Sci 97: 19–33

VERNER K, BURIÁNEK D, VRÁNA S, VONDROVIC L, PERTOLDOVÁ J, HANŽL P, NAHODILOVÁ R (2009) Lithological and structural features of geological units along the northern periphery of the Moldanubian Zone: a review of the geology of the northeastern Variscides. J Geosci 54: 87–100

VERNON RH (2000) Review of microstructural evidence of magmatic and solid-state flow. El Geosci 5: 2, 1–23, doi: 10.1007/s10069-000-0002-3

VONDROVIC L, VERNER K (2010): The record of structural evolution and U–Pb zircon dating of the tonalite intrusions (Polička Crystalline Unit, Bohemian Massif). Trab Geol 30: 316–321

VRÁNA S, BLÜMEL P, PETRAKAKIS K (1995) Moldanubian Zone – Metamorphic Evolution (Chapter VII.C.4). In: DALLMEYER RD, FRANKE W, WEBER K (eds) Pre-Permian Geology of Central and Eastern Europe. Springer-Verlag, Berlin, pp 453–468

WÜRM A (1927) The age of cherts in Hlinsko area. Věst St geol Úst Čs Republ 3: 247–255 (in Czech)

ŽÁK J, SCHULMANN K, HROUDA F (2005) Multiple magmatic fabrics in the Sázava Pluton (Bohemian Massif, Czech Republic): a result of superposition of wrench-dominated regional transpression on final emplacement. J Struct Geol 27: 805–822

ŽÁK J, DRAGOUN F, VERNER K, CHLUPÁČOVÁ M, HOLUB FV, KACHLÍK V (2009) Forearc deformation and strain partitioning during growth of a magmatic arc: the northwestern margin of the central Bohemian Plutonic Complex. Tectonophysics 469: 93–111

ŽÁK J, KRATINOVÁ Z, TRUBAČ J, JANOUŠEK V, SLÁMA J, MRLINA J (2011) Structure, emplacement, and tectonic setting of Late Devonian granitoid plutons in the Teplá–Barrandian Unit, Bohemian Massif. Int J Earth Sci 100: 1477–1495

Paper No. II.

VONDROVIC, L. - VERNER, K. (2010) THE RECORD OF STRUCTURAL EVOLUTION AND U-PB ZIRCON DATING OF THE TONALITE INTRUSIONS (POLIČKA CRYSTALLINE UNIT, BOHEMIAN MASSIF) -TRABAJOS DE GEOLOGÍA, UNIVERSIDAD DE OVIEDO 30: 316-321.

Trabajos de Geología, Universidad de Oviedo, 30 : 316-321 (2010)

The record of structural evolution and U-Pb zircon dating of the tonalite intrusions (Polička Crystalline Unit, Bohemian Massif)

LUKÁŠ VONDROVIC[1,2] AND KRYŠTOF VERNER[1,2]

[1] Institute of Petrology and Structural Geology, Charles University, Albertov 6, Prague, Czech Republic

[2] Czech Geological Survey, Klárov 3, Prague, Czech Republic

e-mail: lukas.vondrovic@geology.cz

Abstract

In this study, we present new structural, AMS, and geochronological data from the Miřetín and Budislav tonalite plutons which intruded the mid-crustal Polička Crystalline Unit (Bohemian Massif, Central European Variscides). Magmatic to solid-state fabrics preserved in the plutons (~350 Ma) presumably reflect strain increments acquired during the last stages of regional tectonometamorphic evolution in the NE part of the Boheminal Massif. We emphasize that careful structural analysis in and around these tonalite plutons integrated with geochronology contributed to the solution of geodynamic evolution in marginal part of the Bohemian Massif during and shortly after the ~350 Ma.

Key words: Variscan orogeny, Bohemian Massif, pluton, fabric, AMS

Many studies have established that structures and fabrics in the plutons may record regional paleostrain fields during and after their crystallization (e.g., Paterson et al., 1998, Miller and Paterson, 2001). Careful structural and geochronological analysis of the plutons may thus provide important constraints on kinematic framework and timing of regional tectonometamorphic processes within orogenic belts. On the basis of this assumption, we carried out detailed structural analysis of two calc-alkaline plutons (the Miřetín and Budislav pluton) to understand the time- and kinematic- frame of tectonometamorphic evolution of the NE part of the Bohemian Massif during Variscan orogeny (e. g. Franke, 1989).

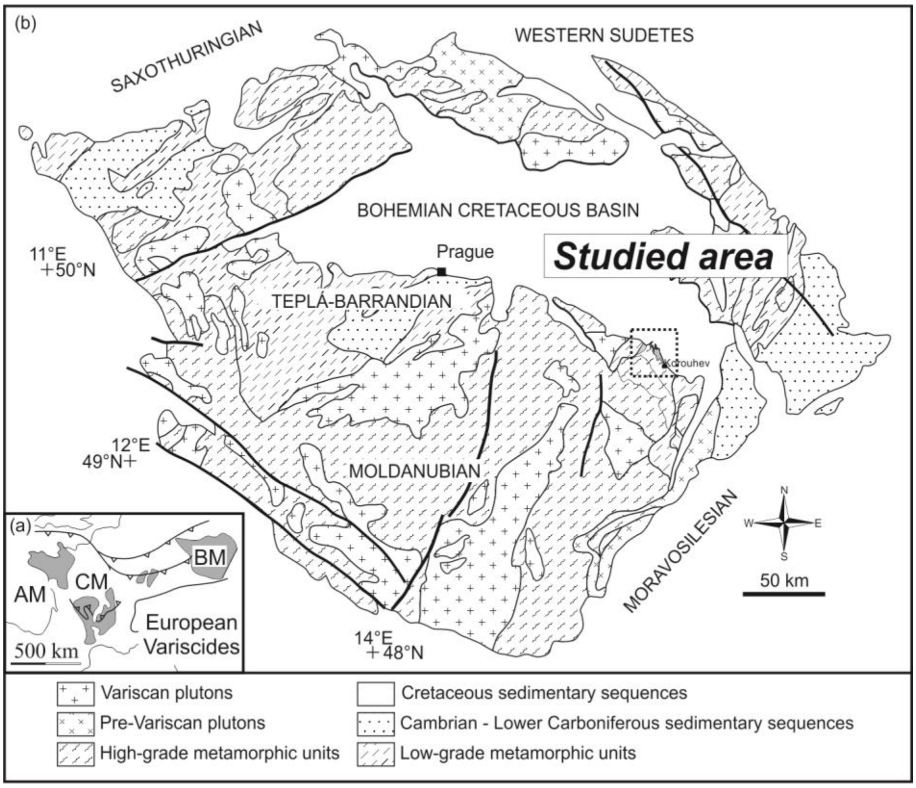


Fig. 1 a) Geological sketch of the European Variscides. AM: Armorican Massif. CM: Central Massif, BM: Bohemian Massif. b) Geological map of the Bohemian Massif with the studied area highlighted.

Methods

We applied the AMS method (Anisotropy of Magnetic Susceptibility; e. g. Hrouda and Tarling 1984) to determine and quantify the internal fabrics of the Budislav pluton. The AMS was measured with the KLY-3S Kappabridge apparatus (Jelínek and Pokorný, 1997) and statistical analysis of AMS data was carried out using the ANISOFT package of programs (Hrouda et al., 1990). The AMS data are represented by the k_m, P, and T parameters defined as follows: $k_m = (k_1 + k_2 + k_3)/3$; $P = k_1/k_3$ and $T = 2\ln(k_2/k_3)/\ln(k_1/k_3) - 1$, where k_1, k_2, k_3 are the axis of the susceptibility ellipsoid. The k_m parameter represents the mean bulk magnetic susceptibility reflecting the qualitative and quantitative content of magnetic minerals in a rock. The P parameter (Nagata, 1961), called the degree of AMS, reflects the eccentricity of the AMS ellipsoid and thus indicates the intensity of the preferred orientation of magnetic minerals in a rock. The higher value of P parameter indicates the stronger preferred orientation. The T parameter (Jelínek, 1981) reflects the symmetry of the AMS ellipsoid. It varies from -1 (linear magnetic fabric) through 0 (transition between linear and planar magnetic fabric) to +1 (planar magnetic fabric). The orientations of the magnetic foliation (poles) and magnetic lineations are presented either in contour diagrams in the geographic coordinate system or as locality means in a map (Fig 2c).

The radiometric age of plutons was established using U-Pb method on zircons (^{207}Pb/ ^{235}U, ^{206}Pb/^{238}U ratios) measured by LA ICP MS (Laser Ablation Inductively Coupled Mass Spectrometry) at the University of Bergen, Norway.

Structural pattern

Metamorphic host rocks (the Polička Crystalline Unit)

The Polička Crystalline Unit (PCU) crops out at the periphery of exhumed orogenic root (referred to as the Moldanubian Unit) in the NE part of the Bohemian Massif (Fig. 1). The PCU is made up of two-mica gneisses with layers of calc-silicate rocks, marbles, and amphibolites. The regional P–T conditions of PCU were estimated at ~0.5Gpa and 590°C (for review see Buriánek et al. 2006). The overall structural pattern of the PCU (Fig. 2.) is defined by regional metamorphic foliation (pervasive schistosity or compositional banding) which dips steeply to moderately to the NE in central part of the PCU, and to the WNW in its western part. This foliation bears well-developed, gently plunging NW–SE stretching lineation associated with right-lateral kinematics. During the Variscan orogeny, the PCU was intruded by numerous intrusions of calc-alkaline composition (e.g. the Miřetín and Budislav plutons; Buriánek et al. 2003). To the W, the PCU and other mid-crustal units are separated from the overlying upper-crustal metasediments (the Hlinsko Zone) by localized ~NNE–SSW normal faults.

The Miřetín pluton

The Miřetín pluton (MP) has a ~NNE–SSW elongated shape and is composed of deformed medium-grained, porphyritic biotite tonalite to granodiorite (Fig. 4). The MP intruded the western margin of the PCU at 348±7 Ma (U-Pb methods on zircons; University of Bergen, Norway). Two distinct solid-state fabrics were recognized in the MP (Fig. 3.): (i) Pervasive HT solid-state fabric defined by the ductile deformation of biotite and partly recrystalized quartz-feldspathic aggregates (Fig. 4 a,b). This HT solid-state foliation is associated with subhorizontal stretching lineation and right-lateral kinematics. The orientation and character of this fabric are consistent with metamorphic foliation and lineation in the host metamorphic rocks. (ii) Discrete LT solid-state fabric developed as spaced cleavage (Fig. 4 a,b). This LT deformation event affected only the western margin of the MP. The LT cleavage dips at moderate angles to the W–NW and is asociated with strongly developed stretching lineation and west-side-down kinematics. This LT fabric is probably connected with normal faulting along the PCU - Hlinsko Zone tectonic boundary.

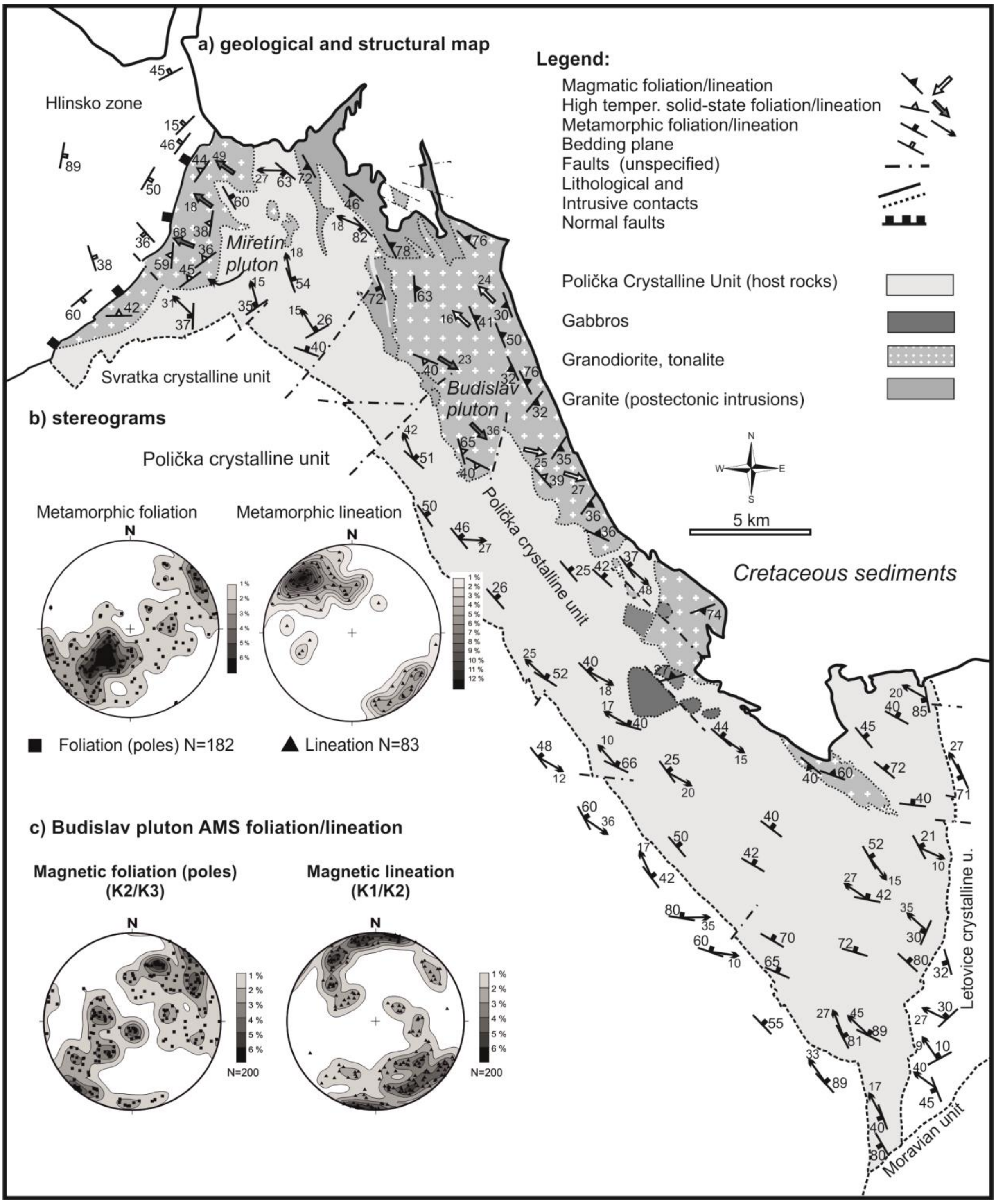


Fig. 2 (A) structural and geological sketch of the mid- to upper-crustal Polička Crystalline Unit including the neighbouring metamorphic complexes; (B) stereograms (lower hemisphere, equal area projection) of metamorphic foliations and lineations, (C) stereograms (lower hemisphere, equal area projection) of AMS fabric in Budislav pluton.

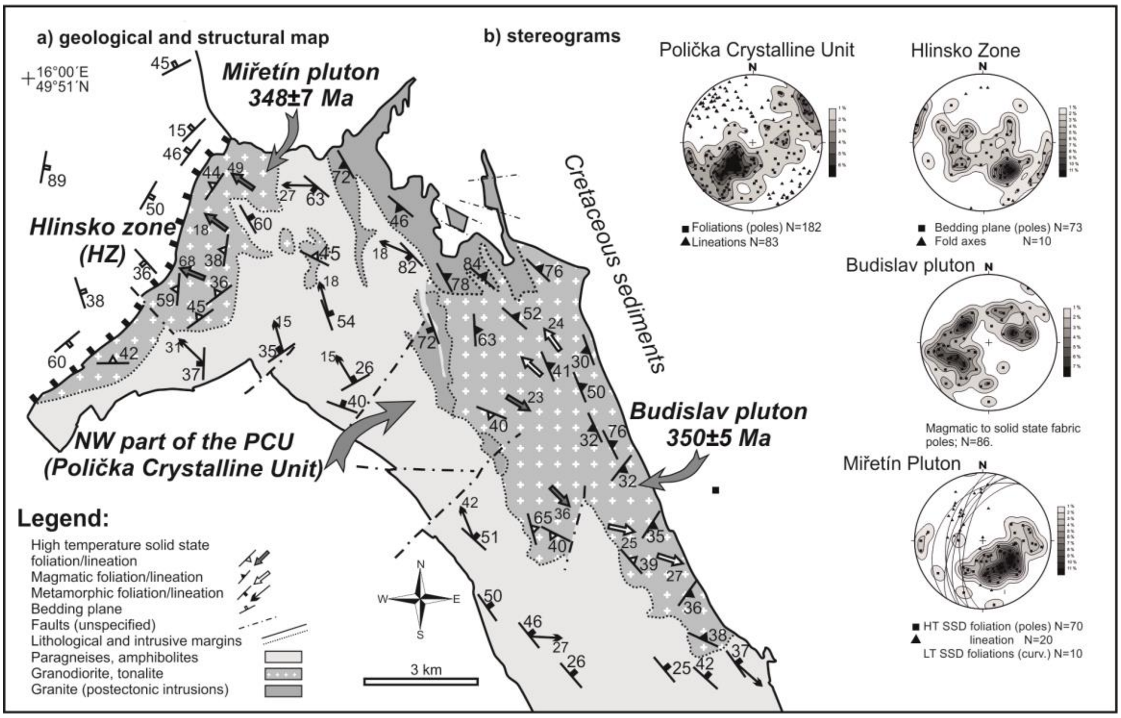


Fig. 3 (A) structural and geological scheme of Polička crystalline Unit, Miřetín and Budislav plutons , (B) stereograms (lower hemisphere, equal area projection) of structural measurements

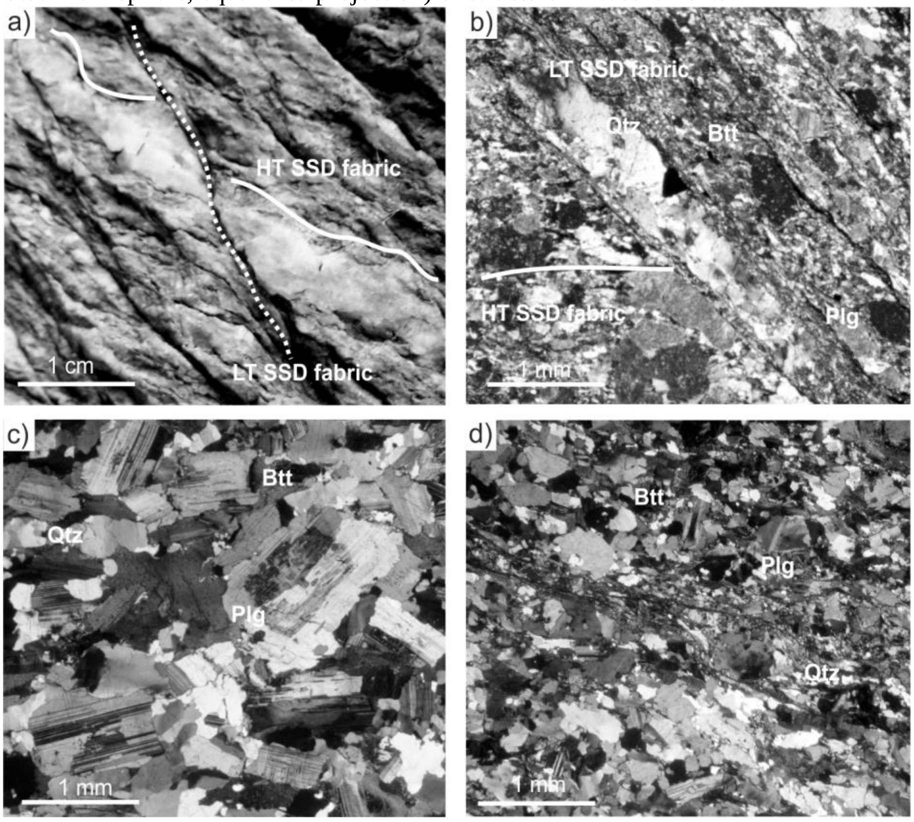


Fig. 4 Macro and microphotographs from Miřetín and Budislav plutons: (A) Miřetín pluton: The LT-cleavage superimposed on the older high-temperature solid state fabric, (B) Miřetín pluton: microstructural record of fig 4a, (C) Budislav pluton: magmatic fabric the alignment of plagioclase and biotite grains coupled with low internal crystal deformation; (D) Budislav pluton: solid state fabric marked by recrystallized biotite, polygonal grains of recrystallized quartz and feldspar. Captions: HTSSD – high temperature solit state; LTSSD – low temperature solid state

The Budislav Pluton

The Budislav pluton (BP) is composed of fine grained amphibole-biotite tonalite to granodiorite (Fig. 4 c,d.). The BP intruded the central part of the PCU at 350±5 Ma (U-Pb method on zircons; University of Bergen, Norway). Multiple magmatic to solid-state fabrics are recognized in the BP (Fig 3): (i) M_1 magmatic foliations, defined by shape preferred orientation of plagioclase and biotite aggregates, dip steeply to the SE and (ii) M_2 magmatic to solid-state foliation, characterized by continuous transition from magmatic to HT solid-state deformation (Fig. 4 c,d), dips moderately to the ~NE/SW. The M_2 foliation is associated with subhorizontal mineral (magmatic) and stretching (solid-state) lineations (L_2). This fabric is parallel both to the pluton margin and to the regional metamorphic fabric in host rocks.

The AMS fabric was investigated on 20 localities in the BP. The mean bulk magnetic susceptibility (k_m) is relatively homogeneous and low, ranging from 171 to 672 x 10^{-6} [SI]. The values of k_m in the order of 10^{-4} indicate that the paramagnetic mineral phases (biotite and amphibole) are the carriers of the AMS. The degree of AMS (P parameter) ranges from 1.033 to 1.218; the P parameter shows no significant gradient in the pluton. In several cases, the higher values of parameter P correlate with the presence of HT solid-state deformation. Susceptibility ellipsoids exhibit prolate to oblate character, T parameter ranges from –0.987 to 0.9. The orientation of magnetic foliations and lineations is consistent with the measured mesoscopic fabrics (Fig. 2c)

Conclusions

The temporal and geometrical relationships of structures and fabrics in and around the studied calc-alkaline plutons provide important constraints for kinematic framework and timing of geodynamic processes along the periphery of exhumed orogenic root in the Bohemian Massif during and shortly after the ~350 Ma:

(1) The formation of HT solid-state fabric in the Miřetín pluton (dated at 348±7 Ma) is clearly connected with the regional orogenic deformation in the western part of the PCU. The overprinting LT cleavage reflects later west-side up normal faulting along the boundary between mid- and upper-crustal units (PCU and Hlinsko Zone, respectively).

(2) The Budislav pluton (dated at 350±5 Ma) intruded the central part of the PCU. Here, the discordant ~NE–SW magmatic foliations likely recorded intrusive strain during the emplacement of the pluton. These fabrics were overprinted by NW–SE regional magmatic to HT solid-state foliation associated with subhorizontal mineral and stretching lineation. The

latter magmatic fabric is interpreted to record increments of the regional orogenic deformation.

(3) The pervasive metamorphic fabric in the PCU is interpreted as being a result of regional dextral shearing under amphibolite facies conditions (P~0.5Gpa and T~590°C) along the NE part of Variscan orogenic root at around 350 Ma.

Acknowledgements: *this research was funded by Czech Geological Survey Research Project No. 6352 (to Jaroslava Pertoldová) and by project of Grant Agengy of Charles University No 81909: The mechanism of emplacement of the particular plutons of northern part of the moldanubia; implications for tectonic evolution of eastern margin of Bohemian Massif. We would like to thank Jan Košler (University of Bergen) for precise zircons geochronology. We also thank David Buriánek for the field cooperation and helpful dicsussion.*

References

Buriánek, D., Němečková, M., Hanžl., P., (2003): Petrology and geochemistry of plutonic rocks from the Polička and Zábřeh crystalline units (NE Bohemian Massif). Bull. Czech Geol Surv., 78: 9–22.

Buriánek, D., Břízová, E., Čech, S., Čurda, J., Fürych, V., Hanžl, P., Kirchner, K., Lysenko, V. Roštínský, P. Rýda, K., Skácelová, D., Skácelová, Z., Verner, K., Vít, J. (2006a): Vysvětlivky k základní geologické mapě ČR 1:25 000 24-112 Jedlová. MŽP, Archiv ČGS.

Franke, W. (1989): Variscan plate tectonics in Central Europe - current ideas and open questions. Tectonophysics, 169: 221-228

Hrouda, F. and Tarling, D.H. (1984): The magnetic anisotropy of rocks. Chapmann and Hall, London, 215 p.

Hrouda, F., Jelínek, V., Hrušková, L. (1990): A package of programs for statistical evaluation of magnetic data using IBM-PC computers. EOS Trans. AGU, San Franscisco,1289.

Jelínek, V. (1981): Characterization of the magnetic fabric of rocks. Tectonophysics, 79**:** 63–67.

Jelínek, V. and Pokorný, J. (1997): Some new concepts in technology of transformer bridges for measuring susceptibility anisotropy of rocks. Physics and Chemistry of the Earth, 22: 179-181.

Miller, R.B. and Paterson, S.R. (2001): Influence of lithological heterogeneity, mechanical anisotropy, and magmatism on the rheology of an arc, North Cascades, Washington Tectonophysics.342,3-4:351-370.

Nagata, T. (1961): Rock Magnetism. Maruzen Ltd. Tokyo, 350 pp.

Paterson, S.R., Fowler, T.K., Schmidt, K.L., Yoshinobu, A.S., Yuan, E.S., Miller, R.B., (1998): Interpreting magmatic fabric patterns in plutons. Lithos, 44: 53-82.

Paper No. III.

VONDROVIC, L. - VERNER, K. - BURIÁNEK, D. – SLÁMA, J - KACHLÍK, V.(2015): EMPLACEMENT AND GEOCHRONOLOGY OF CALC-ALKALINE PLUTONS (EASTERN BOHEMIAN MASSIF): IMPLICATIONS FOR EARLY VARISCAN MAGMATIC AND GEODYNAMIC PROCESSES

Article manuscript

Emplacement and geochronology of calc-alkaline plutons (Eastern Bohemian Massif): Implications for Early Variscan magmatic and tectonic processes

Lukáš Vondrovic[1,2*], Kryštof Verner[1,3], David Buriánek[4], Jiří Sláma[5], Václav Kachlík[7]

[1] *Institute of Petrology and Structural Geology, Charles University, Albertov 6, Prague, 12843, Czech Republic*

[2] Radioactive Waste Repository Autority, Dlážděná 6, Prague 1, 10000

[3] *Czech Geological Survey, Klárov 3, Prague 1, 11821, Czech Republic; krystof.verner@geology.cz*

[4] *Czech Geological Survey, Leitnerova 22, Brno, 602 00, Czech Republic*

[5] Centre for Geobiology and Department of Earth Science, University of Bergen, Allegaten 41, N-5007 Bergen, Norway

[6] Institute of Geology, Academy of Sciences of the Czech Republic, v.v.i., Rozvojová 135, Prague 6, 165 02, Czech Republic

[7] *Institute of Geology and Paleontology, Charles University, Albertov 6, Prague, 12843, Czech Republic*

Abstract

The calc-alkaline Budislav Pluton and Zábřeh Intrusive Complex (newly dated at 346Ma ± 5Ma; and 354± 6Ma U–Pb age on zircons) are plutonic bodies which intrude the variscan mid- tu upper- crustal Polička and Zábřeh Units (eastern margin of the Bohemian Massif). The internal fabric within the plutons and the host rocks indicate synchronicity between magma emplacement and the development of the main tectonometamorphic fabrics in the host rocks. The geochemical composition reveals similarities to other early-variscan calc-alkaline granitoids in the Bohemian Massif (e.g. the Central Bohemian Plutonic Complex) which are interpreted as being the products of the mixing of basic magmas with crustally-derived acid melts. The conditions of the magma crystallisation of the Budislav Pluton (T: 655-730°C and P: 0.4-0.6Gpa) correspond to the peak metamorphic evolution of the host rocks of the north western part of the Polička Unit (T: 620-680°C and P: 0.6 GPa). In the case of the Zábřeh Unit, emplacement conditions (T: 706-795°C and P: 0.3-0.4Gpa)

roughly correspond with the contact metamorphism observed in the host rock (T: ~599-663°C and P: 0.4Gpa). Structural evidence suggests that the plutons under study were emplaced in a zone of dextral transpressive shearing that took place in the Variscan mid- to upper-crustal level in 354-346Ma.

1. Introduction

Orogenic processes related to transpressional deformation are often accompanied by the ascent and emplacement of plutonic bodies (e.g. Tikoff and Greene 1997; Saint Blanquat et al. 1998; Chardon et al. 1999; Brown and Solar 1999; Miller and Paterson 2001; Schmidt and Paterson 2002). The fabrics and structures within plutons formed during and following crystallisation often reflect emplacement mechanisms, the regional strain field and the kinematic and exhumation paths of the host metamorphic rocks (e.g. Paterson et al. 1998; Benn et al. 2001; Miller and Paterson 2001). In recent years a large number of papers have been published which linked magmatic processes and the regional strain field in the Central European Variscides (e.g. Žák et al 2005a,b; Verner et al 2008, 2009; Schulmann et al 2005, 2008, 2009; Lehmann et al. 2013). The Central European Variscides, usually referred to as the Bohemian Massif (Fig. 1a), is the result of a Devonian subduction with related deformation and the Carboniferous collision of Gondwana-derived crustal segments with the Laurusia continent (for a general review see Franke 2000). The Variscan orogeny resulted in an assembly of heterogeneous units which created the geological framework of the western and central parts of the European continent. Following the first stage of Variscan evolution (the subduction of oceanic crust with the intervention of individual Gondwana-derived crustal fragments associated with HP metamorphism ~400-380Ma) crustal thickening occurred during the collisional process at ~355-340Ma followed by the rapid exhumation of deep-seated rocks up to ~335Ma (Hartley and Otava 2001). The final stage of the Variscan orogeny was dominated by wrench tectonic activity at ~330-300Ma (e.g. Edel et al. 2003). The associated magmatic activity in the Central European Variscides consisted of several different periods: (a) Calc-alkaline (I type) magmatism related to subduction and syn-collisional processes (~370 to 346Ma; e.g. Janoušek et al. 2004a; Žák et al. 2005 a,b); (b) the emplacement of ultrapotassic Mg-rich plutons which originated as a result of the mixing of magmas derived from anomalous ultramafic mantle rocks and lower continental crust (~343-335Ma; Holub et al. 1997 a, b; Verner et al. 2005, 2008, Kusiak et al. 2010, Kotková et al. 2010); (c) deformed S-type granite-migmatite associations related to the partial melting and exhumation of deeply-seated metasedimentary rocks (~340Ma; Žák et al. 2011 b); (d) the crystallisation of types I, I/S and S granitoids related to post-collisional extension and magmatic underplating in the Moldanubian Zone (~335-315Ma; Verner et al. 2014) and finally (e) the emplacement of post-collisional ~granodiorites and leucogranites dated at 310-250Ma (Finger et al. 1997). The first magmatic event discussed in this paper was generally connected with the closure of Saxothuringian oceanic crust and the subsequent subduction of the Saxothuringian plate beneath the Teplá-Barrandian Zone (e.g. Franke 1989, 2000; Beard et al. 1995, Kachlík 1997, Finger et al. 1997; Kroner and Romer 2013). The petrogenesis, emplacement, geochronology and tectonic setting of calc-alkaline plutons intruding the western segment of the Teplá-Barrandian Zone and forming the Central Bohemian Plutonic Complex were discussed recently by Holub et al. (1997 a); Venera et al. (2000); Janoušek et al. (2000, 2004 a,b); Buriánek et al. (2003) and Žák et al. (2005, 2011), Fig 1a. Initially, the emplacement of calc-alkaline, normal-K granitoids connected with regional ~WNW-ESE compression at ~370 to 354Ma (e.g. Žák et al. 2010) was followed by high-K magmatic activity in the time range ~354 to 346Ma reflecting WNW–ESE arc-perpendicular shortening and arc-parallel horizontal stretching (Žák et al. 2005 a, b; Hajná et al. 2010). This transpressive deformation continued until circa 346Ma at which time it was replaced by ductile normal shearing associated with the exhumation of the Moldanubian Unit (Holub et al. 1997 b; Žák et al. 2005 a, 2011 a; Janoušek et al. 2010). Similar plutonic bodies in the eastern part of the Bohemian Massif (the eastern margin of the Moldanubian Zone (e.g. Pitra et al. 1994; Schulmann et al. 2005, 2008, 2009; Verner et al. 2009; Pertoldová et al. 2010) have been studied independently in a number of papers to date (Pitra et al. 1994; Parry et al. 1997; Táborská 1997; Hrouda et al. 1999; Lehmann et al. 2013; Verner et al. 2009; Žák et al. 2005 a, b) however, no broad synthesis has yet been compiled. This study aims to contribute to the mosaic of knowledge concerning a collection of early Variscan calc-alkaline plutons which intrude units located on the eastern margin of the Bohemian Massif through the integration of new field structural data, the results of the analysis of the anisotropy of magnetic susceptibility (AMS) and petrological and geochronological data collected from two calc-alkaline plutons which were emplaced in the Variscan mid- to upper-crustal level. It is intended that this will provide for a better understanding of the early Variscan magmatic and orogenic processes which acted between three different lithotectonic units (the Moldanubian Zone, the Teplá-Barrandian Zone and the Saxothuringian Zone) at around ~350Ma.

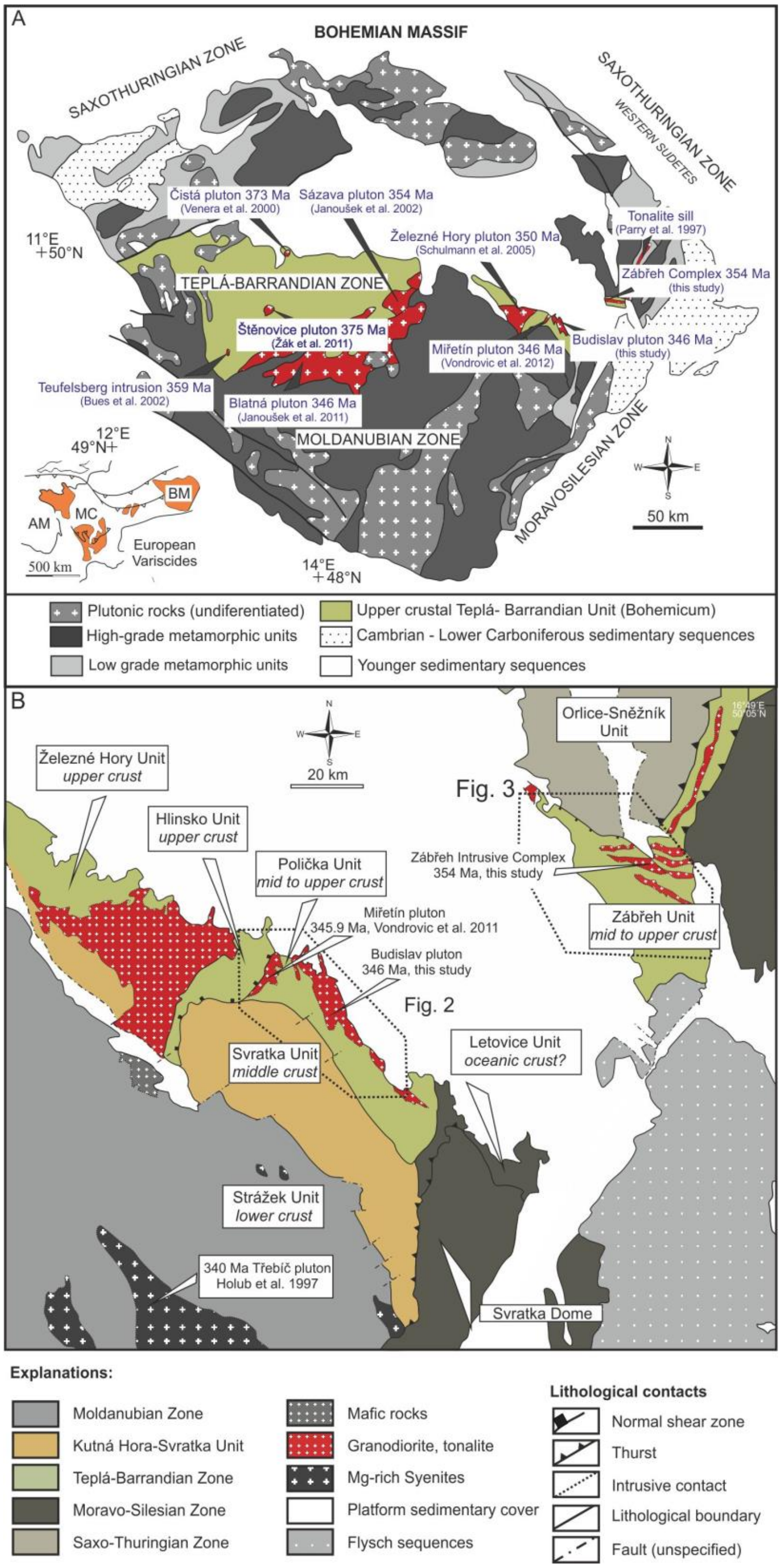


Fig. 1 a) Geological sketch map of the Bohemian Massif with location of the study area at the NE periphery of the Moldanubian Zone and calc-alkaline plutons, b) Simplified geological map of the NE margin of the Bohemian Massif with reference detail the structural maps (Figs 2,3). Compiled from Czech Geological Survey map 1:500 000.

2. Geological setting

The geological framework of the area under study is characterised by three differing crustal units of the Bohemian Massif (Central European Variscides, Fig. 1a,b). The deepest part of the Variscan orogeny which represents the "root" system (Moldanubian Zone) is made up of various high-grade units which resulted from polyphase HP/HT to LP/HT metamorphism and complex regional deformation at ~346–325Ma (e.g. Vrána et al. 1995; Schulmann et al. 2005, 2009, Faryad et al. 2010). The Saxothuringian Zone exhibits an inverse pattern according to which its lowest parts consist of a Cadomian basement (granitoids and the metamorphic envelope thereof overlaid by low- to medium-grade early-Paleozoic metasedimentary sequences) and high-grade (U)HP–HT rocks of Variscan metamorphic age outcrop in the upper parts (Konopásek et al. 2001, Linemann et al. 2008). The Teplá-Barrandian Zone represents a relic originating from polymetamorphosed low- to medium-grade Neoproterozoic rocks (the Cadomian orogenic wedge; Hajná et al. 2011) overlapped non-corformably by a Cambrian and Ordovician to middle-Devonian volcanosedimentary sequence (e.g. Chlupáč and Štorch eds 1992, Chlupáč et al 1998). This unit is situated within the hanging-wall of the Saxothuringian and Moldanubian Zones (Schulmann et al. 2005). A typical feature of the Teplá-Barrandian Zone consists of the presence of several late-Devonian to early Carboniferous calc-alkaline plutons (Fig 1a) originating from the first Variscan magmatic event to take place in the Bohemian Massif (e.g. Holub et al. 1997a,b; Janoušek et al. 2000, 2004).

The area studied (Fig 1a, b) is located in the north eastern part of the Bohemian Massif which forms part of the eastern section of the Bohemicum (Teplá-Barrandian Zone sl., Mísař et al. 1983, Chlupáč and Štorch eds 1992, Melichar 1995) although the regional position of these units remains a matter of discussion; some authors point to similarities between these units and the Lugicum (Cháb et al. 2005) or Moldanubian domain (Schulmann et al. 2005). The Polička Unit (Fig 1b, 2) consists of medium- to low-grade crustal segments composed of metavolcanosedimentary sequences of Neoproterozoic to Lower-Palaeozoic age (Fajst 1976; Buriánek et al. 2003; Buriánek and Pertoldová 2009; Verner et al. 2009; Lehmann et al. 2013). The metamorphic zonality exhibits an increase in metamorphic conditions from the NW to the SE and from greenschist to granulite facies (Buriánek et al. 2009). The Polička Unit can be divided into four different segments according to lithology and P-T evolution (Melichar 1995, Buriánek under rew.): (a) the structurally lower southern part which is made up of migmatitised gneisses and an allochtonous granulite body (Tajčmanová et al. 2010); (b) the central part which consists of a relatively monotonous complex of flysch metasediments with intrusion to the Budislav Pluton (e.g. Kodym and Svoboda 1950; Melichar and Hanžl 1997); (c) the northern part which is lithologically relatively monotonous and very similar to the Hlinsko Unit (Pitra and Guiraud 1996) and was intruded by the Miřetín Pluton at 653-681°C and 0.3-0.4GPa (Vondrovic et al. 2011); (d) the eastern part which consists of micaschist rocks with lenses of quartzites. The tonalite to granodiorite Budislav Pluton under study (Fig 2) exhibits a NW-SE elongated oval shape and its contact with the Polička Unit host rocks is intrusive; the intrusive contacts follow the metamorphic foliation within the host rocks. The Budislav Pluton is intruded by the post-tectonic intrusion of leukogranites - the so-called Zderaz Intrusion (Buriánek et al. 2003) in its northern part. Budislav Pluton and exhibits several varieties of granodiorite to tonalitic rocks, the characteristics of the main types of which are presented in Tab. 3. The P-T conditions of magma crystallisation have been estimated at P: ~0.6GPa and T: 600°C (this study).

The Zábřeh Unit is situated in the hanging wall of exhumed pre-Variscan and early Variscan deep-crustal rocks - the Orlice-Sněžník Unit and consists of a metamorphosed, volcanosedimentary complex. This Unit is made up of two lithological complexes (Fajst 1976; Hanžl et al. 2000, Buriánek et al. 2003). The southern part consists of low-grade metapelites and metabasites while the northern part of the ZU exhibits occurrences of biotite to muscovite-biotite paragneisses (±And, ±St) with intercalations of amphibolites and acid metavolcanites as well as marbles with a relatively high grade of regional metamorphism. The intensity of Variscan metamorphism increases from south to north (towards the OSU). The P-T conditions estimated for the northern part of the Zábřeh Unit fall within the middle part of the amphibolite facies (see chapter 5). The rocks of the northern segment were intruded by numerous sheets of calc-alkaline rocks of ~granodiorite composition known as the Zábřeh Intrusive Complex (Lehmann et al. 2013, Fig 3) which is made up of several granodiorite to tonalite WNW-ESE elongated sheets up to 2km wide emplaced within a ~ 4km-wide belt of migmatitic paragneisses and migmatitic amphibolites. The P-T conditions of the crystallisation of which have been estimated at P: 0.29–0.43Gpa and T: 706–795°C (see chapter 5 of this study).

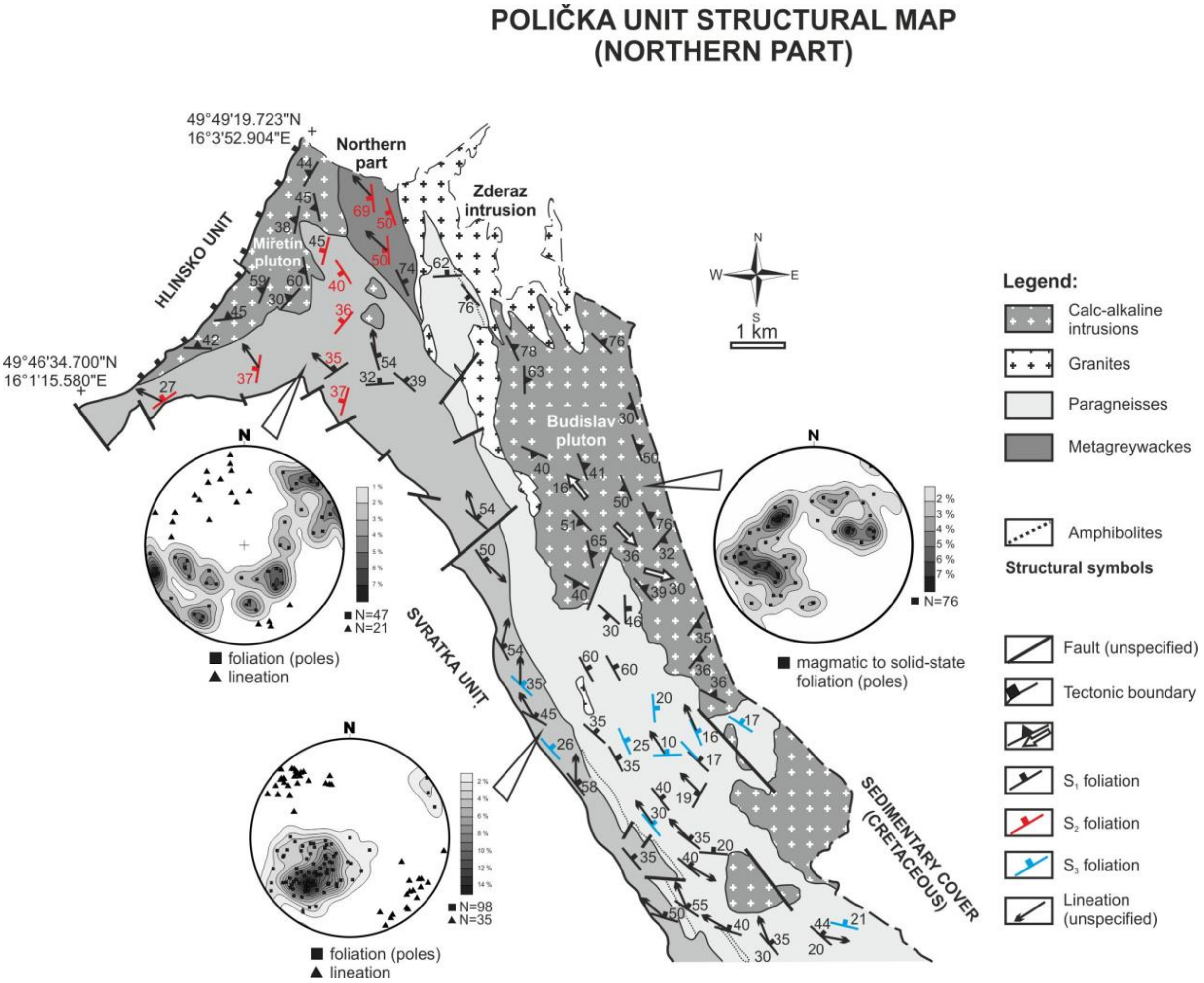


Fig. 2 Structural and geological sketch of the mid- to upper-crustal Polička Unit including the stereograms (lower hemisphere, equal area projection, pole to plane) of metamorphic foliation and magmatic to solid-state foliations.

3. Field structural pattern

3.1 Metamorphic rocks

Polička Unit

The structural pattern of the Polička Unit (Fig 2, Fig. 4 a, b) is characterised by pervasive schistosity with rare relics of older metamorphic fabrics (e.g. rootless and isoclinal folds). Regional foliation S_1 dips in the original position steeply to moderately to the NNE to ENE (Fig. 4a) and exhibits well-developed, gently plunging NW (SE) to WNW (ESE) stretching or mineral lineation (e.g. the lattice preferred orientation of newly-formed micas, elongated and recrystallised quartz and feldspar aggregates). Associated kinematic indicators in the L-par section such as the asymmetric shape of minor folds, ductile deformed mineral aggregates, recrystallisation in pressure shadows and mica-fishes indicate right-lateral shearing. A strong ductile overprint caused by ~NNE-SSW trending transpressional (compressional) S_2 foliation and NW plunging lineation was identified (Vondrovic et al. 2011) in the western flank of the Polička Unit along the boundary with the upper-crustal Hlinsko Unit. In addition, the heterogeneous superimposition of S_3 gently ~N to ~NNE dipping normal ductile to brittle-ductile fabric was identified in the central part of the Polička Unit (Fig 2, Fig 4a). Associated stretching lineations plunge at low angles to the NNW to NNE. The youngest structures consist of planes of spaced cleavage localised along the tectonic boundary between the Polička and low-grade Hlinsko Units. Cleavage planes dip at steep angles to the W to NW and are associated with strongly developed stretching lineation and evidence of west-side-down kinematics (Vondrovic et al. 2011).

Zábřeh Unit

The structural record of the metamorphic rocks of the Zábřeh Unit (Fig. 3) is represented by several distinct metamorphic fabrics. Relatively older steeply to moderately dipping S_1 fabric (sometimes containing the relics of older metamorphic fabric in the form of rootless and isoclinal folds) defined by pervasive schistosity, migmatitic layering and compositional banding dips to the SSW or NNE (see the maxima in the stereograms and structural map; Fig. 3). This fabric is associated with strong subhorizontal stretching lineatios. The S_1 fabric is pervasive primarily in the northern part of the Zábřeh Unit in the proximity of granodiorite sheets (Fig. 4 e). Towards the south this fabric is strongly obliterated by intensive folding that resulted in the development of S_2 fabric represented by flat-lying axial plane cleavage (Fig. 4f). Periodically S_3 fabric occurs in the form of localised kink-bands in rheologically weaker rocks (phyllites). No consistent kinematic data was observed in the rocks of the Zábřeh Unit.

3.2. Calc-alkaline plutons

Two mezoscopically differing fabrics (magmatic and continuous magmatic to solid-state fabrics) were observed in the Budislav Pluton. The older, more rarely preserved, fabric (magmatic foliation) dips steeply to moderately to the SE and is defined by the shape-preferred orientation of plagioclase and biotite phenocrysts. The second fabric is represented by pervasive magmatic foliation which displays a continuous magmatic to high-temperature solid-state character (for details of the microstructural study see chapter 4). This foliation dips under moderate angles to the ~NE or SW and is associated with well-developed mineral and stretching lineations (the lattice preferred orientation of the principal rock-forming minerals) with a subhorizontal (~NW-SE) orientation.

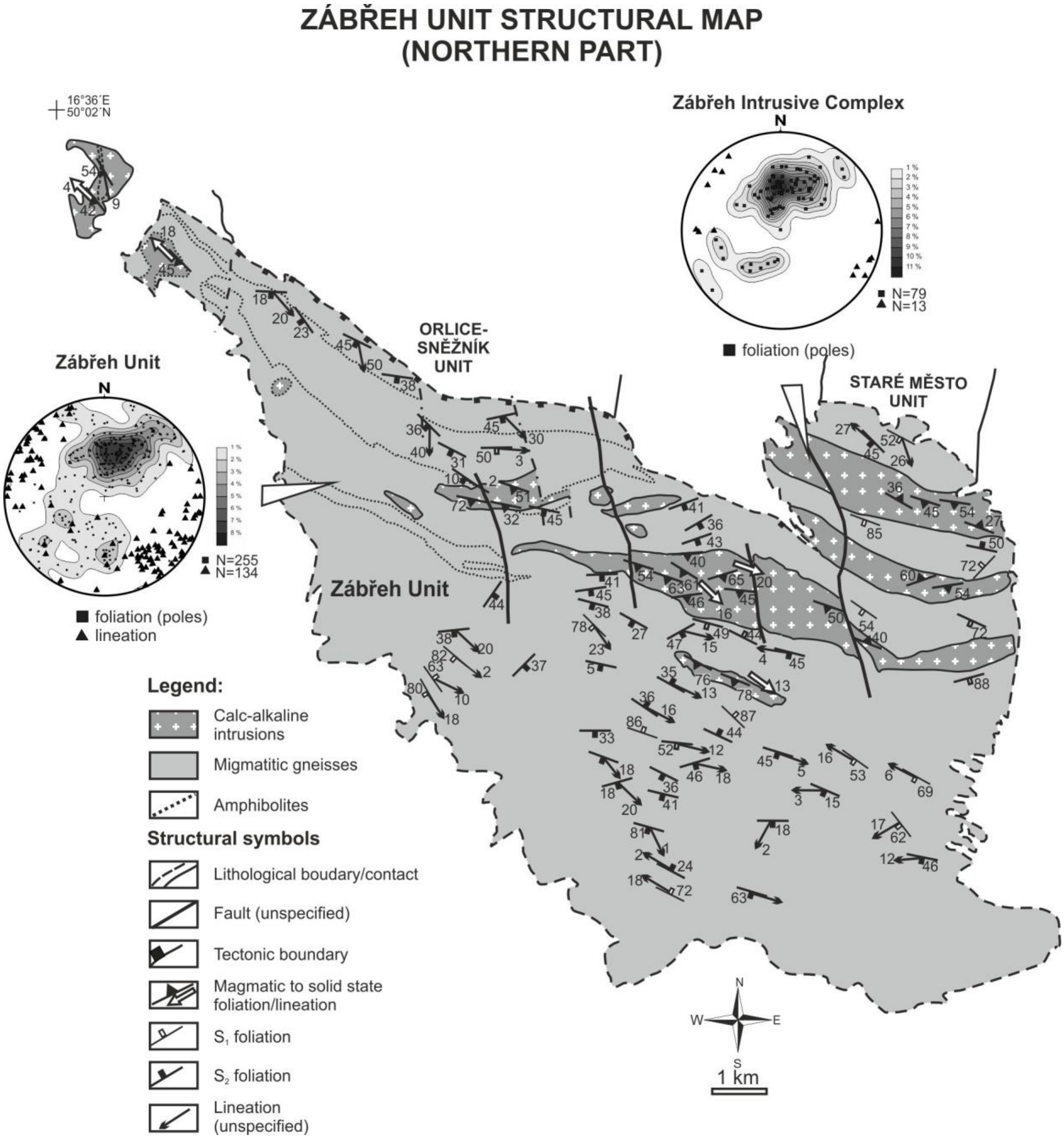


Fig. 3 Structural and geological sketch of the mid- to upper-crustal Zábřeh Unit including the stereograms (lower hemisphere, equal area projection, pole to plane) of metamorphic foliation and magmatic to solid-state foliations.

These fabrics are parallel both to the pluton margin and to the regional metamorphic fabric in the host rocks (Fig. 4 d).The magmatic fabrics in the Zábřeh Intrusive Complex are represented by submagmatic to high-temperature solid-state foliation defined by the ductile deformation of biotite and partly recrystallised quartz-feldspathic aggregates. The intrusive contacts and pervasive foliation in the Zábřeh Intrusive Complex lie roughly parallel to the orientation of the steep regional metamorphic fabric in the northern part of the Zábřeh Unit (S_1, Fig 3). The magmatic to solid state fabric observed in tonalite sheets predominantly follows the S_1 anisotropy of the host rocks (Fig. 4 e). Later folding resulted in the development of changes in dip in the marginal sections of the sheets.

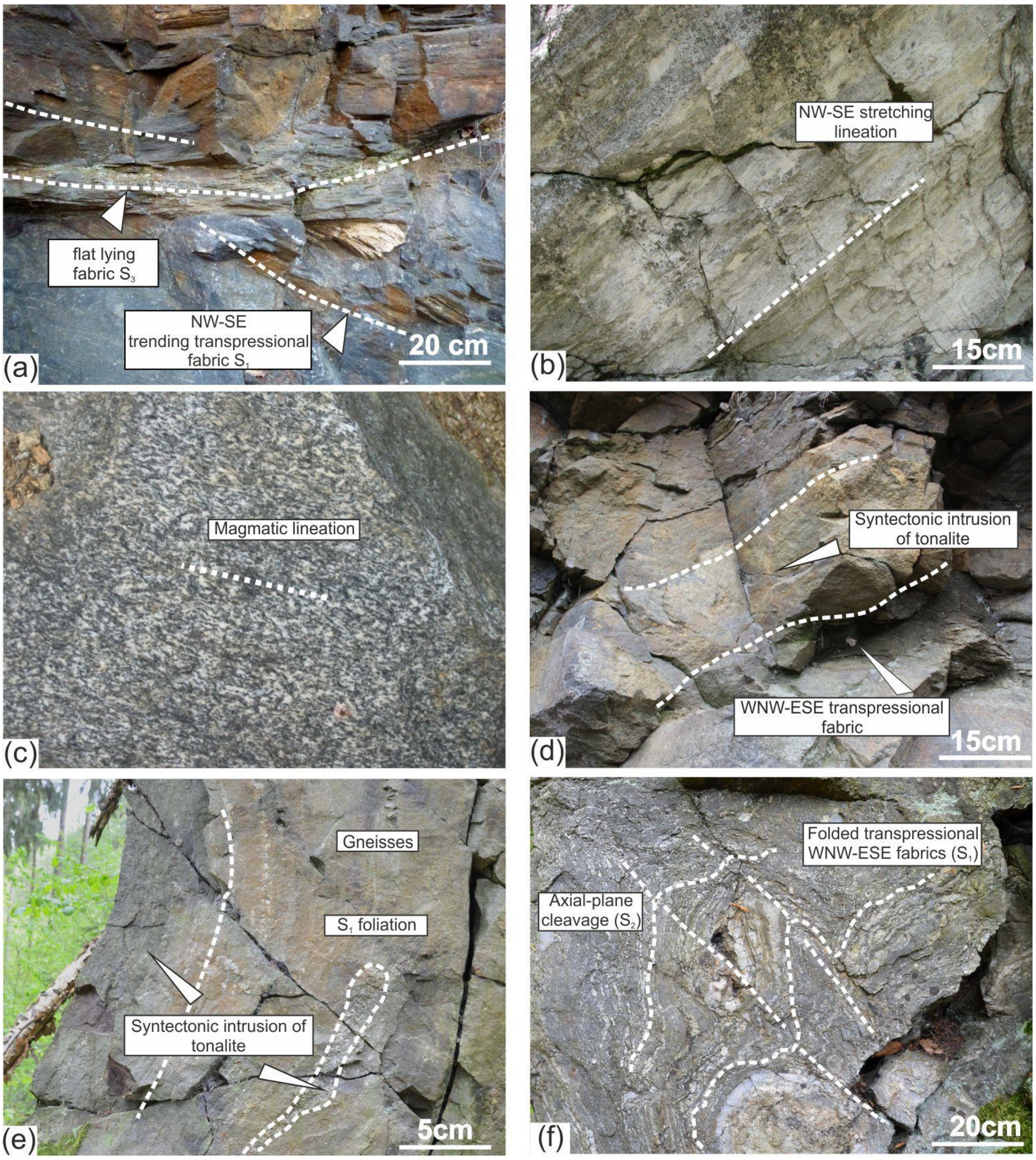


Fig. 4. Field photographs of fabric relationships: a) The relationship beeween distinct metamorphic fabric, Polička Unit (Peklo, migmatitized paragneisses); b) Strong stretching lineation dipping to SE, marbles (Bystré, PU); c) magmatic to solid state lineation plunging to SW (Borová, BP), d) The intrusive contact of Budislav pluton with host rock (Oldříš, PoličkaUnit); (E) The intrusive contact between tonalite and S_1 foliation (Drozdovská pila, ZCC); (F) Relationship between S_1 and S_2 fabric of the Zábřeh Unit (Cotkytle)

4. Microstructural evolution

The calc-alkaline granitoids of the Budislav Pluton and Zábřeh Intrusive Complex exhibit four types of microstructure defined using the criteria of Paterson et al. (1998) and Vernon (2000). The first consists of relic magmatic fabric (Fig.5 a) with no evidence of solid-state deformation and recrystallisation characterised by the presence of subhedral quartz, feldspar, amphibole and biotite grains with no sign of crystal-plastic deformation or recrystallisation. The euhedral to subhedral grains commonly exhibit shape-preferred orientation. Magmatic microstructures are also defined by matrix minerals with anhedral shapes. The magmatic microstrucure occurs in relics in both intrusive bodies. The second type of microstructure consists of transitional magmatic to high-temperature solid state fabric characterised by variable proportions of relic magmatic microstructure overprinted with crystal-plastic deformation (Fig.5 c). The deformation which occurs especially in quartz and feldspars is expressed by the weak stretching of grains and aggregates, lobate grain boundaries, undulatory extinction and the formation of subgrains. This type of microstructure defines the regional fabrics in both plutons. The third type of microstructure was formed chiefly by solid state deformation including the presence of myrmekite, strongly developed undulose extinction in quartz, intensely stretched grains and aggregates, and recrystallised wings on deformed grains. Quartz grains exhibit a chessboard pattern. Plagioclases were affected only by synmagmatic cracking and there is no evidence of other deformation. Biotite and silimanite aggregates often merge into thin folia. This type of microstructure is evident principally near to pluton contacts both in the Budislav Pluton and the Zábřeh Intrusive Complex (<450°C, Fig.5 b,d). Locally, within narrow zones in the Budislav Pluton low-temperature subsolidus microstructures were identified (<450°C, Fig.5 b). In these locations biotite aggregates are largely replaced by chlorite, feldspars are extensively sericitised and quartz aggregates display bulging grain boundaries all of which suggest low-temperature deformation conditions.

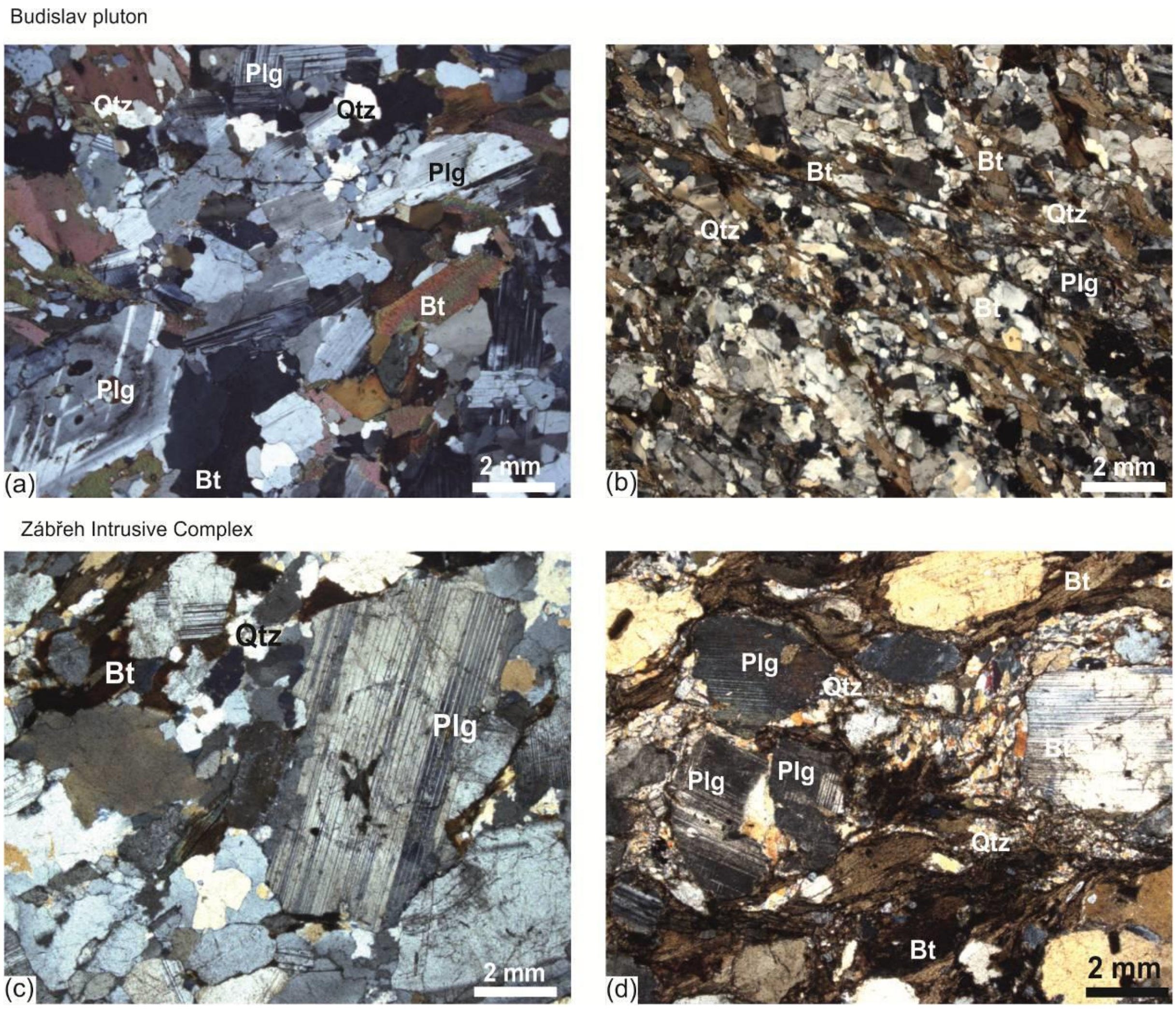


Fig. 5 Microhotographs from Budislav pluton and Zábřeh intrusive complex: (A) magmatic to submagmatic fabric BP (Lubná, tonalite): the alignment of plagioclase and biotite grains coupled with low internal crystal deformation; (B) solid-state fabric BP (Borová tonalite): strongly deformed tonalite, recrystallized biotite, polygonal grains of recrystallized quartz and feldspar; (C) submagmatic fabric (ZIC, Štíty) relic of oscilatory zoning plagioclase, subhedral grains of quartz; (D) solid-state fabric (ZIC, Štíty): strongly deformed tonalite showing ribbon-like folia of extremely fine-grained recrystallized quartz and biotite. The folia anastomose around a deformed porphyroclast of plagioclase.

5. Anisotropy of magnetic susceptibility (AMS)

The the Anisotropy of Magnetic Susceptibility (AMS) method was applied (for a general review see Hrouda and Tarling 1984; Jelínek, 1978) in order to investigate and quantify the internal fabrics of the Budislav Pluton and the Zábřeh Intrusive Complex. AMS data is represented by k, P and T parameters defined as follows: $km = (k1 + k2 + k3)/3$; $P = k1/k3$, and $T = 2 \ln(k2/k3)/\ln(k1/k3) - 1$, where k1, k2, k3 represent the axis of the susceptibility ellipsoid. The km parameter (k - bulk magnetic susceptibility) reflects the quantitative content of magnetic minerals in the rock. The P parameter (P - degree of anisotropy) represents the eccentricity of a fabric ellipsoid to characterise the intensity of the lattice-preferred orientation of magnetic minerals. The T parameter reflects the symmetry of the fabric ellipsoid and it varies from -1 (linear magnetic fabric) to +1 (planar magnetic fabric). In addition, the magnetic minerals were investigated by means of thermomagnetic analysis (KLY-4S Kapabridge and from –196°C to 0°C using CS-L non-magnetic Cryostat apparatus and CS-3 non-magnetic Furnace apparatus for intervals to 700°C).

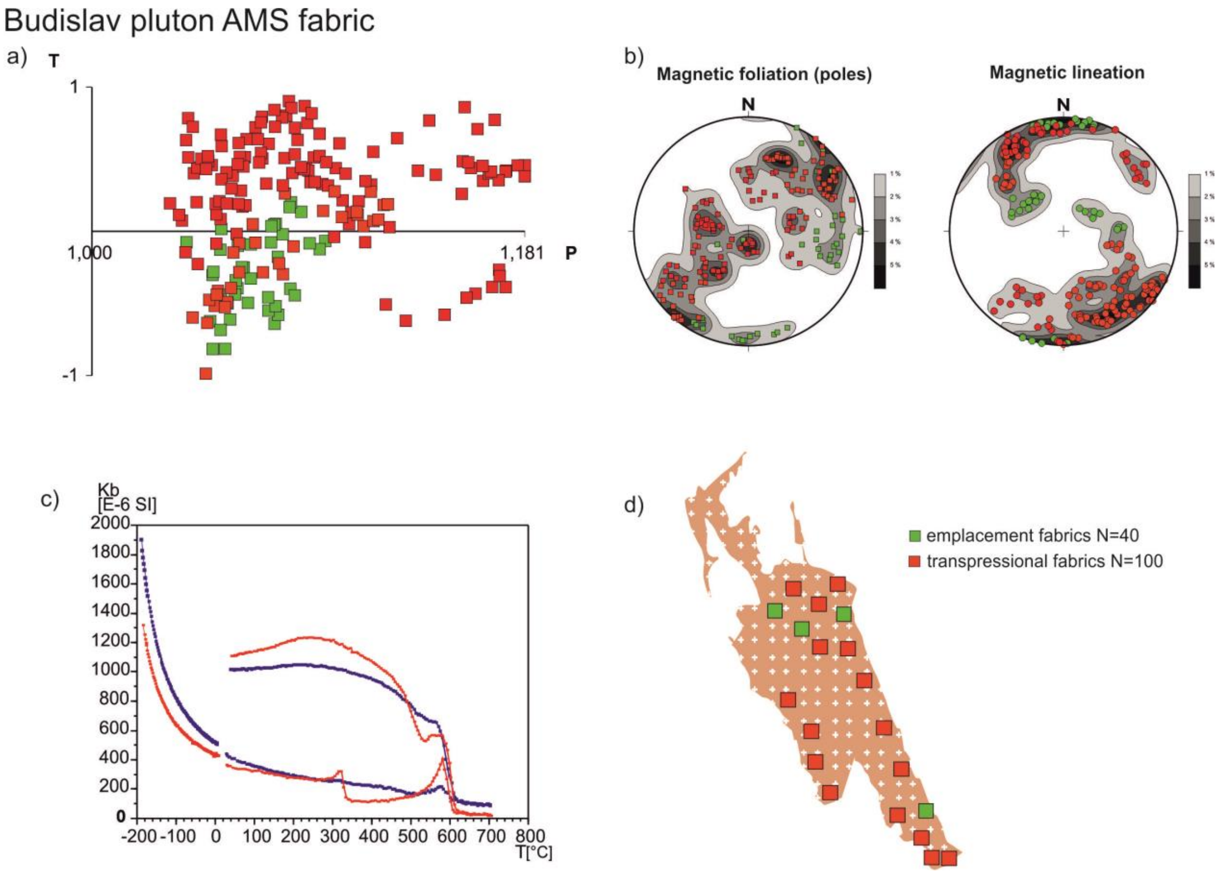


Fig. 6 Budislav pluton AMS fabric: a) P-T plot; b) stereonets of magnetic foliations and lineations (pole to plane), c) thermomagnetic curves, d) sampling localities

The mean bulk magnetic susceptibility (km) is relatively homogeneous and low in the Budislav Pluton, ranging from 171 to 672 x 10^{-6} [SI]. The thermomagnetic curve exhibits hyperbolic shape characteristics for paramagnetic minerals (Fig. 6c). A small peak at 570°C indicates a low content of the ferro-magnetic phase (Fig. 6c). In comparison with the mezoscopical fabric in the tonalite, the author concluded that ferro-magnetic minerals had no, or merely a negligible, influence on the magnetic fabric; the axes of these minerals lie parallel to the foliation plane. In addition, in some cases a small amount of pyrhotite is present according to the curve (not given). Fortunately, the presence of this mineral had no influence on the final geometry of the magnetic fabric. With concern to the Budislav Pluton, two different magnetic fabrics (Fig. 6 a, b, d) could be described: (i) the oldest magnetic steep fabric with an oblate shape and a relatively lower degree of anisotropy, (ii) NW-SE trending magnetic foliation associated with NE or SW dipping magnetic lineation, a higher degree of anisotropy and an AMS ellipsoid with a prolate to oblate shape; and (iii) a late flat-lying magnetic fabric associated with N-dipping lineations, an AMS ellipsoid with an prolate shape and a lower degree of anisotropy.

Zábreh Intrusive Complex AMS fabric

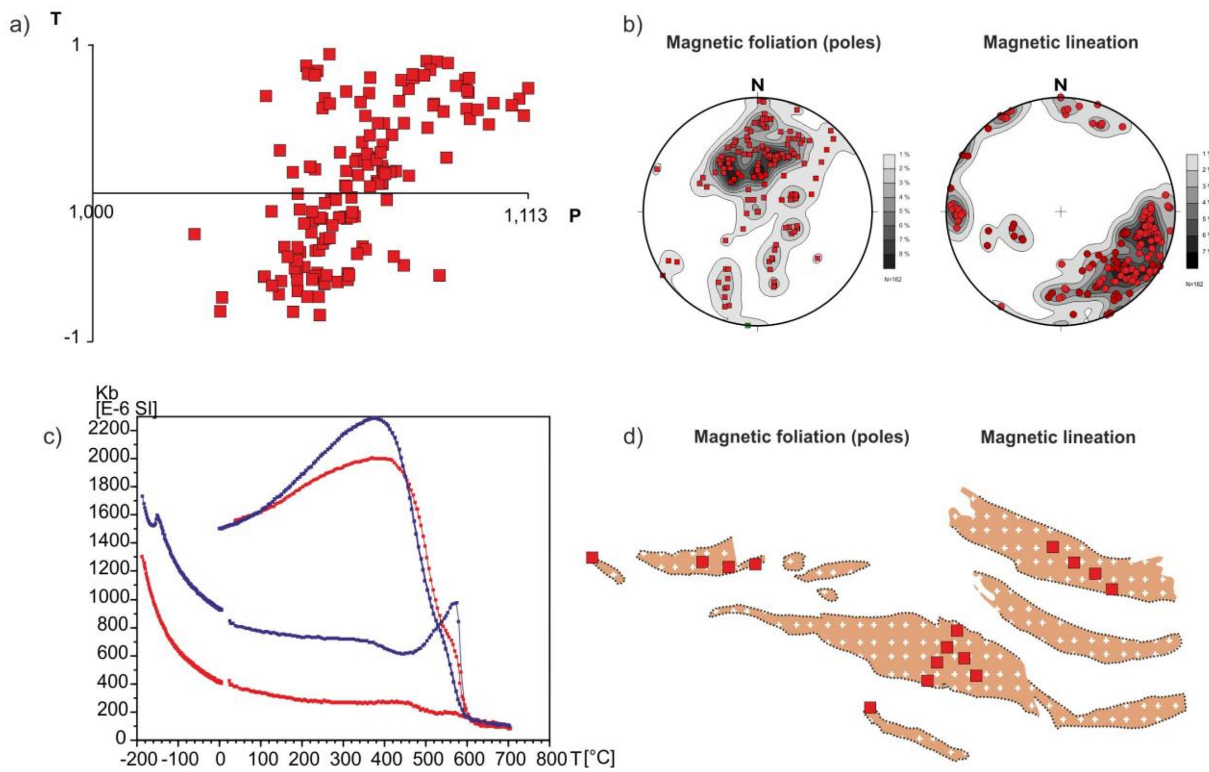


Fig.7 Zábřeh Intrusive Complex AMS fabric: a) P-T plot; b) stereonets of magnetic foliations and lineations (pole to plane), c) thermomagnetic curves, d) sampling localities

In the case of the Zábřeh Intrusive Complex mean bulk magnetic susceptibility values (km) are homogeneous and relatively low indicating a dominant amount of paramagnetic minerals as a provable carrier of magnetic anisotropy. Values range from 216 to 750 x 10^{-6} [SI] with a mean value of 349 x 10^{-6} SI. In contrast, thermomagnetic curves acquired by means of thermomagnetic analysis (Fig.7 c) exhibit a characteristic peak at ~570°C which indicates the presence of a small amount of magnetite. However, this mineral phase does not represent the principal carrier of AMS and thus it could not have exerted a significant influence on the LPO of the magnetic fabric. The sampling strategy followed the necessity of acquiring the AMS fabric of each particular sheet. The magnetic fabric shows simple pattern. The magnetic foliation dips homogeneously under steep to moderate angles to ~S to SW and associated magnetic lineation plunge gently to ~ SE (Fig. 7b). Only small amount of samples bears N of W dipping magnetic lineations. The values of parameter P (P: 1.05 - 1.133) and T (T. –0.833 to 0.927) show good correlation. In samples with P=>1,07 the oblate-shape of fabric elipsoid was detected, whereas the samples with lower degree of P parameter indicate a prolate shape of fabric elipsoid (Fig. 7a). The disrtibution of P-T parameters together with magnetic fabric don´t show any correlation acros particular sheet.

6. Petrology and geothermobarometry

6.1. Methods

The chemical analysis of the minerals was conducted with employing a Cameca SX-100 electron microprobe at the Joint Electron Microprobe Laboratory of the Masaryk University and Czech Geological Survey in Brno. Measurements were taken in wave dispersion mode using a 15kV acceleration voltage, 5µm beam diameter, 30nA of current and an integration time of 20 seconds. The crystallo-chemical formulae of feldspar were recalculated to 8 and those of micas to 22 oxygen atoms. Amphibole formulae were obtained assuming 23 O, 2 (OH, F, Cl) and Fe^{3+}/ Fe^{2+} ratios were estimated based on 13 cations with the exception of Ca, Na and K (Leake et al. 1997). Mineral abbreviations are according to Kretz (1983).

The solidus temperatures of the plutonic rocks were estimated using a Holland and Blundy thermometer (1994) from amphibole and plagioclase rim compositions. These thermometers perform well (± 40°C) in the range 400–1000°C and 0.1–1.5GPa over a broad range of bulk compositions. Usable mineral compositions are restricted to amphiboles with Na^{A}>0.02pfu, ^{VI}Al>1.8pfu, Si of 7.0–6.0pfu and plagioclases with an X_{an} of 0.1–0.9. The Anderson and Smith Al-in-hornblende barometer (1995) is recommended for amphiboles with Fe/(Mg + Fe) ≤ 0.65. The P-T conditions of the metamorphic evolution of the rocks surrounding the calc-alkaline plutons were calculated employing THERMOCALC software (Holland and Powell, 1998). In addition, the solidus temperatures of the calc-alkaline rocks were calculated using amphibole-plagioclase thermometers (Holland and Blundy 1994). In this case, the calculation proceeded based on two differing mineral reactions: (i) edenite-tremolite (4 quartz + edenite = albite + tremolite) and (ii) edenite-richterite (edenite + albite = richterite + anorthite). The mineral composition of these amphiboles corresponds to Na^{A}>0.02pfu, Al^{VI}>1.8pfu, Si in the range of 6.0-7.0pfu and plagioclases with X_{an} > 0.1 and <0.9. The thermometers were calibrated in the range 400-1000°C and 0.1-1.5Gpa.

6.2. Textures and mineral chemistry

Central part of the Polička Unit

Medium-grained, biotite to two mica gneisses forms the principal lithology of the central part of the Polička Unit surrounding Budislav pluton. These rocks, exhibiting a lepidogranoblastic texture, consist of plagioclase (22-38 mod. %), quartz (30-43 mod. %), biotite (18-28 mod. %), muscovite (0-15 mod. %), sillimanite (0-3 mod. %) and garnet (0-10 mod. %) (Fig. 9 a, b). Normally zoned plagioclase grains (Tab. 1, An_{12-23}) together with quartz aggregates form a mosaic of anhedral grains of up to 1mm. Biotite grains in the shape of laths or large subhedral flakes (classified as annite to phlogopite (Al^{IV} = 2.35-2.80apfu; Fe/(Fe+Mg) = 0.35-0.67) (Fig. 8a) are, in certain locations, chloritised. Muscovite aggregates (Al^{IV} = 1.72-1.98apfu, Fe/(Fe+Mg) = 0.41-0.80 apfu (Fig. 8b) occur principally as small grains. The garnets (Alm_{62-77} Sps_{3-26} Pyr_{8-22} Grs_{0-6} Adr_{0-3}) are characterised by weak chemical zoning with a decrease in Alm and Prp and, occasionally, an increase in Sps and Grs content in the rims (Fig. 8 d, e). The garnet porphyroblasts contain fine quartz and/or ilmenite, plagioclase or biotite inclusions. Sillimanite aggregates occur in the form of independent grains (up to 2mm in length) or in the form of inclusions in micas and quartz. Occasionally, the presence of chiastolite textures indicate pseudomorphous after andalusite. The principal lithology contains a spectrum of accessory minerals (e.g. tourmaline (Al = 5.94-6.62 apfu; X_{Fe} = 0.22-0.57; Na = 0.65-0.89), apatite, monazite and ilmenite.

Northern part of the Zábřeh Unit

Medium-grained biotite to two mica locally migmatitised gneisses form the northern part of the Zábřeh Unit in the vicinity of tonalite sheets. The rocks typically display lepidogranoblastic textures with a matrix made up of plagioclase (20-35 mod. %), quartz (30-45 mod. %), biotite (20-27 mod. %), muscovite (0-12 mod. %), K-feldspar (0-14 mod. %) sillimanite (0-3 mod. %), garnet (0-10 mod. %) and cordierite (0-5 mod. %) (Fig 9 c, d). In the proximity of calc-alkaline intrusions a mineral assemblage of Bt + Sill + Cdr ± Grt ± Ms ± Kfs ± St can be observed. Cordierite aggregates (locally pinitised) are relatively homogeneous (Si: 4.85-5.20apfu, Al: 3.96 to 4.14apfu and medium to high Mg with Fe/(Fe+Mg)=0.34-0.42).

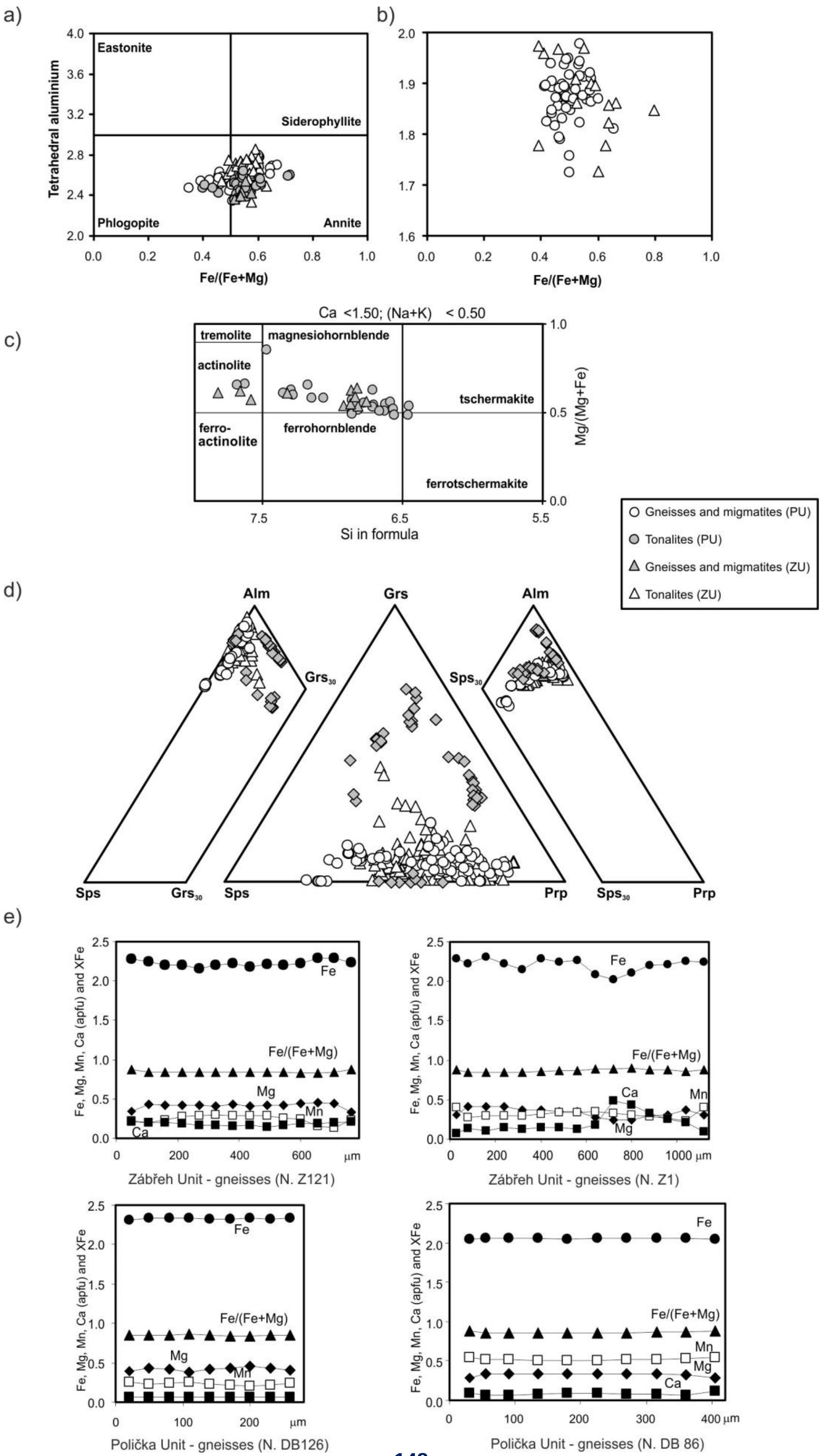

a)
Eastonite
Siderophyllite
Phlogopite
Annite
Tetrahedral aluminium
Fe/(Fe+Mg)
b)
Fe/(Fe+Mg)
c)
Ca <1.50; (Na+K) < 0.50
tremolite
magnesiohornblende
actinolite
tschermakite
ferro-actinolite
ferrohornblende
ferrotschermakite
Mg/(Mg+Fe)
Si in formula
Gneisses and migmatites (PU)
Tonalites (PU)
Gneisses and migmatites (ZU)
Tonalites (ZU)
d)
Alm
Grs
Alm
Grs30
Sps30
Sps
Grs30
Sps
Prp
Sps30
Prp
e)
Fe, Mg, Mn, Ca (apfu) and XFe
Zábřeh Unit - gneisses (N. Z121)
Zábřeh Unit - gneisses (N. Z1)
Polička Unit - gneisses (N. DB126)
Polička Unit - gneisses (N. DB 86)

Fig. 8 Classification diagrams for rock forming minerals forem PU and ZU: a) Fe/Fe+Mg and tetrahedral aluminium diagram of the biotites from gneisses and rocks of tonalite group; b) Fe/Fe+Mg and tetrahedral aluminium diagram for muscovite from; c) classification diagram of amphiboles (Leake et al. 1997); d) Ternary Sps-Alm-Grs30, Sps-Grs-Prp, Sps30-Alm-Prp diagrams of the garnets from gneisses and rocks of tonalite group; e) representative zoning profiles through garnet grains from the ZU (sample Z126 amphibolite, Bušín, sample Z1 migmatitic gneisses, Cotkytle) ; f) representative zoning profiles through garnet grains from the PU (sample DB 126 gneisses, Kamenec, sample DB 86, gneisses, Sádek).

Loc.	SH 154	SH 121	Z1	ZK51	38 / 1	31	70	L3	25	31
Sample	54 / 1	79 / 1	117 / 1	0	db 126 plg	31rul	70 plg 1	87/6	25p91	31/2ton34
SiO_2	61,24	55,49	62,56	63,04	63,36	60,21	62,39	64,28	57,78	55,69
P_2O_5	0,11	0,07	0,10	0,00	0,14	0,00	0,00	0,00	0,00	0,00
Al_2O_3	24,29	27,62	22,74	23,60	22,99	24,45	24,07	22,99	25,83	26,92
FeO	0,11	0,04	0,01	0,11	0,27	0,00	0,00	0,00	0,00	0,00
CaO	5,28	10,34	3,99	4,46	3,99	6,26	5,55	4,24	8,24	9,09
Na_2O	9,16	6,03	10,09	8,52	9,57	7,94	7,60	8,67	6,18	5,76
K_2O	0,12	0,14	0,15	0,20	0,11	0,09	0,19	0,00	0,00	0,30
BaO	0,00	0,06	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
SrO	0,19	0,13	0,11	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Total	100,296	99,730	99,632	99,930	100,426	98,948	99,809	100,178	98,021	97,755
Si	2,714	2,508	2,785	2,784	2,789	2,706	2,762	2,824	2,627	2,555
Al	1,269	1,471	1,193	1,228	1,192	1,295	1,256	1,190	1,384	1,456
Fe3+	0,004	0,002	0,000	0,004	0,010	0,000	0,000	0,000	0,000	0,000
T-site	3,987	3,981	3,979	4,017	3,991	4,001	4,018	4,014	4,012	4,011
K	0,007	0,008	0,008	0,011	0,006	0,005	0,011	0,000	0,000	0,017
Na	0,787	0,528	0,871	0,730	0,816	0,692	0,652	0,739	0,545	0,512
Ca	0,247	0,494	0,188	0,208	0,186	0,297	0,260	0,197	0,396	0,441
Ba	0,000	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Sr	0,005	0,003	0,003	0,000	0,000	0,000	0,000	0,000	0,000	0,000
O-site	1,046	1,035	1,070	0,949	1,008	0,994	0,923	0,936	0,941	0,971
K+Na+Ca	1,041	1,031	1,067	0,949	1,008	0,994	0,923	0,936	0,941	0,971
Mol per cent										
An	23,766	47,947	17,614	21,952	18,414	29,915	28,167	21,058	42,115	45,430
Ab	75,566	51,254	81,598	76,861	80,985	69,548	70,653	78,942	57,885	52,776
Or	0,668	0,800	0,788	1,187	0,602	0,537	1,180	0,000	0,000	1,794

Tab. 1 Chemical composition of plagioclase, The location of studied sample is in appendix 1.

Sillimanite aggregates often occur in fibrous and prismatic forms (up to several mm in dimension). Euhedral to subhedral garnet porphyroblasts contain inclusions of plagioclase, quartz, sillimanite and biotite aggregates. In general, garnets from the cordierite-absent rocks display a relatively lower content of MgO (Alm_{64-73} Sps_{8-17} Pyr_{8-14} Grs_{0-14} Adr_{0-4}).

These garnets are characterised by a flat profile (Fig. 8d, f) with low spessartine content in the core and decreasing pyrope content towards the rim, and exhibit composite zoning with a small core with high Grs and low Alm and Prp contents. Those garnet grains spatially associated with cordierite aggregates exhibit zoning with a moderate increase in almandine and a decrease in spessartine and a subtle increase in pyrope and almost no change in grossular content from core to rim (Alm_{70-78} Sps_{3-14} Pyr_{11-23} Grs_{0-7} Adr_{0-3}). Thus, their outer rims indicate retrograde stages of metamorphism. The micas exhibit a relatively uniform composition (the biotite corresponds to annite to phlogopite; Al^{IV} = 2.34-2.86apfu; Fe/(Fe+Mg) = 0.47-0.63 (Fig. 8a) and muscovite; Al^{IV} = 1.73-2.03apfu, Fe/(Fe+Mg) = 0.39-0.66apfu (Fig. 8**Fig.** b). Subhedral plagioclase grains ($An_{6–52}$) exhibit oscillatory zoning with a basic core and albite-rich rim. Chlorite, which is mostly retrograde, occurs as pseudomorphs after cordierite and very occasionally partially replaced biotite and garnet.

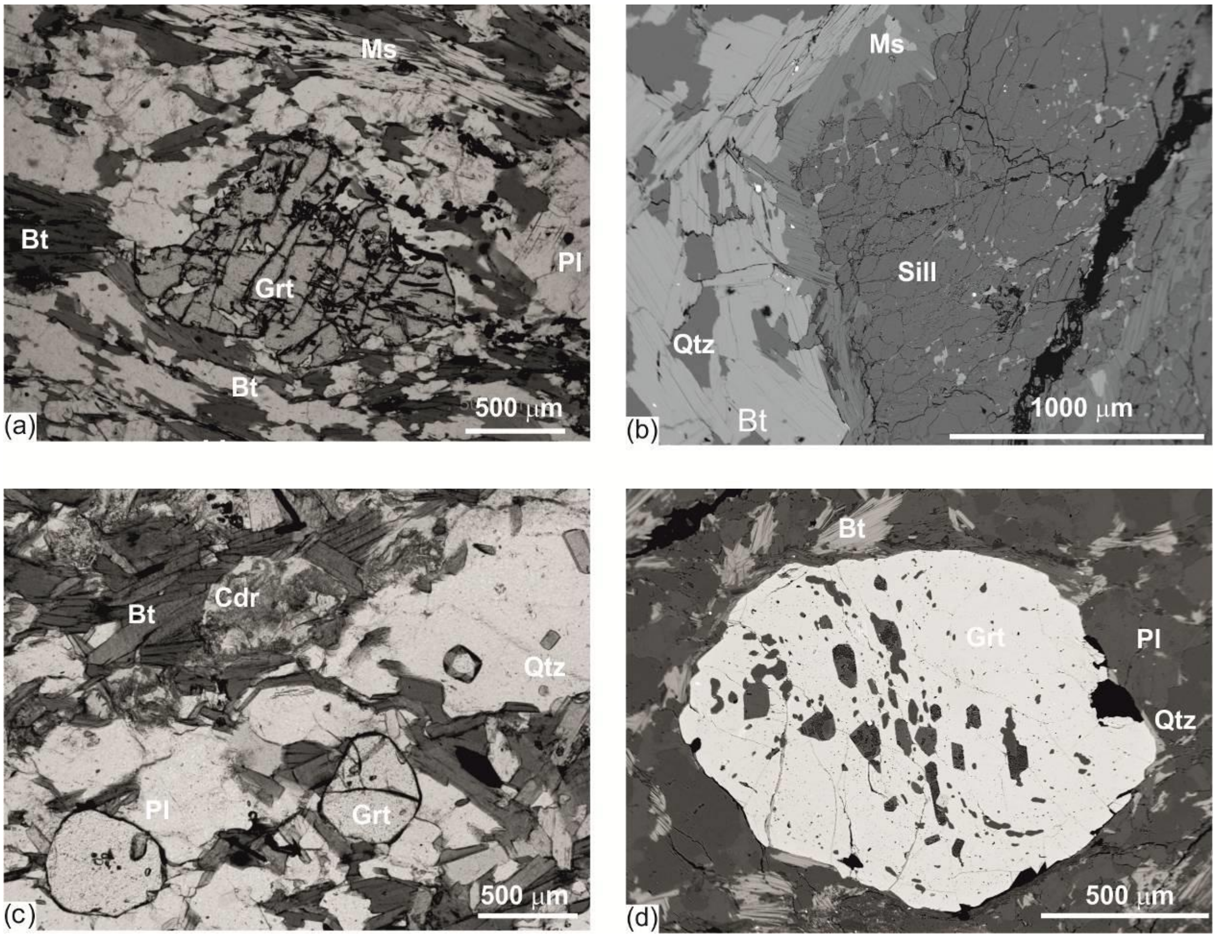


Fig. 9 BSE and microphotograph showing the textural relationships in metapelites from Polička Unit (A, B) and Zábřeh Unit (C, D): a) subhedral garnet porphyroblasts from two mica gneisses (87, Korouhev); b) sillimanite pseudomorph after andalusite from xenolite biotite gneisses in the tonalite (DB 26, Budislav); c) two mica gneiss with cordierite and garnet (SH121, Václavov, Tab. 2); d) two mica gneiss with garnet affected by regional metamorphism, (Z1, Cotkytle).

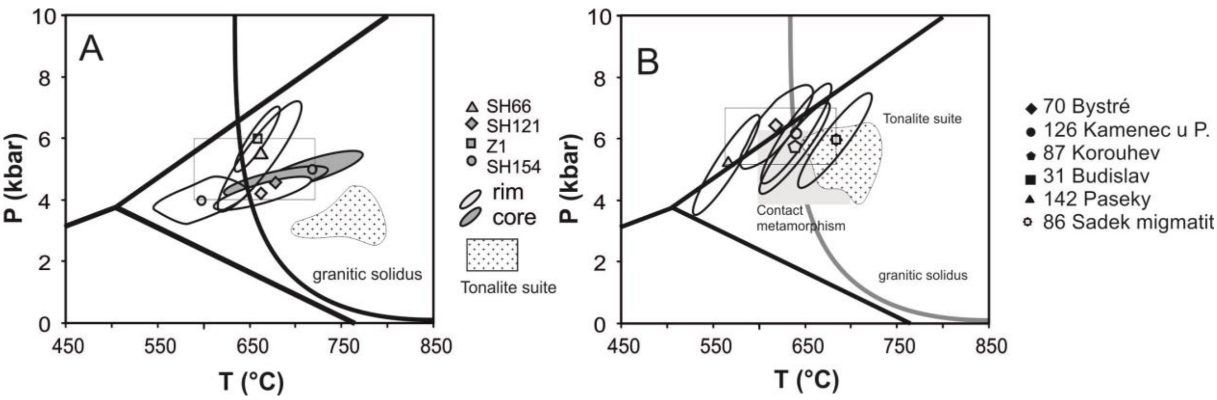


Fig. 10 Diagrams showing the calculated PT conditions a) Zábřeh Unit, b) Polička Unit

No Sample	SH 154 29.1	SH 154 31.1	SH 154 41 / 1	SH 154 43 / 1	SH 154 44 / 1	SH 121 70 / 1	SH 121 71 / 1	SH 121 89 / 1
SiO_2	48,91	48,35	48,59	48,49	49,18	48,75	48,16	48,63
Al_2O_3	33,76	33,33	33,26	33,61	32,83	33,09	33,09	32,83
FeO	8,26	8,58	8,57	9,23	8,80	9,66	9,27	9,42
MnO	0,40	0,40	0,23	0,19	0,41	0,25	0,33	0,22
MgO	8,04	7,98	8,33	8,07	8,01	7,65	7,56	7,34
CaO	0,08	0,01	0,00	0,01	0,00	0,01	0,00	0,08
Na_2O	0,43	0,39	0,33	0,31	0,34	0,20	0,19	0,34
K_2O	0,01	0,03	0,04	0,01	0,01	0,00	0,02	0,02
TOTAL	99,88	99,07	99,35	99,92	99,57	99,62	98,62	98,87
Si	5,088	5,029	5,055	5,045	5,116	5,071	5,010	5,058
Ti	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Al	4,138	4,086	4,077	4,120	4,025	4,057	4,057	4,025
Fe(ii)	0,718	0,746	0,745	0,802	0,765	0,840	0,806	0,819
Mn	0,035	0,035	0,021	0,017	0,036	0,022	0,029	0,020
Mg	1,247	1,237	1,292	1,251	1,241	1,186	1,173	1,138
Ca	0,009	0,001	0,000	0,002	0,000	0,002	0,000	0,009
Na	0,087	0,079	0,066	0,062	0,068	0,041	0,038	0,068
K	0,001	0,004	0,005	0,001	0,002	0,001	0,002	0,002
TOTAL	11,323	11,219	11,261	11,300	11,253	11,219	11,115	11,139

Tab. 2 Representative compositions of cordierite (wt. % and apfu), The location of studied sample is in appendix 1.

Calc-alkaline intrusions of the eastern part of the TBU

The Budislav Pluton is composed of several varieties of calc-alkaline plutonic rocks - amphibole-biotite and biotite tonalites to granodiorites and quartz diorites with, locally, garnet and clinopyroxene containing a large number of xenoliths made up of calc-silicate rocks. The Zábřeh Intrusive Complex is represented by medium-grained, amphibole-biotite tonalites to granodiorites with, locally, pyroxene. The details of the textural and petrochemical composition of these magmatic rocks are shown in Tab. 3 and in corresponding diagrams in Fig. 8.

6.3. Geothermobarometry and P-T evolution

Metapelites from the northern part of the Polička Unit are characterized by stable mineral assemblage *Bt + Ms + Sil + Grt + Pl*. Based on the results of application of THERMOCALC software according to chemical composition and textural relationships of stable mineral association the conditons of regional metamorphism at T: 566 ± 28°C and P: 0.52 ± 0.13 Gpa (for the northern part of the Budislav pluton) and T: 620-680 °C and P: 0.6 Gpa (for the southern part of the Budislav pluton) were determined (Fig. 10a). The solidus temperatures using by Amph-Plg thermometer and Amph- barometer (Holland and Blundy 1994; Anderson and Smith 1995) for the individual rock groups of the calc-alkaline rocks of the Budislav pluton at T: 655-730 °C and P: 0.4-0.6 Gpa were estimated (Fig. 10b).

Microstructural pattern of regional metamorphic fabric in metapelites of the northern part of the Zábřeh Unit suggest that new the mineral reaction *Bti + Sil + Qtz = Crd + melt* has proceeded. The associated stable mineral association *Bt + Sil + Grt + Kfs* shows the condition of regional metamorphic event at T: 660 °C and P: 0.6 Gpa. However, in a narrow domain along the calc-alkaline sheets a contact metamorphic event associated with new mineral assemblage Grt + Bt + Sil +Crd ± Ms ± Kfs was observed. Here the T: 599-663 °C and P: 0.4 Gpa for the garnet rim composition were calculated (Fig. 10b). The solidus stage obtained from the Zábřeh Intrusive Complex indicate the temperatures in range 706-795 °C and pressures at 0.3-0.4 Gpa (Fig. 10a).

Budislav	Plg	Kfs	Qtz	Amf	Bt	Px	Grt	Acc.
Amphibole-biotite tonalites to granodiorites with pyroxene	An_{35-53} hypautomorphic and show oscillatory zoning in CL, with cores having higher basicity than the rims.	Xenomorphic, content in the individual samples is variable	Xenomorphic, content in the individual samples is variable	Subhedral to anhedral grains, sometimes overgrown by biotite. Correspond to magnesiohornblende and passes to ferrotschermakite and ferrohornblende (Fe/(Fe+Mg) = 0.49-0.85, Si = 6.5-7.4 apfu). Younger actinolite (Fe/(Fe+Mg) = 0.54-0.66, Si = 7.5-7.7 apfu)	Corresponding to annite: Al^{IV} = 2.36-2.55 apfu; Fe/(Fe+Mg) = 0.51-0.73. Ti contents are between 0.29-0.44 apfu and contents of F are low (up to 0.04 apfu).	Clinopyroxene forms xenomorphic grains, overgrown by amphibole corresponds to diopside with of Mg/(Mg+Fe) 0.59-0.62.		Apatite, monazite zircone and ilmenites (85-92% ilmenite, 7-11% pyrophanite, 2-4% hematite), rare titanite and pyrhotite.
Biotite granodiorites to tonalities with garnet	Mostly oscillatory-zoned, basicity in the range of An_{25-48}. Average core and rim compositions An_{45} and An_{39}, respectively. Plagioclase from the granodiorites is less calcic, mean core and rim of An41 and An30, respectively	Xenomorphic grains	Xenomorphic grains				Xenomorphic grains enclosing biotite and quartz. Almandine rich Alm_{64-70} Sps_{13-14} Pyr_{5-7} Grs_{11-17} $Adr_{2-3,}$ weak chemical zonation composition (for example with composition of Alm_{64} Grs_{17} Pyr_{5} Sps_{14} on rims and Alm_{69} Grs_{11} Pyr_{7} Sps_{13} in the core)	Apatite, monazite and zircone
Garnet-biotite quartz diorites	Distinct zonation with bytownite core (An_{81}) and labradorite to andesine rim (An_{46-66}).				Annite with composition: Al^{IV} = 2,55-2,52; Fe/(Fe+Mg) = 0,51-0,54. Inclusion in garnet, are Mg richer (Al^{IV} = 2,47-2,65; Fe/(Fe+Mg) = 0,40-0,46)		Euhedral phenocrysts with chemical composition Alm_{68-80} Sps_{2-3} Pyr_{4-16} Grs_{7-16}.	Apatite, zircon, monazite, and rare clinozoisite to allanite.
ZIC								
Amphibole-biotite granodiorites	Automorphic to hypautomorphic, oscillatory-zoned grains An_{21-44} grains, sometimes containing corroded basic cores. Enclose biotite and sphene.	Perthitic hypautomorphic to xenomorphic grains. Locally enclosing automorphic plagioclase grains		Fine grained, often overgrown by biotite. Amphibole has Si contents of 6.8-7.3 apfu and Mg/(Mg+Fe) ratios of 0.54-0.64, and corresponds to magnesiohornblende and tschermakite. Replacement of these amphiboles by younger actinolite locally occurs on rims	Annite (Al^{IV} = 2.37-2.54 apfu; Fe/(Fe+Mg) = 0.51-0.58).	Diopside (Mg/(Mg+Fe) = 0.63-0.65) and forms relicts enclosed in amphibole.		Apatite, monazite and zircone, titanite, rarely Ilmenite.

Tab. 3 Textural type s of calc-alkaline plutons in Polička and Zábřeh Units

N.	DB 86	db 126	70	87	25p93	DB 103	SH 154	SH 121	SH 121	ZK 66a
SiO2	37,63	36,83	38,36	38,12	36,37	37,44	36,42	37,05	37,05	37,02
TiO2	0,01	0,02	0,00	0,00	0,00	0,12	0,02	0,04	0,04	0,04
Al2O3	20,99	20,99	21,09	21,24	20,40	21,01	20,75	20,92	20,92	20,91
Cr2O3	0,02	0,02	0,00	0,00	0,00	0,01	0,00	0,01	0,01	0,09
Fe2O3	0,00	0,33	0,00	0,00	1,24	0,55	0,81	0,59	0,59	0,18
FeO	30,05	34,22	31,14	31,27	29,61	32,45	32,78	32,29	32,29	31,04
MnO	7,91	3,71	3,34	5,20	6,17	1,06	5,93	3,47	3,47	6,59
MgO	2,43	3,16	3,33	3,19	1,70	3,49	2,63	3,49	3,49	3,10
Na2O	0,00	0,03	0,00	0,00	0,00	0,02	0,09	0,04	0,04	0,00
P2O5	0,02	0,00	0,00	0,00	0,00	0,02	0,04	0,01	0,01	0,00
Y2O3	0,00	0,00	0,00	0,00	0,00	0,07	0,00	0,02	0,02	0,00
CaO	1,12	0,80	1,94	1,00	4,65	4,19	0,81	2,25	2,25	1,02
Total	100,17	100,09	99,20	100,02	100,13	100,44	100,29	100,16	100,16	99,98
Si	3,023	2,975	3,055	3,034	2,955	2,981	2,955	2,975	2,975	2,989
P	0,001	0,000	0,000	0,000	0,000	0,002	0,003	0,000	0,000	0,000
Ti	0,001	0,001	0,000	0,000	0,000	0,007	0,001	0,002	0,002	0,002
T - site	3,025	2,976	3,055	3,034	2,955	2,990	2,958	2,977	2,977	2,991
Al	1,987	1,998	1,980	1,993	1,953	1,972	1,984	1,980	1,980	1,990
Cr	0,002	0,001	0,000	0,000	0,000	0,001	0,000	0,001	0,001	0,006
Fe3+	0,000	0,020	0,000	0,000	0,076	0,033	0,050	0,036	0,036	0,011
Ti	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Y	0,000	0,000	0,000	0,000	0,000	0,003	0,000	0,001	0,001	0,000
B - site	1,988	2,019	1,980	1,993	2,029	2,008	2,034	2,017	2,017	2,006
Fe2+	2,041	2,312	2,134	2,128	2,012	2,161	2,224	2,168	2,168	2,096
Mn	0,538	0,254	0,225	0,351	0,424	0,072	0,407	0,236	0,236	0,451
Mg	0,291	0,380	0,395	0,379	0,205	0,414	0,318	0,418	0,418	0,373
Ca	0,096	0,069	0,166	0,085	0,405	0,358	0,071	0,194	0,194	0,088
Na	0,001	0,006	0,000	0,000	0,000	0,004	0,022	0,010	0,010	0,000
A - site	2,967	3,021	2,920	2,942	3,046	3,009	3,042	3,026	3,026	3,008
Almandine	68,814	76,387	73,075	72,320	64,983	71,762	73,070	71,518	71,518	69,527
Andradite	0,000	1,002	0,000	0,000	3,854	1,650	2,391	1,789	1,789	0,550
Grossular	3,161	1,245	5,669	2,899	9,851	10,295	0,000	4,696	4,696	2,109
Pyrope	9,816	12,766	13,540	12,865	6,949	13,869	10,757	14,042	14,042	12,461
Spessartine	18,133	8,532	7,716	11,916	14,364	2,398	13,783	7,926	7,926	15,068
Uvarovite	0,076	0,068	0,000	0,000	0,000	0,025	0,000	0,029	0,029	0,285
	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000

Tab. 4 Representative compositions of garnet (wt. % and apfu)

Sample	Locality	Rock	Unit	Amp-Pl*	Amp bar**
31	Budislav	Amp-Bt tonalite	PU	686-700	5.1-5.3
9	Jedlová	Cpx-Amp-Bt tonalite	PU	655-730	4.6-6.4
1011	Jedlová	Amp-Bt tonalite	PU	655-712	4.2-6.2
341	Crhov	Amp-Bt granodiorite	ZU	706-795	3.0-4.3
342	Zátiší	Amp-Bt granodiorite	ZU	750-790	2.8-3.3

*amphibole–plagioclase thermometer (Holland and Blundy 1994)

**Al-in-hornblende barometer (Anderson and Smith 1995)

Tab. 5 The studied samples of plutonic rocks, their mineral assemblages and estimated P–T conditions The location of studied sample is in appendix 1.

Sample	Locality	Rock (gneiss)	Unit	T (Grt-Bt)*	P (GASP)**	T (Grt-Cdr)***	avT	sd(T)	avP	sd(P)	corr
142	Paseky	Grt-Sill	PU	601	5,3		566	28	5,2	1,3	0,940
87	Korouhev	Grt-Sill	PU	686	6,2		640	30	5,7	1,2	0,919
70	Bystré	Grt-Sill (And)	PU	679	7,1		621	31	6,4	1,1	0,766
DB86	Sádek	Grt-Sill	PU	619	5,4		684	32	6,0	1,2	0,86
DB126	Kamenec	Grt-Sill (And)	PU	598	4,0		640	31	6,2	1,3	0,926
SH121	Václavov	Grt-Sill-Cdr	ZU	625	4,2	652-671	663	43	4,2	0,4	0,807
SH154	Zábřeh	Grt-Sill-Cdr	ZU	542	2,8	592-620	599	40	4,0	0,6	0,444
ZK66	Drozdov	Grt-Sill	ZU	607	5,4		664	38	5,5	1,5	0,917
Z1	Cotkytle	Grt-Sill	ZU	576	3,5		660	21	6,0	0,9	0,924

*Ferry & Spear 1978 calibration
**Hodges & Crowley 1985 calibration
***Dwivedi et al. 1998 calibration

Tab. 6 The studied samples of metamorphic rocks, their mineral assemblages and estimated P–T conditions. The location of studied sample is in appendix 1.

6. Geochemistry and petrogenesis of the calc-alkaline plutons

The chemical composition of igneous rocks from the Zábřeh and Staré Město Units, the Mířetín and Budislav plutons of the Polička unit and Sazava-type granitoids from the Central Bohemian Plutonic Complex were compared in order to determine geochemical similarities. The data was collected from Hájek et al (1997), Holub et al (1997 a, b), Buriánek et al (2003) and Janoušek et al. (2000, 2004). The rocks exhibit a calc-alkaline composition (K_2O+Na_2O = 4.2–7.4) and can be classified as high-K calc-alkaline to calc-alkaline (Peccerillo and Taylor 1976) with wt. % K_2O/Na_2O ratios between 0.4 and 1.4. The granodiorites studied consist of metaluminous to weakly peraluminous rocks (A/CNK = 0.8–1.2) (Fig. 11 a) corresponding to ilmenite-bearing I-type granitoids. According to the TAS diagram (Middelemost 1994, Fig. 11 b), the samples collected from the Mířetín Pluton and Zábřeh and Staré Město Units correspond to quartz monzonite or granodiorite and samples from the other units can be predominantly classified as quartz diorite, tonalite or granodiorite. Most of the samples studied were found to be characterised as having high Ba (148–1570ppm) and Sr (139–837ppm) contents and lower Rb (28–170ppm) and Y (11–35ppm) contents (Buriánek et al. 2003). When fitted to the Pearce et al (1984) Rb/Y+Nb diagram all the samples fitted well with field “volcanic arc granitoid” (Buriánek et al. 2003). All the granitoids exhibit similar chondrite normalised REE patterns (Fig. 11 c,d). The Eu anomaly was found usually to be weakly negative (Eu/Eu* = 0.9–1.1) with only two samples from the Sazava type indicating a distinct positive anomaly (1.5–1.9). Normalised REE patterns (Fig. 11 c,d) exhibit distinct fractionation with moderate LREE enrichment and HREE depletion (La_N/Yb_N = 3.3–14.3).

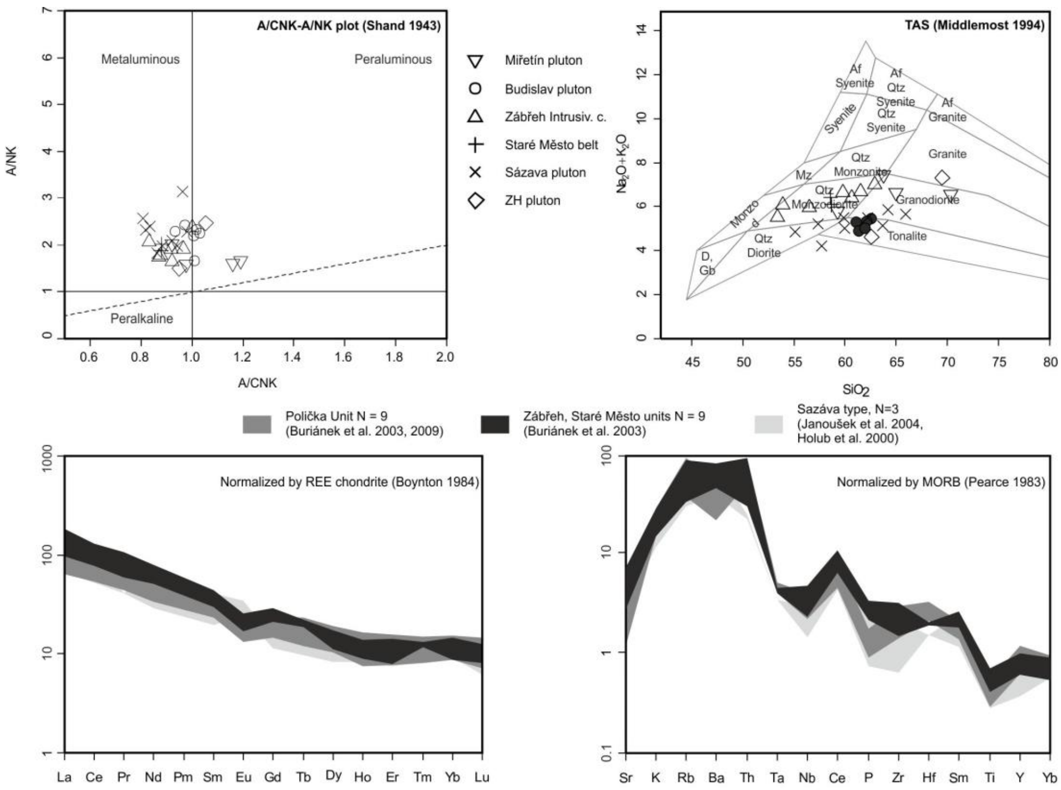


Fig. 11 Geochemical plots for tonalites from Bohemian Massif: a) A/CNK-A/NK plot (Shand 1943), b) TAS (Middlemost 1994), c) REE spider diagram (chondrite normalised), d) REE spider diagram (MORB normalised).

7. U/Pb dating

The isotopic analysis of zircon using ICP-MS laser ablation followed the technique described in Košler et al. (2002) and Košler and Sylvester (2003). A Thermo-Finnigan Element 2 sector field ICP-MS coupled to a 213 NdYAG laser (New Wave Research UP-213) at Bergen University was employed to measure Pb/U and Pb isotopic ratios in zircons. The sample introduction system was modified so as to enable the simultaneous nebulisation of a tracer solution and laser ablation of the solid sample (Horn et al., 2000). Natural Tl (205Tl/203Tl = 2.3871 - Dunstan et al. 1980), ^{209}Bi and enriched ^{233}U and ^{237}Np (>99%) formed the content of the tracer solution which was aspirated to plasma in an argon - helium carrier gas mixture through an Apex desolvation nebuliser (Elemental Scientific) and a T-piece tube attached to the back end of the plasma torch. A helium gas line for transporting the sample from the laser cell to the plasma was also attached to the T-piece tube. The laser was fired at a repetition rate of 10Hz and energy of circa 2.0J/cm^2. Linear laser rasters (50 or 100 microns) were produced by the repeated scanning of the laser beam at a speed of 10 microns/second across the surface of the zircon sample. Typical acquisitions consisted of a 35-second measurement of a blank followed by the measurement of U and Pb signals from zircon for a further 110 seconds. The data was acquired in time resolved - peak jumping - pulse counting mode with 1 point measured per peak for masses 202 (flyback), 203 and 205 (Tl), 206 and 207 (Pb), 209 (Bi), 233 (U), 237 (Np), 238 (U), 249 (233U oxide), 253 (237Np oxide) and 254 (238U oxide). Raw data was corrected to take into account the dead time of the electron multiplier and processed off-line using a spreadsheet-based program (Lamdate – Košler et al. 2002). Data reduction included corrections for gas blanks, the laser-induced elemental fractionation of Pb and U and instrument mass bias. The minor formation of oxides of U and Np was corrected by means of adding signal intensities at masses 249, 253 and 254 to intensities at masses 233, 237 and 238 respectively. No common Pb correction was applied to the data. The zircon reference material 91500 (1065Ma - Wiedenbeck et al. 1995) was analysed periodically during the measurement procedure for quality control purposes.

Eleven of the 21 analysed zircon grains from the Budislav Pluton sample – Borová locality provided concordant U-Pb isotopic ages (Tab. 7) with a mean age of 346±6Ma (2σ, Fig. 13a); this was subsequently interpreted as the magmatic age, i.e. the age of the crystallisation of the zircon host rock. The analysis of 33 zircon grains with clear magmatic oscillatory zoning (Fig. 12), separated from Zábřeh tonalite from the Cotkytle-Bražná valley location, sample CO-G-2, yielded 24 concordant U-Pb isotopic ages (Tab. 7) with a mean age of 354±4Ma (2σ, Fig. 13b). This age was interpreted as the magmatic age, i.e. the age of the crystallisation of the zircon host rock.

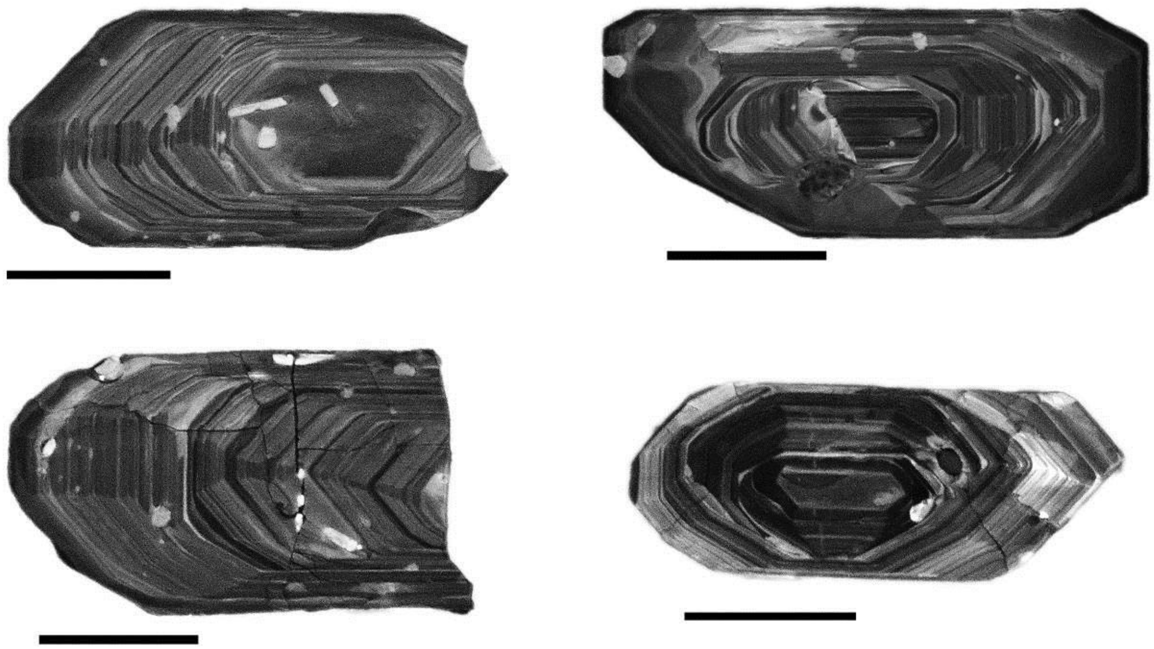


Fig. 12 Representative Cathodoluminescence images of analyzed magmatic zircon grains from the sample of Zabreh tonalite. The scale bar is 100 microns.

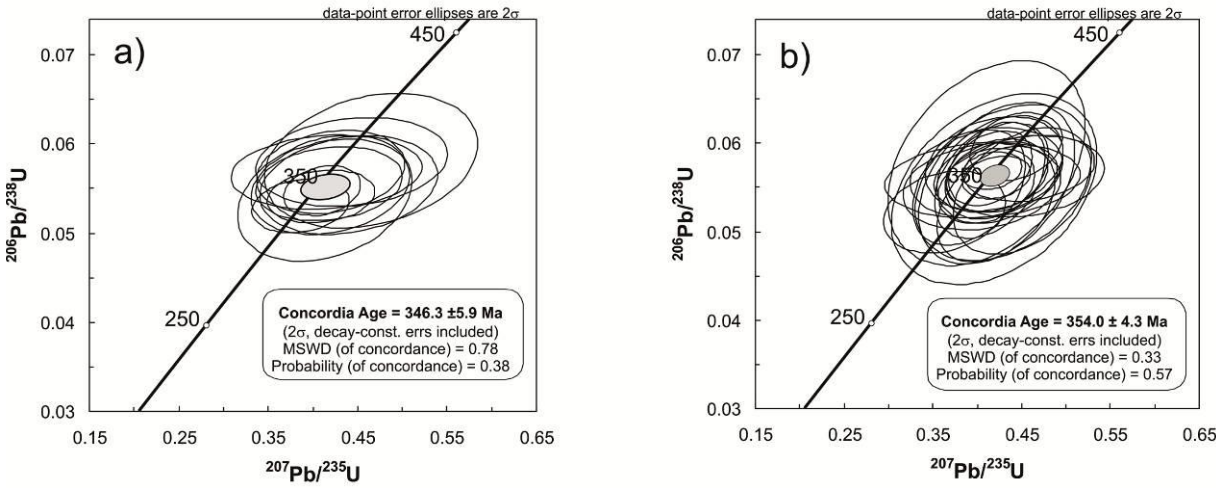


Fig. 13 U-Pb Concordia diagram for zircons from the Budislav pluton (a) and Zabreh tonalite (b). Laser ablation ICP-MS data, total of 11 (a) and 24 (b) analyses. The concordia age ellipse as well as individual analyses are plotted with 2sigma uncertainties.

	Atomic ratios				Apparent ages (Ma)			
Analysis	$^{207}Pb/^{235}U$	1σ (abs)	$^{206}Pb/^{238}U$	1σ (abs)	$^{207}Pb/^{235}U$	1σ (abs)	$^{206}Pb/^{238}U$	1σ (abs)
Budislav Pluton								
060426JKa05	0.3862	0.0223	0.0531	0.0012	331.6	16.3	333.3	7.5
060426JKa06	0.4089	0.0246	0.0541	0.0012	348.1	17.7	339.8	7.4
060426JKa07	0.4103	0.0176	0.0548	0.0011	349.1	12.6	343.7	7.0
060426JKa08	0.4180	0.0335	0.0555	0.0017	354.7	24.0	348.4	10.4
060426JKa14	0.4152	0.0436	0.0568	0.0017	352.6	31.3	356.4	10.3
060426JKa15	0.4197	0.0363	0.0552	0.0022	355.8	26.0	346.5	13.3
060426JKa16	0.4397	0.0406	0.0554	0.0023	370.0	28.6	347.5	13.8
060426JKa18	0.4134	0.0400	0.0539	0.0029	351.3	28.7	338.4	17.7
060426JKa20	0.4650	0.0488	0.0581	0.0031	387.8	33.8	364.1	18.8
060426JKa21	0.4437	0.0438	0.0580	0.0020	372.9	30.8	363.2	12.3
060426JKa25	0.4198	0.0339	0.0569	0.0019	355.9	24.2	356.5	11.6
Zabreh tonalite								
Co-G-2/1-08	0.4440	0.0212	0.0597	0.0016	373.0	14.9	373.7	9.6
Co-G-2/1-09	0.4051	0.0365	0.0552	0.0020	345.3	26.3	346.1	12.2
Co-G-2/1-12	0.4166	0.0138	0.0570	0.0009	353.6	9.9	357.2	5.3
Co-G-2/1-13	0.4193	0.0316	0.0577	0.0022	355.5	22.6	361.8	13.3
Co-G-2/1-14	0.3906	0.0261	0.0551	0.0027	334.8	19.0	345.6	16.3
Co-G-2/1-15	0.4139	0.0255	0.0559	0.0027	351.7	18.3	350.5	16.4
Co-G-2/1-16	0.4208	0.0284	0.0562	0.0016	356.6	20.3	352.8	10.0
Co-G-2/1-17	0.4190	0.0473	0.0549	0.0044	355.3	33.9	344.4	27.0
Co-G-2/1-18	0.4104	0.0351	0.0567	0.0021	349.2	25.3	355.7	12.8
Co-G-2/1-19	0.4260	0.0290	0.0571	0.0025	360.3	20.7	357.9	15.2
Co-G-2/1-20	0.4505	0.0317	0.0547	0.0029	377.6	22.2	343.1	18.0
Co-G-2/1-22	0.4104	0.0223	0.0552	0.0017	349.2	16.0	346.7	10.7
Co-G-2/1-23	0.4103	0.0455	0.0578	0.0047	349.1	32.7	362.3	28.9
Co-G-2/1-28	0.4220	0.0360	0.0555	0.0037	357.5	25.7	348.2	22.8
Co-G-2/1-29	0.4296	0.0407	0.0556	0.0036	362.9	28.9	348.8	22.0
Co-G-2/1-30	0.3627	0.0281	0.0523	0.0019	314.2	21.0	328.5	11.6
Co-G-2/1-32	0.4537	0.0365	0.0563	0.0019	379.9	25.5	353.2	11.4
Co-G-2/1-34	0.4228	0.0234	0.0564	0.0017	358.0	16.7	353.9	10.2
Co-G-2/1-36	0.4059	0.0449	0.0559	0.0017	345.9	32.4	350.6	10.6
Co-G-2/1-37	0.4220	0.0157	0.0562	0.0010	357.5	11.2	352.5	6.0
Co-G-2/1-39	0.4221	0.0239	0.0569	0.0022	357.6	17.1	356.9	13.6
Co-G-2/1-41	0.4147	0.0194	0.0572	0.0017	352.2	13.9	358.8	10.6
Co-G-2/1-43	0.4584	0.0303	0.0573	0.0015	383.1	21.1	358.9	9.4
Co-G-2/1-44	0.4212	0.0271	0.0532	0.0027	356.9	19.4	334.0	16.4

Tab. 3 Laser ablation ICP-MS U-Pb data for zircons from Budislav pluton and Zabreh Intrusive Complex

8. Disscusion

8.1 Fabrics and emplacement of calc-alkaline plutons

The combined structural and AMS study revealed a complex fabric pattern and fabric gradients within the Budislav Pluton and the Zábřeh Intrusive Complex.

In the case of the 346Ma Budislav Pluton intruding the central part of the Polička Unit complexity resulted from the presence of a two pluton-wide magmatic fabric according to the results of mezoscopic structural mapping and AMS analyses. Our interpretation of the complex fabric pattern in the Budislav Pluton is as follows: the older steep magmatic fabrics defined primarily by means of AMS analysis appear to be decoupled from regional deformation since they occur mostly parallel to the pluton / host-rock contact. Moreover, such an orientation is not compatible with the regional dextral transpression observed in the host rocks (e.g. Verner et al. 2009, this study, Buriánek et al. in rew.). The formation of these foliations and lineations most probably resulted from internal magmatic processes (e.g. Paterson et al. 1998). In contrast, the pluton-wide NW-SE magmatic to solid-state fabric associated with gently NW or SE dipping lineations is consistent with the regional metamorphic foliations and lineations that were formed during regional dextral transpression (e.g. Verner et al. 2009, Vondrovic et al. 2011, Žák et al. 2014). The genesis of the final moderately- to flat-lying fabric seen in the AMS pattern (chaper 5, Fig 6b) could be ascribed to the partial transtensional processes in the top if the magma chamber during the overall transpressional regime. The formation of such magmatic and magnetic fabrics geometry can be interpreted as consisting of a record of an increment of the regional tectonic strain within a zone of dextral transpression and later shearing during the late stage of pluton cooling superimposed on intrusive fabrics related to pluton emplacement.

The 354Ma Zábřeh Intrusive Complex was emplaced in the form of several E-W trending strongly elongated sheet-like bodies in the mid-crustal rocks of the Zábřeh Unit. The structural record of this magmatic complex is characterised by the presence of steeply- to moderately-dipping magmatic to solid state fabric reflecting both regional steep- to moderately-dipping foliation and flat-lying fabric (Fig. 4f). Our observation is partly compatible with an interpretation proposed by Lehmann et al. (2013) who interpreted magma emplacement along the steep fabric during a regional folding event. Due to folded intrusive contact and presence within the fabric gradient it is assumed that the fabric observed in the tonalite sheets respects S_1 anisotropy. The observed P-T contact metamorphism conditions, which are comparable with magmatic crystallisation, suggest (later in the text) the intrusion of tonalites in the final stages of the formation of the S_1 steep fabric.

8.2. P–T conditions of regional metamorphism and magmatic crystallization

The estimated P-T conditions of the metamorphism of the metapelitic rocks in the Polička Unit, i.e. T: 566 ± 28°C and P: 0.52 ± 0.13 Gpa (for the northern part of the Budislav Pluton) and T: 620-680°C and P: 0.6 Gpa (for the southern part of the Budislav Pluton) are in the range of amphibolites facies metamorphism. In the case of the Zábřeh Unit, peak mineral assemblage reveals the condition of the regional metamorphic event as T: ~ 660°C and P:

~0.6 Gpa. Such metamorphic conditions confirm similarities between the Polička and Zábřeh Units that were previously suggested by Melichar 1995, Verner et al. 2009 and Pertoldová et al. 2010. The observed increase in metamorphic conditions in the Polička Unit in the section parallel to foliation is described and discussed by Mísař (1962) and Buriánek et al. under rew. The calculated P-T conditions of the crystallisation of the Budislav Pluton (T: 655-730°C and P: 0.4-0.6Gpa) and the Zábřeh Intrusive Complex (706-795°C and pressures of 0.3-0.4Gpa) exhibit good correlation at emplacement depth. Based on the concordance of this P–T data, the plutonic bodies under study were clearly emplaced during or shortly after the peak regional metamorphism of the host Polička and Zábřeh Units. This interpretation is confirmed by the emplacement conditions of the surrounding Miřetín Pluton (crystallisation T = 653–681°C and P = 0.29–0.43GPa with host rock metamorphism up to 559 ± 65°C and 0.3 ± 0.2GPa) which suggests that emplacement post-dated the formation of the main ductile fabric in the Polička Unit (e.g. Pitra et al. 1996, Vondrovic et al. 2011). In summary, lithological compositions as well as estimated P–T conditions from corresponding parts of the Polička and Zábřeh Units suggest that these rocks have a similar protolith and were affected by a comparable P–T Variscan regional metamorphism path over a defined time.

8.3 Geochronology and geochemistry

The time span restricted by the emplacement of the Budislav Pluton and Zábřeh Instrusive Complex (354-346Ma) is comparable to that of the intrusion of geochemically and geochronologically similar plutons in the Bohemian Massif (e.g. the 354 Sázava and 346 Blatná Plutons in the Central Bohemian Plutonic Complex, Holub et al 1997 a, b; Janoušek et al 2004 a, b; Žák et al 2005 a; the Nasavrky Plutonic Complex, Táborská 1997, Hrouda et al 1999) and in the Variscan orogen (Schwarzwald Shaw et al. 1993; tonalitic line in Vosges Hann et al. 2003). In general these granodiorite to tonalitic rocks consist of I type granite with a calc-alkaline differentiation trend (Janoušek et al. 2000, Buriánek et al. 2003, René 1998). It is possible that the original source of magma consisted of the lower crustal segment according to mineral chemistry; its contamination by the upper crustal metasediment was also observed (Janoušek et al. 2000, René 1997, Buriánek 2003). The genesis of such magma was, possibly, related to subduction processes and the source of granodiorite to tonalitic melts was, most likely, the melting of the hydrated and metasomatised mantle and the mixing and assimilation of crustal-derived melts (Janoušek et al. 2000, Barbarin 1999, Finger et al. 1997).

Our observed structural record within host rocks very well fit with the emplacement age of the calc-alkaline plutons. The emplacement age of 354 Ma of Zábřeh Intrusive Complex postdate the formation of S_1 steep foliation. This age is compatible with exhumation age in the surrounding Orlice-Sněžník Unit 346 Ma (Jastrebski 2009) that is comparable with formation of flat-lying foliation that can be correlated with S_2 fabric within the Zábřeh Unit.

In case of Polička Unit the crystallization age 346 Ma of Budislav pluton, that is synchronous with formation of regional transpressional fabric, very well fit with the subsequent emplacement of 345.9 Ma Miřetín pluton (Vondrovic et al 2011) which intruded in different structural position. In global scale the emplacement age very well fit preceed the indentation of Brunia continent (Schulman et al. 2005, 2008).

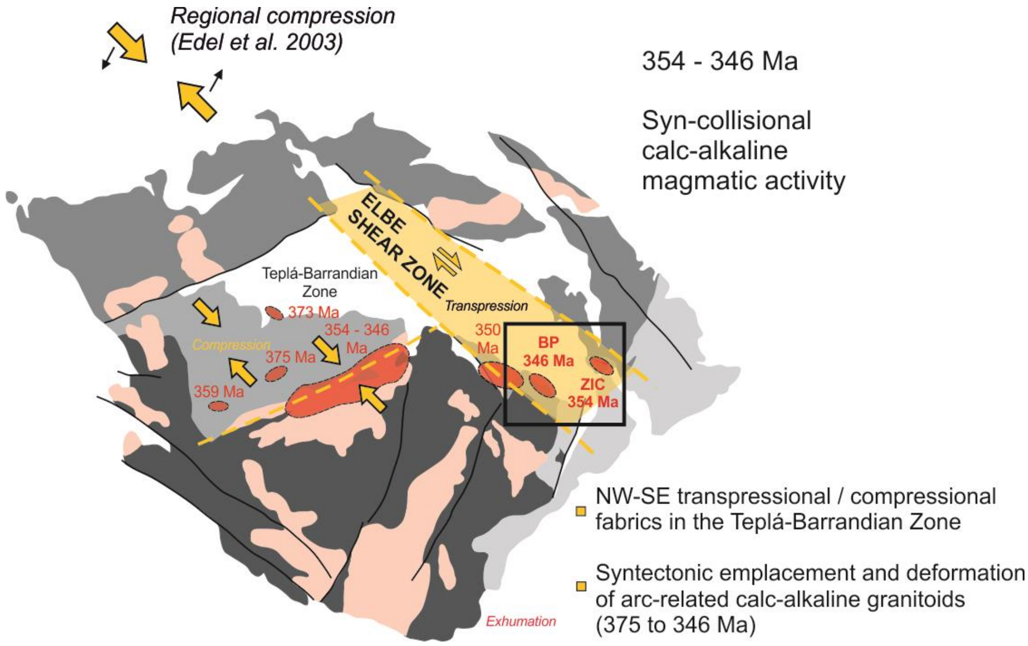


Fig. 14. Greatly idealized sketch describing the spatial and temporal pattern of calc-alkaline magmatism in the eastern periphery of the Moldanubian Zone

8.4 Geodynamic evolution

It has been demonstrated that the fabric within calc-alkaline plutons plays a key role in terms of understanding tectonic evolution in the Variscan mid-to upper-crustal level of the Polička and Zábřeh Units. The emplacement age of 354 to 346Ma defines the time span of the formation of the NNW-SSE trending regional metamorphic fabric in both units associated with shallow- to moderately-dipping stretching lineation. The tectonic evolution of both the Polička and Zábřeh Units consists of different deformational phases (e.g. Mazur et al. 2005, Lehmann et al., Schulmann et al. 2005; Verner et al. 2009; Perdoldová et al. 2010), but the associated fabrics connected with the emplacement of calc-alkaline plutons follow the same deformational event. The regional dextral transpressional deformation zone (Fig. 14) in surrounding units has been previously described (Mazur el al. 2005 and references therein) as well as with regard to the rocks studied herein (e.g. Fajst 1976; Verner et al. 2009; Pertoldová et al. 2010; Žák et al. 2014). Moreover, the regional transpressional tectonometamorphic fabric can be seen in rocks from different units with the same affinity (e.g. Synek and Oliveriová 1993; Kachlík 1999; Scheck et al. 2002; Verner et al. 2009a; Vondrovic et al. 2011). The formation of such a zone of ductile deformation in the time span 354-346 Ma in the Variscan mid- to upper-crustal rock that preceded the 340 Ma deformation of the Moldanubian Zone could be related to the earliest period of activity in the southern part of the so-called Elbe Zone (Fig. 14) which runs across the northern portion of the Bohemian Massif (e.g. Matte et al. 1990, Synek and Oliveriová 1993, Kroner and Romer 2013). The Elbe Zone consists of a zone of dextral shearing with a prolonged kinematic history. At the global scale this zone caused the significant dextral offset of the amalgamated Saxothuringian/Teplá–Barrandian Units. Subsequently, the Elbe Shear Zone was reactivated on multiple occasions in the brittle–ductile and brittle regimes during early Carboniferous times (e.g. Wenzel et al. 1997; Hofmann et al. 2009; Verner et al. 2009).

9. Conclusions

We have drawn the following conclusions:

- The 354-346Ma calc-alkaline plutons intruding the eastern margin of the Bohemian Massif reflect certain regional orogenic processes in their structure: The Budislav Pluton (346 Ma) displays a complex fabric pattern and fabric gradients, a relic magmatic fabric which probably recorded intrusive strain during the emplacement of inner magma pulses, and pluton-wide magmatic to solid state foliation that probably recorded regional strain during the emplacement of BP.
- The Zábřeh Intrusive Complex features a regional submagmatic to solid-state fabric. The intrusion of these sheets was probably synchronous with the late stages of a D_1 deformation event in the rocks of the Zábřeh Unit.
- The PT conditions of crystallization of Budislav Pluton (T: 655-730°C and P: 0.4-0.6 Gpa) roughly correspond with peak metamorphism observed within host rocks (T: 620-680°C and P: 0.6 Gpa). In case of zábřeh Unit the calculated crystallization PT conditions (T:706-795°C and P: 0.3-0.4Gpa) correspond with contact metamorphic event within host rocks (T: 599-663 °C and P: 0.4 Gpa)
- The emplacement age of the calc-alkaline plutons intruding the mid- to upper- crustal units located between Moldanubian nad Saxothuringian domain dating the activity of

the NNW-SSE trenging transpressional shear zone. The pluton emplament is the first evidence of activity of NW-SE trending shear zones in the Central European Variscides.

- The calc-alkaline plutons were emplaced syntectonically in upper- to mid- crustal rocks of the Polička and Zábřeh Units during the formation of regional metamorphic fabrics around 350Ma. In this context, these calc-alkaline intrusions provide excellent time-markers for regional transpressional geodynamic events in the mid- to upper-crustal segment of this part of the Variscan Belt.

References

ANDERSON JL, SMITH DR (1995) The effects of temperature and fO2 on the Al-in-hornblende barometer. Amer Miner 80: 549–559.

BARBARIN B (1999) A review of the relationship between granitoid types, their origins and their geodynamic environments. Lithos 45: 605–626 .

BENN K, PATERSONN SR, LUND SP, PIGNOTTA GS, KRUSE S (2001) Magmatic fabrics in batholiths as markers of regional strains and plate kinematics: example of the Cretaceous Mt. Stuart batholith. Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy, 26 (4–5): 343-354, ISSN 1464-1895.

BROWN M, SOLAR GS (1999) The mechanism of ascent and emplacement of granite magma during transpression: a syntectonic granite paradigm. Tectonophysics 312: 1–33.

BURIÁNEK D (2009) Petrography of the Polička crystalline Complex. Acta Mus Moraviae Sci Nat 94: 3–46 (in Czech).

BURIÁNEK D, NĚMEČKOVÁ M, HANŽL P (2003) Petrology and geochemistry of plutonic rocks from the Polička and Zábřeh crystalline units (NE Bohemian Massif). Bulletin of the Czech Geological Survey 78: 9–22.

BURIÁNEK D (2009) Petrography of the Polička crystalline Complex. Acta Mus Moraviae Sci Nat 94: 3–46 (in Czech).

CHARDON D, ANDRONICOS CL, HOLLISTER LS (1999) Large-scale transpressive shear zone patterns and displacements within magmatic arcs: the Coast Plutonic Complex, British Columbia. Tectonics 18: 278–292.

CHLUPÁČ I., ŠTORCH P. (eds.) (1992) Regionálně geologické dělení Českého masívu na území České republiky (Regional geologic subdivision of the Bohemian Massif). Časopis Mineralalogických Geologických věd. 37: 257–275 (in Czech).

CHLUPÁČ I (1993) Geology of the Barrandian — a field trip guide. Senckenberg-Buch 69, W. Kramer.

CHLUPÁČ I, HAVLÍČEK V, KŘÍŽ J, KUKAL Z, ŠTORCH P (1998) Palaeozoic of the Barrandian (Cambrian–Devonian). Czech Geological Survey, Prague, 183 pp.

DUNSTAN LP, GRAMLICH JW, BARNES IL, PURDY WC (1980) Absolute isotopic abundance and the atomic weight of a reference sample of thallium. J Res Nat Bur Stand 85: 1–10.

EDEL JB, SCHULMANN K, HOLUB FV (2003) Anticlockwise and clockwise rotations of the Eastern Variscides accommodated by dextral lithospheric wrenching: palaeomagnetic and structural evidence. Journal of the Geological Society 160: 209–218.

FAJST M (1976) Nová diskordance v prekambriu Českého masivu. Časopis pro Mineralogii a Geologii 21(3), 257-275 (in Czech).

FARYAD SW, NAHODILOVÁ R, DOLEJŠ D (2010) Incipient eclogite facies metamorphism in the Moldanubian granulites revealed by mineral inclusions in garnet. Lithos 114: 54–69.

FINGER F, ROBERTS MP, HAUNSCHMID B, SCHERMAIER A, STEYRER HP (1997) Variscan granitoids of central Europe: their typology, potential sources and tectonothermal relations. Mineral Petrol 61: 67–96.

FRANKE W (2000) The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. In: FRANKE W, HAAK W, ONCKEN O, TANNER D (eds) Orogenic

Processes: Quantification and Modelling in the Variscan Belt. Geological Society of London Special Publications 179: 35–63.

HOLUB FV, COCHERIE A, ROSSI P (1997) Radiometric dating of granitic rocks from the Central Bohemian Plutonic Complex (Czech Republic); constraints on geochronology of thermal and tectonic events along the Moldanubian-Barrandian boundary. Comptes Rendus de ‘l Academie des Sciences 325: 19–26.

HÁJEK J, ŠPAČEK J, DROZEN J (1997): The Železné hory pluton and its mantle rocks. Sborník geologických věd 31: 51-66.

HAJNÁ J, ŽÁK J, KACHLÍK V (2011) Structure and stratigraphy of the Teplá–Barrandian Neoproterozoic, Bohemian Massif: A new plate-tectonic reinterpretation. Gondwana Research 19: 495–508.

HAJNÁ J, ŽÁK J, KACHLÍK V, Chadima M (2010) Subduction-driven shortening and differential exhumation in a Cadomian accretionary wedge: The Teplá–Barrandian unit, Bohemian Massif. Precambrian Research 176: 27–45.

HANN HP, CHEN F, ZEDLER H, FRISCH W, LOESCHKE J (2003) The Rand Granite in the southern Schwarzwald and its geodynamic significance in the Variscan belt of SW Germany. International Journal of Earth Sciences 92: 821– 842.

HOFMANN M, LINNEMANN U, GERDES A, ULLRICH B, SCHAUER M (2009) Timing of dextral strike-slip processes and basement exhumation in the Elbe Zone (Saxo-Thuringian Zone): the final pulse of the Variscan Orogeny in the Bohemian Massif constrained by LA-SF-ICP-MS U-Pb zircon data. In: Murphy, J. B., Keppie, J. D. & Hynes, A. J. (eds) Ancient orogens and modern analogues. Geological Society, London, Special Publications 327: 197–214.

HOLLAND TJB, BLUNDY J (1994) Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry. Contribution Mineralogy Petrology 116: 433–447.

HOLLAND T, POWELL R (1998) An internally consistent thermodynamic data set with uncertainties and correlations: the system Na2O–K2O–CaO–MgO–MnO–FeO–Fe2O3–Al2O3–SiO2–TiO2–C–H2–O2. Journal of Metamorphic Geology 8: 89–124.

HOLUB FV, COCHERIE A, ROSSI P (1997a) Radiometric dating of granitic rocks from the Central Bohemian Plutonic Complex (Czech Republic): constraints on the chronology of the thermal and tectonic events along the Moldanubian–Barrandian boundary. C R Acad Sci Paris Earth Planet Sci 325: 19–26.

HOLUB FV, MACHART J, MANOVÁ M (1997b) The Central Bohemian Plutonic Complex: Geology, chemical composition and genetic interpretation. Sbor geol Věd, Ložisk Geol Mineral 31: 27–50.

HORN I, RUDNICK RL, MCDONOUGH WF (2000) Precise elemental and isotope ratio determination by simultaneous solution nebulization and laser ablation ICP-MS: application to U–Pb geochronology. Chem Geol 164: 281–301.

HROUDA F, TARLING DH (1984) The magnetic anisotropy of rocks. Chapmann and Hall, London, 215 p.

HROUDA F, TÁBORSKÁ Š, SCHULMANN K, JEŽEK J, DOLEJŠ D (1999) Magnetic fabric and rheology of co-mingled magmas in the Nasavrky Plutonic Complex (E. Bohemia): implications for intrusive strain regime and emplacement mechanism. Tectonophysics 307: 93–111.

JANOUŠEK V, BRAITHWAITE CJR, BOWES DR, GERDES A (2004a) Magma-mixing in the genesis of Hercynian calc-alkaline granitoids: an integrated petrographic and geochemical study of the Sázava intrusion, Central Bohemian Pluton, Czech Republic. Lithos 78: 67–99.

JANOUŠEK V, FINGER F, ROBERTS MP, FRÝDA J, PIN C, DOLEJŠ D (2004b) Deciphering the petrogenesis of deeply buried granites: whole-rock geochemical constraints on the origin of largely undepleted felsic granulites from the Moldanubian Zone of the Bohemian Massif. Transactions of the Royal Society of Edinburgh, Earth Sciences 95: 141–159.

JANOUŠEK V, GERDES A, VRÁNA S, FINGER F, ERBAN V, FRIEDL G, BRAITHWAITE C J R (2006) Low-pressure granulites of the Lišov Massif, Southern Bohemia: Viséan metamorphism of Late Devonian plutonic arc rocks. Journal of Petrology 47: 705–744.

JANOUŠEK V, VRÁNA S, ERBAN V, VOKURKA K, DRÁBEK M (2008) Metabasic rocks in the Varied Group of the Moldanubian Zone, southern Bohemia – their petrology, geochemical character and possible petrogenesis. Journal of Geosciences 53: 31–64.

JANOUŠEK V, WIEGAND B, ŽÁK J (2010) Dating the onset of Variscan crustal exhumation in the core of the Bohemian Massif: new U–Pb single zircon ages from the high-K calc-alkaline granodiorites of the Blatná suite, Central Bohemian Plutonic Complex. Journal of the Geological Society, London, 167: 347–360.

JANOUŠEK V, BOWES DR, ROGERS G, FARROW CM, JELÍNEK E (2000) Modelling diverse processes in the petrogenesis of a composite batholith: the Central Bohemian Pluton, Central European Hercynides. Journal of Petrology 41: 511–543.

JANOUŠEK V, BRAITHWAITE C, BOWES DR, GERDES A (2004) Magma-mixing in the genesis of Hercynian calc-alkaline granitoids: an integrated petrographic and geochemical study of the Sázava intrusion, Central Bohemian Pluton, Czech Republic. Lithos 78: 67–99.

JANOUŠEK V, WIEGAND B, ŽÁK J (2010) Dating the onset of Variscan crustal exhumation in the core of the Bohemian Massif: new U–Pb single zircon ages from the high-K calc-alkaline granodiorites of the Blatná suite, Central Bohemian Plutonic Complex. Journal of Geological Society London 167: 347–360.

JASTRZĘBSKI M (2009) A Variscan continental collision of the West Sudetes and the Brunovistulian Terrane: a contribution from structural and metamorphic record of the Stronie Formation, the Orlica–Śnieżnik Dome, SW Poland. International Journal of Earth Sciences 98: 1901–1923.

JELÍNEK V (1978) Statistical processing of anisotropy of magnetic susceptibility measured on groups of specimens. Studia Geophysica et Geodetica 22: 50–62.

KACHLÍK V (1999) Relationship between Moldanubicum, the Kutná Hora crystalline Unit and Bohemicum (central Bohemia, Czech Republic): a result of the polyphase Variscan nappe tectonics. Journal of Czech Geological Society 44: 201–291.

KONOPÁSEK J, SCHULMANN K, LEXA O (2001) Structural evolution of the central part of the Krušné hory (Erzgebirge) Mountains in the Czech Republic—evidence for changing stress regime during Variscan compression. Journal of Structural Geology 23: 1373–1392.

KOŠLER J, FONNELAND H, SYLVESTER P, TUBRETT M, PEDERSEN RB (2002) U–Pb dating of detrital zircons for sediment provenance studies - a comparison of laser ablation ICP-MS and SIMS techniques. Chemical Geology 182: 605– 618.

KOŠLER J, SYLVESTER PJ (2003) Present trends and the future of zircon in geochronology: Laser ablation ICP-MS. In: Hanchar, J.M., J.M., Hoskin, P.W.O. (Eds.), Zircon. Reviews in Mineralogy and Geochemistry 53: 243–275.

KRETZ R (1983) Symbols for rock-forming minerals. American Mineralogist 68: 277–279.

LEAKE BE, WOOLLEY AR, ARPS CES, BIRCH WD, GILBERT MC, GRICE JD, HAWTHORNE FC, KATO A, KISCH HJ, KRIVOVICHEV VG, LINTHOUT K, LAIRD J, MANDARINO J, MARESCH WV, NICKEL EH, ROCK NMS, SCHUMACHER JC, SMITH DC, STEPHENSON NCN, UNGARETTI L, WHITTAKER EJW, YOUZHI G (1997) Nomenclature of amphiboles. Report of the Subcommittee on Amphiboles of the International Mineralogical Association Commission on New Minerals and Mineral Names. European Journal of Mineralofy 9: 623–651.

KRÖNER U, ROMER RL (2013) Two plates – many subduction zones: the Variscan orogeny reconsidered. Gondwana Research 24: 298–329.

HARTLEY AJ, OTAVA J (2001) Sediment provenance and dispersal in a deep marine foreland basin: the Lower Carboniferous Culm Basin, Czech Republic. Journal of the Geological Society London 158: 137–150.

LEHMANN J, SCHULMANN K, EDEL JB, JEŽEK J, HROUDA F, LEXA O, CHOPIN F (2013)Structural and anisotropy of magnetic susceptibility records of granitoid sheets emplacement during growth of a continental gneiss dome (Central Sudetes). Tectonics 797–820.

LINNEMANN U, PEREIRA F, JEFFRIES TE, DROST K, GERDES A (2008) The Cadomian Orogeny and the opening of the Rheic Ocean: The diacrony of geotectonic processes constrained by LA-ICP-MS U-Pb zircon dating (Ossa-Morena and Saxo-Thuringian Zones, Iberian and Bohemian Massifs). Tectonophysics 461: 1–4.

MATTE PH, MALUSKI H, RAIJLICH P, FRANKE W (1990) Terrane boundaries in the Bohemian Massif: Result of large-scale Variscan shearing: Tectonophysics 177: 151–170.

MAZUR S, ALEKSANDROWSKI P, SZCZEPANSKI J (2005) The presumed Teplá –Barrandian⁄ Moldanubian terrane boundary in the Orlica Mountains (Sudetes, Bohemian Massif): structural and petrological characteristics. Lithos 82: 85–112.

MELICHAR R (1995) The structural analysis of the Polička and Svratka units. Unpublished PhD thesis, Charles University, Prague, pp 1–271 (in Czech).

MIDDLEMOST AK (1994) Naming materials in the magma/igneous rock system. Earth-Sci. Reviews 37: 215–224.

MILLER RB, PATERSON SR (2001) Construction of mid-crustal sheeted plutons: examples from the North Cascades, Washington. Geol Soc Am Bull 113: 1423–1442.

MÍSAŘ Z, DUDEK A, HAVLENA V, WEISS J (1983) Geology of the Bohemian Massif. SPN, Prague, pp 1–334 (in Czech).

PARRY M, ŠTÍPSKÁ P, SCHULMANN K, HROUDA F, JEŽEK J, KRÖNER A (1997) Tonalite sill emplacement at an oblique plate boundary: northeastern margin of the Bohemian Massif. Tectonophysics 280: 61–81.

PATERSON SR, FOWLER TK, SCHMIDT KL (1998) Interpreting magmatic fabric patterns in plutons. Lithos 44: 53–82.

PEARCE JA, HARRIS NW, TINDLE AG (1984) Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology 25: 956–983.

PECCERILLO A, TAYLOR SR (1976) Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, Northern Turkey. Contrib Mineral Petrol 58: 63–81.

PERTOLDOVÁ J, VERNER K, VRÁNA S, BURIÁNEK D, ŠTĚDRÁ V, VONDROVIC L (2010) Comparison of lithology and tectonometamorphic evolution of units at northern margin of the Moldanubian Zone: implications for geodynamic evolution in the northeastern part of the Bohemian Massif. Journal of Geosciences 55(4): 299–319.

PITRA P, BURG JP, SCHULMANN K, LEDRU P (1994) Late-orogenic extension in the Bohemian Massif: petrostructural evidence in the Hlinsko region. Geodin Acta 6: 15–31.

RENÉ M (1998): Evolution of a Tonalite Suite in the Northeastern Part of the Bohemian Massif. Geolines 6: 53.

SAINT BLANQUAT M, TIKOFF B, TEYSSIER CH, VIGNERESSE JL (1998) Transpressional kinematics and magmatic arcs. In: HOLDSWORTH RE, STRACHAN RA, DEWEY JE (eds) Continental Transpressional and Transtensional Tectonics. Geological Society of London Special Publications 135: 327–340.

SCHECK M, BAYER U, OTTO V, LAMARCHE J, BANKA D, PHARAOH T (2002) The Elbe Fault System in North Central Europe – a basement controlled zone of crustal weakness. Tectonophysics 360: 281–299.

SCHMIDT KL, PATERSON SR (2002) A doubly vergent fan structure in the Peninsular Ranges Batholith: transpression or local complex flow around a continental margin buttress? Tectonics 21: 1050–1069.

SCHULMANN K, KRÖNER A, HEGNER E, WENDT I, KONOPÁSEK J, LEXA O, ŠTÍPSKÁ P (2005) Chronological constraints on the pre-orogenic history, burial and exhumation of deep-seated rocks along the eastern margin of the Variscan orogen, Bohemian Massif, Czech Republic. American Journal of Science 305: 407–448.

SCHULMANN K, LEXA O, ŠTÍPSKÁ P, RACEK M, TAJČMANOVÁ L, KONOPÁSEK J, EDEL JB PESCHLER A, LEHMANN J (2008) Vertical extrusion and horizontal channel flow of orogenic lower crust: key exhumation mechanisms in large hot orogens? Journal of Metamorphic Geology 26: 273-297.

SCHULMANN K, KONOPÁSEK J, JANOUŠEK V, LEXA O, LARDEAUX JM, EDEL JB, ŠTÍPSKÁ P, ULRICH S (2009) An Andean type Palaeozoic convergence in the Bohemian Massif. Comptes Rendus Geoscience 341: 266–286.

SHAND SJ (1943) Eruptive Rocks. Their Genesis, Composition, Classification, and Their Relation to Ore-Deposits with a Chapter on Meteorite. New York: John Wiley & Sons.

SYNEK J, OLIVERIOVÁ D (1993) Terrane character of the north-east margin of the Moldanubian Zone: the Kutná Hora Crystalline Complex. Bohemian Massif. Geologische Rundschau 82: 566-582

TÁBORSKÁ Š (1997): Petrogeneze magmatitů nasavrckého plutonického komplexu ve vztahu k jejich vmístění. Unpublished PhD thesis. Charles University, Faculty of Science.

TIKOFF B, GREENE D (1997) Stretching lineations in transpressional shear zones: an example from the Sierra Nevada Batholith, California. J Struct Geol 19: 29–39

VENERA Z, SCHULMANNN K, KRÖNER A (2000) Intrusion within a transtensional tectonic domain: the Čistá granodiorite (Bohemian Massif)—structure and rheological modelling. Journal of Structural Geology 22: 1437–1454.

VERNER K, ŽÁK J, NAHODILOVÁ R, HOLUB FV (2008) Magmatic fabrics and emplacement of the cone-sheet-bearing Knížecí Stolec durbachitic Pluton (Moldanubian Unit, Bohemian Massif): implications for mid-crustal reworking of granulitic lower crust in the Central European Variscides. International Journal of Earth Sciences 97: 19–33

VERNER K, BURIÁNEK D, VRÁNA S, VONDROVIC L, PERTOLDOVÁ J, HANŽL P, NAHODILOVÁ R (2009) Lithological and structural features of geological units along the northern periphery of the Moldanubian Zone: a review of the geology of the northeastern Variscides. J Geosci 54: 87–100

VERNER K, ŽÁK J, ŠRÁMEK J, PACLÍKOVÁ J, ZAVŘELOVÁ A, MACHEK M, FINGER F, JOHNSON K. (2014) Formation of elongated granite–migmatite domes as isostatic accommodation structures in collisional orogens. Journal of Geodynamics 73 100-117.

VERNON RH (2000) Review of microstructural evidence of magmatic and solid-state flow. El Geosci 5: 2, 1–23, doi: 10.1007/s10069-000-0002-3.

VONDROVIC L, VERNER K, BURIÁNEK D, HALODOVÁ P, KACHLÍK V, MÍKOVÁ J (2011): Emplacement, structural and P-T evolution of the ˜346 Ma Miřetín Pluton (eastern Teplá-Barrandian Zone, Bohemian Massif): implications for regional transpressional tectonics. J Geosci 56: 343–357

VRÁNA S, BLÜMEL P, PETRAKAKIS K (1995) Moldanubian Zone – Metamorphic Evolution (Chapter VII.C.4). In: DALLMEYER RD, FRANKE W, WEBER K (eds) Pre-Permian Geology of Central and Eastern Europe. Springer-Verlag, Berlin, pp 453–468

WENZEL T, MERTZ DF, OBERHÄNSLI R, BECKER T. RENNE PR (1997) Age, geodynamic setting, and mantle enrichment processes of a K-rich intrusion from the Meissen Massif (northern Bohemian Massif) and implications for related occurrences from the mid-European Hercynian. Geologische Rundschau 86: 556–570

WIEDENBECK M, ALLE P, CORFU F, GRIFFIN WL, MEIER M, OBERLI F, VON QUADT A, RODDICK JC, SPIEGEL W (1995) Three natural zircon standards for U–Th–Pb, Lu–Hf, trace element and REE analyses. Geostand Newslett 19:1–23

ŽÁK J, HOLUB FV, VERNER K (2005a) Tectonic evolution of a continental magmatic arc from transpression in the upper crust to exhumation of mid-crustal orogenic root recorded by episodically emplaced plutons: the Central Bohemian Plutonic Complex (Bohemian Massif). International Journal of Earth Sciences 94: 385–400.

ŽÁK J, Schulmann K, Hrouda F (2005b) Multiple magmatic fabrics in the Sázava pluton (Bohemian Massif, Czech Republic): a result of superposition of wrench-dominated regional transpression on final emplacement. Journal of Structural Geology 27: 805–82

ŽÁK J, KRATINOVÁ Z, TRUBAČ J, JANOUŠEK V, SLÁMA J, MRLINA J (2011a) Structure, emplacement, and tectonic setting of Late Devonian granitoid plutons in the Teplá–Barrandian unit, Bohemian Massif. International Journal of Earth Sciences 100: 1477–1495

ŽÁK J, VERNER K, FINGER F, FARYAD SW, CHLUPÁČOVÁ M, VESELOVSKÝ F (2011b) The generation of voluminous S-type granites in the Moldanubian unit, Bohemian Massif, by rapid isothermal exhumation of the metapelitic middle crust. Lithos 121: 25-40.

ŽÁK J, VERNER K, JANOUŠEK V, HOLUB FV, KACHLÍK V, FINGER F, HAJNÁ J, TOMEK F, VONDROVIC L, TRUBAČ J (2014a) A plate-kinematic model for assembly of the Bohemian Massif constrained by structural relationships around granitoid plutons. In Schulmann,K.; Martínez Catalán,J.R; Lardeaux,J.M.; Janoušek,V.; Oggiano,G: The Variscan orogeny: extent, timescale and the formation of the European crust, s. 169-196. Special Publications of the Geological Society of London 405.

The structural record of the plutonic bodies in the Bohemian Massif: general implications

4. The structural record of the plutonic bodies in the Bohemian Massif: general implications

The final part summarises the knowledge of the nature, kinematics and timing of movement along major tectonic boundaries in the Bohemian Massif. In addition this part describes how Variscan plutonism and deformation evolved in space and time. This thesis stresses the initial recognised phase of variscan plutonism that took place in the peripheral part of the Moldanubian Zone. This initial magmatic phase was related to the late Devonian-early Carboniferous subduction and continental under-thrusting of the Saxothuringian Unit beneath the Teplá-Barrandian Unit resulted which resulted into orogen-perpendicular shortening and the growth of magmatic arc during circa 354-346Ma followed by orogen parallel shearing. The corresponding part of the article resulting from this thesis describes the activity of the Elbe Shear Zone system in the eastern part of the Bohemian Massif. This zone runs across the northern part of the Bohemian Massif (Hofmann et al. 2009) and probably continue to its eastern part (this thesis part 3,4). Elbe Zone is a broad zone of dextral shearing with a prolonged kinematic history which caused the significant dextral offset of the consolidated Saxothuringian/Teplá - Barrandian units (Žák et al. 2014). The earliest ductile movements were recorded within a roughly 50-100km wide belt of the middle-to upper-crustal rocks between the south western Moldanubian and north eastern Saxothuringian units. The dominant ductile fabric is characterised in this location by NW-SE metamorphic foliation, sub horizontal NW-SE stretching lineation and dextral strike-slip kinematics (Synek and Oliveriová 1993; Kachlík 1999; Scheck et al. 2002; Verner et al. 2009; Vondrovic et al. 2011). The broad Elbe Shear Zone hosts several syntectonic calc-alkaline granodiorite-dominated intrusions in various stages of deformation including the Nasavrky Plutonic Complex (Hrouda et al. 1999), Budislav and Miřetín Plutons Zábřeh Intrusive Complex (Verner et al. 2009a; Vondrovic and Verner 2010; Vondrovic et al. 2011, this thesis part 3,4). The 354 Ma Zábřeh Intrusive complex and 346 Ma Budislav Pluton were coeval with ductile dextral shearing along the Elbe Shear Zone whereas the slightly younger Miřetín Pluton post-dated dextral movements (Pitra et al. 1994; Pertoldova et al. 2010; Vondrovic et al. 2011). The Elbe Shear Zone was letr multiply reactivated in the brittle-ductile and brittle regime during early Carboniferous times (e.g. Wenzel et al. 1997; Hofmann et al. 2009; Verner et al. 2009).

PAPER NO. I.

ŽÁK, J. – VERNER, K. – JANOUŠEK, V. – HOLUB, F. V. – KACHLÍK, V. – FINGER, F. – HAJNÁ, J. – TOMEK, F. – VONDROVIC, L. – TRUBAČ, J. (2014): A PLATE-KINEMATIC MODEL FOR ASSEMBLY OF THE BOHEMIAN MASSIF CONSTRAINED BY STRUCTURAL RELATIONSHIPS AROUND GRANITOID PLUTONS. IN SCHULMANN,K.; MARTÍNEZ CATALÁN,J.R; LARDEAUX,J.M.; JANOUŠEK,V.; OGGIANO,G: THE VARISCAN OROGENY: EXTENT, TIMESCALE AND THE FORMATION OF THE EUROPEAN CRUST, S. 169-196. – SPECIAL PUBLICATIONS OF THE GEOLOGICAL SOCIETY OF LONDON 405. LONDON.

Geological Society, London, Special Publications, first published March 17, 2014; doi 10.1144/SP405.9

A plate-kinematic model for the assembly of the Bohemian Massif constrained by structural relationships around granitoid plutons

JIŘÍ ŽÁK[1][1], KRYŠTOF VERNER[2,3], VOJTĚCH JANOUŠEK[2,3], FRANTIŠEK V. HOLUB[3], VÁCLAV KACHLÍK[1], FRITZ FINGER[4], JAROSLAVA HAJNÁ[1], FILIP TOMEK[1], LUKÁŠ VONDROVIC[2,3], JAKUB TRUBAČ[1,2,3]

[1] *Institute of Geology and Palaeontology, Faculty of Science, Charles University, Albertov 6, Prague, 12843, Czech Republic*

[2] *Czech Geological Survey, Klárov 3, Prague, 11821, Czech Republic*

[3] *Institute of Petrology and Structural Geology, Faculty of Science, Charles University, Albertov 6, Prague, 12843, Czech Republic*

[4] *Division of Mineralogy, University of Salzburg, Hellbrunnerstraße 34, A-5020 Salzburg, Austria*

Abstract

This paper summarizes the current knowledge on the nature, kinematics, and timing of movement along major tectonic boundaries in the Bohemian Massif and demonstrates how the Variscan plutonism and deformation evolved in space and time. Four main episodes are recognized. (1) Late Devonian to early Carboniferous subduction and continental underthrusting of the Saxothuringian Unit beneath the Teplá–Barrandian Unit resulted in the orogen-perpendicular shortening and growth of an inboard magmatic arc during ~354–346 Ma. (2) The subduction-driven shortening was replaced by collapse of the Teplá–Barrandian upper crust, exhumation of the high-grade (Moldanubian) core of the orogen at ~346–337 Ma, and by dextral strike-slip along orogen-perpendicular ~NW–SE shear zones. (3) Following closure of a Rhenohercynian Ocean basin, the Brunia microplate was underthrust beneath the eastern flank of the Saxothuringian/Teplá–Barrandian/Moldanubian ‘assemblage’. This process commenced at *c.* 346 Ma in the northeast and ceased at *c.* 335 in the southwest. (4) Late readjustments within the amalgamated Bohemian Massif included crustal exhumation

[1] Corresponding author. Email: jirizak@natur.cuni.cz

and ~330–327 Ma, mainly S-type granite plutonism along the edge of the Brunia indentor, and peripheral tectonothermal activity driven by strike-slip faulting and possibly mantle delamination around the consolidated Bohemian Massif's interior until late Carboniferous/earliest Permian times.

Introduction

The Bohemian Massif of central Europe is the largest inlier of once continuous but now largely dismembered Ouachita–Appalachian–Variscan orogenic belt (Fig. 1) that formed during the Devonian to Carboniferous closure of the Rheic Ocean and other small oceanic domains by convergence of the Gondwana and Laurussia supercontinents (e.g. Franke 1989; Pin 1990; Matte 2001; Winchester 2002; Winchester *et al.* 2006; Ballévre *et al.* 2009; Faure *et al.* 2009; Faryad & Kachlík 2013; Edel *et al.* 2013; Kroner & Romer 2013). A characteristic feature of the Variscan Orogeny was involvement of multiple microplates of the Cadomian or Avalonian affinity that were partially extended or entirely detached from the northern margin of Gondwana during the late Cambrian to Early Ordovician times (e.g. Pin & Marini 1993; Franke 2000; Matte 2001; Murphy & Nance 2002; Nance & Linnemann 2008; von Raumer & Stampfli 2008; Nance *et al.* 2010, 2012). These microplates were then stuck in a broad collision zone between Gondwana and Laurussia as the two supercontinents converged, resulting in multiple subduction, accretion, and collision events along margins of the neighbouring microplates.

This style of orogeny is greatly exemplified in the Bohemian Massif, which is a mosaic consisting of several lithotectonic units (Figs 1 & 2). The timing and kinematics of their amalgamation and further development during the Variscan Orogeny have been vigorously debated and summarized in several plate-tectonic reconstructions (e.g. Matte 1986, 1991, 2001; Franke 1989; Pharaoh 1999; Pitra *et al.* 1999; Franke & Żelaźniewicz 2002; Winchester 2002; Edel *et al.* 2003; Franke 2006; Finger *et al.* 2007; Schulmann *et al.* 2009; Kroner & Romer 2013). This short contribution is not meant as a comprehensive review, but rather focuses on granitoid and syenitoid plutons as temporal and strain markers of regional deformation, utilizing modern structural data in combination with geochronology, mainly U–Pb dating on zircon. Below, we first briefly describe the principal lithotectonic units in the interior of the Bohemian Massif and then comment on the nature, kinematics, and timing of movements along their boundaries. Based on these data sets, we propose a plate-tectonic model and outline some relevant open questions and possible directions for future research.

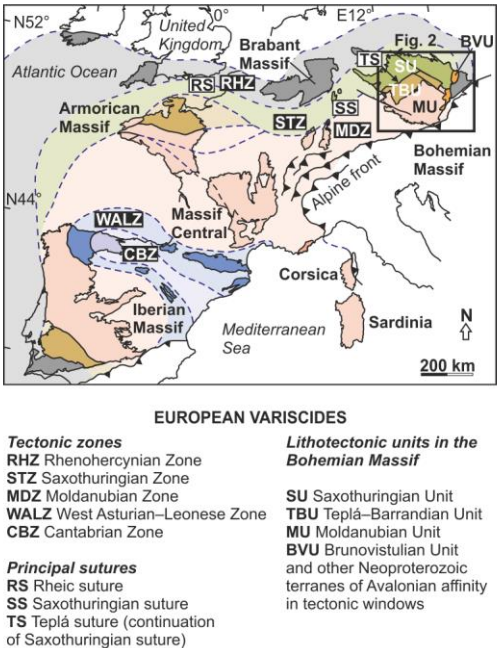


Fig. 1. Overview geological map showing basement outcrop areas and principal lithotectonic zones and sutures of the Variscan orogenic belt in Europe. Bohemian Massif is the easternmost inlier of the orogen. Compiled from Winchester (2002), Asch (2003), and Martínez-Catalán (2011, 2012).

Major lithotectonic units in the interior of the Bohemian Massif

Saxothuringian Unit

The northerly and north-westerly Saxothuringian Unit (Fig. 2) consists of late Neoproterozoic volcano-sedimentary successions, interpreted as a back-arc and retro-arc system of the Cadomian orogen, intruded by a voluminous late Neoproterozoic to early Cambrian granitoid plutonic complex (the Lusatian Massif, LM in Fig. 2; Kröner *et al.* 1994, 1995; Linnemann & Romer 2002; Linnemann *et al.* 2000, 2004, 2008; Tichomirowa *et al.* 2012). The Cadomian basement is overlain unconformably by Lower Palaeozoic volcano-sedimentary passive-margin successions (Buschmann *et al.* 2006) and both units host orthogneisses and bimodal metavolcanic rocks of chiefly Cambro–Ordovician and late Devonian to early Carboniferous protolith ages (Patočka & Smulikowski 2000; Kröner *et al.* 2001; Oberc-Dziedzic *et al.* 2005a, b; Nowak *et al.* 2011). This Neoproterozoic–Early Paleozoic package was affected by Variscan subduction-related HP–LT greenschist/blueschist to (U)HP–HT metamorphism and was then strongly reworked during nappe stacking and extensional unroofing under MP–MT to greenschist-facies conditions. The latter process was associated with, and followed by, strike-slip movements along major ~NW–SE-trending faults (Aleksandrowski *et al.* 1997; Marheine *et al.* 2002; Mazur *et al.* 2006). Importantly, relics of blueschist-facies rocks with cooling ages constrained at around 360 Ma (Cháb & Vrána 1979; Smulikowski 1995; Maluski & Patočka 1997; Marheine *et al.* 2002; Faryad & Kachlík 2013; *cf.* Žáčková *et al.* 2010), together with diamond-bearing metasedimentary rocks and granulites, delineate the margins of the Saxothuringian Unit (Behr *et al.* 1982; Schmädicke 1991; Schäfer *et al.* 1997; Willner *et al.* 1997; Kröner & Willner 1998; Kröner *et al.* 1998; Massonne 2001; Mueller & Massonne 2001; Rötzler & Romer 2001; Willner *et al.* 2002; O'Brien & Rötzler 2003; Konopásek & Schulmann 2005; Schmädicke *et al.* 2010; Kotková *et al.* 2011). Indeed, the Saxothuringian Unit has been regarded as a separate collage of microplates in the framework of the Bohemian Massif (e.g. Cymerman *et al.* 1997; Żelaźniewicz 1997; Mazur *et al.* 2006), though uncertainty exists as to how far it travelled from, or whether it remained attached to, the northern margin of Gondwana in the early Paleozoic Era (Linnemann *et al.* 2004).

During the wanning stages of Variscan Orogeny (*c.* 330–305 Ma; Fig. 3), the Saxothuringian Unit was intruded by several granite plutons of diverse geochemical composition ranging from I-types (e.g. main portion of the Krkonoše–Jizera Plutonic Complex, KJPC in Fig. 2; Słaby & Martin 2008) to strongly peraluminous S- and A-types bearing Sn–W mineralization (most granite units in the Krušné hory/Erzgebirge; Fig. 2; see Förster *et al.* 1999, Štemprok *et al.* 2003, Förster & Romer 2010, and Breiter 2012 for reviews). The plutons continue to the southwest and cross-cut boundaries between lithotectonic units with no apparent change in composition or age (e.g. Northern Oberpfalz, NOP; Figs 2 & 3).

Teplá–Barrandian Unit

The upper-crustal Teplá–Barrandian Unit in the centre of the Bohemian Massif (Fig. 2) occupies the hanging-wall position with respect to the neighbouring Saxothuringian and Moldanubian units and is thus the overriding plate for all the hypothetic subduction zones. Moreover, a large central portion of this unit has never been buried to great depths and thus has escaped the Variscan pervasive metamorphism and ductile deformation (Suchý *et al.* 1996, 2007; Hajná *et al.* 2010, 2011, 2012).

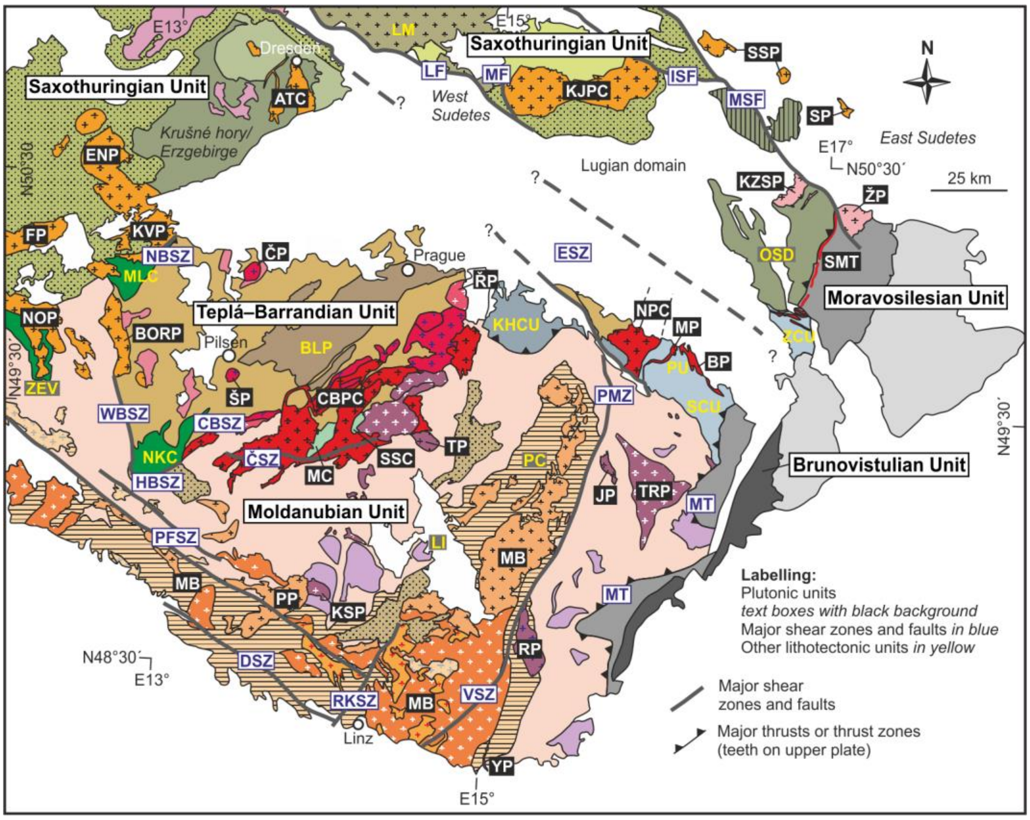


Fig. 2. Greatly simplified geological map of the interior Bohemian Massif emphasizing geologic units and tectonic features discussed in the text. Compiled from Fusán *et al.* (1967) and Cháb *et al.* (2007). Plutonic units: ATC, Altenberg–Teplice caldera; BORP, Bor Pluton; BP, Budislav Pluton; CBPC, Central Bohemian Plutonic Complex; ČP, Čistá Pluton; ENP, Eibenstock–Nejdek Pluton; FP, Fichtelgebirge(Smrčiny) Pluton; JP, Jihlava Pluton; KJPC, Krkonoše–Jizera Plutonic Complex; KSP, Knížecí Stolec Pluton; KVP, Karlovy Vary Pluton; KZSP, Kłodzko–Złoty Stok Pluton; MB, Moldanubian Batholith; MC, Mirotice Complex; MP, Miřetín Pluton; NOP, Northern Oberpfalz Pluton; NPC, Nasavrky Plutonic Complex; PP, Plechý Pluton; RP, Rastenberg Pluton; ŘP, Říčany Pluton; SMT, Staré Město tonalite sill; SP, Strzelin Pluton; ŠP, Štěnovice Pluton; SSC, Staré Sedlo Complex; SSP, Strzegom–Sobótka Pluton; TP, Tábor Pluton; TRP, Třebíč Pluton; YP, Ybbs Pluton; ŽP, Žulová Pluton. Shear zones and faults: CBSZ, Central Bohemian shear zone; ČSZ, Červená shear zone; DSZ, Danube shear zone; ESZ, Elbe shear zone; HBSZ, Hoher Bogen shear zone; ISF, Intra-Sudetic Fault; LF, Lusatian Fault; MF, Machnín Fault; MSF, Marginal-Sudetic Fault; MT, Moldanubian thrust; NBSZ, North Bohemian shear zone; PFSZ, Pfahl shear zone; PMZ, Přibyslav mylonite zone; RKSZ, Rodl–Kaplice shear zone; VSZ, Vitis shear zone; WBSZ, West Bohemian shear zone. Other geologic units: BLP, Barrandian Lower Palaeozoic successions; KHCU, Kutná Hora Crystalline Unit; LI, Lišov granulite; LM, Lusatian Massif; MLC, Mariánské Lázně Complex; NKC, Neukirchen–Kdyně Complex; OSD, Orlica–Snieznik Dome; PC, Pelhřimov Complex; PU, Polička Crystalline Unit; SCU, Svratka Crystalline Unit; ZEV, Erbendorf–Vohenstrauss Zone; ZCU, Zábřeh Crystalline Unit.

The Teplá–Barrandian Unit consists of generally low-grade Neoproterozoic basement intruded by Cambro–Ordovician plutons and overlain unconformably by the early Paleozoic (early Cambrian to middle Givetian) passive margin volcano-sedimentary successions (Fig. 2; Zulauf 1997b; Chlupáč *et al.* 1998; Dörr *et al.* 1998, 2002; Hajná *et al.* 2010, 2011). The largest part of the Teplá–Barrandian Neoproterozoic basement to the south, west, and northwest of the Lower Paleozoic overlap successions was interpreted as a Cadomian accretionary wedge with a related volcanic arc preserved along the southeastern flank of the unit, albeit severely reworked by Variscan deformation (Waldhausrová 1984; Sláma *et al.* 2008a; Hajná *et al.* 2010, 2011). Small remnants of Cadomian intra- and back-arc basins also occur close to the Teplá–Barrandian/Moldanubian boundary (Sláma *et al.* 2008a; Hajná *et al.* 2010, 2011).

There are three important features associated with the Teplá–Barrandian Unit. First, as inferred from seismic anisotropy by Babuška & Plomerová (1992, 2001, 2013), Plomerová *et* *al.* (2005), and Babuška *et al.* (2008, 2010), the Teplá–Barrandian mantle lithosphere exhibits olivine fabric different from that of in the neighbouring Saxothuringian and Moldanubian units, perhaps being inherited from the Cadomian accretion and subduction.

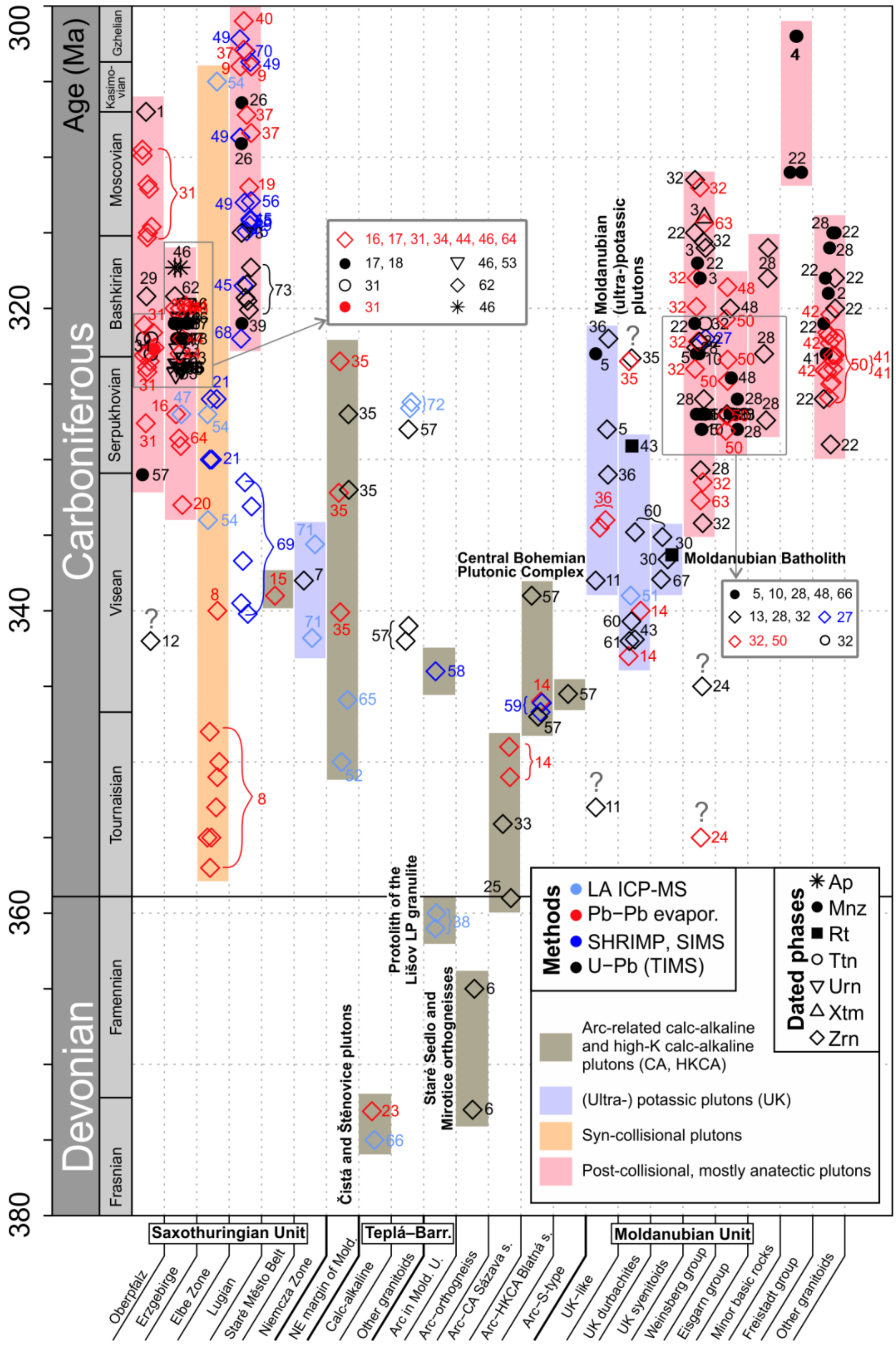


Fig. 3. Overview of the U–Pb and Pb–Pb ages from Late Devonian to late Carboniferous plutonic rocks of the Bohemian Massif. The stratigraphic table is based on International Stratigraphic Chart, version 2013/1 (*http://www.stratigraphy.org/ICSchart/ChronostratChart2013-01.pdf*). Mineral abbreviations after Kretz (1983). References: 1 –Wendt *et al.* (1986); 2 – Frasl & Finger (1991); 3 –von Quadt & Finger (1991); 4 –Friedl *et al.* (1992); 5 – Friedl *et al.* (1993); 6 – Košler *et al.* (1993); 7 – Oliver *et al.* (1993); 8 – Wenzel *et al.* (1993); 9 – Kröner *et al.* (1994); 10 – Friedl *et al.* (1996); 11 – Klötzli & Parrish (1996); 12 –Köhler & Hölzl (1996); 13 – Finger *et al.* (1997); 14 – Holub *et al.* (1997a); 15 – Parry *et al.* (1997); 16 –Tichomirowa (1997); 17 –Förster (1998); 18 –Förster *et al.* (2009); 19 –Hammer *et al.* (1999); 20 –Kempe *et al.* (1999); 21 – Nasdala *et al.* (1999); 22 – Propach *et al.* (2000); 23 – Venera *et al.* (2000); 24 – Klötzli *et al.* (2001); 25 – Bues *et al.* (2002); 26 –Turniak & Bröcker (2002); 27 – Finger *et al.* (2003); 28 – Gerdes *et al.* (2003); 29 – Chen *et al.* (2003); 30 – Janoušek & Gerdes (2003); 31 – Siebel *et al.* (2003); 32 – Chen & Siebel (2004); 33 – Janoušek *et al.* (2004); 34 – Kempe *et al.* (2004); 35 – Schulmann *et al.* (2005); 36 – Siebel *et al.* (2005); 37 –Turniak *et al.* (2005); 38 – Janoušek *et al.* (2006); 39 –Klomínský *et al.* (2007); 40 –Turniak *et al.* (2006); 41 – Siebel *et al.* (2006a); 42 – Siebel *et al.* (2006b); 43 – Kotková *et al.* (2007); 44 – Kovaříková *et al.* (2007); 45 – Machowiak & Armstrong (2007); 46 – Romer *et al.* (2007); 47 –Hofmann *et al.* (2008); 48 – Klein *et al.* (2008); 49 – Kusiak *et al.* (2008); 50 – Siebel *et al.* (2008); 51 – unpublished data cited in Verner *et al.* (2008); 52 –Vondrovic & Verner (2008); 53 – Förster *et al.* (2009); 54 – Hofmann *et al.* (2009); 55 – Kusiak *et al.* (2009); 56 – Awdankiewicz *et al.* (2010); 57 – Dörr & Zulauf (2010); 58 – Finger *et al.* (2010); 59 – Janoušek *et al.* (2010); 60 – Kotková *et al.* (2010); 61 – Kusiak *et al.* (2010); 62 –Romer *et al.* (2010); 63 – Siebel *et al.* (2010); 64 – Tichomirowa & Leonhardt (2010); 65 – Vondrovic *et al.* (2011); 66 – Žák *et al.* (2011a); 67 – Holub *et al.* (2012); 68 – Kryza *et al.* (2012); 69 – Mikulski *et al.* (2013); 70 – Oberc-Dziedzic *et al.* (2013); 71 –Pietranik *et al.* (2013); 72 – Trubač *et al.* (2013); 73 –Žák *et al.* (in print).

Second, its northwestern tip structurally overlies the Mariánské Lázně meta-ophiolite complex (MLC in Fig. 2) which exhibits the earliest Cambrian (*c.* 540 Ma) and early Ordovician (*c.* 480 Ma) protolith ages (Bowes & Aftalion 1991; Timmermann *et al.* 2004), interpreted as recording attachment of oceanic lithosphere and rifting of the ʽproto-Teplá–Barrandian' margin, respectively (Timmermann *et al.* 2004; Sláma *et al.* 2008a). The late Devonian ages (*c.* 380 Ma) in the complex then constrain its Variscan subduction-related eclogite-facies metamorphism (Beard *et al.* 1995; Zulauf 1997b). Taken together, the present-day northwestern margin of the Teplá–Barrandian Unit must have acted repeatedly as an active plate margin with subduction of oceanic crust during both the Cadomian and Variscan orogenies (e.g. Zulauf 1997b; Dörr *et al.* 2002; Dörr & Zulauf 2010).

Third, the Teplá–Barrandian upper crust was intruded by a number of Late Devonian to early Carboniferous calc-alkaline granitoid plutons (Figs 2 & 3) that bear a distinctive geochemical imprint of subduction (Palivcová 1984; Janoušek *et al.* 1995; Holub *et al.* 1997b; Janoušek *et al.* 2000, 2004a, 2006; Verner *et al.* 2009a; Vondrovic *et al.* 2011) and reveal a consistent spatial–temporal–compositional trend (Žák *et al.* 2011a). The earliest, late Devonian (~375–373 Ma) Čistá and Štěnovice plutons occupy the centre (ČP and SP in Fig. 2; Klomínský 1963, 1965; Kopecký *et al.* 1997; Venera *et al.* 2000; Žák *et al.* 2011a), whereas the early Carboniferous (~354–337 Ma) plutons form a large continental magmatic arc along the southeastern flank of the Teplá–Barrandian Unit (the Central Bohemian Plutonic Complex, CBPC in Fig. 2; Holub *et al.* 1997a, b; Dörr *et al.* 1998; Janoušek *et al.* 2004a, 2010; Dörr &

Zulauf 2010). The arc itself shows internal compositional zoning from the older ~354 Ma calc-alkaline intrusions to the north and northwest through ~346 Ma high-K calc-alkaline in the centre to ~343–337 Ma ultrapotassic plutons along its southeastern margin (Fig. 2; Janoušek *et al.* 1995; Holub *et al.* 1997a, b; Žák *et al.* 2005a). The exception are the Late Devonian Mirotice and Staré Sedlo orthogneisses (MC and SSC in Fig. 2; ~380–365 Ma; Košler *et al.* 1993) which also exhibit calc-alkaline arc-related geochemical signature (Košler & Farrow 1994) but occur in the roof of the central part of the plutonic complex (Fig. 2). They were deformed prior to emplacement of at least 20 M.y. younger high-K calc-alkaline and still younger ultrapotassic plutons. Interestingly, dismembered and reworked parts of comparable arc-related rocks can also be found in the Moldanubian Unit (the Lišov granulite, LI in Fig. 2; Janoušek *et al.* 2006).

The Moldanubian Unit

In contrast to the above, the Moldanubian Unit *s.s.* (Fig. 2; considered here without metamorphic complexes along its northeastern margin; Pertoldová *et al.* 2010 and references therein) is deeply eroded middle to lower crust characterized by a complex Variscan tectonometamorphic history (e.g. Vrána *et al.* 1995; Finger *et al.* 2007; Faryad *et al.* 2010; Franěk *et al.* 2011). It has been recently interpreted as representing an orogenic root (Schulmann *et al.* 2005, 2008, 2009). Except for rare Paleoproterozoic (~2.1 Ga) meta-igneous rocks (Wendt *et al.* 1993), large portions of the Moldanubian Unit have Neoproterozoic to early Paleozoic igneous and siliciclastic protoliths, the latter now represented by the LP–HT, commonly sillimanite- and cordierite-bearing and migmatitic biotite paragneisses ('the Monotonous Series'). On the other hand, other meta-sedimentary complexes contain abundant lenses of marble, amphibolite, and quartzite ('the Variegated Series'; Fuchs & Matura 1976; Kröner *et al.* 1988; Fiala *et al.* 1995; Linner 1996) and are, at least partly, Early Palaeozoic in age (Janoušek *et al.* 2008). The Moldanubian Unit also contains intercalations and relics of Neoproterozoic and Cambro–Ordovician orthogneisses (e.g. Friedl *et al.* 2004) as well as (U)HP eclogite- to granulite-facies and mantle rocks (Becker & Altherr 1992; Becker 1997; Kotková *et al.* 1997; Vrána & Frýda 2003; Nakamura *et al.* 2004; Medaris *et al.* 2005, 2006; Naemura *et al.* 2009, 2011). Together with various types of migmatites and migmatized granite gneisses, these rocks have been collectively termed 'the Gföhl assemblage' (see Petrakakis 1997; Franke 2000; Finger *et al.* 2007 and Faryad 2011 for detailed reviews and terminology) and interpreted in previous studies as parts of a single nappe ('the Gföhl nappe'; e.g. Tollmann 1982, 1995; Franke 1999, 2006). This view has been challenged in favour of vertical ʽforcefulʼ exhumation along separate channel-like domains in response to buoyancy forces and crustal shortening (Franěk *et al.* 2006, 2011; Maierová *et al.* 2012). Although exceptions do occur, the inferred ages of the granulite-facies metamorphism concentrate around 340 Ma throughout the Moldanubian Unit (van Breemen *et al.* 1982; Aftalion *et al.* 1989; Wendt *et al.* 1994; Kröner *et al.* 2000; Janoušek *et al.* 2006; Kotková 2007; Sláma *et al.* 2008b; Tajčmanová *et al.* 2010; Friedl *et al.* 2011). Latest findings, however, point to a more complex pre-340 Ma burial and exhumation history of the (U)HP rocks within the Moldanubian Unit (Prince *et al.* 2000; Faryad *et al.* 2009, 2010, 2013` Friedl *et al.* 2011).

The Moldanubian Unit hosts several plutonic suites (Figs 2 & 3). An older, rather specific one is represented by ultrapotassic melagranitoids to melasyenitoids (ʽdurbachitesʼ and related rocks) with U–Pb zircon ages ranging from ~343 to ~335 Ma (Holub 1997; Holub *et al.* 1997a; Janoušek & Gerdes 2003; Janoušek & Holub 2007; Verner *et al.* 2008; Kotková *et al.* 2010; Kusiak *et al.* 2010; Holub *et al.* 2012). The ʽdurbachitesʼ also intruded the upper-crustal rocks along the southeastern flank of the Teplá–Barrandian Unit and the high-K calc-alkaline granitoids of the Central Bohemian Plutonic Complex (Fig. 2). Recent petrogenetic interpretations suggest that the primary (ultra-)potassic magmas, to be subsequently mixed with anatectic melts, were derived from anomalous lithospheric mantle strongly enriched in Large Ion Lithophile Elements (LILE) and Light Rare Earth Elements (LREE) (Janoušek *et al.* 1995; Holub 1997; Wenzel *et al.* 1997; Becker *et al.* 1999; Janoušek *et al.* 2000; Gerdes *et al.* 2000a; von Raumer *et al.* in print). Furthermore, Janoušek & Holub (2007) and Lexa *et al.* (2011) explained the temporal and spatial link between the ultrapotassic plutons and HP granulites (Fig. 2) as a result of contamination of the local mantle by subducted/relaminated Ordovician felsic metaigneous rocks of Saxothuringian provenance, the presumed protolith to the Moldanubian granulites (Janoušek *et al.* 2004b).

The other suites of crustally-derived granitoids include coarse-grained I- to S-type K-feldspar-phyric biotite granites dated at *c.* 331–323 Ma (ʽthe Weinsberg graniteʼ; Figs 2 & 3) and peraluminous S-type two-mica granites dated at *c.* 330 to 328–327 Ma (ʽthe Eisgarn graniteʼ; Fig. 2; U–Pb zircon ages according to Gerdes *et al.* 2003). Together with intrusions of the Freistadt biotite granodiorite (Figs 2 & 3), late highly fractionated granites, and minor basic bodies these two suites compose the Moldanubian Batholith (MB in Fig. 2), the largest plutonic body in the entire Variscan belt (Liew *et al.* 1989; Vellmer & Wedepohl 1994; Holub *et al.* 1995; Klötzli & Parrish 1996; Klečka & Matějka 1996; Finger *et al.* 1997; Gerdes *et al.*

2000a, b, 2003; Gerdes 2001; Klötzli *et al.* 2001; Finger *et al.* 2009; Breiter 2010; Žák *et al.* 2011b). In the map view, the individual intrusive units of the batholith are clustered in two nearly perpendicular segments oriented ~WNW–ESE and ~NNE–SSW (Fig. 2). The former is defined by a number of separate smaller plutons that involve both 'Eisgarn' and 'Weinsberg' granites whereas the latter, hosted by a complex of cordierite-bearing migmatites and migmatized paragneisses, is chiefly made up of the 'Eisgarn granite' (Žák *et al.* 2011b).

Brunovistulian Unit

In contrast to the above units that share the Cadomian or 'West African' affinity (e.g. Drost *et al.* 2004; Linnemann *et al.* 2004; Drost *et al.* 2011), the Brunovistulian Unit (Fig. 2; 'Brunia') underlying the eastern margin of the Bohemian Massif is an exotic terrane of problematic provenance more akin to Avalonia (Friedl *et al.* 2000; Kalvoda *et al.* 2008). Its pre-Variscan evolution was thus rather different from that of the remainder of the Bohemian Massif and involved late Neoproterozoic terrane accretion followed by extensive post-collisional plutonism at around 595–585 Ma and deposition of Neoproterozoic to early Paleozoic successions onto the welded terranes (van Breemen *et al.* 1982; Dudek 1980; Finger *et al.* 1989; Jelínek & Dudek 1993; Finger & Steyrer 1995; Fritz *et al.* 1996; Schulmann & Gayer 2000; Finger *et al.* 2000a, b; Leichmann & Höck 2008).

Key observations on the nature, timing, and kinematics along major tectonic boundaries in the Bohemian Massif and their relation to granitoid plutonism

Orogen-parallel ~NE–SW-trending boundaries

The Teplá suture

The Saxothuringian/Teplá–Barrandian boundary, referred to as the Teplá suture (TS in Fig. 1), is in fact a broad zone consisting of an imbricated stack of NW-directed nappes, involving portions of both subducted oceanic lithosphere and overriding margin of the Teplá–Barrandian Unit, that were exhumed from the suture and thrust over the Saxothuringian foreland (Fig. 2; Behr *et al.* 1982; Franke 1989; Kachlík 1993; Schäfer *et al.* 1997; Mazur & Alexandrowski 2001). Relics of these nappes also extend as a series of klippen further to the west and northwest (Erbendorf–Vohenstrauss Zone, ZEV in Fig. 2, Münchberg, Frankenberg, and Wildenfels nappes). The suture formed initially by the SE-directed subduction and closure of the Saxothuringian Ocean, welding the Saxothuringian and Teplá–Barrandian units at around 380 Ma (Franke 1989; Beard *et al.* 1995; Schäfer *et al.* 1997; Zulauf 1997b). As proposed by O'Brien (2000), Janoušek *et al.* (2004b), Konopásek & Schulmann (2005), Janoušek & Holub (2007), and Lexa *et al.* (2011), the Saxothuringian subduction continued in continental underthrusting until *c.* 340 Ma and its waning stages thus broadly overlapped with the onset of normal movements and collapse of the Teplá–Barrandian Unit at around 346 Ma (Zulauf 1994; Scheuvens & Zulauf 2000; Zulauf *et al.* 2002; Žák *et al.* 2005a; Dörr & Zulauf 2010; Janoušek *et al.* 2010).

In detail, recent structural work suggests that the deformation resulting from the Saxothuringian/Teplá–Barrandian convergence was rather complex in the overriding Teplá–Barrandian plate (Fig. 4). The deformation was strongly partitioned into pure shear-dominated domains that accommodated orogen-perpendicular ~WNW–ESE shortening alternating with narrow, orogen-parallel, high-strain zones that recorded dextral transpression or lateral extrusion (Fig. 4a; Hajná *et al.* 2012). The orogen-parallel zones were localized along pre-existing lithologic boundaries or in the softened thermal aureoles of the arc plutons (Fig. 4b; Žák *et al.* 2005b; Machek *et al.* 2009; Hajná *et al.* 2012). As with the arc-related plutonism, these zones indicate younging of deformation in the overriding Teplá–Barrandian plate from ~370–380 in the northwest to *c.* 346 Ma in the southeast (Hajná *et al.* 2011; Žák *et al.* 2011a).

The Teplá–Barrandian/Moldanubian boundary

This boundary (variously referred to as 'the Central Bohemian suture', 'Central Bohemian shear zone', or 'Gföhl suture') is one of the most intriguing tectonic features of the Bohemian Massif, unique in that every possible sense of movement was invoked to explain its kinematic evolution (Tollmann 1982; Rajlich 1987, 1988; Matte *et al.* 1990; Košler *et al.* 1995; Pitra *et al.* 1999; Scheuvens & Zulauf 2000; Franke 2000; Franke & Żelażniewicz 2002; Medaris *et al.* 2005; Žák *et al.* 2005a, b, 2009a, 2012; Dörr & Zulauf 2010).

The earliest record of the Variscan Orogeny along the Teplá–Barrandian/Moldanubian boundary is preserved in the lower to middle Devonian siliciclastic successions (Chlupáč 1989) and in the late Devonian (~380–365 Ma) Mirotice and Staré Sedlo orthogneisses (Figs 2 & 3). The latter metagranitoids are sheeted, exhibit subhorizontal intrusive contacts, flat-lying solid-state foliation, and ~NE–SW subhorizontal stretching lineation, and are commonly characterized by a prolate fabric ellipsoid (Tomek 2011; Tomek & Žák 2011). A different structural pattern is observed in the earliest, *c.* 354 Ma calc-alkaline intrusions (Sázava suite) of the Central Bohemian Plutonic Complex which were syntectonic with partitioned regional dextral transpression characterized by the ~WNW–ESE arc-perpendicular shortening and arc-parallel horizontal stretching (Fig. 4b; Žák *et al.* 2005a, b, 2009a; Hajná *et al.* 2012). This transpressive deformation lasted till *c.* 346 Ma when it was replaced by ductile normal shearing along the Červená shear zone (ČSZ in Fig. 2) associated with exhumation of the high-grade core of the orogen, the Moldanubian Unit (Fig. 4c; Holub *et al.* 1997b; Žák *et al.* 2005a, 2012; Janoušek *et al.* 2010). The cessation of ductile deformation along the Teplá–Barrandian/Moldanubian boundary is bracketed by the *c.* 336 Ma post-tectonic Říčany Pluton in the northeast (ŘP in Fig. 2; Janoušek *et al.* 1997; Trubač *et al.* 2009) and by undeformed melasyenites including *c.* 338 Ma dykes (Holub *et al.* 2012) and *c.* 337 Ma Tábor Pluton (TP in Fig. 2) that intruded discordantly the Moldanubian gneisses to the southeast of the shear zone (Janoušek & Gerdes 2003; Žák *et al.* 2005a).

The Moldanubian thrust system

Along the eastern margin of the Bohemian Massif, the Moldanubian Unit has been thrust over the Brunia microplate (MT in Fig. 2; e.g. Suess 1912; Dudek 1980; Schulmann *et al.* 1991, 2005, 2008; Fritz & Neubauer 1993; Štípská & Schulmann 1995; Fritz *et al.* 1996; Racek *et al.* 2006; Finger *et al.* 2007; Kalvoda *et al.* 2008). The highly oblique, top-to-the-NNE Saxothuringian–Moldanubian/Brunia collision presumably commenced prior to 346 Ma in the northeast (Schulmann & Gayer 2000; Jastrzębski 2009; Chopin *et al.* 2012), also constrained by the syntectonic Staré Město tonalite sill (SMT in Fig. 2 and 5a; Parry *et al.* 1997, dated at 344.5 ± 1.1 Ma and 339.4 ± 1.1 Ma by Štípská *et al.* 2004). The Brunia underthrusting resulted in a ~NNE–SSW-trending belt of imbricated nappe stacks along the whole eastern margin of the Bohemian Massif (the Moravosilesian Unit; Fig. 2). Geophysical data indicate that the Brunia microplate, exposed in tectonic windows of the Moravian nappes, continues ~70 km westward beneath the Moldanubian rocks (Mísař 1994; Schulmann *et al.* 2008; Guy *et al.* 2011; Verner *et al.* in print). The inferred westernmost front edge of the Brunia microplate at depth coincides with the Přibyslav mylonite zone at the present-day erosional level (PMZ in Fig. 2). This zone was recognized as an important, crustal-scale geophysical and tectonic boundary that cuts across the entire Moldanubian Unit along the ~NNE–SSW direction and was associated with oblique-slip (dextral, W-side-up) movements initiated at around 335 Ma (Fig. 5b; Verner *et al.* 2006; Kotková *et al.* 2010) and renewed at ~330–327 Ma (Fig. 5c; Žák *et al.* 2011b; Verner *et al.* in print).

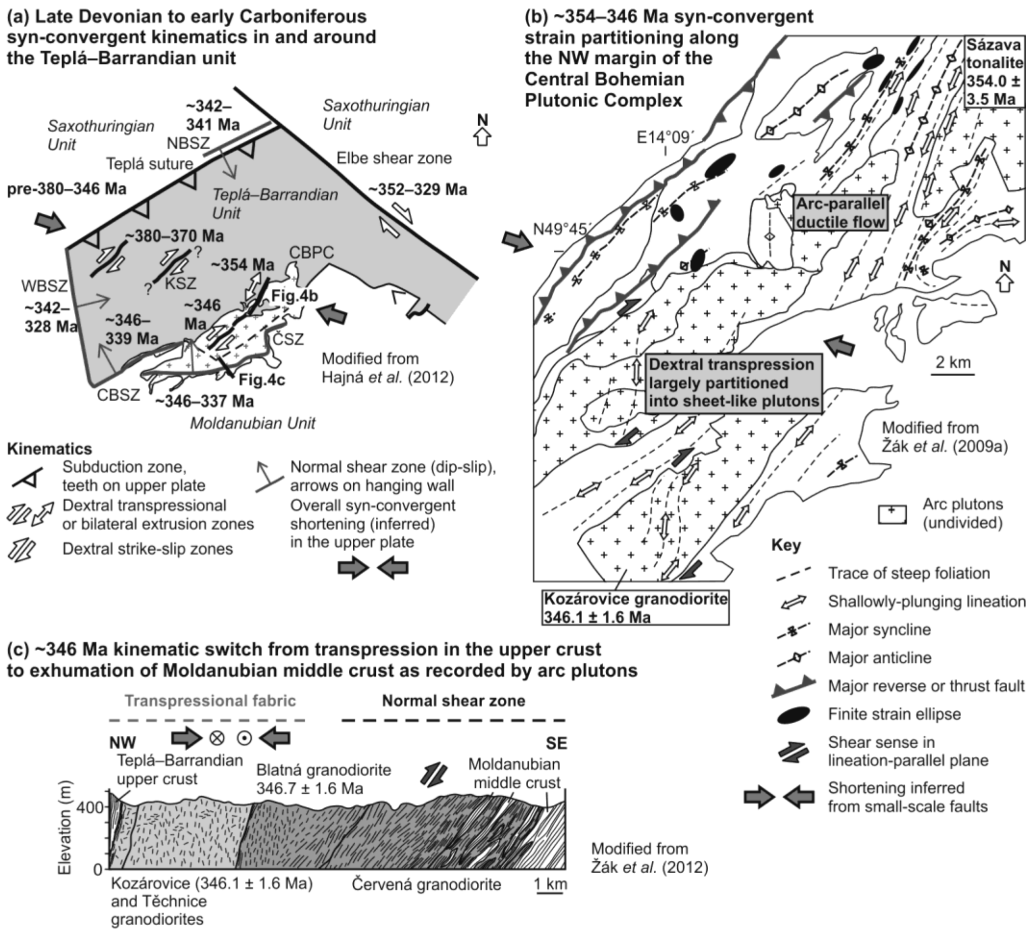


Fig. 4. Structural sketches summarizing deformation, kinematics, and plutonism during prolonged Late Devonian to early Carboniferous convergence of the Saxothuringian and Teplá–Barrandian units. **(a)** Map of major shear zones inside and around the Teplá–Barrandian Unit showing overall ~WNW–ESE shortening in the upper crust replaced by normal movements and onset of exhumation of the Moldanubian Unit from *c.* 346 Ma onwards. See Hajná *et al.* (2012) for details. CBPC, Central Bohemian Plutonic Complex; CBSZ, Central Bohemian shear zone; ČSZ, Červená shear zone; KSZ, Krakovec shear zone; NBSZ, North Bohemian shear zone; WBSZ, West Bohemian shear zone. **(b)** Close-up of the northwestern margin of the Central Bohemian Plutonic Complex. The background ~WNW–ESE shortening was partitioned into arc-parallel ductile flow or dextral transpression depending on the orientation of syn-tectonic plutons. See Žák *et al.* (2009a) for details. **(c)** A kinematic switch from transpression to ductile normal shearing is recorded in the ~346 Ma Blatná and Červená granodiorites of the Central Bohemian Plutonic Complex. This change marks on the onset of exhumation of the southeasterly high-grade Moldanubian Unit. See Žák *et al.* (2005a, 2012) and Janoušek *et al.* (2010) for details.

Orogen-perpendicular ~NW–SE-trending boundaries

The Sudetic fault system

The northeasternmost margin of the Bohemian Massif (‘the Sudetes’) is cut by a series of major faults (Fig. 2; Lusatian, Machnín, Intra-Sudetic, Marginal-Sudetic; e.g. Aleksandrowski *et al.* 1997; Danišík *et al.* 2012), referred to as the Sudetic fault system here. The fault-bounded blocks host several granitoid plutons (Fig. 2; e.g. Strzegom–Sobótka, Strzelin, Kłodzko–Złoty Stok, Žulová; see Mazur *et al.* 2007, Mikulski *et al.* 2013, and Oberc-Dziedzic *et al.* 2013 for reviews) that are largely concealed and their internal fabrics and structural relations are yet to be examined in detail. The exception is the shallow-level Krkonoše–Jizera Plutonic Complex (KJPC in Fig. 2; e.g. Klomínský 1969; Mierzejewski 2002; Słaby & Martin 2008; Žák *et al.* 2009b), a classic area of granite geology that has become world-famous through the pioneering work of Cloos (1925). Existing radiometric ages of granites in this plutonic complex scatter widely from 329 ± 17 Ma (Rb–Sr; Pin *et al.* 1987) to 304 ± 14 Ma (U–Pb; Kröner *et al.* 2001; see Awdankiewicz *et al.* 2010 for review), however, recent U–Pb zircon ages point to a more restricted time span from 322 ± 3 Ma (porphyritic biotite granite; Kryza *et al.* 2012) to 313 ± 3 Ma (dykes cutting the granite; Awdankiewicz *et al.* 2010). The plutonic complex intruded into already cold crust and postdated both the blueschist (>360 Ma) and greenschist (*c.* 340 Ma) facies tectonometamorphic events in its host rocks (Maluski & Patočka 1997; Marheine *et al.* 2002; Mazur *et al.* 2006). The granite generation and emplacement was thus presumably controlled by extensional unroofing and dextral displacement along the Sudetic fault system (Fig. 6; Aleksandrowski *et al.* 1997; Žák *et al.* in print). The early ductile shearing commenced at around 337–335 Ma and was also associated with the opening of a mid-Viséan molasse basin (Turnau *et al.* 2002). Magnetic fabric analysis by Diot *et al.* (1995) and Žák *et al.* (in print) indicates that the plutonic complex recorded ~WNW–ESE horizontal stretching and was also syn-tectonic with dextral movements along the Intra-Sudetic Fault (Fig. 6).

The Elbe shear zone

The more southerly Elbe shear zone (ESZ in Fig. 2), which runs across the northern portion of the Bohemian Massif, is a broad zone of dextral shearing with prolonged kinematic history and causing significant dextral offset of the amalgamated Saxothuringian/Teplá–Barrandian units. The earliest ductile movements were recorded within a ~50–100 km wide belt of the mid- to upper-crustal rocks between the south-westerly Moldanubian and north-easterly Saxothuringian units (Fig. 2). The dominant ductile deformation is characterized here by the ~NW–SE metamorphic foliation, subhorizontal ~NW–SE stretching lineation, and dextral strike-slip kinematics (Fig. 7; Synek & Oliveriová 1993; Kachlík 1999; Scheck *et al.* 2002; Verner *et al.* 2009a; Vondrovic *et al.* 2011). The broad Elbe shear zone hosts several syn-tectonic calc-alkaline, granodiorite-dominated intrusions emplaced at various stages of deformation. These include the Nasavrky Plutonic Complex (NPC in Fig. 2; Hrouda *et al.* 1999), Budislav and Miřetín plutons (BP and MP in Fig. 2; Verner et al. 2009; Verner &

Vondrovic 2010; Vondrovic *et al.* 2011). The latter two intrusions were dated at 350 ± 5 Ma (Vondrovic & Verner 2010) and 346 ± 5 Ma (Vondrovic *et al.* 2011), respectively, and are comparable to the arc-related granitoids of the Central Bohemian Plutonic Complex (Vondrovic *et al.* 2011). The Budislav Pluton was coeval with ductile dextral shearing along the Elbe shear zone whereas the Miřetín Pluton records ~WNW–ESE transpression that post-dates the dextral movements (Fig. 7; Pertoldová *et al.* 2010; Vondrovic *et al.* 2011; *cf.* Pitra *et al.* 1994; Pitra 2012). Subsequently, the Elbe shear zone was multiply reactivated in the brittle–ductile and brittle regime during the early Carboniferous times (e.g. Wenzel *et al.* 1997; Hofmann *et al.* 2009; Verner *et al.* 2009a).

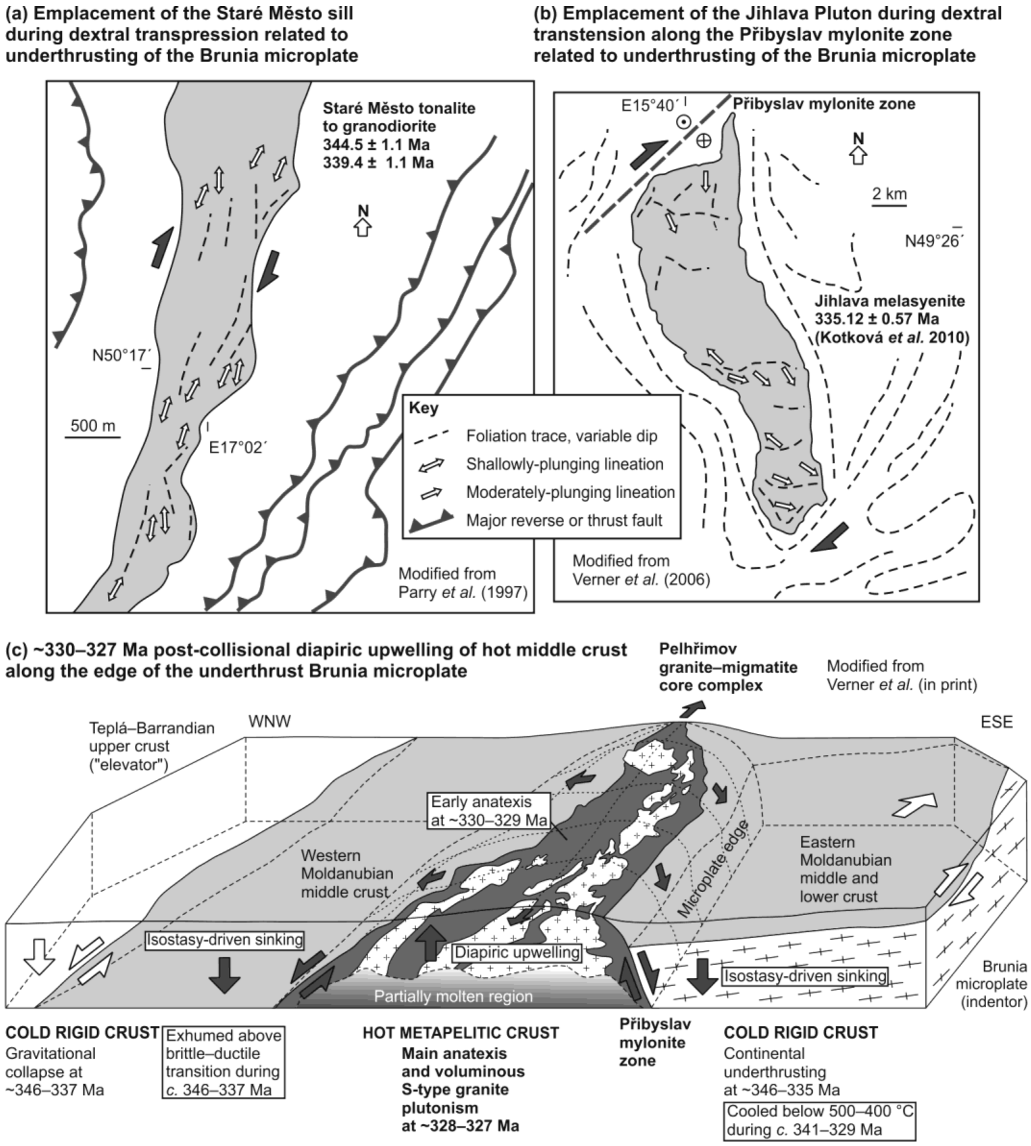


Fig. 5. Examples of syn-tectonic plutons emplaced during and after underthrusting of the Brunia microplate along the eastern margin of the Bohemian Massif. **(a)** The Staré Město sill records syn-magmatic dextral transpression resulting from early stages of the continental underthrusting in the northeast. See Parry *et al.*

(1997) for details. **(b)** Sigmoidal-shaped Jihlava melasyenite was emplaced later (*c.* 335 Ma) during the same process as the Brunia microplate proceeded farther to the south-southwest. See Verner *et al.* (2006) for details. **(c)** Subsequently, the microplate edge acted as a rigid backstop that localized large-scale diapiric upwelling of a granite–migmatite dome, referred to as the Pelhřimov Complex, at around 330–327 Ma. See Žák *et al.* (2011b) and Verner *et al.* (in print) for details.

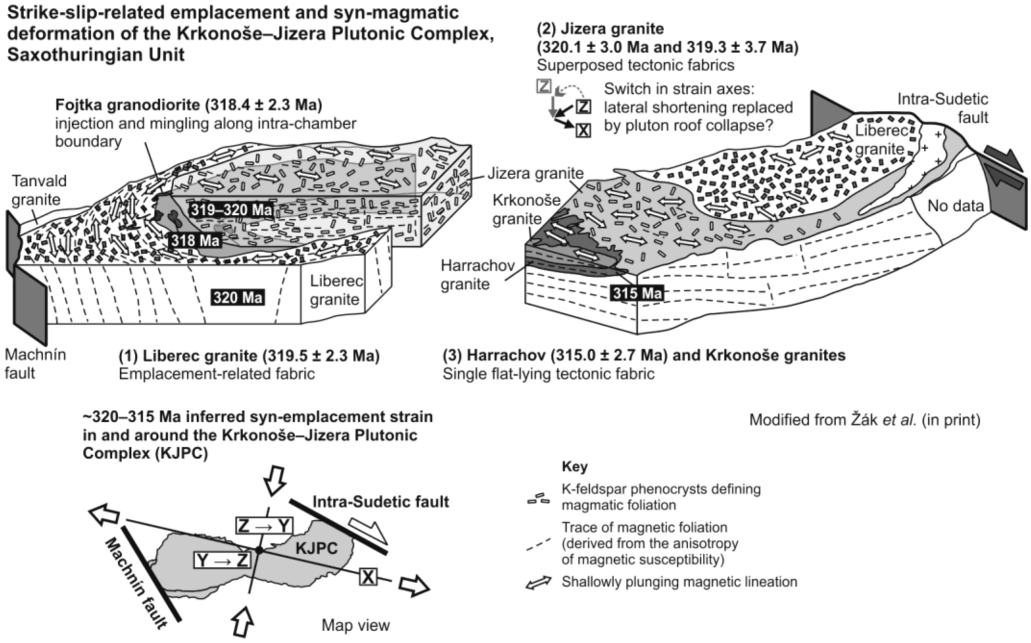


Fig. 6**.** Schematic block-diagram showing the inferred inward- and upward- younging emplacement sequence and fabric evolution recorded in the *c.* 320–315 Ma Krkonoše–Jizera Plutonic Complex. Magmatic fabrics evolve from outer margin-parallel to those recording strain related to strike-slip movements along the major pluton-bounding faults. See Žák *et al.* (in print) for details.

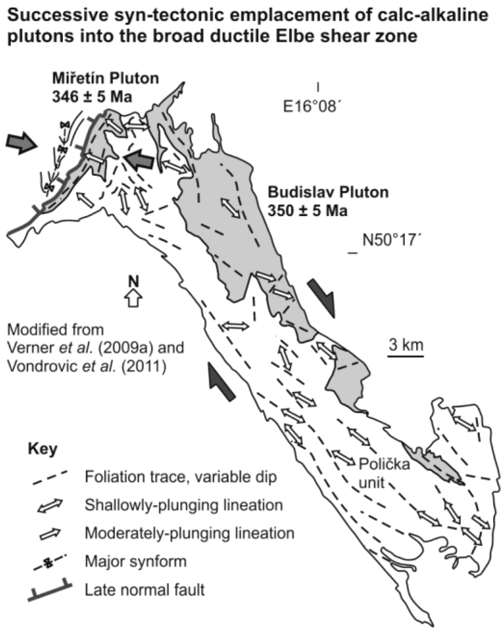


Fig. 7. Fabric patterns of syn-tectonic calc-alkaline plutons emplaced during early stages of ductile movements along the Elbe shear zone at around 350–345 Ma. See Verner *et al.* (2009a) and Vondrovic *et al.* (2011) for details.

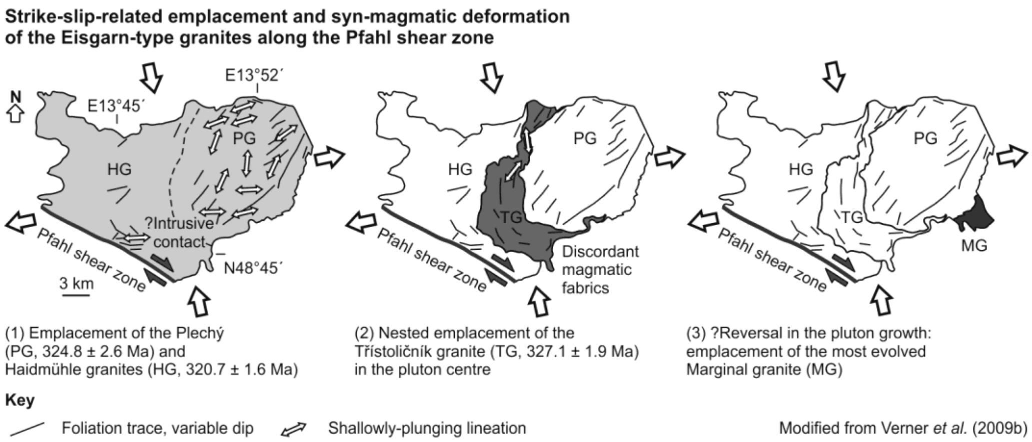


Fig. 8. Magmatic fabric pattern and syn-tectonic emplacement of the 'Eisgarn-type' granites along the dextral Pfahl shear zone as exemplified by the Plechý Pluton. See Verner *et al.* (2009b) for details.

The Pfahl shear zone

The Pfahl shear zone (PSZ in Fig. 2) extends for more than 150 km along strike and together with the sub-parallel south-westerly Danube shear zone (DSZ in Fig. 2) is a major tectonic feature of the southwestern Bohemian Massif (e.g. Peucker-Ehrenbrink & Behr 1993; Brandmayr *et al.* 1995; Büttner & Kruhl 1997; Büttner 2007). The existing U–Pb and Pb–Pb ages and structural relations of granitoid rocks associated with the shear zone indicate the initial stages of dextral shearing at ~342–327 Ma and mylonitic deformation coeval with granite emplacement from ~331–321 Ma (Fig. 8; Chen & Siebel 2004; Siebel *et al.* 2005, 2006b; Verner *et al.* 2009b). Slip along the Pfahl shear zone continued after emplacement of the ~322–323 Ma Patersdorf granite which is truncated by the shear zone (Siebel *et al.* 2006b). Conflicting views exist on whether the shear zone separates two different basement terranes or just intersects the otherwise continuous southwestern Moldanubian Unit (Finger *et al.* 2007, 2010; Siebel *et al.* 2008, 2009; Finger *et al.* 2010; Finger & René, 2009).

A tentative model linking the Variscan orogenic deformation with plutonism in the Bohemian Massif

The Variscan Orogeny in the Bohemian Massif was accompanied by episodic granitoid plutonism with several peaks of the plutonic activity that are now well constrained by geochronologic data. As opposed to an outdated view of granites in the Bohemian Massif as post-tectonic (e.g. Franke 2000, 2006), it has been shown that most of the plutons are in fact syn-tectonic and play a key role in constraining the timing, regime, and kinematics of Variscan orogenic deformations (Figs 4–8; e.g. Diot *et al.* 1995; Büttner & Kruhl 1997; Parry *et al.* 1997; Scheuvens & Zulauf 2000; Venera *et al.* 2000; Žák *et al.* 2005a, b, 2009a, 2011a, b; Verner *et al.* 2006, 2008, 2009a, b; Vondrovic *et al.* 2011; Hajná *et al.* 2012; this study).

The earliest Variscan orogenic deformation in the interior of the Bohemian Massif is recorded by a dramatic change in sedimentation from carbonates to Givetian siliciclastic flysch successions (~388–383 Ma; e.g. Chlupáč 1989; Chlupáč *et al.* 1998; Strnad & Mihaljevič 2005 and references therein). This event may be linked to the onset of the SE-directed frontal subduction of the Saxothuringian Ocean (Fig. 9a) leading to exhumation of (U)HP rocks, uplift and cooling along the western margin of the Teplá–Barrandian Unit (~387–365 Ma; Kachlík 1993; Kotková *et al.* 1995; Zulauf 1997a; Dallmeyer & Urban 1998; Strnad & Mihaljevič 2005; Konopásek & Schulmann 2005; Hajná *et al.* 2012). At approximately the same time, the opposite, southeastern flank of the Teplá–Barrandian Unit was intruded by the ~380–365 Ma protolith to Mirotice and Staré Sedlo orthogneisses (Fig. 9a; Košler *et al.* 1993), interpreted as a sill complex emplaced during previously unrecognized but still enigmatic transtensional event (Tomek 2011). All in all, the Late Devonian oceanic subduction resulted in suturing the Saxothuringian and Teplá–Barrandian units at *c.* 380 Ma (Schäfer *et al.* 1997; Zulauf 1997a) and presumably continued in underthrusting of the Saxothuringian passive margin until the high-grade metamorphism at *c.* 340 Ma (O’Brien 2000; Konopásek & Schulmann 2005; Schulmann *et al.* 2009).

In one view, the Saxothuringian oceanic subduction produced the minor ~373–375 Ma Štěnovice and Čistá granodiorite plutons in the central Teplá–Barrandian Unit (Fig. 9a; Žák *et al.* 2011a) and culminated in the development of a large magmatic arc along its southeastern flank at around 354–346 Ma (Figs 3, 4, 9a; Konopásek & Schulmann 2005; Žák *et al.*, 2005a, 2009a, 2011a, 2012; Janoušek & Holub 2007; Schulmann *et al.* 2009). The associated, southeast-migrating transpressional deformation (from the Teplá suture towards the orogen’s interior) is well recorded in the arc granitoids and is characterized by orogen-perpendicular WNW–ESE to NW–SE shortening and orogen-parallel stretching (Figs 4a, 4b, 9a; Zulauf 1997a; Žák *et al.* 2009a; Hajná *et al.* 2012). In alternative hypotheses, the Staré Sedlo and Mirotice orthogneisses and the Central Bohemian Plutonic Complex are linked to opposite, westward subduction of either Gföhl or Raabs ocean (Franke 1999, 2006; Kachlík 1999; Finger *et al.* 2007; Babuška & Plomerová 2013).

The convergent stage was terminated by a rapid gravity-driven collapse of the thickened Teplá–Barrandian upper crust (Fig. 9b). The main phase of ductile normal shearing lasted from *c.* 346 to *c.* 337 Ma (Fig. 4c; Scheuvens & Zulauf 2000; Žák *et al.* 2005a; Dörr & Zulauf 2010; Janoušek *et al.* 2010; Franěk *et al.* 2011; Holub *et al.* 2012; Žák *et al.* 2012) and was associated with exhumation of the adjacent high-grade core of the orogen, the Moldanubian Unit, including the granulite-facies rocks (Franěk *et al.* 2006, 2011), and with emplacement of (ultra-)potassic ʽdurbachite’ plutons (Fig. 9a; Wenzel *et al.* 1997; Janoušek & Holub 2007; Verner *et al.* 2008).

It is interesting to note that the upper crustal collapse broadly overlapped with the inferred timing of the earliest ductile movements along the orogen-perpendicular ~NW–SE-trending dextral strike-slip shear zones. The northeastern portion of the amalgamated Saxothuringian/Teplá–Barrandian/Moldanubian block has been truncated and dextrally displaced along the Sudetic and Elbe fault zones that parallel the southeastern margin of Baltica (Franke & Żelażniewicz 2002), with movements starting from ~355–346 Ma (Fig. 7; Verner et al. 2009a) and lasting till at least ~315 Ma (Wenzel *et al.* 1997; Hofmann *et al.* 2009; Pertoldová *et al.* 2010; Vondrovic *et al.* 2011). In turn, this suggests that the orogenic processes governed by the prolonged frontal Saxothuringian subduction/underthrusting, including the internal deformation of the Teplá–Barrandian overriding plate, were abruptly replaced by gravity-driven collapse (Figs 4c & 9b; e.g. Zulauf 1994; Zulauf *et al.* 2002; Dörr & Zulauf 2010; Franěk *et al.* 2011; Žák *et al.* 2012) and by dextral strike-slip movements (Fig. 9c), which could have been caused by the overall westward motion of Gondwana with respect to Laurussia since *c.* 345 Ma (e.g. Martínez Catalán 2011 and references therein).

Subsequently, while most of the orogenic ductile deformation and exhumation was completed in the central Bohemian Massif in the vicinity of the Teplá–Barrandian Unit by ~339–337 Ma (Žák *et al.* 2012), the eastern part of the Moldanubian Unit was still involved in an underthrusting/collision with the Brunia microplate, closing oceanic domains correlative with the Rhenohercynian Ocean as witnessed by several fragments of oceanic crust (Höck *et al.* 1997; Soejono *et al.* 2010). Brunia continental underthrusting lead to extrusion of the Moldanubian rocks over the top of Brunia, nappe emplacement at ~341–339 Ma (Štípská & Schulmann 1995), and propagation of the microplate edge as far west as the Přibyslav mylonite zone (Fig. 9b). Our structural data around the Jihlava Pluton suggest that this process overlapped with, and was followed by, dextral, W-side-up shearing along the Přibyslav mylonite zone at ~338–335 Ma (Figs 5b & 3b; Verner *et al.* 2006) and most likely terminated prior to *c.* 330 Ma when the Moldanubian rocks were unroofed and exposed to erosion (Štípská & Schulmann 1995; Scharbert *et al.* 1997; Vrána & Novák 2000; Hartley & Otava 2001; Kotková *et al.* 2007). Later on, Brunia acted as a ʽpassive’ rigid backstop localizing extensive migmatization and rapid exhumation of the Moldanubian metasedimentary rocks along its edge to produce vast volumes of S-type granitoids at ~330–327 Ma (Figs 5c & 9c; the Pelhřimov Complex; Bell *et al.* 2011; Žák *et al.* 2011b; Verner *et al.* in print).

The waning stages of the Variscan Orogeny were characterized by tectonothermal activity in the periphery around the ʽstable' core of the Bohemian Massif (Fig. 9c) and included emplacement of huge volumes of the northerly and westerly granitoids in the Saxothuringian Zone and Northern Oberpfalz (e.g. Hecht *et al.* 1997; Siebel *et al.* 1997; Förster *et al.* 1999; Förster & Romer 2010; Breiter *et al.* 2012) and ~334–321 Ma LP–HT metamorphism, crustal anatexis, and associated plutonism in the southwestern Moldanubian Unit (Fig. 9c; e.g. Kalt *et al.* 1999, 2000; Klein *et al.* 2008; Tropper *et al.* 2006; Finger *et al.* 2009). These late-stage events affected already exhumed crust at shallow levels and were linked to continuing movements along the ~NW–SE strike-slip faults (e.g. the Krkonoše–Jizera Plutonic Complex, Aleksandrowski *et al.* 1997; Plechý Pluton, Verner *et al.* 2009b; Figs 6 & 8) or reflected high heat flux caused by mantle delamination as proposed by Henk *et al.* (2000) and Finger *et al.* (2009). Alternatively, Verner *et al.* (in print) proposed that at least some of these granites, commonly in association with migmatites, may represent large-scale diapir-type instabilities accommodating vertical isostatic re-equilibration of the orogen after the microplate convergence. Later destruction of the orogenic belt, post-orogenic igneous activity, intracontinental basin development, and multiple reactivations along the inherited basement fault zones are another part of the story and are not dealt with in detail here.

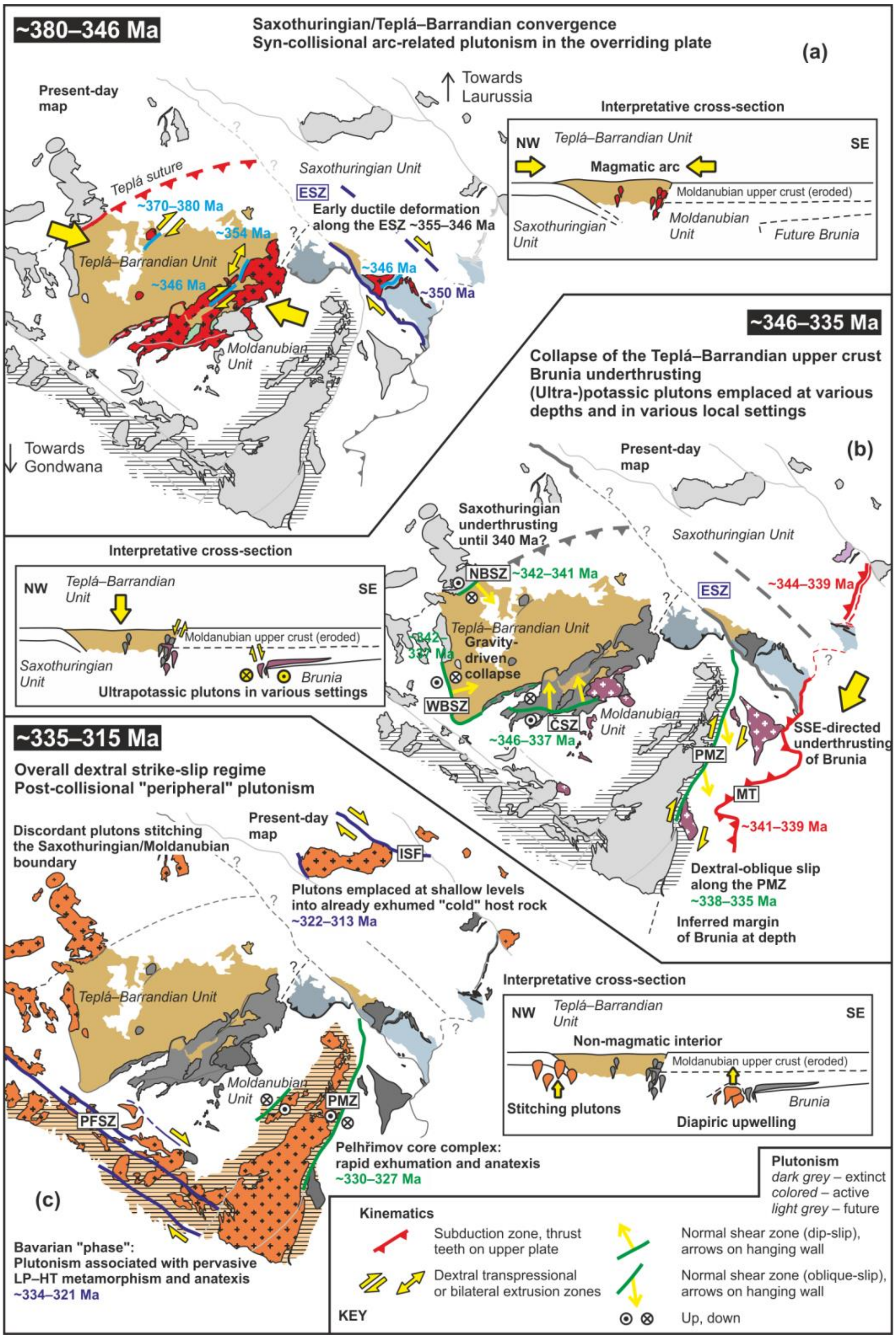


Fig. 9. Greatly idealized sketch emphasizing spatial, temporal, and compositional pattern of Variscan plutonism in the Bohemian Massif. The plutonism is also linked to kinematics and timing of movement along principal tectonic boundaries as inferred from geochronologic and structural data. See text for details and references. Note that the scheme portrays kinematics on the present-day geological background; the exact amount of shortening and of displacement along each shear zone or fault is difficult to reconstruct during relevant time intervals. Also note that Variscan deformations were typically three-dimensional and complex along each boundary. Shear zones and faults: CBSZ, Central Bohemian shear zone; ČSZ, Červená shear zone; ESZ, Elbe shear zone; ISF, Intra-Sudetic Fault; MT, Moldanubian thrust; NBSZ, North Bohemian shear zone; PFSZ, Pfahl shear zone; PMZ, Přibyslav mylonite zone; WBSZ, West Bohemian shear zone.

Concluding remarks and open questions

The above overview is, of course, far from being conclusive and complete. However, it at least clearly demonstrates how the orogenic processes and related deformation and plutonism evolved in space and time. As a consequence of overall convergence of Gondwana and Laurussia, four main episodes can be recognized in the interior Bohemian Massif:

(1) Microplate attachment by prolonged, nearly frontal oceanic subduction and continental underthrusting of the Saxothuringian Unit beneath the Teplá–Barrandian Unit resulted in the orogen-perpendicular shortening and orogen-parallel extension in the overriding plate (Fig. 9a). The plate convergence was crowned by the emplacement of huge volumes of calc-alkaline, magmatic-arc granitoids at ~354–346 Ma (the Central Bohemian Plutonic Complex).

(2) The subduction-driven shortening was replaced by dextral strike-slip along the orogen-perpendicular shear zones as the convergence of intervening microplates became increasingly overridden by overall westward motion of Gondwana and Laurussia during the early Carboniferous times. This was broadly contemporaneous with collapse of the Teplá–Barrandian upper crust, (ultra-)potassic plutonism, and exhumation of the high-grade (Moldanubian) core of the orogen at ~346–337 Ma (Fig. 9b).

(3) Following the subduction and closure of the easterly Rhenohercynian Ocean basins, an Avalonian-type Brunia microplate was underthrust to the south-southwest beneath the eastern flank of the Saxothuringian/Teplá–Barrandian/Moldanubian ‘assemblage’ (~346–335 Ma). This was a dominant process that shaped the eastern margin of the Bohemian Massif and its waning stages were also accompanied by emplacement of the (ultra-)potassic plutons (Fig. 9b).

(4) Late readjustments within the amalgamated Bohemian Massif included rapid exhumation and voluminous ~327–330 Ma S-type-dominated granite plutonism, tectonothermal activity at the periphery around the consolidated orogen’s core (Fig. 9c), followed by destruction of the orogenic belt, post-orogenic igneous activity, continental basin development, and multiple reactivations along the inherited basement fault zones.

Finally, we close our overview by pointing out some of the open issues that we find most controversial or least understood and that could be potential goals for future research, namely: (1) the existence of the ‘Gföhl suture’ between the Teplá–Barrandian and Moldanubian units, i.e. whether they represent once separate microplates surrounded by oceanic lithosphere or are just variously reworked segments of a single microplate; (2) the role of easterly, west-directed subduction zones in generating arc-magmatism in the central Bohemian Massif; (3) amounts of both vertical and horizontal displacements and crustal shortening within the orogen during any of the above four episodes; (4) exact age(s) of the (U)HP metamorphic peak in eclogite–granulite-facies rocks, mechanisms and timing of their exhumation; (5) sense, timing, and amounts of relative microplate rotations in course of the Variscan Orogeny; (6) the evolution of Variscan palaeotopography and possible orogenic plateaux in space and time; (7) the role of mantle delamination in driving granitoid plutonism and related tectonothermal activity, and (8) the nature of forces leading to destruction of the orogenic belt.

We gratefully acknowledge two anonymous reviewers for their constructive comments to the original manuscript and Karel Schulmann for careful editorial handling. Our research into granites was supported from the Grant Agency of the Czech Republic through grants No. P210/11/1168 (to Jiří Žák) and 205/09/0630 (to František Holub) as well as from the Ministry of Education, Youth and Sports of the Czech Republic (Grant No. LK11202, Research Plans No. MSM0021620855 and SVV261203), and Charles University in Prague Research Program PRVOUK P44. This study incorporates parts of Ph.D. research by Jakub Trubač, Lukáš Vondrovic, and Filip Tomek.

References

Aftalion, M., Bowes, D. R. & Vrána, S. 1989. Early Carboniferous U–Pb zircon age of garnetiferous, perpotassic granulites, Blanský les massif, Czechoslovakia. *Neues Jahrbuch für Mineralogie, Monatshefte*, **4**, 145–152.

Aleksandrowski, P., Kryza, R., Mazur, S. & Źaba, J. 1997. Kinematic data on major Variscan strike-slip faults and shear zones in the Polish Sudetes, northeast Bohemian Massif. *Geological Magazine*, **134**, 727–739.

Asch, K. 2003. The 1:5 million international geological map of Europe and adjacent areas: development and implementation of a GIS-enabled concept. *Geologisches Jahrbuch, Sonderhefte*, **A3.** E. Schweizerbart Publishers, Stuttgart

Awdankiewicz, M., Awdankiewicz, H., Kryza, R. & Rodionov, N. 2010. SHRIMP zircon study of a micromonzodiorite dyke in the Karkonosze Granite, Sudetes (SW Poland): age constraints for late Variscan magmatism in Central Europe. *Geological Magazine*, **147**, 77–85.

Babuška, V. & Plomerová, J. 1992. The lithosphere in central Europe – seismological and petrological aspects. Tectonophysics, **207**, 141–163.

Babuška, V. & Plomerová, J. 2001. Subcrustal lithosphere around the Saxothuringian–Moldanubian Suture Zone – a model derived from anisotropy of seismic wave velocities. *Tectonophysics*, **332**, 185–199.

Babuška, V. & Plomerová, J. 2013. Boundaries of mantle-lithosphere domains in the Bohemian Massif as extinct exhumation channels for high-pressure rocks. *Gondwana Research*, **23**, 973–987.

Babuška, V., Plomerová, J. & Vecsey, L. 2008. Mantle fabric of western Bohemian Massif (central Europe) constrained by 3D seismic P and S anisotropy. *Tectonophysics*, **462**, 149–163.

Babuška, V., Fiala, J. & Plomerová, J. 2010. Bottom to top lithosphere structure and evolution of western Eger Rift (Central Europe). *International Journal of Earth Sciences*, **99**, 891–907.

Ballévre, M., Bosse, V., Ducassou, C. & Pitra, P. 2009. Palaeozoic history of the Armorican Massif: models for the tectonic evolution of the suture zones. *Comptes Rendus Geoscience*, **341**, 174–201.

Beard, B. L., Medaris, L. G., Johnson, C. M., Jelínek, E., Tonika, J. & Riciputi, L. R. 1995. Geochronology and geochemistry of eclogites from the Mariánské Lázně Complex, Czech Republic: implications for Variscan orogenesis. *Geologische Rundschau*, **84**, 552–567.

Becker, H. 1997. Petrological constraints on the cooling history of high-temperature garnet peridotite massifs in lower

Austria. *Contributions to Mineralogy and Petrology*, **128**, 272–286.

Becker, H. & Altherr, R. 1992. Evidence from ultra-high-pressure marbles for recycling of sediments into the mantle. *Nature*, **358**, 745–748.

Becker, H., Wenzel, T. & Volker, F. 1999. Geochemistry of glimmerite veins in peridotites from Lower Austria – implications for the origin of K-rich magmas in collision zones. *Journal of Petrology*, **40**, 315–338.

Behr, H. J., Engel, W. & Franke, W. 1982. Variscan wildflysch and nappe tectonics in the Saxothuringian Zone (Northeast Bavaria, West Germany). *American Journal of Science*, **282**, 1438–1470.

Bell, B., Johnson, K., Žák, J., Verner, K. & Schwartz, J. J. 2011. Migmatization and melt generation in the Monotonous Unit, Moldanubian Batholith, Czech Republic: implications of zircon Pb/U (SHRIMP-RG) ages and Hf isotope compositions. *Geological Society of America Abstracts with Programs*, **43**, 66.

Bowes, D. R. & Aftalion, M. 1991. U–Pb zircon isotopic evidence for early Ordovician and late Proterozoic units in the Mariánské Lázně Complex, Central European Hercynides. *Neues Jahrbuch für Mineralogie, Monatshefte*, **7**, 315–326.

Brandmayr, M., Dallmeyer, R. D., Handler, R. & Wallbrecher, E. 1995. Conjugate shear zones in the Southern Bohemian Massif (Austria): implications for Variscan and Alpine tectonothermal activity. *Tectonophysics*, **248**, 97–116.

Breiter, K. 2010. Geochemical classification of Variscan granitoids in the Moldanubicum (Czech Republic, Austria). *Abhandlungen der Geologischen Bundesanstalt*, **65**, 19–25.

Breiter, K. 2012. Nearly contemporaneous evolution of the A- and S-type fractionated granites in the Krušné hory/Erzgebirge Mts., Central Europe. *Lithos*, **151**, 105–121.

Bues, C., Dörr, W., Fiala, J., Vejnar, Z. & Zulauf, G. 2002. Emplacement depths and radiometric ages of Paleozoic plutons of the Neukirchen–Kdyně Massif: differential uplift and exhumation of Cadomian basement due to Carboniferous orogenic collapse (Bohemian Massif). *Tectonophysics*, **352**, 225–243.

Buschmann, B., Elicki, O. & Jonas, P. 2006. The Cadomian unconformity in the Saxo-Thuringian Zone, Germany: palaeogeographic affinities of Ediacaran (terminal Neoproterozoic) and Cambrian strata. *Precambrian Research*, **147**, 387–403.

Büttner, S. H. 2007. Late Variscan stress-field rotation initiating escape tectonics in the south-western Bohemian Massif: a far field response to late-orogenic extension. *Journal of Geosciences*, **52**, 29–43.

Büttner, S. H. & Kruhl, J. H. 1997. The evolution of a late-Variscan high-T/low-P region: the southeastern margin of the Bohemian Massif. *Geologische Rundschau*, **86**, 21–38.

Cháb, J., Stráník, Z. & Eliáš, M. 2007. Geological map of the Czech Republic 1:500,000. Czech Geological Survey, Prague.

Cháb, J. & Vrána, S. 1979. Crossite–actinolite amphiboles of the Krkonoše–Jizera Crystalline Complex and their geological significance. *Bulletin of the Central Geological Survey*, **56**, 143–150.

Chen, F. K. & Siebel, W. 2004. Zircon and titanite geochronology of the Fürstenstein granite massif, Bavarian Forest, NW Bohemian Massif: pulses of the late Variscan magmatic activity. *European Journal of Mineralogy*, **16**, 777–788.

Chen, F., Siebel, W. & Satir, M. 2003. Geochemical and isotopic composition and inherited zircon ages as evidence for lower crustal origin of two Variscan S-type granites in the NW Bohemian Massif. *International Journal of Earth Sciences*, **92**, 173–184.

Chlupáč, I. 1989. Stratigraphy of the Sedlčany–Krásná Hora metamorphic 'Islet' in Bohemia (Proterozoic? to Devonian). *Journal for Mineralogy and Geology*, **34**, 1–16.

Chlupáč, I., Havlíček, V., Kříž, J., Kukal, Z. & Štorch, P. 1998. *Paleozoic of the Barrandian (Cambrian to Devonian)*. Czech Geological Survey, Prague.

Chopin, F., Schulmann, K., Skrzypek, E., Lehmann, J., Dujardin, J. R., Martelat, J. E., Lexa, O., Corsini, M., Edel, J. B., Štípská, P. & Pitra, P. 2012. Crustal influx, indentation, ductile thinning and gravity redistribution in a continental wedge: building a Moldanubian mantled gneiss dome with underthrust Saxothuringian material (European Variscan belt). *Tectonics*, **31**, doi:10.1029/2011TC002951

Cloos, H. 1925. *Einführung in die tektonische Behandlung magmatischer Erscheinungen (Granittektonik). 1. Das Riesengebirge in Schlesien*. Gebrüder Bornträger, Berlin.

Cymerman, Z., Piasecki, M. A. J. & Seston, R. 1997. Terranes and terrane boundaries in the Sudetes, northeast Bohemian Massif. *Geological Magazine*, **134**, 717–725.

Dallmeyer, R. D. & Urban, M. 1998. Variscan vs Cadomian tectonothermal activity in northwestern sectors of the Teplá–Barrandian Zone, Czech Republic: constraints from $^{40}Ar/^{39}Ar$ ages. *Geologische Rundschau*, **87**, 94–106.

Danišík, M., Štěpančíková, P. & Evans, N. J. 2012. Constraining long-term denudation and faulting history in intraplate regions by multisystem thermochronology: an example of the Sudetic Marginal Fault (Bohemian Massif, central Europe). *Tectonics*, **31**, doi:10.1029/2011TC003012

Diot, H., Mazur, S. & Pin, C. 1995. Karkonosze Batholith (NE Bohemian Massif): the evidence for pluton emplacement during transtensional–extensional collapse. *Journal of the Czech Geological Society*, **43**, 62.

Dörr, W. & Zulauf, G. 2010. Elevator tectonics and orogenic collapse of a Tibetan-style plateau in the European Variscides: the role of the Bohemian shear zone. *International Journal of Earth Sciences*, **99**, 299–325.

Dörr, W., Fiala, J., Vejnar, Z. & Zulauf, G. 1998. U–Pb zircon ages and structural development of metagranitoids of the Teplá Crystalline Complex: evidence for pervasive Cambrian plutonism within the Bohemian Massif (Czech Republic). *Geologische Rundschau*, **87**, 135–149.

Dörr, W., Zulauf, G., Fiala, J., Franke, W. & Vejnar, Z. 2002. Neoproterozoic to Early Cambrian history of an active plate margin in the Teplá–Barrandian Unit: a correlation of U–Pb isotopic-dilution-TIMS ages (Bohemia, Czech Republic). *Tectonophysics*, **352**, 65–85.

Drost, K., Linnemann, U., McNaughton, N., Fatka, O., Kraft, P., Gehmlich, M., Tonk, C. & Marek, J. 2004. New data on the

Neoproterozoic–Cambrian geotectonic setting of the Teplá–Barrandian volcano-sedimentary successions: geochemistry, U–Pb zircon ages, and provenance (Bohemian Massif, Czech Republic). *International Journal of Earth Sciences*, **93**, 742–757.

Drost, K., Gerdes, A., Jeffries, T., Linnemann, U. & Storey, C. 2011. Provenance of Neoproterozoic and early Paleozoic siliciclastic rocks of the Teplá–Barrandian unit (Bohemian Massif): evidence from U–Pb detrital zircon ages. *Gondwana Research*, **19**, 213–231.

Dudek, A. 1980. The crystalline basement block of the Outer Carpathians in Moravia: Brunovistulicum. *Transactions of the Czechoslovak Academy of Sciences, Mathematical and Natural Science Series*, **90**, 3–85.

Edel, J. B., Schulmann, K. & Holub, F. V. 2003. Anticlockwise and clockwise rotations of the Eastern Variscides accommodated by dextral lithospheric wrenching: palaeomagnetic and structural evidence. *Journal of the Geological Society, London*, **160**, 209–218.

Edel, J. B., Schulmann, K., Skrzypek, E. & Chopin, F. 2013. Tectonic evolution of the European Variscan belt constrained by palaeomagnetic, structural and anisotropy of magnetic susceptibility data from the Northern Vosges magmatic arc (eastern France). *Journal of the Geological Society, London*, **170**, 785–804.

Faryad, S. W. 2011. Distribution and geological position of high-/ultrahigh-pressure units within the European Variscan belt: a review. *In:* Dobrzhinetskaya, L. F., Faryad, S. W., Wallis, S. & Cuthbert, S. (eds) *Ultrahigh-pressure metamorphism: 25 years after the discovery of coesite and diamond.* Elsevier, Amsterdam, 361–397.

Faryad, S. W. & Kachlík, V. 2013. New evidence of blueschist facies rocks and their geotectonic implication for Variscan suture(s) in the Bohemian Massif. *Journal of Metamorphic Geology*, **31**, 63–82.

Faryad, S. W., Dolejš, D. & Machek, M. 2009. Garnet exsolution in pyroxene from clinopyroxenites in the Moldanubian zone: constraining the early pre-convergence history of ultramafic rocks in the Variscan orogen. *Journal of Metamorphic Geology*, **27**, 655–671.

Faryad, S. W., Nahodilová, R. & Dolejš, D. 2010. Incipient eclogite facies metamorphism in the Moldanubian granulites revealed by mineral inclusions in garnet. *Lithos*, **114**, 54–69.

Faryad, S.W., Jedlička, R. & Ettinger, K. 2013. Subduction of lithospheric upper mantle recorded by solid phase inclusions and compositional zoning in garnet: example from the Bohemian Massif. *Gondwana Research*, **23**, 944–955.

Faure, M., Lardeaux, J. M. & Ledru, P. 2009. A review of the pre-Permian geology of the Variscan French Massif Central. *Comptes Rendus Geoscience*, **341**, 202–213.

Fiala, J., Fuchs, G. & Wendt, J. I. 1995. Moldanubian Zone – stratigraphy. *In:* Dallmeyer, R. D., Franke, W. & Weber, K. (eds) *Pre-Permian geology of Central and Eastern Europe.* Springer, Berlin, 417–428.

Finger, F. & René, M. 2009. A comment on ‘Two distinctive granite suites in the SW Bohemian Massif and their record of emplacement: constraints from geochemistry and zircon $^{207}Pb/^{206}Pb$ chronology’ by Siebel et al. Journal of Petrology 49, 1853–1872. *Journal of Petrology*, **50**, 591–593.

Finger, F. & Steyrer, H. P. 1995. A tectonic model for the eastern Variscides: indications from a chemical study of amphibolites in the south-eastern Bohemian Massif. *Geologica Carpathica*, **46**, 137–150.

Finger, F., Frasl, G., Höck, V. & Steyrer, H. P. 1989. The granitoids of the Moravian Zone of northeastern Austria: products of Cadomian active continetal margin? *Precambrian Research*, **45**, 235–245.

Finger, F., Roberts, M. P., Haunschmid, B., Schermaier, A. & Steyrer, H. P. 1997. Variscan granitoids of central Europe: their typology, potential sources and tectonothermal relations. *Mineralogy and Petrology*, **61**, 67–96.

Finger, F., Hanžl, P., Pin, C., von Quadt, A. & Steyrer, H. P. 2000a. The Brunovistulian: Avalonian Precambrian sequence at the eastern end of the Central European Variscides? *In:* Franke, W., Haak, V., Oncken, O. & Tanner, D. (eds) *Orogenic processes: quantification and modelling in the Variscan belt.* Geological Society, London, Special Publications, **179**, 103–112.

Finger, F., Tichomirowa, M., Pin, C. & Hanžl, P. 2000b. Relics of early-Panafrican metabasite-metarhyolite formation in the Brno Massif, Moravia, Czech Republic. *International Journal of Earth Sciences*, **89**, 328–335.

Finger, F., Doblmayr, P., Friedl, G., Gerdes, A., Krenn, E. & von Quadt, A. 2003. Petrology of the Weinsberg granite in the South Bohemian Batholith: new data from the mafic end members. *Journal of the Czech Geological Society*, **48**, 46–47.

Finger, F., Gerdes, A., Janoušek, V., René, M. & Riegler, G. 2007. Resolving the Variscan evolution of the Moldanubian sector of the Bohemian Massif: the significance of the Bavarian and the Moravo–Moldanubian tectonometamorphic phases. *Journal of Geosciences*, **52**, 9–28.

Finger, F., Gerdes, A., René, M. & Riegler, G. 2009. The Saxo-Danubian Granite Belt: magmatic response to post-collisional delamination of mantle lithosphere below the south-western sector of the Bohemian Massif (Variscan orogen). *Geologica Carpathica*, **60**, 205–212.

Finger, F., Dunkley, D. J. & René, M. 2010. Remnants of Early Carboniferous I-type granodiorite plutons in the Bavarian Forest and their bearing on the tectonic interpretation of the south-western sector of the Bohemian Massif (Bavarian Zone). *Journal of Geosciences*, **55**, 321–332.

Förster, H. J. 1998. The chemical composition of REE–Y–Th–U-rich accessory minerals in peraluminous granites of the Erzgebirge–Fichtelgebirge region, Germany: Part I, the monazite-(Ce)–brabantite solid solution series. *American Mineralogist*, **83**, 259–272.

Förster, H.J. & Romer, R. L. 2010. Carboniferous magmatism. In: Linnemann, U. & Romer, R. L. (eds) *Pre-Mesozoic geology of Saxo-Thuringia – from the Cadomian active margin to the Variscan orogen*. Schweizerbart Publishers, Stuttgart, 287–308.

Förster, H. J., Tischendorf, G., Trumbull, R. B. & Gottesmann, B. 1999. Late-collisional granites in the Variscan Erzgebirge, Germany. *Journal of Petrology*, **40**, 1613–1645.

Förster, H. J., Romer, R. L., Gottesmann, B., Tischendorf, G. & Rhede, D. 2009. Are the granites of the Aue–Schwarzenberg Zone (Erzgebirge, Germany) a major source for metalliferous ore deposits? A geochemical, Sr–Nd–Pb isotopic, and geochronological study. *Neues Jahrbuch für Mineralogie, Abhandlungen*, **186**, 163–184.

Franěk, J., Schulmann, K. & Lexa, O. 2006. Kinematic and rheological model of exhumation of high pressure granulites in the Variscan orogenic root: example of the Blanský les granulite, Bohemian Massif, Czech Republic. *Mineralogy and Petrology*, **86**, 253–276.

Franěk, J., Schulmann, K., Lexa, O., Tomek, Č. & Edel, J. B. 2011. Model of syn-convergent extrusion of orogenic lower crust in the core of the Variscan belt: implications for exhumation of high-pressure rocks in large hot orogens. *Journal of Metamorphic Geology*, **29**, 53–78.

Franke, W. 1989. Variscan plate tectonics in Central Europe – current ideas and open questions. *Tectonophysics*, **169**, 221–228.

Franke, W. 1999. Tectonic and plate tectonic units at the north Gondwana margin: evidence from the central European Variscides. *Abhandlungen der Geologischen Bundesanstalt*, **54**, 7–14.

Franke, W. 2000. The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. *In:* Franke, W., Haak, V., Oncken, O. & Tanner, D. (eds) *Orogenic processes: quantification and modelling in the Variscan belt.* Geological Society, London, Special Publications, **179**, 35–61.

Franke, W. 2006. The Variscan orogen in Central Europe: construction and collapse. *In:* Gee, D. G. & Stephenson, R. A. (eds) *European Lithosphere Dynamics.* Geological Society, London, Memoirs, **32**, 333–343.

Franke, W. & Żelażniewicz, A. 2002. Structure and evolution of the Bohemian Arc. *In:* Winchester, J. A., Pharaoh, T. C. & Verniers, J. (eds) *Palaeozoic amalgamation of Central Europe.* Geological Society, London, Special Publications, **201**, 279–293.

Frasl, G. & Finger, F. 1991. Geologisch-petrographische Exkursion in den österreischischen Teil des Südböhmischen Batholiths. *Beihefte European Journal of Mineralogy*, **3**, 23–40.

Friedl, G., von Quadt, A., Frasl, G. & Finger, F. 1992. Neue U/Pb Altersdaten aus der südlichen Böhmischen Masse. *Frankfurter Geowissenschaftliche Arbeiten Serie A. Geologie-Paläontologie*, **A11**, 217–218.

Friedl, G., von Quadt, A., Ochsner, A. & Finger, F. 1993. Timing of the Variscan Orogeny in the southern Bohemian Massif (NE-Austria) deduced from new U–Pb zircon and monazite dating. *Terra Abstracts*, **5**, 235–236.

Friedl, G., von Quadt, A. & Finger, F. 1996. Timing der Intrusionstätigkeit im Südböhmischen Batholith. In: *Symposion Tektonik–Strukturgeologie–Kristallingeologie, Salzburg, 10–15 April 1996, Book of Abstracts*. Fakultas Universitätsverlag,Vienna, 127–130.

Friedl, G., Finger, F., McNaughton, N. J. & Fletcher, I. R. 2000. Deducing the ancestry of terranes: SHRIMP evidence for South America-derived Gondwana fragments in central Europe. *Geology*, **28**, 1035–1038.

Friedl, G., Finger, F., Paquette, J. L., von Quadt, A., McNaughton, N. J. & Fletcher, I. R. 2004. Pre-Variscan geological events in the Austrian part of the Bohemian Massif deduced from U/Pb zircon ages. *International Journal of Earth Sciences*, **93**, 802–823.

Friedl, G., Cooke, R., Finger, F., McNaughton, N. & Fletcher, I. 2011. Timing of Variscan HP–HT metamorphism in the Moldanubian Zone of the Bohemian Massif: U–Pb SHRIMP dating on multiply zoned zircons from a granulite from the Dunkelsteiner Wald Massif, Lower Austria. *Mineralogy and Petrology*, **102**, 63–75.

Fritz, H. & Neubauer, F. 1993. Kinematics of crustal stacking and dispersion in the south-eastern Bohemian Massif. *International Journal of Earth Sciences*, **82**, 556–565.

Fritz, H., Dallmeyer, R. D. & Neubauer, F. 1996. Thick-skinned versus thin-skinned thrusting: rheology controlled thrust propagation in the Variscan collisional belt (the southeastern Bohemian Massif, Czech Republic–Austria). *Tectonics*, **15**, 1389–1413.

Fuchs, G. & Matura, A. 1976. Zur Geologie des Kristallins der südlichen Böhmischen Masse. *Jahrbuch der Geologischen Bundesanstalt*, **119**, 1–43.

Fusán, O., Kodym, O., Matějka, A. & Urbánek, L. 1967. Geological map of Czechoslovakia 1:500,000. Central Geological Survey, Prague.

Gerdes, A. 2001. Magma homogenization during anatexis, ascent and/or emplacement? Constraints from the Variscan Weinsberg granites. *Terra Nova*, **13**, 305–312.

Gerdes, A., Wörner, G. & Finger, F. 2000a. Hybrids, magma mixing and enriched mantle melts in post-collisional Variscan granitoids: the Rastenberg Pluton, Austria. *In:* Franke, W., Haak, V., Oncken, O. & Tanner, D. (eds) *Orogenic processes: quantification and modelling in the Variscan belt.* Geological Society, London, Special Publications, **179**, 415–431.

Gerdes, A., Wörner, G. & Henk, A. 2000b. Post-collisional granite generation and HT–LP metamorphism by radiogenic heating: the Variscan South Bohemian Batholith. *Journal of the Geological Society, London*, **157**, 577–587.

Gerdes, A., Friedl, G., Parrish, R. R. & Finger, F. 2003. High-resolution geochronology of Variscan granite emplacement – the South Bohemian Batholith. *Journal of the Czech Geological Society*, **48**, 53–54.

Guy, A., Edel, J. B., Schulmann, K., Tomek, Č. & Lexa, O. 2011. A geophysical model of the Variscan orogenic root (Bohemian Massif): implications for modern collisional orogens. *Lithos*, **124**, 144–157.

Hajná, J., Žák, J., Kachlík, V. & Chadima, M. 2010. Subduction-driven shortening and differential exhumation in a Cadomian accretionary wedge: the Teplá–Barrandian Unit, Bohemian Massif. *Precambrian Research*, **176**, 27–45.

Hajná, J., Žák, J. & Kachlík, V. 2011. Structure and stratigraphy of the Teplá–Barrandian Neoproterozoic, Bohemian Massif: a new plate-tectonic reinterpretation. *Gondwana Research*, **19**, 495–508.

Hajná, J., Žák, J., Kachlík, V. & Chadima, M. 2012. Deciphering the Variscan tectonothermal overprint and deformation partitioning in the Cadomian basement of the Teplá–Barrandian Unit, Bohemian Massif. *International Journal of Earth Sciences*, **101**, 1855–1873.

Hammer, J., Eidam, J., Röber, B. & Ehling, C. 1999. Prävariszischer und variszischer granitoider Magmatismus am NE-Rand des Böhmischen Massivs – Geochemie und Petrogenese. *Zeitschrift für Geologische Wissenschaften*, **27**, 401–415.

Hartley, A. J. & Otava, J. 2001. Sediment provenance and dispersal in a deep marine foreland basin: the Lower Carboniferous Culm Basin, Czech Republic. *Journal of the Geological Society, London*, **158**, 137–150.

Hecht, L., Vigneresse, J. L. & Morteani, G. 1997. Constraints on the origin of zonation of the granite complexes in the Fichtelgebirge (Germany and Czech Republic): evidence from a gravity and geochemical study. *Geologische Rundschau*, **86**, S93–S109.

Henk, A., von Blanckenburg, F., Finger, F., Schaltegger, U. & Zulauf, G. 2000. Syn-convergent high-temperature metamorphism and magmatism in the Variscides: a discussion of potential heat sources. *In:* Franke, W., Haak, V., Oncken, O. & Tanner, D. (eds) *Orogenic processes: quantification and modelling in the Variscan belt.* Geological Society, London, Special Publications, **179**, 387–399.

Höck, V., Montag, O. & Leichmann, J. 1997. Ophiolite remnants at the eastern margin of the Bohemian Massif and their bearing on the tectonic evolution. *Mineralogy and Petrology*, **60**, 267–287.

Hofmann, M., Linnemann, U., Gerdes, A. & Ullrich, B. 2008. Closure of the Rheic Ocean and the final pulse of the Variscan Orogeny in the Bohemian Massif – timing of large-scale strike-slip processes and basement exhumation by LA-ICP-MS U–Pb zircon dating from the Elbe Zone (Saxo-Thuringian Zone, Germany). In: Königshof, P. & Linnemann, U. (eds) *From Gondwana and Laurussia to Pangaea: dynamics of oceans and supercontinents*. Final Meeting of IGCP 497 and IGCP 499, 20th International Senckenberg-Conference & 2nd Geinitz-Conference, Abstracts and Programme, 53.

Hofmann, M., Linnemann, U., Gerdes, A., Ullrich, B. & Schauer, M. 2009. Timing of dextral strike-slip processes and basement exhumation in the Elbe Zone (Saxo-Thuringian Zone): the final pulse of the Variscan Orogeny in the Bohemian Massif constrained by LA-SF-ICP-MS U-Pb zircon data. *In:* Murphy, J. B., Keppie, J. D. & Hynes, A. J. (eds) *Ancient orogens and modern analogues.* Geological Society, London, Special Publications, **327**, 197–214.

Holub, F. V. 1997. Ultrapotassic plutonic rocks of the durbachite series in the Bohemian Massif: petrology, geochemistry and petrogenetic interpretation. *Journal of Geological Sciences, Economic Geology, Mineralogy*, **31**, 5–26.

Holub, F. V., Cocherie, A. & Rossi, P. 1997a. Radiometric dating of granitic rocks from the Central Bohemian Plutonic Complex (Czech Republic): constraints on the chronology of thermal and tectonic events along the Moldanubian-Barrandian boundary. *Comptes Rendus de l'Academie de Sciences – Serie IIa: Sciences de la Terre et des Planetes*, **325**, 19–26.

Holub, F. V., Machart, J. & Manová, M. 1997b. The Central Bohemian Plutonic Complex: geology, chemical composition and genetic interpretation. *Journal of Geological Sciences, Economic Geology, Mineralogy*, **31**, 27–50.

Holub, F. V., Klečka, M. & Matějka, D. 1995. Igneous activity. *In:* Dallmeyer, R. D., Franke, W. & Weber, K. (eds) *Pre-Permian geology of Central and Eastern Europe.* Springer Verlag, Berlin, 444–452.

Holub, F. V., Schmitz, M. D., Verner, K., Janoušek, V. & Veselovský, F. 2010. Geochemical and temporal relations of ultrapotassic plutons and dyke swarms in South Bohemia . *In:* Kohút, M. (ed.) *Dating 2010. Conference proceedings.* State Geological Institute of Dionýz Štúr, Bratislava, 13–14.

Holub, F.V., Verner, K. & Schmitz, M.D. 2012. Temporal relations of melagranite porphyry dikes and durbachitic plutons in South Bohemia. *Geoscience Research Reports for 2011*, 23–25.

Hrouda, F., Táborská, Š., Schulmann, K., Ježek, J. & Dolejš, D. 1999. Magnetic fabric and rheology of co-mingled magmas in the Nasavrky Plutonic Complex (E Bohemia): implications for intrusive strain and emplacement mechanism. *Tectonophysics*, **307**, 98–111.

Janoušek, V. & Gerdes, A. 2003. Timing the magmatic activity within the Central Bohemian Pluton, Czech Republic: conventional U–Pb ages for the Sázava and Tábor intrusions and their geotectonic significance. *Journal of the Czech Geological Society*, **48**, 70–71.

Janoušek, V. & Holub, F. V. 2007. The causal link between HP–HT metamorphism and ultrapotassic magmatism in collisional orogens: case study from the Moldanubian Zone of the Bohemian Massif. *Proceedings of the Geologists' Association*, **118**, 75–86.

Janoušek, V., Rogers, G. & Bowes, D. R. 1995. Sr–Nd isotopic constraints on the petrogenesis of the Central Bohemian Pluton, Czech Republic. *Geologische Rundschau*, **84**, 520–534.

Janoušek, V., Rogers, G., Bowes, D.R. & Vaňková, V. 1997. Cryptic trace-element variation as an indicator of reverse zoning in a granitic pluton: the Říčany granite, Czech Republic. *Journal of the Geological Society, London*, **154**, 807–815.

Janoušek, V., Bowes, D. R., Rogers, G., Farrow, C. M. & Jelínek, E. 2000. Modelling diverse processes in the petrogenesis of a composite batholith: the Central Bohemian Pluton, Central European Hercynides. *Journal of Petrology*, **41**, 511–543.

Janoušek, V., Braithwaite, C. J. R., Bowes, D. R. & Gerdes, A. 2004a. Magma-mixing in the genesis of Hercynian calc-alkaline granitoids: an integrated petrographic and geochemical study of the Sázava intrusion, Central Bohemian Pluton, Czech Republic. *Lithos*, **78**, 67–99.

Janoušek, V., Finger, F., Roberts, M. P., Frýda, J., Pin, C. & Dolejš, D. 2004b. Deciphering the petrogenesis of deeply buried granites: whole-rock geochemical constraints on the origin of largely undepleted felsic granulites from the Moldanubian Zone of the Bohemian Massif. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, **95**, 141–159.

Janoušek, V., Gerdes, A., Vrána, S., Finger, F., Erban, V., Friedl, G. & Braithwaite, C. J. R. 2006. Low-pressure granulites of the Lišov Massif, Southern Bohemia: Viséan metamorphism of Late Devonian plutonic arc rocks. *Journal of Petrology*, **47**, 705–744.

Janoušek, V., Vrána, S., Erban, V., Vokurka, K. & Drábek, M. 2008. Metabasic rocks in the Varied Group of the Moldanubian Zone, southern Bohemia – their petrology, geochemical character and possible petrogenesis. *Journal of Geosciences*, **53**, 31–64.

Janoušek, V., Wiegand, B. & Žák, J. 2010. Dating the onset of Variscan crustal exhumation in the core of the Bohemian Massif: new U–Pb single zircon ages from the high-K calc-alkaline granodiorites of the Blatná suite, Central Bohemian Plutonic Complex. *Journal of the Geological Society, London*, **167**, 347–360.

Jastrzębski, M. 2009. A Variscan continental collision of the West Sudetes and the Brunovistulian Terrane: a contribution from structural and metamorphic record of the Stronie Formation, the Orlica–Śnieżnik Dome, SW Poland. *International Journal of Earth Sciences*, **98**, 1901–1923.

Jelínek, E. & Dudek, A. 1993. Geochemistry of the subsurface Precambrian plutonic rocks from the Brunovistulian Complex in the Bohemian Massif, Czechoslovakia. *Precambrian Research*, **62**, 103–125.

Kachlík, V. 1993. The evidence for late Variscan nappe thrusting of the Marianské Lázně Complex over the Saxothuringian Terrane (west Bohemia). *Journal of the Czech Geological Society*, **38**, 43–58.

Kachlík, V. 1999. Relationship between Moldanubicum, the Kutná Hora Crystalline Unit and Bohemicum (Central Bohemia, Czech Republic): a result of polyphase Variscan nappe tectonics. *Journal of the Czech Geological Society*, **44**, 201–291.

Kalt, A., Berger, A. & Blümel, P. 1999. Metamorphic evolution of cordierite-bearing migmatites from the Bayerische Wald (Variscan Belt, Germany). *Journal of Petrology*, **40**, 601–627.

Kalt, A., Corfu, F. & Wijbrans, J. R. 2000. Time calibration of a P–T path from a Variscan high-temperature low-pressure metamorphic complex (Bayerischer Wald, Germany), and the detection of inherited monazite. *Contributions to Mineralogy and Petrology*, **138**, 143–163.

Kalvoda, J., Bábek, O., Fatka, O., Leichmann, J., Melichar, R., Nehyba, S. & Špaček, P. 2008. Brunovistulian Terrane (Bohemian Massif, Central Europe) from late Proterozoic to late Paleozoic: a review. *International Journal of Earth Sciences*, **97**, 497–518.

Kempe, U., Wolf, D., Ebermann, U. & Bombach, K. (1999). 330 Ma Pb/Pb single zircon evaporation ages for the Altenberg Granite Porphyry, Eastern Erzgebirge (Germany): implications for Hercynian granite magmatism and tin mineralisation. *Zeitschrift für Geologische Wissenschaften*, **27**, 385–400.

Kempe, U., Bombach, K., Schlothauer, T., Hutschenreuter, J., Wolf, D., Matukov, D. & Sergeev, S. 2004. Pb/Pb and U/Pb zircon dating of subvolcanic rhyolite as a time marker for Hercynian granite magmatism and Sn mineralisation in the Eibenstock granite, Erzgebirge, Germany: considering effects of zircon alteration. *Mineralium Deposita*, **39**, 646–669.

Klečka, M. & Matějka, D. 1996. Moldanubian Batholith – an example of the evolution of the Late Palaeozoic granitoid magmatism in the Moldanubian Zone, Bohemian Massif (Central Europe). *In:* Srivastava, R. K. & Chandra, R. (eds) *Magmatism in relation to diverse tectonic settings.* Oxford & IBH Publishing Co., New Delhi, 353–373.

Klein, T., Kiehm, S., Siebel, W., Shang, C.K., Rohrmüller, J., Dörr, W. & Zulauf, G. 2008. Age and emplacement of late-Variscan granites of the western Bohemian Massif with main focus on the Hauzenberg granitoids (European Variscides, Germany). *Lithos*, **102**, 478–507.

Klomínský, J. 1963. Geology of the Čistá Massif. *Journal of Geological Sciences, Geology*, **3**, 7–27.

Klomínský, J. 1965. The Štěnovice granodiorite Massif. *Journal of Geological Sciences, Geology*, **8**, 75–98.

Klomínský, J. 1969. The Krkonoše–Jizera granitoid Massif. *Journal of Geological Sciences, Geology*, **15**, 1–134.

Klomínský, J., Schovánek, P., Jarchovský, T., Sulovský, P. & Toužimský, M. 2007. Contact of the Tanvald and Liberec granites near Jablonec nad Nisou. *Geoscience Research Reports for 2006*, 24–29.

Klötzli, U. S. & Parrish, R. R. 1996. Zircon U/Pb and Pb/Pb geochronology of the Rastenberg granodiorite, South Bohemian Massif, Austria. *Mineralogy and Petrology*, **58**, 197–214.

Klötzli, U. S., Koller, F., Scharbert, H. G. & Höck, V. 2001. Cadomian lower-crustal contributions to Variscan granite petrogenesis (South Bohemian Pluton, Austria): constrains from zircon typology and geochronology, whole-rock, and feldspar Pb–Sr isotope systematics. *Journal of Petrology*, **42**, 1621–1642.

Konopásek, J. & Schulmann, K. 2005. Contrasting Early Carboniferous field geotherms: evidence for accretion of a thickened orogenic root and subducted Saxothuringian crust (Central European Variscides). *Journal of the Geological Society, London*, **162**, 463–470.

Kopecký, L., Chlupáčová, M., Klomínský, J. & Sokol, A. 1997. The Čistá–Jesenice pluton in western Bohemia: geochemistry, geology and ore potential. *Journal of Geological Sciences, Economic Geology, Mineralogy*, **31**, 97–127.

Košler, J. & Farrow, C. M. 1994. Mid-late Devonian arc-type magmatism in the Bohemian Massif: Sr and Nd isotope and trace element evidence from the Staré Sedlo and Mirotice gneiss complexes, Czech Republic. *Journal of the Czech Geological Society*, **39**, 56–58.

Košler, J., Aftalion, M. & Bowes, D. R. 1993. Mid-late Devonian plutonic activity in the Bohemian Massif: U–Pb zircon isotopic evidence from the Staré Sedlo and Mirotice gneiss complexes, Czech Republic. *Neues Jahrbuch für Mineralogie, Monatshefte*, **1993**, 417–431.

Košler, J., Rogers, G., Roddick, J. C. & Bowes, D. R. 1995. Temporal association of ductile deformation and granitic plutonism: Rb–Sr and ^{40}Ar–^{39}Ar evidence from roof pendants above the Central Bohemian Pluton, Czech

Republic. *Journal of Geology*, **103**, 711–717.

Kotková, J., Kröner, A., Todt, W. & Fiala, J. 1995. Zircon dating of north Bohemian granulites, Czech Republic: further evidence for the Lower Carboniferous high-pressure event in the Bohemian Massif. *Geologische Rundschau*, **85**, 154–161.

Kotková, J., Harley, S. L. & Fišera, M. 1997. A vestige of very high-pressure (c. 28 kbar) metamorphism in the Variscan Bohemian Massif, Czech Republic. *European Journal of Mineralogy*, **9**, 1017–1033.

Kotková, J., Gerdes, A., Parrish, R. R. & Novák, M. 2007. Clasts of Variscan high-grade rocks within Upper Visean conglomerates – constraints on exhumation history from petrology and U–Pb chronology. *Journal of Metamorphic Geology*, **25**, 781–801.

Kotková, J., Schaltegger, U. & Leichmann, J. 2010. Two types of ultrapotassic plutonic rocks in the Bohemian Massif – coeval intrusions at different crustal levels. *Lithos*, **115**, 163–176.

Kotková, J., O'Brien, P. J. & Ziemann, M. A. 2011. Diamond and coesite discovered in Saxony-type granulite: solution to the Variscan garnet peridotite enigma. *Geology*, **39**, 667–670.

Kovaříková, P., Siebel, W., Jelínek, E., Štemprok, M., Kachlík, V., Holub, F. V. & Blecha, V. 2007. Petrology, geochemistry and zircon age for redwitzite at Abertamy, NW Bohemian Massif (Czech Republic): tracing the mantle component in Late Variscan intrusions. *Chemie der Erde – Geochemistry*, **67**, 151–174.

Köhler, H. & Hölzl, S. 1996. The age of the Leuchtenberg granite (NE Bavaria, Germany). A revision on account of new U–Pb zircon ages. *Neues Jahrbuch für Mineralogie, Monatshefte*, **5**, 212–222.

Kretz, R. 1983. Symbols for rock-forming minerals. *American Mineralogist*, **68**, 277–279.

Kröner, A. & Willner, A. P. 1998. Time of formation and peak of Variscan HP–HT metamorphism of quartz-feldspar rocks in the Central Erzgebirge, Saxony, Germany. *Contributions to Mineralogy and Petrology*, **132**, 1–20.

Kröner, A., Wendt, I., Liew, T. C., Compston, W., Todt, W., Fiala, J., Vaňková, V. & Vaněk, J. 1988. U–Pb zircon and Sm–Nd model ages of high-grade Moldanubian metasediments, Bohemian Massif, Czechoslovakia. *Contributions to Mineralogy and Petrology*, **99**, 257–266.

Kröner, A., Hegner, E., Hammer, J., Haase, G., Bielicki, K. H., Krauss, M. & Eidam, J. 1994. Geochronology and Nd–Sr systematics of Lusatian granitoids – significance for the evolution of the Variscan orogen in East- Central-Europe. *Geologische Rundschau*, **83**, 357–376.

Kröner, A., Willner, A. P., Hegner, E., Frischbutter, A., Hofmann, J. & Bergner, R. 1995. Latest Precambrian (Cadomian) zircon ages, Nd isotopic systematics and P–T evolution of granitoid orthogneisses of the Erzgebirge, Saxony and Czech Republic. *Geologische Rundschau*, **84**, 437–456.

Kröner, A., Jaeckel, P., Reischmann, T. & Kroner, U. 1998. Further evidence for an early Carboniferous (c. 340 Ma) age of high-grade metamorphism in the Saxonian granulite complex. *Geologische Rundschau*, **86**, 751–766.

Kröner, A., O'Brien, P. J., Nemchin, A. A. & Pidgeon, R. T. 2000. Zircon ages for high pressure granulites from South Bohemia, Czech Republic, and their connection to Carboniferous high temperature processes. *Contributions to Mineralogy and Petrology*, **138**, 127–142.

Kröner, A., Jaeckel, P., Hegner, E. & Opletal, M. 2001. Single zircon ages and whole rock Nd isotopic systematics of early Palaeozoic granitoid gneisses from the Czech and Polish Sudetes (Jizerské hory, Krkonoše Mountains and Orlice–Sněžník Complex). *International Journal of Earth Sciences*, **90**, 304–324.

Kroner, U. & Romer, R. L. 2013. Two plates – many subduction zones: the Variscan orogeny reconsidered. *Gondwana Research*, **24**, 298–329.

Kryza, R., Crowley, Q. G., Larionov, A. Pin, C., Oberc-Dziedzic, T., & Mochnacka K. 2012. Chemical abrasion applied to SHRIMP zircon geochronology: an example from the Variscan Karkonosze Granite (Sudetes, SW Poland). *Gondwana Research*, **21**, 757–767.

Kusiak, M. A., Dunkley, D. J., Suzuki, K., Kachlík, V., Kedzior, A., Lekki, J. & Opluštil, S. 2010. Chemical (non-isotopic) and isotopic dating of Phanerozoic zircon – a case study of durbachite from the Třebíč Pluton, Bohemian Massif. *Gondwana Research*, **17**, 153–161.

Kusiak, M. A., Dunkley, D. J., Słaby, E., Martin, H. & Budzyń, B. 2009. Sensitive high-resolution ion microprobe analysis of zircon reequilibrated by late magmatic fluids in a hybridized pluton. *Geology*, **37**, 1063–1066.

Kusiak, M. A., Suzuki, K., Dunkley, D. J., Lekki, J., Bakun-Czubarow, N., Paszkowski, M. & Budzyń, B. 2008. EPMA and PIXE dating of monazite in granulites from Stary Gieraltów, NE Bohemian Massif, Poland. *Gondwana Research*, **14**, 675–685.

Leichmann, J. & Höck, V. 2008. The Brno Batholith: an insight into the magmatic and metamorphic evolution of the Cadomian Brunovistulian Unit, eastern margin of the Bohemian Massif. *Journal of Geosciences*, **53**, 281–305.

Lexa, O., Schulmann, K., Janoušek, V., Štípská, P., Guy, A. & Racek, M. 2011. Heat sources and trigger mechanisms of exhumation of HP granulites in Variscan orogenic root. *Journal of Metamorphic Geology*, **29**, 79–102.

Liew, T. C., Finger, F. & Höck, V. 1989. The Moldanubian granitoid plutons in Austria: chemical and isotopic studies bearing on their environmental setting. *Chemical Geology*, **76**, 41–55.

Linnemann, U. & Romer, R. L. 2002. The Cadomian Orogeny in Saxo-Thuringia, Germany: geochemical and Nd–Sr–Pb isotopic characterization of marginal basins with constraints to geotectonic setting and provenance. *Tectonophysics*, **352**, 33–64.

Linnemann, U., Gehmlich, M., Tichomirowa, M., Buschmann, B., Nasdala, L., Jonas, P., Lützner, H. & Bombach, K. 2000. From Cadomian subduction to Early Palaeozoic rifting: the evolution of Saxo-Thuringia at the margin of Gondwana in the light of single zircon geochronology and basin development (Central European Variscides, Germany). *In:* Franke, W., Haak, V., Oncken, O. & Tanner, D. (eds) *Orogenic processes: quantification and modelling in the Variscan Belt.* Geological Society, London, Special Publications, **179**, 131–153.

Linnemann, U., McNaughton, N. J., Romer, R. L., Gehmlich, M., Drost, K. & Tonk, C. 2004. West African provenance for Saxo-Thuringia (Bohemian Massif): did Armorica ever leave pre-Pangean Gondwana? U/Pb-SHRIMP zircon evidence and the Nd-isotopic record. *International Journal of Earth Sciences*, **93**, 683–705.

Linnemann, U., Pereira, F., Jeffries, T. E., Drost, K. & Gerdes, A. 2008. The Cadomian orogeny and the opening of the Rheic Ocean: the diacrony of geotectonic processes constrained by LA-ICP-MS U-Pb zircon dating (Ossa-Morena and Saxo-Thuringian Zones, Iberian and Bohemian massifs). *Tectonophysics*, **461**, 21–43.

Linner, M. 1996. Metamorphism and partial melting of paragneisses of the Monotonous Group, SE Moldanubicum (Austria). *Mineralogy and Petrology*, **58**, 215–234.

Machek, M., Ulrich, S. & Janoušek, V. 2009. Strain coupling between upper mantle and lower crust: natural example from the Běstvina granulite body, Bohemian Massif. *Journal of Metamorphic Geology*, **27**, 721–737.

Machowiak, K. & Armstrong, R. 2007. SHRIMP U–Pb zircon age from the Karkonosze granite. *Mineralogia Polonica Special Papers*, **31**, 193–196.

Maierová, P., Čadek, O., Lexa, O. & Schulmann, K. 2012. A numerical model of exhumation of the orogenic lower crust in the Bohemian Massif during the Variscan orogeny. *Studia Geophysica et Geodaetica*, **56**, 595–619.

Maluski, H. & 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. *Geological Magazine*, **134**, 703–716.

Marheine, D., Maluski, H., Kachlík, V., Patočka, F. & Żelaźniewicz, A. 2002. The $^{40}Ar/^{39}Ar$ ages from the West Sudetes (NE Bohemian Massif): constraints on the Variscan polyphase tectonothermal development. *In:* Winchester, J. A., Pharaoh, T. C. & Verniers, J. (eds) *Palaeozoic amalgamation of Central Europe.* Geological Society, London, Special Publications, **201**, 133–155.

Martínez Catalán, J. R. 2011. Are the oroclines of the Variscan belt related to late Variscan strike-slip tectonics? *Terra Nova*, **23**, 241–247.

Martínez Catalán, J. R. 2012. The Central Iberian arc, an orocline centered in the Iberian Massif and some implications for the Variscan belt. *International Journal of Earth Sciences*, **101**, 1299–1314.

Massonne, H. J. 2001. First find of coesite in the ultrahigh-pressure metamorphic area of the central Erzgebirge, Germany. *European Journal of Mineralogy*, **13**, 565–570.

Matte, P. 1986. Tectonics and plate-tectonics model for 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. 2001. The Variscan collage and orogeny (480–290 Ma) and the tectonic definition of the Armorica microplate: a review. *Terra Nova*, **13**, 122–128.

Matte, P., Maluski, H., Rajlich, P. & Franke, W. 1990. Terrane boundaries in the Bohemian Massif: result of large-scale Variscan shearing. *Tectonophysics*, **177**, 151–170.

Mazur, S. & Alexandrowski, P. 2001. The Tepla(?)/Saxothuringian suture in the Karkonosze–Izera Massif, western Sudetes, central European Variscides. *International Journal of Earth Sciences*, **90**, 341–360.

Mazur, S., Aleksandrowski, P., Kryza, R. & Oberc-Dziedzic, T. 2006. The Variscan Orogen in Poland. *Geological Quarterly*, **50**, 89–118.

Mazur, S., Aleksandrowski, P., Turniak, k., Awdankiewicz, M. 2007. Geology, tectonic evolution and Late Palaeozoic magmatism of Sudetes – an overview. *In:* Kozłowski, A., Wiszniewska, J. (eds) *Granitoids in Poland*. Archivum Mineralogiae Monograph, **1**, 59–87.

Medaris, L. G., Wang, H., Jelínek, E., Mihaljevič, M. & Jakeš, P. 2005. Characteristics and origins of diverse Variscan peridotites in the Gföhl Nappe, Bohemian Massif, Czech Republic. *Lithos*, **82**, 1–23.

Medaris, L. G., Beard, B. L. & Jelínek, E. 2006. Mantle-derived, UHP garnet pyroxenite and eclogite in the Moldanubian Gföhl nappe, Bohemian Massif: a geochemical review, new P–T determinations, and tectonic interpretation. *International Geology Review*, **48**, 765–777.

Mierzejewski, M. P. 2002. Additional data and remarks to Hans Cloos' work in the Karkonosze Mts (Riesengebirge). *Zeitschrift der geologischen Wissenschaften*, **30**, 37–48.

Mikulski, S. Z., Williams, I. S., Bagiński, B. 2013. Early Carboniferous (Viséan) emplacement of the collisional Kłodzko–Złoty Stok granitoids (Sudetes, SW Poland): constraints from geochemical data and zircon U–Pb ages. *International Journal of Earth Sciences*, **102**, 1007–1027.

Mísař, Z. 1994. Terranes of eastern Bohemian Massif: tectonostratigraphic and lithological units of the Moravicum and Moldanubicum. *Journal of the Czech Geological Society*, **39**, 71–73.

Mueller, H. J. & Massonne, H. J. 2001. Experimental high pressure investigation of partial melting in natural rocks and their influence on V–P and V–S. *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy*, **26**, 325–332.

Murphy, J. B. & Nance, R. D. 2002. Sm–Nd isotopic systematics as tectonic tracers: an example from West Avalonia in the Canadian Appalachians. *Earth-Science Reviews*, **59**, 77–100.

Naemura, K., Hirajima, T. & Svojtka, M. 2009. The pressure–temperature path and the origin of phlogopite in spinel–garnet peridotites from the Blanský les Massif of the Moldanubian Zone, Czech Republic. *Journal of Petrology*, **50**, 1795–1827.

Naemura, K., Ikuta, D., Kagi, H., Odake, S., Ueda, T., Ohi, S., Kobayashi, T., Svojtka, M. & Hirajima, T. 2011. Diamond and other possible ultradeep evidence discovered in the orogenic spinel–garnet peridotite from the Moldanubian Zone of the Bohemian Massif, Czech Republic. *In:* Dobrzhinetskaya, L. F., Faryad, S. W., Wallis, S. & Cuthbert, S. (eds) *Ultrahigh-pressure metamorphism: 25 years after the discovery of coesite and diamond.* Elsevier, Amsterdam, 78–111.

Nakamura, D., Svojtka, M., Naemura, K. & Hirajima, T. 2004. Very high-pressure (>4 GPa) eclogite associated with the Moldanubian Zone garnet peridotite (Nové Dvory, Czech Republic). *Journal of Metamorphic Geology*, **22**, 593–603.

Nance, R. D. & Linnemann, U. 2008. The Rheic Ocean: origin, evolution, and significance. *GSA Today*, **18**, 4–12.

Nance, R. D., Gutiérrez-Alonso, G., Keppie, J. D., Linnemann, U., Murphy, J. B., Quesada, C., Strachan, R. A. & Woodcock, N. H. 2010. Evolution of the Rheic Ocean. *Gondwana Research*, **17**, 194–222.

Nance, R.D., Gutiérrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A. & Woodcock, N.H. 2012. A brief history of the Rheic Ocean. *Geoscience Frontiers*, **3**, 125–135.

Nowak, I., Żelaźniewicz, A., Dörr, W., Franke, W. & Larionov, A. N. 2011. The Izera metabasites, West Sudetes, Poland: geologic and isotopic U–Pb zircon evidence of Devonian extension in the Saxothuringian Terrane. *Lithos*, **126**, 435–454.

Nasdala, L., Wenzel, T., Pidgeon, R. T. & Kronz, A. 1999. Internal structures and dating of complex zircons from Meissen Massif monzonites, Saxony. *Chemical Geology*, **156**, 331–341.

O'Brien, P. J. 2000. The fundamental Variscan problem: high-temperature metamorphism at different depths and high-pressure metamorphism at different temperatures. *In:* Franke, W., Haak, V., Oncken, O. & Tanner, D. (eds) *Orogenic processes: quantification and modelling in the Variscan Belt.* Geological Society, London, Special Publications, **179**, 369–386.

O'Brien, P. J. & Rötzler, J. 2003. High-pressure granulites: formation, recovery of peak conditions and implications for tectonics. *Journal of Metamorphic Geology*, **21**, 3–20.

Oberc-Dziedzic, T., Kryza, R., Klimas, K., Fanning, M. C. & Madej, S. 2005a. Gneiss protolith ages and tectonic boundaries in the NE part of the Bohemian Massif (Fore-Sudetic Block, SW Poland). *Geological Quarterly*, **49**, 363–378.

Oberc-Dziedzic, T., Pin, C. & Kryza, R. 2005b. Early Palaeozoic crustal melting in an extensional setting: petrological and Sm–Nd evidence from the Izera granite-gneisses, Polish Sudetes. *International Journal of Earth Sciences*, **94**, 354–368.

Oberc-Dziedzic, T., Kryza, R., Pin, C. & Madej, S. 2013. Sequential granite emplacement: a structural study of the late Variscan Strzelin intrusion, SW Poland. *International Journal of Earth Sciences*, **102**, 1289–1304.

Oliver, G. J. H., Corfu, F. & Krogh, T. E. 1993. U–Pb ages from SW Poland: evidence for a Caledonian suture zone between Baltica and Gondwana. *Journal of the Geological Society, London*, **150**, 355–369.

Palivcová, M. 1984. Basic series of an 'Andinotype' batholithic association in the Variscan Central Bohemian Pluton. *Geologica Carpathica*, **35**, 39–60.

Parry, M., Štípská, P., Schulmann, K., Hrouda, F., Ježek, J. & Kröner, A. 1997. Tonalite sill emplacement at an oblique plate boundary: northeastern margin of the Bohemian Massif. *Tectonophysics*, **280**, 61–81.

Patočka, F. & Smulikowski, W. 2000. Early Palaeozoic intracontinental rifting and incipient oceanic spreading in the Czech/Polish East Krkonoše/Karkonosze Complex, West Sudetes (NE Bohemian Massif). *Geologia Sudetica*, **33**, 1–15.

Pertoldová, J., Verner, K., Vrána, S., Buriánek, D., Štědrá, V. & Vondrovic, L. 2010. Comparison of lithology and tectonometamorphic evolution of units at the northern margin of the Moldanubian Zone: implications for geodynamic evolution in the northeastern part of the Bohemian Massif. *Journal of Geosciences*, **55**, 299–319.

Petrakakis, K. 1997. Evolution of Moldanubian rocks in Austria: review and synthesis. *Journal of Metamorphic Geology*, **15**, 203–222.

Peucker-Ehrenbrink, B. & Behr, H. J. 1993. Chemistry of hydrothermal quartz in the post-Variscan 'Bavarian Pfahl' system, F.R. Germany. *Chemical Geology*, **103**, 85–102.

Pharaoh, T. C. (1999). Palaeozoic terranes and their lithospheric boundaries within the Trans-European Suture Zone (TESZ): a review. *Tectonophysics*, **314**, 17–41.

Pietranik, A., Storey, C. & Kierczak, J. 2013. The Niemcza diorites and monzodiorites (Sudetes, SW Poland): a record of changing geotectonic setting at ca. 340 Ma. *Geological Quarterly*, **57**, 325–334.

Pin, C. 1990. Variscan oceans: ages, origins and geodynamic imlications inferred from geochemical and radiometric data. *Tectonophysics*, **177**, 215–227.

Pin, C. & Marini, F. 1993. Early Ordovician continental break-up in Variscan Europe: Nd–Sr isotope and trace element evidence from bimodal igneous associations of the Southern Massif Central, France. *Lithos*, **29**, 177–196.

Pin, C., Mierzejewski, M. & Duthou, J. L. 1987. Rb–Sr isochron age of the Karkonosze granite from the Sklarska Poreba Huta quarry and the determination of initial $^{87}Sr/^{86}Sr$ ratio in this granite. *Przegłąd Geologiczny*, **10**, 512–517.

Pitra, P. 2012. Emplacement, structural and P–T evolution of the ~346 Ma Miřetín Pluton (eastern Teplá–Barrandian Zone, Bohemian Massif): implications for regional transpressional tectonics – Discussion. *Journal of Geosciences*, **57**, 189–191.

Pitra, P., Burg, J. P., Schulmann, K. & Ledru, P. 1994. Late orogenic extension in the Bohemian Massif: petrostructural evidence in the Hlinsko region. *Geodinamica Acta*, **7**, 15–30.

Pitra, P., Burg, J. P. & Guiraud, M. 1999. Late Variscan strike-slip tectonics between the Teplá–Barrandian and Moldanubian terranes (Czech Bohemian Massif). *Journal of the Geological Society, London*, **156**, 1003–1020.

Plomerová, J., Vecsey, L., Babuška, V., Granet, M. & Achauer, U. 2005. Passive seismic experiment mosaic – a pilot study of mantle lithosphere anisotropy of the Bohemian Massif. *Studia Geophysica et Geodaetica*, **49**, 541–560.

Prince, C. I., Košler, J., Vance, D. & Günther, D. 2000. Comparison of laser ablation ICP-MS and isotope dilution REE analyses – implications for Sm–Nd garnet geochronology. *Chemical Geology*, **168**, 255–274.

Propach, G., Baumann, A., Schulz-Schmalschlager, M. & Grauert, B. (2000). Zircon and monazite U–Pb ages of Variscan granitoid rocks and gneisses in the Moldanubian Zone of eastern Bavaria, Germany. *Neues Jahrbuch für*

Geologie und Paläontologie, Monatshefte, **6**, 345–377.

Racek, M., Štípská, P., Pitra, P., Schulmann, K. & Lexa, O. 2006. Metamorphic record of burial and exhumation of orogenic lower and middle crust: a new tectonothermal model for the Drosendorf Window (Bohemian Massif, Austria). *Mineralogy and Petrology*, **86**, 221–251.

Rajlich, P. 1987. Variszische duktile Tektonik im Böhmischen Massiv. *Geologische Rundschau*, **76**, 755–786.

Rajlich, P. 1988. Variscan shearing kinematics in the Bohemian Massif: Moldanubian and Moravo–Silesian junction. *Acta Universitatis Carolinae, Geologica*, **1988**, 387–400.

Romer, R. L., Thomas, R., Stein, H. J. & Rhede, D. 2007. Dating multiply overprinted Sn-mineralized granites – examples from the Erzgebirge, Germany. *Mineralium Deposita*, **42**, 337–359.

Romer, R. L., Förster, H. J. & Štemprok, M. 2010. Age constraints for the late-Variscan magmatism in the Altenberg–Teplice Caldera (Eastern Erzgebirge/Krušné hory). *Neues Jahrbuch für Mineralogie, Abhandlungen*, **187**, 289–305.

Rötzler, J. & Romer, R. L. 2001. P–T–t evolution of ultrahigh-temperature granulites from the Saxon Granulite Massif, Germany. Part I: petrology. *Journal of Petrology*, **42**, 1995–2013.

Schäfer, J., Neuroth, H., Ahrendt, H., Dorr, W. & Franke, W. 1997. Accretion and exhumation at a Variscan active margin, recorded in the Saxothuringian flysch. *Geologische Rundschau*, **86**, 599–611.

Scharbert, S., Breiter, K. & Frank, W. 1997. The cooling history of the southern Bohemian Massif. *Journal of the Czech Geological Society*, **42**, 24.

Scheck, M., Bayer, U., Otto, V., Lamarche, J., Banka, D. & Pharaoh, T. 2002. The Elbe Fault System in North Central Europe – a basement controlled zone of crustal weakness. *Tectonophysics*, **360**, 281–299.

Scheuvens, D. & Zulauf, G. 2000. Exhumation, strain localization, and emplacement of granitoids along the western part of the Central Bohemian shear zone (Bohemian Massif). *International Journal of Earth Sciences*, **89**, 617–630.

Schmädicke, E. 1991. Quartz pseudomorphs after coesite in eclogites from the Saxonian Erzgebirge. *European Journal of Mineralogy*, **3**, 231–238.

Schmädicke, E., Gose, J. & Will, T. M. 2010. The P–T evolution of ultra high temperature garnet-bearing ultramafic rocks from the Saxonian Granulitgebirge Core Complex, Bohemian Massif. *Journal of Metamorphic Geology*, **28**, 489–508.

Schulmann, K. & Gayer, R. 2000. A model for continental accretionary wedge developed by oblique collision: the NE Bohemian Massif. *Journal of the Geological Society, London*, **157**, 401–416.

Schulmann, K., Ledru, P., Autran, A., Melka, R., Lardeaux, J. M., Urban, M. & Lobkowicz, M. 1991. Evolution of nappes in the eastern margin of the Bohemian Massif: a kinematic interpretation. *Geologische Rundschau*, **80**, 73–92.

Schulmann, K., Kröner, A., Hegner, E., Wendt, I., Konopásek, J., Lexa, O. & Štípská, P. 2005. Chronological constraints on the pre-orogenic history, burial and exhumation of deep-seated rocks along the eastern margin of the Variscan orogen, Bohemian Massif, Czech Republic. *American Journal of Science*, **305**, 407–448.

Schulmann, K., Lexa, O., Štípská, P., Racek, M., Tajčmanová, L., Konopásek, J., Edel, J. B., Peschler, A. & Lehmann, J. 2008. Vertical extrusion and horizontal channel flow of orogenic lower crust: key exhumation mechanisms in large hot orogens? *Journal of Metamorphic Geology*, **26**, 273–297.

Schulmann, K., Konopásek, J., Janoušek, V., Lexa, O., Lardeaux, J. M., Edel, J. B., Štípská, P. & Ulrich, S. 2009. An Andean type Palaeozoic convergence in the Bohemian Massif. *Comptes Rendus Geoscience*, **341**, 266–286.

Siebel, W., Trzebski, R., Stettner, G., Hecht, L., Casten, U., Höhndorf, A. & Müller, P. 1997. Granitoid magmatism of the NW Bohemian Massif revealed: gravity data, composition, age relations and phase concept. *Geologische Rundschau*, **86**, S45–S63.

Siebel, W., Chen, F. & Satir, M. 2003. Late-Variscan magmatism revisited: new implications from Pb- evaporation zircon ages on the emplacement of redwitzites and granites in NE Bavaria. *International Journal of Earth Sciences*, **92**, 36–53.

Siebel, W., Blaha, U., Chen, F. & Rohrmüller, J. 2005. Geochronology and geochemistry of a dyke-host rock association and implications for the formation of the Bavarian Pfahl shear zone, Bohemian Massif. *International Journal of Earth Sciences*, **94**, 8–23.

Siebel, W., Hann, H. P., Shang, C. K., Rohrmüller, J. & Chen, F. 2006a. Coeval late-Variscan emplacement of granitic rocks: an example from the Regensburg Forest, NE Bavaria. *Neues Jahrbuch für Mineralogie, Abhandlungen*, **183**, 13–26.

Siebel, W., Thiel, M. & Chen, F. 2006b. Zircon geochronology and compositional record of late- to post-kinematic granitoids associated with the Bavarian Pfahl zone (Bavarian Forest). *Mineralogy and Petrology*, **8**, 45–62.

Siebel, W., Shang, C. K., Reitter, E., Rohrmüller, J. & Breiter, K. 2008. Two distinctive granite suites in the SW Bohemian Massif and their record of emplacement: constraints from geochemistry and zircon $^{207}Pb/^{206}Pb$ chronology. *Journal of Petrology*, **49**, 1853–1872.

Siebel, W., Shang, C.K., Reitter, E., Rohrmüller, J. & Breiter, K. 2009. Two distinctive granite suites in the southwestern Bohemian Massif: reply to F. Finger and M. René. *Journal of Petrology*, **50**, 595–599.

Siebel, W., Hann, H., Danišík, M., Shang, C., Berthold, C., Rohrmüller, J., Wemmer, K. & Evans, N. 2010. Age constraints on faulting and fault reactivation: a multi-chronological approach. *International Journal of Earth Sciences*, **99**, 1187–1197.

Słaby, E. & Martin, H. 2008. Mafic and felsic magma interaction in granites: the Hercynian Karkonosze Pluton (Sudetes, Bohemian Massif). *Journal of Petrology*, **49**, 353–391.

Sláma, J., Dunkley, D. J., Kachlík, V. & Kusiak, M. A. 2008a. Transition from island-arc to passive setting on the continental margin of Gondwana: U–Pb zircon dating of Neoproterozoic metaconglomerates from the SE margin of the Teplá–Barrandian Unit, Bohemian Massif. *Tectonophysics*, **461**, 44–59.

Sláma, J., Košler, J., Condon, D. J., Crowley, J. L., Gerdes, A., Hanchar, J. M., Horstwood, M. S. A., Morris, G. A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M. N. & Whitehouse, M. J. 2008b. Plešovice zircon – a new natural reference material for U–Pb and Hf isotopic microanalysis. *Chemical Geology*, **249**, 1–35.

Smulikowski, W. 1995. Evidence of glaucophane-schist facies metamorphism in the East Karkonosze Complex, West Sudetes, Poland. *Geologische Rundschau*, **84**, 720–737.

Soejono, I., Žáčková, E., Janoušek, V., Machek, M. & Košler, J. 2010. Vestige of an Early Cambrian incipient oceanic crust incorporated in the Variscan orogen: Letovice Complex, Bohemian Massif. *Journal of the Geological Society, London*, **167**, 1113–1130.

Štemprok, M., Holub, F. V. & Novák, J. 2003. Multiple magmatic pulses of the Eastern Volcano-Plutonic Complex, Krušné hory/Erzgebirge batholith, and their phosphorus contents. *Bulletin of Geosciences*, **78**, 277–296.

Štípská, P. & Schulmann, K. 1995. Inverted metamorphic zonation in a basement-derived nappe sequence, eastern margin of the Bohemian Massif. *Geological Journal*, **30**, 385–413.

Štípská, P., Schulmann, K. & Kröner, A. 2004. Vertical extrusion and middle crustal spreading of omphacite granulite: a model of syn-convergent exhumation (Bohemian Massif, Czech Republic). *Journal of Metamorphic Geology*, **22**, 179–198.

Strnad, L. & Mihaljevič, M. 2005. Sedimentary provenance of Mid-Devonian clastic sediments in the Teplá–Barrandian Unit (Bohemian Massif): U–Pb and Pb–Pb geochronology of detrital zircons by laser ablation ICP-MS. *Mineralogy and Petrology*, **84**, 47–68.

Suchý, V., Rozkošný, I., Žák, K. & Franců, J. 1996. Epigenetic dolomitization of the Přídolí formation (Upper Silurian), the Barrandian basin, Czech Republic: implications for burial history of the Lower Paleozoic strata. *Geologische Rundschau*, **85**, 264–277.

Suchý, V., Sýkorová, I., Melka, K., Filip, J. & Machovič, V. 2007. Illite ‘crystallinity’, maturation of organic matter and microstructural development associated with lowest-grade metamorphism of Neoproterozoic sediments in the Teplá–Barrandian unit, Czech Republic. *Clay Minerals*, **42**, 503–526.

Suess, F. E. 1912. Die moravische Fenster und ihre Beziehung zum Grundgebirge des Hohen Gesenkes. *Denkschriften Österreichische Akademie der Wissenschaften, Mathematisch-naturwissenschaftliche Klasse*, **88**, 541–631.

Synek, J. & Oliveriová, D. 1993. Terrane character of the north-east margin of the Moldanubian Zone: the Kutná Hora Crystalline Complex, Bohemian Massif. *Geologische Rundschau*, **82**, 566–582.

Tajčmanová, L., Soejono, I., Konopásek, J., Košler, J. & Klötzli, U. 2010. Structural position of high-pressure felsic to intermediate granulites from NE Moldanubian domain (Bohemian Massif). *Journal of the Geological Society, London*, **167**, 329–345.

Tichomirowa, M. 1997. ^{207}Pb/^{206}Pb-Einzelzirkondatierungen zur Bestimmung des Intrusionsalters des Niederbobritzscher Granites. *Terra Nostra*, **8**, 183–184.

Tichomirowa, M. & Leonhardt, D. 2010. New age determinations (Pb/Pb zircon evaporation, Rb/Sr) on the granites from Aue-Schwarzenberg and Eibenstock, Western Erzgebirge, Germany. *Zeitschrift für Geologische Wissenschaften*, **38**, 99–123.

Tichomirowa, M., Sergeev, S. A., Berger, H. J. & Leonhardt, D. 2012. Inferring protoliths of high-grade metamorphic gneisses of the Erzgebirge using zirconology, geochemistry and comparison with lower-grade rocks from Lusatia (Saxothuringia, Germany). *Contributions to Mineralogy and Petrology*, **164**, 375–396.

Timmermann, H., Štědrá, V., Gerdes, A., Noble, S. R., Parrish, R. R. & Dörr, W. 2004. The problem of dating high-pressure metamorphism: a U–Pb isotope and geochemical study on eclogites and related rocks of the Marianské Lázně Complex, Czech Republic. *Journal of Petrology*, **45**, 1311–1338.

Tollmann, A. 1982. Großräumiger variszischer Deckenbau im Moldanubikum und neue Gedanken zum Variszikum Europas. Geotektonische Forschungen, **64**, 1–91.

Tollmann, A. 1995. Das Ausmass des variszischer Deckbaues im Moldanubikum. *Krystalinikum*, **18**, 117–132.

Tomek, F. 2011. *The Late Devonian to Early Carboniferous kinematic evolution of the Teplá–Barrandian/Moldanubian boundary*. Diploma thesis, Charles University in Prague.

Tomek, F. & Žák, J. 2011. The Late Devonian to early Carboniferous kinematic evolution of the Teplá–Barrandian/Moldanubian boundary. Proceedings of the 2nd Congress of the Czech and Slovak geological societies, 94.

Tropper, P., Deibl, I., Finger, F. & Kaindl, R. 2006. P–T–t evolution of spinel–cordierite–garnet gneisses from the Sauwald Zone (Southern Bohemian Massif, Upper Austria): is there evidence for two independent late-Variscan low-P/high-T events in the Moldanubian Unit? *International Journal of Earth Sciences*, **95**, 1019–1037.

Trubač, J., Žák, J., Chlupáčová, M. & Janoušek, V. 2009. Magnetic fabric of the Říčany granite, Bohemian Massif: a record of helical magma flow? *Journal of Volcanology and Geothermal Research*, **181**, 25–34.

Trubač, J., Janoušek, V., Žák, J. & Gerdes, A. 2013. Geochemistry and petrogenesis of a nested granite intrusion – the Sedmihoří composite Stock (Bohemian Massif). *Mineralogical Magazine*, **77**, 2360.

Turnau, E., Żelaźniewicz, A. & Franke W. 2002. Middle to early late Viséan onset of late orogenic sedimentation in the Intra-Sudetic Basin, West Sudetes: miospore evidence and tectonic implication. *Geologia Sudetica*, **34**, 9–16.

Turniak, K. & Bröcker, M. 2002. Age of the two-mica granite from the Strzegom–Sobótka Massif: new data from U/Pb monazite and xenotime study. *Mineralogical Society of Poland – Special Papers*, **20**, 211–213.

Turniak, K., Tichomirowa, M. & Bombach, K. 2005. Zircon Pb-evaporation ages of granitoids from the Strzegom–Sobótka Massif (SW Poland). *Mineralogical Society of Poland – Special Papers*, **25**, 241–245.

Turniak, K., Tichomirowa, M. & Bombach, K. 2006. Pb-evaporation zircon ages of post-tectonic granitoids from the Strzelin Massif (SW Poland). *Mineralogia Polonica – Special Papers*, **29**, 212–215.

van Breemen, O., Aftalion, M., Bowes, D. R., Dudek, A., Mísař, Z., Povondra, P. & Vrána, S. 1982. Geochronological studies of the Bohemian Massif, Czechoslovakia, and their significance in the evolution of Central Europe. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, **73**, 89–108.

Vellmer, C. & Wedepohl, K. H. 1994. Geochemical characterization and origin of granitoids from the South Bohemian Batholith in Lower Austria. *Contributions to Mineralogy and Petrology*, **118**, 13–32.

Venera, Z., Schulmann, K. & Kröner, A. 2000. Intrusion within a transtensional tectonic domain: the Čistá granodiorite (Bohemian Massif) – structure and rheological modelling. *Journal of Structural Geology*, **22**, 1437–1454.

Verner, K., Žák, J., Hrouda, F. & Holub, F. V. 2006. Magma emplacement during exhumation of the lower- to mid-crustal orogenic root: the Jihlava syenitoid pluton, Moldanubian Unit, Bohemian Massif. *Journal of Structural Geology*, **28**, 1553–1567.

Verner, K., Žák, J., Nahodilová, R. & Holub, F. 2008. Magmatic fabrics and emplacement of the cone-sheet-bearing Knížecí Stolec durbachitic pluton (Moldanubian Unit, Bohemian Massif): implications for mid-crustal reworking of granulitic lower crust in the Central European Variscides. *International Journal of Earth Sciences*, **97**, 19–33.

Verner, K., Buriánek, D., Vrána, S., Vondrovic, L., Pertoldová, J., Hanžl, P. & Nahodilová, R. 2009a. Tectonometamorphic features of geological units along the northern periphery of the Moldanubian Zone. *Journal of Geosciences*, **54**, 87–100.

Verner, K., Žák, J., Pertoldová, J., Šrámek, J., Sedlák, J., Trubač, J. & Týcová, P. 2009b. Magmatic history and geophysical signature of a post-collisional intrusive center emplaced near a crustal-scale shear zone: the Plechý granite pluton (Moldanubian batholith, Bohemian Massif). *International Journal of Earth Sciences*, **98**, 517–532.

Verner, K., Žák, J., Šrámek, J., Paclíková, J., Zavřelová, A., Machek, M., Finger, F. & Johnson, K. in print. Formation of elongated granite–migmatite domes as isostatic accommodation structures in collisional orogens. *Journal of Geodynamics*, doi:10.1016/j.jog.2013.10.002

Vondrovic, L. & Verner, K. 2008. The record of structural evolution and U–Pb zircon dating of the tonalite intrusions (Polička Crystalline Unit, Bohemian Massif). In: Poblet, J., Medina, M.G., Pedreira, D. & Fernández, C.L. (eds) *International meeting of young researchers in structural geology and tectonics – programme and extended abstracts*. University of Oviedo, Spain, 369–373.

Vondrovic, L. & Verner, K. 2010. The record of structural evolution and U–Pb zircon dating of the tonalite intrusions (Polička Crystalline Unit, Bohemian Massif). *Trabajos de Geología*, **30**, 316–321.

Vondrovic, L., Verner, K., Buriánek, D., Halodová, P., Kachlík, V. & Míková, J. 2011. Emplacement, structural and P–T evolution of the ~346 Ma Miřetín Pluton (eastern Teplá–Barrandian Zone, Bohemian Massif): implications for regional transpressional tectonics. *Journal of Geosciences*, **56**, 343–357.

von Quadt, A. & Finger, F. 1991. Geochronologische Untersuchungen im österreichischen Teil des Südböhmischen Batholiths: U–Pb Datierungen an Zirkonen, Monaziten und Xenotimen des Weinsberger Granits. *Beihefte European Journal of Mineralogy*, **1**, 281.

von Raumer, J. F. & Stampfli, G. M. 2008. The birth of the Rheic Ocean – Early Palaeozoic subsidence patterns and subsequent tectonic plate scenarios. *Tectonophysics*, **461**, 9–20.

von Raumer, J. F., Finger, F., Veselá, P. & Stampfli, G. M. in print. Durbachites–vaugnerites – a geodynamic marker in the central European Variscan orogen. *Terra Nova*, doi:10.1111/ter.12071

Vrána, S. & Frýda, J. 2003. Ultrahigh-pressure grossular-rich garnetite from the Moldanubian Zone, Czech Republic. *European Journal of Mineralogy*, **15**, 43–54.

Vrána, S. & Novák, M. 2000. Petrology and geochemistry of granulite clasts in the Visean Luleč conglomerate, Kulm in central Moravia, Czech Republic. *Bulletin of the Czech Geological Survey*, **75**, 405–413.

Vrána, S., Blümel, P. & Petrakakis, K. 1995. Moldanubian Zone – metamorphic evolution. *In:* Dallmeyer, R. D., Franke, W. & Weber, K. (eds) *Pre-Permian geology of Central and Eastern Europe.* Springer, Berlin, 453–468.

Waldhausrová, J., 1984. Proterozoic volcanics and intrusive rocks of the Jílové Zone (Central Bohemia). *Krystalinikum*, **17**, 77–97.

Wendt, I., Lenz, H. & Delisle, G. 1986. Gesamtgesteins- und Mineraldatierungen des Falkenberger Granits. *Geologisches Jahrbuch*, **E34**, 1–85.

Wendt, J. I., Kröner, A., Fiala, J. & Todt, W. 1993. Evidence from zircon dating for existence of approximately 2.1 Ga old crystalline basement in southern Bohemia, Czech Republic. *Geologische Rundschau*, **82**, 42–50.

Wendt, J. I., Kröner, A., Fiala, J. & Todt, W. 1994. U–Pb zircon and Sm–Nd dating of Moldanubian HP/HT granulites from south Bohemia, Czech Republic. *Journal of the Geological Society, London*, **151**, 83–90.

Wenzel, T., Hengst, M. & Pilot, J. 1993. The plutonic rocks of the Elbe Valley-Zone (Germany): evidence for the magmatic development from single-zircon evaporation and K–Ar age determinations. *Chemical Geology*, **104**, 75–92.

Wenzel, T., Mertz, D. F., Oberhänsli, R., Becker, T. & Renne, P. R. 1997. Age, geodynamic setting, and mantle enrichment processes of a K-rich intrusion from the Meissen Massif (northern Bohemian Massif) and implications for related occurrences from the mid-European Hercynian. *Geologische Rundschau*, **86**, 556–570.

Willner, A. P., Rötzler, K. & Maresch, W. V. 1997. Pressure–temperature and fluid evolution of quartzo-feldspathic metamorphic rocks with a relic high-pressure, granulite-facies history from the central Erzgebirge (Saxony, Germany). *Journal of Petrology*, **38**, 307–336.

Willner, A. P., Sebazungu, E., Gerya, T. V., Maresch, W. V. & Krohe, A. 2002. Numerical modelling of PT-paths related to rapid exhumation of high-pressure rocks from the crustal root in the Variscan Erzgebirge Dome (Saxony/Germany). *Journal of Geodynamics*, **33**, 281–314.

Winchester, J. A. 2002. Palaeozoic amalgamation of Central Europe: new results from recent geological and geophysical investigations. *Tectonophysics*, **360**, 5–21.

Winchester, J. A., Pharaoh, T. C., Verniers, J., Ioane, D. & Seghedi, A. 2006. Palaeozoic accretion of Gondwana-derived terranes to the East European Craton: recognition of detached terrane fragments dispersed after collision with promontories. *In:* Gee, D. G. & Stephenson, R. A. (eds) *European lithosphere dynamics.* Geological Society, London, Memoirs, **32**, 232–332.

Žáčková, E., Konopásek, J., Jeřábek, P., Finger, F. & Košler, J. 2010. Early Carboniferous blueschist facies metamorphism in metapelites of the West Sudetes (Northern Saxothuringian Domain, Bohemian Massif). *Journal of Metamorphic Geology*, **28**, 361–379.

Žák, J., Holub, F. V. & Verner, K. 2005a. Tectonic evolution of a continental magmatic arc from transpression in the upper crust to exhumation of mid-crustal orogenic root recorded by episodically emplaced plutons: the Central Bohemian Plutonic Complex (Bohemian Massif). *International Journal of Earth Sciences*, **94**, 385–400.

Žák, J., Schulmann, K. & Hrouda, F. 2005b. Multiple magmatic fabrics in the Sázava pluton (Bohemian Massif, Czech Republic): a result of superposition of wrench-dominated regional transpression on final emplacement. *Journal of Structural Geology*, **27**, 805–822.

Žák, J., Dragoun, F., Verner, K., Chlupáčová, M., Holub, F. V. & Kachlík, V. 2009a. Forearc deformation and strain partitioning during growth of a continental magmatic arc: the northwestern margin of the Central Bohemian Plutonic Complex, Bohemian Massif. *Tectonophysics*, **469**, 93–111.

Žák, J., Verner, K., Klomínský, J. & Chlupáčová, M. 2009b. 'Granite tectonics' revisited: insights from comparison of K-feldspar shape-fabric, anisotropy of magnetic susceptibility (AMS), and brittle fractures in the Jizera granite, Bohemian Massif. *International Journal of Earth Sciences*, **98**, 949–967.

Žák, J., Kratinová, Z., Trubač, J., Janoušek, V., Sláma, J. & Mrlina, J. 2011a. Structure, emplacement, and tectonic setting of Late Devonian granitoid plutons in the Teplá–Barrandian unit, Bohemian Massif. *International Journal of Earth Sciences*, **100**, 1477–1495.

Žák, J., Verner, K., Finger, F., Faryad, S. W., Chlupáčová, M. & Veselovský, F. 2011b. The generation of voluminous S-type granites in the Moldanubian Unit, Bohemian Massif, by rapid isothermal exhumation of the metapelitic middle crust. *Lithos*, **121**, 25–40.

Žák, J., Verner, K., Holub, F.V., Kabele, P., Chlupáčová, M. & Halodová, P. 2012. Magmatic to solid state fabrics in syntectonic granitoids recording early Carboniferous orogenic collapse in the Bohemian Massif. *Journal of Structural Geology*, **36**, 27–42.

Žák, J., Verner, K., Sláma, J., Kachlík, V. & Chlupáčová, M. in print. Multistage magma emplacement and progressive strain accumulation in the shallow-level Krkonoše–Jizera plutonic complex, Bohemian Massif. *Tectonics*, doi:10.1002/tect.20088

Żelaźniewicz, A. 1997. The Sudetes as a Palaeozoic orogen in central Europe. *Geological Magazine*, **134**, 691–702.

Zulauf, G. 1994. Ductile normal faulting along the West Bohemian Shear Zone (Moldanubian/Teplá–Barrandian boundary): evidence for late Variscan extensional collapse in the Variscan Internides. *Geologische Rundschau*, **83**, 276–292.

Zulauf, G. 1997a. Constriction due to subduction: evidence for slab pull in the Mariánské Lázně Complex (central European Variscides). *Terra Nova*, **9**, 232–236.

Zulauf, G. 1997b. From very low-grade to eclogite-facies metamorphism: tilted crustal sections as a consequence of Cadomian and Variscan orogeny in the Teplá–Barrandian unit (Bohemian Massif). *Geotektonische Forschungen*, **89**, 1–302.

Zulauf, G., Bues, C., Dörr, W. & Vejnar, Z. 2002. 10 km minimum throw along the West Bohemian shear zone: evidence for dramatic crustal thickening and high topography in the Bohemian Massif (European Variscides). *International Journal of Earth Sciences*, **91**, 850–864.

General conclusions

5. General conclusions

This thesis provide important insights into first stage of Variscan calc-alkaline magmatic event in the eastern part of the Bohemian Massif. The studied 354 Ma Zábřeh Intrusive Complex and 346 Ma Budislav pluton are in global scale connected with closure of early variscan Rheic ocean and subsequent subduction of Saxothuringian Zone under upper crustal Teplá-Barrandian Unit. The structural record and geotectonic position of studied intrusions emplaced to mid- to upper- crustal rocks corresponds with the earliest ductile movements along the orogen-perpendicular ~NW–SE-trending dextral strike-slip shear zones. The northeastern segment of the amalgamated Saxothuringian/Teplá–Barrandian/Moldanubian block has been truncated in the time span 354-346 Ma and dextrally displaced along the Sudetic and Elbe fault systems that was parallel the southeastern margin of Baltica (Franke and Żelaźniewicz 2002). Theese shear zones were multiply reactivated and activity lasted till at least ~315 Ma (Wenzel et al. 1997; Hofmann et al. 2009). In studied are the end of activity of Elbe Zone system is posdated by intrusion of the 345.9 Ma Miřetín pluton (Vondrovic et al. 2011). Theese ductile movements were later replaced by gravity-driven collapse of upper crustal levels (Franěk et al. 2011; Žák et al. 2012) and by dextral strike-slip movements along NW-SE oriented boundaries (Žák et al. 2014).

In the studied area of eastern margin of Bohemian Massif, with respect to new metamorphic, geochronological and structural data from the Polička and Zábřeh Units presented in this thesis, a new sketch of the Variscan geodynamic evolution of the north eastern Bohemian Massif is proposed. Three distinct phases can be defined: the oldest ~NW-SE to WNW to ESE metamorphic foliation associated with well-developed sub horizontal ~NW-SE stretching lineation mostly bearing right-lateral kinematic indicators (first phase, Fig. 1a) in the rocks of the Polička and Zábřeh Units was formed during a period of oblique transpressional shearing between ~354 and 346Ma (Verner et al. 2009; Žák et al. 2005, 2014) reflecting a regional ~NW-SE compression stress field (Edel et al. 2003). This transpressional deformation was enforced mainly within a ~50-100km wide ~WNW-ESE trending “Elbe Zone” belt which consisted of a thermally weakened zone of mid- to upper-crustal rocks of the Teplá-Barrandian Zone with the presence of syntectonic calc-alkaline granitoids dated at ~354 to 346Ma (e.g. Verner et al. 2009; Vondrovic et al. 2011; Žák et al. 2014, this thesis Part III, Fig 1a). In the Polička Unit the associated ~LP to MP/MT metamorphism increasing south eastwards in a fabric-parallel direction was dated using the U/Pb method on monazites revealing distinct maxima at an age of ~346Ma (this thesis part II).

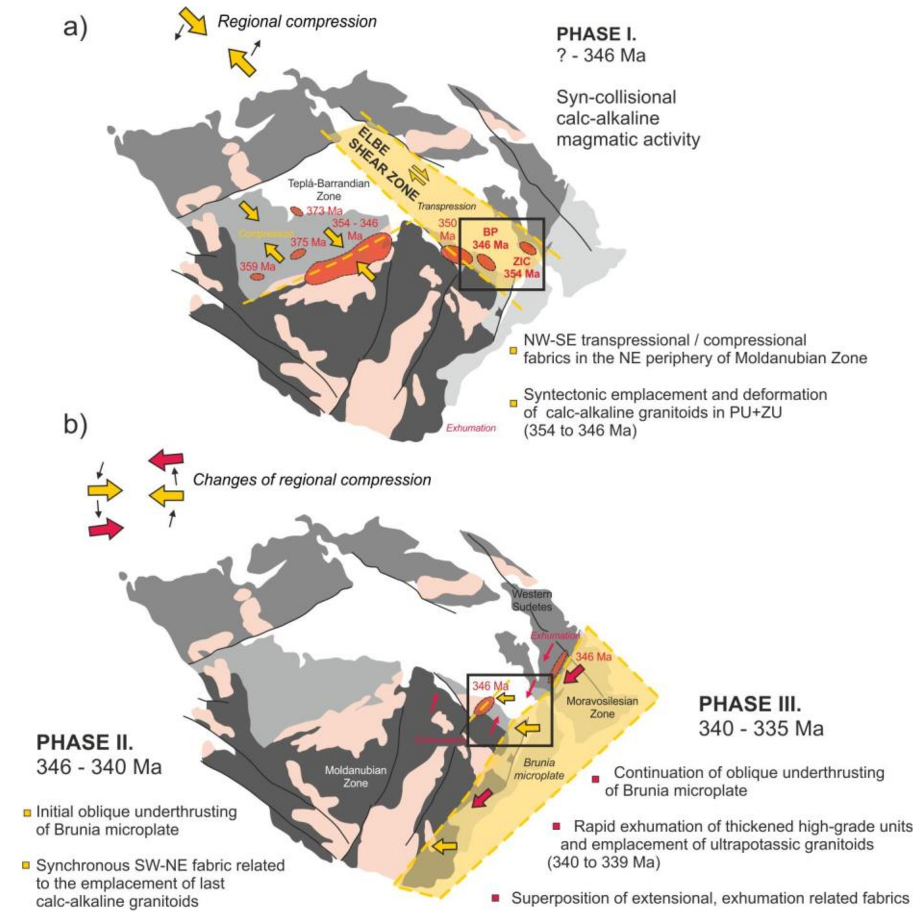


Fig. 1 Greatly idealized sketch describing the spatial and temporal pattern of geological evolution of the eastern periphery of the Moldanubian Zone .

This age most likely corresponds to the main episode of regional deformation and the partial recrystallization of prevailing gneisses supported by heightened heat flow due to the synchronous emplacement of calc-alkaline granitoids dated similarly at ~346Ma (Verner et al. 2009; Vondrovic et al. 2011; Žák et al. 2014, this thesis part III).In Polička Unit the origin of high-pressure granulites (Vír granulite) such as in the south eastern part of the Polička Unit dated at 354Ma (U/Pb on zircons; Tajčmannová et al. 2010) probably reflects the peak P-T conditions attained during an early compressional event and the crustal thickening of the Variscan orogenic root. According to a similar fabric pattern in granulites and the host south eastern Polička Unit, this unit was juxtaposed during transpressional deformation along the "Elbe Zone". With the continuation of a continental collision during the heterogeneous anti-clockwise rotation of the regional stress field from a ~NW-SE to SW-NE direction (Edel et al. 2003) the successive ~NNE-SSW trending oblique under thrusting of the Brunia microplate caused metamorphic inversion, structural reworking and the thickening of the continental crust along the whole eastern termination of the Bohemian Massif (e.g. Fritz & Neubauer 1993; Schulmann et al. 2005, 2008; Kalvoda et al. 2008). The initiation of this event was dated by the origin of regional flat-lying foliation in the central part of the Orlice-Snieznik Dome and probably in the Zábřeh Unit dated at ~346Ma (Jastrebski et al. 2009). The termination of oblique under thrusting must have taken place before the exhumation of the migmatite-granite Pelhřimov core complex to the south dated at 329Ma (Verner et al. 2014). In the Polička Unit and its surroundings this event was associated with the heterogeneous superimposition of ~NNE-SSW foliation and gently plunging stretching lineation (second phase, Fig. 1b) which affected principally the western and eastern flanks of the region. The assumed response to the growth of crustal thickness and the relative decrease in the compressional strain-rate consisted of the relatively rapid exhumation of the crust associated with the formation of heterogeneous gently-dipping metamorphic foliation in several places bearing normal kinematic indicators (last phase, Fig 1b). During the time-span of the (probably) overlapping second and third phases all the rocks underwent heterogeneous retrograde metamorphism and partial recrystallization under MP/LP and MT conditions (Tajčmannnová et al. 2010). This event can be timed by the partial melting of the exhumed amphibolites of the southern Polička Unit at 342Ma (this thesis part II), by the origin of the retrograde mineral assemblage in HP granulites at 340 Ma (Tajčmanová et al. 2010). The relatively higher grade of retrograde metamorphism and, most likely, the accrual rate of crustal exhumation towards the E or SE of the region where the Brunia continent passes beneath the units under study may explain the general increase in the degree of metamorphism in this direction. This event was completed prior to both the post-tectonic emplacement of ultrapotassic Mg-rich granitoids (durbachites) along the north-eastern edge of the Moldanubian Zone (dated at 338Ma; Verner et al 2009) and the sharp superimposition of the ~NNE-SSW right-lateral Přibyslav Mylonite Zone at around 336Ma (Verner et al. 2006).

GEOLOGICKÝ PARK UNIVERZITY KARLOVY

Horniny a geologický vývoj Českého masivu

SERVICE FOR SCIENTIFIC COMMUNITY

Lukáš Vondrovic
Kryštof Verner
Přírodovědecká fakulta UK
Ústav petrologie a strukturní geologie

Geologický park Univerzity Karlovy
Botanická zahrada PřFUK
Na Slupi 433/16
Praha 2

6. Service for scientific community

Last part of this thesis presents the activities in the area of popularization of the rocks and geological evolution of the Bohemian Massif. The main activity in this field that has a full-society impact is creating of the Geological exposition Albertov. This permanent installation is located in the Botanical garden of the Charles University, Faculty of Science, Prague. The main authors are Lukáš Vondrovic nad Kryštof Verner. The building was funded by Charles University, Faculty of Science and Geological section as well as from private supporters.

In a scale of Czech Republic this exhibition shows the most important rocks connected with significant geological events that take place in the time span from late cadomian proces to late tertiary volcanic activity in the Bohemian massif. The layout of the exhibition respects the NW-SE section of the Bohemian Massif from the Saxothuringian domain to the Moravo-Silesian Zone. Additionally the platform sedimentary cover is represented in separate section.

The rock composition of the Bohemian massif is made by rock complexes that dislay complex geological evolution in the time span of 600 million years. The reconstruction of this evolution starts with opening and closing of sedimentary basins in late proterozoic and early paleozoic (600-370 Ma) with the abundant fossil material. In 370-310 Ma the geological evolution continued by collision of two continents Gondwana and Laurusia. This event called Variscan orogeny was connected with intensive magmatic activity, rock deformation and metamorphism. Last event is the sedimentary and volcanic activity in mezozoic to tertiary. The intensive research of this world unique rock mass has been lasting for over two centuries. Current state of art knowledge allows us to present the temporal and space scheme of overall orogenic proces to scientific- and non-scientific society. One of the possibilities is represented by outdoor geological expositions.

The exhibition is made by 54 rock samples (size 70x70x120 cm, weight approx. 500-1200 kg) in 30 stations. It is introduced by two A0 posters that contain information about origin and evolution of planet Earth, plate tectonic, rock origin and classification, regional-geology division and geological evolution. Exposition is divided into five sections according to the main geological units in the Czech republic and according to the geological evolution. Each section is introduced by small poster as well as rocks sample. The text about each rock brings information about locality, mineral composition and use of this material. Each rock contain polished part for showing the internal structure. The geological exposition Albertov is very popular among the public visitors of Botanical garden and in the scientific community. This exhibition also serves for the education of students in all levels of educational system.

7. Literature

BRANDMAYR M, DALLMEYER RD, HANDLER R, WALLBRECHER E (1995) Conjugate shear zones in the Southern Bohemian Massif (Austria): implications for Variscan and Alpine tectonothermal activity. Tectonophysics 248: 97–116.

BURIÁNEK D, NĚMEČKOVÁ M, HANŽL P (2003) Petrology and geochemistry of plutonic rocks from the Polička and Zábřeh crystalline units (NE Bohemian Massif). Bull Czech Geol Surv 78: 9–22.

BURIÁNEK D, VERNER K, VONDROVIC L (2015) Tectonometamorphic evolution and geochronology of the Polička Unit (NE Bohemian Massif): from successive oblique collision to crustal exhumation in preparation.

BUSCHMANN B, ELICKI O, JONAS P (2006) The Cadomian unconformity in the Saxo-Thuringian Zone, Germany: palaeogeographic affinities of Ediacaran (terminal Neoproterozoic) and Cambrian strata. Precambrian Research 147: 387–403.

EDEL JB SCHULMANN K, HOLUB FV (2003) Anticlockwise and clockwise rotations of the Eastern Variscides accommodated by dextral lithospheric wrenching: palaeomagnetic and structural evidence. Journal of the Geological Society, London 160: 209–218.

FARYAD S W (2011) Distribution and geological position of high-/ultrahigh-pressure units within the European Variscan belt: a review. In: Dobrzhinetskaya, L. F., Faryad, S. W., Wallis, S. & Cuthbert, S. (eds) Ultrahigh-pressure metamorphism: 25 years after the discovery of coesite and diamond. Elsevier, Amsterdam, 361–397.

FINGER F, ROBERTS MP, HAUNSCHMID B, SCHERMAIER A, STEYRER HP (1997) Variscan granitoids of central Europe: their typology, potential sources and tectonothermal relations. Mineralogy and Petrology 61: 67–96.

FINGER F, GERDES A, JANOUŠEK V, RENÉ M, RIEGLER G (2007) Resolving the Variscan evolution of the Moldanubian sector of the Bohemian Massif: the significance of the Bavarian and the Moravo–Moldanubian tectonometamorphic phases. Journal of Geosciences 52: 9–28.

FINGER F, DUNKLEY DJ, RENÉ M (2010) Remnants of Early Carboniferous I-type granodiorite plutons in the Bavarian Forest and their bearing on the tectonic interpretation of the south-western sector of the Bohemian Massif (Bavarian Zone). Journal of Geosciences 55: 321–332.

FRANĚK J, SCHULMANN K, LEXA O, TOMEK Č, EDEL JB (2011) Model of syn-convergent extrusion of orogenic lower crust in the core of the Variscan belt: implications for exhumation of high-pressure rocks in large hot orogens. Journal of Metamorphic Geology 29: 53–78.

FRANKE W (2000). The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. In: Franke, W., Haak, V., Oncken, O. & Tanner, D. (eds) Orogenic processes: quantification Fritz&Neubauer1993;

FRANKE W (2006) The Variscan orogen in Central Europe: construction and collapse. In: Gee, D. G. & Stephenson, R. A. (eds) European Lithosphere Dynamics. Geological Society, London, Memoirs, 32: 333–343

GERDES A, WÖRNER G, FINGER F (2000a) Hybrids, magma mixing and enriched mantle melts in post-collisional Variscan granitoids: the Rastenberg Pluton, Austria. In: Franke, W., Haak, V., Oncken, O. & Tanner, D. (eds) Orogenic processes: quantification and modelling in the Variscan belt. Geological Society, London, Special Publications, 179, 415–431.

GERDES A, WÖRNER G, HENK A (2000b) Post-collisional granite generation and HT–LP metamorphism by radiogenic heating: the Variscan South Bohemian Batholith. Journal of the Geological Society, London, 157: 577–587

HAJNÁ J, ŽÁK J, KACHLÍK V, CHADIMA M (2010) Subduction-driven shortening and differential exhumation in a Cadomian accretionary wedge: the Teplá–Barrandian Unit, Bohemian Massif. Precambrian Research, 176: 27–45.

HAJNÁ J, ŽÁK J, KACHLÍK V (2011) Structure and stratigraphy of the Teplá–Barrandian Neoproterozoic, Bohemian Massif: a new plate-tectonic reinterpretation. Gondwana Research 19: 495–508.

HOFMANN, M., LINNEMANN, U., GERDES, A., ULLRICH, B. & SCHAUER, M. 2009. Timing of dextral strike-slip processes and basement exhumation in the Elbe Zone (Saxo-Thuringian Zone): the final pulse of the Variscan Orogeny in the Bohemian Massif constrained by LA-SF-ICP-MS U-Pb zircon data. In: Murphy, J. B., Keppie, J. D. & Hynes, A. J. (eds) Ancient orogens and modern analogues. Geological Society, London, Special Publications, 327: 197–214.

HOLLAND T, POWELL R (1998) An internally consistent thermodynamic data set with uncertainties and correlations: the system Na2O–K2O–CaO–MgO–MnO–FeO–Fe2O3–Al2O3–SiO2–TiO2–C–H2–O2. J Metamorph Geol 8: 89–124

HOLUB FV, COCHERIE A, ROSSI P (1997a) Radiometric dating of granitic rocks from the Central Bohemian Plutonic Complex (Czech Republic): constraints on the chronology of the thermal and tectonic events along the Moldanubian–Barrandian boundary. C R Acad Sci Paris Earth Planet Sci 325: 19–26

HOLUB FV, MACHART J, MANOVÁ M (1997b) The Central Bohemian Plutonic Complex: Geology, chemical composition and genetic interpretation. Sbor geol Věd, Ložisk Geol Mineral 31: 27–50

HROUDA F, TARLING DH (1984) The magnetic anisotropy of rocks. Chapmann and Hall, London, 215 p.

CHLUPÁČ I, HAVLÍČEK V, KŘÍŽ J, KUKAL Z, ŠTORCH P (1998) Paleozoic of the Barrandian (Cambrian to Devonian). Czech Geological Survey, Prague.

JANOUŠEK V, BRAITHWAITE CJR, BOWES DR, GERDES A (2004) Magma-mixing in the genesis of Hercynian calc-alkaline granitoids: an integrated petrographic and geochemical study of the Sázava intrusion, Central Bohemian Pluton, Czech Republic. Lithos 78: 67–99.

JASTRZĘBSKI M (2009) A Variscan continental collision of the West Sudetes and the Brunovistulian Terrane: a contribution from structural and metamorphic record of the Stronie Formation, the Orlica–Śnieżnik Dome, SW Poland. International Journal of Earth Sciences 98: 1901–1923.

KACHLÍK V (1999) Relationship between Moldanubicum, the Kutná Hora Crystalline Unit and Bohemicum (Central Bohemia, Czech Republic): a result of polyphase Variscan nappe tectonics. Journal of the Czech Geological Society, 44, 201–291.

KALT A, BERGER A, BLÜMEL P (1999) Metamorphic evolution of cordierite-bearing migmatites from the Bayerische Wald (Variscan Belt, Germany). Journal of Petrology, 40, 601–627.

KALT A, CORFU F, WIJBRANS JR (2000) Time calibration of a P–T path from a Variscan high-temperature low-pressure metamorphic complex (Bayerischer Wald, Germany), and the detection of inherited monazite. Contributions to Mineralogy and Petrology, 138, 143–163.

KALVODA J, BÁBEK O, FATKA O, LEICHMANN J, MELICHAR R, NEHYBA S, ŠPAČEK P (2008) Brunovistulian Terrane (Bohemian Massif, Central Europe) from late Proterozoic to late Paleozoic: a review. International Journal of Earth Sciences 97: 497–518.

KONOPÁSEK J, SCHULAMNN K, ŠTAUDOVÁ S (1997) Kontrastní PT a strukturní vývoj vírské granulitové megabudiny a okolních metapelitů: Poličské krystalinikum, východní okraj Českého masivu . In Sborník II. semináře České tektonické skupiny. Ostrava : Česká geologická společnost 97: 69–70

KRONER U, ROMER RL (2013) Two plates – many subduction zones: the Variscan orogeny reconsidered. Gondwana Research 24: 298–329.

LEHMANN J, SCHULMANN K, EDEL JB, JEŽEK J, HROUDA F, LEXA O, CHOPINN F (2013)Structural and anisotropy of magnetic susceptibility records of granitoid sheets emplacement during growth of a continental gneiss dome (Central Sudetes). Tectonics 797–820.

LINNEMANN U, ROMER RL (2002) The Cadomian Orogeny in Saxo-Thuringia, Germany: geochemical and Nd–Sr–Pb isotopic characterization of marginal basins with constraints to geotectonic setting and provenance. Tectonophysics 352: 33–64.

LINNEMANN U, GEHMLICH M, TICHOMIROWA M, BUSCHMANN B, NASDALA L, JONAS P, LÜTZNER H, BOMBACH K (2000) From Cadomian subduction to Early Palaeozoic rifting: the evolution of Saxo-Thuringia at the margin of Gondwana in the light of single zircon geochronology and basin development (Central European Variscides, Germany). In: Franke, W., Haak, V., Oncken, O. & Tanner, D. (eds) Orogenic processes: quantification and modelling in the Variscan Belt. Geological Society, London, Special Publications, 179, 131–153.

MELICHAR R (1995) The structural analysis of the Polička and Svratka units. Unpublished PhD thesis, Charles University, Prague, pp 1–271 (in Czech)

NOWAK I, ŻELAŻNIEWICZ A, DÖRR W, FRANKE W, LARIONOV AN (2011) The Izera metabasites, West Sudetes, Poland: geologic and isotopic U–Pb zircon evidence of Devonian extension in the Saxothuringian Terrane. Lithos 126: 435–454.

PERTOLDOVÁ J, VERNER K, VRÁNA S, BURIÁNEK D, ŠTĚDRÁ V, VONDROVIC L (2010) Comparison of lithology and tectonometamorphic evolution of units at the northern margin of the Moldanubian Zone: implications for geodynamic evolution in the northeastern part of the Bohemian Massif. Journal of Geosciences 55: 299–319.

PHARAOH TC (1999). Palaeozoic terranes and their lithospheric boundaries within the Trans-European Suture Zone (TESZ): a review. Tectonophysics 314: 17–41.

PITRA P (2012) Emplacement, structural and P–T evolution of the ~346 Ma Miřetín Pluton (eastern Teplá–Barrandian Zone, Bohemian Massif): implications for regional transpressional tectonics – Discussion. Journal of Geosciences 57: 189–191.

PITRA P, BURG JP, SCHULMANN K, LEDRU P (1994) Late orogenic extension in the Bohemian Massif: petrostructural evidence in the Hlinsko region. Geodinamica Acta 7: 15–30.

PRIOR DJ, BOYLE AP, BRENKER F, CHEADLE MC, DAY A, LOPEZ G, PERUZZO L, POTIS GJ, REDDY S, SPIESS R, TIMMS NE, TRIMBY P, WHEELER J, ZETTRSTROM L (1999) The application of electron backscatter diffraction and orientation contrast imaging in the SEM to textural problems in rocks. Amer Miner 84: 1741–1759.

SCHECK M, BAYER U, OTTO V, LAMARCHE J, BANKA D, PHARAOH T (2002) The Elbe Fault System in North Central Europe – a basement controlled zone of crustal weakness. Tectonophysics 360: 281–299.

SCHULMANN K, KRÖNER A, HEGNER E, WENDT I, KONOPÁSEK J, LEXA O, ŠTÍPSKÁ P (2005) Chronological constraints on the pre-orogenic history, burial and exhumation of deep-seated rocks along the eastern margin of the Variscan orogen, Bohemian Massif, Czech Republic. American Journal of Science 305: 407–448.

SCHULMANN K, LEXA O, ŠTÍPSKÁ P, RACEK M, TAJČMANOVÁ L, KONOPÁSEK J, EDEL JB, PESCHLER A, LEHMANN J (2008) Vertical extrusion and horizontal channel flow of orogenic lower crust: key exhumation mechanisms in large hot orogens? Journal of Metamorphic Geology 26: 273–297.

SLÁMA J, DUNKLEY DJ, KACHLÍK V, KUSIAK MA (2008) Transition from island-arc to passive setting on the continental margin of Gondwana: U–Pb zircon dating of Neoproterozoic metaconglomerates from the SE margin of the Teplá–Barrandian Unit, Bohemian Massif. Tectonophysics 461: 44–59.

SYNEK J, OLIVERIOVÁ D (1993) Terrane character of the north-east margin of the Moldanubian Zone: the Kutná Hora Crystalline Complex, Bohemian Massif. Geol Rundsch 82: 566-582

TAJČMANOVÁ L, SOEJONO I, KONOPÁSEK J, KOŠLER J, KLÖTZLI U (2010) Structural position of high-pressure felsic to intermediate granulites from NE Moldanubian domain (Bohemian Massif). Journal of the Geological Society, 167: 329–345.

TROPPER P, DEIBL I, FINGER F, KAINDL R (2006) P–T–t evolution of spinel–cordierite–garnet gneisses from the Sauwald Zone (Southern Bohemian Massif, Upper Austria): is there evidence for two independent late-Variscan low-P/high-T events in the Moldanubian Unit? International Journal of Earth Sciences 95: 1019–1037.

VERNER K, ŽÁK J, HROUDA F, HOLUB FV (2006) Magma emplacement during exhumation of the lower- to mid-crustal orogenic root: the Jihlava syenitoid pluton, Moldanubian Unit, Bohemian Massif. Journal of Structural Geology 28: 1553–1567.

VERNER K, ŽÁK J, NAHODILOVÁ R, HOLUB F (2008) Magmatic fabrics and emplacement of the cone-sheet-bearing Knížecí Stolec durbachitic pluton (Moldanubian Unit, Bohemian Massif): implications for mid-crustal reworking of granulitic lower crust in the Central European Variscides. International Journal of Earth Sciences, 97: 19–33.

VERNER K, BURIÁNEK D, VRÁNA S, VONDROVIC L, PERTOLDOVÁ J, HANŽL P, NAHODILOVÁ R (2009) Tectonometamorphic features of geological units along the northern periphery of the Moldanubian Zone. Journal of Geosciences, 54, 87–100.

VERNER K, ŽÁK J, ŠRÁMEK J, PACLÍKOVÁ J, ZAVŘELOVÁ A, MACHEK M, FINGER F, JOHNSON K (2014). Formation of elongated granite–migmatite domes as isostatic accommodation structures in collisional orogens. Journal of Geodynamics, doi:10.1016/j.jog.2013.10.002

VONDROVIC L, VERNER K (2010) The record of structural evolution and U–Pb zircon dating of the tonalite intrusions (Polička Crystalline Unit, Bohemian Massif). Trabajos de Geología 30: 316–321.

VONDROVIC L, VERNER K, BURIÁNEK D, HALODOVÁ P, KACHLÍK V, MÍKOVÁ J (2011) Emplacement, structural and P–T evolution of the ~346 Ma Miřetín Pluton (eastern Teplá–Barrandian Zone, Bohemian Massif): implications for regional transpressional tectonics. Journal of Geosciences 56: 343–357.

VRÁNA S, BLÜMEL P, PETRAKAKIS K (1995) Moldanubian Zone – metamorphic evolution. In: Dallmeyer, R. D., Franke, W. & Weber, K. (eds) Pre-Permian geology of Central and Eastern Europe. Springer, Berlin, 453–468.

WENZEL T, MERTZ DF, OBERHÄNSLI R, BECKER T, RENNE PR (1997) Age, geodynamic setting, and mantle enrichment processes of a K-rich intrusion from the Meissen Massif (northern Bohemian Massif) and implications for related occurrences from the mid-European Hercynian. Geologische Rundschau 86: 556–570.

WILLNER AP, SEBAZUNGU E, GERYA TV, MARESCH WV, KROHE A (2002) Numerical modelling of PT-paths related to rapid exhumation of high-pressure rocks from the crustal root in the Variscan Erzgebirge Dome (Saxony/Germany). Journal of Geodynamics 33: 281–314.

WINCHESTER JA (2002) Palaeozoic amalgamation of Central Europe: new results from recent geological and geophysical investigations. Tectonophysics, 360, 5–21.

ŽÁK J, HOLUB FV, VERNER K (2005) Tectonic evolution of a continental magmatic arc from transpression in the upper crust to exhumation of mid-crustal orogenic root recorded by episodically emplaced plutons: the Central Bohemian Plutonic Complex (Bohemian Massif). International Journal of Earth Sciences, 94, 385–400.

ŽÁK J, KRATINOVÁ Z, TRUBAČ J, JANOUŠEK V, SLÁMA J, MRLINA J (2011) Structure, emplacement, and tectonic setting of Late Devonian granitoid plutons in the Teplá–Barrandian unit, Bohemian Massif.

International Journal of Earth Sciences, 100, 1477–1495.

ŽÁK J, VERNER K, JANOUŠEK V, HOLUB FV, KACHLÍK V, FINGER F, HAJNÁ J, TOMEK F, VONDROVIC L, TRUBAČ J (2014) A plate-kinematic model for assembly of the Bohemian Massif constrained by structural relationships around granitoid plutons. In Schulmann,K.; Martínez Catalán,J.R; Lardeaux,J.M.; Janoušek,V.; Oggiano,G: The Variscan orogeny: extent, timescale and the formation of the European crust, s. 169-196. Special Publications of the Geological Society of London 405.