Silva Gabreta	vol. 16 (3)	p. 127–148	Vimperk, 2010

Lithological composition and geodynamic evolution of the south-eastern part of the Bohemian Forest (Moldanubian Zone, Bohemian Massif)

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Abstract
The SE part of the Šumava Mts. (the Bohemian Forest) offers a unique opportunity to observe the interaction of deformations in high-grade metamorphic rocks with development of magmatic fabrics in contemporaneous intrusions in a fluid state, proceeding at temperatures above ~700°C and pressures corresponding to depths of ~20–30 km. The geological history is related to the Variscan orogenic processes, which, in this region of the so-called Moldanubian Zone, can be divided into (1) exhumation of the deep-seated rocks at ~343–335 Ma associated with emplacement of ultrapotassic, Mg-K-rich (durbachite) intrusions, immediately followed by an LP–HT metamorphic event and anatexis; (2) intrusion of large volumes of high-K I-type Weinsberg granitoids into the partially exhumed Moldanubian rocks syntectonic with distinct younger deformations at ~332–320 Ma, overlapping with emplacement of peraluminous S-type Eisgarn posttectonic granites contemporaneous with the activity of the Pfahl Shear Zone at ~325 Ma. Synoptic petrological and geochemical description of the involved rock types is also presented.

Keywords: Šumava Mountains, Bohemian Forest, Variscan orogeny, Moldanubian Zone, tectonometamorphic processes, structures

Introduction

This article is concerned with the lithological composition and structural pattern of granitoid intrusions and host high-grade metamorphic rocks, based on a multidisciplinary approach stemming from a combination of different data sets (structural and petrological research, geochemistry and geochronology). The internal fabrics and structures of the studied rocks reflect the kinematic history and evolution of the regional strain field. The examined area provides crucial constraints for the geodynamic models of geological evolution of deeper parts of the Variscan orogen in the SW part of the Bohemian Massif (Fig. 1). For this purpose, we have studied particularly the durbachitic Knížecí Stolec pluton and two distinct granite intrusions built by Weinsberg and Eisgarn types (Strážný and Plechý plutons). These rocks intruded the high-grade Moldanubian Zone during and shortly after a regional low-pressure (LP) and high-temperature (HT) metamorphic event. Our examination of the evolution of the Variscan orogenic processes then focused on two distinct time periods: (i) ~343–335 Ma – the episode of rapid exhumation of high-grade rocks associated with polyphase deformation and HT–LP retrograde metamorphism. These processes were associated with the emplacement of magnesium-rich ultrapotassic plutons (e.g. mela-syenite to mela-granite, also called durbachite). (ii) ~335–310 Ma – the time after the main period of retrograde metamorphism in the innermost part of the orogenic belt. In this time period, the exhumed lower to middle crust was intruded by large volumes of peraluminous, S and transitional I/S type granitoids (e.g. the Weinsberg and Eisgarn granite, which belong to the Moldanubian Plutonic Complex) (Verner et al. 2009 and references therein).

Geological setting

The European Variscides formed during collision of Gondwana-derived crustal segments with the Old Red continent during Middle Devonian to Carboniferous times (e.g. Franke 1989).

The Moldanubian Zone (MZ) represents exhumed lower- to mid-crustal rocks of the central part of the Variscan orogen (e.g. Urban & Synek 1995). In general, the structures of the MZ resulted from several Variscan tectonometamorphic events: (i) crustal thickening (~350–341 Ma; e.g. Franěk et al. 2006); (ii) rapid exhumation of lower to mid-crustal rocks and the HT–LP metamorphic event (~343–335 Ma; e.g. Friedl et al. 1993); (iii) regional transpressive events affecting the southern part of the MZ (~332–320 Ma, e.g. Finger et al. 2007) and (iv) later (Permian) localized wrench tectonics (e.g. Brandmayr et al. 1995).

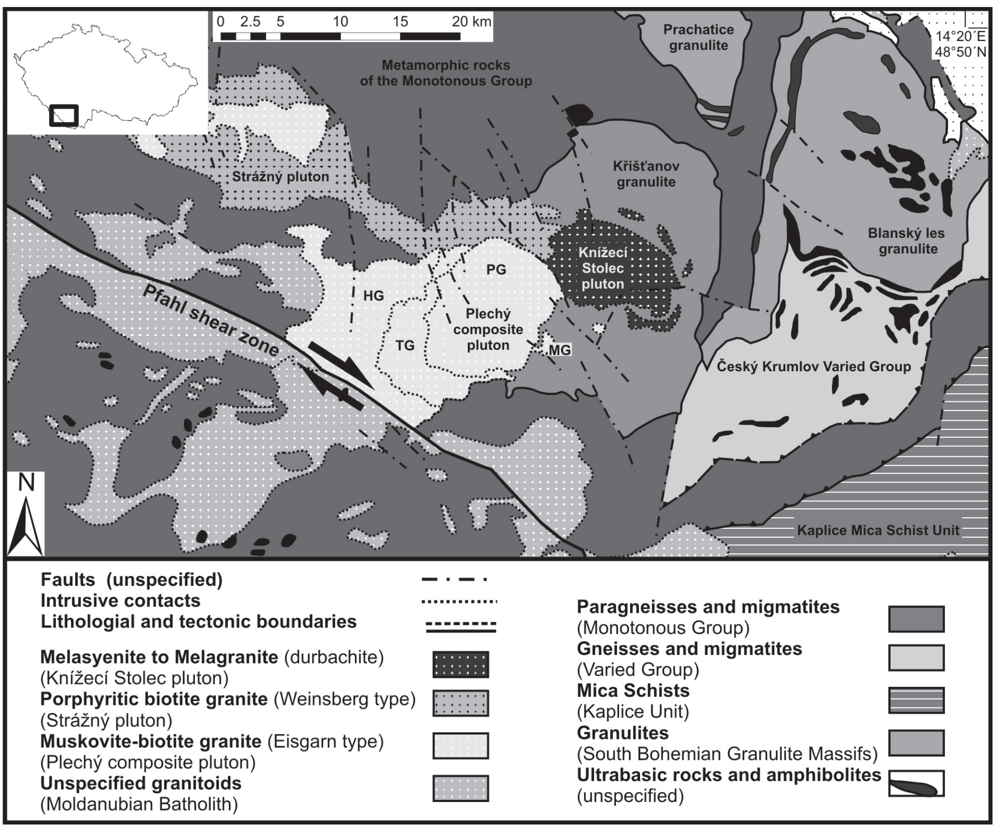

Fig. 1. Geological map of the studied region based on the 1:500,000 geological map published by the Czech Geological Survey. HG – Haidmüller granite, TG – Třístoličník granite, PG – Plechý granite, MG – Marginal granite.

The Moldanubian Zone comprises two major units with contrasting tectonometamorphic evolution: (i) the mid-crustal unit including Monotonous and Varied Groups and (ii) the lower-crustal Gföhl Unit (GU). The rocks of the mid-crustal unit consist of metamorphosed sedimentary and volcanosedimentary sequences of problematic protolith age (partially Lower Paleozoic; Drábek & Stein 2003) with PT conditions of regional metamorphism ~630–760°C and ~0.4–0.8 GPa (e.g. Petrakakis 1997; Kalt et al. 1999). The high-grade GU is composed of orthogneisses, felsic migmatites, granulites, eclogites, and peridotites. Estimations of PT conditions of peak metamorphism in the GU are ~950–1050°C and ~1.4–2.1 GPa, followed by retrograde metamorphism at ~600–800°C and ~0.6–0.8 GPa (Owen & Dostal 1996, Medaris et al. 2005).

The tectonometamorphic history of the MZ described above was associated with magmatic activity during the partial stages of the geodynamic evolution (see Finger et al. 1997): (i) Syn-collisional Late Devonian–Early Carboniferous metaluminous, calc-alkaline and high-K, I-type intrusions (~370–340 Ma); (ii) Exhumation of the deep-seated rocks at ~343–336 Ma was associated with ascent of the ultrapotassic, magnesium-rich plutons (e.g. Holub et al. 1997, Verner et al. 2008); (iii) During and shortly after the LP–HT metamorphic event (~332–310 Ma), the exhumed rocks of the MZ were intruded by large volumes of peraluminous, S-type and high-K I-type granitoids, the last of which were of calc-alkaline composition (e.g. Gerdes 2001; Siebel et al. 2008).

Lithology and petrological evolution

Metamorphic rocks

Monotonous and Varied Groups

Based on the lithological composition, the mid-crustal rocks are traditionally divided into the Monotonous and Varied Groups. In addition to high-grade paragneisses, the Varied Group contains numerous intercalations of amphibolites, marbles, calc-silicate rocks, orthogneisses, quartzites and graphitic gneisses. The Monotonous Group, which predominates in the study area (see Fig. 1), consists of only paragneisses with less abundant intercalations of quartzites and amphibolites.

Bt-paragneisses (Fig. 2) represent the most frequent rock type, which originated by metamorphism of greywackes under higher amphibolite-facies conditions. They crop out in the E part of the described area, S and W of the granulite massifs and in a N–S trending Lhenice Zone amongst them. These fine-grained grey to brown-grey lepidogranoblastic rocks often exhibit signs of migmatitization. The melt usually segregates into ~cm thick bands or lenses parallel to the foliation planes, leaving mesosome and melanosome layers in between. The mineral assemblage of these rocks is Bt – Pl – Kfs – Qtz – Grt – Crd – Mu – Sil; in rare cases, the rocks contain lenses of segregation quartz. The compositions of the main rock-forming minerals are relatively homogeneous (e.g. Pl (An 10–30), Bt (phlogopite–annite, X_{Fe} = 2.9, TiO_2 = 2.9 wt%) and Grt (Alm 66–84, Prp 8–24, Grs 1–6, Sps 2–4)). Sillimanite occurs both as the fibrolitic and, less frequently as the prismatic form, while cordierite is observed in two distinct generations (older pinitized grains or garnet reaction rims). The accessory minerals are spinel, ilmenite, pyrhotite, apatite and monazite. The petrological evolution of the paragneisses can be untangled in detail only for the last stages of metamorphic history, due to poor preservation of relict older mineral assemblages. In domains with stable Grt and Crd (in SW part of the studied area), the metamorphic conditions were estimated at ~700–710°C and ~0.44–0.46 GPa. For development of local Spl-bearing domains enclosed in Crd grains, the PT conditions were approximately 670–700°C at 0.28–0.30 GPa (PERTOLDOVÁ eds. 2006). The paragneisses to migmatites of the Monotonous Group are geochemically highly variable (for a general review, see VRÁNA 1992 and references therein).

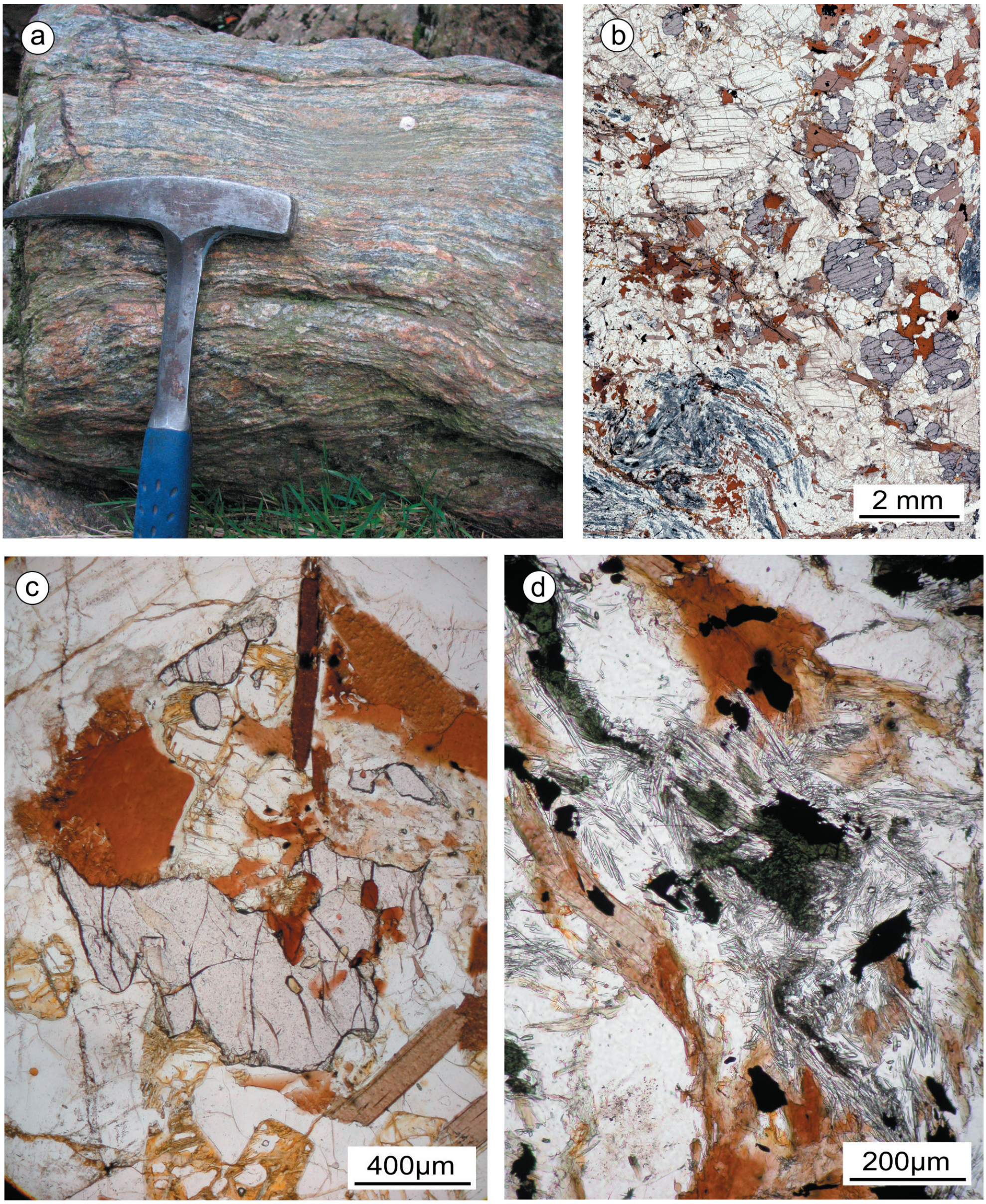

Fig. 2. Monotonous and Varied Groups. (a) Late WNW–ESE fabric developed in Crd-bearing migmatized paragneiss. (b) Grt- and Sil-rich domains folded inside Sil–Crd migmatized paragneiss. Scan of a thin section. (c) Relic of Grt, pinitised Crd and Bt, which breaks down to a Bt–Qtz symplectite. II nicols. (d) Crd rim around Grt. Spl crystalizes in this reaction rim between Crd and mixture of Sil with Bt. II nicols.

The SiO_2 contents range between 56 and 72 wt%, FeO, MgO, CaO and Al_2O_3 concentrations depending on the leucosome content (Table 1). Generally, these rocks exhibit high K_2O/Na_2O (1.4–3.4) and A/CNK (1.5–3) ratios. Compared to the upper crustal values averaged by Taylor & McLennan (1985), the paragneisses are depleted in Sr and Zr, but slightly enriched in Y, Yb, Th, U, Rb and Ba. The REE are relatively abundant (115–315 ppm) with an LREE fractionation trend (Ce_n/Sm_n = 2.4–3.2) and a negative Eu anomaly (Eu/Eu^* = 0.6), characterizing a normalized curve (Patočka 1991).

Bt and Grt–Bt orthogneisses forms numerous asymmetric intercalations up to ~1 km long distributed irregularly throughout the described area. Their orientations are mostly parallel to the regional metamorphic fabrics. The composition corresponds especially to leucocratic Bt-granite. These rocks consist of quartz and plagioclase (often weakly zoned and lamellar oligoclase), Kfs (microcline) and garnet. Biotite aggregates occur, often intergrown with Mu or Sil. The main accessory minerals are zircon and turmaline.

Calc-silicate rocks (Fig. 3, 4a–c) occur in lenses elongated parallel to the foliation. These

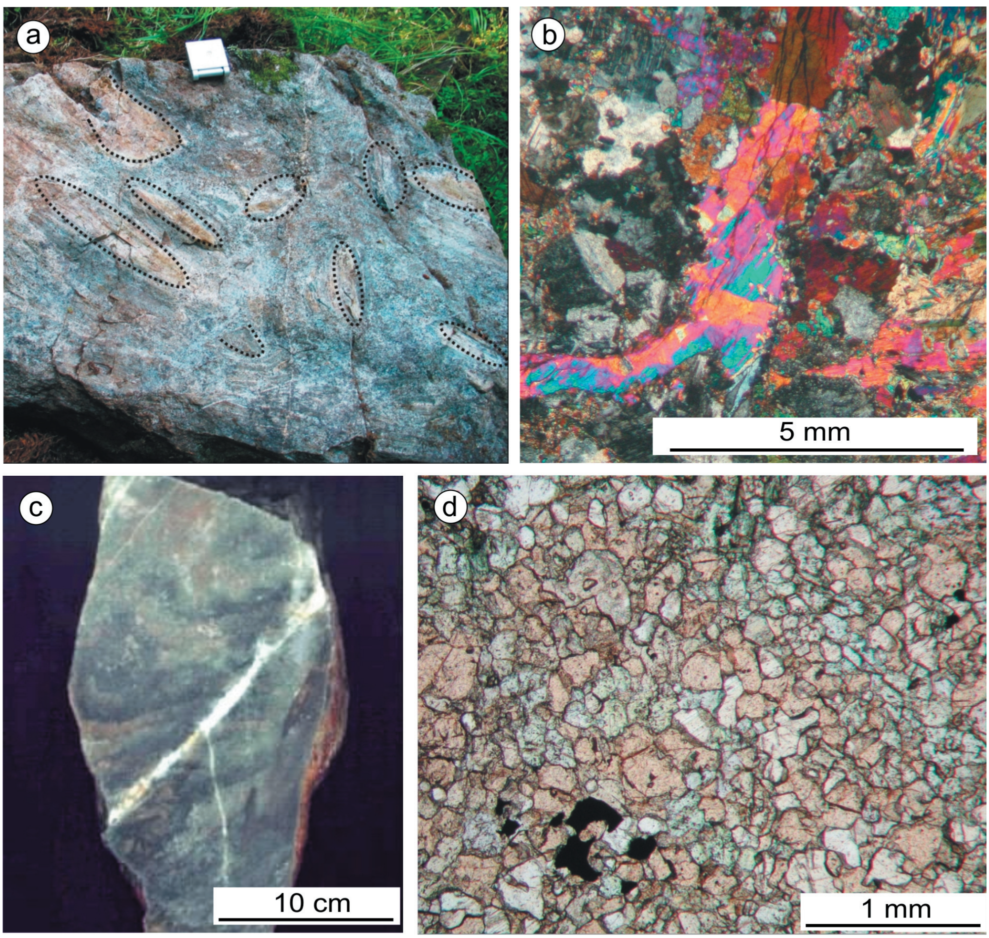

Fig. 3. (a) Calc-silicate rock – lenses of erlan embedded in fine-grained granitoids. (b) Calc-silicate rock – pyroxenic erlan crosscut by a vein of epidote, X nicols. (c) Skarn – compositional banding of Cpx, Grt and Hbl crosscut by a younger carbonate vein. (d) Cpx–Grt skarn with magnetite. II nicols.

rocks can be divided into erlans and skarns. Both of them represent a transitional rock type between carbonate and alumosilicate rocks, which implies their high compositional variability. In one locality, the erlans enclose nodules of a special tremolitic rock bearing Cr-spinel and Co–Ni mineralization (Čopjaková et al. 2005).

The erlans are fine-grained green-grey rocks, which contain Cpx (Di–Hd mixture with Di prevalence, partially recrystallized to Mg-rich Hbl), Pl (An 3–54, rarely even An 99, partially sericitized) and Epi–Czo minerals as the main constituents. The assemblage is complemented by amphibole (Act–Tr), partially chloritized Bt (X_{Fe} = 0.45, with very low Al^{IV} ~ 2.05), Kfs and Qtz.

The Grt–Px skarns are distinguished from the erlans by the presence of Grt (inhomoge-

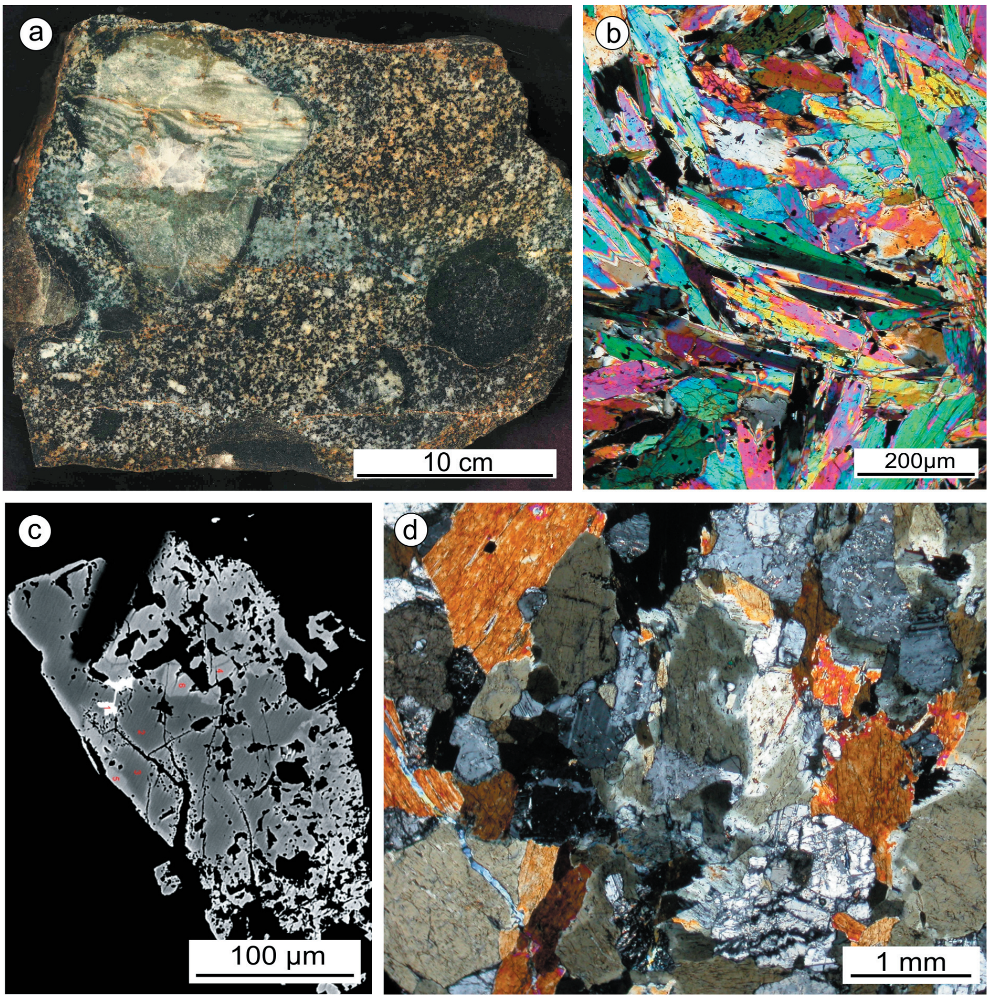

Fig. 4. (a) Tremolitic rock – nodules of the tremolitic rock enclosed in a fine-grained granitoid rock. Railroad cut at Nová Pec. (b) Tremolitic rock – tremolite needles from a tremolitite nodule, with cores of anthophyllitic composition. X nicols. (c) Tremolitic rock – inhomogenous grain of Cr-spinel from the tremolitic rock. BSE image. (d) Amphibolite – equlibrated texture of a coarser-grained amphibolite from the Monotonous Group. X nicols.

Table 1. Representative chemical analyses of the most common rock types. MME refers to Mafic Microgranular Enclaves in the durbachites. All values are presented in wt%. PP – Plechý pluton, SP – Strážný pluton, KG – Křišťanov granulite, BLG – Blanský Les granulite, MG – Monotonous Group, KS – Knížecí Stolec pluton.

	PP	PP	PP	SP		KG	BLG	MG	KS	KS	MG
	mu-bt granite	**mu-bt granite**	**mu granite**	**bt granite**	**leuco-granite**	**granulite**	**granulite**	**migmatite**	**durba-chite**	**MME**	**calc-silica-te rock**
SiO_2	72.36	74.10	73.94	68.22	71.53	71.96	71.98	56.25	54.71	50.27	52.88
TiO_2	0.17	0.36	0.08	0.61	0.21	0.40	0.42	1.09	1.22	1.34	1.24
Al_2O_3	14.66	12.64	14.35	15.16	14.52	17.80	13.53	21.10	12.92	13.87	11.25
Fe_2O_3	0.82	0.60	0.28	0.92	0.34	0.61	1.18	1.14	0.89	1.41	1.20
FeO	0.60	1.35	0.50	2.39	0.92	1.76	2.10	7.44	5.65	5.86	6.12
MgO	0.32	0.41	0.14	0.84	0.30	0.84	0.73	3.43	7.96	8.82	6.72
MnO	0.04	0.04	0.04	0.05	0.03	0.05	0.03	0.12	0.11	0.14	0.28
CaO	0.63	0.72	0.65	1.79	1.77	0.94	1.93	0.37	4.51	4.97	15.28
SrO	0.01	<0.01	n.a.	0.01	n.a.	0.01	n.a.	0.01	0.05	0.05	0.03
BaO	0.05	0.01	n.a.	0.07	0.02	0.06	n.a.	0.09	0.19	0.20	0.06
Li_2O	0.03	0.03	0.03	0.02	0.03	0.01	n.a.	0.02	0.01	0.02	0.01
Na_2O	2.09	2.65	4.20	2.75	3.20	2.71	2.76	1.22	1.78	1.50	1.72
K_2O	5.10	4.65	4.20	5.24	5.35	5.70	4.01	4.18	6.57	7.37	1.70
P_2O_5	0.30	0.37	0.25	0.22	0.26	0.20	0.15	0.10	0.95	1.19	0.66
F	0.09	0.30	0.05	0.10	0.10	0.09	n.a.	0.13	0.29	0.29	0.19
CO_2	<0.01	0.01	n.a.	0.02	0.02	0.01	0.03	0.01	0.02	0.01	0.03
S(tot)	0.01	<0.01	n.a.	<0.01	0.01	<0.01	n.a.	0.02	0.04	0.02	0.01
H_2O^+	0.75	1.17	n.a.	1.22	0.87	1.50	0.56	2.15	I.70	1.93	1.37
H_2O^-	0.17	0.11	0.15	0.24	0.15	0.16	0.22	0.20	0.11	0.15	0.11
F(ekv)	n.a.	<0.01	0.02	<0.01	<0.01	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
S(ekv)	n.a.	<0.01	n.a.	1.00	<0.01	<0.01	n.a.	<0.01	<0.01	<0.01	<0.01
Total	99.20	99.88	99.30	99.89	99.46	100.06	99.63	99.12	99.71	99.44	100.09

nous hypidiomorphic grains of the average composition Alm 20–38, Sps 21–33, Grs 27–48, Prp 1–5, Adr 2–3). In addition, they contain Cpx (roughly equal admixture of Di and Hd) and Pl (An 41–97).

The tremolitic rock forms almost monomineralic, oval-shaped nodules ~1–30 cm in size, sharply bounded with respect to the surrounding calc-silicate rocks. The amphiboles correspond to tremolite or Mg-rich actinolite; the tremolites enclose relics of Mg-rich cummingtonite–grunerite or Mg-rich anthophyllite–gedrite amphiboles. The accessory minerals are represented by nickeline, gersdorffite (Co = 0.5–7.3 at%) and Cr-spinel. Low Mg# and increased Zn and Mn indicate that the primary magmatic composition of the spinels was affected by regional metamorphism. The rock probably represents an ultramafic protolith from the crust–mantle transition tectonically incorporated in the calc-silicate rock before regional metamorphism under amphibolite-facies conditions (Čopjaková et al. 2005).

Amphibolite (Fig. 4d) forms most of the intercalations in the Varied Group, occurring either alone or spatially related to marbles. The distribution is heterogeneous with zones extremely rich in amphibolites and zones almost lacking them. An up to 500m thick dismembered stripe of amphibolite occurs along the boundary of the granulite massifs. In other cases, the intercalations parallelized to surrounding fabrics are up to several km long with a smaller thickness. High chemical variability is reflected in the wide spectrum of varieties ranging from leucocratic amphibolites to very dark ones. A common fine-grained amphibolite consists of green hornblende, plagioclase (andesine–labradorite) and quartz. Some occurrences also contain clinopyroxene, garnet, K-feldspar, tremolitic amphibole and higher amounts of ore minerals. Bt-amphibolites represent a transition to Hbl-paragneisses.

Marbles to dolomitic marbles form thin bodies elongated parallel to the surrounding foliation, especially in some parts of the Varied Group. The high chemical variability of these fine- to medium-grained rocks ranges from marbles through dolomitic marbles to rare metadolomites, with variable contents of Qtz and silicate minerals. The mineral assemblage is thus very heterogeneous, containing, in addition to Cc and Dol, also diopsidic pyroxene usually consumed by tremolite, phlogopite, scapolite, plagioclase (andesine to anortite), titanite, graphite, clinozoisite, sulphides, forsterite and chondrodite. The colour depends predominantly on the content of graphite and silicates, ranging from white through light green to dark grey.

Quartzites form elongated bodies parallel with the foliation, usually shorter than 1 km and ~10 m thick. The dominant Qtz is accompanied by Pl (basic oligoclase to andesine), Kfs, Bt and locally Mu, Grt, Sil or Cpx.

Graphitic gneisses occur in the Varied Group, forming lenses up to 10 m thick, usually in the neighbourhood of marbles. The graphite content ranges from X.0 to 40 %, so that these rocks were mined for graphite from historical times to the recent past. Except for Grf, the mineral composition is comparable to the gneisses; Grf in lower concentrations was also observed in Qtz-paragneisses and Si-rich erlans.

South Bohemian granulite massifs

In our study area, high pressure rocks are represented by two large massifs of felsic granulites (Fig. 1, 5), the Křišťanov and Blanský Les massifs, which enclose small bodies of mafic granulites, serpentinized peridotites, mantle eclogites and rare hornblendite. Altogether, these rocks represent distinct high-grade metamorphics, which were exhumed from the Variscan lower crust, probably from the crust–mantle transition. The most abundant rock type, felsic granulites, underwent heterogeneous retrogression during their ascent and emplacement into the present-day tectonic position. This heterogeneity resulted in a variety of felsic rocks that record different stages of their exhumation, which nevertheless share a common protolith.

This is also evident from numerous geochemical analyses, which document that the felsic granulites in various stages of retrogression are compositionally a very homogenous group of rocks (Janoušek et al. 2004). They are composed of 69–73 wt% of SiO_2, 13–18% Al_2O_3, 2.6–3.5% Na_2O, 3.4–5.7% K_2O, 0.9–2% CaO, 1.5–3.3% FeO and 0.5–1.4% MgO (Table 1; Janoušek et al. 2004). With higher Si content, the rocks have systematically lower Fe, Mg and Ti contents. The granulite gneisses are weakly depleted in LIL elements (Rb 50–320 ppm, Sr 20–130 ppm), with more pronounced depletion in Th (up to 10 ppm), U (up to 7 ppm) and Zr (30–170 ppm). Higher concentrations of Y (30–50 ppm) are characteristic for

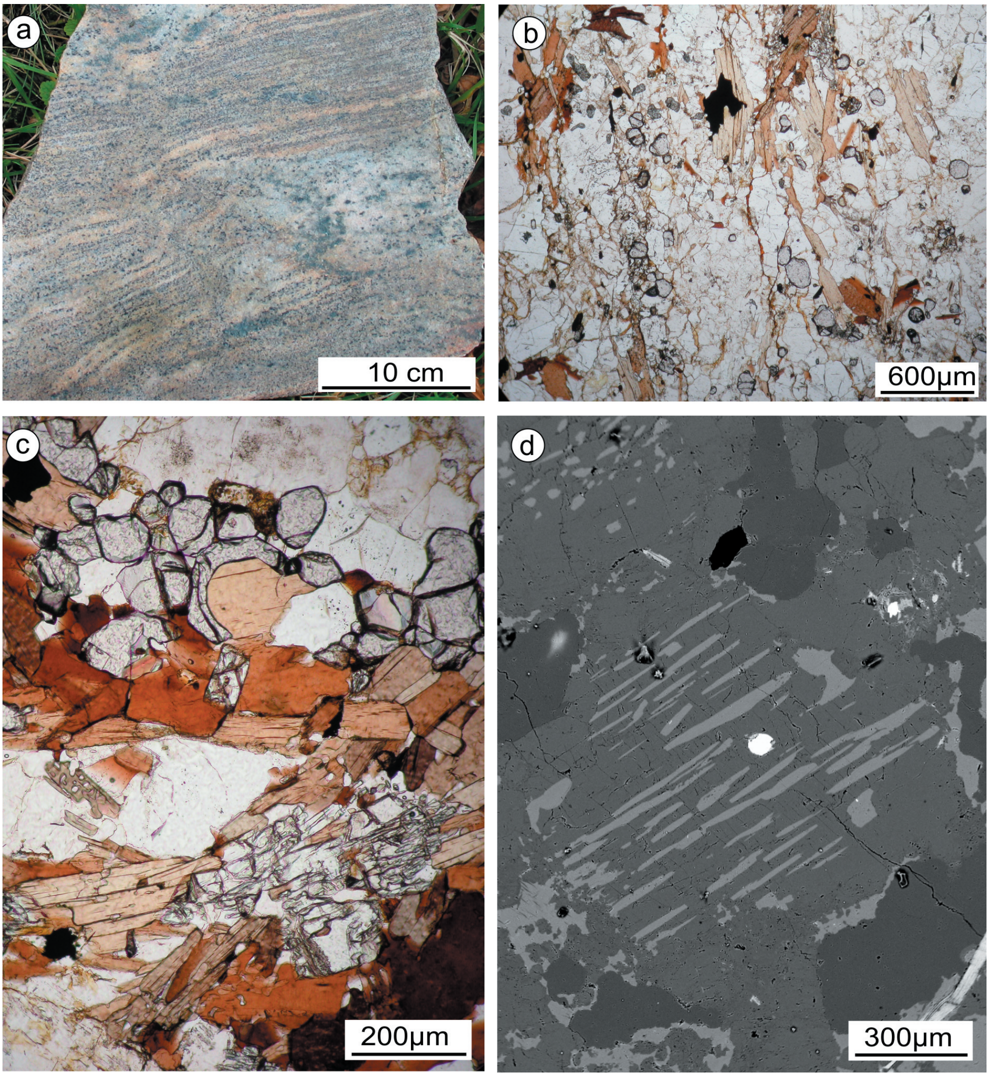

Fig. 5. Granulite and retrogressed granulite. (a) Grt–Bt granulitic gneiss of lower degree of retrogression. (b) Grt–Bt retrogressed granulite. II nicols. (c) Detail of a Grt–Bt–Sil intergrowth from a retrogressed felsic granulite. II nicols. (d) Antiperthitic exsolutions of K-feldspar in oligoclasse, forming originally a single ternary feldspar. BSE image.

the felsic granulites, while the REE contents range from 120 to 170 ppm. REE normalized curves exhibit very similar trends for all the available analyses with fractionated LREE (Ce_n/Sm_n = 1.3–3.4) and a flat trend of HREE (Eu_n/Yb_n = 0.5–0.8). The samples exhibit a typical negative Eu anomaly (Eu/Eu^* = 0.14–0.62). The chemical evolution indicates that the precursor of these rocks could have been metamorphosed Lower Paleozoic granitoids or high-pressure melts of granitic composition (Jakeš 1969, Fiala et al. 1987; Vrána 1989, Wendt et al. 1994; Janoušek et al. 2006 and references therein).

The metamorphic conditions of the Křišťanov granulite massif were recently examined by Verner et al. (2008). Two samples of the Křišťanov granulite were analysed to characterize the metamorphic evolution of the granulite and to estimate the P–T conditions of regional fabric formation. Using the chemical composition of the two felsic granulite samples, a PT pseudosection in an NCKFMASH system (Na_2O – CaO – K_2O – FeO – MgO – Al_2O_3 – SiO_2 – H_2O) was calculated in the Thermocalc software (Powell & Holland 1999). Based on detailed petrological study of an early steep foliation developed in this massif, the mineral association of peak metamorphic conditions was identified as Kfs – Pl (core to rim: Ab 74 to 75, An 24 to 25, Or 1 to 2) – Grt (Grs 2–10, Prp 18–20, Alm 66–73, Sps 1–2) – Ky – Qtz, which corresponds to the Kfs – Pl – Qtz – Grt – Ky – Liq field in the pseudosection. Microchemical analyses of the involved minerals then indicate PT conditions of 831±69°C and 1.11±0.16 GPa. The retrograde metamorphism related to the development of a younger flat-lying foliation is characterized by breakdown of Ky to Sil and Grt to Bt with Sil to develop the Grt II – Bt – Sil – Pl – Kfs – Qtz assemblage. The chemical composition of the retrograde minerals (Grt – Grs 2 Prp 20 Alm 76 Sps 2, Bt X_{Mg} = 0.50–0.56, Kfs – Ab 11–17 An 0–1 Or 82–89, Pl – Ab 70 An 29 Or 1) indicates PT conditions of their growth at 768±76°C and 0.75±0.18 GPa (Verner et al. 2008). With an increasing degree of retrogression, the felsic granulites contain dark bands with strong preferred orientation of abundant biotite aggregates. The petrological studies of the Blanský Les massif are much more extensive, but the majority of this massif occurs outside the area of interest. Due to better preservation of early granulite-facies fabrics, the peak metamorphic conditions based on study of both felsic and mafic granulites indicate temperatures of 850–1000°C at pressures of 1.6–2.0 GPa (e.g. Kröner et al. 2000). The retrograde PT conditions then follow the same path as the neighbouring Křišťanov granulite. Numerous geochronological studies focused on the south Bohemian granulites cluster around 340 Ma, with a few exceptions of older ages (for review see e.g. Kröner et al. 2000, Svojtka et al. 2002).

The description of subordinate rock types below is given in the order of increasing basicity of the rocks.

Pyroxenic to amphibolic granulites form only small bodies with the character of boudins up to several metres in size, especially in granulite massifs. These rocks have a fine-grained texture and are composed of Pl (An 35–45), Cpx, Grt, brown to green Hbl, Bt, Opx and Qtz. Accessory minerals comprise Ap, Zr, Ttn and ore minerals. The contacts with the surrounding felsic granulites are predominantly sharp. In rare cases, the crosscutting relations document intrusions of the younger felsic material into the older mafic material.

Hornblendites occur in the SW tip of the Blanský Les massif as several ~100 m long lenses enclosed in felsic granulites in the vicinity of mantle peridotite bodies. This fine- to medium-grained massive rock is composed of primary Hbl (magnesiohornblende), Cpx (with lamellar exsolutions of Opx), Grt (with dominant Prp component) and small amounts of symplectite evolved by retrogressive breakdown of these minerals. Accessories represent Rt, Zo and An.

Serpentinites and serpentinized peridotites crop out predominantly at the margins of the granulite massifs as oval to highly elongated lenses from dm to several km in size, with

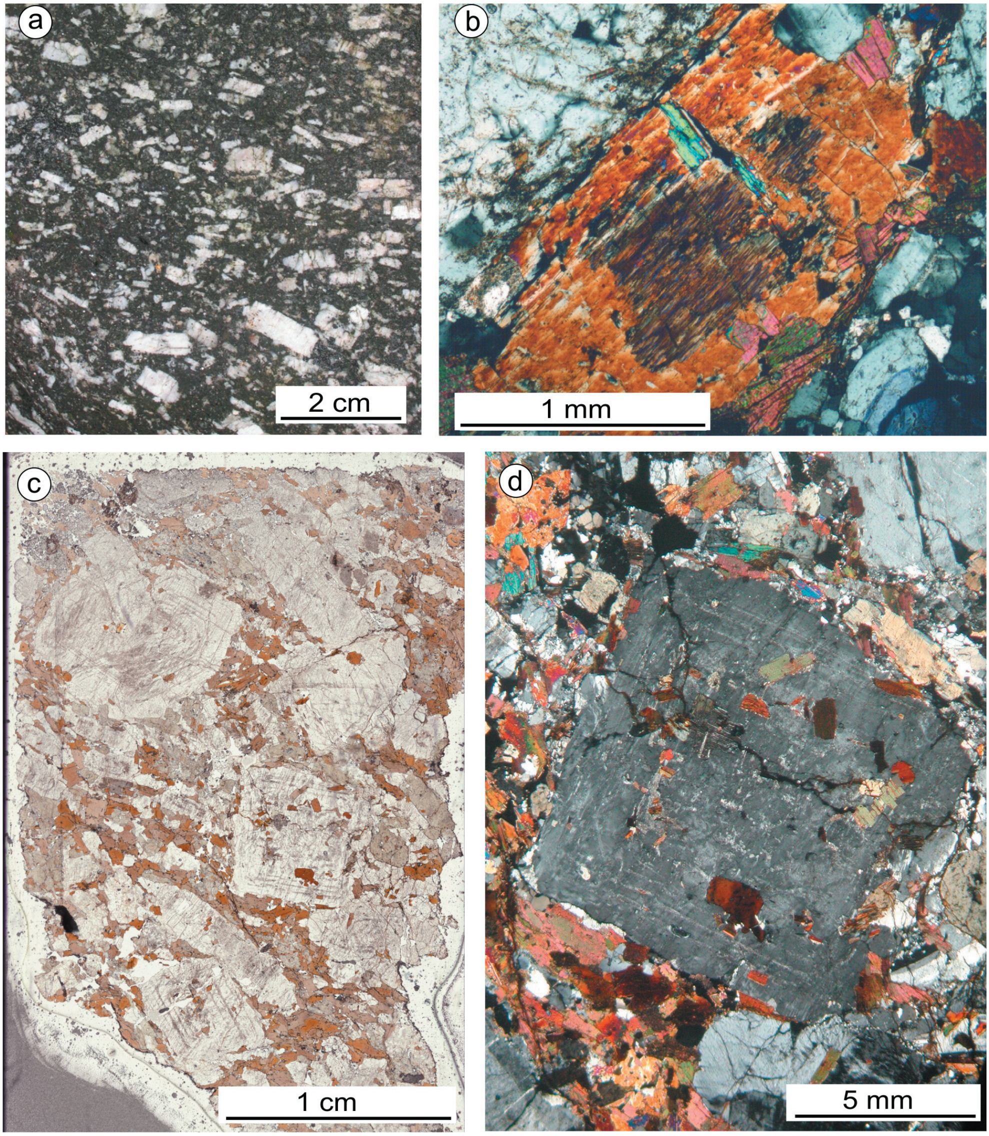

Fig. 6. Durbachites. (a) The Amf–Bt melasyenite (durbachite) exhibiting a magmatic fabric defined by preferred orientation of large Kfs porphyroblasts. (b) Detail of a Hbl crystal enveloping a core of older Cpx. X nicols. (c) Scan of porphyritic durbachite thin section depicting zonal grains of Kfs porphyroblasts. (d) Zoned K-feldspar porphyroblast with inclusions of Hbl, Bt and Qtz. X nicols.

sharp contacts with the surrounding granulites. These rocks represent slices of lithospheric mantle with dm to m scale compositional banding. Dominant Ol (~Fo_{90}) is accompanied by variable amounts of Cpx, Opx, Grt or Spl. The Grt-peridotites contain higher concentrations of Al_2O_3 and CaO, with Grt partially retrogressed to a kelyphitic rim. The serpentinization affected all of the peridotites very heterogeneously, ranging from 5 to almost 100%.

Magmatic rocks

Durbachites of the Knížecí Stolec pluton

The ultrapotassic magmatic rocks (porphyritic amphibole-biotite melasyenite to melagranite, see Fig. 6) are geochemically specific, characterized by relatively higher contents of Mg, K, Cr, Ni, Rb, Cs, U and Th. Durbachites of the Knížecí Stolec pluton are compositionally homogeneous and their chemical composition (major oxides) varies within narrow ranges (see Table 1; Fig. 7). They are relatively rich in SiO_2 (56–62 wt%) but magnesian (MgO 5–9 wt%, commonly 6–8 wt%; 100Mg/(Mg + Fe_{tot}) 51–54) and ultrapotassic (K_2O 6–7 wt%, typical K_2O/Na_2O ~4). In general, their petrogenesis has been interpreted as being a result of mixing of magmas generated from anomalous domains of the sub-continental upper mantle with melts from the lower continental crust (Holub et al. 1997; Gerdes et al. 2000; Janoušek & Holub 2007). Durbachites of the Knížecí Stolec area show variations in the composition of the rock-forming minerals. Phenocrysts of perthitic K-feldspar contain Bt and Pl inclusions and exhibit zoning from core Or_{92} to rim Or_{97}. The plagioclase composition varies from core An_{63} to rim An_{10}. Biotite is compositionally homogeneous with $Fe^{2+}/(Fe^{2+} + Mg) = 0.4$. Amphibole (actinolite) cores contain relics of diopside and actinolite with increased Mg. Fine-grained granitoids contain plagioclase of albitic to oligoclase composition and relatively homogeneous K-feldspar (Or_{89} to Or_{99}). Biotite exhibits variation in the Mg/Fe^{2+} ratio and Al^{IV} content and deformed granites contain biotite with increased Mg. Verner et al. (2008) have dated the intrusion of the durbachites to 340±8 Ma using the U–Pb isotopic system in zircon.

Porphyric Bt granite to granodiorite of the Weinsberg type

Coarse-grained porphyric Bt granite to granodiorite (Fig. 8) is present in the SE part of the Šumava Mts. in two types of intrusions in relation to the content of mineral phases and the geochemical composition (Table 1; Fig. 7). The more acid members (the Strážný and Vítkův Kámen plutons) exhibit SiO_2 contents of up to 68% and are overall weakly peraluminic to

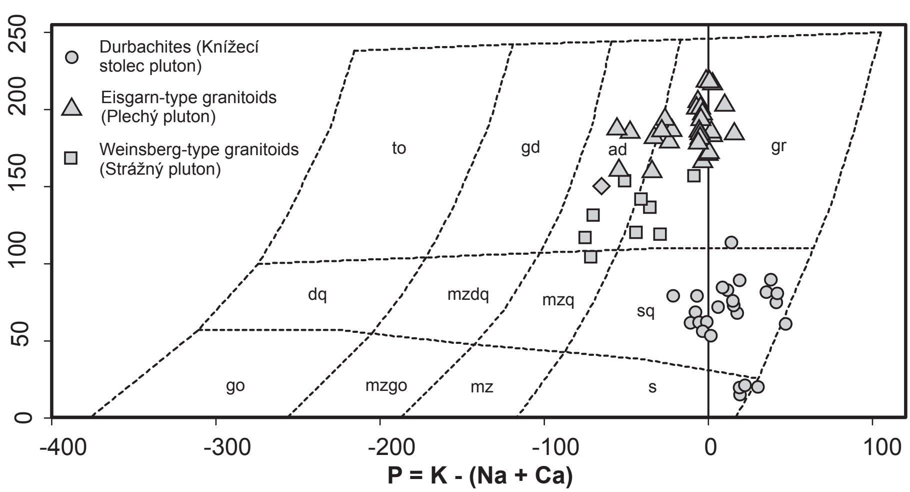

Fig. 7. Geochemical composition of the most prominent rock types. P–Q classification of granitoids according to Debon & Le Fort (1988).

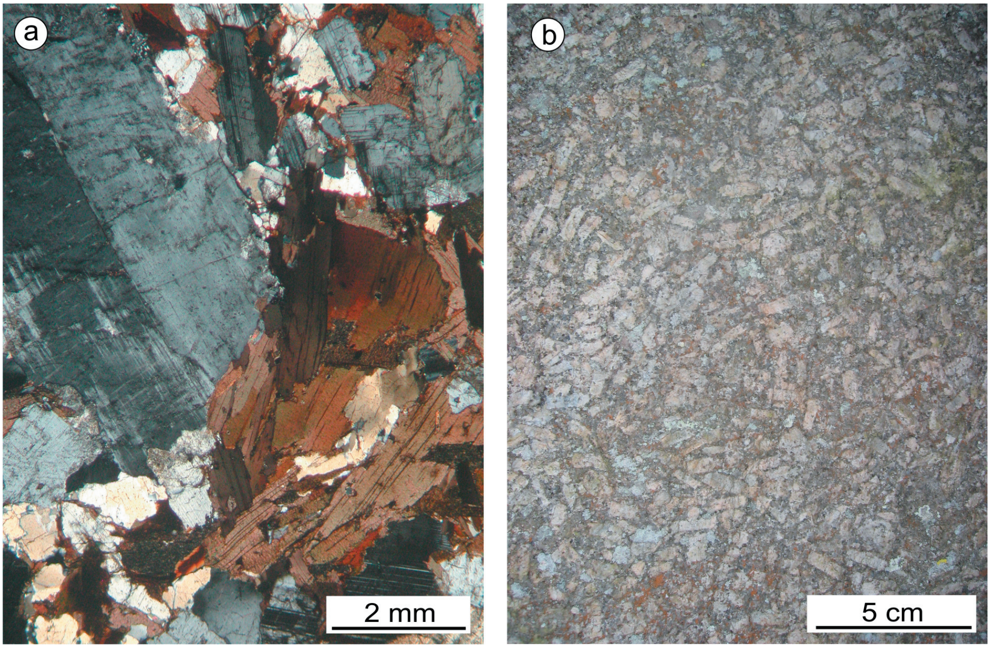

Fig. 8. Weinsberg-type granite and granodiorite. (a) Twinned Kfs crystal embedded in a Bt-rich finer-grained matrix. X nicols. (b) Outcrop of the granodiorite bearing large Kfs and Pl porphyroblasts.

metaluminic granites with higher K_2O contents (3.9–5.3 wt%). The main rock-forming minerals in the biotitic granite are plagioclase (An 27–31), quartz, K-feldspar and two generations of biotite. The older biotite forms partly corroded aggregates, which are enclosed by the second generation of biotite, which differs in TiO_2 content. The TiO_2 in older biotites varies between 3.2 and 3.7 wt%, while the interval for the younger generation is 0.42–0.65 wt%. Accessory minerals include ilmenite (frequently enclosed in biotite) and also apatite, zircon and monazite. Up to approx. 2 vol% of the rock consists of corroded garnet (Alm 78, Prp 7–12, Sps 6–10, Adr 3).

Compared with the more acid variety, the more basic variety – porphyric biotitic granodiorite ("mela-Weinsberg" e.g. at the Říjiště area) – has a lower content of SiO_2 (~62 wt%) and higher content of biotite. The basicity and structure of the plagioclases are similar to those in the more acid variety (An 29–37). The chemical composition of the biotite corresponds to annite with relatively higher TiO_2 content (~4.1 wt%). Accessory minerals include monazite, zircon, ilmenite and apatite. As the Si content increases, the trace element content also changes, with increasing Rb (170–240 ppm) and decreasing Sr (190–130 ppm) and Zr (420–220 ppm). Compared to the average values given for the upper crust (Taylor & McLennan, 1985), these rocks are slightly enriched in Rb, Th and U and poorer in Sr and Nb. The REE contents are relatively high, in the range of 218–322 ppm, while the total REE content decreases with increasing Si. Characteristic features include a strongly negative Eu anomaly ($Eu/Eu^* = 0.39–0.44$) and clear LREE fractionation ($La_n/Sm_n = 2.7–3.2$).

In general, for genesis of granitoids of the Weinsberg type, partial melting of the Moldanubian crust, followed by rapid ascent and crystallization of the magmas (Vellmer & Wedepohl 1994; Gerdes et al. 2000 and references therein).

Plechý composite pluton

The pluton was emplaced into several metamorphic and older plutonic rocks in range ~328 to ~321 Ma (for general review see Verner et al. 2009; Siebel et al. 2008). The Plechý pluton is complexly zoned and is made up of four varieties of S-type granites (Fig. 9): (i) coarse-grained Haidmüller granite (located in the SW part of the pluton), (ii) porphyritic Třístoličník granite (arcuate-shaped unit in the central part of the pluton), (iii) coarse- to medium-grained, weakly porphyritic Plechý granite (NE part of the pluton) and (iv) fine- to medium-grained Marginal granite (small irregular body at the SE margin of the pluton).

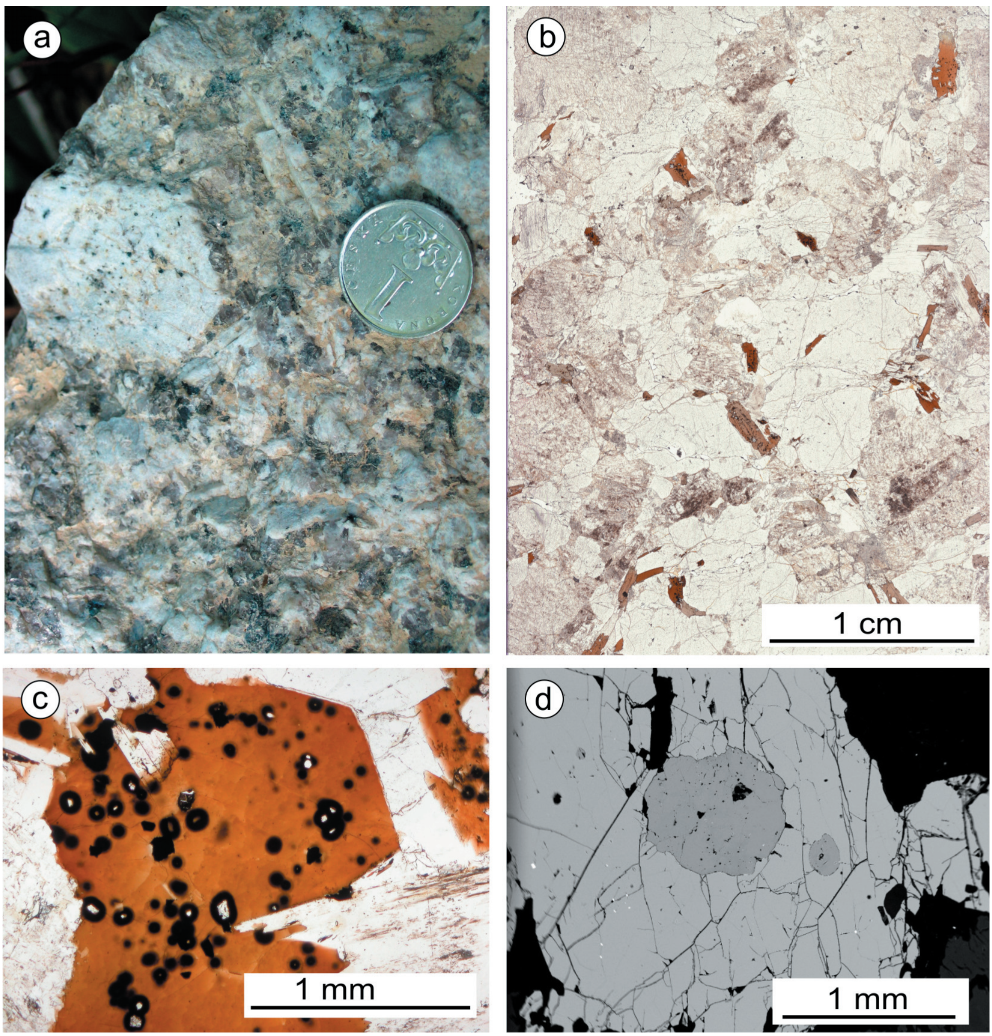

Fig. 9. Eisgarn granites of the Plechý pluton. (a) Plechý variety with only scarce porphyroblasts of feldspar. (b) Plechý Bt–Mu variety, scan of a thin section. (c) Mnz inclusions in Bt from the Třístoličník variety. II nicols. (d) Magmatic Grt grain (light grey) from the Marginal variety, with Ap inclusion (medium gray). BSE image.

The major oxide contents, based on the analysis of 37 whole rock samples, are similar in the four granite varieties (see Fig. 7; Table 1): 71–74% SiO_2, 0.1–1.9% FeO, 0.1–0.7% MgO, 0.4–1% CaO, 1.9–4% Na_2O, 4–6.2% K_2O and 0.1–0.4% P_2O_5. However, the varieties differ considerably in their trace element abundances, as exemplified by the K vs. Rb plot and REE patterns. The content of REE is relatively higher in the Třístoličník granite (with a remarkable negative Eu anomaly), slightly lower in the Plechý granite, and significantly lower in the Marginal granite. In addition, our new extensive data sets from field gamma-spectrometry (Pertoldová et al 2006) clearly indicate that the U and Th contents decrease from the Třístoličník granite (Th 18–65 ppm; U 4–26 ppm) through the Plechý and Haidmühler granites to the Marginal granite.

On the basis of the petrological and geochemical parameters, the emplacement of large volumes of porphyritic granites (the Plechý and Haidmühler granites) was followed by intrusion of the Třístoličník granite into the central part of the pluton. Finally, the outermost and the most evolved garnet-bearing granite (the Marginal granite) was emplaced along the south-eastern margin of the Plechý granite (Verner et al. 2009).

Structural pattern

Metamorphic rocks

Granulites

The Blanský Les granulite (BLG) forms the largest granulite body in Southern Bohemia covering ~278 km^2, and exhibits sigmoidal geometry and a complex structural pattern (Fig. 10, for a detailed review, see e.g. Franěk et al. 2006). The oldest fabrics developed under granulite-facies conditions are defined by weak compositional banding. These foliations dip moderately to steeply to the W or E, being associated with strongly developed subhorizontal stretching lineation. This stage of evolution bears signs of syntectonic decompression in the form of elongated Pl coronas around Ky or Grt grains. These early fabrics were extensively reworked by amphibolite-facies mylonitic steeply dipping foliations, which dominate in this granulite body. The steep foliation constitutes an ~18 km wide sigmoidal asymmetric fold parallel to the margins of the BLG, whose axial planes trend ~N–S with subvertical attitude. This second stage exhibits syntectonic breakdown reactions of Grt to Bt and Ky to Sil, resulting in a rock type called "granulitic gneiss". The retrogression process is accompanied by heterogeneous hydration in the outer parts of the granulite body, which resulted in partial melting to form migmatitic orthogneisses. The older work of Kodym (1972) presents similar results; nevertheless Rajlich et al. (1986) interpret the individual parts of the massif as fragments of large-scale crustal shear zones and Svojtka et al. (2002) interpret the BLG as a positive fan-like structure.

The Křišťanov granulite (KG) horseshoe-like body, 154 km^2 in size, crops out W of the BLG. The oldest fabrics preserved in the KG roughly correspond to the steep amphibolite-facies foliation in the BLG described above. Compared to the BLG, the orientation of these fabrics is less complex, forming a ~15 km wide, single, large-scale fold parallel to the margins of the massif, with subvertical axis and roughly N–S steep axial plane. This steep fabric is heterogeneously reworked by a younger ductile deformation, which resulted in development of shallowly NW dipping to flat-lying regional foliation (Fig. 11a). This younger fabric bears stretching lineation plunging to ~N. The corresponding kinematic indicators suggest a right-lateral movement in the direction of the lineation.

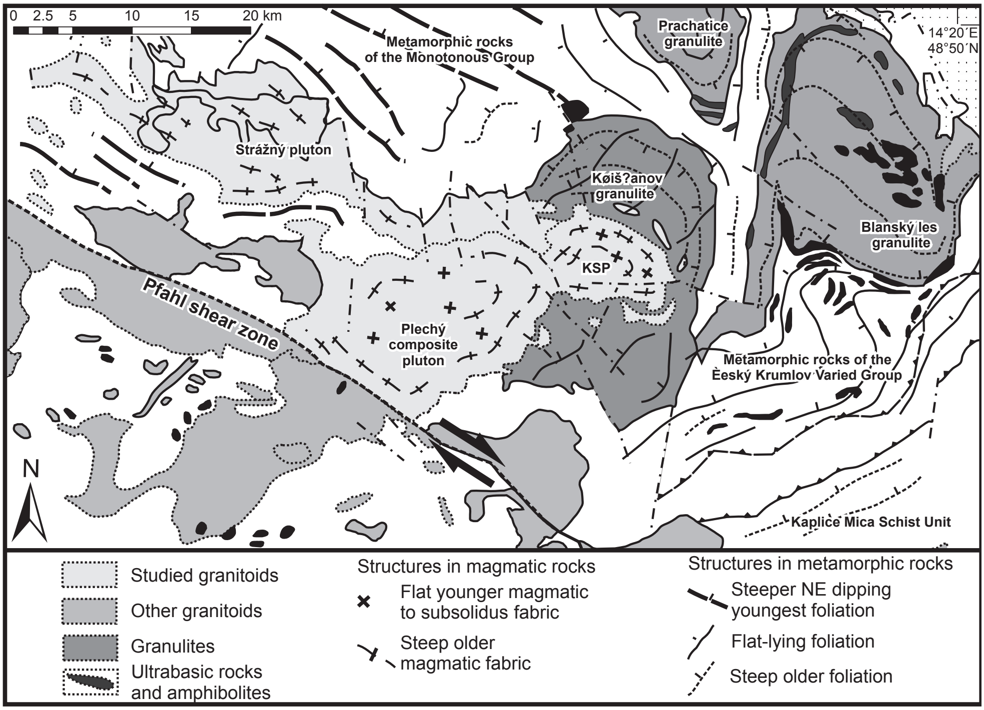

Fig. 10. Simplified structural map of the studied area (compiled on the basis of Franěk et al. 2006; Verner et al. 2008, 2009).

Mid-crustal rocks

From a structural point of view, the rocks of the mid-crustal level can be divided into the Český Krumlov Varied Group SE of the granulite bodies, Lhenice Zone among the granulites and Monotonous Group forming the western part of the studied area (see Fig. 1).

In a ~2 km vicinity of the granulite massifs, the fabric in all the metasediments is parallel to the geometry of the steep amphibolite-facies foliation inside the granulites. Farther to the SE, the Monotonous and Varied rocks exhibit a uniform structural pattern, where the older fabrics in general dip steeply to the NW. In the central part of the Český Krumlov Varied Group, ~km-scale open folds are developed, with moderately NW dipping axes and axial planes dipping steeply to the NE below the BLG. Towards the SE, the rock fabrics acquire the common NE–SW regional trend (Fig. 10).

The steep fabrics are intensively overprinted by a flat-lying foliation, which also dips predominantly to the NW (Fig. 11b). Further, in the westernmost part of the studied area, this flat foliation is overprinted by crenulation cleavage with axial planes dipping moderately to steeply to the ~NNW. The intensity of this overprint increases west- and south-westward to the German part of the MZ, where this fabric becomes dominant. This youngest ductile fabric is mostly parallel to the Pfahl Shear Zone located more to the S. All the three regional deformational fabrics bear syntectonic mineral assemblages broadly corresponding to amphibolite-facies conditions of deformation.

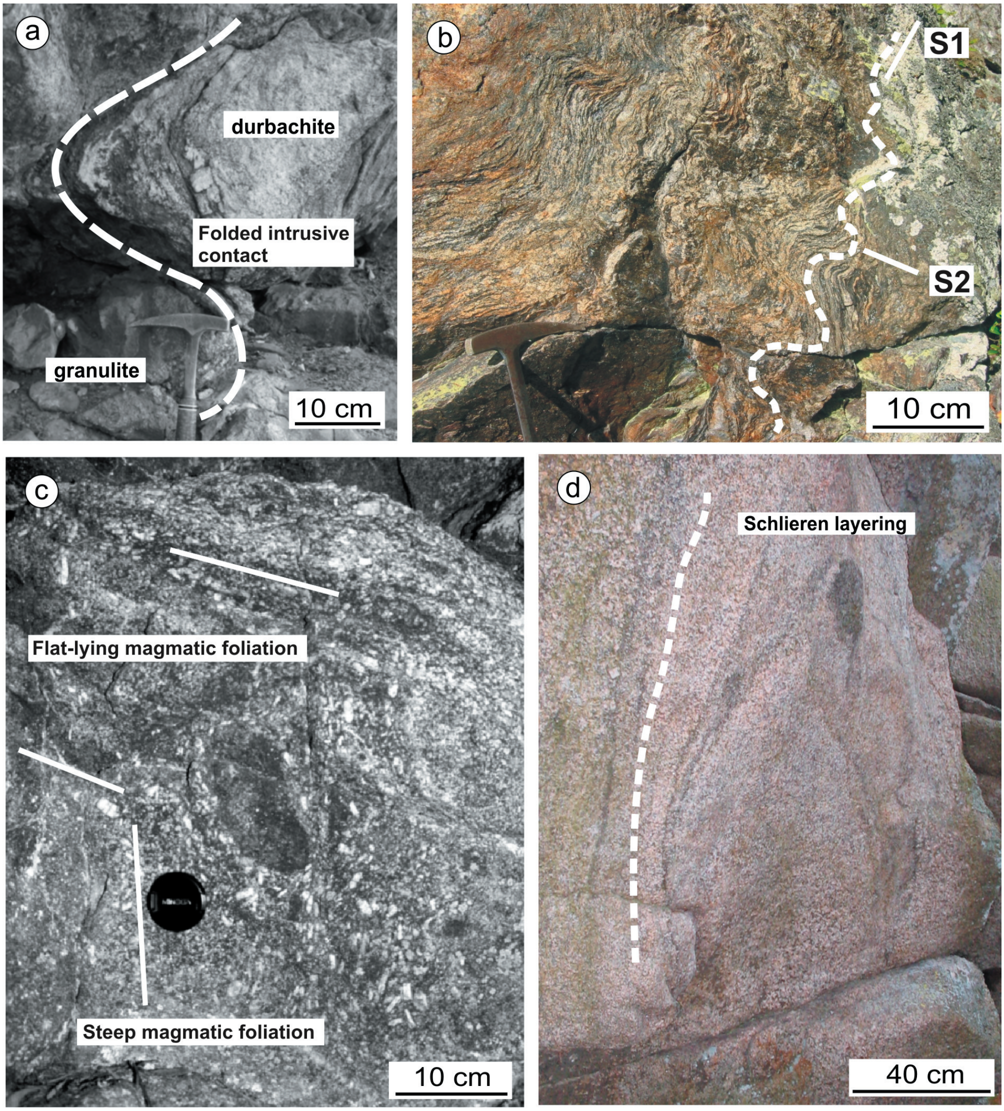

Fig. 11. Structural relations in the individual units. (a) Folded intrusive contact between partly retrogressed felsic granulites of the Křišťanov massif and durbachites of the Knížecí Stolec pluton. (b) Crenulation cleavage superimposed on NNE–SSW steeply dipping metamorphic foliation (early stage of the transposition into "flat-lying" regional fabric), migmatitized paragneisses of the Monotonous Group. (c) Relationships of two distinct magmatic fabrics in the durbachites of the Knížecí Stolec pluton. (d) Magmatic fabrics expressed as schlieren layers in the Eisgarn granite (Plechý pluton).

Brittle tectonics

All the studied rocks are affected by brittle deformation along different sets of steeply to moderately dipping faults, shear fractures, and extensional joints. The first group comprises ~WNW–ESE trending discontinuities parallel to the Pfahl shear zone, which often bear subhorizontal lineations (striations) and accommodated predominantly right-lateral strikeslip movements. The other group represents ~NNE–SSW trending faults and fractures (bounding e.g. the granulite massifs). Vrána & Šrámek (1999) suggested an ~8 km vertical movement along these faults bordering the E margin of the northerly Prachatice granulite massif. Both of these fault families acted as important discontinuities and, along which the highlands-like Blanský Les, Knížecí Stolec and Šumava Mountains, rose up since Cretaceous times.

Magmatic rocks

Durbachites of the Knížecí Stolec pluton

The ~340 Ma Knížecí Stolec pluton (KSP) crops out in the SW part of the Moldanubian Zone (for a review, see Verner et al. 2008). The KSP intruded the centre of the Křišťanov granulite body (Fig. 11a), which was already juxtaposed against the mid-crustal metamorphic rocks of the Monotonous Group. The pluton evolved from a deep-seated cone-sheet-bearing complex followed by the nested intrusion of large magma pulse(s) into the centre of the outer sheeted complex. Margin-parallel, steeply dipping magmatic fabrics are interpreted to record intrusive strain during pluton emplacement. After the emplacement but prior to final solidification, the pluton was overprinted by regional flat-lying magmatic to subsolidus foliation bearing shallowly plunging lineations (Fig. 10, 11a,c). This superimposed regional flat-lying fabric indicates subvertical contraction of the Variscan orogenic root in the studied region. In the Křišťanov granulite, the PT conditions of this flat-lying fabric formation were estimated at 768±76°C and 0.75±0.18 GPa (Verner et al. 2008).

Weinsberg granite intrusion

In contrast to the durbachites, the Weinsberg-type Strážný pluton exhibits a simple structural pattern (Fig. 10). The fabrics are represented predominantly by a monoclinal magmatic foliation subparallel to the youngest NE dipping foliation in the surrounding Monotonous Group. The intrusive contacts between them are always concordant, suggesting that the granites were emplaced syntectonically during the latest ductile deformations recorded in the MZ.

Plechý composite pluton

The early Carboniferous (~325Ma) Plechý pluton (PP) represents a typical post-collisional intrusive centre emplaced near a syn-magmatic regional WNW–ESE Pfahl shear zone (Verner et al. 2009).

The Plechý pluton has roughly elliptical outline (24×16 km) in a map view. Magmatic fabrics in all the varieties of the Plechý pluton are defined by planar and linear shape-preferred orientation of rock-forming minerals and rare schlieren layering (Fig. 11d), clearly discordant to the regional structures. Steeply dipping magmatic foliation, which is parallel to the outer contact of the pluton and to internal contacts, is overprinted by flat-lying to gently dipping (0–30° dip) magmatic foliation. To the south (~1 km from the Pfahl shear zone), the magmatic foliation changes into steep ~NW–SE orientation, and is sub-parallel or slightly oblique to the mylonitic foliation within the Pfahl shear zone. Here, the magmatic foliation bears strong sub-horizontal ~NW–SE magmatic lineation that is sub-parallel to the stretching lineation in the shear zone mylonites.

Gravity modelling of the Plechý pluton was carried out along a ~NW–SE transect across the Plechý granite (Verner et al. 2009). These results indicate that the Plechý granite is a steep-sided body and extends to depth down to at least 5.5 km below the present-day erosion level.

Verner et al. (2009) interpreted the Plechý pluton as a composite, post-collisional visco-elastic diapir emplaced near the regional Pfahl Shear Zone in at least three separately evolved large magma batches. The finite magmatic fabric pattern corresponds to a "transition zone" in diapiric intrusions, characterized by the collapse of vertical foliations during divergent flow, oblate shapes of the fabric and AMS ellipsoid, and low AMS intensity. The marginal parts of the Plechý massif were emplaced post-tectonically in relation to deformational evolution of the region. It is thus the youngest granite massif in the area.

Discussion and conclusions

The results of the structural, petrological, geochemical and geochronological research contribute to the following polyphase evolution scenario of the Moldanubian Zone in south-eastern part of the Šumava Mts. (see Fig. 12).

The first episode, recorded exclusively in granulite-facies mylonites inside the granulite massifs, relates to the exhumation of large volumes of these lower-crustal felsic rocks. In spite of the large extent of the granulites, their exhumation-related features are scarce, so that the process cannot be defined in a precise way. The limited evidence indicates that the rocks rose almost isothermally from the peak metamorphic conditions at ~60 km depths to mid-crustal levels, where they became juxtaposed to the Varied and Monotonous rocks. According to new geochronological data (e.g. Kröner et al. 2000) exhumation of these high-grade rocks into mid-crustal level proceeded between ~343–339 Ma, which suggests a high exhumation rate of ~10 mm per year.

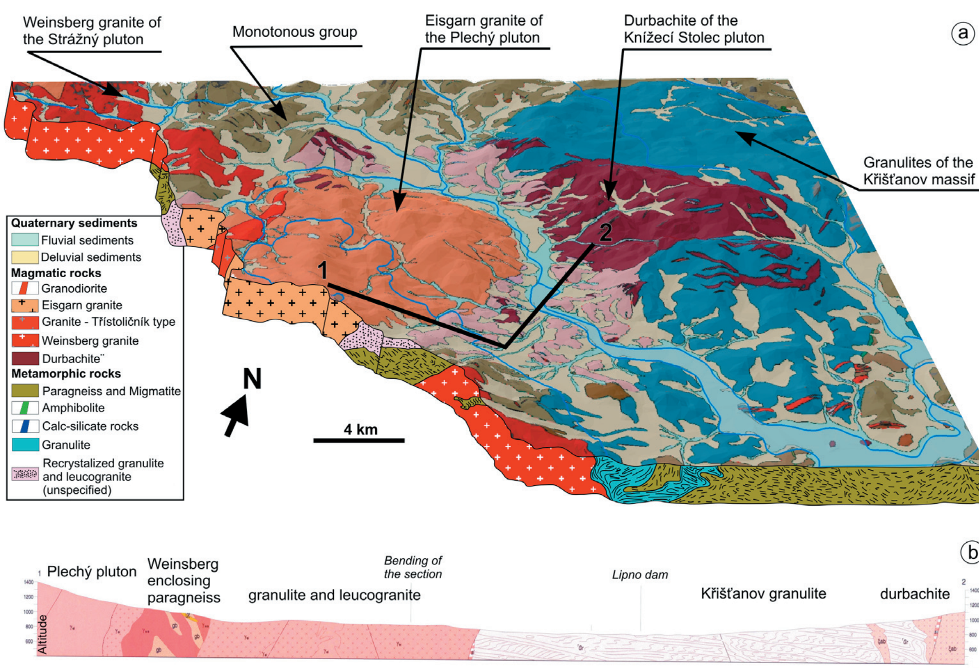

Fig. 12. (a) Digital elevation model of the area of interest covered by a simplified geological map; the edges are complemented by interpretative geological sections. Modified after Babůrek et al. (2006). (b) Interpretative geological profile across the studied region, roughly perpendicular to the depicted structures.

The first regional planar fabrics (WNW or ESE steeply dipping metamorphic foliations) resulted from ESE–WNW shortening and final stacking of the rock complex of the Gföhl, Monotonous and Varied units. The structural record of the Křišťanov granulite massif can be directly correlated to the Blanský Les and northern Prachatice massifs, all of which exhibit the arcuate geometry of these steep fabrics, in contrast to uniform strikes outside the granulites (Fig. 10). Such a complex geometry probably results from the distinct mechanical behaviour of the granulite bodies, which acted as stiffer boudins in a matrix of weaker mid-crustal rocks dominated by paragneisses (Franěk et al. 2006). These deformations proceeded at depths of ~32 km, as is indicated by petrological evidence from the felsic granulites. The age of this episode is determined as ~340 Ma by the end of the previous stage described above and the onset of a next episode discussed below.

Across the whole studied region, the steep fabrics described above are heterogeneously overprinted by the flat-lying metamorphic foliation that dips predominantly to the ~NW. According to PT estimates from the flat fabrics in the granulites, this tectonometamorphic episode proceeded at a depth of ~25 km (Verner et al. 2008). During this stage, the KG was intruded by the Knížecí Stolec durbachites at ~340 Ma. The intrusive contacts are partly discordant to the steep foliations, while the HT subsolidus fabrics, developed heterogeneously in the Knížecí Stolec durbachite, exhibit orientations similar to the flat-lying fabrics in the surrounding granulite. The field evidence also indicates that these two foliations developed contemporaneously; thus, the age obtained from the durbachites also marks the development of the flat foliations.

The youngest ductile structures are represented by heterogeneously developed, moderately to steeply NE-dipping amphibolite facies foliations (structures mostly parallel to the Bavarian Pfahl shear system; e.g. Finger et al. 2007). This tectonometamorphic event was observed only in the south-western part of the studied area, while the granulites and their immediate surroundings remained almost untouched during this stage. The PT estimates and geochronological data from analogous metamorphic fabrics and syntectonic granitoids in the Bavarian part of the Moldanubian Zone suggest that this last stage took place at a depth of ~20 km (Kalt et al. 2000; Galadí-Enríquez et al. 2010). The intensity of deformation increases towards the SW, indicating a sort of indentation process into the MZ from the SW. The indentor remains unknown, probably being hidden below the Alpine foredeep. The Strážný pluton built by the Weinsberg-type granite exhibits weak signs of these fabrics developed in a magmatic stage, suggesting syntectonic emplacement of this body. The younger Plechý pluton (~325 Ma) was emplaced post-tectonically. Both of these plutons occur in a region dominated by the youngest NE-dipping fabrics, suggesting that the last ductile deformations started after ~340 Ma and diminished before ~325 Ma.

Nevertheless, approaching the Pfahl Shear Zone, the magmatic fabric in the Plechý pluton recorded instantaneous strain increments associated with dextral shearing. Such features interconnect the emplacement of this magmatic body with even younger activity of this WNW–ESE trending zone of localized right-lateral shearing during the final stages of Variscan collision in the Bohemian Massif at ~325 Ma.

Acknowledgments. The authors gratefully acknowledge the funding by the Czech Geological Survey, in the framework of the project of geological mapping of the Šumava National Park and adjacent areas (No. 6201 and 390002).

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Received: 22 May 2009
Accepted: 30 September 2010