Original paper

Metabasic rocks in the Varied Group of the Moldanubian Zone, southern Bohemia – their petrology, geochemical character and possible petrogenesis

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Metabasic rocks form an important constituent of the Chýnov and Český Krumlov units belonging to the Varied Group (Moldanubian Zone, south Bohemia). The amphibolites are dominated by amphibolite-facies mineral assemblages of mainly tschermakitic amphibole and plagioclase. Hornblendes show compositional variation with Si ~ 6.5 apfu, Mg/(Mg + Fe) ~ 0.5 and $(Na + K)_A$ ~ 0.5 apfu. Garnet with clinopyroxene are subordinate and occur in a few samples only. No relics of previous greenschist- or granulite-facies assemblages have been observed, most likely due to the relatively simple metamorphic history.

The petrology indicates rather close correlation of the Chýnov and Český Krumlov units. The similarities include presence of dolomite in carbonate bodies, graphite schists, rocks with marialitic scapolite, locally also Ti-andradite (± magnetite, epidote) oxidic assemblages and thin layers of Mn-rich garnet-quartz rocks. However, there is a major difference in the oxidation state. Most Chýnov amphibolites have Fe_2O_3/FeO = 0.70–1.00 and their protolith probably experienced an early incipient oxidation. Great deal of the parental basalts thus could have been effusive. The Český Krumlov amphibolites have $Fe_2O_3/FeO \leq 0.4$, perhaps because they show much closer association with graphite schists that could have been responsible for the reduction of the adjacent rock units.

The dataset is dominated by EMORB-like tholeiite basalts interpreted as having been derived by Early Palaeozoic melting of a strongly depleted mantle source (ε_{Nd}^{500} = +8.6 to +9.4; T_{Nd}^{DM} = 0.43–0.50 Ga). This argues stoutly against Precambrian age of the Varied Group in south Bohemia. The composition of the remaining samples reflects contamination by upper continental crust (ε_{Nd}^{500} = +3.1 to +1.3, progressive enrichment in Th, development of a significant negative Nb, and lesser P and Ti anomalies on the NMORB-normalized spiderplots).

A much smaller group of amphibolites is characterised by steep REE patterns (La_N/Yb_N = 5.5–11) and high contents of HFSE (Nb, Ta, Zr and P). It is of a clear OIB affinity, with parental alkali basalt (Nb/Y = 0.7–1.6) generated by a low degree of partial melting of a deep, garnet-bearing asthenospheric mantle source (ε_{Nd}^{500} = +4.5 to +6.1; T_{Nd}^{DM} = 0.75–0.83 Ga).

Metamorphosed doleritic/gabbroic dykes cutting the Palaeoproterozoic Světlík orthogneiss show rather unradiogenic Nd isotopic composition (ε_{Nd}^{500} = +0.1 and –3.6; T_{Nd}^{DM} = 1.34 and 2.03 Ga). This precludes closed-system crystallization from depleted mantle derived melts in Phanerozoic times. The exact age and nature of their parental magma remain enigmatic but any genetic link with the amphibolites in the structurally overlying Český Krumlov Varied Unit seems ruled out.

Overall, the most likely tectonic setting of the magmatism was attenuated lithosphere, subjected to an Early Palaeozoic extension, leading eventually to fragmentation of the northern Gondwana margin. The minor OIB component preserved as alkali basalts as well as some contribution to the EMOR-like basaltic magmas was probably added by a rising mantle plume.

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1. Introduction

Constraining the age and petrogenesis of dismembered and metamorphosed pre-Variscan volcanosedimentary complexes represents one of real challenges in collisional orogens, with the European Variscan chain being no exception. As the reconstruction of the primary fabrics, structures, petrography and mineralogy of the original volcanosedimentary sequences is often difficult, if not impossible, an alternative approach has to be sought. Whole-rock geochemical as well as Sr-Nd isotopic compositions of the volcanic rocks – and basic ones in particular – are sensitive indicators of the source composition and consequently also of the geotectonic setting (e.g., Wilson 1989 and references therein).

Fortunately many petrogenetically significant trace elements are relatively immobile during alteration and metamorphism. Especially those with intermediate ionic potential (such as HFSE and REE) can provide useful information even in rocks subjected to a high-grade (up to upper amphibolite-facies) metamorphic overprint (Floyd and Winchester 1975, 1978; Winchester and Floyd 1976, 1977; Wood et al. 1979; Wood 1980; Pearce 1996). Similarly the Nd isotopic system is rather resistant to metamorphic resetting, unless CO_2-rich fluids are involved (DePaolo 1988; Dickin 1995; Faure 2001). The radiogenic isotopic ratios do not change during closed-system fractional crystallization, and should thus still reflect the source composition. Alternatively, the radiogenic isotopes are capable of providing vital constraints on the extent and mechanism of open-system interactions affecting compositions of the basic parental magmas, for instance crustal assimilation, which is usually coupled with fractional crystallization (DePaolo 1981).

Taken together, careful petrologic, whole-rock geochemical and Nd isotopic studies of metabasic rocks, and metabasalts in particular, seem a promising line of research that should contribute to our better understanding of the primary evolution and geotectonic environment of the volcanosedimentary sequences. The Variscides are a typical example of a collisional orogen, in which the original information on field relations, palaeogeographic configuration and geotectonic position of individual older volcanic suites has been, largely or completely, wiped out by the intense tectonometamorphic reworking. Indeed, the combined petrologic, geochemical and isotopic approach has been successfully applied to several rock complexes in the Bohemian Massif, which forms a key Central European part of the Variscan chain. It yielded invaluable information concerning their character, classification, age, genesis and tectonic significance (e.g., Patočka 1987; Winchester et al. 1998; Floyd et al. 1996, 2000; 2002).

Metabasites represent an important constituent of the Moldanubian Zone, which is considered to be the orogenic root of the Variscan orogen in Bohemian Massif (Schulmann et al. 2005, 2008). They are abundant, associated with prevalent gneisses and subordinate carbonate rocks, in the amphibolite-facies Varied Group, particularly at the contact with the HP–HT Gföhl Unit. Modern studies utilizing whole-rock geochemical data from the Moldanubian metabasic rocks are still regrettably scarce (Matějovská 1987; Patočka 1991; Finger and Steyrer 1995; Fritz 1995; Kachlík 1999; Mayer et al. 2005) and their Nd isotopic compositions remain nearly unconstrained (but cf. Mayer et al. 2007).

Given the high-grade metamorphism of the Varied Group (mainly second sillimanite isograd), polyphase deformation history, and the superimposed effects of later Variscan contact metamorphism, it is difficult to reconstruct primary features of the original basaltic rocks. In this contribution we present new data for metabasic rocks from two prominent and interesting segments of the pre-Variscan volcanosedimentary crust of the Varied Group, the Chýnov and Český Krumlov units in southern Bohemia (Fig. 1). The most interesting finding is that they contain Early Palaeozoic tholeiitic and subordinate alkaline metabasalts, providing more evidence for the probable Early Palaeozoic age for the Varied Group in southern Bohemia and the mechanism of the fragmentation of the Gondwana margin in general.

2. Geological setting

2.1. Subdivision of the Moldanubian Zone

The Moldanubian Zone (MZ) in the Bohemian Massif is a heterogeneous crustal (and upper mantle) stack of several major allochthonous units or terranes, assembled during the Variscan orogeny and modified by several superimposed deformation and metamorphic recrystallization events. In southern Bohemia, these units are termed traditionally the Monotonous, Varied and Gföhl groups or units (Fiala et al. 1995) (Fig. 1). Moreover, displaced segments of older basement are incorporated in the structure of the MZ, including the Palaeoproterozoic Světlík orthogneiss in southern Bohemia (Wendt et al. 1993; Fiala et al. 1995) and the Mesoproterozoic Dobra gneiss in Lower Austria (Gebauer and Friedl 1994; Friedl et al. 2004).

2.1.1. Gföhl Unit

The high-grade Gföhl Unit, with its typical occurrence in Lower Austria, contains mainly nebulitic biotite migmatites, bodies of felsic granulites and minor pyroxene granulites accompanied by pyrope peridotites, garnet clinopyroxenites, eclogites, amphibolites and minor paragneisses/migmatites. A comparable assemblage of rock types occurs in several parts of the MZ, including southern Bohemia (Fig. 1).

As summarised by Janoušek et al. (2004), the protoliths to Gföhl gneisses/migmatites and felsic granulites seem predominantly Ordovician to Devonian in age (*c.* 470–430, 400 and 360 Ma: Wendt et al. 1994; Kröner et al. 2000; Friedl et al. 2004). The granulitic rocks of the Gföhl Unit equilibrated at high pressures, corresponding to eclogite-facies conditions (O’Brien and Rötzler 2003; O’Brien 2006, 2008), and were assembled and tectonically emplaced to higher crustal levels at around 340 Ma (Kröner et al. 2000 and references therein). The

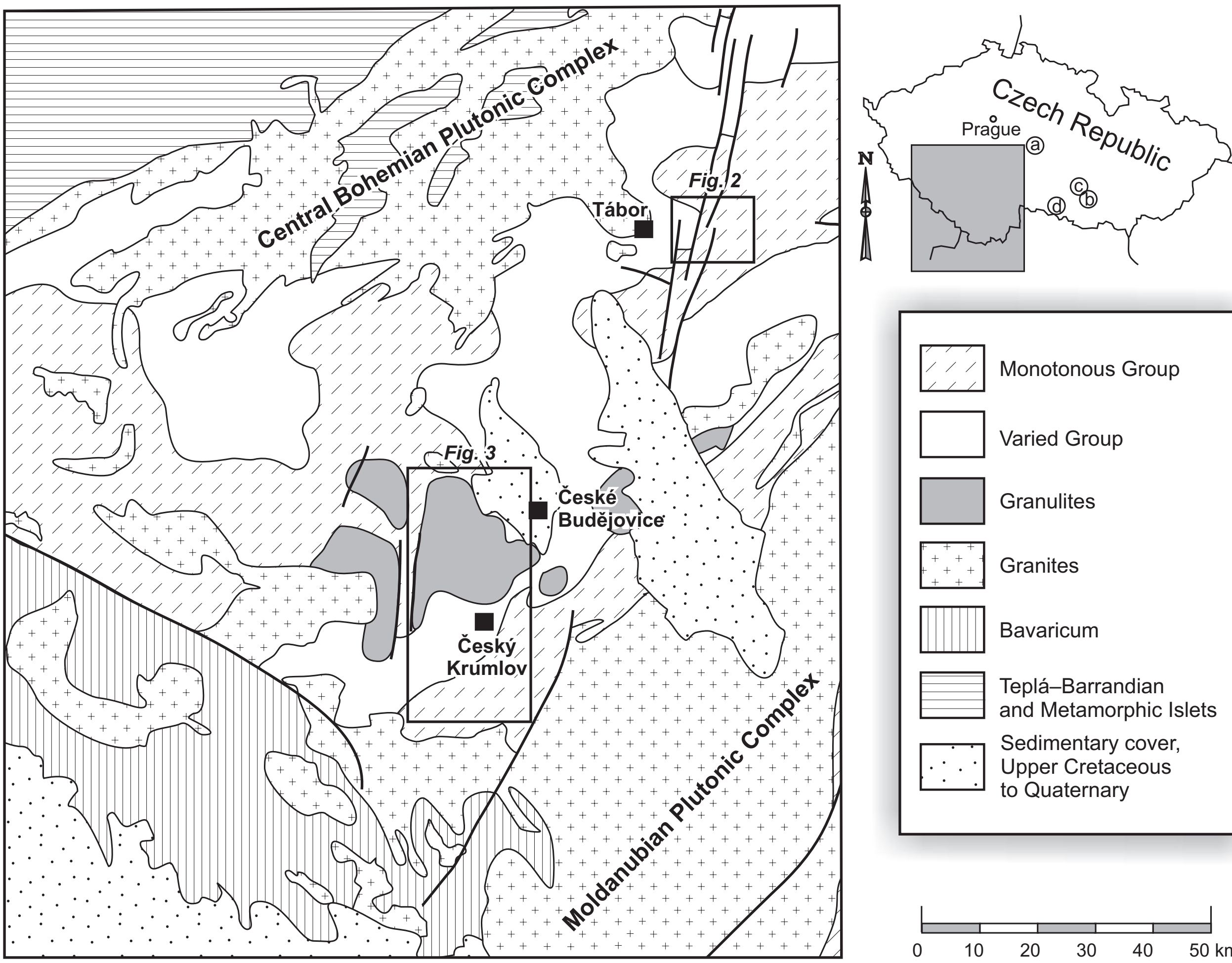


Fig. 1 Geological sketch of the southern Bohemia showing the regional context the studied metabasic occurrences (simplified from Fiala et al. 1995). The rectangles refer to the location of more detailed maps for the Chýnov and Český Krumlov areas within the Moldanubian Zone (Figs 2 and 3). Inset: position of the main map area in the Czech Republic. Labelled are also other localities mentioned in the text: (a) – Rataje Zone, (b) – Moravský Krumlov, (c) – Náměšť, (d) – Jemnice.

nappe structures in southern Bohemia, if ever present, were strongly modified by later deformation (Rajlich et al. 1986; Vrána and Šrámek 1999; Franěk et al. 2006) and this may be so even for the classic Austrian terrain (Racek et al. 2006).

2.1.2. Monotonous Group

The Monotonous Group mainly consists of biotite-sillimanite paragneisses (±cordierite), which are partly migmatitic and contain intercalations of orthogneisses, quartzites and minor amphibolites. Eclogites are scarce. Rare direct U-Pb geochronological evidence indicates a likely Neoproterozoic age (< 727 ± 106 Ma) for the metasedimentary sequence of the Monotonous Group in the Kaplice area (Kröner et al. 1988). The Variscan amphibolite-facies metamorphism has been dated conventionally by the same authors at 367^{+18}_{-20} Ma.

2.1.3. Varied Group

Both the Varied and Monotonous groups contain biotite paragneisses and migmatites as the dominant lithology. However, the Varied Group is characterised by the presence of numerous intercalations of marble (± dolomite), amphibolite, calc-silicate gneiss, graphitic gneiss and quartzite. The characteristics of the Varied Group in various parts of the MZ indicate that all the occurrences are probably not coherent and may in part reflect differences in age (see e.g. Finger et al. 2007 for a review). Hence, it may be appropriate to designate individualized areas of the Varied Group as separate units.

2.2. Moldanubian amphibolites

2.2.1. Amphibolite occurrences in the Moldanubian Zone

Amphibolite occurrences are scattered throughout the Varied Group of the MZ both in the Czech Republic and adjacent areas of Lower Austria, especially in the so-called Raabs Unit, sandwiched along the contact between the Varied Group and the Gföhl Unit (Finger and Steyrer 1995; Fritz 1995; Mayer et al. 2005, 2007).

Metabasites in the Bohemian part of the Moldanubian Zone form small, elongated bodies, typically concordant with the fabrics in the adjacent metasedimentary rocks. Their most abundant occurrences are in the Rataje Zone in the Sázava valley, in the Varied Group around Chýnov and Český Krumlov, in the region between Náměšť and Moravský Krumlov and around Jemnice (see Moravcová 1999, fig. 1, for a synoptical map). The amphibolites consist of mainly tschermakitic amphibole and plagioclase (andesine–labradorite); types with garnet and relict clinopyroxene are comparably rare (Němec 1995).

2.2.2. Previous geochemical studies

In W Moravia, amphibolite bodies encircle the Náměšť granulite Massif (Šichtářová 1981; Němec 1996a). Matějovská (1987) studied the chemistry of amphibolites in SW Moravia, in a belt extending from Slavonice by the Austrian border to the occurrences within the Náměšť granulite Massif. The various types of amphibolites in the Strážek Unit NE of the Třebíč durbachite pluton were the subject of detailed reports by Němec (1994, 1995, 1996b, 1997). Metamorphic changes to the whole-rock geochemical signatures of the Moldanubian amphibolites were investigated by Němec (1999).

The work of Kachlík (1999) dealt with the structural geology, petrology, mineral and whole-rock geochemistry of rock complexes in the so-called Rataje Zone, i.e. at the contact between the Varied Group, Kutná Hora Crystalline Unit and Central Bohemian Plutonic Complex/Bohemicum. He concluded that the geochemical signature of amphibolites from the Šternberk–Čáslav Unit resembles that of the amphibolites in Varied Group of southern Bohemia.

Patočka (1991) concentrated on the geochemistry of the various amphibolite types from around Český Krumlov. The whole-rock geochemistry of the Chýnov area near Tábor was described in short, preliminary reports by Janoušek et al. (1997) and René (2007). A more detailed contribution by Němec (1998) dealt with Mg-rich amphibolites, interpreted as metamorphosed Ol- and Cpx-rich cumulates.

3. Analytical techniques

3.1. Electron microprobe

Mineral analyses were carried out with the CamScan 3400 electron microscope using energy dispersion analyser Link ISIS at the Czech Geological Survey, Prague-Barrandov (CGS). Analytical conditions were 2.5 nA, 15 kV, 60 s counting time on sample, 120 s on standard (J. Malec, analyst). Mineral formulae were recalculated using the R language package *GCDkit-Mineral* (Janoušek et al. 2006a).

3.2. Whole-rock geochemistry

Most of the major-element whole-rock analyses were performed by wet chemical methods in the laboratories of the Czech Geological Survey, Prague-Barrandov. The trace elements were analysed in the ACME Analytical Laboratories, Vancouver, Canada. Most were determined by $LiBO_2/Li_2B_4O_7$ fusion and ICP-MS/ES, except for precious and base metals determined by aqua regia digestion followed by ICP-MS. Data management, recalculation, plotting and statistical evaluation of the data were facilitated using the R language package *GCDkit* (Janoušek et al. 2006b).

3.3. Radiogenic isotopes (Sr and Nd)

For the isotopic study, samples were dissolved using a combined HF–HCl–HNO_3 attack. Strontium and bulk REE of the **Chýnov set** were isolated by standard cation-exchange chromatography techniques on quartz columns with BioRad AG50Wx8 resin. Nd was further separated on quartz columns with Biobeads S-X8 coated with HDEHP (Richard et al. 1976). The Rb and Sr concentrations, and the Rb/Sr ratios, were determined using XRF apparatus in the CGS by an approach similar to Harvey and Atkin (1981 and references therein). The Sm and Nd concentrations were obtained by isotope dilution using ^{149}Sm and ^{148}Nd spikes (Richard et al. 1976; Vokurka 1995).

Strontium of the **Český Krumlov set** was isolated by exchange chromatography techniques on PP columns with Sr.spec Eichrom resin and bulk REE on PP columns filled with TRU.spec Eichrom resin (Pin et al. 1994). The Nd was further separated on PP columns with Ln.spec Eichrom resin (Pin and Zalduegui 1997). Further analytical details were recently reported by Míková and Denková (2007). The Rb, Sr, Sm and Nd concentrations were obtained by ICP-MS in Acme Analytical Laboratories, Canada, as given above.

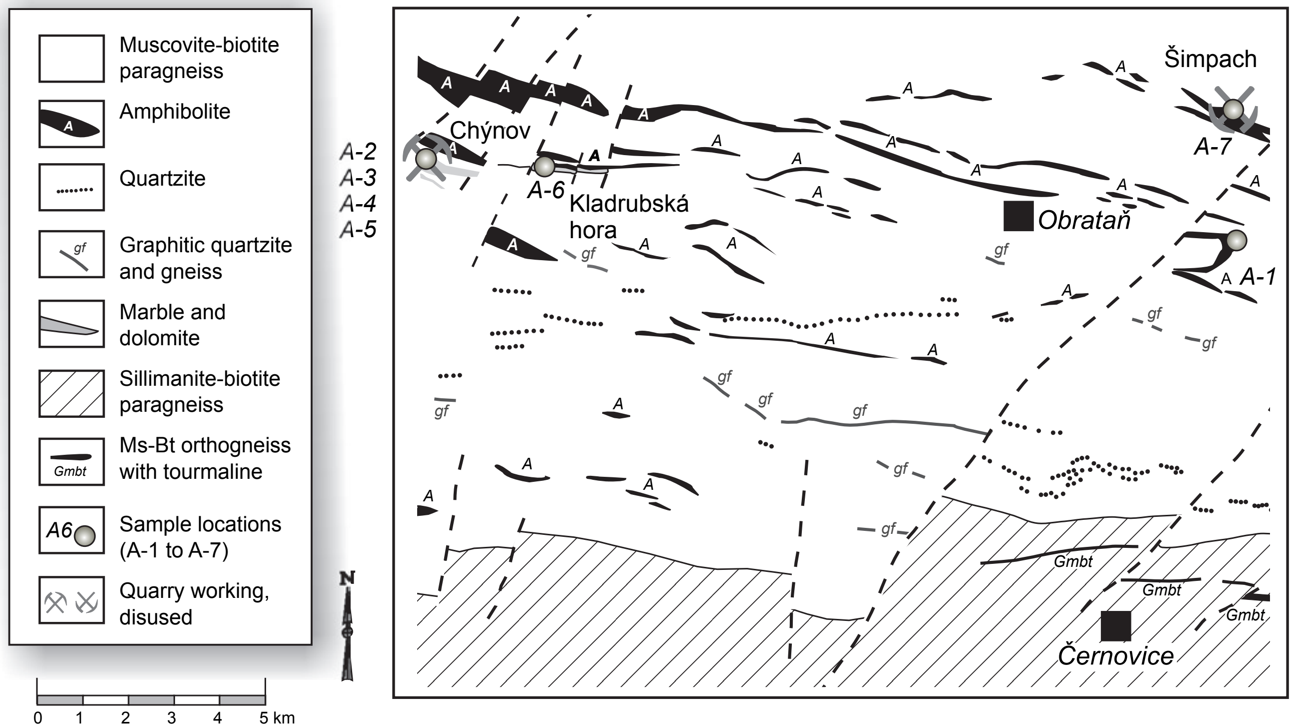


Fig. 2 Sample location and geology of the Chýnov area. Simplified from Czech Geological Survey map 1: 25 000.

For both datasets, isotopic analyses were performed on a Finnigan MAT 262 thermal ionization mass spectrometer in static mode using a double Re filament assembly (CGS). The $^{143}Nd/^{144}Nd$ ratios were corrected for mass fractionation to $^{146}Nd/^{144}Nd = 0.7219$, $^{87}Sr/^{86}Sr$ ratios assuming $^{86}Sr/^{88}Sr = 0.1194$. External reproducibility for the Chýnov samples is given by results of repeat analyses of the La Jolla ($^{143}Nd/^{144}Nd = 0.511858 \pm 26$ (2σ), n = 18) and the NBS 987 ($^{87}Sr/^{86}Sr = 0.710250 \pm 24$ (2σ), n = 10) isotopic standards. For the Český Krumlov series, the repeat analyses of the La Jolla standard yielded $^{143}Nd/^{144}Nd = 0.511851 \pm 14$ (2σ, n = 24).

The decay constants applied to age-correct the isotopic ratios are from Steiger and Jäger (1977 – Sr) and Lugmair and Marti (1978 – Nd). The ε^{i}_{Nd} values and single-stage CHUR Nd model ages were obtained using Bulk Earth parameters of Jacobsen and Wasserburg (1980), the single-stage Depleted Mantle Nd model ages (T^{DM}_{Nd}) were calculated after Liew and Hofmann (1988).

4. Field relations for the studied samples

The relations of the Varied Unit in the Chýnov and Český Krumlov areas probably indicate rather close lithological correlations. Analogies include the presence of dolomite in the carbonate bodies, association with graphite schists, presence of schists with marialitic scapolite, occurrence of localized Ti-andradite (± magnetite, epidote) assemblages, and thin layers of Mn-rich garnet-quartz rocks including Mn-rich garnetiferous gneisses. Recurrence of such unusual rock types is an important link in comparing the two units.

4.1. Chýnov Varied Unit

Amphibolites in the Chýnov area represent an interesting subject for a study for several reasons:

(a) The region between Chýnov and Obrataň (Fig. 2) is characterised by a relatively simple tectonic structure, and in particular the preservation of relatively old fabrics (most likely ?D_1), with the main foliation and varied intercalations trending WNW–ESE. This means that the Chýnov region was unaffected by younger deformation and recrystallization events that obscured the situation in many places in the Moldanubian Zone.

(b) Apart form amphibolites the local sequence of the Varied Group also includes marbles (dolomites), quartzites and graphite-bearing rocks (Fig. 2), facilitating lithological correlations.

(c) Its position is distant from regions affected by migmatitization and contact metamorphism caused by the Moldanubian (South Bohemian) Plutonic Complex.

(d) There is a surprising dearth of detailed geochemical studies from these rocks.

Amphibolites in the broader environs of Chýnov village were sampled at several locations (Fig. 2).

A-1 outcrop 2.7 km ESE of Obrataň, 15 km east of Chýnov, 49º25'23.33" N; 14º58'8.79" E

This sample comes from a several metres thick layer of amphibolite surrounded by biotite paragneiss. The rock is homogeneous, fine-grained and exhibits distinct foliation and lineation.

A-2 to A-5 working quarry at Pacovská hora Hill, 2.2 km NNE of Chýnov, 49º25'47.89"N; 14º49'49.53" E

Samples A-2 to A-5 were collected in large, then (1995) working quarry on the western slopes of the Pacovská hora hill. The quarry exposed crystalline limestones, calc-silicate gneisses, amphibolites and muscovite-biotite paragneisses ± sillimanite. Amphibolites form conformable layers several metres up to tens of metres thick, interbanded with calcite- and dolomite–calcite marble or paragneiss. Due to a strong metamorphic overprint and high rates of deformation, it is difficult to decide whether they originally represented sills, lava flows or tuff horizons. Rather high oxidation state indicates syn-sedimentary lavas deposited in a shallow sea, with possible episodes of subaeric exposure, as the prevailing protolith.

A-6 disused quarry at the Kladrubská hora hill, 3.6 km NE of Chýnov, 49º25'49.37" N; 14º51'11.93" E

Sample is a fine-grained, strongly foliated rock with widely scattered mineral aggregates 1–2 mm across, rich in plagioclase.

A-7 disused quarry in forest 0.8 km SE of Šimpach, 49º26'5.91" N; 14º59'7.37" E

Amphibolite A-7 is a fine-grained, foliated rock with plagioclase-rich aggregates (1–3 mm), which are somewhat streaky and stretched parallel to the foliation. The amphibolite body at Šimpach is intimately associated with Mg-rich clinopyroxenite.

4.2. Amphibolites and metadolerites/metagabbros in the Český Krumlov area

Five samples of amphibolites from the surroundings of the town of Český Krumlov and three samples of metadolerites/metagabbros from the Světlík and Kovářov areas (Fig. 3) were obtained for comparison with the data from the Chýnov Varied Unit. Photographs showing the

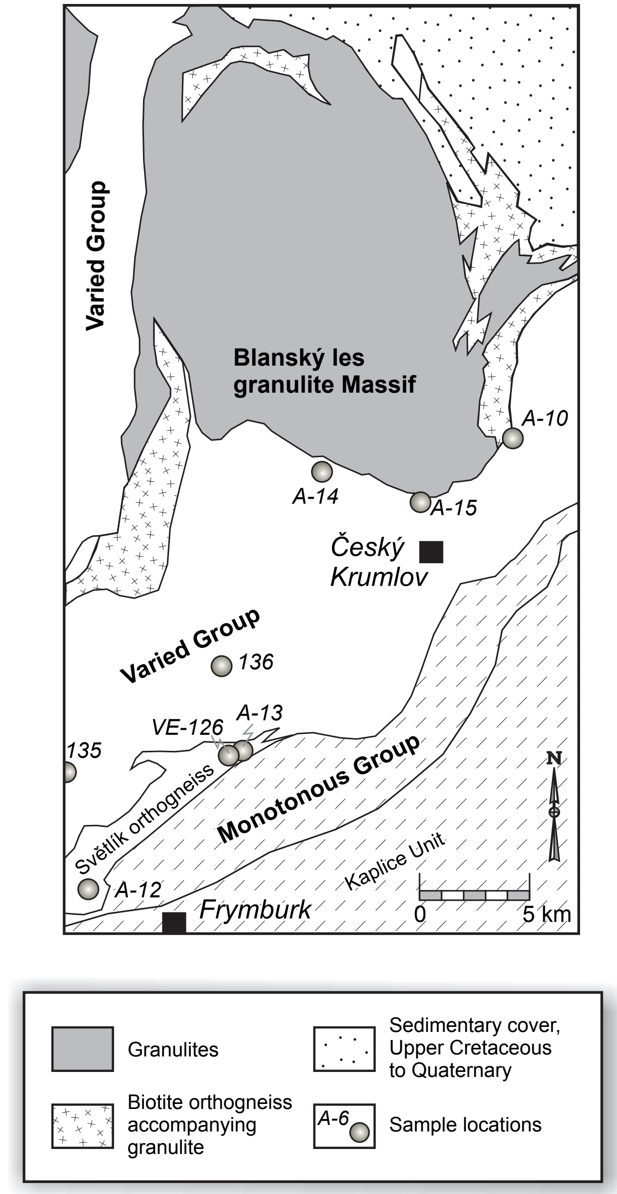


Fig. 3 Sample location and simplified geological sketch of the Český Krumlov area. Adopted from Czech Geological Survey map 1 : 50 000.

variable textures of samples from the Český Krumlov area are presented in Fig. 4.

4.2.1. Amphibolites

The amphibolite samples studied come from a variety of geological settings: A-10 (Zlatá Koruna) from near the Blanský les Granulite Massif; both A-14 (Lazec) and A-15 (Vyšný) from the northern, and 135 (Lískovec) with 136 (Hořice na Šumavě) from the SW parts of the Český Krumlov Varied Unit (Fig. 3).

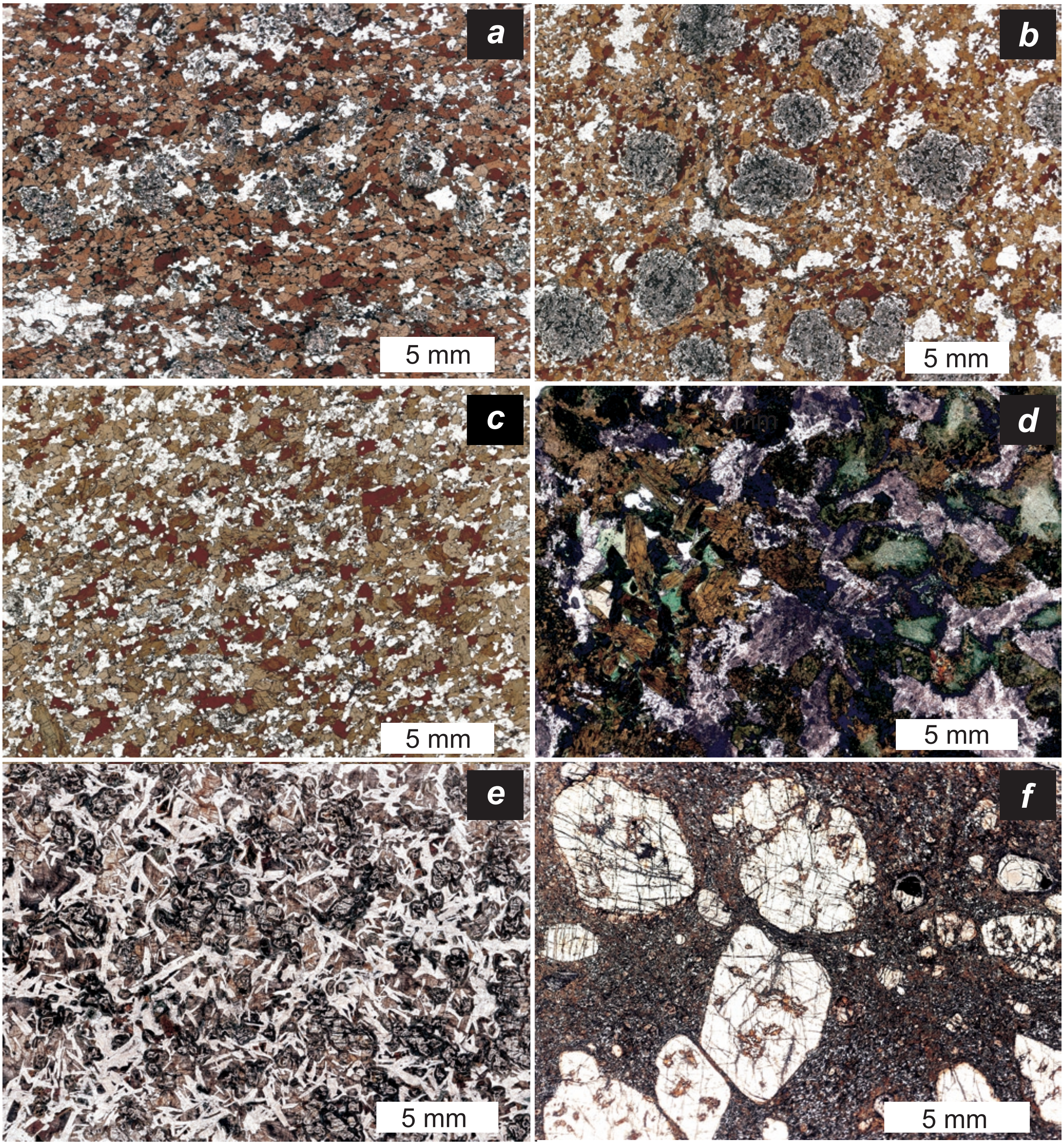


Fig. 4 Textures of amphibolites and metadolerites/metagabbros from the Český Krumlov area. **a** – A-10 Zlatá Koruna, amphibolite, **b** – A-14 Lazec, garnet amphibolite, **c** – A-15 Vyšný, amphibolite, **d** – A-12 Kovářov, amphibole metagabbro, **e** – A-13 Světlík, olivine metadolerite, **f** – VE-126 Světlík, porphyritic olivine-pyroxene metadolerite. All photographs represent scanned thin sections.

A-10 Zlatá Koruna, rock outcrop in the Vltava river valley, in forest c. 400 m W of Zlatá Koruna abbey, 48º51'18.49" N; 14º21'48.13" E

This sample is a garnet amphibolite with sulphides forming several-metres thick layers in biotite migmatite.

A-14 waste dump of graphite mine NE of Lazec, 5 km NW of the centre of Český Krumlov, 48º50'6.67" N; 14º16'15.45" E

The amphibolites in the Lazec graphite mine occur as a part of a varied assemblage of graphite gneiss, amphibolite and marble. The garnet amphibolites similar to sample A-14 are associated with dolomite–calcite marble with the mineral assemblage forsterite – spinel – clinohumite (chondrodite?) – phlogopite + brucite pseudomorphs after periclase.

A-15 Vyšný, disused marble quarry, 3 km NW of the centre of Český Krumlov, 48º49'34.00" N; 14º18'23.53" E

This sample comes from clinopyroxene-bearing amphibolite layers in marble in a disused quarry at Vyšný. The amphibolites form infrequent layers or boudins, very often with thin (< 1 cm) diopside-rich reaction rims at the amphibolite–marble interface.

135 Lískovec, amphibolite quarry at Lískovec Hill (805 m a.s.l.), 500 m W of Bližná, 48°43'21.88"N; 14°5'16.96"E

136 Hořice na Šumavě, amphibolite outcrop 400 m E of Hořice na Šumavě, 48°45'43"N; 14°11'2.21"E

Both samples come from amphibolite intercalations in amphibole-biotite paragneisses.

4.2.2. Metadolerites and metagabbros

A-13 boulders in fields, 1.5 km W of the village of Světlík, 0.3 km S of the road Světlík–Muckov, 48º43'56.03" N; 14º12'9.92" E

VE-126 boulders in fields, 1.5 km W of the village of Světlík, 48º43'48.89" N; 14º12'9.06" E

The coronitic metadolerite A-13 and porphyritic metadolerite VE-126 occur as dykes in the Světlík orthogneiss, with a Palaeoproterozoic protolith 2.1 Ga old (Wendt et al. 1993; Patočka et al. 2003). This mode of occurrence was important for preservation of the primary textures and for minimal recrystallization of dolerite dykes, which nevertheless were transformed to foliated amphibolite in local shear zones. Poor exposure did not permit study of field relations to the country rocks or possible compositional variation often encountered in intrusive sills of the less disturbed and better exposed terrains.

A-12 Plánský vrch, boulders and small rock outcrops in forest 400 m NE of Kovářov, 48º41'41.4" N; 14º7'34.41" E

Sample of a coarse-grained, foliated metagabbro A-12 comes from a partly sheared dyke about 1 km long, intruded in biotite migmatite and biotite orthogneiss of granitic composition. The orthogneiss remains undated but possibly correlates with the Palaeoproterozoic Světlík orthogneiss, which has dominantly a composition of amphibole–biotite tonalite or diorite. In outcrop the foliated metagabbro grading to amphibolite is seen as cm to metre wide shear zones alternating with massive, unfoliated metagabbro.

5. Petrology and mineral chemistry

5.1. Amphibolites from the Chýnov Varied Unit

A-1 Obrataň, fine-grained amphibolite

The rock contains ~ 60 vol. % of grey-green magnesiohornblende (Tab. 1, Fig. 5) and ~ 40 vol. % of intermediate plagioclase. Opaque minerals are almost exclusively ilmenite (1 vol. %); titanite, zircon and chlorite are accessory.

A-2 Pacovská hora Hill, fine-grained amphibolite

The sample contains ~ 45 vol. % of green edenite, 50 vol. % intermediate plagioclase forming often oikocrysts enclosing abundant ilmenite, and ~ 5 % opaque minerals. Amphibole shows a tendency to poikiloblastic growth of somewhat larger grains. Biotite, titanite and apatite are accessory. The opaque minerals comprise *c.* 2/3 of ilmenite containing ~ 15 % of unmixed lenticular hematite, 1/3 of magnetite formed by oxidation of pyrrhotite and carrying minute chalcopyrite inclusions inherited from pyrrhotite, minor residual pyrrhotite and traces of sphalerite.

A-3 Pacovská hora Hill, fine-grained amphibolite

The petrography of this sample is very similar to A-2, including quantitative ratio of edenite and plagioclase, and the presence of accessory minerals with traces of chalcopyrite and sphalerite. However, opaque minerals are absolutely dominated by ilmenite, with unmixed hematite accounting only for 2.5 vol. %. The fabric of ilmenite inclusions in somewhat coarser plagioclase indicates $s_i//s_e$ relations and points to prolonged plagioclase growth. Titanite, apatite, zircon and chlorite are accessory.

A-4 Pacovská hora Hill, fine-grained amphibolite

The petrography is very similar to that of samples A-2 and A-3. The bluish-green amphibole is edenite associated with intermediate plagioclase. Accessory minerals are quartz, biotite, titanite, apatite, chlorite (each < 1 %) and opaque minerals. The opaque phases (4 vol. %) are dominated by ilmenite (3/4) with 15 vol. % of unmixed hematite, magnetite (1/10), pyrrhotite (1/7) plus traces of chalcopyrite and sphalerite.

A-5 Pacovská hora Hill, fine-grained amphibolite

The rock contains ~ 35 vol. % of bluish-green ferropargasite to ferrohornblende, 55 % intermediate plagioclase, 8 % diopsidic pyroxene in equilibrium with other minerals, 5 % titanite and 3 % carbonate. Apatite, chlorite and opaque minerals are accessory. The opaque minerals (1 %) include 1/5 ilmenite, 2/5 magnetite, 1/5 pyrrhotite plus traces of chalcopyrite and sphalerite.

Table 1a Representative analyses of amphibole from the Chýnov area amphibolites (wt. %) recalculated on the basis of 23 (O, OH) equivalents.

Sample No.	A2	A2	A5	A5	A4	A4	A1	A1	A7	A7
Analysis No.	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6	Ch7	Ch8	Ch9	Ch10
SiO_2	44.94	43.57	43.05	40.98	44.15	43.07	47.46	45.04	48.65	42.79
TiO_2	0.72	0.77	1.31	1.08	0.82	0.77	0.86	0.43	0.45	0.56
Al_2O_3	10.92	11.68	12.04	11.52	10.93	12.19	10.29	14.50	8.03	11.58
Cr_2O_3	0.07	NA	NA	NA	0.02	0.08	0.12	0.02	0.19	0.20
FeOt	15.11	15.83	18.81	18.75	15.73	16.03	12.10	12.89	10.45	12.20
MnO	0.25	0.22	0.35	0.37	0.16	0.20	0.08	0.07	0.15	0.12
MgO	12.21	11.78	8.50	9.12	11.33	10.88	14.19	12.34	15.61	13.04
CaO	11.13	10.79	11.89	11.37	11.62	11.72	11.89	11.67	12.08	13.14
Na_2O	1.66	2.11	1.02	2.08	1.41	1.44	1.26	1.58	1.45	1.91
K_2O	0.24	0.25	1.18	1.14	0.51	0.56	0.20	0.25	0.28	0.49
Total	97.25	97.00	98.15	96.41	96.68	96.94	98.45	98.79	97.34	96.03
Number of atoms										
Si	6.665	6.520	6.491	6.348	6.628	6.472	6.823	6.482	7.035	6.427
Al	1.335	1.480	1.509	1.652	1.372	1.528	1.177	1.518	0.965	1.573
T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al	0.573	0.580	0.631	0.452	0.562	0.632	0.567	0.941	0.403	0.478
Ti	0.080	0.087	0.149	0.126	0.093	0.087	0.093	0.047	0.049	0.063
Cr	0.008	0.000	0.000	0.000	0.002	0.010	0.014	0.002	0.022	0.024
Mg	2.699	2.628	1.911	2.106	2.536	2.437	3.041	2.648	3.365	2.920
Fe^{2+}	1.639	1.706	2.310	2.316	1.807	1.834	1.285	1.362	1.161	1.515
C	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Mn	0.031	0.028	0.045	0.049	0.020	0.025	0.010	0.009	0.018	0.015
Fe^{2+}	0.235	0.276	0.062	0.113	0.168	0.180	0.170	0.189	0.102	0.017
Ca	1.733	1.697	1.893	1.838	1.812	1.794	1.821	1.800	1.872	1.968
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.008	0.000
B	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Na	0.477	0.612	0.298	0.625	0.410	0.420	0.351	0.438	0.399	0.556
Ca	0.035	0.033	0.028	0.049	0.057	0.093	0.011	0.000	0.000	0.147
K	0.045	0.048	0.227	0.225	0.098	0.107	0.037	0.046	0.052	0.094
A	0.558	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
VcA	0.442	0.307	0.447	0.101	0.435	0.380	0.601	0.516	0.550	0.203

A-6 Kladrubská hora, fine-grained amphibolite

The sample contains ~ 55 vol. % green amphibole, 40 % intermediate plagioclase, 4 % quartz, with accessory titanite, apatite, carbonate and chlorite. Opaque minerals (~2 vol. %) are represented by 3/10 ilmenite with unmixed hematite, 4/10 magnetite, 2/10 pyrrhotite, 1/10 chalcopyrite and traces of sphalerite.

A-7 Šimpach, fine-grained amphibolite

The amphibole in this sample shows a wide range in Al/Si ratio. It is grey-green pargasite to magnesiohornblende (~60 vol. %) with Mg/Fe ratio somewhat higher than in the other samples. Plagioclase (30 %) of intermediate composition is in part concentrated in aggregates 1–3 mm across arranged parallel to the foliation. Clinopyroxene (5 %) is a coarser-grained early diopsidic Cpx_I and local Cpx_{II} with elevated Fe/Mg ratio in symplectitic aggregates with plagioclase and zoisite, which may have formed by reaction of minor garnet (?). Accessory minerals include titanite, clinozoisite/zoisite and only 0.5 % of opaque minerals (ilmenite, rutile and chalcopyrite).

5.2. Amphibolites from the Český Krumlov Varied Unit

A-10 Zlatá Koruna, garnet amphibolite

The sample is a garnet amphibolite with an assemblage amphibole + garnet + plagioclase; common accessories

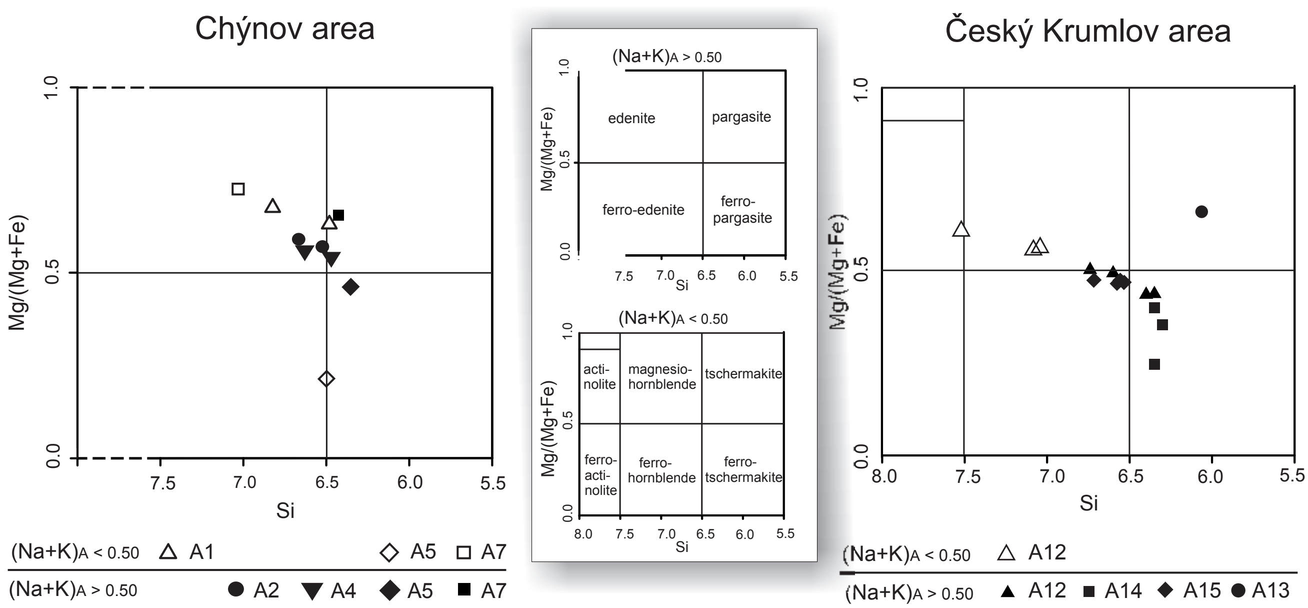


Fig. 5 Classification plot for the studied amphiboles (Leake et al. 1997). Total iron is calculated as Fe^{2+}.

are ilmenite (~ 2 %), apatite, minor sulphides, biotite and quartz; the rock has only indistinct foliation. Dark brown amphibole accounts for *c.* 55 vol. %, plagioclase with a strong inverse compositional zoning 30 % and quartz 5 %. The granular matrix of amphibole and plagioclase (0.2–1.0 mm) contains grains of poikilitic garnet 0.2–1.0 mm across (Fig. 4a). Garnet forms *c.* 8 % of the rock volume and encloses quartz, ilmenite and hornblende inclusions. Replacement of garnet by plagioclase is variable in extent.

A-14 Lazec, garnet amphibolite

The rock has a finely granular matrix (0.1–0.5 mm) with garnet porphyroblasts 2.5–3.5 mm across (Fig. 4b). Garnet appears to form *c.* 25 vol. % of the rock but the garnets are strongly poikiloblastic with abundant plagioclase, ilmenite and titanite inclusions, so that the true garnet content is near 12 %. Amphibole accounts for *c.* 45 %, plagioclase 35 % and quartz 8 % of the rock volume. Accessory Ca-rich clinopyroxene is enclosed in garnet. The other important accessories are ilmenite, titanite, sulphides, apatite and carbonate. Dark brown amphibole is ferrotschermakite with Al^{IV} 1.75–1.79 apfu and the Mg/Fet ratio is well inside the ferrotschermakite compositional field (Fig. 5, Tab. 2a). Plagioclase composition corresponds to andesine $An_{36–37}$. Clinopyroxene is augite containing 30–32 mol. % ferrosilite and 1.0–1.2 mol. % jadeite (Tab. 2b). Garnet is almandine–grossular containing $Alm_{52.8–54.5}$, $Grs_{30.9–35.6}$, $Prp_{6.9–7.2}$, $Adr_{3.0–3.6}$, $Sps_{1.5–3.5}$ mol. % (Tab. 2c). The low *Prp* and high *Grs* contents probably indicate early crystallization of garnet at moderate temperature and increased pressure. Matrix mineral assemblage indicates equilibrium relations.

A-15 Vyšný, clinopyroxene-bearing amphibolite

This fine-grained rock (0.5–1.5 mm; Fig. 4c) contains c. 50–55 vol. % of brown amphibole, 40 % plagioclase, 6 % Ca-clinopyroxene and 3 % quartz. Ilmenite dominates the opaque minerals; titanite, apatite, sulphides and zircon are also common. Dark brown amphibole is ferrotschermakite with Al^{IV} 1.50–1.63 apfu and Mg/Fet ratio near tschermakite compositional field. Plagioclase is andesine $An_{36–46}$ (Tab. 2b). Clinopyroxene is colourless diopside–augite containing 19 mol. % ferrosilite and 1.4–3.1 mol. % jadeite.

135 Lískovec, amphibolite

Dark green (brownish green) amphibole and plagioclase 0.3–1.5 mm across form a regular granoblastic texture and a weak planar-preferred orientation. Amphibole makes *c.* 70 vol. %, plagioclase with a strong inverse zoning 25 % and quartz 3 % of the rock volume. Ilmenite, apatite and titanite are the common accessories.

136 Hořice na Šumavě, amphibolite

Brownish green (khaki) amphibole and plagioclase 0.3–1.3 mm form a regular granoblastic planar texture. The bulk of the rock consists of amphibole (60 vol. %) and plagioclase with a strong inverse zoning (35 %). Quartz, rutile, ilmenite with minor apatite, sulphide, titanite, and biotite are common accessories.

Table 1b Representative analyses of clinopyroxene, ilmenite and biotite from the Chýnov area amphibolites (wt. %) recalculated on the basis of 4 cats, 2 cats and 22 (O, OH) equivalents, respectively.

Mineral	Cpx	Cpx I	Cpx II	Ilm	Ilm	Ilm	Bt
Sample No.	A5	A7	A7	A4	A1	A2	A4
Analysis No.	Ch11	Ch12	Ch13	Ch15	Ch16	Ch17	Ch14
SiO_2	51.72	52.23	50.44	0.20	0.14	0.18	36.63
TiO_2	0.09	0.21	0.16	49.59	50.68	48.89	2.50
Al_2O_3	1.90	2.31	2.32	0.09	0.00	0.05	14.89
Cr_2O_3	0.00	0.00	0.46	0.05	0.07	0.19	0.01
FeOt	10.88	6.84	12.75	48.09	46.15	49.69	19.59
MnO	0.59	0.20	0.33	0.71	0.41	0.67	0.00
MgO	11.20	14.17	9.79	0.21	0.31	0.09	11.45
NiO	0.00	0.00	0.00	0.12	0.08	0.25	0.12
CaO	22.76	23.17	22.55	0.10	0.01	0.16	0.00
Na_2O	0.71	0.48	0.65	0.00	0.00	0.05	0.02
K_2O	0.00	0.01	0.05	0.00	0.01	0.02	10.19
Total	99.85	99.62	99.50	99.16	97.86	100.24	95.40
Number of atoms							
Si	1.950	1.937	1.928	0.005	0.004	0.005	5.64
Ti	0.003	0.006	0.005	0.944	0.980	0.920	0.29
Al	0.084	0.101	0.105	0.003	–	0.001	2.70
Cr	–	–	0.014	0.001	0.001	0.004	0.00
Fe^{3+}	0.062	0.049	0.068	0.097	0.032	0.148	–
Fe^{2+}	0.281	0.163	0.339	0.921	0.960	0.892	2.52
Mn	0.019	0.006	0.011	0.015	0.009	0.014	–
Ni	–	–	–	0.002	0.002	0.005	0.02
Mg	0.629	0.783	0.558	0.008	0.012	0.003	2.63
Ca	0.919	0.920	0.923	0.003	–	0.004	–
Na	0.052	0.035	0.048	–	–	0.002	0.00
K	–	–	0.002	–	–	0.001	2.00

5.3. Metadolerites/metagabbros from the Český Krumlov Varied Unit

A-12 Kovářov, foliated amphibole metagabbro

The rock is fine- to medium-grained. Recrystallized matrix, including fine amphibole and plagioclase crystals, has a grain size 0.05–0.2 mm (Fig. 4d); relict grains of primary plagioclase are 1–3 mm across. Monomineralic granular pseudomorphs of magnesiohornblende after primary diopside–augite contain 0.56–0.66 Al^{IV} (apfu), which corresponds to a composition near the actinolite field (Fig. 5). The predominant brown-green amphibole is magnesio-hornblende to ferrotschermakite with Al^{IV} 1.19–1.77 apfu. Plagioclase is largely preserved in cloudy relict grains, partly recrystallized to a fine-grained mosaic. Its composition varies between andesine An_{37} and labradorite An_{66}: newly formed albite An_4 is rare. The total plagioclase content is 40–45 vol. %. Locally chlorites up to 1 mm across form clusters in coarse brown-green amphibole. Other accessory minerals are titanite, opaque minerals, rare partly chloritized biotite, and apatite. The newly formed mineral assemblage corresponds to recrystallization under amphibolite-facies conditions. Minor chlorite and albite indicate local low temperature alterations, possibly due to an influx of hydrothermal fluids.

A-13 Světlík, olivine-pyroxene metadolerite

The rock shows outstandingly well preserved ophitic texture (Fig. 4e) with an average grain size 0.5–1 mm but some strongly poikilitic crystals of augite are 2 to 5 mm long. Lath-shaped plagioclase (*c.* 50 vol. %) and clinopyroxene (30 %) are fresh and free of alteration, though both phases show some clouding. Augite has 0.15 Al^{IV} apfu and 13.7 mol. % ferrosilite. Pleochroic

Table 2a Representative analyses of amphiboles from the Český Krumlov area amphibolites and metadolerites/metagabbros (wt. %) recalculated on the basis of 23 (O, OH).

Sample No.	A12	A12	A12	A12	A12	A12	A12	A14	A14	A14	A15	A15	A15	A15	A13
Analysis No.	2	3	5	6	10	12	13	17	23	28	41	42	101	102	35
SiO_2	51.16	44.17	47.85	48.00	44.63	41.74	41.48	41.39	39.70	40.59	43.36	43.42	44.49	43.30	41.09
TiO_2	0.00	0.18	0.67	0.66	0.61	1.59	1.36	2.52	2.25	2.27	1.76	1.80	1.76	1.63	NA
Al_2O_3	3.95	11.65	7.19	7.84	10.31	11.52	12.02	11.43	10.77	11.90	10.93	11.05	9.45	11.05	16.77
Cr_2O_3	0.00	0.00	0.34	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.24	NA	NA
MgO	13.54	9.70	11.70	11.19	9.74	8.41	8.38	7.52	4.59	6.55	8.86	8.95	9.35	9.09	12.47
FeOt	15.61	17.81	16.30	16.22	17.24	19.49	19.28	20.10	24.99	21.33	18.41	18.20	18.38	18.41	11.62
MnO	0.37	0.31	0.41	0.28	0.35	0.33	0.19	0.25	0.27	NA	0.33	0.34	0.14	0.26	NA
CaO	11.86	12.34	12.30	12.32	11.85	11.41	11.86	11.36	10.79	11.33	11.37	11.40	11.72	11.63	11.88
Na_2O	0.83	1.55	1.31	1.10	1.61	1.89	1.88	1.70	1.50	1.71	1.84	1.81	1.74	1.92	2.79
K_2O	0.14	0.75	0.50	0.50	0.67	1.08	0.94	1.70	1.47	1.76	0.43	0.44	0.43	0.48	0.70
Total	97.46	98.46	98.57	98.11	97.01	97.46	97.39	97.97	96.33	97.44	97.29	97.41	97.70	97.77	97.32
Number of atoms															
Si	7.521	6.596	7.054	7.080	6.739	6.396	6.353	6.350	6.352	6.301	6.569	6.562	6.707	6.535	6.058
Al	0.479	1.404	0.946	0.920	1.261	1.604	1.647	1.650	1.648	1.699	1.431	1.438	1.293	1.465	1.942
T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al	0.205	0.646	0.304	0.443	0.574	0.476	0.523	0.417	0.383	0.479	0.521	0.530	0.386	0.501	0.971
Ti	0.000	0.020	0.074	0.073	0.069	0.183	0.157	0.291	0.271	0.265	0.201	0.205	0.200	0.185	0.000
Cr	0.000	0.000	0.040	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.029	0.000	0.000
Mg	2.967	2.159	2.571	2.461	2.192	1.921	1.913	1.720	1.095	1.516	2.001	2.016	2.101	2.045	2.741
Fe^{2+}	1.828	2.175	2.010	2.001	2.165	2.419	2.407	2.572	3.251	2.740	2.278	2.248	2.284	2.268	1.288
Mn	0.000	0.000	0.001	0.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
C	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Mn	0.046	0.039	0.050	0.013	0.045	0.043	0.025	0.032	0.037	0.000	0.042	0.044	0.018	0.033	0.000
Fe^{2+}	0.092	0.050	0.000	0.000	0.012	0.078	0.063	0.007	0.093	0.029	0.055	0.052	0.033	0.055	0.144
Ca	1.862	1.911	1.943	1.947	1.917	1.873	1.912	1.867	1.850	1.885	1.846	1.846	1.893	1.881	1.856
Na	0.000	0.000	0.007	0.040	0.026	0.006	0.000	0.094	0.021	0.087	0.057	0.059	0.056	0.031	0.000
B	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Na	0.237	0.449	0.367	0.275	0.446	0.556	0.558	0.412	0.444	0.428	0.483	0.472	0.452	0.531	0.797
Ca	0.006	0.063	0.000	0.000	0.000	0.000	0.034	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.021
K	0.026	0.143	0.094	0.094	0.129	0.211	0.184	0.333	0.300	0.349	0.083	0.085	0.083	0.092	0.132
A	0.268	0.655	0.461	0.369	0.575	0.767	0.776	0.745	0.744	0.777	0.566	0.557	0.535	0.624	0.950
VcA	0.732	0.345	0.539	0.631	0.425	0.233	0.224	0.255	0.256	0.223	0.434	0.443	0.465	0.376	0.050

Table 2b Representative analyses of plagioclase and clinopyroxene from the Český Krumlov area amphibolites and metadolerites/metagabbros (wt. %) recalculated on the basis of 8 O and 4 O, respectively.

Mineral	Pl*	Pl*	Pl	Pl	Pl	Pl	Pl	Pl*	Pl*		Cpx	Cpx	Cpx*	Opx*
Sample No.	A12	A12	A12	A14	A14	A15	A15	A13	A13		A14	A15	A13	A13
Analysis No.	14	8	4	18	30	104	45	39	38		25	106	32	36
SiO_2	58.43	51.05	67.90	59.31	56.19	59.65	56.81	54.92	51.04		50.37	51.36	49.68	52.13
TiO_2	NA	NA	NA	NA	NA	NA	NA	NA	NA		0.17	0.19	0.74	0.66
Al_2O_3	25.96	30.55	20.15	25.40	27.13	25.31	27.19	27.87	30.82		0.89	1.40	5.01	1.97
Cr_2O_3	NA	NA	NA	NA	NA	NA	NA	NA	NA				0.56	
MgO	NA	NA	NA	NA	NA	NA	NA	NA	NA		7.18	10.73	13.67	21.68
FeOt	0.22		0.50		0.25	0.12		0.35			20.26	12.56	9.44	22.66
MnO	NA	NA	NA	NA	NA	NA	NA	NA	NA			0.51	0.27	0.43
CaO	7.69	13.97	0.85	7.59	9.89	7.55	9.67	11.01	15.41		20.70	22.73	19.70	0.58
Na_2O	7.01	3.85	11.30	7.36	6.14	7.42	6.29	5.42	3.66		0.41	0.42	0.57	
K_2O	0.16	0.10	0.10	0.26	0.13	0.14	0.07				NA	NA	NA	NA
Total	99.47	99.52	100.80	99.92	99.73	100.19	100.03	99.56	100.03		99.57	99.90	99.64	100.10
Number of atoms														
Si	2.626	2.329	2.952	2.648	2.530	2.657	2.547	2.488	2.320	Si	1.972	1.952	1.852	1.945
Ti										Ti	0.005	0.005	0.021	0.019
Al	1.375	1.642	1.032	1.337	1.440	1.329	1.437	1.488	1.651	Al	0.041	0.063	0.220	0.087
Cr										Cr	0.000	0.000	0.017	0.000
Fe^{3+}	0.008	0.000	0.018	0.000	0.009	0.004	0.000	0.013	0.000	Fe^{3+}	0.036	0.053	0.059	0.000
Mg										Mg	0.419	0.608	0.760	1.206
Fe^{2+}										Fe^{2+}	0.628	0.346	0.235	0.707
Mn										Mn	0.000	0.016	0.009	0.014
Ca	0.370	0.683	0.040	0.363	0.477	0.360	0.465	0.534	0.707	Ca	0.868	0.926	0.787	0.023
Na	0.611	0.340	0.952	0.637	0.536	0.641	0.547	0.476	0.323	Na	0.031	0.031	0.041	0.000
K	0.009	0.006	0.006	0.015	0.007	0.008	0.004	0.000	0.000	Wo	41.57	43.55	35.63	1.15
Ab	61.68	33.09	95.48	62.77	52.52	63.50	53.85	47.11	31.34	En	20.06	28.60	34.40	60.06
An	37.39	66.35	3.97	35.77	46.75	35.71	45.75	52.89	68.66	Fs	31.76	19.55	13.71	35.89
Or	0.93	0.57	0.56	1.46	0.73	0.79	0.39	0.00	0.00	Ac	1.49	1.46	1.87	0.00
										Jd	1.24	1.36	3.53	0.00

* primary magmatic minerals in metagabbros; NA = not analysed

Table 2c Representative analyses of ilmenite, garnet and olivine from the Český Krumlov area amphibolites and metadolerites/metagabbros (wt. %) recalculated on the basis of 2 cats, 8 cats and 3 cats, respectively.

Mineral	Ilmenite	Ilmenite	Ilmenite*	Ilmenite*		Grt	Grt	Grt		Olivine*
Sample No.	A14	A15	A12	A13		A14	A14	A13		A13
Analysis No.	27	107	15	40		19	21	34		31
SiO_2	0.27		0.28	0.22		37.97	37.79	39.23		36.19
TiO_2	51.19	51.91	51.97	50.99		0.16				
Al_2O_3	0.11	0.14	0.11			20.67	20.53	21.58		
MgO	0.05	0.15		0.48		1.79	1.78	8.30		27.87
FeOt	46.29	46.29	45.49	47.00		25.46	26.27	22.85		35.71
MnO	0.93	1.39	2.46	0.42		0.67	1.62	1.22		0.37
CaO	0.30					13.30	11.58	6.44		
Total	99.14	99.88	100.31	99.10		100.01	99.56	99.62		100.14
Number of atoms										
Si	0.007	0.000	0.007	0.006		2.999	3.008	3.011		1.005
Ti	0.977	0.985	0.982	0.972		0.010	0.000	0.000		
Al	0.003	0.004	0.003	0.000		1.924	1.926	1.952		
Mg	0.002	0.006	0.000	0.018		0.211	0.211	0.950		1.153
Fe^{3+}	0.028	0.027	0.019	0.045		0.067	0.074	0.048		
Fe^{2+}	0.954	0.949	0.937	0.950		1.615	1.675	1.419		0.829
Mn	0.020	0.030	0.052	0.009		0.045	0.109	0.079		0.009
Ca	0.008	0.000	0.000	0.000		1.126	0.988	0.530		
					Prp	6.89	6.85	30.94	Fo	57.93
					Alm	52.79	54.36	46.23	Fa	41.64
					Sps	1.47	3.54	2.58	Tep	0.44
					Adr	3.28	3.56	2.31		
					Grs	35.57	30.87	16.84		

* primary magmatic minerals in metagabbros

red-brown orthopyroxene (parallel to Z) is an accessory component; it contains 35.9 mol. % ferrosilite and 0.06 apfu Al^{IV}. Olivine grains 0.5–1.5 mm in diameter exhibit two regular kelyphitic reaction zones 0.2–0.3 mm wide. The inner zone is of enstatite containing 32 mol. % ferrosilite with Al^{IV} 0.04 apfu, oriented perpendicular to the olivine surface. The outer zone is composed of a microcrystalline aggregate of grey-green tschermakite (Fig. 5) with minute spinel crystals < 2 µm. The amphibole has 2.0 Al^{IV} apfu, but part of the Al is in spinel microcrysts and analysis No. 35 (Tab. 2a) is not strictly monomineralic. Minor garnet crystals, 10–20 µm in size, with a composition of $Alm_{46.2}$, $Prp_{30.9}$, $Grs_{16.8}$, $Adr_{2.3}$ and $Sps_{2.6}$ mol. % occur at the interface of the inner Opx and outer amphibole zone. Olivine inside these kelyphitic shells is fresh, containing 41.6 mol. % fayalite. The original olivine content prior to alteration could have been near 20 vol. %. Accessory phases include primary ilmenite and titanomagnetite, minor primary red-brown biotite and apatite. The kelyphite zones around olivine and minor garnet of the given composition indicate partial (local) metamorphic reactions corresponding to higher-temperature amphibolite-facies conditions at rather low fluid activity.

VE-126 Světlík, olivine-pyroxene porphyritic metadolerite

This rock, nominally similar to sample A-13, has a significantly different chemical composition with 17.43 wt. % MgO (Tab. 3). Its highly magnesian composition reflects the abundance of phenocrysts of clinopyroxene and olivine up to 12 mm long, accounting for *c.* 20–30 % of the rock volume (Fig. 4f).

The rock can be interpreted as having crystallized from a melt containing a significant proportion of pyroxene-olivine cumulate. The preservation of the primary minerals is surprisingly good, as in sample A-13, which it also resembles in having two kelyphitic zones around olivine and minor, newly formed garnet. The metamorphic characteristics are also similar to sample A-13.

Table 3 Major- and minor-element whole-rock geochemical analyses for the metabasic rocks from the South Bohemian Varied Group (wt. %)

Chýnov

Sample	A-1	A-2	A-3	A-4	A-5	A-6	A-7
Locality	Obrataň amphibolite	Chýnov amphibolite	Chýnov amphibolite	Chýnov amphibolite	Chýnov amphibolite	Kladr. h. amphibolite	Šimpach amphibolite
SiO_2	48.12	47.07	47.26	47.15	46.22	48.05	45.51
TiO_2	1.50	2.76	2.56	2.63	2.83	1.36	0.70
Al_2O_3	14.46	14.77	16.08	15.59	14.60	15.67	15.88
Fe_2O_3	3.62	5.97	5.86	5.52	6.61	5.10	3.53
FeO	7.89	8.48	5.87	6.41	7.14	7.01	5.82
MnO	0.18	0.23	0.18	0.19	0.26	0.19	0.15
MgO	8.22	5.30	6.09	6.17	4.95	6.80	9.67
CaO	11.64	8.01	8.58	8.73	9.97	9.14	13.16
Na_2O	1.66	4.14	4.37	4.37	4.20	3.23	1.98
K_2O	0.25	0.32	0.41	0.42	0.70	0.62	0.38
P_2O_5	0.17	0.44	0.55	0.56	0.48	0.12	0.05
CO_2	0.07	0.27	0.09	0.09	0.54	0.28	0.25
H_2O^+	1.71	1.31	1.17	1.25	1.22	1.75	1.85
F	0.04	0.08	0.08	0.08	0.08	0.04	0.03
S	0.17	0.25	0.02	0.01	0.10	0.14	0.02
H_2O^-	0.13	0.16	0.07	0.07	0.10	0.13	0.14
Sum	99.83	99.56	99.24	99.24	100.00	99.63	99.12
mg#	56.8	40.6	49.4	49.1	40.3	51.1	65.7
K_2O/Na_2O	0.15	0.08	0.09	0.10	0.17	0.19	0.19
Fe_2O_3/FeO	0.46	0.70	1.00	0.86	0.93	0.73	0.61

Český Krumlov

Sample	A-10	A-14	A-15	126	127	A-12	A-13	VE-126
Locality	Zlatá Koruna amphibolite	Lazec amphibolite	Vyšný amphibolite	Bližná (Lískovec) amphibolite	Hořice amphibolite	Plánský Kopec metagabbro	Světlík metadolerite	Světlík metadolerite
SiO_2	46.14	49.84	48.92	46.10	49.17	46.32	47.12	47.16
TiO_2	3.56	2.55	1.74	2.69	1.54	1.52	0.48	1.31
Al_2O_3	13.19	12.63	13.50	11.04	14.57	17.93	17.21	8.36
Fe_2O_3	1.67	1.25	1.03	5.23	2.59	1.42	0.81	1.25
FeO	13.71	13.60	11.35	14.20	9.26	9.24	9.09	9.46
MnO	0.27	0.26	0.23	0.21	0.21	0.20	0.16	0.17
MgO	5.23	4.56	6.63	5.72	6.48	5.85	10.40	17.43
CaO	10.70	10.74	11.80	10.28	10.53	11.76	11.15	9.91
Na_2O	1.94	1.95	2.72	1.94	2.68	2.62	2.27	1.32
K_2O	0.94	0.95	0.30	0.24	0.37	0.87	0.20	0.32
P_2O_5	0.60	0.24	0.15	0.14	0.17	0.12	0.04	0.13
CO_2	0.02	0.09	0.21	0.02	0.02	0.14	0.11	0.42
H_2O^+	1.75	1.15	1.35	2.10	1.55	1.96	0.99	1.74
F	0.11	0.13	0.07	0.05	0.05	0.12	0.07	0.02
S	0.40	0.36	0.17	0.02	0.01	0.06	0.08	0.11
H_2O^-	0.17	0.07	0.05	0.20	0.17	0.11	0.08	0.08
Sum	100.39	100.37	100.21	100.18	99.37	100.23	100.27	99.19
mg#	38.0	35.6	49.1	50.1	51.1	49.8	65.4	74.6
K_2O/Na_2O	0.48	0.49	0.11	0.12	0.14	0.33	0.09	0.24
Fe_2O_3/FeO	0.12	0.09	0.09	0.37	0.28	0.15	0.09	0.13

6. Whole-rock geochemistry

6.1. Rock classification

The newly-obtained major- and minor-element analyses for the metabasic rocks from the South Bohemian Varied Unit (Tab. 3) have been supplemented by data from Němec (1998), René (2007) (amphibolites from around Chýnov) and Patočka (1991) (amphibolites of the Český Krumlov Varied Unit). In view of their association with marble, the question of whether these could not be para-amphibolites of Fe-rich dolomitic origin needs to be discussed. In fact the chemical indicators all consistently show that the studied rocks are orthoamphibolites. For instance, in the diagram Ni vs. Zr/TiO_2 of Winchester et al. (1980) (not shown), all the analyses plot below the dividing line, separating the fields for metabasic rocks with the sedimentary (higher Zr/TiO_2 at the given Ni contents) and igneous parentage.

On a standard Total Alkali–Silica (TAS) diagram of Le Bas et al. (1986) (Fig. 6a), the metavolcanics classify exclusively as basalts. Most data points fall beneath the dividing line between the alkaline and subalkaline (tholeiitic/calc-alkaline) domains as defined by Irvine and Baragar (1971). Analyses with alkaline affinity are considerably rarer; only samples A-2, A-3, A-4 and A-5 in our data set classify as such.

However, for metamorphosed basic volcanic rocks, the mobility of elements with low ionic potential is a major concern. Therefore, immobile elements, such as HFSE, are preferred for classification purposes (Winchester and Floyd 1976; Floyd and Winchester 1978). A popular diagram utilizing relatively immobile element ratios (Nb/Y vs. Zr/Ti) was proposed by Winchester and Floyd (1977). As it was designed before publication of the TAS diagram, the field definition for the Nb/Y vs. Zr/Ti plot was subsequently modified by Pearce (1996) and this form of the plot is preferred here (Fig. 6b). All rocks are again basaltic in composition; the elevated Nb/Y ratios of samples A-3, A-4, A-10 and A-12 indicate their alkaline nature. The Nb/Y ratio of amphibolite A-7 is an estimate only, as the Nb is below the detection limit of 0.5 ppm and thus its Nb/Y should be < 0.027.

The tholeiitic (and not calc-alkaline) affinity of the subalkaline part of the dataset is documented by the AFM ternary plot of Irvine and Baragar (1971) (Fig. 6c) and is confirmed using less mobile elements in the multicationic ternary plot Al – Fe^T + Ti – Mg of Jensen (1976) (Fig. 6d).

6.2. Major elements

The newly obtained data for the amphibolites confirm that we are dealing exclusively with basic rocks (SiO_2 = 45.51–49.84 wt. %, the least siliceous being the Chýnov sample A-5). The mg numbers [*mg#* = molar Mg/(Mg + Fe_t)] span a fairly wide range, indicating a variable – but usually rather high – degree of fractionation: 35.6 (A-14) to 65.7 (A-7). The *mg#* for the metadolerites/metagabbros are even more variable (49.8–74.6).

As often so with basic igneous rocks, MgO seems to be a more appropriate fractionation index than silica. The MgO variation is fairly large (4.56–9.67 wt. %; the lowest content being in the Chýnov sample A-5, the highest in amphibolite A-7 from Šimpach). Some of the metadolerites/metagabbros have even higher MgO contents (5.85–17.43).

Binary plots of MgO versus oxides of major- and minor elements (sometimes termed Fenner plots) are shown in Fig. 7a. Some diagrams are characterised by nearly linear negative (TiO_2 and FeO_t) or positive (CaO and Al_2O_3) trends, while others feature an inflection at MgO ~ 6.5–7.0 wt. % (SiO_2, P_2O_5). For instance the silica shows an initial increase with decreasing MgO (increasing degree of fractionation), and at around MgO ~ 7 wt. % the trend breaks into a strongly positive one.

The K_2O/Na_2O ratios for the studied metabasites are variably low (0.08–0.49), and, except for samples A-10 and A-14, are all under 0.20. But, as sodium is a highly mobile element, the K_2O/Na_2O ratios may reflect metamorphic modification rather than primary igneous variation. Indeed, as expected in such a high-grade metamorphic terrain, Na_2O fails to define any clear trend and K_2O yields only a rough negative correlation with MgO.

The degree of Fe oxidation is highly variable. The Chýnov samples are in general more oxidized, especially the alkaline types (Fe_2O_3/FeO = 0.86–1.00: A-3, A-4; Tab. 3) followed by the other two samples from the Pod Pacovou horou quarry (Fe_2O_3/FeO = 0.70–0.93: A-2, A-5). The least oxidized of the Chýnov set are samples A-1, A-7 and A-6 (Fe_2O_3/FeO = 0.46–0.73). By contrast, the Český Krumlov metabasic rocks have low Fe_2O_3/FeO ratios (< 0.4), which, except for amphibolites 126 and 127, does not exceed 0.15.

The box plots shown in Fig. 7b underpin several important differences between the amphibolites from the Chýnov and Český Krumlov varied units, some already apparent from the Fenner plots. Please note that only new analyses obtained by identical methods in the same laboratories were used here for the sake of reproducibility. The Český Krumlov amphibolites clearly tend to have considerably lower Al_2O_3, Na_2O and Fe_2O_3/FeO and higher FeO_t, CaO and MnO contents than those from Chýnov.

6.3. Trace elements

The trace-element contents and evolution with progressive differentiation are shown in binary plots with MgO

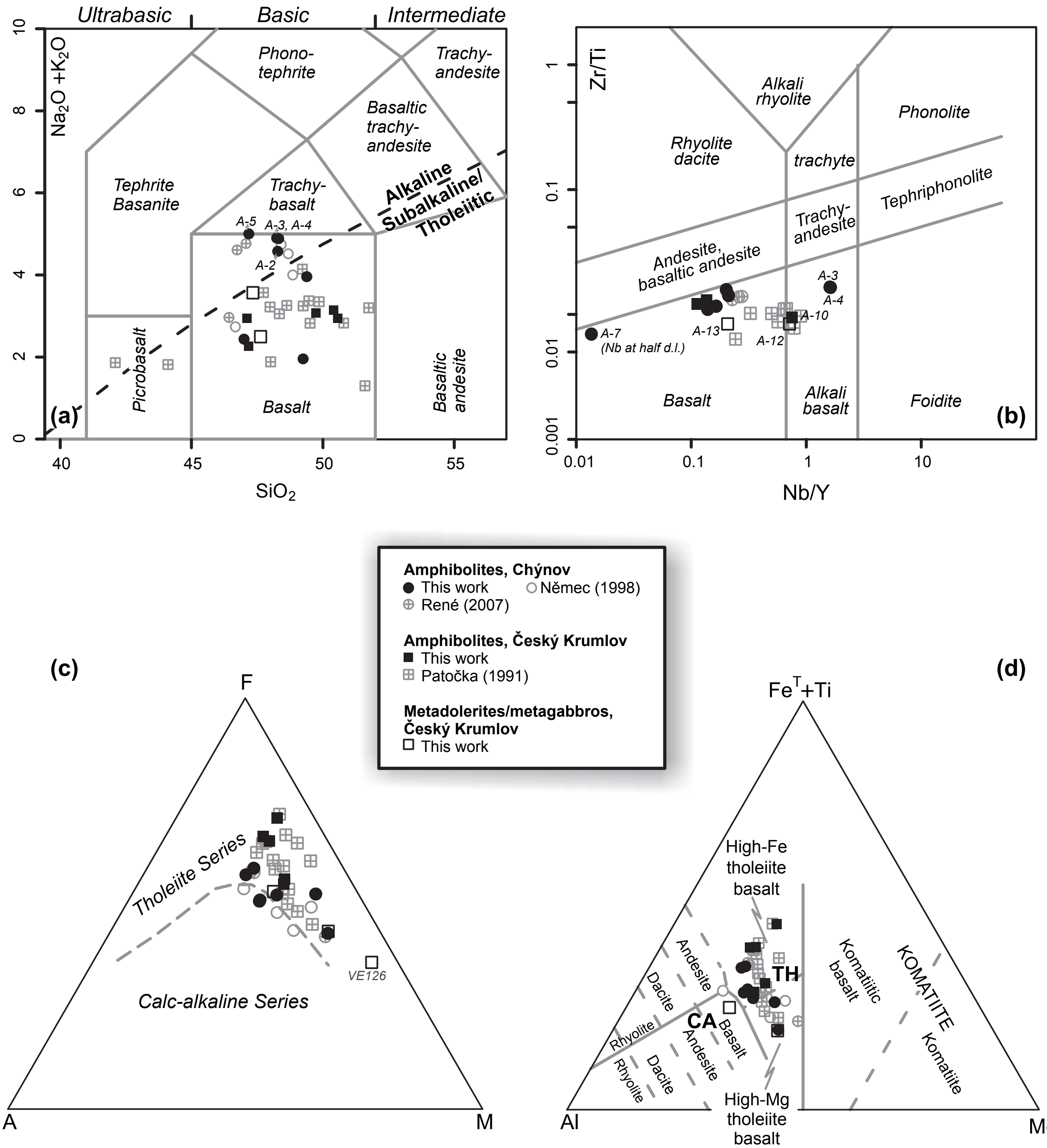


Fig. 6a – Diagram SiO_2 – (Na_2O + K_2O) (TAS) of Le Bas et al (1986). The dividing line between the subalkaline and alkaline domains is after Irvine and Baragar (1971). **b** – Classification plot Nb/Y vs. Zr/Ti after Pearce (1996), in which almost all the samples classify as subalkaline basalts. **c** – AFM diagram (A = Na_2O + K_2O, F = FeO_t, M = MgO: Irvine and Baragar 1971) illustrating the tholeiitic trend shown by the south Bohemian metabasites. **d** – Cationic plot Al – Fe^T + Ti – Mg of Jensen (1996) confirming the tholeiitic character of the subalkaline amphibolites.

on abscissa (Fig. 8a). Fairly good positive trends are observed in diagrams involving compatible elements (transition metals Cr and Ni). The Cr and Ni contents in some samples are high, reaching their maxima in the Šimpach amphibolite A-7 (Cr = 363 and Ni = 262 ppm; Tab. 4a). This probably indicates a considerable proportion of cumulus olivine and magnetite in this rock (e.g., Pearce 1996). All the amphibolite samples, regardless the

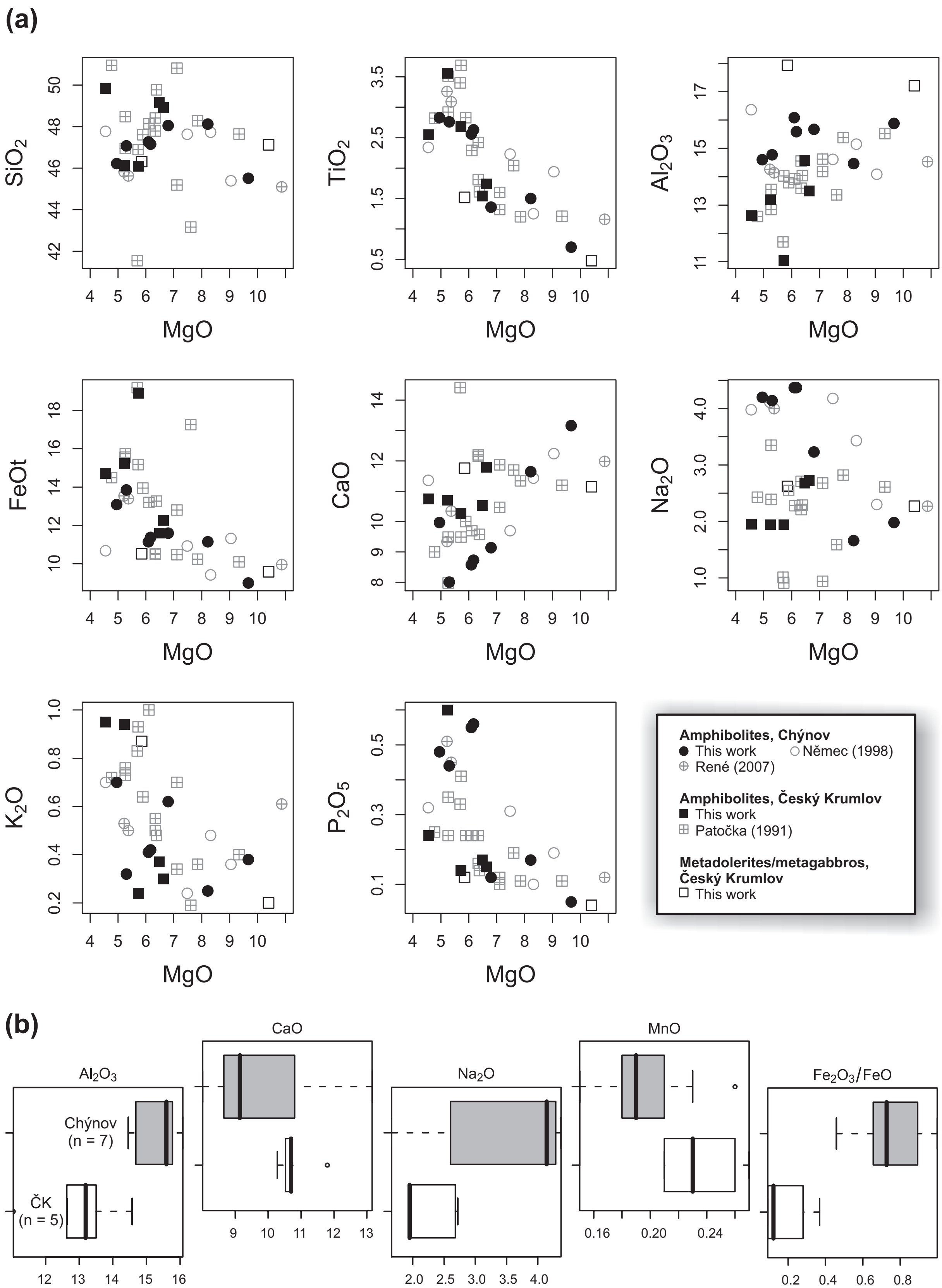


Fig. 7a – Binary plots of MgO versus major- and minor elements for the studied metabases. **b** – Box plots for selected oxides comparing the newly obtained data for the amphibolites from the Chýnov (top) and Český Krumlov (ČK, bottom) varied units (wt. %; see also Tab. 3).

Table 4a Trace-element whole-rock geochemical analyses for the amphibolites from the Chýnov Varied Unit (ppm)

Sample	A-1	A-2	A-3	A-4	A-5	A-6	A-7
Locality	Obrataň	Chýnov	Chýnov	Chýnov	Chýnov	Kladr. h.	Šimpach
	amphibolite	amphibolite	amphibolite	amphibolite	amphibolite	amphibolite	amphibolite
Rb	4.0	3.2	7.8	7.6	8.2	13.9	6.9
Sr	242.1	238.4	466.8	469.9	223.3	135.4	167.1
Ba	21.3	52.5	210.4	173.9	81.4	52.6	20.6
Cs	0.6	0.2	2.0	2.0	0.4	1.2	0.1
Cr	349	21	116	123	48	144	630
Ni	159	13	65	72	17	62	267
Co	48.8	42.7	40.1	43.2	44.5	47.7	55.0
Sc	40	38	25	26	41	43	34
V	347	515	308	336	482	329	217
Mo	0.2	0.8	0.8	0.8	0.4	0.2	0.1
Cu	94	43	102	78	52	103	82
Pb	0.4	0.6	1.3	1.2	0.3	0.9	0.6
Zn	12	40	29	26	48	26	14
Ga	18.9	23.8	22.8	25.0	23.9	20.8	14.8
Zr	104	260	252	260	239	89	29
Hf	3.0	6.9	6.4	6.7	6.4	2.7	1.1
Nb	4.9	11.2	40.7	42.9	10.7	4.2	<0.5
Ta	0.4	0.8	2.7	2.9	0.8	0.3	<0.1
Th	0.5	1.6	2.7	3.3	1.1	2.2	<0.1
U	0.2	0.6	1.1	1.0	0.9	0.5	0.1
La	5.30	18.30	29.60	30.70	14.00	11.60	0.80
Ce	15.90	46.00	71.10	74.80	39.10	24.50	2.70
Pr	2.52	6.61	9.13	9.56	5.78	3.31	0.57
Nd	12.00	31.10	38.20	40.80	28.00	14.50	3.90
Sm	3.80	8.40	7.60	8.10	7.80	3.60	1.50
Eu	1.30	2.90	2.62	2.59	2.58	1.41	0.69
Gd	4.54	8.85	6.53	7.00	8.90	4.67	2.53
Tb	0.90	1.71	1.01	1.04	1.56	0.87	0.47
Dy	5.42	10.21	5.36	5.75	9.40	5.45	3.41
Ho	1.10	1.98	0.95	0.95	1.87	1.10	0.71
Er	3.13	5.77	2.46	2.46	5.17	3.17	2.00
Tm	0.45	0.85	0.33	0.33	0.77	0.47	0.31
Yb	2.95	5.03	1.79	2.19	4.72	2.87	1.84
Lu	0.41	0.80	0.26	0.28	0.68	0.45	0.27
Y	29.8	55.6	25.0	26.7	50.7	30.2	18.5
Eu/Eu*	0.96	1.03	1.14	1.05	0.95	1.05	1.08
La_N/Yb_N	1.21	2.45	11.15	9.45	2.00	2.72	0.29
La_N/Sm_N	0.88	1.37	2.45	2.38	1.13	2.03	0.34
Sum REE	59.72	148.51	176.94	186.55	130.33	77.97	21.70

unit they belong to, also have high V (217–519 ppm) and Sc (25–46 ppm) contents. While Sc fails to define any trend with MgO (not shown), the MgO – V plot displays a reasonable negative correlation. The Chýnov dataset tends to have higher Cr and Ni, and lower V with Sc, than the Český Krumlov samples (Fig. 8b).

The high-field strength elements (HFSE) show much more complex relationships. The MgO–Th plot features an inflection at MgO ~ 6–7 wt. %; Zr and, to a large extent, Nb define negative trends for all but the most MgO-poor samples.

The MgO–Sr graph is considerably scattered. The plots with ΣREE and Ce_N/Yb_N (the latter parameter chosen instead of La_N/Yb_N due to the dubious quality of La determinations in the data set of Patočka 1991) clearly represent mixtures of two trends, a positive one,

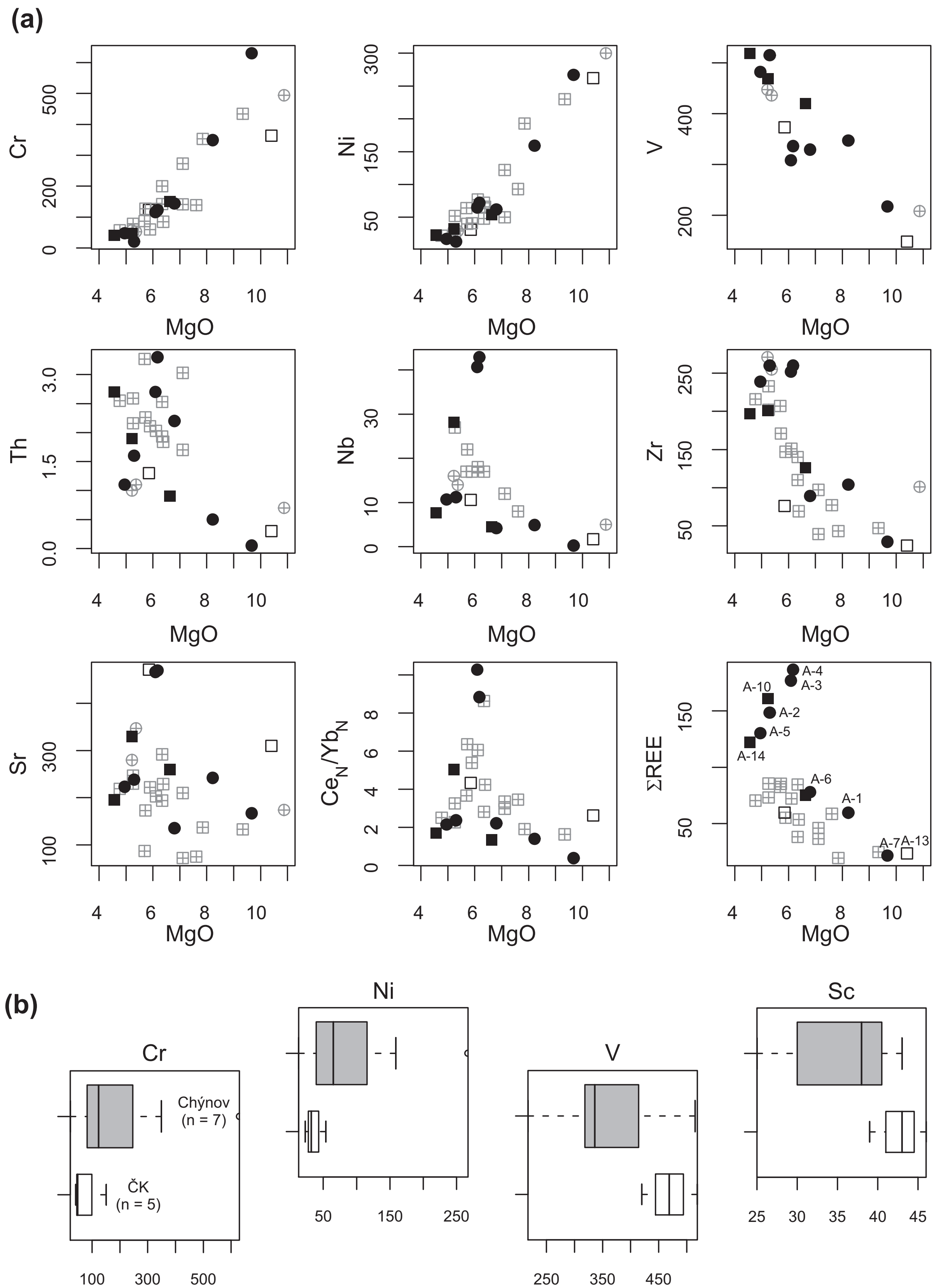


Fig. 8a – Binary diagrams of MgO versus selected trace elements (ppm). The Ce_N/Yb_N is the ratio of chondrite-normalized values (Boynton 1984). **b** – Box plots for selected transition metal concentrations comparing the Chýnov and Český Krumlov (ČK) amphibolites (ppm; Tab. 4).

Table 4b Trace-element whole-rock geochemical analyses for the metabasic rocks from the Český Krumlov Varied Unit (ppm)

Sample	A-10	A-14	A-15	A-12	A-13
Locality	Zlatá Koruna	Lazec	Vyšný	Plánský Kopec	Světlík
	A	A	A	G	D
Rb	10.2	15.1	8.0	28.9	4.1
Sr	329.8	195.6	259.9	471.4	310.0
Ba	231.0	86.2	76.7	163.6	60.0
Cs	0.5	0.1	0.2	1.9	0.3
Cr	48	41	151	123	363
Ni	32	23	54	31	262
Co	52.0	50.7	49.5	44.3	66.0
Sc	39	43	46	27	21
V	469	519	420	373	148
Mo	0.9	0.4	0.5	0.3	0.3
Cu	86	25	45	22	64
Pb	1.0	0.3	0.5	4.6	0.4
Zn	39	39	14	24	4
Ga	23.2	23.6	19.1	22.2	16.2
Zr	201	197	126	76	24
Hf	5.9	5.7	3.9	2.1	0.7
Nb	28.2	7.7	4.5	10.6	1.7
Ta	1.9	0.5	0.3	0.7	0.1
Th	1.9	2.7	0.9	1.3	0.3
U	0.9	0.7	0.3	0.4	0.1
La	24.20	13.90	6.90	9.10	2.90
Ce	57.60	34.50	19.40	21.60	7.30
Pr	7.70	5.07	2.98	2.81	1.01
Nd	34.10	25.40	15.20	12.50	5.00
Sm	8.00	6.80	4.60	2.90	1.30
Eu	3.02	2.13	1.69	1.08	0.60
Gd	8.26	8.35	5.60	2.75	1.55
Tb	1.25	1.60	1.15	0.49	0.26
Dy	7.74	9.98	7.18	2.99	1.58
Ho	1.37	1.94	1.38	0.51	0.30
Er	3.78	5.74	4.25	1.41	0.82
Tm	0.50	0.85	0.62	0.19	0.10
Yb	2.96	5.28	3.74	1.29	0.72
Lu	0.41	0.75	0.57	0.18	0.10
Y	37.5	56.9	39.9	14.8	8.2
Eu/Eu*	1.14	0.86	1.02	1.17	1.29
La_N/Yb_N	5.51	1.77	1.24	4.76	2.72
La_N/Sm_N	1.90	1.29	0.94	1.97	1.40
Sum REE	160.89	122.29	75.26	59.80	23.54

A = amphibolite, G = metagabbro, D = metadolerite

restricted only to some of the less magnesian samples (MgO < 6 wt. %) and negative for the rest of the dataset covering the whole MgO spectrum.

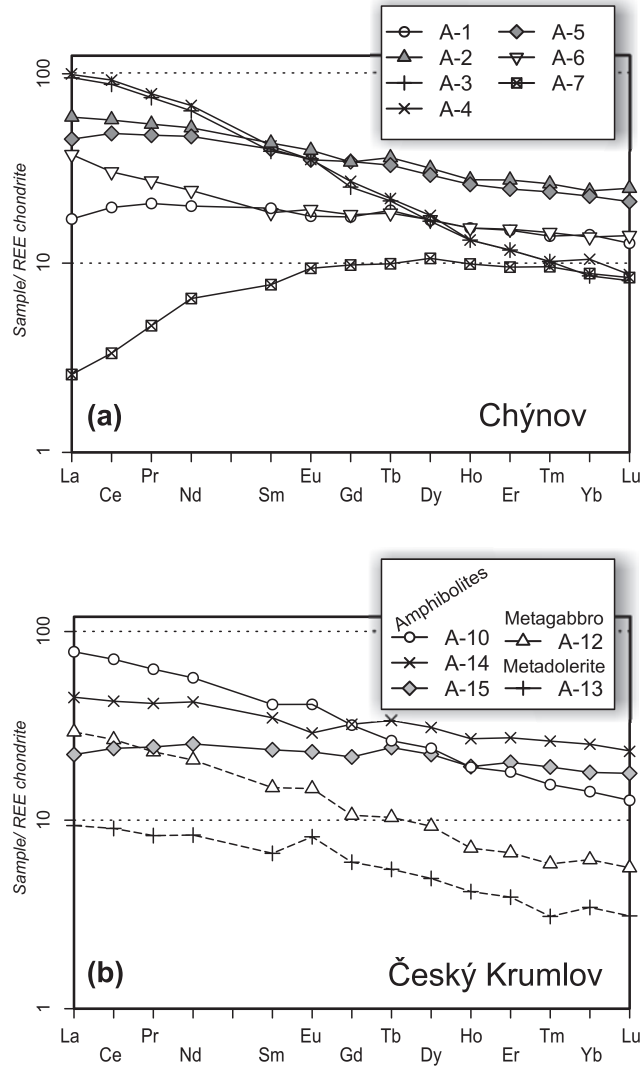
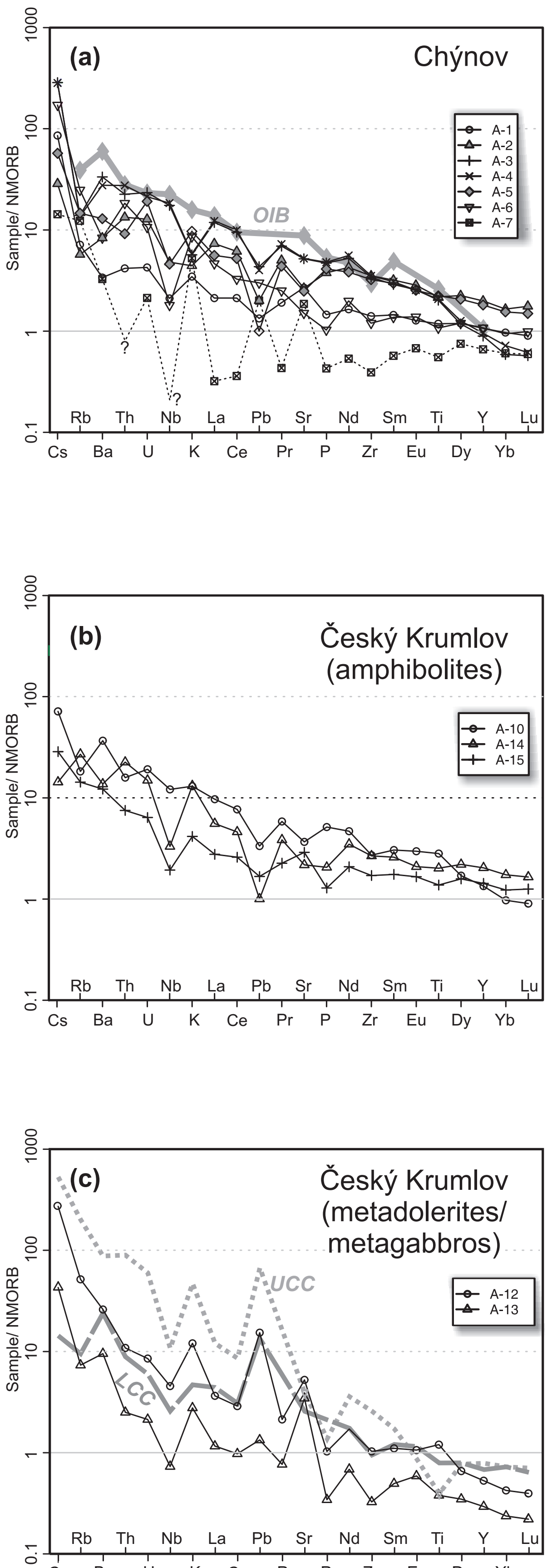


Fig. 9 Chondrite-normalized (Boynton 1984) REE patterns for the metabasic rocks from the Chýnov and Český Krumlov Varied units.

The chondrite-normalized (Boynton 1984) REE patterns for the Chýnov set are very variable (Fig. 9a), with total REE concentrations ranging between 59.7 and 186.6 ppm. The most primitive is the pattern for sample A-7, which shows strong LREE depletion (La only 2.6 × chondritic value) relative to MREE and HREE (about 10 × chondrite, $La_N/Yb_N = 0.29$) (Fig. 9a). This pattern resembles normal Mid-Ocean Ridge Basalts (NMORB). The other patterns show variable enrichments of LREE over HREE. For samples A-1, A-6, A-2 and A-5 profiles are all relatively flat ($La_N/Yb_N = 1.21–9.45$), with the total concentrations lower for the former two (ΣREE 59.7 and 78.0 ppm) than for the latter two amphibolites (ΣREE 148.5 and 130.3 ppm). The patterns for the remaining alkaline samples A-3 and A-4 are steep, starting at about 100 × chondritic value and dropping sharply with



an increasing atomic number to less than 9 (La_N/Yb_N = 9.45–11.15, ΣREE = 176.9–186.6). The Eu anomaly is absent or nearly so in all analysed amphibolites of the Chýnov set (Eu/Eu* = 1.14–0.95).

The REE distribution for amphibolites from the Český Krumlov area (Fig. 9b) resembles the previous group, except for the magnitude of the Eu anomaly, which tends to be more variable. The most primitive seems the pattern for sample A-15 (La_N/Yb_N =1.2, ΣREE = 75.3, Eu/Eu* = 1.02), followed by A-14 (La_N/Yb_N =1.8, ΣREE = 122.3, Eu/Eu* = 0.86). The most fractionated is amphibolite A-10 from Zlatá Koruna (La_N/Yb_N = 5.5, ΣREE =160.9, Eu/Eu* = 1.14).

Both metadolerite and metagabbro are characterised by relatively low total REE contents (23.5–59.8), notable enrichment of LREE over HREE (La_N/Yb_N = 2.72–4.76) and marked positive Eu anomalies (Eu/Eu* = 1.17–1.29).

The NMORB normalized (Sun and McDonough 1989) spider plots of the studied metabasic rocks are all variably enriched in LILE (Fig. 10). The most primitive seems to be sample A-7, with a striking zigzag pattern apparently caused by some element mobility. The presumably less mobile REE (La, Ce, Pr, Nd, Sm, Eu, Dy, Yb and Lu) plus some HFSE (Zr, Ti, Y, with Th and Nb) remain relatively low, some even below their detection limits (indicated by question marks in Fig. 10a). By contrast P (0.32–0.75 × NMORB), and the hydrous fluid mobile elements (Cs, Rb, Ba, U, K, Pb, Sr) are several times enriched. Sample A-1 shows a relatively flat pattern enriched only in Rb and Cs; there is a slight depletion in Nb and Pb as well as weak enrichment in Sr. Overall, the pattern resembles EMORB (e.g., Wilson 1989; Pearce 1996). Amphibolite A-6 shows a striking Nb depletion and less marked P and Zr impoverishment. The least compatible elements are of similar concentration to the preceding sample, but the contents of alkalis with Th and U are significantly higher.

Amphibolites A-2 and A-5 contain generally comparable contents of the incompatible elements up to K, but the contents of the remaining elements are significantly higher than in A-6. The samples are characterised by marked Nb, Pb and Sr troughs. Finally, the patterns of alkali metabasalts A-3 and A-4 closely follow each other. Their normalized trace-element concentrations are overall relatively high, with exception of the HREE that

⇦

Fig. 10 The NMORB-normalized (Sun and McDonough 1989) spider plots for the analysed metabasites. **a** – Amphibolites from the Chýnov area, question marks indicate values below detection limit in sample A-7. The pattern labelled OIB is from an average composition of Ocean Island Basalts (Sun et al. 1980). **b** – amphibolites from the Český Krumlov Varied Unit. **c** – metadolerite and metagabbro from the Světlík area. For assessment of the possible crustal contamination, shown are average crustal compositions after Taylor and McLennan (1995): UCC = Upper Continental Crust, LCC = Lower Continental Crust.

show a marked depletion. Troughs for Rb, K and Pb are also characteristic. Apart from these three elements, the trace-element distribution for amphibolites A-3 and A-4 strongly resembles the average compositions of Ocean Island Basalts (OIB), as determined by Sun et al. (1980).

In the Český Krumlov amphibolite dataset (Fig. 10b), the lowest NMORB-normalized trace-element contents are those of sample A-15, starting at around 14 × NMORB (Rb) and dropping to nearly 1 for Lu. The pattern displays slight negative anomalies for Nb, Pb and P. Sample A-14 is similar, but its total trace-element contents are markedly higher and the Nb, Pb, Sr and P troughs deeper. The pattern of sample A-10 resembles closely the Chýnov alkali types A-3 and A-4; only the negative K anomaly is lacking.

Overall, the spider plots for the metadolerite and metagabbro are similar to each other (Fig. 10c), but sample A-12 has significantly higher total trace-element concentrations. The patterns are characterised by increasing positive anomalies of K, Pb and Sr, reflecting, together with the REE distribution characterised by an emerging positive Eu anomaly (Fig. 9b), an accumulation of mainly plagioclase and biotite.

7. Radiogenic isotopes (Sr and Nd)

The Nd isotopic analyses for the studied metabasic rocks are given in Tab. 5, together with initial ε^{i}_{Nd} age-corrected for 350 and 500 Ma (Fig. 11a). Also presented are single-stage Nd model ages calculated relative to Depleted Mantle (T^{DM}_{Nd} : Liew and Hofmann 1988) (Fig. 11b).

7.1. *Chýnov Varied Unit*

The single-stage Depleted-mantle Nd model ages show considerable variation. The tholeiitic samples A-1, A-2, A-5 and A-7 yield Cambro–Ordovician model ages (T^{DM}_{Nd} = 0.43–0.50 Ga) (Fig. 11b). The model ages for the alkaline amphibolites A-3 and A-4 are much higher (T^{DM}_{Nd} = 0.83 Ga), but the Kladrubská hora sample A-6 has the highest model age (T^{DM}_{Nd} = 1.47 Ga). As the derivation of these basic rocks from a source other than Earth's mantle is considered impossible, at least at reasonable degrees of partial melting, the single-stage Nd should provide a maximum constraint upon the age of their intrusion (see also Fig. 11b).

Assuming, for the sake of discussion, an identical protolith age of *c.* 500 Ma, ε^{500}_{Nd} values can be calculated. These are all positive, corresponding to mantle-derived melts, but their range is large (Tab. 5; Fig. 11). The most primitive (i.e., most radiogenic) is Nd in the tholeiitic samples: A-5 (Pod Pacovou horou quarry, ε^{500}_{Nd} = +9.1), A-7 (Šimpach, ε^{500}_{Nd} = +9.0), followed by amphibolites A-1

Table 5 Sr–Nd isotopic data for the studied metabasic rocks from the Chýnov and Český Krumlov varied units

Sample	Rock	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2 s.e.	$(^{87}Sr/^{86}Sr)_{500}$	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2 s.e.	ε^{350}_{Nd}	ε^{500}_{Nd}	$T^{DM}_{Nd\ LH}$ (Ga)
A-1	amphibolite	4.0	242.1	0.04782	0.706757	0.000052	0.706416	3.8	12.9	0.1794	0.513023	0.000032	8.3	8.6	0.49
A-2	amphibolite	3.2	238.4	0.03884	0.705806	0.000028	0.705529	9.5	36.5	0.1580	0.512951	0.000034	7.8	8.6	0.50
A-3	amphibolite	7.8	466.8	0.04836	0.708015	0.000032	0.707670	8.0	39.5	0.1227	0.512624	0.000016	3.0	4.5	0.83
A-4	amphibolite	7.6	469.9	0.04681	0.707966	0.000032	0.707632	8.1	39.8	0.1230	0.512629	0.000012	3.1	4.5	0.83
A-5	amphibolite	8.2	223.3	0.10626	0.705481	0.000018	0.704724	7.9	29.4	0.1634	0.512995	0.000008	8.5	9.1	0.43
A-6	amphibolite	13.9	135.4	0.29722	0.710730	0.000120	0.708612	4.0	14.9	0.1603	0.512585	0.000028	0.6	1.3	1.47
A-7	amphibolite	6.9	167.1	0.11952	0.708469	0.000016	0.707617	1.6	3.8	0.2548	0.513289	0.000014	10.1	9.0	0.59
A-10	amphibolite							8.0	34.1	0.1418	0.512771	0.000020	5.1	6.1	0.75
A-12	metagabbro							2.9	12.5	0.1403	0.512458	0.000024	-1.0	-3.6	1.34
A-13	metadolerite							1.3	5.0	0.1572	0.512323	0.000028	-4.4	2.0	2.03
A-14	amphibolite							6.8	25.4	0.1619	0.512624	0.000090	1.3	3.1	1.40
A-15	amphibolite							4.6	15.2	0.1830	0.512754	0.000028	2.9	6.7	1.68
126	amphibolite							3.8	10.3	0.2228	0.513068	0.000012	7.2	9.4	-3.36
127	amphibolite							2.9	9.0	0.1951	0.513114	0.000026	9.4	-3.6	0.24

$T^{DM}_{Nd\ LH}$ = single-stage Nd model ages calculated after Liew and Hofmann (1988).

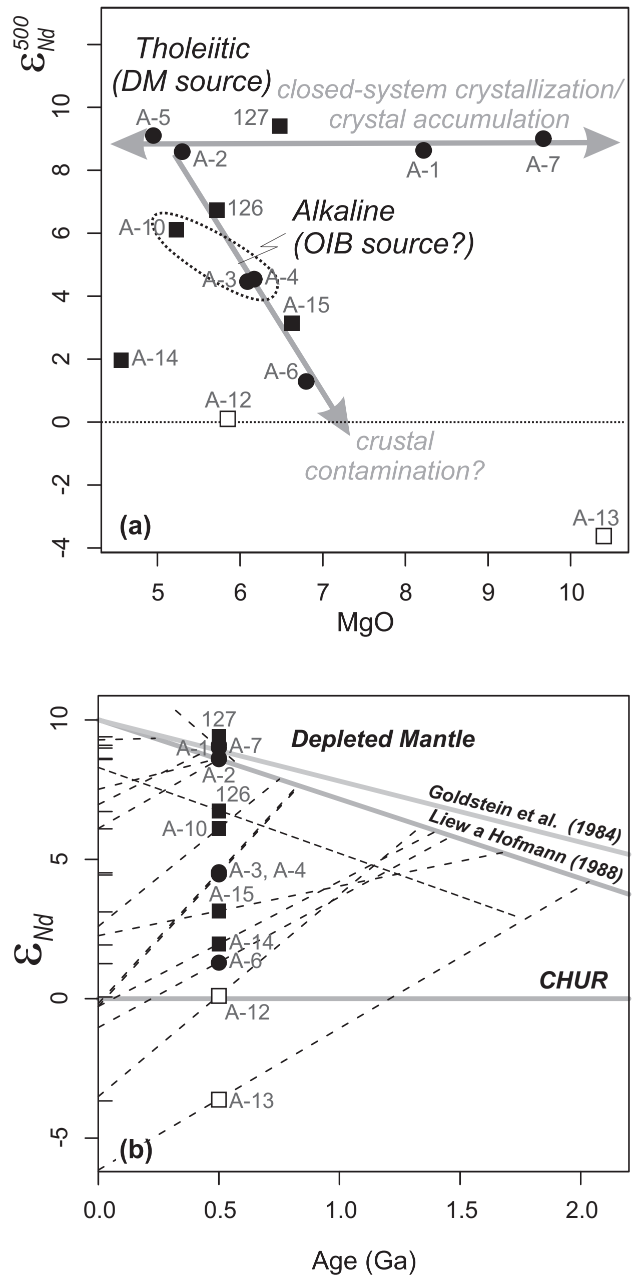


Fig. 11a – Binary plot of MgO vs. ε_{Nd}^{500} for the studied metabasites. The field for alkaline amphibolites is outlined. Also drawn are vectors showing tentative evolution by closed-system fractionation (fractional crystallization or crystal accumulation) and crustal contamination. **b** – Single-stage Nd development diagram showing ranges of ε_{Nd}^{500} values and Depleted-mantle model ages in the amphibolites and metadolerite with metagabbro from the southern Bohemian Varied Group (Chýnov and Český Krumlov areas). DM = Depleted Mantle evolution lines after Goldstein et al. (1984) and Liew and Hofmann (1988).

and A-2 (Obrataň and Pod Pacovou horou quarry, ε_{Nd}^{500} = +8.6). The least radiogenic are the alkaline amphibolites with steep REE patterns from the last mentioned locality (A-3 and A-4, ε_{Nd}^{500} = +4.5) and, in particular, the Kladrubská hora sample (A-6, ε_{Nd}^{500} = +1.3). At least part of this variation, shown graphically in Fig. 11a, may be due to crustal contamination as discussed below.

Initial ratios of Sr for amphibolites from the Chýnov area calculated for the same age cover a wide range (0.7044–0.7083). Again, the most primitive is the tholeiitic sample A-5 (Pod Pacovou horou, $^{87}Sr/^{86}Sr_{500}$ = 0.7047), while sample A-6 (Kladrubská hora) has the highest ratio (0.7086), and the Sr isotopic signature of samples A-7 (Šimpach, 0.7076) and A-3 (Pod Pacovou horou, 0.7077) are also relatively radiogenic.

7.2. Český Krumlov area

In the Český Krumlov area, only Nd isotopic compositions have been determined. The ε_{Nd}^{500} values are almost as variable as in the Chýnov Varied Unit. The most radiogenic amphibolite is sample 127 from Hořice (ε_{Nd}^{500} = +9.4), followed in turn by 126 (Lískovec, ε_{Nd}^{500} = +6.7), A-10 (Zlatá Koruna, ε_{Nd}^{500} = +6.1, T_{Nd}^{DM} = 0.75 Ga), A-15 (Vyšný, ε_{Nd}^{500} = +3.1, T_{Nd}^{DM} = 1.68 Ga) and A-14 (Lazec, ε_{Nd}^{500} = +2.0, T_{Nd}^{DM} = 1.40 Ga).

The metadolerite and metagabbro have significantly less radiogenic Nd isotopic signatures (A-12 from Kovářov: ε_{Nd}^{500} = +0.1, T_{Nd}^{DM} = 1.34 Ga; A-13 from Světlík: ε_{Nd}^{500} = -3.6, T_{Nd}^{DM} = 2.03 Ga). The Nd isotopic composition thus precludes a closed-system crystallization of these rocks from Depleted Mantle derived melts in Palaeozoic times.

8. Discussion

8.1. Metamorphic development

8.1.1. Conditions of metamorphism

The studied amphibolites lack relict minerals from either their igneous protoliths or of metamorphic stages other than the amphibolite-facies metamorphism, e.g. greenschist or granulite facies. Hence it is likely that the amphibolites formed by an intense, single-stage metamorphic recrystallization of the original igneous protolith and the rocks have not recorded any further metamorphic history.

Ilmenite in Chýnov samples A-2, A-3, A-4 contains about 15 vol. % of unmixed hematite in minute lenticular particles. This, together with slightly elevated Fe_2O_3 content in host ilmenite, indicates somewhat increased O_2 fugacity in these particular amphibolites. Note that comparable increased oxygen fugacity was not observed in samples from the Český Krumlov area, which contain ilmenite free of hematite, either in solid solution or unmixed. The future will tell whether this is not simply because of sampling bias, as the current data set is rather small. Still it is clear that the oxygen fugacity was not uniform throughout the south Bohemian Varied Group (see also Němec 1998) and the amphibolites represent a heterogeneous set in this respect.

8.1.2. Geochemical changes due to metamorphism

The sampling strategy was chosen in order to minimize the effects of Variscan metamorphism upon the whole-rock geochemical signature. Relatively large and fresh blocks of metabasic rocks were utilized, showing little effects of alteration and subsequent low-grade metamorphic overprint or deformation. Unlike their counterparts enclosed in gneisses, amphibolites forming layers in marbles are much less susceptible to an increase in LILE contents, as these elements are not present in significant amounts in the host carbonate rocks. The only LILE enriched should be clearly Sr and Ba (Němec 1999). The samples associated with carbonates were obtained from the quarries Pod Pacovou horou (A-2 to A-5) and Vyšný (A-15). None of these analyses showed Sr or Ba spikes in NMORB-normalized spider plots, and thus even these elements seem to have been relatively immobile geochemically in our data set.

On the other hand, effects of LILE influx from the host rocks are apparent in some of the remaining samples, but nowhere are they as severe as in the otherwise most depleted sample A-7 (Fig. 10a). Its radiogenic Nd and Sr isotopic ratios also demonstrate some Sr mobility and relatively conservative Nd behaviour.

Even though some scatter in the binary plots involving alkalis and perhaps Sr (Figs 7a and 8a), together with minor irregularities in the spider plots for the studied metabasites (Fig. 10), undoubtedly reflects metamorphic mobility of the elements with low ionic potential, no systematic changes were observed by plotting these against H_2O^+ as an index of alteration (Pearce 1996). Overall, the contents of volatile components remain relatively low, bearing witness that the superimposed alteration of the whole-rock geochemical signature was relatively minor in all the studied samples.

8.2. Petrogenesis and age of the basaltic/gabbroic protoliths

8.2.1. Nature of the volcanism

Amphibolites in the Pacovská hora quarry are accompanied by impure silicate marbles and calc-silicate rocks carrying assemblages with epidote, Ti-andradite and minor magnetite, which independently point to increased oxygen activity. Comparably high and variable degree of Fe oxidation shows that at least part of the amphibolites represents original subaerial (or submarine) effusions. It is possible that they represent an association of a relatively shallow (shelf?) sea, an idea supported by the occurrence of the strongly oxidized association Ti-andradite–epidote–magnetite in carbonate–metabasic rocks and, in particular, Mn-rich garnet gneisses at the margin of the amphibolite layer in the Pod Pacovou horou quarry (Vrána 1992). This model is in line with previous work – for instance, the shallow sea/lagoon reef sedimentation for the Český Krumlov Varied Unit has been suggested already by Jenček and Vajner (1968), Kříbek et al. (1997) and Drábek et al. (1999).

It is thus probable that the protolith of some basaltic rocks in the Chýnov area experienced an incipient oxidation early in the depositional history of the local sequence, a feature which survived the amphibolite-facies regional metamorphism. Unfortunately, geological and petrological evidence does not permit safe distinction of alternatives such as basaltic lava flows, shallow sills or somewhat later dykes, as structural transposition imposed by deformation obliterated the original structural relations.

On the other hand, the amphibolites of the Český Krumlov Varied Unit are not so oxidised, possibly because of their direct association with graphite schists; the organic matter present in the latter could have caused reduction in the adjacent rock complexes. In contrast, in the Chýnov area the association between amphibolites and the graphite-bearing rocks is not so intimate.

8.2.2. Relationship between amphibolites and metadolerites/metagabbros in the Český Krumlov area

The Světlík orthogneiss was interpreted as an old basement, on which the Český Krumlov Varied Unit was deposited (Wendt et al. 1993). It is possible that the basic (doleritic/gabbroic) dykes cutting the Světlík orthogneiss represent former conduits of basaltic melts, which formed syn-sedimentary extrusive sheets or shallow sills in the overlying Český Krumlov Varied Unit. Alternatively, the basic dykes may be older than, or unrelated to, the amphibolites in the Varied Unit.

The whole-rock geochemical signature of the metadolerites/metagabbros seems to imply that they contain a sizeable admixture of cumulus crystals (dominated by plagioclase) derived from fairly basic magmas. Their rather unradiogenic Nd isotopic composition precludes closed-system crystallization of melts derived from Depleted Mantle in Palaeozoic times. The metadolerites/metagabbros must be significantly older, have originated from a less depleted mantle domain, and/or they received a significant crustal component – either in the form of country-rock assimilation or by mixing with crustally-derived magmas. As both the samples seem to be cumulates to some extent, their relatively low SiO_2 accompanied by high MgO, Cr, Ni and *mg#* does not seem to reflect the original composition of the magma they have crystallized from. If true, the parental melt could have been more acid (even tonalitic) and thus could have been, largely or fully, intracrustally derived, spanning from partial melting of pre-existing metabasic lower crust (Rapp et al. 1991; Wolf and Wyllie 1994).

Without a larger dataset for the metadolerites/metagabbros, the nature of their parental magma remains enigmatic. Even so, a genetic link between the studied metadolerites/metagabbros and amphibolites of the Český Krumlov Varied Unit seems unlikely. The substantial differences in the Nd isotopic compositions (metagabbro with metadolerite are much less radiogenic) rule out their connection via closed-system fractional crystallization/accumulation (Fig. 11).

8.2.3. Age of the Varied Group in southern Bohemia

The age and petrogenesis of the Varied Group of the Moldanubian Zone in southern Bohemia are still a matter of passionate discussion. The great majority of the earlier authors have championed its Proterozoic sedimentation (see Chaloupský 1978). The reports on finds of microfossils from the Český Krumlov Varied Unit (Konzalová 1981; Pacltová and Štemprok 1994), taken by some as an evidence for the Early Palaeozoic age of the Varied Group, are still far from being generally accepted.

An attempt to date the Varied Group carbonates in Austria directly using Sr isotopes was made by Frank et al. (1990) and the idea was recently resurrected by Procházka (2007). The authors inferred a Proterozoic age, arguing that the measured $^{87}Sr/^{86}Sr$ ratios were too low for the carbonates to have precipitated from Phanerozoic seawater.

However the Sr stratigraphy underwent a speedy development over the past two decades and the existence of some potential pitfalls became obvious. The first are diagenetic changes to the Sr isotopic ratios. As the whole-rock samples are the most sensitive to such effects, analyses of carefully picked fresh fossils of the genera that tend to recrystallize only a little in course of the diagenesis (conodonts, brachiopods,…) are preferred. Moreover, additional checks, such as CL screening, are employed. Other potential problems in the Moldanubian carbonates seem to be the presence of possible clastic/volcanic admixture and the danger of Sr mobility during high-grade Variscan metamorphism. Most important objection is though that in such a dismembered metamorphic terrain, there is no guarantee that the basin, in which the carbonates were deposited, communicated with the world's ocean reservoir. Obviously, in an isolated basin, the Sr isotopic composition could have been completely unconstrainable, depending simply on the balance of fluxes from individual sources and the nature of the eroded material (McArthur 1998; Prokoph and Veizer 1999; Veizer et al. 1999).

Last but not least, with a few exceptions (Houzar and Novák 2002), there is no convincing evidence that the individual Moldanubian domains in both Austria and Czech Republic with relatively abundant amphibolites and carbonates indeed belong to a single "Varied Unit" in a lithostratigraphic sense (see also Finger et al. 2007 and references therein). The fact that the situation may be rather complex even within a single metamorphic terrain has been indicated by the recent study of metabasites from the Raabs Unit, Lower Austria, which yielded a range of compositions and LA ICP-MS zircon ages (Mesoproterozoic–Silurian, Mayer et al. 2005; 2007).

The age of the south Bohemian Varied Group may be deduced from the garnet-rich kinzigitic gneisses from Ktiš in the Lhenice Graben, which contain a complex population of zircons dated by the Pb-Pb evaporation method at 1.6–2.0 Ga and 549 ± 5 Ma (Wendt 1989; Fiala et al. 1995). The younger population puts an upper constraint upon the maximum age of sedimentation.

However, the only direct age determination from the south Bohemian Varied Group (Český Krumlov Varied Unit) to date remains the Re–Os dating of molybdenite scattered in carbonate from the Bližná graphite mine (495 ± 2 Ma: Drábek and Stein 2003). Moreover, betafite from the same deposit has a primitive Nd isotopic composition (ε_{Nd}^{450} = +7.9), and a high Sm/Nd ratio, permitting a calculation of the Nd model age (T_{Nd}^{DM} = 0.53 Ga) with considerable precision. This datum can be interpreted as providing additional, maximum constraint for the age of Mo–Nb–Th–REE mineralization in Bližná (Drábek et al. 1999).

The dating by Drábek and Stein (2003) confirms the earlier Nd isotopic data for amphibolites of the south Bohemian Varied Group, presented in the preliminary report by Janoušek et al. (1997) and, in a more detail, in the current work. The Nd isotopic compositions for tholeiitic amphibolites A-1, A-2, A-5 and A-7 from the Chýnov area as well as the sample 136 from Český Krumlov Varied Unit does document their Early Palaeozoic magmatic age.

8.2.4. Presumed mantle sources and further development of the basaltic melts

The primitive Nd isotopic signature and EMORB-like chemistry of many of the tholeiitic samples indicate basaltic protolith derivation from a strongly depleted mantle source. The other tholeiitic samples probably suffered some crustal contamination, as indicated by the binary plots of independent geochemical parameters versus initial epsilon Nd values (e.g., Fig. 11a).

Also the alkaline amphibolites (A-3, A-4: Chýnov, A-10: Český Krumlov area) contain much less radiogenic Nd than the uncontaminated tholeiitic metabasalts do. Their less radiogenic initial Nd isotopic compositions (and thus more "crustal" signature) can be explained by: (1) older (Proterozoic) age, (2) origin by partial melting of a less depleted mantle domain, (3) contamination by a material rich in MgO, CaO, REE, Sr, and with crustal Sr–Nd isotopic signature.

However, the alkaline basalts are different from their tholeiitic counterparts in a number of additional parameters – they show steep REE patterns, and contain high concentrations of HFSE, especially Nb, Ta, Zr and P. The NMORB-normalized spider plots resemble OIB but cannot be explained by contamination with mature continental crust (see e.g. the lack of negative Nb anomaly). The patterns feature a marked depletion in HREE indicating a derivation from a garnet-bearing source. All these observations point in the same direction, namely that the alkaline types originated by relatively deep, low-degree partial melting of a less depleted, OIB-like asthenospheric mantle source.

At the same time, there is an intimate association between the tholeiitic and alkaline basalts, which may indicate that the two suites intruded at about the same time. Further evidence that the alkaline volcanism could have been contemporaneous with the deposition of the Český Krumlov Varied Unit is the presence of volcano-detritic component enriched in REE, Y, Th, Nb a Zr in the mineralized carbonates of the Bližná mine (Drábek et al. 1999).

8.2.5. Geotectonic setting

The geotectonic setting for the basic volcanism in the Bohemian part of the Moldanubian Zone has been explained in various ways, in accord with its likely temporal and geochemical heterogeneity as well as improvement in the analytical facilities with time. Matějovská (1987) assumed for her Fe-rich tholeiites (TMORB) from the region between Jemnice and Náměšť (SW Moravia) an origin in a rift-related basin that formed at the margin of the Moldanubian Unit. Patočka (1991) interpreted tholeiites from the Český Krumlov Varied Unit as relics of an accretionary wedge built up close to a subduction zone as a melange of volcanic-arc derived sediments (now paragneisses), ocean floor and ocean island basalts (later metamorphosed to amphibolites).

Most recently, Moravcová (1999) attempted to decipher the original geotectonic setting of the Moldanubian metabasic rocks. She interpreted most of them as TMORB and offered a wide palette of possible geotectonic contexts (initial volcanic arc, volcanic arc with back-arc basin, rift-related or collisional tectonics). This is hardly surprising, given that a significant interpretative power was ascribed to highly mobile LILE. Moreover, the dataset was heterogeneous, blending, without petrologic control, analyses for samples from the whole Moldanubian Zone in Bohemian Massif, carried out by different methods in different laboratories.

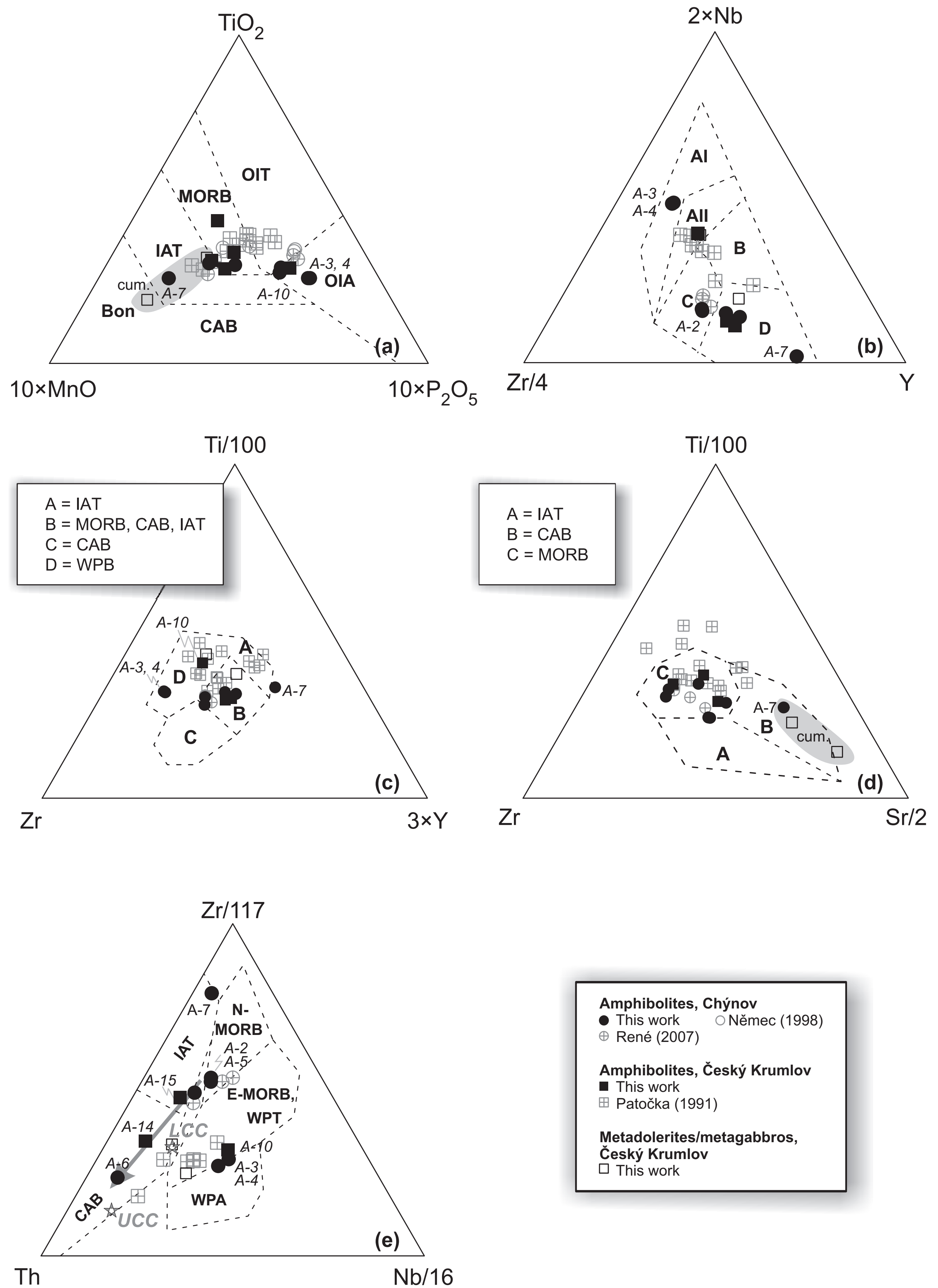
Indeed, the great majority of the Moldanubian amphibolites seem to be tholeiitic, with a distinct MORB affinity (Němec 1995; 1998) even though their chemistry has been, to some extent, modified by Variscan metamorphism (Němec 1999). Basic rocks probably linked to active subduction (Fe-rich gabbros) are only subordinate (Němec 1996b).

The NMORB-normalized spider plots (Fig. 10) already highlighted some geochemical features, which have a bearing on the probable geotectonic setting of the studied metabasic rocks from the Chýnov and Český Krumlov varied units. Most of the tholeiitic amphibolites resemble EMORB, with the rarer alkaline types being close to OIB. The only sample with clear NMORB affinity, albeit modified by ?olivine accumulation and LILE contamination, is A-7. The likely geotectonic setting was further constrained using several discrimination plots, summarized in Fig. 12.

The $10\times MnO - TiO_2 - 10\times P_2O_5$ diagram (Fig. 12a) of Mullen (1983) utilizes relatively immobile minor elements Mn, Ti and P. The studied samples show an affinity to MORB, straddling the boundaries of the adjacent tholeiitic domains and entering the OIA field (occupied by the alkaline samples with the highest phosphorus contents). Amphibolite A-7 is, together with metadolerite A-13, shifted towards the MnO apex, probably as a result of crystal accumulation.

Similar conclusions can be drawn using the ternary diagram $Zr/4 - 2\times Nb - Y$ of Meschede (1986) (Fig. 12b). The samples span the compositions of mid-ocean ridge basalts (the prevalent tholeiitic metabasalts), as well as within-plate tholeiitic and alkaline basalts (alkaline samples, in particular A-3 and A-4).

Two diagrams defined by Pearce and Cann (1973) were also plotted. On a $Zr - Ti/100 - 3\times Y$ ternary diagram (Fig. 12c), the samples mainly occupy fields D (Within Plate Basalts, WPB) and B, shared by the MORB, Island Arc Basalts (CAB) and Low-K Tholeiites (IAT). This distribution resembles strongly basaltic rocks associated with attenuated lithosphere (see e.g. fig. 9 in Pearce 1996 and discussion in the text). Better discrimination of the MORB from the arc-related rock types is achieved in the $Zr - Ti/100 - Sr/2$ triangular plot (Fig. 12d), in which the overwhelming majority of the samples fall into the MORB domain. Only three samples, A-7, metagabbro A-12 and metadolerite A-13, form a linear array towards


TiO2
10×MnO
10×P2O5
OIT
MORB
IAT
OIA
Bon
CAB
cum.
A-7
A-3, 4
A-10
(a)
2×Nb
Zr/4
Y
AI
AII
B
C
D
A-3
A-4
A-2
A-7
(b)
Ti/100
Zr
3×Y
A = IAT
B = MORB, CAB, IAT
C = CAB
D = WPB
A-10
A-3, 4
A-7
A
B
C
D
(c)
Ti/100
Zr
Sr/2
A = IAT
B = CAB
C = MORB
A-7
cum.
A
B
C
(d)
Zr/117
Th
Nb/16
N-MORB
IAT
E-MORB, WPT
CAB
WPA
LCC
UCC
A-7
A-2
A-5
A-15
A-14
A-6
A-10
A-3
A-4
(e)
Amphibolites, Chýnov
This work
Němec (1998)
René (2007)
Amphibolites, Český Krumlov
This work
Patočka (1991)
Metadolerites/metagabbros, Český Krumlov
This work

the Sr apex, probably reflecting the presence of cumulus plagioclase.

Finally, in a Th – Zr/117 – Nb/16 ternary diagram (Fig. 12e) (Wood 1980), the alkaline types occupy the field of within-plate alkaline basalts (WPA). However the remaining analyses do not plot solely in the NMORB field, but also cross the boundary into the adjacent CAB domain, spreading towards the average upper crustal composition as determined by Taylor and McLennan (1995). This, together with the Nd isotopic data array formed by the same amphibolites A-15, A-14 and A-6 (Fig. 11b) is taken as an evidence for crustal contamination (see also Floyd et al. 1996; Pearce 1996).

Apart from enrichment in Th, this crustal contamination is also documented by the development of the negative Nb, and much less apparent, P and Ti anomalies in the NMORB-normalized spider plots (cf. the UCC pattern in Fig. 10c, representing average composition of the Upper Crust after Taylor and McLennan 1995). Apart from likely metamorphic modification, the lack of a positive Pb peak can be due to the fact that the contaminant could have been a relatively young (Neoproterozoic/Early Palaeozoic?) crust. On the other hand, it clearly cannot represent the common Moldanubian paragneisses (as they have too low MgO, CaO and ΣREE) pure carbonates or seawater (too low ΣREE). One viable possibility could be the agency of CO_2–rich fluids, presumably related to diagenesis of the associated carbonate rocks (see also Vrána 1992).

Taken together, despite some minor differences between the Chýnov and Český Krumlov Varied units, the studied amphibolites seem to represent a single association, dominated by EMORB tholeiitic basalts. These were derived by relatively shallow melting of a strongly depleted mantle source in Early Palaeozoic times. The whole-rock and Nd isotopic signature in several cases reflects contamination by upper continental crust, probably during the ascent of the parental melts towards the surface.

⇦

Fig. 12 Geotectonic discrimination diagrams for the metabasites from the south Bohemian Varied Group. **a** –Triangular plot with apices 10×MnO – TiO_2 – 10×P_2O_5 proposed by Mullen (1983). Abbreviations used represent the following geotectonic settings: CAB: Calc-Alkaline Basalts, IAT: Island Arc Tholeiites, MORB: Mid-Ocean Ridge Basalts, OIA: Ocean Island Andesites, OIT: Ocean Island Tholeiites. **b** – Triangular diagram Zr/4 – 2×Nb – Y of Meschede (1986). AI–AII: Within-Plate Alkaline Basalts, AII–C: Within-Plate Tholeiites, B: P-type Mid-Ocean Ridge Basalts, D: N-type Mid-Ocean Ridge Basalts, C–D: Volcanic Arc Basalts**. c–d** – Set of two ternary plots, Zr – Ti/100 – 3×Y and Zr – Ti/100 –Sr/2, proposed by Pearce and Cann (1973). Following abbreviations are used: IAT: Low-K Tholeiites, MORB: Ocean Floor Basalts, CAB: Island Arc Basalts, WPB: Within Plate Basalts. **e** – Triangular diagram with apices Th, Zr/117 and Nb/16 after Wood (1980). IAT: Island-arc Tholeiites, CAB: Calc-alkaline Basalts, N-MORB: N-type Mid-ocean Ridge Basalts, E-MORB: E-type Mid-ocean Ridge Basalts, WPT: Within-plate Tholeiites, WPA: Alkaline Within-plate Basalts. Shown are average crustal compositions after Taylor and McLennan (1995): UCC = Upper Continental Crust, LCC = Lower Continental Crust.

A minority of the samples are alkaline, showing a clear OIB affinity and requiring a genesis by low degrees of partial melting of a deeper, garnet-bearing asthenospheric mantle source. Their age remains unconstrained but the intimate association with the tholeiites and the presence of an exotic carbonatite-like volcano-sedimentary component in some of the Moldanubian carbonates (Drábek et al. 1999; Houzar and Novák 2002) suggest that they may be also Early Palaeozoic.

In general, as stressed by Pearce (1996) in his excellent review, the problem remains the discrimination of basalts from environments transitional between those of the principal three end-members (MORB, WPB and VAB). Thus even for the studied tholeiitic, EMORB-like amphibolites of the Varied Group, an emplacement in essentially intracrustal and not a truly oceanic setting is to be assumed. This idea is supported by the association between prevalent MORB-like and subordinate WPB-like basalts (nicely documented for instance by the position in the Zr – Ti/100 – 3×Y ternary), relatively significant role for mature crustal contamination needed to explain the geochemical signature some of the samples as well as intimate association with shallow-water (lagoonal) sediments.

The most likely tectonic setting of the volcanism was thus attenuated lithosphere, subjected to a significant extension and initial stages of rifting, marking the onset of the fragmentation of the northern Gondwana margin producing the Armorica Terrane Assemblage (e.g., Franke 2000; Floyd et al. 2000). The minor OIB component preserved in the form of alkali basalts as well as some contribution to the EMOR-like basaltic magmas was probably contributed by a mantle plume. Such a plume was indeed thought to have assisted the early stages of the fragmentation of Gondwana and the accompanying extensive igneous activity (e.g., Crowley et al. 2000; Floyd et al. 2000).

7. Conclusions

(1) Amphibolites from the Chýnov and Český Krumlov units of the Moldanubian Zone in south Bohemia are dominated by amphibolite-facies mineral assemblages of plagioclase and hornblendes with Si ~ 6.5 apfu, Mg/(Mg + Fe) ~ 0.5 and $(Na + K)_A$ ~ 0.5 apfu, straddling mainly the fields of edenite, pargasite, ferropargasite, and magnesiohornblende, ferrohornblende and ferrotschermakite. Garnet and clinopyroxene are subordinate and occur in a few samples only. No relics of previous greenschist- or granulite-facies mineral assemblages have been

observed, most likely as a result of a relatively simple metamorphic history.

(2) The petrology indicates a rather close correlation of the Chýnov and Český Krumlov units. The similarities include the presence of dolomite in carbonate bodies, association with graphite schists, occurrence of rocks with marialitic scapolite, locally also of Ti-andradite (±magnetite, epidote) assemblages and thin layers of Mn-rich garnet-quartz rocks.

(3) However, there is a major difference in the oxidation state of the studied amphibolites. Most Chýnov samples have Fe_2O_3/FeO = 0.70 to 1.00. Accessory ilmenite containing *c.* 15 vol. % of unmixed hematite and appreciable hematite in solid solution are typical. It is probable that the protolith of basaltic rocks experienced an incipient oxidation early in the depositional history of the local sequence. At least some of the parental basalts were probably effusive, either subaerial or subaqueous.

(4) The Český Krumlov amphibolites have typically Fe_2O_3/FeO ≤ 0.4, ilmenite is free of unmixed hematite and contains little hematite in solid solution. They show much closer association with graphite schists, in which the organic matter could have been responsible for reduction of the adjacent rock units.

(5) The dataset is dominated by EMORB-like tholeiitic metabasalts derived by melting of a strongly depleted mantle source in Early Palaeozoic times (ε^{500}_{Nd} = +8.6 to +9.4; T^{DM}_{Nd} = 0.43– 0.50 Ga). The rather unradiogenic Nd isotopic composition of several of the samples reflects probably contamination by upper continental crust (ε^{500}_{Nd} = +3.1 to +1.3). This is in line with gradual enrichment in Th, a significant negative Nb, and lesser P and Ti anomalies on the NMORB-normalized multielement patterns for the more contaminated samples.

(6) The previously considered indications of Precambrian age of Moldanubian varied sequences in Austria, which were based on whole-rock Sr isotopic compositions of carbonates, are doubtful and not directly applicable to the Varied Group in south Bohemia. As shown in the current study, the Nd model ages for the least contaminated tholeiitic basalts in intimate association with reef/lagoonal carbonates argue for the Early Palaeozoic protolith age of the Chýnov and Český Krumlov units.

(7) Subordinate are alkaline metabasalts (Nb/Y = 0.7–1.6) with high total REE contents, steep chondrite-normalized REE patterns (La_N/Yb_N = 5.5–11) and high concentrations of HFSE, especially Nb, Ta, Zr and P. Their NMORB-normalized spiderplots show a clear OIB affinity (ε^{500}_{Nd} = +4.5 to +6.1; T^{DM}_{Nd} = 0.75–0.83 Ga).

(8) Basic dykes cutting the Palaeoproterozoic Světlík orthogneiss are represented by amphibole metagabbro, ophitic olivine metadolerite and porphyritic olivine-pyroxene metadolerite. These rocks show a rather unradiogenic Nd isotopic composition, which precludes closed-system crystallization of melts derived from depleted mantle source in Palaeozoic times (ε^{500}_{Nd} = +0.1 and –3.6; T^{DM}_{Nd} = 1.34 and 2.03 Ga). The nature of their parental magma remains enigmatic; however any genetic link between the studied metadolerites/metagabbros and amphibolites in the structurally overlying Český Krumlov Varied Unit seems unlikely.

(9) Geotectonic position, as inferred from commonly used geotectonic diagrams, is contrasting for the two amphibolite groups defined. The dominant tholeiitic amphibolites show (E)MORB chemistry, whereas the alkaline samples (A-3, A-4 and A-10) tend to plot into fields reserved for the within-plate basalts with OIB affinity. Tholeiites formed most likely by partial melting of a shallow, strongly depleted mantle source, with variable role for subsequent contamination by mature continental crust. Low-degree partial melting of a garnet-bearing asthenospheric mantle is the most plausible scenario for the generation of the alkaline basalts.

(10) Taken together, the most likely tectonic setting of the volcanism was attenuated lithosphere, subjected to a significant extension leading to intracontinental rifting. This period marked the onset of the fragmentation of the northern Gondwana margin producing eventually the Armorica Terrane Assemblage. The minor OIB component preserved in the form of alkali basalts as well as some contribution to the EMOR-like basaltic magmas was probably added by a rising mantle plume.

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