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Geochemistry and Primary Tectonic Environment of the Amphibolites from the Český Krumlov Varied Group (Bohemian Massif, Moldanubicum)

With 14 Figures and 3 Tables

By FRANTIŠEK PATOČKA*)

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Bohemian Massif
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Amphibolites
Major Element Analyses
Trace Element Analyses
REE Abundances
Paleotectonic Implications

Contents

Geochemie und primäres tektonisches Umfeld der Amphibolite der Bunten Serie von Český Krumlov (Böhmische Masse, Moldanubikum).

Zusammenfassung

Der kristalline Komplex der Bunten Serie von Český Krumlov tritt im Südteil des Moldanubikums des Böhmischen Massivs auf. In diesem Komplex kommen zahlreiche Amphibolite von primär magmatischer Herkunft vor. Diese Gesteine haben zumindest eine tiefere Metamorphose, wahrscheinlich in Eklogitfazies, noch vor der amphibolitfaziellen Metamorphose durchlaufen. Das Ausgangsgestein der Amphibolite könnte im unteren Paläozoikum entstanden sein. Nach den Gehalten an Haupt- und Spurenelementen zeigen die Amphibolite der bunten Serie die Geochemie von tholeiitischen Basalten und Basalten, die einen Übergang zu alkalischen Typen von ozeanischen Inseln und Ozeanböden bilden. Hypothetisch kann man die Bunte Serie von Český Krumlov als Relikt eines tektonisch fragmentierten Akkretionsprismas interpretieren.

Abstract

The crystalline sequence of the Český Krumlov Varied Group is exposed in the southern part of the Bohemian Massif (Moldanubicum). Amphibolites of primary magmatic origin are abundant within the sequence. The mafic meta-igneous rocks underwent at least one single high-grade metamorphism (presumably of eclogite facies) before the amphibolite facies event took place. The amphibolite protolith could be formed during the Lower Paleozoic. According to major and trace element content the Varied Group amphibolites show a geochemistry of tholeiitic basalts and transition to alkaline ocean-island and ocean-floor basalts. A tentative interpretation, regarding the Český Krumlov Varied Group as a relic of a dismembered accretionary wedge, is suggested.

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*) Author's address: Dr. FRANTIŠEK PATOČKA, Geological Institute, Czechoslovak Academy of Science, Rozvojová 135, ČSFR-16500 Praha 6 – Suchdol, Czechoslovakia.

1. Introduction and Geological Setting

The Český Krumlov Varied Group is a prototype of the "varied" units of the Moldanubian complex, representing both the major crystalline core of the Bohemian Massif and the easternmost segment of the Moldanubian Zone within the European Hercynides. These "varied" units – approximately equivalent in age – are regarded as the upper stratigraphic member of the Moldanubian sequence (ZOUBEK et al., 1988).

The Český Krumlov Varied Group forms a narrow belt running in an SW–NE direction from the vicinity of Horní Planá town (48°43' N lat; 14°07' E long) across the Černá and Český Krumlov region, the Rudolfov horst, below the Meso- and Cenozoic sediments of the Třeboň basin into the area of Kardašova Řečice town (49°12' N lat; 14°54' E long); to the NE from Český Krumlov it is interrupted by the Blanský Les granulite body. The length of the belt is about 80 km, its width varies widely between 4 and 20 km. The real thickness of the Český Krumlov Varied Group is estimated to be from 500 to 1,300 m (KODYM Jr., 1966; RAJLICH et al., 1986 etc.).

The principal rocks of the Český Krumlov Varied Group are several types of plagioclase-biotite paragneisses – originally greywacke to pelitic shales (SUK, 1974); turbidite character of the shale sedimentation was identified there by KADOUNOVÁ (1987). According to paragneiss geochemistry, their sedimentary precursors were derived from progressive differentiated calc-alkaline igneous rocks and took origin in an active plate-

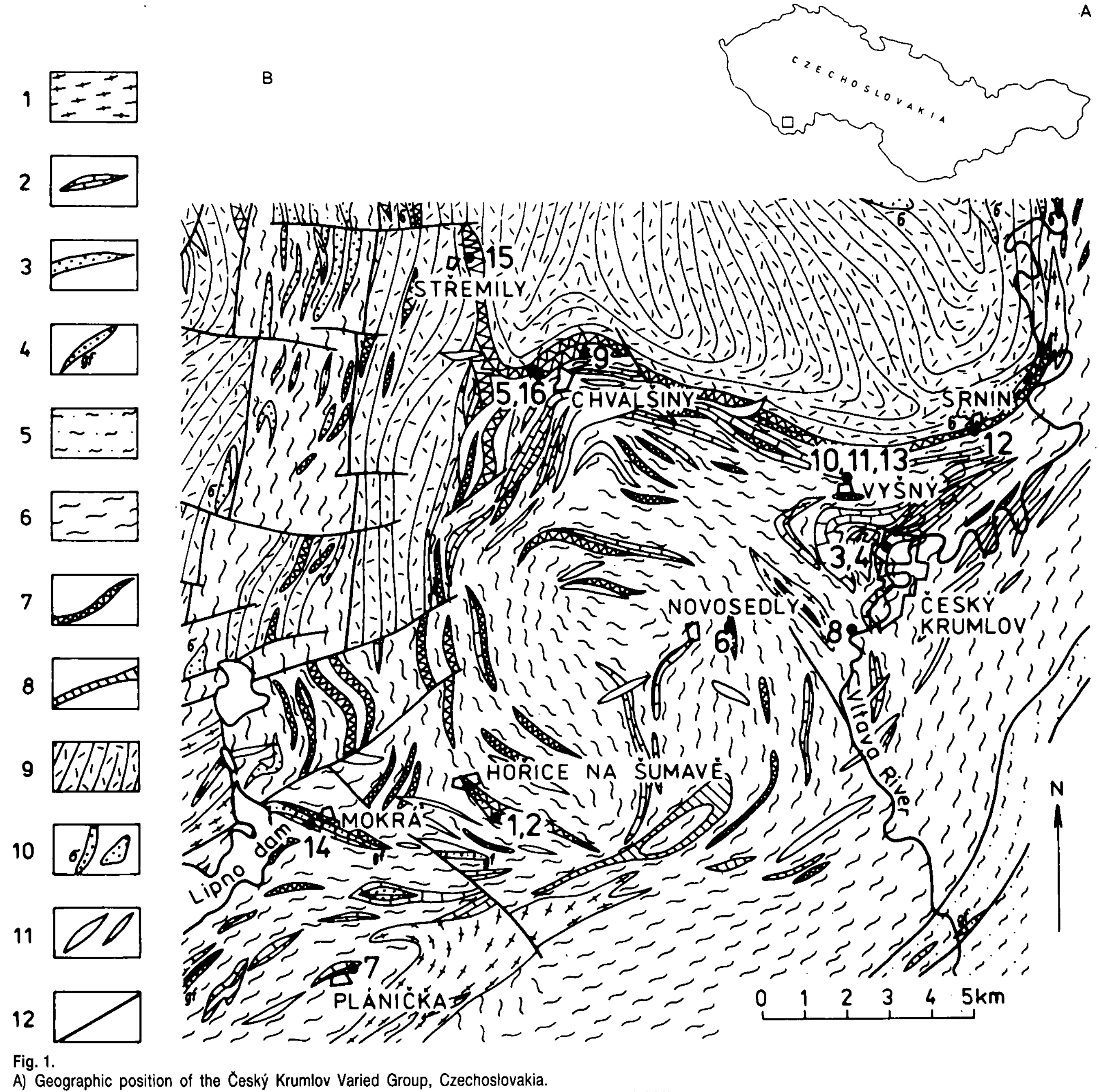

Fig. 1.
A) Geographic position of the Český Krumlov Varied Group, Czechoslovakia.
B) Simplified geologic map of the studied area based on the map after FIALA & LOSERT (1980):
1 = biotite orthogneisses to migmatites; 2 = marbles; 3 = quartzites and quartzitic paragneisses; 4 = graphitic rocks; 5 = two-mica paragneisses; 6 = plagioclase-biotite paragneisses; 7 = amphibolites; 8 = calc-silicate rocks; 9 = granulites; 10 = serpentinites; 11 = Hercynian intermediate to acid dykes; 12 = faults.

margin environment (PATOČKA, in print). The "varied" interlayers of sedimentary parentage are represented by quartzitic paragneisses, quartzites, calc-silicate rocks, marbles, graphitic gneisses and graphitic quartzites (HEGENBARTH, 1936; KODYM Jr., 1966; DUDEK, 1983). The layers and lenses of calcitic marbles, exceeding 300 m in thickness in the Český Krumlov area, thin out towards the NE and some of them disappear (ZOUBEK et al., 1988). JENČEK & VAJNER (1968) recognized the reef character of primary limestones. As the marble layers grade upwards into psammitic beds, ZOUBEK (1953) spoke about regressive type of carbonate sedimentation.

The frequent layers of amphibolites and hornblende gneisses – from several m to several tens of m thick – are of volcanogenic origin (KODYM Jr., 1966; SUK, 1971; DUDEK, 1983) (Fig. 1). The synsedimentary bodies as well as intrusions are presumed to be primeval forms of these metavolcanics (HEGENBARTH, 1936; RAJLICH et al., 1986).

FIALA et al. (1982), considering the association of basic metavolcanics with metapelites and marbles, concluded that the Český Krumlov Varied Group sedimented in an environment of volcanic islands. On the basis of the Nd-whole rock model ages KRÖNER et al. (1988) suggested an Archean to Mid-Proterozoic source terrain for the Moldanubian metasediment precursors. Nevertheless, the progressively differentiated trace element composition of the Český Krumlov Varied Group plagioclase-biotite paragneisses does not indicate a significant contribution of recycled Archean material (PATOČKA, in print).

The pre-metamorhic age of the Český Krumlov Varied Group is still disputed. Exclusively Precambrian age of its primary origin is advocated by KODYM Jr. (1966), CHALOUPSKÝ (1977), ZOUBEK (1979) etc. On the other hand, some recent finds of possibly Lower Paleozoic microfossils (ANDRUSOV & ČORNÁ, 1976; KONZALOVÁ, 1980; PACLTOVÁ, 1984) seem to support the concept of SUESS (1926), regarding the Lower Paleozoic as a time of the Varied Group sedimentation. However, the oldest known meta-igneous rock of the Bohemian Massif was discovered in the vicinity of Český Krumlov town – an orthogneiss exposed in small tectonic lenses within the metasediments; the bulk size zircon fraction analysis yielded magmatic crystallization age of the orthogneiss protolith equal to 2,048±12 Ma (WENDT et al., 1988).

Český Krumlov Varied Group was repeatedly intricately deformed. At least two generations of folds can be distinguished there. The older folds have directions NW–SE to N–S, the younger ones are oriented NE–SW (DUDEK, 1983). According to opinion of RAJLICH et al. (1986), the Varied Group deformation is related to the NW–SE thrusting of large crustal masses during the Hercynian orogeny. Three deformation phases affecting this unit were inferred from the detailed structural analysis performed by the authors mentioned. The structural development started with isoclinal folds formation; at the end of the initial stage, these folds were strongly flattened and boudinage developed in the competent rocks. The second phase of deformation is characterized by various style folds formed around rigid inclusions. The youngest phase produced spectacular boudinage and folding of the vertically oriented planes.

During the polyphase deformation the Český Krumlov Varied Group rocks were metamorphosed into the garnet-amphibolite facies; migmatization and aplite injections occurred through the metamorphism. Metamorphic grade is growing towards the Blanský Les granulite body (e. g. ZOUBEK et al., 1988). The metamorphism temperature, ranging from 400°C to 600°C, was determined by means of an isotopic graphite-carbonate thermometer (ČÍŽEK et al., 1984). Geochronological studies on zircons from the rocks of the Moldanubian crystalline sequences defined the age of the metamorphic event to 345±5 Ma (VAN BREEMEN et al., 1982) and between 367 and 347 Ma (KRÖNER et al., 1988).

2. Petrography

The Český Krumlov Varied Group amphibolites are dark, almost black, medium- to coarse-grained rocks. Some amphibolites are strongly foliated and sometimes they show a linear fabric too; on the other hand, some of these metamorphics lack the foliation completely. However, between both extremes a continuous sequence of transitional structural types can be established. The amphibolites were classified into following petrographic types:

1) Banded variety of amphibolite s. s.: This rock type, displaying somewhat indistinct alternating bands of dark and light material, comprises 60–70 % green hornblende, 20–30 % andesine to labradorite plagioclase, 5 % K-feldspar and 5 % quartz. Accessory minerals include sphene, pyrite, pyrrhotite and carbonates. The lighter bands, i. e. bands relatively poorer in hornblende, are much thinner compared with the dark ones. The former are up to several mm thick only, the latter have thickness of 2–3 cm usually.
2) Massive variety of amphibolite s. s.: These metamorphics consist of green to brown-green hornblende (50–70 %), andesine plagioclase (25–40 %), K-feldspar and quartz (both minerals up to 5 %). Usual accessories are biotite, garnet, sphene, pyrite and pyrrhotite.
3) Biotite amphibolite: It is composed by 50 % of green to brown-green hornblende, 40 % of plagioclase (andesine), 5 % of K-feldspar, 5 % of chloritized biotite (forming local accumulations) and 1–2 % of quartz. Accessories are pyrite, pyrrhotite and ilmenite.
4) Garnet amphibolite variety poor in garnet poikiloblasts: The predominant constituents are green-brown to brown hornblende (60–70 %), andesine to labradorite plagioclase (20 %) quartz (up to 10 %), K-feldspar (up to 5 %) and garnet (about 3 %). Garnet poikiloblasts, having 3 mm in diameter at most, are relatively rare. Small subhedral to euhedral crystalloblasts of plagioclase, hornblende and occasional sphene are scattered within the garnet; similarly shaped grains of these minerals surround the poikiloblasts. Accessoric minerals include biotite, sphene, zircon, pyrite, pyrrhotite, apatite and carbonates.
5) Garnet amphibolite variety rich in garnet poikiloblasts: This amphibolite type comprises 40–60% green-brown to brown hornblende, 30–45% plagioclase-andesine to labradorite, up to

10% quartz, 5% K-feldspar and 5–12% garnet. Usual accessories are ilmenite, sphene, zircon, pyrite, pyrrhotite and apatite. The poikiloblasts of garnet (with diameter 2–5 mm) contain numerous inclusions – idioblastic to hypidioblastic plagioclase and hornblende are the most common ones, subordinate inclusions are K-feldspar, quartz, sphene, ilmenite and phyrrhotite. All garnets are surrounded by rims, composed of small crystalloblasts corresponding to the inclusions, up to one half of the poikiloblast diameter thick. Large spheric accumulations of small crystalloblasts of the minerals mentioned above, enclosing garnet remnants, can be found in some samples.

6) Pyroxene amphibolite: The principal minerals are green-brown to brown hornblende (50 %), labradorite to bytownite plagioclase (30–35 %), colourless diopside (up to 20 %) and quartz (5–10 %). Accessories include fairly abundant sphene (max. 5 % locally), ilmenite, zircon and pyrrhotite. Diablastic textures – consisting of intricately intergrown pyroxene, hornblende and plagioclase – are quite common in this particular amphibolite type.
7) Eclogitic amphibolite: The last amphibolite type comprises 20–50 % brown hornblende, 30 % garnet, 10 % grey to colourless diopside and 10 % plagioclase (labradorite). Accessory minerals are ilmenite, zircon, pyrite and pyrrhotite. Garnet is present in a form of large poikiloblasts having 3 to 6 mm in diameter; these are penetrated by numerous inclusions of palgioclase, hornblende and pyroxene. The garnet poikiloblasts are surrounded by diablastic intergrowths analogous to those developed in the pyroxene amphibolites.

3. Analytical methods

The samples of the Český Krumlov Varied Group amphibolites, taken with the aim to cover the region between the southern border of the Blanský Les granulite body and the Lipno dam (Fig. 1), were analyzed for major and trace element abundances (Tables 1 and 2). Major element concentrations were determined in the laboratories of the Geological Survey, Prague (analysts M. HUKA and co-workers) using wet chemical analysis. Trace element abundances were established by X-ray fluorescence analysis in the Unigeo laboratories in Brno (analysts M. JANÁČKOVÁ and co-workers). Analyses of rare earth elements were done by neutron activation in the Central laboratories of the Geoindustria, Prague (analysts J. MOUČKA and co-workers).

4. Geochemistry

4.1. Major elements

On the basis of the volatile-free silica contents the Český Krumlov Varied Group amphibolites correspond to basic and ultrabasic igneous rocks; the basic rocks, characterized by fairly narrow range of the SiO_2 content – 48 to 52 wt.-%, absolutely prevail (Fig. 2). In the SiO_2 vs. $Na_2O + K_2O$ diagram the amphibolites (except the eclogitic type) fall on the subalkaline side of the dividing line, defined by IRVINE & BARAGAR (1971) –

Table 1.
Major element composition of the amphibolites from the Český Krumlov Varied Group.
1–6 = amphibolites s.s.; 7 = biotite amphibolite; 8 and 9 = garnet amphibolites poor in garnet poikiloblasts; 10–13 = garnet amphibolites rich in garnet poikiloblasts; 14–15 = pyroxene amphibolites; 16 = eclogitic amphibolite.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	47.64	48.28	47.79	45.19	49.77	47.61	50.81	46.89	48.14	50.95	46.86	46.95	48.48	48.41	43.16	41.55
TiO_2	1.21	1.20	1.81	1.60	1.61	2.83	1.32	3.69	2.29	2.82	2.84	3.51	2.92	2.42	2.04	3.40
Al_2O_3	15.52	15.38	13.59	14.62	14.04	13.79	14.18	14.03	13.92	12.60	12.67	12.84	13.55	14.55	13.36	11.70
Fe_2O_3	2.56	2.64	1.10	1.55	2.50	2.14	1.78	1.96	2.64	8.08	1.89	3.38	2.14	1.79	5.20	2.82
FeO	7.79	7.86	9.54	9.08	11.02	12.02	11.20	13.41	10.82	12.62	12.61	12.70	13.63	8.88	12.58	16.65
MnO	0.16	0.19	0.16	0.14	0.17	0.20	0.21	0.22	0.18	0.22	0.21	0.20	0.21	0.18	0.24	0.30
MgO	9.34	7.85	6.34	7.11	6.38	5.89	7.11	5.72	6.11	4.77	4.69	5.26	5.26	6.34	7.61	5.69
CaO	11.20	11.34	12.15	11.87	9.58	10.00	10.47	9.49	9.70	9.00	8.79	9.49	7.98	12.20	11.70	14.41
Na_2O	2.61	2.82	2.71	2.68	2.29	2.55	0.94	0.91	2.28	2.43	3.00	2.39	3.35	2.21	1.59	1.01
K_2O	0.40	0.36	0.50	0.70	0.48	0.64	0.34	0.93	1.00	0.72	1.08	0.76	0.73	0.55	0.19	0.83
P_2O_5	0.11	0.11	0.16	0.12	0.14	0.24	0.10	0.41	0.24	0.25	0.25	0.35	0.24	0.24	0.19	0.33
CO_2	0.04	0.06	1.05	2.00	0.03	0.02	0.10	0.05	0.02	0.08	0.09	0.07	0.17	0.02	0.02	0.04
H_2O^+	1.77	1.63	2.12	2.60	1.78	1.78	1.78	2.28	2.19	1.57	1.51	1.76	1.64	2.00	1.88	1.46
H_2O^-	0.09	0.10	0.20	0.17	0.11	0.15	0.15	0.06	0.30	0.08	0.06	0.14	0.09	0.14	0.25	0.12
total	100.44	99.82	99.22	99.51	99.90	99.85	100.49	100.05	99.83	100.19	99.55	99.82	100.39	99.70	100.01	100.31
K_2O/Na_2O	0.15	0.13	0.19	0.26	0.21	0.25	0.36	1.02	0.44	0.30	0.36	0.32	0.22	0.23	0.12	0.82
FeO^t/MgO	1.08	1.30	1.62	3.00	2.08	2.37	1.80	2.65	2.16	3.03	3.05	3.00	2.96	1.66	2.27	3.37

Table 2.
Minor element composition of the amphibolites from the Český Krumlov Varied Group.
1–6 = amphibolites s.s.; 7 = biotite amphibolite; 8 and 9 = garnet amphibolites poor in garnet poikiloblasts; 10–13 = garnet amphibolites rich in garnet poikiloblasts; 14–15 = pyroxene amphibolites; 16 = eclogitic amphibolite.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Sr	133.00	137.00	194.00	210.00	229.00	222.00	72.00	173.00	203.00	219.00	204.00	247.00	230.00	292.00	75.00	87.00
Rb	-	-	11.00	20.00	8.00	10.00	11.00	32.00	12.00	21.00	22.00	-	32.00	8.00	-	12.00
Th	-	-	2.53	3.03	1.84	2.11	1.70	2.26	2.03	2.55	3.07	2.16	2.59	1.93	-	3.27
Ta	-	1.23	-	-	-	-	2.01	3.37	1.49	2.21	-	-	-	-	1.77	-
Nb	-	-	-	12.00	-	17.00	-	22.00	18.00	-	-	27.00	-	17.00	8.00	17.00
Zr	47.00	43.00	110.00	97.00	69.00	147.00	39.00	171.00	151.00	216.00	213.00	233.00	202.00	140.00	77.00	207.00
Hf	2.31	2.21	5.35	1.30	5.54	3.50	6.06	9.31	4.43	-	3.16	6.99	7.51	4.30	-	16.80
Sc	32.80	32.50	41.60	37.30	36.20	33.30	34.70	34.70	24.60	32.80	33.70	35.80	40.00	39.00	50.00	39.70
Cr	434.00	353.00	142.00	141.00	85.00	60.00	273.00	127.00	126.00	57.00	58.00	78.00	60.00	200.00	139.00	87.00
Ni	230.00	193.00	48.00	50.00	66.00	41.00	122.00	40.00	77.00	22.00	26.00	52.00	25.00	72.00	93.00	64.00
La	1.73	1.27	4.73	3.67	10.40	13.80	5.90	16.00	12.40	11.90	11.60	16.20	12.70	24.00	7.53	13.50
Ce	16.30	13.00	25.40	26.30	35.50	32.70	32.50	58.00	50.80	45.30	40.70	54.90	45.20	51.70	41.50	54.80
Sm	2.28	1.97	3.44	2.74	3.18	4.38	2.64	5.61	4.43	5.40	5.35	5.64	5.60	4.30	3.95	6.65
Eu	1.01	0.56	1.38	0.90	1.37	1.64	0.88	2.27	1.63	1.34	1.74	2.43	1.46	2.22	1.04	1.64
Tb	<1	<1	<1	<1	<1	<1	<1	<1	<1	1.23	1.24	1.34	2.20	<1	<1	1.18
Yb	2.59	1.77	2.34	2.03	2.17	1.57	2.83	2.36	2.17	4.68	4.71	4.36	5.16	1.55	3.11	3.87
Lu	0.42	0.38	0.45	0.43	0.59	0.71	0.80	0.62	0.33	0.62	0.90	0.67	0.89	0.39	1.09	1.02
Y	22.00	22.00	32.00	24.00	18.00	30.00	22.00	28.00	28.00	47.00	50.00	40.00	52.00	19.00	33.00	52.00
ΣREE	23.32	18.39	36.36	35.17	51.84	53.16	44.22	82.59	70.13	67.90	63.36	81.77	69.55	81.94	57.18	79.82
Ce/Yb	6.29	7.34	10.85	12.96	16.36	20.83	13.66	24.58	23.41	9.68	8.64	12.59	8.76	33.35	13.34	14.16
Eu/Eu*	1.18	0.78	1.14	0.93	1.22	1.11	0.92	1.19	1.08	0.70	0.90	1.21	0.72	1.45	0.74	0.17

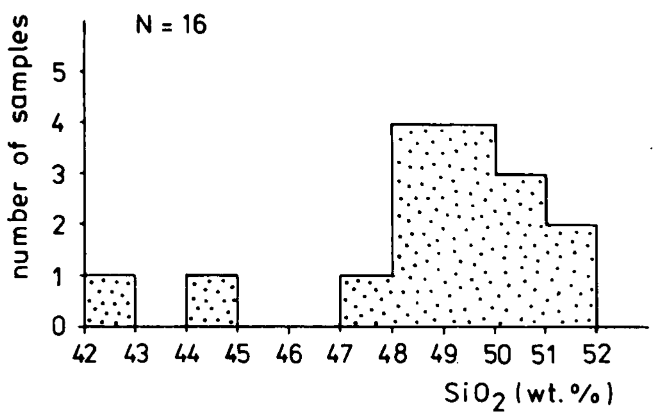

Fig. 2.
Distribution of the volatile free SiO_2 content in the Český Krumlov Varied Group amphibolites.

nevertheless, some of them approach the alkaline field closely (Fig. 3). In the diagram, adapted by LE BAS et al. (1986), the amphibolites occupy fields of basalts s. s., and picritic basalts.

The amphibolite specimens mostly have the concentrations of Na_2O either equal to or higher than 2.21 wt.-%; however, four of the rock samples are distinguished by remarkably low Na_2O content – below 1.60 wt.-%. Two of the Na-poor amphibolites show abnormally high K_2O/Na_2O values – 0.82 and 1.02, while the vast majority of the studied rocks display the alkali oxide ratio much lower than 0.36 (Table 1).

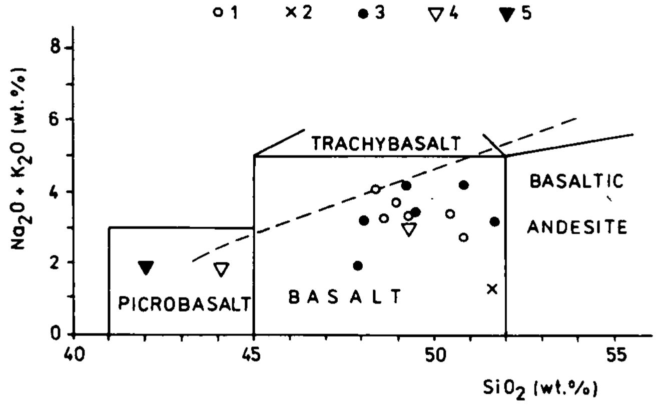

Fig. 3.
Alkali-silica diagram of the amphibolites from the Český Krumlov Varied Group.
1 = amphibolites s. s.; 2 = biotite amphibolite; 3 = garnet amphibolites; 4 = pyroxene amphibolites; 5 = eclogitic amphibolite.
Dashed line divides the fields of alkaline and subalkaline rocks (IRVINE & BARAGAR, 1971); full lines mark the fields of common volcanic rock types (LE BAS et al., 1986).

Since the alkali abundances can be substantially changed by any secondary process, the Al_2O_3-FeO^t+TiO_2-MgO cation plot (JENSEN, 1976) was applied too. Almost all amphibolites can be classified as Fe-tholeiitic basalts according to this diagram (Fig. 4). As the predominance of Fe over Mg in the amphibolite compositions is well demonstrated by Fig. 4, it has to be pointed out that high FeO^t/MgO ratios (being above 2.00 usually, when both oxide concentrations are in wt.-%) are specific for the greater part of the specimens studied (Table 1).

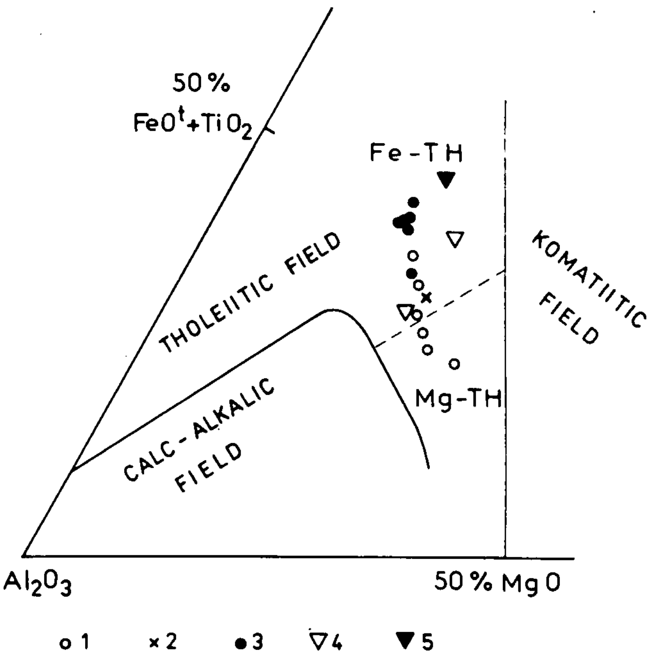

Fig. 4.
The Český Krumlov Varied Group amphibolites in cation plot after JENSEN (1976).
Symbols as in Fig. 3.

The Český Krumlov Varied Group amphibolites for the most part are markedly enriched in TiO_2, FeO^t and K_2O (or at least either in FeO^t and K_2O or in TiO_2 and K_2O) compared to modern mid-ocean ridge basalt (MORB) after WEDEPOHL (1981). On the other hand, they are depleted in MgO usually; the low Na_2O abundances, specific for several samples, show themselves in this comparison too (Fig. 5). Only the banded variety of amphibolites s. s. reveal the major element composition almost identical to MORB-one except a high K_2O content (Fig. 5a).

4.2. Trace elements

Four types are discernible among the Český Krumlov Varied Group amphibolites on the basis of a diagram employing Ce/Yb ratio and total REE abundance (Fig. 6). The garnet content (i. e. an Yb concentration in this case) is a cause of distribution of the amphibolite samples into two groups in this diagram. The amphibolites with abundant garnet – i. e. garnet amphibolites rich in garnet poikiloblasts and eclogitic amphibolite – form an especially compact group, showing the ΣREE : Ce/Yb average value more than two times higher compared with the rest of the rocks studied. The relation between REE fractionation degree (expressed as Ce/Yb ratio) and total lanthanide content in the rock samples seem to be a reason of nearly linear arrangement of the amphibolite data within both groups.

The amphibolites lacking garnet as main constituent mineral and garnet amphibolites poor in garnet poikiloblasts are classified further into three types – distinguished by low, medium and high REE total concentrations as well as by low, medium and high Ce/Yb values (Figs. 6 and 7a, b and c). The amphibolites with abundant garnet, forming a fairly dense cluster in the diagram in Fig. 6, are regarded as the fourth type characterized by high total REE abundances and medium Ce/Yb values (Fig. 7d).

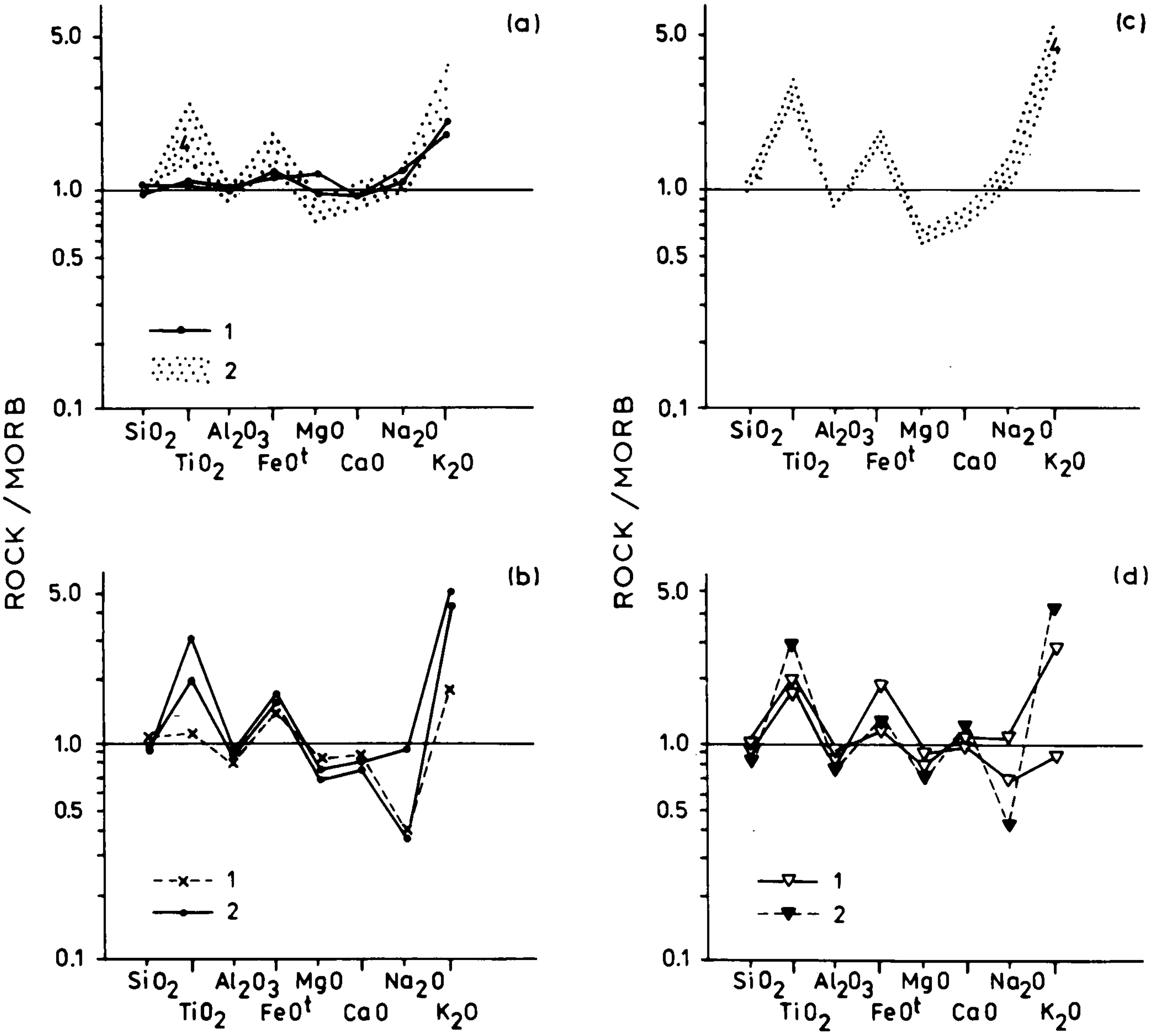

Fig. 5.
The Český Krumlov Varied Group amphibolite major element abundances normalized to MORB composition after WEDEPOHL (1981).
a = amphibolites s. s.: banded variety (1) and massive one (2); b = biotite amphibolite (1) and garnet amphibolites poor in garnet poikiloblasts (2); c = garnet amphibolites rich in garnet poikiloblasts; d = pyroxene amphibolites (1) and eclogitic one (2).
Numbers in dotted fields represent the numbers of samples.

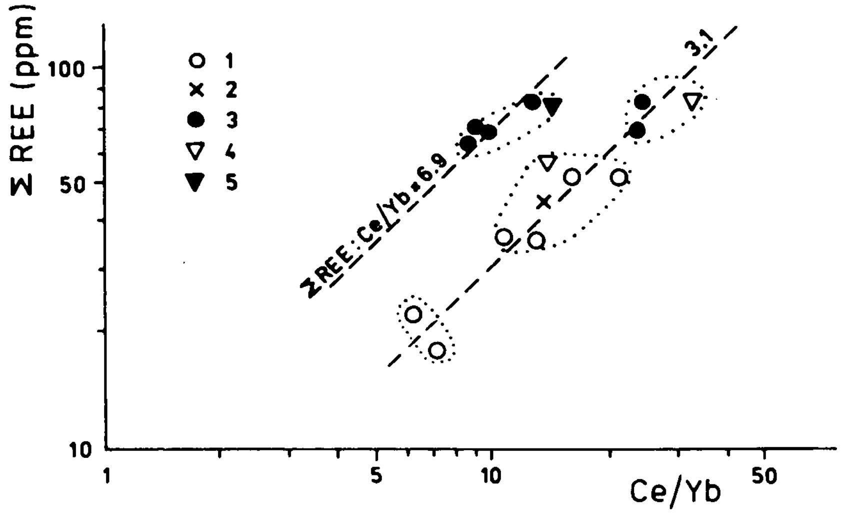

Fig. 6.
The amphibolites of the Český Krumlov Varied Group in the Ce/Yb vs. ΣREE diagram.
1 = amphibolites s.s.; 2 = biotite amphibolite; 3 = garnet amphibolites; 4 = pyroxene amphibolites; 5 = eclogitic amphibolite.
The four amphibolite-types distinguished according to different total REE abundances and Ce/Yb ratios are encircled by dotted line. The amphibolites with abundant garnet (i. e. the garnet amphibolites rich in garnet poikiloblasts and eclogitic amphibolite) are characterized by higher ratio of the values plotted.

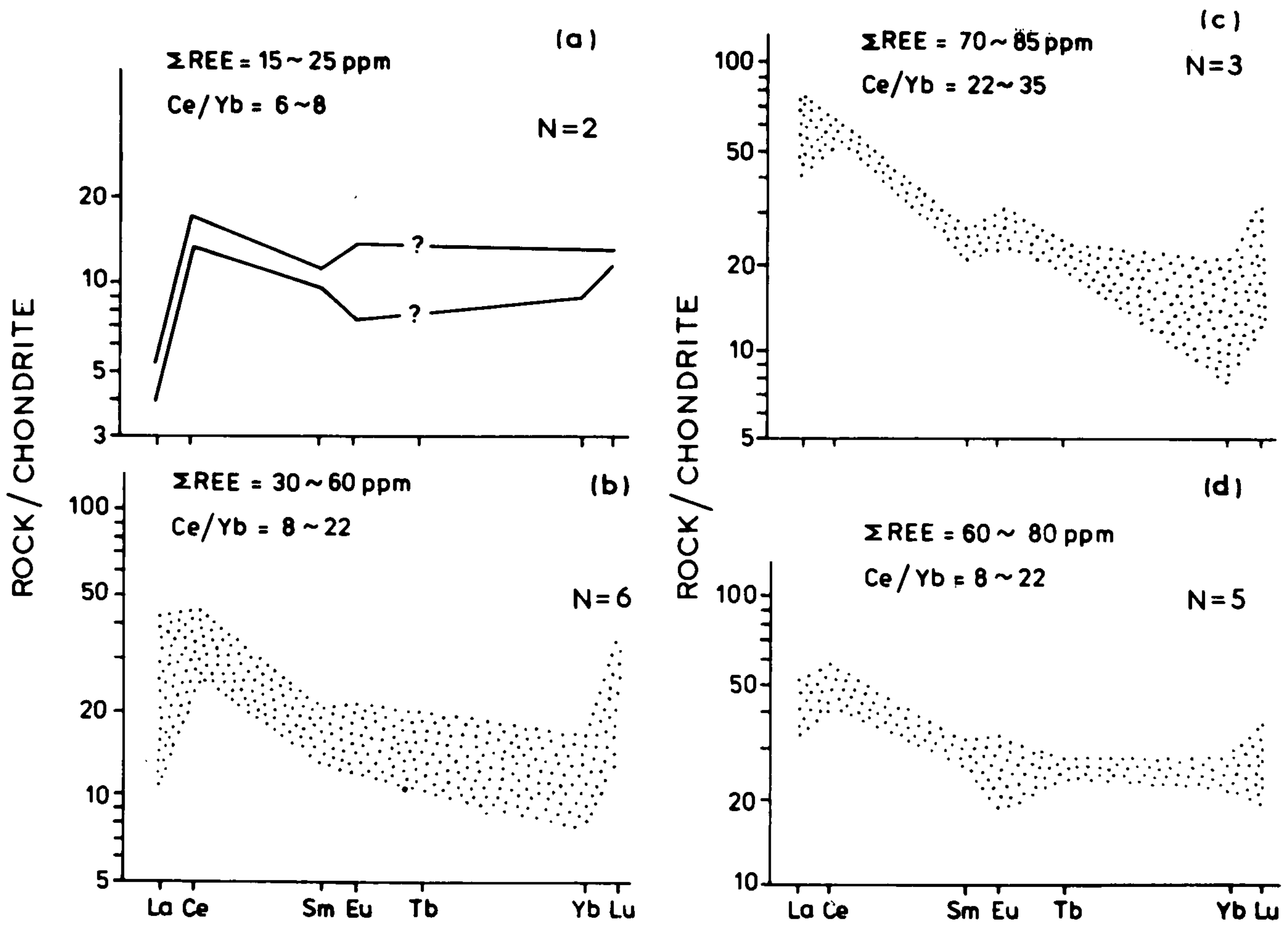

Fig. 7.
Chondrite-normalized REE distributions in the Český Krumlov Varied Group amphibolites.
a = low-REE and low-Ce/Yb type (banded amphibolites s.s.); b = medium-REE and medium-Ce/Yb type (massive amphibolites s.s., biotite amphibolite and single sample of pyroxene amphibolite); c = high-REE and high-Ce/Yb type (garnet amphibolites poor in garnet poikiloblasts and single sample of pyroxene amphibolite); d = high-REE and medium-Ce/Yb type (garnet amphibolites rich in garnet poikiloblasts and eclogitic amphibolite).
Cf. Fig. 6. Numbers of samples are presented in the figure. Chondrite REE values are taken from HERRMANN (1970).

The amphibolite samples of the first and second types are remarkably enriched in K, Rb, Ba, Th, Ta and Nb (i. e. in the most mantle-incompatible elements) compared to mid-ocean ridge basalt (MORB) after PEARCE (1982); abundances of P, Zr, Hf, Sm and Ti (I. e. moderately incompatible elements), Y and Yb (compatible with garnet) and Sc and Cr (compatible with all mafic minerals) are comparable to MORB-concentrations (Figs. 8a and b). The third and fourth amphibolite types display an enrichment both in the most incompatible elements and in moderately incompatible ones as well as depletion in Sc and Cr, like a common feature of MORB-normalized patterns. However, they essentially differ in garnet-compatible element abundances – the former are depleted in Y and Yb relative to MORB (Fig. 8c) and the latter are enriched in these elements compared with MORB (Fig. 8d).

5. Discussion

5.1. Secondary Changes in the Chemical Composition of Rocks

The studied amphibolites probably have not suffered any significant hydrothermal alteration after the amphibolite facies metamorphism took place, as their volatile component (i. e. H_2O and CO_2) contents are very low (Table 1).

The amphibolite samples described in this study show relatively uniform chemistry of major elements (Fig. 5 and Table 1) as well as distinct arrangement along a tholeiitic differentiation trend (Fig. 4). That is why the major element contents in the amphibolites can be considered as largely unchanged by secondary processes (regional metamorphism and/or hydrothermal alteration); this feature seems to be common to all Moldanubian amphibolites (cf. SUK, 1971; ŠICHTAŘOVÁ, 1981; MATĚJOVSKÁ, 1987; SCHÜSSLER et al., 1989). Low abundances of Na, characterizing several rock samples, were presumably caused either prior to metamorphism by rock-seawater (or seawater-resembling solution) interaction (SEYFRIED & BISCHOFF, 1981 etc.) or by regional metamorphism, during which alkalis (especially Na) tend to be the most mobile elements (e. g. WINKLER, 1979).

Among the minor elements, the REE group is regarded to be the most resistent in the course of any secondary process and thus to be the best indicator of initial rock characteristics (BERNARD-GRIFFITHS et al., 1986; MØRK & BRUNFELT, 1988 etc.). Nevertheless, coherent secondary changes of REE contents (HELLMAN et al., 1979) producing in some cases pseudo-magma-

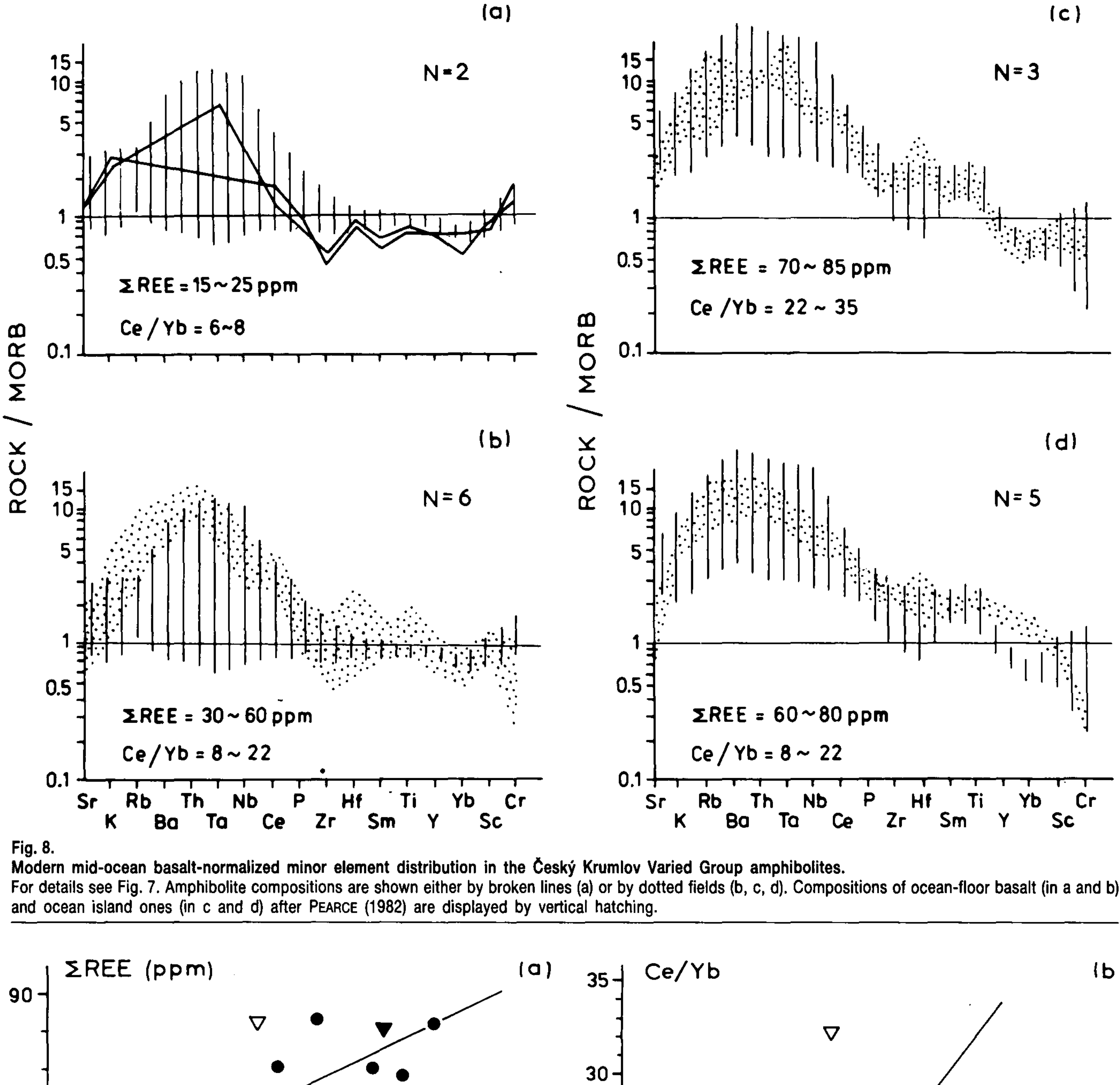

Fig. 8.
Modern mid-ocean basalt-normalized minor element distribution in the Český Krumlov Varied Group amphibolites.
For details see Fig. 7. Amphibolite compositions are shown either by broken lines (a) or by dotted fields (b, c, d). Compositions of ocean-floor basalt (in a and b) and ocean island ones (in c and d) after PEARCE (1982) are displayed by vertical hatching.

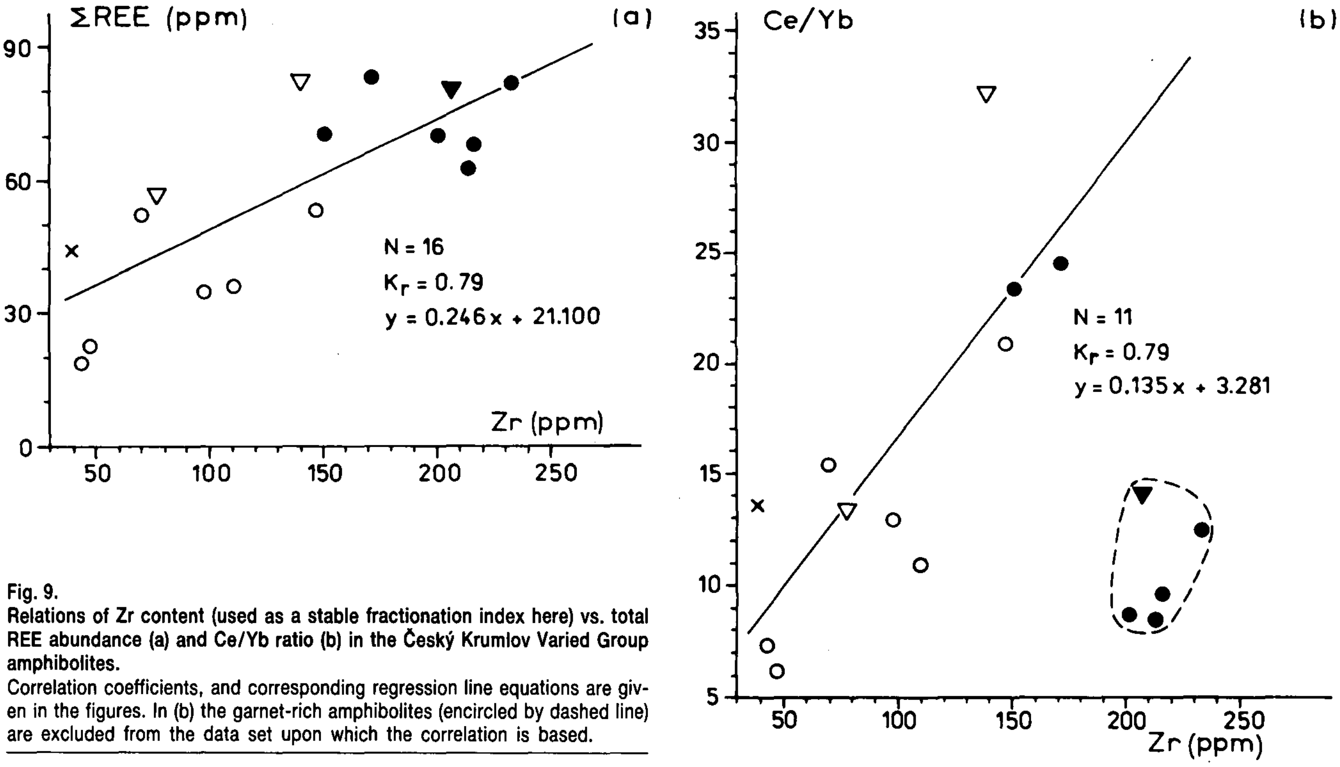

Fig. 9.
Relations of Zr content (used as a stable fractionation index here) vs. total REE abundance (a) and Ce/Yb ratio (b) in the Český Krumlov Varied Group amphibolites.
Correlation coefficients, and corresponding regression line equations are given in the figures. In (b) the garnet-rich amphibolites (encircled by dashed line) are excluded from the data set upon which the correlation is based.

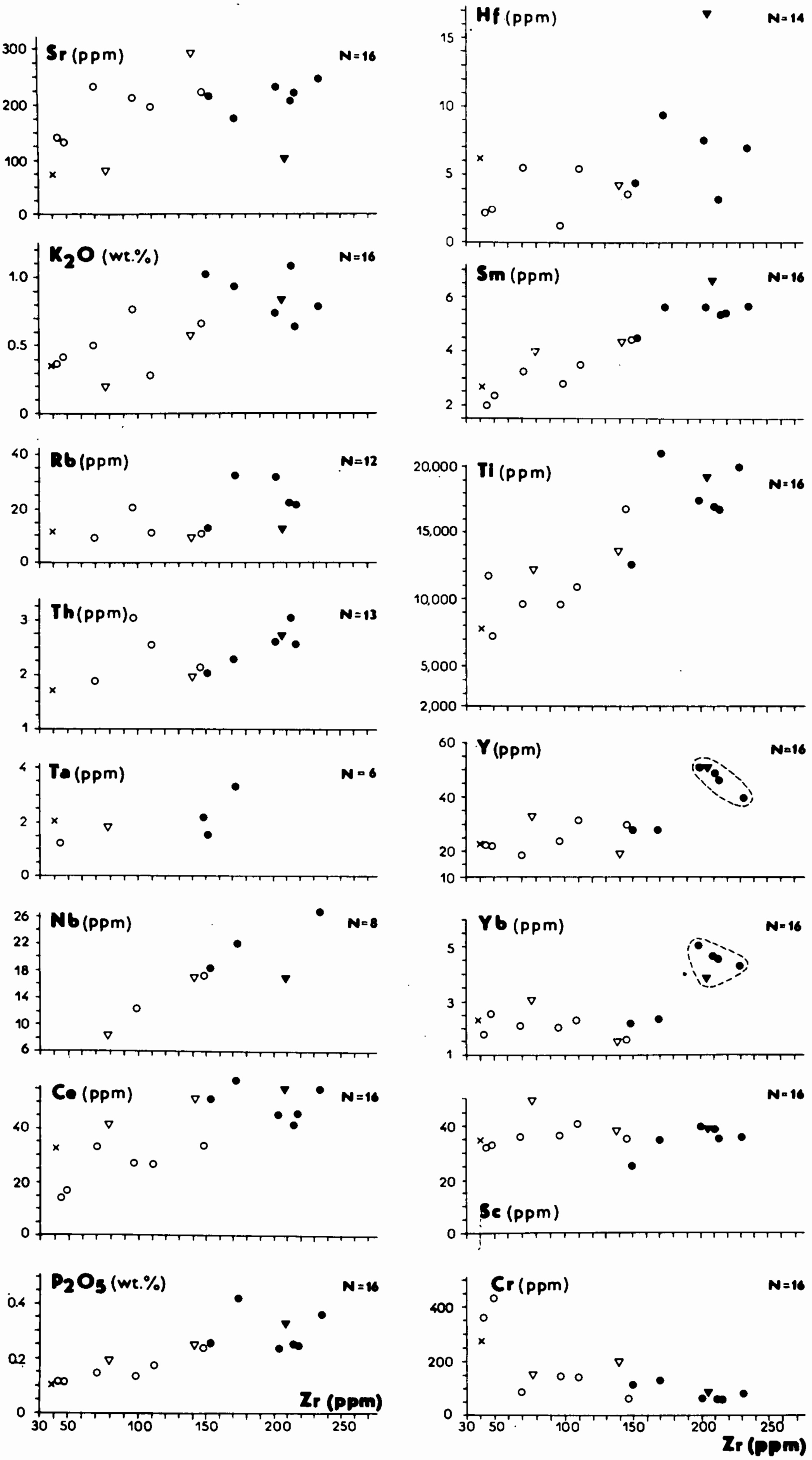

Fig. 10.
Diagrams of Zr content (used as a stable fractionation index here) against the abundances of minor elements (including K), utilized in the MORB-normalized geochemical patterns after PEARCE (1982), for the Český Krumlov Varied Group amphibolites. See also Table 3. Numbers of data are given in all plots. The garnet-rich amphibolites are shown separately in the Zr-Y and Zr-Yb diagrams.
Symbols as in Fig. 6.

tic lanthanide patterns, have to be taken into account. To evaluate a possible extent of REE mobility in the amphibolites, the total lanthanide concentrations as well as Ce/Yb values were compared with the abundances of Zr in individual rock samples (Fig. 9). As the principal Zr-bearing mineral phase – i. e. zircon – belongs to chemically most stabe minerals (GRAUERT et al., 1973; WATSON & HARRISON, 1983), Zr is largely immobile during the alteration of rocks owing to metamorphism, hydrothermal events and weathering (e. g. FLOYD & WINCHESTER, 1978; FINLOW-BATES & STUMPFL 1981; GÖKTEN & FLOYD, 1987); according to the last named authors, this element can be utilized as a stable fractionation index, too. In the amphibolites the total REE abundances are correlated with Zr contents quite well (Fig. 9a). The same holds for the Ce/Yb values and Zr abundances in the garnet-lacking amphibolites and garnet-poor ones (Fig. 9a). However, the amphibolites with abundant garnet form a separated group in the latter diagram due to the high concentration of Yb, characterizing these particular rocks; unfortunately, their number is too small to be able to demonstrate any kind of correlation between the values plotted. In conclusion it is thought that the REE patterns of the studied amphibolites (Fig. 7) have original features relatively unaffected by subsequent regional metamorphism and possible hydrothermal alterations.

The Zr vs. arbitrary element diagram proved itself to be useful when mobility of the minor elements (including K), employed in the MORB-normalized geochemical patterns after PEARCE (1982) (Fig. 8), was evaluated in the Český Krumlov Varied Group amphibolites (Fig. 10 and Table 3).

Distinguishing correlations between Zr contents on abscissa and abundances of K, Nb, Ce, P, Sm, Ti and Cr on ordinata, shown in Fig. 10 and Table 3, indicate a negligible secondary mobility of the enumerated elements. A certain mobility of Sr, Rb and Th can be inferred from unsignificant correlations of these element abundances relative to Zr concentrations. However, poor correlations within the element pairs Zr-Hf and Zr-Ta are explainable rather by insufficient amount of data (in the case of the Zr-Ta pair) or by analytical error (in the case of the Zr-Hf pair) than by any secondary abundance changes, since Ta and Hf are considered as almost immobile through regional metamorphism (e. g. GALE & PEARCE, 1982; GIRAUD et al., 1984).

Table 3.
Correlation of selected minor elements (including K) relative to Zr.
N = number of data; K_r = coefficient of linear correlation; P = occurrence probability of data being out of the set characterized by particular K_r value.

element	N	K_r	P
Sr	16	0.459	0.074
K	16	0.796	0.001
Rb	12	0.535	0.073
Th	13	0.483	0.095
Ta	6	0.550	0.258
Nb	8	0.854	0.007
Ce	16	0.760	0.001
P	16	0.839	<0.001
Hf	14	0.511	0.062
Sm	16	0.939	<0.001
Ti	16	0.914	<0.001
Cr	16	-0.754	0.001

Limited variation of the Sc content in the amphibolites (coefficient of Sc abundance variation – V_{Sc} – is equal to 15.1 % only) seems to reflect a limited mobility of this element regardless the absence of correlation relative to Zr (Fig. 10) (cf. GÖKTEN & FLOYD, 1987). The same feature is specific for the abundances of Y and Yb, indicating probably low mobility of these elements, too. Nevertheless, since Y and Yb are strongly compatible to garnet, the garnet-poor amphibolites together with the garnet-lacking ones and the amphibolites rich in this mineral have to be treated as two separate groups at the calculation of the element content variation coefficients. As to the amphibolites with abundant garnet these coefficients – Y_Y and Y_{Yb} – are equal to 10.4 % and 10.5 % respectively; the rest of the amphibolites is characterized by $V_Y = 20.5$ % and $V_{Yb} = 20.0$ %.

In summary, the amphibolites show presumably well preserved primary concentrations of the least mobile minor elements, i. e. of HFSE group (except Hf and Ta), REE and compatible elements (Figs. 9 and 10, Table 3). Furthermore, accordant behaviour of LIL elements within the MORB-normalized minor element patterns of the amphibolites (Fig. 8) as well as very good correlation of K relative to Zr in these rocks (Figs. 10 and Table 3) indicate a coherent LILE mobility; that is, the LIL abundance proportions seem to remain close to pre-metamorphic ones. Consequently, minor element composition of the Český Krumlov Varied Group amphibolites for the most part can be considered as comparable to the primary one.

5.2. Metamorphic Development and Magmatic Affinities

The amphibolite samples mutually differ in the hornblende colour, varying from green to brown. The brown hornblende-bearing amphibolites are mostly associated with the southern margin of the Blanský Les granulite body, while the green-brown to green hornblende-containing types are scattered within the paragneisses and marbles farther to SW (Fig. 1). The describd systematic change of the hornblende colour semms to be a result of the metamorphic grade growth (e. g. REINISCH, 1973), oriented towards the granulite body as reported by ZOUBEK et al. (1988) etc.

The diablastic textures are fairly frequent in the pyroxene amphibolites and in the eclogitic one too. Moreover, the accumulations of small plagioclase and hornblende crystalloblasts, enclosing large garnet poikiloblasts in all garnet-bearing amphibolite samples, can be interpreted as totally recrystallized diablastic intergrowths. The mentioned textures indicate at least single high-grade metamorphic event preceeding the Hercynian amphibolite metamorphism of the studied rocks; presumably, this event was an eclogite facies metamorphism (cf. SUK, 1971; MATĚJOVSKÁ, 1987).

An intrusive and/or effusive primary origin of Moldanubian amphibolites was inferred by ONDŘEJ (1922), KOUTEK (1933), KODYM Jr. (1966), SUK (1971) etc. In the

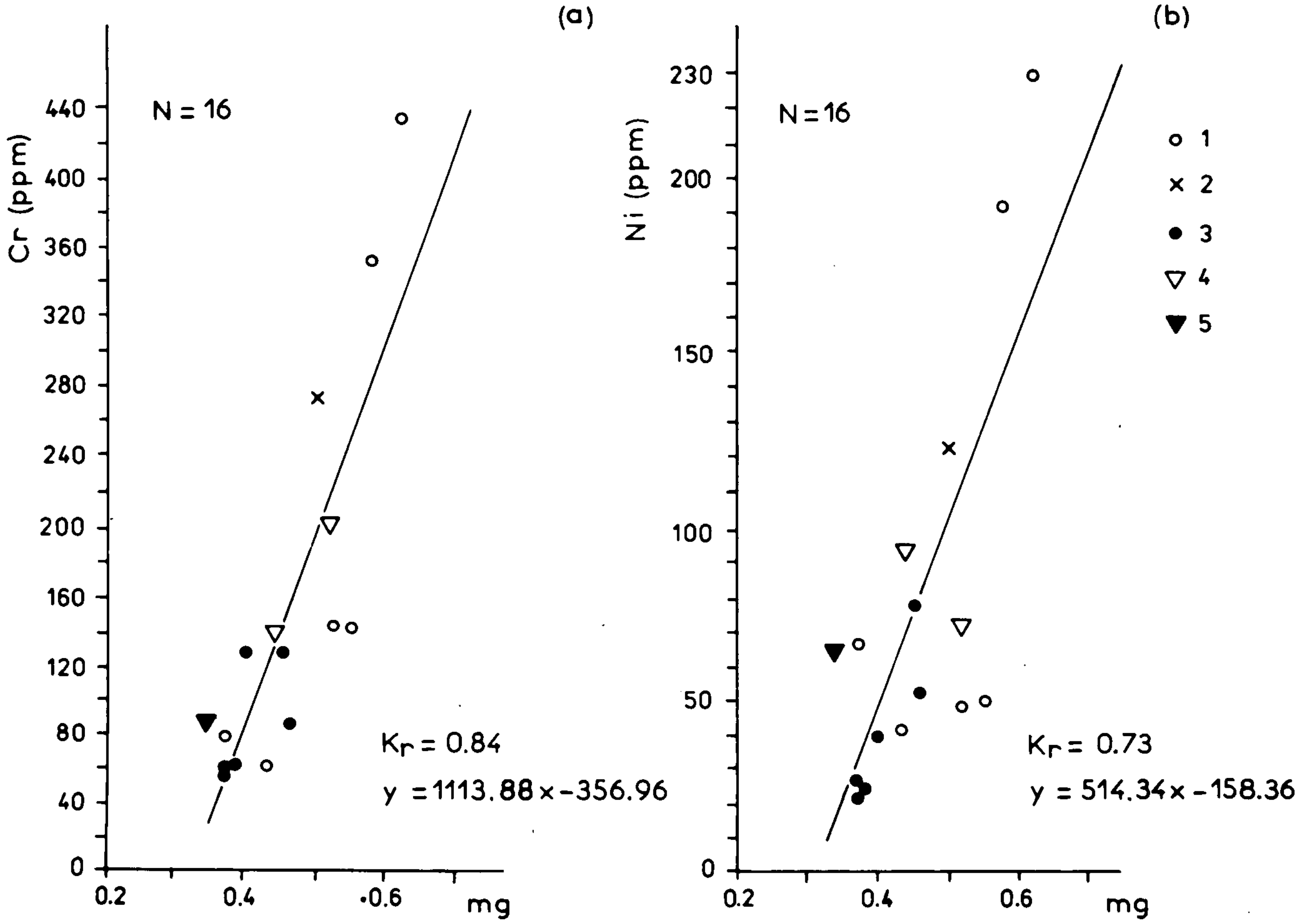

Fig. 11.
Relations of Niggli mg value vs. Cr content (a) and Ni one (b) after LEAKE (1964) in the amphibolites of the Český Krumlov Varied Group. Numbers of data, correlation coefficients and corresponding regression line equations are presented in the figures. Symbols as in Fig. 6.

studied samples the Cr vs. Mg, Ni vs. Mg and Ni vs. Zr/TiO_2 relations (Figs. 11 and 12) and magmatic differentiation trend features, displayed in Figs. 4, 6, 9 and 10, demonstrate an igneous origin of the amphibolite protolith rocks. A limited sedimentary admixture can be expected only in the biotite amphibolite – nevertheless, its influence on the meta-igneous geochemistry of this amphibolite type seems to be negligible.

The studied amphibolites for the most part show more or less fractionated REE distribution patterns closely resembling those distinguishing transitional and alkaline ocean-floor basalts and/or ocean-island ones (e. g. BASALTIC VOLCANISM STUDY PROJECT, 1981) as well as continental tholeiites (DUPUY & DOSTAL, 1984) (Figs. 7b, c and d). According to the last named authors a depletion of Nb and Ta and an enrichment of Th relative to La are specific for continental tholeiites as a result of their melt contamination by continental crust. None of these characteristics seem to be fully proper to the studied amphibolites (Fig. 13) – that is, only an oceanic litosphere related environment could be potential as a primary emplacement setting of the amphibolite protoliths.

Two remaining amphibolite samples – the rocks defined by low total REE contents and low Ce/Yb values (Figs. 6 and 7a) – have the REE features of ocean-floor tholeiitic basalts (BASALTIC VOLCANISM STUDY PROJECT, 1981) beyond any question.

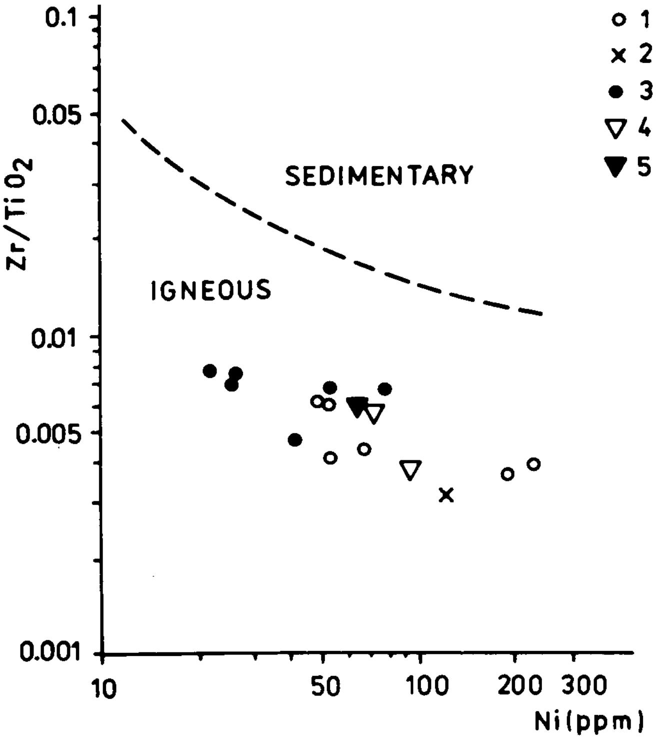

Fig. 12.
The Český Krumlov Varied Group amphibolites in the Ni vs. Zr/TiO_2 plot (WINCHESTER & MAX, 1982) distinguishing between ortho- and para-amphibolites. Symbols as in Fig. 6.

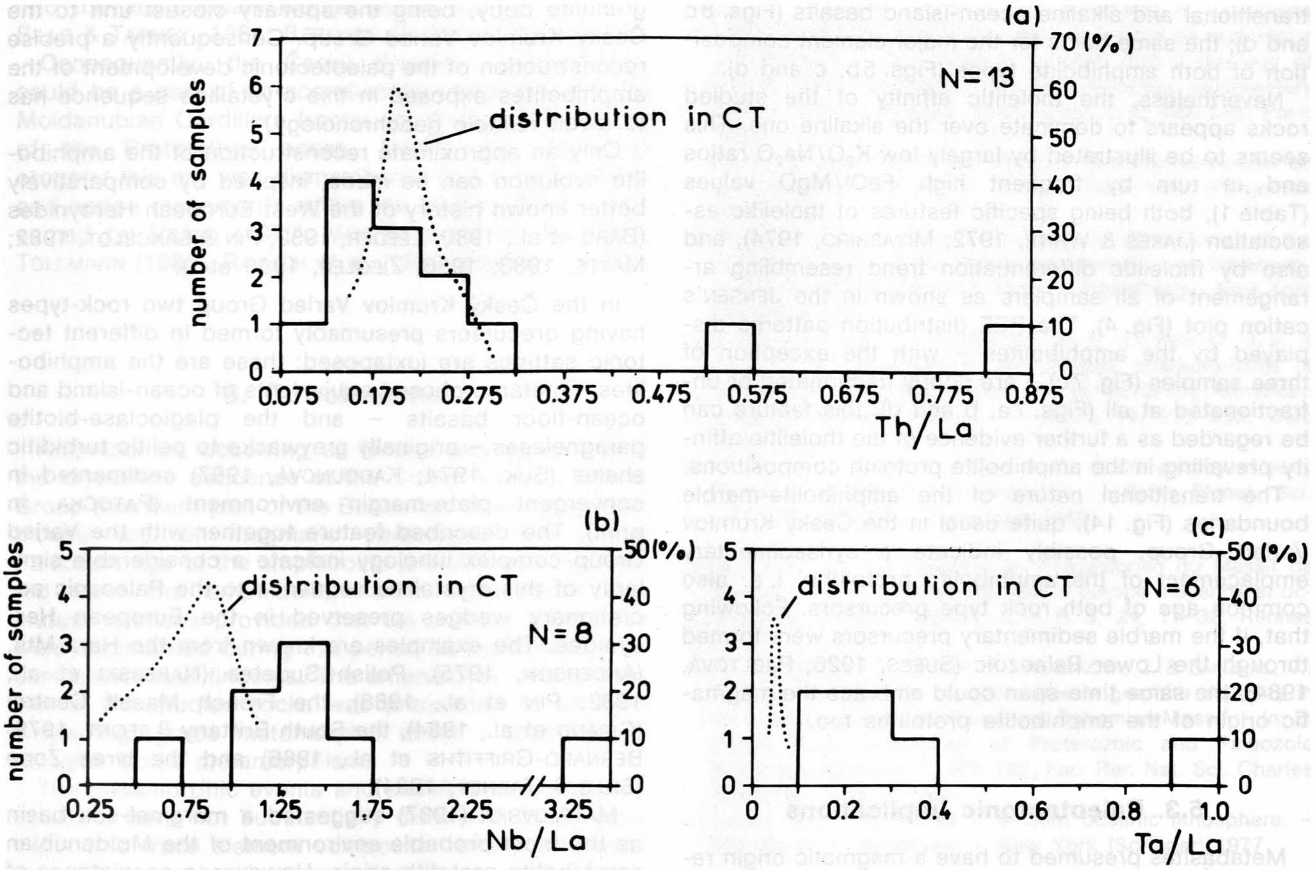

Fig. 13.
Distribution histograms of Th/La (a), Nb/La (b) and Ta/La (c) ratios for the Český Krumlov Varied Group amphibolites compared with the same ratio distributions in continental tholeiites (CT).
Data on 69 samples of CT (recalculated to 100 % here) are taken from Bertrand et al. (1982), Dostal et al. (1983), Mantovani et al. (1985) and Jolly (1987).

The low-REE and low-Ce/Yb amphibolites are very similar to LILE-enriched mid-ocean ridge basalts (Wood, 1980), i. e. to types transitional between tholeiitic and alkaline mid-ocean ridge basalts (Pearce, 1982), both in major and in minor element composition (Figs. 5a and 8a). Also the amphibolites characterized by medium total REE abundances and medium Ce/Yb ratios can be compared to transitional mid-ocean ridge basalts; however, an increased content of TiO_2, FeO^t, K_2O, depletion of MgO and moderate enrichment of HFS elements, distinguishing these rocks (Figs. 5a, b, d and 8b), point out to analogy with ocean-island transitional basalts, too (Dostal et al., 1982; Pearce, 1982; Lanphere & Frey, 1987). The high-REE and high-Ce/Yb amphibolites as well as the high-REE and medium-Ce/Yb ones – having HFS elements substantially enriched relative to the previous type – show trace element distribution patterns equal to those of

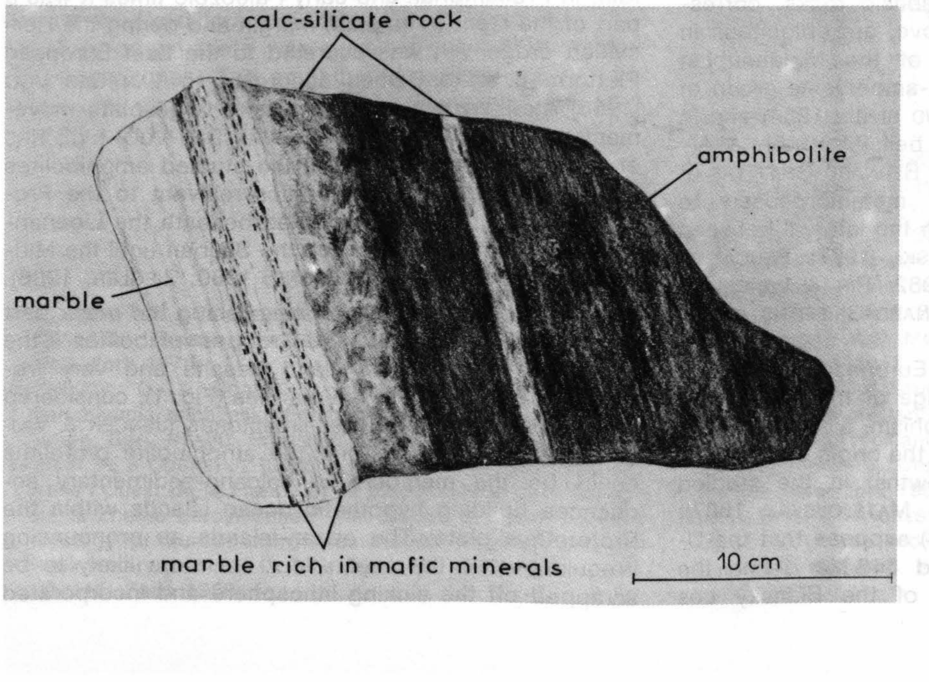

Fig. 14.
Transitional boundary between amphibolite and marble.
The Vyšný quarry, Český Krumlov Varied Group (cf. Fig. 1).

transitional and alkaline ocean-island basalts (Figs. 8c and d); the same holds for the major element composition of both amphibolite types (Figs. 5b, c and d).

Nevertheless, the tholeiitic affinity of the studied rocks appears to dominate over the alkaline one. This seems to be illustrated by largely low K_2O/Na_2O ratios and in turn by frequent high FeO^t/MgO values (Table 1), both being specific features of tholeiitic association (JAKEŠ & WHITE, 1972; MIYASHIRO, 1974), and also by tholeiitic differentiation trend resembling arrangement of all samplers as shown in the JENSEN's cation plot (Fig. 4). The REE distribution patterns displayed by the amphibolites – with the exception of three samples (Fig. 7c) – are poorly fractionated or unfractionated at all (Figs. 7a, b and d); this feature can be regarded as a further evidence of the tholeiitic affinity prevailing in the amphibolite protolith compositions.

The transitional nature of the amphibolite-marble boundaries (Fig. 14), quite usual in the Český Krumlov Varied Group, possibly indicate a synsedimentary emplacement of the amphibolite protoliths, i. e. also common age of both rock type precursors. Following that, if the marble sedimentary precursors were formed through the Lower Paleozoic (SUESS, 1926; PACLTOVÁ, 1984), the same time-span could embrace the magmatic origin of the amphibolite protoliths too.

5.3. Paleotectonic Implications

Metabasites presumed to have a magmatic origin related to oceanic lithosphere are not unique in the Bohemian Massif Moldanubicum. Amphibolites showing composition similar to the studied rocks were found in the SE part of the Moldanubicum (ŠICHTAŘOVÁ, 1981; MATĚJOVSKÁ, 1987) and in the Zone Erbendorf–Vohenstrauss, i. e. in the westernmost part of the Bohemian Massif (SCHÜSSLER et al., 1989). Moreover, eclogites of analogous geochemistry are exposed in the Münchberg Gneiss Massif (MATTHES, 1978; WERNER, 1981), considered to be an equivalent of the rock units forming the NW margin of the Moldanubicum (e. g. BEHR, 1983). The eclogite facies metamorphism of this complex peaked at 380 Ma BP (GEBAUER & GRÜNENFELDER, 1979).

Metamorphosed basic to ultrabasic rocks, corresponding to those mentioned above, are ubiquitous in the West European segments of the Moldanubian Zone, for instance in the leptyno-amphibolite group of the French Massif Central (GIRAUD et al., 1984) and in the South Brittany metamorphic belt (MONTIGNY & ALLERGE, 1974; PEUCAT et al., 1982; BERNARD-GRIFFITHS et al., 1986). These rocks were metamorphosed to blueschists and eclogites through the interval between 430 Ma and 390 Ma BP (MALUSKI, 1977; PEUCAT & COGNÉ, 1977; PEUCAT et al., 1982; PIN & LANCELOT, 1982; DUCROT et al., 1983; BERNARD-GRIFFITHS et al., 1986 etc.).

By analogy with the West European high-grade metamorphism period and the age of the Münchberg Gneiss Massif eclogite metamorphism, a similar timing could be tentatively attributed to the origin of the high-grade relics (diablastic intergrowths) in the studied Moldanubian amphibolites (cf. MATĚJOVSKÁ, 1987). Nevertheless, WENDT et al. (1988) suppose that the U-Pb zircon data grouped around 348 Ma define the high-grade metamorphism age of the Blanský Les granulite body, being the spatially closest unit to the Český Krumlov Varied Group. Consequently a precise reconstruction of the paleotectonic development of the amphibolites exposed in this crystalline sequence has to await reliable geochronology.

Only an approximate reconstruction of the amphibolite evolution can be made, inspired by comparatively better known history of the West European Hercynides (BARD et al., 1980; LEEDER, 1982; PIN & LANCELOT, 1982; MATTE, 1983, 1986; ZIEGLER, 1986 etc.).

In the Český Krumlov Varied Group two rock-types having precursors presumably formed in different tectonic settings are juxtaposed: these are the amphibolites – metamorphosed equivalents of ocean-island and ocean-floor basalts – and the plagioclase-biotite paragneisses – originally greywacke to pelitic turbiditic shales (SUK, 1974; KADOUNOVÁ, 1987) sedimented in convergent plate-margin environment (PATOČKA, in print). The described feature together with the Varied Group complex lithology indicate a considerable similarity of this crystalline sequence to the Paleozoic accretionary wedges preserved in the European Hercynides. The examples are known from the Harz Mts. (ANDERSON, 1975), Polish Sudetes (NAREBSKI et al., 1982; PIN et al., 1988), the French Massif Central (GIRAUD et al., 1984), the South Brittany (LEFORT, 1979; BERNARD-GRIFFITHS et al., 1986) and the Ivrea Zone (SILLS & TARNEY, 1984).

MATĚJOVSKÁ (1987) suggested a marginal-sea basin as the most probable environment of the Moldanubian amphibolite protolith origin. However, a coexistence of terrigenous sediment and oceanic setting related basic rocks within an accretionary wedge, comprising rocks of widely diverse orgin, in itself does not impose any limitation on a width of a closed oceanic basin. It has to be pointed out that only 0.001 % of the ocean-crust volume escapes a destruction in subduction zone (COLEMAN, 1977) and that the transversal reconstruction of plate convergence and collision is hardly possible when paleomagnetic data are insufficient (e. g. DEWEY, 1976; VAN DER VOO, 1983).

WENDT et al. (1988) speculated on the basis of the Nd-whole rock ages and available paleomagnetic results that the Moldanubicum is a displaced ancient terrain; in Precambrian and early Paleozoic times it was a part of the Gondwana plate margin and during the Hercynian orogeny it was accreted to the East European Platform (i. e. to Baltica according to VAN DER VOO [1983] etc.). In this concept a very large plate movement has to be involved (e. g. VAN DER VOO, l. c.; KRS et al., 1987). Following that, the studied amphibolites can be interpreted as the relics relevant to the Prototethys ocean plate, subducted beneath the Ligerian-Moldanubian Cordillera since the Silurian until the Middle Devonian (AUTRAN & COGNÉ, 1980; ZIEGLER, 1986).

Two important features distinguishing the major part of the Český Krumlov Varied Group amphibolites – the geochemistry of ocean-island basalts and very frequent association with the marbles (Fig. 1), considered to be metamorphosed reef limestones (JENČEK & VAJNER, 1968) – point to that the amphibolite protoliths could be the members of volcano-sedimentary sequences building hypothetic ocean islands within the Prototethys plate. The ocean-islands as pronouncing irregularities of the ocean-floor are more likely to be scrapped off the sinking lithosphere and incorporated into the accretionary wedge during subduction (e. g. SILLS & TARNEY, 1984; BERNARD-GRIFFITHS et al., 1986).

Consequently, the Český Krumlov Varied Group could be a part of an accretionary wedge forming the Moldanubian Cordillera frontal arc through the closing of the Prototethys ocean. During the Hercynian orogeny this arc was dismembered due to large shear and nappe movements within the Moldanubicum, presumed by VRÁNA (1979), VAN BREEMEN et al. (1982), TOLLMANN (1985), RAJLICH et al. (1986) and FIALA (1988).

6. Conclusions

Amphibolites occurring as lenses and layers within the crystalline sequence of the Český Krumlov Varied Group (southern part of the Bohemian Massif Moldanubicum) are of magmatic parentage. The Lower Paleozoic age of the amphibolite protolith can be inferred from the amphibolite-marble coexistence and mutual relations provided that the primary limestones were sedimented during this period as indicated by recent microfossil findings. The amphibolite metamorphism of the studied rocks was preceeded by at least single high-grade metamorphic event – probably an eclogite facies metamorphism.

The metamorphic events and possible secondary alterations have not substantially disturbed the primary major and trace element compositon of the amphibolites. The geochemistry revealed these mafic meta-igneous rocks as metamorphosed equivalents of predominantly tholeiitic and transitional to alkaline ocean-island and ocean-floor basalts.

Since the Český Krumlov Varied Group comprises the amphibolites and plagioclase-biotite paragneisses possessing the geochemistry pointing to pre-metamorphic origin in contrasting tectonic settings, i. e. in ocean-islands and ocean-floor in case of the amphibolites and in active plate-margin environment in case of the paragneisses, a tentative interpretation can be made, regarding this crystalline sequence as a remnant of an accretionary wedge. This accretionary wedge – dismembered through the Hercynian shear and nappe movements – could be formed on the Ligerian-Moldanubian Cordillera southern flank where the Prototethys ocean plate was possibly subducted in Mid-Paleozoic times. The amphibolite protolith could take origin in hypothetic ocean-islands within the Prototethys and on a floor on this ocean.

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