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A TECTONIC MODEL FOR THE EASTERN VARISCIDES: INDICATIONS FROM A CHEMICAL STUDY OF AMPHIBOLITES IN THE SOUTH-EASTERN BOHEMIAN MASSIF

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Abstract: Metabasaltic amphibolites are a common rock type in the South-Eastern Bohemian Massif. Most of them range chemically from WPB type to MORB type, however, some data suggest local influxes from a subduction modified mantle source. The rocks appear to document passive rifting in the back arc realm of the northern Gondwana margin in the Early Paleozoic. Geological evidence suggests that a marginal Panafrican plutonic arc terrane (Moravo-Silesian plate) split off from Gondwana, opening a small Variscan sea behind (Raabs sea). This Raabs sea closed again by southward subduction below another Gondwana derived "Moldanubian" continental terrane, which finally overrode the Moravo-Silesian terrane during the Variscan collision.
We propose that the Raabs sea was originally situated in the eastern continuation of the Saxothuringian rift, and that the Moravo-Silesian plate correlates with the Cadomian basement of mid Germany and North Brittanny, i.e. with the northern branch of the Variscan orogen. According to our model, the northern flank of the Variscan fold belt bends sharply southwards in the Eastern Bohemian Massif, in response to the forceful indentation of a Moldanubian terrane from the south.

Key words: Variscides, Bohemian Massif, amphibolites, geochemistry, tectonic model.

Introduction

Basic metaigneous rocks are common constituents of the lithological record of collision zones, and their trace-element compositions are useful in revealing primary tectonic environments and ancient terrane boundaries (e.g. Pearce 1980; Neubauer et al. 1989; Donato 1991). This paper presents chemical data from metabasaltic amphibolites, which were collected from various tectonic horizons of the high-grade metamorphic Variscan nappe pile of the South-Eastern Bohemian Massif, Austria. Relying preferably on trace elements, that behave immobile during metamorphism, we have attempted to classify the amphibolites by means of conventional tectonic-chemical discrimination diagrams for basaltic rocks. The results, when critically correlated with the tectono-stratigraphic background, show a meaningful regional distribution of various chemical types of amphibolites and provide a good basis for putting forward a new geological model of the eastern Variscides for discussion.

Geological background

The South-Eastern Bohemian Massif consists of a thick crystalline nappe complex formed during the Early Carboniferous in the Variscan collision zone between the megacontinents Gondwana and Laurasia. In geological maps, the area is traditionally subdivided into a higher Moldanubian part and an overthrust lower Moravian part (Suess 1926) with the boundary represented by the mylonitic Bittesch Gneiss Body (Fig. 1). This classic tectonic subdivision is, however, largely arbitrary (Frasl 1977), and difficult to reconcile in the light of modern terrane concepts.

The major lithological units of the South-Eastern Bohemian Massif and their tectonic arrangement are outlined in Figs. 1b and 1c. Granulite klippen and distinct orthogneisses (Gföhl Gneiss) on top of the Moldanubian complex are commonly regarded as relics of a highest, allochthonous nappe (**Gföhl Unit** in Fig. 1). Below the Gföhl Unit lies a formation of paragneisses with abundant intercalations of amphibolites and ultrabasites (Raabs Unit in Fig. 1, cf. Thiele 1984; Fuchs 1976). The Raabs Unit has been interpreted by some authors as representing an important intra-Moldanubian suture zone (e.g. Matte 1986; Frasl 1991; Fritz & Neubauer 1993). The footwall of the **Raabs Unit** consists of a variegated formation of strongly deformed Precambrian granitoids (Dobra Gneiss, Spitz Gneiss), paragneisses, marbles, graphite schists, quartzites and amphibolites. At least some of the metasediments may be of Paleozoic age (Matura 1976). This **Variegated Unit** ("Bunte Serie" in the Austrian literature - Thiele 1984) is probably an intra-Moldanubian continuation of a large, Eocambrian consolidated foreland terrane at the eastern end of the Central European Variscides (see Fig. 1). This foreland terrane is usually termed the Moravo-Silesian or Brunovistulian terrane (Dudek 1980) and includes the classic "Moravian Unit". Some important arguments for a correlation of the Variegated Unit with the Moravo-Silesian terrane will be discussed later.

The basement of the Moravo-Silesian plate, although largely covered with Paleozoic sediments and Neogene molasse, has recently been recognized as a Cadomian Pacific-type plate margin terrane (Finger et al. 1995). By the end of the Precambrian,

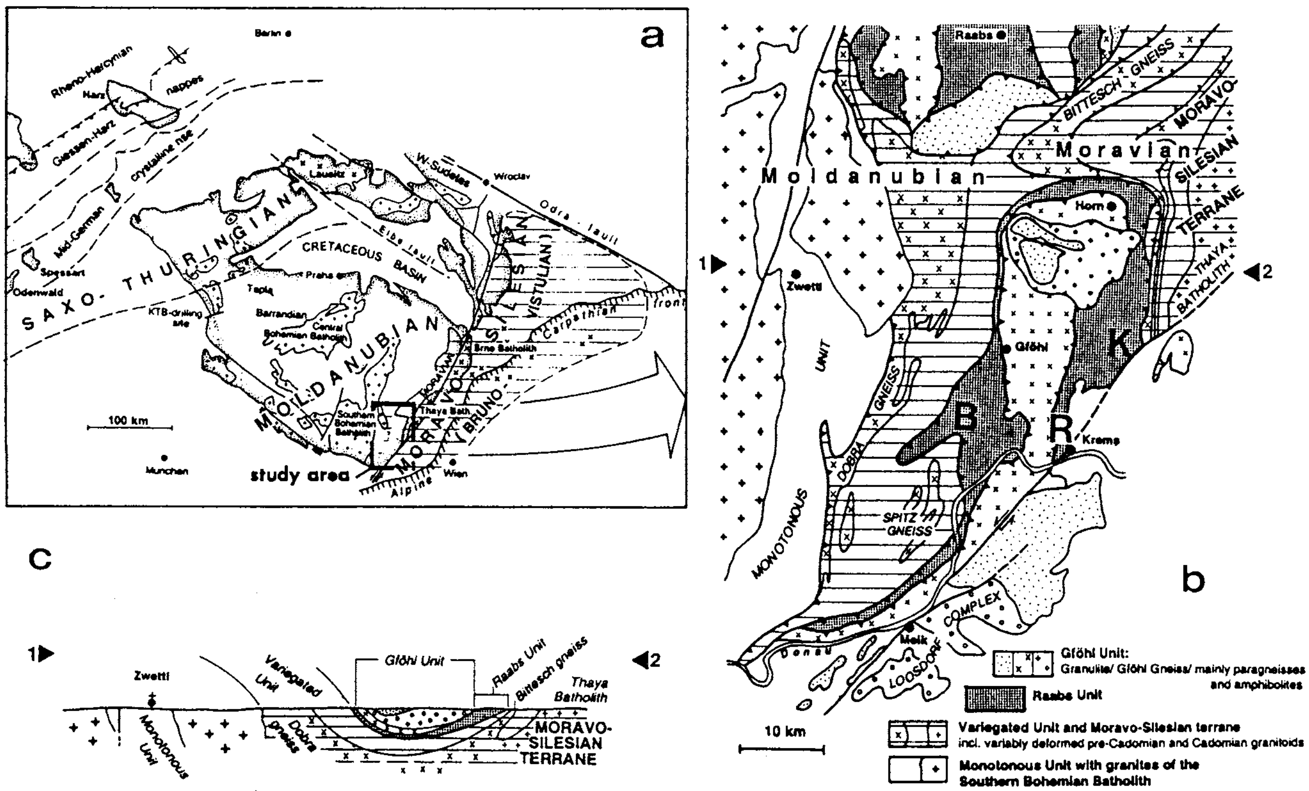

Fig. 1. Sketches showing the geology of the study area and its position within the geological frame of central Europe. **Fig. 1a** after Franke (1989) and Dudek (1980). **Fig. 1b** mainly after Thiele (1984) and Fuchs (1976). Letters B, K and R refer to major amphibolite complexes in the Raabs Unit (**B** = Buschandlwand Complex, **K** = Kamp Complex, **R** = Rehberg Complex). **Fig. 1c** East-west section across the study area; tectonic interpretation mainly according to Matura (1976).

this terrane was probably situated at the northern Gondwana coast, where the Tornquist ocean had been subducted (Cogne 1990). Cadomian granitoid rocks in the eastern part of the Brno Batholith (Fig. 1a) have chemical signatures that suggest an outer arc or island arc tectonic environment (Jelínek & Dudek 1993), while the chemistry of the western Brno Batholith and the Thaya Batholith in Austria rather suggests an inner arc setting. Thus, a westward dipping geometry of the Cadomian paleo-subduction zone, relative to the present orientation of the Moravo-Silesian plate, may be inferred (Finger et al. 1995).

Concerning the kinematics of Variscan crustal stacking in the South-Eastern Bohemian Massif, it is generally accepted that nappe propagation was broadly east-directed (Thiele 1984; Weber & Duyster 1990), very probably with an additional northward transpressional component (Schulmann et al. 1991; Fritz & Neubauer 1993). Earlier models, that suggested an intra-Moldanubian westward tectonics of Caledonian age (Fuchs 1976), are unrealistic in the light of U/Pb radiometric data, that indicate metamorphism of Cadomian and Variscan age, but as yet no definite regional metamorphic events of Caledonian age. Concordant U/Pb monazite ages of ca. 340 Ma, that have been measured in all major tectonic units of the Moldanubian nappe pile (Schenk & Todt 1984; van Breemen et al. 1982; Friedl et al. 1992; Gebauer & Friedl 1995), document the peak of Variscan collisional metamorphism (Friedl et al. 1994). This metamorphism is highest at the base of the Gföhl Unit (ca. 800°C, 8 kb - O'Brien & Carswell 1993) and decreases more or less continuously towards the lower structural units. Variscan metamorphism finally fades away in the Moravo-Silesian (Frasl 1970, 1977). A high pressure (subduction related?) metamorphic event, which appears to be restricted to the Gföhl Unit, is probably 20-30 Ma older (Carswell & Jamtvait 1990).

In the west, the Variegated Unit follows a monotonous paragneiss formation (the "Monotone Serie" of the classic Austrian literature), that is increasingly intruded towards west by the post-collisional late Visean to Namurian granitoids of the Southern Bohemian Batholith (von Quadt & Finger 1991; Friedl et al. 1993). This **Monotonous Unit** is often combined with the Variegated Unit, and referred to as the "Drosendorf Unit or terrane" (e.g. Thiele 1984; Matte et al. 1990; Franke 1989; Weber & Duyster 1990). However, apart from the obvious lithological differences (e.g. active versus passive margin type sedimentation - see Linner 1992; Fuchs 1976), there is a significant contrast in metamorphism (low-pressure in the Monotonous Unit vs. medium pressure in the Variegated Unit - Blümel 1990). It appears that the Monotonous Unit was separated from the Variegated Unit and brought into juxtaposition relatively late during the Variscan orogeny, probably along a major SSW-NNE trending steep dextral shear zone just west of the Dobra Gneiss Body (see also Linner 1992). Thus, tectonic models, that include both the Monotonous Unit and the Austrian Variegated Unit into one Drosendorf terrane, are unrealistic. To avoid misunderstandings, the term Drosendorf terrane is not used in this paper. However, it should be noted, that the "Variegated Series" of the Czech Moldanubian Zone is not necessarily the exact equivalent of the Austrian Variegated Unit (Misař 1994). More suitable counterparts of the Austrian Variegated Unit in Czechia are probably the Vranov and Vratenin Units, that are commonly integrated in the "Moravian" by Czech workers (Mísař 1994).

Results of field work

Variegated Unit

Syngenetic amphibolites: Most amphibolites in the Variegated Unit are concordant layers between 0.5 and 3 meters thickness, intercalated with marginal-sea-type metasediments, i.e. marbles, (graphite) schists and quartzites. Much of the amphibolite material is fine-grained and quite massive, and probably goes back to former lava flows. Frequently, small relics of phyric plagioclases can be observed. Banded, garnet-bearing amphibolites commonly occur as transition zones between massive amphibolites and metasediments. These banded amphibolites may probably be interpreted as former tuffs and tuffites.

A sample of syngenetic amphibolites from near Drosendorf was taken for geochronological work and an upper intercept zircon age of 358±6 Ma was obtained (Friedl et al. 1993). This confirms a Paleozoic age for the metasedimentary rocks of the Austrian Variegated Unit, as suggested by Matura (1976).

Epigenetic amphibolites: The Dobra Gneiss of the Variegated Unit, as well as the Moravian Bittesch Gneiss as probable pendant (Fig. 1), locally contain dark, fine-grained, sometimes porphyric amphibolite layers from dm to m in thickness. These amphibolite layers are generally believed to be metamorphosed basic dikes, that intruded Precambrian granitoid basement (Frasl 1989; Weber & Duyster 1990). In some places, the Dobra Gneiss is intensely crosscut by parallel swarms of such dikes. The picture is similar to basic dike systems in tensional continental regimes (e.g. Oslo rift, - G. Frasl, pers. comm.).

During field work, similar basic dikes were also found in the Spitz Orthogneiss (Fig. 1), for which a Cadomian protolith age is most likely (Friedl et al., in prep.). Therefore, the basic dike magmatism in the Variegated Unit may be best interpreted in terms of an Early Paleozoic rifting event. As there exist no definitive tectonic boundaries between the orthogneisses and the metasediments of the Variegated Unit, an origin for the basic dikes as feeders for the synsedimentary eruptive volcanism may be possible.

Moravian Unit

Epigenetic amphibolites, i.e. metamorphosed basic dikes, comparable to those in the Moldanubian Dobra and Spitz Gneisses, are also known in the Moravian Bittesch Gneiss. These are found in the hangingwall of the gneiss body (Suess 1926; Frasl 1989, 1991). Commonly, they are strongly deformed and transformed into biotite schists. Unlike the Variegated Unit, amphibolite layers intercalated between metasediments are rare in the Moravian Unit. Some are described from the Czech territory (Matejovská 1987).

Raabs Unit

Field work was carried out in three different realms of the Raabs Unit.

1 - *Buschandlwand area*: A voluminous assemblage of amphibolites south-west of Gföhl (Fig. 1b) is commonly referred to as the Buschandlwand Amphibolite Body (Matura 1976). Most of the rocks are fine-grained, massive metabasalts. Lenses of metagabbros and ultrabasites also occur, and this gives an ophiolitic character to the Buschandlwand Amphibolite Body. Also, there are intercalations of metatuffs, metatuffites (i.e. banded amphibolites), paragneisses, sometimes also graphite-quartzites and marbles. These rocks do not represent the typical sedimentary cover of a mid-ocean ridge, but are rather indicative of a near continent setting.

Exposed near the castle of Hartenstein, is an interesting interlayering of amphibolites and fine-grained plagioclase-rich orthogneisses (Matura 1976). The contacts of these distinctive rock-types are very diffuse. It is likely that the light gneiss is a metamorphosed plagiogranite (Steyrer & Finger 1995). A concordant U/Pb zircon age of 428±6 Ma has been obtained from this rock (Finger & von Quadt 1995). This suggests a Silurian age for the whole Buschandlwand Amphibolite Complex.

The above intercalations of contemporaneous basic and felsic magmatites are, however, only local features. Therefore, the Raabs Unit is not well comparable with the leptynite-amphibolite complexes, which are quite abundant in other parts of the Variscan orogen (e.g. Pin & Lancelot 1982).

2 - *Area north of Krems*: A number of amphibolites are exposed along the Kamp Valley ("Kamp Amphibolite Complex" in Fig. 1). The amphibolites here look not very much different from the Buschandlwand area and are also associated with minor ultrabasite bodies. Some amphibolites show well preserved gabbroic textures. Fine-grained concordant amphibolites between paragneisses have often weakly phyric textures and appear to represent basalt flows. Other amphibolites display weak banding features and may be metatuffs (Schiltern type: Marchet 1941).

In the quarry of Rehberg (Krems Valley, Fig. 1), coarse-grained low-strain metagabbros are intruded by metabasaltic dikes (see also Montag & Höck 1993). Locally, e.g. at a large roadcut in the Krems Valley just north of Krems, there exists an intimate interlayering between former lavaflows, tuffs, tuffites and paragneisses.

3 - *Amphibolites immediately at the base of the Gföhl Gneiss*: The amphibolites in the very hangingwall horizon of the Raabs Unit have often been considered as an own group of Moldanubian amphibolites, mainly because of their somewhat coarser grain size and their generally migmatitic textures (e.g. Waldmann 1931). It appears however, that they were originally not very much different from the metabasalts in the Buschandlwand area or Kamp Complex. The quite coarse-grained appearance of the rocks is mainly an effect of advanced recrystallization due to a higher metamorphic overprint. During field work, we found no tectonic boundary between the migmatitic amphibolites at the base of the Gföhl Gneiss and the lower sections of the Raabs Unit.

Gföhl Unit

Metabasites occur also in the hangingwall of the Gföhl Gneiss. These amphibolites are relatively coarse-grained, well recrystallized massive amphibolites, that are macroscopically not significantly different from the amphibolites in the footwall of the Gföhl Gneiss. We have studied and sampled such rocks in the Kamp Valley, west of Horn.

However, it should be noted, that the exact delimitation of the Gföhl Nappe is not clear: The Gföhl Gneiss has been recently interpreted as a Variscan syn-tectonic granite, that formed near the hot base of the Gföhl Nappe (Finger & Frasl 1990).

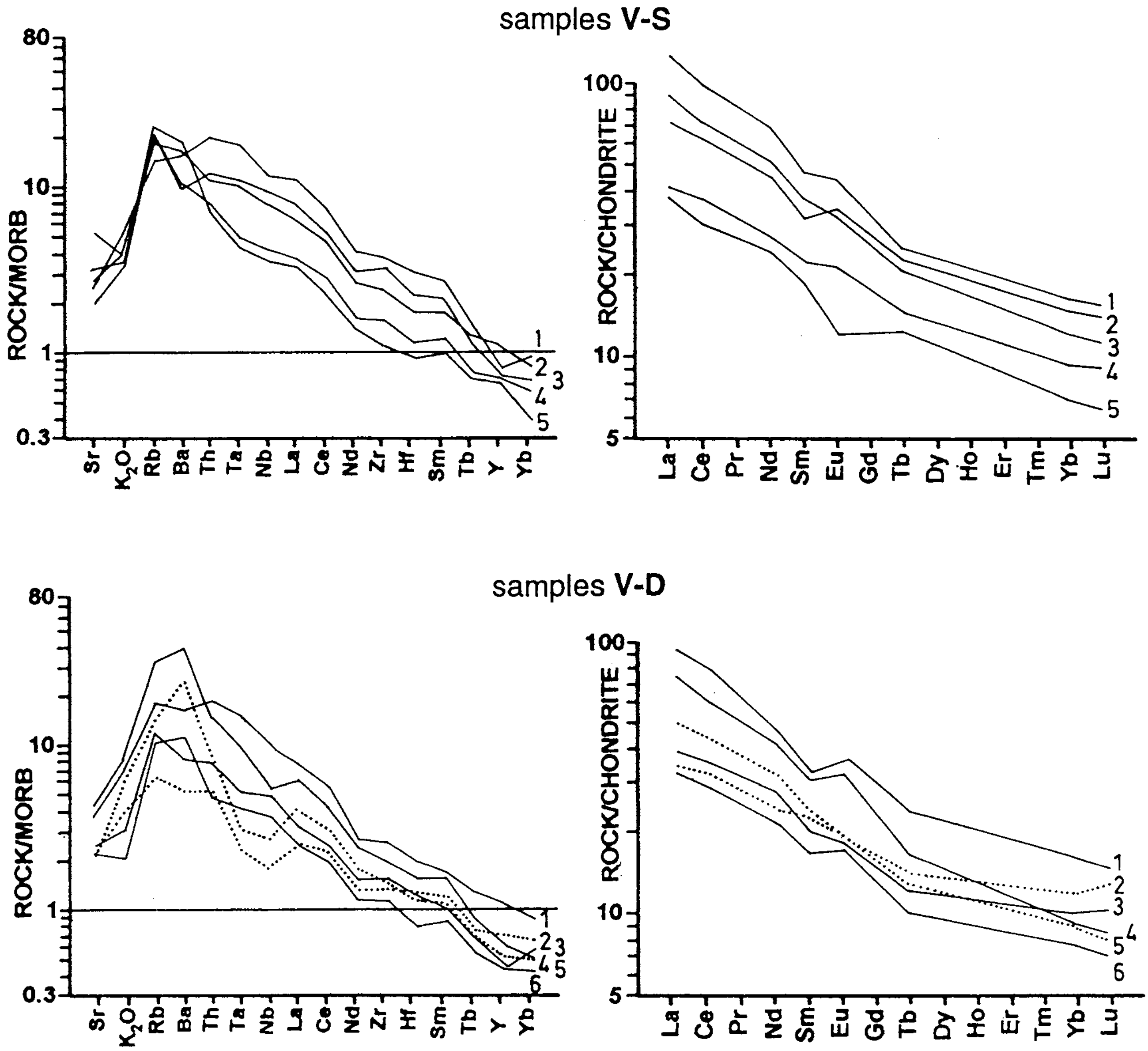

Fig. 2. Trace element and REE characteristics of amphibolites from the Variegated Unit, illustrated on the basis of Morb- and chondrite-normalized diagrams (normalizing values are from Hofmann (1988) and Wakita et al. (1971); for sample locations see appendix 2).

If so, than the protolith of the Gföhl Gneiss perhaps had been able to intrude and to overlap tectonic structures, and the rock then is inconvenient for defining terrane boundaries. This means that even rocks in the hangingwall of the Gföhl Gneiss, i.e. rocks in a tectonic position between Gföhl Gneiss and granulites (Fig. 1b, c), may still be parts of a "Raabs terrane".

Chemical data

Analytical techniques and sample selection

Representative amphibolite samples that were unweathered and showed as little deformation as possible, were chosen for analyses. REE, Hf, Ta, Th and Cr were determined by INNA, V and Ni by DCP, while all other elements were analysed by conventional XRF techniques.

Following the suggestions and criteria given in Pearce (1982), only analyses were used for the discrimination procedure, that approached a basaltic melt composition for the major elements. Several samples turned out to be cumulates. Evolved metabasalts or rocks of andesitic compositions were only rarely found. Obvious metatuffites were not sampled.

The chemical characteristics of the amphibolites was compared and classified mainly by means of conventional MORB-normalized multi-element plots (normalizing values from Hofmann 1988) and chondrite normalized REE plots (normalizing values from Wakita et al. 1971). Representative analyses are listed in the appendix.

Variegated Unit

Syngenetic amphibolites (amphibolite samples V-S): When drawn in conventional MORB-normalized multi-element plots,

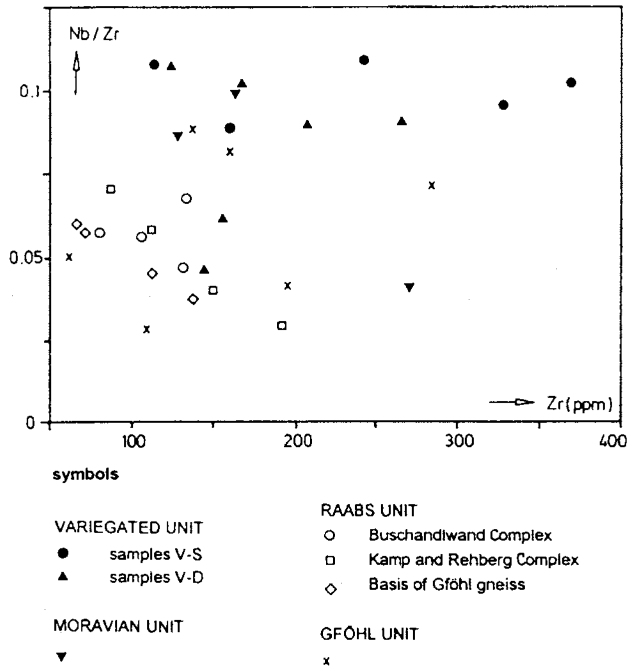

Fig. 3. Nb/Zr versus Zr diagram with plots of amphibolites from the different units of the study area.

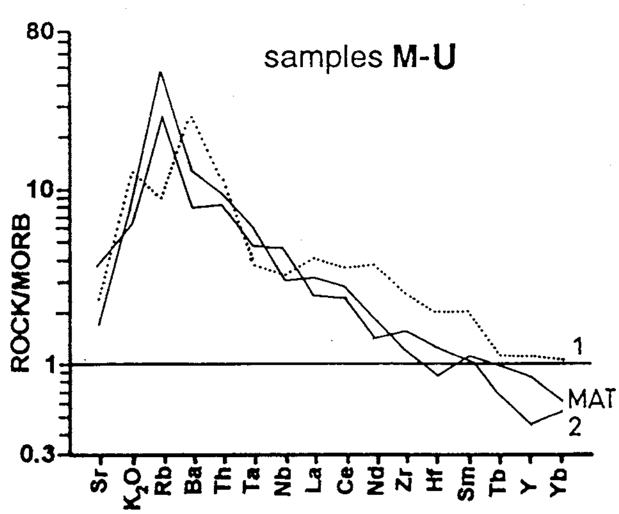

Fig. 4. Trace element characteristics of amphibolites from the Moravian Unit (for sample locations see appendix 2).

the five analysed samples, although from very different localities (see appendix), all yield the characteristically humped array of "within-plate-basalts" (Fig. 2). The trends of the patterns are subparallel between Th and Yb, indicating that the original magmatic relations are preserved for these elements. However, serious irregularities occur in the range of the LIL-elements. E.g., the sample with the lowest Th content has the highest Rb and Ba values. Potassium shows a better correlation with Th. This implies that Rb and Ba were quite mobile either during regional metamorphism or earlier due to post-magmatic rock alterations. The patterns suggest average net gains for both elements.

Chondrite normalized REE-patterns of samples V-S (Fig. 2) illustrate a strong enrichment towards the LREE with $(La/Lu)_n$ ratios between ca. 5 and 10.

In a Nb/Zr vs. Zr diagram (Fig. 3), a useful tool for comparison of source compositions (Pearce & Norry 1979), samples V-S plot typically around Nb/Zr ratios of 0.1.The subalkalic WPB type chemistry of samples V-S fits well to the passive continental margin-type sedimentary environment and indicates melt derivation from an enriched subcontinental mantle, or from a deeper enriched mantle plume, although this latter possibility is less likely from geological constraints (see discussion section).

Metamorphosed basic dikes (amphibolite samples V-D): The metamorphosed basic dike rocks in the Spitz and Dobra Gneisses, which are considered from geological grounds to indicate an Early Paleozoic continental rifting process, are not of a uniform geochemical type. Most are very similar in their element spectrum to the syngenetic amphibolite layers in the Variegated Unit and apparently derived from the same enriched mantle source (see Figs. 2, 3).

However, other dike samples (stippled in Fig. 2) display patterns transitional between within-plate and shoshonitic continental arc basalts in having high LIL and LREE contents, but negative Ta and Nb anomalies. As Late Precambrian calc-alkaline plutonism was very widespread throughout the Moravo-Silesian terrane, one could speculate, that the metamorphosed basic dikes with shoshonitic affinities are marking the transition from Cadomian subduction to an Early Paleozoic rifting. On the other hand, crustal contamination effects may also have played a role.

Moravian Unit

Two epigenetic amphibolites sampled within the Moravian Bittesch Gneiss Body are chemically similar to the epigenetic amphibolites in the Spitz- and Dobra-gneiss (Fig. 4). One (MU-2) is again the "normal" WPB type, while the second (MU-1) displays a transitional VAB-WPB pattern.

A sample of a syngenetic amphibolite in metasediments from the Czech part of the Moravian Unit (MAT), quoted in Matejovská (1987), is also of the WPB-type and shows a Nb/Zr ratio close to 0.1, similar to samples V-S of the Austrian Variegated Unit (Fig. 3).

Thus the mantle reservoir below the Moravian and the Variegated Unit was probably of the same kind and affected by the same processes, and both units may well have been originally connected, as illustrated in Fig. 1.

Raabs Unit

The *amphibolite samples* from the Raabs Unit show a significantly different chemistry when compared to the amphibolites of the Variegated Unit (Fig. 5). In chondrite-normalized REE-diagrams they yield all flat to mildly enriched patterns with $(La/Lu)_n$ ratios between 0.8 and 2 (vs. 5-10 in the Variegated Unit). The rocks also display relatively flat curves in conventional MORB-normalized spider diagrams, as far as the HFS-elements are concerned. Nb, Ta and the LREE are mostly slightly enriched compared to the right hand tails of the patterns (Zr to Yb). Thus, most amphibolites of the Raabs Unit may well be classified as basalts derived from a mildly enriched MORB source. Only a few samples feature HFSE and REE patterns that approach an N-MORB composition (R-K-1, R-H 2).

A positive Rb-Ba anomaly is present in practically all patterns. However, we do not think that this is indicative of magma generation above an active subduction zone. Firstly, the Rb and

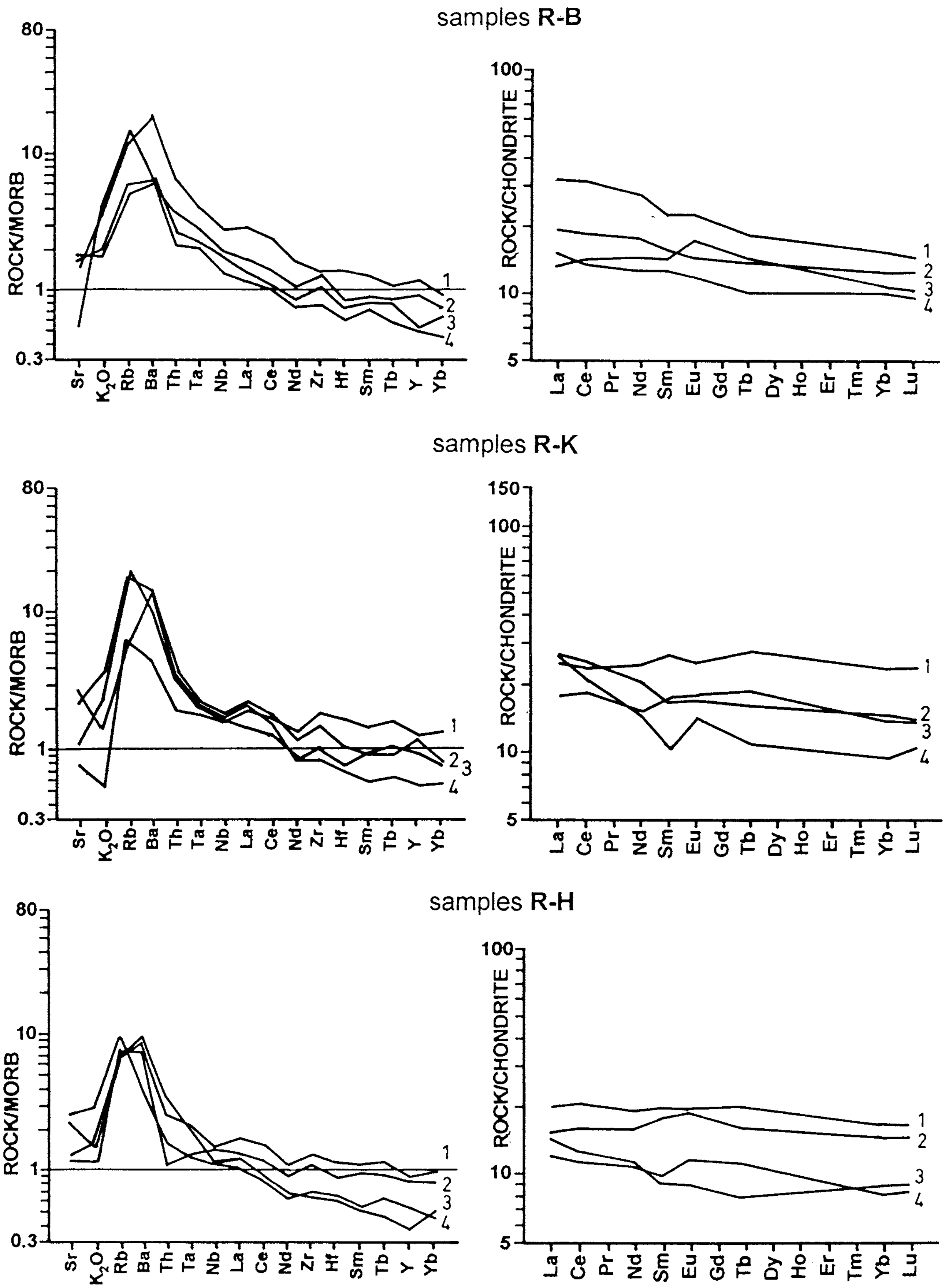

Fig. 5. Trace element characteristics of amphibolites from the Raabs Unit (for sample locations see appendix 2).

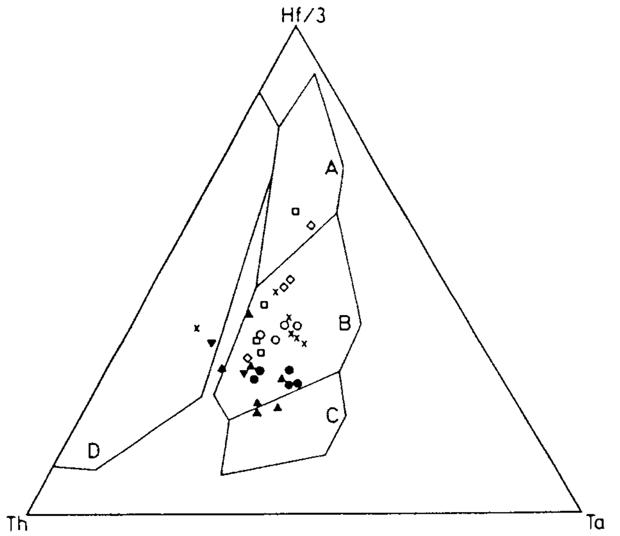

Fig. 6. Th-Ta-Hf/3 triangle of Wood (1979) for the tectonic discrimination of basaltic rocks with fields of N-MORB (A), E-MORB and tholeiitic WPB (B), alkalic WPB (C), and volcanic arc basalts (D); symbols as in Fig. 3.

Ba enrichment seems to be quite irregular and therefore no primary feature. Secondly, there are no additional chemical arguments for a subduction zone component: e.g., the K_2O and the Sr contents are mostly not enhanced relative to E-MORB values, and also in the Th/Hf/Ta triangle of Wood (1979) the data points are (with one exception) within the MORB-fields (Fig. 6). Also La/Nb and La/Ta ratios are generally not significantly enhanced relatively to E-MORB, if the values in Floyd et al. (1991) are used as reference. At best, few patterns like R-K 2 or R-K 4 (Fig. 5) may be classified as transitional between MORB and VAB because of slightly higher La/Nb ratios.

The phenomenon of secondary Rb and Ba enrichment in MORB amphibolites is often reported in the literature and may theoretically be arising from variable reasons (magma contamination, ocean floor alteration, metamorphism etc. - see e.g. Patočka 1991; Staudigel & Hart 1983; Neubauer et al. 1989). As mentioned earlier, there is also some evidence for secondary additions of Rb and Ba in the WPB type amphibolites of the Variegated Unit.

Gföhl Unit

Amphibolites from the Gföhl Unit are chemically quite heterogeneous (Fig. 7). Some (G-U 3, 6) correspond to the E-MORB amphibolites from the Raabs Unit. Other samples (G-U 2, 4, 5) display more enriched patterns that are transitional between MORB- and WPB-type with $(La/Lu)_n$ ratios around 3-4, and Nb/Zr ratios of ca. 0.07-0.09. Finally, we found one metabasalt (G-U 1), that shows an element distribution resembling a VAB pattern.

The Ba and Rb contents of all amphibolites from the Gföhl Unit again appear to be disturbed by secondary processes.

Literature data of amphibolites from the South-Eastern Bohemian Massif

Just like our data set, the literature data of Moldanubian amphibolites feature mainly a chemical variation from WPB to E-MORB with only some possible local contribution from a subduction modified mantle:

Matejovská (1987) reported chemical data of amphibolites from the Czech part of the Gföhl Unit and classified the rocks as transitional MORBs. Fritz (1994) presented some REE data of amphibolites from the Raabs Unit, that were collected near the town of Raabs (Fig. 1). These were interpreted as former E-MORB basalts and as part of an ophiolite sequence.

Montag & Höck (1993) published chemical data of amphibolites from the Rehberg area (Fig. 1). Particularly in more felsic samples (SiO_2 57-68 wt. %), they found relatively high Th/Ta ratios between 3 and 10. On the basis of these data, they concluded that the Rehberg amphibolites formed in a subduction setting. The question is, whether the VAB-affinities of at least some of these rocks, that depart seriously from "true" basaltic melt compositions, cannot be explained in terms of crustal contamination as well (tuffites?). Nevertheless, it is interesting to note that two amphibolites just from the area north

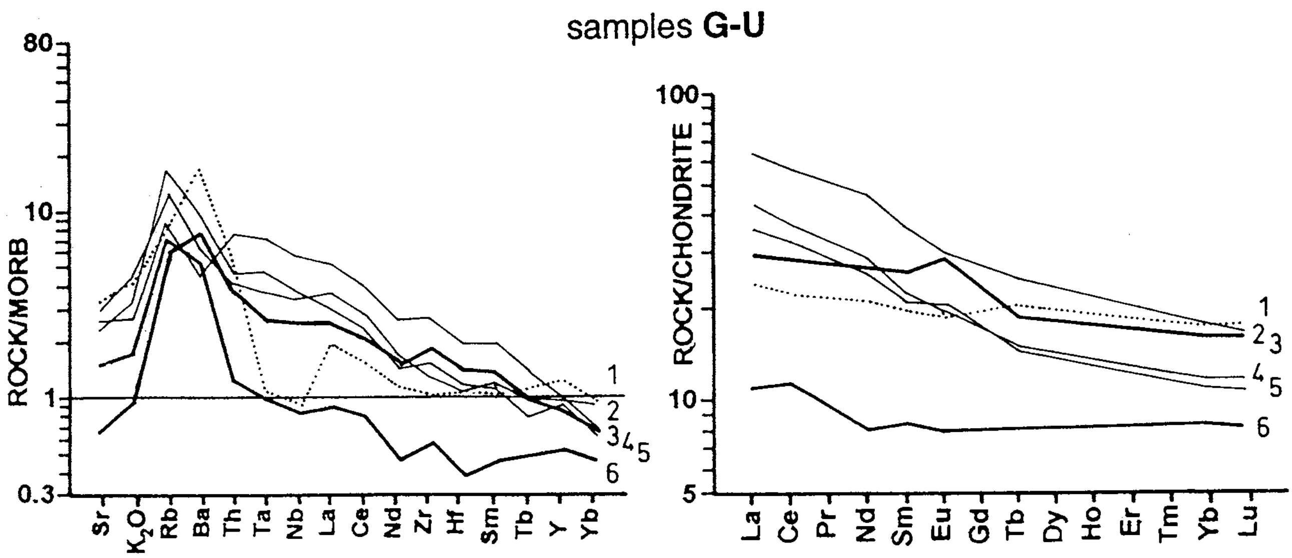

Fig. 7. Trace element characteristics of amphibolites from the Gföhl Unit (for sample locations see appendix 2).

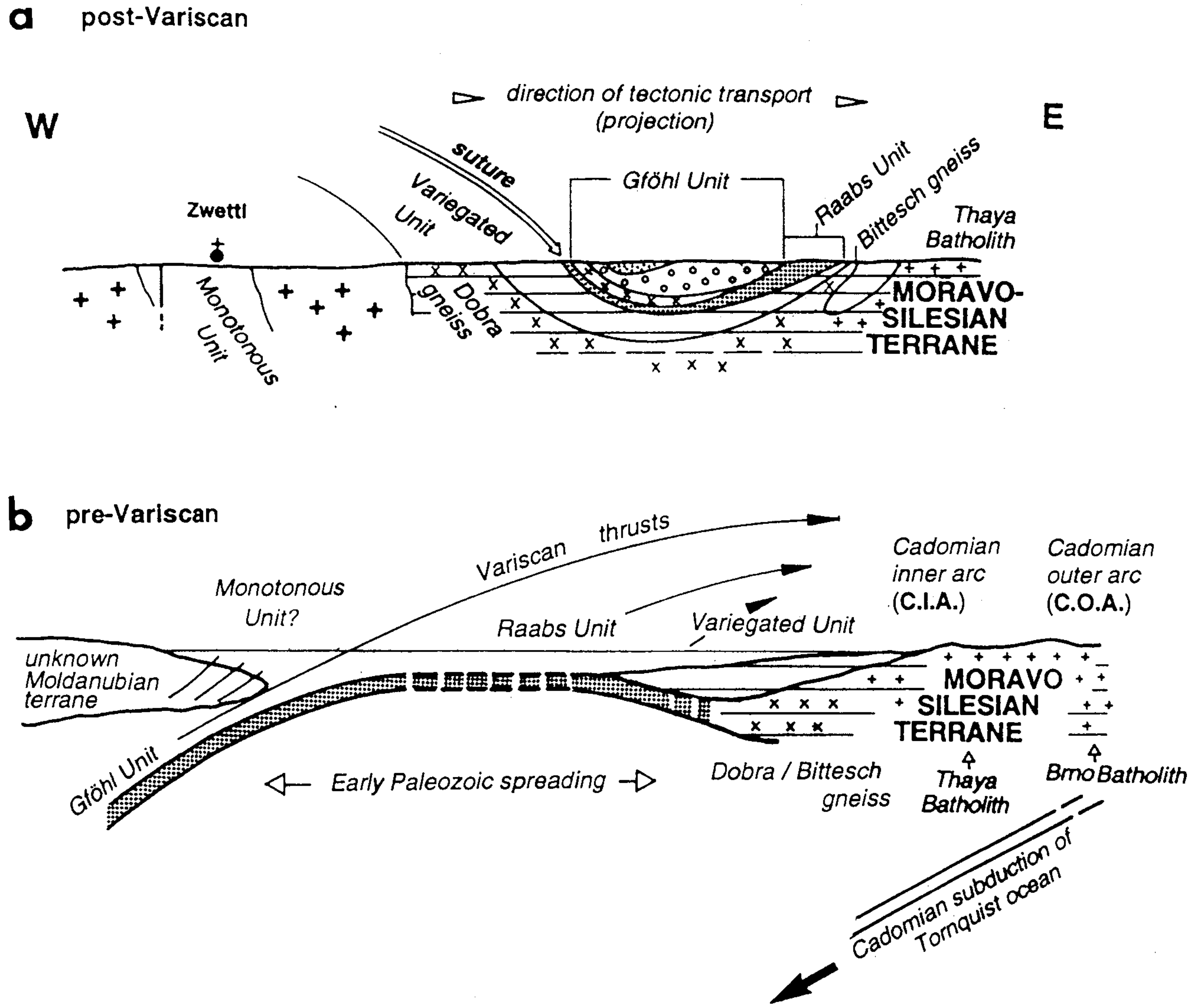

Fig. 8. Tentative model for the tectonic evolution of the South-Eastern Bohemian Massif (rock legend and profile in 8a as in Fig. 1).

of Krems approach a transitional VAB/MORB characteristics also in our sample set. From the Weitental (Variegated Unit) and the Dunkelsteiner Wald (Gföhl Unit) Montag & Höck (1993) reported amphibolite occurrences with WPB-type characteristics.

Hödl (1985) presented major elements and some trace element data from several amphibolite occurrences in the Raabs Unit. He came to the conclusion that the rocks are resembling MORB rather than VAB or WPB.

Patočka (1991) investigated amphibolites from the Český Krumlov area. This area possibly corresponds to the Austrian Gföhl Unit. Geochemical discriminations of these rocks show characteristics ranging from MORB to WPB.

Discussion and tentative tectonic model

The Raabs terrane – a Variscan oceanic suture

The widespread presence of amphibolites with MORB-like chemistry supports the assumption of Matte et al. (1990) that the Raabs Unit is a part of a former oceanic terrane and now a suture zone within the South-Eastern Bohemian Massif, separating a lower Moravo-Silesian block from a higher Gföhl Unit.

The likelihood that the Gföhl, the Raabs and the Variegated Unit (as a part of the Moravo-Silesian terrane) were brought into juxtaposition by (north)-eastward directed Variscan crustal stacking (Fritz & Neubauer 1993), implies an Early Paleozoic age for the Raabs ocean and a paleogeographic situation as illustrated in Fig. 8. Respective geochronological evidence has been supplied during this study by the work Finger & von Quadt (1995), where a Silurian age for a plagiogranite-gneiss from the Raabs Unit was obtained.

Judging from the geometry of the Cadomian paleo-subduction zone in the Moravo-Silesian terrane and the maturing of this arc type crust westwards (cf. page 138), the Raabs sea opened through a process of continental back-arc rifting (Fig. 8). This means that the Raabs sea was probably spreading above a mantle domain, that had been modified by subduction processes. Thus, the local presence of amphibolites with chemical affinities to volcanic arc basalts may well be attributed to a residual arc-type mantle source. The question is, if the high Rb and Ba contents of the Raabs amphibolites may as well be attributed, to a certain degree, to such a remnant subduction modified mantle. However, as mentioned earlier, we found no sound chemical arguments that a subduction zone was still active below the spreading axis of the Raabs sea in the Paleozoic.

Calcareous and graphitic metasediments that are sometimes associated with the amphibolites, suggest that the Raabs sea was not very wide, but rather an enlarged continental rift that reached only a nascent stage of oceanization. The scarcity of N-MORBs points in the same direction. The situation in the South-Eastern Bohemian Massif thus seems to support the common assumption that the intra-Variscan oceans were all relatively small rift-zones. However, as Pin (1990) argued, the few oceanic remnants that escaped subduction are not necessarily representative for the oceanic crust of that time. It might be that the most typical ocean floor of the early Variscan oceans was consumed by subduction.

The scarcity of OIB-like metabasalts in the Raabs Unit, on the other hand, makes it unlikely that an enriched astenospheric mantle plume was involved in the rifting process. Thus, the Raabs rift was probably generated passively, i.e. by lithospheric stretching (back-arc extension) and not actively by a mantle plume.

The Variegated Unit - a passive rift margin of the Moravo-Silesian terrane

Basement: It is a reasonable assumption that the orthogneisses of the Variegated Unit may constitute the intra-Moldanubian continuation of the Moravo-Silesian granitoid basement as shown in Fig. 8a. Correlation of the Dobra Gneiss and the Moravian Bittesch Gneiss seems very plausible, in view of the corresponding macroscopic appearance (Frasl 1977) and very similar petrographic and chemical data of these two rocks: Both display, for example, a distinct SiO_2 rich, high-Na_2O calc-alkaline geochemistry with remarkably low Rb/Sr ratios and low HFS element contents. Furthermore, the morphology of the zircons is strikingly similar in both gneisses (Finger & Sturm 1994). Although the actual formation ages are still not absolutely clear (Cadomian or older), isotopic data have shown that both orthogneiss bodies contain very old crustal elements: Gebauer & Friedl (1994) found 1.37 Ga old zircons in the Dobra Gneiss, and van Breemen et al. (1982) reported a discordant Pb/Pb age of ca. 900 Ma for a zircon fraction of the Bittesch Gneiss. Both orthogneisses display also very high Nd model ages (T_{Dm} 2.1 and 2.5 Ga respectively), that contrast to the generally lower Nd model ages of the surrounding Variscan crust (e.g. Gföhl Unit, Monotonous Unit and Southern Bohemian Batholith), which lie around 1.5 Ga (Liew & Hofmann 1988; Kröner et al. 1988; Liew et al. 1989; Valbracht et al. 1994).

This suggests that the Dobra Gneiss of the Variegated Unit and the Bittesch Gneiss represent repeatedly recycled Archean continental crust, located inboard of a Cadomian (Panafrican) Moravo-Silesian arc, which then becomes increasingly juvenile towards east (Finger et al. 1995).

The metabasaltic dike swarms in the Dobra Gneiss, Spitz Gneiss and Bittesch Gneiss indicate rifting of the inner continental part of the Moravo-Silesian arc and display, consequently, features of melts derived from a heterogenous mantle reservoir transitional between enriched subcontinental and remnant subduction modified mantle.

Unfortunately, as yet there is little reliable geochronological data from the Variegated Unit. However, back arc rifting of Moravo-Silesian basement could have set in already in the Eocambrian. Late-stage Cadomian granites in the Moravian Unit with chemical features intermediate between I-type and A-type (Finger et al. 1995), might indicate a transition from subduction to a rifting environment as well. This does not necessarily mean that subduction at the northern Gondwana margin had completely ceased at that time. Perhaps the locus of subduction migrated outwards and did not further affect the mantle area below the Moravian and the Variegated Unit (i.e. below the former inner arc). The presence of Early Ordovician granitoid rocks with volcanic arc affinities in NE Czech Republic (Kröner et al. 1994) might argue for the latter interpretation.

The age at which back-arc rifting in the Moravo-Silesian overstepped the continental stage and gave rise to the birth of the Raabs ocean, either in the Ordovician or Cambrian or later in the Silurian, remains unconstrained. More U/Pb dating is required to clarify this.

Sedimentary cover: Figure 8 illustrates that, during the Early Paleozoic, the Variegated Unit was most likely positioned at the rifted Moravo-Silesian margin of the Raabs ocean. Fuchs (1976) has already drawn attention to the marginal sea type of the sedimentary record of the Variegated Unit, that fits very well into our rifting model, as well as the within-plate character of the synsedimentary metabasalts. As mentioned earlier, one of these amphibolites was dated with a protolith age of 358±6 Ma (Friedl et al. 1993). This suggests, that the Variegated Unit formed part of a passive continental margin up to the Devonian/Carboniferous boundary and that the Raabs ocean probably existed up to the Variscan collision. However, it remains unconstrained, how far the stratigraphy of the Austrian Variegated Unit reaches back to the Ordovician or Cambrian.

Frank et al. (1990) reported Sr initial ratios of marbles from the Variegated Unit in the range of 0.705, that are not typical for Paleozoic seawater. This means that remnants of pre-Paleozoic sediments may be preserved in the Variegated Unit, as they do in the Moravian Unit (Frasl 1991).

The Gföhl Unit – a tectonic melange rather than a true terrane

It has been repeatedly speculated that the granulites of the South-Eastern Bohemian Massif (and possibly also the Gföhl Gneiss) received their high-pressure metamorphism in a pre-collisional, early Variscan subduction setting of Late Devonian age, prior to medium-pressure collisional metamorphism during the Visean (Matte 1986; Carswell 1991; Carswell & O'Brien 1993; Friedl et al. 1993). Thus an important aim of this study was to determine whether the amphibolites of the Gföhl Unit would yield definite imprints of a volcanic arc setting. However, this is not the case. As shown in Fig. 7, the rocks are mostly intermediate between the E-MORB amphibolites of the Raabs Unit and the WPB-type amphibolites of the Variegated Unit in composition. Only one sample displays affinities to VAB.

As mentioned earlier, many amphibolites of the Gföhl Unit may well have been basalts from the realm of the Raabs terrane. In view of their high tectonic position within the Moldanubian nappe pile and considering the regional top-to-northeast tectonics (Fritz & Neubauer 1993), it may in fact be speculated that most represent early subducted remnants of older oceanic crust from the Raabs ocean formed in a very nascent (Cambrian-Ordovician?) stage of seafloor spreading. Thus, their chemistry may well have been strongly influenced by a relictic, enriched (and locally subduction-modified ?)

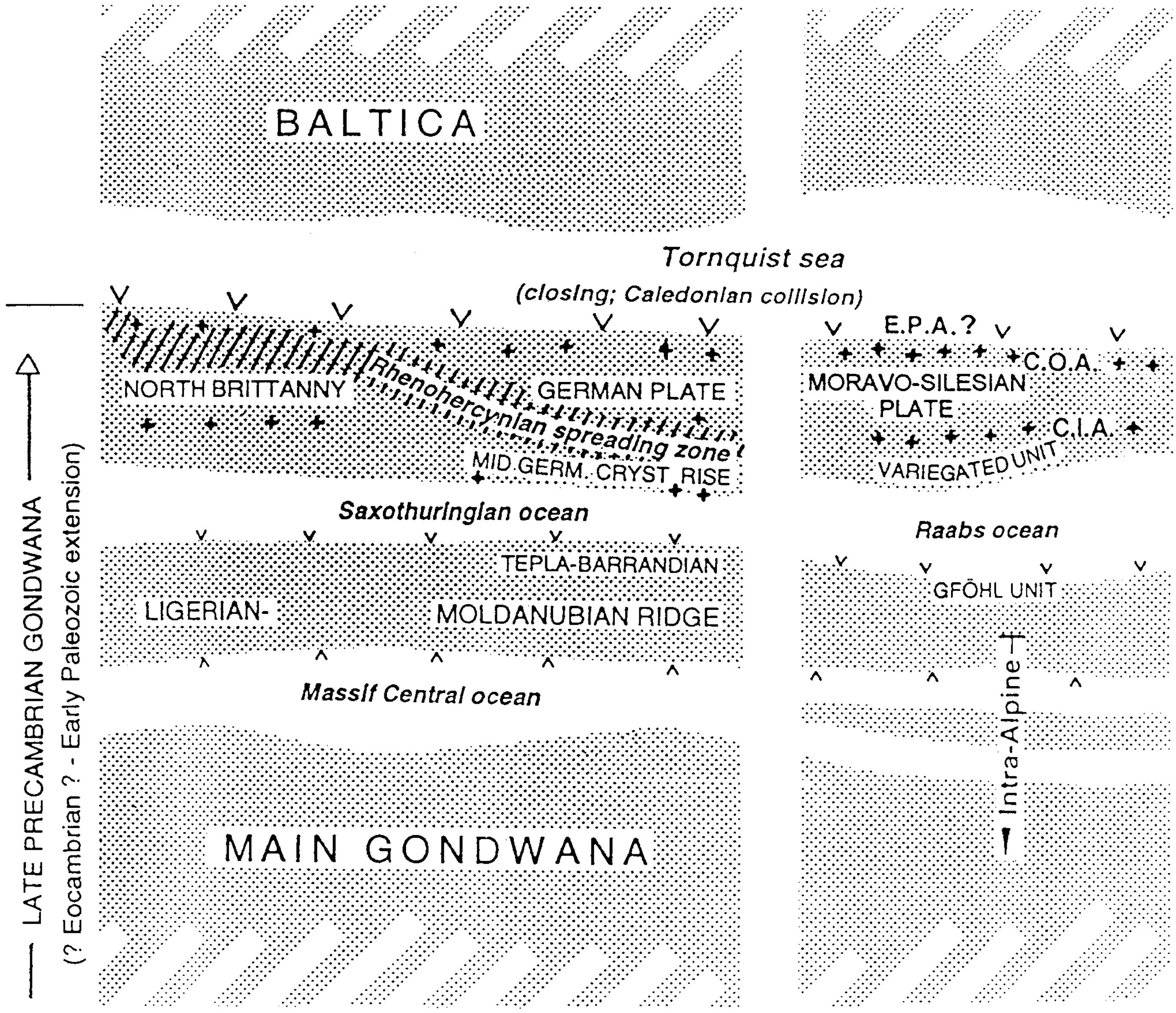

Fig. 9. Tentative sketch illustrating a possible paleogeographic correlation between the geological units of the Eastern Bohemian Massif (right side) and the mid- and western European Variscides. C.O.A.: Cadomian outer arc; C.I.A.: Cadomian inner arc (see also Fig. 8). An Early Paleozoic arc (E. P. A.) could have existed in the north of the Moravo-Silesian terrane.

subcontinental mantle source. However, since our data set is too limited, and any reliable age information is missing, the possibility cannot be ruled out, that early Variscan (i.e. Late Devonian) subduction basalts are as well present in the Gföhl Unit (sample G-G 1?).

Judging from its poorly defined boundaries and its heterogeneous rock inventory, the Austrian Gföhl Unit probably does not represent a terrane in the true sense. The "Gföhl Nappe" (Thiele 1984), is more likely to be a tectonic melange of rocks with variable origins and metamorphic histories, welded together at a destructive plate margin as shown in Fig. 8, and finally juxtaposed as a result of collision during the Variscan. Former hangingwall parts of the Gföhl Nappe, that would allow identification of the original overlying "Moldanubian" active continental margin terrane (see Fig. 8), are now mostly, if not completely, eroded. Some remnants may be preserved in the Loosdorf Unit (Thiele 1984). However, this unit may as well be an overturned portion of the Variegated Unit or the Raabs Unit, as suggested by Fritz & Neubauer (1993).

The Monotonous Unit

Due to uncertain age and tectonic relations with other units, it is quite problematic to include the Monotonous Unit in the above considerations. Unlike previous models, this model does not combine the Monotonous Unit with the Variegated Unit. A better interpretation of the Monotonous Unit might be that it represents Devonian to Early Carboniferous trench and accretionary wedge sediments, that were deposited at the active "Moldanubian" margin (see Fig. 8).

Intra-Variscan correlations

Remnants of Early Paleozoic oceanic crust have been recognized in various parts of the mid-European Variscides (see compilation and discussion in Pin 1990). Data suggest that there were probably three main, roughly parallel, oceanic troughs in the Variscan realm, i.e. the Rhenohercynian and the Saxothu-

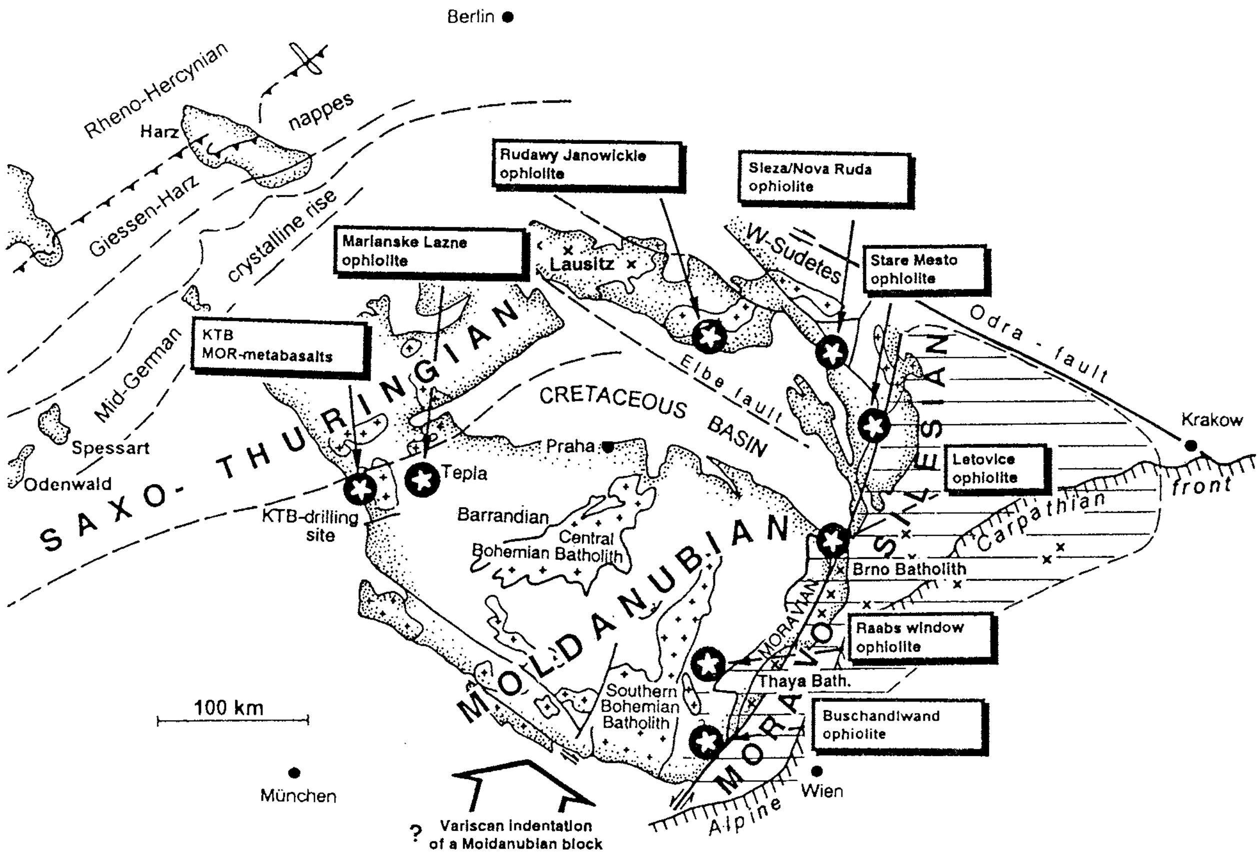

Fig. 10. Occurrences of ophiolites straddling the border zones between Saxothuringian and Moldanubian (s.l.) and Moravo-Silesian and Moldanubian, respectively. Data from Bowes & Aftalion (1991), Mísař et al. (1984), Fritz (1994), von Quadt (1994), Oliver et al. (1993). Geological units as in Fig. 1a.

ringian oceans in the north and the Massif Central ocean south of the Moldanubian Unit (Matte 1986; Franke 1989). The Saxothuringian and the Massif Central ocean opened during the very Early Paleozoic inboard of the northern margin of the Gondwana continent, and closed again through Variscan subduction below a Moldanubian microcontinent (see sketch in Fig. 9). The Rhenohercynian ocean probably opened later in the Devonian and closed by southward subduction during the Variscan collision.

Matte et al. (1990) and Neugebauer (1988) have tried to correlate the Moldanubian units of the South-Eastern Bohemian Massif with the southern Variscan units of France and suggested that the Moravo-Silesian terrane was the largely stable southern foreland of the Variscan fold belt (i.e. an interior part of Gondwana in the Late Precambrian). However, on the basis of chemical data, Finger et al. (1995) have argued that the Cadomian Moravo-Silesian granitoids formed in a magmatic arc setting close to the Late Precambrian northern Gondwana margin, where the Tornquist sea was being subducted. Furthermore, remnants of Early Paleozoic oceanic crust have been recognized in the basement thrust sheets of the Alps and Carpathians (Frisch & Neubauer 1989), that can be favourably correlated with the southern Variscan fold belt flank and the Massif Central ocean of Matte (1986).

Bearing this in mind, we suggest that the Moravo-Silesian terrane was part of the external northern flank of the Variscan fold belt, just like the Cadomian basement of eastern England, northern Brittanny, and the German plate (Fig. 9). All these continental blocks consist of Panafrican arc-type crust and probably rifted off in Cambrian-Ordovician times from the Gondwana megacontinent (Franke 1989). They may well have formed a coherent ridge of continental fragments (Avalonia?), that moved in the forefield of main Gondwana towards Baltica, opening a northern Variscan ocean behind, but closing at the same time the Tornquist sea. The Raabs sea, as it opened in the back-arc realm of the Moravo-Silesian plate, may have been an eastern part of this elongated, but probably narrow ocean (Fig. 9). Considering the regional distribution of ophiolites (Fig. 10), we believe that this northern Variscan suture runs today in a sharp curvature across the Bohemian Massif, i.e. from the western Czech Republic (Mariánské Lázně Ophiolite) eastward to the Sudetes (Rudawy Janowickie and Sleza/Nova Ruda Ophiolite) and from there along the Moravo-Silesian plate margin towards the south (Staré Mesto and Letovice Ophiolite, Raabs Unit).

The sharp southward bending of the suture in the Sudetes may be related to a forceful indentation of a "Moldanubian terrane" from the south during the Variscan collision (Fig. 10).

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Appendix 1: Representative chemical analyses.

	VARIEGATED UNIT					RAABS UNIT		
	VS-2	VS-5	VD-3	VD-6		RB-2	RK-3	RH-2
SiO_2	47.50	48.90	48.60	49.60		48.50	44.40	48.50
TiO_2	3.09	1.48	1.76	1.00		1.58	1.82	1.70
Al_2O_3	13.00	15.20	16.70	15.00		14.90	13.30	14.80
Fe_2O_3	15.90	12.50	11.90	11.90		11.80	14.20	12.40
MnO	0.24	0.18	0.18	0.17		0.18	0.23	0.21
MgO	4.95	6.39	4.99	7.12		7.31	7.44	7.50
CaO	9.84	10.40	11.80	10.30		10.30	12.10	10.70
Na_2O	2.56	2.79	2.22	2.54		2.78	1.81	2.98
K_2O	0.80	0.67	0.66	0.44		0.39	0.48	0.25
P_2O_5	0.43	0.22	0.22	0.20		0.17	0.13	0.16
total	98.31	98.73	99.03	98.27		97.91	95.91	99.20
LOI	0.31	1.00	0.77	0.77		0.54	3.93	0.85
Cr	46	230	45	370		200	220	280
Ni	44	87	51	102		79	91	85
Co	45	46	42	40		37	50	48
Sc	36	24	33	29		39	46	45
V	385	231	269	246		308	370	273
Cu	68	60	81	40		23	66	5
Zn	148	128	115	113		110	109	129
Rb	23	27	15	13		6	24	9
Ba	222	243	114	155		79	129	104
Sr	300	346	276	254		180	113	132
Ta	1.90	0.80	1.00	0.80		0.50	0.40	0.25
Nb	26	12	17	13		6	6	5
Hf	5.00	3.05	3.80	2.40		2.40	2.20	2.60
Zr	238	111	166	121		129	104	111
Y	39	23	16	16		32	33	30
Th	2.10	1.40	1.70	1.00		0.70	0.70	0.21
U	1.10	b.d.l.	1.10	b.d.l.		0.90	3.20	b.d.l.
La	23.6	12.4	12.6	10.3		6.2	5.55	5.1
Ce	53.0	26.0	30.0	24.0		16.0	15.3	14.0
Nd	28.0	15.0	17.0	13.0		11.0	9.0	10.0
Sm	6.4	3.7	4.0	3.3		3.2	3.4	3.6
Eu	2.6	0.9	1.4	1.3		1.1	1.3	1.5
Tb	1.1	0.6	0.6	0.5		0.7	0.9	0.8
Yb	3.2	1.5	2.2	1.7		2.8	3.0	3.2
Lu	0.46	0.21	0.35	0.24		0.43	0.46	0.49

(major elements: wt. %; trace elements and rare earth elements: ppm)

Appendix 2: Sample locations.

VARIEGATED UNIT:

Samples V-S (syngenetic amphibolites)
1: Drosendorf; **2, 3**: Vießling, 4 km WSW Spitz Donau; **4**: Weiten, 8.5 km NW Melk/ Donau; **5**: Ötzbach, 8 km NW Spitz/Donau

Samples V-D (epigenetic amphibolites)
1: Spitz/Donau; **2**: Spitz Valley, 2 km W Spitz/ Donau; **3**: Gut am Steg, 1.5 km SW Spitz/ Donau; **4**: Dobra Valley 15 km E Zwettl; **5**: Allensteig, 12 km NE Zwettl; **6**: Scheideldorf, 13 km NNE Zwettl.

MORAVIAN UNIT:

Samples M-U (Moravian Unit)
1: Messern, Taffa Valley, 11 km NW Horn; **MAT**: Thaya Valley, 7 km NE Drosendorf (Matejovská 1987), **2**: Messern, Taffa Valley, 11.5 km NW Horn.

RAABS UNIT:

Samples R-B (Buschandlwand Complex)
1: Seiber, 5 km NNE Spitz/Donau; **2**: Hartenstein, 9 km N Spitz/Donau; **3**: Seeb, 4 km SW Gföhl; **4**: Zintring, 7 km NNE Melk/Donau.

Samples R-K (Kamp and Rehberg Complex)
1: Rehberg, 1km N Krems; **2**: Kamp Valley between Schönberg and Kamegg; **3-4**: Senftenberg, 4 km NW Krems/Donau.

Samples R-H (Basis of Gföhl Gneiss)
1, 3: Leiben, 4 km NW Melk/Donau; **2**: Wegscheid, 10 km N Gföhl; **4**: Untermeisling, 4 km S Gföhl.

GFÖHL UNIT:

Samples G-U (Gföhl Unit)
1-6: Kamp Valley, between Krumau and Steinegg, ca. 10 km N Gföhl.

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