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The Raabs Series: A Probable Variscan Suture in the SE Bohemian Massif

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Die Raabser Serie: Eine variszische Sutur in der südöstlichen Böhmischen Masse?

Zusammenfassung

Eine tektonostratigraphische Gliederung der südöstlichen Böhmischen Masse umfaßt zwei kontinentale Blöcke („Terranes“), die von einer ozeanischen Sutur getrennt wurden. Das Proterozoische Terrane besteht aus dem Moravo-Silesischen Parautochthon, den Moravischen Decken, der Moldanubischen Bunten Serie und der Moldanubischen Monotonen Serie. Das Paläozoische Terrane umfaßt den Moldanubischen Gföhler Gneis und die Granulit Klippen. Beide kontinentalen Blöcke wurden durch eine ozeanische Sutur getrennt, die durch den Letovice Ophiolith (CR) und die Raabser Serie (Österreich) repräsentiert ist. Diese Sutur stellt eine Plattengrenze dar, deren heutige Position innerhalb des Moldanubischen Deckenstapels liegt.

Die Raabser Serie wird als eine tektonische Melange, bestehend aus einem unvollständigen Ophiolith und einer kalkalkalinen Suite gedeutet. Der Ophiolithkomplex besteht aus einem metamorphen Peridotit, Metagabbros, basaltischen Laven mit N- bis E-Typ-MORB-Charakter und einer Sedimenthülle, die kalkalkaline Suite aus metamorphen Andesiten.

Die tektonische Entwicklung der südöstlichen Böhmischen Masse beinhaltet
1) Paläozoische Krustenextension und Bildung eine ophiolitischen Suite,
2) Paläozoische Konvergenz (Subduktion) mit der Bildung kalkalkaliner Magmen,
3) Variszische Kontinent-Kontinent-Kollision unter Einbeziehung des ozeanischen Krustenmaterials in den Variszischen Deckenstapel.

Die generelle kinematische Entwicklung während der Deckenstapelung läßt vermuten, daß sich diese ozeanische Sutur südlich vom heutigen Südrand der Böhmischen Masse entwickelt hatte.

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Abstract

The tectonostratigraphy within the southeastern Bohemian Massif suggests the existence of two continental blocks. These include

1) a late Proterozoic terrane composed of major portions of Moravo-Silesian foreland units, the Moravian Nappe assembly and the Moldanubian Variegated and Monotonous Series, and
2) a Paleozoic terrane, composed of the Gföhl gneiss and Granulite nappes.

These contrasting continental blocks are separated by a suture zone including the Raabs Series in Austria and the Letovice Complex north of Brno. New geochemical data suggest that the Raabs Series represents a tectonic melange which includes serpentinites and ortho-amphibolites in different tectonic levels. The lower structural level magmatic sequence is interpreted to represent a dismembered ophiolite suite including E-type MORBs which probably formed within a back-arc setting. Upper structural level amphibolites are interpreted as metamorphosed andesites with calcalkaline geochemical signature. A sequence of magmatic events within the Raabs Series includes

1) Paleozoic extension tectonics and formation of an ophiolite suite, subsequently followed by
2) Paleozoic plate convergence and formation of andesites.

Both sequences display opening and closure of an oceanic domain. These sequences have been metamorphosed and dismembered during late Variscan collisional tectonics. The site of this oceanic domain had been located southwest to the recent southern margin of the Bohemian Massif.

1. Introduction

Oceanic fragments and relics of the upper mantle origin are of major importance for the interpretation of geodynamic settings in collisional orogenic belts, because these rocks are usually interpreted as sutures separating collided plates. Unfortunately there are many processes in orogenic belts which modify primary features and prevent the recognition of these suture zones. Primary mineral assemblages are modified by metamorphism and the original stratigraphy of oceanic fragments is dismembered by tectonics. Nevertheless, combined petrological, structural and geochemical investigations, especially the variation of immobile elements, can help to characterize the geodynamic setting of the protoliths, even in highly metamorphic terranes.

The Variscan belt of Central Europe provides a prominent example for the sources of errors which arise from veiled suture zones. The apparent lack of ophiolitic sequences in the German Variscides led to the interpretation of an intracontinental orogeny associated with an A-type subduction (MURATA & WEBER, 1983; WEBER & BEHR, 1983). This model has been rejected as soon as remnants of oceanic crust have been reported from this orogen along the northeastern margin of the Bohemian Massif (e.g., FRANKE, 1989; OKRUSCH et al., 1990).

In this paper the geodynamic significance of some units along the southeastern margin of the Bohemian Massif is discussed and a possible candidate for a Variscan suture zone, the Raabs Series, is introduced. Various types of amphibolites and serpentinites have been geochemically analysed to constrain their geodynamic significance. Primary associations of the rock assemblages are obscured by intense deformation and primary petrological assemblages have been modified by metamorphism which reached amphibolite facies conditions and partly even partial melting due to migmatisation. Therefore primary geochemical compositions of the rocks may have changed due to element mobility during metamorphism. To avoid misinterpretations of the chemical data special care has been taken in choosing the samples and only relatively immobile elements have been considered for the interpretation.

2. Geological Overview

The evolution of the Variscan orogenic belt in Central Europe is related to amalgamation of various continental blocks, or microplates with Laurussia and Africa during Devonian and Late Carboniferous times (e.g., MATTE, 1986, 1991; MATTE et al., 1990; FRANKE, 1989). The bivergency of this orogen has been classically explained by bipolar collision. According to this concept, the Moldanubian zone in the Bohemian Massif has been interpreted as root zone of high-grade metamorphic nappes which have been thrusted outward, onto their northwestern foreland (the Saxothuringian zone) and towards their southeastern foreland (the Moravo-Silesian zone) respectively (e.g. TOLLMANN, 1982; MATTE et al., 1985). Consequently, the possible sutures should be located along these boundaries. Indeed, remnants of ophiolitic sequences have been reported by OKRUSCH et al. (1990) from the Moldanubian/Saxothuringian boundary, and another ophiolitic sequence, the Letovice Formation (MISAR et al., 1984) marks the Moldanubian/Moravo-Silesian boundary in the Czech Republic. However, a closer look to the geodynamic significance of the Moldanubian and Moravo-Silesian units in the southeastern Bohemian Massif suggest deviating tectonostratigraphic division and hence different possible suture zones.

FRANKE (1989) and MATTE et al. (1990) have argued that three distinct crustal pieces (terranes) accreted during the Variscan collision to form the present crust in the southeastern Bohemian Massif. These include

1) the Moravian parautochthon,
2) a lower Drosendorf terrane composed of Monotonous and Variegated Series and
3) a Gföhl terrane with Gföhl gneiss and granulites on the structural top.

However, FRITZ & NEUBAUER (1993) proposed a different model for the Variscan collisional orogen based on geochronological arguments, petrological considerations and structural investigations. Two distinct crustal pieces are distinguished:

1) A late Proterozoic terrane including the Moravian Nappe Complex and the Moldanubian Variegated and Monotonous Series; and
2) an Early Paleozoic terrane including Gföhl gneiss and granulites (arguments for this subdivision are listed below).

Both, Moravian and Moldanubian units are a structural cover of the Moravo-Silesian foreland (FRITZ et al., in press) assembled during the late Carboniferous. Following this concept, oceanic fragments should be located between Moldanubian Granulite and Gföhl terrane and Moldanubian Variegated Series. Indeed, the Raabs Series and the Letovice Formation fulfill these requirements.

3. Tectonostratigraphy

The tectonostratigraphy of the nappe pile in the southeastern Bohemian Massif with subdivision into the Moldanubian unit in the hangingwall and the Moravian unit in the footwall goes back to SUESS (1908, 1912). Both, Moldanubian and Moravo-Silesian units represent nappe-complexes with various tectonostratigraphic units.

3.1. The Late Proterozoic Terrane

Rocks which include late Proterozoic protolith ages are distributed among the Moravo-Silesian Nappe Complex (including Moravo-Silesian foreland and Moravian nappes) and the Moldanubian Variegated and probably the Monotonous units.

The Moravian Nappe Complex comprises from bottom to top:

1) The late Proterozoic composite batholiths (Thaya, Svratka and Brno batholiths) (DUDEK & MELKOVA, 1975; SCHARBERT & BATIC, 1980; VAN BREMEN et al., 1982; FRITZ et al., in press) which intruded late Proterozoic metasediments (Therasburg Formation) (HÖCK et al., 1990; LIBOWIZKY, 1990).
2) The Moravian nappes in the hangingwall include highly deformed gneisses and metasedimentary sequences, both of probable Late Proterozoic age (SCHARBERT, 1977; MORAUF & JÄGER, 1982; VAN BREMEN et al., 1982; FRANK et al., 1990).

The Moldanubian Nappe Complex, in the following described from structural bottom to top, contains several major structural units with distinct metamorphic P-T paths and different protolith ages. Rocks with late Proterozoic protolith ages include:

1) The “Monotone Serie” (Monotonous Series) consists largely of migmatitic paragneisses (FUCHS & MATURA, 1976; LINNER, 1993), calcsilicates and rare eclogites (EXNER, 1970). In general a Late Proterozoic age has been suggested for this series (FRANKE, 1989, for a review of stratigraphic data).
2) The “Bunte Serie” (Variegated Series) is composed of micaschists, marbles, quartzites, amphibolites, the acidic Dobra gneiss at the structural base, and of a sheet-like Rehberg amphibolite at the structural top of the sequence. A Precambrian age has recently been reported for the marbles in the Variegated Series based on very low $^{87}Sr/^{86}Sr$ ratios which are only compatible with Precambrian sea water ratios (FRANK et al., 1990). U/Pb zircon ages of about 600 Ma are interpreted to date the magmatic source of the Rehberg amphibolite (GEBAUER & GRÜNENFELDER, 1982).

3.2. The Paleozoic Terrane

Series with predominantly Paleozoic protolith ages are regarded to represent a coherent Gföhl terrane (FRANKE, 1989; MATTE et al., 1990; FRITZ & NEUBAUER, 1993). This structural unit includes:

1) The Gföhl gneiss which consists predominantly of orthogneisses of probable Ordovician protolith age (SCHARBERT, 1977; FRANK et al., 1990; HAMMER, 1992).
2) The structural uppermost parts of the Moldanubian Nappe Complex are composed of granulite klippen which include subordinate ultramafic rocks.

The latter were interpreted to represent tectonically emplaced mantle slices (CARSWELL, 1991). Sm/Nd ages from these garnet-bearing peridotites (CARSWELL & JAMTVEIT, 1990) suggest 370–430 Ma age for the maximum metamorphic pressure conditions.

Based on these data and the structural position of the sequences, the Gföhl and granulite nappes are regarded to compose the upper plate, whereas Moravian units and the Moldanubian Drosendorf unit (FRANKE, 1989: Monotonous and Variegated Series) are interpreted to represent lower plate rocks during late Variscan collision (FRITZ, 1991, 1994). Thus candidates for oceanic sutures should be located between the Proterozoic series including the Moravian unit and the Moldanubian Drosendorf unit, and the Paleozoic Gföhl Gneiss and granulite nappe, rather than between Moravian and Moldanubian units. Indeed, the tectonic position of the Letovice Formation (MISAR et al., 1984) fits this model. North of Brno the ophiolites occur at the structural base of the Gföhl nappe. In this region the nappe edifice is modified by low-angle normal faults (FRITZ & NEUBAUER, 1993) which caused local juxtaposition of the Gföhl nappe with the Moravian unit. A possible candidate for a suture zone in Austria is the Raabs tectonic unit which is structurally imbricated with Moldanubian rocks (Text-Fig. 1) but occurs mostly between Gföhl and granulite nappes and Variegated Series.

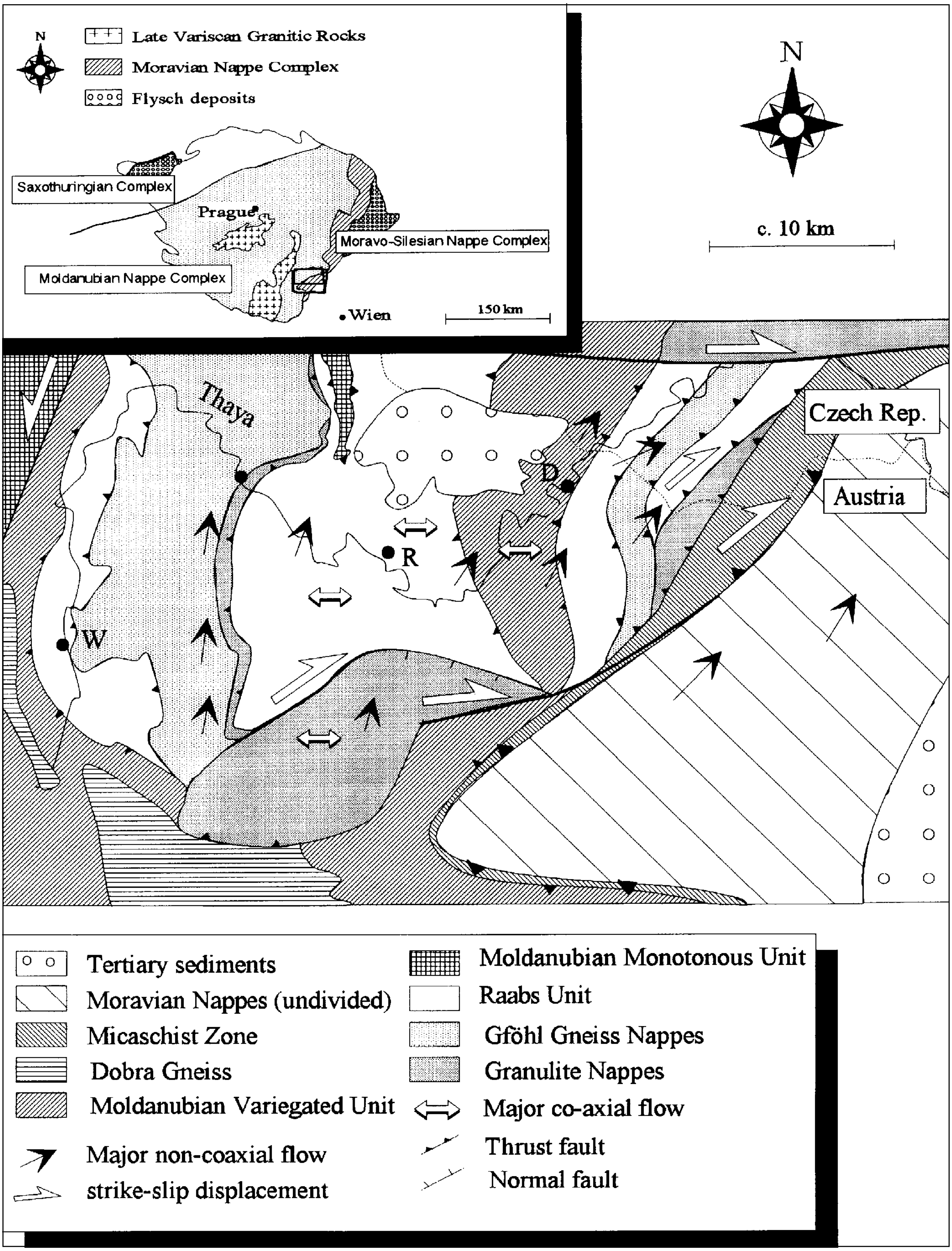
4. The Raabs Series

The Raabs Unit generally separates the Gföhl / granulite structural unit from the Drosendorf structural unit. Polyphase Variscan stacking, however, is responsible for the wide distribution of the Raabs Unit within the SE Bohemian Massif (Text-Fig. 1); and, on the other hand for internal imbrication and folding (FRITZ, submitted). The largest occurrence of Raabs Unit which provides best information about primary relations is, although also internally imbricated, close to the village Raabs (Text-Fig. 2). The following description mainly refers to this area.

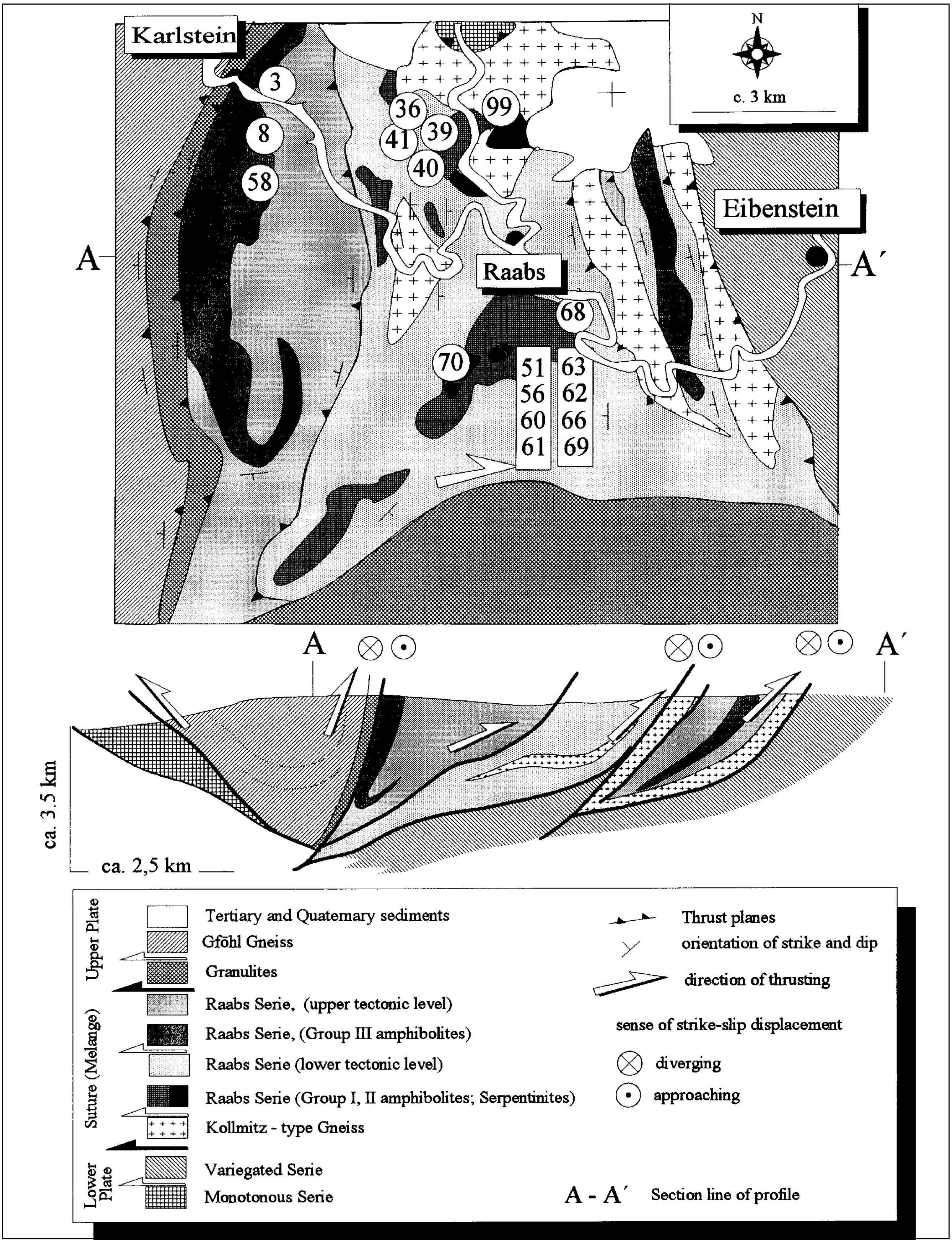
The Raabs Unit is defined by a metasedimentary sequence which is closely related to various types of amphibolites, serpentinites and orthogneisses. DAURER (1977) and THIELE (1977) described this unit as highly metamorphosed and migmatized sequence of sedimentary rocks, volcanics and intrusive rocks. Metasedimentary rocks include sillimanite and garnet bearing plagioclase gneisses, amphibole and biotite gneisses, and, to a small extent, calcsilicates, marbles and quarzites. The gneisses show frequently migmatitic banding and include occasionally schollen of coarse amphibolites within highly deformed gneisses.

Minimum regional metamorphic overprint is of amphibolite facies conditions (e.g. PRESSEL, 1993). Partly the rocks suffered partial melting due to migmatisation. Gneisses exhibit high-temperature migmatic banding with quartz-plagioclase layers as leucosome and garnet and biotite rich melanosome layers. Viscosity contrast between competent amphibolites and the incompetent acidic rocks arises in the formation of boudinage structures and amphibolite schollen within ductily deformed gneisses. Amphibolites suffered only minor melting, trondhjemitic melt formed occasionally along marginal portions of amphibole schollen and within boudin-necks.

The mineral textures of acidic rocks are completely transposed due to syntectonic recrystallisation of quartz and plagioclase. This high-temperature deformation is penetrative in gneisses. In addition, low-temperature localized shear zones developed in quartz-rich portions. In the presence of acidic rocks the amphibolites are



Text-Fig. 1.
Distribution of the Raabs Series within the southeastern Bohemian Massif (redrawn after Suess et al., 1925; Fuchs & Matura, 1976; Thiele, 1987).
West of the Moldanubian/Moravian boundary the primary tectonostratigraphy is dismembered by a late Variscan positive flower structure which developed between two major strike-slip faults.
W: Waidhofen a.d. Thaya; R: Raabs; D: Drosendorf. The study area is marked in the inset.



Text-Fig. 2.
Geological sketch-map of the Raabs Series at the village Raabs (redrawn after FUCHS & MATURA, 1976; THIELE, 1987).
Numbers mark the sample locations of amphibolites (3: R3, 8: R8...). Serpentinite samples have been derived from the serpentinite bodies north of Raabs.
The schematic cross section (A-A') includes east to northeast-directed thrusting in eastern portions and west-directed back-thrusting in western portions of the section. Thrust planes are modified and reactivated by strike-slip faults.

surprisingly well preserved. Due to the competence contrast between gneisses and amphibolites a major amount of deformation is accomodated within the quartzo-feldspatic rocks, whereas the competent amphibolites are more or less unaffected by penetrative deformation. Coarse grained, unfoliated amphibolites occur as boudins within the gneisses. In some larger scale this phenomenon is also observed, lenses of unfoliated mafic and ultramafic bodies occur within the Raabs Unit. The strain concentration within the quartzo-feldspatic domains offers a good chance to study primary composition of the mafic rocks which had been only marginally affected by penetrative deformation.

Retrogression of amphibolites and postmetamorphic alteration is very weak. Locally amphiboles have been transposed to chlorite which, in addition, crystallized within sealed extension veins. Plagioclase is partly transposed to white mica.

From field relations three types of amphibolites and a serpentinite body can be distinguished. Amphibolites differ in composition and occur in different levels within the Raabs unit. Based on field relations and restoration of imbricated and folded sections (Text-Fig. 2) a general sequence includes:

1) A basal group (group I) of amphibolites is closely connected with ultramafic rocks, now transformed to serpentinites (for sample locations see Text-Fig. 2). Medium to fine grained amphibolites (Samples R36, R39, R40, R41, R99) contain 54 % to 60 % brownish to green amphibole, 35 % to 45 % plagioclase, sphene and occasionally garnet. The shape preferred orientation of the amphiboles suggests solid state deformation. Two samples (R56, R68) are not in contact with serpentinites but show similar petrological features and occur in a similar structural level. Serpentinites (Samples R25, R38/1, R42, R43, R72, R73, R74, R86, R87, R88) are massive and very uniform in composition. The degree of serpentinisation is variable but magmatic mineral assemblages and textures are frequently preserved. Olivine and orthopyroxene up to cm in size form an equigranular texture. Colourless hornblende and Cr-spinel are common. Minor deformational features are observed in weakly serpentinized rocks (harzburgites). The coarse-grained weakly deformed harzburgites probably correspond to the “ridge coarse texture“ of NICOLAS et al. (1980).
2) The second amphibolite type (group II) includes very coarse grained amphibolites (R51, R60, R61, R62, R63, R66) with very weak mineral preferred orientation. Mineral assemblages are rather uniform with 55 % to 60 % brownish to green amphibole and sometimes pyroxene, 30 % to 45 % plagioclase and occasionally quartz and opaques. In contrast to the finegrained amphibolites of the first type these coarse amphibolites have gabbroic textures. One sample (R69) is extremely rich in very coarse amphibole (83 %). Textures probably correspond to a cumulate origin with mobilized phases like plagioclase and rare quartz as intercumulus phase.
3) A third type of amphibole and pyroxene bearing rocks (group III) occurs in two separated units along the western and eastern margins of the Raabs unit (Text-Fig. 2), but also in the hangingwall of the former unit (R3, R8, R58, R70). These rocks contain 25 % to 35 % amphibole and pyroxene, 50 % to 65 % plagioclase, some K-feldspar, quartz and sphene.

Field relations suggest that group I and group II amphibolites together with serpentinites, although internaly dismembered, belong to a single stratigraphic succession. Therefore, they are treated together. Group III amphibolites occcur in a separate structural and stratigraphic level and are described separately.

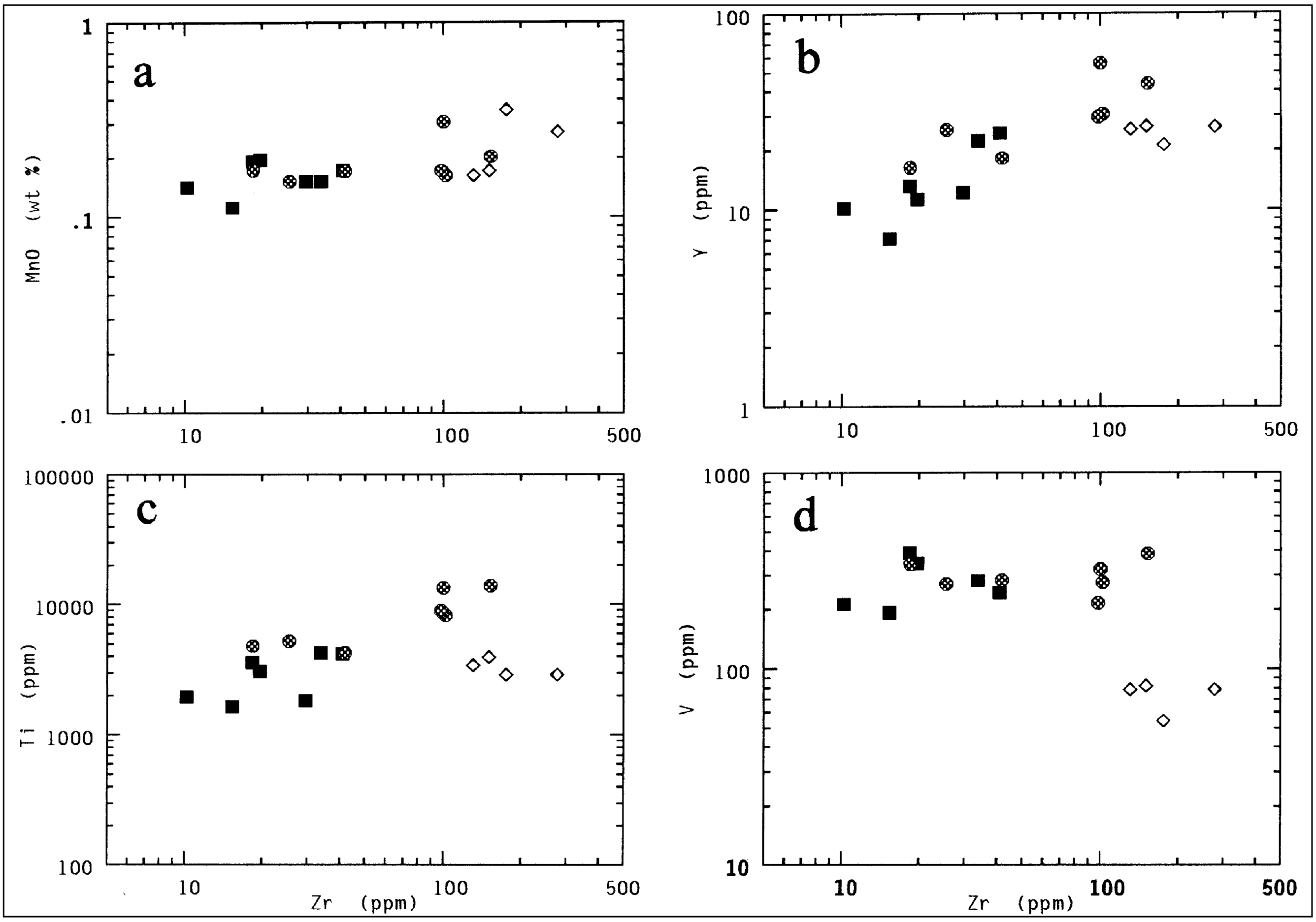
5. Geochemistry

A total of 32 samples including amphibolites and serpentinites were analysed for major and trace elements by standard X-ray fluorescence (XRF) spectrometry. A subset of 14 samples was also analysed for rare earth elements (REE) by inductively coupled plasma source spectrometry (ICP). Analytical procedures were done in the laboratory of the C.N.R.S, Nancy. Special care has been taken in collecting fresh, unretrogressed and unaltered samples, and also in choosing samples which have been unaffected by migmatisation. The chemical variation of major-, trace-, and REE elements is listed in Tab. 1.

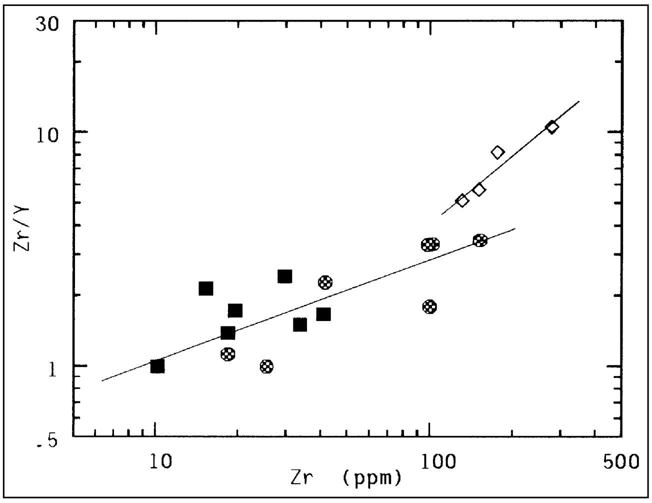
5.1. Chemical Variation of Elements

As the studied rocks have undergone strong metamorphism, element mobility has to be discussed. A low degree of alteration is evident from geochemical analyses. All samples are non-corundum normative, and the percentage of hydration is very low as indicated by the low percentage of loss-of-ignation (LOI). LOI-values are mostly <1 % in amphibolites. The high LOI-values in ultramafic rocks (around 10 %: Tab. 1) are explained by serpentinisation of harzburgite. Large ion lithophile (LIL) elements (Sr, K, Rb, Ba) and Na seemed to have been mobile in all rocks because there is no correlation between these elements and Zr which is regarded to be immobile during metamorphism. REE, high field strength elements (HFSE) such as Ti, P, Y and some transition metals, such as Mn, Cr, V, do not indicate strong migration and show a rather good correlation with Zr (some examples of covariation diagrams are shown in Fig 3a–d). These elements are, therefore, regarded as relatively immobile during metamorphism. Al- and Ca-concentrations are very similar in all rocks and independent from the Zr content. Concentration of Nb and Th, usually regarded as immobile elements, are close or below detection limit. Consequently only relatively immobile elements have been used for geochemical discrimination.

Although a magmatic source for the amphibolites is very probable because of similar element abundances to basaltic, gabbroic and andesitic igneous rocks, their close relation with harzburgites and, on the other hand, their petrological homogenity over a wide area, a sedimentary origin cannot, a priori, be excluded. Arguments for a magmatic source arise from low Zr/Ti relations compared with Zr as suggested by WINCHESTER & MAX (1980). A common, or at least similar magma reservoir for groups I and II is suggested by the Zr/Y-Zr relations (Text-Fig. 4). There is a rather good correlation of group I and group II amphibolites in these covariation diagrams and they are interpreted to be coeval and crystallized from a single parent magma source. Group III amphibolites do not correlate with the former ones (Text-Fig. 4) suggesting a different magma source. In addition, field relations suggest close relation between group I and group II rocks (amphibolites, metagabbros and serpentinites) whereas group III amphibolites occur in a different tectonostratigraphic level. Therefore they are treated separately.



Text-Fig. 3.
Selected covariation diagrams of the relative immobile element Zr against MnO (a), Y (b), Ti (c), V (d).
Data points are consistently drawn for all subsequent plots. Ornamented circles = group I amphibolites; black squares = group II amphibolites; white diamonds = group III amphibolites; Group I, II amphibolites are interpreted to have evolved from a single magma source, group II amphibolites display a different source.



Text-Fig. 4.
Zr versus Zr/Y ratios suggest two different magma sources.
Group I,II amphibolites (⊗, ■) display a common trend-line which is deviating from group II amphibolites (◇).
For further explanation see text.

5.1.1. Group I, II Amphibolites and Serpentinites

The chemical variation of group I, II amphibolites is within the variation of common basalts with SiO_2-contents between 47 % and 50 %. The SiO_2 versus Zr/TiO_2 plot (Text-Fig. 5a) after WINCHESTER & FLOYD (1977) reflects these relations, amphibolites plot in the field of Subalkalibasalts. Serpentinites display little variation in chemical composition with SiO_2 between 43 % and 46 % and MgO between 40–45 %. FeO*, a critical value for magma characteristics is generally high for group I (10 %–14 %) and somewhat lower in group II (8 %–11 %) which points to subalkaline basalts. In an A-F-M diagram (Text-Fig. 5b) the rock compositions of group I and II together with the serpentinites show progressive FeO* enrichment which is closely analogous to modern oceanic rocks (MIYASHIRO & SHIDO, 1980; BEYERLY, 1980) with tholeiitic affinity.

Serpentinites

The serpentinites are very homogenous in chemical composition (Tab. 1). Their CIPW compositions correspond to that of harzburgites which is in good agreement with observations from thin sections. In an Al_2O_3–CaO–MgO plot (Text-Fig. 6a) serpentinites cover the field of metamorphic peridotites (COLEMAN, 1977). The tectonic environment derived from the mineralogical composition (COLEMAN, 1977; BONATTI & MICHAEL, 1989) covers the field of oceanic or active margin peridotites (Text-Fig. 6b).

Amphibolites

Spidergrams and REE pattern:

Trace element pattern normalized to a typical N-type MORB (normalisation after PEARCE, 1982) and distribution of rare earth elements (REE) compared with primordial magmas provide good means to characterize magmas. In view of the metamorphic overprint, preferably the ratios of

Table 1.
Geochemical data of the Raabs Series.

Raabs Serie amphibolites of groupI								Raabs Serie amphibolites group II							Raabs S ie amphiboli s group III			
Sample	R36	R39	R40	R41	R56	R68	R99	R51	R60	R61	R62	R63	R66	R69	R3	8	R58	R70
SiO_2	49.35	46.82	49.07	47.89	49.57	48.48	48.31	51.21	47.07	46.89	48.53	47.23	49.40	56.20	59.15	.25	57.67	54.22
TiO_2	0.79	2.17	1.35	2.29	0.70	1.47	0.86	0.69	0.59	0.50	0.32	0.27	0.70	0.30	0.48	.48	0.65	0.56
Al_2O_3	17.00	18.17	15.38	14.16	16.78	16.57	19.16	14.05	12.91	14.13	18.75	19.38	18.51	6.32	11.71	.14	15.30	14.91
Fe_2O_3	10.96	12.93	10.88	13.93	10.57	10.99	10.94	9.64	12.08	11.03	8.61	7.78	10.41	7.58	10.00	.74	5.75	5.20
MnO	0.17	0.30	0.16	0.20	0.17	0.17	0.15	0.17	0.19	0.19	0.14	0.11	0.15	0.15	0.35	.27	0.17	0.16
MgO	6.05	3.67	7.50	7.16	7.10	6.81	4.95	8.69	10.64	11.41	8.23	8.60	5.91	15.73	1.79	.16	3.33	3.17
CaO	9.89	8.41	10.44	9.85	11.08	10.16	10.85	10.51	13.92	12.03	12.36	13.38	10.35	11.58	11.83	.85	11.08	17.73
Na_2O	3.52	3.39	3.22	3.04	2.70	3.40	3.04	2.72	1.31	1.41	1.86	1.72	3.00	0.78	4.05	.00	1.76	1.29
K_2O	0.96	2.22	0.68	0.52	0.43	0.83	0.83	0.88	0.30	0.40	0.13	0.17	0.35	0.30	0.32	.55	2.88	0.86
P_2O_5	0.13	0.32	0.34	0.27	0.20	0.22	0.20	0.16	0.13	0.12	0.13	0.15	0.17	0.04	0.19	.20	0.24	0.17
Total	97.89	97.30	98.09	98.12	98.40	98.16	98.36	97.90	98.11	97.17	98.33	98.13	98.06	98.33	99.02	.90	98.34	97.83
LOI	1.01	1.30	0.76	0.50	0.54	0.71	0.52	1.10	0.64	1.08	0.77	1.04	0.86	0.75	0.04	.14	0.89	1.52
Cr	28	257	317	251	194	155	3	349	507	542	71	153	106	988	49	0	84	66
Ni	21	64	80	56	40	7	3	25	86	132	38	50	31	142	22	2	43	32
Co	78	55	62	64	76	31	51	82	75	126	68	69	63	75	53	6	57	71
Sc	41	40	36	43	40	34	42	40	55	46	40	37	35	39	13	4	16	17
V	336	314	271	379	279	213	268	239	382	335	210	190	277	109	54	8	81	77
Cu	14	35	47	52	48	14	43	14	53	12	51	102	55	7	5	3	53	7
Zn	78	88	79	96	77	95	97	97	72	69	55	49	67	75	38	6	82	109
Mo	0.36	0.22	0.41	0.34	0.40	0.38	0.31	0.47	0.47	0.51	0.49	0.53	0.36	0.67	0.15	0.20	0.37	0.38
Rb	23	81	13	12	13	14	15	17	10	18	5	8	10	8	6	11	105	37
Ba	127	549	193	119	49	171	174	157	26	57	27	25	93	5	59	78	668	245
Sr	243	471	275	180	295	188	440	163	170	164	306	304	347	21	288	47	389	416
Ga	12	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	17	12	<5	<5	<5	22
Nb	<5	12	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	6	11	13
Zr	18	97	100	149	41	96	25	40	18	19	10	15	33	29	174	74	148	128
Y	16	54	30	43	18	29	25	24	13	11	10	7	22	12	2878	78	3897	357
Th	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	33	<5	<5	<5	21	26	26	25
Be															<5	<5	7	17
La	-	30.81	9.47	6.21	4.91	7.83		7.80	3.70	3.76	2.75	2.88	-		28.95	.38	37.25	3.19
Ce	-	70.82	27.43	23.55	17.41	21.74		21.69	2.52	11.88	10.11	13.43	-		58.73	.72	69.23	4.57
Nd	-	34.68	17.01	15.60	9.24	14.09		12.09	5.65	4.95	4.78	4.66	-		23.00	.90	31.27	2.80
Sm	-	9.36	4.97	5.40	2.65	4.08		3.49	1.99	1.66	1.34	1.44	-		4.75	.48	6.29	2.48
Eu	-	2.58	1.35	1.66	0.79	1.38		0.86	0.63	0.56	0.49	0.44	-		1.04	.15	1.23	0.55
Gd	-	9.68	5.56	6.75	3.07	4.50		3.83	2.31	1.68	1.45	1.39	-		4.43	.99	5.53	2.62
Dy	-	9.64	5.34	7.76	2.87	5.12		3.92	2.12	1.87	1.57	1.17	-		3.66	.30	4.40	1.89
Er	-	5.25	3.38	4.74	2.09	3.22		2.60	1.52	1.46	1.27	1.08	-		2.17	.45	2.57	1.09
Yb	-	4.69	2.66	4.08	1.58	2.62		2.10	1.09	0.97	0.87	0.59	-		1.91	.35	2.10	0.96
Lu	-	0.79	0.48	0.72	0.31	0.45		0.38	0.22	0.18	0.18	0.12	-		0.36	.38	0.37	0.18
$^{87/86}Sr$	-	-	.7067	.7059	-	.7053		-	.7045	.7496	.7038	.7040						

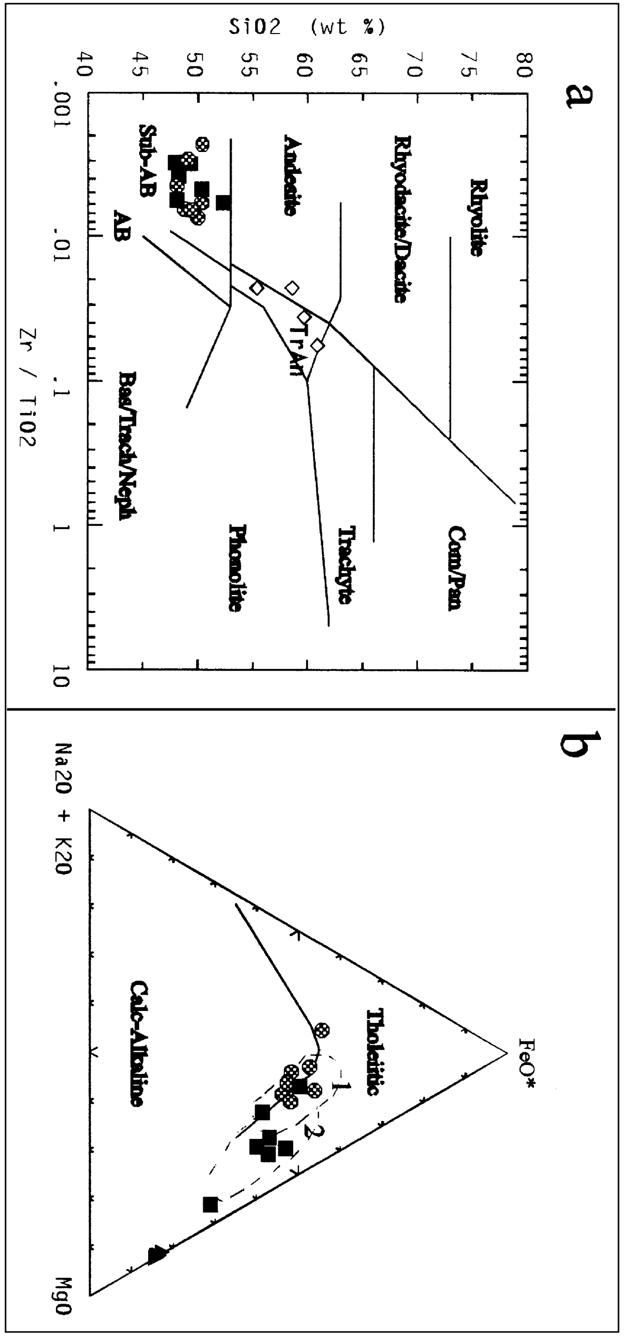
Table 1 (continued).

Serpentinites Raabs Unit										
Sample	R25	R38/1	R42	R43	R72	R73	R74	R86	R87	R88
SiO_2	36.87	39.28	39.56	39.43	39.06	39.31	39.35	38.57	40.86	39.57
TiO_2	traces	traces	traces	traces	traces	traces	traces	traces	traces	traces
Al_2O_3	1.20	2.15	2.02	2.00	2.09	1.93	2.09	2.02	2.33	2.41
Fe_2O_3	8.30	7.94	7.85	7.83	7.83	7.83	7.91	7.80	8.14	7.88
MnO	0.10	0.11	0.11	0.11	0.12	0.11	0.10	0.10	0.11	0.10
MgO	38.84	36.51	35.25	35.82	36.75	36.04	36.65	37.28	34.40	35.42
CaO	0.71	1.62	2.22	1.67	2.31	1.62	0.71	0.38	1.66	1.08
Na_2O	0.06	0.11	0.10	0.07	0.16	0.15	0.04	0.01	0.16	0.10
K_2O	traces	traces	traces	traces	traces	traces	traces	traces	traces	traces
P_2O_5	traces	traces	traces	traces	traces	traces	0.03	traces	traces	traces
Total	85.40	87.07	86.47	86.29	87.68	86.35	86.24	85.54	87.01	85.93
LOI	12.49	10.27	11.32	11.70	10.38	11.32	11.59	12.51	10.30	11.39
Cr	1791	2500	2331	2435	>2500	2485	>2500	>2500	>2500	>2500
Ni	2040	1819	1795	1914	1854	1896	2088	1866	1939	1765
Co	118	109	94	97	103	92	86	84	98	95
Sc	8	12	13	12	13	12	13	12	13	13
V	33	55	51	51	55	44	48	39	54	52
Cu	6	21	15	21	22	12	66	22	34	18
Zn	51	50	46	49	47	46	53	48	57	53
Rb	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Ba	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Sr	9	5	7	10	15	14	<5	<5	16	10
Ga	5	7	6	6	7	5	<5	<5	<5	<5
Nb	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Zr	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Y	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Th	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Be	<.5	<.5	<.5	<.5	<.5	<.5	<5	<5	<5	<5

the relative immobile elements including HFS-elements and RE-elements are used for discrimination of the tectonic setting. The enrichment in large ion lithophile (LIL) elements (Sr, K, Rb, Ba) in all groups relative to N-type MORB may be interpreted by some addition of these elements during metamorphism. These elements have been avoided for interpretation.

High field strength (HFS) element patterns of group I amphibolites (Text-Fig. 7a) are close to the unity line suggesting close similarity to MORB, although there is a very weak tendency to a "spiky" pattern. Selective enrichment of Ce, P, and Sm relative to N-type MORB could be interpreted with some calcalkaline component.

The relatively strong depletion of all incompatible elements in group II amphibolites (Text-Fig. 7b) cannot be explained exclusively by low absolute abundances typical for island-arc tholeiites. This element pattern is rather explained by the small crystal/liquid partition coefficients for these in-

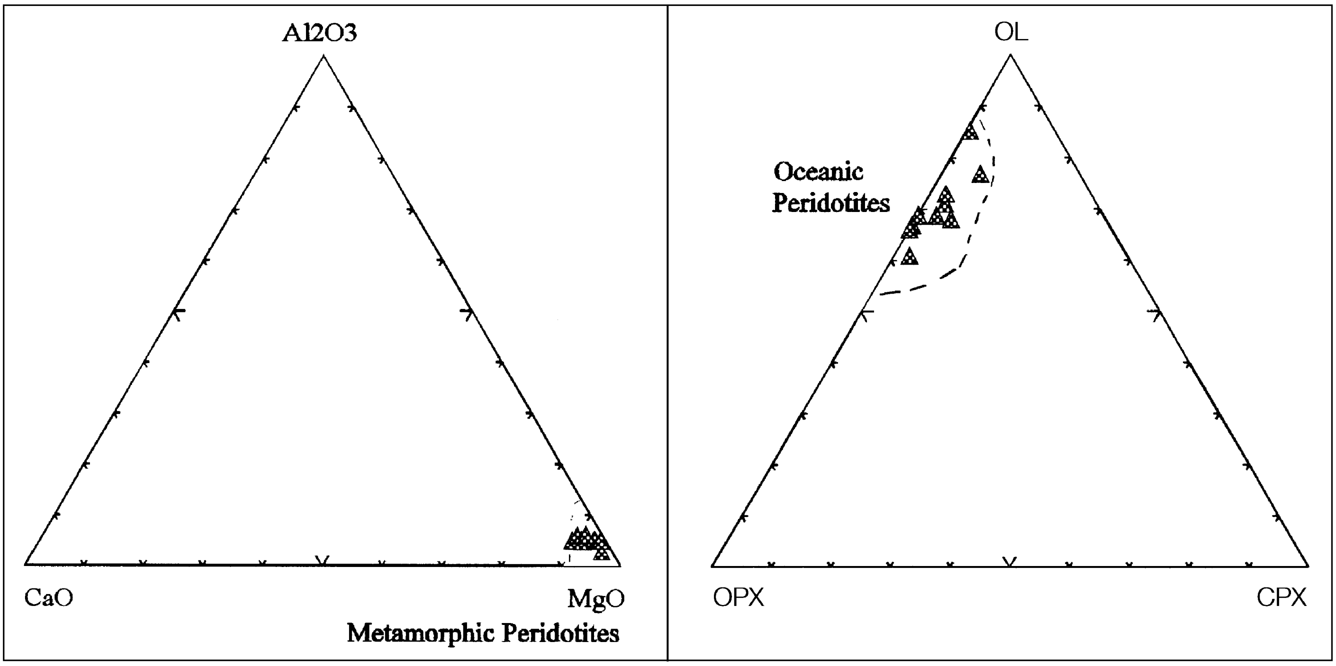


Text-Fig. 5.

a) SiO_2 versus Zr/TiO_2 plot after WINCHESTER & FLOYD (1977). Group I, II amphibolites cover the field of subalkalibasalts, group III amphibolites the field of andesites.

b) The A-F-M diagram displays a tholeiitic trend for the cogenetic group I, II amphibolites and serpentinites. Group I amphibolites cover the field of abyssal tholeiites, group II amphibolites the field of oceanic gabbros (MIYASHIRO & SHIDO, 1980). Serpentinites (black triangles) plot in the field of metamorphic peridotites.

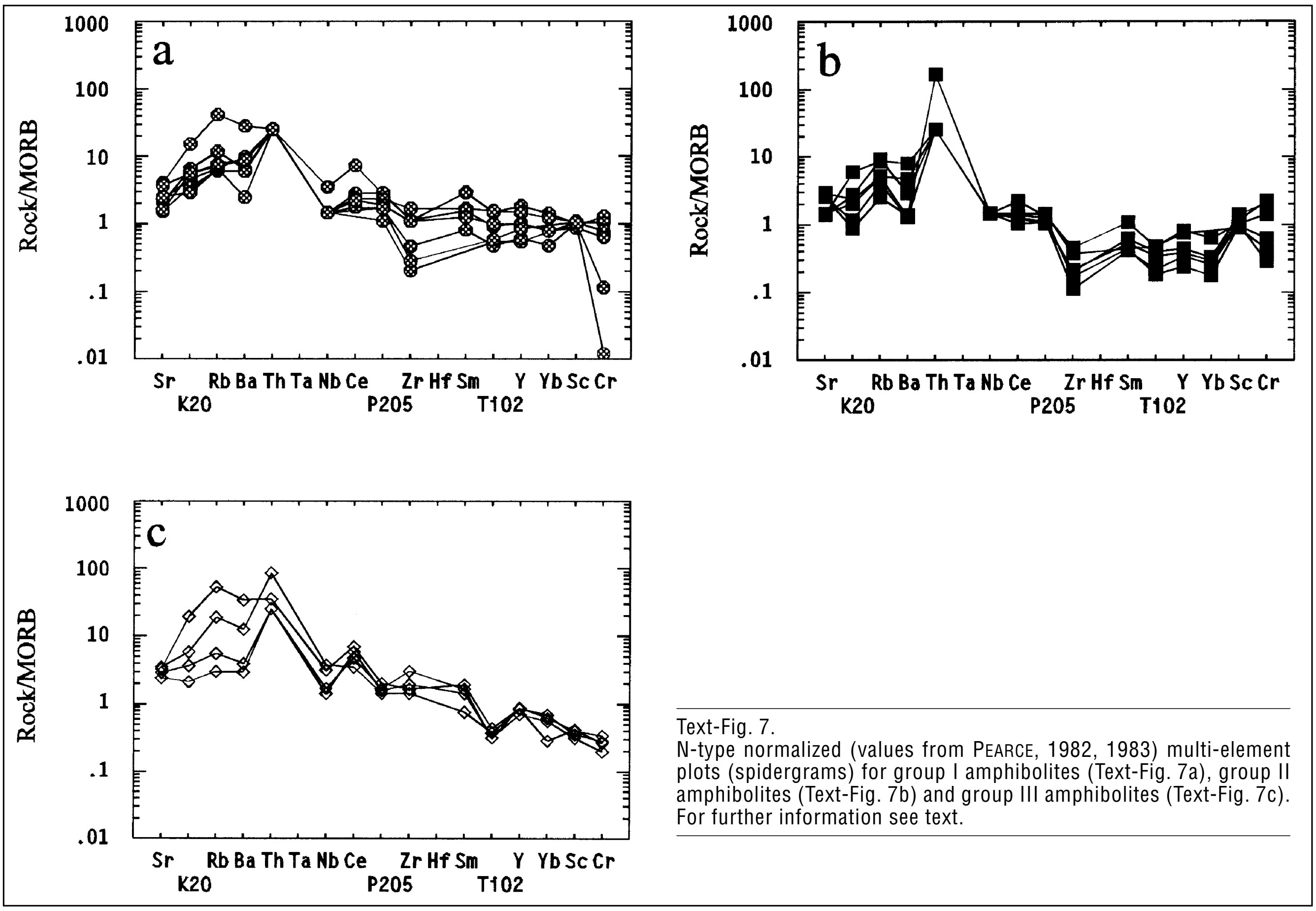
Symbols as in Text-Fig. 3.



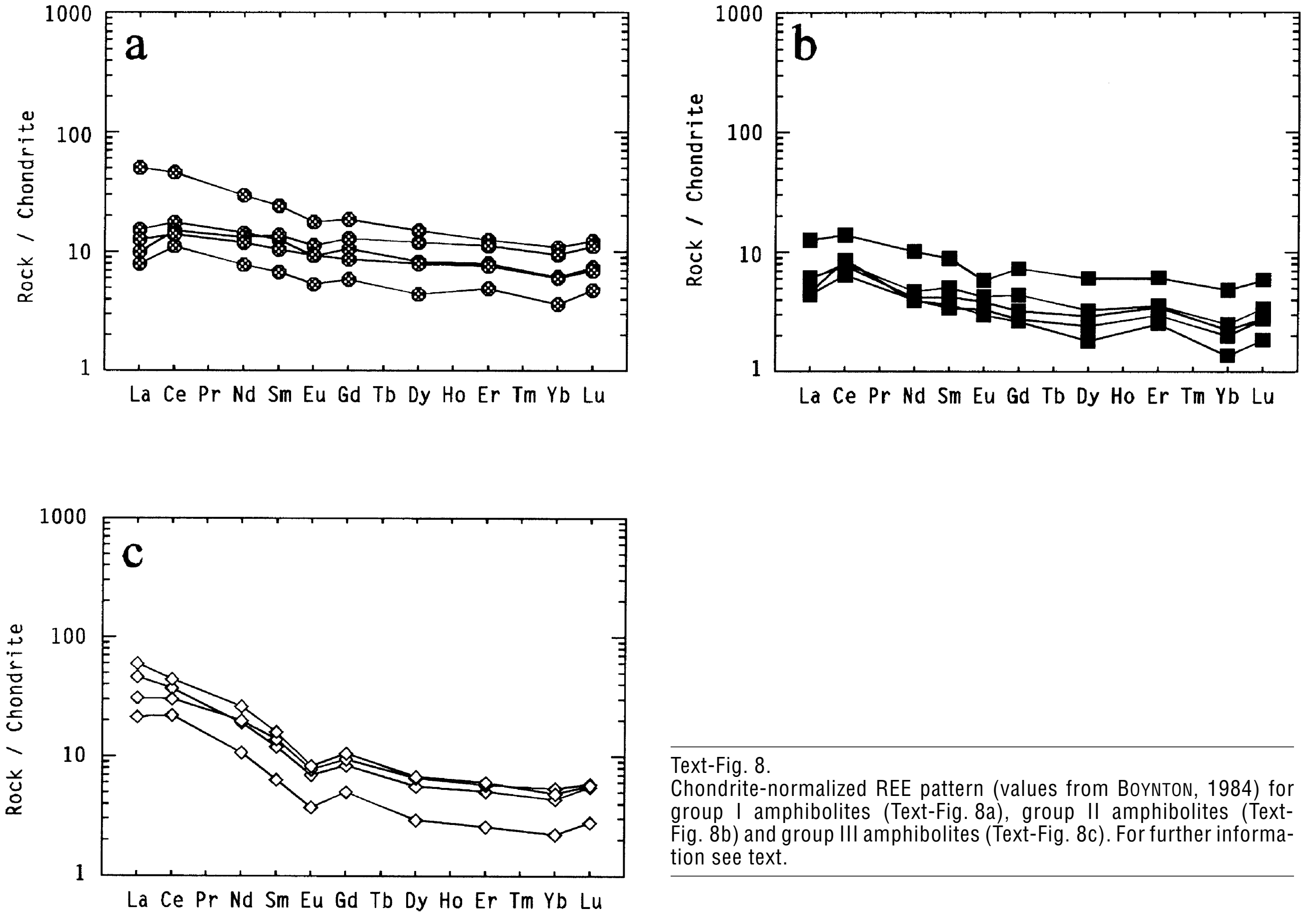
Text-Fig. 6.
a) Al_2O_3 – CaO – MgO relations of serpentinites (triangles) are similar to the chemical composition of metamorphic peridotites (Coleman, 1977).
b) Compositional distribution (O = Olivine, OPX = Orthopyroxe, CPX = Clinopyroxene) of peridotites (triangles) covers the field of oceanic peridotites (from Bonatti & Michael, 1989).

compatible elements and hence fractionation processes to form gabbros.

Amphibolites of group I and group II display a flat REE-pattern subparallel to average normalized chondrite abundances, however group II has lower absolute abundances (Text-Fig. 8a, b). Both groups do not display depletion of light REE as typically observed from primitive N-type MORB, their flat distribution with minor enrichment of LREE is commonly observed in E-type MORBs (Bonynton, 1984; Saunders, 1984; Sun et al., 1979; Tarney et al., 1981; Floyd et al., 1991). Lower absolute abundances of group II amphibolites may be interpreted to reflect fractio-

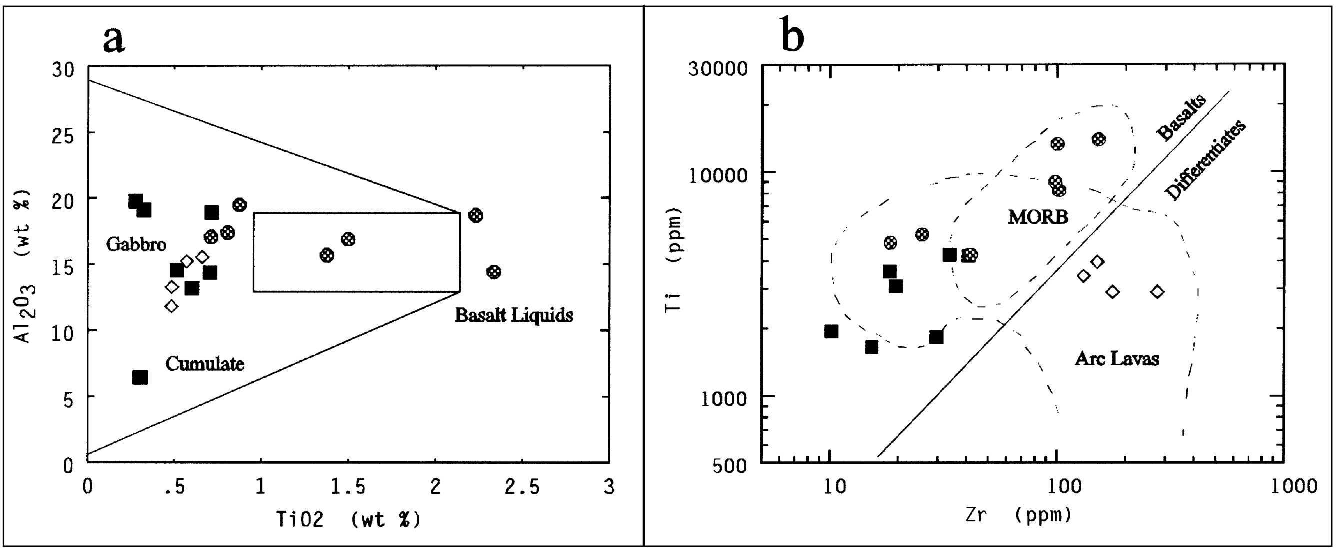


Text-Fig. 7.
N-type normalized (values from Pearce, 1982, 1983) multi-element plots (spidergrams) for group I amphibolites (Text-Fig. 7a), group II amphibolites (Text-Fig. 7b) and group III amphibolites (Text-Fig. 7c). For further information see text.

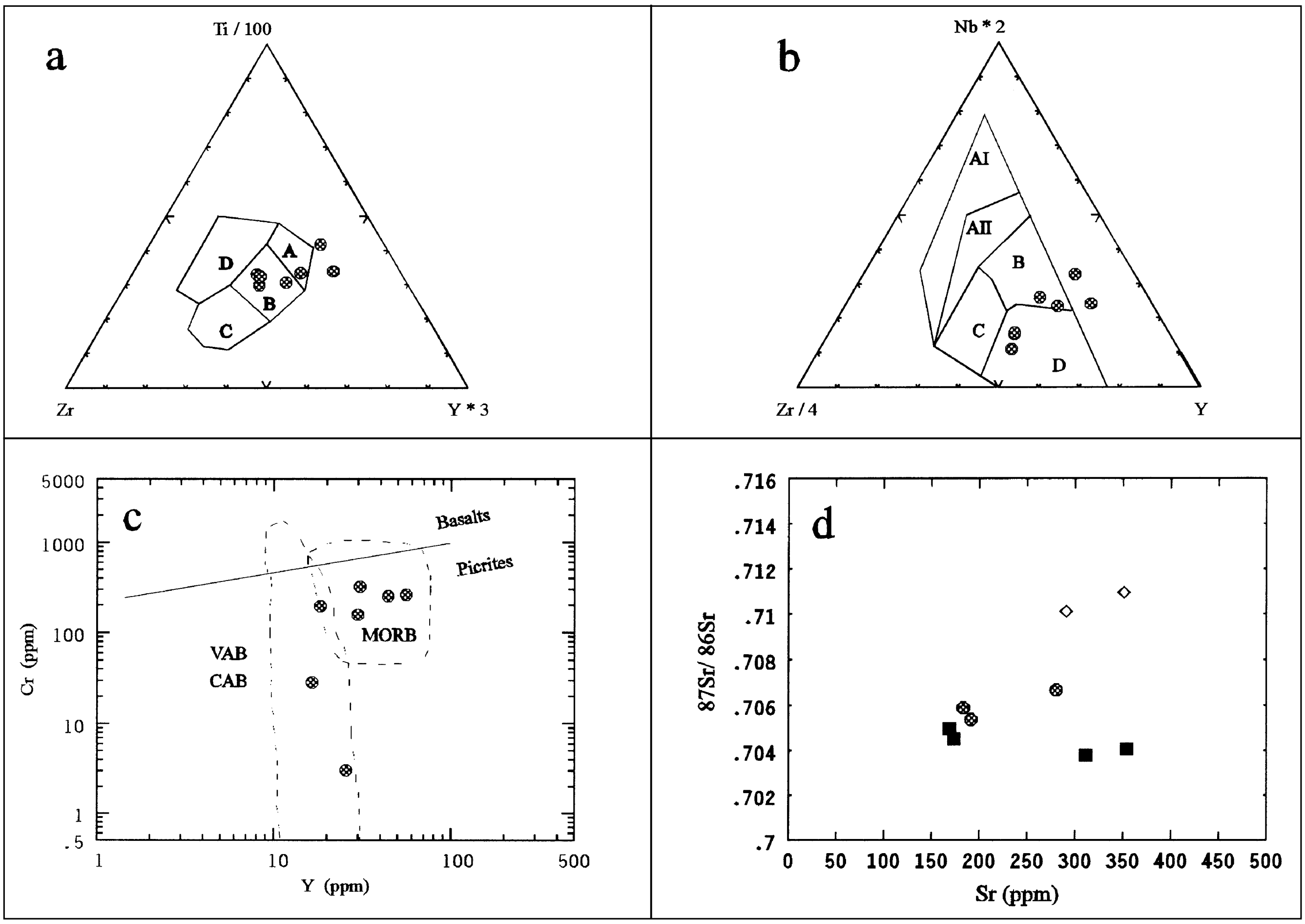


Text-Fig. 8.
Chondrite-normalized REE pattern (values from BOYNTON, 1984) for group I amphibolites (Text-Fig. 8a), group II amphibolites (Text-Fig. 8b) and group III amphibolites (Text-Fig. 8c). For further information see text.

nation processes in gabbro respectively cumulate rocks. Comparison of normalized ratios of (La/Sm)N and (La/Yb)N may be used to discriminate N-type, T-type and E-type MORB (e.g., SUN & VUAGNAT, 1992). (La/Sm)N ratios of 0.7–1.2 (group I) and 1.2–1.4 (group II), and (La/Yb)N ratios of 1.1–2.4 (group I) and 2.3–3.4 (group II) suggest transitional (T-type) MORB commonly interpreted to originate within back arc setting. Additionally low $^{87}Sr/^{86}Sr$ ratios of group I, II amphibolites ranging between 0.704 to 0.706 (Text-Fig. 10d) suggest generation from a primitive magma source without major crustal contamination (e.g. WILSON, 1988).



Text-Fig. 9.
a) Al_2O_3 versus TiO_2 ratios from group I amphibolites cover largely the field of basalt liquids. Those of group II, III amphibolites the fields of differentiated rocks (after PEARCE, 1983).
b) Ti-Zr diagram to distinguish between basic and evolved magmas (after PEARCE et al., 1981) with further subdivision into MORB and Arc lavas. Group I, II amphibolites cover largely the field of MORB to arc lavas, those of group III the field of differentiates.
Symbols as in Text-Fig. 3.



Text-Fig. 10.
Group I amphibolites displayed in basalt discrimination diagrams.

a) Ti-Zr-Y plot (A: island-arc tholeiites; B: ocean-floor basalts; C: calcalkaline basalts; D: within-plate basalts) after PEARCE & CANN (1973),
b) Nb-Zr-Y plot (AI, AII: within-plate basalts; B: P-type MORB; D: N-type MORB; C,D: volcanic-arc basalts) after MESCHEDE (1986),
c) Cr-Y plot (c) after PEARCE et al. (1981). In all diagrams group I amphibolites cover fields transitional between MORB and arc-basalts with a tendency to E-type MORB.
d) $^{87}Sr/^{86}Sr$ versus Sr ratios show low $^{87}Sr/^{86}Sr$ ratios for group I (ornamented circles) and group II amphibolites (black squares) and higher $^{87}Sr/^{86}Sr$ ratios for group III amphibolites (white diamonds). Low $^{87}Sr/^{86}Sr$ ratios of group I, II amphibolites point to a primitive magma source, those of group III amphibolites to a more evolved magma.

Basalt discrimination plots

To discriminate basalt liquids from gabbros and cumulate rocks Al_2O_3/TiO_2 and Ti/Zr relations have been proposed by PEARCE (1983) (Text-Fig. 9a, b). According to PEARCE (1983) basalt liquids are restricted to specific Al_2O_3/TiO_2 relations. TiO_2 abundances of group I between 0.8 % and 2.3 % and Al_2O_3 abundances between 15 and 20 % are in the range of average basalts, group II with TiO_2 abundances lower than 0.6 % are in the range of gabbros. Low abundances of Al_2O_3 in sample R69, however, may be explained by fractional crystallisation of a cumulus phase (Text-Fig. 10a). The Ti/Zr plot (Text-Fig. 10b) after PEARCE et al. (1981) discriminates basalt liquid from differentiated rocks on the base of the incompatible element Zr which is increasingly incorporated in more evolved rocks. In addition, the transition to intermediate magma character is marked by crystallisation of Fe-Ti oxide as a cumulus phase which causes a sudden fall in the Ti/Zr ratio of the residual magma (e.g. ALABASTER et al., 1982). In this plot (Text-Fig. 9b) group I and II amphibolites occupy the basalt field with group I in the MORB-field. Group III amphibolites cover the field of differentiates.

Several plots are suggested to discriminate basaltic lavas of different tectonic settings. Because these diagrams are restricted to true basalts, only group I amphibolites which fulfill these requirements are displayed. In the most familiar Ti-Zr-Y plot (Text-Fig. 10a) after PEARCE & CANN (1973) the amphibolites cover the domain of MOR-basalts respectively island arc tholeiites. Based on Nb-Zr-Y abundances a plot has been suggested by MESCHEDE (1986) to discriminate between different tectonic settings and for further discrimination between N-type and P-type MORBs. In this diagram (Text-Fig. 10b) the amphibolites cover the fields of P- to N-type MOR basalts. Considering that upper limits of Nb (Nb is mainly beneath the detection limit) are plotted the data points would even shift towards the field of N-type MORBS.

5.1.2. Group III Amphibolites

The chemical variation of group III amphibolites with 55 % to 60 % SiO_2 and increased Zr abundances is typical for andesites. Within the SiO_2 versus Zr/Ti plot (Text-Fig. 5a) after WINCHESTER & FLOYD (1977) they cover the field of andesites. TiO_2 abundances (< 0.6 %) are generally lower than those of group I and group II and typical for calcalcaline magmas (SUN & NESBIT, 1978). Ti/Zr ratios (Text-Fig. 9b) reflect this situation, group III amphibolites cluster within the field of differentiated magmas (PEARCE et al., 1981). In addition, higher $^{87}Sr/^{86}Sr$ ratios of 0.71 and

0.72 of group III amphibolites suggest major crustal contamination (Text-Fig. 10d).

The spidergram pattern of group III amphibolites suggests enhanced fractionation processes or element mobility (Text-Fig. 7c). The "spiky" pattern with depletion of Nb and the low Ti-concentrations argue for an early crystallisation of Fe-Ti oxides, typical for calcalkaline rocks. Those trends are similar to transitional VAB with back-arc basalt variations (PEARCE, 1982; WEAVER et al., 1979). Low absolute abundances in Sc and Cr may be explained by early crystallisation of olivine in intermediate rocks (PEARCE, 1982).

The REE pattern (Text-Fig. 8c) generally displays higher absolute abundances compared to group I and II amphibolites and a pronounced enrichement of light REE. The negative Eu-anomaly suggests plagioclase fractionation within the melt. These patterns are commonly interpreted as a result from calcalkaline magmas and/or crustal contamination (e.g. SAUNDERS, 1984).

6. Interpretation

Magmatic rocks within the Raabs unit are interpreted to be differentiates from two different magma sources. Group I and II amphibolites together with the serpentinites occur in a deeper tectonostratigraphic level together with metapelites and rare carbonates. They are interpreted to represent a dismembered incomplete ophiolite sequence. Serpentinites represent the metamorphic peridotite and display a ridge coarse texture. Group II amphibolites are interpreted to represent the gabbro layer including cumulate rocks, group I amphibolites are interpreted as the basaltic liquid phase. Metapelites including rare occurrences of carbonates could represent the oceanic sediments. The tectonic setting interpreted from HFS elements and REE pattern are best interpreted as differentiates of an E-type MORB, probably within a back-arc setting.

Group III amphibolites occur within a higher tectonostratigraphic level and are interpreted to be differentiates from a different magma source. They display andesitic bulk rock-chemistry and a higher degree of differentiation. HFS element and REE patterns are best explained by calcalkaline differentiation. These magmas could have been evolved within a collisional regime of an island-arc or magmatic arc setting.

There is indirect evidence for the protolith age of the amphibolites. Their tectonic position, sandwiched between late Proterozoic rocks (protolith ages) of the Variegated and partly Monotonous Series, and the Paleozoic granulites (protolith ages) suggests a Paleozoic protolith age of these rocks. On the other hand the amphibolites suffered a common deformation history with the granulite nappe and the Variegated Series including a top-to-the northwest directed shear followed by subvertical flattening (FRITZ & NEUBAUER, 1993). This deformation is most probably of late Variscan age (FRITZ et al., in press). From these data a Paleozoic protolith age for the amphibolites of the Raabs Series is suggested. Recently FINGER & von QUADT (1995) argued for a Paleozoic age of plagiogranite gneisses within an ophiolite-like suite in a comparable tectonic level based on U/Pb Zircon data.

The geochemical data, together with the tectonic position of the Raabs Series, sandwiched between two continental blocks, the Gföhl terrane in the hangingwall and the Drosendorf terrane (Variegated Unit) in the footwall, suggest that the Raabs Series represents a suture zone between these blocks. A model for the geodynamic evolutions includes:

1) Formation of an ophiolite during Paleozoic extension tectonics, probably within a back-arc setting, subsequently followed by,
2) plate convergence and formation of calcalkaline magmas within an island arc or magmatic arc milieu; and,
3) incorporation of the Raabs (and Letovice) oceanic domains to the nappe assembly by Variscan continental collision tectonics.

Overall kinematics (FRITZ & NEUBAUER, 1993; FRITZ et al., submitted) suggest the root zone of the Variscan nappes in a southwestern position. The Variscan Raabs-Letovice ocean should consequently be located southward to the southernmost occurrences of the footwall terrane. This covers an area within the recent position of the Alpine chain.

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