Geochemistry and REE magmatic fractionation patterns of the Prijakt amphibolitized eclogites of the Schobergruppe, Austroalpine basement (Eastern Alps)

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Abstract

In the Prijakt area (Schobergruppe, Eastern Tyrol, Austroalpine basement to the south of the Tauern Window, Austria), a 400 m thick metabasite sequence in the basal part of the metapsammopelitic unit (MPU) is concordantly interlayered by strongly foliated orthogneisses, paragneisses and mica schists. The rocks suffered a post-Upper-Ordovician deformation with coeval high-pressure (550–650 °C / 14–16 kbar), followed by high-temperature amphibolite facies metamorphism. Whole-rock compositions of the amphibole-eclogites, garnet-amphibolites and amphibolites are tholeiitic and vary considerably in mg-numbers. The systematic correlations of major, trace and rare-earth elements in the metabasites are attributed to fractional crystallization processes and cannot be related to metasomatism or to post-eclogitic overprinting. High field-strength element abundances and element ratios like Ti/V are in the range of present-day MORB. Compared to N-MORB, the large ion lithophile elements Rb, Sr, K, Ba are slightly enriched. Chondrite-normalized rare-earth element patterns are slightly enriched in LREE when compared to N-MORB, with Ce_N/Yb_N ranging from 1.4 to 3.2 at 10–50 times chondrite abundances. The degree of REE enrichment is strictly correlated with mg-numbers and the patterns with slight negative Eu and positive Ce anomalies are parallel. A peculiar but regularly repeated four-stage "saw-tooth" like linear increase and decrease of REE, Hf, Ta, Th, Cs, Tb and Zr with decreasing mg-numbers is observed in Zr-REE coordinates. This may be explained by a discontinuous cyclic magmatic fractionation process with enrichment of REE and Zr in the remaining melt while Fe–Mg minerals successively crystallized. When the geochemical data from the Prijakt metabasites are interpreted in terms of a geotectonic setting, the former layered dyke or sill could be related to basalts which intruded during early-Palaeozoic or Precambrian continental extension at incipient ocean floor spreading.

Keywords: amphibolitized eclogites, geochemistry, REE-patterns, pre-Variscan, Austroalpine basement, Eastern Alps.

Introduction

The Austroalpine basement complex in the Eastern Alps has undergone a multistage metamorphic and magmatic evolution during pre-Alpine and Alpine times (FRISCH et al., 1990; VON RAUMER and NEUBAUER, 1993). Geochemical and radiochronological signatures in metabasites provide valuable data for recognizing this pre-Alpine history (e.g. REIMANN and STUMPFL, 1981; MOGESSIE et al., 1985; FRISCH et al., 1987; MAGGETTI and GALETTI, 1988; MILLER et al., 1988; MILLER, 1990; NEUBAUER et al., 1989; POLI, 1989; GODIZART, 1989; VON RAUMER et al., 1990; KREUTZER, 1991; LOESCHKE and HEINISCH, 1993).

The Austroalpine basement complex to the south of the Tauern Window (Fig. 1 a, b) consists of a metapsammopelite-amphibolite-marble unit (AMU) exposed to the north, a monotonous metapsammopelitic unit (MPU), the phyllitic sequences of the Thurntaler complex (TC) and the Kreuzeckgruppe, and the Gailtal metamorphic basement to the south (SCHULZ et al., 1993). Rb–Sr whole-rock isochrons (BORSI et al., 1973; BRACK, 1977; HAMMERSCHMIDT, 1981) and U–Pb zircon ages (CLIFF, 1980) between 445 and 427 Ma from orthogneisses in the AMU and MPU are interpreted to date the intrusion of granitoids after a poorly known pre-Upper-Ordovician evolution. The end of a Variscan metamorphism with an early high-pressure stage

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and a subsequent amphibolite facies high-temperature stage (SCHULZ et al., 1993) in AMU and MPU is marked by late-Variscan mica Rb–Sr and K–Ar ages around 300 Ma (BORSI et al., 1978) and the intrusion of pegmatites (BORSI et al., 1980; data compiled by HOKE, 1990). The porphyroids in the early-Palaeozoic phyllitic sequences of the Thurntaler complex (TC) to the south are probably the volcanoclastic equivalents of the Upper-Ordovician granitoids in the AMU and MPU. A Variscan greenschist to lower amphibolite facies metamorphism has been described from the Thurntaler complex (HEINISCH and SCHMIDT, 1982; KREUTZER, 1991; SCHULZ et al., 1993). Early- and late-Alpine overprinting of northern parts of the Austroalpine basement is obvious from 70–90 Ma and 15–30 Ma Rb–Sr and K–Ar mica ages (BORSI et al., 1978; TROLL, 1978; HOKE, 1990).

This paper describes the geochemistry of the amphibolitized eclogites in the Prijakt area, Schobergruppe, in the lower part of the MPU. Apart from the thick occurrences of the Prijakt and Schleinitz in the Schobergruppe, metabasites are rare and thin in this mainly psammopelitic lithological unit (SCHULZ et al., 1993). Usually, many distinct locations are sampled for geochemical studies in a metamorphic terrain in order to obtain the most complete range of differentiated rocks of each magmatic event. In contrast, for this geochemical study of the amphibolitized eclogites, all samples come from a large single outcrop. This allowed a better control on the variations of major, trace and rare-earth elements in the metabasites and recognition of the primary geochemical features of the differentiated rocks which suffered multistage metamorphism and deformation.

Geological setting and petrography

In the Prijakt area of the Schobergruppe (Eastern Tyrol, Austria, Fig. 1), two large bodies of a 400 m thick metabasite sequence occur in the basal part of the metapsammopelitic unit (MPU) and belong to the "Hangendkomplex" referred to by CLAR (1927), TROLL and HÖLZL (1974) and TROLL et al. (1976; 1980). Strongly foliated orthogneisses partly exceeding 10 m thickness, paragneisses and mica schists concordantly overlie, underlie and are intercalated with the metabasites. Heterogeneous cm- to dm-scale banding of the metabasites is the result of variable grain size and modes in rare eclogites and abundant amphibole-eclogites, symplectitic garnet-amphibolites (sometimes re-
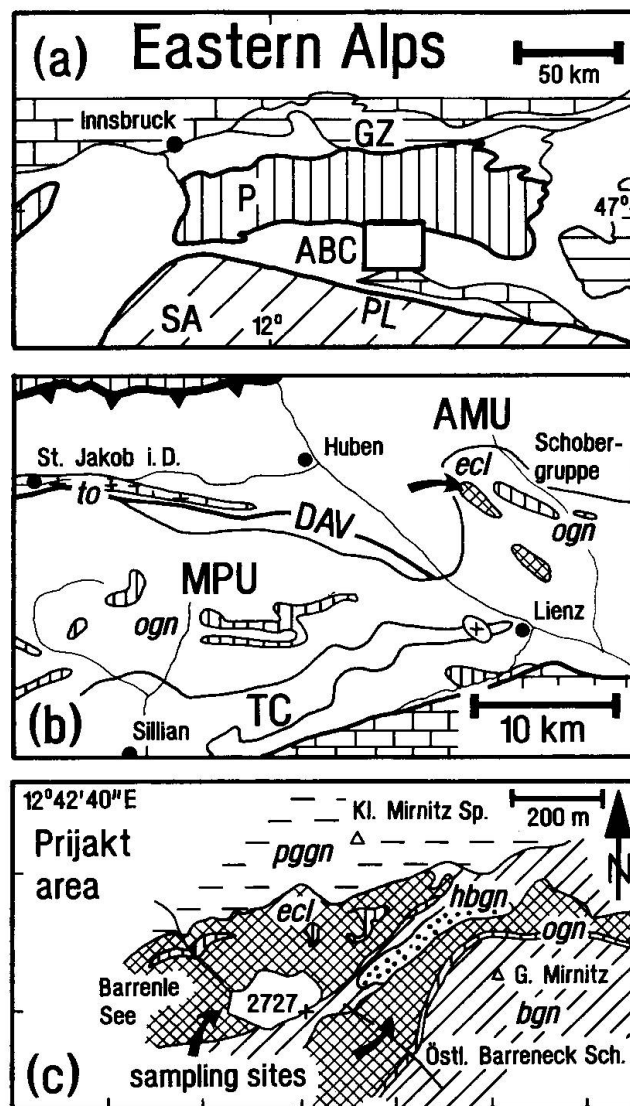
Fig. 1 (a), (b) General geological setting of the Austroalpine basement complex (ABC) with its pre-Alpine units to the south of the Tauern Window. AMU metapsammopelite-amphibolite-marble unit; DAV Defereggen-Antholz-Vals-Line (late-Alpine); ecl amphibolitized eclogites of the Schobergruppe; GZ Grauwackenzone; MPU metapsammopelitic unit; ogn orthogneisses; P Penninic unit (Tauern Window); PL Periadriatic Lineament; SA Southern Alps; TC Thurntaler complex; to tonalite (late-Alpine). (c) Geological map of the Prijakt area, after TROLL et al. (1976); ecl amphibolitized eclogites; hbgn hornblende-biotite-gneiss; ogn orthogneisses; pggn paragneisses.

ferred as "eclogitic amphibolites" or "amphibolitized eclogites"), garnet-amphibolites, amphibolites and zoisite-amphibolites. Individual layers show several metres of lateral extension. The lithological changes define a planar structural element ("foliation") which is parallel to the gently SE dipping foliation (S_2) of the host rocks. A linear fabric of the metabasites by preferen-

tially oriented amphibole, clinopyroxene and zoisite is parallel to the linear structures in the orthogneisses, paragneisses and mica schists. A presumably early generation of open to tight folds (B_2 of TROLL et al., 1976) shows fold hinge lines parallel to the SE-plunging lineation. Later folds with NE–SW striking hinge lines deform the lineation and are minor structures of kilometre-scale syn- and antiforms (D_i of BEHRMANN, 1990) with gently dipping axial planes. The parallel mesoscopic structures and microstructures of metabasites, paragneisses, mica schists and orthogneisses (former Upper-Ordovician granitoids) were produced by a polyphase post-Upper-Ordovician deformation of the rocks. Flattening and non-coaxial shearing could have considerably reduced the original thickness of the metabasites. A syndeformative (Variscan) metamorphism with a high-pressure stage at 550–650 °C/14–16 kbar and a subsequent high-temperature stage near 700 °C/9 kbar has been recorded by both metabasites and mica schists. Later (Alpine) overprinting occurred at temperatures below 500 °C (SCHULZ, 1993). The lithological, structural and petrological observations in the Prijakt area give no hints to a possible "exotic" origin of the metabasites or to the relative ages of basic and acid magmatic protoliths, but confirm a common history of the sequence since early-Palaeozoic times. Amphibolites are observed in xenoliths within the acid orthogneisses in other parts of the basement and their protoliths should be older as the Upper-Ordovician plutonic activity (PECCERILLO et al., 1979).

At the sampling locations immediate to the NW and SE of the Barrenle-See to the SE of the Hochschoberhütte (Schobergruppe to the south of the Hohe Tauern, Fig. 1c), the two metabasite bodies are separated by some m-thick layers of biotite-gneiss and hornblende-biotite-gneiss (TROLL and HÖLZL, 1974). In order to avoid the analysis of possible metasomatic geochemical changes, all samples have been taken from the central parts of the metabasite bodies at several meters distant to the contacts of host rocks, and the interlayered hornblende-biotite-gneiss has not been considered. The two sampling sites include a surface area of several tens of square meters. Thus the sample suite does not represent a lithostratigraphic pile from the base to the top of the metabasite bodies. The analyzed 15 samples belong to six types of rocks (Tab. 1):

Eclogite (sample 11, symbol ⊗) with 43% clinopyroxene, 23% garnet, 4% green amphibole, 4% quartz and plagioclase and clinozoisite (8%) shows only little mineralogical changes due to de-

compression reactions. The latter are obvious from thin submicroscopically fine-grained symplectitic rims around clinopyroxene.

The fine-grained amphibole-eclogites (samples 1, 2, 15, symbol ×) contain green amphibole (8–22%), garnet (11–26%, 1–3 mm in diameter), clinopyroxene (16–21%), clinozoisite, quartz, plagioclase, rutile, sphene and ilmenite. Amphibole, clinopyroxene and clinozoisite are oriented with their long axes parallel to the lineation. Garnet shows numerous inclusions of quartz, plagioclase and sometimes epidote. Some clinopyroxenes are rimmed by thin submicroscopically fine-grained symplectites. In some mm-thick layers, clinopyroxene is completely symplectitic and garnet has been pseudomorphed by epidote, amphibole and plagioclase (sample 2). Garnets in sample 15 are 3 mm in diameter and the symplectitic rims of clinopyroxene are broader as in sample 2. Some white mica is found in samples 1 and 15. This group of samples represents high-pressure rocks with only little mineralogical changes due to reactions driven by decompression. Garnets are zoned with 15–23% pyrope, 27–22% grossular, 53–52% almandine and 3–1% spessartine from cores to rims. The plagioclase is albitic with 7–9% anorthite and the clinopyroxenes are zoned omphacites with jadeite contents of 35% in the cores and 42% in the rims. Chemical compositions of green amphiboles allow to classify the porphyroblasts as pargasite, hastingsite and ferri-pargasitic hornblende with variable (Na + K)$_A$ (1.0–0.6), Al^{IV} (2.4 to 1.2) at nearly constant Al^{VI} (1.0, always per formula unit p.f.u.) contents. Epidotes in garnet cores have lower Al (4.33) and higher Fe (2.11) contents than homogeneous long prismatic zoisites and clinozoisites (Al 5.2, Fe 0.9) in the anisotropic matrix. The white micas are paragonite with Na 1.6, Mg 0.035, Fe 0.05, Si 6.0, which may have crystallized at high pressures and high temperatures (SCHULZ, 1993).

In symplectitic garnet-amphibolites (samples D, C, 9, 13, symbol Δ), mineralogical changes due to decompression reactions are abundant. Half of the garnets (7–17%, 1.5 mm in diameter) are rimmed by green amphibole. Clinopyroxene has broad symplectitic rims and white mica is partly to completely replaced by symplectitic fine-grained biotite and plagioclase. Preferentially oriented green amphibole porphyroblasts (22–32%) define the mineral lineation. In sample 13, newly formed epidote is abundant in decussate porphyroblasts. Clinopyroxene is completely decomposed to submicroscopically fine-grained first order symplectites (sample 9) and coarser second order amphibole-plagioclase-symplectites (samples C, 13). The garnets show partial re-

Tab. 1 Modal compositions (vol.%) of the Prijakt metabasite samples, determined by point counting (1000 points). Stars mark modes of coarse-grained amphibole-plagioclase symplectites.

	△	□	✳	△	✳	×	✳	△	×	△	⊗	×	○	○	○
	D	B	16	C	10	1	6	9	15	13	11	2	4	5	E
GARNET	8.7	10.6	0.4	7.4	1.0	11.3	-	17.7	24.4	10.6	23.2	26.9	13.4	13.6	13.4
CLINOPYROXENE	-	-	-	-	-	16.6	-	1.0	18.4	-	43.4	21.4	-	1.7	6.3
SYMPLECTITE	20.6	1.4*	1.1*	41.5*	-	29.8	18.9*	25.2	18.5	42.9*	15.3	9.5	19.8	46.5	34.2
AMPHIBOLE	54.8	60.4	67.2	26.7	50.3	8.0	61.4	32.8	20.1	22.6	3.9	22.3	36.1	13.8	15.6
EPIDOTE	0.5	0.7	-	2.6	4.9	2.8	1.8	-	-	8.5	-	3.2	2.0	5.8	3.8
CLINOZOISITE	8.4	11.1	10.5	8.9	6.7	10.3	-	1.1	1.3	1.6	8.0	1.6	1.0	1.7	12.7
MICA	-	3.3	-	1.2*	4.0	5.3	-	10.9	6.4	1.4*	-	-	6.1	3.8	0.6
PLAGIOCLASE	2.5	6.9	11.9	3.3	26.1	1.4	7.8	2.0	3.9	2.9	1.2	3.9	7.1	2.7	4.4
QUARTZ	2.9	3.7	7.0	4.0	3.6	6.4	5.4	5.5	4.5	6.4	1.9	7.7	7.2	1.0	3.8
SPHENE	0.9	0.1	1.9	0.2	2.4	1.4	0.4	1.3	1.9	1.2	2.0	2.4	2.6	2.4	2.6
OPAQUES	0.7	1.8	-	0.9	1.0	2.2	4.3	2.5	1.3	1.9	1.1	1.1	4.7	6.5	2.0
CALCITE	-	-	-	3.3	-	4.5	-	-	-	-	-	-	-	0.5	0.6
ΣREE (ppm)	43.02	52.02	64.44	75.37	84.14	59.17	59.18	91.96	96.23	105.31	88.49	86.64	96.41	99.92	125.88
mg#	51	48	43	40	38	37	35	34	33	32	30	30	26	25	25

placement by chlorite. Apart from the changes due to decompression reactions, samples C and 13 display additional changes by water-consuming reactions of retrogressive replacement.

Another group of symplectitic garnet-amphibolites (samples 4, 5, E, symbol ○) shows a symplectitic matrix with coarse garnet (14%, 3 mm in diameter) and green amphibole (length 1.5 mm). The garnets sometimes occur in lens-shaped clusters (sample 4). In samples 5 and E the lenticular clusters are 6 mm in diameter and the garnet crystals of the clusters are less than 1 mm in diameter. No isolated individual garnet idioblasts as in the other samples (described above) are found.

A garnet-amphibolite (sample B, symbol □) contains isolated garnets (10%, 3 mm in diameter) in a matrix of large green amphibole (60%), zoisite and epidote porphyroblasts and plagioclase (7%). Some coarse-grained amphibole-plagioclase-symplectites occur.

Amphibolites (samples 6, 10, 16, symbol ★) contain optically zoned green amphibole (length 1-2 mm) with preferential orientation or as decussate porphyroblasts. In sample 6 some coarse-grained amphibole-plagioclase-symplectites give evidence of the former presence of clinopyroxene.

No systematic spatial variation or distribution of these rock types and the lithological layers has been found in the two metabasite bodies. The groups of samples represent a range of an increasing degree of metamorphic overprinting of high-pressure rocks by decompression and cooling. Corresponding observed mineralogical changes are:

clinopyroxene$_I$ → clinopyroxene$_{II}$ + plagioclase (fine-grained symplectite)
clinopyroxene → amphibole + plagioclase (coarse symplectite)
garnet → green amphibole
garnet → epidote + chlorite
amphibole → epidote + chlorite
white mica → biotite + plagioclase + quartz (symplectite)

The decomposition of omphacite to symplectitic diopside and plagioclase was interpreted as isochemical by JOANNY et al. (1991). In contrast, O'BRIEN et al. (1992) proposed an anisochemical reaction $Cpx_I + SiO_2aq = Cpx_{II} + Pl$ balanced by O_2, Mg, Na and Fe for formation of first order fine-grained symplectites. Correspondingly, the formation of coarse-grained second order symplectites via a reaction $Cpx_I + SiO_2aq + H_2O = Cpx_{II} + Am + Pl$ (FRANZ et al., 1986) should be balanced by Na, K and Ca.

Reactions pertaining to the development of amphibole from garnet-clinopyroxene assemblages may be of the form $Cpx + Ab + H_2O = Prg + An + Qtz$ or $Grt + Cpx + Pl + H_2O = Hbl + Qtz$, the latter could be responsible for the formation of green amphibole rims around garnet porphyroblasts.

Transformation of amphibole to epidote and chlorite could have been controlled by reactions of the type $Am + An + H_2O = Ep/Zo + Chl + Qtz$. The decomposition of white mica was formulated as $Phe_I + SiO_2 = Phe_{II} + Bt + Pl$ and balanced by Na, K, Ca by FRANZ et al. (1986).

Tab. 2 Bulk rock composition of the analyzed Prijakt metabasites, in weight% for oxides and in ppm for trace and rare-earth elements. Specific weight (ρ) in g/cm³. Stars mark INA analyses.

	△	□	✳	△	✳	×	✳	△	×	△	⊗	×	○	○	○
	D	B	16	C	10	1	6	9	15	13	11	2	4	5	E
SiO_2	48.57	46.75	48.14	46.78	49.96	47.34	47.97	49.46	48.07	49.56	48.17	48.04	47.78	47.37	48.45
TiO_2	0.66	1.29	1.41	1.64	1.73	1.48	1.97	1.83	1.92	1.79	2.00	2.04	2.92	2.67	2.37
Al_2O_3	15.93	16.86	16.23	16.39	15.33	16.45	16.60	14.56	15.13	15.26	14.07	14.11	14.03	14.26	14.76
FeO_{tot}	10.05	10.05	11.24	11.61	11.88	10.96	12.98	13.39	14.26	13.43	14.53	14.64	15.88	14.73	14.39
MnO	0.22	0.15	0.19	0.15	0.17	0.15	0.22	0.20	0.20	0.22	0.20	0.22	0.22	0.22	0.22
MgO	9.32	8.42	7.66	7.00	6.55	5.82	6.41	6.23	6.32	5.65	5.65	5.76	4.95	4.47	4.26
CaO	10.89	11.44	10.48	11.03	9.03	11.28	9.38	9.26	9.03	9.23	11.39	11.19	9.41	11.05	10.05
Na_2O	2.63	2.67	2.47	2.95	3.02	3.60	3.20	4.12	3.89	2.93	3.44	3.27	3.95	3.57	3.69
K_2O	0.19	0.25	0.28	0.24	0.32	0.56	0.14	0.35	0.40	0.64	0.01	0.01	0.22	0.08	0.10
P_2O_5	0.14	0.20	0.24	0.30	0.27	0.19	0.27	0.22	0.22	0.22	0.22	0.22	0.27	0.30	0.30
CO_2	0.05	0.37	0.20	0.21	0.21	1.03	0.05	0.05	0.08	0.05	0.07	0.13	0.06	0.30	0.49
H_2O+	1.82	1.95	2.07	2.04	2.25	1.19	1.69	0.78	0.90	1.80	0.53	0.49	0.74	0.84	1.12
total	100.47	100.40	100.61	100.34	100.72	100.05	100.88	100.45	100.42	100.78	100.27	100.12	100.43	99.86	100.20
Ba	<5	157	30	79	<5	26	54	46	74	76	5	7	34	32	76
Co	40	38	39	42	30	32	42	43	44	38	46	47	48	44	36
Cr	431	310	249	280	231	246	173	240	211	180	125	146	90	84	123
Cu	78	78	65	60	64	37	30	94	78	85	65	79	57	71	74
Ga	6	19	24	20	23	<5	29	24	22	23	24	23	25	33	29
Nb	<5	<5	5	6	6	<5	7	5	6	6	5	6	9	8	7
Ni	175	179	138	125	123	157	77	184	139	99	176	236	175	179	115
Rb	9	14	10	9	14	15	6	9	9	17	<5	<5	6	5	8
Sc	36	36	38	42	37	43	39	47	49	44	48	49	44	41	41
Sr	107	226	249	221	134	174	141	71	83	52	124	113	28	156	242
V	192	237	249	287	287	255	309	315	301	285	373	366	438	424	322
Y	18	24	29	31	39	33	34	46	56	52	46	47	52	49	58
Zn	99	73	83	92	98	88	99	100	108	100	97	105	135	106	104
Zr	38	70	94	111	142	99	128	173	185	211	170	174	216	197	224
La	3.78	4.44	6.22	7.83	9.66	3.20	4.92	7.90	8.16	10.75	6.76	6.69	8.02	8.44	10.67
Ce	16.89	19.15	21.29	28.47	30.82	22.09	25.98	27.87	30.04	33.65	29.21	28.07	29.47	31.89	42.86
Nd	7.59	10.60	12.95	15.70	18.07	11.41	11.13	19.45	20.03	22.05	17.98	18.15	21.32	21.89	25.71
Sm	2.50	3.60	4.06	4.91	5.57	3.96	3.49	6.95	6.88	7.28	6.08	6.10	7.02	7.01	8.57
Eu	0.86	1.14	1.38	1.58	1.65	1.35	1.07	1.99	2.11	2.07	1.93	1.81	2.00	2.20	2.61
Gd	3.49	4.28	4.90	5.18	6.05	4.94	3.84	7.77	8.10	7.99	6.99	7.01	7.55	8.15	9.83
Dy	3.44	3.95	5.26	5.50	6.34	5.50	3.91	8.86	9.28	9.37	8.50	8.25	9.29	9.26	10.68
Er	2.10	2.31	3.04	2.83	3.71	2.99	2.30	5.12	5.34	5.49	4.99	4.75	5.38	5.08	6.00
Yb	1.99	2.15	2.87	2.85	3.64	3.17	2.13	5.18	5.39	5.72	5.19	4.99	5.42	5.13	6.12
Lu	0.38	0.40	0.47	0.52	0.63	0.56	0.41	0.87	0.90	0.94	0.86	0.82	0.94	0.87	1.05
Tb*	0.44	0.60			1.03	0.99			1.22		1.24				1.78
Th*	0.57	-			1.35	0.34			1.23		0.81				1.38
Cs*	-	0.30			0.76	0.66			0.38		-				0.81
Hf*	1.63	2.29			4.15	3.30			5.54		5.26				7.60
Ta*	0.11	0.12			0.41	-			-		0.14				0.34
$(Ce/Yb)_N$	2.20	2.31	1.92	2.59	2.19	1.80	3.16	1.39	1.44	1.52	1.46	1.46	1.41	1.61	1.81
g/cm^3	3.10	3.07	3.02	3.07	3.00	3.16	3.03	3.14	3.22	3.06	3.42	3.39	3.24	3.28	3.09
mg#	51	48	43	40	38	37	35	34	33	32	30	30	26	25	25

Rock chemistry

After grinding in an agate mill, the set of 15 samples has been analyzed by XRF and ICP-AES (Centre de Recherches Pétrographiques et de Géochimiques à Vandœuvre-lès-Nancy) for 26 major and trace elements, and for rare-earth elements. Data for Th, Ta, Hf, Tb, Cs and some other REE was obtained by INA analysis (Lehrstuhl für Angewandte Mineralogie und Geochemie der TU München). Contents of CO_2 and H_2O+ were determined by wet chemical methods. Table 2 contains the analyses and figure 2 shows selected elements plotted against the mg-number (mg# = 100 (MgO/(MgO + FeO)) for FeO/Fe_2O_3 = 0.15). Apart from the samples 4, 5, E (symplectitic garnet-amphibolites with garnet clusters) which have the lowest mg-numbers, the other rock groups are not sharply distinguished by their mg-numbers and the values of the groups overlap in the whole range between mg# 25 to 51. CIPW-values (calculated for FeO/Fe_2O_3 = 0.15) show ol-hy normative to slightly ne-normative compositions.

On binary diagrams with mg# or Zr as fractionation index, random distributions of SiO_2,

CaO, Ba, Sr and no correlation of K_2O are obvious (Fig. 2). Especially alkali elements are considered to be very susceptible to mobility and redistribution during metamorphism. Tight clusters of the data in a $Na_2O + K_2O$ vs SiO_2 plot (not shown) and smooth trends in the AFM diagram with no outliers indicate that samples with possibly mobilized alkali elements have not been taken. K and Rb contents are low (< 5000 and < 20 ppm) and show a linear and positive correlation in Rb–K coordinates (not shown). Generally

the low K_2O contents (< 0.7%) in combination with the small mode of white mica exclude a pervasive K-metasomatism. Possible spilitization causes typical element patterns (STILLMAN and WILLIAMS, 1978). The range of CaO contents is small (9–11.5%) compared to observations from other studies (e.g. DÜRR et al., 1993) and a tight cluster of the data in Na_2O vs CaO coordinates with no outliers provides no hint of spilitization. Na_2O contents between 2.5 and 4.0% increase with decrease of H_2O from 2.25 to 0.5%. There is
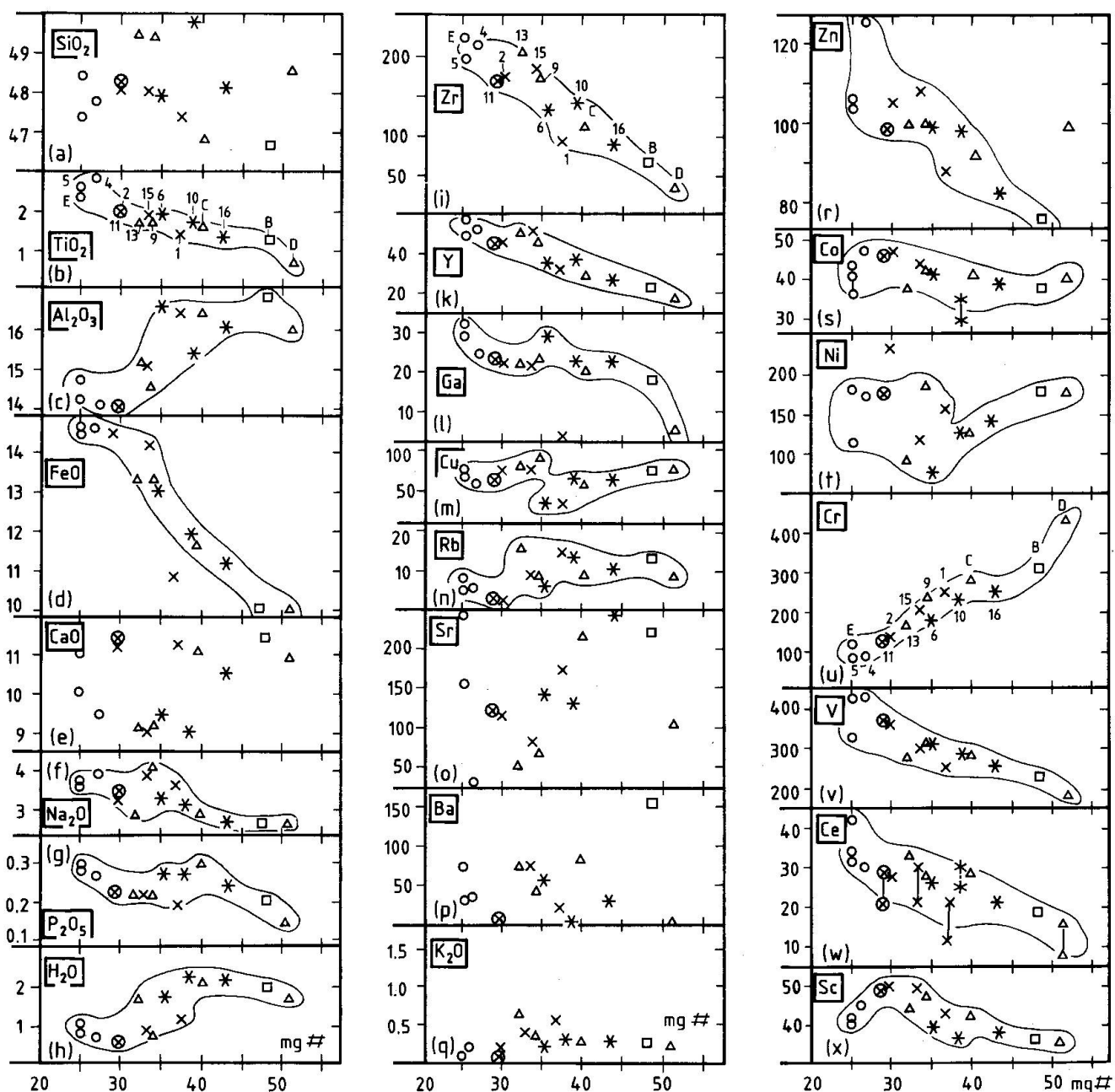

Fig. 2 (a) – (x) Bulk rock composition of metabasites from the Prijakt area, Schobergruppe, as a function of the mg-number (mg# = 100 (MgO/MgO + FeO), for FeO/Fe_2O_3 = 0.15). Scales in a–h and q are in weight%, the other scales are in ppm. ⊗: eclogite. ×: amphibole-eclogites. △: symplectitic garnet-amphibolites. ○: symplectitic garnet-amphibolites with coarse garnet and garnet clusters. □: garnet-amphibolites. *: amphibolites.

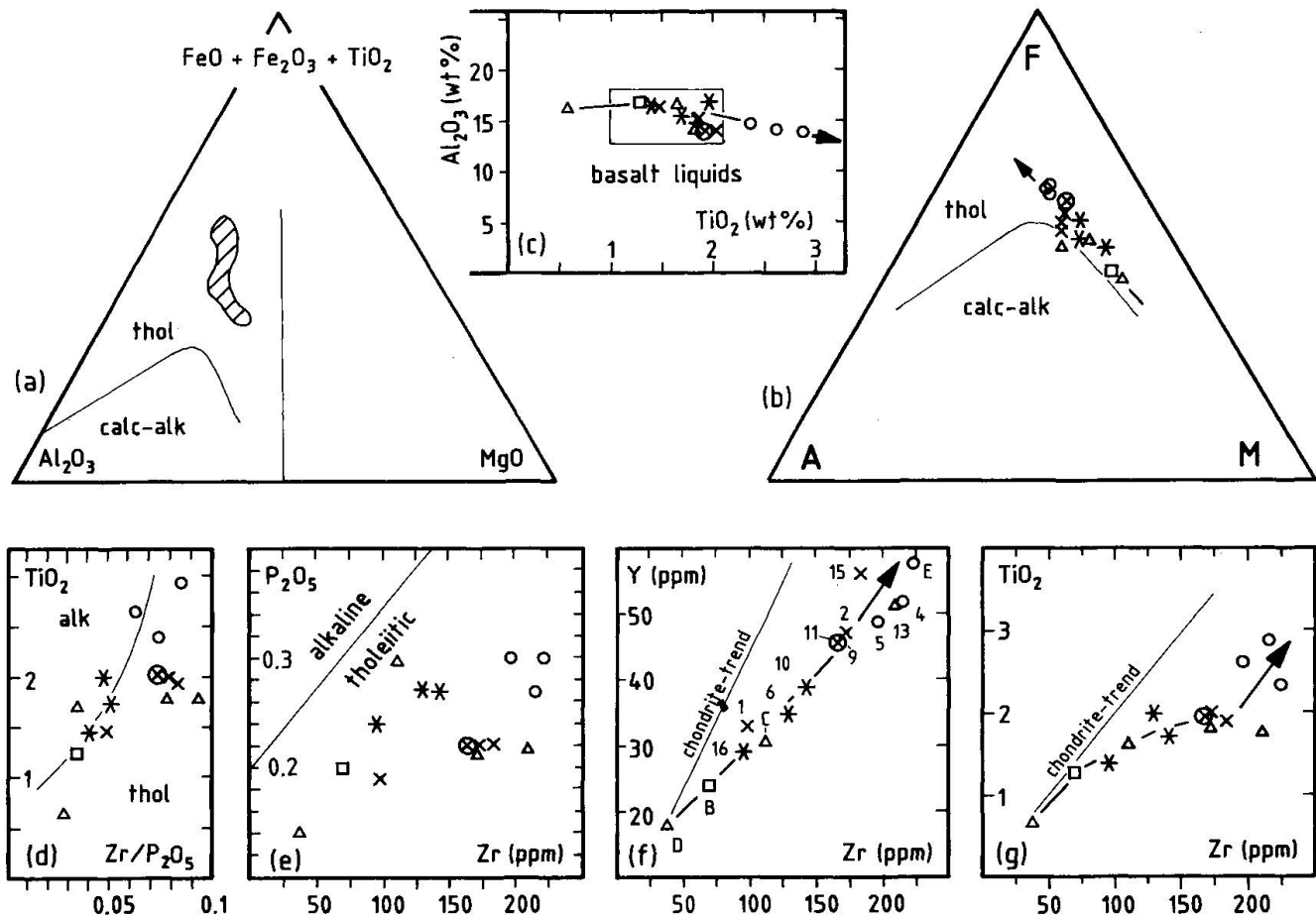*Fig. 3* Major element compositions of the metabasites in the Jensen cation plot (a) and (b) in the AFM diagram with $A = Na_2O + K_2O$; $F = FeO_{tot}$; $M = MgO$. (c) TiO_2–Al_2O_3 diagram after PEARCE (1983), rectangle: field of basaltic liquids. (d) Metabasites plotted in the discrimination diagram of FLOYD and WINCHESTER (1975). alk alkaline basalts; calc-alk calc-alkaline basalts; thol tholeiitic basalts. (e) Diagram after WINCHESTER and FLOYD (1976a; 1976b). (f), (g) Zr–Y and Zr–TiO_2 correlation diagrams to test the immobility of incompatible trace elements. Symbols as in figure 2. Arrows indicate chemical trends from high to low mg-numbers of samples.

no systematic correlation between the water contents, a possible indicator of the degree of retrogression, and these elements. In contrast, H_2O shows weak positive correlation with mg#. The degree of post-eclogitic overprinting visible by petrographic methods is independent of bulk composition. Multi-element patterns normalized to average N-type MORB (Fig. 5d) show enrichment relative to MORB for the elements with low ionic potential (Sr, K, Rb, Ba) and concentrations close to unity for the elements with intermediate to high ionic potential (P, Zr, Sm, Ti, Y, Yb, Sc, Cr). The first group of elements tends to be mobile during sea-floor weathering, metamorphism or metasomatic alteration (PEARCE, 1975; 1976). However, SiO_2, CaO, K, Rb, Ba, Sr show no distinct relation to the degree of post-eclogitic metamorphic overprinting or possible pre-eclogitic processes and thus are considered to represent original geochemical properties of the protoliths.

A positive correlation with mg# is shown by Cr. For Ni such a positive correlation is only realized for the early fractionation stages (mg# 51–30) and not for the more evolved samples (Fig. 2 t, u). Weak positive correlation with mg# are observed for Al_2O_3 and H_2O (Fig. 2 c, h). FeO, TiO_2, Na_2O, P_2O_5 as well as Zr, Y, Ga, Ce, Sm, Nd, Zn display clear negative correlations with the mg# fractionation index (Fig. 2). Systematic trends in AFM and Jensen cation plots, and systematic MORB-normalized distribution patterns are observed (Fig. 3 a, c, 5d). Similar correlations are observed with Zr as fractionation index. They indicate the postmagmatic immobility of these elements.

It is generally accepted that REE could be reliable geochemical tracers due to their relative unsolubility and refractory nature. However, there is some debate about the possible mobile behaviour of REE during weathering and meta-
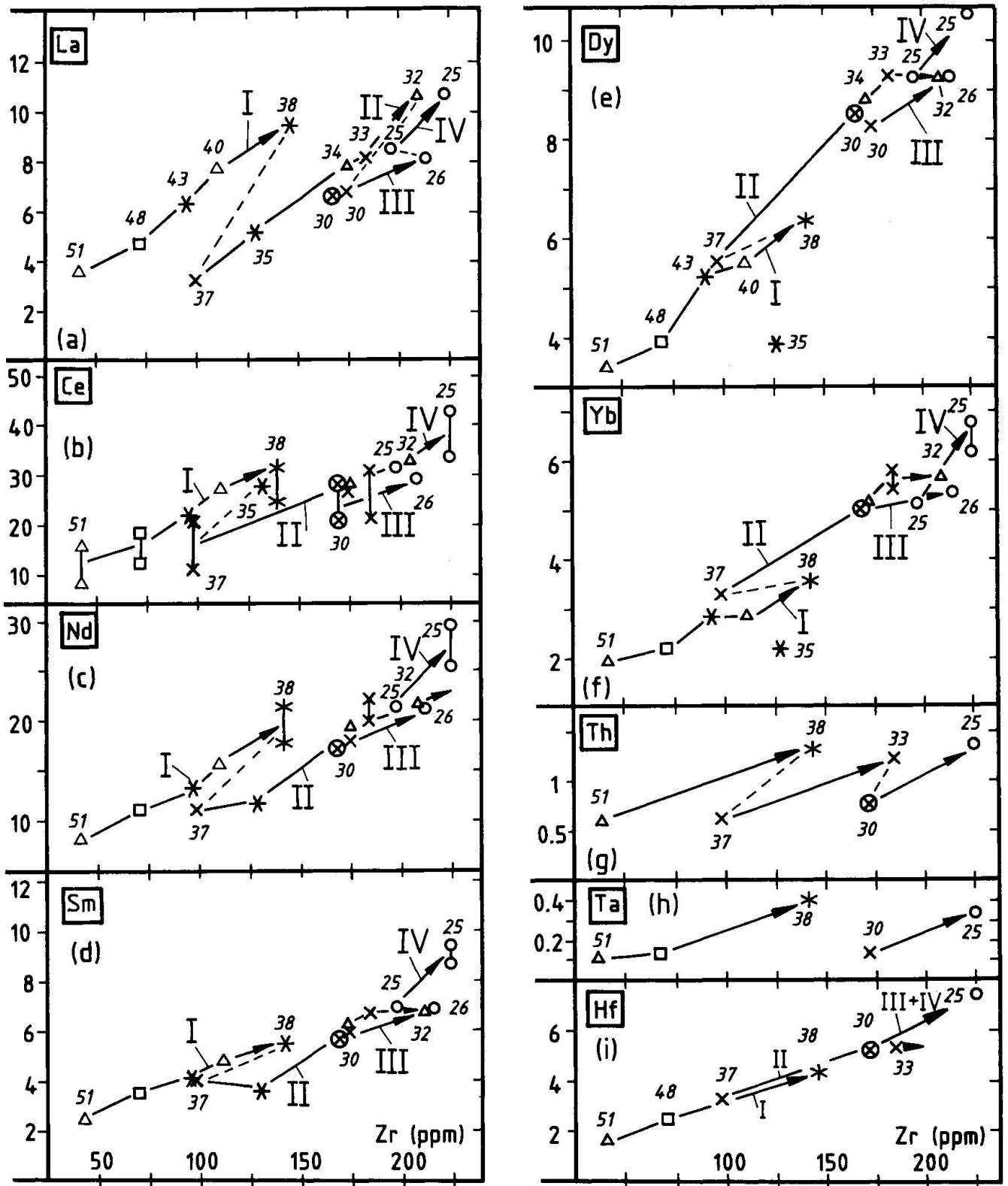
Fig. 4 (a) – (i) Rare-earth element and Th, Ta, Hf versus Zr correlation diagrams, all scales in ppm. Symbols as in figure 2. The numbers are the mg-numbers; the arrows indicate the magmatic REE fractionation cycles I–IV along decreasing mg-numbers and increasing-decreasing Zr. Note sample 6 with mg# 35 which does not fit into the general trends in (e) and (f).

morphism. BERNARD-GRIFFITHS et al. (1985), BERNARD-GRIFFITHS and CORNICHET (1985) and SHATSKY et al. (1990) demonstrated the immobility of REE in metabasites during eclogitic high-pressure and amphibolite-facies high-temperature metamorphism. In contrast, HELLMAN et al. (1979) stated that REE patterns from metadomains may be subparallel to each other and to those of relic domains within the same basalt flow. They argued that such regular parallel patterns may result from coherent REE mobility. Thus, from parallel patterns alone it is not possible to exclude REE immobility during rock alteration. It has been further suggested that strong variations in La/Yb, La/Sm and Ce/Yb as in the Prijakt metabasites (La/Yb 1.0–2.74; La/Sm 0.80–1.73 and Ce/Yb 1.44–3.16) could be a result of REE mobility. Another criterion by which the immobility of REE and also Ti, Zr and Y has been assessed is whether there exists a straight line correlation between such "immobile" elements and REE (MUECKE et al., 1979).

In order to test the data for possible shifts by mobile behaviour, the REE were plotted versus Zr and mg# as fractionation indexes (Fig. 4). A linear increase of La from low to almost maximal values with increasing Zr and mg# is observed. This trend stops at mg# 38. For the sample with mg# 37 the La as well as the Zr values are considerably lower. For mg# 37 to 32 the La and Zr contents again display a straight linear increase. This increase ends at mg# 32 and is repeated for the mg# 30 to 26, again starting at lower La and Zr contents compared to the sample with the mg# 32. A third repetition of these linearly increasing La and Zr contents is observed from the two samples with mg# 25 (Fig. 4a). This four-stage "sawtooth" like linear increase-decrease of the REE and Zr along decreasing mg-numbers is similarly observed from the LREE, the HREE, ΣREE and can be recognized as well for Hf, Ta, Th, Cs and Tb of which only a few analyses exist (Fig. 4). The slopes for the increasing REE and Zr segments are quite constant, but the amount of decrease of the REE between mg# 38 to 37, 32 to 30 and 26 to 25 appears to get lower with higher atomic numbers of the REE.

Usually, garnet and epidote group minerals contain a major part of the bulk REE in metamorphic basic rocks. However, there is no linear or systematic relationship between ΣREE and modes of garnet, modes of epidote group minerals or the sum of these modes (Tab. 1). These peculiar but systematic relationships among REE, Zr and mg-numbers suggest an element distribution controlled by a magmatic process. The samples with the different Zr contents and mg-numbers could

represent "frozen" steps along a progressive, cyclic and discontinuous magmatic fractionation. Presumably REE and Zr were enriched in the remaining melt and increased when magmatic Fe-Mg minerals (e. g. olivine, orthopyroxene, clinopyroxene, amphibole) successively crystallized along the decreasing mg-numbers 52–38, 37–32, 30–26 and 25. Only sample 6 (amphibolite, mg# 35) with very low HREE contents, low mode of epidote and no garnet, and sample 2 (amphibole-eclogite, mg# 30) with slightly lower HREE contents do not fit into this complex scheme (Fig. 4 e, f). This may give a hint to a possible post-magmatic depletion of HREE in these two samples.

The C1-chondrite normalized patterns (NAKAMURA, 1974) are almost parallel for all studied samples (Fig. 5e). In contrast to the observations of HELLMAN et al. (1979), the degree of REE enrichment (15–50 times chondrite) is strictly correlated with the mg-numbers. Samples with lower mg-numbers are more enriched in REE. A slight negative Eu anomaly, usually thought to indicate the influence of plagioclase fractionation during basaltic magma genesis, is preserved in all patterns. Similarly a positive Ce anomaly is also observed in all samples. Thus, the parallel REE patterns indicate an enrichment along a fractionation trend and systematic shifts of REE during post-magmatic processes can be excluded. In each case the behaviour of REE contents versus two fractionation indexes (Zr and mg#) gives more detailed information on possible re-distribution, mobility and magmatic fractionation processes in a set of samples as the chondrite-normalized patterns alone.

Origin of the metabasites

The substantial preservation of geochemical signatures in the metabasites allows conclusions of the provenance and characteristics of the magmatic protoliths. Several attempts have been made to discriminate metasedimentary amphibolites from metagabbros or metabasalts (e.g. EVANS and LEAKE, 1960; FRÖHLICH, 1960; LEAKE, 1964; EVANS et al., 1981). High Cr contents exceeding 100 ppm, positive correlation of Cr with mg# and Cr/Ni ratios mostly higher than one provide arguments for a magmatic origin of the metabasites. PEARCE (1983) proposed an Al_2O_3/TiO_2 screen to separate cumulates from true basaltic liquids. Apart from sample D which is the most primitive and samples 4, 5, E which are the most evolved, the others plot in the basalt liquid field (Fig. 3c). PFEIFER et al. (1989) demonstrated that the original grain size (fine-grained

basalts, coarse-grained gabbros), at least for Mesozoic rocks, was largely preserved even during polyphase high-grade metamorphism. Accordingly, the grain sizes of the Prijact metabasites suggest volcanic or subvolcanic rather than plutonic protoliths. However, a considerable uncertainty of this interpretation results from the almost complete recrystallization of the rocks during metamorphism and coeval deformation. In addition, the TiO_2 contents (< 0.66%) and the V contents (> 192 ppm) exclude a gabbroic origin (PFEIFER et al., 1989) for the Prijakt metabasites.

The samples show tholeiitic to slightly alkaline basalt compositions in the discrimination diagram of FLOYD and WINCHESTER (1975) of figure 3d. Significant trends of Fe-enrichment in the Jensen cation plot and in AFM coordinates (Fig. 3 a, b), as well as positive correlation of FeO/MgO with FeO, TiO_2 and V determine a tholeiitic character of the metabasites. Enrichment of FeO along a fractionation index is also typical for tholeiitic magmatic series (Fig. 2d).

Concentrations of Ti, Zr, Y and Cr in the samples are typical for mid-ocean ridge basalts. In the Ti–Zr–Y diagram after PEARCE and CANN (1973) the analyses plot into the field of MORB and island arc tholeiites. Apart of sample D which is the most primitive, the other samples have only slightly elevated Zr/Y ratios compared to C3 chondrite in Zr vs Zr/Y coordinates (Fig. 5c), typical for N-MORB composition (PEARCE, 1980) and follow a distinct trend in the MORB field of the Ti/Cr vs Ni coordinates of BECCA-LUVA et al. (1983). Ti/V ratios of 20–44 correspond to values for MORB and within plate basalts (Fig. 5b). Contents of HFSE are Zr 38–224 ppm, Y 18–58 ppm and Nb < 5–9 ppm. The slight negative slope between P and Y signifies Zr/Y ratios (2.11–4.15), Zr/Nb ratios (18–35) and TiO_2/P_2O_5 ratios from 4.71–10.81 in the MORB compositional field. In the Th–Hf–Ta diagram (not shown), however, the Prijact metabasites plot near the Th–Hf/3 tie line in the field of magma series at destructive plate margins (WOOD, 1980). Summing up, in most classical trace element diagrams (cf. PEARCE, 1983) the majority of the analyses falls into the field of mid ocean ridge basalts (MORB), but some with high mg-numbers straddle the limit between mid-ocean ridge and island arc basalts (Fig. 5a–c).

Despite their origin from a single metabasite outcrop, the samples exhibit limited and systematic trace element variations and compositions which strongly suggest a magmatic differentiation series. However, in the MORB-normalized distribution diagram (Fig. 5d), the large ion litho-phile elements show an enrichment compared to N-MORB or the typical N-MORB pattern. Such an enrichment of Sr, K, Rb, Ba, Nb corresponds to patterns observed from tholeiitic within-plate basalts (PEARCE, 1982). In the chondrite-normalized representation (NAKAMURA, 1974), the HREE follow the typical flat N-MORB enrichment pattern with 10–50 times chondritic abundances. This is not true for the LREE which display a slightly higher degree of enrichment as the HREE (Fig. 5e). Ratios of $(Ce/Yb)_N$ are between 1.39 and 3.16, the ratio $(La/Ce)_N$ is < 1 for all samples. Furthermore, a slight negative Eu-anomaly can be observed. Both LIL and LRE elements enrichments can be interpreted to reflect an influence of continental crust or a "crustal component" during melt formation. Thus, the protoliths of the metabasites could be characterized as enriched N-MOR basalts.

The good positive or negative correlations of numerous major, trace and RE elements with Zr or mg-numbers reflect strong fractional crystallization control. Furthermore, the continuous, parallel and fractionation-dependent sequences of enrichment in normalized element patterns indicate derivation from a single fractionating source of enriched N-MORB character. Due to their relatively low Ni contents (125–180 ppm) the least evolved metabasites do not correspond to primitive mantle derived melts but are differentiated products of such melts. A 10–20% melting of a plagioclase lherzolite (C3) source is suggested to have produced the primary magmas of the protoliths when the absolute Cr (84–431 ppm) and Y (18–58 ppm) contents of the metabasites are considered in the model of PEARCE (1980). The evolution trend in the Zr–Zr/Y diagram (PEARCE, 1980) signalizes a partial melting trend for a slightly depleted-C3 chondrite mantle source, with a subsequent closed system fractional crystallization. The slope of the trend in Zr vs Zr/Y coordinates approximates the olivine-clinopyroxene-plagioclase crystallization vectors, suggesting that these were dominant phases, and the source area was therefore subject to low-pressure fractionation. Thus the data from the Prijakt metatholeiites favour a provenance of the protoliths from a mantle source in < 30 km depth, with Zr/Y ratios lower as the C3-chondrite and depleted in incompatible elements (Fig. 5c).

Magmatic differentiation is well known from diabase dikes (PAPEZYK and HODYCH, 1980) and it appears possible that the Prijakt metabasites represent a former thick layered dyke or sill which intruded the psammopelitic host rocks. Until now, no meta-ultramafic rocks have been described from the MPU unit. The isolated oc-
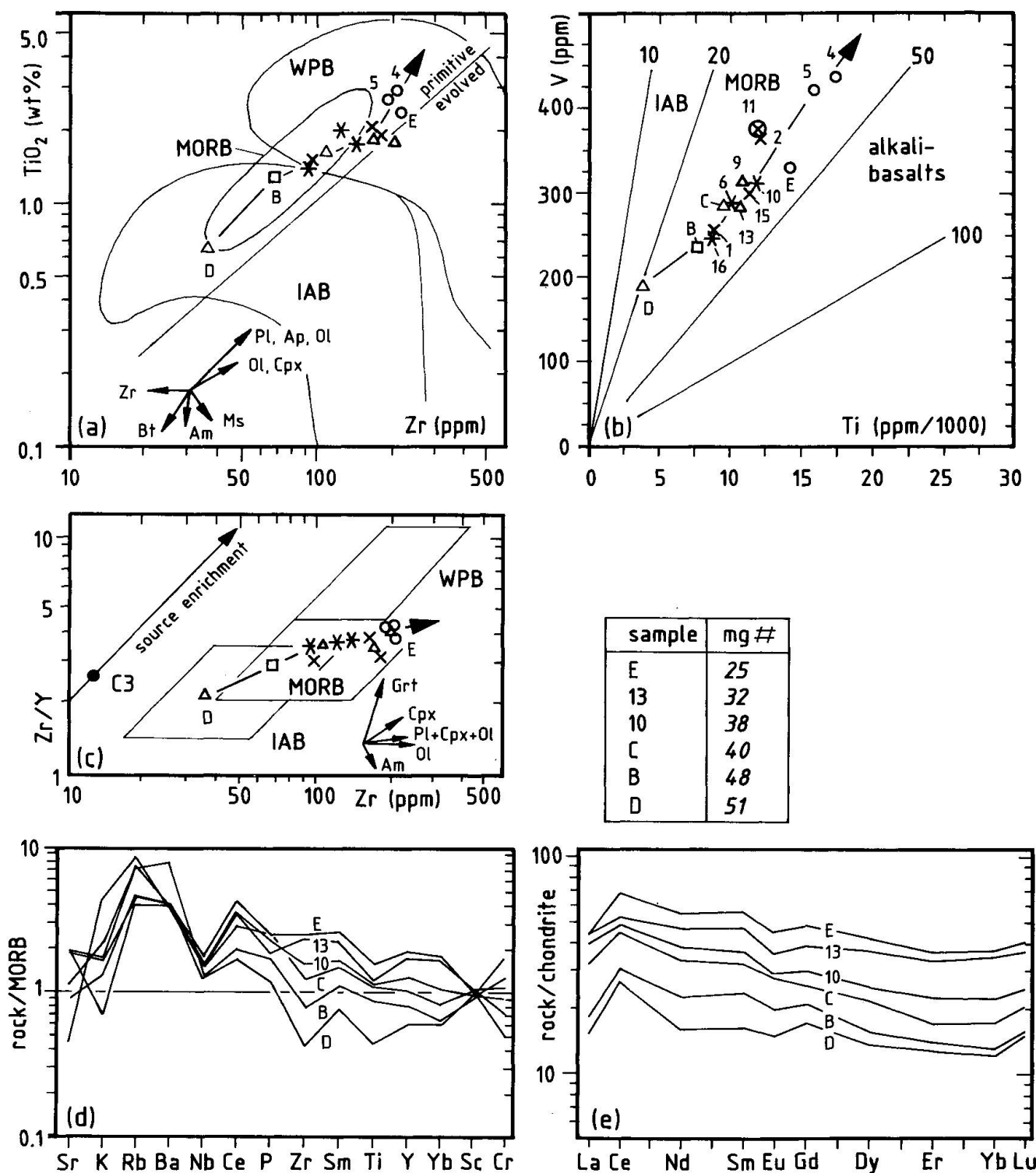
Fig. 5 (a) TiO₂-Zr diagram after PEARCE and CANN (1973). The metabasites plot into the field of MORB. Differentiation trends for specific minerals are shown. IAB island arc basalts; MORB mid-ocean ridge basalts; WPB within-plate basalts. (b) V-Ti/1000 diagram (SHERVAIS, 1982). The metabasite analyses cluster in the field of mid-ocean ridge basalts. (c) Zr-Zr/Y diagram of PEARCE and NORRY (1979). The analyses plot in the MORB field. Fractionation trends of specific mineral assemblages are shown. C3 is a plagioclase-lherzolite source. The arrows indicate the fractionational crystallization trend of the samples from high to low mg-numbers. (d) MORB-normalized variation diagram (HOFMANN, 1988) of several selected samples. (e) Chondrite (C1) normalized REE variation diagram (NAKAMURA, 1974) of selected samples. The patterns are parallel for samples with different mg-numbers and show increasing enrichment with decreasing mg#.

currence of the metabasites in predominant meta-psammopelitic sequences do not favour a mid-ocean ridge or island-arc setting of the protoliths. Commonly, metabasites with general geochemical characteristics as outlined above are interpreted in a context of lithospheric extension in the pre-Alpine basement units (MAGGETTI and GILLETTI, 1988; VON RAUMER et al., 1990; MÉNOT and PAQUETTE, 1993). It seems likely that the magmatic protoliths were related to a plate margin setting along an incipient continental rift zone at the onset of ocean floor spreading and continental breakup.

This interpretation about the former geotectonic setting of the protoliths could be enlarged by some specific geochemical characteristics of the Prijakt metabasites. Due to $(Tb/Ta)_N$ from 0.93–3.31 and $(Th/Ta)_N$ between 1.38 and 2.50, all four analyzed metabasite samples (10, D, 11, E) plot into the narrow field of back-arc basin basalts between N-MORB and subduction-zone OIA/IA basalts in the revised and corrected Th–Tb–Ta diagram of THIÉBLEMONT et al. (1994). The $(Th/Ta)_N$ ratios do not exceed 2.5 as observed in subduction-zone basalts (JORON and TREUIL, 1977) but are higher as found in N-MORB. A possible back-arc setting of the Prijakt metabasites is additionally supported by their distinct LIL element (Sr to Th) enrichment (Fig. 5d). As reported by FRISCH and RAAB (1987) and HÖCK (1993) from the Habach formation (Tauern Window), such an enrichment could be interpreted as a "subduction component", resulting of a release of highly mobile LIL elements from the downgoing slab and their later incorporation into the overlying mantle wedge. Possibly, a lithospheric extension in the Austroalpine realm with the emplacement of the Prijakt basic rocks has been triggered by a subduction zone situated far to the north.

Position of the metabasites in the Austroalpine basement

Despite their metamorphic history, the Prijakt metabasites have preserved chemical patterns of an igneous differentiation series with enriched N-MORB characteristics. It is of interest to discuss the position of the Prijakt amphibolitized eclogites among the other metabasites in the Austroalpine basement complex to the south of the Tauern Window. Metabasites are abundant in the AMU unit. These amphibolites are metamorphosed basic magmatites. GODIZART (1989) recognized that pre-Alpine and Alpine events had caused no significant changes of HFSE and REE

variation trends in these rocks and distinguished two groups: Group 1 metabasites are low in incompatible elements and show affinities to MORB with respect to HFSE abundances and Zr/Y, Zr/Nb and Ti/V element ratios. Group 2 metabasites with transitional to alkaline compositions are similar to OIB (SCHULZ et al., 1993). The Prijakt metabasites from the MPU are similar to the Group 1 metabasites, however, some differences exist: The Prijakt metabasites are slightly more enriched in LREE and display an "undulating" pattern of HFS elements compared to the plane pattern of Group 1 amphibolites. Furthermore, the Ti/Cr vs Ni trends during fractionation are different with quite constant Ni contents in the Prijakt metabasites and decreasing Ni in Group 1 amphibolites when Ti/Cr increases (not shown). Group 2 transitional to alkaline metabasites in the AMU are significantly enriched in HFSE and LREE and depleted in HREE. Their REE patterns are fractionated with La_N/Yb_N 14.6–19.6. These amphibolites cannot be related to Group 1 and Prijakt metabasites by simple magmatic fractionation processes or different degrees of partial melting. They are interpreted to have developed from an enriched deep mantle source in a within-plate setting (GODIZART, 1989). Until now, a further group of metabasites in the sequence of the Schwarze Wand (Croda Nera) in the southern part of the AMU has not been classified by geochemical methods. No geochemical data exist from the other metabasites of the MPU. KREUTZER (1991) described the metabasites in the eastern part of the phyllitic Thurntaler Complex as former tholeiitic within-plate basalts. Within-plate alkalibasalts of Ordovician, Silurian and Devonian age in the other Palaeozoic sequences of the Eastern Alps are interpreted to testify a long lasting extensional process, generally thinning of continental crust and subsidence of marginal basins (LOESCHKE and HEINISCH, 1993).

As long as no radiometric data exist for the AMU and MPU metabasites and the geochemical data are incomplete, it could be speculated that Group 1 rocks represent an early stage, the Prijakt metabasites and the within-plate transitional to alkaline basalts of Group 2 later stages of the magmatic evolution during a continental extension by incipient rifting. No geochemical and genetic linkage between the Upper-Ordovician calc-alkaline acid plutonism in the AMU and MPU, the contemporaneous acid volcanism in the phyllitic and Palaeozoic sequences, and the basic magmatism in the Austroalpine has been found yet (PECCERILLO et al., 1979; HEINISCH, 1981; KREUTZER, 1991). The geotectonic

consequences and relationships of these magmatic events in the Austroalpine realm still have to be investigated.

References

BECCALUVA, L., DI GIROLAMO, P., MACCIOTTA, G. and MORRA, V. (1983): Magma affinities and fractionation trends in ophiolites. Ofioliti, 8, 307–324.

BEHRMANN, J.H. (1990): Zur Kinematik der Kontinent-kollision in den Ostalpen. Geotekt. Forsch., 76, 1–180.

BERNARD-GRIFFITHS, J. and CORNICHET, J. (1985): Origin of eclogites from southern Brittany, France: A Sm–Nd isotopic and REE study. Chemical Geology, 52, 185–201.

BERNARD-GRIFFITHS, J., PEUCAT, J.-J., CORNICHET, J., PONCE DE LÉON, M.I. and IBARGUCHI, J.I.G. (1985): U–Pb, Nd isotope and REE geochemistry in eclogites from the Cabo Ortegal complex, Galicia, Spain: an example of REE immobility conserving MORB-like patterns during high-grade metamorphism. Chemical Geology, 52, 217–225.

BORSI, S., DEL MORO, A., SASSI, F.P., VISONA, D. and ZIRPOLI, G. (1980): On the existence of Hercynian aplites and pegmatites in the lower Aurina Valley (Ahrntal, Austrides, Eastern Alps). N. Jb. Miner. Mh., 1980, 501–514.

BORSI, S., DEL MORO, A., SASSI, F.P. and ZIRPOLI, G. (1973): Metamorphic evolution of the Austridic rocks to the south of the Tauern Window (Eastern Alps): radiometric and geopetrologic data. Mem. Soc. Geol. Ital., 12, 549–571.

BORSI, S., DEL MORO, A., SASSI, F.P., ZANFERRARI, A. and ZIRPOLI, G. (1978): New geopetrologic and radiometric data on the Alpine history of the Austridic continental margin south of the Tauern Window. Mem. Ist. Geol. Min. Univ. Padova, 32, 1–17.

BRACK, W. (1977): Geochronologische Untersuchungen an Gesteinen des Altkristallins in der Schobergruppe, Österreich. Dissertation Ludwig-Maximilians-Universität München (unpubl.).

CLAR, E. (1927): Ein Beitrag zur Geologie der Schobergruppe bei Lienz in Tirol. Mii. Naturwiss. Ver. Steiermark, 63, 72–90.

CLIFF, R.A. (1980): U–Pb isotopic evidence from zircons for lower Palaeozoic tectonic activity in the Austroalpine nappe, the Eastern Alps. Contrib. Mineral. Petrol., 71, 283–288.

DÜRR, S.B., RING, U. and FRISCH, W. (1993): Geochemistry and geodynamic significance of North Penninic ophiolites from the Central Alps. Schweiz. Mineral. Petrogr. Mitt., 73, 407–419.

EVANS, B.W. and LEAKE, B.E. (1960): The composition and origin of the striped amphibolites of Connemara, Ireland. J. Petrol., 1, 337–362.

EVANS, B.W., TROMMSDORFF, V. and GOLES, G.G. (1981): Geochemistry of high-grade eclogites and metarodingites from the Central Alps. Contrib. Mineral. Petrol., 76, 301–311.

FLOYD, P.A. and WINCHESTER, J.A. (1975): Magma type and tectonic setting discrimination using immobile elements. Earth Planet. Sci. Lett., 27, 211–218.

FRANZ, G., THOMAS, S. and SMITH, D.C. (1986): High-pressure phengite decomposition in the Weissenstein eclogite, Münchberger Gneiss Massif, Germany. Contrib. Mineral. Petrol., 92, 71–85.

FRISCH, W., MÉNOT, R.-P., NEUBAUER, F. and VON RAUMER, J. F. (1990): Correlation and evolution of the Alpine basement. Schweiz. Mineral. Petrogr. Mitt., 70, 265–285.

FRISCH, W., NEUBAUER, F., BRÖCKER, M., BRÜCKMANN, W. and HAISS, N. (1987): Interpretation of geochemical data from the Caledonian basement within the Austroalpine basement complex. In: FLÜGEL, W., SASSI, F.P. and GRECULA, P. (eds): Pre-Variscan and Variscan events in the Alpine-Mediterranean mountain belts, 209–226. Alfa Publishers (Bratislava).

FRISCH, W. and RAAB, D. (1989): Early Paleozoic backarc and island-arc settings in greenstone sequences of the central Tauern Window (Eastern Alps). Jb. Geol. B.-A., 129, 545–566.

FRÖHLICH, F. (1960): Ein Beitrag zur Geochemie des Chroms. Geochim. Cosmochim. Acta, 20, 215–240.

GODIZART, G. (1989): Gefüge, retrograde Metamorphose und Geochemie der Amphibolite im ostalpinen Altkristallin südlich des westlichen Tauernfensters (Südtirol, Italien). Dissertation Universität Erlangen-Nürnberg, 156 S. (unpubl.).

HAMMERSCHMIDT, K. (1981): Isotopengeologische Untersuchungen am Augengneis vom Typ Campo Tures bei Rain in Taufers, Südtirol. Mem. Ist. Geol. Min. Univ. Padova, 34, 273–300.

HEINISCH, H. (1981): Zum ordovizischen "Porphyroid"-Vulkanismus der Ost- und Südalpen. Jahrb. Geol. Bundesanst., 124, 1–109.

HEINISCH, H. and SCHMIDT, K. (1982): Zur Genese der Augengneise im Altkristallin der Ostalpen. N. Jb. Geol. Paläont. Mh., 1982, 211–239, Stuttgart.

HELLMAN, P.L., SMITH, R.E. and HENDERSON, P. (1979): The mobility of the rare earth elements: evidence and implications from selected terrains affected by burial metamorphism. Contrib. Mineral. Petrol., 71, 23–44.

HÖCK, V. (1993): The Habach-Formation and the Zentralgneis – a key in understanding the Palaeozoic evolution of the Tauern Window (Eastern Alps). In: VON RAUMER, J.F. and NEUBAUER, F. (eds): The pre-Mesozoic Geology of the Alps, 361–374. Springer Verlag (Heidelberg).

HOFMANN, A.W. (1988): Chemical differentiation of the earth: the relationship between mantle, continental crust, and oceanic crust. Earth Planet. Sci. Lett., 90, 297–314.

HOKE, L. (1990): The Altkristallin of the Kreuzeck Mountains, SE Tauern Window, Eastern Alps – basement crust in a convergent plate boundary zone. Jb. Geol. B.-A., 133, 5–87.

JOANNY, V., VAN ROERMUND, H. and LARDEAUX, J.M. (1991): The clinopyroxene/plagioclase symplectite

in retrograde eclogites: a potential geothermobarometer. Geol. Rundsch., 80, 303–320.

JORON, J.L. and TREUIL, M. (1977): Utilisation des propriétés des éléments fortement hygromagmaphiles pour l'étude de la composition chimique et de l'hétérogénéité du manteau. Bull. Soc. géol. France, XIX, (6), 1197–1205.

KREUTZER, S. (1991): Zur Geologie des östlichen Thurntaler Quarzphyllitkomplexes und seiner tektonischen Einbindung in das Ostalpin der südöstlichen Deferegger Alpen, Osttirol. Dissertation Rheinisch-Westfälische Technische Hochschule Aachen, 166 S.

LEAKE, B.E. (1964): The chemical distinction between ortho- and para-amphibolites. J. Petrol., 5, 238–254.

LOESCHKE, J. and HEINISCH, H. (1993): Palaeozoic volcanism of the Eastern Alps and its palaeotectonic significance. In: VON RAUMER, J. F. and NEUBAUER, F. (eds): The pre-Mesozoic Geology of the Alps, 441–455. Springer Verlag (Heidelberg).

MAGGETTI, M. and GALETI, G. (1988): Evolution of the Silvretta eclogites: metamorphic and magmatic events. Schweiz. Mineral. Petrogr. Mitt., 68, 467–484.

MÉNOT, R.-P. and PAQUETTE, J.L. (1993): Geodynamic significance of basic and bimodal magmatism in the External Domain. In: VON RAUMER, J.F. and NEUBAUER, F. (eds): The pre-Mesozoic Geology of the Alps, 241–254. Springer Verlag (Heidelberg).

MILLER, C. (1990): Petrology of the type locality eclogites from the Koralpe and Saualpe (Eastern Alps), Austria. Schweiz. Mineral. Petrogr. Mitt., 70, 287–300.

MILLER, C., STOSCH, H.-G. and HOERNES, S. (1988): Geochemistry and origin of eclogites from the type locality Koralpe and Saualpe, Eastern Alps, Austria. Chemical Geology 67, 103–118.

MOGESSIE, A., PURTSCHELLER, F. and TESSADRI, R. (1985): Geochemistry of amphibolites from the Oetztal-Stubai complex (northern Tyrol/Austria). Chem. Geol., 51, 103–113.

MUECKE, G.K., PRIDE, C. and SARKAR, P. (1979): Rare-earth element geochemistry of regional metamorphic rocks. In: AHRENS, L.H. (ed.): Physics and Chemistry of the Earth, II. Origin and distribution of the elements, 449–463. Pergamon (New York).

NAKAMURA, N. (1974): Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. Geochim. Cosmochim. Acta, 38, 757–775.

NEUBAUER, F., FRISCH, W., SCHMEROLD, R. and SCHLÖSER, H. (1989): Metamorphosed and dismembered ophiolite suites in the basement units of the Eastern Alps. Tectonophysics, 164, 49–62.

O'BRIEN, P.J., RÖHR, C., OKRUSCH, M. and PATZAK, M. (1992): Eclogite facies relics and a multistage breakdown in metabasites of the KTB pilot hole, NE Bavaria: implications for the Variscan tectonometamorphic evolution of the NW Bohemian Massif. Contrib. Mineral. Petrol., 112, 261–278.

PAPEZYK, V.S. and HODYCH, J.P. (1980): Early Mesozoic diabase dikes of the Avalon Peninsula, Newfoundland: Petrochemistry, mineralogy and origin. Canad. J. Earth Sci., 17, 1417–1430.

PEARCE, J.A. (1975): Statistical analyses of major element patterns in basalts. J. Petrol., 17, 15–43.

PEARCE, J.A. (1976): Basalt geochemistry used to investigate past tectonic environments on Cyprus. Tectonophysics, 25, 41–67.

PEARCE, J.A. (1980): Geochemical evidence for the genesis and eruptive setting of lavas from Tethyan

Ophiolites. In: PANAYIOTOU, A. (ed.): Ophiolites. Proc. Int. Ophiol. Symp. Cyprus 1979, 261–272.

PEARCE, J.A. (1982): Trace element characteristics of lavas from destructive plate boundaries. In: THORPE, R.S. (ed.): Andesites, 526–546. Wiley (New York).

PEARCE, J.A. (1983): A "users guide" to basalt discrimination diagrams. Unpubl. Report, The Open University, Milton Keynes, 37 pp.

PEARCE, J.A. and CANN, J.R. (1973): Tectonic setting of basic volcanic rocks determined using trace element analyses. Earth Planet. Sci. Lett. 19, 290–300.

PEARCE, J.A. and NORRY, M.J. (1979): Petrogenetic implications of Ti, Zr, Y and Nb variations in volcanic rocks. Contrib. Mineral. Petrol. 69, 33–47.

PECCERILLO, A., POLI, G., SASSI, F.P., ZIRPOLI, G. and MEZZACASA, G. (1979): New data on the Upper Ordovician acid plutonism in the Eastern Alps. - N. Jb. Mineral. Abh., 137, 162–183, Stuttgart.

PFEIFER, H.-R., COLOMBI, A. and GANGUIN, J. (1989): Zermatt-Saas and Antrona zone: A petrographic and geochemical comparison of polymetamorphic ophiolites of the West-Central Alps. Schweiz. Mineral. Petrogr. Mitt., 69, 217–236.

POLI, S. (1989): Pre-Hercynian magmatism in the Eastern Alps: the origin of metabasites from the Austroalpine basement. Schweiz. Mineral. Petrogr. Mitt., 69, 407–421.

VON RAUMER, J.F. and NEUBAUER, F. (1993): Late Precambrian and Palaeozoic evolution of the Alpine basement – an overview. In: VON RAUMER, J. F. and NEUBAUER, F. (eds): The pre-Mesozoic Geology of the Alps, 625–639. Springer Verlag (Heidelberg).

VON RAUMER, J.F., GALETTI, G., PFEIFER, H.-R. and OBERHÄNSLI, R. (1990): Amphibolites from Lake Emosson/Aiguilles Rouges, Switzerland: Tholeiitic basalts of a Paleozoic continental rift zone. Schweiz. Mineral. Petrogr. Mitt., 70, 419–435.

REIMANN, C. and STUMPFL, E.F. (1981): Geochemical setting of stratabound stibnite mineralization in the Kreuzeck Mountains, Austria. Trans. Instn. Min. Metall. Sect. B, 90, 126–132.

SCHULZ, B. (1993): Mineral chemistry, geothermobarometry and pre-Alpine high-pressure metamorphism of eclogitic amphibolites and mica schists from the Schobergruppe, Austroalpine basement, Eastern Alps. Mineralogical Magazine, 57, 189–202.

SCHULZ, B., NOLLAU, G., HEINISCH, H. and GODIZART, G. (1993): Austroalpine basement complex to the south of the Tauern Window. In: VON RAUMER, J.F. and NEUBAUER, F. (eds): The pre-Mesozoic Geology of the Alps, 493–512. Springer Verlag (Heidelberg).

SHATSKY, V.S., KOZMENKO, O.A. and SOBOLEV, N.V. (1990): Behaviour of rare-earth elements during high-pressure metamorphism. Lithos, 25, 219–226.

SHERVAIS, J.W. (1982): Ti–V plots and the petrogenesis of modern and ophiolitic lavas. Earth Planet. Sci. Lett., 59, 101–118.

STILLMAN, C.J. and WILLIAMS, C.T. (1978): Geochemistry and tectonic setting of some Upper Ordovician volcanic rocks in East and Southeast Ireland. Earth Planet. Sci. Lett., 41, 288–310.

THIÉBLEMONT, D., CHÈVREMONT, P., CASTAING, C., TRIBOULET, C. and FEYBESSE, J.-L. (1994): La discrimination géotectonique des roches magmatiques basiques par les éléments traces. Réévaluation d'après une base de donnés et application à la chaîne panafricaine du Togo. Geodinamica Acta, 7, 139–157.

TROLL, G. (1978): The "Altkristallin" of Eastern Tyrol between Tauern Window and Periadriatic Linea-

ment. In: CLOSS, H., ROEDER, D. and SCHMIDT, K. (ed.): Alps, Apennines, Hellenides. Inter-Union Commission on Geodynamics Scientific Report No. 38, 149–154. Schweizerbart (Stuttgart).

TROLL, G., BAUMGARTNER, S. and DAIMINGER, W. (1980): Zur Geologie der südwestlichen Schobergruppe (Osttirol, Österreich). Mitt. Ges. Geol. Bergbaustud. Österr., 26, 277–295.

TROLL, G., FORST, R., SÖLLNER, F., BRACK, W., KÖHLER, H. and MÜLLER-SOHNIUS, D. (1976): Über Bau, Alter und Metamorphose des Altkristallins der Schobergruppe, Osttirol. Geol. Rundsch., 65, 483–511.

TROLL, G. and HÖLZL, E. (1974): Zum Gesteinsaufbau des Altkristallins der zentralen Schobergruppe, Osttirol. Jahrb. Geol. Bundesanst., 117, 1–16.

WINCHESTER, J.A. and FLOYD, P.A. (1976a): Geochemical discrimination of different magma series and their differentiation products using inmobile elements. Chemical Geology, 20, 325–343.

WINCHESTER, J.A. and FLOYD, P.A. (1976b): Geochemical magma type discrimination: Application to altered and metamorphed basic igneous rocks. Earth Planet. Sci. Lett., 28, 459–469.

WOOD, D.A. (1980): The application of a Th–Hf–Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. Earth Planet. Sci. Lett., 50, 11–30.