Amphibolites from Lake Emosson/Aiguilles Rouges, Switzerland : tholeiitic basalts of a Paleozoic continental rift zone

Amphibolites from Lake Emosson/Aiguilles Rouges, Switzerland: Tholeiitic basalts of a Paleozoic continental rift zone

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Abstract

In the northern part of the external Aiguilles Rouges massif, two 1 to 5 m thick zones of amphibolite interlayered in micaschists can be followed over a distance of several kilometers. The whole series is strongly folded and shows polyphase metamorphic mineral assemblages grading from eclogite to upper amphibolite facies. The mineralogy is quite variable, but two major types of amphibolites can be distinguished: garnet-plagioclase amphibolites and plagioclase-amphibolites with rare garnet-pseudomorphs. The amphibole compositions vary from magnesio-hornblende to rare actinolitic amphibole and garnets are rich in almandine and grossular. The whole-rock composition of both types of amphibolites is tholeiitic, but vary considerably in the Mg-Fe-ratio (Mg-number) and some trace elements: the plagioclase-amphibolites with high Mg-numbers, rich in Cr and Ni, but poor in Ti, Zr and Y correspond to little evolved and the garnet-amphibolites to more fractionated tholeiitic magmas similar to present-day mid ocean ridge basalts (MORB). Chondrite-normalized rare earth element patterns are flat or slightly enriched in light rare earths ranging between 10 and 40 times chondrite, but do not differ significantly from one type to the other, corresponding to transitional type MOR-basalts. However, K-, Rb- and Ba-contents approach values typical for plume-type, rather enriched MOR-basalts. Such compositions are typical for continental rift zones with strong extension, leading at the end to the formation of oceanic crust, like the Jurassic flood basalt provinces of southern Africa and Brasil or the Tertiary opening of the Red Sea. The large compositional variability and the small volume suggest that the protoliths of these amphibolites were subvolcanic sills or dikes.

Keywords: Lake Emosson, Aiguilles Rouges massif, Switzerland, amphibolite, dike, geochemistry, metamorphism.

Introduction

The Emosson area lies in the pre-Carboniferous crystalline basement of the Helvetic realm of the Western Alps in the Swiss part of the Aiguilles Rouges massif. This Variscan basement area is part of the northernmost lying, external massifs and has undergone only minor thrusting during the Alpine orogeny. The accompanying metamorphism was of very low grade (max. 2 kb, 270 °C, VON RAUMER, 1984a), thus preserving relics of older events. The external massifs represent, regardless of their present outcrop area, small pieces of pre-Permian polymetamorphic crust (VON RAUMER, 1976, 1981, 1984a). Among the metamorphic rock suites that outcrop near the lake of Emosson, amphibolites are, thanks to their possibly preserved geochemical signatures, particularly suitable to unravel the paleotectonic environment of this complex rock unit.

Geological setting and petrography

The first geologic outline of the Emosson area was presented by COLLET et al. (1952). Actual field work reveals a strongly folded, complex lithology (Fig. 1). A metasedimentary zone up to 1.5 km large is intruded by granitoid rocks limited in the east by a major Carboniferous shear zone. The metasediments derived from detrital sediments of Late Precambrian to Early Paleozoic age (VON RAUMER, 1988) build up a reduced series of inter-

layers of metagreywackes, quartzites and metapelites, where just one important micaschist layer can be recognized. These rock series suffered deformation and metamorphism of Caledonian- or Variscan age, summarized as follows (cf. VON RAUMER, 1984b, 1987): The earliest recognizable metamorphic event of the Aiguilles Rouges massif is preserved as meta-eclogites, which occur 15 km to the southwest of the study area. Their minimum P-T conditions have been estimated at 11 kb, 780 °C by LIÉGOIS and DUCHESNE (1980). According to PAQUETTE et al. (1989), this event is Caledonian in age

(425–395 Ma). Within the study area eclogite relics are only rarely found (see below), but the subsequent history can be reconstructed from the metapelitic rocks, which are characterized by a Barrovian type of metamorphism. Kyanite-garnet assemblages, estimated to have formed at 8–10 kb, 550 °C, are associated with large scale folds (F_2, F_3) of kilometer scale and are thought to be of Silurian age (VON RAUMER, 1984 a, b). Sillimanite overgrowing kyanite, together with local anatexis, indicate a later increase in temperature and decrease in pressure (4–5 kb, 600–700 °C). This event is proba-
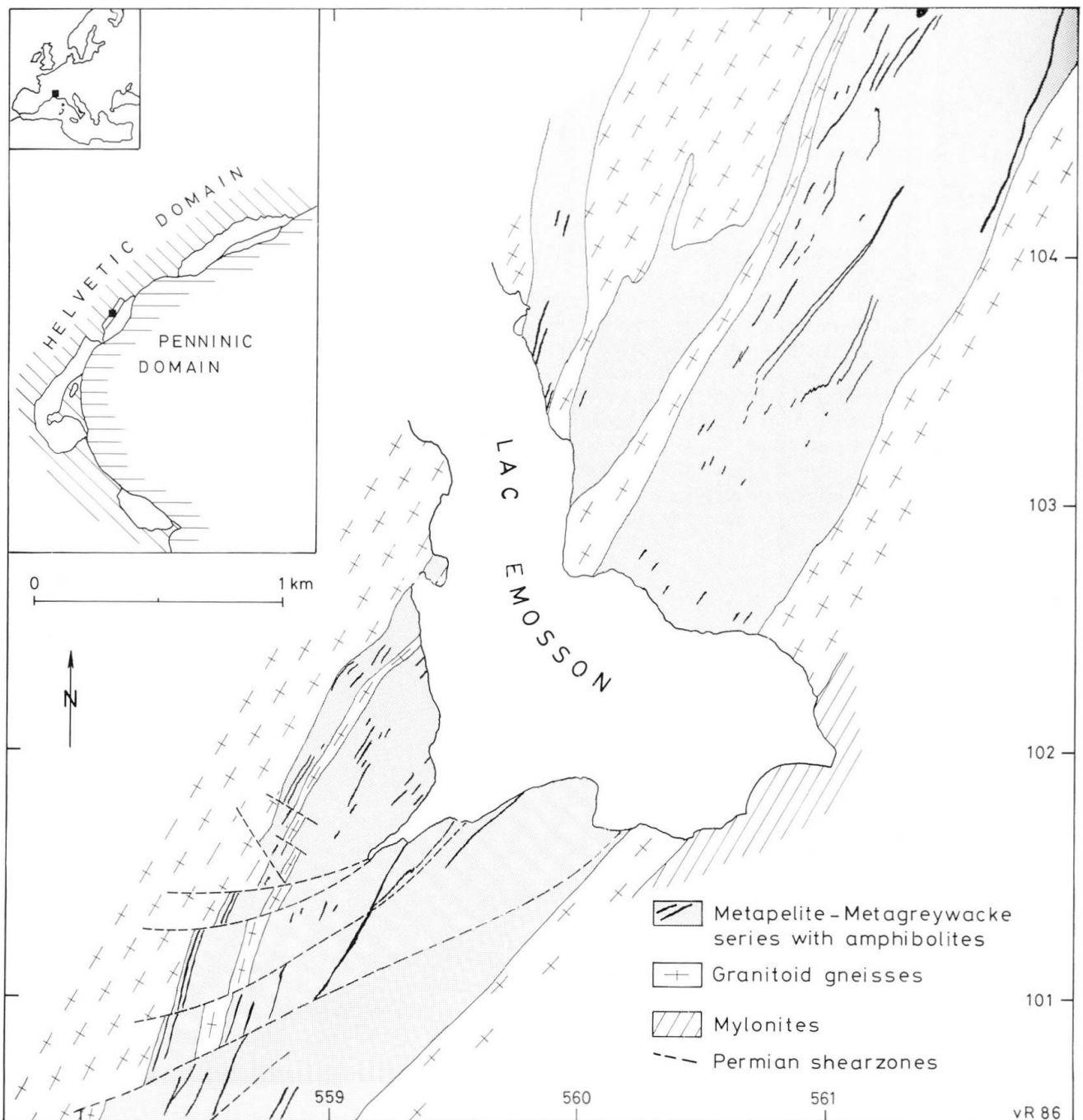

Fig. 1 Geological map of the Emosson area with the main lithologic units and the isoclinal fold pattern of amphibolites (black). In the southeast a series of Permian faults dissects all rock units.

bly of Devonian or Early Carboniferous age and is associated with open folds (F_4) in a NE–SW direction (JOYE, 1989). The late stage of the evolution is documented by Late Carboniferous shear zones (Fig. 1) accompanied by fluid migration and retrograde transformations. The presence of small quantities of pumpellyite and prehnite are attributed to the weak Tertiary metamorphic overprint (VON RAUMER, 1974).

The amphibolites are relatively scarce in comparison to the granitic and pelitic country rocks; they can be mapped over several kilometers and display a complex fold pattern (Fig. 1). They are mostly limited to the micaschist layer mentioned above and only locally found in the adjacent metagreywackes. At one locality a discordant contact with metaquartzites has been observed. Within a given layer, the amphibolites appear as lens shaped boudin-like bodies of 5 to 20 m in length. Such huge lenses with internal fold structures are interpreted as the hinge zones of older fold structures.

The amphibolites can be divided up into five types (Tab. 1) well distinguishable in the field which may occur together in one same lens; a garnet-plagioclase type (group 1) and a plagioclase type (group 2), both groups representing the volumetrically most significant rock types (Fig. 2) forming parallel layers. Of less importance are the clinozoisite bearing type (group 3), an amphibole-garnet schist (group 4) and a biotite-actinolite-garnet-plagioclase schist (group 5). Each of these is described below. Most types show a more or less lepidoblastic texture and are finegrained (0.5–1 mm). The schistosity, which is sometimes of mylonitic origin, is underlain by fine, plagioclase bearing layers, which may contain small garnets (type 1B).

The *garnet-plagioclase-amphibolites of group 1* contain garnet, amphibole and plagioclase as main phases. Three subtypes can be distinguished, based on grainsize (c.f. Tab. 1). The coarse grained type amphibolite (type 1A, e.g. sample 1604) always occurs at the limit between the amphibolite bodies

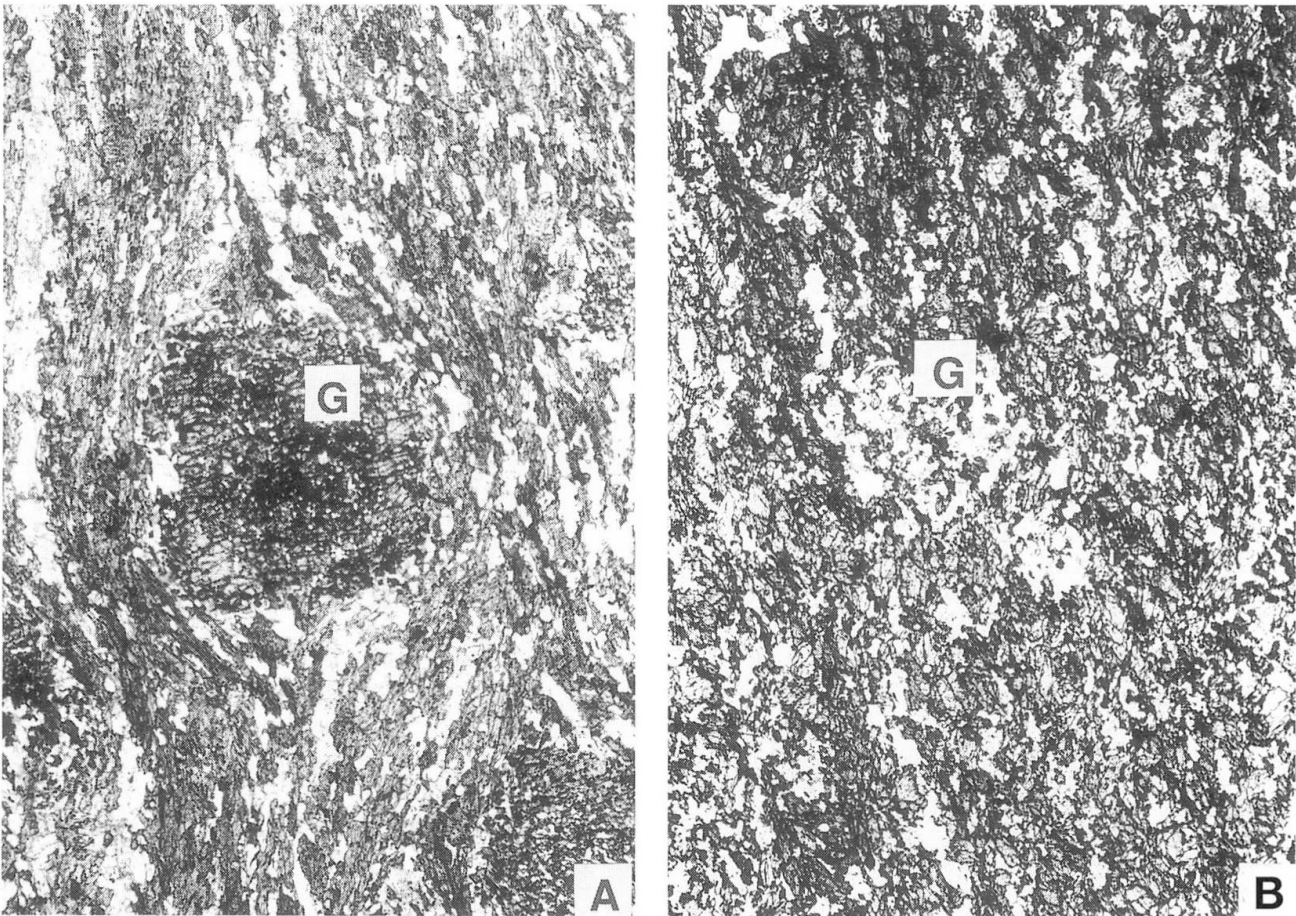*Fig. 2* Photomicrographs of the two major types of amphibolite of the Lake Emosson area.
A) Garnet (G) in plagioclase-garnet amphibolite with amphibole (grey) and plagioclase (white, rock type 1A, sample no. 1544).
B) Garnet (white field in the center) replaced by plagioclase (white) and amphibole prisms (grey) in a matrix of amphibole and plagioclase (rock type 2B, sample no. 1538). Diameter of garnet 2 mm.

Tab. 1   Typical modal compositions of the five types of amphibolites distinguished (c.f. chapt. petrography) determined by point counting.

Mineral	Rock type and sample number										
	1A 1604	1B 1507	1C 1513	1C 1527	2A 1515	2B 1523	2B 1538	2C 1554	3 1548	4 1536	5 1542
Amphibole	57	71	68	55	61	74	70	79	71	41	8
Plagioclase	32	28	27	30	32	22	30	21	7	35	15
Garnet	6	< 1	1	0	0	0	0	0	0	22	18
Quartz	3	< 1	3	15	0	1	< 1	< 1	15	2	14
Sphene	2	0	1	0	7	3	0	0	0	0	0
Ilmenite	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Biotite	0	0	0	< 1	0	0	0	0	0	0	45
Clinozoisite	0	0	0	0	0	0	0	0	6	0	0

and the surrounding metapelite. The nearly euhedral garnets of about 5–8 mm diameter are surrounded by amphibole and plagioclase (Fig. 2A). In the blastomylonitic type amphibolites (type 1B, sample 1507) small garnets appear in thin plagioclase rich layers. In the main type garnet-plagioclase amphibolites (type 1C) garnets are lenticular in shape, and are very often partially replaced by plagioclase.

The majority of the *plagioclase-amphibolites of group 2* contain essentially plagioclase and amphibole in a granular texture (type 2B, sample 1523; Fig. 2B). The rare presence of textural relicts of garnet, consisting of granular plagioclase including some small prisms of amphibole, ilmenite, sphene and clinozoisite, show that a few of the plagioclase amphibolites samples represent the final stage of a transformation of former garnet amphibolites (type 2A, sample 1515). A few samples are characterized by large amphiboles that sometimes overgrow other phases (type 2C, sample 1554).

The *clinozoisite-bearing amphibolites of group 3* are a special feature found locally in the outer rim of the amphibolite bodies. White needles of cm-size consisting of clinozoisite, plagioclase, some quartz and calcite are interpreted as pseudomorphs after zoisite.

The *amphibole-garnet-schists of group 4* (sample 1544) occur in the center of some larger boudins. The large garnets contain inclusions of green or blue-green amphibole, sphene, and ilmenite and are surrounded by large prisms of actinolite and some plagioclase. In analogy to similar rocks from the nearby Lake Cornu area (LIÉGOIS and DUCHESNE, 1981) we interpret these rocks as relic eclogites. As they are strongly altered (plagioclase replaced by white mica, amphibole by calcite and chlorite) they have not been used for a more detailed investigation.

Finally the *biotite-plagioclase-actinolite-schists of group 5* appear as irregular lumps in a feldspar-rich zone in the border zone of larger amphibolite boudins. Euhedral, zoned garnets or garnet relics occur in a matrix of large biotites with few prisms of actinolite. Plagioclase generally shows an equigranular growth. It obviously represents a reaction rim between the amphibolites and their country rock. Because of intense replacement by sericitic white mica of all minerals no further investigation was undertaken.

Mineral chemistry

The composition of the main mineral phases has been analyzed on an ARL-SEMQ microprobe of the university of Bern, using natural and synthetic minerals as standards. The operating conditions were 15 kV accelerating voltage and 20 μA sample current. The corrections were made with a Bence-Albee type of program.

AMPHIBOLES

As the microprobe only permits the determination of total iron, the chemical data were normalized after LAIRD (1978) and LAIRD and ALBEE (1981a) estimating Fe^{3+}/Fe^{2+} from charge balance and assigning endmembers from the formula proportions (Tab. 2A, Fig. 3a). In the nomenclature of LEAKE (1978) all amphiboles correspond to calcic amphiboles, most of them to magnesiohornblende, and only few to actinolites. Their composition is mainly characterized by Tschermak substitution (THOMPSON et al., 1981; Fig. 3a), whereas the edenite- and glaucophane-substitutions are less important. The few observed zoned amphiboles reveal an evolution from early actinolite composition to late magnesiohornblende by Tschermak substitution. Our amphiboles plot on a field corresponding to those from amphibolites accompanied by sillimanite-bearing assemblages in metapelitic rocks of LAIRD and ALBEE (1981b), Fig. 3b. In an ACF-diagram, the amphiboles plot close to the bulk rock composition.

Tab. 2 Mineral compositions (explanation of sample numbers: see text)

A: Chemical composition of amphiboles

Sample	1554[1]	1604[1]	1523 rim[1]	1523 Core[2]	1515[1]	1507[1]
SiO_2	46.58	44.78	45.30	51.50	45.89	47.52
Al_2O_3	13.61	12.40	10.89	4.74	11.06	8.02
TiO_2	0.00	0.75	0.00	0.00	0.00	0.70
Cr_2O_3	0.13	0.08	0.00	0.00	0.00	0.00
FeO	12.30	15.79	14.32	14.10	15.01	15.69
MgO	11.96	10.12	10.90	12.87	11.13	11.61
MnO	0.09	0.15	0.35	0.31	0.29	0.27
CaO	10.81	11.16	11.46	11.56	11.71	11.82
Na_2O	1.36	1.26	1.15	0.50	1.43	1.16
K_2O	0.35	0.21	0.18	0.09	0.10	0.12
H_2O stoic.	2.30	2.30	2.30	2.30	2.30	2.30
Total	99.49	99.00	96.85	97.97	98.92	99.21
Si	6.660	6.581	6.795	7.596	6.754	7.007
Al^{IV}	1.340	1.419	1.205	0.404	1.246	0.993
Sum T	8.000	8.000	8.000	8.000	8.000	8.000
Al^{VI}	0.954	0.730	0.721	0.421	0.673	0.401
Ti	0.000	0.083	0.000	0.000	0.000	0.078
Cr	0.015	0.009	0.000	0.000	0.000	0.000
Fe^{2+}	0.852	1.341	1.365	1.631	1.396	1.587
$Fe^{(3+3)}$	0.619	0.600	0.413	0.109	0.452	0.348
Mg	2.549	2.218	2.438	2.830	2.442	2.552
Mn	0.011	0.019	0.044	0.039	0.036	0.034
Sum M1–3	5.000	5.000	5.000	5.000	5.000	5.000
Na M4	0.344	0.243	0.158	0.143	0.153	0.133
Ca	1.656	1.757	1.842	1.827	1.847	1.867
Sum M4	2.000	2.000	2.000	2.000	2.000	2.000
Na A	0.033	0.117	0.176	0.000	0.255	0.199
K	0.064	0.039	0.034	0.017	0.019	0.023
Sum A	0.097	0.156	0.210	0.017	0.274	0.222

1): normalized to Σ cations-Ca-Na-K = 13 (Na can be on A- and M4-site;
2): normalized to Σ cations-K = 15 (only K on A-site);
3): calculated using charge balance (LAIRD and ALBEE, 1981a).

Analyst: R. Oberhänsli

B: Chemical composition of plagioclases

Sample	1554	1604	1523	1515	1507
SiO_2	56.57	59.82	55.88	60.50	53.19
CaO	9.90	7.88	10.25	7.33	12.40
Al_2O_3	27.02	25.80	28.24	25.93	29.84
Na_2O	5.93	7.30	6.32	7.28	4.64
K_2O	0.04	0.11	0.08	0.03	0.04
Total	99.46	100.91	100.78	101.07	100.11
Si	2.55	2.65	2.50	2.66	2.40
Al	1.44	1.35	1.49	1.35	1.59
Sum	3.99	4.00	3.99	3.01	3.99
Ca	0.48	0.37	0.49	0.35	0.60
Na	0.52	0.63	0.55	0.62	0.41
K	0.00	0.01	0.00	0.00	0.00
Sum	1.00	1.01	1.04	0.97	1.01
%An	48	37	45	33	60

1): normalized to 8 oxygen atoms.

Analyst: R. Oberhänsli

C: Chemical composition of garnets

Sample	1604 core	1604 rim	1544	1507 core	1507 rim
SiO_2	38.35	38.10	38.27	38.28	38.86
Al_2O_3	20.64	20.94	20.82	20.86	21.40
Cr_2O_3	0.10	0.00	0.14	0.05	0.05
FeO	27.65	30.08	26.51	22.34	22.72
MnO	1.35	0.81	1.46	2.72	3.11
MgO	1.70	3.06	1.83	2.34	2.21
CaO	10.89	8.17	12.10	13.56	13.39
Total	100.68	101.16	101.13	100.15	101.74
Formula [1]:					
Si	3.030	2.990	3.000	3.005	3.006
Al^{IV}	0.000	0.010	0.000	0.000	0.000
Sum T	3.030	3.000	3.000	3.005	3.006
Al^{VI}	1.953	1.927	1.925	1.935	1.958
Fe3+ [2]	0.040	0.073	0.066	0.062	0.039
Sum	1.993	2.000	1.991	1.997	1.997
Fe^{2+}	1.787	1.901	1.673	1.405	1.431
Mn	0.090	0.054	0.097	0.181	0.204
Mg	0.200	0.359	0.214	0.274	0.255
Ca	0.922	0.689	1.017	1.140	1.110
Sum	2.999	3.003	3.001	3.000	3.000
Mol% Almandin	58.2	61.1	53.7	45.4	46.7
Mol% Pyrope	6.5	11.5	6.9	8.8	8.3
Mol% Gross.[3]	30.0	22.1	32.7	36.8	36.2
Mol% Spessar.	2.9	1.7	3.1	5.8	6.7
Mol% Andrad.	2.0	3.5	3.2	3.0	1.9
Mol% Uvarov.	0.3	0.0	0.4	0.2	0.2

1): normalized to 8 cations, 2): calculated using charge balance, i.e. Fe^{3+} = 2- Al^{VI}- Ti- Cr. 3): % Gross. = $(Ca - \frac{2}{3} Cr - \frac{2}{3} Fe^{3+}) / Al^{VI} + Fe^{3+} + Ti + Cr$ (COLOMBI, 1990).

Analyst: R. Oberhänsli

PLAGIOCLASE

Plagioclase is the most abundant phase after amphibole with an overall range of An30 to An60 in which andesine compositions dominate. The variation of individual minerals is more restricted (Fig. 3b). Based on only few analyses (Tab. IIB), it seems that plagioclases from the plagioclase amphibolites have slightly higher An-contents than those from the garnet-amphibolites.

GARNET

Two generations of garnet are observed in type 1 amphibolites. Their garnets display a chemical zonation where the earlier generation preserved in the center of large garnets (e.g. sample 1604, Tab. IIC) corresponds to a grossularite-rich almandine with the general formula of $Alm_{58}Py_7Gr_{30}S_{p3}$-$Andr_2$. It has a similar composition to the garnets from the amphibole-garnet-schists (type [4], sample 1544). The rims of the large garnets of rock type (1A) have a general composition of $Alm_{61}Py_{12}Gr_{22}Sp_2Andr_3$.

Rock chemistry

DATA

A set of 55 samples has been analyzed by X-ray fluorescence for 30 major and trace elements. Tab. 3 contains representative analyses for the main rock

types and Fig. 4 shows selected elements plotted against the Mg-number (Mg/Mg + Fe^{2+}). On the basis of the latter, three fairly well distinguishable chemical groups can be recognized, corresponding respectively to the plagioclase-amphibolites of group 2 with high Mg-numbers, to the garnet-amphibolites with relictic garnets of group 1C with medium Mg-numbers, and to the coarse-grained garnet-amphibolites of group 1A with low Mg-numbers. The garnet-amphibolites are in general poorer in Ni but richer in Fe, V and most incompatible elements like P, Ti, Zr and Y than the plagioclase-amphibolites. The garnet-amphibolite sample 1527 (belonging to group 1C and collected from a small amphibolite boudin of only 50 cm, surrounded by granitoid gneisses) shows a compositional trend approaching the garnet-amphibolites of group 1A.

Rare earth elements (REE) of 20 samples have been analyzed by instrumental neutron activation (Tab. 4, Fig. 5), including samples that show considerable replacement of plagioclase by sericitic white mica. The fresh, non-sericitized samples show, aside from mainly negative Eu-anomalies, flat patterns at an average enrichment level of 15 to 20 in comparison to chondrites (Fig. 5 a, b). Some of the garnet-amphibolites are slightly more enriched (20 to 30 times chondrites). The garnet-amphibolite sample no. 1527 displays a rather horizontal pattern with a general enrichment of about 40 for all REE.
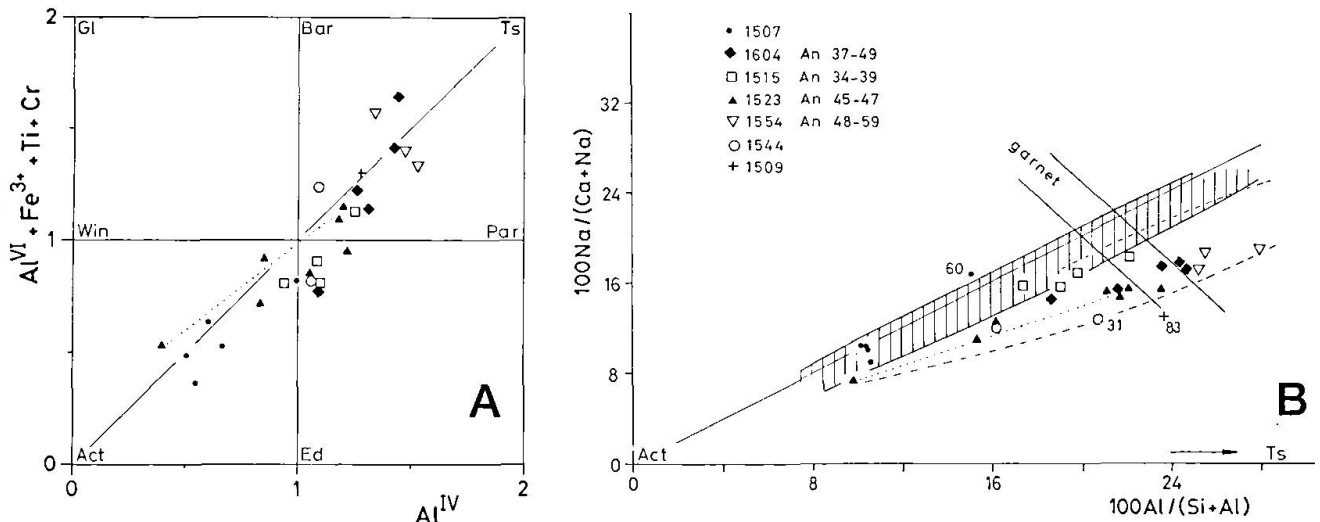

Fig. 3   Mineral composition of Amphiboles.
A: Plot of the formula proportions of Al^{VI}, Fe^{3+}, Ti and Cr against Al^{VI} The dotted line links the composition of core and rim of a zoned amphibole in sample 1523. Abbreviations: Act: actinolite, Ts: tschermakite, Par: pargasite, Gl: glaucophane, Ed: edenite, Win: winchite, Bar: barroisite.
B: Major element trends of amphiboles in a diagram proposed by Laird and Albee (1981b) for mafic schist in Vermont, with compositional fields of their amphiboles occurring with different minerals of mafic and pelitic rocks: oligoclase in mafic rocks (shaded area); sillimanite (limited by dashed lines) and garnet (solid lines) in pelitic rocks. Numbers indicate plagioclase composition (% anorthite) for a given rock. The amphiboles plot in the sillimanite field, confirming their upper amphibolite facies character. The dotted line links the composition of core and rim of a zoned amphibole in sample 1523. Sample-numbers: see text.

Tab. 3 Bulk rock composition of the analyzed amphibolites (% for oxides, ppm for traces).

Element	Type 1A 1604	Type1B 1507	Type 1C Fresh (14)*	Type 1C repl. (7)*	Type 1C contam. 1527	Type 2 fresh (13)*	Type 2 repl. (9)*
SiO₂	50.58	49.98	49.17	50.11	52.67	48.62	48.07
TiO₂	2.83	1.25	1.31	1.41	2.13	0.99	1.00
Al₂O₃	13.62	15.11	15.63	16.09	13.28	16.11	16.65
Fe₂O₃	2.88	1.98	1.85	1.61	3.31	1.76	1.47
FeO	11.80	8.43	8.72	8.80	9.65	7.70	7.74
MnO	0.28	0.20	0.20	0.23	0.19	0.19	0.19
MgO	5.99	7.99	8.24	7.50	6.74	9.51	9.53
CaO	8.69	10.64	10.16	8.47	6.70	10.07	9.82
Na₂O	1.74	2.43	2.18	1.21	2.24	2.13	1.41
K₂O	0.19	0.38	0.47	1.32	0.97	0.56	1.13
P₂O₅	0.29	0.14	0.16	0.17	0.30	0.09	0.10
H₂O⁺	0.58	1.27	1.52	2.40	1.80	2.05	2.56
Total	99.47	99.79	–	–	99.98	–	–
Zr	173.	90.	86.	95.	293.	62.	61.
Y	46.	21.	22.	25.	77.	17.	17.
Sr	123.	300.	256.	231.	113.	217.	241.
Rb	3.	18.	18.	81.	29.	23.	49.
Pb	11.	11.	10.	10.	11.	12.	11.
Ga	23.	15.	16.	17.	21.	14.	13.
Zn	150.	90.	89.	93.	217.	102.	102.
Cu	70.	99.	64.	41.	60.	39.	58.
Ni	45.	52.	61.	50.	56.	106.	120.
Co	50.	43.	45.	44.	45.	44.	43.
Cr	135.	134.	240.	156.	179.	438.	411.
V	326.	217.	216.	205.	237.	180.	167.
Ce	54.	40.	16.	22.	55.	16.	17.
Nd	53.	7.	23.	18.	56.	19.	9.
Ba	110.	164.	178.	619.	216.	209.	401.
La	29.	6.	9.	11.	21.	7.	4.
Sc	62.	51.	51.	52.	54.	48.	44.
S	508.	103.	388.	503.	2325.	14.	107.

* mean values, in parenthesis: number of averaged samples. "repl.": extensive replacement of plagioclase by sericitic white mica.

Methods used: Major elements analyzed on fused beads (sample : Li₂BO₃ = 1 : 5) and corrected for matrix effects, absorption etc. with fundamental alpha-factors (DE JONGH, 1979). Traces analyzed on pressed powder pellets according to NISBET et al. (1979). FeO determined with colorimetric methods (WILSON, 1960). H₂O calculated from ignition loss.

Analyst: G. Galetti (major elements), J.C. Lavanchy (traces).

The complete data set of 55 samples is available from the Artemise data bank of the Centre de Recherches Pétrographiques et Géochimiques du CNRS at Nancy, France.

METASOMATIC CHANGES

Before trying to determine possible protoliths and their paleotectonic environment, evident metasomatic changes during the certainly complex history have to be considered and discussed.

The most obvious alteration is the replacement of plagioclase grains by fine grained white mica (sericite). The amphibolites with sericitized plagioclases ("repl." in Tab. 3) show a loss of CaO, Sr and Na₂O and the enrichment in K₂O, Rb, Ba and S relative to the corresponding amphibolites with well-preserved plagioclases ("fresh" in Tab. 3). V, Nd and Cr are slightly diminished and Tb is strongly enriched in the sericitized samples. Two explanations are offered: either the protoliths underwent an early postdepositional transformation or the amphibolites suffered a later (Permian or Tertiary-alpine) alteration. HUMPHRIS (1984) describes enrichment in Tb and La from basalts that have been
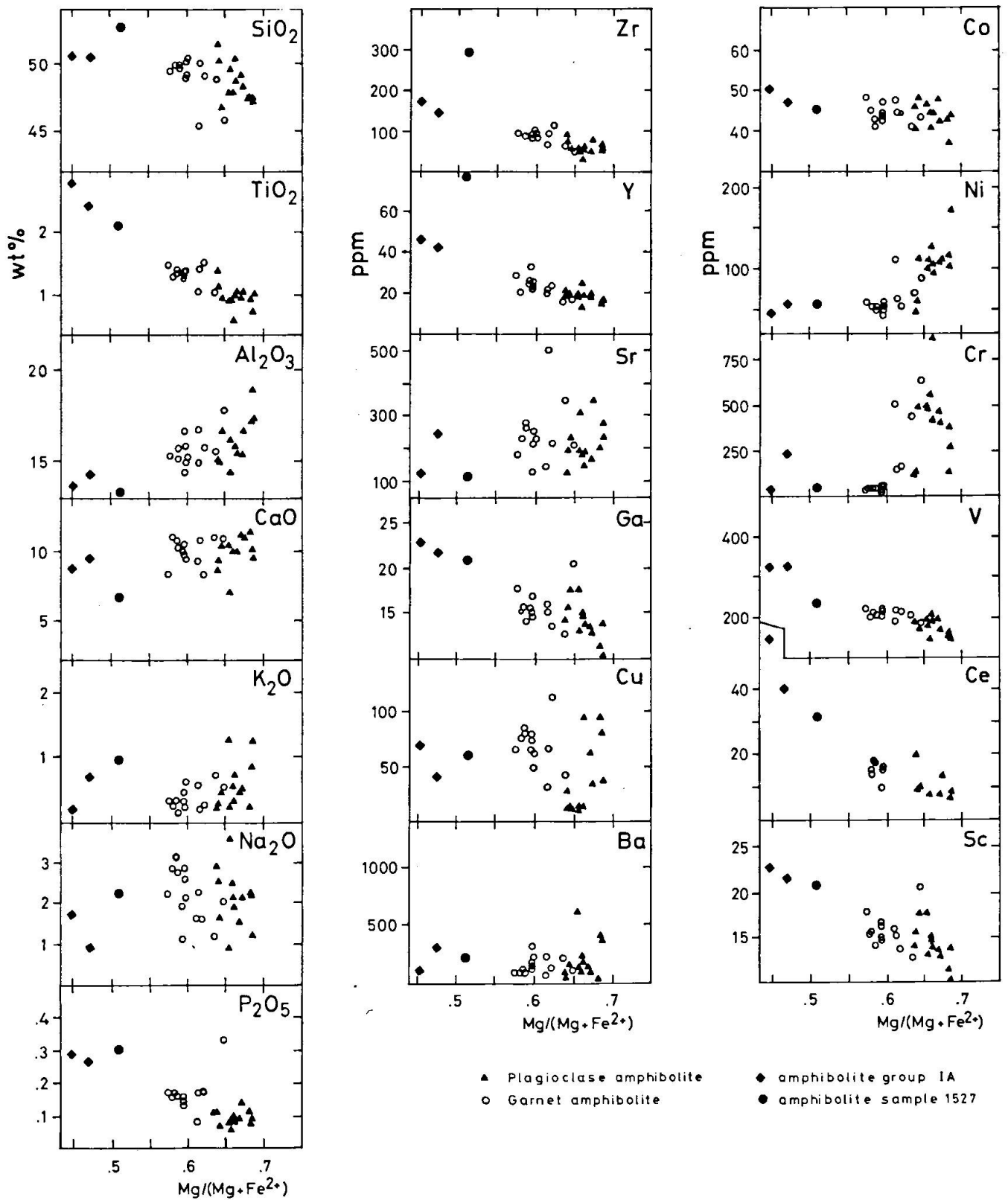
Fig. 4 Bulk rock composition of amphibolites from the Emosson area as a function of the Mg-number (Mg/ (Mg+Fe^{2+}), calculated with the assumption that Fe$_2$O$_3$/FeO = 0.1, the mean ratio for unaltered basalts). Diamonds: garnet-plagioclase-amphibolites (type 1A). Open circles: garnet-plagioclase-amphibolites with relic garnets (type 1C). Triangles: plagioclase-amphibolites (type 2). Filled circle: garnet-amphibolite no. 1527 from a small amphibolite boudin.

Tab. 4   Rare earth analyses of selected 20 amphibolite samples (second line: rock types, c.f. chapter petrography of the text; r = plagioclase replaced by sericitic white mica; cont.: contaminated by country rock).

	1505 1c	1514 1c	1515 1c	1519 1c	1520 1c	1521 1c	1523 1c	1527 cont	1509 1c-r	1512 1c-r
La	11.21	12.24	10.89	7.10	6.16	6.97	3.17	12.93	10.52	10.90
Ce	16.48	17.71	16.95	15.50	16.58	15.81	10.02	31.52	16.44	14.48
Nd	12.35	14.08	13.07	9.15	9.29	10.38	8.48	18.01	6.35	11.94
Sm	5.02	4.84	4.90	3.03	3.20	3.01	3.13	8.19	4.58	4.63
Eu	1.27	1.18	1.13	0.18	1.08	1.12	0.94	2.27	1.12	1.06
Tb	1.19	2.84	1.31	0.55	1.10	1.19	1.19	2.06	2.94	1.17
Yb	3.80	3.60	4.25	2.10	2.49	2.34	3.98	8.82	3.41	4.46
Lu	0.62	0.49	0.53	0.29	0.30	0.35	0.48	1.13	0.49	0.59
SREE	51.94	56.98	53.03	37.90	40.20	41.37	31.41	84.93	50.33	49.23
La/Sm	2.23	2.53	2.22	2.34	1.93	2.32	1.02	1.58	2.30	2.35
La/Yb	2.95	3.40	2.56	3.38	2.47	2.98	0.80	1.47	3.09	2.44

	1502 2	1511 2	1518 2	1526 2	1532 2	1540 2	1545 2	1547 2	1503 2-r	1504 2-r
La	4.34	4.22	11.64	2.95	4.52	3.62	3.14	3.77	4.61	4.52
Ce	13.26	6.74	19.86	7.48	9.85	8.48	9.08	7.91	13.18	9.03
Nd	8.75	6.35	14.17	7.94	9.42	9.69	8.47	6.94	11.11	9.63
Sm	2.48	2.65	4.92	1.89	2.38	1.98	2.40	2.14	2.50	3.56
Eu	1.13	0.66	0.83	0.86	1.39	0.83	0.18	0.83	1.00	0.94
Tb	1.19	0.24	1.47	1.49	1.09	0.81	0.58	1.06	0.77	1.87
Yb	2.10	2.75	4.61	2.15	2.33	2.07	2.17	1.87	2.24	3.37
Lu	0.24	0.37	0.50	0.27	0.29	0.24	0.32	0.30	0.28	0.49
SREE	33.49	23.98	58.00	25.03	31.27	27.72	26.34	24.82	35.69	33.41
La/Sm	1.75	1.59	2.37	1.56	1.90	1.83	1.31	1.76	1.84	1.27
La/Yb	2.07	1.53	2.52	1.37	1.94	1.75	1.45	2.02	2.06	1.34

R. A. Oliver and G. Vivier (Grenoble) analysts; INA analysis; uncertainties: La = ± 5%; Ce = ± 5%; Nd = ± 15%; Sm = ± 5%; Eu = ± 10%; Tb = ± 10%; Yb = ± 5%; Lu = ± 10%.

either weathered or zeolitized by oceanic metamorphism. As the trend of Tb-enrichment is also visible in the other samples, most samples have probably been slightly influenced by circulating fluids and/or weathering. However the most probable cause of the formation of sericite are the low grade hydrothermal alterations of Permian age, during which sulfides were precipitated along local fault zones in the whole Aiguilles Rouges massif (Fig. 1, cf. also VON RAUMER, 1987).

The direct chemical exchange with the adjacent metapelitic country rock is best illustrated with two samples from the marginal parts of the amphiolite boudins (no. 1527 and 1604). The garnet amphibolite 1527 had been collected in a small boudin surrounded by granitoid gneisses. It contains biotite in small amounts, while the normal garnet-amphibolites have none. Consequently, it is enriched in SiO_2, TiO_2, total Fe, K_2O, Rb, P_2O_5, Zn, Ce, Ba, S, Y, Zr and REE, whereas Al_2O_3, MgO, CaO, Sr and Cr

were depleted. It has obviously interacted with the adjacent metagreywackes and has been contaminated, including the formation of biotite. Similar tendencies are found for all 3 samples of the garnet-amphibolite group 1A (example: sample 1604), all collected from the limit between amphibolite and surrounding high grade metapelites. The strong zonation of garnets of the same samples, described above, are interpreted as a metasomatic change as well. Most likely these compositional changes occurred during the decompressional phase of the metamorphism, during which fluids may have had partial access to the rocks in question.

Taking into account all these secondary changes discussed above, there are 27 samples left that show no evidence for metasomatic changes. They all have been sampled in the central part of large amphibolite bodies. Only the non-sericitized samples have been plotted on diagrams of Figs 6 to 8 and have been retained for a discussion of their origin.

Origin of the amphibolites

POSSIBLE PROTOLITHS

Despite several attempts to chemically define metasedimentary amphibolites (FRÖHLICH, 1960;

Leake, 1964; Moine, 1969) based on major and common trace elements, no satisfactory scheme exists to discriminate metagabbros or metabasalt rocks from metamarls. Studies of magmatic amphibolite-ultramafic rock series lying in probable metasedimentary amphibolite-bearing series (Schläpfer, 1979; Evans et al. 1981; Schmidt, 1989), show a very limited trace element variation close to modern oceanic basalts for the supposedly magmatic amphibolites and a irregular trace element distribution for the probably metasedimentary amphibolites. As can be seen from Figs 4 to 8, the Emosson amphibolites are quite well grouped in most diagrams. According to Fröhlich (1960), who found contents larger than 150 ppm of Cr and Cr/Ni ratios higher than 1 for typical magmatic mafic rocks, 80% of our samples are of magmatic
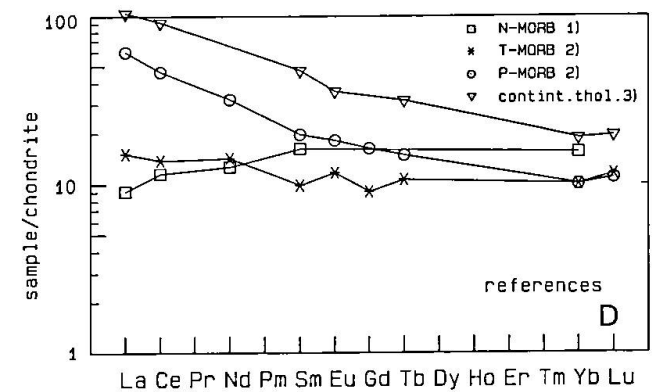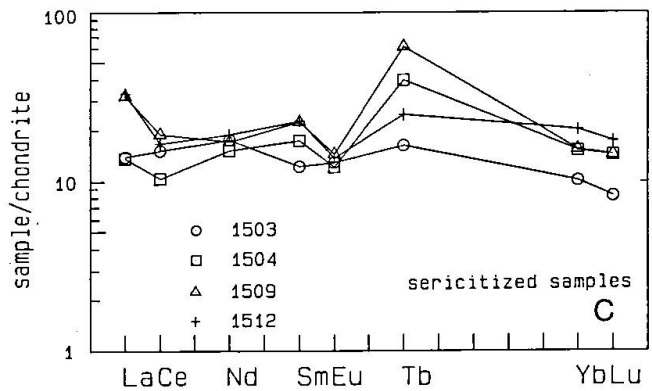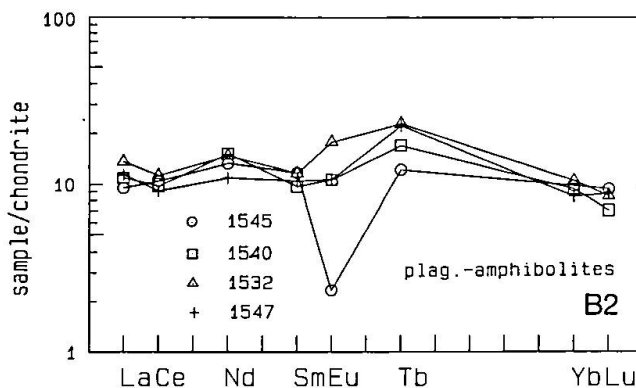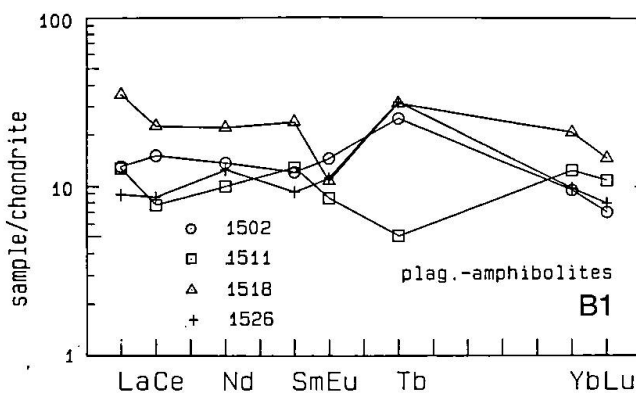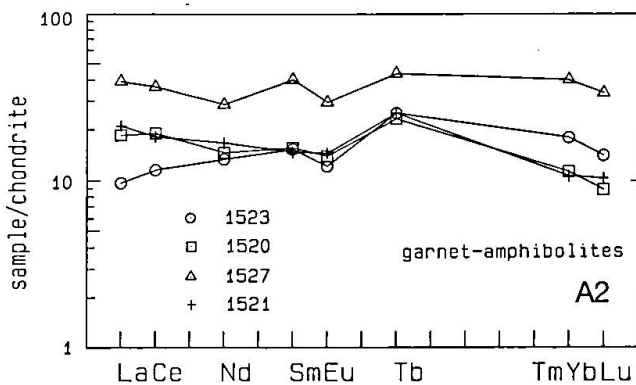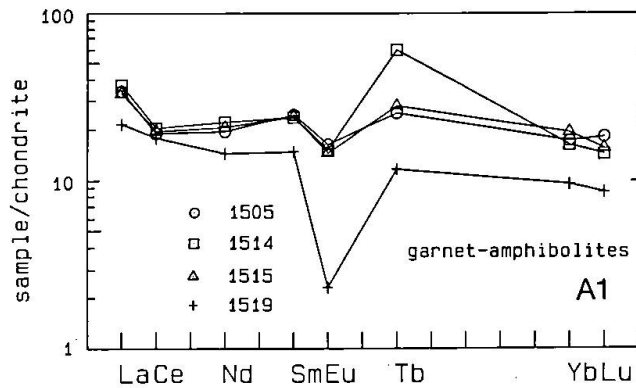
Fig. 5 REE abundance patterns of selected samples normalized to chondrite of Nakamura (1974), Tb: Haskin et al. (1968) as reported in Henderson (1984), Tab. 1.5.
A: garnet-amphibolites. B: plagioclase-amphibolites. C: Amphibolites showing extensive replacement of plagioclase by sericitic white mica. D: Reference patterns of different tholeiitic basalts. 1) normal mid ocean ridge basalt (MORB) after Pearce (1982). 2) transitional (T-)type MORB and plume (P-)type MORB after Wood et al. (1979b, sample 411 and 413-1). 3) Continental tholeiite after Dostal et al. (1983, sample 718).
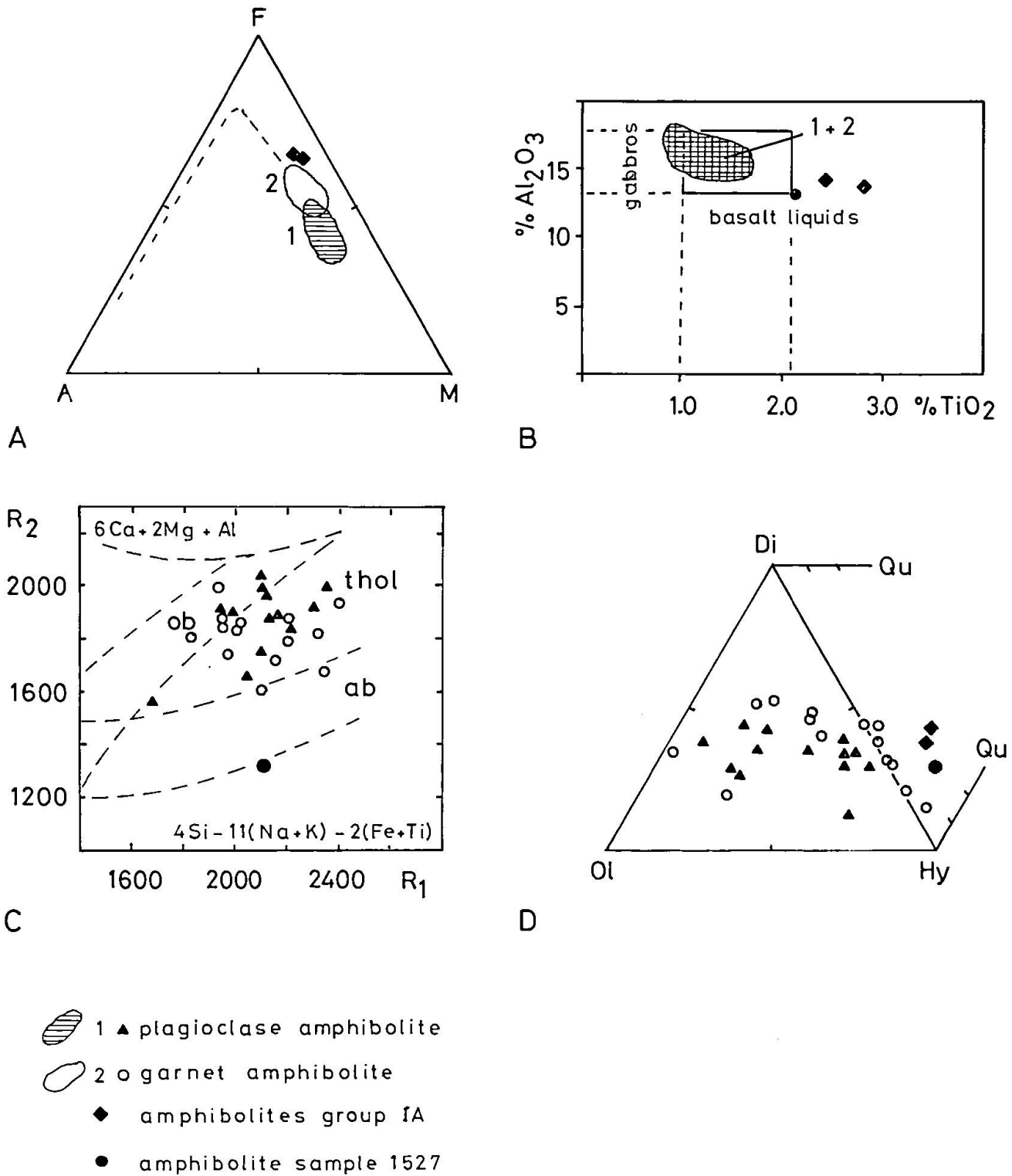
1 ▲ plagioclase amphibolite

2 o garnet amphibolite

◆ amphibolites group IA

● amphibolite sample 1527

Fig. 6 Major element composition of the amphibolites (possibly metasomatized samples excluded).
A: AFM-diagram, A = Na_2O + K_2O; F = FeO_{tot}; M = MgO; field 1: garnet amphibolites (types 1B, 1C), field 2: plagioclase amphibolites (type 2), diamonds: group 1A with large garnets. Dashed line: Skaergaard evolution-trend after WAGER (1960). B: TiO_2–Al_2O_3-diagram after PEARCE (1984), rectangle: field of basaltic liquids. C: R1-R2 diagram after DE LA ROCHE et al. (1980), modified by BELLIENI et al. (1984), ob = olivine-basalts; th = tholeiites; ab = andesitic basalt. D: CIPW normative composition of the amphibolites plotted in the projection diopside-olivine-hypersthene-quartz. Diamonds: garnet-amphibolites with large garnets (type 1A), open circles: garnet-plagioclase-amphibolites with relic garnets (type 1C), triangles: plagioclase-amphibolites (type 2), full circle: garnet-amphibolite sample no. 1527.

origin. The remaining samples plot in the ambiguous domain between 20 and 150 ppm of Cr. The following additional arguments are all consistent with a magmatic origin: most samples lie within the basaltic liquid field of PEARCE (1984), Fig. 6b. The two main groups (1C and 2) are tholeiitic (Figs 6c, 7, 8). Alltogether, our samples exhibit a compositional trend strongly suggesting a magmatic differentiation series (cf. Fig. 4; see discussion below).

PFEIFER et al. (1989) demonstrated that the original grain size (fine-grained basalts, coarsegrained gabbros), at least for Mesozoic rocks, was largely preserved even during polyphase high grade metamorphism. The fine grain size of our
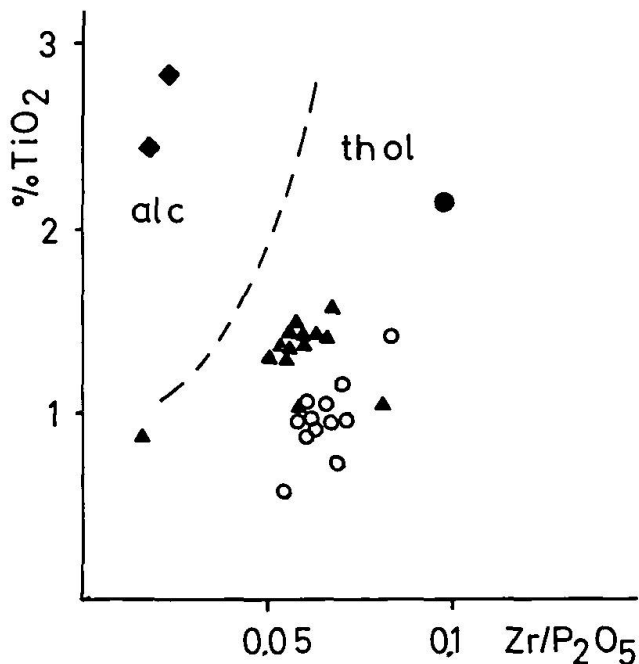

Fig. 7   Amphibolites plotted in the discrimination diagram of FLOYD and WINCHESTER (1975). alc: alkaline basalts, thol: tholeiitic basalts.
Meaning of symbols: as in Fig. 6.

samples therefore suggests volcanic or subvolcanic rather than plutonic protoliths. In addition, the TiO_2 contents (> 0.5%, Fig. 6b) and the V-contents (> 100 ppm) exclude a gabbroic origin (PFEIFER et al., 1989).

When comparing common trace element behavior in tholeiitic rocks (PRINZ, 1967; CARMICHAEL et al., 1974) to the amphibolites from Emosson, we can draw the following conclusions (Tab. 3): elevated values of Cr and Ni are observed in the plagioclase amphibolites, which could represent early differentiates. The garnet-plagioclase-amphibolites are enriched in V and P suggesting that they are more evolved than the plagioclase-amphibolites, which consequently must have formed prior to crystallization of magnetite and apatite. Also the elevated concentrations of Zr and

Ti indicates that garnet amphibolites are more evolved. Thus, the indications of the Mg-number are confirmed by the trace elements.

Compared to modern tholeiitic lavas, it appears as if the plagioclase-amphibolites were relatively undifferentiated normal spinel-olivine-tholeiites and the garnet-plagioclase-amphibolites more evolved hypersthene- or even quartz-tholeiites, a tendency which appears again in the CIPW-norm (Fig. 8), where most rocks are olivine-diopside-hyperstene-normative and only few have norms containing quartz.

PALEOTECTONIC ENVIRONMENT

An attempt to determine the paleotectonic environment can be made based mainly on the least mobile trace elements, most REE, Ti, Zr, Y, V and possibly Ni and Cr. Fig. 8 contains the usually employed classical trace element diagrams (cf. PEARCE, 1984). In most of them (Fig. 8 a, b, d, f) the two major groups of amphibolite fall into the field of mid ocean ridge basalts (MORB), but in some they fall onto the limit between MORB and island arc tholeiites (Fig. 8 c, e). Especially the plagioclase-amphibolites, with their more primitive character, have unusually low Zr and Y values and plot outside the MORB field. A similar tendency has been reported from amphibolites from the Belledonne massif in France (MÉNOT, 1987). Since there is no indication of a metasomatic event, we interpret this as a primitive character, typical for subvolcanic rocks with a trace element composition between gabbroic and basaltic volcanic rocks (e.g. two samples from a sill at Wright Valley, Antarctica reported by THOMPSON et al., 1983; PAPEZYK and HODYCH, 1980; or ophiolitic dikes in PFEIFER et al., 1989). Fig. 9 (normalization to normal MORB compositions) contains a comparison with different types of MOR-basalts and continental tholeiites. They show once more the great compositional span of certain elements within the same group (especially Rb, Ba, K), but otherwise indicate a close similarity to enriched plume-type MORB and continental tholeiites. For the latter, DUPUY and DOSTAL (1984) and WEAVER and TARNEY (1983) report highly variable element ratios, leading to the typical humps in the MORB-normalized diagrams and this is exactly what is observed in the Emosson amphibolites (Figs 9 b, c). However, the chondrite-normalized diagram indicates, with its rather flat patterns, a closer affinity to less enriched transitional MOR basalts (Fig. 5d). Such apparently contradictionary results have been reported from continental rift zones with strong extension leading to the formation of oceanic crust (BER-
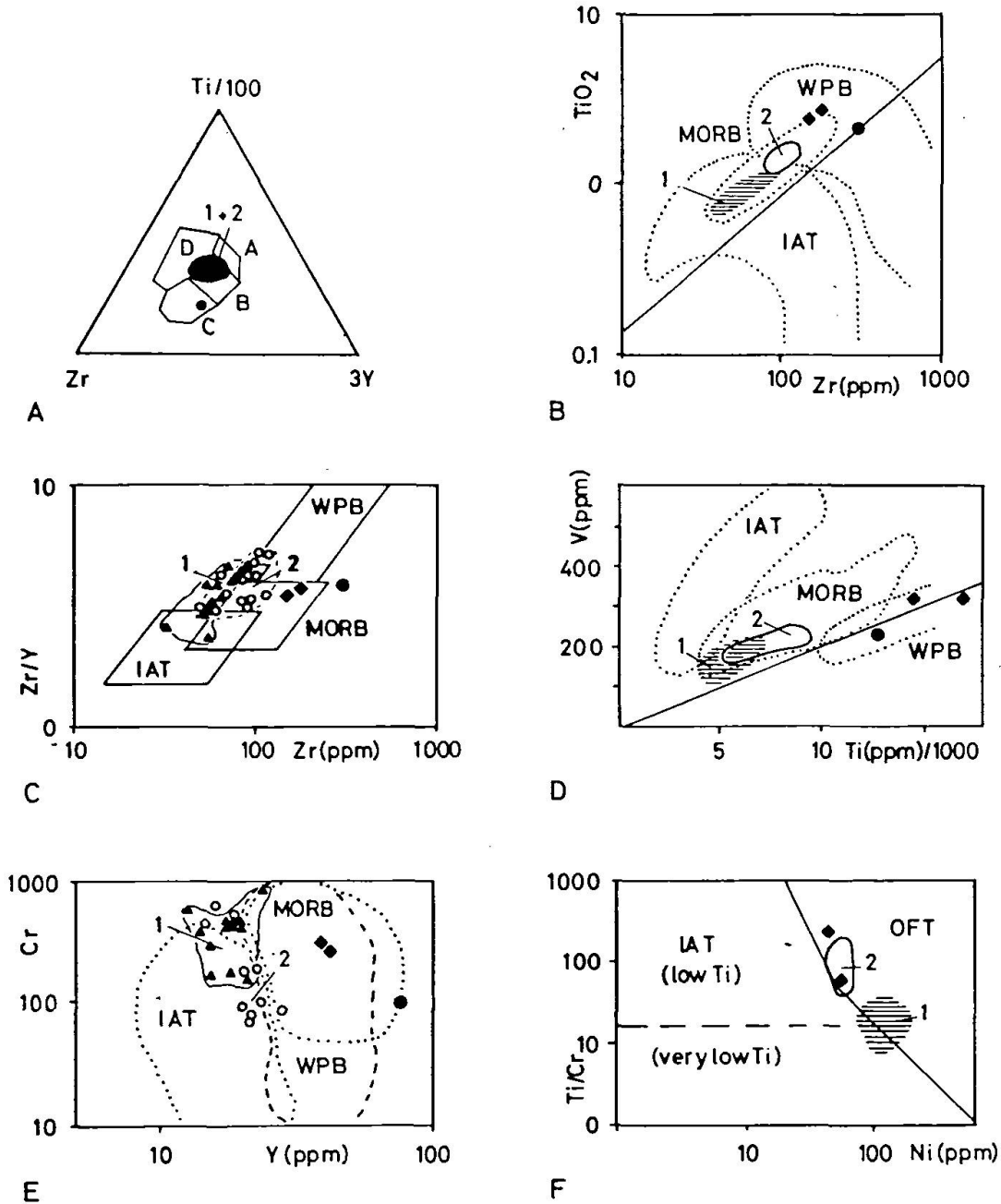
Fig. 8 Classical trace element diagrams to determine the paleotectonic environment of basalts applied to the amphibolites. 1: garnet-amphibolites, 2: plagioclase amphibolites. Symbols see Fig. 6.

Abbreviations: WPB: within plate basalts; MORB: mid ocean ridge basalts; IAT: island arc tholeiites; OIB: ocean island basalts; LKT: low potassium tholeiites; CAB: calc-alcaline basalts.

(A): PEARCE and CANN (1973): Most samples (black area) plot into the field B (ocean floor basalts, low potassium tholeiites); dot: contaminated amphibolite 1527. A = LKT; B = CAB + LKT; C = CAB; D = WPB. (B): PEARCE (1980): The amphibolites plot into the field of MORB, but they are clearly separated into the three main rock types: 1: plagioclase amphibolites, 2: normal garnet-amphibolites and garnet-amphibolites with large garnets (group 1A; diamonds). (C): PEARCE and NORRY (1979): the amphibolites plot into the field of MORB, but they are clearly separated into the three main rock types. (D): SHERVAIS (1982): the amphibolites follow a line parallel to the Ti/V ratio of 50, that separates the field of MORB and the field of OIB-WPB. Plagioclase-amphibolites (group 2) plot closer to the origin of the diagram than the group of garnet amphibolites. (E): PEARCE (1980): the different amphibolites are more or less separated, but no special attribution is possible. (F): BECCALUVA et al. (1983): the plagioclase-amphibolites (group 2) plot between the island arc tholeiites (IAT) and ocean floor tholeiites (OFT), whereas most garnet amphibolites (type 1C and also type 1A, diamonds) plot into the area of ocean floor tholeiites.
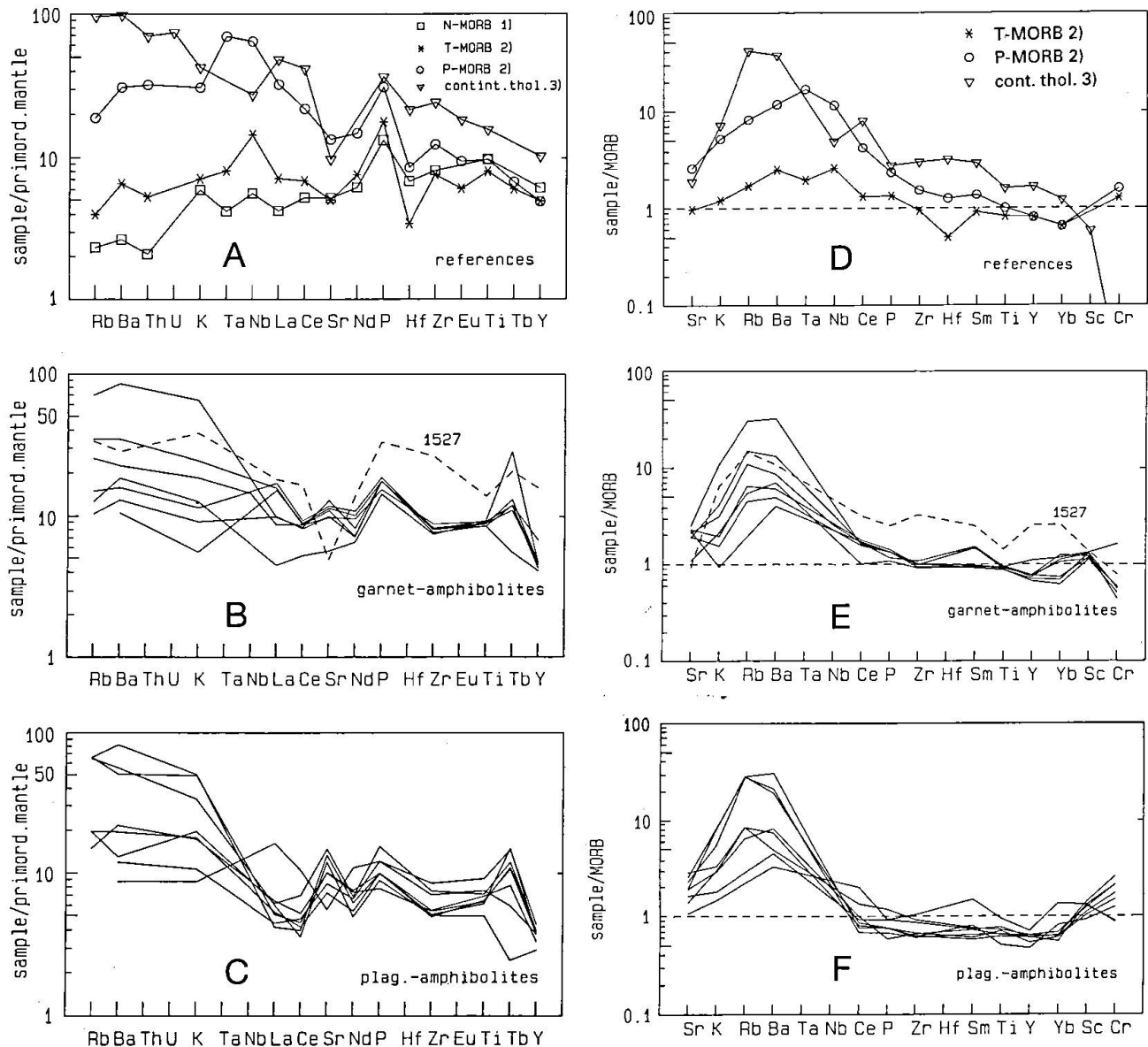
Fig. 9   Trace elements of the different amphibolites compared to typical oceanic and continental tholeiites.
A–C: Normalized with the primordial mantle composition of WOOD et al. (1979a).
D–F: Normalized with the N-MORB composition of PEARCE (1980). References: 1) normal mid-ocean ridge basalt
(MORB) after PEARCE (1980). 2) transitional (T-)type MORB and plume (P-) type MORB after WOOD et al. (1979b,
sample 411 and 413-1). 3) Continental tholeiite after DOSTAL et al. (1983, sample 718).

TRAND et al., 1982; COX, 1983; BELLIENI et al., 1984; UPTON et al., 1984; FODOR and VETTER, 1984; COLEMAN and McGUIRE, 1988).

Conclusions

The studied amphibolites have suffered a poly-phase high-grade metamorphism of Caledonian and Variscan age (VON RAUMER 1984b, 1987, 1988). After the early formation of eclogites the metabasic rocks followed the Barrovian evolution trend involving decompression and a temperature increase as indicated by the petrology of the accompanying metapelites. During this second metamor-

phic event, limited chemical exchange took place between the metapelitic country rocks and the small amphibolite boudins and the marginal zones of larger ones. During hydrothermal activity of Permian age, plagioclases were partly replaced by sericitic white mica. In contrast the Tertiary overprint was almost negligeable (local pumpellyite-prehnite).

Despite this complex metamorphic history, the described amphibolites have preserved a chemical pattern interpreted as an igneous differentiation series of transitional MORB characteristics as is typical for continental rift zones at the onset of ocean floor spreading. As the volume of the mafic rocks is small and occurs as several hundred-meter-

long thin layers, it is very likely that the studied mafic rocks were sills or dikes which intruded detrital sediments of continental character (today metapsammitic and metapelitic gneisses and schists). Their unusual high contents in K, Rb and Ba can be explained by enrichment from the surrounding wall (FRATTA and SHAW, 1974; WEAVER and TARNEY, 1981; GILL and BRIDGWATER, 1979; GOLDBERG et al., 1986). Magmatic differentiation from olivine-tholeiite to hypersthene-tholeiite is well known from diabase dikes (PAPEZYK and HODYCH, 1980). Magma chilling at the contact and later crystallization of the central parts may explain the differences in composition.

The overall chemical variation of the described amphibolites with its transitional MORB trend, but enriched in K, Rb and Ba is typical for continental rift zones charaterized by sub-alkalic basalts (WILSON, 1988) and has been hypothesized for the Aiguilles Rouges massif by PAQUETTE et al. (1989). A model of the inferred paleotectonic environment

during the formation of the basaltic rocks of Lake Emosson is presented in Fig. 10. It corresponds to the tentative model of the External Massifs in general by VON RAUMER (1987) and is also in good agreement with the general picture of the Paleozoic Central Europe as proposed by ZWART and DORNSIEPEN (1980).
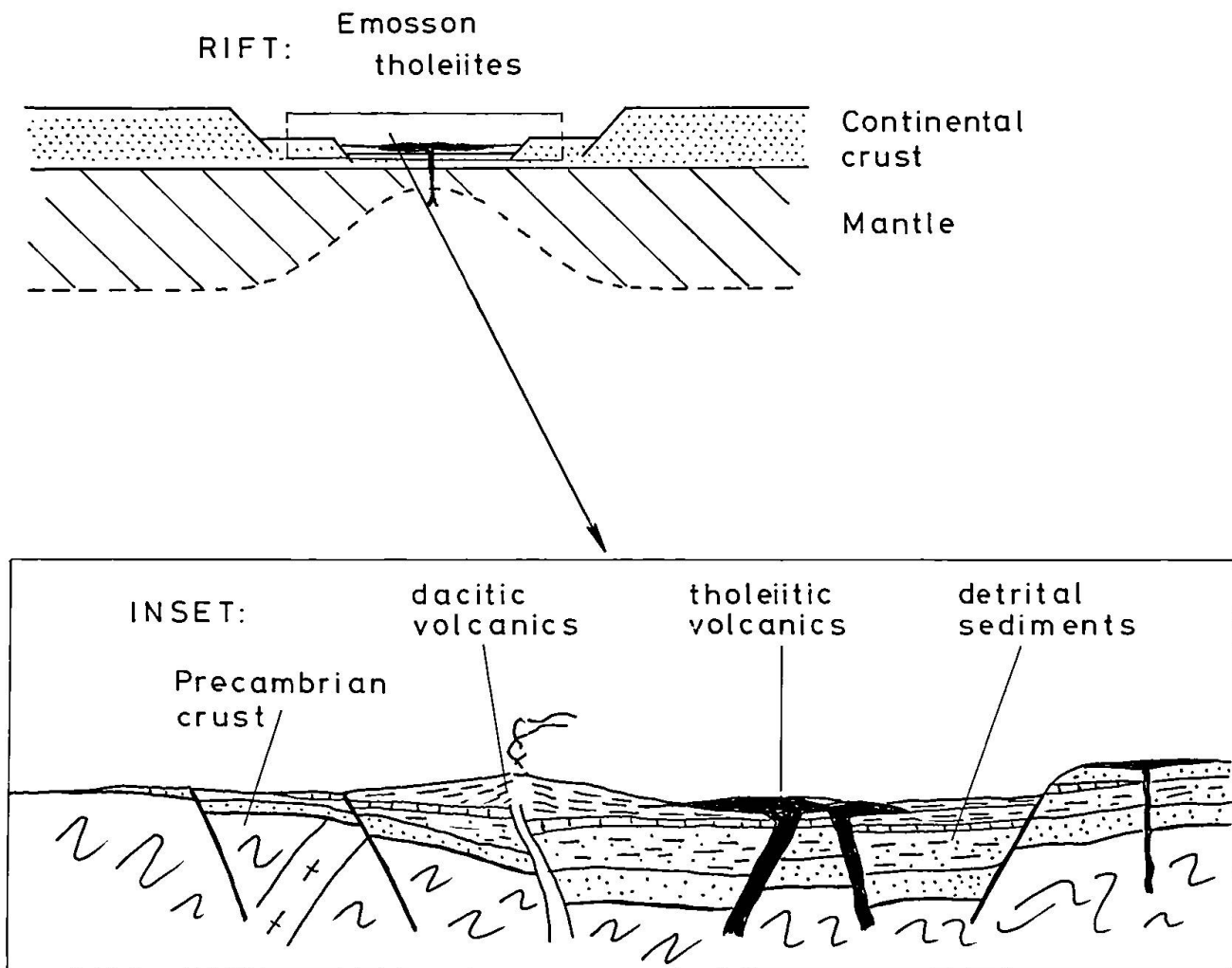
Fig. 10 Diagrammatic sections illustrating the hypothetical paleotectonic situation of the Emosson amphibolites as former tholeiitic eruptions in an extending continental crust, following the models of FODOR and VETTER (1984) and UPTON et al. (1984) and the paleotectonic interpretations (inset) of VON RAUMER (1987).

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