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Mineralogy and Alpine metamorphism of meta-lamprophyres from the Central Swiss Alps

by *R. Oberhänsli*[1]

Abstract

Along a north-south profile from the Black Forest to the Pennine nappes of the Lepontine area, this is, from areas with no Alpine metamorphism into the center of Tertiary Alpine metamorphism, lamprophyres, unaffected by Variscan metamorphic events, have been investigated. Lamprophyres from non metamorphic terrains show considerable authohydrothermal alteration which produced chlorite, actinolite, epidote and in some cases biotite; the same phases which would be produced by a lower greenschist facies overprint. Detailed investigations on mineral chemistry with the microprobe allow to distinguish between the early retromorphic and the later metamorphic overprint. In amphiboles, a decrease in edenite, plagioclase and tschermak's substitution due to retromorphic reactions is followed by an increase of plagioclase and tschermak's substitution along with metamorphic overprint. The edenite vector still decreases under the weak overprint in the Aar- and northern Gotthardmassif. Biotite shows a redistribution of Ti and Fe coupled with a tschermak's substitution. Along the investigated N–S profile, the area, where progressive metamorphic overprint causes reequilibration of earlier autohydrothermal products, can be located north of Göschenen. Si contents in phengites formed during Alpine metamorphism, reveal pressure differences of several kilobars (2–3) between the northern and southern margins of the Aar- and Gotthardmassif respectively. This pressure distribution pattern is interpreted as to reflect the nappe like structures of these crystalline complexes.

Keywords: Mineralogy, metamorphism, lamprophyres, Central Alps, Switzerland.

List of abbreviations

ab:	albite	act:	actinolite
alm:	almandine component	an:	anorthite
and:	andesine	ank:	ankerite
ap:	apatite	bi:	biotite
cc:	calcite	chl:	chlorite
cm:	clay minerals	cmts:	calcium tschermakite component
cpx:	clinopyroxene	cr-ts:	chrome tschermakite component
czo:	clinozoisite	di:	diopside
En:	enstatite component	ep:	epidote
Fo:	forsterite component	Fs:	ferrosilite component
gr:	garnet	gross:	grossular component
hbl:	hornblende	hem:	hematite
idd:	iddingsite	ilm:	ilmenite
jd:	jadeite component	kfsp:	kalifeldspar
lab:	labrador	leux:	leucoxene
mgt:	magnetite	mont:	montmorillonite
mu:	muscovite	myr:	myrmekite
ol:	olivine	olig:	oligoclase

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opx:	orthopyroxene	ort:	orthite
phe:	phengite	phl:	phlogopite
pic:	picotite	plg:	plagioclase
px:	pyroxene	py:	pyroxmangite component
pyr:	pyrope component	qtz:	quartz
ser:	sericite	serp:	serpentine
sid:	siderite	spess:	spessartine component
tit:	sphene	ti-px:	titanium pyroxene component
tr:	tremolite	wo:	wollastonite component
zo:	zoisite	zr:	zircon

Symbols

△ Schwarzwald	▽ uralitized amphiboles Schwarzwald
⋇ Vogesen	× anchibasalts Vogesen
◇ Aarmassif	+ uralitized amphiboles Aarmassif
⊡ Gotthardmassif	⧄ anchibasalts Gotthardmassif
⊙ Ticino	

Introduction

The aim of this study is to investigate the effects of low grade Tertiary Alpine metamorphism on lamprophyres belonging to the late Variscan orogenic cycle which had escaped earlier Variscan metamorphism. The mafic dike rocks were expected to be more susceptible than the enclosing acid rock types to metamorphic as well as retromorphic reactions. Thus, one of the hopes was that a detailed study of the meta-lamprophyres, sampled along a cross section from areas unaffected by Alpine metamorphism through anchimetamorphic regions, greenschist facies zones into amphibolite facies zones, might yield a finer resolution of metamorphic zoning than is apparent in the enclosing, largely quartzo-feldspathic rocks. Therefore meta-lamprophyres were examined mineralogically and geochemically (Oberhänsli, 1985, 1987).

Lamprophyres and meta-lamprophyres where investigated along a north-south profile (Fig. 1) from the Schwarzwald (Black Forest) to the Ticino, thus combining samples from the unmetamorphosed non-Alpine massifs (Vogesen and Schwarzwald) with meta-lamprophyres from the increasingly overprinted external (Aarmassif) and internal (Gotthardmassif) massifs and the Penninic nappes (Ticino).

The zonation pattern of Tertiary Alpine metamorphism is shown in fig. 2.

Sample locations are given in fig. 1 showing the Vogesen (V), Schwarzwald (S), Aar- and Gotthardmassif (A, G) as well as the Penninic realm in the Ticino (T).

Petrographic descriptions

Unmetamorphosed samples from the Schwarzwald massif (Black Forest) in northern Switzerland show generally significant autohydrothermal alterations. In the groundmass (41–88 vol.%) of minettes from a drillhole at Leuggern, primary phases K-feldspar (10–25%), plagioclase (5–15%), andesine-oligoclase, myrmekite, biotite (20–35%), apatite (1–3%), quartz (5–10%) are altered to albite, sericite, muscovite, chlorite, calcite, clay minerals, leucoxene, Fe-oxides, clinozoisite, epidote and magnetite. Olivine (5–15%), clinopyroxene (5–10%), hornblende (3–10%), rare biotite, plagioclase or K-feldspar occur as phenocrysts (13–35%). They are altered to ser-

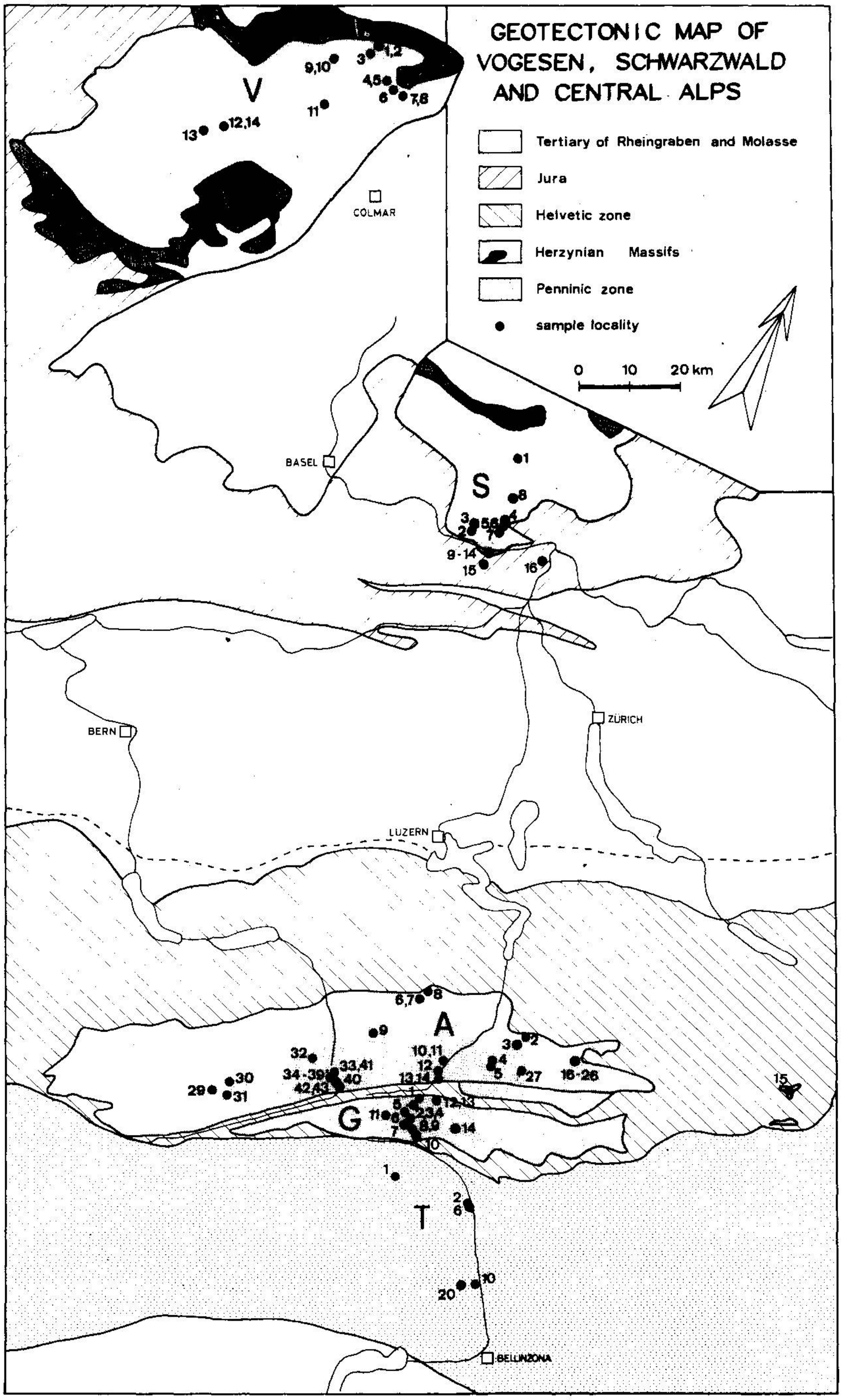

Fig. 1 Sample locality index map. Detailed sample descriptions are given in OBERHÄNSLI (1987).

pentine, talc, calcite, siderite (?), ankerite (?), tremolite/actinolite, Fe-Mg-chlorite, iddingsite, muscovite, phengite, quartz, biotite and hematite.

In weakly metamorphosed samples from the Aarmassif, depending on the state of structural/textural preservation, lamprophyres with completely preserved magmatic textures and mineralogy can be found. In most samples, however the phenocrysts have been altered by Alpine retromorphic events (e.g. chloritized, sercitized) whereas the matrix, surprisingly, was preserved. Progressively deformed lamprophyres show first completely altered phenocrysts in a partly altered matrix, and finally samples in which all of the pre-Alpine structures are overprinted, though primary minerals may still be conserved as relics. Thus, phenocrysts of diopside, biotite, phlogopite, hornblende, quartz or pilite-pseudomorphs after olivine with idiomorphic habitus were found. The ophitic groundmass contains phlogopitic biotite, pyroxene, K-feldspar, plagioclase, calcite, apatite, epidote, orthite, sphene and chlorite. Where Alpine metamorphism overprinted the primary mineralogy, the products are sometimes difficult to distinguish from the autohydrothermal minerals mentioned earlier, including actinolite, chlorite, calcite, epidote/clinozoisite, sericite/muscovite-phengite and leucoxene. Where recristallization occurred without deformation, the distinction between autohydrothermal and weakly metamorphic assemblages is mostly impossible.

Further to the south, in the Gotthard area, where the metamorphic overprint is stronger ("staurolite - in" isograd), only epidote/clinozoisite inclusions in the cores of plagioclase attest to originally anorthite-rich primary feldspar. Biotite and hornblende are completely recrystallized and form an apparently stable paragenesis together with albite, epidote/clinozoisite and quartz. Rarely additional, spessartine-rich garnet can be found as a metamorphic mineral. Metamorphic green biotite and bluegreen to green amphibole are commonly retromorphosed to chlorite ± calcite. Magmatic apatite, sphene and zircon seem unaffected by the metamorphic overprint.

In the Penninic nappes of the Ticino, complete recrystallization of lamprophyres produced rocks with biotite, actinolite, quartz, K-feldspar, epidote/clinozoisite and plagioclase. The anorthite-component of plagioclase increases systematically from N to S (compare WENK, 1962, and WENK and KELLER, 1969).

Mineral distributions maps

Maps of the regional distribution of magmatic relics and metamorphic minerals are given in figures 2 to 5.

The first occurrence of green metamorphic biotite (Fig. 2) in meta-lamprophyres coincides with the index line of first occurrence for green biotite in meta-granitic rocks of the Aarmassif (STECK and BURRI, 1971). Brown relics of magmatic biotite persist farther south toward the Gotthard massif. There and in the Lepontine nappe of the Ticino, metamorphic brown biotite is found in several samples.

Nevertheless, the first occurrence of green to olive-coloured biotite is determinable in thin section and seems to be confined to the area where green biotite occurs in meta-granitic rocks.

Relics of magmatic pyroxene (Fig. 3) are less abundant but can be found in meta-lamprophyres in the stilpnomelane zone of the Aarmassif. Two pyroxene bearing meta-lamprophyres were also found in the northern part of the Gotthard massif, south of the "chloritoid - in" isograd. In the southern, more highly metamorphosed part, magmatic pyroxene relicts are absent. In the few recognizable meta-lamprophyres from the Ticino no newly formed metamorphic pyroxene has been found.

From the Austroalpine nappes W and E of the culmination of the central Alps, magmatic pyroxene is also reported.

The map of amphibole distribution (Fig. 4) shows a different picture. Relics of magmatic hornblende are found throughout the Aarmassif and are widespread in the in the northern part of the Gotthard massif. Metamorphic amphibole of actinolitic composition is described from the non-Alpine massifs (Vogesen and Schwarzwald) (MÜLLER, 1982). Ca-amphiboles also occur at the northern rim of the Aarmassif. As mentioned earlier, amphibole can be the reaction product of the pilitization of olivine as well as of the uralitization of pyroxene. MÜLLER (1982) described amphiboles with high birefrengence from olivine pseudomorphs as a typical product of pilitization these amphiboles could belong to the cummingtonite series.

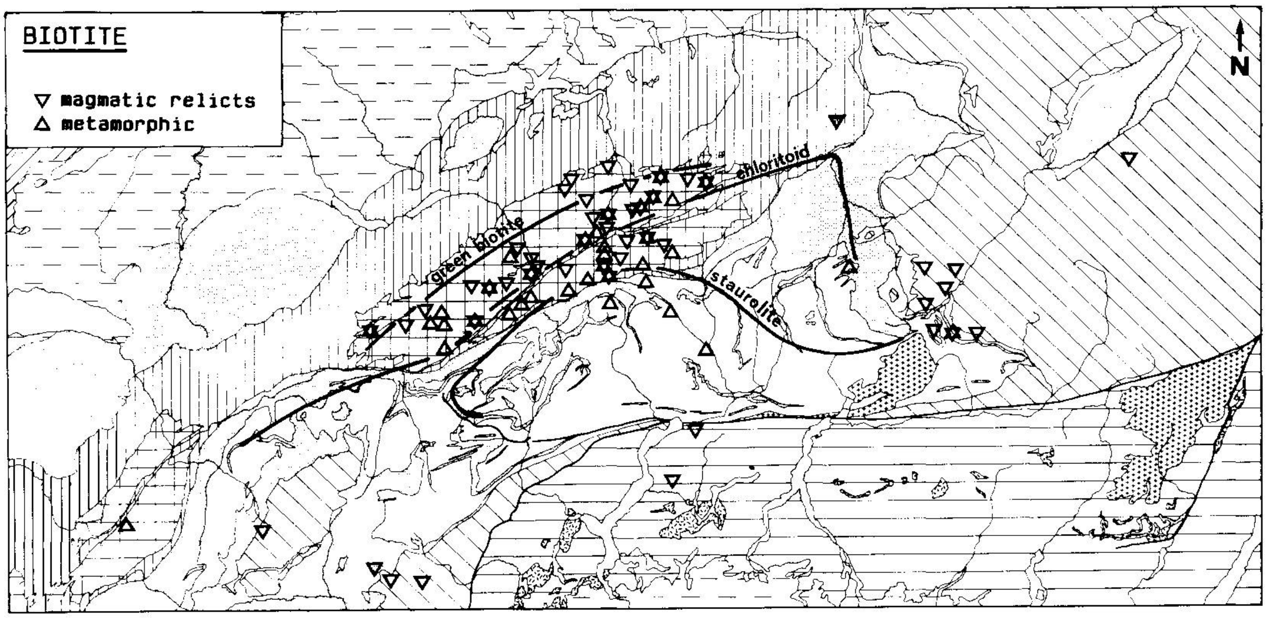

Fig. 2 Distribution of biotite in meta-lamprophyres (literature and this study) and metamorphic zonation pattern of the Tertiary Alpine metamorphism after NIGGLI (1970).

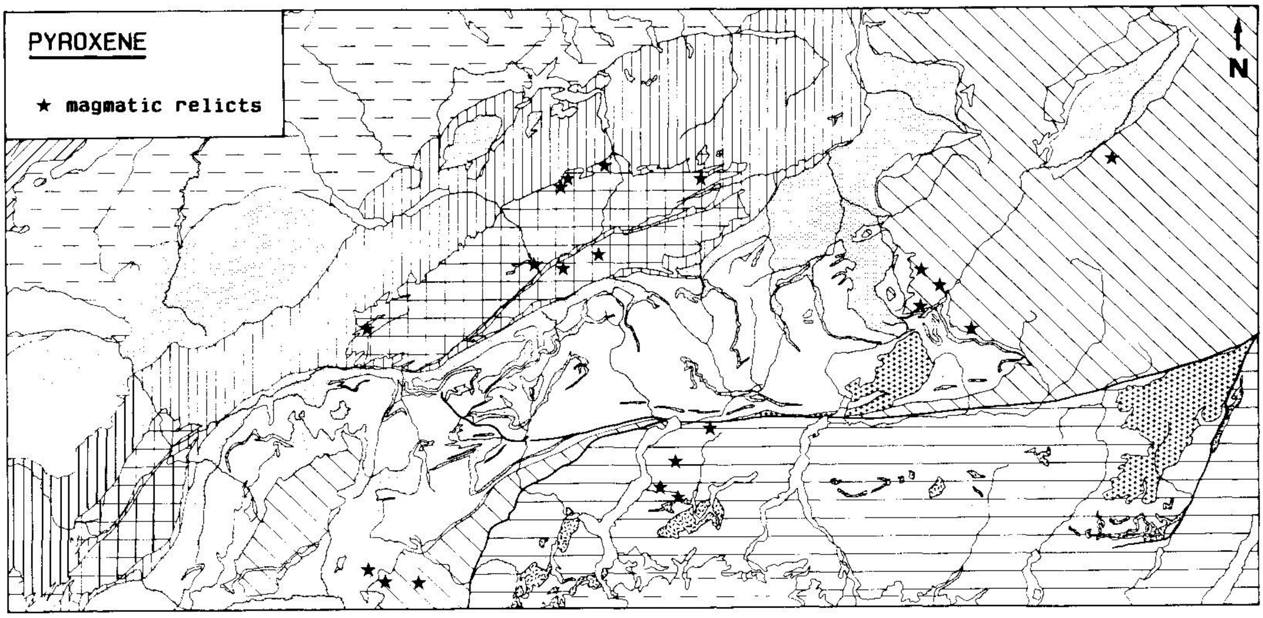

Fig. 3 Distribution of pyroxene relics in meta-lamprophyres (literature and this study).

- ☐ Molasse
- ▨ Jura
- ▥ Helvetic zone
- ░ Penninic sediment nappes
- ☐ Penninic crystalline nappes
- ⊞ Massifs Aar, Gotthard, Mont Blanc Aiguilles Rouges
- ▧ Austroalpine nappes
- ▤ Southern Alps
- ▒ Paleozoic magmatites
- ▦ Tertiary intrusions
- — faults

GEOTECTONIC MAP OF THE CENTRAL ALPS

0 50km

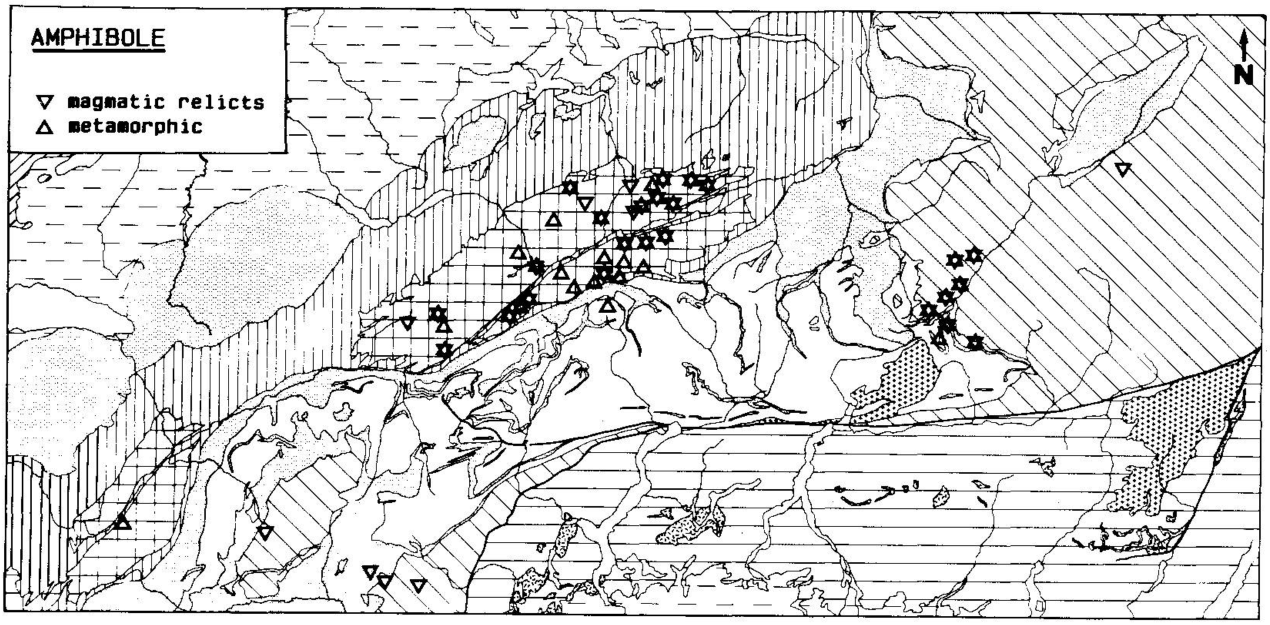

Fig. 4 Distribution of hornblende relics and amphibole in meta-lamprophyres (literature and this study).

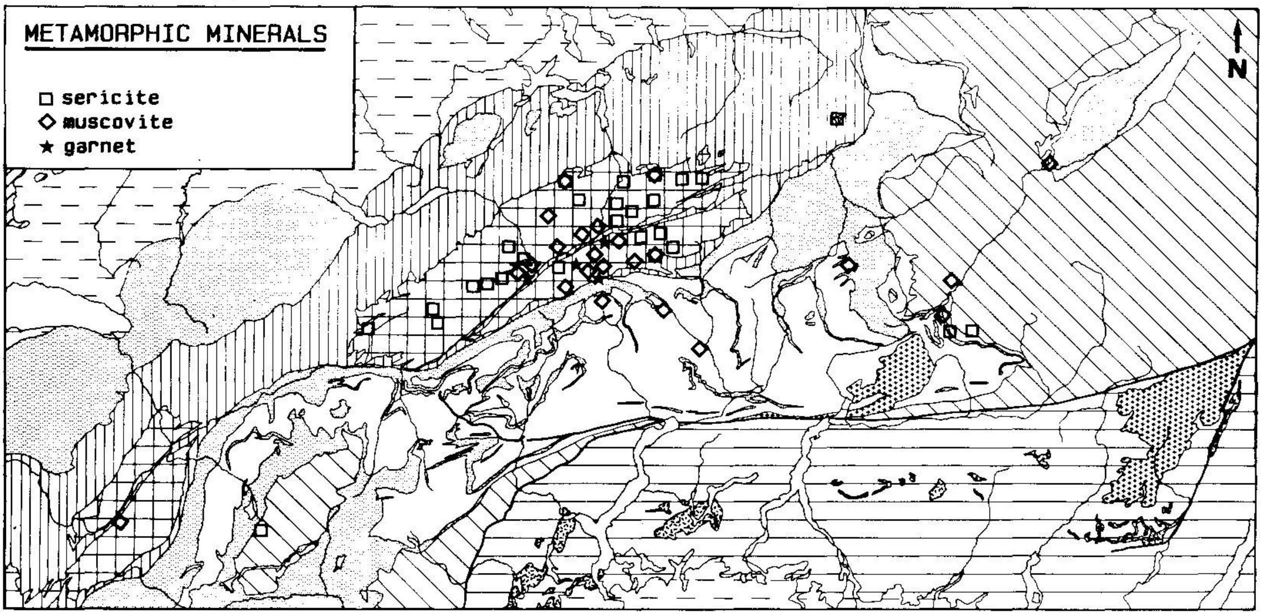

Fig. 5 Distribution of metamorphic minerals in meta-lamprophyres (literature and this study).

▭	Molasse	▧	Austroalpine nappes
▨	Jura	▤	Southern Alps
▥	Helvetic zone	░	Paleozoic magmatites
░	Penninic sediment nappes	▒	Tertiary intrusions
☐	Penninic crystalline nappes	—	faults
▦	Massifs Aar, Gotthard, Mont Blanc Aiguilles Rouges		

GEOTECTONIC MAP OF THE CENTRAL ALPS

0 50 km

Data on the distribution of white mica in meta-lamprophyres are compiled in figure 5. Due to deformation and instability of feldspar, sericite is formed throughout the Central Alps. Crystallization of muscovite begins in the Aarmassif and is also found farther south in the Gotthardmassif and in the Penninic nappes.

Mineralogy[1]

PSEUDOMORPHS AFTER OLIVINE

Olivine is not reported from lamprophyres of the Central Alps but pseudomorphs after olivine (pilites, CHELIUS, 1907) can be found in weakly overprinted regions of the northern Aarmassif. In non-metamorphic terrains olivine can be replaced either by chl ± cc; by tc ± cc ± qtz ± bi ± pic; by cc ± chl ± qtz; by mont ± cc ± qtz or by act ± cc ± chl (VELDE, 1968).

In the metamorphic Alpine terrains either act ± chl ± bi ± oxides/hydroxides or chl ± qtz ± cc or qtz ± chl ± cc occur in pseudomorphs of olivine. Due to deformation, these olivine pseudomorphs tend to disappear early during the metamorphic evolution. Serpentine was not mentioned as a reaction product in lamprophyres until it was recently found in drill holes into the Schwarzwald massif (MEYER, 1987) and in the Aarmassif (SCHALTEGGER, 1984).

In the Schwarzwald, picotite can be found as inclusions in the pseudomorphs after olivine. Analyses given by MÜLLER (1982) are represented by the general formula $(Mg_{.68}Fe^{2+}_{.31})(Cr_{1.35}Al_{.45}Fe^{3+}_{.16}Ti_{.04})O_4$. In the Central Alps no relics of chrome-spinel are known from meta-lamprophyres. In the course of this study tc, chl, act, cc and qtz were found in olivine-pseudomorphs. Talc analyses yield $X_{Mg} = .906$, which could be derived from Fo 90 for the original olivine, in agreement with measured compositions from Buell Park minette (RODEN and SMITH, 1979).

PYROXENES

Figure 6 gives an overview of the pyroxenes and allows comparison with data from the literature. According to the compilation of ROCK (1984), pyroxenes in calc-alkaline lamprophyres show a diopsidic composition with $Al_2O_3 < 6$ wt.% and $TiO_2 < 2$ wt.%. In the Schwarzwald, pyroxenes are very diopside-rich with a ferrosilite-component generally < 10 mol% (MÜLLER, 1982). KÜPFER (1977) reports even more diopside-rich pyroxenes. Samples reported in the present study range from similar calcic pyroxenes to more augitic compositions with ferrosilite up to 15 mol% while the diopside component drops from 96 mol% to 80 mol%. It is not clear whether the augitic composition is of primary magmatic origin or the change in composition to augite is due to the autohydrothermal alteration.

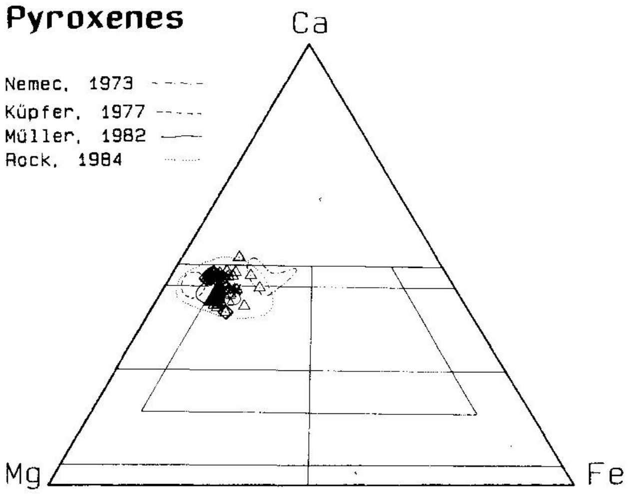

Fig. 6 Composition of magmatic pyroxenes from lamprophyres and lamprophyric dikes from the Alps in comparison to such pyroxenes reported in the literature.
(Symbols see list of abbreviations.)

Alteration of calcic cpx to amph is common. Whereas cpx and amph can clearly be distinguished optically, intermediate biopyribole phases might nevertheless exist along the transitional zone of cpx–amph.

Investigation of zoned pyroxene crystals shows that they often exhibit a corroded inner core richer in Fe, Al and Cr than the homogeneous outer part of the core. The rims also are enriched in Fe and Al. SCHALTEGGER (1984) described inclusions of tschermakitic to pargasitic hornblende, chlorite and calcite in the corroded inner cores, where amphibole compositions in the inner core are similar to the rimming amphibole.

In figure 7, two populations of pyroxene can be distinguished. One is Al-free and fol-

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[1] Microprobe analyses of minerals are available from the author on request.

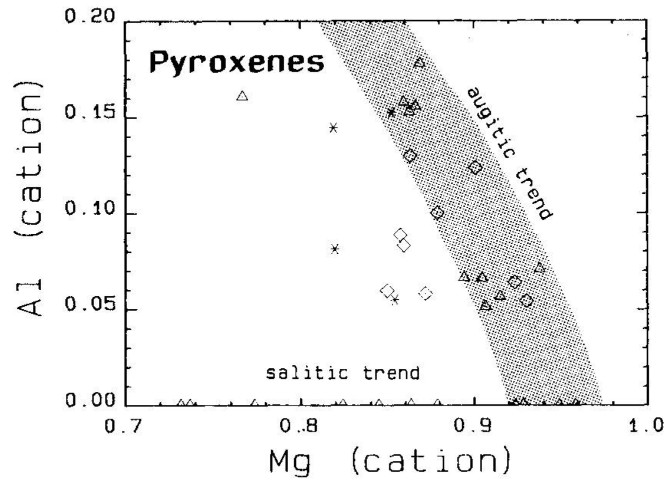

Fig. 7 Pyroxenes from lamprophyres and lamprophyric dikes. The samples demonstrate two trend lines: an augitic trend and a salitic trend. Shaded area: augitic trend for cpx in lamprophyres from the Adamello massif (ULMER et al., 1983).
(Symbols see list of abbreviations.)

lows a salitic trend. All samples following this trend are from the Schwarzwald. A second group roughly follows an augitic trend with Al_2O_3 up to 4 wt.%. The latter is observed in samples from the Vogesen, Schwarzwald and the Aarmassif. Cr_2O_3 ranges up to .65 wt.%. TiO_2 is generally low and ranges between 0 to 1.1. wt.%. The relatively primitive character of the pyroxenes is evident from figure 8 where Ti is constantly low (0.02–0.03 cations per formula unit) at variing Al^{IV} contents (0.01–0.17 cations per formula unit). This relationship demonstrates differences in bulk composition rather than changes following a magmatic evolution trend similarly to the one proposed by ULMER et al. (1983) for the lamprophyres from the Adamello massif.

AMPHIBOLES

The amphibole compositions from lamprophyres and meta-lamprophyres vary considerably. Beside relics of magmatic hornblende, metamorphic amphibole occurs in all lamprophyres, formed by uralitization of pyroxene or pilitization of olivine. In the compilation of ROCK (1984), no data on amphiboles from vogesites are reported. Hornblendes of such rocks consist of magnesio-hastingsitic cores and alumino-tschermakitic rims.

Magmatic relics disappear in meta-lamprophyres when subjected to increasingly higher metamorphic degree in the Central Alps (Fig. 4). Metamorphic amphiboles in meta-lamprophyres belong to the group of calcic amphiboles.
In figure 9 magmatic relics plot along the line from hastingsite towards hornblende, whereas metamorphic amphiboles follow a trend towards more actinolitic composition; initially partly filled A-sites tend to be vacant.

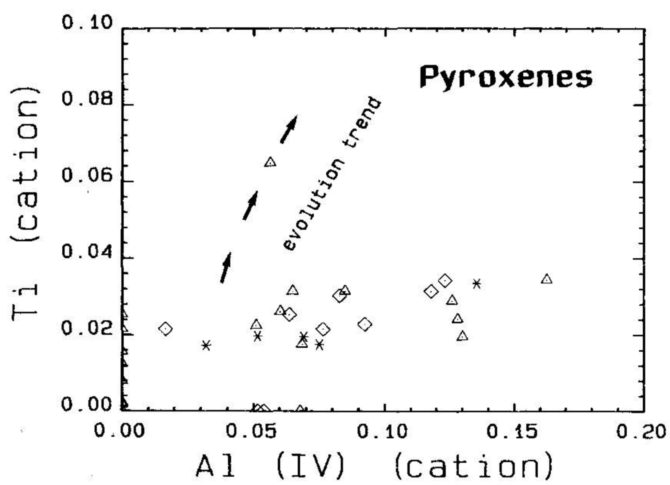

Fig. 8 Pyroxenes in lamprophyres from the Central Alps are relatively primitive and do not follow the magmatic evolution trend found for cpx in lamprophyres from the Adamello massif (ULMER et al., 1983).
(Symbols see list of abbreviations.)

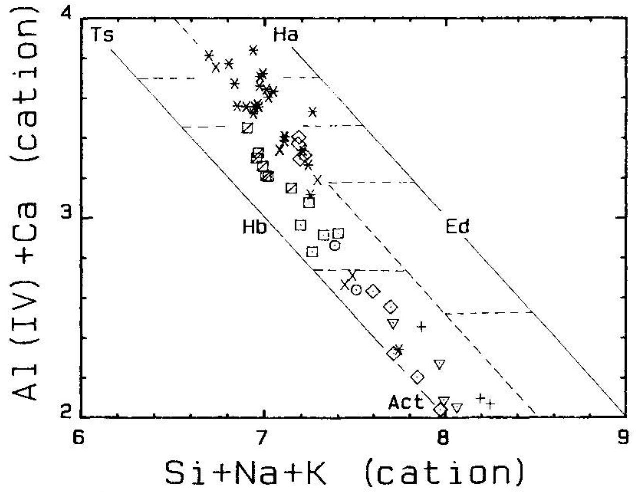

Fig. 9 Amphibole classification diagram (GIRET et al., 1980), showing a trend from magnesio-hastingsite to actinolite for amphiboles from lamprophyres and meta-lamprophyres.
(Symbols see list of abbreviations.)

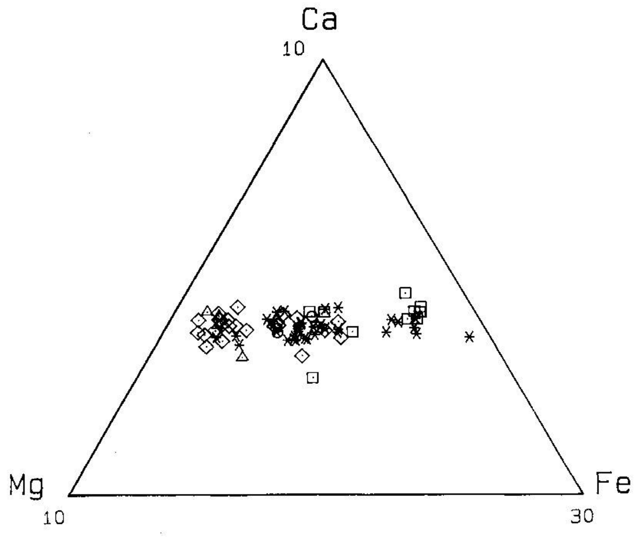

Fig. 10 Compositional triangle for amphiboles. The amphiboles in the group at the left are products of uralitization. The amphiboles in the right group are from anchibasaltic rocks.
(Symbols see list of abbreviations.)

In figure 10 which is analogue to figure 6 for pyroxenes, three groups of amphiboles can be recognized on the basis of the Fe–Mg distribution. In the first group, Fe is low (FeO 7–9 wt.%) whereas Mg is very high (MgO 14–19 wt.%), Ti is generally absent, Al and the alkalis vary at low values (Al_2O_3 0–3 wt.%; Na_2O 0–0.5 wt.%; K_2O 0–0.1 wt.%). This group includes amphiboles from the Schwarzwald and the Aarmassif. They are products of the uralitization or pilitization of pyroxenes and olivine respectively. The second group is characterized by higher Fe (FeO 10–12 wt.%) and lower Mg (MgO 13–14 wt.%) contents. Ti, Al and the alkalis are high (TiO_2 2–4 wt.%, Al_2O_3 12–13 wt.%, Na_2O 1.8-2.2. wt.%, K_2O 1.1.-1.3 wt.%). This amphibole group includes magmatic relics and metamorphic amphiboles from the metamorphic terrains. The third group finally contains high Fe, low Mg amphiboles (FeO 14–16 wt.%, MgO 9–10 wt.%). Ti, Al and the alkalis are intermediate compared to the other groups (TiO_2 0.5–2.6 wt.%, Al_2O_3 11–17 wt.%, Na_2O 1.6–1.8 wt.%, K_2O 0.3–1.1 wt.%). This group includes amphiboles from metamorphic and non metamorphic terrains of semilamprophyric and anchibasaltic rocks. The three groups of amphiboles can further be distinguished in a diagram which tentatively shows the oxidation state of the amphiboles (Fig. 11). The distribution of Fe^{2+} and Fe^{3+} has been calculated assuming stoichiometric and charge balance. Amphiboles belonging to the first group, considered to be products of uralitization of pyroxenes or pilitization of olivine, are free of Fe^{3+}. Those of the two other groups show a distinct Fe^{3+} enrichment. One sample plotting almost along the Mg,Fe^{3+} tie-line represents a brown magmatic relic with a symplectitic overgrowth of metamorphic amphibole. This rimmed amphibole is zoned and shows an increase of Fe^{3+} towards its outer zones. The inner rim (I), with low Fe^{3+}, could be interpreted as a decomposition product of the magmatic hornblende during autohydrothermal alteration.

A plot of Ti vs. Al^{IV} discriminates between the magmatic and metamorphic amphiboles (Fig. 12c) independent of their rock types. Magmatic hornblendes from anchibasalts and lamprophyres show high Al^{IV} (up to 1.9 cations per formula unit) and high Ti contents, whereas metamorphic amphiboles scatter widely in Al^{IV} but have virtually no Ti. Al^{IV} values for amphiboles in lamprophyres from the Adamello massif are generally higher, reaching up to 2.2 cations per formula unit (ULMER et al., 1983). Potassium, as titanium, tends to be lower in metamorphic amphiboles. The mag-

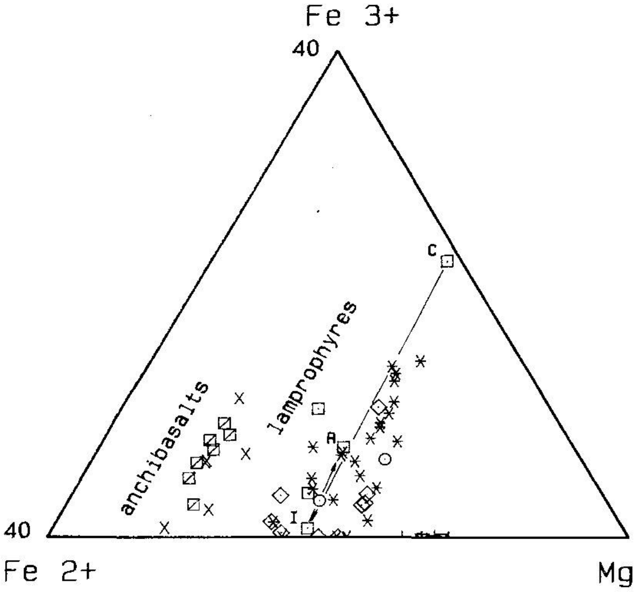

Fig. 11 Fe^{2+},Fe^{3+},Mg triangular plot, tentatively showing the oxidation state of amphiboles. Metamorphic amphiboles are less oxidized than magmatic hornblendes. This is also indicated by the line (C-I-R) connecting core and rims of an amphibole from the Gotthardmassif. Amphiboles from anchibasaltic rocks are well separated.
(Symbols see list of abbreviations.)

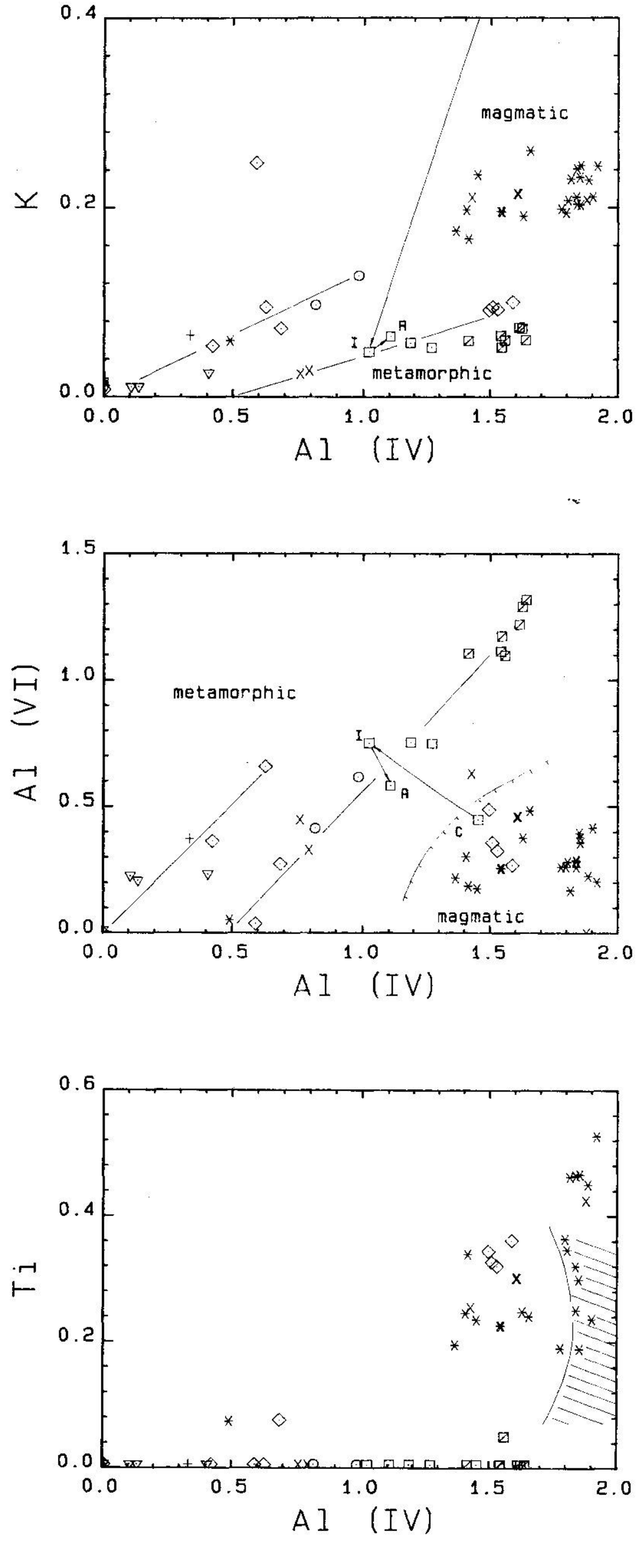

Fig. 12 Plot showing a separation of magmatic and metamorphic amphiboles. Metamorphic amphiboles in a) und b) are grouped in relation to the original magmatic mineralogy (see text). Hatched area in c: lamprophyres from the Adamello massif (ULMER et al., 1983).
(symbols see list of abbreviations.)

matic and metamorphic amphiboles are well separated in two diagrams K vs. Al^{IV} and Al^{VI} vs. Al^{IV} respectively (Figs. 12a and 12b). The metamorphic amphiboles are grouped along two trend lines, a first leading to very low Al^{IV} values and a second, parallel to the first, leading towards Al^{IV} values of 0.5 cations per formula unit. Amphiboles from anchibasaltic rocks or semilamprophyres plot on this second line. The two populations in meta-lamprophyres are characterized on the one hand (low Al^{IV}) by samples containing magmatic biotite and on the other hand (high Al^{IV}) by samples containing only metamorphic biotite. The samples from amphibolite facies terranes (Ticino), however, line up on the lower Al^{IV} trend in fig. 12a and on the higher Al^{IV} trend in fig. 12b. In those samples no primary minerals are observed. Complete recrystallization does not allow identification of the primary mineralogy.

In the set of plots (Fig. 13) with the exchange vectors tschermakite ($X_{ts}^{amph} = Al^{VI} + Fe^{3+} + Cr + 2\ Ti$), edenite ($X_{ed}^{amph} = (Na + K)^{A}$) and plagioclase ($X_{pl}^{amph} = Na^{M4}$), the separation in Al^{VI} is less obvious. The representative zoned hornblende of sample G 2 shows (Fig. 13) that all three vectors drop from the magmatic core (C) to the first weakly metamorphic (autohydrothermal?) amphibole-rim (I). With increasing metamorphism the tschermakite and plagioclase vectors increase whereas the edenite vector drops further. In amphiboles from mafic schists, the edenite vector is known to increase up to the biotite zone before dropping in the higher grade garnet and staurolite-kyanite zones (LAIRD and ALBEE, 1981).

BIOTITE

Biotites from calc-alkaline lamprophyric dikes are generally Ti-rich members of the phlogopite-siderophyllite series (VELDE, 1969 a, b; KRAMER, 1976; NEMEC, 1972; KÜPFER, 1977; MÜLLER, 1982); biotites from minettes are richer in Mg than biotites from kersantites (VELDE, 1969b). No such difference in X_{Mg} can be found in the samples from the Schwarzwald and Vogesen studied here. However, independent of lamprophyre type and degree of metamorphic overprint, biotites plot along the phlogopite-siderophyllite line in the standard Fe–Al–Mg triangle (Fig. 14), showing a consi-

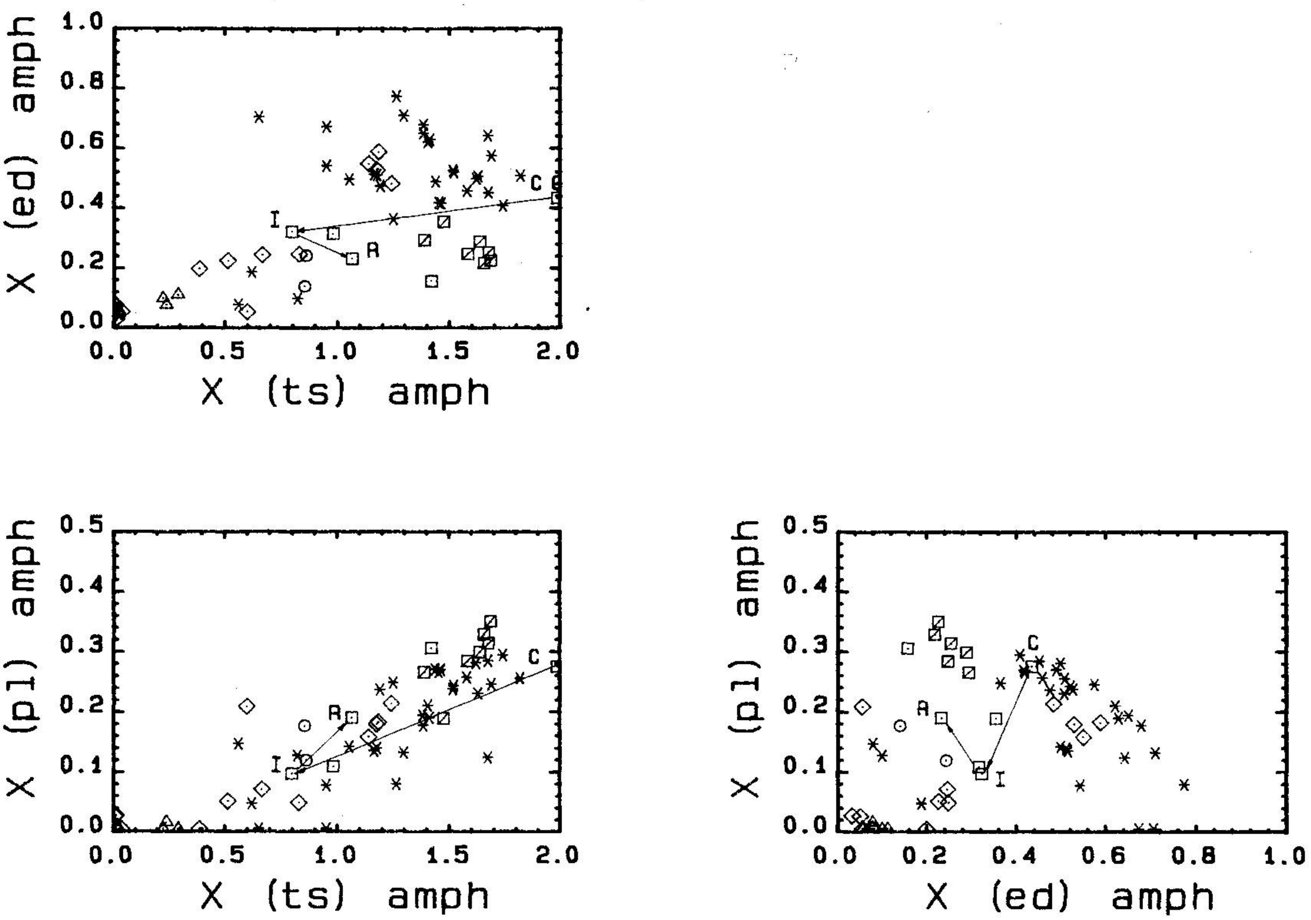

Fig. 13 The tschermak's, edenite and plagioclase exchange vectors for amphiboles (LAIRD and ALBEE, 1981). Plagioclase and tschermak's vector drop from magmatic to metamorphic amphiboles but increase again with metamorphic overprint as depicted by a line from core to rim (C-I-R) for a representative amphibole from the Gotthardmassif. The edenite vector drops with metamorphic overprint.
(Symbols see list of abbreviations.)

derable variation in X_{Mg}. Biotites reported from other lamprophyres (NEMEC, 1972, ROCK, 1984) tend to be slightly richer in Mg than biotites from the Schwarzwald (MÜLLER, 1982). In figure 14, the Mg-rich end of the data field contains samples from the Schwarzwald and the northernmost end of the Aarmassif. The Fe-rich end comprises only samples from the Gotthardmassif. Detailed studies of biotite from the Punteglias area, eastern Aarmassif (KÜPFER, 1977), showed that phenocrysts are phlogopitic (Mg/Fe > 2/1, X_{Mg} 0.60–0.90) and contain up to 1.6 wt.% Cr_2O_3. Cr and Mg contents decrease, while Fe increases towards the darker rim. Matrix-biotites from this area show lower Cr and Mg contents but are slightly enriched in Ti and Fe (X_{Mg} 0.50–0.65). A general distinction between magmatic biotite, biotite relics and metamorphic biotite is demonstrated in figure 15. Metamorphic biotite contains less TiO_2 (0–2.5 wt.%) than the magmatic biotite (3–6.8 wt.%), although exceptions to the later exist in the Schwarzwald (TiO_2 1–2 wt.%). In addition, compositions of metamorphic biotite are slightly shifted towards the Fe-corner. In a Fe vs. Ti plot (Fig. 16) a first evident trend, indicated by the large arrows, shows the effect of metamorphism. The originally large scatter in Ti contents is reduced in metamorphic biotite, where Ti is preferentially replaced by Fe. The metamorphic biotite in lamprophyric rocks achieve a tightly grouped distribution of Fe/Ti cation ratio around 8. Prior to this clearly metamorphic exchange, the original Ti and Fe content might change as a function of local bulk or magma composition at a late magmatic stage. In figure 16 such changes are indicated by the thin arrows, which connect core and rim

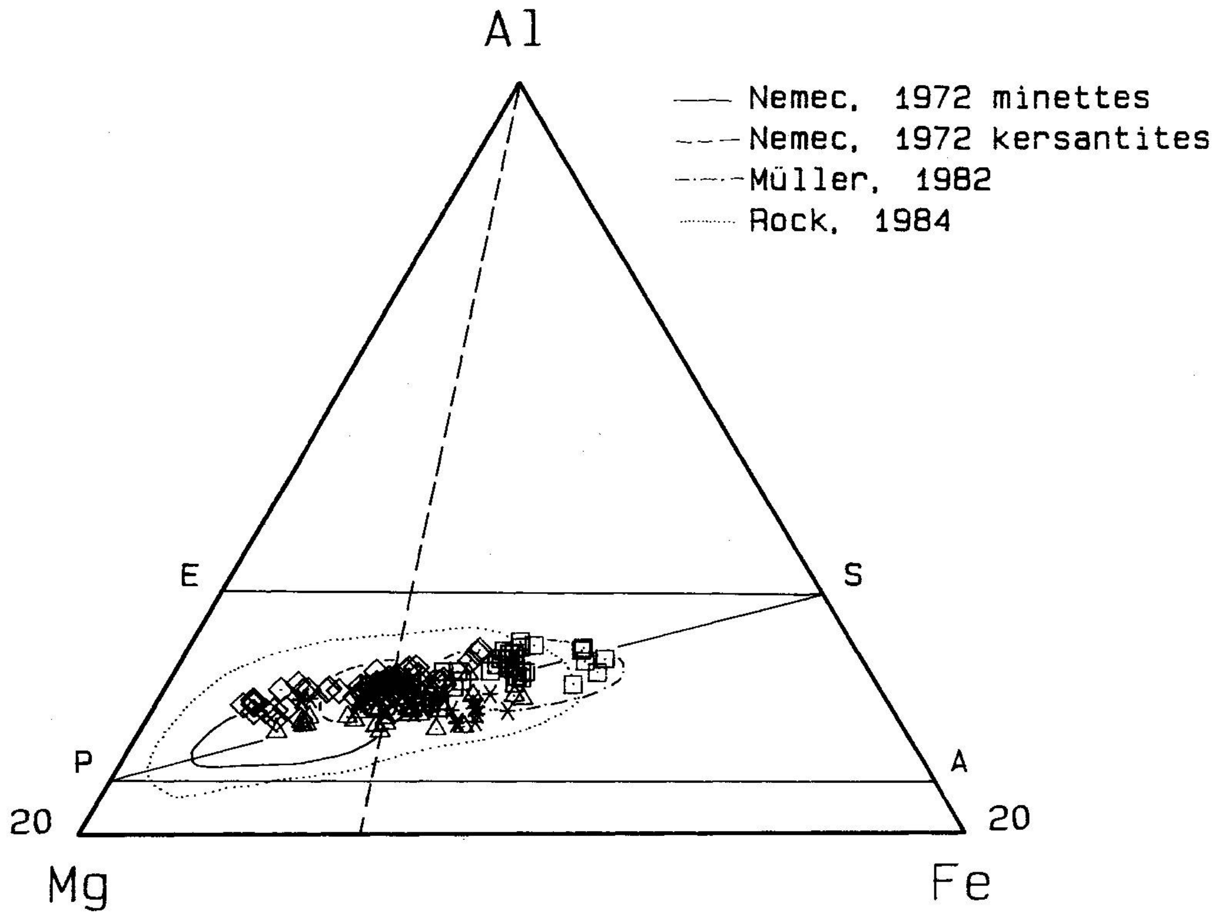

Fig. 14 Biotite compositions plot along a line from phlogopite to siderophyllite. For comparison, biotite compositional fields reported in the literature are given. E: eastonite, P: phlogopite, A: annite, S: siderophyllite.
(Symbols see list of abbreviations.)

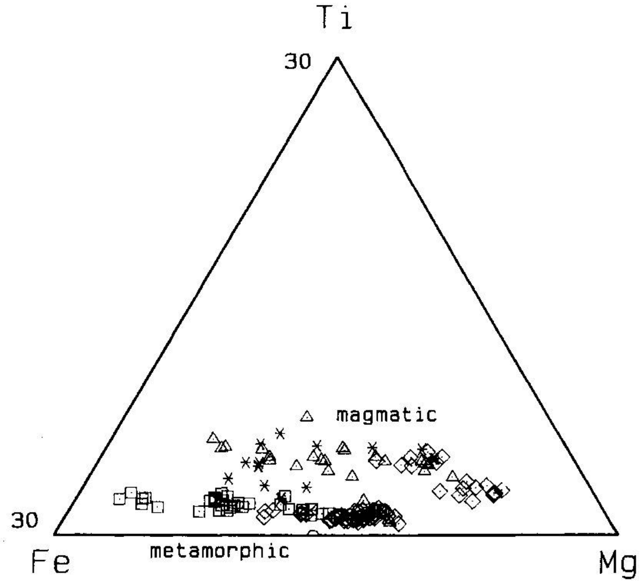

Fig. 15 Fe, Mg and Ti distribution in biotites discriminates metamorphic from magmatic samples. Metamorphic biotites are depleted in Ti and enriched in Fe.
(Symbols see list of abbreviations.)

of magmatic biotites. Rims are generally enriched in Fe and to a lesser extent also in Ti, but the reverse zonation paths can be observed as well.

A diagramm of X_{Ti} vs. Al^{VI} is given in figure 17, although calculations of site occupancy deduced from microprobe analyses of micas are doubtful and may be misleading. This diagram shows that the Fe–Ti substitution is coupled to a Si–Al substitution. Compared to magmatic biotite, metamorphic samples not only group at a given Fe/Ti ratio but show a lower degree of Si substitution by Al and enrichment in Fe and Al^{VI} (or Si) relative to Ti and Al^{IV}. The negative Al^{VI} values for the magmatic biotite may indicate, in addition to analytical problems, structural inhomogenities, e.g. dioctahedral domains in the trioctahedral biotite or simply charge balance effects due to the high Ti contents.

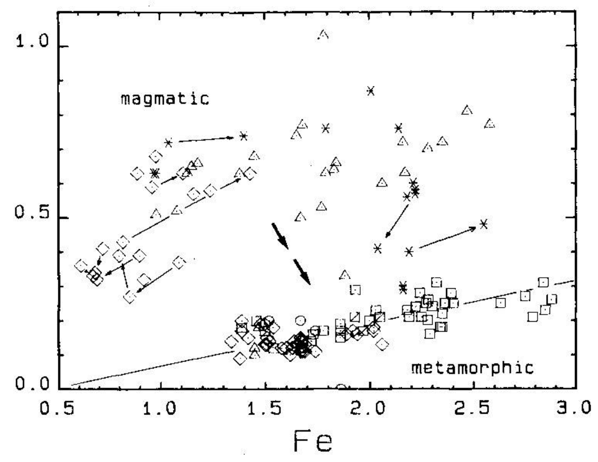

Fig. 16 Ti vs. Fe distribution for biotites. Thin arrows indicate zonation patterns in magmatic biotites. The thick arrows indicate the effect of metamorphic overprint (see text).
(Symbols see list of abbreviations.)

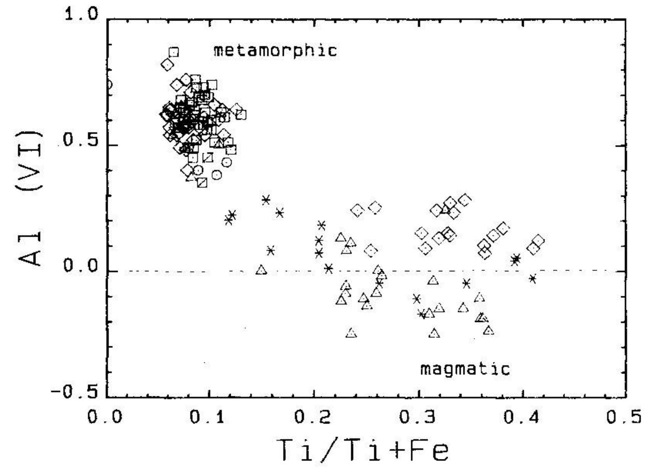

Fig. 17 Biotites may show the coupled substitution Fe + Ti for Al^{IV} + Si.
(Symbols see list of abbreviations.)

FELDSPARS

In the nonmetamorphic lamprophyres and in the undeformed dikes of the northern Aarmassif, distinction between feldspar phenocrysts and matrix crystals is possible. However, with increasing metamorphic overprint and deformation, primary feldspar textures are rapidly blurred.

Feldspar *phenocrysts* belong generally to the plagioclase-series. Occasionally K-feldspars are known from the Schwarzwald (MÜLLER, 1982). In the Alps plagioclase phenocrysts from meta-lamprophyres are strongly albitized and saussuritized. Complete replacement by albite, sericite and clinozoisite is common, leaving only outlines of the original plagioclase. In some cases, plagioclase phenocrysts or their pseudomorphs show resorption textures.

In the fine grained aphanitic *groundmass,* feldspar crystals are 10 to 100 times smaller than the phenocrysts. Though exolutions (perthite, mesoperthite) and myrmecitic textures are visible in fresh samples, deuteric or metamorphic transformations are common and stronger than in the phenocrysts.

The compositions of feldspars from lamprophyres and meta-lamprophyres are compiled in figure 18. Feldspars from the nonmetamorphic samples of the Vogesen and Schwarzwald (crosses and triangles respectively) are dispersed over the whole diagram with clusters at labradorite and sanidine. While these compositions likely represent magmatic kfsp and plag, the wide field of alkalifeldspar compositions as well as Ca-rich K-feldspar compositions are difficult to interpret. They might represent mixtures of fine-grained material rather than real feldspar compositions.

Feldspars from meta-lamprophyres cluster at albite and oligoclase composition and, with a few exceptions, trace the peristerite gap. (Only magmatic plagioclase compositions from the Schwarzwald and Vogesen ground-

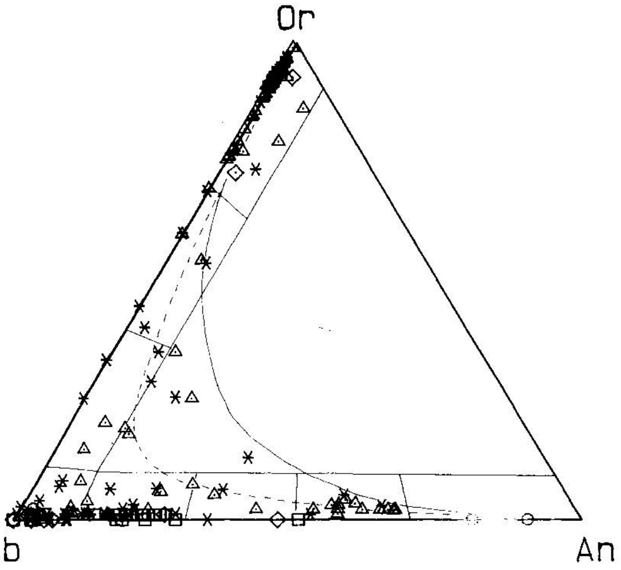

Fig. 18 Co positional diagram anorthite (An), orthoclase (Or), albite (Ab) for feldspar minerals after SMITH (1974).
(Symbols see list of abbreviations.)

mass feldspars plot inside the peristerite gap.) Few plagioclases from the Alps still have labradorite composition and sanidine relics can be found in the Aarmassif and the Gotthardmassif. One sample (T10) from the Ticino plots towards the An corner of the diagram. This might be expected from its high metamorphic grade, as plagioclase in amphibolites and marbles from the same area have anorthite contents higher than 40 and 70, respectively (WENK, 1962; WENK and KELLER, 1969).

WHITE MICA

In most of the meta-lamprophyres from the Alps, white micas can be found. In the northern Aarmassif mostly sericite occurs as an alteration product of K-feldspar. With increasing metamorphic degree, muscovites-phengites occur (Fig. 19), in which FeO varies from 2.05 to 6.11 wt.% and MgO ranges between 1.43 to 5.10 wt.%, indicating a strong phengite component. The paragonite component (Na_2O 0.08–1.52 wt.%) ranges up to 20 mol% whereas the margarite molecule is generally negligible. Some phengites from the Gotthardmassif show significant TiO_2 contents (up to 1.2 wt.%). They are probably derived from biotite. In figure 19, Si vs. Al is plotted indicating roughly 50% of ferrimuscovite substitution. No relation between the white mica composition and metamorphic grade is evident. Samples from the Aarmassif, the Gotthardmassif and the Ticino cannot be clearly devided, although the Ticino samples tend to be the most enriched in phengite component.

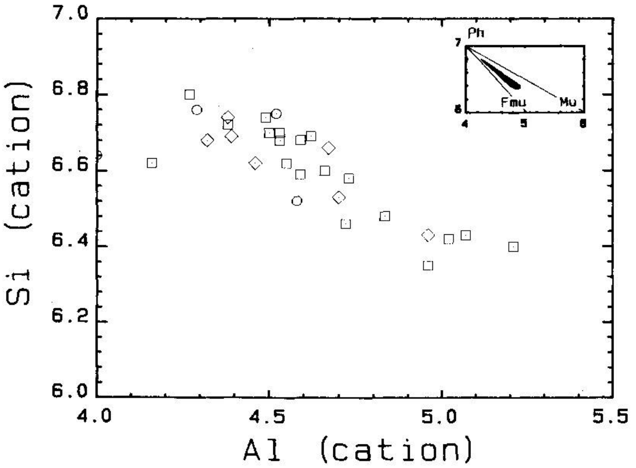

Fig. 19 Al vs. Si diagram for the white micas showing the shift towwards ferrimuscovite and phengite. (Symbols see list of abbreviations.)

The regional distribution of white K-mica polymorphs in the Central Alps has been compiled by FREY et al. (1983). Their study is based on 2M/3T-polymorph distributions and compares X-ray data with the RM-values (= 2 Fe_2O_3 + FeO + MgO in molar proportions) (CIPRIANI et al., 1968). On the basis of their analyses with $Fe^{3+}/Fe^{2+} = 1/2$, "RM" estimates for the micas of this study have been made. Calculated "RM" values scatter from .05 to .22 and Al decreases with increasing "RM". FREY et al. (1983) showed that RM > 0.12 coincides with 3T polymorphs which occur in areas with eo-Alpine high pressure overprint. As already mentioned by FREY et al. (op. cit.), high RM values do occur in the Aarmassif. The micas investigated in this study show high "RM" values for the Aar- and Gotthardmassifs as well as the northern Ticino, thus possibly indicating relics of a pressure dominated metamorphic phase.

The tschermak's substitution $(Mg,Fe)Si\,Al^{VI}_{-1}\,Al^{IV}_{-1}$ in these samples (Fig. 19) shows no regional distribution and thus cannot be used to trace the increase of metamorphic overprint as has convincingly been done by TEUTSCH (1982) for the calcschists of the Mesocco valley.

CHLORITES

Chlorite is present in practically all lamprophyre samples. In nonmetamorphic terrains it occurs as alteration product of olivine, pyroxene, hornblende or biotite/phlogopite, whereas in greenschist facies metamorphic terrains it is observed as a phase of the stable paragenesis chl, ab, ep and act. The trend-arrow in fig. 20 from high Si and low Fe to low Si and high Fe merely reflects the composition of the original mineral now replaced by chlorite. A few examples of talc-chlorite (Si > 7) are thought to derive from olivine. All chlorites from nonmetamorphic terrains show higher Si values than the ones from metamorphic terrains, where chlorites are grouped at Si values between 5.6 and 5.8. KÜPFER (1977) as well as SCHALTEGGER (1984) stress that X_{Fe} is higher for chlorite in the matrix than in resorbed phenocrysts, consistent with mafic minerals in the groundmass having lower Mg/Fe-ratios

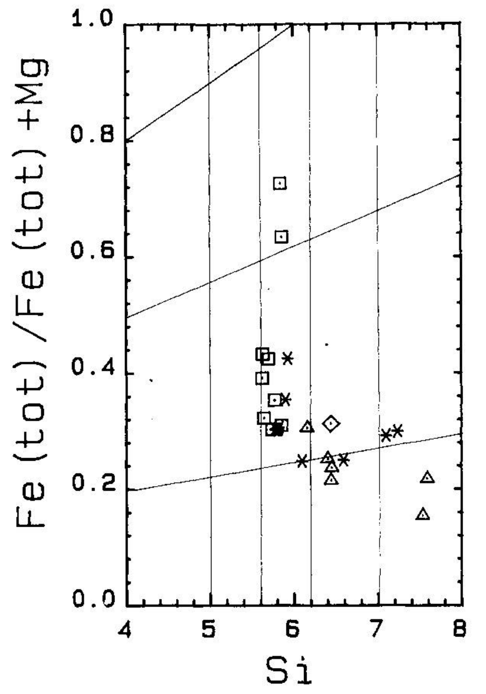

Fig. 20 Chlorite analyses plotted in the classification diagram (HAY, 1954). Chlorites in metamorhic samples (field m) have low Si values.
(Symbols see list of abbreviations.)

than the mafic phenocrysts. In meta-lamprophyres with the stable paragenesis chl, ab, act and ep, chlorite composition reflects bulk rock composition, i.e. Fe–Mg exchange equilibrium is approached.

GARNET

Only three meta-lamprophyre samples along the profile through the Central Alps have been found to contain garnet. In the southern Aarmassif, garnets are small idiomorphic grains mostly mantled by chlorite, though clean contacts with Alpine biotite can be found. The garnets from meta-lamprophyres in the southern Aarmassif are very Mn-rich (MnO 20–23 wt.%) and contain up to .68 wt.% Cr_2O_3. MgO is generally below 1 wt.% and CaO varies between 7 and 9 wt.%. These garnets are zoned and may demonstrate a prograde evolution with Mn decreasing from the core to rim, while Fe and Mg increase. On the other hand the zonation might reflect local depletion in Mn at constant P and T. Garnet compositions range from alm_{27} $spess_{50}$ pyr_2 $gross_{21}$ in the cores to alm_{36} $spess_{41}$ pyr_4 $gross_{19}$ in the rims. Compared to Alpine garnets in granitic rocks from the Aarmassif (alm_{33} $spess_{33}$ $gross_{33}$, STECK and BURRI, 1971) the garnets from meta-lamprophyres are thus richer in the spessartine component. The $KD^{gr/bi}_{(Mg/Fe)} = .058$ from meta-lamprophyres in the southern Aarmassif however is in the range of values given for the Central Aar-granite (0.028–0.06) by STECK and BURRI (1971).

EPIDOTE MINERALS

Minerals of the epidote group occur in all investigated lamprophyric rocks. They are very rich in Al, close to clinozoisite composition, where they are alteration products of plagioclase. In the groundmass of samples from the Schwarzwald and Vogesen, where it is not possible to trace their origin, epidote minerals have high Fe_2O_3 contents (12.5 to 14.1 wt.%). These epidotes might be deuteric in origin or even late magmatic, where they are stable under moderately high pressure (8 kb, ZEN and HAMMARSTROM, 1984).

Epidotes from the Alps tend to have significantly lower Fe_2O_3 contents (5–10 wt.%), though Fe-rich epidotes also occur.

SPHENE

This mineral occurs throughout in all lamprophyres and meta-lamprophyres and has been considered as a magmatic as well as metamorphic mineral by various authors. Sphene in leucoxene is found as a minor constituent in lamprophyres from the Vogesen and the Schwarzwald. Microscopic observation strongly suggests that it is a secondary phase and is, most probably, due to autohydrothermal alteration.

OXIDE MINERALS

Rutile, magnetite or hematite occur in addition to the primary magmatic picotite as stable oxide phases in lamprophyres from the Schwarzwald and Vogesen. Together with these oxide phases, limonite and goethite and leucoxene occur as secondary phases. In the northern Aarmassif, magnetite is interpreted as a product of the pilitization of olivine; ilmenite is found as well, commonly rimmed by sphene. This transformation has been interpreted as late magmatic reaction (SCHALTEGGER, 1984). Ilmenite and magnetite are also found in the Gotthardmassif.

Metamorphic conditions

Autohydrothermal events at the end of dike intrusion produced phases similar or equal to those which are stable under lower greenschist conditions. Amphibole, rarely brown biotite as well as sericite / muscovite can occur as secondary minerals in lamprophyres from non-metamorphic terrains. Chlorite forms as an alteration product of mafic phenocrysts. Plagioclase and alkali-feldspar are albitized. Therefore, where deformation is absent or weak, the effect of Alpine metamorphism in meta-lamprophyres from the Aarmassif is difficult to distinguish from the autohydrothermal alteration and stable paragenesis can only be defined with reluctance.

However, in these rocks, deformation is a very evident indicator of Alpine metamorphic events in the northern Aarmassif. Whereas in the southern Gotthardmassif prograde mineralogical changes are visible in the field.

The production of phengitic mica can most probably be assigned to an event of the Alpine metamorphism. Deuteric alteration produced saussuritic white mica. It has been shown above, by the "RM" values of some of the phengites from the Aar- and Gotthardmassif, that they are high, similar to 3T phengites from eo-Alpine high pressure terrains. To estimate pressures on the base of phengite component in white mica from the lamprophyres, temperatures for the different areas were taken from FREY et al. (1980). Along the profile from Altdorf to the Ticino they give the following temperature and pressure estimates for the Tertiary Alpine metamorphism: 300–350 °C and 2 kb for the northern Aarmassif, 450 °C and 3 kb for the southern Aarmassif and the Gotthardmassif and 600–650 °C and 6–7 kb for the northern Ticino.

Calculations based on the geobarometer of POWELL and EVANS (1983) on phengites from meta-lamprophyres showed that in the southern Aarmassif and in the northern Gotthardmassif as well as in the Penninic nappes elevated pressures (4 to 5 kb) are conserved. The rims of these latter phengites as well as phengites from the northern Aarmassif indicate lower pressures (2 to 3 kb). Application of MASSONES (1981) geobarometer revealed even higher pressures. The deduced pressure differences between the northern and the southern end of the Aar- and Gotthardmassif respectively, shown by both geobarometer, could reveal a geological significance, even if the absolute values are questionable.

Rocks of deeper crustal levels, indicated by higher pressures at the southern ends of the massifs are juxtaposed against rocks of higher crustal levels, indicated by lower pressures at the northern ends. In both Aar- and Gotthardmassif this could be interpreted as differential uplift and might demonstrate the nappe structure of the two crystalline complexes. By faulting and block tilting, deeper crustal levels were uplifted along listric faults; thus producing the imbricated, nappe like structures.

As indications of the Tertiary, meso-Alpine metamorphism mineralogical investigation showed, that:

Amphibole recrystallized under the influence of the Alpine metamorphism and shows a retrogressive tschermak's substitution compared to magmatic hornblende but a progressive substitution with metamorphic overprint (Fig. 12b).

Biotite, as discussed above, recrystallized with increasing metamorphic overprint at a given Ti–Fe ratio, but the tschermak's substitution indicates a retrometamorphic event. The Alpine biotites cannot be distinguished from secondary biotites found in lamprophyres from non-metamorphic terrains, i.e. drillholes into the Schwarzwaldmassif.

Chlorite, similar to biotite, seems to converge to a certain Si content when it occurs as metamorphic mineral, whereas the Si content does not converge in alteration products.

Along the north-south profile, systematic changes of physical conditions and their consequences in mineralogy are expected:

The relation between the albite component in plagioclase and Na in the A-site of amphibole represents the mass transfer reaction ab + tr = ed + qtz (SPEAR, 1981). The negative slope of the tie-lines plagioclase-amphibole steepens with increasing metamorphic degree. Such a pattern has been shown by TEUTSCH (1982) along a profile of mafic rocks in the Misox.

In meta-lamprophyres from the Alps tie-lines of these mineral components (Fig. 21) plot chaotically. The tie-lines (plag-amph) have negative slopes as expected. The stronghly metamorphosed sample from the Ticino (T 10) is an exception. There is no regular succession in tie-line inclination from north to south. The Aarmassif samples simulate a me-

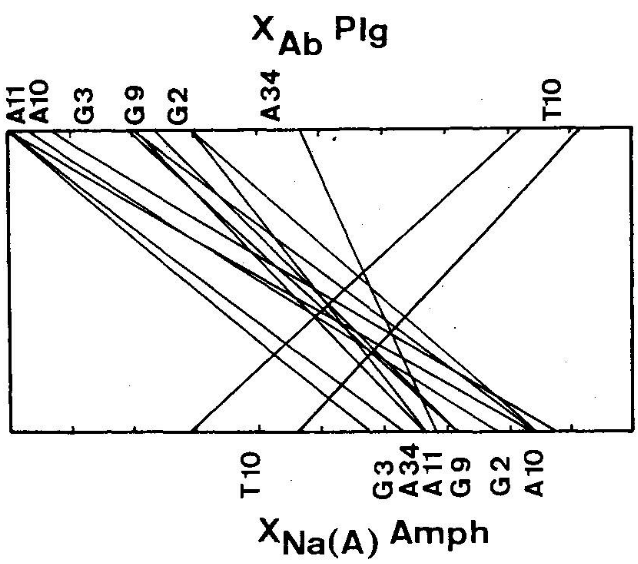

Fig. 21 Relation between albite component in plagioclase and Na in A-site of amphibole (Spear, 1981). Crossing tie-lines reflect non-equilibrium conditions.

tamorphic evolution with albite in samples A 10, A 11 and oligoclase-andesine in sample A 34. The higher metamorphic samples from the Gotthardmassif drop back into more albitic compositions. The observed pattern can be explained by the fact that the Aarmassif samples have not been fully equilibrated. The higher metamorphic samples from the Gotthardmassif and the Ticino are the only ones to show the effect of the tertiary metamorphism accurately. Nevertheless, it is not possible to locate exactly where retromorphic and prograde metamorphic overprint replace one another.

A diagram displaying KD-value along the north–south profile (Fig. 22) shows that $KD^{\mathrm{chl/amph}}_{(\mathrm{Fe}^{2+}/\mathrm{Mg})}$ and $KD^{\mathrm{bi/amph}}_{(\mathrm{Fe+Mn/Mg})}$ do not vary significantly whereas, expectedly, the $KD^{\mathrm{plag/amph}}_{(\mathrm{Ca/Na})}$ shows a general increase from north towards south. Samples north of A 10 do not show equilibrium conditions. Reequilibration between plagioclase and amphibole as indicated by sample A 10 (area of Göschenen) starts further north than for biotite and amphibole or chlorite and amphibole.

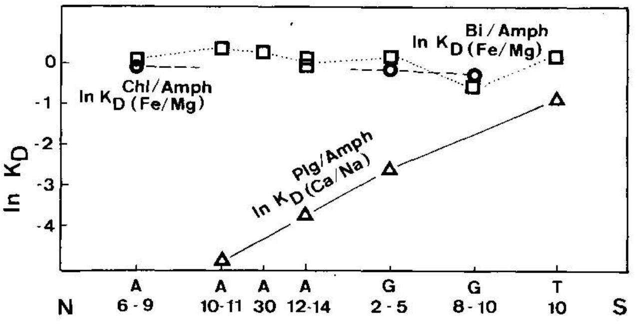

Fig. 22 KD-values for chlorite-amphibole, biotite-amphibole and plagioclase-amphibole plotted along the N-S profile of sampling. Only KD plag-amph shows a dependence of metamorphic overprint.

In conclusion, in meta-lamprophyres, the prograde metamorphic overprint by Tertiary Alpine metamorphism is only clearly distinguishable from the late Hercynian retromorphic and autohydrothermal effects within and south of the southern Aarmassif. North of Göschenen and north of the Grimsel area, the effects of the different events cannot be clearly separated in lamprophyric dikes.

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