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Metabasite dikes in the southeastern part of the Chortiatis series (Northern Greece): petrology and P-T conditions of metamorphism

by *A. Kassoli-Fournaraki*[1]

Abstract

Metabasite dikes belonging to the southeastern parts of the Chortiatis series (Chalkidiki peninsula, Northern Greece) are examined in terms of petrology, geotectonic setting and P-T conditions of metamorphism. They contain the assemblage amphibole + plagioclase + quartz + epidote group minerals ± biotite ± sphene ± opaques. According to their bulk chemistry they display a tholeiitic nature with calc-alkaline affinities corresponding to destructive plate margin settings connected with subduction conditions. Application of cations' relations of amphiboles and biotite in discriminant diagrams assign the examined rocks to the biotite zone up to lower garnet zone of the lower amphibolite facies. Rough estimation of pressure and temperature conditions gives a range of 2–4 kb for P and 550-560 °C for T. Optical and chemical data of the minerals reveal retrograde processes in the range of the biotite zone.

Keywords: Amphibole, biotite, metabasite, tholeiite, low-pressure conditions, Chalkidiki peninsula, Greece.

Introduction

The area of the examined metabasites belongs to the southeastern parts of the Chortiatis series (Chalkidiki peninsula), within the Circum Rhodope belt, at the west border of the Serbomacedonian massif, and is surrounded by the Middle Eocene Sithonia granite (Fig. 1). The ~5 km thick Chortiatis series, referred as "Chortiatis magmatic suite" by KOCKEL and MOLLAT (1977), was emplaced during the earliest upper Jurassic (MUSSALLAM and JUNG, 1986). It is in tectonic contact with its surroundings, having the Thessaloniki ophiolites at its western border and the Triassic-Middle Jurassic Svoula flysch in the east. Lithologically it is composed mainly of quartz-dioritic to dioritic rocks; a regional metamorphism of the upper greenschist to amphibolite facies has been determined in many parts of the suite (SCHUNEMANN, 1985; MUSSALLAM and JUNG, 1986).

This paper concerns a small rare spacing complex of metabasite dikes ranging in width between ~ 0.50 and 0.80 m and alternating with the previously mentioned salic rocks at the southeastern part of the Chortiatis series (Fig. 1). Preliminary petrological results have been reported by KASSOLI-FOURNARAKI et al. (1989). In this study the metabasites are examined in terms of their tectonic setting and P-T conditions of metamorphism.

Petrography

Texturally the examined metabasites are mainly massive, medium- to fine-grained, unfoliated with mostly unoriented aggregates of minerals (mainly amphiboles) in a fine-grained mass. The mineralogical composition is: amphibole, plagioclase, quartz, epidote, clinozoisite and zoisite as main constituents; biotite (sometimes chloritized), sphene and pyrite participate as minor accessories. Traces of chalkopyrite and gold are also present.

Amphibole is the dominant mineral with a light greenish or pale blue-green to green pleochroism. It appears mostly in aggregrates of hypidiomorphic to xenomorphic crystals as well as in individual grains with a size of 0.1 to 0.8 mm.

Plagioclase (basic oligoclase to sodic andesine) appears xenomorphic to hypidiomorphic in shape, with a varying size up to 1 mm. Some very small

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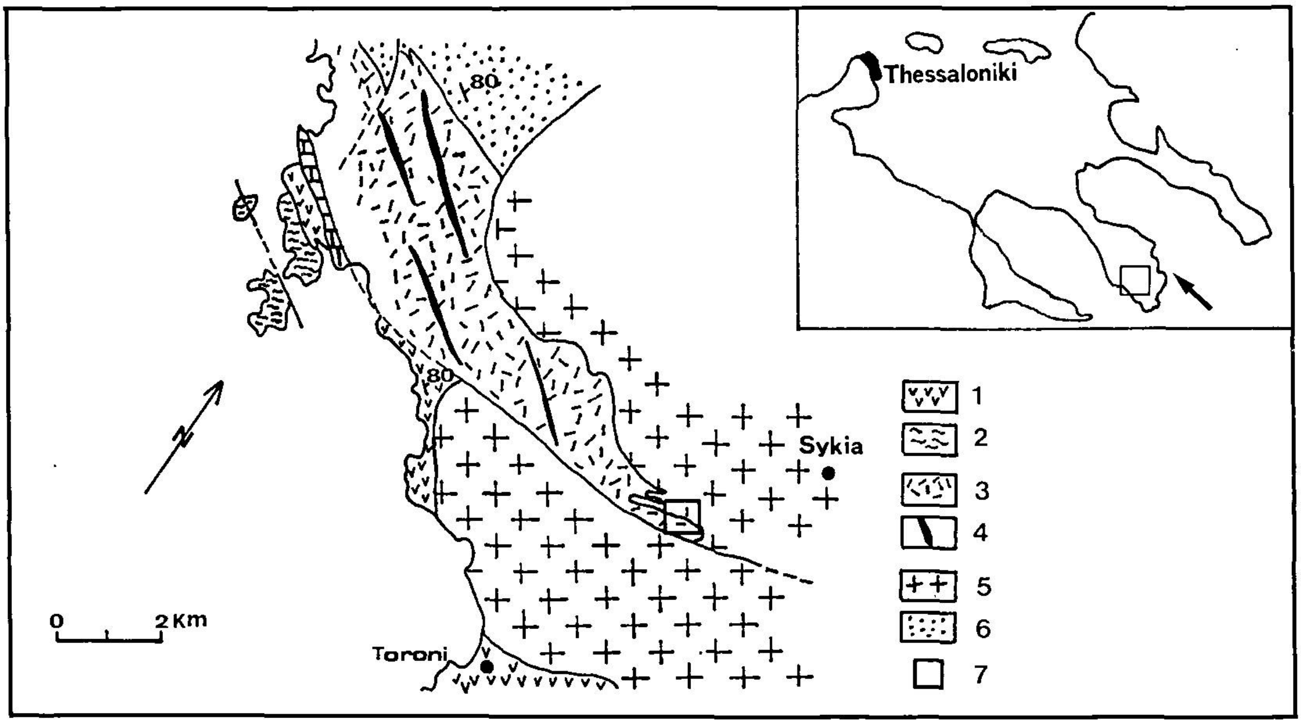

Fig. 1 Geological sketch map of the southwestern part of the Sithonia peninsula (after Jung and Mussallam, 1985). 1 = basic volcanic rocks, 2 = sheeted dike complex, 3 = metadiorite to metaquartz-diorite (Chortiatis magmatic suite), 4 = intermediate to acidic dikes, 5 = Sithonia granite (50 Ma), 6 = Svoula flysch (middle Jurassic), 7 = metabasites (this study).

grains of primary igneous plagioclase (basic andesine to bytownite) are preserved. In some cases an albitization at the rims of some metamorphic plagioclase grains was noticed.

Quartz appears xenomorphic, very often recrystallized and sometimes slightly deformed. Recrystallized grains may enclose amphibole or zoisite.

Amphibole and plagioclase participate also in the fine-grained matrix together with epidote group minerals. Epidote sometimes forms from amphibole. Biotite has a brownish pleochroism and is not present in all the examined samples.

Chemistry

ANALYTICAL TECHNIQUES

Chemical analyses on selected rock samples were performed in the Analytical Laboratory of the Swedish Geological Co., Lulea, Sweden, by the inductively coupled plasma method. Mineral analyses (amphibole and biotite) were made on a C.A.M.E.C.A. CAMEBAX probe, using an energy dispersive spectrometer, at the Department of Geology, University of Manchester, England. Operating conditions were 15 kV accelerating potential and 3 nA beam current. All analyses were made using 100 second counting times. Natural minerals or pure metals were used as standards. Element concentrations have been calculated with a ZAF-4/FLS software.

Amphibole Fe^{3+} values were determined by normalizing cations (Ca + Na + K) to 13 and (Na + K) to 15 and by getting the mean formula. Site occupancies were assigned according to the system of Leake (1978) on the basis of 23 oxygens assuming the general formula: $A_{0-1}(M_4)_2(M_{1,2,3})^{VI}_5(T1)_4$-$(T2)^{IV}_4O_{22}(OH,F,Cl)_2$.

Biotite was normalized as follows: Total cations-less (K + Na + Ca) = 14, $Al^{IV} = 8\text{–}Si$, $Al^{VI} = Al_{total}\text{–}Al^{IV}$, $Fe^{3+} = Al^{IV}\text{–}1\text{–}Al^{VI}\text{–}2\,Ti$ and $Fe^{2+} = Fe_{total}\text{–}Fe^{3+}$ so as to maintain charge balance.

CHEMICAL FEATURES

Rocks

Representative whole rock chemical analyses of the examined metabasites are given in Tab. 1 (for more chemical data see Kassoli-Fournaraki et al., 1989). All samples are quartz normative. According to their normative composition they plot in the fields of gabbros (Fig. 2a) after O'Connor (1965) as well as in the fields of tonalites-trondjemites and diorites (Fig. 2b) or the equivalent field of andesites/basalts after Streckeisen (1976). Field,

Tab. 1 Chemical composition (wt% for major oxides, Fe_2O_3 as total iron, ppm for trace elements) of the metabasites.

	SY_1	SY_2	SY_3
SiO_2	54.40	53.90	53.90
TiO_2	0.36	0.34	0.32
Al_2O_3	14.60	14.90	14.20
Fe_2O_3	9.30	8.80	9.20
MnO	0.13	0.13	0.14
MgO	8.60	8.30	8.70
CaO	10.70	10.30	11.60
Na_2O	1.50	2.80	1.20
K_2O	0.34	0.37	0.37
P_2O_5	0.12	0.12	0.10
LOI	0.60	0.60	0.80
Total	100.65	100.56	100.53
Ba	18	110	126
Co	60	53	56
Cr	330	234	406
Cu	88	110	36
Ni	83	64	102
Pb	< 10	< 10	35
Sc	39	40	40
Sr	178	211	172
V	239	245	240
Y	10	10	10
Zn	62	49	110
Zr	12	14	10
Th	< 62	< 60	< 63

* More chemical data are available one request from the author.

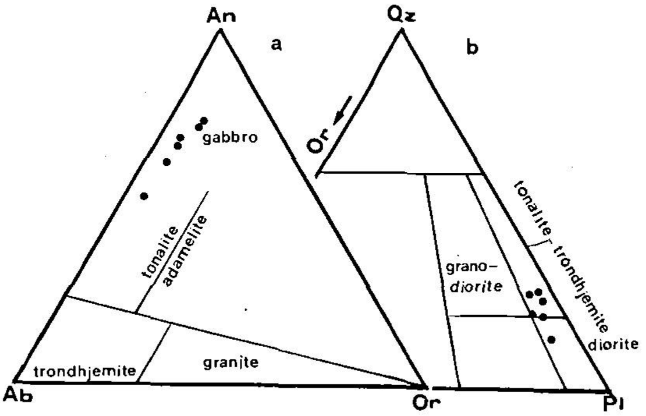

Fig. 2 Normative composition of the examined metabasites. a) after O'Connor (1965); b) after Streckeisen (1976).

macroscopic as well as microscopic observations could not offer any help for the type of igneous mafic protolith (plutonic or volcanic). A chemical distinction based on comparison with literature data revealed affinities more with plutonic than volcanic rocks. MgO/FeO_{tot} vs. SiO_2 and Al_2O_3 vs. TiO_2 relations show the examined rocks plotting in the fields characterized by Colombi (1988) and Pfeifer et al. (1989) as clinopyroxene-plagioclase gabbros, well outside the field of basalts, after Pearce (1984), (Fig. 3 a, b). Similar affinities result from the Cr, Ni, vs. Zr relations (Fig. 4), where again the examined rocks plot outside the field of the Mesozoic meta-basalts of the West-Central Alps (Pfeifer et al., 1989). According to their SiO_2 vs. Zr/TiO_2 and ($Na_2O + K_2O$) vs. SiO_2 in the Winchester and Floyd (1977) and Le Bas et al. (1986) classification diagrams, they show compositions corresponding to andesites or basaltic andesites, respectively.

A tholeiitic nature for the examined metabasites is deduced according to their Al_2O_3 values as well as according to the relation Al_2O_3 vs. norma-

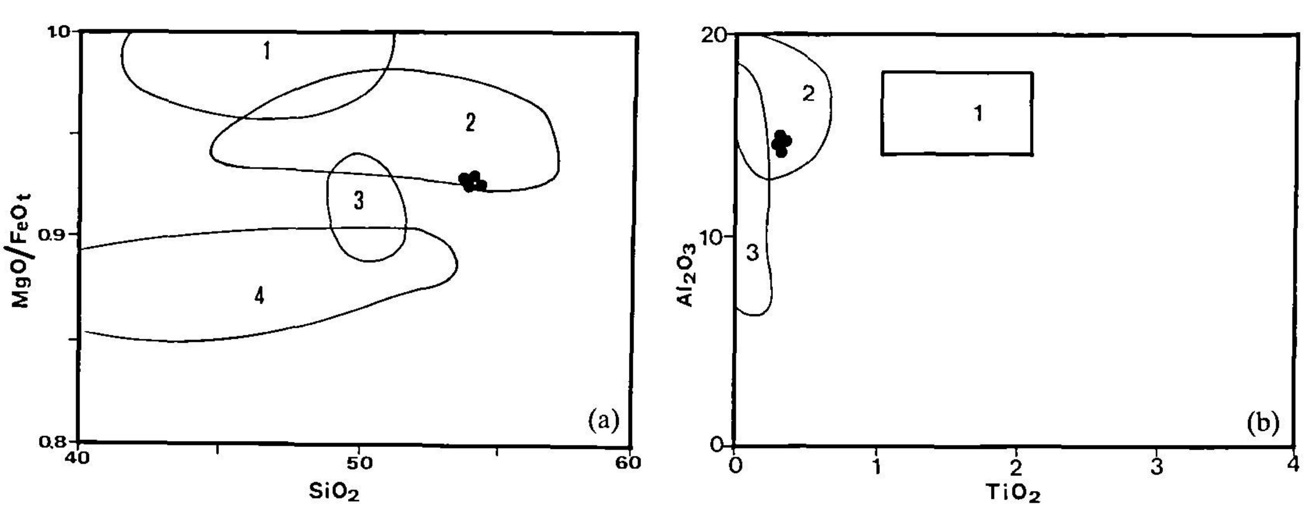

Fig. 3 MgO/FeO_t vs. SiO_2, and Al_2O_3 vs. TiO_2 diagrams discriminating between basalts and gabbros, a) 1: olivine-gabbros + troctolites, 2: clinopyroxene-plagioclase gabbros, 3: basalts, 4: ferrogabbros + norites (fields correspond to literature data compiled by Colombi, 1988). b) 1: basalt liquids, after Pearce (1984), 2: clinopyroxene-plagioclase gabbros, 3: olivine gabbros, troctolites (2 and 3 = literature data compiled by Colombi, 1988).

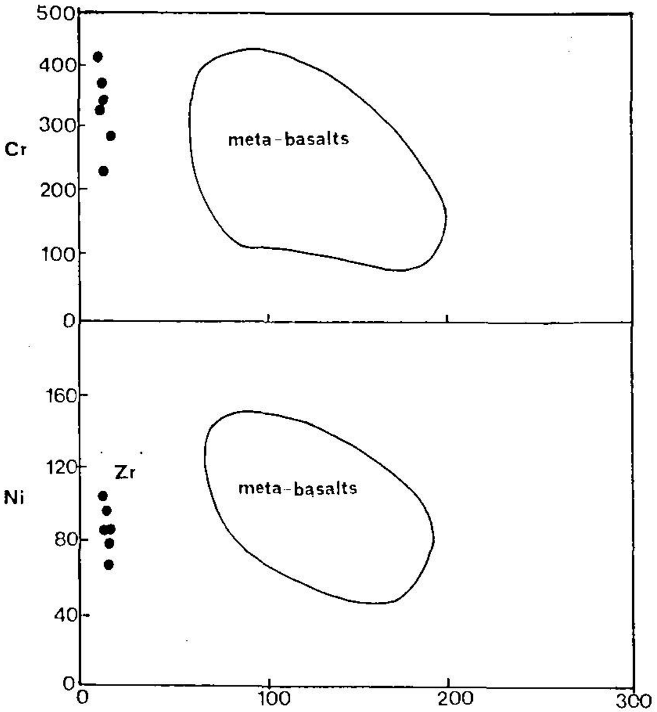

Fig. 4 Cr and Ni vs. Zr variation of the examined metabasites. Closed-line area = meta-basalts after PFEIFER et al. (1989).

tive plagioclase composition (Fig. 5a, after IRVINE and BARAGAR, 1971). The same tholeiitic nature is also supported by the alkalies vs. SiO_2 and AFM diagrams (KASSOLI-FOURNARAKI et al., 1989). Concerning their K_2O vs. SiO_2 relation they correspond to the low-K tholeiites (according to PECCERILLO and TAYLOR, 1976) in the field of andesites. An abyssal tholeiitic character results according to V vs. Cr (Fig. 5b) relation (after MIYASHIRO and SHIDO, 1975). On the other hand SiO_2 vs. Cr relation (Fig. 6) according to MIYASHIRO and SHIDO (1975) yields a calc-alkaline character, due to high SiO_2 content.

SCHUNEMANN (1985) accepts a mainly calc-alkaline character for the majority of the Chortiatis series at Central Chalkidiki with some tholeiitic affinities. MUSSALLAM and JUNG (1986) agree for a dominant calc-alcaline trend but they accept also a contribution of a tholeiitic melt. The investigated metabasites (occurring in the southeastern part of the Chortiatis series) indicate a tholeiitic nature with calc-alkaline affinities probably due to contamination.

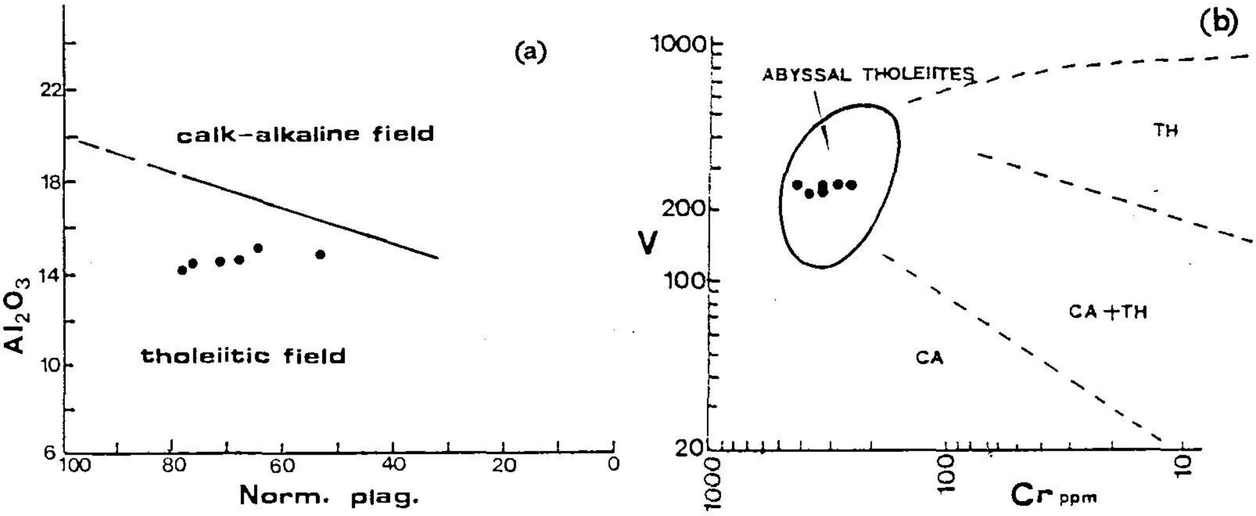

Fig. 5 Plotting of the metabasites in the a) Al_2O_3 vs. normative plagioclase (after IRVINE and BARAGAR, 1971) and b) V vs. Cr (after MIYASHIRO and SHIDO, 1975) discriminant diagrams.

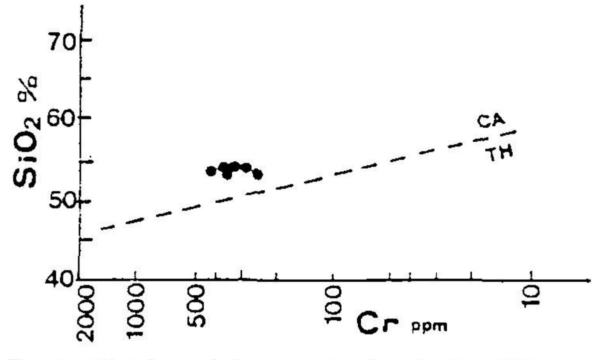

Fig. 6 Plotting of the metabasites in the SiO_2 vs. Cr discriminant diagram (after MIYASHIRO and SHIDO, 1975).

A MORB as well as a within-plate and back-arc origin is excluded for the examined metabasites (Fig. 7 a, b). On the contrary an island arc tholeiitic affinity seems more probable. The same affinity is also expressed by the Ni vs. FeO_t/MgO and Cr vs. Y relations according to MIYASHIRO and SHIDO (1975) not shown in the figures. SiO_2, Al_2O_3, FeO_t, K_2O oxide values as well as the amounts of the incompatible elements Ba, Sr, Pb and Th favour an island arc tholeiitic affinity compared to calc-alkaline series of island arcs and continental margins. La/Yb ratios also support an IAT affinity, and a rock/MORB normalization of trace elements (Fig. 8)

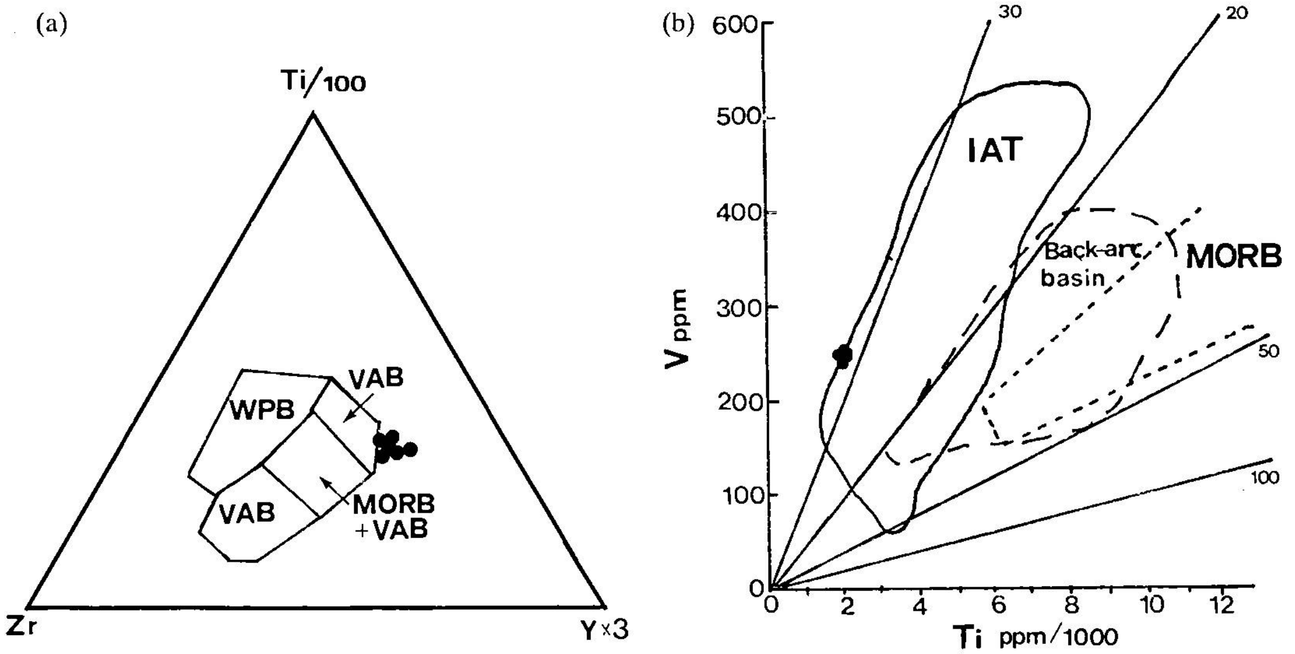

Fig. 7 Plotting of the metabasites in the a) Ti–Zr–Y (after Pearce and Cann, 1973), and b) V vs. Ti (after Shervais, 1982), discriminant diagrams.

resembles the trend of basalts related to subductions (CAB/IAT), (Pearce, 1982).

Minerals

Representative amphibole analyses are presented in Tab. 2. For their classification the nomenclature of Leake (1978) was used (Fig. 9). All the analyzed amphiboles belong to the group of "calcic amphiboles" and plot in the field of magnesio-hornblende (except one sample which is actinolitic hornblende) displaying a slight range of composition mainly according to Si values. Two groups of amphiboles were distinguished according to their chemical and optical features: group A (samples SY_1–SY_4 of Tab. 2) which are richer in the actinolitic member, and display a pleochroism of pale blue-green to green colours, and group B (samples SY_5–SY_8) which display an olive-green to green pleochroism. Patchy compositional domains were not observed optically. The amphiboles of group B coexist with biotite while the last is absent from the samples of group A.

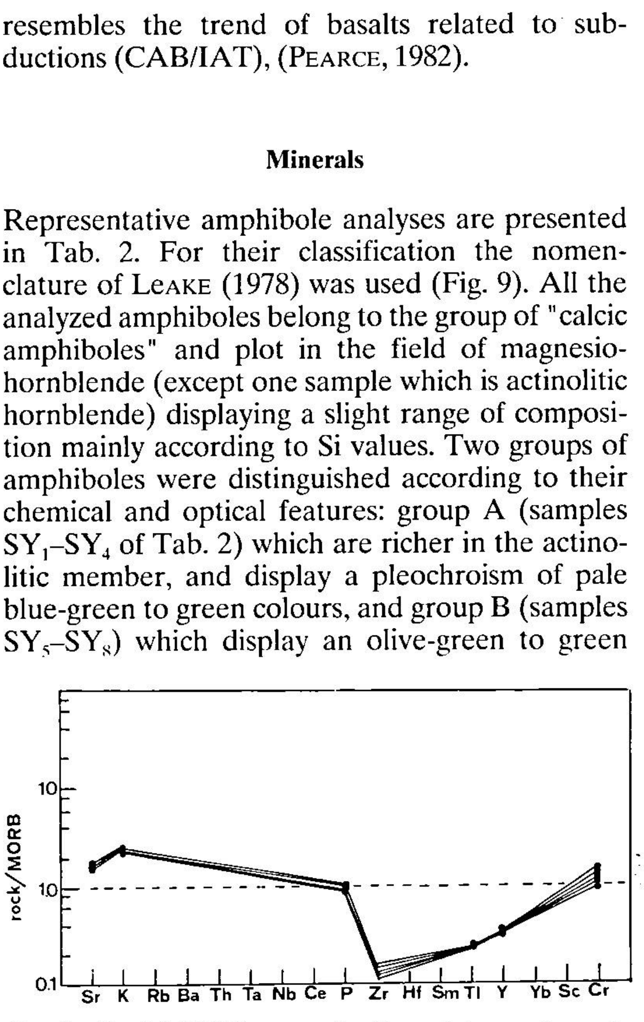

Fig. 8 Rock/MORB normalization of trace elements for the examined metabasites.

Table 3 presents biotite analyses coexisting with the amphiboles of group B. All biotite grains analyzed have Mg : Fe < 2 : 1 and plot between annite and phlogopite enriched in Mg (Fig. 10).

P-T conditions of metamorphism

The mineralogical assemblage of the examined metabasites assign the rocks to the lower amphibolite facies of the medium grade range in terms of the Barrovian zones.

Many investigations have been made regarding the relation of metamorphic grade to the chemical composition of the minerals and the host rock. Much emphasis has been given to the amphibole as well as biotite compositions including their change in Al^{IV}, Al^{VI}, Ti, Mg/(Mg + Fe^{2+}) and alkalies with rising temperature and pressure (e.g. Shido and Miyashiro, 1959; Engel and Engel, 1960; Binns, 1965a, 1969; Leake, 1965; Bard, 1979: Ramsay, 1973 and Raase, 1974).

Stephenson (1977) accepts that metamorphic grade appears to influence the Ti, Mn and Fe^{2+} contents of amphiboles and biotites and that the Mg/(Mg + Fe^{2+}) ratio of the amphibole shows a close relationship to the host rock MgO/(MgO + FeO) but seems to be independent of the metamorphic grade and mineral paragenesis. On the other

Tab. 2 Representative amphibole microprobe analyses and structural formulae.

	Group A				Group B			
	SY_1	SY_2	SY_3	SY_4	SY_5	SY_6	SY_7	SY_8
SiO_2	48.88	49.18	48.54	48.55	47.72	47.18	47.08	47.46
TiO_2	0.46	0.49	0.34	0.40	0.61	0.51	0.55	0.45
Cr_2O_3	n.d.	n.d.	n.d.	n.d.	0.18	0.36	0.21	0.14
Al_2O_3	7.70	7.12	7.70	8.05	8.47	8.61	9.37	8.52
FeO_{tot}	13.15	12.80	12.56	12.91	14.34	13.63	13.24	14.25
MnO	0.12	0.45	0.15	0.28	0.24	0.19	0.09	0.25
MgO	14.56	14.80	13.50	13.88	14.13	13.89	13.96	13.76
NiO	n.d.	n.d.	n.d.	n.d.	0.17	0.21	0.00	0.00
CaO	11.77	11.58	12.12	12.00	10.07	10.28	11.07	10.77
Na_2O	0.79	1.00	1.00	0.85	1.36	1.21	1.48	0.88
K_2O	0.22	0.32	0.28	0.17	0.17	0.37	0.22	0.28
Total	97.65	97.74	96.19	97.09	97.46	97.44	97.27	96.76
Cations on the basis of 23 (0)								
Si	7.020	7.077	7.146	7.042	6.873	6.882	6.820	6.890
Al^{IV}	0.980	0.923	0.854	0.958	1.127	1.118	1.180	1.110
T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al^{VI}	0.324	0.285	0.484	0.419	0.311	0.362	0.419	0.348
Ti	0.050	0.054	0.037	0.043	0.066	0.056	0.059	0.049
Fe^{3+}	0.483	0.437	0.069	0.322	0.722	0.606	0.460	0.690
Fe^{2+}	1.114	1.117	1.479	1.256	1.034	1.078	1.160	1.066
Cr	–	–	–	–	0.020	0.042	0.024	0.016
Ni	–	–	–	–	0.020	0.024	0.000	0.000
Mn	0.015	0.055	0.019	0.034	0.029	0.023	0.011	0.031
Mg	3.014	3.052	2.912	2.926	2.798	2.809	2.867	2.800
M_{1-3}	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Mg	0.102	0.122	0.050	0.076	0.235	0.212	0.147	0.178
Ca	1.812	1.785	1.911	1.865	1.554	1.607	1.719	1.675
Na	0.086	0.093	0.039	0.059	0.211	0.181	0.134	0.147
M_4	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Na	0.133	0.182	0.246	0.180	0.168	0.161	0.282	0.102
K	0.041	0.059	0.051	0.031	0.031	0.068	0.042	0.051
A	0.174	0.241	0.297	0.211	0.199	0.229	0.324	0.153

* More chemical analyses are available on request from the author.

hand, according to Hynes (1982), the variation in the rock Mg/Fe does not appear to have a considerable influence on the amphibole chemistry though it effects the temperature at which reactions occur. Al substitution in amphiboles takes place at higher temperatures for rocks with lower Mg/Fe (Harte and Graham, 1975).

Ti content of the amphiboles changes also independently of the TiO_2 content in the host rock, though it is generally accepted that the first increases with increasing metamorphic grade. The amphibole Ti content of the examined metabasites correlates with the lower-grade amphibolite facies according to the Ti values given by Raase (1974). It is commonly accepted that the Ti content of the amphiboles is combined also with the colour variation along the Z axis of the mineral and consequently with the metamorphic grade (Engel and Engel, 1962; Binns, 1965b). This variation was verified in the amphiboles of the examined metabasites. The amphiboles of group B display stronger olive-green to green colour and higher Ti values compared to the green to pale green colours and lower Ti values of group A amphiboles.

According to Laird and Albee (1981), amphiboles with the "common" assemblage (i.e. amphibole + chlorite + epidote + plagioclase + quartz + Ti-phase ± carbonate ± mica ± Fe^{3+}-oxides) range in composition from actinolite in the biotite zone to hornblende in the garnet zone. In the diagrams of Fig. 11 (after Laird and Albee, 1981) the examined amphiboles plot in the field of the biotite zone

Tab. 3 Representative biotite microprobe analyses and structural formulae.

	SY_5	SY_6	SY_7	SY_8	SY_9	SY_{10}
SiO_2	37.77	37.82	37.79	37.67	36.91	36.31
TiO_2	2.07	2.28	1.98	1.88	2.25	1.83
Cr_2O_3	0.00	0.10	0.00	0.12	0.18	0.00
Al_2O_3	16.93	16.69	17.08	17.53	17.65	17.64
$FeO_{tot.}$	14.11	13.99	14.05	13.60	14.05	14.33
MnO	0.00	0.06	0.25	0.00	0.04	0.14
MgO	13.43	13.21	13.14	13.57	14.04	14.03
NiO	0.01	0.20	0.00	0.08	0.16	0.05
CaO	0.07	0.00	0.08	0.23	0.17	0.19
Na_2O	0.23	0.35	0.00	0.18	0.30	0.43
K_2O	9.65	9.74	9.67	9.12	8.85	8.56
Total	94.27	94.44	94.04	93.98	94.60	93.51
Ions on the basis of 22 (0)						
Si	5.804	5.826	5.816	5.763	5.593	5.554
Al^{VI}	2.196	2.174	2.184	2.237	2.407	2.446
	8.000	8.000	8.000	8.000	8.000	8.000
Al^{VI}	0.869	0.856	0.914	0.925	0.746	0.735
Ti	0.239	0.263	0.230	0.216	0.256	0.211
Cr	0.000	0.012	0.000	0.015	0.022	0.000
Ni	0.002	0.025	0.000	0.009	0.019	0.006
Fe^{3+}	0.236	0.213	0.192	0.237	0.396	0.484
Fe^{2+}	1.578	1.589	1.616	1.504	1.383	1.348
Mn	0.000	0.008	0.032	0.000	0.007	0.017
Mg	3.076	3.034	3.016	3.094	3.171	3.199
	6.000	6.000	6.000	6.000	6.000	6.000
Ca	0.011	0.000	0.013	0.038	0.027	0.030
Na	0.069	0.103	0.000	0.053	0.087	0.129
K	1.893	1.914	1.899	1.780	1.712	1.670

revealing again a distinction between group B amphiboles which plot near to the boundary of the garnet zone, and group A amphiboles which plot lower in the biotite zone. Plotting in Fig. 11a is independent of the normalization scheme.

Diagrams 100 Na/(Ca + Na) vs. 100 Al/(Si + Al) and NaM_4 vs. Na^A + K (Fig. 12 a, b) reflect mainly medium pressure conditions, though there is a significant overlapping of the low and medium pressure fields making very difficult to distinguish between low- and medium-pressure amphiboles in the upper greenschist and lower amphibolite facies on the basis of their Na or Al contents.

Brown (1977) and Laird and Albee (1981) found higher values of NaM_4 in Ca-amphiboles from high pressure areas than in those form lower pressure conditions, proving that Na and Na^{M4} content could be a useful indicator for low to medium grade metamorphic rocks. On the other hand according to Hynes (1982), the amount of glaucophane substitution in amphiboles of medium pressures is so small that it does not permit a clear distinction between medium- and low-pressure metabasites. What Hynes (1982) accepts as indicative of the low-pressure metabasites is the generally higher Ti content of the amphiboles compared to medium-pressure. Ti values of the metabasites of this study justify rather medium pressures according to Hynes' (1982) distinction, though even this author refers some cases with low Ti values in low-pressure metabasites. Brown (1977) gave a relative estimation of pressure of metamorphism according to Na^{M4} and Al^{IV} relationship. Correlation of the above parameters in the examined amphiboles gives a rough estimation of pressure about 3 kb for group B and 2 kb for group A.

Biotite can also be used to some extent as an indicator of metamorphic grade. Biotite in metamorphic rocks is formed under a wide range of P-T conditions and its presence in metabasites is nearly not connected with the major reactions that occur as a function of grade. It is usual to attribute its existence to the small amount of $KAlO_2$ present in metabasites in the low and medium pressures or to the reaction of calcic amphiboles with muscovite at higher metamorphic grades (Miyashiro, 1973; Laird, 1982).

The biotites examined in this study have Al^{VI} values ranging between 0.735 and 0.925 and Mg/(Mg + Fe_t) between 0.625 and 0.640, that is in the limits of 0–1 for Al^{VI} and 0.3–1 for Mg/(Mg + Fe_t)

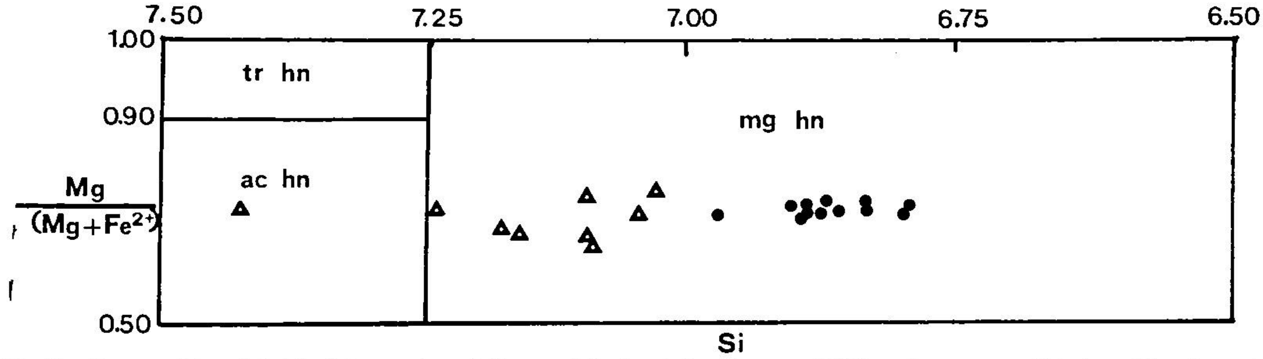

Fig. 9 Compositional field of the analyzed Ca-amphiboles (after Leake, 1978), tr hn = tremolitic hornblende, ac hn = actinolitic hornblende, mg hn = magnesio-hornblende.
▲ = Group A amphiboles, ● = Group B amphiboles

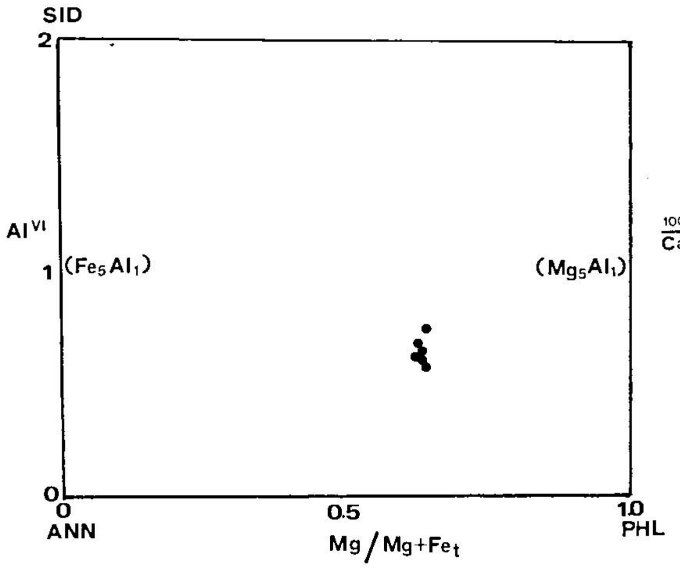

Fig. 10 Plotting of the analyzed biotites according to Al^{VI} vs. $Mg/Mg + Fe^{2+}$ (after Guidotti, 1984). SID = siderophyllite, ANN = annite, PHL = phlogopite, EAST = eastonite.

given for amphibolite-grade biotites. Plotting of the examined biotites according to their Al^{VI} and Ti vs. Al^{IV} in the discriminant diagrams of Laird and Albee (1981) reveal garnet zone conditions (Fig. 13).

In the examined metabasites an association of biotite with the magnesio-hornblende of group B was defined, while it is absent from the samples of group A amphiboles which are more enriched in the actinolitic member. Combining this observation with the indications of the diagrams (Figs 11–13) as well as with the pleochroism of the amphibole grains in groups A and B it is concluded that the data for the samples of group B reflect upper biotite to low garnet-zone conditions while the samples of group A display a little lower P-T conditions in the biotite zone, most possibly due to retrograde metamorphism. The chloritization of biotite as well as the albitization of plagioclases support the above explanation.

Plagioclase composition, as mentioned in the petrography chapter, ranges from basic oligoclase to sodic andesine thus defining a pressure of 3–4 kb if combined with the Al content of amphiboles, according to Plyusnina's (1982) thermobarometer. On the basis of the An content of plagioclase (~ 30–35%) the temperature is estimated at about 550–560 °C according to the variation diagram of the same author.

Conclusions

1. The metabasite dikes of the southeastern part of the Chortiatis series display a tholeiitic nature with calc-alkaline affinities and features corresponding

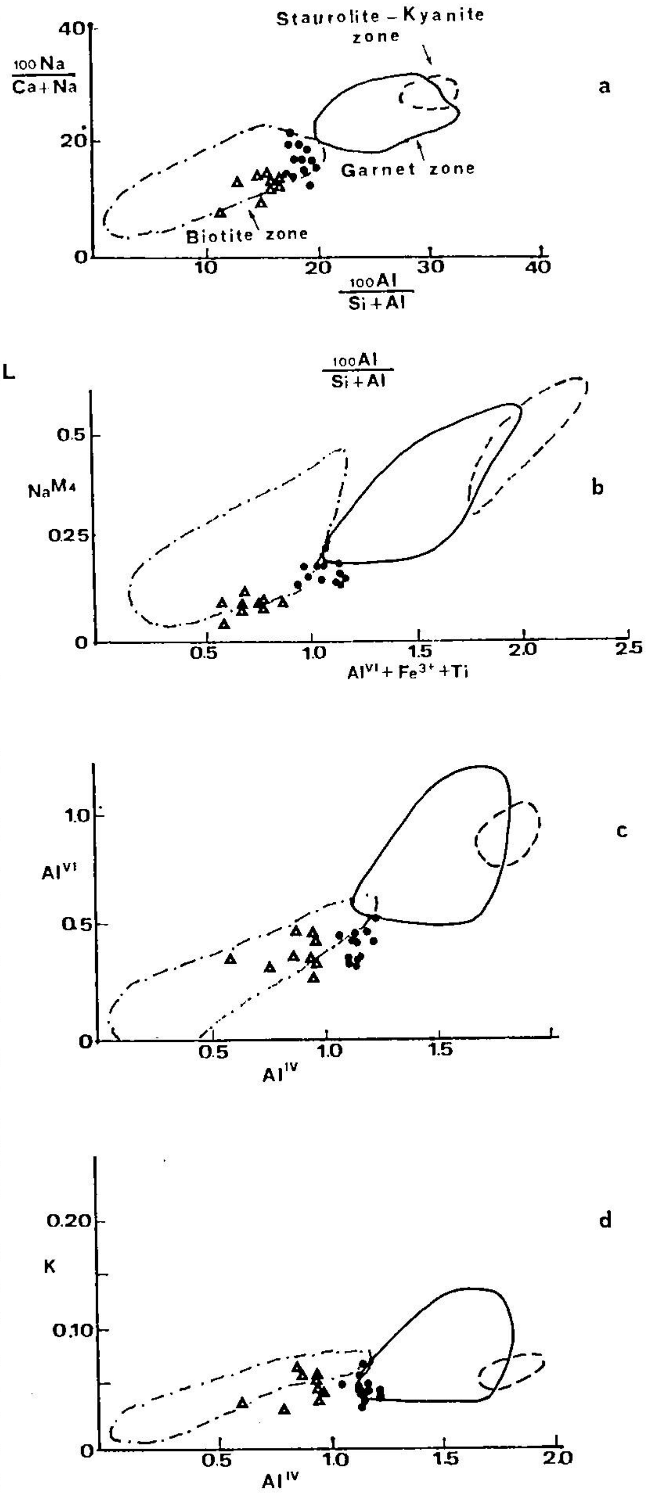

Fig. 11 Amphiboles formula proportion variation diagrams in relation to Laird's and Albee's (1981) defined zones. Diagram a is independent of normalization method, the other diagrams are dependent on normalization. Symbols as Fig. 9.
– · – · – · Biotite zone ——— Garnet zone
– – – – – Staurolite-kyanite zone

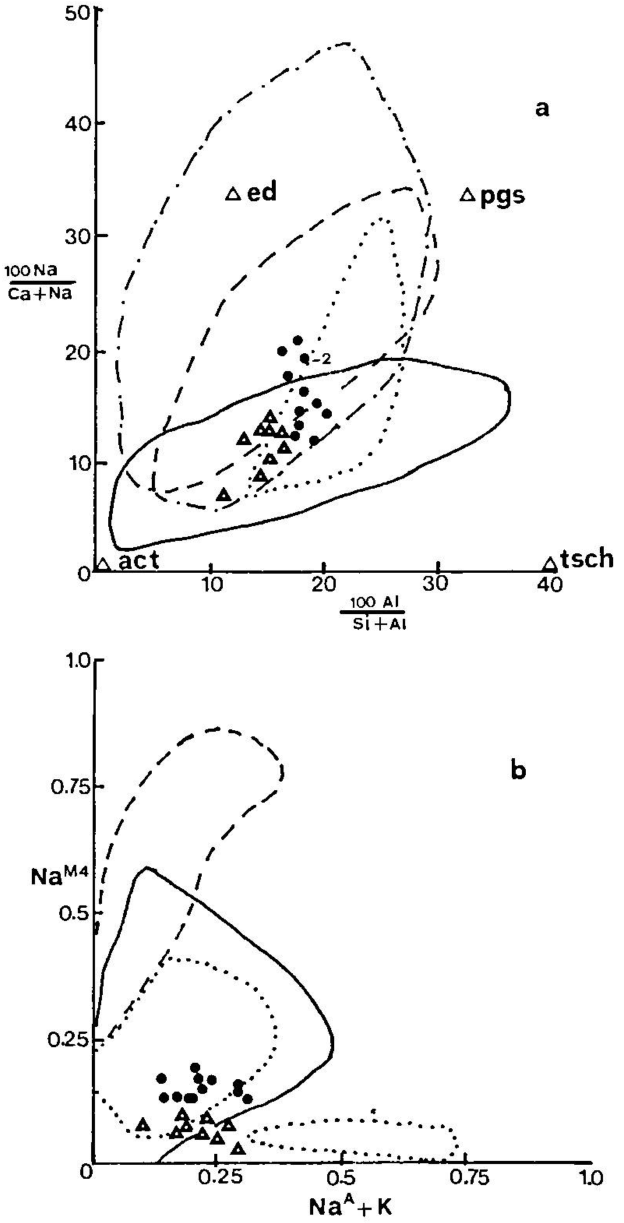

Fig. 12 a) 100 Na/(Ca + Na) vs. 100 Al/(Si + Al) amphiboles plot in the diagram (after LAIRD and ALBEE, 1981) for calcic and sodic-calcic amphiboles from various word-wide occurrences of mafic schists; that is, the high-pressure facies series Sanbagawa terrane in Japan, the high-pressure Franciscan terrane in California, the medium-pressure Dalradian terrane in south-western Scotland, the medium-pressure Haast River schist group in New Zealand and the low-pressure Abukuma terrane in Japan. Symbols as Fig. 9.

act = actinolite, tsch = tschermakite, ed = edenite and pgs = pargasite.

–·–·– Sanbagawa and Franciscan ..... Abukuma
----- Dalradian —— Haast River

b) Na^{M4} vs. $Na^A + K$ plot of the amphiboles in the diagram (after LAIRD and ALBEE, 1981 for calcic and sodic-calcic amphiboles in Vermont mafic schists). Symbols as Fig. 9.

----- high pressure .... low pressure
——— medium pressure

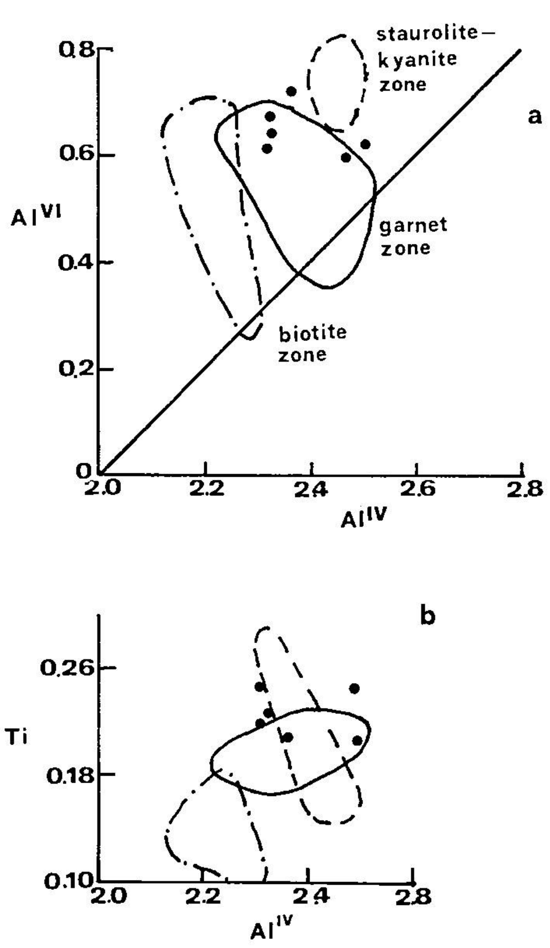

Fig. 13 Formula proportion diagrams of the biotites according to LAIRD and ALBEE (1981).

to destructive plate margin settings connected wlth subduction conditions.

2. According to its chemistry, amphibole appears in the range of magnesio-hornblende while biotite is enriched in Mg.

3. The mineralogical assemblage combined with the amphiboles' and biotite's chemistry place the examined metabasites in the lower amphibolite facies in terms of the Barrovian zones. Relations of the different cations in the amphibole and biotite structural formulae reveal conditions in the range of biotite to lower garnet zone. A rough estimation of P-T conditions gives values in the range of 2–4 kb (P) and 550–560 °C (T).

4. Retrogration phenomena are traced as follows:

a) Variation in the amphibole chemistry and pleochroism.

b) Coexistence of biotite with the magnesio-hornblende grains which correspond to relatively higher P-T conditions while absence of biotite from the samples where the magnesiohornblende grains are enriched in the actionolitic member.

c) Chloritization of biotite and albitization of some plagioclase grains.

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References

Bard, J.P. (1970): Composition of hornblendes formed during the Hercynian progressive metamorphism of the Aracena metamorphic belt (SW Spain). Contr. Min. Petrol., 28, 117–134.

Binns, R.A. (1965a): Hornblendes from some basic hornfelses in the New England region, New South Wales. Min. Mag., 34, 52–65.

Binns, R.A. (1965b): The mineralogy of metamorphosed basic rocks from Willyama Complex, Broken Hill district, New South Wales, Pt. I. Hornblendes. Min. Mag., 35, 305–326.

Binns, R.A. (1969): Ferromagnesian minerals in high-grade metamorphic rocks. Geol. Soc. Austr. Spec. Publs., 2, 323–332.

Brown, E.H. (1977): The crossite content of Ca-amphibole as a guide to pressure of metamorphism J. Petrol., 18, 53–72.

Colombi, A. (1988): Métamorphisme et géochimie des roches mafiques des Alpes Ouest-centrales (géoprofil Viège–Domodossola–Locarno). Ph.D. thesis, Univ. Lausanne, 195 p.

Engel, A.E. and Engel, C.G. (1960): Progressive metamorphism and granitization of the major paragneiss, northwest Adirondack Mountains, New York. Part II Mineralogy. Geol. Soc. Am. Bull., 71, 1–58.

Engel, A.E. and Engel, C.G. (1962): Hornblendes formed during progressive metamorphism of amphibolites, northwest Adirondack Mountains, New York. Geol. Soc. Amer. Bull., 73, 1499–1514.

Guidotti C.V. (1984): Micas in metamorphic rocks: In Micas. Min. Soc. Am. Reviews in Mineralogy, 13, 357–456.

Harte, B. and Graham, C.M. (1975): The graphical analysis of greenschist to amphibolite facies mineral assemblages in metabasites. J. Petrol., 16, 347–370.

Hynes, A. (1982): A comparison of amphiboles from medium- and low-pressure metabasites. Contr. Miner. Petrol., 81, 119–125.

Irvine, T.N. and Baragar, W.R. (1971): A guide to the chemical classification of the common volcanic rocks. Can. J. Earth Sci., 8 (5), 523–548.

Jung, D. and Mussallam, K. (1985): The Sithonia ophiolite: A fossil oceanic crust. Ofioliti, 10(2/3), 329–342.

Kassoli, A., Filippidis, A., Soldatos, T. and Thimiatis, G. (1989): Chemical investigation of basic meta-igneous rocks in Sykia, South Sithonia, Northern Greece, XIV congress CBGA, Sofia, 1, 210–213.

Kockel, F. and Mollat, H. (1977): Erläuterungen zur Geologischen Karte der Chalkidiki und angrenzender Gebiete 1 : 100 000 (Nord-Griechenland). Mit einem Beitrag von H.H. Walther. Bundesanstalt für Geowissenschaften und Rohstoffe Hannover, 1 Karte in 4 Blättern, 119 p.

Laird, J. (1982): Amphiboles in metamorphosed basaltic rocks: Greenschist facies to amphibolite facies. In: Veblen, O.R and Ribbe, P.H. eds. Reviews in Mineralogy 913, 113–135.

Laird, J. and Albee, A. (1981): Pressure, temperature, and time indicators in mafic schist: Their application to reconstructing the polymetamorphic history of Vermont. Amer. J. Sci., 281, 127–175.

Le Bas, M., Le Maître, R., Streckeisen, A. and Zanettin, B. (1986): A chemical classification of volcanic rocks based on the total alkali-silica diagram. J. Petrol. 27, 745–750.

Leake, B.E. (1965): The relationship between tetrahedral aluminum and the maximum possible octahedral aluminum in natural calciferous and sub-calciferous amphiboles. Amer. Mineral., 50, 843–851.

Leake, B.E. (1978): Nomenclature of amphiboles. Amer. Mineral., 63, 1023–1053.

Miyashiro, A. (1973): Metamorphism and metamorphic belts. John Wiley and Sons, New York, 492 p.

Miyashiro, A. and Shido, F. (1975): Tholeiitic and calc-alkalic series in relation to the behaviors of titanium, vanadium, chromium and nickel. Am. J. Sci., 275, 265–277.

Mussallam, K. and Jung, D. (1986): Petrology and geotectonic significance of salic rocks preceding ophiolites in the eastern Vardar Zone, Greece. Tschermacks Min. Petr. Mitt., 35, 217–242.

O'Connor, J.T. (1965): A classification for quartz-rich igneous rocks based on feldspar ratios. US. Geol. Surv. Prof. Pap. 525-B, 79–84.

Pearce, J.A. (1982): Chemical and isotope characteristics of destructive margin magmas. In: Thorpe R.S. Andesites. John Wiley and sons. (1982), 525–548.

Pearce, J.A. (1984): A user's guide to basalt discrimination diagrams. Unpubl. Manuscript.

Peccerillo, A. and Taylor, S.R, (1976): Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, Northern Turkey. Contr. Min. Petrol., 58, 63–81.

Pfeifer, H.R., Colombi, A. and Ganguin, J. (1989): Zermatt-Saas and Antrona zone: A petrographic and geochemical comparison of polyphase metamorphic ophiolites of the West-Central Alps. Schweiz. Mineral. Petrogr. Mitt., 69, 217–236.

Plyusnina, L.P. (1982): Geothermometry and Geobarometry of plagioclase-hornblende bearing assemblages. Contr. Miner. Petrol, 80, 140–146.

Raase, P. (1974): Al and Ti contents of hornblende, indicators of pressure and temperature of regional metamorphism. Contr. Miner. Petrol., 45, 231–236.

Ramsay, C.R. (1973): Controls of biotite zone mineral chemistry in Archaean meta-sediments near Yellowknife, Northwest Territories, Canada J. Petrol., 14, 467–488.

Schunemann, M. (1985): Contributions to the geology, geochemistry and tectonics of the Chortiatis series metamorphic calc-alkaline suite, Chalkidiki, Northern Greece. Diss. Hamburg, 181 p.

SHERVAIS, J.W. (1982): Ti-V-plots and the petrogenesis of modern and ophiolitic lavas. Earth Planet. Sci. Lett., 59, 101–118.
SHIDO, F. and MIYASHIRO, A. (1959): Hornblendes of the basic metamorphic rocks Tokyo Univ. Fac. Sci. J. Sec. II, 12, 85–102.
STEPHENSON, N.C. (1977): Coexisting hornblendes and biotites from Precambrian gneisses of the south coast of Western Australia. Lithos, 10, 9–27.
STRECKEISEN, A. (1976): To each plutonic rock its proper name. Earth Sci. Rev., 12, 1–33.
WINCHESTER, J.A. and FLOYD, P.A. (1977): Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chem. geol., 20, 325–343.

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