Origin and evolution of sub-ophiolitic amphibolites from Angelona (SE Peloponneus, Greece), and their significance within the Pindos Ocean

Konstantin Hatzipanagiotou and Basilios Tsikouras[1]*

[1] University of Patras, Department of Geology, Section of Earth Materials, GR-265 00 Patras, Greece

ABSTRACT. — Two geochemically distinct groups of amphibolites have been found both as fragments in an ophiolite mélange and as a remnant subophiolitic metamorphic sole at the base of the Angelona ophiolite sequence. Group-1 shows T-MORB and group-2 WPB geochemical signatures. Basaltic fragments, considered to represent the amphibolitic protoliths in the ophiolite mélange, also show twofold chemistry and are divided in two groups with affinities similar to the amphibolites. The WPB rocks are similar to rift-related Triassic lavas from Pindos, Koziakas and Argolis, thus suggesting the operation of Triassic rifting in Angelona. The T-MORB rocks suggest that the ophiolite was generated in a typical oceanic environment, which was slightly influenced by the contribution of a mantle plume component. Geochemical and age constraints point to the hypothesis that the Angelona ophiolite is the link between the continental Hellenides to the North, and the Crete ophiolite, to the South within the Pindos ocean.

The metamorphic evolution of the two amphibolite groups occurred at around 450-500°C and 500-550°C, respectively, at estimated pressures at approximately 6-8 MPa. A reaction series, which is possibly related to the amphibolite formation, suggests that metamorphism occurred during pressure increase and cooling, conditions analogous to other amphibolite subophiolitic metamorphic soles.

* Corresponding author, E-mail: v.tsikouras@upatras.gr.

RIASSUNTO. — Alla base della sequenza ofiolitica di Angelona sono stati rinvenuti due gruppi distinti di anfiboliti sia come frammenti in un *melange* ofiolitico che come resti di un substrato metamorfico.

Il gruppo-1 mostra caratteri geochimici tipo T-MORB, il gruppo-2 tipo WPB.

I frammenti basaltici, considerati protoliti delle anfiboliti del *melange* ofiolitico, mostrano anch'essi due tipi di chimismo che ripetono le affinità geochimiche delle anfiboliti.

Le rocce tipo WPB sono simili alle lave triassiche di Pindos, Koziakas ed Argolis legate ad ambienti di *rift* suggerendo la presenza di ambienti analoghi ad Angelona.

Le rocce tipo T-MORB indicano che le ofioliti hanno avuto origine in un tipico ambiente oceanico solo leggermente modificato dalla presenza di una componente di *plume*.

I dati geochimici, unitamente alle età, permettono di ipotizzare che le ofioliti di Angelona rappresentano un anello di congiunzione tra le Ellenidi continentali, a Nord, e le ofioliti di Creta, a Sud all'interno dell'Oceano di Pindos.

L'evoluzione metamorfica dei due gruppi di ofioliti è avvenuta per temperature comprese, rispettivamente, tra 450-500°C e 500-550°C e in intervalli barici dell'ordine di 6-8 Mpa. Una serie di reazioni, probabilmente da ricollegare alla formazione delle anfiboliti, indicano un metamorfismo sviluppatosi per pressioni crescenti ma in regime di raffreddamento.

east of Angelona (Fig. 1). It covers an area of around 2000 m² and underlies, via a thrust fault, a large peridotite body; its apparent thickness is up to a few tens of meters. Both its contacts, with the overlying ophiolite and the underlying ophiolite mélange, are tectonic. The amphibolite sole displays tight folds primarily parallel to the thrust plane. Frequent tectonic blocks of this amphibolite sole are also found within the ophiolite mélange (some of them have been mapped and presented in the map provided; see Fig. 1). Two groups of amphibolite have been recognized: a fine-grained (group-1) and a coarse-grained (group-2) locally containing minor fragments of garnet-bearing mica-schists.

Petrography of the Amphibolites

The two amphibolite groups display significant petrographic differences. Group-1 has a nematoblastic texture, is fine-grained and very well foliated. It has the assemblage amphibole + plagioclase + chlorite + epidote ± Fe-oxides. Chlorite forms after amphibole, whereas epidote has replaced plagioclase. Primary plagioclase has been completely altered and only secondary albite is present. Actinolite occurs as retrograde crystals either at the rims of the amphibole, or as individual crystals dispersed in the matrix. This amphibolite displays strong synmetamorphic fabrics, with the minerals showing lineation and commonly orientation parallel to microfolds, whereas locally mylonitic textures occur, too. In places, some porphyroblasts are strained and/or rotated. Calcite veins cross-cut the rocks.

The group-2 amphibolite displays lepidoblastic and locally granoblastic textures, and it is clearly less affected by deformation compared to group-1. Amphibole and plagioclase are roughly oriented. Chlorite forms after amphibole, and epidote is typically included in plagioclase; locally, epidote shows orientation within the plagioclase. Rare titanite and Fe-oxides are present as interstitial grains.

Analytical Methods

Care was taken in screening the samples since deformation and metamorphism have affected most of them. Whole-rock chemical analyses were performed at ACTLABS, Ancaster, Ontario, by XRF for major elements, and by ICP for trace elements. REE determinations were made by INAA. Major elements have been measured on fused pellets, trace elements on totally digested samples, and Nb and Rb were measured by XRF methods on pressed pellets. Detection limit for XRF for major elements is 0.01%. The analytical precision, as calculated from replicate analyses of one sample, is better than 1% for most major elements, and better than 5% for most trace elements. A precision of better than 5% was achieved for the REE.

Mineral analyses were quantitavely analysed in wavelength-dispersive mode with a Cameca CAMEBAX electron microprobe at the Department of Mineralogy, University of Bochum, Germany. Operating conditions were 15 kV accelerating voltage and 18 nA beam current, and the raw data were corrected with a PAP procedure.

Mineral chemistry

Amphiboles

Different types of amphibole crystals have been recognised in the two amphibolite groups (Table 1). The Fe^{3+}/Fe^{2+} ratio has been calculated according to the method of Papike *et al.* (1974). Group-1 contains magnesiohornblende and actinolite, whereas group-2 contains pargasite (nomenclature after Leake *et al.*, 1997). Both the pargasite and the magnesiohornblende crystals show no systematic core-to-rim zonation. The homogeneous nature of large areas of the amphibole suggests that alteration of the original compositions was not severe. The magnesiohornblende shows higher abundance of Si and octahedral alumina, and lower

TABLE 1

Representative microprobe analyses from the Angelona amphibolites

Amphiboles

	group-1				group-2			
Analysis #	Am 3.1	Am 3.2	Am 6.1	Am 6.2	Am1.1	Am 1.2	Am 2.2	Am 3.4
SiO_2	44.78	48.38	46.21	47.35	42.93	41.54	42.23	42.24
TiO_2	0.43	0.27	0.30	0.32	0.94	1.17	1.16	1.06
Al_2O_3	13.86	10.11	12.84	11.61	13.35	14.25	14.16	14.52
FeO^t	13.68	13.91	13.78	13.65	16.33	16.02	15.94	15.60
Cr_2O_3	0.04	—	0.16	0.01	—	0.03	0.04	—
MnO	0.19	0.20	0.25	0.25	0.27	0.25	0.27	0.13
MgO	10.94	12.58	10.87	11.68	9.89	9.93	9.95	10.12
CaO	10.67	10.65	10.81	10.75	11.00	11.25	11.15	10.90
Na_2O	2.14	1.88	2.13	2.07	2.07	2.07	2.00	2.09
K_2O	0.27	0.31	0.28	0.32	0.95	0.98	0.98	0.99
Total	97.00	98.29	97.63	98.01	97.73	97.49	97.88	97.65
Si	6.589	6.996	6.776	6.895	6.398	6.206	6.275	6.273
Al^{IV}	1.411	1.004	1.224	1.105	1.602	1.794	1.725	1.727
	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al^{VI}	0.990	0.717	0.993	0.887	0.742	0.713	0.752	0.812
Cr	0.005	—	0.019	0.001	—	0.004	0.005	—
Fe^{+3}	0.260	0.295	0.153	0.189	0.264	0.283	0.277	0.303
Fe^{+2}	1.423	1.387	1.537	1.474	1.772	1.719	1.703	1.634
Ti	0.048	0.029	0.033	0.035	0.105	0.131	0.130	0.118
Mg	2.400	2.712	2.376	2.536	2.197	2.212	2.204	2.240
Mn	0.024	0.024	0.031	0.031	0.034	0.032	0.034	0.016
Ca-B	1.682	1.650	1.698	1.677	1.757	1.801	1.775	1.734
Na-B	0.169	0.185	0.160	0.171	0.129	0.106	0.120	0.141
Na-A	0.442	0.342	0.446	0.413	0.469	0.494	0.457	0.461
K	0.051	0.057	0.052	0.059	0.181	0.680	0.186	0.188

Plagioclases

	group-1			group-2		
	Plg 2.1	Plg 3.2	Plg 4.3	Plg 3.1	Plg 3.2	Plg 4.2
SiO_2	59.17	60.71	65.64	62.99	64.41	66.70
TiO_2	—	—	—	0.01	0.03	0.02
Al_2O_3	26.20	24.78	20.71	22.28	22.09	20.12
$Fe_2O_3^t$	0.06	0.03	0.16	1.33	0.20	0.05
MnO	—	—	0.03	0.04	0.02	0.01
MgO	—	0.02	—	0.97	—	0.03
CaO	7.52	5.86	1.30	2.26	2.82	0.64
Na_2O	7.43	8.39	11.20	10.07	10.23	12.10
K_2O	0.08	0.07	0.05	0.09	0.07	0.09
Total	100.46	99.86	99.09	100.04	99.87	99.76
Si	2.629	2.702	2.911	2.788	2.844	2.937
Al	1.371	1.299	1.082	1.161	1.149	1.043
Fe^{+3}	0.002	0.001	0.005	0.044	0.007	0.002
Ti	—	—	—	0.001	0.001	0.001
Mn	—	—	0.001	0.001	0.001	—
Mg	—	0.001	—	0.064	—	0.002
Ca	0.358	0.279	0.062	0.107	0.133	0.030
Na	0.640	0.724	0.963	0.864	0.876	1.033
K	0.005	0.004	0.003	0.005	0.004	0.005
Ab	63.81	71.90	93.68	88.52	86.48	96.72
An	35.69	27.71	6.03	10.96	13.13	2.81
Or	0.50	0.40	0.29	0.51	0.39	0.47

Epidotes

	group-1		group-2	
	Ep 2.1	Ep 2.3	Ep 3.2	Ep 6.2
SiO_2	38.41	38.60	39.72	39.84
TiO_2	0.16	0.17	0.12	0.15
Al_2O_3	25.88	25.54	28.47	27.51
$Fe_2O_3^t$	9.44	9.91	6.58	8.49
Cr_2O_3	0.07	0.04	0.01	0.02
MnO	0.13	0.18	0.13	0.17
MgO	0.09	0.12	0.08	0.07
CaO	23.29	23.24	22.70	22.61
Na_2O	—	0.03	0.06	0.01
K_2O	0.03	0.03	—	0.01
Total	97.50	97.86	97.87	98.88
Si	6.048	6.064	6.129	6.124
Al	4.799	4.725	5.174	4.980
Ti	0.019	0.020	0.014	0.017
Cr	0.009	0.005	0.001	0.002
Fe^{+3}	1.117	1.170	0.763	0.981
Mn	0.017	0.024	0.017	0.022
Mg	0.021	0.028	0.018	0.016
Ca	3.929	3.912	3.753	3.724
Na	—	0.009	0.018	0.003
K	0.006	0.006	—	0.002
Ps.	18.88	19.85	12.85	16.46

tetrahedral Al, Ti and Ca contents than the pargasite. Raase (1974) plotted Al^{VI} vs. Si of amphibole from metamorphic terrains of known pressure, and observed a linear correlation of Al^{VI} with pressure. High Al^{VI} contents in the amphiboles from the Angelona metamorphic sole are consistent with relatively high pressures of formation. Amphibole chemistry is generally related to P-T variations. Laird and Albee (1981) suggested that several elements such as Al^{VI}, Ti and K also show linear relationships with Al^{VI}, which is chosen as an index of increasing metamorphic grade. However, the $(100*Na)/(Ca+Na)$ vs. $(100*Al)/(Al+Si)$ plot is considered as the most versatile diagram for the estimation of metamorphic conditions. The analysed amphiboles from Angelona plot within the field defined for amphiboles from garnet zone metabasites (except the retrograde actinolites), indicating relatively high pressure and temperature conditions of metamorphism (Fig. 2).

A variable behaviour, in terms of the $Mg/(Mg+Fe^{+2})$ ratios against Al^{IV}, between the two groups, is illustrated in Figure 3. The magnesiohornblendes (and the actinolites) are clearly higher in $Mg/(Mg+Fe^{+2})$, suggesting growth in lower f_{O2} conditions, relative to the
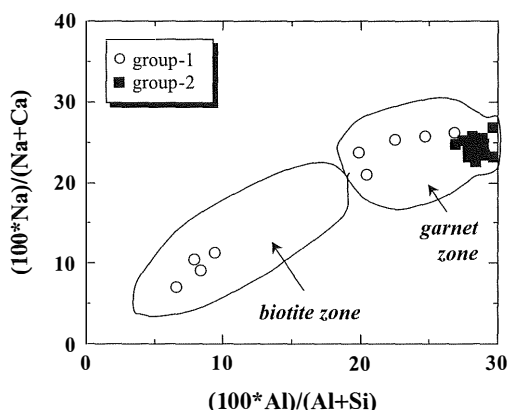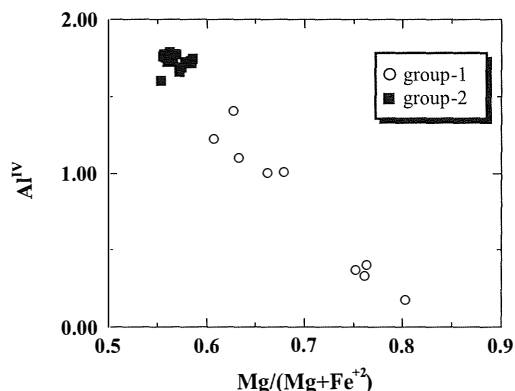

Fig. 3 – $Mg/Mg+Fe^{+2}$ vs. Al^{IV} plot for amphiboles from the two amphibolite groups.

pargasites, which cluster at lower $Mg/(Mg+Fe^{+2})$ values. Moreover, the magnesiohornblendes have been probably evolved during continuous increasing f_{O2} conditions, as suggested by their inverse linear correlation of $Mg/(Mg+Fe^{+2})$ with Al^{IV}.

Epidote

Epidote analyses are also diverse in the two amphibolite groups (Table 1). Particularly, epidote crystals from group-1 display higher Al^{VI} and lower Fe^{+3}, thus having lower pistacitic contents relative to those from group-2 amphibolites (see Table 1). These higher Ps. contents in the group-2 are also consistent with development of these rocks under higher f_{O2} conditions.

Plagioclase

Representative plagioclase analyses from the two amphibolite groups are listed in Table 1. Plagioclase occurring in the group-1 amphibolites is only retrograded albite, while that in the group-2 is classified as oligoclase-andesine (with few exceptions that yield albitic compositions due to retrogression). The Or content in all, but one, crystals is very low lying below 1.8 mole %.

Fig. 2 – $(100*Na)/(Ca+Na)$ vs. $(100*Al)/(Al+Si)$ plot (after Laird and Albee, 1981) for amphiboles from the two amphibolite groups.

GEOTHERMOBAROMETRIC CALCULATIONS

Estimation of temperature of formation of the amphibolites was carried out with the geothermometers of Spear (1980) and Blundy and Holland (1990), that use the coexistence of amphibole and plagioclase. Pressure estimation was made with the geobarometer of Hammartstrom and Zen (1986), based on the partition of Al in the amphiboles. Furthermore, both P-T conditions were estimated from the geothermobarometer of Plyusnina (1982) that uses the Ca and Al^t contents in coexisted plagioclase and amphibole, respectively. In all calculations, the compositions of rims of amphiboles (except the actinolites) and plagioclases were used, occurring in direct contact, to ensure equilibrium conditions. In each case, estimates were made with the assumption that all Fe is Fe^{+2} because the geothermometers were calibrated on this basis. Table 2 shows the ranges of P-T from several amphibole-plagioclase pairs, as well as mean values.

Temperatures obtained from the geothermometer of Spear (1980) and the geothermobarometer of Plyusnina (1982) yielded cohesive results at approximately 450-500°C for group-1, and 500-550°C for group-2 (see Table 2). However, the geothermometer of Blundy and Holland (1990) yielded considerably higher estimations at 745-830°C and 875-920°C for the two amphibolite groups, respectively. The latter geothermometer is based on the partitioning of Al^{IV} in amphibole; it yields better results for igneous rocks, and there may be considerable errors for expected temperatures below 600°C, due to cation redistribution in plagioclase and amphibole (Blundy and Holland, 1990).

Pressure estimations give rather uncertain results. Chemistry of amphiboles in both groups suggests growth at high pressures (see above). The high NaM4 in the amphiboles indicate pressures higher than 6 MPa for both groups, as well (see Brown, 1977). The Plyusnina's geothermobarometer yielded 7-8 MPa for both groups, while some samples from group-1 fall beyond the limit of the experimentally studied upper limit of 8 MPa. The geobarometer of Hammartstrom and Zen (1986) yielded pressures at approximately 5-7 MPa for group-1, while the analyses from group-2 plot at an area outside the reference line of 1-7 MPa and at a place of higher pressure (Table 2). The actinolites are clearly retrograde products during a latter cooling episode and hence they are not used for geothermobarometric calculations.

WHOLE-ROCK GEOCHEMISTRY

Whole-rock chemical analyses from the basalts and the amphibolites from Angelona are listed in Table 3. Loss on ignition displays a variable range and the high values are

TABLE 2

Range and mean of thermobarometric data for amphibole-plagioclase pairs from the Angelona metamorphic sole. Suggested errors are: Spear (1980) ± 50°C; Plyusnina (1982) ± 50°C and ± 1 kbar; Blundy and Holland (1990) ± 60°C and ± 1 kbar. (* plot beyond the limit of 7 kbars)

Plyusnina °C		Spear °C		Blundy & Holland °C		Hammarstrom & Zen (kbars)		Plyusnina (kbars)	
n=5	n=9	n=5	n=9	n=5	n=9	n=5	n=9	n=5	n=9
group-1	group-2	group-1	group-2	group-1	group-2	group-1	group-2	group-1	group-2
460-500	530-550	450-490	500-530	745-830	875-920	5-7	*	7->8	7-8
mean: 480	mean: 540	mean: 470	mean: 515	mean: 787	mean: 897	mean: 6			mean: 7.5

TABLE 3

Whole-rock geochemical analyses of the amphibolites.
Data from basalts and gabbros are given for comparison.

Major elements %

| | Amphibolites | | | | | | | | Basalts | | | | Gabbros | |
| | Group-1 | | | | Group-2 | | | | Group-1 | | Group-2 | | | |
	Agl.60	Agl.86c	Agl.23	Agl.101	Agl.94	Agl.53	Agl.74	Agl.39	Agl.64	Agl.98	Agl.96	Agl.33	Agl.68	Agl.47
SiO_2	43.24	42.42	46.34	44.48	52.13	45.60	50.43	49.37	41.79	48.77	67.02	59.00	50.35	46.58
TiO_2	0.98	0.89	1.15	1.43	1.70	2.46	1.59	1.78	1.02	1.17	0.65	1.15	0.38	0.17
Al_2O_3	13.75	12.10	12.83	13.80	13.61	11.47	16.99	15.24	16.76	13.95	13.45	13.26	13.43	19.98
Fe_2O_3	4.35	2.87	4.31	5.17	3.68	2.20	3.61	3.47	3.57	5.95	1.94	5.16	0.65	1.20
FeO	4.20	5.26	5.35	6.81	5.98	7.27	5.51	5.87	3.55	6.36	1.63	2.36	5.63	2.93
MnO	0.13	0.17	0.16	0.19	0.15	0.31	0.13	0.17	0.07	0.21	0.07	0.51	0.12	0.08
MgO	3.59	7.37	5.69	6.20	6.90	6.54	4.81	6.12	4.07	4.79	2.55	2.80	10.55	8.36
CaO	17.31	15.44	14.69	14.10	9.57	14.31	8.43	9.77	13.15	5.60	4.59	3.22	15.44	14.23
Na_2O	3.55	2.30	2.08	2.04	3.44	0.05	3.75	2.98	3.87	4.06	0.06	3.04	1.10	1.18
K_2O	0.05	0.46	0.09	0.20	0.75	2.50	1.63	1.01	0.31	0.72	2.65	3.27	0.02	1.50
P_2O_5	0.12	0.12	0.15	0.16	0.30	0.38	0.33	0.35	0.12	0.15	0.10	0.25	0.06	0.05
LOI	7.98	9.93	6.31	4.31	1.52	6.11	1.97	3.12	10.77	7.36	5.01	5.67	1.98	3.26
Total	99.25	99.33	99.15	98.89	99.73	99.20	99.18	99.25	99.05	99.09	99.72	99.69	99.71	99.52

Trace elements ppm

Ba	17	64	27	18	245	780	420	280	19	243	692	434	19	85
Rb	12	19	9	12	17	66	27	24	9	23	53	63	5	42
Sr	170	140	153	159	478	513	436	385	165	166	194	213	66	175
Y	26	21	28	33	21	33	27	32	18	19	19	28	12	5
Zr	72	74	70	69	129	135	132	133	71	76	133	90	15	4
Nb	7	8	8	8	19	21	18	18	7	36	9	19	8	7
Zn	63	154	81	85	83	71	92	86	74	127	22	111	40	29
Ni	79	85	85	105	198	138	140	120	147	20	17	116	187	142
Cr	358	271	223	312	312	240	152	220	239	220	60	278	442	427
Sc	32	33	33	39	20	36	16	28	30	25	22	27	33	21

REE ppm

La	8.5	9.1	12.2	6.3	27.3	93.0	30.2	69.5	13.6	16.2	78.6	28.6	6.1	8.4
Ce	7.7	9.3	10.3	11.4	44.3	151.0	50.4	74.8	10.6	10.3	38.6	48.0	3.0	1.7
Pr	1.2	1.3	1.5	1.7	5.0	14.4	5.7	9.4	1.4	1.1	4.4	4.9	0.4	0.2
Nd	6.8	7.0	8.4	9.3	21.2	51.9	24.1	37.8	7.2	7.1	18.6	20.5	2.6	0.9
Sm	2.4	2.2	2.9	3.2	5.0	8.7	5.7	6.8	2.3	2.2	4.1	4.3	1.0	0.4
Eu	1.0	0.9	1.1	1.3	1.7	3.4	2.2	2.4	1.0	0.8	1.2	1.5	0.4	0.3
Gd	2.8	3.2	4.4	5.0	5.3	7.6	6.1	6.6	3.1	2.9	4.2	4.8	1.7	0.6
Dy	4.6	3.8	5.2	5.9	4.5	6.7	5.4	6.2	3.5	3.2	4.3	4.6	2.1	0.8
Ho	1.0	0.8	1.1	1.2	0.8	1.3	1.0	1.1	0.7	0.6	0.8	0.9	0.5	0.2
Er	2.8	2.2	3.1	3.6	1.9	2.7	2.4	2.5	1.9	1.7	1.5	2.3	1.3	0.5
Yb	2.7	2.2	2.8	3.1	1.6	2.6	2.1	2.3	1.8	1.6	1.4	2.2	1.4	0.4
Lu	0.4	0.4	0.4	0.4	0.2	0.3	0.4	0.4	0.3	0.2	0.2	0.4	0.3	0.1

considered to be the result of alteration. Therefore, little useful information can be obtained from mobile major elements. However, the immobile elements can provide useful information. Comparison of the two amphibolite groups reveals significant differences between them. The group-1 amphibolite has lower contents in Ti, P, Nb, Y, Zr, LREE and MREE than the group-2 amphibolites; contrarily the group 1 amphibolite is richer in Ca and slightly in HREE. Furthermore, group-1 has low Nb/Y ratios, ranging from 0.25 to 0.38 and low P_2O_5 contents from 0.12 to 0.16 %, displaying a sub-

alkaline character. Group-2 has Nb/Y ranging from 0.56-0.90 and P_2O_5 from 0.30-0.38 %, and shows affinities similar to alkaline formations.

The geochemical variability of the two amphibolite groups is further illustrated in Figure 4. The group-1 amphibolite displays chemical affinities, which are analogous to MORB. Particularly, when the Nb content is considered (Fig. 4c), these rocks display a geochemical character analogous to plume-type (or E-type) MORB formations. On the other hand, the group-2 amphibolites have trace element geochemistry, which resembles the modern WPB formations (Fig. 4).
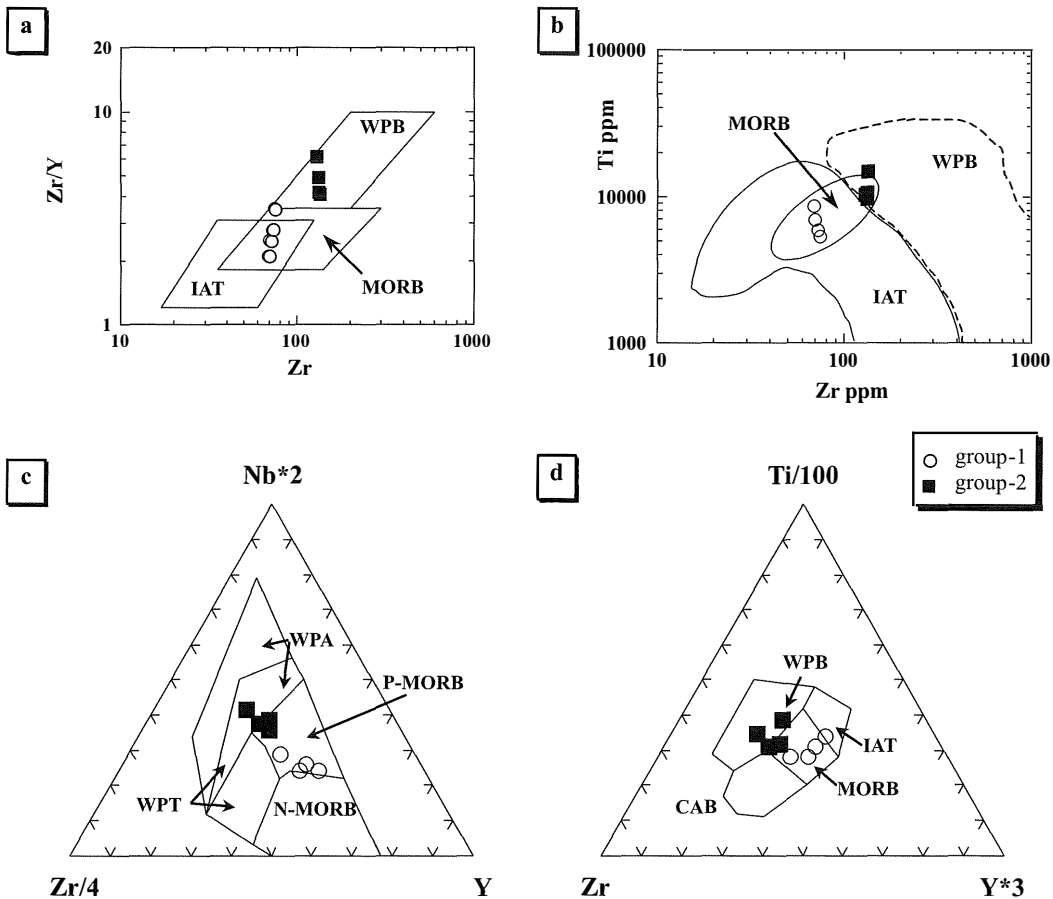
Fig. 4 – Selected discrimination diagrams for the Angelona amphibolites: a. Zr/Y-Zr, after Pearce and Norry (1979); b. Ti-Zr, after Pearce (1982); c. Nb-Zr-Y, after Meschede (1986); d. Ti-Zr-Y, after Pearce and Cann (1973).

The MORB-normalised patterns of the analysed group-1 amphibolite samples are mostly parallel with normalised incompatible element values close to unity that resemble MORB-type rocks. Nb and P are enriched but the overall element variations in these patterns does not resemble E-type MORB rocks (Fig. 5a). Enrichments in Rb and Ba are assigned to alteration. On the other side, the group-2 patterns illustrate common characteristics with some WPB-type rocks, having most of their incompatible HFS elements enhanced with respect to average MORB (Fig. 5b).

An analogous decoupling between the two groups is illustrated in the REE-normalised patterns (Fig. 6). Group-1, with lower light and medium REE, shows unfractionated patterns at

about 10-20 times the chondritic values, similar to T-MORB. Significant La enrichments are probably due to alteration effects. Group-2 is strongly enriched in LREE and moderately enriched in MREE relative to group-1, but slightly poorer in HREE, showing affinities analogous to alkali WP basalts. Both groups do not show negative Eu-anomalies.

It is noteworthy, that the associated volcanic rocks from the Angelona ophiolite mélange show an analogous diversity with respect to the MORB-normalised and REE-normalised patterns, having also bimodal affinities. One group concerns basalts (represented by samples Agl.64 and Agl.98) similar to the group-1 amphibolites. It shows subparallel MORB-normalised patterns, analogous to basalts from
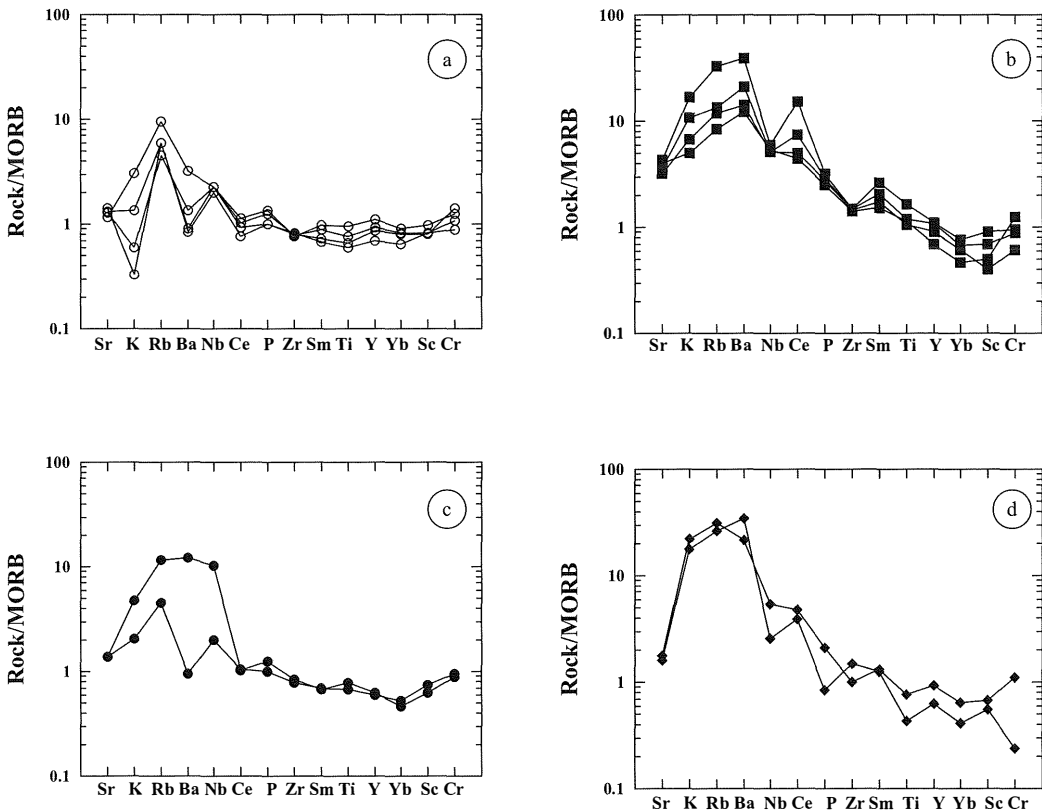
Fig. 5 – MORB-normalised spiderdiagrams for the group-1 amphibolites (a), group-2 amphibolites (b), group-1 basalts (c) and group-2 basalts (d) from Angelona (normalizing values after Pearce, 1982).
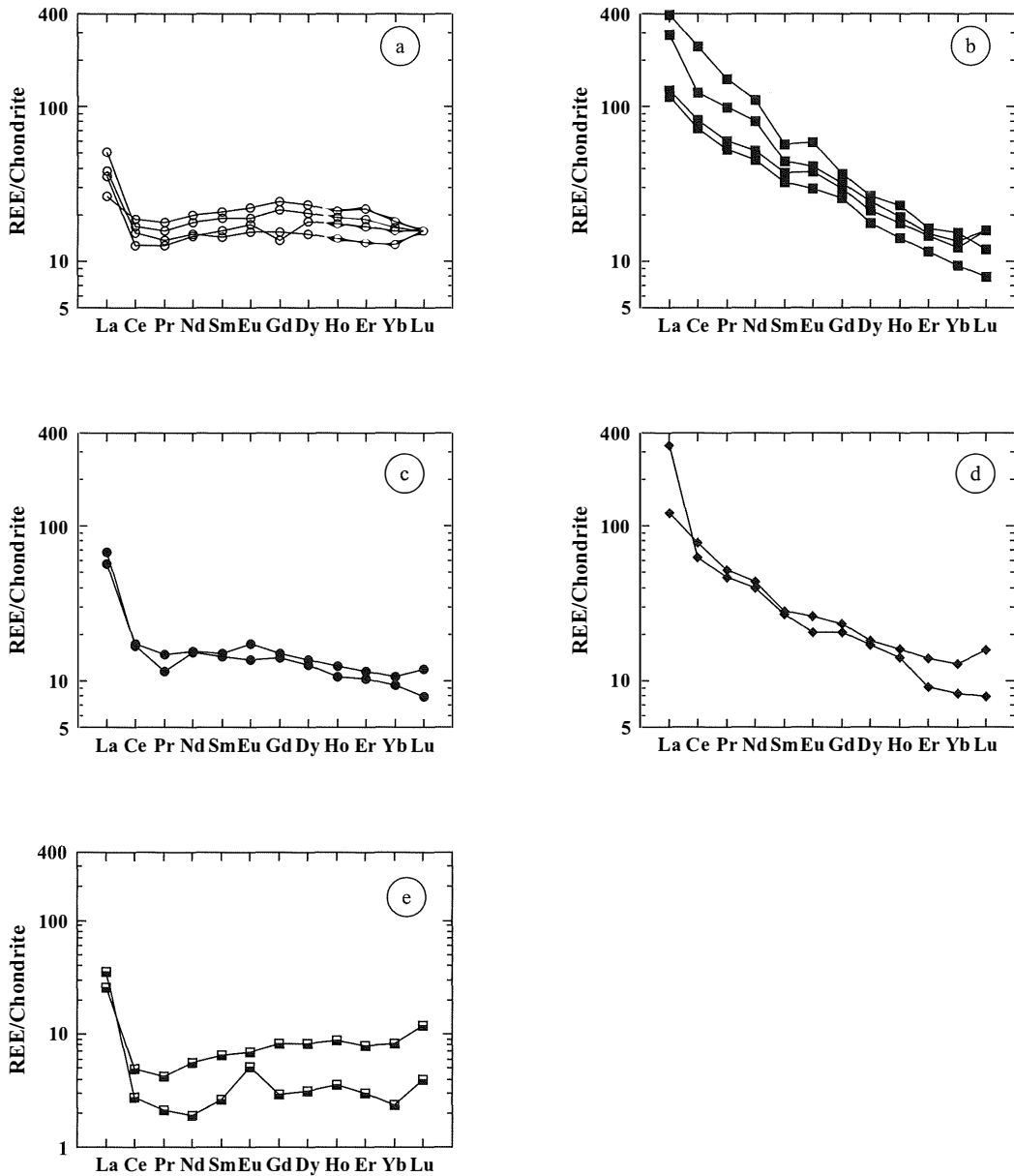
Fig. 6 – Chondrite-normalised REE spiderdiagrams for the group-1 amphibolites (a), group-2 amphibolites (b), group-1 basalts (c), group-2 basalts (d) and gabbros (e) from Angelona.

oceanic environments, but with relative Nb enrichments, and flat REE-normalised patterns at about 10-20 times the chondritic values (Figs. 5c, 6c). A second group of rocks, ranging in composistion from basalts to andesites (represented by samples Agl.33 and

Agl.96), displays trace element and REE affinities similar to the group-2 amphibolites (Figs. 5d, 6d). Two gabbros, collected as fragments from the ophiolite mélange, are considered as the basic plutonic member of the ophiolite, have flat REE-patterns and can be genetically related only to the first group of basalts and amphibolites, having parallel patterns at lower absolute REE abundances (Fig. 6e). The most primitive of these samples displays a marked positive Eu-anomaly, an effect commonly observed in cumulate gabbros, generally attributed to plagioclase accumulation.

PETROGENETIC MODELING

The metamorphic evolution of the Angelona amphibolite can be modeled within the CaO-MgO-SiO_2-Al_2O_3-FeO-H_2O system based on mineral and whole rock compositions. Using the computer program TWQ (Berman, 1991) and the thermodynamic database of Berman (1988; 1990), the equilibria among the co-existing minerals were investigated and a possible P-T path is suggested (Fig. 7). Diopside has not been observed in the amphibolite, however, its occurrence in the assemblage of the basalts and gabbros, presumably the precursors of the amphibolites, allowed the assumption of its partitioning during the first stages of the amphibolite evolution.

Mineral reactions, responsible for the evolution of the amphibolites, are shown in Figure 7. Reactions 1, 2 and 3 best describe the formation of amphibole and epidote after clinopyroxene, chlorite and plagioclase. They are compatible with the petrographic evidence that amphibole and epidote are the first appearing phases during amphibolite metamorphism. The reactant chlorite, in reactions 1 and 2, is apparently a product of the incipient ocean-floor alteration, which is commonly observed in the ophiolites worldwide. Reactions 4 and 5 are thought to be responsible for the development of a new generation of chlorite after amphibole and further development of epidote. This evidence

is consistent with the petrographic observation that chlorite forms at the expense of hornblende. Despite the uncertainty in pressure estimation, an average range between 6 and 8 MPa can be assumed. The positive slopes of the reactions shown on the P-T diagram suggest that a possible petrogenetic path implies pressure-increase and cooling, during the evolution of the Angelona amphibolites (Fig. 7). Reaction 1 sets the onset of the metamorphism and indicates a temperature of 430-480°C, for pressures ranging at approximately between 6 and 8 MPa, which are slightly lower, but generally consistent, than those estimated by geothermometric calculations. The uncertainty of pressure estimation still exists in the P-T diagram, due to the steep dP/dT slope of the reactions over a wide pressure range and the absence of invariant points (Fig. 7). Due to the absence of newly formed diopside, it is plausible that reaction 6 has not been encountered, hence providing a lower thermal boundary at around 360°C if pressure ranges between 6 and 8 MPa, as previously mentioned, during the amphibolite evolution (see Fig. 7).

To encounter reactions 1 to 5, which are thought to be responsible for the evolution of the Angelona amphibolites, a decrease in temperature is needed (see arrow in Fig. 7). There is no other evidence for pressure evolution, but the steep, positive slopes of the reactions, as well as the temperature decrease suggest that the amphibolites were developed during pressure increase (path indicated by the arrow in Fig. 7), similar to other metamorphic soles at the bottom of ophiolites suites worldwide.

GEOCHEMICAL COMPARISONS AND AGE OF THE GREEK OPHIOLITES

The ophiolite outcrops occurring in Argolis peninsula, to the north of Angelona, have been studied in detail by several authors (e.g. Hatzipanagiotou *et al.*, 1987/1988; Tsikouras *et al.*, 1989; Dostal *et al.*, 1991; Clift and Dixon, 1998; Bortolotti *et al.*, 2002).
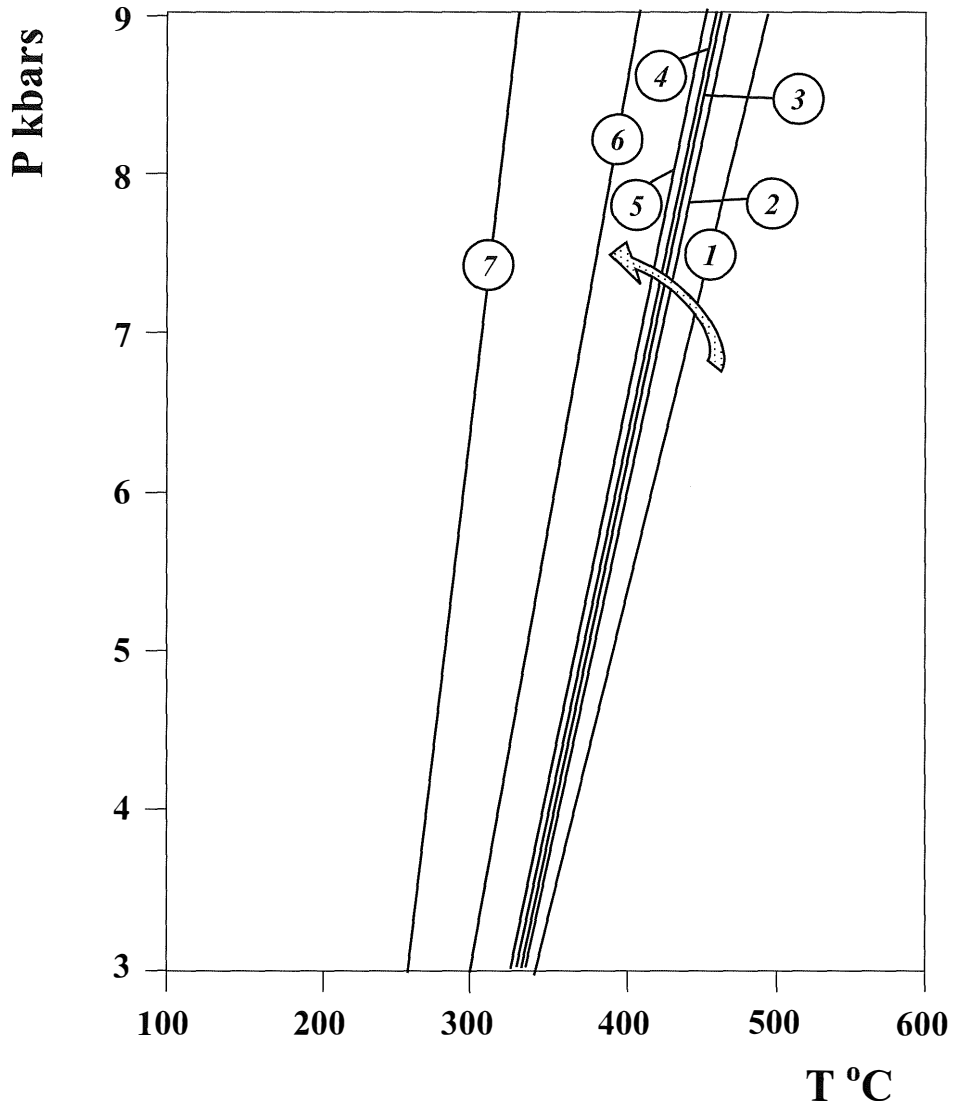
Fig. 7 – P-T diagram and suggested path for the evolution of the Angelona amphibolites.

Indicated reactions:
1: 5 tr + 6 czo ⇆ 8 qz + 15 di + 2 chl + 7 An
2: 9 tr + 30 czo ⇆ 35 di + 2 chl + 43 An + 16 H_2O
3: 2 qz + tr + 6 czo ⇆ 5 di + 9 An + 4 H_2O
4: chl+ 9 qz + 12 czo ⇆ 5 di + 19 An + 10 H_2O
5: 6 czo + 7 qz + chl ⇆ 10 An + tr + 6 H_2O
6: 5 qz + 5 di + chl ⇆ An + 2 tr + 2 H_2O
7: 9 chl + 50 di + 43 qz ⇆ 6 czo + 19 tr + 14 H_2O
(Assemblages on the left are stable on the left of the curves)

Abbreviations: chl: chlorite, tr: tremolite, czo: clinozoisite, di: diopside, An: anorthite, qz: quartz.

Clift and Dixon (1998) mentioned the existence of three types of basalts: a «low Nb» group, a «moderate Nb» group and a «picritic» group. The «low Nb» group has trace and rare earth element characteristics intermediate between N-type MORB and E-type MORB. The «moderate Nb» group is enriched in several incompatible elements and in LREE relative to average MORB, while the HREE values are similar to those from the «low Nb» group. The third type has very low Zr/Nb values, high Mg contents and moderate LREE enrichment relative to HREE. Similar results have been drawn by Dostal *et al.* (1991). However, they noted the occurrence of boninites with typical U-shaped immobile element patterns. These rocks are considered by Clift and Dixon (1998) as analogous to their «picritic» group and the different geochemical features of the basalts are assigned by the last authors to different degrees of partial melting of the same source.

Comparison of our data with basalts from Argolis peninsula indicates that the Angelona T-type basalts are almost identical to the «low Nb» group. The WPB rocks from Angelona show some trace element geochemical similarities with the «moderate Nb» group. However, they display a considerably higher LREE enrichment in comparison to the HREE relative to that observed in the Argolis «moderate Nb» basalts ($(La/Lu)_n$=7.8-17.9 in Angelona and $(La/Lu)_n$=3.4-5.8 in Argolis).

Nevertheless, the WPB rocks from the Angelona ophiolite mélange, display significant similarities, particularly in incompatible trace and rare earth elements, with some Triassic volcanic rocks occurring in the Hellenides. Figure 8 illustrates REE profiles from the Angelona WPB amphibolites and volcanic rocks (combined in one envelope) in comparison with analogous Triassic volcanic rocks. The Angelona WPB rocks closely resemble the alkali basaltic rocks from the Avdella mélange,
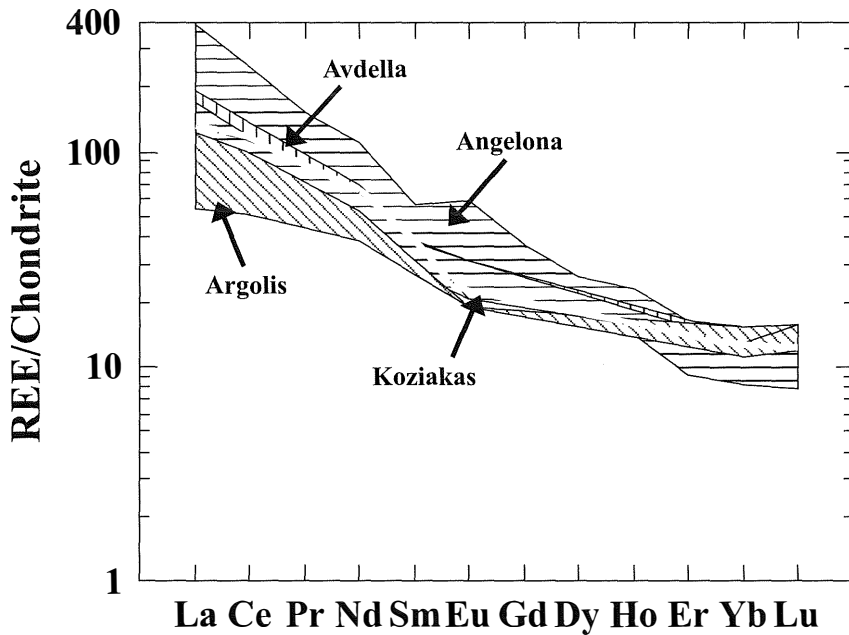

Fig. 8 – REE/Chondrite normalized envelopes for the group-1 rocks from Angelona, in comparison with some Triassic volcanic rocks from the Hellenides. Data for Angelona are from this paper and for other areas are from Capedri *et al.* (1997).

in northern Pindos. This formation is associated with subduction of Pindos Ocean and contains basalts of variable composition of Late Anisian-Scythian age (Migiros and Tselepidis, 1990; Capedri *et al.*, 1997; Jones and Robertson, 1990). Moreover, the Angelona WPB rocks are broadly similar to the Triassic volcanic rocks from Argolis and Koziakas. In Argolis, these rocks comprise mainly dacites with basaltic xenoliths, evidence for magma mixing processes, and are overlain by ammonite-bearing limestones of Carnian-Norian age (Clift and Robertson, 1990). The Triassic volcanic rocks in Koziakas are rare and are associated with conodont-bearing limestone and radiolarites of Norian age (Capedri *et al.*, 1997)

Age determination of the ophiolites and their underlying subophiolitic metamorphic soles are
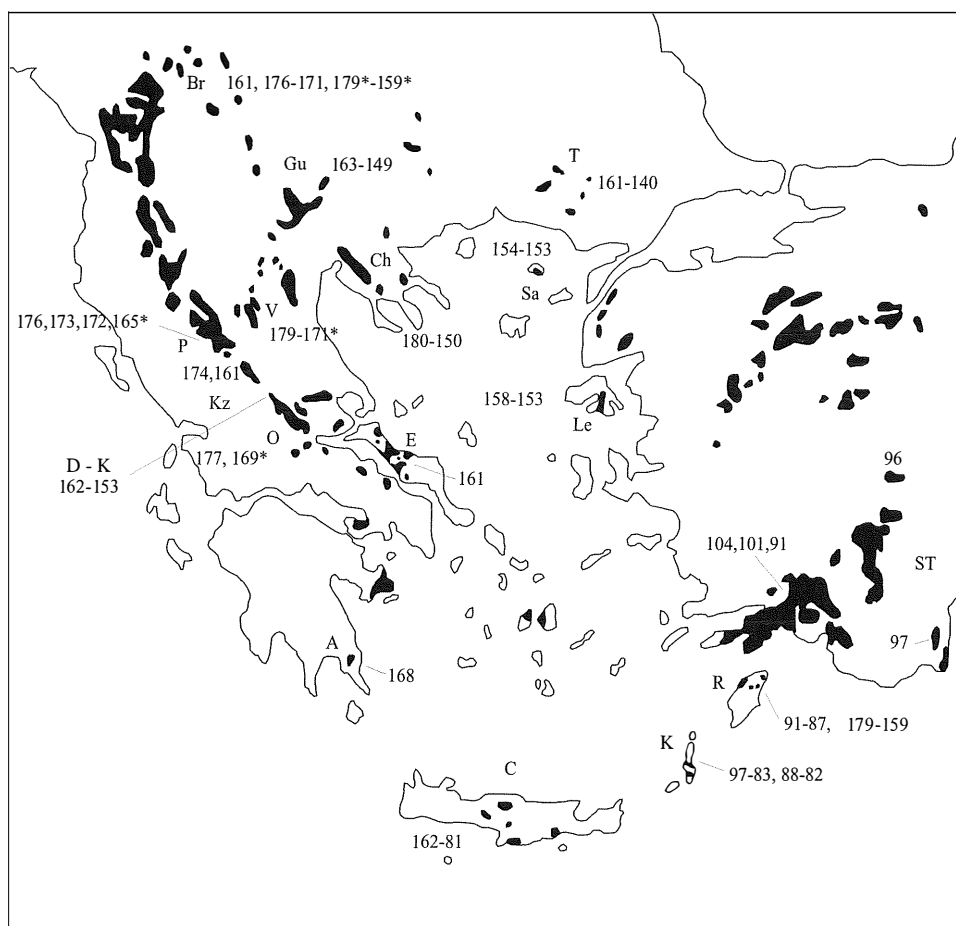

Fig. 9 – K-Ar radiometric ages (in Ma) of ophiolites in the Eastern Mediterranean: (P) Pindos (Spray and Roddick 1980; Thuizat *et al.*, 1981); (V) Vourinos and (O) Othrys (Spray and Roddick, 1980); (D-K) Dafnospilia-Kedros (Hatzipanagiotou *et al.*, 1994); (Kz) Koziakas (Pomonis *et al.* 2002); (E) Euboea (Koepke *et al.*, 1985); (R) Rhodes and (K) Karpathos (Hatzipanagiotou, 1983; 1991; Koepke *et al.*, 1985); (Gu) Guevgueli (Spray *et al.*, 1984); (CH) Chalkidiki (Jung *et al.*, 1980); (T) Thraki (Bigazzi *et al.*, 1989); (Sa) Samothraki (Tsikouras *et al.*, 1990), (Le) Lesvos (Hatzipanagiotou and Pe-Piper, 1995); (C) Crete (Seidel *et al.*, 1981; Koepke *et al.*, 1985); (A) Angelona (Koepke *et al.*, 1985); (Br) Brezovica (Okrusch *et al.*, 1978; Karamata and Lovriæ, 1978); (ST) South Turkey (Thuizat *et al.*, 1981).

subjects of great interest. Figure 9 illustrates the main ophiolite bodies from the Balkan Peninsula, Cyprus and Turkey, together with their radiometric dates. These dates are from both infra-ophiolitic dykes, which indicate the igneous events, and subophiolitic metamorphic soles, which provide evidence for the time of initiation of subductions. Comparison of the ages of these two events indicates a restricted time span. The ophiolites of the Balkan Peninsula have been formed in Upper Jurassic-Lower Cretaceous, but there is a small age difference (~20 Ma.) between the western and the eastern belts. Furthermore, the Tauride and Cyprus ophiolites, as well as those from Rhodes and Karpathos have been formed during late Early Cretaceous, with the exception of the Rhodes amphibolite, which gives an Upper Jurassic-Lower Cretaceous age (Hatzipanagiotou, 1991).

Radiometric dates from the amphibolites of the Angelona area yielded ages at around 168 Ma (Koepke *et al.*, 1985), suggesting that the host ophiolite correlates with the western ophiolite belt of the Balkan Peninsula, comprising the southernmost edge of it in the continental Greece. This correlation is in agreement with geochemical evidence, which indicates that the Angelona ophiolite has similar affinities with that of Argolis, within the Pindos oceanic strand.

Discussion

The amphibolites from Angelona display low Zr/Ti ratios similar to orthoamphibolites elsewhere. The parallel REE-normalised patterns (Fig. 6) indicate a genetic relationship of the samples within each group, through fractionation (prior to metamorphism). The linear relationship on the Al_2O_3/TiO_2 vs. Ti diagram suggests that these elements were immobile; mineral fractionation vectors on this diagram are compatible with the involvement of clinopyroxene and plagioclase fractionation in both groups (Fig. 10). The absence of negative Eu-anomalies, in the REE-normalised
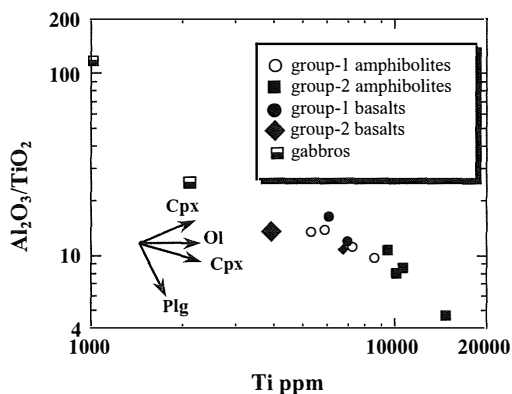

Fig. 10 – Al_2O_3/TiO_2 vs. Ti plot for rocks from the Angelona ophiolite (mineral vectors after Pearce and Flower, 1977).

patterns, suggests oxidizing crystallization conditions rather than lack of significant plagioclase fractionation. Whole-rock geochemistry of the two amphibolite groups is almost identical to the two groups of basalts, respectively. Therefore, it is plausible to consider these basalts as the precursors of the amphibolites, and thus, it is highly unlikely that plagioclase was not present in the magmatic evolution. Under oxidizing conditions most of the Eu turns into trivalent state and does not enter plagioclase (Hess, 1989). This assumption is also compatible with aforementioned mineralogical data.

The geochemical data coupled with the petrographic investigation clearly point to the hypothesis of the evolution of at least two amphibolite groups. Plots of the analysed samples on selected discrimination diagrams further demonstrate the diversity between the two groups. The geochemical differences between group-1 and group-2 cannot be explained in terms of different degrees of partial melting, since such a process should result in variable Y contents. However, the Y values in both the amphibolite (and the corresponding volcanic rocks) groups are similar. On the other hand, the variability of REE/Chondrite, Rock/MORB normalised patterns, and the Zr and Nb contents suggest

different mantle sources for the two groups that is compatible with the data shown on Figure 4.

Group-1 shows geochemical affinities similar to T-MORB and hence they represent formations of a normal spreading center, variably contributed by a mantle plume (Fig. 4). The group-2 amphibolites is richer in Nb, Zr, Zr/Y and poorer in Zr/Nb, relative to group-1, having a WPB chemistry (Fig. 4). Rock/MORB and REE normalised patterns also support this evidence (Figs. 5 and 6).

The origin of group-2 is clearly affected by melting of an enriched mantle source (plume). Similar metamorphic rocks have also been encountered in Palea Epidavros, as tectonic blocks within a mélange, which belongs to the Argolis peninsula ophiolite. This suite is located just to the north of Angelona (Migdhalitsa ophiolite, after Clift and Dixon, 1998) and shows analogous affinities with the Angelona ophiolite. Additionally, mafic rocks, of similar chemistry, have been found as blocks in the ophiolitic mélange of the Pindos ophiolite (Jones and Robertson, 1991), and as thrust slices under the Oman ophiolite (Lippard *et al.*, 1986).

Furthermore, the WPB rocks from Angelona display significant geochemical similarities with Triassic rocks found in Pindos, Koziakas and Argolis. The Triassic volcanism in Greece is generally related to early rifting in the Hellenides, which probably initiated in Late Permian and lasted until Middle Triassic. This event culminated in continental break-up in Late Triassic and eventually lead to the Jurassic oceanic evolution (Capedri *et al.*, 1997; Pe-Piper, 1998). Thus, the Triassic volcanic rocks are considered as the precursors of the ophiolite rocks. Alkali basalts, similar to the group-2 rocks in Angelona, represent one of the four types of Triassic rift related volcanism identified in Greece; it is suggested that a small plume component has been involved in their evolution (Pe-Piper, 1998).

Spatial relationship and geochemical comparisons between the Angelona and the Argolis ophiolites suggest that these two suites have a common origin. Bortolloti *et al.* (2002)

have shown the occurrence of Triassic radiolarites associated with basalts in Argolis. Clift and Dixon (1998) refer to the occurrence of rocks with boninitic affinities and hence, they assume the occurrence of an intraoceanic subduction in Argolis. There is no geochemical evidence for the operation of such a process in Angelona, because no boninitic rocks were found that area. However, the occurrence of a subduction zone (either intraoceanic or not) is a prerequisite for the presence of the amphibolite sole. Further geological evidence supporting this interpretation include:

1) The sole containing the amphibolites consistently occurs as thrust sheet between the ophiolite above and the obduction-related ophiolitic mélange below.

2) The amphibolites display strong synmetamorphic fabrics (mineral foliation and associated stretching lineation) parallel to the basal thrust faults beneath the overlying peridotites.

3) The intercalated metasedimentary rocks show well-developed foliation and metamorphic textures parallel to those in the amphibolites.

4) Structures in the metamorphic sole (i.e. mineral foliation and associated stretching lineation, fold axes parallel to mineral lineations) and structural relations between the sole and the overlying ophiolite indicate that deformation was related to horizontal shortening and vertical thickening, associated with thrust faults rather than to strike-slip faulting or stretching or ocean-floor hydrothermal metamorphism.

Formation of the ophiolite was probably coincident with ductile extension in the lower oceanic crust that generated the high-T conditions for the amphibolites. Crystallization was rapidly followed by structural stacking of an ophiolitic slab of ca. 18-24 km thick (based on our pressure estimates of 6-8 MPa and assuming a mean geobarometric gradient of 0.33 MPa/km) onto the adjacent oceanic crust. The subduction must have been accompanied by metamorphism near the spreading centre. Basalts on the top of the downgoing plate were metamorphosed in the amphibolite facies by

the heat of the hot hanginwall of the subduction zone. The amphibolites were scrapped off the downgoing plate and accreted to the upper plate. As subduction continued the hangingwall cooled as amphibolite remained at depth and overprinting mineral assemblages grew under conditions of increasing P/T ratio.

This model is similar to those proposed by Suppe and Foland (1978), Brown *et al*. (1982), Wakabayashi (1990) and Chamberlain and Karabinos (1987). Furthermore, it is consistent with the thermal models proposed by Cloos (1985), Peackock (1988) and Hacker (1990), suggesting a rapid cooling for rocks accreted to the hangingwall of a newly formed subduction zone.

Metamorphic rocks up to amphibolite facies, similar to those developed in the Angelona area, commonly occur at the base of many allochthonous Tethyan ophiolites. The rocks from Angelona have many features in common with such sub-ophiolitic metamorphic rocks, but it is difficult to observe the characteristic inverse metamorphic gradient. However, the suggested P-T path advocates such a hypothesis. The progressively increasing pressure with simultaneous decrease in temperature is a characteristic feature that has been observed in several other sub-ophiolitic metamorphic rocks (e.g. Önen and Hall, 1993; Dilek and Whitney, 1997; Wakabayashi, 1990) and the suggested P-T path closely approximates the initial stage of the so-called counterclockwise P-T-t evolution of several metamorphic soles.

CONCLUSIONS

Amphibolitic rocks have been found in an ophiolite remnant body at Angelona area, both as fragments in the ophiolite mélange and as a relict subophiolitic metamorphic sole. This sole crops out between ultramafic rocks and the ophiolite mélange. Two amphibolitic types have been recognized based on their geochemical features: group-1 shows affinities similar to T-MORB formations, while group-2 has WPB affinity, resembling some Triassic, rift-related volcanic rocks. Notably, two groups of volcanic rocks have also been recognized and display geochemical signatures similar to the two amphibolite groups. Group-1 includes basalts while group-2 contains basalts and andesites. Samples from both groups were collected as fragments from the ophiolite mélange.

The two distinct geochemical signatures of both the amphibolites and the volcanic rocks are interpreted as a result of evolution during two magmatic episodes. It is likely that continental rifting initiated during Triassic and generated the volcanic rocks with WPB affinity. This rifting consequently developed in a typical oceanic spreading center, partially affected by a plume-mantle component, within the Pindos strand of the Mesozoic Tethys and generated the T-type MORB rocks in Angelona.

Intraoceanic subduction was responsible for the metamorphic evolution of the amphibolites, at moderate metamorphic grade. Geothermobarometric estimations yielded temperatures at around 450-500°C and 500-550°C for the two groups, respectively, while the estimated pressure lies at approximately 6-8 MPa for both groups. A reaction series, thought to be responsible for the amphibolites evolution, on a P-T diagram, suggests that metamorphism of the mafic precursors occurred during pressure increase and cooling, a feature that is common in several sub-ophiolitic metamorphic soles worldwide. This evolution resembles the initial stages of a counterclockwise P-T-t evolutionary path, which produces an inverse metamorphic profile in analogous rocks elsewhere.

Geochemical similarities between the Argolis and the Angelona ophiolites point to the hypothesis for a common origin. The proposed geotectonic regime for the Angelona ophiolite shows many similarities to models proposed for the evolution of the Argolis peninsula ophiolite, located to the north of Angelona (Clift and Dixon, 1998; Bortolloti *et al*. 2002), which itself is considered to be a continuation of the Tethyan Mesozoic Pindos

ocean of the Hellenides. The ophiolites southeastwards in the Hellenides have Cretaceous ages, and hence, they are not connected to the Jurassic ophiolites occurring in the continental Greece. Therefore, the Angelona ophiolite must be considered to represent the southernmost link of the continental Hellenides, with the southern tip of the Pindos oceanic environment, represented by the ophiolites of Crete Island.

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