PLAGIOGRANITES IN THE HELLENIC OPHIOLITES

Konstantin Hatzipanagiotou and **Basilios Tsikouras**

Department of Geology, Section of Earth Materials, University of Patras, GR-265 00 Patra, Greece (e-mail: K.Hatzipanagiotou@upatras.gr).

Keywords: *plagiogranite, ophiolite, Jurassic. Guevgueli, Samothraki, Koziakas, Rhodes, Crete*

ABSTRACT

Plagiogranites have been studied from the areas of Guevgueli, Samothraki Island, Koziakas Mountains, Rhodes Island and Crete. They are typical trondhjemites (plus Qz-diorites in Guevgueli) while an unusual Qz-monzonite (geochemically defined) occurs at Rhodes. Furthermore, a leucogranite assemblage is associated with the plagiogranite in Samothraki; it has been derived by partial melting of the plagiogranite during a collision event. Geochemical results show that all the plagiogranitic rocks are differentiates of a mafic magma. In addition, at Guevgueli and Samothraki, a subsequent filter pressing process resulted in flowage of the leucocratic melt into cracks of the country rocks with the formation of a net-veined structure. The plagiogranites from Samothraki, Koziakas and Crete have chemistries similar to Volcanic Arc Granites, whereas the Guevgueli plagiogranite has an affinity closer to Ocean Ridge Granites. However, this variation is attributed to heterogeneities of the subducted lithosphere since all the above plagiogranites are associated with ophiolites of marginal basin origin.

INTRODUCTION

"Oceanic plagiogranites" or "plagiogranites" (Coleman and Peterman, 1975; Thayer, 1977; Coleman and Donato, 1979) comprise sparse leucocratic assemblages of intermediate to acid character within ophiolite suites. They are encountered from either the upper plutonic members of ophiolite complexes (e.g., Wilson, 1959; Glennie et al., 1974; Bébien, 1991) or within ultramafic rocks (e.g., Parrot, 1977; Hatzipanagiotou et al., 1995), amphibolites (e.g., Malpas, 1979; Pedersen and Malpas, 1984), ophiolite mélanges (e.g., Hatzipanagiotou, 1986) or from dykes, veins and small bodies in the ophiolites (e.g., Ohnenstetter and Ohnenstetter, 1980; Ohnenstetter et al., 1981; Sivell and Waterhouse, 1984; Bébien, 1991; Tsikouras et al., 1998). Plagiogranite petrogenesis offers a considerable contribution to the knowledge of the evolution of ophiolitic complexes. They are usually considered as extreme differentiates derived by fractionation of a sub-alkaline, tholeiitic magma (Wilson, 1959; Thayer, 1963; Coleman and Peterman, 1975; Barbieri et al., 1994). However, several authors have proposed that silicate liquid immiscibility is an important process in the origin of such rock-types, due to the extensive compositional gap that sometimes exists between the mafic members and the plagiogranites of an ophiolite (Dixon and Rutherford, 1979). A third model that suggests plagiogranites are not comagmatic with the rest ophiolitic members, implies that they are products of partial melting of mafic lithologies under hydrous conditions (Payne and Strong, 1979; Gerlach et al., 1981; Pedersen and Malpas, 1984).

The present study deals with the comparison of geological and geochemical features, and an investigation of the geotectonic setting, of plagiogranites from the Guevgueli (Greece-FYROM international border), Samothraki Island (NE Aegean), Koziakas (Central Greece), Rhodes Island (SE Aegean) and Crete (South Aegean) ophiolites.

GEOLOGY OF THE HELLENIC PLAGIOGRANITE OCCURRENCES

The regional geological setting and the stratigraphic positions of the Hellenic plagiogranites are summarized in Fig. 1. The Guevgueli ophiolite is a parautochthonous, Late Jurassic complex comprising gabbroic cumulates, diorites associated with plagiogranites, a hypabyssal sheeted-dyke complex and mafic lavas. According to Ivanov et al. (1987), Bébien et al. (1986, 1987) and Zachariadou and Dimitriadis (1995) the ophiolite overlies a metasedimentary succession, where the lavas lie conformably on the metasediments, while Danelian et al. (1996) argue for a tectonic contact. Chemically the ophiolite displays a heterogeneous geochemical signature: some basaltic rocks display a high-field-strength element (HFSE) nature similar to MORB, whereas others are relatively depleted in HFSE and hence have a major influence from an IAT component, similar to SSZ-type ophiolites (Bébien 1982; Bébien et al., 1986; 1987). In this complex two plagiogranitic assemblages are found: a trondhjemite, which forms dykes (or the matrix in composite dykes hosting doleritic and gabbroic enclaves) and a quartz diorite that occurs within the upper plutonic members of the suite (Bébien, 1991). The trondhjemites usually occur as veins brecciating ferrodioritic rocks, which consequently are regarded as enclaves. These ferrodiorites display a mesocumulate texture and are thought to be parents to the plagiogranites (Bébien, 1991).

The Samothraki ophiolite is a parautochthonous sequence consisting, from bottom to top, of cumulate gabbro, isotropic gabbro, hornblende-diorite associated with leucocratic rocks, two sets of dolerite dykes, massive dolerite and basaltic lavas. It overlies a Late Jurassic Basement Unit composed of shallow marine to terrestrial metasedimentary rocks and metamorphosed in the low greenschist facies (Davis, 1963; Heimann et al. 1972; Kotopouli et al., 1989; Tsikouras and Hatzipanagiotou, 1995; 1998a). Radiometric dating on primary hornblende separates suggest a late Jurassic age for the host diorite (Tsikouras et al., 1990). The ophiolite contains basalts and massive dolerites similar to MORB, bimodal diorites of both MORB and IAT affinities and rare lavas similar to boninites. It has been interpreted as a back-arc basin ophiolite with a magmatic evolution involving the partial melting of a heterogeneous mantle under limited hydrous conditions (Tsikouras and Hatzipanagiotou, 1998a). Plagiogranitic and leucogranitic assemblages form

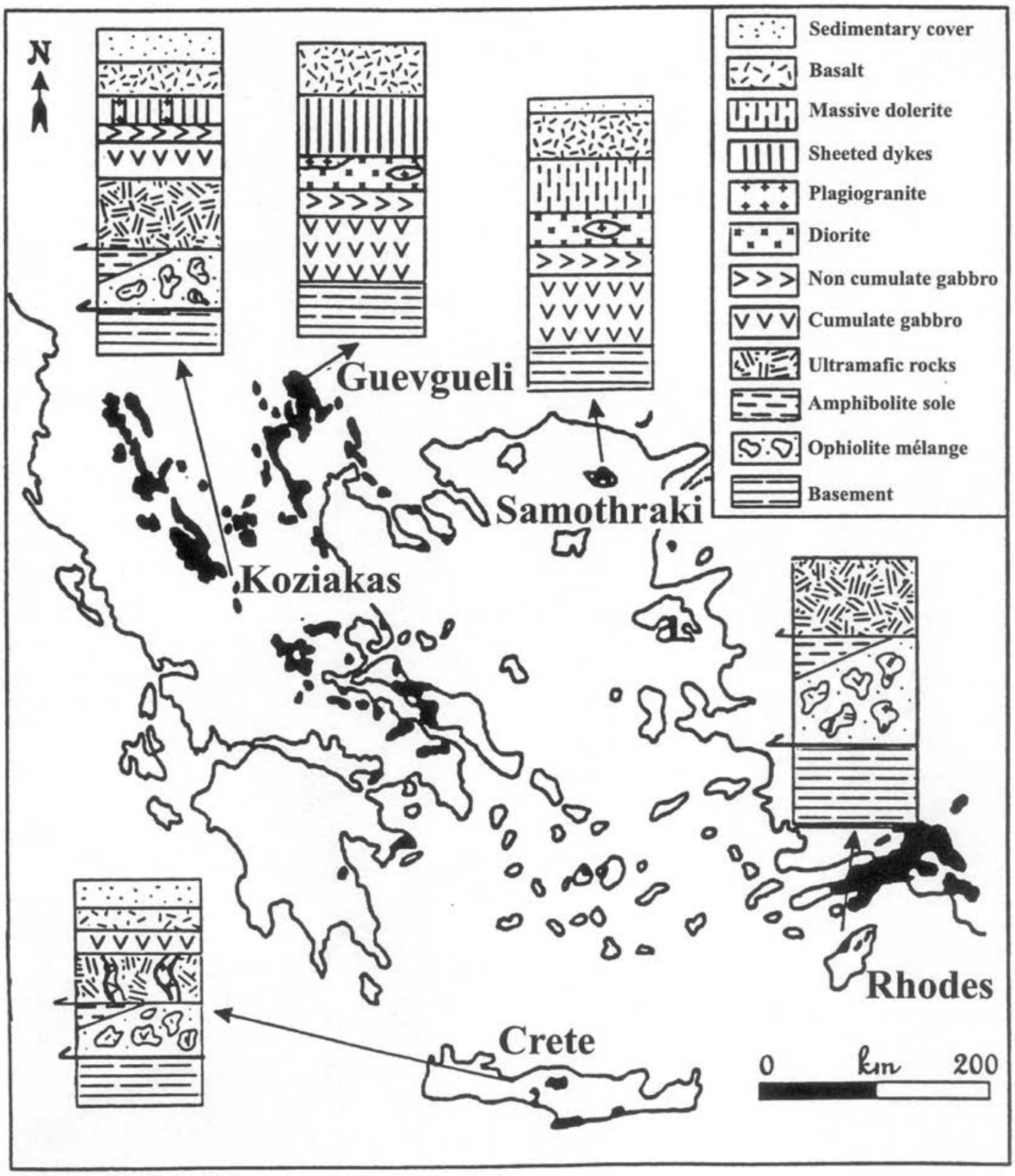


Fig. 1 - Occurrences of the main Hellenic ophiolites (black areas) and stratigraphic sections of the sequences that contain the plagiogranites (data from: Ivanov et al., 1987; Bébien et al., 1986; 1987; Bébien, 1991 for Guevgueli; Tsikouras and Hatzipanagiotou, 1995; 1998a; Tsikouras et al., 1998 for Samothraki; Capedri et al., 1985 for Koziakas; Hatzipanagiotou, 1983; 1988 for Rhodes; Koepke et al., 1985; Koepke, 1986 for Crete).

randomly oriented veins, in sharp contact with the host rocks, with mutual cross-cutting relationships. They display variable thickness from a few mm to several cm and are usually associated with shear-zones. They are sometimes found as pods or lenses of a few cm up to a few metres size or as intrusive bodies, emplaced in the deformed diorite (Tsikouras et al., 1998).

The Koziakas ophiolite is composed of serpentinized harzburgites, a sheeted dyke complex, and pillow lavas accompanied by deep-sea sediments (Capedri et al., 1985, Richter et al., 1992). An ophiolite mélange occurs at the base of the sequence. The ophiolite is tectonically emplaced upon a pelagic platform of Dogger-Malm age (Capedri et al., 1985). The lavas have a variable geochemical signature, but in general are similar to MORB-type rocks (Capedri et al., 1985). The plagiogranites in this suite are found as dykes associated with the doleritic sheeted dyke formation; no chilled margins or cross-cutting relationships have been observed between the plagiogranite and the dolerite arguing for emplacement of the leucocratic melt in hot dolerite (Hatzipanagiotou et al., 1995).

The Rhodes ophiolite is regarded as the link between the Jurassic ophiolites of the Balkan peninsula and the Cretaceous Turkish ophiolites. It comprises serpentinites and relict harzburgites intruded by dolerite dykes, while an ophiolite mélange lies tectonically at the bottom. The whole sequence has obducted on the autochthonous flysch and limestone formations of the Pindos Zone. (Hatzipanagiotou, 1983; 1988; Koepke et al., 1985). Geochronological investigation of clasts from the ophiolite mélange yielded Cretaceous ages for gabbros and Middle Jurassic ages for amphibolites (Hatzipanagiotou 1991). The plagiogranites in Rhodes Island are encountered as fragments, up to a few dm in size, within the ophiolite mélange usually associated with gabbroic rocks.

The Crete ophiolite is a dismembered suite resting tectonically on both the Pindos and the Gavrovo-Tripolitza nappes. It contains peridotites of lherzolitic composition and subordinate gabbro and basalt; composite gabbrodioritic dykes intrude the ultramafic rocks. The lower parts of the ophiolite nappe consist of an amphibolite sole and an ophiolite mélange (Seidel et al., 1977; Koepke et al., 1985; Koepke, 1986; Koepke and Seidel, 1999). Geochronological results from infra-ophiolitic hornblendites associated with serpentinites suggest a Middle Jurassic age for the Cretan ophiolite, while dating of the dykes yielded younger ages of Late Jurassic. The ultramafic members of this ophiolite display affinities similar to rocks generated at mid-ocean ridges while the dykes show a calc-alkaline affinity and an island-arc imprint; hence the origin of the whole sequence is related to a marginal basin setting (Koepke et al., 1985; Koepke, 1986; Capedri et al., 1987). The plagiogranites in Crete are found as parts of the composite dykes and are closely associated with the gabbrodioritic lithologies (Koepke et al., 1985).

PETROGRAPHIC CHARACTERISTICS OF THE HELLENIC LAGIOGRANITES

The investigated plagiogranites show common petrographic characteristics. They are medium-grained with hypidiomorphic-allotriomorphic granular textures. Their assemblages include quartz (20-35%) and plagioclase (60-80%) of oligoclase-andesine composition. Plagioclase, when subhedral, forms squat crystals and quite often is rimmed by a thin albitic layer. The Rhodes plagiogranites differ in having lower quartz (10-20 %). Quartz is interstitial between plagioclase and usually reveals undulatory extinction and/or elongated grains, as a result of plastic deformation. Textures range from granular (where quartz is dominant) to granophyric or graphic, produced by plagioclase and quartz intergrowths. Occasionally vermicular quartz-plagioclase intergrowths, interpreted as a primary magmatic textural feature (Coleman and Donato, 1979), have been observed. Amphibole (2-3%) and titanite (3-5%) are also present while traces of K-feldspar are occasionally seen in the Koziakas plagiogranites. Small quantities of apatite, zircon, allanite, titanomagnetite and ilmenite occur as accessory phases. Since mafic minerals do not exceed 10 vol. % of the mode, these rocks are classified as trondhjemites (Barker 1979). Hydrothermal metamorphism resulted in the development of epidote, clinozoisite, albite, chlorite, titanite, leucoxene and calcite; prehnite occurs occasionally at Koziakas. It has been assumed that the metamorphism of plagiogranites is a result of static, thermal events related to high-heat flow near spreading centres (Gass and Smewing, 1973).

The leucogranites that are closely associated with the plagiogranites in Samothraki Island (Tsikouras et al., 1998) display hypidiomorphic granular texture and have a granitic modal composition due to the presence of considerable amounts of K-feldspar (up to 20%). They contain plagioclase of albite to oligoclase composition (30-50%) and quartz (30-40%) but the contribution of all mafic phases (i.e. amphibole, titanite and opaques) is negligible (less than 2%). Their constituents are clearly less affected by deformation and no undulatory extinctions or elongated grains were observed. Secondary albite, epidote, clinozoisite and calcite were formed due to subsequent hydrothermal metamorphism.

GEOCHEMICAL CHARACTERISTICS OF THE HELLENIC PLAGIOGRANITES

Representative geochemical analyses from the investigated plagiogranites and the Samothraki leucogranites are shown in Table 1. All the plagiogranites have chemical affinities analogous to low-alumina trondhjemites and display low K, Sr and Rb contents similar to oceanic plagiogranites.

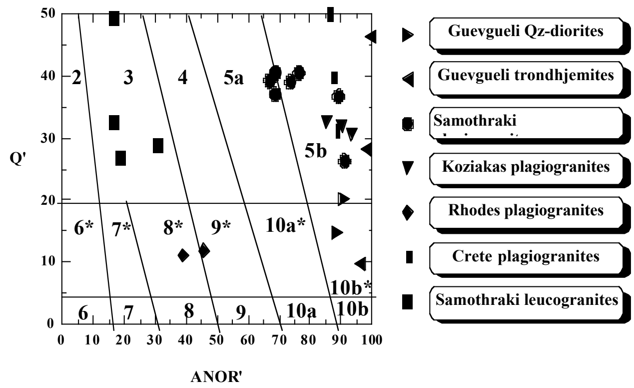


Fig. 2 - Plot of the Hellenic plagiogranites on the Q'-ANOR' classification diagram (after Streckeisen and Le Maitre, 1979). Field numbers correspond to those of the IUGS classification. Data from: Bébien (1991) for Guevgueli; Tsikouras et al. (1998) for Samothraki; Hatzipanagiotou et al. (1995) and our unpublished data for Koziakas; Hatzipanagiotou (1986) for Rhodes; Koepke (1986) for Crete.

Plot of normative mineral compositions on a Q'-ANOR' diagram (Streckeisen and Le Maitre, 1979), reveals that the plagiogranites from Guevgueli, Samothraki, Koziakas and Crete plot into the tonalite field while those from Rhodes plot as Qz-monzonites, mainly due to lower normative quartz and higher normative An (Fig. 2). This last classification is exceptional for such rock-types, but it has also been referred from a plagiogranite vein in the Indian Ocean (Engel and Fischer, 1975). The Samothraki leucogranites plot in the granite field. On a K_2O-SiO_2 diagram (Coleman, 1977), the plagiogranite samples fit well with the oceanic plagiogranite field and on the Or-Ab-An diagram (Coleman, 1977), they plot in the low-pressure, trondhjemite-tonalite field (not shown). Normative orthoclase of the plagiogranites from all localities, lies typically below 4%, and is certainly much lower than the average value of continental granophyres (20%; Coleman, 1977) while norm-Or of the Samothraki leucogranites is approximately 20-25 %.

The plagiogranites have suffered secondary alteration in the lower greenschist facies. This episode has largely effected the large-ion-lithophile elements (LILE) and the SiO_2 contents. Particularly, the alkalies are very sensitive to alteration and are highly variable in the Hellenic plagiogranites, hence all the above classifications are in part a consequence of element mobilisation during low-grade alteration and secondary silicification. Stable element ratios, such as Zr/TiO_2 (Winchester and Floyd, 1977), are consistent with intermediate to acid compositions for the Hellenic plagiogranites. This ratio indicates that the Samothraki plagiogranites and the Guevgueli trondhjemites have rhyodacitic (and their plutonic equivalent) compositions (with Zr/TiO_2 = 400-750), whereas the Koziakas and Crete plagiogranites as well as the Guevgueli Qz-diorites are mostly andesitic (Zr/TiO_2 = 30-130). High-field-strength element (HFSE) patterns (see below) are more stable and broadly comparable to other oceanic plagiogranites (e.g., Floyd and Winchester, 1978; Pallister and Knight, 1981; Floyd et al., 1998) whereas LILE contents are highly variable and not typically uniform as in most plagiogranites.

Figure 3 illustrates geochemical distinctions among the Hellenic plagiogranites. The Guevgueli plagiogranites differ in having higher Y contents (similar to ORG), relative to those from the other places, while the Qz-diorites are moreover rich in Ti. On the other hand, the plagiogranites from Rhodes display low Ti contents. Although accuracy of Nb

Table 1 - Representative geochemical analyses of plagiogranites from the Hellenic ophiolites

	Guevgueli		Samothraki			Koziakas				Rhodes		Crete	
	Qz-diorite	Trondhjemite	plagiogranites		leucogranite	plagiogranites			gabbro	plagiogranites		plagiogranites	
Major Elements %													
Sample	GV 78	GV 755	S 284A	S 323	S 459a	MM 49	MM 51	A 87	A 60	R 1	R 2	51	55
SiO_2	56.97	68.13	73.89	67.79	70.19	69.56	71.15	63.63	47.01	65.50	66.40	67.70	75.20
TiO_2	1.89	0.30	0.26	0.48	0.69	0.23	0.31	0.17	0.19	0.09	0.08	0.35	0.22
Al_2O_3	14.50	10.40	13.56	15.71	13.57	14.71	13.81	19.41	17.56	16.90	16.30	15.10	13.20
Fe_2O_3	10.59	3.54	1.76	3.19	3.38	1.75	1.90	0.53	6.45	3.52	3.45	6.32	3.02
MnO	0.13	0.10	0.02	0.04	0.06	0.03	0.05	0.01	0.10	0.05	0.05	0.12	0.05
MgO	3.59	0.76	0.58	0.21	1.02	0.95	1.05	0.73	13.71	1.82	1.78	0.95	0.18
CaO	4.43	7.90	1.75	6.45	2.25	2.54	2.17	5.32	11.33	0.28	0.29	5.27	3.00
Na_2O	5.89	4.12	5.01	5.34	4.45	5.90	6.10	8.98	1.86	8.84	8.92	2.92	3.51
K_2O	0.26	0.01	0.64	0.30	3.04	0.14	0.18	0.08	0.09	0.30	0.24	0.65	0.41
P_2O_5	0.00	--	0.06	0.09	0.14	0.04	0.05	0.03	0.02	0.04	0.04	0.07	0.04
LOI	1.08	4.34	1.98	0.70	1.65	3.64	2.83	0.92	2.03	1.73	1.65	1.26	1.05
Total	99.33	99.61	99.51	100.30	100.44	99.49	99.60	99.81	100.35	99.07	99.20	100.71	99.88
Trace Elements ppm													
Ba	*	*	241	56	879	11	38	5	9	*	*	49	33
Rb	10	5	19	5	71	7	--	3	3	*	*	8	5
Sr	145	132	244	553	213	77	105	77	113	84	95	131	130
Y	53	56	8	11	46	6	8	15	5	*	*	17	10
Zr	180	292	104	280	356	7	12	48	8	*	*	27	28
Nb	7	6	6	6	17	7	--	--	--	*	*	--	--
Ni	*	*	9	10	10	20	6	15	170	--	--	10	5
Cr	*	*	10	16	12	43	21	12	920	8	21	10	6
Hf	*	*	*	6.9	9.1	*	*	1.7	0.2	*	*	*	*
Ce	*	*	*	50	103	*	*	2.6	1.1	*	*	*	*
Sm	*	*	*	2.2	6.99	*	*	0.9	0.5	*	*	*	*

Data from: Guevgueli: Bébien (1991); Samothraki: Tsikouras et al., (1998); Koziakas: MM 49 and MM 51, Hatzipanagiotou et al., (1995); A 87 and A 60, this paper; Rhodes: Hatzipanagiotou (1986); Crete: Koepke (1986). (-- below detection limit; * not determined)

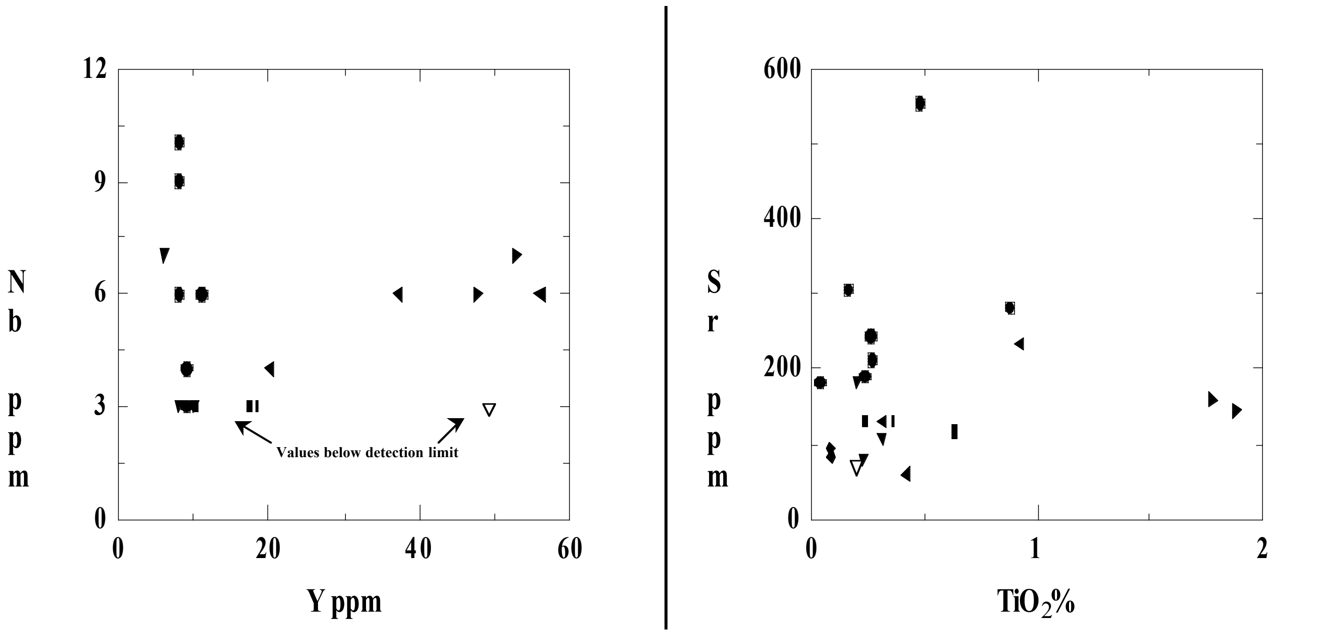


Fig. 3 - Chemical distinctions among the Hellenic plagiogranites (symbols as in Fig. 2; open triangle is plagiogranite sample A 87 from Koziakas, from our unpublished data).

determinations may not be very good, the plagiogranites from Koziakas and Crete have very low Nb (mostly below detection limit) compared to the other equivalents. The Samothraki plagiogranites show relatively higher Sr contents and few samples have high Cr and Ni contents (see also Table 1). In that terms they display an affinity similar to adakites (see e.g., Drummond and Defant, 1990; Drummond et al., 1996; Stern and Kilian, 1996; Martin, 1999). Nevertheless, their Fe_2O_3+MgO+MnO+TiO_2 contents and Mg# are lower while their HREE are higher than typical adakitic rocks (for REE of the Samothraki plagiogranites see Tsikouras et al., 1998).

Trace element profiles normalized to ORG (Ocean Ridge Granite) composition (Pearce et al., 1984) are illustrated in Fig. 4. Although some elements are missing and the spidergrams appear to be incomplete several arguments can be made. The Guevgueli trondhjemites and Qz-diorites display low K_2O contents (particularly the trondhjemites) and are similar to ORG, in respect of their Nb, Zr and Y normalized values (Fig. 4a). This hypothesis is not contradicted by their chondrite-normalized plagiogranite patterns, which are also similar to a parental Fe-diorite indicating a comagmatic origin (Fig. 5a). However, the positive Ti-anomaly in the Fe-diorite turns to weak negative Ti-anomalies in the plagiogranite patterns.

The patterns of the Samothraki (Fig. 4b), Koziakas (Fig. 4c) and Crete (Fig. 4d) plagiogranites are rather depleted in the incompatible HFS elements, relative to the variably enriched LIL elements, similar to Volcanic Arc Granites (VAG). The Samothraki plagiogranites display chondrite-normalized patterns broadly similar to those of their dioritic parents with weak negative Ti-anomalies (Fig. 5b). However, their absolute elemental abundances, and particularly the HFSE, are lower than those expected via a single fractionation from the diorites. This is probably a result of the involvement of a filter-pressing episode which accounts for a new crystal-liquid arrangement and crystallization under different conditions (see also Tsikouras et al., 1998).

The Koziakas plagiogranite patterns are mostly subparallel to the patterns of the gabbroic rocks and display a strong negative P-anomaly and a weak negative Ti-anomaly (Fig. 5c). This fact implies that the plagiogranite and the mafic plutonic rocks in the Koziakas ophiolite can be genetically correlated via a fractionation episode.

The plagiogranites from Crete are also closely related to the associated gabbrodioritic dykes, showing parallel patterns and strong P-anomalies, while Nb values are extremely low in both rock-types (Fig. 5d). A weak negative Ti-anomaly is also evident. Unfortunately trace elements results from the Rhodes plagiogranites are not available, thus their interpretation is not rigorous.

The Samothraki leucogranites show a significantly different chemical affinity relative to the plagiogranite, mainly due to the presence of K-feldspar and albite. They are richer in K_2O and much poorer in CaO while their normative orthoclase is much higher ranging from 6.47 to 25.60 wt %. They are also higher in some incompatible trace elements, e.g., Rb, Nb and Ba. On the Q'-ANOR' diagram, their normative mineralogy plots in the granite field, away from the plagiogranite samples (Fig. 2) and hence their interpretation in the framework of ocean-floor magmatism is problematic. The ORG-normalized patterns (Fig. 4e) of these samples are similar to VAG (Pearce et al., 1984). Compared to the Samothraki plagiogranite diagrams, they appear to be broadly similar, particularly considering the HFSE. The relative enrichment in K and Rb, as well as the weak to moderate Ba negative anomalies are attributed to the presence of K-feldspar.

PETROGENETIC CONSIDERATIONS

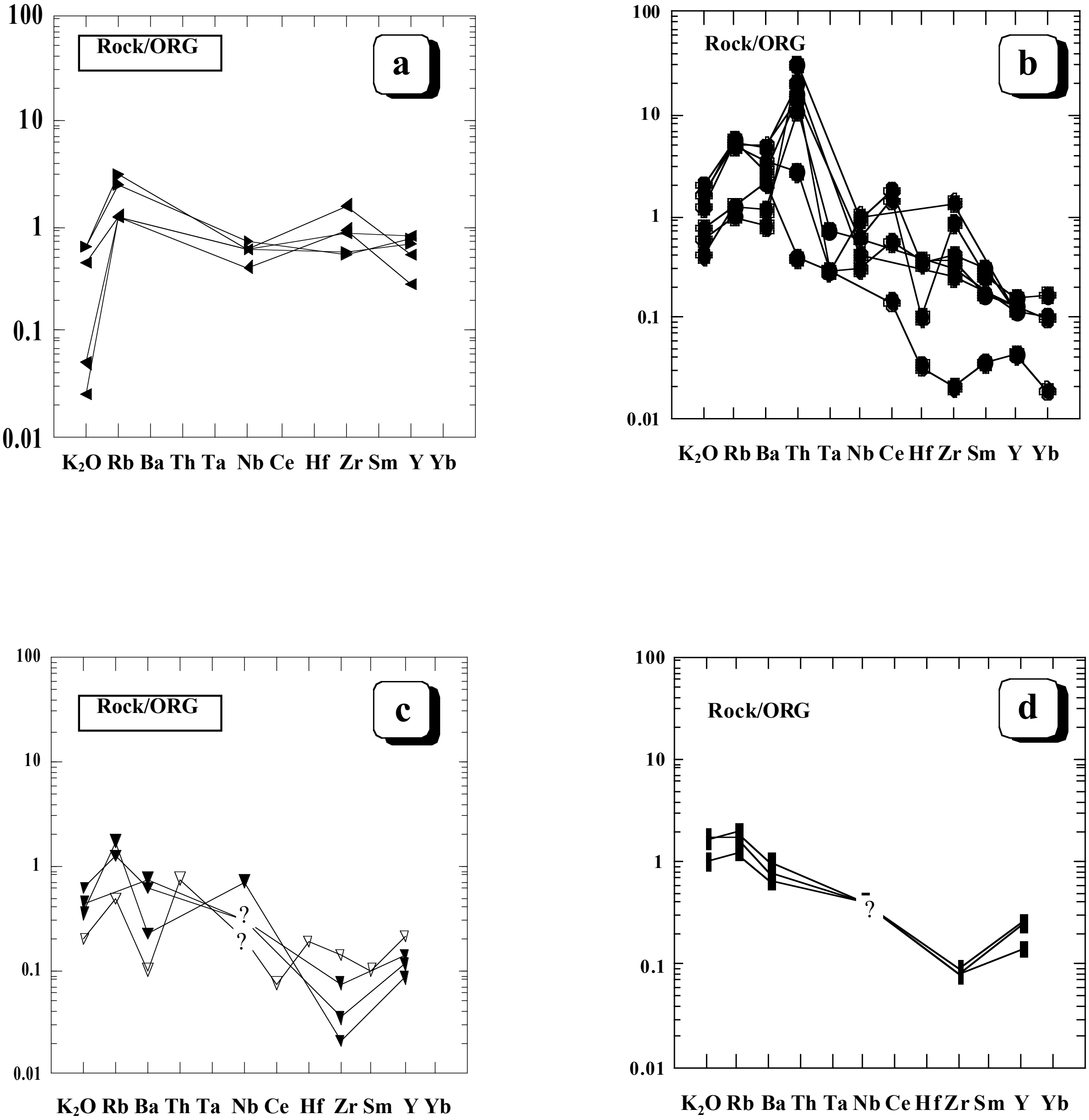
The Guevgueli Qz-diorites show approximately the same geochemical composition as some microdioritic sills (Mavro Dendro sills in Bébien, 1991) while the trondhjemites are richer in Si, Zr and poorer in Fe, Mg and Ti. On Harker variation diagrams, both the leucocratic rocks lie along the same fractionation trend with sills of doleritic and microdioritic compositions and a ferrodioritic enclave implying a cogenetic relationship (involving plagioclase fractionation) for these lithologies (Fig. 7 in Bébien, 1991). The origin of the Qz-diorites is assigned to extreme fractional crystallization effects of a ferrodioritic liquid, involving precipitation of Fe-oxides and rapid crystallization. A comparison between the Fe-diorite and the plagiogranites is illustrated in Fig. 5a. The change from a positive Ti-anomaly in the Fe-diorite to a negative Ti-anomaly in the plagiogranites is consistent with the appearance of titanomagnetite amongst the cumulus minerals in the former rock-type and the consequent titanomagnetite fractionation during the ferrodioritic crystallization towards the plagiogranites (Bébien, 1991). The trondhjemites are late products of incomplete consolidation of the ferrodiorites and the development of the interstitial liquid towards acid compositions. This episode was further promoted by a hydraulic fracturing process and flowage of the trondhjemitic melt into the cracks (Bébien, 1991).

The compositional spectrum of the Samothraki plagiogranites defines linear trends of incompatible trace elements on Harker variation diagrams and a pertinent geochemical correlation with their host hornblende-diorite (Fig. 4 in Tsikouras et al., 1998). However, a compositional gap between these two rocks is evident, which has been interpreted as a result of fractional crystallization involving a filter-pressing episode. The occurrence of the plagiogranite as small veins, pods and isolated bodies in a net-veined complex further supports this interpretation. Variation diagrams (particularly their Ca, Nb, Y, P_2O_5, Zr, TiO_2 and Fe_2O_3 inflections) and chondrite-normalized patterns suggest that the plagiogranite evolution was dominated mainly by plagioclase and minor hornblende, apatite, zircon, titanomagnetite and/or ilmenite fractionation from the diorite.

The Samothraki leucogranites have been derived by partial melting of the plagiogranites, as it is suggested by their broad geochemical similarity and the K, Rb and Ba enrichments in the leucogranites. Modelling of this episode, using immobile, incompatible trace elements, yielded low degrees of partial melting at around 3.5 % and 6.5 % (Tsikouras et al., 1998). A mantle component, indicated by the Y, Nb, Hf and Ta abundances, and a crustal contamination effect, suggested by the high Ba and Cs contents (which display cohesive linear trends on Harker diagrams, thus precluding mobility; see Fig. 4 in Tsikouras et al., 1998), have both been involved in the leucogranitic petrogenesis. This co-existence of mantle and crustal components coupled with the high Ba/Zr ratios in the leucogranites are strongly suggestive of their emplacement during a collision event (Harris et al., 1986).

The chemistry of the Koziakas plagiogranite compares well with other well-known plagiogranitic compositions and an origin from extreme differentiation of a basic magma has been envisaged from field (Hatzipanagiotou et al., 1995) and geochemical evidence (see above). These plagiogranites have been derived from crystallization of the gabbroic rocks. The negative P- and Ti- anomalies are consistent with a crystallization that involved fractionation of apatite and possibly titanite. The extremely low Nb contents in some samples from Koziakas indicate that amphibole probably was not a significant crystallizing phase.

Due to the absence of a broad range of lithologies in



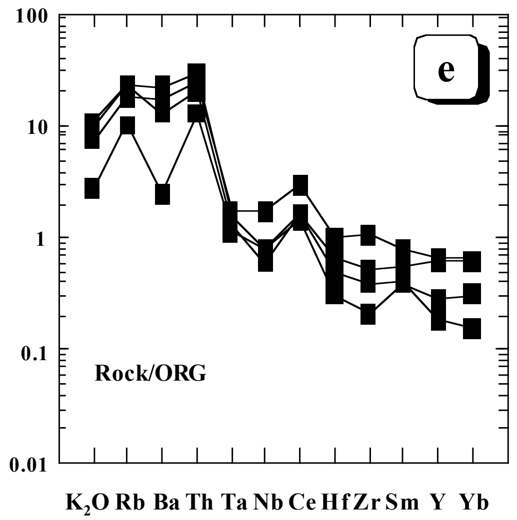


Fig. 4 - ORG-normalized spiderdiagrams for the Hellenic plagiogranites: **a.** Guevgueli Qz-diorites and trondhjemites (symbols as in Fig. 2); **b.** Samothraki plagiogranites; **c.** Koziakas plagiogranites (open triangle is sample A 87); **d.** Crete plagiogranites; **e.** Samothraki leucogranites; ?: for Nb values below detection limit.

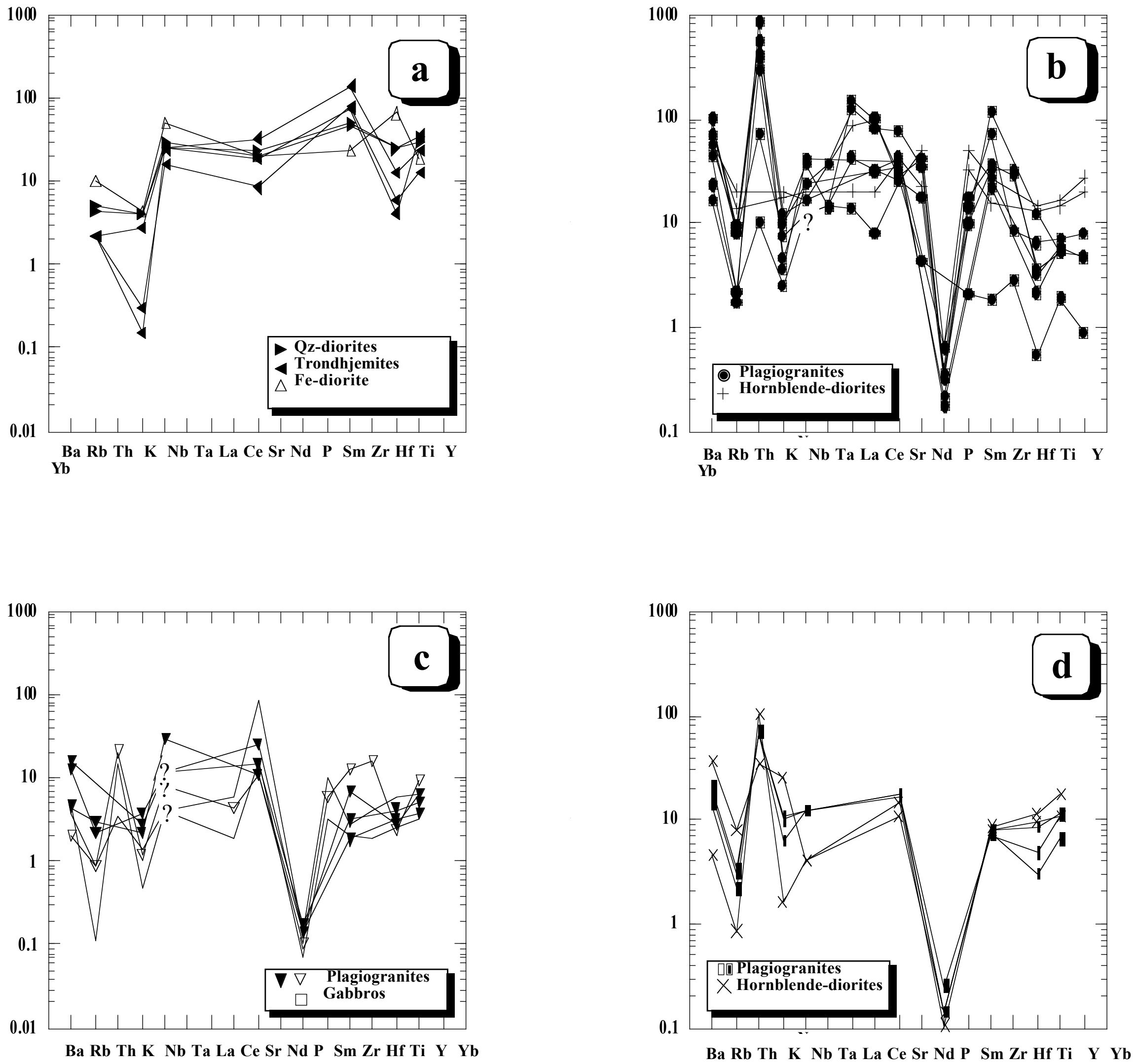


Fig. 5 - Chondrite-normalized spiderdiagrams for the Hellenic plagiogranites and their mafic parents (normalizing values after Sun and McDonough, 1989): **a.** Guevgueli; **b.** Samothraki; **c.** Koziakas, **d.** Crete; **?** for Nb values below detection limit. The two gabbros and one plagiogranite (open triangle) from Koziakas are from our unpublished data.

Rhodes Island, it is difficult to establish a clear relationship between the plagiogranites and a particular mafic rock from this suite. However, on a K_2O vs. SiO_2 diagram the plagiogranites plot at the end of a more or less linear trend defined by the Rhodes basalt and gabbro, thus suggesting derivation of these leucocratic rocks from the mafic ones via a magmatic differentiation process.

Geochemical results from the plagiogranites and dykes of Crete, when plotted on Harker variation diagrams show predictable inflections indicating a continuous magmatic differentiation from hornblende-gabbronorites via hornblende gabbrodiorites to the plagiogranites (Fig. 43 in Koepke, 1986). Ca and Al variations are compatible with the involvement of plagioclase in the crystallization history of the plagiogranites. The strong negative P anomalies (Fig. 5d) suggest that apatite was significantly involved during the plagiogranite fractionation while the negative T-anomalies indicate the possible coexistence of Ti-oxides.

GEOTECTONIC SETTING

Incompatible trace elements are useful indicators for the evaluation of the petrotectonic regime at which plagiogranites have been formed. Plagiogranites generated at mid-ocean ridges display ORG affinities while those from arcs and back arc basins display VAG contributions. The plagiogranites from Samothraki (including the leucogranites), Koziakas and Crete plot clearly in the VAG fields on petrotectonic diagrams, while samples from the Guevgueli ophiolite plot close to the boundary between ORG and VAG (Fig. 6); spidergrams support an ORG origin for the Guevgueli plagiogranites (Fig. 4c). The patterns, which are illustrated for the other plagiogranites, are consistent with a VAG origin (Fig. 4a, b, d).

The generation of these SSZ Hellenic plagiogranites fits well with regional interpretations of their geotectonic environments, which have been assigned to marginal basins (Samothraki: Tsikouras and Hatzipanagiotou, 1998a, b; Koziakas: our unpublished data; Crete: Koepke et al., 1985; Capedri et al., 1987). The Guevgueli ophiolite has a heterogeneous geochemistry with both MORB and IAT affinities and it has been suggested to has been originated at a marginal basin setting (Bébien et al., 1987; Zachariadou and Dimitriadis, 1995; Tsikouras and Hatzipanagiotou, 1998b). Thus, it is plausible to assume that the ORG-like Guevgueli

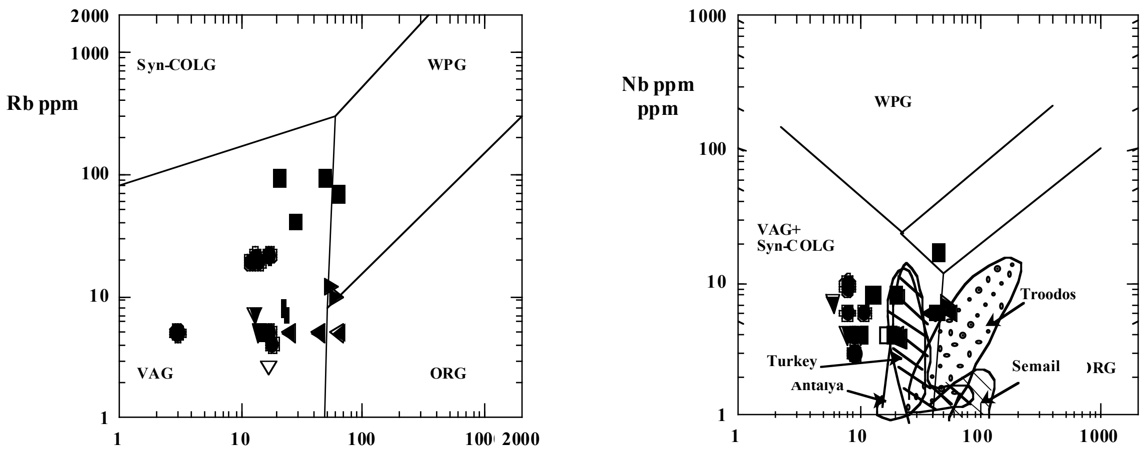


Fig. 6 - Plot of the Hellenic plagiogranites on petrotectonic discrimination diagrams (after Pearce et al., 1984; symbols as in Fig. 2). For comparison fields from other Neotethyan ophiolitic plagiogranites are shown (Troodos: Aldiss, 1978; Semail: Alabaster et al., 1982; Antalya: Cocherie, 1978; Turkey (Central Anatolian Complex): Floyd et al., 1998).

plagiogranite derivation is related to the MORB-like phase of the magmatic evolution, which probably occurred at a late stage that had a negligible, if at all, contribution from the subducted lithosphere.

An analogous diversity of plagiogranitic rocks has also been reported from the Albanian ophiolites, which together with the Yugoslavian ones represent the "Dinnaric extension" of the Hellenic ophiolites. The plagiogranite group of the Kimëz unit is intruded by low-Ti basaltic and andesitic dykes and displays a chemical affinity similar to ORG but with low Nb and Ta. The second plagiogranite group of the Shëmri pluton penetrates low-Ti basalts and andesites and exhibits geochemical signature similar to VAG. However, both these plagiogranites have been related to marginal basins and fore-arc areas, and their chemistries are thought to reflect geochemical heterogeneities of the evolved magmas (Bébien et al., 1997).

CONCLUSIONS

Plagiogranites in the Hellenic ophiolites have been studied in the areas of Guevgueli, Samothraki Island, Koziakas Mountains, Rhodes Island and Crete. They occur as dykes/veins in the Guevgueli, Samothraki, Koziakas and Crete ophiolites, as parts of the upper plutonic members in the Guevgueli ophiolite and as fragments in the ophiolite mélange from Rhodes, and display similar petrographic features. They comprise mainly trondhjemites while Qz-diorites are additionally reported from Guevgueli. Stable element ratios indicate also rhyodacitic to andesitic compositions. Their petrogenesis is related to magmatic differentiation processes and moreover in Guevgueli and Samothraki a concurrent filter-pressing episode has acted and induced the plagiogranitic melt to flow into cracks of the country rocks. These plagiogranites formed from fractionation of evolved basic lithologies, which, besides plagioclase, involved Fe-Ti oxides in the case of Guevgueli, hornblende, zircon, apatite and Fe-oxides in Samothraki, apatite and titanite in Koziakas and apatite and Ti-oxides in Crete. An unusual, for oceanic rocks, occurrence of leucogranite crops out in Samothraki. It is rich in K-feldspar and has a VAG chemistry; its origin is attributed to partial melting of the Samothraki plagiogranite during a collision episode.

The chemistries of the Hellenic plagiogranites are broadly similar having rather high LILE and low HFSE abundances, with the exception of the Guevgueli plagiogranite that has an approximately flat ORG-normalized patterns and an affinity similar to ORG. However, all these rocks are associated with marginal basin ophiolite suites and have been evolved in subduction related environments; their geochemical differences are related to heterogeneities in the suprasubduction zone lithosphere similar to those found in some Albanian ophiolites.

Acknowledgments

The authors are grateful to Prof. J. Bébien and Dr. P.A. Floyd for their constructive reviews, which greatly improved the manuscript, and to Dr. Eero Hanski for editorial handling and thoughtful comments.

REFERENCES

Alabaster T., Pearce J.A. and Malpas J., 1982. The volcanic stratigraphy and petrogenesis of the Oman ophiolite. Contrib. Mineral. Petrol., 81: 168-183.

Aldiss D.T., 1978. Granitic rocks of ophiolites. Ph.D. Thesis Open University, UK.

Barbieri M., Caggianelli A., Di Florio M.R. and Lorenzoni, S., 1994. Plagiogranites and gabbroic rocks from the Mingora ophiolitic mélange, Swat Valley, NW Frontier Province, Pakistan. Min. Mag., 58: 553-566.

Barker, F. 1979. Trondhjemite: Definition, environment, and hypothesis of origin. In: F. Barker (Ed.). Trondhjemites, dacites, and related rocks, Developments in Petrology, 6, Elsevier, p. 1-12.

Bébien J., 1982. L'association ignée de Guevgueli (Macédoine Grecque). Expression d'un magmatisme ophiolitique dans une déchirure continentale. Thèse d'Etat, Univ. Nancy, 467 pp.

Bébien J., 1991. Enclaves in plagiogranites of the Guevgueli ophiolitic complex, Macedonia, Greece. In: J. Didier and B. Barbarin (Eds.), Developments in petrology, 13, Elsevier, p. 205-219.

Bébien J., Baroz F., Capedri S. and Venturelli G., 1987. Magmatismes basiques associes à l'ouverture d'un bassin marginal dans les Hellénides internes au Jurassique. Ofioliti, 12 (1): 53-70.

Bébien J., Dautaj N., Shallo M. Turku I. and Bernard B., 1997. Diversité des plagiogranites ophiolitiques: l'exemple albanais. C.R. Acad. Sci. Paris, 324: 875-882.

Bébien J., Dubois R. and Gauthier A., 1986. Example of an ensialic ophiolites emplaced in a wrench zone. Innermost Hellenic ophiolite belt (Greek Macedonia). Geology, 14: 1016-1019.

Capedri S., Lekkas E., Papanikolaou D., Skarpelis N., Venturelli G. and Gallo F., 1985. The ophiolite of the Koziakas range, western Thessaly (Greece). Neues Jb. Miner., Abh., 152: 45-64.

Capedri S., Salvioli-Mariani E., Celestini S., Kokolakis S. and Zerbi, M., 1987. Petrology of pillow lavas of the Arvi unit, Central Crete. Neues Jb. Miner., Abh., 156: 231-246.

Cocherie A., 1978. Geochimie des terres rares dans les granitoids. PhD Thesis, Rennes University, France.

Coleman R.G., 1977. Ophiolites. Ancient oceanic lithosphere? Springer-Verlag, Berlin, Heidelberg, New York, 229 pp.

Coleman R.G. and Donato M.M., 1979. Oceanic plagiogranite revisited. In: F. Barker (Ed.), Trondhjemites, dacites and related rocks. Developments in Petrology, 6, Elsevier, Amsterdam, p. 149-168.

Coleman R.G. and Peterman Z.E., 1975. Oceanic plagiogranites. J. Geophys. Res., 80: 1099-1108.

Danelian T., Robertson A.H.F. and Dimitriadis S., 1996. Age and significance of radiolarian sediments within basic extrusives of the marginal basin Guevgueli Ophiolite (northern Greece). Geol. Mag. 133: 127-136.

Davis E.N., 1963. Der geologischer Bau der Insel Samothraki. Annal. Géol. Pays Hellen., 14: 133-212.

Dixon S. and Rutherford M.J., 1979. Plagiogranites as late-stage immiscible liquids in ophiolite and mid-ocean ridge suites: an experimental study. Earth Planet. Sci. Lett., 45: 45-60.

Drummond M.S. and Defant M.J., 1990. A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparisons. J. Geophys. Res., 95: 21503-21521.

Drummond M.S., Defant M.J. and Kepezhinskas P.K., 1996. The petrogenesis of slab derived trondhjemite-tonalite-dacite/adakite magmas. Trans. R. Soc. Edinburgh, Earth Sci., 87: 205-216.

Engel C.G. and Fischer R.L., 1975. Granitic to ultramafic complexes of the Indian Ocean ridge system, Western Indian Ocean. Bull. Geol. Soc. Am., 86: 1553-1578.

Floyd P.A. and Winchester J.A., 1978. Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements. Chem. Geol., 21:291-306.

Floyd P.A., Yaliniz M.K. and Gonguoglu M.C., 1998. Geochemistry and petrogenesis of intrusive and extrusive ophiolitic plagiogranites, Central Anatolian crystalline complex, Turkey. Lithos, 42: 225-241.

Gass I.G. and Smewing J.D., 1973. Intrusion, extrusion and metamorphism at constructive plate margins: Evidence from Troodos massif, Cyprus. Nature, 242: 26-29.

Gerlach D.C., Leeman W.P. and Ave Lallemant H., 1981. Petrology and geochemistry of plagiogranite in the Canyon Mountain Ophiolite, Oregon. Contrib. Mineral. Petrol., 77: 82-92.

Glennie K.W., Beuf M.G.A., Hughes Clarke M.W., Moody-Stuart M., Pilaar W.F. and Reinhardt B.M., 1974. Geology of the Oman mountains. Verh. k. Nederl. **g**eol. Mijnbouwkd. Gennot., 31: 1-423.

Harris N.B.W., Pearce J.A. and Tindle A.G., 1986. Geochemical characteristics of collision-zone magmatism. In: M.P. Coward and A.C. Ries (Eds.), Collision tectonics, Geol. Soc. London Spec. Publ., 19: 67-81.

Hatzipanagiotou K., 1983. Die oberste Einheit des süd-ägäischen Deckenstapels auf Rhodos und Karpathos (Dodekanes/Griechenland): Relikte eines Ophiolith-Komplexes. Unpubl. Diss., TU Braunschweig, 163 pp.

Hatzipanagiotou K., 1986. Plagiogranites in the ophiolitic mélange of Rhodes, Dodecanese, Greece. Neues Jb. Miner. Mh., H. 9: 400-406.

Hatzipanagiotou K., 1988. Einbindung der obersten Einheit von Rhodos und Karpathos (Griechenland) in den alpidischen Ophiolith-Gürtel. Neues Jb. Geol. Paläont. Abh., 176: 395-422.

Hatzipanagiotou K., 1991. K-Ar dating of ophiolites from Rhodes and Karpathos islands, Dodekanese, Greece. Geol. Balcanica, 21/5: 69-76

Hatzipanagiotou K., Lekkas E. and Migiros G., 1995. Plagiogranites in the ultrabasic rocks of the Koziakas Mountains (Central Greece). Z. Dt. Geol. Ges., 146: 479-486.

Heimann K.O., Lebkuchner H. and Kretzler W., 1972. Geological map of Greece, Samothraki sheet, 1:50000, IGME, Athens.

Ivanov T., Misar Z., Bowes D.R., Dudek A., Dumurdzanov N., Jaros J., Jelinek E. and Pacesova M., 1987. The Demir Kapija-Gevgelija ophiolite massif, Macedonia, Yugoslavia. Ofioliti, 12: 457-478.

Koepke J., 1986. Die ophiolithe der Südägäischen Inselbrücke: Petrologie und Geochronologie. Unpubl. Diss. TU Braunschweig, 204 pp.

Koepke J., Kreuzer H. and Seidel E., 1985. Ophiolites in the southern Aegean arc (Crete, Karpathos, Rhodes) - Linking the ophiolite belts of the Hellenides and the Taurides. Ofioliti, 10: 343-354.

Koepke J. and Seidel E., 1999. Ophiolites on the Southern Aegean islands Crete, Karpathos and Rhodes: Composition, geochronology and position within the ophiolite belts of the Eastern Mediterranean. EUG 10, Strasbourg. J. Conf. Abstracts, 4 (1): 407.

Kotopouli C.N., Hatzipanagiotou K. and Tsikouras B., 1989. Petrographic and geochemical characteristics of the ophiolitic rocks in Northern Samothrace, Greece. Geol. Balcanica, 19: 61-67.

Malpas J., 1979. Two contrasting trondhjemite associations from transported ophiolites in western Newfoundland. Initial report. In: F. Barker (Ed.), Trondhjemites, dacites and related rocks. Developments in Petrology, 6, Elsevier, p. 465-487.

Martin H., 1999. Adakitic magmas: modern analogues of Archaean granitoids. Lithos, 46: 411-429.

Ohnenstetter M. and Ohnenstetter D., 1980. Comparison between Corsican albites and oceanic plagiogranites. Arch. Sci. Genève, 33: 201-220.

Ohnenstetter M., Ohnenstetter D., Vidal Ph., Cornichet J., Hermitte D. and Mace J., 1981. Crystallization and age of zircon from Corsican ophiolitic albitites: consequences for oceanic expansion in Jurassic times. Earth Planet. Sci. Lett., 54: 397-408.

Pallister J.S. and Knight R.J., 1981. Rare-earth element geochemistry of the Samail ophiolite near Ibra, Oman. J. Geophys. Res., 86: 2673-2697.

Parrot J.F., 1977. Assemblage ophiolitique du Baër-Bassit et termes effusifs du volcanosédimentaire. Trav. Docum. O.R.S.T.O.M., 72, 333 pp.

Payne J.G and Strong D.F., 1979. Origin of the Twillingate trondhjemite, north-central Newfoundland: Partial melting in the roots of an island arc. In: F. Barker (Ed.), Trondhjemites, dacites and related rocks. Developments in Petrology, 6, Elsevier, p. 489-516.

Pearce J.A., Harris N.B.W. and Tindle A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. J. Petrol., 25: 956-983.

Pedersen R.B. and Malpas J., 1984. The origin of oceanic plagiogranites from the Karmoy ophiolite, western Norway. Contrib. Mineral. Petrol., 88: 36-52.

Richter D., Müller C. and Mihm A., 1992. Die faziellen Beziehungen zwischen Parnass-und Pindos-Zone sowie die Vulkanite im Gebiet nördlich von Eratini (Kontinentalgriechenland). Z. Dt. Geol. Ges., 142: 67-86.

Seidel E., Schliested M., Kreuzer H. and Harre W., 1977. Metamorphic rocks of Late Jurassic age as components of the ophiolitic mélange on Gavdos and Crete (Greece). Geol. Jb., B 28: 3-21.

Sivell W.J. and Waterhouse J.B., 1984. The Patuki intrusive suite-closed-system fractionation, beneath a slow spreading ridge. Lithos, 17: 1-17.

Stern C.R. and Kilian R., 1996. Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Austrian Volcanic Zone. Contrib. Mineral. Petrol., 123: 263-281.

Streckeisen A.L. and Le Maitre R.M., 1979. A chemical approxi-

mation to the modal QAPF classification of the igneous rocks. Neues Jb. Mineral., Abh., 136: 169-206.
Sun S.S. and McDonough W.F., 1989. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. In: A.D. Saunders and M.J. Norry (Eds.), Magmatism in the ocean basins, Geol. Soc. London Spec. Publ., 42: 313-345.
Thayer T.P., 1963. Flow layering in alpine peridotite-gabbro complexes. Mineral. Soc. Am. Spec. Pap., 1: 55-61.
Thayer T.P., 1977. Some implications of sheeted dike swarms in ophiolitic complexes. Geotectonics, 11: 419-426.
Tsikouras B. and Hatzipanagiotou K., 1995. The geological evolution of Samothraki island (N. Aegean, Greece): An incomplete ophiolitic sequence in the Circum-Rhodope Zone. Geol. Soc. Greece, sp. publ., 4/1, Proc. XV Congr. Carpatho-Balcan Geol. Ass., September 1995, Athens, p. 116-126.
Tsikouras B. and Hatzipanagiotou K., 1998a. Petrogenetic evolution of an ophiolite fragment in an ensialic marginal basin, northern Aegean (Samothraki Island, Greece). Eur. J. Mineral., 10: 551-567.
Tsikouras B. and Hatzipanagiotou K., 1998b. Two alternative solutions for the development of a marginal basin in NE Greece. Ofioliti, 23: 83-92.
Tsikouras B., Hatzipanagiotou K. and Seymour K.St., 1998. Plagiogranite and leucogranite relationships in an ophiolite of the Tethys Ocean (Samothraki, N. Aegean, Greece). Neues Jb. Miner. Mh., 1: 13-35.
Tsikouras B., Pe-Piper G. and Hatzipanagiotou K., 1990. A new date for an ophiolite of the northeastern margin of the Vardar zone, Samothraki, Greece. Neues Jb. Miner. Mh., 11: 512-527.
Wilson R.A.M., 1959. The geology of Xeros-Troodos area.-Cyprus Geol. Surv. Dept. Mem, 1, 135 pp.
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.
Zachariadou S. and Dimitriadis S., 1995. Aspects of the tectonomagmatic evolution of the Late Jurassic Guevgueli complex, Macedonia, Greece. Geol. Soc. Greece, Spec. Publ. 4, Proc. XV Congr. Carpatho-Balcan Geol. Ass., September 1995, Athens, p. 143-146.

Received, December 31, 1998
Accepted, October 21, 1999