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Geochemical characteristics of the Cretaceous ophiolitic rocks of Ikaria island, Greece

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Abstract – Scattered occurrences of ophiolitic rocks are widespread in the Cyclades islands of Greece and are important for understanding the later Mesozoic ocean spreading and collisional history of the region, which has been obscured by Cenozoic nappe stacking, metamorphism, plutonism and extension. Ophiolitic rocks in the Upper Tectonic Unit of Ikaria are preserved in a mélange underlying Triassic limestones in the Kefala Unit and in a coarse-grained conglomerate at Faros directly overlying the mid-crustal detachment fault. The geochemistry of these rocks has been determined, their mineralogy investigated by electron microprobe, and K–Ar radiometric dating was carried out. Sole rocks are amphibolite of alkaline basalt protolith. Most ophiolitic samples from Ikaria consist of hornblende gabbro with MORB geochemistry that underwent sea-floor hydration, deformation and metamorphism. The large variation in degree of deformation, grade of metamorphism, and radiometric ages suggest syn-spreading extensional deformation at a slow-spreading ridge. The ophiolitic mélange on Ikaria, because it is unaffected by younger metamorphism, provides clear evidence for Late Cretaceous ocean-crust formation in the Cyclades region.

Keywords: ophiolite, mélange, conglomerate, Cyclades, Cretaceous.

1. Introduction

The island of Ikaria in the east-central Aegean sea (Fig. 1) is composed of two main tectonic units (Photiades, 2002, 2004). The Lower Tectonic Unit, of gneissic basement and overlying platform metasediments, is similar to the Basal Cycladic Unit elsewhere in the Cyclades and is homologous with the Pelagonian zone of mainland Greece (Martin *et al.* 2004). The Upper Tectonic Unit consists of ophiolitic mélange with tectonically intercalated Upper Triassic limestone. This Upper Tectonic Unit is correlative with the non-metamorphic Upper Cycladic Unit elsewhere in the Cyclades (Dürr, 1986) and is separated from the Lower Tectonic Unit by a regional extensional detachment fault, across which many kilometres of tectonic erosion have occurred.

Ophiolitic rocks are widespread in the Cyclades (Fig. 1, inset), occurring in the intermediate structural units that have undergone blueschist metamorphism (e.g. Blueschist Unit of Tinos, Bröcker & Enders, 1999) and in the Upper Cycladic Unit. In general, it is not well understood whether these ophiolites correlate with the Middle Jurassic ophiolites of the Pindos ocean in western Greece (Rassios & Smith, 2000) or with the Upper Cretaceous ophiolites of western Turkey (Robertson *et al.* 1996).

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The Upper Tectonic Unit of Ikaria crops out in two main areas (Fig. 1). In the centre of the island, the Kefala Unit consists of a large klippe of marbles (with upper Triassic fossils) overlying a tectonic ophiolitic mélange dated radiometrically as Late Cretaceous (Altherr *et al.* 1994). In the eastern part of the island, the Upper Tectonic Unit consists of a mid-Cenozoic conglomerate unit described as an 'ophiolitic molasse' by Photiades (2002, 2004) and termed the Faros Molasse Unit in this paper. The geology of these two units is described in greater detail below.

The scope of this paper is: (1) to describe the detailed petrography and mineralogy of representative igneous clasts from the Faros Molasse Unit and igneous lithologies from the Kefala Unit; (2) to establish the age of the igneous lithologies from the Faros Unit; (3) to compare the petrology and geochemistry of the igneous rocks of these two units among themselves and with other similar occurrences elsewhere in the Cycladic islands and the Hellenides in general.

2. Geological setting

2.a. The geology of the ophiolitic rocks of Ikaria

The Lower Tectonic Unit of Ikaria consists of two main successions. The basal Ikaria unit (Papanikolaou, 1978*a*; Dürr, 1986) comprises a series of metapelitic gneisses, quartzites, amphibolites and marbles, with minor leucocratic orthogneiss. By analogy with other

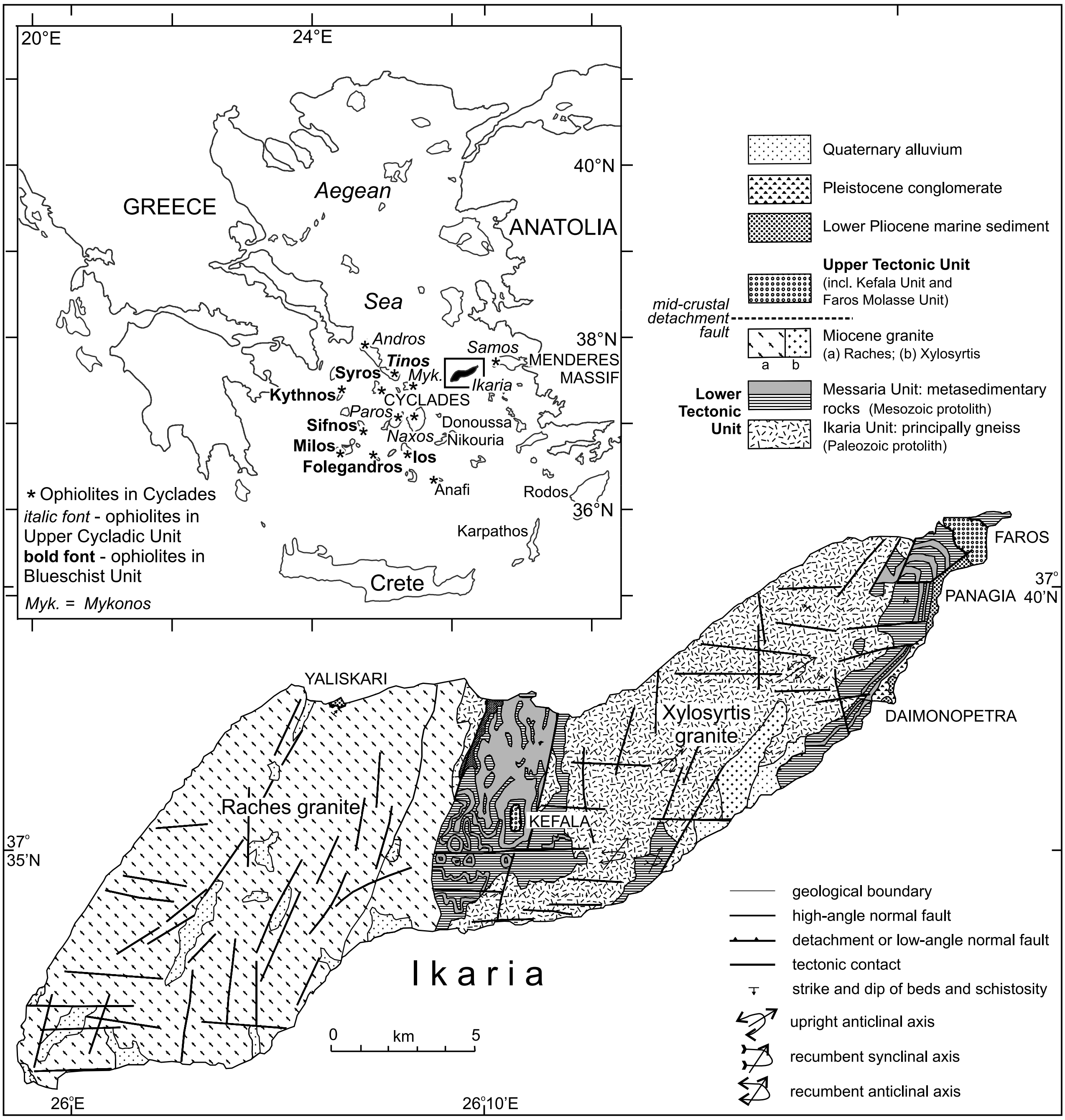

Figure 1. Geological map of Ikaria (modified after Photiades, 2004). Inset shows islands of the Cyclades on which ophiolites are found.

parts of the Cyclades, such as Naxos, Photiades (2002) interpreted this unit as Palaeozoic basement. It is overlain by the Messaria unit consisting of greenschist-facies marbles, phyllites and calc-mica schists, interpreted as a platform succession of Mesozoic sedimentary rocks correlative with those in Naxos and Paros. Zircons from rocks in the Ikaria unit show rounded inherited cores with thin metamorphic overgrowths that yield ages of 45–50 Ma, correlative with the Eocene high-*P* low-*T* metamorphism elsewhere in the Cyclades, and 25–30 Ma, correlative with the Late Oligocene–Early Miocene Barrovian metamorphic event. This suggests that the Palaeozoic basement (Ikaria unit) and the overlying Messaria unit are both dominated by the same Cenozoic metamorphism (Martin *et al.* 2004). The Lower Tectonic Unit was intruded by an I-type biotite granite, known as the Raches granite (Fig. 1) in the western part of the island and the smaller S-type Xylosyrtis biotite–muscovite granite in the eastern part of the island. Both granites are strongly ductilely deformed with top-to-NE motion (Boronkay & Doutsos, 1994).

The Upper Tectonic Unit in the central part of the island (Kefala Unit of Papanikolaou, 1978*a*) consists of a large klippe of marbles (with upper Triassic fossils) overlying a tectonic ophiolitic mélange with diorite, rare amphibolite, schistose volcanic rocks and red mudstone (Altherr *et al.* 1994). Four K–Ar dates on separated hornblendes have been reported for diorites and amphibolite (Altherr *et al.* 1994). The age for unaltered diorite was 70.4 ± 1.1 Ma, for two hydrothermally altered diorites 67.4 ± 1.0 and 80.5 ± 1.4 Ma and for the amphibolite 84.4 ± 2.4 Ma. These authors described the diorites as dykes, whereas Photiades (2002) found only tectonic contacts. Altherr *et al.* (1994) considered the age of the unmetamophosed diorite of 70.4 Ma as a cooling age of what they interpreted as 'intrusive' diorite dykes that cut the amphibolites. The ages of the two hydrothermally altered diorites were interpreted as having been influenced by argon loss or gain during hydrothermal overprint.

At Faros, a coarse-grained terrestrial conglomerate (Faros Molasse Unit) directly overlies the detachment fault over the mid-crustal Lower Tectonic Unit. The basal part of this conglomerate consists principally of ophiolitic clasts, whereas Triassic limestones become increasingly important higher in the succession. Rare Eocene nummulitic limestone clasts are found. Similar small occurrences of conglomerate are found at Yaliskari, Daimonopetra and Panagia (Fig. 1; see Photiades, 2002, for details). Even where the unit overlies the Raches granite at Yaliskari, granite clasts are lacking, suggesting an age pre-dating the uplift and exposure of the granite in the Late Miocene (7–9 Ma) (Altherr *et al.* 1982). The basal part of the conglomerate unit shows some top-to-NE brittle deformation, with hydrothermal mineralization of quartz, carbonate and iron minerals. Conglomerates occupying a similar tectonic position are known from Naxos (Kuehlemann *et al.* 2004), Paros and Mykonos (Sánchez-Gómez, Avigad & Heimann, 2002). At the top of the Faros Molasse Unit, olistoliths of Triassic limestone are present. The Faros Molasse Unit is unconformably overlain by transgressive Early Pliocene littoral sediments. The coarse grain size and local character of the Faros Molasse Unit, in contrast to more polymictic and distal deposits in the central Cyclades, suggest shedding of sediment from local wrench-fault scarps developed during Miocene extension.

2.b. Ophiolitic rocks elsewhere in the Cyclades

Ophiolitic rocks are widespread in the Cyclades, occurring both in the intermediate structural units that have undergone blueschist metamorphism (hereafter Blueschist Unit) and in the Upper Cycladic Unit. In the Blueschist Unit, ophiolites are best known on Tinos (Fig. 1, inset), where metabasites have boninitic, IAT and MORB geochemical affinities and are associated with Cr- and Ni-rich metasedimentary rocks (Bröcker & Okrusch, 1987; Bröcker, 1990, 1991). The ophiolites have yielded a high-pressure metamorphic age of 61–63 Ma by U–Pb on zircon (Bröcker & Enders, 1999). Nearby, on Kythnos, are metamorphosed gabbro and epidote–zoisite schists (Smeth, 1975). On Syros, the ophiolites comprise serpentinite bodies (in part now ecologitic), metagabbros, and metabasaltic schists, overlain by manganese rich schists with intercalations of metamorphosed basalt and felsic volcanic rocks (Dürr, 1986) and have yielded an age of 78 ± 1 Ma by U–Pb on zircon for the high pressure metamorphic event (Bröcker & Enders, 1999). The ophiolitic mélange of Syros has been identified as having a back-arc basin origin (Seck *et al.* 1996). B. Mocek (unpub. Ph.D. thesis, Univ. Hanover, 1994) interpreted the blueschist unit of Sifnos as having a boninitic protolith. Ultramafic lenses (now eclogite and glaucophane schists) occur in a similar setting in Ios (Maar, 1980) and serpentinite bodies occur in schists in Folegandros (A. Sowa, unpub. dissertation, Univ. Erlangen, 1985). Xenoliths of high-pressure metamorphic rocks in volcanic rocks of Milos may have protoliths of ophiolitic ferrogabbro and MORB tholeiite (Kornprobst, Kienast & Vilminot, 1979). Small mafic and ultramafic lenses within the Marble-Schist sequence on Naxos (Jansen, 1977; Pe-Piper & Kotopouli, 1996) include MORB metabasalts. Blueschist facies ophiolitic remnants are intercalated with Cretaceous marbles in the upper part of the Menderes massif in southwestern Turkey (Candan *et al.* 1997).

In the Upper Cycladic Unit, ophiolites are well developed in Tinos and include metabasalt, metagabbro, serpentinite and an amphibolitic sole (Katzir *et al.* 1996; Stolz, Engi & Rickli, 1997). The amphibolites are of MORB character and yielded K–Ar hornblende ages from 77 to 67 Ma. Mafic phyllites are also of MORB character, but have particularly low Nb; gabbros are principally of MORB affinity, with minor boninitic gabbro. On the island of Andros, the Pelagonian Makrotantalon Unit tectonically overlies lenses of serpentinized peridotite (Papanikolaou, 1978*b*). On the island of Mykonos, the upper tectonic unit includes greenschists of uncertain age and affinity (Dürr & Altherr, 1979). On Paros, the ophiolites consist of sheared serpentinitic slivers and have a weathered upper surface overlain by Barremian limestones (Papageorgakis, 1969). In Samos, the uppermost Kallithea nappe includes alkaline basalt and MORB intercalated with Triassic sedimentary rocks (Pe-Piper & Kotopouli, 1991) tectonically overlying a mélange including large bodies of peridotite (Pomonis & Hatzipanagiotou, 1998).

South of the Cyclades, at a high structural level in Crete, Karpathos and Rodos, there is both stratigraphic and radiometric evidence for ophiolites of Middle Jurassic age and of Late Cretaceous age (Seidel *et al.* 1981; Bonneau, 1984; Koepke, Seidel & Kreuzer, 2002). On the island of Anafi (Reinecke *et al.* 1982), an ophiolitic mélange is intruded by Upper Cretaceous granitoid rocks, and similar Upper Cretaceous granitoid rocks are found on Crete and the small islands of Donoussa and Nikouria (Altherr *et al.* 1994).

3. Methods

Five samples were collected and studied from the igneous rocks of the Kefala Unit and 21 clasts from the Faros Molasse Unit (of which three were not chemically analysed). Rock powders for whole-rock geochemistry were prepared by removing all altered surfaces, chipping, and then washing the chips in de-ionized water after putting them through an ultrasonic bath within a beaker for about one minute to remove any loose contaminants. Samples were crushed using a shatterbox with an iron bowl at the Mineral Engineering centre of Dalhousie University, Canada. Major and trace elements were determined by Activation Laboratories (Ontario, Canada) according to their Code 4Lithoresearch and Code 4B1 packages, which combine lithium metaborate/tetraborate fusion ICP major-element analysis with ICP-MS analysis of trace elements.

Mineral chemistry in selected samples was determined using a JEOL-733 electron microprobe equipped with four wavelength spectrometers and a Tracor Northern 145-eV energy dispersive detector. Operating conditions were at 15 kV with a 20 nA beam current and a beam diameter of 1 micron. The calibration was with geological standards and specific reference minerals, and the data were reduced using a Tracor Northern ZAF matrix-correction program.

4. Petrography and mineralogy

4.a. Petrography

The main petrographic characteristics of all studied samples are summarized in Table 1 and the highlights of these descriptions are as follows.

Table 1. Petrographic characteristics of the ophiolitic rocks of Ikaria

Unit	Rock type	Samples	Grain size and crystal form	Mineralogy	Alteration
Faros	Non-foliated gabbro	133, 134, 143, 144, 233, 235, 236	Fine- to medium-grained; interlocking, dominantly anhedral crystals with rare subhedral grains	Hbl + pl with <2% qtz; accessory phases: ttn, zrn, ap (commonly as incl), ilm, rt (134)	Pl is variably altered to sericite; some ilm is probably altered (iron staining surrounding some grains)
Faros	Slightly foliated gabbro	135, 136, 137, 138, 139, 142, 234, 237	Fine- to medium-grained; interlocking anhedral crystals; hbl grains in 135 are anhedral to subhedral	Hbl + pl (+ act + ep in 237) with <2% qtz; accessory phases: ttn, zrn, ap (commonly as incl), ilm, rt (in samples 135, 138, 139, 235)	Pl is variably altered; hbl is unaltered except in 237 where post-solidus alteration to act is common and in 237 and 137 where there are trace amounts of chl from alteration of hbl
Faros	Foliated gabbro	149A, 149B	Fine-grained; anhedral to subhedral crystals	Hbl + pl + ep with <2% qtz; accessory phases: ttn, zrn, ap, hem, ilm, ?mgt	Pl is variably altered; trace amount of chl from alteration of amph
Faros	Amphibolite	145, 147, 232	Very fine-grained; subhedral to euhedral crystals	Hbl + pl + qtz + ep with cal-rich lenses; accessory phases: ttn, zrn, ilm, hem, chl, py (145)	Pl is slightly altered in some samples
Faros	Pyroxenite	146	Medium-grained; anhedral amph + pl fill interstices between subhedral cpx crystals	Cpx + amph with <5% plag; accessory phases: ttn, rt (as incl)	Pl is heavily altered
Kefala	Metagabbro	I163, I164, I165, I166	Very fine-grained with fine- to medium-grained porphyroclasts	Chl + ser + cal with p'clasts of hbl + cpx + pl and cal-rich lenses; 166 has abundant pl p'clasts, and is more chl-rich and cal-poor than other samples; accessory phases: ttn, ilm, mgt	Heavily altered, porphyroclasts are highly corroded
Kefala	Amphibolite	I175	Very fine-grained; anhedral to subhedral crystals	Amph + bt + qtz + pl + ep with chl developed along fractures; qtz-rich layers up to ∼2 mm thick; accessory phases: ilm, hem, ttn	No apparent alteration

Mineral abbreviations after Kretz (1983). Other abbreviations: incl – inclusions, p'clasts – porphyroclasts, ser – sericite.

Faros Molasse Unit clasts. All these clasts are fine- to medium-grained rocks and three lithological types have been identified:

(a) Gabbro: These rocks are variably foliated (Table 1) and consist principally of hornblende (> 60 %), feldspar and a small amount (< 2 %) of quartz. The accessory minerals may include titanite, zircon, apatite, ilmenite, and rutile. The samples are fresh, with only rare traces of actinolite and/or epidote. Some samples contain trace amounts of pyrite and chalcopyrite. Although the clasts have the mineralogy of diorite, their chemistry is gabbro (see Section 6) and thus they are termed hornblende gabbro.
(b) Amphibolite: These rocks are foliated and consist of blue-green hornblende, plagioclase and quartz. Accessory minerals include titanite, zircon, ilmenite, hematite and pyrite, and secondary minerals include chlorite, epidote and calcite.
(c) Pyroxenite: One clast of this lithology consists of about 80 % clinopyroxene, 15–20 % of hornblende megacrysts (brown in the core, pale brown or greenish in the margin) and some (< 5 %) highly altered plagioclase.

Kefala Unit igneous rocks. Two lithological types are identified.

(a) Metagabbro consists of hornblende, clinopyroxene and plagioclase, and these minerals are partially to highly altered to chlorite, sericite and calcite. Accessory minerals include titanite, ilmenite and magnetite. Petrographically, the metagabbros differ from the gabbros at Faros in their degree of greenschist metamorphism or alteration.
(b) Amphibolite consists of hornblende, biotite, quartz, plagioclase, epidote and chlorite. The accessory minerals include ilmenite, hematite and titanite.

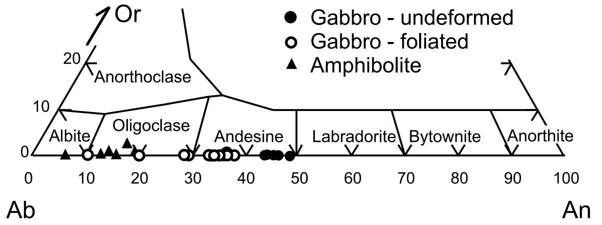

Figure 2. Feldspar compositions of the ophiolitic rocks of the Faros Molasse Unit, Ikaria.

4.b. Mineral chemistry

The plagioclase in the undeformed gabbro is andesine. In the foliated gabbro, andesine also predominates, but with minor oligoclase. The plagioclase in the amphibolite from the Faros unit is of oligoclase to albite (Fig. 2).

The amphiboles present in the gabbros include magnesio-hornblende, pargasitic hornblende, edenitic hornblende and edenite in the nomenclature of Leake *et al.* (1997) (Table 2, Fig. 3), all these being amphibole compositions commonly found in igneous rocks. The

Table 2. Geochemical analyses of amphibole and clinopyroxene

Sample	Position	SiO_2	TiO_2	Al_2O_3	FeO_t	MnO	MgO	CaO	Na_2O	K_2O	Total
Amphiboles											
234 (slightly foliated gabbro)	Core	45.35	1.25	8.93	16.61	0.30	11.39	11.65	1.43	0.31	97.22
	Rim	44.73	0.85	10.11	17.25	0.28	10.86	11.93	1.64	0.44	98.09
	Core	45.20	1.12	8.52	16.51	0.45	11.35	11.62	1.46	0.37	96.88
	Rim	45.27	1.09	9.11	16.71	0.29	11.30	11.97	1.46	0.41	97.61
237 (slightly foliated gabbro)	Core	44.16	1.11	12.52	10.87	b.d.	14.53	11.42	2.51	0.22	97.34
	Rim	44.63	1.06	12.43	11.10	b.d.	14.56	11.64	2.42	0.21	98.05
	Core	44.55	1.28	12.48	11.06	b.d.	14.50	11.54	2.47	0.25	98.13
	Rim	44.54	1.13	12.43	11.07	b.d.	14.59	11.63	2.42	0.22	98.03
145 (amphibolite)	Core	41.08	1.03	11.92	17.61	b.d.	10.28	11.81	2.52	1.15	97.40
	Rim	41.58	1.22	11.32	16.82	b.d.	10.57	11.78	2.40	0.90	96.84
	Core	42.70	0.63	10.41	16.94	b.d.	11.06	11.63	2.40	0.63	96.64
	Rim	43.05	0.70	10.65	17.62	b.d.	10.84	11.90	2.28	0.62	97.66
134 (gabbro)	Core	46.84	1.04	9.33	13.32	0.29	13.48	12.14	1.48	0.20	98.12
	Rim	45.39	0.77	11.44	13.80	b.d.	12.55	11.82	1.42	0.27	97.46
146 (pyroxenite)	Rim	51.84	0.87	5.39	7.90	b.d.	18.01	12.63	0.82	0.39	97.85
	Core	48.88	1.45	7.60	9.15	b.d.	16.42	12.39	1.03	0.68	97.86
	Core	51.57	0.92	6.20	8.17	b.d.	17.69	12.68	0.91	0.50	99.01
	Rim	51.06	0.96	6.24	8.12	b.d.	17.38	12.84	0.98	0.49	98.07
Clinopyroxene											
146 (pyroxenite)	Core	53.94	b.d.	0.81	4.81	b.d.	15.86	25.03	0.36	b.d.	100.81
	Rim	51.44	1.09	5.60	7.80	b.d.	18.19	13.32	0.93	0.39	98.76
	Rim	54.29	b.d.	0.84	5.12	b.d.	16.32	24.35	0.44	b.d.	101.36
	Core	54.27	b.d.	0.74	4.90	0.29	16.14	24.41	0.34	b.d.	101.09
	G'mass	54.53	b.d.	0.70	5.05	b.d.	16.17	24.57	b.d.	b.d.	101.02

b.d. – below detection limit; G'mass – groundmass.

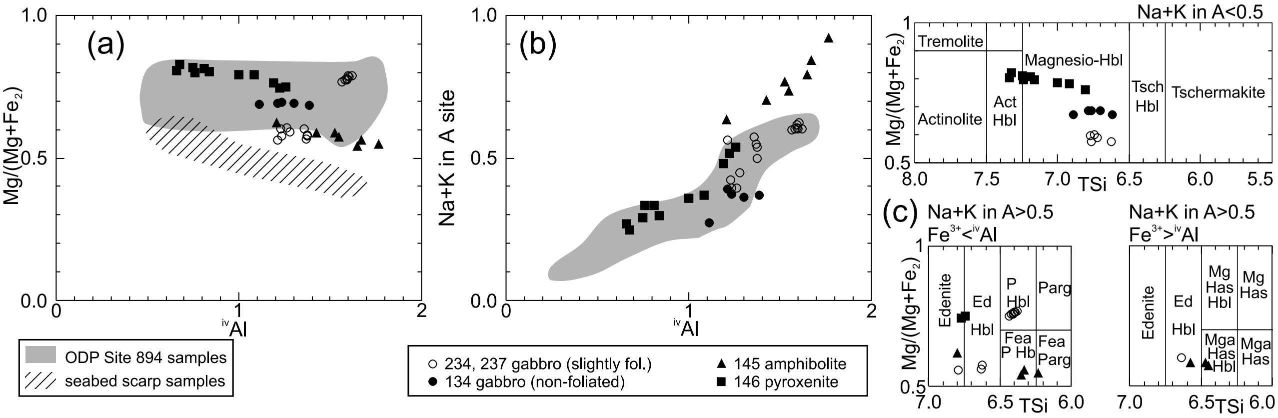

Figure 3. Amphibole compositions (expressed as atomic formula units on the basis of 23 oxygens) of the ophiolitic rocks of Ikaria, compared with amphiboles in oceanic crust at Hess Deep, from ODP Site 894 and samples from a seafloor scarp (from Manning, MacLeod & Weston, 2000). Nomenclature in panels (c) from Leake *et al.* (1997), abbreviations as follows: Act – actinolitic; Ed – edenitic; Fea – ferroan; Has – hastingsite, hastingsitic; Hb, Hbl – hornblende; Mg – magnesio; Mga – magnesian; P – pargasitic; Parg – pargasite; Tsch – tschemakitic.

Table 3. K–Ar dating of a hornblende separate

Sample	%K	$^{40}Ar_{rad}$ nl/g	% $^{40}Ar_{air}$	Age (Ma)
134	0.165	0.476	37.3	74.2 ± 2.3

The separate contained a small amount of a mix of feldspar and quartz (confirmed by SEM). The K concentration was determined by ICP. The Argon analysis was performed using the isotope dilution procedure on noble gas mass spectrometry in duplicate.

amphiboles present in the amphibolites include ferroan pargasitic hornblende, Mg-hastingsitic hornblende and edenitic hornblende, and those present in the pyroxenite are magnesio-hornblende and tremolite. The clinopyroxene of the pyroxenite sample is diopside (Table 2).

5. Age

Radiometric dating by K–Ar on hornblende was carried out on a hornblende gabbro clast from the Faros Molasse Unit that lacked evidence of low-temperature alteration. An age of 74.2 ± 2.3 Ma was obtained (Table 3), which compares well with the ages of Altherr *et al.* (1994) for the *in situ* rocks of the Kefala unit.

6. Geochemistry

Whole-rock geochemical data for 18 clasts from the Faros Molasse Unit and five rock samples from the Kefala Unit are presented in Table 4. Standard geochemical diagrams have then been used (a) to evaluate the similarities/differences among samples from the same unit and between samples from both units and (b) to define type(s) of the magmatism that produced these rocks.

Most of the Faros Molasse Unit gabbro clasts define a tight cluster or a normal differentiation trend in variation diagrams of elements plotted against MgO, used as an index of differentiation (Figs 4, 5). The Kefala Unit metagabbros plot within the same cluster or trend, generally with lower abundances of HFSE and higher abundances of lithophile elements. Amphibolite and pyroxenite plot outside these trends or clusters.

In terms of elements such as Ti, Cr, Ni, Y, Zr and Nb, all the gabbros and metagabbros geochemically resemble MORB (Figs 4, 5, 6, 7). They have flat unfractionated REE patterns characteristic of oceanic tholeiite (Fig. 8). Although multi-element variation diagrams normalized to primitive mantle show a negative peak at Nb, abundances of Nb are similar to or greater than the standard n-MORB value of 2.3 ppm reported by Sun & McDonough (1989) (Fig. 7c). More evolved rocks have a higher TiO_2 content, to a maximum of 2.2 % (Fig. 4). Unevolved gabbro at MgO = 8 % has FeO_t = 8–9 %, within the range of normal MORB and showing no evidence for elevated potential temperature in the mantle (cf. Lassiter & de Paolo, 1997). In contrast, the amphibolite clasts from the Faros Molasse Unit have high TiO_2 (Fig. 4), exceptionally high Nb (Fig. 5), high HFSE (Fig. 7), strongly fractionated REE patterns (Fig. 8) and fall in the within-plate basalt field on most discrimination diagrams (Fig. 6). One Faros gabbro clast (137) falls in the volcanic-arc field on plots of Ti, Zr and Y (Fig. 6), but other elements (e.g. Ti, Zr, Nb) are MORB-like (Figs 4, 5). Some Faros gabbro clasts have a Zr/Y ratio interpreted by Pearce & Norry (1979) as characteristic of within-plate basalt and have slightly higher TiO_2 content, but otherwise differ little from those gabbros that consistently show MORB characteristics (Figs 4, 5).

The amphibolite sample from the Kefala Unit shows elemental abundances intermediate between the MORB gabbros and the Faros alkaline amphibolites.

Table 4. Whole-rock geochemical analyses

Lithology†	ga	ga	ga	ga	ga	ga	ga	ga	amph	py	ga	ga	amph	ga	ga	ga	ga	ga	mga	mga	mga	mga	amph
Sample	133	134	135	137	138	139	142	143	145	146	149A	149B	232	233	234	235	236	237	I163	I164	I165	I166	I175
Unit	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Faros	Kefala	Kefala	Kefala	Kefala	Kefala
Major elements (wt %)																							
SiO_2	50.17	50.06	49.79	49.66	49.97	48.91	50.86	50.37	41.84	53.33	49.25	49.98	38.39	50.29	51.60	48.86	50.07	49.75	44.63	45.74	42.85	47.58	50.04
TiO_2	1.34	1.31	1.53	1.29	1.38	1.69	1.41	1.54	1.96	0.47	1.45	1.47	1.84	1.55	1.69	1.22	2.17	1.26	1.14	0.94	1.09	0.97	2.18
Al_2O_3	16.22	17.84	15.84	15.57	15.33	15.49	15.35	14.84	12.86	7.60	16.44	16.65	12.76	15.61	15.37	16.11	14.63	17.13	14.26	14.99	13.60	16.15	15.73
Fe_2O_3t	9.31	8.25	9.70	9.56	10.23	9.74	9.40	10.27	7.92	5.57	9.10	9.23	7.37	10.10	10.62	8.73	13.00	8.72	8.26	8.66	8.54	7.89	11.52
MnO	0.15	0.14	0.17	0.17	0.18	0.19	0.18	0.18	0.10	0.12	0.16	0.17	0.11	0.17	0.17	0.15	0.20	0.17	0.13	0.15	0.12	0.11	0.19
MgO	7.26	6.62	8.31	7.91	7.99	8.43	7.20	7.08	5.23	13.12	6.92	7.00	7.79	7.07	6.09	8.73	6.25	8.72	6.87	7.76	7.37	6.71	5.31
CaO	10.38	10.45	9.82	10.39	10.43	10.22	9.49	10.42	17.81	18.28	10.45	10.55	21.00	10.48	10.09	10.86	10.38	9.81	9.90	12.24	10.17	6.73	8.55
Na_2O	3.78	3.64	3.45	3.30	3.44	3.27	3.95	3.48	4.12	1.38	3.99	4.01	1.54	3.41	3.77	3.38	3.41	4.34	3.00	2.19	2.07	3.78	3.70
K_2O	0.19	0.15	0.14	0.16	0.20	0.13	0.41	0.40	0.47	0.51	0.28	0.29	1.28	0.64	0.36	0.22	0.35	0.19	0.40	0.11	0.71	0.70	1.47
P_2O_5	0.15	0.15	0.16	0.13	0.13	0.18	0.15	0.17	0.50	0.02	0.20	0.20	0.64	0.19	0.22	0.14	0.28	0.14	0.10	0.10	0.09	0.09	0.35
L.O.I	1.65	1.43	1.13	1.11	0.80	0.74	1.39	1.04	7.78	1.08	1.35	1.39	7.46	0.80	0.84	1.18	0.56	0.84	10.53	5.84	12.07	8.90	0.82
Total	100.60	100.04	100.04	99.25	100.08	98.99	99.79	99.79	100.59	101.48	99.59	100.94	100.18	100.31	100.82	99.58	101.30	101.07	99.22	98.72	98.68	99.61	99.86
Trace elements (ppm)																							
Ba	158	b.d.	206	16	103	85	303	193	299	15	59	178	223	13	11	138	196	b.d.	231	44	128	118	97
Rb	16	16	14	14	14	14	17	16	15	23	17	17	23	18	16	16	13	17	18	4	29	25	49
Sr	198	184	171	157	152	157	184	168	554	184	184	188	561	172	197	154	174	246	213	189	198	169	220
Y	29	28	32	34	31	34	33	34	25	18	29	30	29	35	36	27	43	24	23	20	24	22	41
Zr	93	91	96	61	84	106	112	103	143	36	111	110	134	135	132	82	148	99	75	65	67	73	187
Nb	4	3	3	5	2	2	3	5	45	2	3	4	46	4	5	1	7	3	3	2	2	2	10
Pb	3	12	14	6	15	b.d.	11	4	b.d.	11	2	1	7	b.d.	2	5	10	7	7	6	8	b.d.	b.d.
Ga	17	19	17	15	15	20	17	16	13	9	18	17	15	15	20	13	23	17	14	16	14	14	18
Zn	74	51	79	82	82	61	79	83	56	46	71	70	61	77	53	65	55	64	51	58	51	64	105
Cu	63	26	105	37	42	52	26	21	13	7	79	70	18	59	5	33	5	51	40	13	40	17	50
Ni	105	79	73	94	83	94	70	70	208	293	99	94	197	69	59	148	47	140	110	91	98	85	59
V	222	199	237	223	229	270	204	234	202	136	220	230	197	238	242	203	288	190	207	200	214	191	283
Cr	299	257	321	299	334	256	233	278	343	709	265	270	454	212	142	327	96	248	172	215	261	172	102
La	5.0	4.6	11.0	7.0	5.1	3.5	7.6	3.0	37.4	5.2	11.0	2.0	22.00	17.00	13.00	3.00	n.d.	2.00	3.10	2.50	2.56	3.78	13.50
Ce	n.d.	13	56	n.d.	15	13	21	n.d.	65	14	15	23	115	n.d.	n.d.	n.d.	52	n.d.	9.04	7.39	7.54	10.10	32.30
Pr	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.52	1.26	1.30	1.58	4.62
Nd	20	10	25	9	10	11	13	30	30	9	6	9	15	12	12	18	14	20	8.3	6.6	7.0	7.7	20.9
Sm	n.d.	3.27	n.d.	n.d.	3.29	3.74	4.33	n.d.	5.39	2.62	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.73	2.25	2.54	2.45	6.09
Eu	n.d.	1.35	n.d.	n.d.	1.40	1.26	1.55	n.d.	1.86	0.73	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.10	0.99	1.00	1.06	1.93
Gd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3.80	3.17	3.48	3.26	7.15
Tb	n.d.	0.8	n.d.	n.d.	0.8	0.9	1.0	n.d.	0.9	0.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.71	0.59	0.67	0.62	1.34
Dy	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	4.32	3.58	4.19	3.83	8.12
Ho	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.90	0.77	0.90	0.81	1.63
Er	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.79	2.35	2.70	2.49	4.89
Tm	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.41	0.35	0.40	0.37	0.72
Yb	n.d.	2.82	n.d.	n.d.	2.88	3.43	3.52	n.d.	1.75	1.29	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.57	2.13	2.51	2.32	4.38
Lu	n.d.	0.44	n.d.	n.d.	0.44	0.53	0.54	n.d.	0.27	0.19	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.38	0.31	0.37	0.34	0.65
Co	46.0	32.2	45.0	44.0	41.4	38.1	34.6	50.0	39.4	38.1	38.0	44.0	32	42	50	45	60	38	30	29	33	26	32
Cs	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.2	0.3	1.8	0.7	5.8
Hf	n.d.	2.4	n.d.	n.d.	2.4	3.2	3.0	n.d.	3.2	1.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.4	2.1	2.2	2.4	5.4
Sb	n.d.	n.d.	n.d.	n.d.	0.10	n.d.	0.10	n.d.	0.10	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3.9	2.4	3.1	3.2	0.6
Sc	9.0	33.2	28.0	17.0	42.2	37.7	33.2	n.d.	20.7	41.9	11.0	12.0	n.d.	25	33	n.d.	4	n.d.	28	27	33	26	33
Ta	n.d.	b.d.	n.d.	n.d.	b.d.	b.d.	b.d.	n.d.	3.70	b.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.08	0.06	0.05	0.05	0.76
Th	n.d.	0.2	n.d.	n.d.	0.6	b.d.	0.6	n.d.	4.6	0.2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.19	0.12	0.15	0.37	1.70
U	1.0	0.3	1.0	1.0	b.d.	b.d.	b.d.	2.0	1.6	0.3	2.0	1.0	2	1	2	1	2	1	0.07	0.04	0.23	0.13	0.62

†amph – amphibolite; ga – gabbro; mga – metagabbro; py – pyroxenite. n.d. – not determined; b.d. – below detection limit.

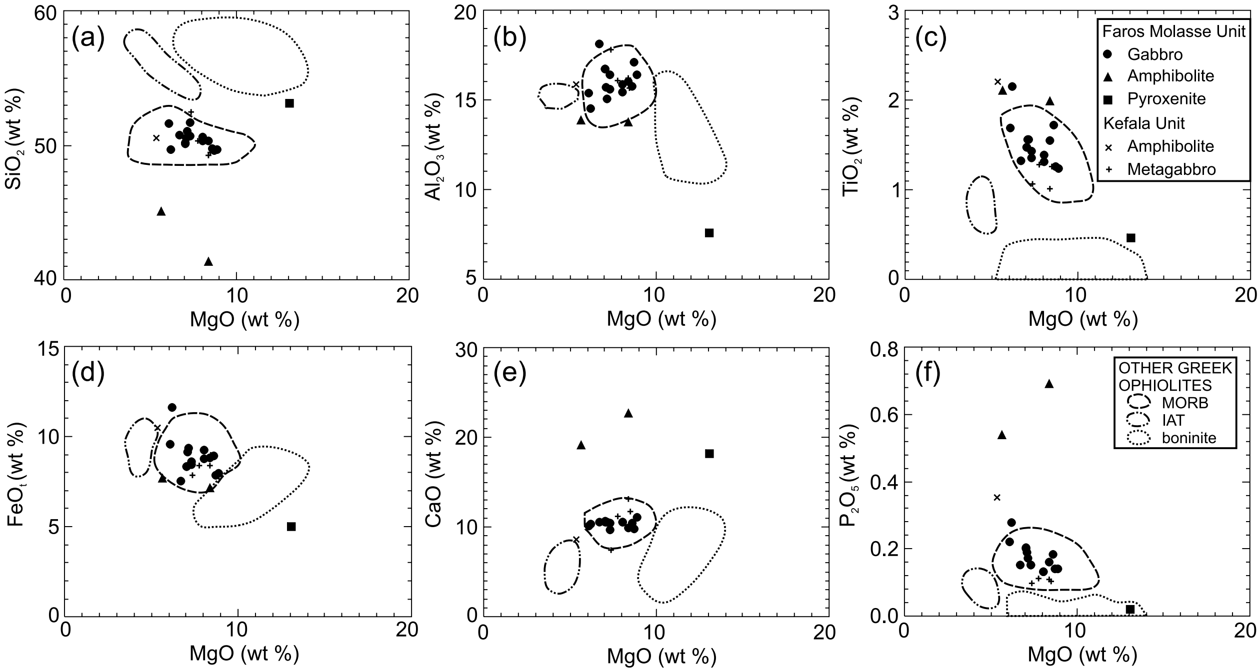

Figure 4. Variation of selected major elements with MgO (an index of differentiation) for the ophiolitic rocks of Ikaria. Fields for mid-ocean ridge basalt (MORB), island-arc tholeiite (IAT) and boninite from other Greek ophiolites based on analyses in Dostal *et al.* (1991), Capedri *et al.* (1996), Stolz, Engi & Rickli (1997), and Pe-Piper, Tsikouras & Hatzipanagiotou (2004).

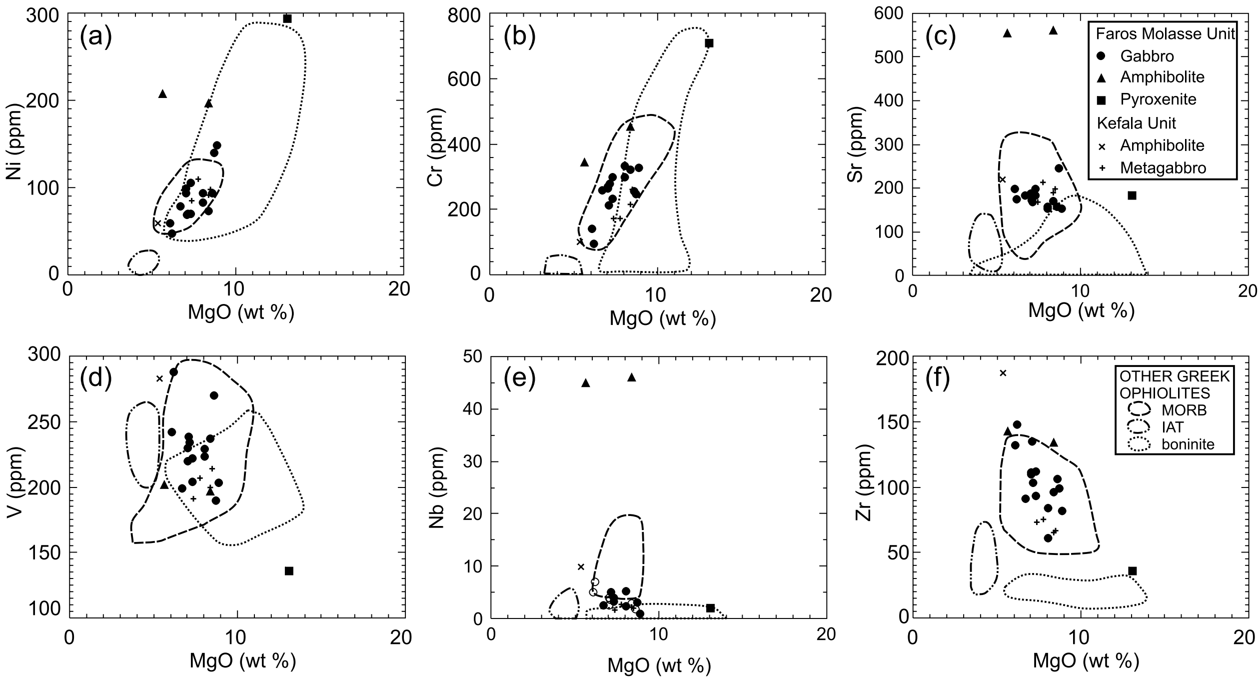

Figure 5. Variation of selected trace elements with MgO (an index of differentiation) for the ophiolitic rocks of Ikaria.

It plots on the boundary of the alkaline and tholeiitic fields in terms of P and Zr content (Fig. 6a). It lacks the strong fractionation of REE and abundance of HFSE found in the alkaline amphibolites and its abundance in elements such as Ti, Fe, Mg, Ni, Cr, Sr, Zr and Nb lies on trends defined by the Faros Molasse Unit gabbros (Figs 4, 5). It resembles sample P41 analysed from the Avdella mélange by Pe-Piper, Tsikouras & Hatzipanagiotou (2004) that they interpreted as of evolved MORB origin. However, an origin in seamount alkaline basalt cannot be excluded.

The pyroxenite appears to be a magmatic rock on the basis of its textures and hornblende megacrysts. Its REE pattern (Fig. 8) is the opposite of that expected from

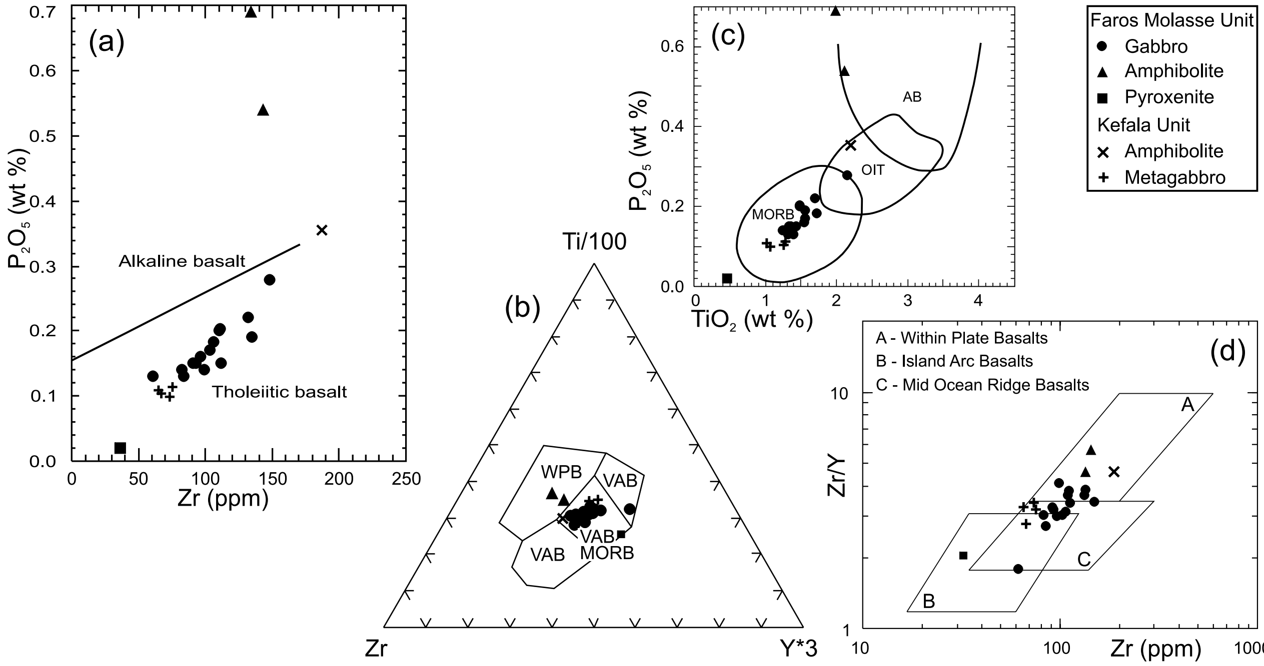

Figure 6. Various discrimination diagrams for mafic rocks. (a) after Winchester & Floyd (1977); (b) after Pearce & Cann (1973); (c) after Ridley *et al.* (1974); (d) after Pearce & Norry (1979). AB – alkaline basalt; MORB – mid-ocean ridge basalt; OIT – ocean island tholeiite; VAB – volcanic arc basalt; WPB – within-plate basalt.

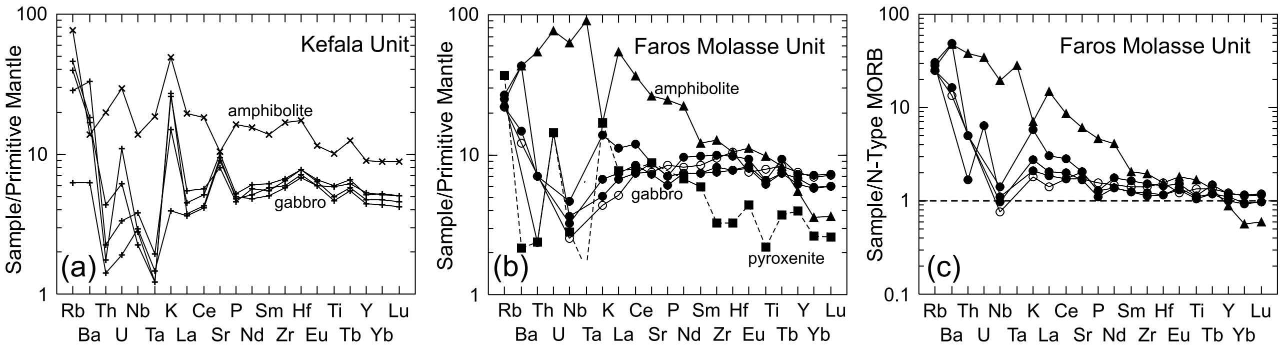

Figure 7. Trace element abundance in selected ophiolitic rocks of Ikaria normalized to primitive mantle (a,b) and MORB (c). Normalizing values from Sun & McDonough (1989).

a cumulate pyroxenite, in which the more compatible HREE tend to be enriched (Fujimaki, Tatsumoto & Aoki, 1984), arguing for an evolved magmatic origin. The bulk composition is rather depleted in elements such as Ti, Zr, Nb and Hf that tend to be depleted in gabbros of boninitic affinity (Figs 3, 4), but its REE pattern (Fig. 8) lacks the ampbibole dominated U-shaped pattern of classic bonitites.

7. Discussion

7.a. Geochemical types

Three geochemical types are recognized in the analysed rocks:

(1) The analysed amphibolites from Faros have high Ti, P, and particularly high Nb. The rocks are primitive, with high Ni and Cr. These rocks plot in the 'within plate' field of most discrimination diagrams. Their alkaline geochemistry is similar to that of 'within-plate' basalts from Mesozoic ophiolitic mélanges elsewhere in Greece (e.g. Avdella: Jones, Robertson & Cann, 1991; Pagondas: Simantov & Bertrand, 1987) and they have been interpreted by Robertson *et al.* (1991) as derived from off-axis alkaline basalt seamounts.

(2) All analysed gabbros are of MORB composition, with variations in Ti, Fe and Mg resulting from normal fractionation processes. They plot in the MORB field in most discrimination diagrams. Those that have slightly higher Zr/Y ratio, falling just out of the MORB field on the Pearce & Norry (1979) diagram (Fig. 6d) appear to be a little more fractionated, with lower MgO, Cr and Ni and higher TiO_2. There is no systematic variation

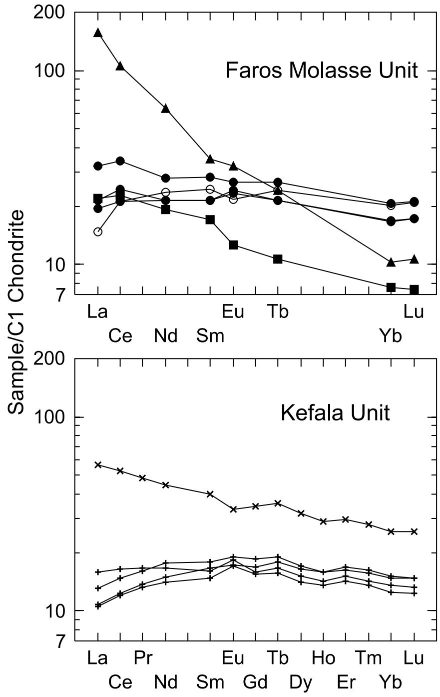

Figure 8. REE abundance in selected ophiolitic rocks of Ikaria normalized to C1 chondrite.

in chemistry with degree of foliation. There is no evidence in the analysed samples for gabbros of IAT or boninitic composition (Figs 4, 5). The one analysed amphibolite from Kefala is rather similar. It is quite evolved, with low Ni and Cr, but has abundances of most elements in the same range as for the more evolved gabbros.

(3) The single pyroxenite clast appears to be magmatic, but compared with the MORB rocks is depleted in HREE and HFSE. It has a bulk geochemistry similar to gabbros interpreted as boninitic in affinity (Figs 4, 5), except that it lacks strong depletion in the middle REE. The preservation of clinopyroxene in this lithology, compared with the dominance of amphibole in the gabbros, suggests that it could represent a late-phase melt.

7.b. Metamorphic history

Meta-gabbro from the Kefala Unit shows considerable greenschist facies metamorphism to chlorite, sericite and calcite. The apparent enrichment in Sr and K (Fig. 7) suggests that this is likely the result of seafloor metamorphism by circulating hydrothermal water. A similar degree of metamorphism is not seen in the Faros Molasse Unit clasts, not even in the foliated gabbros. The composition of hornblende from the Faros Molasse Unit gabbros (Fig. 3) is similar to that found in modern hydrated oceanic crust, such as had been drilled by the Ocean Drilling Program at Hess Deep (Manning, MacLeod & Weston, 2000). In contrast, the Faros Molasse Unit amphibolite includes amphiboles of ferroan pargasite and magnesian hastingsite composition, beyond the range found at Hess Deep. The higher ^{iv}Al content of the amphiboles in the amphibolite suggests higher pressure formation (Anderson & Smith, 1995) and is likely related to sole metamorphism. Similar compositions were found by Patzak, Okrusch & Kreuzer (1994) for amphibolitic sole rocks in Tinos. Foliated gabbro contains more edenitic amphiboles, compared with magnesio-hornblende in the unfoliated gabbro (Fig. 3). The amphibolite and some foliated gabbro have albite-oligoclase (Fig. 2). Whether these mineralogical changes in the weakly foliated gabbro took place within oceanic crust prior to ophiolite emplacement (cf. the shear zones described by Robinson *et al.* 2000) or is related to low-grade metamorphism of an ophiolitic sole is unknown. There is no evidence in amphibole compositions for retrograded high-pressure metamorphism of the type found in meta-ophiolites of the Blueschist Unit of the western Cyclades.

7.c. Tectonic setting of the ophiolite

The ophiolitic rocks are clearly of MORB type: there is no geochemical evidence for formation in a supra-subduction zone (SSZ) setting. The hornblende gabbro is therefore not the result of crystallization from a hydrous magma, but rather a consequence of amphibolite-facies sea-floor metamorphism.(e.g. Manning, MacLeod & Weston, 2000). The presence of variably foliated gabbro and amphibolite of MORB composition suggests that the MORB spreading centre experienced slow spreading, with the resulting detachment faulting and extensional deformation of the gabbroic ocean crust (Lagabrielle *et al.* 1998).

7.d. Significance of radiometric ages

The new age from the undeformed hornblende gabbro of the Faros molasse unit of 74.2 ± 2.3 Ma is interpreted to date the cooling of the gabbro following sea-floor metamorphism, either as a result of ocean floor extensional detachment faulting or of ophiolite emplacement.

Altherr *et al.* (1994) determined an age of 84.4 ± 2.4 Ma for an amphibolitic layer that was described as being within the Kefala marbles. It is unclear whether this amphibolite was part of the ophiolite sequence, or whether it was a mafic unit intercalated with marbles, such as is found in Naxos (Pe-Piper & Kotopouli, 1996). If part of the ophiolite sequence, it could be either a sole rock similar to that dated from the Faros molasse unit, or a strongly foliated MORB gabbro similar to the analysed 'amphibolite' in this study.

Fresh diorite (likely equivalent to hornblende gabbro of this study) from Kefala yielded an age of 70.4 ± 1.1 Ma (Altherr *et al.* 1994). Two hydrothermally altered diorites gave ages of 67.4 ± 1.0 and $80.5 \pm$

1.4 Ma (Altherr *et al.* 1994). This range of ages is that expected from extensional crustal tectonics at slow spreading ridges (e.g. as discussed by Thy & Dilek, 2000), in which there is great spatial variability in the hydrothermal circulation of seawater, the development of foliated fabrics, and the cooling of oceanic crust as a result of detachment faulting.

7.e. Comparison with other Upper Cretaceous mélanges in the Cyclades

The ophiolitic rocks of Ikaria resemble those of the Upper Cycladic Unit of the island of Tinos (Stolz, Engi & Rickli, 1997), where the ophiolitic rocks are principally of MORB composition, but including minor boninitic gabbros, perhaps analogous to the pyroxenite of Ikaria. The ages of the Ikaria ophiolitic rocks also compare well with the dates from Tinos, where amphibolite ages range from 77 to 66 Ma (Patzak, Okrusch & Kreuzer, 1994). Older ages of 77–72 Ma may represent original or partially reset ages for the sole thrust, whereas a cluster of ages around 67 Ma are interpreted as a thermal event, perhaps related to a compressional tectonic event at that time. This younger event may correlate with the Barrovian metamorphism and granite emplacement on Donoussa, Nikouria and Anafi (Reinecke *et al.* 1982; Altherr *et al.* 1994) which has yielded K–Ar cooling ages of 60–64 Ma. On Ikaria, there is no evidence for younger metamorphism; the radiometric dates from Ikaria thus provide clear evidence for Late Cretaceous formation of ocean crust.

The ophiolites of the Cyclades probably represent a wide range of spreading and emplacement histories (cf. Robertson, 2002). The initial age of formation of ophiolitic rocks in the Cyclades is unknown, although both Jurassic and Cretaceous ophiolitic rocks are known in Crete. The ophiolites in Paros, which are overlain by Barremian limestones, are probably similar to ophiolites of the Pindos ocean emplaced on the southwestern Pelagonian zone. Katzir *et al.* (1996) inferred that the Tinos ophiolites were probably obducted in the Late Cretaceous, as part of the subduction–accretion event of that age that is recognized widely throughout the Cyclades and Crete and a similar age for the Ikaria ophiolites is apparent from this study. Serpentinite in Palaeogene flysch in Anafi has a similar setting to the ophiolitic rocks of Ermioni (Clift, 1996). Important Late Cretaceous collisional metamorphism and granite emplacement in areas to the south (Crete, Donoussa, Nikouria, Anafi), and a possibly correlative thermal event in Tinos, do not appear to have influenced Ikaria.

8. Conclusions

Ophiolitic rocks in the Upper Tectonic Unit of Ikaria are preserved in a mélange at the Kefala Unit and in a coarse-grained conglomerate at Faros, directly overlying the mid-crustal detachment fault. Sole rocks are amphibolite, in part of alkaline basalt protolith. Most ophiolitic rock consists of hornblende gabbro with MORB geochemistry that underwent sea-floor hydration, deformation and metamorphism. The large variation in degree of deformation, grade of metamorphism, and radiometric ages suggests syn-spreading extensional deformation at a slow-spreading ridge. The ophiolitic mélange on Ikaria does not appear to have experienced Late Cretaceous collisional metamorphism, in contrast to areas to the south (Donoussa, Nikouria, Anafi) and west (Tinos). It thus provides clear evidence for formation of Late Cretaceous ocean crust with a slow-spreading ridge in the Cyclades region.

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