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The ophiolite of the Koziakas range Western Thessaly (Greece)

By

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With 6 figures and 6 tables in the text

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Abstract: First petrographic and chemical data are reported for the Koziakas ophiolite whose geological setting is unique in the Hellenides. It is Jurassic and consists mainly of ultramafites and pillow basalts, while gabbros and dykes are rare. The magmatic activity was contemporaneous with the deposition of radiolarites and red clays. The ultramafic rocks are spinel-harzburgites and plagioclase-harzburgites, with variable content of clinopyroxene. The basaltic rocks resemble oceanic products and have variable geochemical imprint (normal, transitional and enriched MORB), as suggested by Nb/Y and Nb/Zr ratios, and clinopyroxene composition. One dyke cutting the ultramafites has unusual features, i. e. very low Ti, P, Zr, Y, and high Cr, Ni and Mg contents. One gabbro dyke (plagioclase-olivine-clinopyroxene-spinel) is peculiar in having exceptionally low V and Sc contents.

Key words: Ophiolite, ultramafite, pillow basalt, petrography, mineral composition, chemical composition; Thessaly (Koziakas).

Introduction

During the last years, great efforts have been made to shed light upon the geology and petrology of the Greek ophiolites, nonetheless a satisfactory knowledge of their petrogenesis and significance has not been reached jet. The aim of this work is to present first petrographic and geochemical data on the ophiolitic rocks of the Koziakas belt and to discuss their geological setting.

The Koziakas mountains are located in Western Thessaly (Fig. 1). They consist of a sedimentary sequence of limestones, radiolarites and clastic formations of Triassic to Eocene age as well as of ophiolites. The sedimentary sequence crops out mainly in the western and central part of the Koziakas range, and it is subdivided in two parts which correspond to two tectonic subunits (Aubouin, 1959; Papanikolaou & Sideris, 1979): a) the upper part comprising the

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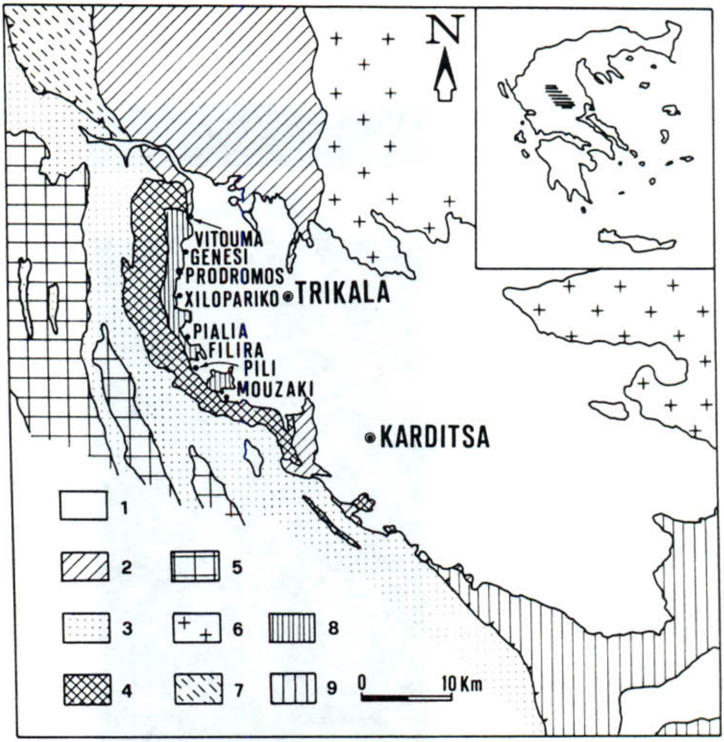


Fig. 1. Geological sketch map of the area of Western Thessaly. 1 = Quaternary; 2 = Oligocene-lower Miocene molassic sediments; 3 = Tertiary flysch of Pindos Unit; 4 = Unit of Western Thessaly (Koziakas and Thymiama sequence); 5 = Mesozoic sequence of Pindos Unit; 6 = Metamorphic Units of Eastern Greece (Pelagoniqum s.l.); 7 = Northern Pindos ophiolite; 8 = Koziakas ophiolite; 9 = Othris ophiolite and transgressive Cretaceous sediments.

uppermost Jurassic-Eocene part of the stratigraphic sequence known as Thymiama, b) the lower part comprising the upper Triassic-upper Jurassic part of the stratigraphic sequence known as Koziakas. The ophiolites crop out mainly in the eastern part of the Koziakas range and they have been considered a) as outliers of a Tertiary nappe (Aubouin, 1959), b) as related to the upper Jurassic of Koziakas subunit without a major Tertiary overthrust (Papanikolaou & Lekkas, 1979).

The ophiolites of Koziakas occur along a NW–SE alignment of ophiolite outcrops with the Northern Pindos ophiolites to the NW and the Othris ophiolites to the SE. The Northern Pindos ophiolites are overthrusted on the Eocene flysch of the Pindos Unit. The Othris ophiolites are overthrusted together with their transgressive Cretaceous cover also on the Eocene flysch of the Pindos Unit. The unit of Western Thessaly together with the Koziakas ophiolite is also thrusted over the Eocene Pindos flysch to the west. To the east the Koziakas ophiolite is covered by the Quaternary deposits of the Thessalian basin or by the Oligocene-Miocene molassic sediments of the Meso-Hellenic trough.

Geologic setting

The geological setting of the Koziakas ophiolite will be analysed with the use of a schematic stratigraphic diagram showing the probable relations of Pindos, Western Thessaly and Eastern Greece Units (Fig. 2a) and of a general geological section of Koziakas range showing the actually observed formations and structures (Fig. 2b).

The relations between Pindos, Western Thessaly and Eastern Greece have been schematically given by PAPANIKOLAOU & LEKKAS (1979) as being lateral equivalent palaeogeographic domains, especially during the paleo-Alpine orogeny of upper Jurassic-Lower Cretaceous. Thus, (i) the lateral transition between the upper Cretaceous and Eocene formations of Pindos and Western Thessaly was observed in the area of Tavropos whereas their equivalent in Eastern Greece is the Cretaceous cover of the ophiolites. (ii) The underlying formations of lower Cretaceous with the "first flysch" of the Pindos Unit to the west and the upper part of the "Beotian flysch" in the center are located where the ophiolites occur to the east. (iii) The upper Jurassic formations are represented mainly by radiolarites in all three units with significant occurrences of ophiolite bodies and clastic formations close to the main ophiolite outcrop to the east. (iv) The older formations of Jurassic and upper Triassic are similar in Pindos and Western Thessaly with the exception of the neritic oolitic limestones of Dogger-Malm cropping out in Koziakas range. It should be noted that in Othris the Maliac Unit has very similar lithologies as the upper Triassic-Jurassic of Koziakas (FERRIÈRE, 1982).

Generally, the geological setting of the Koziakas ophiolite is considered as a fossilified paleofront of the ophiolite emplacement during late Jurassic-early Cretaceous over the Unit of Western Thessaly marking the boundary between the paleotectonised Units to the east and the units tectonised only during the Eocene-Oligocene orogeny to the west.

The actual geometry of the Koziakas range is the result mainly of the Tertiary orogeny. Thus, besides the overthrust of the Unit of Western Thessaly on the Eocene flysch of the Pindos Unit, there are several thrusts within the unit itself. The most important thrust is that separating the Thymiama from the Koziakas subunit (Fig. 2b). It should also be noted that the "Beotian flysch" of upper Jurassic-lower Cretaceous age crops out in both subunits and that ophiolitic detritus and small bodies are present within Thymiama and Koziakas formations and become more abundant near the main ophiolite body in the east. A lateral transition between the oolitic limestones

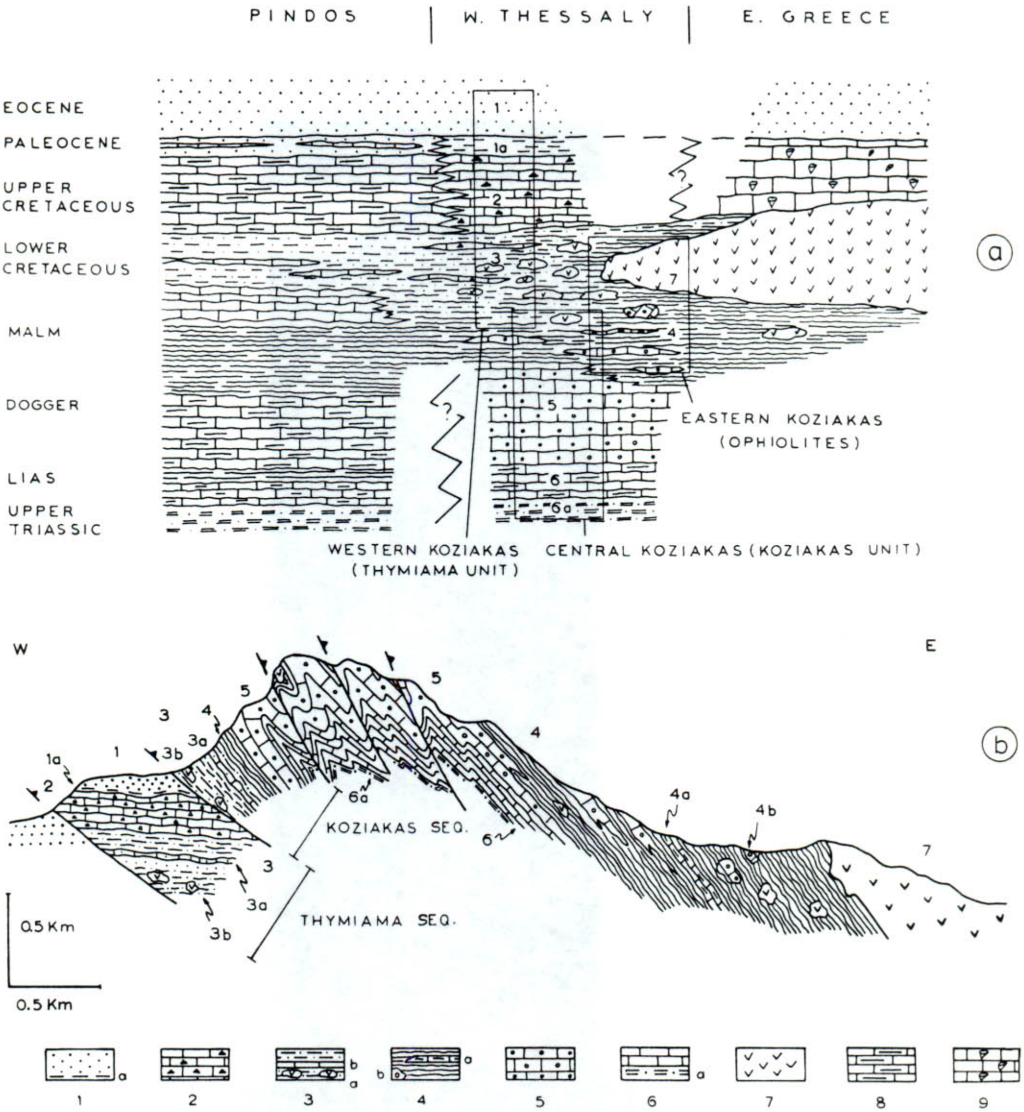


Fig. 2. a) Schematic stratigraphic diagram showing the probable relations between the Units of Pindos, Western Thessaly and Eastern Greece (after Papanikolaou & Lekkas, 1979, modified). – b) General geological section of the Koziakas range.
1 = Tertiary flysch; 1 a-Paleocene red pelites; 2 = Upper Cretaceous breccia limestones (Thymiama); 3 = Upper Jurassic-lower Cretaceous clastic sequence (flysch) rich in ophiolite detritus; 3 a = *Calpionella* bearing limestones; 3 b = breccia of mafic volcanic rocks and ultramafics; 4 = Radiolarites and red pelites; 4 a = Pelagic limestones within the radiolarites; 5 = Oolitic limestones of Dogger-Malm; 6 = Upper Triassic-lower Jurassic limestones; 6 a = Triassic clastic formation; 7 = Ophiolitic rocks; 8 = Platty limestones with silex; 9 = *Rudists* bearing limestones.

of Dogger-Malm and the radiolarites is observed along the eastern slopes of Kozikas mountains

Petrography and mineral chemistry

A) Ultramafites

Spinel-harzburgites (Turckishvrisi and Paliouri) and plagioclase-harzburgites (Genesi and Xilopariko) occur in the studied area. They exhibit the texture of mantle tectonites, containing irregularly shaped porphyroclasts of variable size set in a finer-grained equigranular granoblastic groundmass. The foliation is generally scarce. The porphyroclastic portions may be composed of harzburgite, dunite, pyroxenite assemblages, but also of single olivine, orthopyroxene, clinopyroxene and rarely spinel grains. The porphyroclastic phases are strongly deformed, i. e. olivine is kinked, while banding is a common feature for pyroxenes; the crystal boundaries are irregular and serrate. Nevertheless, sometimes porphyroclasts preserving former protogranular texture (rational boundaries and equiangular triple points) can be seen. The phases of the groundmass are only slightly deformed in respect to the porphyroclasts, but the matrix in spinel-harzburgites exhibits stronger deformation than the matrix of plagioclase-harzburgites.

Spinel and plagioclase harzburgites have comparable chemical composition (Table 1). Chemical composition of the phases are reported in Table 1. Olivine is the dominant phase (60–90% vol.) and is compositionally homogeneous (Fo% = 89.6–90.3). Orthopyroxene varies in modal proportions (5–30% vol.). Porphyroclastic orthopyroxene is unmixed, while orthopyroxene of the matrix is more homogeneous (En% = 89.7–90.6). Porphyroclastic orthopyroxene contains appreciable amounts of Al_2O_3 (normally >4%) while matrix orthopyroxene has less but variable alumina (0.61–2.39%). Clinopyroxene (diopside with rather high Na_2O, Al_2O_3, Cr_2O_3) is scarce (<10% vol.) but locally concentrated in porphyroclastic aggregates. Brown spinel occurs as anhedral grains both in the porphyroclastic portions and in the matrix. Porphyroclastic spinels of the spinel-harzburgites are significantly higher in Al_2O_3 and MgO in respect to the spinels of the recrystallized matrix containing plagioclase (Table 1). Plagioclase (<10% vol., An% ~ 90) forms frequently coronas around matrix spinel; however, it occurs also as separate anhedral grains undeformed and locally concentrated in thin and discontinuous rods set parallel to the foliation plane. The amount of plagioclase is inversely correlated to the spinel content and was formed through spinel breakdown at shallower depths. The mineral assemblages are clearly in disequilibrium as suggested by the large range of temperatures (e.g. 1150–760 °C for Turkishvrisi and Paliouri) obtained using different geothermometers (FABRIÈS, 1979; ROEDER et al., 1979; SACHTHLEBEN & SECK, 1981).

Light brown to yellowish amphibole is occasionally present in the matrix of plagioclase-bearing harzburgites. Minor secondary phases are chlorites,

Table 1. Composition of ultramafites and related mineral phases from Koziakas.

	Turkishvrisi			Paliouri				
	Ol-P (4)	Opx-P (5)	Sp-P (5)	Ol-P (1)	Opx-P (2)	Opx-M (2)	Cpx-P (2)	Sp-P (2)
SiO_2	40.6	55.2		41.0	55.3	56.1	51.8	
TiO_2		0.05	0.05		0.07	0.07	0.29	0.05
Al_2O_3		4.51	46.5		4.66	2.60	5.86	53.3
Cr_2O_3		0.85	20.1		0.52	0.34	0.87	12.2
FeO_{tot}	9.51	6.15	15.0	10.1	6.50	6.50	2.38	11.8
MgO	48.8	32.6	17.2	48.9	31.8	32.1	14.8	19.2
CaO		0.73			0.47	0.49	22.3	
Na_2O					0.07		1.00	

	Genesi				Xilopariko	
	Ol-P (2)	Opx-P (1)	Opx-M (2)	Sp-M (4)	Opx-P (2)	Sp-P (3)
SiO_2	40.5	55.2	57.7		54.7	0.02
TiO_2		0.06	0.11	0.37	0.14	0.04
Al_2O_3		4.26	1.50	26.5	3.34	36.7
Cr_2O_3		0.70	0.79(1)	37.4	1.01	29.9
FeO_{tot}	9.51	6.36	6.38	23.3	6.25	15.8
MgO	48.7	32.2	33.6	10.9	30.9	14.5
CaO		1.18	0.77		2.34	

Whole rock chemistry

	101(T)	141(X)	151(X)		101(T)	141(X)	151(X)
SiO_2	45.8	42.6	43.7	Zr(ppm)	4	5	3
TiO_2	0.02	0.05	0.05	Nb	[1]	[1]	[1]
Al_2O_3	1.15	2.22	1.98	Y	[1]	3.5	3
Fe_2O_3*	9.41	8.63	8.91	Sr	< 5	<5	< 5
MnO	0.15	0.13	0.15	Co	109	101	101
MgO	38.4	35.0	33.6	Cr	3173	2552	2902
CaO	1.79	1.55	1.95	Ni	2185	1938	1947
Na_2O	0.50	0.42	0.54	V	68	64	73
K_2O	0.01	0.01	0.01	Sc	14.7	12.3	12.4
LOI	2.45	9.33	9.19				

P: porphyroclastic; M: matrix phase; T: Turkishvrisi (spinel-harzburgite); X: Xilopariko (plagioclase-harzburgite); *: total iron as Fe_2O_3; ( ): number of analyses averaged; [ ]: less accurate values.

opaques, tremolitic amphibole, and prehnite as well as hydrogarnet replacing plagioclase.

B) Gabbros

Olivine-gabbro outcrops only close to Xilopariko village where it forms a dyke (60 cm thick) intruding serpentinized ultramafites. The plagioclase/mafic phases ratio varies producing a banding parallel to the margins of the dyke. The magmatic phases are frequently porphyroclastic and strongly deformed: plagioclase is glide-twinned, clinopyroxene is banded, and olivine is flattened; such deformations decrease in intensity inwards. The dyke underwent HT recrystallization with the development of polygonized structures. The HT metamorphic phases are undeformed and exhibit frequently equiangular triple junctions. Plagioclase forms small grains and is arranged in mosaic texture. Magmatic clinopyroxene forms big crystals, strongly unmixed; it recrystallized to HT metamorphic clinopyroxene forming small undeformed grains and characterized by lower Al_2O_3 in respect to the magmatic clinopyroxene. Olivine grains, pseudomorphed by serpentine, contain frequently euhedral and deep-brown chromian spinel. Crystallization of light brown amphibole and pronounced exsolution of small anhedral grains of spinel from magmatic clinopyroxene occurred also during the HT recrystallization. This spinel (Table 2) has lower Al_2O_3 and MgO and higher Cr_2O_3 than the magmatic spinel. The high $MgO/FeO_{tot.}$ ratio and the Cr_2O_3 content in the magmatic clinopyroxenes of the gabbro suggest that it generated from a quite primitive magma. Moreover, the low Zr content of the rocks suggests that the trapped liquid is very low or practically absent. Despite the abundant clinopyroxene,

Table 2. Chemical composition of gabbro dyke 140 (Xilopariko village) and related phases.

	Cpx-M (2)	Cpx-R (8)	Sp-M (1)	Sp-R (6)	Whole rock composition (2)			
SiO_2	52.1	53.1		0.03	SiO_2	43.0	Zr(ppm)	4
TiO_2	0.25	0.17	0.02	0.10	TiO_2	0.01	Nb	[2]
Al_2O_3	3.64	2.52	44.7	34.0	Al_2O_3	16.6	Y	[2]
Cr_2O_3	0.90	0.77	21.0	30.1	Fe_2O_3*	4.07	Rb	-
FeO_{tot}	3.12	2.86	16.0	22.7	MnO	0.08	Sr	195
MgO	15.8	16.2	16.2	11.9	MgO	14.9	Co	41
CaO	22.5	23.0		0.06	CaO	12.2	Cr	922
Na_2O	0.67	0.56			Na_2O	0.87	Ni	241
					K_2O	0.01	V	24
					LOI	8.25	Sc	4.4

R: recrystallized phase; M: magmatic phase; ( ): number of analyses averaged; *: total iron as Fe_2O_3; [ ]: less accurate values.

Table 3. Parageneses of the metabasalts from Koziakas.

GROUP I

	Structure	Phenocrysts	Groundmass	Phases analyzed
110*	Subophitic		Cpx, *Pl*, Ores, Carb, *Glass*, Pump, Chl	Cpx
111	Intergranular	*Ol*, Sp (<1%)	*Pl*, Cpx, Ores, Carb, Chl, Ep, Zeol	
112	Intergranular	*Ol*, *Pl*, Sp (<1%)	*Pl*, Cpx, Ores, Carb, Chl, Pump	
113	Intergranular	*Ol*, Sp, *Pl* (<1%)	*Pl*, Cpx, Ores, Carb, Chl	
131*	Intergranular	Mg	*Pl*, Cpx, Ores, Chl, Carb, Sph	Cpx
132*	Intergranular	Mg	*Pl*, Cpx, Chl, Ores, Carb	Cpx
133	Intergranular	*Ol*, Sp (<1%)	*Pl*, Cpx, Ores, Chl, Carb, Sph	
134	Intergranular		*Pl*, Cpx, Ores, Chl, Carb, Pump	
135	Intergranular	*Ol*, Sp, *Pl*, *Cpx* (10%)	*Pl*, Ores, *Cpx*, Carb, Chl, Qu	Sp
136	Intergranular	*Ol*, Sp, *Pl* (<1%)	*Pl*, Cpx, Ores, Carb, Chl	
137	Intergranular	*Ol*, Sp (<1%)	*Pl*, *Cpx*, Ores, Carb, Chl	Cpx, Sp
138*	Subophitic		Cpx, *Pl*, Ores, Chl, Carb, Sph	Cpx
139*	Intergranular		*Pl*, Cpx, Ores, Carb, Chl, Sph	Cpx

GROUP IIA

	Structure	Phenocrysts	Groundmass	Phases analyzed
122*	Subophitic		*Pl*, Cpx, Ores, Chl, Preh, Zeol, Sph	Cpx
144*	Ophitic	*Pl* (<1%)	Cpx, *Pl*, Ores, Chl, Carb, Sph	
145*	Ophitic	*Pl* (<1%)	Cpx, *Pl*, Ores, Carb, Chl, Zeol, Sph	Cpx
146*	Intergranular		*Pl*, Cpx, Ores, Chl	
147*	Subophitic		Pl, Cpx, Ores, *Glass*, Carb	Cpx
148*	Subophitic		*Pl*, Cpx, Ores, *Glass*, Pump, Chl	Cpx

GROUP IIB

	Structure	Phenocrysts	Groundmass	Phases analyzed
108*	Subophitic		*Pl*, Cpx, Act, Chl, Ep, Sph, Ores	
152*	Ophitic	*Ol*, Sp (10%)	Cpx, *Pl*, Hbl, Ores, Hdg, Chl, Act, Serp	Cpx
153*	Ophitic		*Pl*, Cpx, Ores, Act, Sph, Chl, Carb, Ep	Cpx
157*	Subophitic		*Pl*, Cpx, Act, Ep, Ores, Chl, Sph	
159*	Ophitic	S	*Pl*, Cpx, Ores, Chl, Sph, Preh	Cpx

GROUP III

	Structure	Phenocrysts	Groundmass	Phases analyzed
117	Porphyritic	*Ol*, Sp (10%)	Act, Chl, Ep, Ores, Cpx, *Pl*	
118*	Porphyritic	*Ol*, Sp (10%)	Act, Chl, Ep, Ores, Cpx, *Pl*	Cpx, Sp

*: samples analyzed for major and trace elements. The mineral phases are listed in order of decreasing modal abundance. Act: actinolite; Carb: carbonates; Chl: chlorites; Cpx: clinopyroxenes; Ep: epidote; Hbl: hornblende; Hdg: hydrogarnet; Ol: olivine; Pl: plagioclase; Preh: prehnite; Pump: pumpellyite; Qu: quartz; S: sulfides; Sp: Cr-spinel; Sph: Sphene; Zeol: zeolites. In *italics:* phases pseudomorphed by secondary minerals; underlined: phases sobstituted partially by secondary minerals. ( ): modal proportions refer to total phenocrysts present.

Sc and V contents of the gabbro are very low (4.4 and 24 ppm respectively) (Table 2) and, surprisingly, they are lower than in ultramafites (12–15 and 64–73 ppm respectively) which contain less than 10% clinopyroxene. These features might be related to unusual physico-chemical conditions, i.e. low $D^{Sc}_{cpx/melt}$ and $D^{V}_{cpx/melt}$ in relation to high oxygen fugacity and high temperature (cf. LINDSTROM, 1976).

C) Basalts

Basalts usually occur as pillow lavas. Only exceptionally they form small dykes intruding the ultramafites. Most basalts are aphyric, but slightly porphyritic lavas are also present (see Table 3). Many basalts have variolitic texture and the varioles are filled with carbonates and, subordinately, with chlorites, opaques and silica. Small carbonate veins are frequent. The basalts are strongly spilitized but clinopyroxene and spinel survived alteration. Olivine is pseudomorphed by secondary phases and relics of primary plagioclase (An% ~ 57) are very rare. The low-grade metamorphic minerals are represented mostly by albite, chlorites, opaques, carbonates, silica and, subordinately, by actinolite, prehnite, pumpellyite, zeolites, epidote in order of decreasing abundance. On the basis of textural and mineralogical features and occurrence, the basalts may be subdivided into the following groups.

Group I. (Prodromos and Vourloto-Filira areas). Most basalts are intergranular, with frequent skeletic plagioclase and clinopyroxene which suggest that the magma solidified under supercooled conditions. The basalts are frequently porphyritic (exceptionally up to 10% vol. phenocrysts), with olivine (pseudomorphed by secondary phases) and Cr-spinel forming small euhedral grains deep brown in colour included mostly in olivine, as the characteristic phenocrysts. Plagioclase is very rare and clinopyroxene phenocrysts are exceptional. Opaques are generally scarce, but in some samples they are abundant, and are confined mostly to the groundmass.

Group II. (Xilopariko and Mavromatio area, Group IIA; Paliouri area, Group IIB). These rocks have ophitic to subophitic texture and crystallized under lower cooling rate than basalts of Group I. The lavas do not contain olivine and Cr-spinel; plagioclase and opaques are very scarce as phenocrysts. Only sample 152 – a rodingitized dyke with ophitic texture from the Paliouri area – contains olivine and Cr-spinel phenocrysts.

Group III. (Close to Genesi). It refers to a dyke (samples 117 and 118) cutting the ultramafites. The rock is spilitized and contains phenocrysts of olivine (altered) and Cr-spinel set in a groundmass composed of chlorites, actinolite, rare opaques and exceptional clinopyroxene relics. The rocks are comparable in texture and composition to the "dykes D" cutting the ophiolitic sequence of the Aspropotamos Valley, Northern Pindos, located NW of the investigated area (CAPEDRI et al., 1980 a, 1980 b, 1981, 1982).

Clinopyroxene. All the analyzed clinopyroxenes are matrix phases (Table 4).

Table 4. Average composition of clinopyroxenes of basaltic lavas and dykes from Koziakas.

	GROUP I					GROUP IIA			
	110 (4)	131 (2)	132 (2)	138 (3)	139 (4)	122 (2)	147 (3)	148 (2)	145 (3)
SiO_2	47.0	44.0	43.5	48.1	48.2	57.7	52.0	51.3	51.3
TiO_2	2.78	4.54	4.62	1.63	1.97	0.71	0.76	1.04	0.92
Al_2O_3	6.53	6.91	7.21	5.34	6.42	3.00	2.76	4.25	3.01
FeO_{tot}	10.5	11.7	11.7	7.63	8.96	8.73	9.50	11.2	9.02
MgO	10.9	9.71	9.37	13.6	12.4	16.1	15.7	15.6	15.0
CaO	21.2	21.5	22.0	21.5	20.8	18.1	18.3	16.2	19.4
Na_2O	0.41	0.66	0.64	0.29	0.34	0.42	0.30	0.54	0.29

	GROUP IIB				GROUP III
	152 (2)	153 (2)	156 (1)	159 (2)	118 (1)
SiO_2	53.6	52.2	51.4	51.9	52.3
TiO_2	0.54	0.48	0.90	0.86	0.13
Al_2O_3	2.57	2.67	4.21	3.35	1.57
FeO_{tot}	6.70	6.16	8.48	6.63	6.67
MgO	17.9	17.2	17.9	16.1	15.3
CaO	18.2	19.1	15.0	19.5	22.1
Na_2O	0.27	0.29	1.11	0.37	0.11

Clinopyroxenes of Group I are distinctly pinkish in colour, while those of Group IIA are only slightly coloured; clinopyroxenes of the other groups are colourless.

In the quadrilateral of Fig. 3, clinopyroxenes of Group I (salite) define a trend with variable Mg/(Mg+Fe) ratio and slight Ca-enrichment (trend A), while clinopyroxenes of Group IIA and Group IIB (augite and subordinately salite and diopside) exhibit wide variation in Ca content (field B in Fig. 3). Fields A and B cannot be ascribed to equilibrium and quench crystallization respectively, as supposed for some tholeiitic basalts of oceanic environment (MUIR & MATTEY, 1982, and references therein). In fact the basalts containing clinopyroxenes of field A have finer grain size and thus presumably cooled faster than those containing the clinopyroxenes of field B. The chemical features of the analyzed clinopyroxenes depend reasonably on (i) different crystallization history and (ii) on the chemical imprint of the parental magma. In fact the basalts containing olivine (Group I) plot in field A, while those where plagioclase forms phenocrysts and/or crystallized before clinopyroxene (e. g.

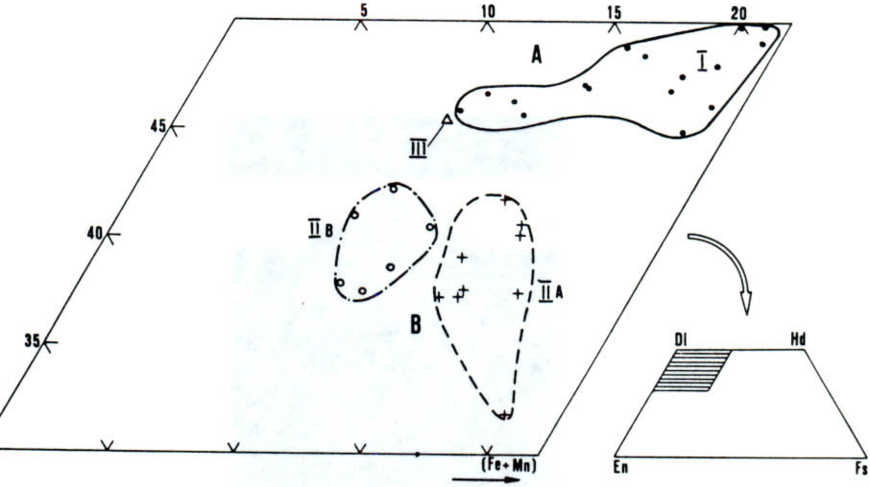


Fig. 3. Ca–Mg–Fe plot for clinopyroxenes of ophiolitic metabasalts from Koziakas. The olivine-phyric lavas (I, III) and the olivine-free lavas (IIA, IIB) fill two different areas (A and B respectively).

in ophitic samples) define field B. Furthermore the relationships between the magma type and clinopyroxene composition are well defined: the rocks of Group I, whose clinopyroxene plots in field A, have higher Nb/Zr, Zr/Y and Ti/V ratios than the rocks containing clinopyroxenes of field B (Group I basalts); the sample 118 (Group II) with high Cr, Ni and very low Zr, Y and TiO_2 contains clinopyroxenes with very low Ti/Al ratio.

In the diagram Ti/Al vs Mg/(Mg+Fe) of Fig. 4 clinopyroxenes of Koziakas basalts are compared with clinopyroxenes from the sequence of the Aspropotamos Valley (Capedri et al., 1980 a, 1980 b, 1981). Clinopyroxenes of Group I have, in comparison, higher Ti/Al ratio while clinopyroxene of sample 118 is strictly comparable to those occurring in the strongly depleted dykes D of the Aspropotamos Valley.

Cr-spinel. Spinels have been analyzed only in few samples (Table 5). Spinel of sample 118 has very high Cr/(Cr+Al) ratio and low Mg/(Mg+Fe) values (Fig. 5) and is comparable to the spinels of some high-Mg andesites (boninitic rocks) and of strongly depleted dykes (dykes D) of the Aspropotamos sequence (Capedri et al., 1981). The spinels of the other samples have lower Cr/(Cr+Al) and higher Mg/(Mg+Fe) ratios and are comparable to the spinels analyzed in MORB and in massive basalts and dolerites from Northern Pindos (Capedri et al., 1981).

Chemistry of the basaltic rocks

Selected chemical analyses of basalts are listed in Table 6. The high values of LOI and the abnormally high CaO content of some samples indicate that sec-

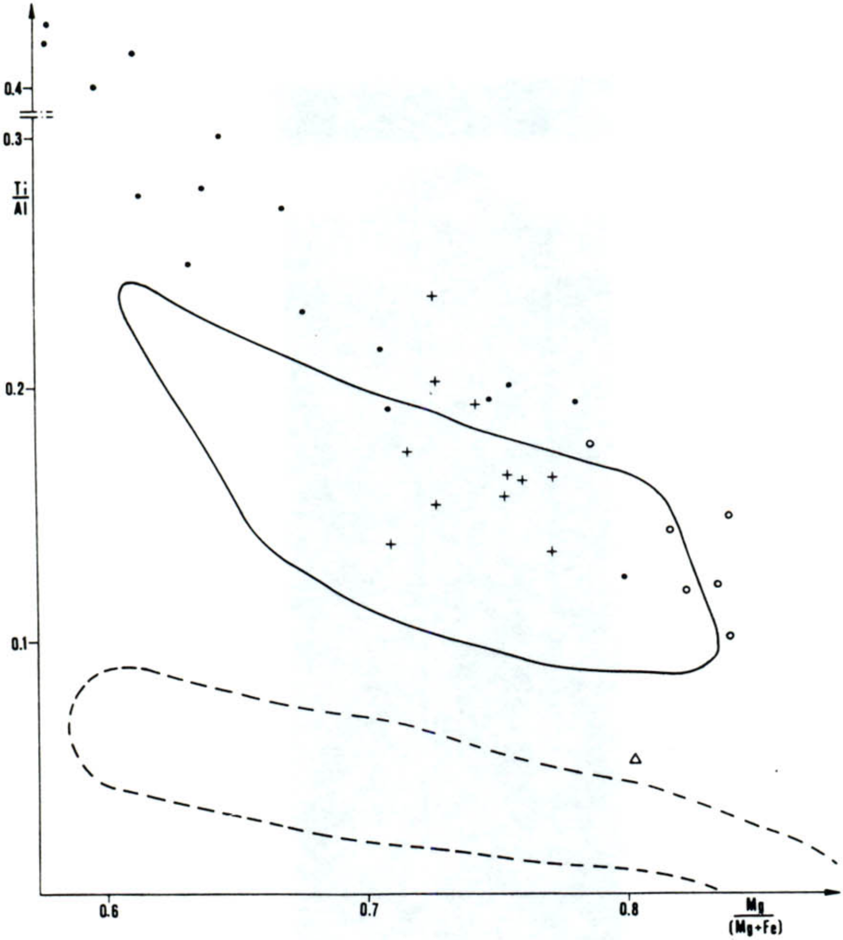


Fig. 4. Ti/Al vs Mg/(Mg+Fe) (atomic ratios) of clinopyroxenes from the metabasalts. The symbols for the different groups are as follows: Group I, dots; Group IIA, crosses; Group IIB, open circles; Group III, triangle. The areas defined by clinopyroxenes from dolerites and massive basalts (continuous line) and from the strongly depleted dykes (dotted line) from the Aspropotamos sequence (CAPEDRI et al., 1981) are reported for comparison.

ondary processes produced chemical changes in the studied basalts. On the basis of the Ti, Zr, Y, Cr, Ni distribution the investigated rocks resemble OFB having in some cases a "within plate" tendency (e. g. samples 131 and 132). The only exception is the dyke 118 which exhibits very low Zr, Y, P_2O_5, TiO_2, Al_2O_3 and high Ni, Cr, MgO contents; the chemical features of this sample cannot be related to cumulus processes only (see Table 3). Most analyzed samples have subalkalic affinity but some are transitional (samples 110, 138,

Table 5. Chemical composition of spinels of basaltic lavas and dykes from Koziakas.

	GROUP I		GROUP III
	135 (1)	137 (2)	118 (1)
SiO_2	0.08	0.09	
TiO_2	0.90	0.62	0.04
Al_2O_3	35.3	29.3	4.49
Cr_2O_3	24.9	33.7	60.5
FeO_{tot}	21.8	20.0	32.6
MgO	15.2	15.2	1.62
CaO	0.90	0.79	0.15
$\frac{Cr}{(Cr+Al)}$	0.32	0.44	0.90
$\frac{Mg}{(Mg+Fe)}$	0.55	0.57	0.08

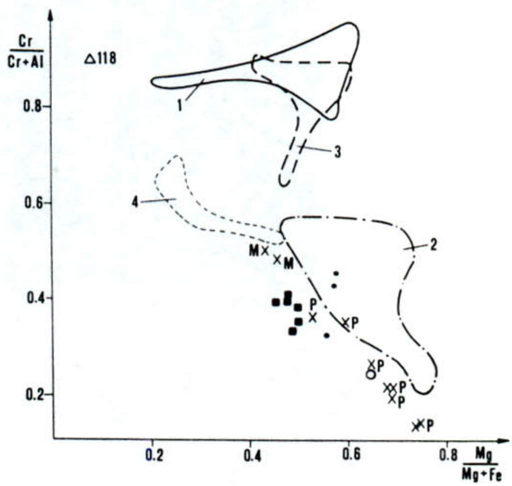


Fig. 5. Cr/(Cr+Al) vs Mg/(Mg+Fe) (atomic ratios) for spinels in rocks from the Koziakas area. Symbols: basalts of Group I, dots; ultramafites, crosses; (P, porphyroclasts; M, matrix phase); recrystallized spinels from gabbros, solid squares; magmatic spinels of gabbros, open circles. Field 1 includes spinels from boninites (Geology of the Philippine Sea floor, 1980; Shiraki et al., 1977); field 2 refers to spinels from MAR basalts (Sigurdsson & Shilling, 1976); fields 3 and 4 refer respectively to the strongly depleted dykes and to the cumulitic gabbros from the Aspropotamos sequence (Capedri et al., 1981).

139) to alkalic as suggested by the Nb/Y ratio (PEARCE & CANN, 1973) and by the P_2O_5 and Zr distribution (WINCHESTER & FLOYD, 1976).

In agreement with the petrographic features and chemical characteristics of clinopyroxene, the samples can be distinguished into three main groups (Fig. 6).

Group I includes samples 110, 131, 132, 138 and 139. On the basis of Nb/Y (1 – 1.2) and Nb/Zr (0.19 – 0.36) ratios they are comparable to enriched MORB (cf. ERLANK & KABLE, 1976; SUN et al., 1979; WOOD et al., 1979).

Group IIA includes samples 122, 144, 145, 146, 147, 148 which have intermediate Nb/Y (0.34 – 0.45) and Nb/Zr (0.13 – 0.17) ratios and are comparable to transitional MORB (PEARCE, 1982).

Group IIB includes samples 108, 152, 153, 157, 159. They are strongly depleted in Nb (Nb/Y = 0.08 – 0.15; Nb/Zr = 0.03 – 0.04) and are comparable to normal MORB (cf. ERLANK & KABLE, 1976; PEARCE, 1982).

Group III includes only sample 118 and has the chemical features already described.

The absence of positive correlation between Nb and Zr (Fig. 6 b) for the less evolved magmas suggests that the different groups of basalts were not generated through porgressive partial melting of the same source. Moreover, the decreasing Y content proceeding from Group IIB to Group I might indicate that melting occurred at different depth.

The chemical variations observed within each group cannot be related only to processes of fractional crystallization at shallow depth. However, the presence of olivine and Cr-spinel phenocrysts in Group I suggests potential separation of these phases. This is supported by the decreasing contents of Ni, Co, Cr in samples 138, 139 and 110 in the order. In Group IIA there is no petrographic evidence of olivine and clinopyroxene fractionation, while plagioclase, present as phenocryst, is a potential separating phase. The subordinate role played by olivine is suggested by the small variations in Ni and Co.

Summary

In the Koziakas area during the Jurassic a carbonate platform margin merged laterally (to the east) to a pelagic sequence consisting mainly of radiolarites which alternate with red clays of Dogger-Malm age and contain magmatic products.

The igneous rocks and associated ultramafites constitute an ophiolitic sequence which was emplaced on the old continental margin.

The ultramafites are mantle tectonites and range from spinel-harzburgites to plagioclase-harzburgites as the consequence of a decompressional path.

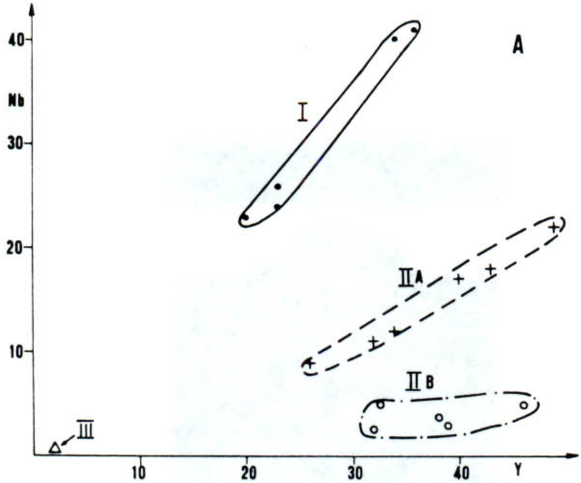
The igneous rocks are mainly pillow lavas mostly MORB-like but with variable geochemical imprint (normal, transitional and enriched MORB) and clinopyroxene composition. Only one basaltic dyke has strongly deviating geochemical features (low TiO_2, P_2O_5, Zr, Y, and high Cr, Ni, MgO) and may

Table 6. Major (wt. %) and trace (ppm) element distribution in ophiolitic metabasalts from Koziakas.

	GROUP I					GROUP IIA						GROUP IIB					GROUP III
Sample	110	131	132	138	139	122	144	145	146	147	148	108	152	153	157	159	118
SiO_2	43.7	46.7	44.5	46.2	43.4	51.9	46.0	45.8	47.3	49.7	49.3	48.4	35.4	44.7	48.2	47.9	40.0
TiO_2	1.14	2.13	2.27	1.05	1.01	1.68	1.49	1.43	1.35	2.05	1.87	2.10	1.47	1.41	1.24	1.55	0.08
Al_2O_3	13.3	15.5	15.4	14.8	14.1	14.8	15.2	14.8	15.9	12.5	12.8	12.1	13.0	13.0	11.3	14.6	9.13
$Fe_2O_3^*$	8.17	8.06	9.85	8.77	8.48	10.2	9.91	11.1	11.0	13.3	12.9	15.0	10.9	12.2	10.0	10.7	11.6
MnO	0.17	0.19	0.21	0.32	0.15	0.20	0.19	0.18	0.16	0.21	0.28	0.28	0.22	0.66	0.55	0.21	0.21
MgO	4.42	2.81	3.30	10.6	4.98	4.72	5.16	5.33	5.27	5.47	6.82	6.38	13.8	6.44	7.31	8.09	22.3
CaO	15.9	11.5	12.7	7.51	14.3	7.29	12.3	11.1	9.71	8.42	9.60	7.78	15.3	10.7	12.1	8.64	9.28
Na_2O	4.78	5.46	4.75	3.98	3.51	4.85	3.92	4.18	3.92	2.83	2.70	4.04	0.49	4.06	3.56	4.25	0.05
K_2O	0.19	0.68	0.33	0.23	0.74	0.53	0.54	0.62	0.46	0.20	0.07	0.20	0.05	0.17	0.09	0.19	0.01
P_2O_5	0.26	0.41	0.45	0.24	0.22	0.25	0.18	0.17	0.15	0.29	0.22	0.17	0.21	0.11	0.12	0.20	0.01
LOI	7.97	6.60	6.32	6.40	9.06	3.58	5.06	5.28	4.82	5.00	3.44	3.60	9.15	6.53	5.52	3.62	7.34

Zr	78	207	223	66	64	113	73	71	76	167	130	130	153	84	80	117	[7]
Nb	26	40	41	24	23	17	9	12	11	22	18	5	5	3	3	4	[1]
Y	23	34	36	23	20	40	26	34	32	49	43	46	34	39	32	38	3
Rb	2.5	9	6		8	6	44	120	8	3	2	6	2	4	2	3	0.4
Sr	329	245	299	322	360	190	225	168	277	97	93	81	74	131	171	295	< 5
Co	14	39	31	39	33	39	44	35	47	43	44	43	42	43	37	37	70
Cr	174	215	220	275	256	78	201	195	399	53	70	113	309	173	248	265	2104
Ni	54	133	133	144	114	48	73	72	101	51	53	65	192	79	100	74	475
V	245	268	284	336	261	370	327	337	332	400	416	481	186	333	272	297	223
Sc	26.2	31.8	31.8	34.2	29.4	44.1	37.3	37.1	40.9	37.8	38.3	53.8	27.5	40.4	36.5	39.2	49.3
Nb/Zr	0.33	0.19	0.18	0.36	0.36	0.15	0.12	0.16	0.14	0.13	0.14	0.04	0.03	0.04	0.04	0.03	[0.15]
Zr/Y	3.39	6.09	6.19	2.87	3.20	2.83	2.81	2.09	2.38	3.41	3.02	2.83	4.50	2.15	2.50	3.08	[2.3]
Nb/Y	1.13	1.18	1.14	1.04	1.15	0.43	0.35	0.35	0.34	0.45	0.42	0.11	0.15	0.08	0.09	0.11	[0.3]
Zr/Ti	1.14	1.62	1.64	1.05	1.06	1.12	0.82	0.83	0.94	1.38	1.13	1.03	1.74	0.99	1.08	1.26	1.56
Y/Sc	0.88	1.07	1.13	0.67	0.68	0.91	0.70	0.92	0.78	1.30	1.12	0.86	1.24	0.97	0.88	0.97	0.06
Ti/V	27.9	47.6	47.9	18.7	23.2	27.2	27.3	25.4	24.4	30.7	26.9	26.2	47.4	25.4	27.3	31.3	2.15

*: total iron as Fe_2O_3; [ ]: less accurate values. Analytical methods: Na, phlame photometry; Mg, atomic absorption; all other elements, X-ray fluorescence.



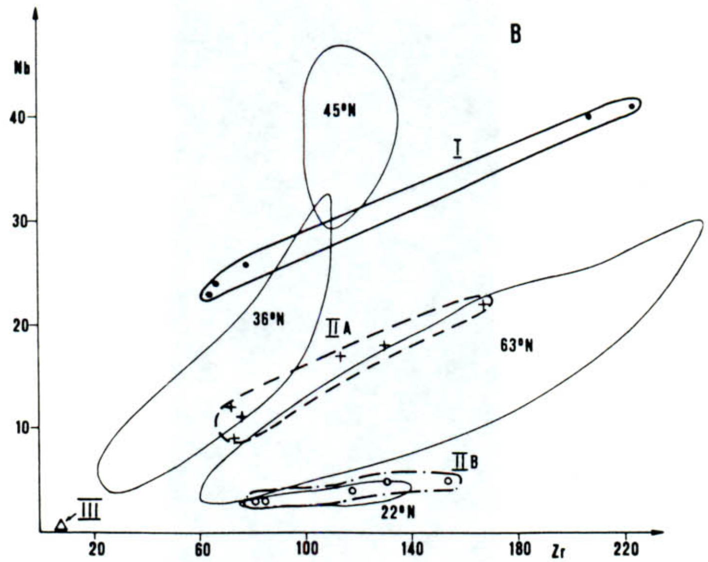


Fig. 6. Nb – Y (6A) and Nb – Zr (6B) plots for the metabasalts from the Koziakas sequence. The fields defined by basalts drilled in the North Atlantic (IPOD Leg 49, Wood et al., 1979; Legs 45 and 46, Bougoult et al., 1980) are also reported for comparison.

be interpreted as a high degree partial melting product of a more depleted mantle source. Gabbros are rare (only one dyke has been sampled) and have unusual chemical features, i. e. abnormally low V and Sc contents.

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