

Metamorphic sole rocks and their mafic dykes in the eastern Tauride belt ophiolites (southern Turkey): implications for OIB-type magma generation following slab break-off

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Abstract – The metamorphic sole rocks observed between the Pozantı–Karsantı ophiolite and the melange unit are located on the eastern part of the Tauride carbonate platform. They consist of ortho-amphibolites at the top and metasedimentary lithologies at the base. Amphibolites from the metamorphic sole rocks are represented by OIB, MORB and IAT based on their major, trace and REE compositions. The isolated dolerite dykes intrude both the metamorphic sole rocks and the ophiolitic unit at different structural levels. The dolerite dykes cutting the metamorphic sole rocks are enriched in LILE and depleted in HFSE. Enrichment in LILE such as Th, relative to HFSE, is indicative of the presence of a subduction component. Flat-lying REE patterns of the dolerite dykes also confirm an IAT source. Pyroxenite and albitite dykes also cut the metamorphic sole rocks. REE patterns of pyroxenite dykes show prominent LREE enrichment, similar to that observed in within-plate alkaline basalts. The alkaline isolated pyroxenite dykes were probably the result of late-stage magmatism fed by melts that originated from an OIB source, shortly before the emplacement of the Pozantı–Karsantı ophiolite onto the Tauride carbonate platform. A hydrothermal alteration stage is characterized by albitite formation in the joints of the metamorphic sole rocks and by secondary mineralization along the contact zones of dolerite dykes. Mineral parageneses in the metamorphic sole rocks exhibit amphibolite and greenschist-facies assemblages. Geothermobarometric studies based on a newly recognized mineral assemblage (e.g. kyanite) and chemical compositions of minerals in the metamorphic sole rocks indicate that the metamorphic temperature during the metamorphism was 570–580 °C and the pressure was around 5–6 kbar.

Keywords: ophiolite, geochemistry, metamorphic rocks, dykes, East Mediterranean.

1. Introduction

The Tauride belt in southern Turkey consists of a succession of nappe systems. It is composed of Palaeozoic and Early Mesozoic platform carbonates, Palaeozoic to Early Mesozoic volcano-sedimentary and epiclastic rocks, Cretaceous ophiolite complexes, Late Cretaceous and younger post-collisional sedimentary and volcanic rocks (e.g. Özgül, 1976). The Tauride Belt Ophiolites are a remnant of the Mesozoic Neotethyan Ocean (Juteau, 1980) (Fig. 1). The Neotethyan Ocean started to close between the Eurasian and Afro-Arabian plates by intra-oceanic thrusting and subsequent ophiolite emplacement during Late Cretaceous times (Şengör & Yılmaz, 1981; Robertson & Dixon, 1984; Dilek & Moores, 1990; Çelik, Delaloye & Feraud, 2006). Petrographic and geochemical analytical results of ophiolite-related intrusives and extrusives suggest that the Late Cretaceous ophiolites of the Tauride belt were formed in a supra-subduction zone environment (e.g. Pearce, Lippard & Roberts, 1984; Parlak, 2000; Parlak, Delaloye & Bingöl, 1996; Parlak, Höck & Delaloye, 2000, 2002; Çelik, Delaloye & Feraud, 2006).

The Tauride Belt Ophiolites do not exhibit a complete section and are located on the Tauride platform carbonates as dispersed slices. The deepest parts, such as tectonites, have been best preserved, and in the upper parts of the assemblage, sheeted dykes have generally disappeared. All the ophiolites of the Tauride belt comprise basaltic lavas and associated sediments such as radiolarites and pelagic limestones. The ophiolite-related alkaline volcanic rocks are very extensive along the Tauride belt and can be observed either below or above the ophiolitic massifs (Whitechurch, Juteau & Montigny, 1984). These alkaline volcanic rocks have been thought to be Late Triassic in age and interpreted as the product of the initial rifting stage of the Neotethyan Ocean (Marcoux, 1976; Robertson & Woodcock, 1981). Tholeiitic volcanic rocks have been observed in the Antalya, Pozantı–Karsantı and Mersin ophiolites (A. S. Çataklı, unpub. D.Sc. thesis, Univ. Nancy, 1983; Robertson & Waldron, 1990; Parlak, Delaloye & Bingöl, 1995). Tauride belt ophiolites are commonly underlain by ophiolite-related metamorphic sole rocks and Cenomanian ophiolitic melange. The age of the metamorphic sole rocks along the Tauride belt ophiolites ranges from 91 to 93 Ma, based on ⁴⁰Ar–³⁹Ar geochronology (Dilek *et al.* 1999; Çelik, Delaloye & Feraud, 2006).

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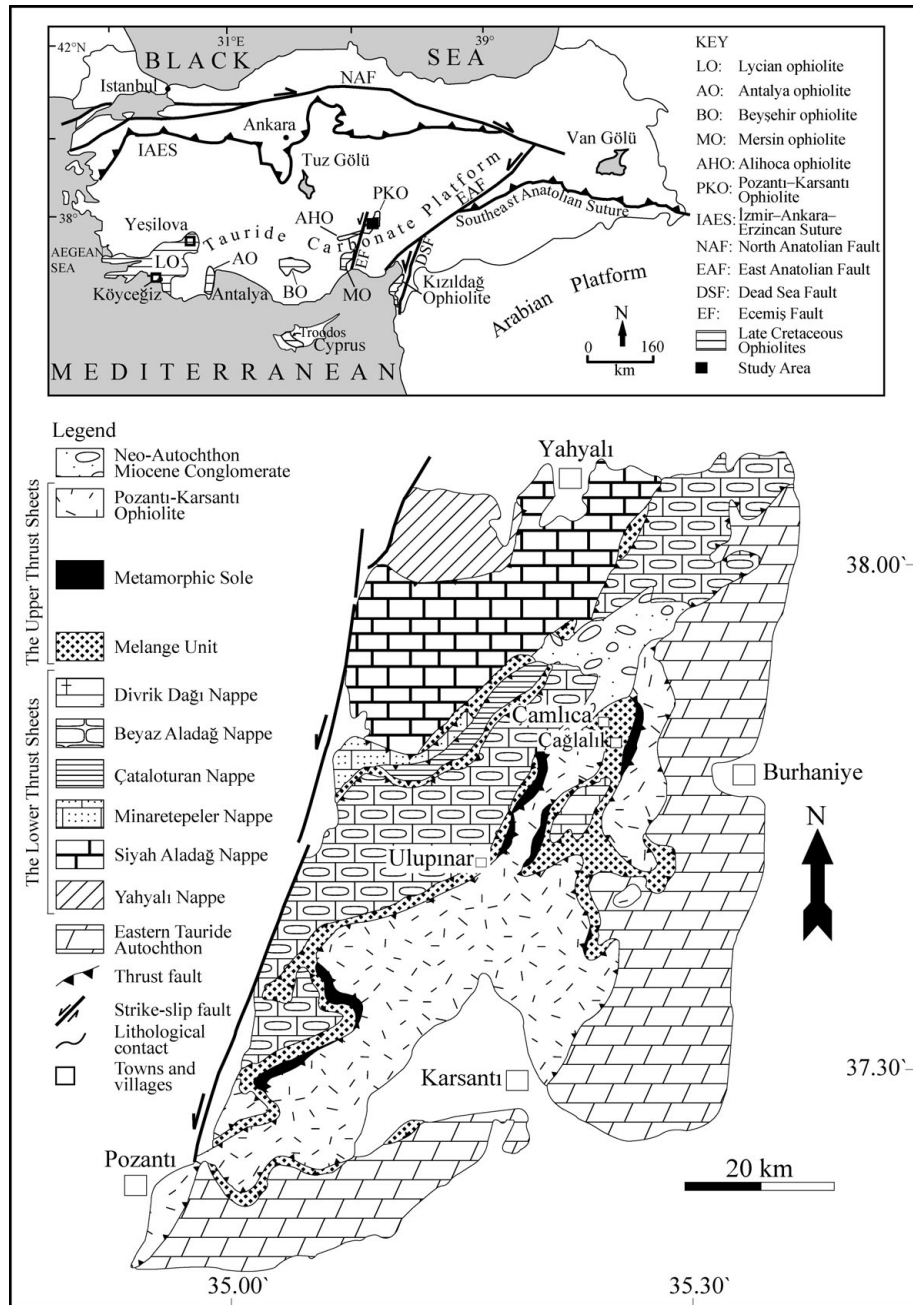


Figure 1. Regional geological map of the study area (modified after Tekeli *et al.* 1983; Polat, Casey & Kerrich, 1996).

The metamorphic sole rocks from the Pozantı-Karsanti ophiolite are the best exposures along the Tauride Belt Ophiolites. Lytwyn & Casey (1995) reported that amphibolites within the metamorphic sole rocks of the Pozantı-Karsanti ophiolite are similar to alkali basalts, whereas greenschist-facies metabasalts are similar to the normal mid-ocean ridge basalts (N-MORB). Polat, Casey & Kerrich (1996) reported that ocean island basalt-like alkali basalts were accreted to the base of the Pozantı-Karsanti ophiolite and metamorphosed under amphibolite-facies conditions. They also postulated that the ocean floor tholeiitic

basalts (N- to E-MORB) and their pelagic cover were metamorphosed under greenschist-facies conditions.

The main objective of this paper is to present detailed whole rock (major, trace and rare earths elements) and mineral chemical data to determine the origin, geodynamic environment and geothermobarometric evolution of the metamorphic sole rocks and the cross-cutting dolerite dykes. An additional objective is to investigate the significance of the late stage pyroxenite dykes which were intruded shortly before the emplacement of the Pozantı-Karsanti ophiolite onto the Tauride platform carbonates.

2. Geological setting

The nappe structures of the Tauride belt were first reported by Blumenthal (1952), who investigated their morphological, stratigraphical and structural features. Özgül (1976) separated different rock units in the Tauride belt based on their different basin conditions. Tekeli *et al.* (1983) indicated that the nappe structure of the eastern Taurides is the result of the ophiolite obduction at the end of Maastrichtian times. The allochthonous upper thrust sheets consist of Early to Late Cretaceous Pozantı–Karsantı ophiolite with metamorphic sole rocks, and the underlying melange unit. The lower thrust sheets are composed of parautochthonous units, including platform carbonates of Late Devonian through Early Cretaceous age (Tekeli *et al.* 1983). However, Campanian and Maastrichtian (Polat, Casey & Kerrich, 1996) and Late Cretaceous or Early Paleocene (Lytwyn & Casey, 1995) were reported for the emplacement age of the Pozantı–Karsantı ophiolite onto the Tauride carbonate platform.

The Pozantı–Karsantı ophiolite and underlying platform carbonates are separated from the Alihoca and the Mersin ophiolites by the left-lateral Ececiş fault (Fig. 1). The Pozantı–Karsantı ophiolite is one of the largest Late Cretaceous oceanic lithosphere remnants observed in the eastern Tauride belt. It is more than 100 km long and 30 km wide. The Pozantı–Karsantı ophiolite presents a complete oceanic lithosphere and consists, from bottom to top, of tectonized peridotites (harzburgites and dunites), ultramafic cumulates (dunite, wehrlite and pyroxenite), mafic layered cumulates (gabbro and hornblende-gabbro), isotropic gabbros and minor plagiogranites, scattered tectonized slices of sheeted dyke complex and basaltic pillow lavas (Fig. 2). Swarms of fine- to coarse-grained doleritic and gabbroic dykes cut the entire ophiolite sequence as well as the metamorphic sole rocks but these dykes do not cut the ophiolitic melange and the platform carbonates, nor do they show any folding structures. Accordingly, dyke injection has been interpreted to have developed in the oceanic environment prior to obduction of oceanic crust onto the Tauride platform carbonates but after ductile deformation of the metamorphic sole rocks.

The highly folded and faulted metamorphic sole rocks at the base of the mantle tectonites of the Pozantı–Karsantı Ophiolite are 400 to 500 m thick. The fold axes of the amphibolites vary between NW–SE and E–W. However, dykes cutting the metamorphic sole rocks have a general trend between N50E and E–W. The contacts between the metamorphic sole rocks and the overlying ophiolites are defined by a 3–5 m thick strongly sheared serpentinized mantle tectonite. Both amphibolites and harzburgites present well-developed foliation and schistosity along the contact with metamorphic sole rocks and ophiolites. These foliations are parallel to each other along the contact.

The amphibolites are represented by compositional banding of hornblende and plagioclase near the contact with the peridotites. The prominent foliation and compositional banding can be interpreted to have formed during the initial detachment of the ophiolite. During this movement, mylonitic fabric could be developed within the basal peridotite. The melange unit is divided into three tectonostratigraphic units (Polat, Casey & Kerrich, 1996): (a) the upper tectonic slice consisting of serpentinitic matrix with ophiolitic and metamorphic blocks; (b) the middle tectonic slice composed of red pelitic matrix surrounding ophiolitic blocks at the top and limestone blocks at the bottom; and (c) the lower tectonic slice consisting of pelitic matrix at the top and tectonic breccia at the bottom. The contacts in the Pozantı–Karsantı ophiolite and surrounding units are all tectonic.

3. Mineralogy and petrography

The upper part of the metamorphic sole rocks consists mainly of amphibolites, whereas the lower part is composed of micaschists, marble and quartzite. However, the micaschists are observed as small slices within the amphibolites. The foliation in the amphibolites is very common and defined by subparallel alignment of amphibole–epidote and amphibole–plagioclase crystalloblasts. The most conspicuous textures of the amphibolites are granoblastic, granonematoblastic, porphyronematoblastic and poikiloblastic. Plagioclase is commonly altered and polysynthetic twinning is generally missing. It is replaced by albite or epidote in some amphibolitic rocks, but variable anorthite content in the same sample indicates continuous alteration and recrystallization. Spinel is commonly observed along the foliation planes and as inclusions in amphibole crystalloblasts. It is also parallel to the lineation plane of the amphibole crystalloblast and it could have been developed during the deformation stage of the metamorphic sole rocks. In the coarse-grained amphibolites quartz is absent, whereas towards the lower part of the sole it becomes very abundant. As the lower part of the metamorphic sole rocks was more affected by tectonism, recrystallization of quartz with mosaic texture is common. Apatite was observed only in the upper part of the metamorphic sole rocks as an accessory mineral. Epidote, clinozoisite and zoisite are very abundant constituents of the upper part of the metamorphic sole rocks. They occur as primary and secondary minerals. Pyroxene is observed exclusively in samples PK-2 (Fig. 3d) and PK-29. Both pyroxenes and amphiboles in sample PK-29 exist as equidimensional crystalloblasts and present a clear contact between them, whereas the pyroxene of sample PK-2 is located in the texture as porphyroblasts. Since the upper parts of the metamorphic rocks of the Pozantı–Karsantı ophiolite present variable mineral

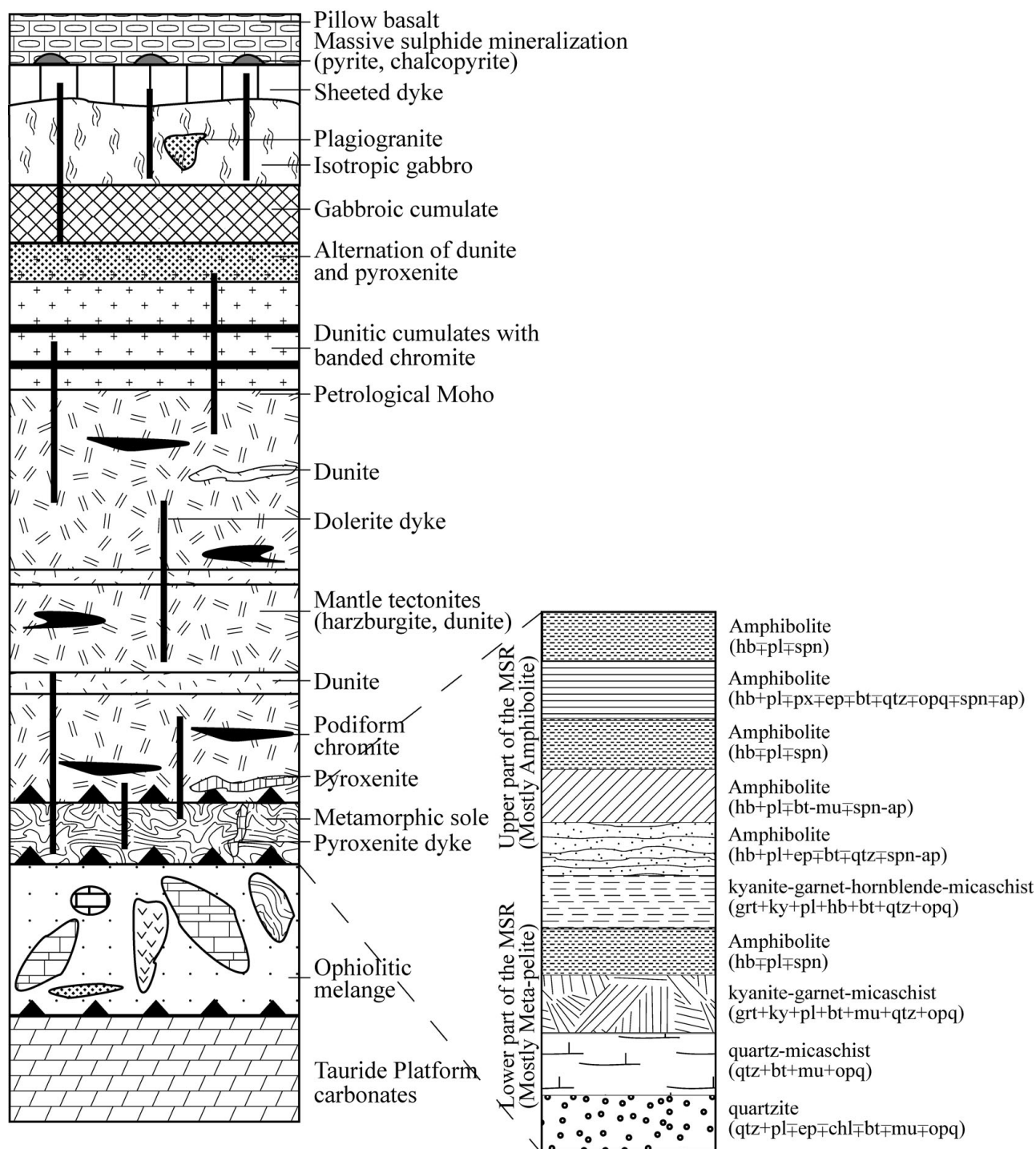


Figure 2. Synthetic log of the Pozanti-Karsanti ophiolite (modified from A. F. Bingöl, unpub. D.Sc. thesis, Univ. Strasburg, 1978; Parlak, Höck & Delaloye, 2002), and the rock types of the metamorphic sole rocks (MSR). Mineral abbreviations: hb – hornblende; pl – plagioclase; px – pyroxene; grt – garnet; ky – kyanite; ep – epidote; bt – biotite; mu – muscovite; qtz – quartz; chl – chlorite; spn – sphene; ap – apatite; opq – opaque minerals.

parageneses and textures, they were grouped according to their mineralogical assemblages.

Group (A): amphibole + plagioclase ± pyroxene ± epidote ± biotite ± quartz ± opaque (mostly ilmenite) ± accessory minerals such as sphene and apatite (Fig. 3a). For example, in modal composition, sample PK-2 is represented by 80 % hornblende, 10 % plagioclase, 8 % pyroxene, 2 % sphene.

Group (B): amphibole ± accessory minerals. In modal composition, amphibolite samples are represented by hornblende 99 % and accessory minerals 1 %.

Group (C): amphibole + plagioclase ± biotite and muscovite ± accessory minerals. In modal composition, for example, sample PK-9 consists of hornblende 80 %, plagioclase 18 %, accessory minerals 1 % and opaques 1 %.

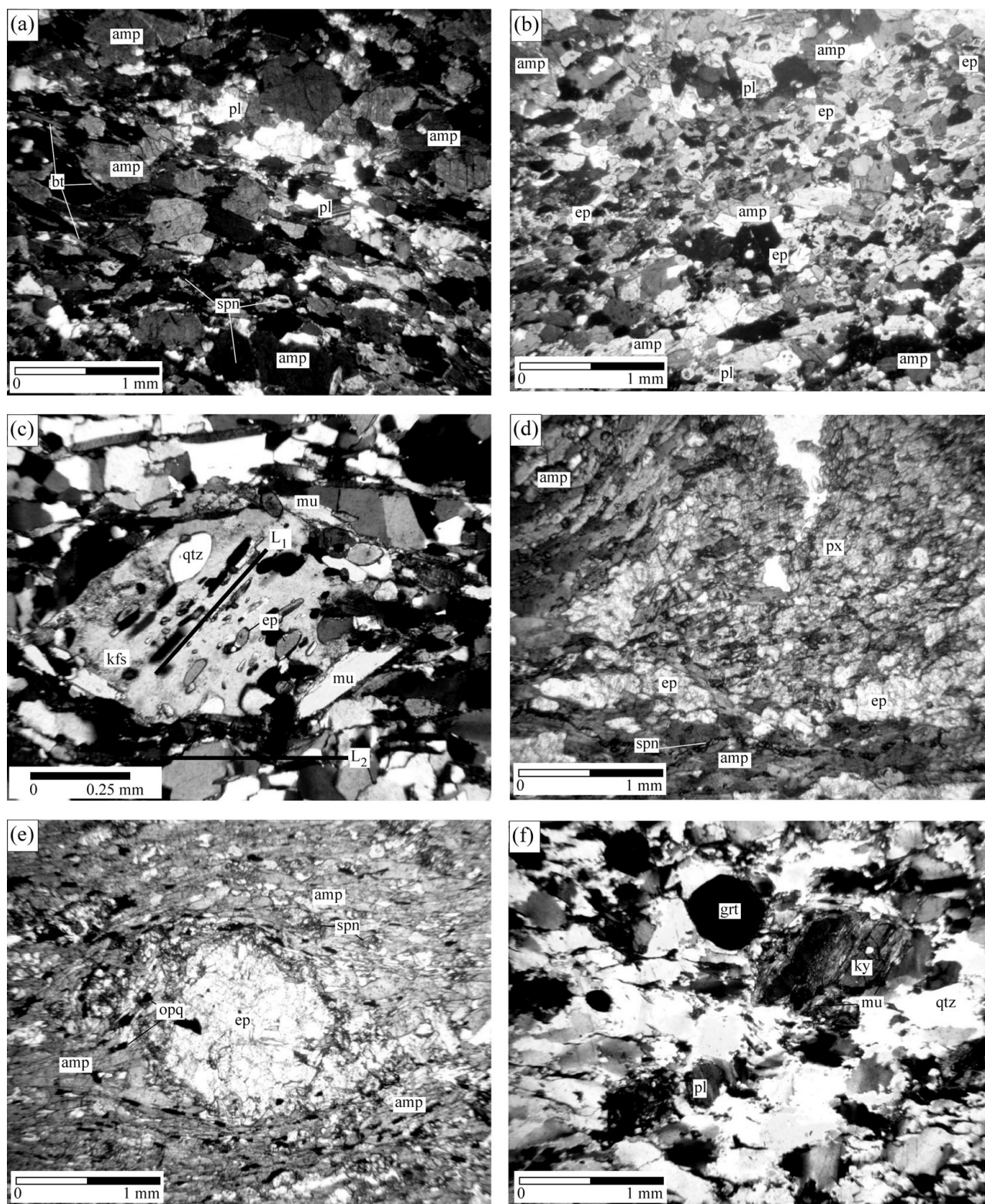


Figure 3. Photomicrographs of different mineral phases and some textural relations in the metamorphic sole rocks: (a) amphibolite showing nematoblastic texture from the upper part of the metamorphic sole rocks; (b) epidote–amphibolite; (c) pronounced L_1 and L_2 lineation in micaschist; (d) clinopyroxene and amphibole association exhibiting porphyronematoblastic texture; (e) epidote–amphibolite showing augen structure; (f) kyanite–garnet bearing micaschist and muscovite development around a kyanite porphyroblast. Mineral abbreviations as in Figure 2.

Group (D): amphibole + plagioclase + epidote $\pm$ biotite $\pm$ quartz $\pm$ calcite $\pm$ accessory minerals (Fig. 3b). In modal composition, samples are

composed of hornblende 60 %, plagioclase 10 %, epidote 26 %, quartz 2 %, biotite 1 % and sphene 1 %.

The lower part of the metamorphic sole rocks is composed mainly of garnet–kyanite–quartz–feldspar–micaschist, garnet–kyanite–amphibole–quartz–feldspar–micaschist, quartz–micaschist and quartzite. Muscovite is very abundant in the lower part of the metamorphic sole rocks and is the main K-bearing mineral. Garnet is an abundant mineral in the micaschists, but is absent in the amphibolites. A quartz–micaschist from the lower part of the metamorphic sole rocks exhibits pronounced L1 and L2 lineations (Fig. 3c). L1 lineation is observed with epidote and quartz minerals in an K-feldspar. L2 lineation is defined by mica minerals and was probably generated during tectonic transportation. The existence of kyanite in the metamorphic sole rocks of the Pozantı–Karsanti ophiolite is first recognized in this study. Kyanite is usually surrounded by muscovite and chlorite. During the retrograde rehydration or deformational stage, kyanite probably reacted with plagioclase to form muscovite and chlorite (Fig. 3f).

The dykes present chilled margins and their thicknesses vary between 10 cm and 20 m. They show an ophitic, subophitic and intergranular texture, but the original textures have been largely affected by hydrothermal alteration. Both doleritic and gabbroic dykes consist mainly of amphibole, pyroxene, plagioclase, quartz, epidote, sphene and ilmenite. Amphibole is an abundant phase in the mineral parageneses. Plagioclases exhibit alterations but fresh plagioclases in the same rocks are also observed, indicating recrystallization during the hydrothermal alteration phase. Pyroxene is more abundant in dykes which have a thickness over 30 cm. Ilmenite is generally observed as dendritic crystals in the dolerite dykes and is usually observed in pyroxene-rich rocks. Epidote is a common mineral along contacts with plagioclase and amphibole, but is not observed in contact with pyroxene. This may indicate that epidote is likely to be generated during the hydrothermal alteration phase. In some samples, near the contact of the dykes, epidote is replaced by amphibole. Quartz is an abundant phase forming as an intersertal xenomorph mineral in some doleritic and gabbroic dykes, possibly generated during late hydrothermal activity. The presence of epidote in association with chlorite, actinolite, sphene and calcite in dykes suggests a low-temperature hydrothermal alteration in upper greenschist-facies conditions (Spear, 1981). Chlorite occurs as fibrous aggregates and probably formed during alteration of hornblende and plagioclase. The presence of chlorite and actinolite in dolerite indicates alteration at temperatures between 350 °C and 450 °C (Liou, Kuniyoshi & Ito, 1974; Spear, 1981; Stakes, Taylor & Fisher, 1984).

Albitite and pyroxenite dykes in the metamorphic sole rocks of the Pozantı–Karsanti ophiolite are first described in this study. Albitites consist of plagioclase + epidote + apatite and opaque minerals and show granular texture. They also cut the metamorphic sole

rocks and their thicknesses do not exceed 30 cm. Albitites do not exhibit a chilled margin. They do not present planar contact with amphibolite. For these reasons, it could be thought that they were formed in the joints of the metamorphic sole rocks in an oceanic environment during the hydrothermal alteration stage.

Pyroxenite dykes consist of pyroxene 95 %, plagioclase 2 %, epidote 2 % and sphene 1 %. They cut amphibolite rocks so that they were generated after the main metamorphism of the metamorphic sole rocks. They have a thickness between 10 and 30 cm and present a granular texture.

4. Analytical methods

Geochemical studies on the amphibolites and dyke rocks were performed both on whole rocks and minerals. A total of 104 samples from the metamorphic sole rocks (66), isolated dolerite and gabbro dykes (28), pyroxenite dykes (7) and albitite dykes (3) were analysed for major and trace element contents. A subset of 19 samples was analysed for rare earth elements (REE). Major and trace element concentrations of the rock samples were determined by the XRF technique at Lausanne University (Switzerland). Compositions were determined on glass beads fused in a gold–platinum crucible at 1150 °C from ignited powders to which $\text{Li}_2\text{B}_4\text{O}_7$ was added in the proportion of 1 part of rock to 5 parts of flux. REE were analysed using the inductively coupled plasma-mass spectrometry (ICP-MS) technique (Actlabs, Ancaster, Ontario, Canada). Representative major, trace and REE analyses of the metamorphic sole rocks and dyke rocks are documented in Table 1. Mineral analyses were performed on a Cameca SX50 electron microprobe at the University of Lausanne equipped with wavelength dispersive spectrometry. Operating conditions were 15 kV accelerating voltage and 15 nA sample current. Counting times of 10–30 s were applied. Representative analyses for the minerals are given in Tables 2 and 3.

5. Whole rock geochemistry

5.a. Metamorphic sole rocks and dolerite–gabbro dykes

Geochemical indicators consistently show that the amphibolites from the Pozantı–Karsanti ophiolite are ortho-amphibolites. On a Zr/TiO₂ v. Nb/Y diagram, amphibolites plot mostly in an alkali basalt field corresponding to alkali amphibolites derived from ocean island alkali basalt or seamount compositions (Fig. 4a). Moreover, some amphibolites exhibit subalkaline basalt affinity, which would correspond to the amphibolites derived from MORB and island arc tholeiites (IAT) in the Neotethyan Ocean. The lower part of the metamorphic sole rocks is represented by kyanite–garnet-bearing micaschists, micaschists,

Table 1. Representative chemical analyses of amphibolites, mica-schists and dykes from the metamorphic sole rocks of the Pozanti-Karsanti ophiolite

Rock Sample	amp PK-1	amp PK-9	amp PK-17	amp PK-26	amp PK-27	amp PK-28	amp PK-29	amp PK-62	amp PK-72	d-dyke PK-54	d-dyke PK-67	d-dyke PK-74	d-dyke PK-213	d-dyke PK-215	d-dyke PK-216	px-dyke PK-180	px-dyke PK-222	px-dyke PK-224	m-schist PK-44	m-schist PK-59
SiO ₂	45.58	46.79	52.06	44.90	43.92	44.14	45.02	44.94	45.30	52.80	53.21	50.84	51.30	51.81	51.76	49.92	40.48	50.22	68.53	90.91
Al ₂ O ₃	11.77	10.36	11.23	10.98	16.05	13.94	15.27	11.18	11.80	15.03	15.03	15.01	15.18	15.42	14.82	2.43	15.60	1.28	9.36	4.02
TiO ₂	2.44	2.95	2.15	2.07	0.82	0.94	0.78	2.83	2.99	1.11	0.53	1.07	0.90	1.03	0.97	2.54	2.20	3.14	1.55	0.29
Fe ₂ O ₃	12.42	15.30	13.23	12.90	9.89	11.56	9.48	11.92	13.46	12.01	8.76	10.13	10.32	10.27	9.96	10.78	11.63	11.41	8.24	1.89
MnO	0.17	0.39	0.32	0.17	0.15	0.19	0.15	0.19	0.19	0.18	0.15	0.17	0.17	0.18	0.18	0.23	0.14	0.24	0.15	0.02
MgO	11.87	9.91	8.75	13.50	9.87	12.36	9.02	12.03	9.09	4.50	7.29	6.37	5.61	5.87	6.18	9.48	2.85	10.00	4.83	0.63
CaO	11.56	8.49	7.59	11.53	15.81	12.17	16.01	12.00	11.65	7.30	11.39	9.38	8.21	9.92	10.21	22.74	24.92	22.57	2.08	0.44
Na ₂ O	2.09	3.34	1.52	1.68	1.30	2.10	1.64	2.15	2.72	2.86	1.52	3.77	2.33	2.63	2.33	0.79	0.19	0.85	1.49	0.38
K ₂ O	0.42	0.40	0.85	0.54	0.15	0.36	0.59	0.38	0.40	2.09	0.30	0.68	3.36	0.31	0.39	0.10	0.02	n.d	1.87	1.30
P ₂ O ₅	0.38	0.03	0.35	0.32	0.09	0.09	0.08	0.23	0.37	0.09	0.04	0.10	0.07	0.10	0.09	0.17	0.85	0.02	0.24	0.08
LOI	1.52	0.91	1.27	1.54	1.79	1.54	1.44	1.04	1.13	1.77	2.14	1.37	2.30	1.98	2.10	0.19	1.24	0.25	1.12	0.59
Total	100.22	98.87	99.32	100.13	99.84	99.39	99.48	98.86	99.09	99.74	100.37	98.9	99.74	99.52	99.00	99.37	100.12	99.98	99.45	100.55
V	257	196	265	211	224	281	197	269	308	411	272	287	346	323	316	73	324	85	123	43
Cr	343	416	342	889	519	748	469	537	492	30	193	66	44	77	103	455	343	756	71	13
Co	16	71	53	80	64	69	64	30	74	56	49	67	56	77	73	78	81	71	116	153
Ni	n.d	160	62	520	175	416	185	90	136	66	43	23	29	39	45	253	206	221	85	16
Cu	27	20	72	48	66	40	82	54	100	73	64	70	57	55	64	20	21	n.d	126	27
Zn	n.d	96	n.d	160	n.d	87	33	n.d	112	82	n.d	69	79	74	71	81	85	155	78	28
Ga	7	14	16	15	14	14	13	9	20	17	13	18	17	17	16	6	34	5	12	8
Rb	4	4	20	6	1	8	6	2	4	46	7	27	78	9	10	2	5	n.d	48	28
Sr	275	223	80	249	168	65	130	324	200	142	98	251	149	120	112	249	886	190	250	57
Y	23.4	27.2	58.8	17.2	22.4	23.4	22.2	25.7	25.6	24.6	15.2	29.3	24	24	24	33.8	22.4	45.4	27	15
Zr	152	228	192	145	33	40	32	150	195	56	27	64	56	64	60	241	171	411	129	48
Nb	21.6	16.3	59.3	28.8	1.6	3	2	25.1	53.5	1.2	0.7	1.8	2	3	3	46.7	47.3	63.3	30	18
Ba	103	96	87	106	7	19	23	54	102	440	26	107	702	57	63	19	21	15	225	201
Hf	4.3	5.7	5.7	3.7	1.1	1.4	1.1	5	6	1.8	0.9	2.2	5	1	4	6.5	4.5	9.2	8	13
Ta	2.7	1.5	5.8	2.2	0.4	0.3	0.4	3.1	3.7	0.4	0.5	0.5	n.d	n.d	n.d	4.0	3.8	6.0	n.d	n.d
Th	3.1	7.6	6.6	2.9	0.3	0.2	0.2	3.3	4.9	0.2	0.2	0.3	n.d	n.d	n.d	9.1	5.0	11.8	5	4
U	0.9	0.3	1.5	0.6	0.2	n.d	0.2	0.9	1.1	0.1	0.1	0.1	n.d	n.d	n.d	2.8	1.7	2.0	n.d	n.d
La	28.5	48.6	39.4	22.4	2.99	1.84	2.44	32	42.8	1.99	1.18	2.89	2.08	2.72	2.50	55.50	45.70	97.70		
Ce	60	89.4	86.4	47.7	7.1	6.17	6.2	69.9	89	6.29	3.53	9.19	6.14	7.83	7.27	116	82.7	204		
Pr	6.63	9.32	9.35	5.53	1.15	1	1.06	7.85	9.64	0.99	0.54	1.4	1.18	1.45	1.37	13.3	10.3	22.5		
Nd	27.9	36.9	40.8	23.5	5.96	5.9	5.82	33.6	41.4	5.6	3.23	8.35	6.03	7.35	7.10	51.7	41.3	84.6		
Sm	6.01	7.34	10.4	4.81	2.12	2.08	2.04	7.19	8.12	2.1	1.24	2.93	2.30	2.65	2.62	9.83	7.53	15.7		
Eu	2.28	2.14	3.4	1.54	0.91	0.86	0.88	2.72	2.83	0.88	0.53	1.19	1.01	1.12	1.11	3.10	2.43	5.04		
Gd	6.21	6.82	11.8	4.5	2.82	3.44	2.73	7.6	7.97	3.33	1.97	4.29	3.37	3.85	3.64	8.34	6.23	14.2		
Tb	0.97	1.06	2.21	0.69	0.61	0.66	0.6	1.09	1.16	0.68	0.42	0.84	0.76	0.82	0.81	1.30	0.90	2.10		
Dy	5.2	5.6	12.7	3.62	3.85	4.36	3.79	5.95	6.07	4.5	2.84	5.52	4.23	4.60	4.49	7.02	4.77	10.5		
Ho	0.96	0.98	2.3	0.64	0.79	0.95	0.77	1.11	1.09	1.01	0.62	1.16	1.06	1.15	1.11	1.33	0.84	1.85		
Er	2.36	2.67	5.83	1.68	2.42	2.81	2.34	2.79	2.7	3	1.89	3.31	2.81	3.10	2.96	3.26	1.98	4.73		
Tm	0.31	0.35	0.77	0.22	0.37	0.422	0.36	0.35	0.33	0.44	0.28	0.50	0.56	0.60	0.58	0.45	0.24	0.53		
Yb	1.79	2.03	4.38	1.29	2.28	2.76	2.12	2.03	1.9	2.89	1.82	3.1	2.75	2.98	2.82	2.65	1.53	3.39		
Lu	0.24	0.27	0.59	0.17	0.36	0.40	0.34	0.28	0.247	0.46	0.3	0.46	0.58	0.61	0.60	0.37	0.21	0.44		

n.d. – not determined; amp – amphibolite; d-dyke – dolerite dyke; px-dyke – pyroxenite dyke; m-schist – mica-schist

Table 2. Representative microprobe analyses of amphibole and mica from metamorphic sole rocks of the Pozantı-Karsantı ophiolite

Sample Rock type Mineral	PK-9-5c amphibolite amphibole	PK-9-12c amphibolite amphibole	PK-50-1c amphibolite amphibole	PK-206-2 amphibolite amphibole	PK-69-5c d-dyke amphibole	PK-69-7c d-dyke amphibole	PK-44-2c m-schist amphibole	PK-44-7c m-schist amphibole	Sample Rock type Mineral	PK-20-18 m-schist mica	PK-20-19 m-schist mica	PK-20-20 m-schist mica	PK-20-21 m-schist mica	PK-20-23 m-schist mica	PK-20-25 m-schist mica
SiO ₂ (wt %)	43.91	43.78	41.97	45.43	49.62	47.3	43.3	43.8	SiO ₂	47.76	47.42	47.21	47.03	47.22	47.05
TiO ₂	1.04	1.09	1.96	0.61	0.66	1.61	0.64	0.6	TiO ₂	1.25	1.36	1.12	1.02	1.21	1.11
Al ₂ O ₃	12.43	11.61	11.92	11.57	5.88	7.37	15.2	15	Al ₂ O ₃	32.48	32.23	32.84	32.76	32.78	32.67
Fe ₂ O ₃ (c)	5.67	5.04	0.87	2.64	2.81	6.38	9.44	11.01	Cr ₂ O ₃	0.05	0.06	0	0.25	0	0.13
FeO(c)	9.55	10.8	16.88	12.3	13.86	11.9	3.46	1.59	FeO	3.68	3.78	3.82	4.15	4.18	3.78
MnO	0.47	0.37	0.29	0.21	0.22	0.35	0.66	0.81	MnO	0	0.01	0.09	0	0.11	0
MgO	11.28	11.21	9.13	11.32	12.09	11.1	12.3	12.9	MgO	1.63	1.83	1.54	1.75	1.64	1.67
CaO	10.4	10.64	11.21	11.1	11.96	10.81	10.2	9.99	CaO	0.01	0.01	0.03	0.03	0.01	0.02
Na ₂ O	2.63	2.7	2.67	2.43	0.98	1.45	2.33	2.28	Na ₂ O	0.92	0.95	1.01	0.97	0.96	0.92
K ₂ O	0.73	0.67	1.35	0.63	0.06	0.09	0.32	0.33	K ₂ O	6.2	6.25	6.43	6.29	6.35	6.25
Total	98.1	97.86	98.23	98.23	98.17	98.4	97.84	98.31	BaO	0.37	0.41	0.34	0.38	0.41	0.36
<i>Based on 23 O</i>									Total	94.34	94.3	94.43	94.63	94.86	93.94
Si (apfu)	6.427	6.459	6.335	6.648	7.251	6.926	6.214	6.225	<i>Based on 22 O</i>						
Ti	0.115	0.121	0.222	0.067	0.073	0.177	0.069	0.064	Si (apfu)	6.341	6.316	6.284	6.258	6.279	6.285
Al ^{IV}	1.573	1.541	1.665	1.352	0.749	1.074	1.786	1.775	Ti	0.124	0.136	0.113	0.103	0.121	0.112
Al ^{VI}	0.572	0.477	0.456	0.643	0.264	0.197	0.785	0.738	Al ^{IV}	1.659	1.684	1.716	1.742	1.721	1.715
Fe ³⁺	0.625	0.559	0.099	0.29	0.309	0.702	1.019	1.177	Al ^{VI}	3.424	3.375	3.435	3.396	3.416	3.428
Fe ²⁺	1.17	1.332	2.131	1.505	1.694	1.457	0.415	0.189	Cr	0.005	0.006	0.000	0.026	0.000	0.014
Mn	0.059	0.046	0.037	0.026	0.028	0.044	0.08	0.098	Fe ²⁺	0.408	0.421	0.425	0.462	0.465	0.423
Mg	2.46	2.464	2.055	2.468	2.633	2.422	2.631	2.733	Mn	0.000	0.001	0.010	0.000	0.013	0.000
Ca	1.631	1.682	1.813	1.74	1.872	1.696	1.568	1.521	Mg	0.323	0.363	0.305	0.347	0.324	0.332
Na	0.748	0.773	0.781	0.688	0.277	0.412	0.648	0.628	Ca	0.001	0.001	0.004	0.004	0.001	0.003
K	0.137	0.126	0.259	0.117	0.011	0.016	0.059	0.06	Na	0.237	0.245	0.260	0.249	0.247	0.239
X _{Mg}	0.678	0.649	0.491	0.621	0.608	0.624	0.864	0.935	K	1.050	1.062	1.093	1.067	1.077	1.066
									Ba	0.019	0.021	0.018	0.02	0.021	0.019
									X _{Mg}	0.442	0.463	0.417	0.429	0.411	0.44

d-dyke – dolerite dyke; m-schist – mica-schist

Table 3. Representative microprobe analyses of pyroxene, garnet and feldspar from metamorphic sole rocks of the Pozanti-Karsanti ophiolite

Sample	PK-29-2c	PK-29-10c	PK-182-1	PK-182-2	Sample	PK-20-4c	PK-20-4r1	PK-20-6r10	PK-44-2c	PK-44-2r3	Sample	PK-44-1c	PK-44-1r1	PK-50-14	PK-50-11
Rock type	amphibolite	amphibolite	amphibolite	amphibolite	Rock type	micaschist	micaschist	micaschist	micaschist	micaschist	Rock type	micaschist	micaschist	amphibolite	amphibolite
Mineral	pyroxene	pyroxene	pyroxene	pyroxene	Mineral	garnet	garnet	garnet	garnet	garnet	Mineral	feldspar	feldspar	feldspar	feldspar
SiO ₂	53.67	54.15	53.11	52.99	SiO ₂	37.55	37.76	37.08	38.41	37.93	SiO ₂	58.01	59.54	65.79	67.94
TiO ₂	0.05	0.03	0.06	0.05	TiO ₂	0.1	0.11	0.81	0.03	0.04	Al ₂ O ₃	25.14	25.4	22.3	20.13
Al ₂ O ₃	1.16	1.22	1.07	0.83	Al ₂ O ₃	20.53	20.54	19.99	20.93	21.11	Fe ₂ O ₃	0	0	0.02	0
Cr ₂ O ₃	0.04	0.12	0.11	0.11	Cr ₂ O ₃	0	0.05	0.03	0	0	MgO	0.02	0	0	0.01
Fe ₂ O ₃ (c)	0.35	0	0.78	1.08	Fe ₂ O ₃ (c)	2.33	2.41	2.39	1.28	1.91	CaO	7.71	7.62	2.54	0.24
FeO(c)	5.51	5.43	9.85	10.12	FeO	13.97	14.1	14.88	19.65	18.95	Na ₂ O	7.47	7.42	9.56	11.72
MnO	0.27	0.27	0.28	0.28	MnO	15.31	15.6	14.82	7.39	7.7	K ₂ O	0.07	0.05	0.26	0.05
MgO	14.16	14.04	11.02	11.06	MgO	5.96	5.9	5.83	7.27	7.58	Total	98.42	100.03	100.47	100.1
CaO	24.02	24.3	22.63	22.84	CaO	3.81	3.78	3.73	4.59	4.01	<i>Based on 8 O</i>				
Na ₂ O	0.52	0.44	1.03	0.87	Total	99.55	100.25	99.56	99.56	99.22	Si	2.636	2.655	2.873	2.968
Total	99.74	99.99	99.95	100.23	Si	2.968	2.969	2.944	2.998	2.968	Al ^{IV}	1.346	1.335	1.148	1.037
<i>Based on 6 O</i>					Ti	0.006	0.007	0.048	0.002	0.002	Al ^{VI}	0	0	0.001	0
Si	1.987	1.996	2	1.995	Al ^{IV}	0.032	0.031	0.056	0.002	0.032	Mg	0.001	0	0	0
Ti	0.001	0.001	0.002	0.001	Al ^{VI}	1.881	1.872	1.814	1.923	1.915	Ca	0.376	0.364	0.119	0.011
Al ^{IV}	0.013	0.004	0	0.005	Cr	0	0.003	0.002	0	0	Na	0.658	0.642	0.809	0.993
Al ^{VI}	0.037	0.049	0.047	0.032	Fe ³⁺	0.139	0.142	0.143	0.075	0.113	K	0.004	0.003	0.015	0.003
Cr	0.001	0.003	0.003	0.003	Fe ²⁺	0.923	0.927	0.988	1.282	1.24	Ab	63.421	63.601	85.713	98.614
Fe ³⁺	0.01	0	0.022	0.031	Mn ²⁺	1.025	1.039	0.997	0.489	0.51	An	36.207	36.079	12.602	1.126
Fe ²⁺	0.171	0.167	0.31	0.319	Mg	0.703	0.692	0.69	0.845	0.884	Or	0.372	0.278	1.559	0.251
Mn	0.008	0.008	0.009	0.009	Ca	0.323	0.318	0.317	0.384	0.336					
Mg	0.781	0.771	0.618	0.621	Pyrope	23.624	23.254	23.069	28.175	29.752					
Ca	0.953	0.959	0.913	0.921	Almandine	31.05	31.146	33.023	42.74	41.758					
Na	0.038	0.031	0.075	0.063	Spessartine	34.466	34.907	33.3	16.292	17.178					
Wo(Ca)	50.03	50.551	49.579	49.512	Andradite	6.857	7.036	7.106	3.766	5.554					
En(Mg)	41.009	40.631	33.576	33.361	Uvarovite	0.001	0.161	0.088	0.001	0.001					
Fs(Fe ²⁺)	8.961	8.818	16.845	17.127	Grossular	4.003	3.496	3.415	9.027	5.758					
X _{Mg}	0.821	0.822	0.666	0.661	X _{Mg}	0.432	0.427	0.411	0.397	0.416					

c – core; r – rim

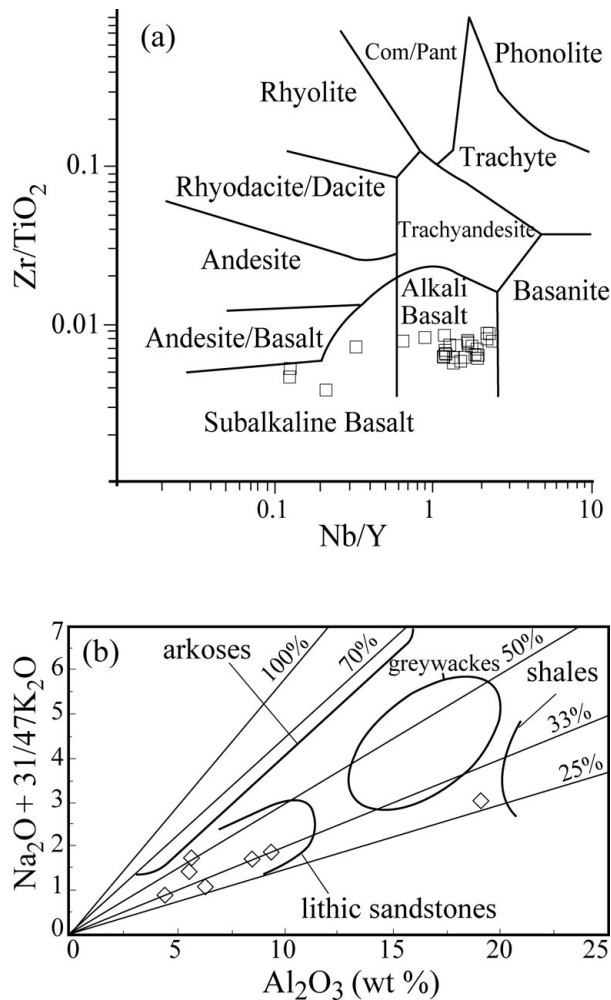


Figure 4. (a) Zr/TiO_2 v. Nb/Y diagram showing possible protoliths for amphibolites of the metamorphic sole rocks from the Pozanti–Karsanti ophiolite (after Winchester & Floyd, 1977). (b) Alkalis v. Al_2O_3 diagram showing the original sedimentary lithologies of the micaschists from the metamorphic sole rocks of the Pozanti–Karsanti ophiolite (after M. Fonteilles, unpub. D.Sc. thesis, Univ. Paris, 1976).

marble and quartzite. They were derived from sedimentary and volcano-sedimentary rocks. SiO_2 contents of the micaschists vary from 68 to 90 wt %. Al_2O_3 and MgO values are less than in the upper part of the sole rocks and vary between 4–9 wt % and 0.6–4 wt %, respectively. According to the $Na_2O + 31/47K_2O$ v. Al_2O_3 diagram, the garnet–kyanite-bearing micaschists and the micaschists cluster in the field of a lithic sandstone protolith (Fig. 4b).

Almost all amphibolite samples have low loss-on-ignition ($< 2.0\%$), indicating that alteration was not common during or after the metamorphism. This is in agreement with petrographical observations. Hydrothermal alteration is mostly observed in the dolerite dykes and is likely to affect the dykes along their contact zones. On the total alkalis versus silica diagram of Rickwood (1989), amphibolite samples present an alkaline and subalkaline character, whereas doleritic

and gabbroic dyke samples present a subalkaline or low potassium tholeiitic character (Fig. 5a). The alkaline character of the amphibolites is common along the Tauride Belt Ophiolites (Lytwyn & Casey, 1995; Parlak, Delaloye & Bingöl, 1995; Polat, Casey & Kerrich, 1996; Çelik & Delaloye, 2003, 2006). The arc signature of the dyke samples is shown in the Zr/Y v. Zr (Fig. 5b) and Ti v. V diagrams (Fig. 5c), where most of the amphibolite rocks are represented by within-plate basalts (WPB), with some amphibolite samples displaying IAT and MORB signatures.

REE patterns of the amphibolites display two different groupings (Fig. 6a). The first is characterized by LREE enrichment typical of WPB or seamount. The second group, including the dolerite dykes, exhibits a flat pattern of IAT. The LREE enrichment of the dykes and amphibolites compared to the N-MORB suggests a volcanic arc component. On the N-MORB normalized spider diagram, the first group of the amphibolites exhibits enriched multi-element patterns compared to N-MORB. They exhibit similar patterns of the ocean island basalt (OIB) type basalts. However, the second group of amphibolite and dolerite dyke samples exhibits enrichment in large ion lithophile elements (LILE) such as K, Rb, Sr and Ba, relative to some high field strength elements (HFSE) such as Nb, Zr and Ti (Fig. 6b). Nb depletion and Th enrichment is typical of a subduction influence (Pearce, Lippard & Roberts, 1984; Saunders & Tarney, 1979, 1984).

5.b. Pyroxenite and albitite dykes

Although pyroxenite dykes are common in the mantle tectonites and the cumulates along the Tauride Belt Ophiolites, they were not previously reported in the metamorphic sole rocks. Pyroxenites are observed as discontinuous exposures in the upper part of the metamorphic sole rocks, near the contact with the peridotites. Since pyroxenite dykes cut the metamorphic sole rocks, they were generated after the metamorphism of those rocks. REE patterns of the pyroxenites clearly exhibit a LREE enrichment similar to those of the OIB-like amphibolites (Fig. 7a). N-MORB-normalized trace element patterns of pyroxenites exhibit LILE enrichment relative to HFSE and support their alkaline natures (Fig. 7b). The Ce/Sm v. Sm/Yb ratios were used to characterize mantle source regions for the pyroxenites, amphibolites and dolerite dykes (Fig. 8a). The high Sm/Yb and Ce/Sm ratios of the alkaline amphibolites and the pyroxenites suggest that they were derived from melting of an OIB-like enriched mantle source, whereas the dolerite dykes and some amphibolites with low Sm/Yb and Ce/Sm ratios plot in the field of tholeiitic amphibolites beneath the Tauride Belt Ophiolites. In the Th/Y v. Nb/Y diagram, pyroxenites suggest a derivation from an enriched mantle source region, more akin to an OIB source, whereas the tholeiitic amphibolites and the isolated

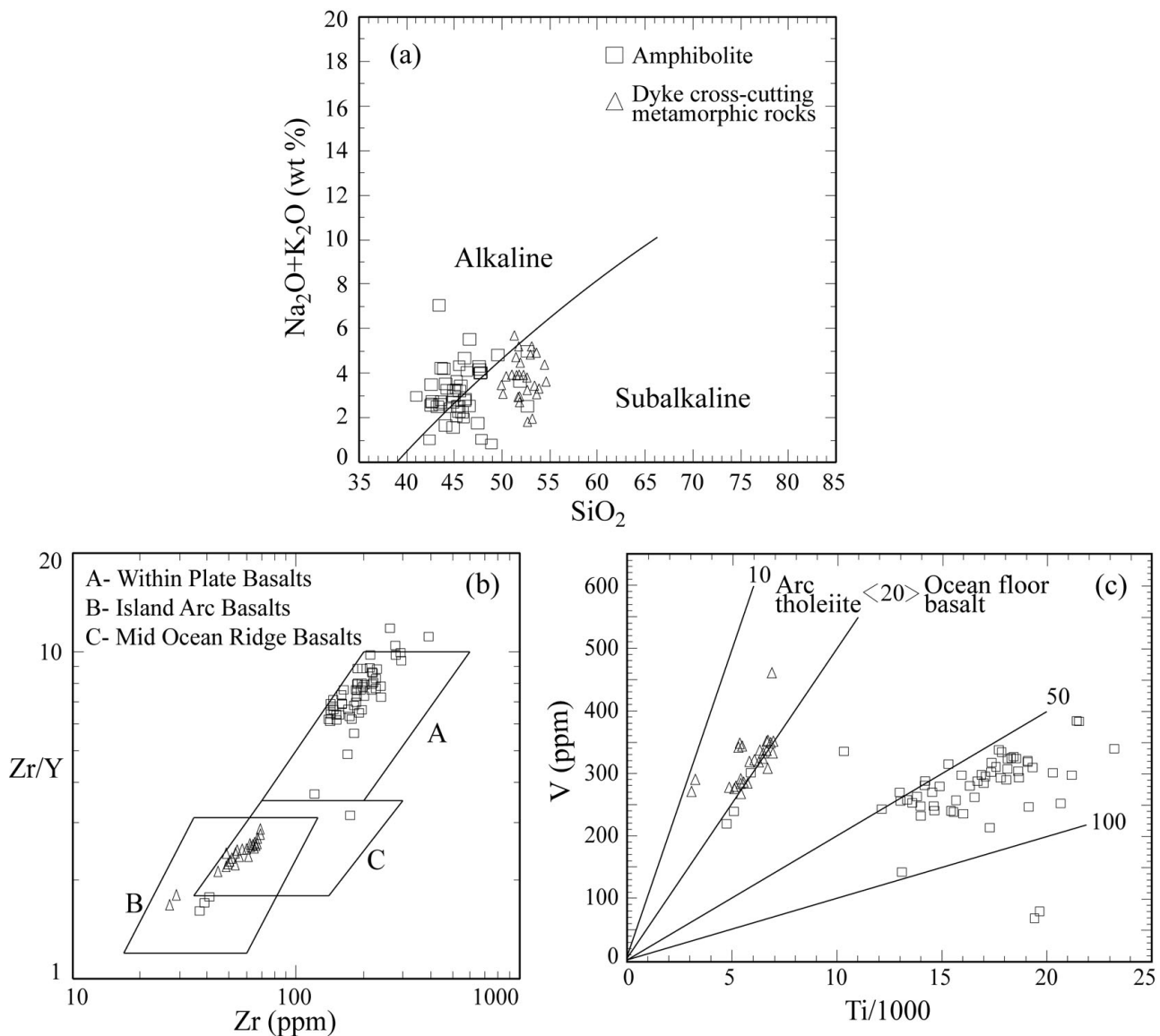


Figure 5. (a) Total alkalis v. silica diagram for the amphibolites and the dolerite dykes in the metamorphic sole rocks from the Pozanti–Karsanti ophiolite, after Rickwood (1989). (b) Zr/Y v. Zr discrimination diagram after Pearce & Norry (1979). (c) V v. Ti diagram showing tectonomagmatic environment of dolerite and amphibolite rocks in the metamorphic sole rocks of the Pozanti–Karsanti ophiolite, after Shervais (1982).

dolerite dykes clearly exhibit subduction influence (Fig. 8b).

Albitites in the metamorphic sole rocks present granular texture and consist mostly of coarse-grained albite crystals. Rocks of this type cutting the gabbroic sequence were also observed in the Montgenèvre Ophiolite and were interpreted as a last production of the magma chamber by Bertrand & Vuagnat (1979). Geochemical compositions of the albitite from the Pozanti–Karsanti ophiolite are between 57 and 66 wt % for SiO_2 , between 0.01 and 0.07 wt % for TiO_2 , and between 18 and 22 wt % for Al_2O_3 . They show high Ba (270–616 ppm), Sr (1439–2339 ppm) and low Zr, Y, Nb, Rb values (1–6 ppm). High Na_2O (8–10 wt %) and Sr values, which are associated with very low values of trace and rare earth elements, can be interpreted as

due to a very efficient hydrothermal alteration phase similar to that observed in the doleritic dykes.

6. Mineral chemistry

6.a. Amphibole

Based on the classification of Leake *et al.* (1997), all amphiboles are represented by calcic amphibole compositions (Fig. 9). Amphibole compositions are characterized by SiO_2 = (41.7–55 %), Al_2O_3 = (2.3–15.6 %), FeO = (0.4–16.8 %), MgO = (9.1–16.9 %) and K_2O = (0.2–1.3 %). X_{Mg} values ($\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$) of amphiboles range from 0.49 to 0.98. The amphiboles become richer in Fe with increasing Al_2O_3 and decreasing SiO_2 content. The total Al contents are

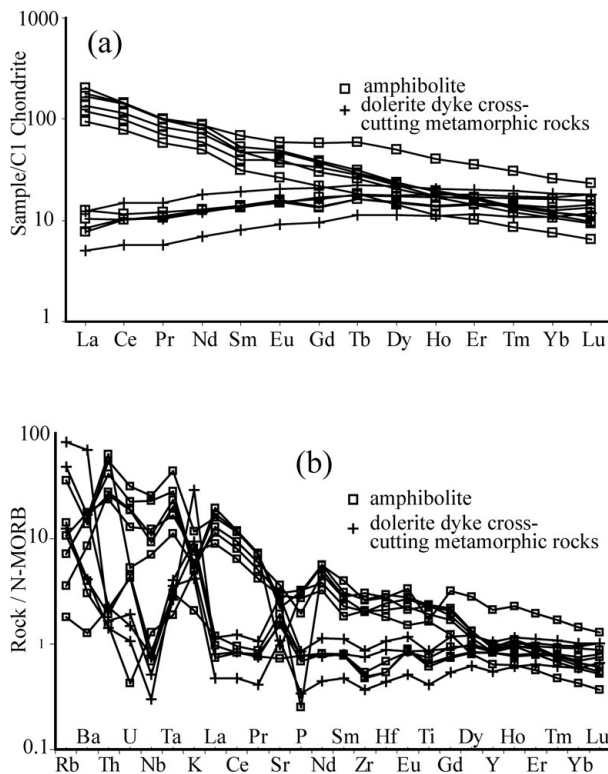


Figure 6. (a) Chondrite-normalized REE plots for amphibolites and dyke rocks from the metamorphic sole rocks of the Pozanti–Karsanti ophiolite (normalizing values from Sun & McDonough, 1989). (b) MORB-normalized trace element patterns of the amphibolites and cross-cutting dolerite dykes from the metamorphic sole rocks of the Pozanti–Karsanti ophiolite.

between 0.4 and 2.7 atoms per formula unit (apfu). Al-poor amphiboles are mainly actinolite, whereas the Al-rich ones are represented by magnesio-hornblende, tschermakite to magnesio-hastingsite and edenites. Amphibole in sample PK-2 from the amphibolites of group (A) shows only an edenite composition. Amphiboles in samples PK-9 and PK-50 from the amphibolites of group (C) range from magnesio-hastingsite, edenite and magnesio-hornblende to actinolite. However, some amphibole grains in sample PK-9 show compositional changes from edenite in the core to magnesio-hornblende at the rim and magnesio-hastingsite in the core to magnesio-hornblende and edenite at the rim. Actinolite was also observed in sample PK-9 as individual crystalloblasts. Amphiboles in group (D) are represented by magnesio-hornblende, magnesio-hastingsite and edenite. Sample PK-17 from the upper part of the sole rocks is the only sample to include quartz crystals. Its amphibole is tschermakite. Sample PK-44 from the lower part of the metamorphic sole rocks consists of kyanite, garnet, amphibole, quartz, biotite and opaque minerals. Amphiboles in this sample are characterized by a tschermakite composition. The FeO content of PK-44 is apparently

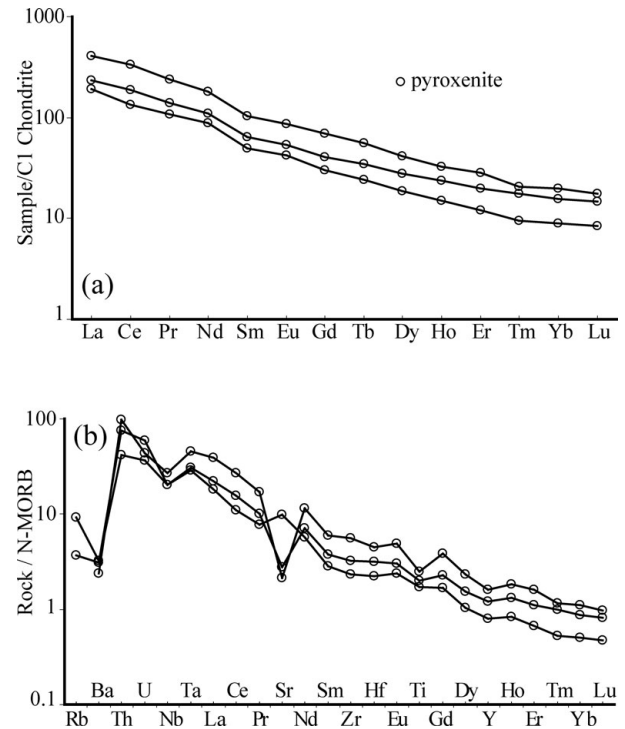


Figure 7. (a) Chondrite-normalized REE plots for pyroxenite dykes cutting the metamorphic sole rocks of the Pozanti–Karsanti ophiolite (normalizing values from Sun & McDonough, 1989). (b) MORB-normalized trace element patterns for pyroxenite dykes of the metamorphic sole rocks from the Pozanti–Karsanti ophiolite.

low (between 1.4 and 4.2 %) compared with those of the upper part of the metamorphic sole rocks. All amphiboles in the dolerite dyke (sample PK-69) are also calcic.

6.b. Pyroxene

Pyroxene in sample PK-2 is observed as xenomorphic–porphyritic minerals and in sample PK-29 as equidimensional crystalloblasts. A Ti + Cr + Na v. Al discrimination diagram (Berger *et al.* 2005) was used to determine their igneous and metamorphic origins (Fig. 10a). Pyroxene in sample PK-2 plots in the igneous field with the pyroxenes of the pyroxenite dyke (PK-182). Pyroxenes from sample PK-29 (epidote–amphibolite) are characterized by both an igneous and a metamorphic origin. The relict primary igneous clinopyroxene is diopside (Fig. 10b), with Al (0.05–0.31 apfu) and Na (0.02–0.09 apfu) contents but a relatively low Si content (1.89–2 apfu). Metamorphic clinopyroxene consists of diopside with Al (0.02–0.07 apfu) and Na (0.02–0.04 apfu) contents and a higher Si content (1.96–1.99 apfu). Pyroxenes from the pyroxenite dyke (sample PK-182) are also diopsidic in composition with Al (0.03–0.05 apfu), Na (0.05–0.09 apfu) and Si (1.98–2 apfu).

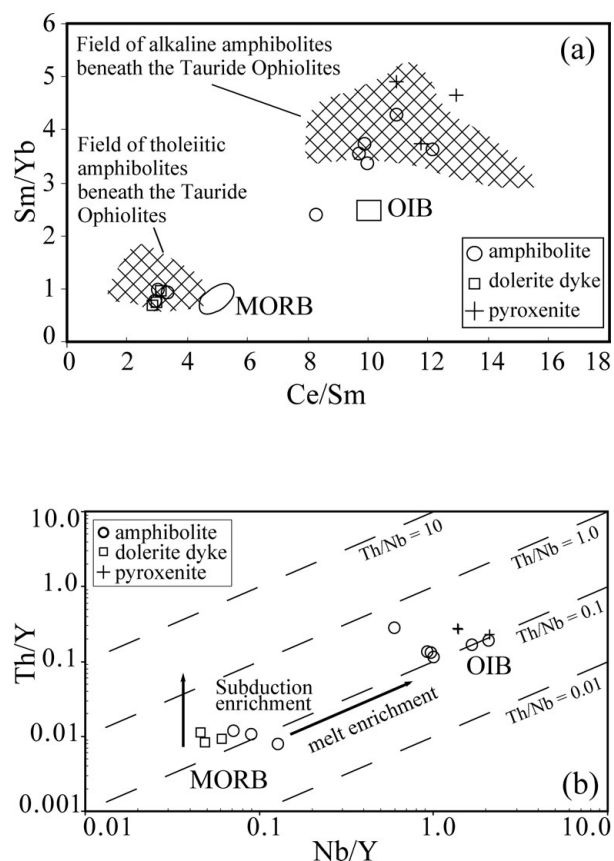


Figure 8. (a) Sm/Yb v. Ce/Sm diagram, after Pearce (1982), showing source characteristics for the dolerite and pyroxenite dykes and the amphibolites. Fields of OIB and MORB are from Harms *et al.* (1997). (b) Th/Y v. Nb/Y diagram for the source characteristics of the dolerite and pyroxenite dykes and the amphibolites. Dashed lines are contours of a fixed Th/Nb ratio. Fields of OIB and MORB are from Kempton, Hawkesworth & Fowler (1991).

6.c. Garnet

Garnet was observed only in the lower part of the sole rocks. The garnets in sample PK-20, which is composed of garnet, plagioclase, quartz, muscovite, biotite and opaque minerals, are represented by spessartine with variable compositions of $\text{Sps}_{32-37}\text{Alm}_{29-37}\text{Prp}_{17-24}\text{Gr}_{50-10}$. The garnet in sample PK-44 (micaschist) is represented by almandine. Its composition varies with $\text{Alm}_{45-41}\text{Prp}_{28-31}\text{Sps}_{10-17}\text{Gr}_{50-9}$. No compositional zoning from core to rim was observed in garnets.

6.d. Plagioclase

Plagioclases are characterized by albite to andesine. Samples PK-2 (pyroxene-amphibolite) and PK-9 (amphibolite) contain albite (An_{0-5}). This plagioclase composition can be generated either from the alteration phase or from subsequent low-grade metamorphism. Samples PK-50 and PK-206 have albite and oligoclase (An_{1-14}). Sample PK-44 (micaschists) is from the lower part of the sole rocks and its plagioclase is characterized

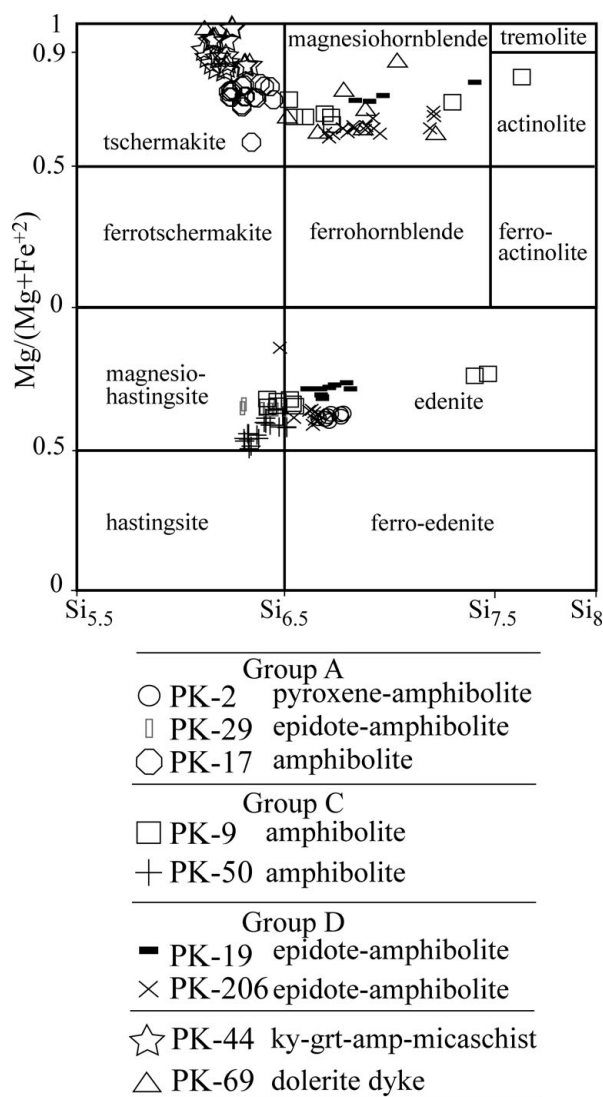


Figure 9. Chemical composition of amphiboles in the metamorphic sole rocks of the Pozanti-Karsanti ophiolites.

mostly by an andesine composition (An_{28-37}). Plagioclase from the albitite dyke (sample PK-225) is of albite (An_{1-7}). In dolerite dyke (sample PK-69) plagioclase is represented by oligoclase. Saussuritization and albite generation were also observed in the dykes, suggesting hydrothermal alteration.

6.e. Micas

Micas were plotted in an Al-Si-M²⁺ (M²⁺ = Mg²⁺ + Fe²⁺, after Deer, Howie & Zussman, 1992) triangular diagram, which displays the principal variations in mica compositions. White micas plot between phengite and muscovite. Biotites having high Mg+Fe²⁺ plot close to phlogopite (Fig. 11). The Si content of white micas in the Pozanti-Karsanti ophiolite does not vary greatly and ranges between 3.12 and 3.18 atoms per formula unit (apfu). No zonation was observed in the white micas. The sum of the interlayer cations (Ca+Na+K) varies between 0.62 and 0.82. X_{Mg} and

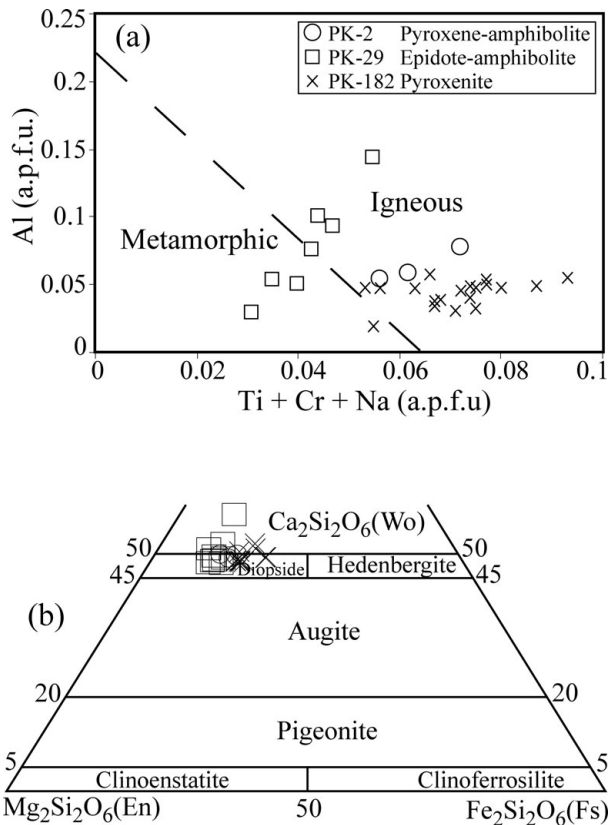


Figure 10. (a) Al v. (Ti + Cr + Na) for clinopyroxenes showing their compositional spectrum. (b) Chemical composition of pyroxenes in amphibolite and pyroxenite (after Morimoto, 1988).

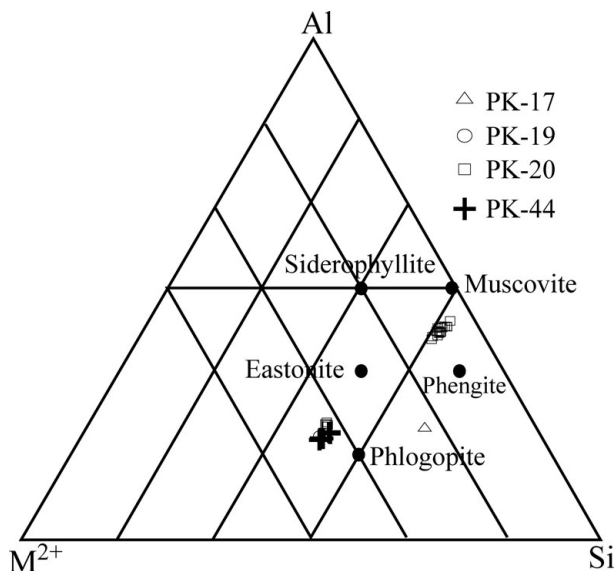


Figure 11. Al-Si- M^{2+} triangular diagram showing mica compositions in amphibolite and micaschist from the metamorphic sole rocks of the Pozanti-Karsanti ophiolite.

X_{Na} ($\text{Na}/(\text{Na}+\text{K})$) values in white micas vary between 0.41 and 0.57, and 0.15 and 0.19, respectively. Biotites are characterized by X_{Mg} between 0.72 and 0.74 and TiO_2 as high as 1.5 wt %.

6.f. Epidote

$X_{\text{Fe}^{3+}}$ ($\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Al})$) from epidotes in sample PK-2 varies between 0.16 and 0.19. In zoisite, $X_{\text{Fe}^{3+}}$ is between 0 and 0.03.

7. Thermobarometric investigations

The restricted mineral assemblages provide only limited information for the metamorphic condition of the upper part (close to peridotite) of the metamorphic sole rocks which consist mainly of amphibole and plagioclase. However, the lower part of the metamorphic sole rocks contains various minerals that can be used to calculate their physical conditions at the time of metamorphism.

The Na content in the M4 site of amphibole may be a useful semi-quantitative geobarometer for amphibolites in amphibolite and greenschist facies (Brown, 1977; Laird, Lanphere & Albee, 1984). The Na^{M4} concentrations of all analysed amphiboles (except PK-44) are between 0.01 and 0.4 apfu. The pressure for the metamorphic sole rocks, deduced from the proportions of $\text{Na}^{\text{M4}}\text{-Al}^{\text{IV}}$ and $\text{Al}^{\text{VI}}\text{-Si}$ numbers of amphiboles, is around 5 kbar (Fig. 12a, b). Using the Newton & Haselton (1981) and Koziol & Newton (1988) geobarometers, pressure for the sole rocks was estimated as 5.2–6.1 kbar and 5.9–6.9 kbar, respectively. These pressure estimates are in agreement with the compositions of all analysed amphiboles that plot in the low-pressure (LP) to medium-pressure (MP) domain of the Laird, Lanphere & Albee (1984) diagram (Fig. 12c). A pressure estimate was also obtained from the phengite barometer of Massonne & Schreyer (1987). Pressures from phengites for sample PK-20 (micaschist) are 4.8–5.4 kbar in the temperature interval 550–600 °C.

Temperature conditions at the time of metamorphism for the metamorphic sole rocks were calculated using the hornblende-plagioclase thermometer of Holland & Blundy (1994). Sample PK-9 consists of hornblende, plagioclase, sphene and opaque minerals. Since quartz is absent in the assemblage, the edenite-richterite thermometer was used on the formula. The mean calculated temperature is 447 °C. Sample PK-206 is composed of hornblende, plagioclase, quartz, epidote, sphene and opaque minerals. As quartz is present in the assemblage, the edenite-tremolite thermometer was used on the formula. Temperatures vary from 520 °C to 580 °C with a mean value of 534 °C. Sample PK-50, composed of hornblende, plagioclase, biotite and sphene, yielded a temperature between 550 and 600 °C with a mean value of 578 °C. Sample PK-44 from the lower part of the sole rocks consists of garnet ($\text{Alm}_{45-41}\text{Prp}_{28-31}\text{Sps}_{10-17}\text{Grs}_{0-9}$), tschermakite, kyanite, plagioclase ($\text{Ab}_{61-71}\text{An}_{18-37}$), biotite, quartz and opaque minerals. Using the geothermometer of Holland & Blundy (1994), the temperature was

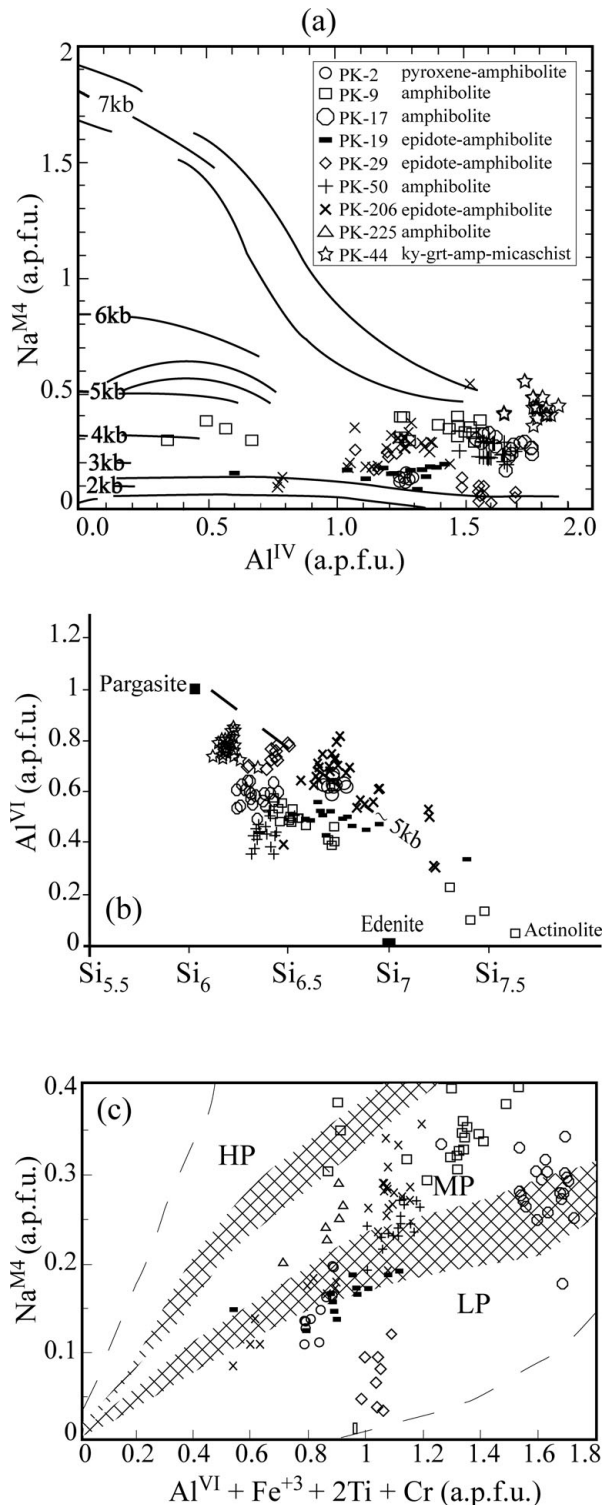


Figure 12. (a) Comparison of Na^{M4} and Al^{IV} for amphibole from amphibolites and micaschists of the Pozanti-Karsanti ophiolite (after Brown, 1977). (b) Al^{VI} v. Si diagram after Raase (1974) for amphiboles in the amphibolites and micaschists. (c) Amphibole from the metamorphic sole rocks of the Pozanti-Karsanti ophiolite plotted in the pressure discriminative diagram of Laird, Lanphere & Albee (1984).

calculated in the range of 569 °C to 583 °C. Using the geothermometer of Graham & Powell (1984), the temperature from garnet-hornblende pairs was estimated to be around 573 °C.

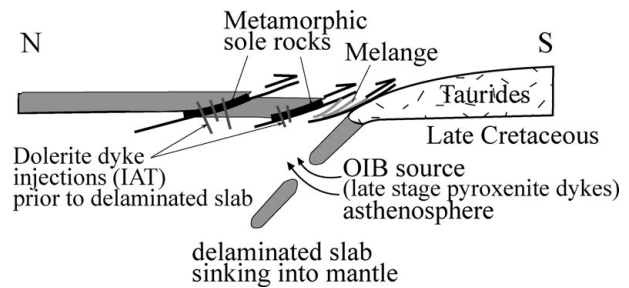


Figure 13. Tectonic diagram illustrating a slab break-off model for the generation of the OIB source in the metamorphic sole rocks of the Pozanti-Karsanti ophiolite.

8. Discussion

Lytwyn & Casey (1995) and Polat, Casey & Kerrich (1996) reported that the metamorphic sole rocks of the Pozanti-Karsanti ophiolite generally exhibit an alkaline character. They also indicated that greenschist-facies metabasalts are represented by N-MORB, while OIB-like amphibolites were metamorphosed under amphibolite-facies conditions. However, MORB-like amphibolites, for instance, samples PK-48 and PK-57, were metamorphosed in amphibolite-facies conditions. In addition, in the lower part of the metamorphic sole rocks, kyanite and garnet-bearing metasedimentary rocks suggest amphibolite-facies metamorphism. As indicated in the geochemistry section, the amphibolites of the metamorphic sole rocks from the Pozanti-Karsanti ophiolite are generally metamorphosed equivalents of within-plate alkali to tholeiitic basalts and their protoliths are not only basalts from OIB and N-MORB but also IAT. The supra-subduction nature of the Pozanti-Karsanti ophiolite was reported by Parlak, Höck & Delaloye (2000). The IAT nature of the amphibolites at the base of the Tauride Belt Ophiolites is probably related to the basalts of the supra-subduction type ophiolite (Çelik & Delaloye, 2003; Çelik, Delaloye & Feraud, 2006). The alkaline nature of the amphibolites was also observed in the other metamorphic sole rocks along the Tauride Belt Ophiolites, for example, in Köyceğiz, Yeşilova, Antalya, Beyşehir, Mersin and Pınarbaşı (Parlak, Delaloye & Bingöl, 1995; Dilek *et al.* 1999; Vergili & Parlak, 2005; Çelik & Delaloye, 2003, 2006). Within-plate alkali basalt-like amphibolites in the metamorphic sole rocks of the Pozanti-Karsanti ophiolite are similar to ocean island alkali basalts from the Azores (White, Tapia & Schilling, 1979) and the Ankara melange (Floyd, 1993). Three different geodynamic environments (IAT, MORB and OIB) were also observed in the metamorphic sole rocks of the Lycian ophiolites (Çelik & Delaloye, 2003). The generation of metamorphic sole rocks with these three different sources was previously discussed and a double subduction model was proposed for the Tauride belt ophiolites (Çelik, Delaloye & Feraud, 2006).

The latest stage of magmatic activity in a supra-subduction zone setting is dominated by the eruption

of MORB-like or OIB lavas on top of earlier arc-related tholeiitic lavas. Alternatively, these magmas may intrude as dykes (Shervais, 2001). This has been interpreted as off-axis alkaline magmatism representing melts that possibly originated from an asthenospheric window beneath the displaced oceanic lithosphere in the upper plate (Shervais, 2001; Dilek & Flower, 2003). Late-stage magmatic activity prior to the ophiolite emplacement onto the Tauride platform carbonates was represented by the intrusion of pyroxenite dykes with alkali basalt-like chemistry into the metamorphic sole rocks of the Pozanti–Karsanti ophiolite. The OIB source for the pyroxenites should have been produced from an asthenospheric window due to slab break-off in previously subducted older and denser oceanic lithosphere (Çelik, 2002) (Fig. 13). A similar model has been proposed by Shervais (2001) for Salahi volcanic rocks in the Oman ophiolite and by Shervais *et al.* (2004) and Shervais, Schuman & Hanan (2005) for the generation of dykes and late flows of lavas (MORB and OIB-like) in the Coast Range ophiolite of California. A slab break-off model was recently proposed by Parlak, Yılmaz & Boztuğ (2006) for isolated dykes cutting the metamorphic sole rocks of Divriği ophiolite in Turkey.

Some pyroxenes (Fig. 3d) in the amphibolites exhibit a relict magmatic origin, suggesting that relatively large pyroxene crystals in the protolith of the amphibolite were not affected by the metamorphism and remained as relict pyroxenes. However, in an epidote–amphibolite sample (PK-40) showing augen structure, groups of epidote minerals display the contours of garnet-like minerals (Fig. 3e). Lineation is marked by stretching of the amphiboles around the epidote mineral. Actinolite, magnesio-hornblende and edenite associations were observed in some amphibolites. Some coexisting actinolite–hornblende pairs may alternatively be an indication of progressive (gradual or sudden) metamorphism rather than immiscibility (Deer, Howie & Zussman, 1992). Some amphibolite samples contain albite (An_{0-5}). This plagioclase composition can be generated either from the alteration phase or from the subsequent low-grade metamorphism. The Pozanti–Karsanti ophiolite displays the same plateau ages (^{40}Ar – ^{39}Ar) between amphiboles and white mica, suggesting that the metamorphic sole rocks generated at the basal Pozanti–Karsanti ophiolites were rapidly cooled after their generation (Çelik, Delaloye & Feraud, 2006). All these data suggest the idea of a retrograde metamorphism during exhumation of the amphibolite, that is, the amphibolites underwent a relatively high-grade metamorphism at the base of hot oceanic lithosphere, then they were rapidly exhumed by tectonic forces to a relatively shallow level where they were metamorphosed under low-grade conditions.

9. Conclusions

The metamorphic sole rocks of the Pozanti–Karsanti ophiolite were divided into two parts. The upper

part is near the contact with the peridotites and is composed mainly of amphibolitic rocks with magmatic origin. The lower part, on the other hand, consists of micaschists, marble and quartzite. However, the micaschists, including kyanite–garnet–amphibole-bearing micaschists, could be observed as small slices within the amphibolites.

The protolith of the amphibolite is likely to be basalt and/or gabbro. Absence of plagioclase in some amphibolites suggests their derivation from ultramafic cumulates such as pyroxenite or aphyric basalt. The protoliths of the micaschist are lithic sandstones.

Garnet was only observed in the lower part of the metamorphic sole rocks (in micaschists) and is commonly represented by almandine. All amphibole minerals in the metamorphic sole rocks are calcic amphiboles. In the association of kyanite–garnet-bearing micaschist, amphiboles also present a tschermakitic composition, suggesting relatively medium- to high-grade metamorphism. Geothermobarometry studies suggest that the protoliths of the metamorphic sole rocks were metamorphosed around 570–580 °C at 5–6 kbar.

Amphibolites represent three different geochemical environments: OIB, MORB and IAT. Protoliths of IAT-type amphibolites are likely to have originated from the supra-subduction-type ophiolite. MORB and OIB-type amphibolites are interpreted to represent the subducted N-MORB-type oceanic crust and the seamount formed above the MORB crust, respectively.

The late-stage pyroxenite dykes cutting the amphibolites may be interpreted to be a result of off-axis magmatism fed by melts that originated within an asthenospheric window due to slab break-off, before the emplacement of the Pozanti–Karsanti ophiolites onto the Tauride carbonate platform in Late Cretaceous times. Albitites were formed in the joints of the metamorphic sole rocks in an oceanic environment during the hydrothermal alteration stage.

The isolated dolerite dykes cutting the metamorphic sole rocks do not show any folding structures or metamorphic signatures. They have the geochemical signature of IAT. Accordingly, dyke injection is interpreted to have developed in the oceanic environment prior to obduction of oceanic crust onto the Tauride platform carbonates but after ductile deformation of the metamorphic sole rocks. The pyroxenite dykes also cut the metamorphic sole rocks but they have the geochemical signature of an OIB source. This may indicate that the pyroxenite dyke emplacement into the metamorphic sole rocks occurred after the isolated dolerite dyke injections, possibly via a slab break-off.

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