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Origin and Tectonic Significance of the Metamorphic Sole and Isolated Dykes of the Divriği Ophiolite (Sivas, Turkey): Evidence for Slab Break-off prior to Ophiolite Emplacement

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Abstract: The Late Cretaceous Divriği ophiolite of east-central Anatolia comprises, from bottom to top, an ophiolitic mélange, metamorphic sole and remnants of oceanic lithosphere. The ophiolitic mélange has been thrust onto the Lower Carboniferous–Campanian Munzur Limestone (Tauride platform), and is in turn tectonically overlain by the metamorphic sole. The metamorphic-sole rocks are represented by amphibolite, plagioclase amphibolite, plagioclase-amphibole schist, plagioclase-epidote-amphibole schist and calc-schist. The oceanic-lithosphere remnant exhibits a complete section, excluding volcanic rocks, comprising mantle tectonites, ultramafic to mafic cumulates, isotropic gabbros and sheeted dykes. Isolated dykes intrude the metamorphic sole and mantle tectonites at different structural levels. The metamorphic-sole rocks beneath the Divriği ophiolite can be divided into two groups with distinct geochemical features. The first group is tholeiitic (Nb/Y=0.07–0.18), whereas the second group is alkaline (Nb/Y=1.77–3.48) in chemistry. Chondrite-normalized REE patterns, N-MORB-normalized spider diagrams and tectonic discrimination diagrams suggest that the protolith of the first group was similar to island-arc tholeiitic basalts, whereas the protolith of the second group was more akin to within-plate alkali basalts. The isolated dykes cutting the metamorphic sole and the mantle tectonites exhibit alkaline (Nb/Y=0.68–2.11) character and are geochemically similar to within-plate alkaline basalts. The geochemical evidence suggests that the Late Cretaceous Divriği ophiolite formed in a suprasubduction zone tectonic setting to the north of the Tauride platform. During intraoceanic subduction/thrusting, the IAT type and seamount-type alkaline basalts were metamorphosed and accreted to the base of the Divriği ophiolite. The alkaline isolated dykes were probably the result of late-stage magmatism fed by melts that originated within an asthenospheric window due to slab break-off, shortly before the emplacement of the Divriği ophiolite onto the Tauride platform to the south.

Key Words: isolated dyke, amphibolite, alkaline magma, tholeiitic magma, slab break-off, Divriği, Turkey

Divriği Ofiyolitindeki (Sivas, Türkiye) Metamorfik Dilim ve İzole Daykların Kökeni ve Tektonik Önemi: Ofiyolit Yerleşmesinden Önce Dalan Levhanın Kopmasına İlişkin Veriler

Özet: Orta Anadolunun doğusunda yer alan Geç Kretase yaşlı Divriği ofiyoliti tabandan tavana doğru ofiyolitik melanj, metamorfik dilim ve okyanusal litosfer kalıntılarını içermektedir. Ofiyolitik melanj tabanda Erken Karbonifer–Kampaniyen yaşlı Munzur Kireçtaşlarını (Toros platformu) bindirmeli bir dokanakla üzerler ve tavanda ise metamorfik dilim tarafından tektonik dokanakla örtülür. Metamorfik dilim amfibolit, plajiyoklaslı amfibolit, plajiyoklas-amfibol şist, plajiyoklas-epidot-amfibol şist ve kalk-şist kayaçları ile temsil edilmektedir. Okyanusal litosfer kalıntıları volkanikler hariç tam bir kesit sunarlar ve manto tektonitleri, ultramafik-mafik kümülatlar, izotropik gabrolar ve levha daykları ile temsil edilirler. İzole dayklar metamorfik dilim ve manto tektonitlerini değişik yapısal seviyelerde keserler. Divriği ofiyolitinin tabanında yer alan metamorfik dilime ait kayaçlar farklı jeokimyasal özelliklerine göre iki farklı gruba ayrılabilirler. Birinci grup toleyitik (Nb/Y=0.07–0.18) ikinci grup ise alkalen (Nb/Y=1.77–3.48) kimyadadır. Kondrite göre normalize edilmiş nadir toprak element diyagramı, N-MORB'a göre normalize edilmiş örümcek diyagramı ve tektonik ortam belirleme diyagramları birinci gruba ait metamorfik kayaçların ada yayı toleyitik bazaltlarından, ikinci gruba ait metamorfik kayaçların ise kıta içi alkali bazaltlarından türediklerini işaret etmektedir. Metamorfik dilim ve manto tektonitlerini kesen izole dayklar alkalen (Nb/Y=0.68–2.11) karakterde olup jeokimyasal açıdan kıta içi bazaltlarına benzemektedir. Jeokimyasal veriler Divriği ofiyolitinin Geç Kretase'de Toros platformunun kuzeyinde okyanus içi dalma-batma zonu üzerinde oluştuğunu göstermektedir. Okyanus içi dalma-batma/bindirme sırasında ada yayı toleyitik bazaltları ve okyanus adası alkali bazaltlarının metamorfizmaya maruz kalıp Divriği ofiyolitinin tabanına yerleşmiştir. Alkalen izole dayklar ise dalan levhanın kopması ile açılan astenosferik pencereden nüfuz eden zenginleşmiş eriyiklerin beslediği geç-evre magmatizması sonucu Divriği ofiyolitinin Toros platformu üzerine yerleşmesinden hemen önce gelişmiştir.

Anahtar Sözcükler: izole dayk, amfibolit, alkali magma, toleyitik magma, levha kopması, Divriği, Türkiye

Introduction

The Late Cretaceous ophiolites of Turkey define the Neotethyan sutures that resulted from the closure of oceanic basins between the Eurasian and Afro-Arabian plates during the Late Triassic to Late Cretaceous period. From north to south, these suture zones are named: (a) the İzmir-Ankara-Erzincan, (b) the Inner Tauride, and (c) the SE Anatolian suture zones (Şengör & Yılmaz 1981; Görür *et al.* 1984; Robertson & Dixon 1984; Dilek & Moores 1990; Yılmaz 1993; Robertson 2004). Available petrographic and geochemical data on ophiolitic extrusives and intrusives suggest that the Neotethyan ophiolites of Turkey formed in a suprasubduction zone environment (SSZ) (e.g., Pearce *et al.* 1984; Parlak 1996; Parlak *et al.* 1996, 2000, 2002, 2004; Yalınız *et al.* 1996, 2000; Beyarslan & Bingöl 2000; Floyd *et al.* 2000; Robertson 2002, 2004; Çelik & Delaloye 2003).

The ophiolites of southern Turkey are located along two lineaments, namely the Bitlis-Zagros suture zone and the Tauride belt (Figure 1). The Bitlis-Zagros suture zone includes complete and undeformed oceanic lithospheric remnants of the southern branch of Neotethys, such as Troodos in Cyprus, Kızıldağ in Turkey and Baer-Bassit in Syria (Figure 1). The Tauride ophiolite belt is characterized by dismembered ophiolitic units rooted to the north of the Tauride platform (Şengör & Yılmaz 1981; Andrew & Robertson 2002; Robertson 2002, 2004; Parlak & Robertson 2004). These are, from west to east, the Lycian, Tekirova, Beyşehir-Hoyran, Alihoca, Mersin, Pozantı-Karsantı, Pınarbaşı and Divriği ophiolites (Figure 1). The ophiolite-related units in this latter belt are characterized, from bottom to top, by ophiolitic mélanges that tectonically overlie the Tauride carbonate platform, metamorphic soles and ophiolitic rocks. Well-developed thin metamorphic soles, ranging in thickness from 100 to 400 m, crop out beneath the serpentinized mantle tectonites. Protoliths of the metamorphic soles suggest the presence of both tholeiitic and alkaline magma types from various tectonic settings, such as OIB, MORB and IAB (Parlak *et al.* 1995; Parlak 1996; Çelik 2002; Çelik & Delaloye 2003; Vergili & Parlak 2005). Isolated microgabbro and diabase dykes intrude the metamorphic soles, mantle tectonites and cumulates of the Tauride ophiolites. The geochemistry of the dykes shows that they formed in a subduction-related environment and indicates their derivation from an island-arc tholeiite (IAT) (Parlak *et al.* 1995; Parlak & Delaloye 1996; Dilek *et al.* 1999; Elitok 2001; Çelik & Delaloye 2003; Vergili & Parlak 2005).

The latest stage of magmatic activity in a suprasubduction 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). Examples of this type of magmatism are found in the Coast Range ophiolite of California (Shervais & Beaman 1991), the Oman ophiolite (Alabaster *et al.* 1982; Ernewein *et al.* 1988; Dilek & Flower 2003), and the Tauride ophiolites of Turkey (Lytwyn & Casey 1995; Dilek *et al.* 1999). The late-stage magmas, represented by isolated dykes in the Tauride ophiolites, range in composition from basalts to andesites characteristic of evolved island-arc tholeiites, and have been interpreted as having been derived from an asthenospheric window created by the subduction of a ridge system in the Inner Tauride ocean (Lytwyn & Casey 1995; Dilek *et al.* 1999). Çelik (2002) documented exclusively alkaline pyroxenite dykes cutting the metamorphic sole of the Pozantı-Karsantı ophiolite in southern Turkey. The isolated alkaline microgabbro to diabase dykes of our study area, which intrude metamorphic soles and oceanic lithospheric remnants, have not previously been recorded in Turkish ophiolites. Thus, the Divriği ophiolite is an interesting example of alkaline-type melt generation in the early obduction stages of oceanic lithosphere onto the continental margin.

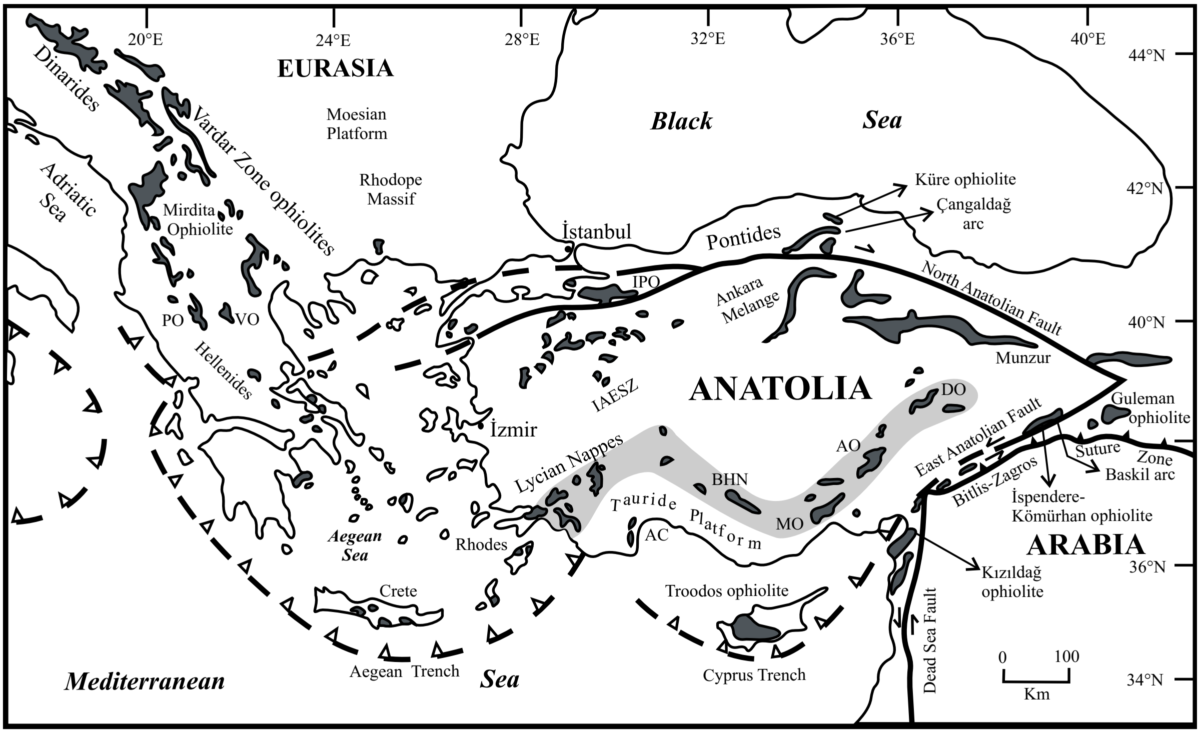

Figure 1. Distribution of the Neotethyan ophiolites and major tectonic features of the eastern Mediterranean region (from Dilek & Flower 2003). AC– Antalya Complex; IPO– Intra-Pontide Ophiolites; BHN– Beyşehir-Hoyran Nappes; IAESZ– İzmir-Ankara-Erzincan Suture Zone; MO– Mersin Ophiolite; PO– Pindos Ophiolite; VO– Vourinos Ophiolite; AO– Aladağ Ophiolite; DO– Divriği Ophiolite.

This paper (1) presents the major- and trace-element chemistry of the metamorphic sole and isolated dyke rocks intruding both the metamorphic sole and the mantle tectonites, (2) investigates possible protoliths of the material accreted to the base of mantle tectonites during intraoceanic subduction, and (3) presents the evidence for late-stage dyke intrusions fed by melts that originated within an asthenospheric window due to slab break-off, shortly before the emplacement of the Divriği ophiolite onto the Tauride platform in the Late Cretaceous.

Geological Setting

The Divriği region in east-central Anatolia comprises the Tauride platform unit, ophiolitic mélange, ophiolite-related metamorphic rocks, ophiolitic rocks, a volcano-sedimentary unit, granitoid rocks and Tertiary cover sediments (Figure 2). Detailed (1:25000-scale) geological mapping of the internal stratigraphy of the ophiolitic units of the Divriği region was first carried out by Yılmaz *et al.* (2001). The structurally lowest unit in the study area is the Munzur Limestone. The Munzur Limestone is present in the Mesozoic carbonate sequence of most of the autochthonous and allochthonous units of the Tauride belt (Özgül & Turşucu 1984). The base of the Munzur limestone is not exposed in the study area, and this unit is tectonically overlain by the Yeşiltaşyayla ophiolitic mélange and above that, the metamorphic sole and Divriği ophiolite (Figures 2 & 3). The Munzur Limestone comprises, from bottom to top, algal limestone, oolitic limestone, algal and foraminiferal limestone, cherty limestone, neritic limestone, rudistic limestone and pelagic limestone (Özgül & Turşucu 1984). The type locality of the Munzur Limestone has yielded an Early Triassic–Campanian age (Özgül & Turşucu 1984); however, the fossil content of this unit in the study area indicates an Early Carboniferous–Campanian age (Öztürk & Öztunalı 1993; Yılmaz *et al.* 2001).

The Yeşiltaşyayla mélange tectonically overlies the Munzur Limestone east of Ekinbaşı and Maltepe villages, and is tectonically overlain by either metamorphic-sole

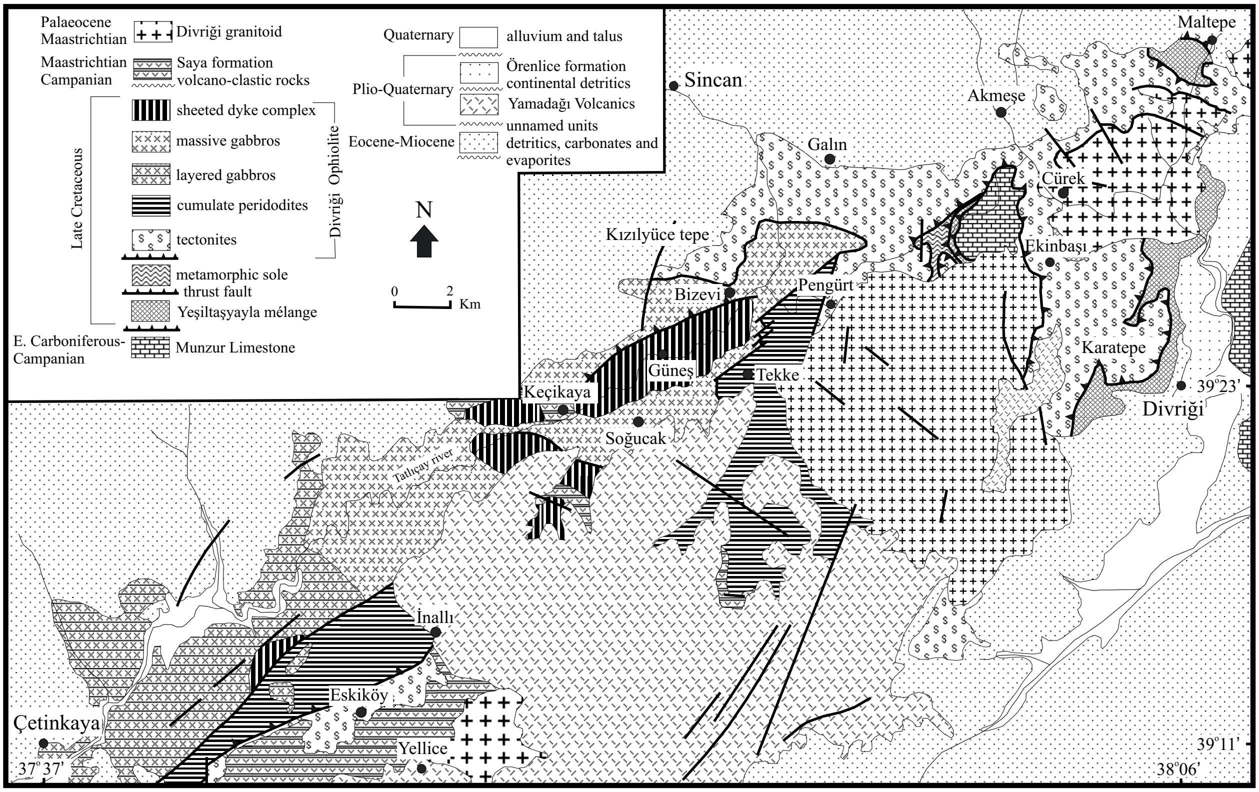

Figure 2. Geological map of the area between Divriği and Çetinkaya (Sivas) (modified from Yılmaz *et al.* 2001; Yılmaz & Yılmaz 2004).

rocks or serpentinized mantle rocks. This unit is also unconformably overlain by Tertiary cover sediments near Divriği (Figures 2 & 3). The mélange unit contains limestone blocks and metamorphic-rock fragments set in a serpentinized matrix. The limestone blocks typically range from tens of metres to several hundred metres in size. The metamorphic-rock fragments are represented by gneiss, amphibolite, metavolcanic rocks, metaquartzite, calc-schist, and mica schist.

The metamorphic sole lies consistently between the mantle tectonites and the Yeşiltaşyayla mélange to the east of Ekinbaşı, and shares sheared contacts with the units above and below (Figure 2). A pronounced regional foliation, mineral lineations and intrafolial folds were produced during intraoceanic deformation. The main lithology of the metamorphic sole is amphibolite, with subordinate greenschist, marble and metachert. The metamorphic sole exhibits a classic inverted metamorphic gradient, from amphibolite-facies metamorphic rocks downward into greenschist-facies rocks. The metamorphic sole is cut by unmetamorphosed diabase/ microgabbro dykes.

The Divriği ophiolite is located between Çetinkaya and Maltepe in the study area (Figure 2). It displays an almost complete oceanic lithospheric section, represented by serpentinized mantle tectonites, cumulates, isotropic gabbros and sheeted dykes (Figures 2 & 3). Ophiolitic volcanic rocks and associated sediments are absent. The transitions from cumulate to isotropic gabbros and from isotropic gabbros to sheeted dykes are gradual, and are exposed along the Tatlıçay river between Güneş and Çetinkaya (Figure 2). The contacts between the other units of the ophiolite are tectonic (Figure 2). The exposures of the mantle tectonite are located between Pengürt and Maltepe, and are dominated by serpentinized harzburgite that contains dunitic lenses and subordinate lherzolite. A number of chromite deposits within the dunitic lenses were mined at Pengürt, north of Bizevi and south of Galın (Figure 2). The tectonites are intruded by pyroxenite and gabbroic to diabasic dykes at different

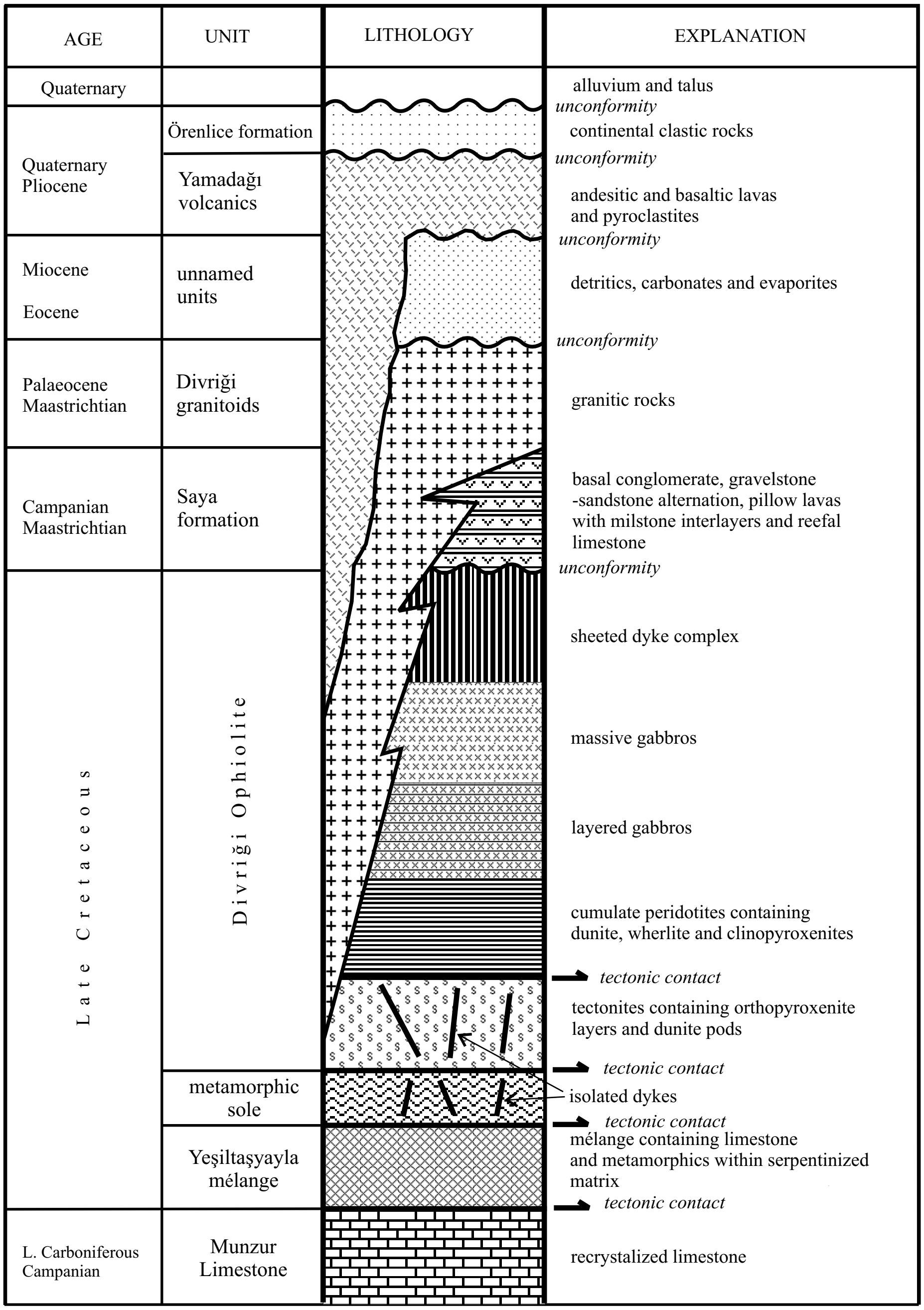

Figure 3. Columnar section of units in the study area (modified from Yılmaz *et al.* 2001; Yılmaz & Yılmaz 2004).

structural levels. The ultramafic cumulate rocks crop out mainly to the south of Pengürt and to the northeast of Yellice (Figure 2). The ultramafic cumulates comprise dunite, wehrlite, olivine websterite and scarce lherzolite. The gabbroic cumulates are observed along the Tatlıçay river to the northeast of Çetinkaya (Figure 2) and are represented by normal gabbro and olivine gabbro. The cumulate gabbro passes transitionally into isotropic gabbroic rocks along the Tatlıçay river near Keçikaya and to the northeast of İnalli (Figure 2). It is represented by gabbro and diorite. The sheeted dykes are sparsely represented in the upper parts of the isotropic gabbros and increase in frequency upwards. The dyke thicknesses range from 20 to 50 cm. The sheeted dykes are characterized by diabase and microdiorite.

The volcano-sedimentary unit, named the Saya formation, is well exposed around Yellice and southwest of Güneş village (Figure 2). The Saya formation unconformably overlies the Divriği ophiolite, and comprises conglomerates at the base in which ophiolite-derived pebbles are dominant. The basal conglomerate passes into alternations of sandstone-mudstone-marl, limestone lenses, agglomerate, tuff and spilitic volcanics. This volcano-sedimentary unit is intruded by basic dykes. The fossil content of the limestone lenses yielded a Campanian-Maastrichtian age (Yılmaz *et al.* 2001).

The granitoid rocks, intruding all of the pre-existing units, are observed at Yellice, Pengürt and Ekinbaşı (Figure 2). They are A-type granitoid bodies, consisting of felsic monzonitic/syenitic and mafic monzogabbroic/ monzodioritic rocks and monzodiorite, and are themselves intruded by numerous aplite and diabase dykes (Yılmaz *et al.* 2001; Boztuğ *et al.* 2005). The granitoid body cuts the volcano-sedimentary unit of Campanian–Maastrichtian age and is unconformably overlain by Eocene basal conglomerates (Doğan *et al.* 1989; Yılmaz *et al.* 2001). Thus, the intrusion age of the granitoid body is thought to be between Maastrichtian and Eocene (Figures 2 & 3).

The Tertiary cover sediments, cropping out between Divriği and Çetinkaya, range in age from Eocene to Quaternary and are represented by detrital material, carbonate rocks, evaporites, volcanic rocks and alluvium (Figure 2). The base of the cover sediments unconformably overlies the former units and begins with an Eocene basal conglomerate in which pebbles of granitoid rock, ophiolitic rocks and iron ore are dominant (Gürsoy 1986; Doğan *et al.* 1989; Yılmaz *et al.* 2001).

Petrography

The isolated dyke intrusions in the mantle tectonites of the Divriği ophiolite are widespread and are represented by microgabbro-diabase and pyroxenite whereas the metamorphic sole is only intruded by microgabbro-diabase dykes. The dykes have sharp contacts with their host rocks but chilled margins are not observed. The pyroxenite dykes have thicknesses ranging from 10 to 25 cm and show granular texture. They are made up exclusively of orthopyroxenes, which are recognised in thin section by their first-order colours and lamellar structure. In some cases, they contain clinopyroxene exsolution lamellae (Figure 4a). The microgabbro-diabase dykes have 30 cm to 1 m thickness and exhibit intergranular to microgranular-ophitic textures (Figure 4b–d). They are composed mainly of plagioclase, amphibole and clinopyroxene. The plagioclase shows extensive saussuritization. The clinopyroxene occurs as relict grains surrounded by reaction rims of green to green-brown hornblende. In some dykes, biotite is observed together with amphibole (Figure 4c). The secondary phases include epidote and chlorite, and accessory minerals are titanite and ilmenite. Calcite and quartz are also found in veins.

The metamorphic-sole rocks of the Divriği ophiolite comprise four mineralogical associations. These are (1) amphibolite, (2) plagioclase amphibolite, (3) plagioclase-amphibole schist and (4) plagioclase-epidote-amphibole schist. The amphibolites have no pronounced foliation, are characterized by granoblastic texture, and are composed exclusively of green hornblende (Figure 4e). The plagioclase-amphibolite rocks have granoblastic texture and are made up of brown hornblende (65–75 %), plagioclase (25–35 %), epidote (< 5 %) and opaque minerals (Figure 4f). The plagioclase is intensely altered to saussurite and sericite. Quartz, epidote and calcite are observed in veins. The plagioclase-amphibole schist has nematoblastic texture and exhibits pronounced foliation due to the preferred orientation of hornblende (70–75 %) and plagioclase (25–30 %) (Figure 4g). The plagioclase-epidote-amphibole schist has nematoblastic texture and comprises plagioclase (5–10 %), epidote (10–15 %) and green to brown hornblende (70–75 %) (Figure 4h).

Analytical Techniques

A total of 29 samples from the metamorphic-sole rocks (17) and isolated mafic dykes (12) were analysed for their major- and trace-element contents. The major- and trace-element analyses were carried out in the Mineralogy Department of the University of Geneva (Switzerland). The major elements were determined by XRF spectrometry on glass beads fused from ignited powders

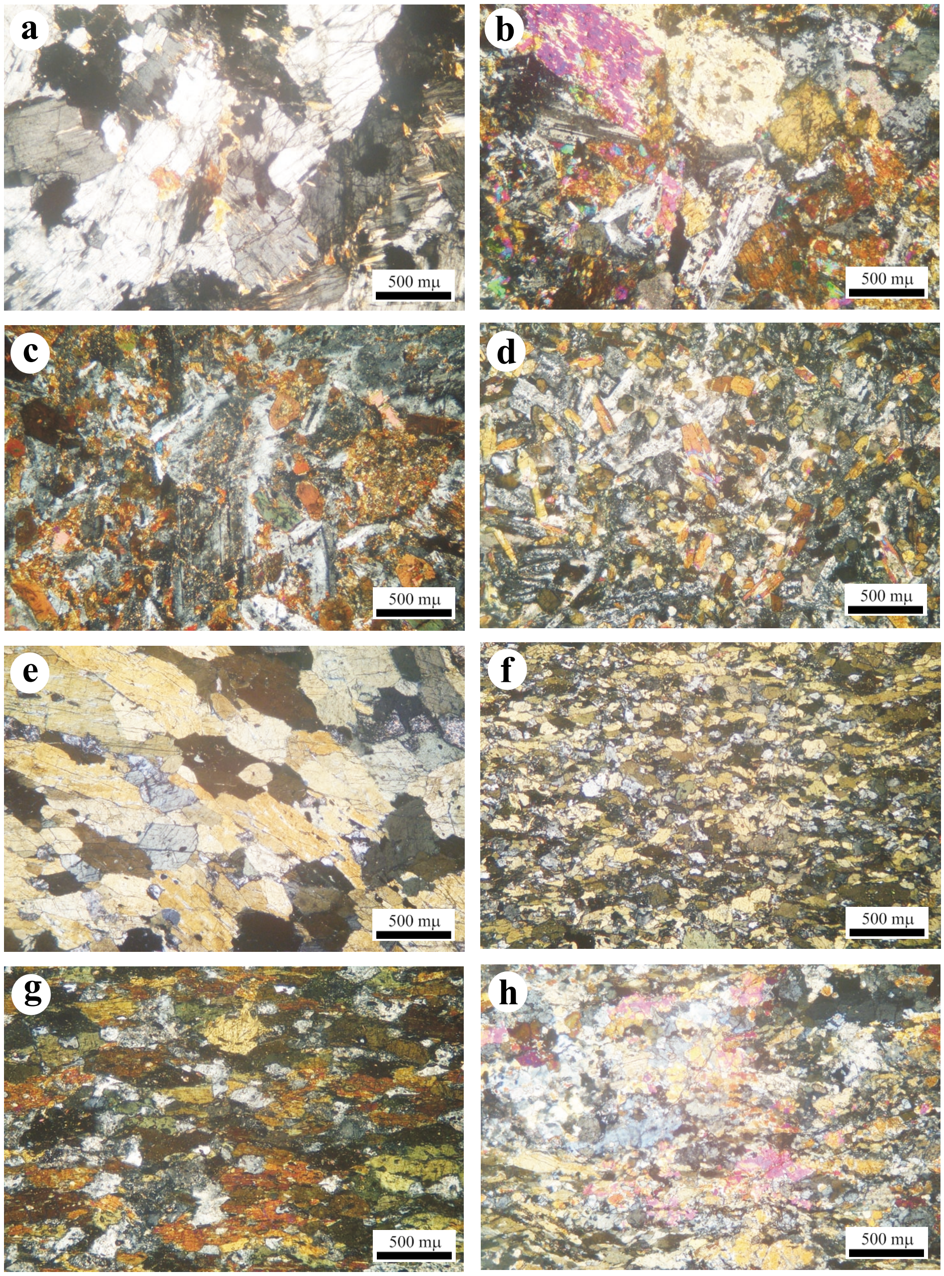

Figure 4. Microscopic views from the isolated dyke (a-d) and metamorphic-sole rocks (e-h) of the Divriği ophiolite.

– to which $Li_2B_4O_7$ had been added (1:5) – in a gold-platinum crucible at 1150 ºC. The trace elements were analyzed on pressed powder pellets by the same instrument. A subset of 11 samples was analysed for trace elements (including REE) by ICP-MS at Acme Analytical Laboratories in Canada. A subset of 3 samples was also analysed for rare-earth elements (REE) by the same method in the Minerology Department of the University of Geneva.

Geochemistry

The major-, trace- and rare-earth-element contents of the metamorphic-sole and isolated dyke rocks from the Divriği ophiolite are given in Tables 1 to 3. The metamorphic-sole rocks and the isolated dykes of the Divriği ophiolite have a wide range of loss-on-ignition (LOI) values, ranging from 0.8 to 11.03 (Tables 1 & 2). The wide variation in LOI is a crude measure of the degree of rock alteration and reflects the contribution by secondary hydrated and carbonate phases. Humphris & Thompson (1978) and Thompson (1991) stated that under medium grades of metamorphism involving hydrous fluids, some degree of selective element mobility is to be expected, especially for the large-ion-lithophile (LIL) elements. Characterization and discrimination of metamorphic (e.g., amphibolites) and magmatic suites has been done on the basis of trace elements generally considered relatively stable (immobile) during alteration, such as the high-field-strength (HFS) elements and rare-earth elements (Pearce & Cann 1973; Smith & Smith 1976; Floyd & Winchester 1978, 1983). Good linear coherence between pairs of stable incompatible elements, and smooth normalized patterns for REE or a sequence of incompatible elements mirror pre-metamorphic/ alteration magmatic compositional variations (Floyd *et al.* 1996; Winchester *et al.* 1998; Vergili & Parlak 2005).

The amphibolitic rocks from the metamorphic sole exhibit two geochemically distinguishable magma types on the basis of the Zr/Ti versus Nb/Y diagram of Pearce (1996). The first group plots in the alkali-basalt field and is characterized by high concentrations of TiO_2 (1.81 to 5.04 wt %), P_2O_5 (0.2 to 1.55 wt %), Zr (150 to 339 ppm), Nb (30 to 115 ppm) and Nb/Y (1.77 to 3.48) whereas the second group plots in the tholeiitic-basalt field and is represented by low concentrations of TiO_2 (0.61 to 0.99 wt %), P_2O_5 (0.05 to 0.21 wt %), Zr (38 to 72 ppm), Nb (2 to 4 ppm) and Nb/Y (0.07 to 0.18) (Figure 5).

The isolated dykes cutting the metamorphic sole and the mantle tectonites are nepheline normative (Table 2). They plot in the alkali-basalt to trachy-andesite field and contain high values of TiO_2 (0.5 to 1.76 wt %), P_2O_5 (0.11 to 0.49 wt %), Zr (128 to 217 ppm), Nb (17 to 89 ppm) and Nb/Y (0.68 to 2.11) (Figure 5). While the Divriği subophiolitic amphibolitic rocks exhibit geochemical features similar to metamorphic-sole rocks occurring elsewhere in the Tauride belt, the Divriği isolated dykes differ from other isolated dykes in the belt in terms of their alkaline nature. The isolated dykes at Mersin, Pınarbaşı, Pozantı-Karsantı, Antalya and Köyceğiz in southern Turkey have tholeiitic chemistry.

The plots in Figure 6a, b illustrate the broad range of variable Zr/Y and Zr/Ti ratios for the amphibolites. The alkaline amphibolites are characterized by high Zr/Y (11.66 to 7.77) and Zr/Ti (0.008 to 0.025) ratios whereas the tholeiitic amphibolites have low Zr/Y ratios (2.11 to 3) and Zr/Ti (0.01 to 0.013). The isolated dykes display similar geochemical behaviour to the alkaline amphibolites in terms of Zr/Y (4.16 to 10.08) and Zr/Ti (0.015 to 0.065) ratios (Figure 6a, b). Both amphibolites and dykes display coherent trends in Ti, Y and FeO*/MgO with increasing Zr (Figure 6a–c). The FeO*/MgO variation diagram in Figure 6c shows that the internal chemical variation is governed largely by mafic fractionation that produced a typical Fe-enrichment trend for the alkaline to tholeiitic amphibolites and alkaline isolated dykes. The tholeiitic amphibolites appear to define a different fractionation trend, however, they exhibit geochemical features similar to the other data at lower values of Zr. Figure 6d presents two ratios (Ce/Yb vs Zr/Nb) of pairs of elements of different degrees of incompatibility. On this plot, the degree of partial melting increases from upper left to lower right. Thus, the protolith of the alkaline amphibolites is thought to have formed as a result of smaller degrees of partial melting than the protolith of the tholeiitic amphibolites. The data from the isolated dykes plot between those of the alkaline and tholeiitic amphibolites, suggesting that they formed as a result of smaller degrees of partial melting compared to the tholeiitic amphibolites and higher degrees of partial melting compared to the alkaline amphibolites (Figure 5d). These geochemical aspects will be discussed later in more detail.

The chondrite-normalized REE patterns of the metamorphic sole rocks and isolated dykes are presented in Figure 7. The metamorphic-sole rocks display two distinct REE patterns. The alkaline amphibolites exhibit LREE-enriched patterns (La_N/Yb_N=8.80 to 21.95) whereas the tholeiitic ones exhibit flat REE patterns (La_N/Yb_N=0.59 to 1.25). The alkaline amphibolites display geochemical trends similar to LREE-enriched patterns of ocean-island basalts (Sun & McDonough 1989) whereas the tholeiitic amphibolites are more akin to the flat-lying REE patterns of basaltic rocks formed in subduction-

Table 1. Major- and trace-element contents of the metamorphic sole rocks.

Metamorphic-Sole Rocks	Tholeiitic Amphibolites				Alkaline Amphibolites												
Sample	PD-1	PD-2	PD-4	PD-5	PD-19	PD-20	PD-23	PD-24	PD-27	PD-28	PD-29	PD-30	PD-31	PD-32	PD-33	PD-71	PD-72
SiO_2	41.14	44.11	40.31	46.59	41.15	41.68	41.67	46.32	49.73	49.84	43.15	46.68	41.23	42.65	36.58	44.98	44.53
TiO_2	0.99	0.99	0.84	0.61	4.72	5.04	2.57	3.31	2.15	2.29	3.32	2.83	4.08	4.06	1.81	3.91	4.03
Al_2O_3	17.27	16.58	12.59	16.30	12.12	12.23	10.53	16.24	17.09	16.99	13.03	11.75	13.68	14.68	9.09	14.32	14.88
FeO*	11.47	12.08	9.57	9.30	15.82	16.01	13.05	14.25	11.27	11.51	15.81	12.81	15.13	14.63	9.40	13.81	13.03
MnO	0.38	0.31	0.30	0.16	0.29	0.28	0.17	0.20	0.27	0.24	0.24	0.22	0.21	0.22	0.42	0.12	0.09
MgO	5.02	4.30	5.57	7.50	7.74	6.87	8.63	2.77	3.26	3.26	8.03	8.80	7.31	5.17	5.98	5.75	5.50
CaO	14.38	10.85	15.39	14.65	10.90	11.05	19.92	7.10	7.29	6.91	10.57	11.08	13.14	11.60	22.39	10.70	11.43
Na_2O	2.79	4.39	2.93	2.05	2.03	2.36	0.76	4.53	4.83	4.85	2.29	2.54	2.06	3.02	2.05	2.88	2.37
K_2O	1.38	1.52	0.91	0.46	1.41	1.41	0.59	2.04	2.38	2.11	1.07	0.96	1.17	1.30	0.88	1.92	2.40
P_2O_5	0.20	0.21	0.12	0.05	0.84	0.87	0.42	1.55	0.78	0.84	0.20	0.36	0.59	0.60	0.24	0.70	0.65
Cr_2O_3	0.11	0.10	0.06	0.07	0.03	0.03	0.10	0.00	0.00	0.00	0.09	0.08	0.01	0.01	0.12	0.02	0.01
NiO	0.03	0.03	0.02	0.01	0.02	0.01	0.05	0.00	0.00	0.00	0.05	0.03	0.01	0.01	0.03	0.01	0.01
LOI	4.95	4.55	11.03	2.41	1.97	1.60	1.82	1.30	0.92	0.80	1.30	1.49	0.91	1.28	10.37	0.83	0.99
Total	100.11	100.04	99.65	100.14	99.06	99.42	100.27	99.60	99.96	99.65	99.13	99.62	99.54	99.23	99.36	99.96	99.92
Nb	2	3	4	2	67	67	53	112	115	110	47	39	66	64	30	50	59
Zr	72	70	66	38	238	252	181	339	331	320	207	171	276	280	150	242	270
Y	27	27	22	18	27	27	19	41	33	34	26	22	24	24	13	27	32
Sr	698	476	123	107	497	553	252	1235	1435	1864	354	244	671	583	254	1215	613
U	2	2	2	3	2	2	13	2	3	2	2	2	2	2	2	2	2
Rb	29	32	23	12	16	16	7	41	40	41	19	20	17	18	20	66	79
Th	2	2	2	3	2	2	2	2	8	3	2	2	2	2	2	2	2
Pb	15	18	13	13	2	2	10	2	9	6	3	3	2	2	3	2	2
Ga	18	15	12	15	17	19	15	23	16	15	19	17	22	20	12	19	22
Zn	123	113	82	67	134	145	117	173	100	85	132	104	137	152	73	85	58
Cu	82	19	43	67	25	24	85	4	7	5	46	29	63	39	164	24	15
Ni	208	202	108	95	119	113	327	10	4	4	340	175	89	47	147	69	40
Co	64	61	43	41	55	54	75	23	11	9	69	56	51	42	50	48	32
Cr	857	761	440	531	219	260	723	10	5	12	692	589	77	48	974	109	87
V	221	231	214	234	333	367	280	99	25	32	277	286	377	368	245	328	328
Ce	14	16	15	14	114	108	39	171	126	136	47	45	91	76	16	89	97
Nd	11	9	10	10	43	39	30	68	60	61	23	20	48	38	22	39	42
Ba	112	182	54	10	464	546	114	683	1776	1230	339	162	290	397	254	398	837
La	8	10	4	4	21	21	51	45	67	74	16	25	37	28	33	30	27
S	10	3	8	23	3	3	3	3	529	229	27	3	578	1882	528	1219	779
Hf	1	1	6	1	5	5	3	6	12	11	2	2	8	11	4	5	9
Sc	26	26	18	47	35	33	27	10	11	11	39	41	32	26	2	27	20
As	6	7	5	5	3	7	5	8	5	5	5	8	8	5	6	11	7
Ti/Y	219.5	220.4	230.2	201.5	1048.9	1118.5	811.7	483.4	390.6	404.0	764.6	770.4	1019.7	1013.4	834.3	867.6	754.9
Nb/Y	0.07	0.11	0.18	0.11	2.48	2.48	2.79	2.73	3.48	3.24	1.81	1.77	2.75	2.67	2.31	1.85	1.84
Zr/Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 2. Major- and trace-element contents and CIPW norms of the isolated dykes.

	Isolated Dikes											
Sample	PD-3	PD-6	PD-7	PD-8	PD-10	PD-11	PD-12	PD-13	PD-14	PD-16	PD-17	PD-18
SiO_2	51.15	46.39	46.12	49.00	46.60	46.87	49.37	49.39	50.22	51.57	55.39	46.20
TiO_2	1.41	1.33	1.31	1.76	1.14	1.17	1.31	1.35	1.22	0.50	0.50	1.15
Al_2O_3	19.62	15.63	15.88	17.56	16.89	15.98	17.87	17.71	17.11	23.74	24.62	15.10
FeO*	7.58	9.33	9.48	10.27	9.06	8.22	8.53	8.90	8.05	0.70	0.86	8.67
MnO	0.13	0.16	0.17	0.15	0.12	0.12	0.12	0.12	0.11	0.02	0.01	0.23
MgO	6.94	7.08	7.07	3.85	7.23	7.94	5.88	6.19	6.26	1.59	0.53	6.82
CaO	0.85	12.90	12.27	5.61	12.17	13.68	8.60	8.19	7.92	7.70	8.28	10.03
Na_2O	7.25	2.78	2.81	5.01	3.22	2.70	4.39	4.46	3.93	5.19	7.53	2.71
K_2O	0.34	1.00	1.15	2.64	1.42	1.41	2.33	2.27	3.32	4.39	0.61	3.26
P_2O_5	0.35	0.36	0.35	0.42	0.33	0.24	0.47	0.49	0.42	0.14	0.11	0.37
Cr_2O_3	0.01	0.02	0.02	0.00	0.01	0.03	0.03	0.03	0.03	0.00	0.00	0.01
NiO	0.02	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01
LOI	3.76	3.24	3.32	3.21	2.17	2.15	1.26	1.04	1.34	4.75	1.50	5.04
Total	99.41	100.22	99.97	99.49	100.37	100.52	100.18	100.15	99.95	100.29	99.94	99.58
Nb	19	17	17	27	17	17	25	24	24	80	89	17
Zr	131	129	128	217	130	140	159	163	164	193	179	136
Y	13	24	24	32	25	23	28	28	29	38	43	24
Sr	88	281	290	244	381	697	763	623	682	402	697	519
U	5	3	2	4	3	2	3	3	3	6	9	4
Rb	12	18	21	33	67	57	78	76	104	217	25	59
Th	13	10	10	16	10	5	8	10	10	38	36	11
Pb	3	16	20	5	10	8	33	5	6	3	3	14
Ga	23	16	15	21	16	13	16	18	17	18	20	15
Zn	57	70	83	72	39	40	288	53	47	34	27	73
Cu	2	30	56	52	18	25	59	34	5	5	8	98
Ni	149	81	81	3	61	67	82	88	97	21	16	74
Co	21	42	42	27	41	36	30	34	27	3	3	38
Cr	145	154	168	21	72	204	234	239	268	8	33	61
V	390	238	242	262	234	231	188	189	186	16	10	229
Ce	23	31	47	86	46	42	62	67	62	117	113	56
Nd	4	17	27	36	25	25	30	30	28	45	50	28
Ba	65	322	389	674	618	444	1076	819	1318	443	228	1627
La	5	32	29	40	43	29	31	45	46	79	102	43
S	3	85	115	487	29	103	309	205	59	49	147	817
Hf	1	3	1	6	1	8	3	9	3	4	7	5
Sc	49	35	37	23	37	33	19	22	22	8	9	34
As	5	4	7	4	3	3	4	4	3	3	3	4
Ti/Y	652.3	331.2	328.4	330.0	274.5	306.1	281.2	288.2	252.9	78.2	70.0	287.0
Nb/Y	1.46	0.71	0.71	0.84	0.68	0.74	0.89	0.86	0.83	2.11	2.07	0.71
Zr/Ti	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.06	0.06	0.02
	CIPW Norms											
Plagioclase	72.45	47.07	47.30	52.90	43.14	39.32	47.99	48.69	42.61	48.59	81.37	30.97
Orthoclase	2.38	7.15	8.24	18.24	9.94	9.91	15.77	15.35	22.43	28.54	3.86	23.48
Nepheline	0.43	6.27	6.41	8.12	10.27	9.64	9.49	9.11	8.28	15.36	9.18	10.13
Corundum	5.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diopside	0.00	26.12	23.75	5.50	22.84	29.00	12.51	11.36	12.39	5.98	3.03	21.33
Wollastonite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.70	0.00
Olivine	16.14	9.58	10.52	10.80	10.44	9.01	10.55	11.65	10.88	0.59	0.00	10.56
Ilmenite	1.71	1.65	1.63	2.11	1.38	1.42	1.54	1.58	1.43	0.56	0.55	1.43
Magnetite	1.07	1.35	1.37	1.43	1.28	1.16	1.16	1.21	1.09	0.09	0.11	1.25
Apatite	0.77	0.81	0.79	0.91	0.72	0.53	1.00	1.04	0.89	0.29	0.22	0.84
Total	100.00	100.00	100.01	100.01	100.01	99.99	100.01	99.99	100.00	100.00	100.02	99.99

Table 3. Trace-element and REE compositions of the subset of samples analysed by ICP-MS.

	Metamorphic-Sole Rocks								Isolated Dikes					
Sample	PD-2	PD-5	PD-20	PD-23	PD-24	PD-27	PD-29	PD-30	PD-3	PD-7	PD-10	PD-14	PD-16	PD-18
Rb	31.10	8.10	20.80	nd	50.80	46.00	nd	23.90	6.80	18.00	71.10	109.90	174.50	nd
Ba	150.50	15.70	516.50	nd	695.00	1545.30	nd	147.80	25.10	345.50	490.90	1220.40	481.30	nd
Th	0.20	< 0.1	5.50	nd	10.40	8.50	nd	3.30	6.00	6.00	5.20	7.40	36.30	nd
U	0.20	< 0.1	1.80	nd	1.80	2.80	nd	1.20	3.30	2.20	2.90	3.10	6.60	nd
Nb	1.80	0.70	79.80	nd	124.70	116.50	nd	43.30	20.00	16.70	15.80	24.80	75.10	nd
Ta	0.1	< 0.1	4.4	nd	6.7	6.60	nd	2.5	1.2	1	1.00	1.4	4.4	nd
Pb	0.90	0.60	0.50	nd	1.80	2.70	nd	0.40	3.00	6.30	3.40	0.70	7.40	nd
Sr	508.40	113.70	631.10	nd	1362.90	1447.80	nd	285.70	106.10	345.80	380.80	794.70	458.90	nd
Zr	55.40	28.10	248.50	nd	337.50	310.30	nd	164.70	146.30	128.00	117.90	159.50	168.70	nd
Hf	1.60	0.90	7.00	nd	8.40	7.70	nd	4.60	4.00	3.00	3.30	3.70	2.20	nd
Y	30.80	17.70	33.60	nd	45.10	40.60	nd	21.90	8.80	25.40	24.20	25.30	34.30	nd
La	5.30	1.50	63.20	38.12	107.10	80.90	26.61	32.60	5.70	23.50	22.20	32.30	48.00	23.88
Ce	7.70	3.80	132.60	83.06	215.90	173.80	64.87	66.00	10.80	46.30	48.00	60.80	100.60	49.34
Pr	1.80	0.77	15.98	9.68	25.21	19.06	7.94	7.98	1.28	5.58	5.49	6.93	10.70	5.83
Nd	9.70	4.30	69.40	38.79	106.80	78.30	34.29	35.50	4.90	23.60	23.50	27.70	38.80	23.63
Sm	3.30	1.50	12.00	7.73	18.10	13.50	7.84	6.50	1.10	5.00	4.80	5.50	6.30	4.90
Eu	1.18	0.65	3.96	2.12	6.16	4.78	2.42	2.17	0.20	1.47	1.30	1.51	1.26	1.38
Gd	4.28	2.05	10.33	6.27	15.04	10.69	7.05	6.30	1.14	4.66	4.11	4.93	4.98	4.40
Tb	0.76	0.55	1.66	0.84	2.18	1.70	1.00	1.04	0.18	0.80	0.82	0.81	1.02	0.65
Dy	4.69	2.82	6.86	4.51	9.93	8.02	5.82	4.56	1.22	4.40	4.02	4.23	5.48	3.91
Ho	1.00	0.67	1.18	0.79	1.68	1.40	1.06	0.79	0.31	0.83	0.85	0.87	1.12	0.77
Er	3.03	1.94	3.03	2.02	4.12	3.58	2.77	2.04	1.01	2.40	2.30	2.54	3.41	2.24
Tm	0.50	0.38	0.46	0.26	0.61	0.45	0.37	0.28	0.21	0.38	0.30	0.40	0.54	0.31
Yb	3.04	1.82	2.55	1.54	3.50	2.89	2.17	1.84	1.29	2.25	2.06	2.46	3.91	2.02
Lu	0.39	0.33	0.31	0.21	0.44	0.41	0.31	0.24	0.26	0.32	0.31	0.34	0.47	0.31

nd = not determined; < = below detection limit.

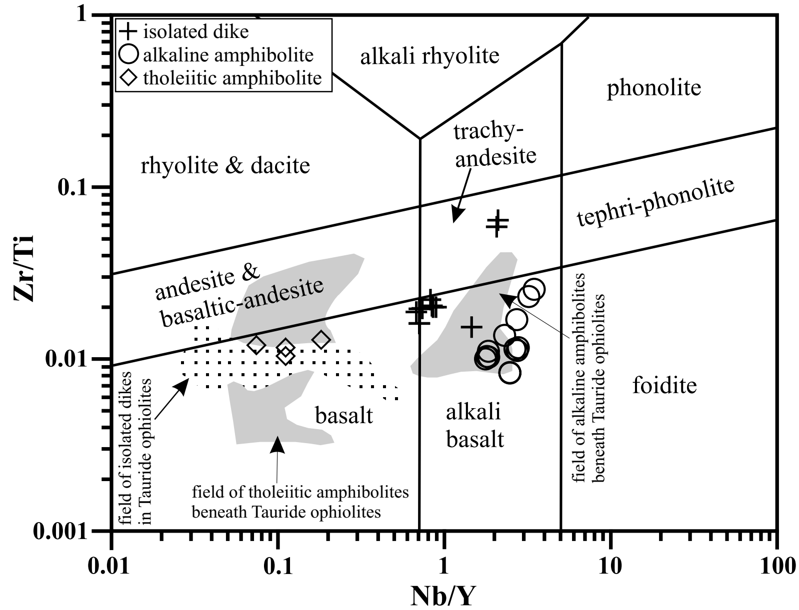

Figure 5. Rock classification diagram for the metamorphic sole and isolated dykes from the Divriği ophiolite (after Pearce 1996). Field of metamorphic soles and mafic dykes from the Tauride ophiolites are from Parlak *et al.* (1995), Lytwyn & Casey (1995), Dilek *et al.* (1999), Parlak (2000), Çelik & Delaloye (2003).

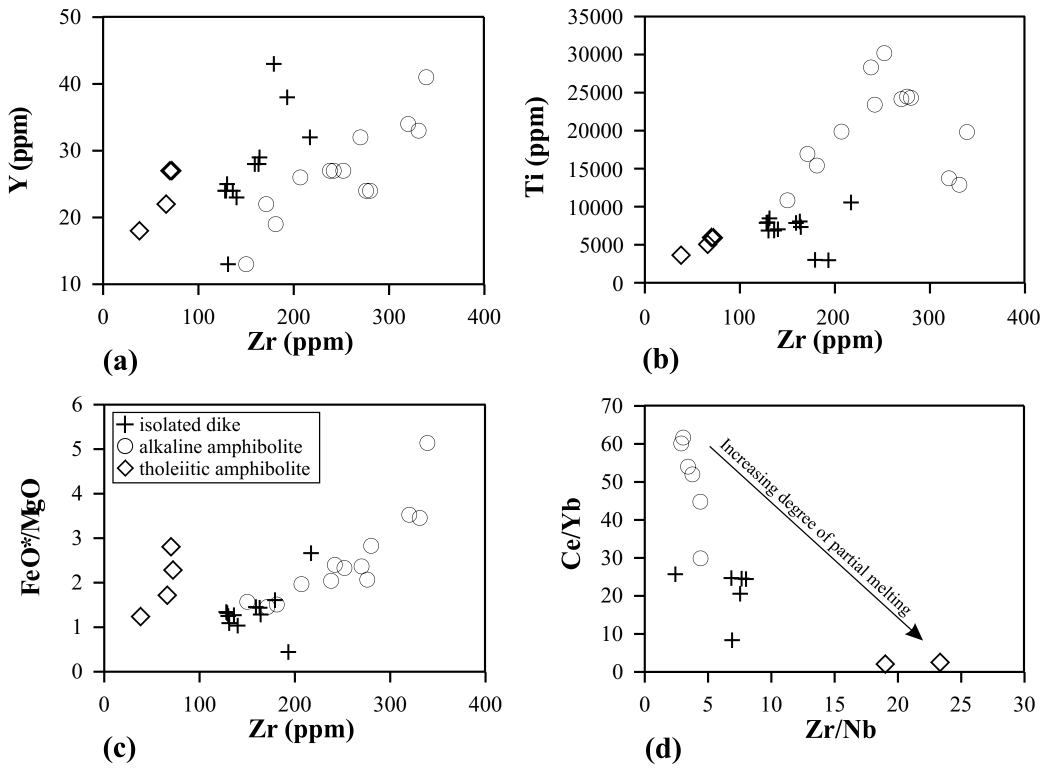

Figure 6. Characterization of metamorphic-sole rocks and isolated diabase dykes in terms of (a) Zr-Y, (b) Zr-Ti, (c) Zr-FeO*/MgO and (d) Zr/Nb-Ce/Yb.

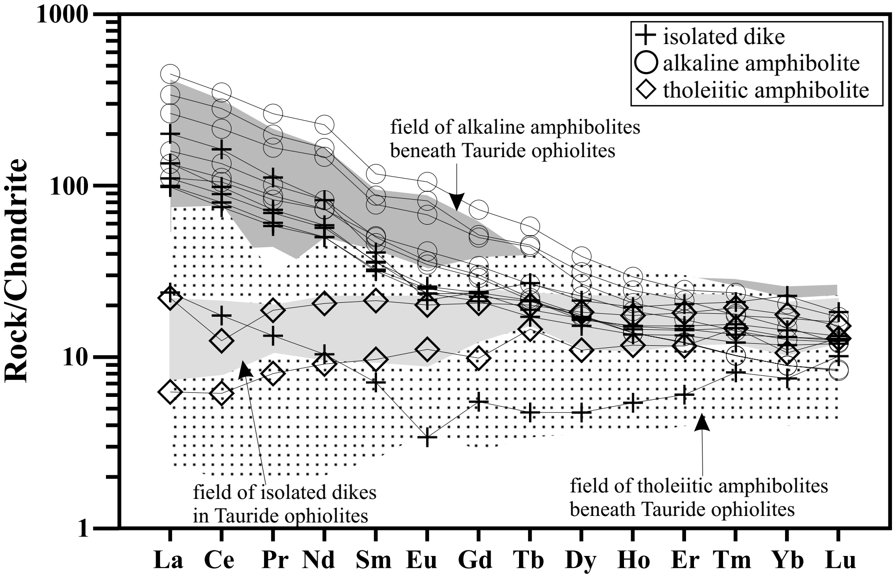

Figure 7. Chondrite-normalized REE patterns of the isolated dykes and metamorphic-sole rocks of the Divriği ophiolite (normalizing values are from Sun & McDonough 1989). Data for the metamorphic soles and mafic dykes from the Tauride ophiolites are the same as in Figure 5.

related settings. These two REE patterns are typical of other metamorphic soles beneath Tauride-belt ophiolites and are interpreted to indicate that basaltic volcanics formed in mid-ocean ridge (MORB), within- plate (WPB) and island-arc (IAT) settings were metamorphosed during intraoceanic subduction in a Neotethyan oceanic basin (Parlak *et al.* 1995; Lytwyn & Casey 1995; Dilek *et al.* 1999; Çelik & Delaloye 2003; Vergili & Parlak 2005). The isolated dykes have LREE-enriched, differentiated patterns (La_N/Yb_N=3.17 to 9.42) that are distinct from the REE patterns of isolated dykes elsewhere in the Tauride-belt ophiolites (Parlak *et al.* 1995; Lytwyn & Casey 1995; Parlak & Delaloye 1996; Çelik & Delaloye 2003; Vergili & Parlak 2005). The LREE-enrichment patterns of the isolated dykes from the Divriği ophiolite display similarity to LREE-enrichment patterns of ocean-island basalts (Sun & McDonough 1989). One sample of the isolated dykes (PD-3) exhibited lower fractionation (La_N/Yb_N=3.17) and concentrations of REE compared to the others (Figure 7); this may be due to different degrees of partial melting at different depths.

The multi-element diagrams for the isolated dykes, alkaline and tholeiitic amphibolites are presented in Figure 8. The isolated dykes exhibit enriched multi-element patterns compared to N-MORB and the isolated dykes in other Tauride-belt ophiolites (Figure 8a). They exhibit similar patterns to OIB-type basalts in general (Figure 8a). But the isolated alkaline dykes seem to exhibit small relative Nb depletions with respect to the adjacent elements and LIL-element enrichments such as Rb, Ba and Th. This may reflect a slight contribution from a subduction-modified source to the alkaline melts. The alkaline amphibolites can be directly compared chemically with ocean-island basalt (OIB) and show multi-element patterns similar to the other analysed amphibolites from the base of the Tauride-belt ophiolites (Sun & McDonough 1989; Parlak *et al.* 1995; Lytwyn & Casey 1995; Çelik & Delaloye 2003; Vergili & Parlak 2005) (Figure 8b). The tholeiitic amphibolites are different from OIB-type basaltic rocks but exhibit multi-element patterns similar to the other tholeiitic amphibolites beneath the Tauride-belt ophiolites (Figure 8c). They are characterized by enrichment of LIL elements (i.e., Rb, Ba, Th, K), Nb depletion, and flat patterns of HFS elements relative to MORB (Figure 8c). All of this evidence suggests that the protolith of the tholeiitic amphibolites formed in a subduction-related setting.

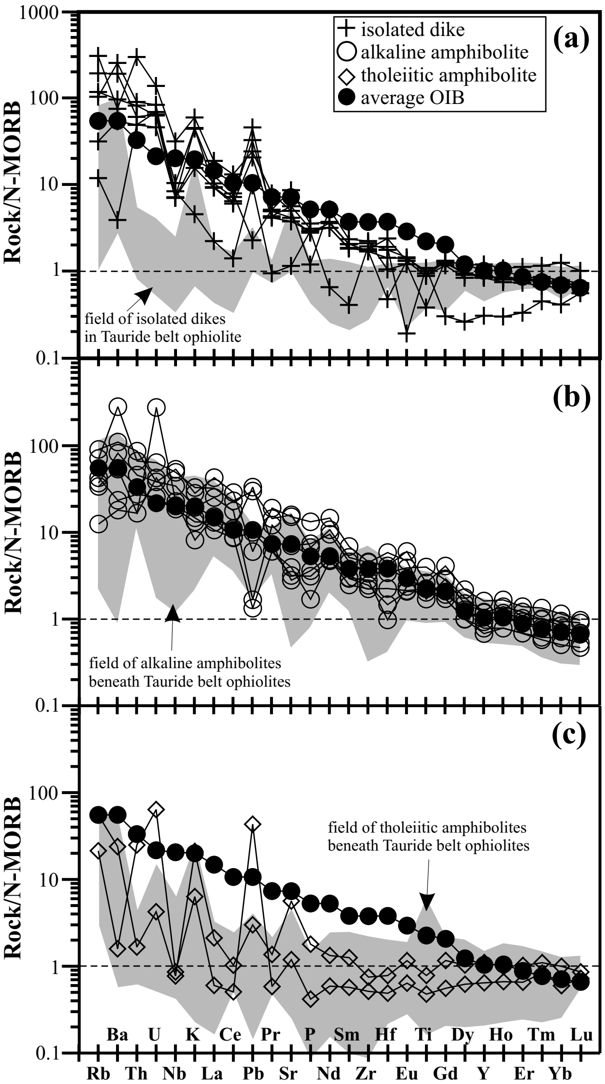

Figure 8. N-MORB-normalized spider diagram for the isolated diabase dykes (a), alkaline amphibolite (b) and tholeiitic amphibolites (c) of the Divriği ophiolite (normalizing values are from Sun & McDonough 1989). Data for the metamorphic-sole rocks and mafic dykes from the Tauride ophiolites are the same as in Figure 5.

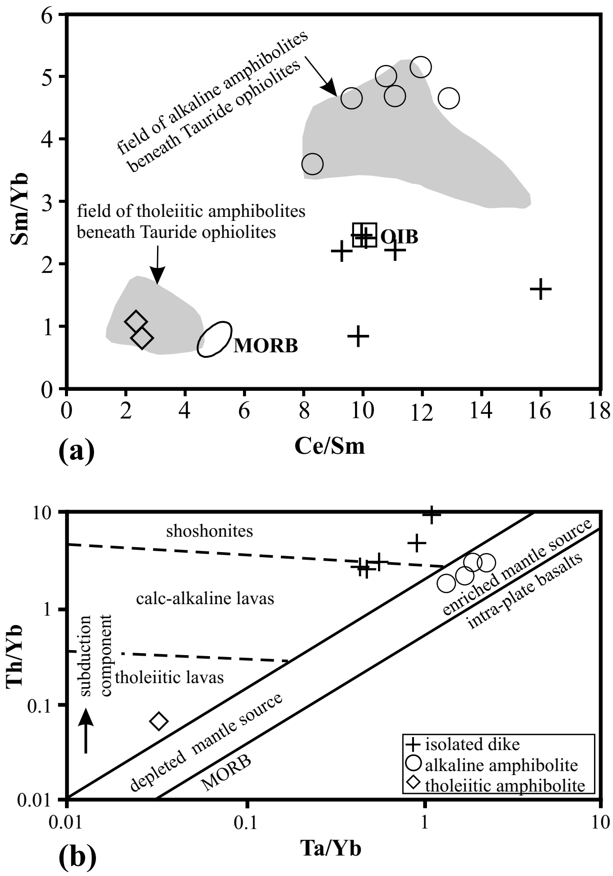

Figure 9. (a) Sm/Yb versus Ce/Sm diagram and (b) Ta/Yb versus Th/Yb diagram (after Pearce 1982), showing source characteristics for the metamorphic-sole rocks and isolated dykes of the Divriği ophiolite. Fields of OIB and MORB are from Harms *et al.* (1997). Data for the mafic dykes of the Tauride ophiolites are the same as in Figure 5.

To characterize mantle source regions for the metamorphic-sole and isolated dyke rocks of the Divriği ophiolite, ratio/ratio plots of incompatible elements were used in Figure 9a, b. The Ce/Sm versus Sm/Yb ratios are plotted in Figure 9a together with OIB and MORB compositions. The high Sm/Yb and Ce/Sm ratios of the alkaline amphibolites and isolated dykes suggest that they were derived by melting of an OIB-like enriched mantle source, whereas the low Sm/Yb and Ce/Sm ratios of the tholeiitic amphibolites suggest derivation from a more depleted MORB-like mantle source (Figure 9a). Both the tholeiitic and alkaline amphibolites show geochemical behaviour similar to other amphibolites beneath the Tauride ophiolites in terms of Ce/Sm and Sm/Yb ratio plots, whereas the isolated dykes are chemically distinct from the amphibolites. Th and Ta show similar degrees of enrichment and depletion in most mantle source regions, however, Th alone is enriched in mantle wedges above subduction zones (Pearce 1982; Alabaster *et al.* 1982). Thus, in Figure 9b, MOR basalts and intraplate basalts fall in a broad band with a slope of unity. The single sample of tholeiitic amphibolite suggest that it was derived from a depleted mantle source region modified by the addition of a subduction component, whereas the four samples of alkaline amphibolites appear to have been derived from an enriched mantle source region with no subduction component (Figure 9b). The five samples of isolated dykes exhibit a shift towards higher Th values and were probably derived from an enriched mantle source, modified by the addition of a subduction component (Figure 9b).

Tectonic-environment discrimination diagrams based on immobile trace elements are presented in Figure 10. The Zr-Nb-Y triangular plot of Meschede (1986) and the Zr/Y versus Zr plot of Pearce & Norry (1979) show within-plate affinities for the alkaline amphibolites and isolated dykes, and island-arc affinities for the tholeiitic amphibolites of the Divriği ophiolite.

Discussion

Shervais (2001) reviewed the literature on subduction-related ophiolites and proposed an evolutionary scenario that consisted of five stages, overlapping each other in time and space. In his analysis, he compared ophiolite evolution to the biological life cycle: namely, the birth, youth, maturity, death and resurrection stages. Each of these stages has its own geological, petrographical and geochemical features. The eastern Mediterranean ophiolites possessed most of these characteristics during their evolution – from birth to resurrection stages. One of the most important stages in this cycle appears to be the death stage, at which time the high-grade metamorphic sole is formed and OIB-type enriched magmas supply lavas or dykes which invade plutonites and the metamorphic sole prior to ophiolite emplacement. A number of ophiolite examples possess these features, including the Coastal Range ophiolite of California (the Stonyford Volcanic Complex) (Shervais & Hanan 1989; Shervais & Beaman 1991), the Oman ophiolite (the Salahi volcanics) (Alabaster *et al.* 1982), and the Pozantı-Karsantı ophiolite in Turkey (the pyroxenite dykes) (Çelik 2002). Dilek & Flower (2003) proposed a tectonic model depicting the late-stage (i.e., prior to trench-passive margin collision and subsequent ophiolite emplacement) petrogenetic evolution of the Semail (Oman) ophiolite. The latter authors suggested that the late-stage alkali basalts and dykes of the Salahi unit were probably the result of off-axis magmatism fed by melts that originated within an asthenospheric window as a result of delamination of subducting lithosphere shortly before the emplacement of the ophiolite onto the Arabian continental margin.

The magmatic and metamorphic processes during the death stage of the suprasubduction-zone life cycle of the Divriği ophiolite are well constrained by the presence of

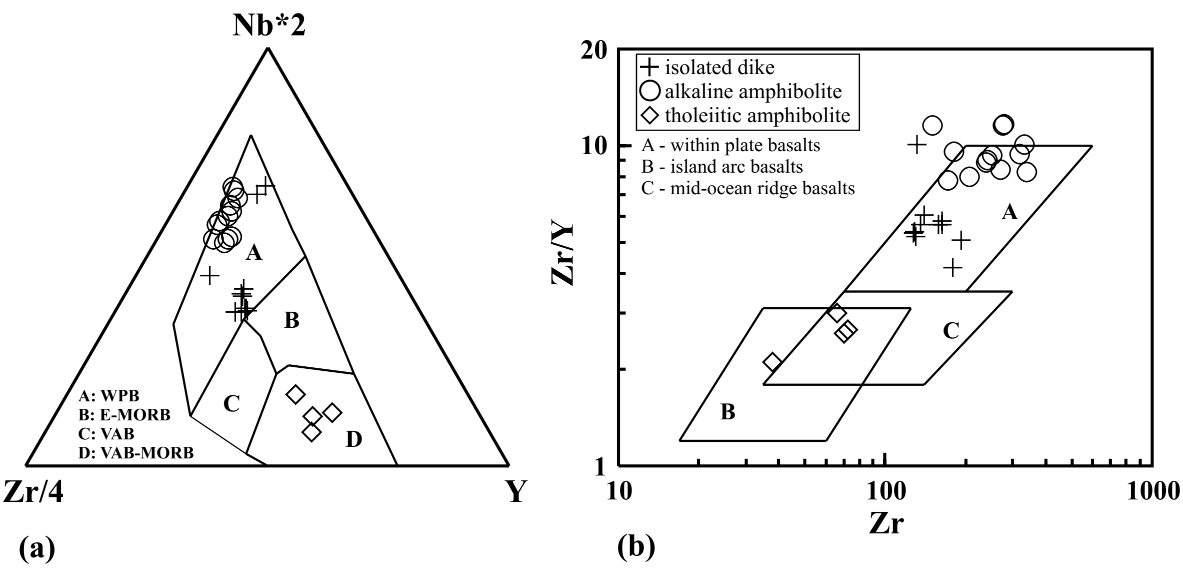

Figure 10. Tectonomagmatic discrimination diagrams for the metamorphic-sole rocks and isolated diabase dykes of the Divriği ophiolite. (a) after Pearce & Norry (1979) and (b) after Meschede (1986).

the metamorphic sole and the alkaline isolated dykes. The protoliths of the metamorphic-sole rocks include both alkaline and tholeiitic magma types. The major-, trace- and rare-earth-element geochemistry of the alkaline amphibolites suggest that these rocks were derived from an enriched mantle source and do not exhibit a subduction-zone component on the basis of Th/Yb and Ta/Yb ratios (Figure 9b). Therefore, these rocks are geochemically similar to seamount-type alkaline basalts. Jurassic–Cretaceous seamount-type alkaline basalts crop out extensively along the Neotethyan sutures of Turkey (e.g., Floyd 1993; Parlak *et al.* 1995; Lytwyn & Casey 1995; Dilek *et al.* 1999; Parlak 2000; Rojay *et al.* 2001; Çelik & Delaloye 2003; Vergili & Parlak 2005). These rocks are considered to have accreted to the base of the Neotethyan ophiolites to form metamorphic soles during the Late Cretaceous. The tholeiitic amphibolites of the metamorphic sole were derived by the metamorphism of an IAT-type basaltic protolith during intraoceanic thrusting/subduction, and show a minor subduction-zone component based on the Th/Yb and Ta/Yb ratios (Figure 9b). These volcanic rocks were presumably detached from the front of the overriding SSZ-type crust and were then underplated and metamorphosed. The alkaline isolated dykes cutting the metamorphic sole and mantle tectonites were probably derived from an asthenospheric window with some modification by a subduction component based on the evidence of Th/Yb and Ta/Yb ratios (Figure 9b).

The Late Cretaceous Neotethyan palaeogeography of the eastern Mediterranean region involved three different branches of oceanic basins separated by continental fragments and platform carbonates. These are northern Neotethys, southern Neotethys and the Inner Tauride ocean (Şengör & Yılmaz 1981; Robertson & Dixon 1984; Görür *et al.* 1984; Dilek *et al.* 1999). The Divriği ophiolite is located within the Tauride belt in the eastern part of Central Anatolia. Although there have been numerous studies on the origin of the Tauride ophiolites, their root zone is still debated. Göncüoğlu *et al.* (1996-1997) and Gürer & Aldanmaz (2002) suggested that the Tauride ophiolites formed in a suprasubduction-zone tectonic setting in the northern branch of Neotethys and were thrust over the Kırşehir-Niğde metamorphics massifs, then over the Bolkardağ/Aladağ carbonate platforms in the Late Cretaceous (Figure 11). According to some workers (Özgül 1976, 1984; Monod 1977; Şengör & Yılmaz 1981; Lytwyn & Casey 1995; Polat & Casey 1995; Polat *et al.* 1996; Dilek & Whitney 1997; Collins & Robertson 1998; Dilek *et al.* 1999; Parlak & Robertson 2004), all of the Late Cretaceous Tauride ophiolites are interpreted as remnants of a single vast ophiolitic thrust sheet generated within Neotethys to the north of the Tauride carbonate platform, called the Inner Tauride Ocean (Görür *et al.* 1984). They concluded that the Tauride ophiolites formed above a N-dipping intraoceanic subduction zone (SSZ-type) between the Anatolides to the north and the Tauride carbonate platform to the south (Figure 11). There are several lines of evidence, supporting this model of ophiolite emplacement over the Tauride carbonate platform. These are as follows: The Central Anatolian ophiolites differ lithologically and chemically from those emplaced over the Tauride platform. There are number of isolated dismembered ophiolites lying structurally above the Kırşehir and Niğde metamorphic massifs (Yalınız & Göncüoğlu 1998; Floyd *et al.* 2000). Their overall stratigraphy is as follows: the lowest part is composed of ultramafic rocks overlain by layered and isotropic gabbros. These are followed upwards by plagiogranite, then dolerite dykes, pillow basalts and acidic extrusives. Epiophiolitic sediments are of middle Turonian–early Santonian age according to Yalınız (1996). Both ophiolite and overlying sediments were later intruded by postcollisional quartz monzonite dated as 81–67 Ma (Yalınız *et al.* 1999). Geochemical data indicate that the basalts and dolerites of the volcanic sequence are of IAT type, whereas the late dolerite dykes have compositions more akin to N-MORB (Yalınız *et al.* 1996). By comparison, the Tauride ophiolites display more intact ophiolite stratigraphy. A thick slab of residual mantle dominated mainly by harzburgite is tectonically underlain by dynamothermal metamorphic soles exhibiting inverted metamorphic gradient (from amphibolite to greenschist facies), well-preserved ultramafic and mafic cumulates with a thickness of over 3 km, isotropic gabbros, basaltic pillow lavas and associated sediments. Isolated dolerite/diabase dykes intruded the Tauride ophiolites and the underlying metamorphic soles. Both the basaltic rocks in the volcanic sequence and the isolated diabase dykes which intrude the ophiolites are of IAT type (Parlak & Delaloye 1996; Parlak 2000; Elitok 2001; Çelik & Delaloye 2003). Dilek & Whitney (1997) and Okay (1989) mentioned the local presence of HP/LT metamorphic rocks along the northern edge of the Bolkardağ platform and in Tavşanlı (Kütahya) region, perhaps due to subduction and later exhumation of the

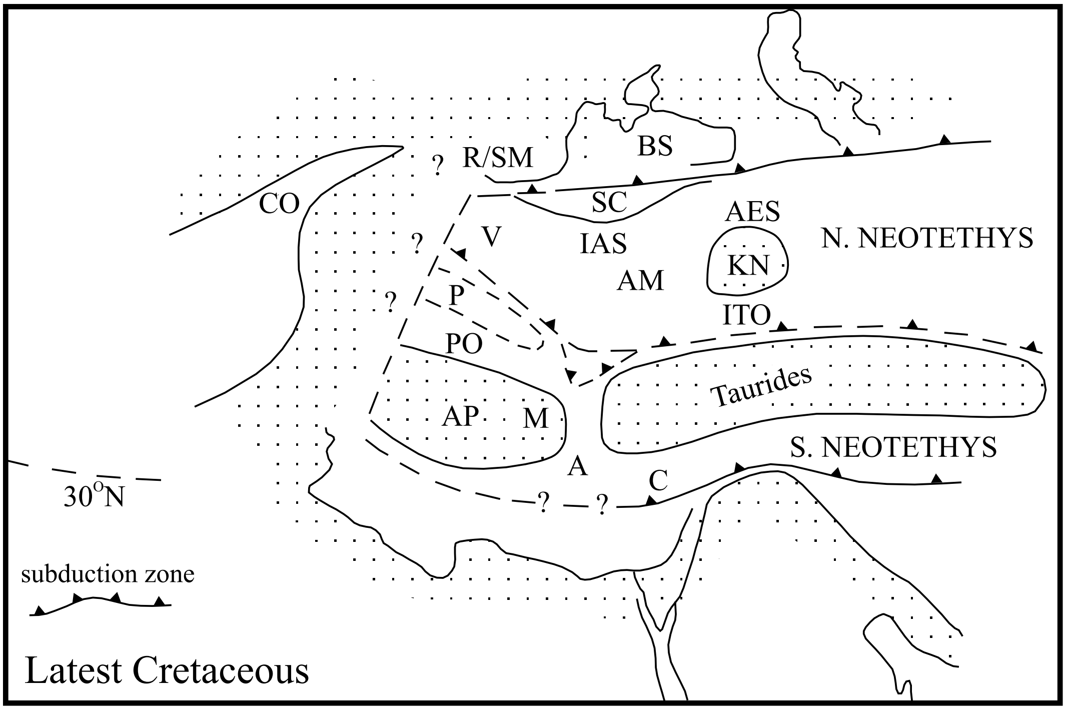

Figure 11. Simplified palaeogeographic sketch map of the eastern Mediterranean during the Late Cretaceous (from Robertson, 2002). A– Antalya, AES– Ankara-Erzincan suture zone, AM– Ankara mélange, AP– Apulia, BS: Black Sea marginal basin, C– Cyprus, CO– Carpathian ocean, IAS– İmir-Ankara suture zone, ITO– Inner Tauride ocean, KN– Kırşehir/Niğde metamorphic massif, M– Menderes Massif, P– Pelagonian, PO– Pindos ocean, R/SM– Rhodope/Serbo-Macedonian, SC– Sakarya metamorphic massif, V– Vardar.

leading edge of the Tauride platform. Robertson (2002) noted that, if the Kırşehir/Niğde metamorphic rocks formed part of the Tauride platform, a large amount of continental crust would have to be subducted. There is very little evidence of regional HP/LT metamorphism within the Kırşehir/Niğde metamorphic units. The ophiolite geology and the geochemical features of the Tauride ophiolites suggest that an oceanic basin existed in the interval from Late Triassic to the Late Cretaceous, and was located between the Tauride platform to the south and the Anatolides to the north (Figure 11).

The geological, geochemical and regional tectonic context of the Tauride belt is consistent with the following evolving scenario: The Divriği ophiolite formed above a north-dipping subduction zone (SSZ setting) within the Inner Tauride Ocean (Görür *et al.* 1984), between the Kırşehir Massif to the north and the Tauride platform to the south, in the Late Cretaceous (Figure 12a) (Parlak *et al.* 2005). During intraoceanic subduction, IAT-type volcanic rocks were detached from the forward edge of the overriding SSZ-type crust while seamount alkaline volcanic rocks from the top of the subducting plate were metamorphosed to amphibolite facies as the plate was subducted (Figure 12b). Late-stage magmatic activity prior to the emplacement of the Divriği ophiolite was represented by the intrusion of isolated dykes that were generated in an asthenospheric window due to slab break-off (Figure 12c). A similar model has been proposed by Dilek & Flower (2003) for the Salahi volcanics in the Oman ophiolite. Boztuğ *et al.* (2005) reported that the A-type Dumluca and Murmana granitoids intrude Late Cretaceous ophiolitic units in the Divriği (Sivas) area. They concluded that these granitoids resulted from the slab break-off stage of the Neotethyan convergence system.

Conclusions

The Divriği ophiolite comprises three tectonic units (in ascending order): the ophiolitic mélange, the

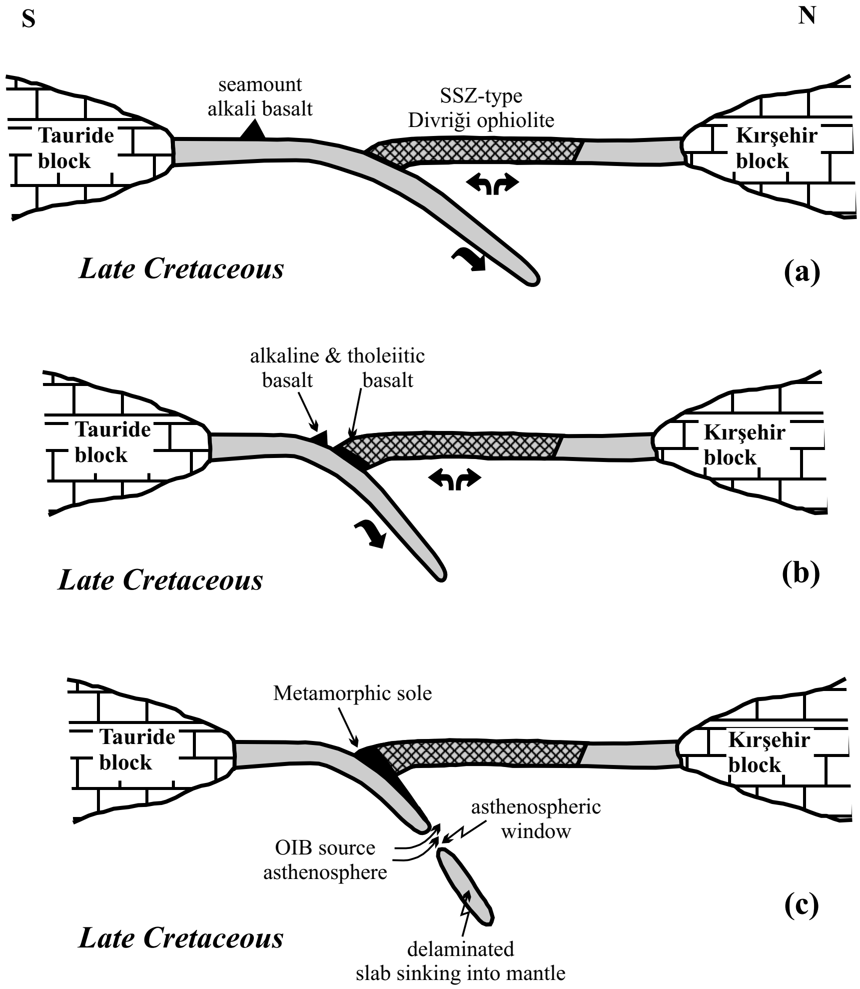

Figure 12. A tectonic model for the genesis of the Divriği ophiolite and metamorphic-sole rocks.

metamorphic sole and the ophiolite unit. Its tectonostratigraphy is similar to that found in other parts of the Tauride ophiolite belt. Therefore the Divriği ophiolite is thought to have been derived from the Inner Tauride ocean which was located between the Kırşehir block and the Tauride platform in the Late Cretaceous.

The metamorphic-sole rocks comprise two distinct geochemical groups. The first group is alkaline (Nb/Y=1.77–3.48), whereas the second group is tholeiitic (Nb/Y=0.07–0.18) in nature. The REE patterns, multi-element and tectonomagmatic discrimination diagrams suggest that the alkaline amphibolites formed as a result of metamorphism of seamount-type basaltic rocks in an intraoceanic subduction-zone setting, whereas the tholeiitic amphibolites formed as result of intraoceanic thrusting in a suprasubduction-zone (SSZ) basin.

The isolated dykes exhibit alkaline (Nb/Y=0.68–2.11) affinity. The major-, trace- and rare-earth-element geochemistry of the dykes show that they formed in a within-plate environment. The Th values of the isolated dykes are higher than normal within-plate alkaline magmas; this situation is interpreted as indicating that the isolated dykes were probably derived from an enriched mantle source modified by the addition of a subduction component.

The late-stage isolated dykes may be a result of off-axis magmatism fed by melts that originated within an asthenospheric window due to slab break-off, shortly before the emplacement of the Divriği ophiolite onto the Tauride passive margin in the Late Cretaceous.

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