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# Petrogenesis of the Refahiye Ophiolite and its Tectonic Significance for Neotethyan Ophiolites Along the İzmir-Ankara-Erzincan Suture Zone

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**Abstract:** The Refahiye ophiolite, situated near Erzincan in the eastern part of the İzmir-Ankara-Erzincan Suture Zone (İAESZ), is one of the best exposures of oceanic lithosphere in the northern branch of the Neotethyan Ocean. The ophiolite, mainly thrust southwards, transported on an ophiolitic mélange, over the Early Triassic–Campanian Munzur Limestone of the Anatolide-Tauride Platform, was also emplaced by north-directed backthrusting onto the Pontides in the Late Cretaceous. It displays an almost complete ophiolite series unconformably overlain by Tertiary volcano-sedimentary units. The mantle peridotites are dominated by harzburgites, with dunite bands and lenses locally cut by isolated diabase dykes, whereas the mafic-ultramafic cumulates of the mantle-crust transitional zone consist of dunites, wehrlites, pyroxenites and gabbros. The diabase dykes of the sheeted-dyke complex show a magmatic boundary with the underlying massive gabbros which are in places crosscut by plagiogranite dykes. The basic and leucocratic rocks exhibit greenschist facies assemblages of ocean floor metamorphism. The spilitic pillow basalts and cover sediments (radiolarites, pelagic limestones) of the upper units of the oceanic crust are preserved as megablocks in the ophiolitic mélange.

Petrological features of the ophiolitic rocks show that the ultramafic, mafic and leucocratic rocks belong to a co-magmatic differentiated tholeiite series. The crystallization order is olivine-clinopyroxene (locally with orthopyroxene)-plagioclase. The gabbros and diabases are tholeiitic (Nb/Y= 0.05–0.5). Whereas the LIL elements (K, Sr, Rb, Ba), with the exception of Th, show variable scatter because of ocean floor hydrothermal alteration, the HFSE (Nb, Ti, Zr, Y) and the LREE (La, Ce, Nd) have been depleted relative to N-MORB. The ratios of the selected trace elements (Ti/V, Zr/Y, Th/Y, Ti/Zr) and the tectonomagmatic discrimination diagrams for Ti-poor gabbros and dykes suggest that the Refahiye ophiolite has island arc tholeiitic (IAT) and possibly boninitic affinities. The mantle peridotites have very low REE concentrations, showing U-shaped REE patterns. The isotropic gabbros and plagiogranites exhibit high REE concentrations with positive and negative Eu anomalies respectively, patterns typical of SSZ magmatism. The ultramafic-mafic and leucocratic rocks of the Refahiye ophiolite were formed in the earliest stages of island arc development in a suprasubductional, forearc tectonic setting in the northern branch of the Neotethyan Ocean, similar to most of the Cretaceous Eastern Mediterranean ophiolites.

**Key Words:** Refahiye (Erzincan), İzmir-Ankara-Erzincan Suture Zone, ophiolite, forearc, suprasubduction

## İzmir–Ankara-Erzincan Kenet Kuşağındaki Neotetis Ofiyolitlerinden Refahiye Ofiyolitinin Petrojenezi ve Tektonik Önemi

**Özet:** İzmir-Ankara-Erzincan Kenet Kuşağı'nın (İAEKK) doğu kısmında yer alan Refahiye ofiyoliti, Neotetis Okyanusu'nun kuzey kolunu temsil eden okyanusal litosfer kalıntısının en iyi örneklerinden biridir. Erzincan dolayında bulunan Refahiye ofiyoliti, Geç Kretase'de, altındaki ofiyolitik melanjla birlikte başlıca güneydeki Anatolid-Torid Platformu'nun Erken Triyas–Kampaniyen yaşlı Munzur Kireçtaşının üzerine bindirme ile yerleşmiştir. Ayrıca kuzeye doğru retroşariyaj ile Pontidlere de bindirmiştir. Hemen hemen tamamen kesiksiz bir ofiyolit istifi sunar ve Tersiyer'e ait volkanosedimanter birimler tarafından uyumsuzlukla üzerlenir. Yer yer izole diyabaz daykları tarafından kesilen manto peridotitlerinde dunit bandlarını ve merceklerini içeren harzburjitler hakimdir. Manto-kabuk geçiş zonunun mafik-ultramafik kayaçları olarak dunitler, verlitler, piroksenitler ve gabrolar bulunur. Masif gabrolarla magmatik dokanaklı levha dayk kompleksin diyabazları, bazen plajiyogranit daykları tarafından kesilir. Bu bazik ve lökokratik kayaçlar, okyanus-tabanı metamorfizmanın yeşilşist fasiyesinin mineral topluluklarına dönüşmüştür. Okyanus kabuğunun üst birimleri olan spilitik yastık bazaltlar ve örtü sedimanları (radyolaritler, pelajik kireçtaşları), ofiyolitik melanjda megabloklar olarak gözlenmiştir.

Ofiyolitik kayaçların petrolojik özelliklerine göre ultramafik-mafik-lökokratik kayaçlar, aynı kökenli subalkalin toleyitik magmanın ayrımlaşma ürünleridir. Kristallenme sırası, olivin, klinopiroksen (bazen ortopiroksen eşlik eder) ve plajiyoklas şeklindedir. Gabrolar ve diyabazlar toleyitik karakterlidir (Nb/Y= 0.05–0.5). N-MORB'a göre, Th dışındaki LIL elementler (K, Sr, Rb, Ba) okyanus tabanı hidrotermal alterasyondan dolayı değişken bir dağılım sunarken HFS elementleri (Nb, Ti, Zr, Y) ve LREE (La, Ce, Nd) tüketilmiştir. Ti'ce fakir gabro ve dayklardaki iz element oranları (Ti/V, Zr/Y, Th/Y, Ti/Zr) ve tektonomagmatik ayırım diyagramları, Refahiye ofiyolitinin adayayı toleyitik (IAT) ve muhtemelen boninitik karakterli olduğunu işaret eder. Manto peridotitlerinin çok düşük REE içerikleri U-şekilli dağılım sunar. İzotropik gabrolar ve plajiyogranitler ise yüksek nadir toprak element (NTE) konsantrasyonlarına sahip olup izotropik gabrolarda pozitif Eu ve plajiyogranitlerde negatif Eu anomalisi gözlenir. Bu NTE dağılımları, SSZ magmatizmasının tipik özellikleri olarak kabul edilir. Doğu Akdeniz ofiyolitlerinin çoğunda gözlendiği gibi jeokimyasal verilere göre Refahiye ofiyolitinin ultramafik-mafik ve lökokratik kayaçları, Neotetis Okyanusu'nun kuzey kolunun içerisindeki suprasübdüksiyon tektonik ortamdaki adayayı gelişiminin erken evrelerinde yani yayönü bölgesinde oluşmuştur.

Anahtar Sözcükler: Refahiye (Erzincan), İzmir-Ankara-Erzincan Kenet Zonu, ofiyolit, yayönü, suprasübdüksiyon

## Introduction

The İzmir-Ankara-Erzincan Suture Zone (İAESZ), formed by the closure of the northern Neotethys Ocean, separating the Pontides from the Anatolide-Tauride Platform, extends from north of İzmir and the Sevan-Akera Zone to northeast of Erzincan (Şengör & Yılmaz 1981). The ophiolitic nappes along this suture zone form high mountain ranges, and include the Orhaneli (Bursa), Harmancık (Bursa), Tavşanlı (Kütahya), Dağküplü (Eskişehir) and Sivrihisar-Mihalıççık (Eskişehir) ophiolites in the western part of the İAESZ (Asutay *et al*. 1989; Göncüoğlu *et al*. 2000; Özen & Sarıfakıoğlu 2002; Önen 2003; Bacak & Uz 2003; Manav *et al*. 2004; Sarıfakıoğlu *et al*. 2006a, b), the Beynam (Ankara), Eldivan (Çankırı), Sarıkaraman (Aksaray) and Divriği (Sivas) ophiolitic slabs in Central Anatolia (Akyürek *et al*. 1979; Çapan & Floyd 1985; Yalınız *et al*. 1996; Tankut *et al*. 1998; Dilek & Thy 2006; Parlak *et al*. 2006), and the Refahiye (Erzincan), Kop-Palandöken (Erzurum) and Ağrı ophiolitic slabs at the east end of the İAESZ (Bektaş 1982; Yılmaz *et al*. 1989; Aktimur *et al*. 1995; Özen *et al*. 2006).

Tethyan ophiolites cropping out along İAESZ are significant, as they shed light on the location, palaeogeography, and evolution of different seaways in the Tethys Ocean. Field and petrochemical studies suggest that the Late Cretaceous ophiolites from the İAESZ were derived from island arc tholeiitic (IAT) magma formed in a suprasubductional setting fringing the Late Triassic–Early Cretaceous MORB-type basalts of the Neotethys Ocean (Göncüoğlu *et al*. 2000; Okay *et al*. 2001; Robertson 2002; Tekin *et al*. 2002; Önen 2003; Sarıfakıoğlu 2006).

The Refahiye (Erzincan) ophiolitic slab is located where the Kırşehir Massif thins out near Erzincan (Figure 1). The ultramafic-mafic rocks here form a thin strip, trending approximately E–W, separating the Pontides from the Anatolide-Tauride Platform and representing the remnants of the northern branch of the Neotethys Ocean. As the Refahiye ophiolite lies at the triple junction between the Kırşehir Massif, the Pontides and the Anatolide-Tauride Platform, it is an important component of the orogenic belt, and played a key role in its tectonic evolution.

The ophiolites represent fragments of oceanic lithosphere located along the suture zones of the main collisional belts in Turkey. Their pseudostratigraphy, type, age and evolution in different tectonic settings helps reveal the geodynamic modelling of Turkey and provides important constraints on the generation of the Eastern Mediterranean ophiolites.

This study aims to distinguish the mafic-ultramafic rock assemblages of the Refahiye ophiolite, and to discuss the tectonic setting of this ophiolite within the northern branch of the Neotethys Ocean, using new results from the latest field observations and petrochemical studies.

## Regional Geology

The Eastern Pontides are divided into two sections, namely the Outer Eastern Pontides and the Inner Eastern Pontides, based on the rocks reflecting different tectonostratigraphic environmental conditions (Ketin 1966; Şengör & Yılmaz 1981). The Outer Eastern Pontides include arc-related plutonic-volcanic rocks, whereas the Inner Eastern Pontides, including the study area, incorporate rock units of the Sakarya Zone, ophiolitic, forearc volcano-sedimentary and pelitic rocks with flysch character (Akın 1978; Şengör & Yılmaz 1981; Buket & Ataman 1982; Yılmaz 1985; Bergougnan 1987; Koçyiğit 1990; Aktimur *et al*. 1995; Elmas 1995; Okay & Şahintürk 1998; Okay & Tüysüz 1999). Okay and Şahintürk (1998) suggested that the Refahiye ophiolite in the Inner Eastern Pontides and the volcanic arc in the Outer Eastern Pontides are both related to the northward subduction of the Tethys Ocean beneath the Eastern Pontide continental margin.

The dextral strike-slip North Anatolian Fault cuts through the 450 km long part of the study area near

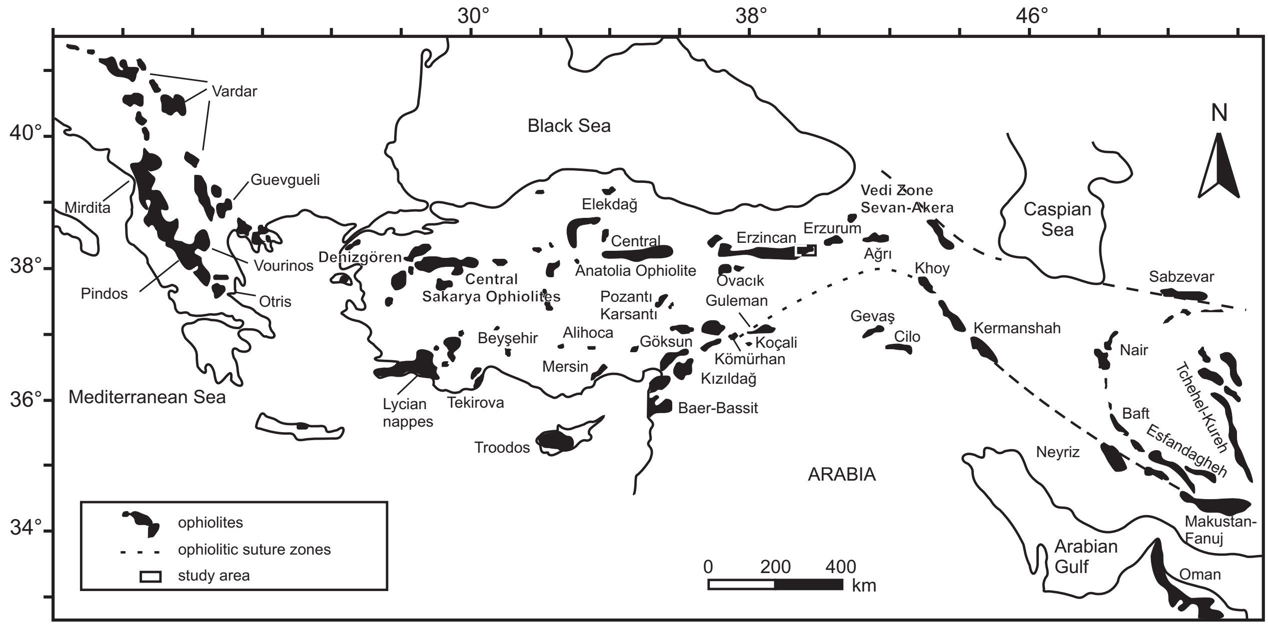


**Figure 1.** Distribution of the Neotethyan Ophiolites in the Eastern Mediterranean Region (modified by Dilek & Moores 1990; Lippard *et al.* 1986).

Erzincan (Figures 2 & 3). In the NNE of Erzincan the Late Cretaceous ophiolites were mainly thrust southward over the Munzur Limestone of the Anatolide-Tauride Platform, immediately south of the North Anatolian Fault and backthrust northward onto the metamorphic rocks of the Sakarya Zone (Okay 1984), which extends from the Biga Peninsula eastwards to the Eastern Pontides. The Sakarya Zone comprises the variably metamorphosed and deformed Permo–Triassic volcano-sedimentary rocks of the Karakaya Complex (Bingöl *et al.* 1975), and unmetamorphosed clastic, volcanic and carbonaceous rocks of Mesozoic–Tertiary age. The Early Triassic–Campanian Munzur Limestone, in contrast, comprises the eastern section of the Mesozoic '*Limestone Axis*' of the Taurus ranges (Ricou 1980; Özgül 1981).

The thrust sheets of the Refahiye ophiolite, which are in tectonic contact with other lithological units, show an almost intact suite and ordered sequence. The Refahiye ophiolite mainly exposes mantle harzburgites, with smaller outcrops of ultramafic-mafic cumulates, with isotropic gabbros, sheeted dykes and plagiogranites covering a limited area. Blocks of pillow basalts, radiolarites, and pelagic limestone crop out within the 500-m-thick ophiolitic mélange, which consists of a block-against-block mélange with very little matrix, consisting of highly sheared serpentinite and shale.

The Refahiye ophiolite is overlain unconformably by upper Maastrichtian and Eocene turbiditic flysch, interbedded with volcaniclastic rocks, consisting of clastic sediments, imestones, tuffs and agglomerates, sometimes over 2 km thick, formed in both deep and shallow marine environments. The medium- to thin-bedded conglomerate, sandstone, mudstone and clayey-sandy limestone intercalations pass laterally into tuffs and lava flows. Ophiolite-derived olistholiths and olisthostromes were observed just above the lower contact of the turbiditic flysch with the Refahiye ophiolite. Seismic movements in the deep sea environment may have caused these large clasts to be transported into the sedimentary basin. These lithological units are interpreted as forearc basin deposits (Aktimur *et al.* 1995; Elmas 1995; Okay & Şahintürk 1998; Okay & Tüysüz 1999).

In the study area, Miocene clastic rocks include seams of coal and gypsum. The Plio–Quaternary Erzincan volcanics (Ketin 1951) crop out in the Erzincan plain, which is drained by the Fırat River, and widely covered by Quaternary alluvium.

## Geology of the Refahiye Ophiolite

The Refahiye ophiolite, which crops out north of Erzincan on Dağınık Mountain and the Esence Mountains, is

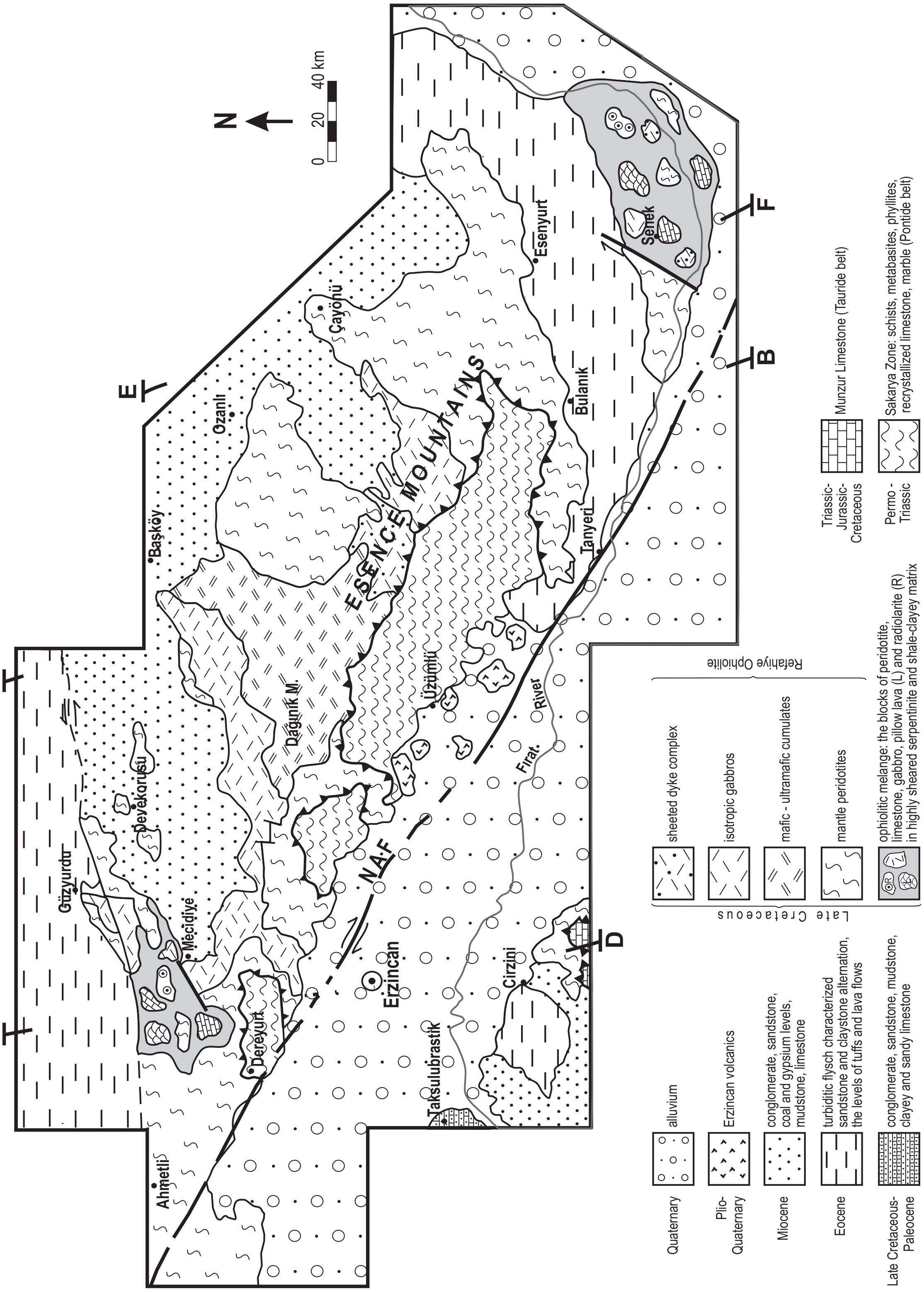


Figure 2. Geological map of the study area around Erzincan (revised from Aktimur *et al.* 1995; Özen *et al.* 2006).

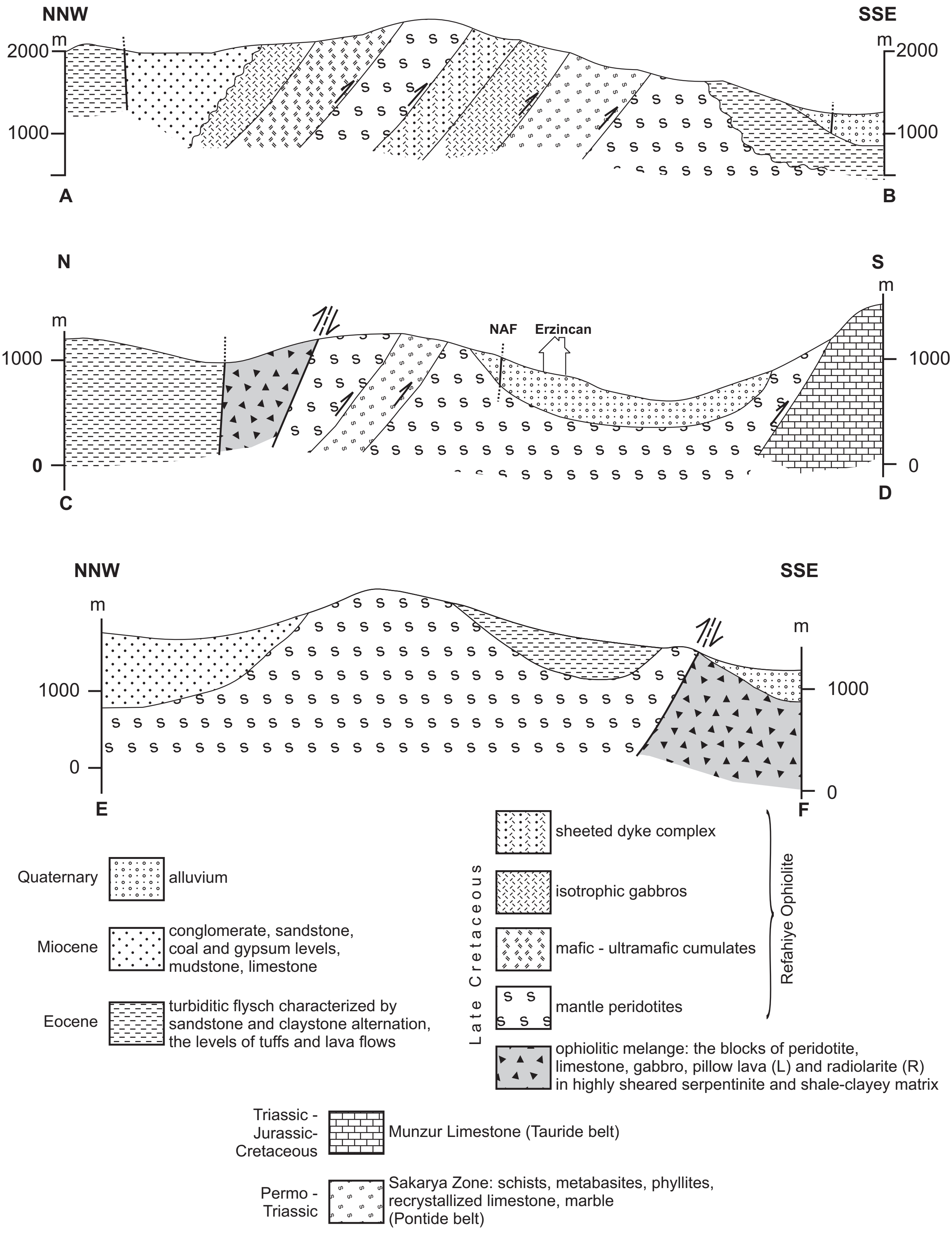


Figure 3. A-B, C-D and E-F cross-sections, showing relationships between the ophiolitic rocks and other units in the field.

approximately 1.5 km thick and displays an almost complete and regular ophiolitic sequence (Figure 4). Ultramafic tectonites representing mantle peridotites are widespread and consist mostly of harzburgites locally interlayered with dunite bands and lenses (Figure 5a). The dunites contain podiform-type chromites occurring as disseminated grains and/or massive chromitite bands. These peridotites are sporadically cut by microgabbros and isolated diabase dykes. The latter extend for tens of metres and range in thickness from 50 cm to 3 m. The isolated diabases are occasionally rodingitized. The layered ultramafic cumulates of the mantle-crust transition zone were observed as dunite-wehrlite-pyroxenite intercalations, whereas the layered mafic cumulates occur as laminated and/or layered gabbros (Figure 5b, c). The cumulate gabbros, interlayered with ultramafic cumulates, are in tectonic contact with the tectonite peridotites. The isotropic gabbros grade downward into planar-laminated gabbros. The alternation of light (plagioclases) and dark minerals (mafic minerals) were observed at millimetre or centimetre intervals in the laminated or layered gabbros (Figure 5d). The isotropic gabbros and sheeted dykes of the oceanic crust grade into each other. The sheeted dyke complex, entirely formed of diabase dykes, crops out in a narrow area and forms blocky-weathering, hard and massive outcrops. Locally whitish, light grey plagiogranite dykes, between a few cm and 75 cm thick and up to 10 m long, are found between the isotropic gabbros and sheeted diabase dykes and locally cut the diabases (Figure 5e). Pillow lavas and deep marine deposits (radiolarites and pelagic limestones) were observed in the ophiolitic mélange, which developed on the slip surface during the emplacement of the ophiolitic slab. Thus the basalts are the most poorly preserved member of the ophiolite pseudostratigraphy in the Refahiye ophiolite. Within the tectonic ophiolitic mélange, hard, pinkish-red, medium- to thick-bedded radiolarites, cherts, pelagic limestones, greenish grey spilitic pillow basalts and diabases were observed.

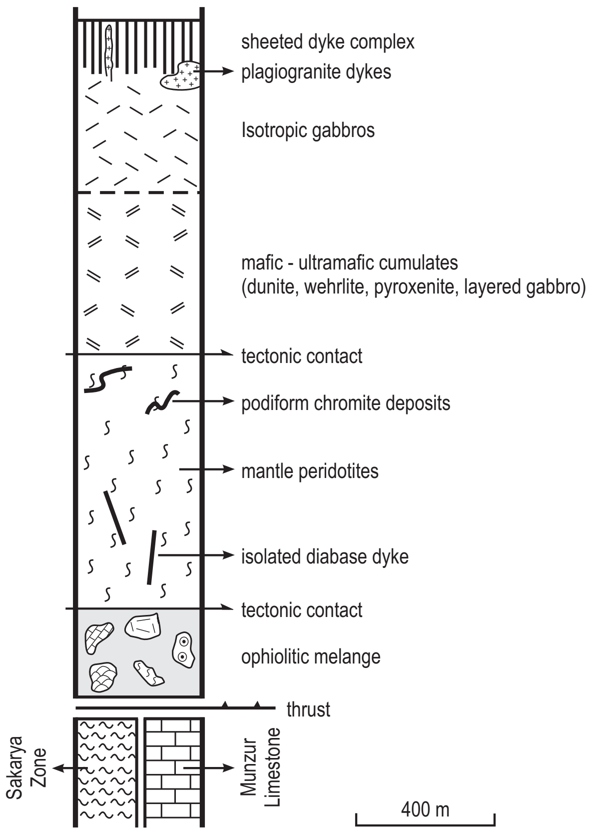


Figure 4. Schematic columnar section of the Refahiye ophiolite.

## Petrography

The mantle harzburgites have a porphyroclastic texture and are mainly made up of olivine (75–80%) and orthopyroxene (20–25%). The orthopyroxene crystals are generally warped and fractured. Locally they display clinopyroxene exsolution lamellae (Figure 6a). The mantle dunites, which have a granoblastic texture, are mostly made up of fragmental olivine crystals, which locally display deformation lamellae and kink-bands characterized by wavy extinction. The mantle peridotites are generally serpentinized and are cut by isolated plagioclase-rich diabase dykes, 0.5–3 m thick and up to 20 m long, with intersertal texture. The voids between the plagioclase laths are filled by secondary mineral assemblages (tremolite, actinolite, chlorite, titanite and Fe-Ti oxide minerals such as ilmenite). Plagioclase is altered partly into clay minerals and partly into hydrogarnet and prehnite. The rock is cut by thin veins filled by secondary prehnite. The isolated diabase dykes affected by hydrothermal ocean floor metamorphism have been extensively rodingitized.

Dunite, wehrlite and pyroxenite layers were observed in the layered ultramafic cumulates. The wehrlites have meso-cumulate textures and contain 65% olivine and 35% clinopyroxene (Figure 6b). Olivine crystals are partly serpentinized along fractures, and some clinopyroxene crystals have been replaced by actinolite. The proportion

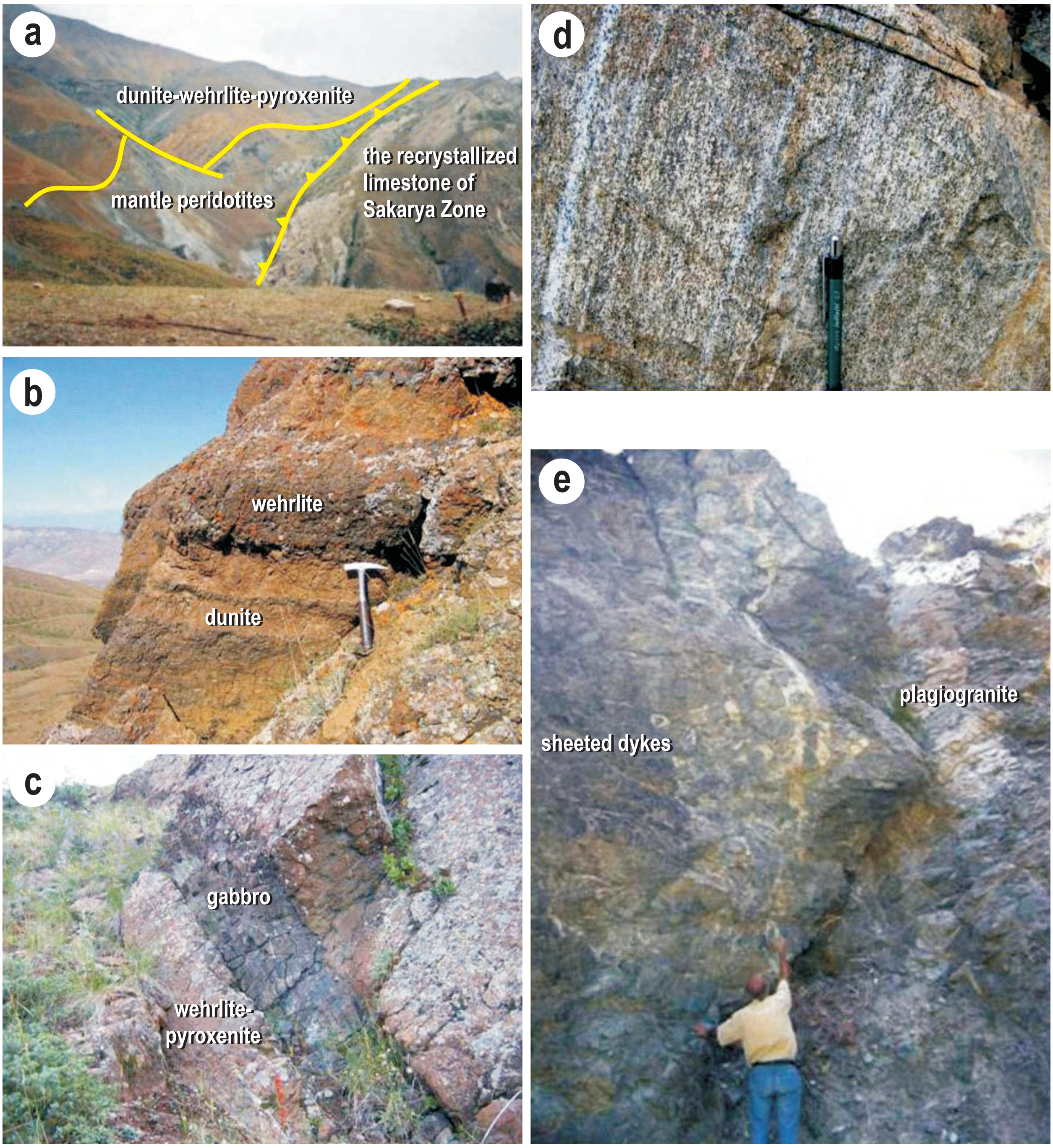


Figure 5. Field aspects of ultramafic-mafic and leucocratic rocks of the Refahiye ophiolite: (a) mantle peridotites near the contact with ultramafic cumulates thrust over recrystallized limestones of the Sakarya Zone; (b) the cumulate layers with dunite and wehrlite; (c) the layering of the cumulate wehrlite-pyroxenite and gabbro; (d) the layered gabbro with alternation of light (plagioclases) and dark (mafic minerals) levels ranging in thickness from millimetre to centimetre scale; (e) the plagiogranite dyke intruding the sheeted dykes.

of clinopyroxene was observed to increase in wehrlite-clinopyroxenite transition zones. The pyroxenites, dominated by clinopyroxene, locally contain subordinate orthopyroxene (5–10%) and are then termed websterite.

Gabbros occur as mafic cumulates, which may be magmatically interlayered with ultramafic cumulates as gabbro-wehrlite, thereby showing an alternation of parallel dark and pale bands formed from concentrations

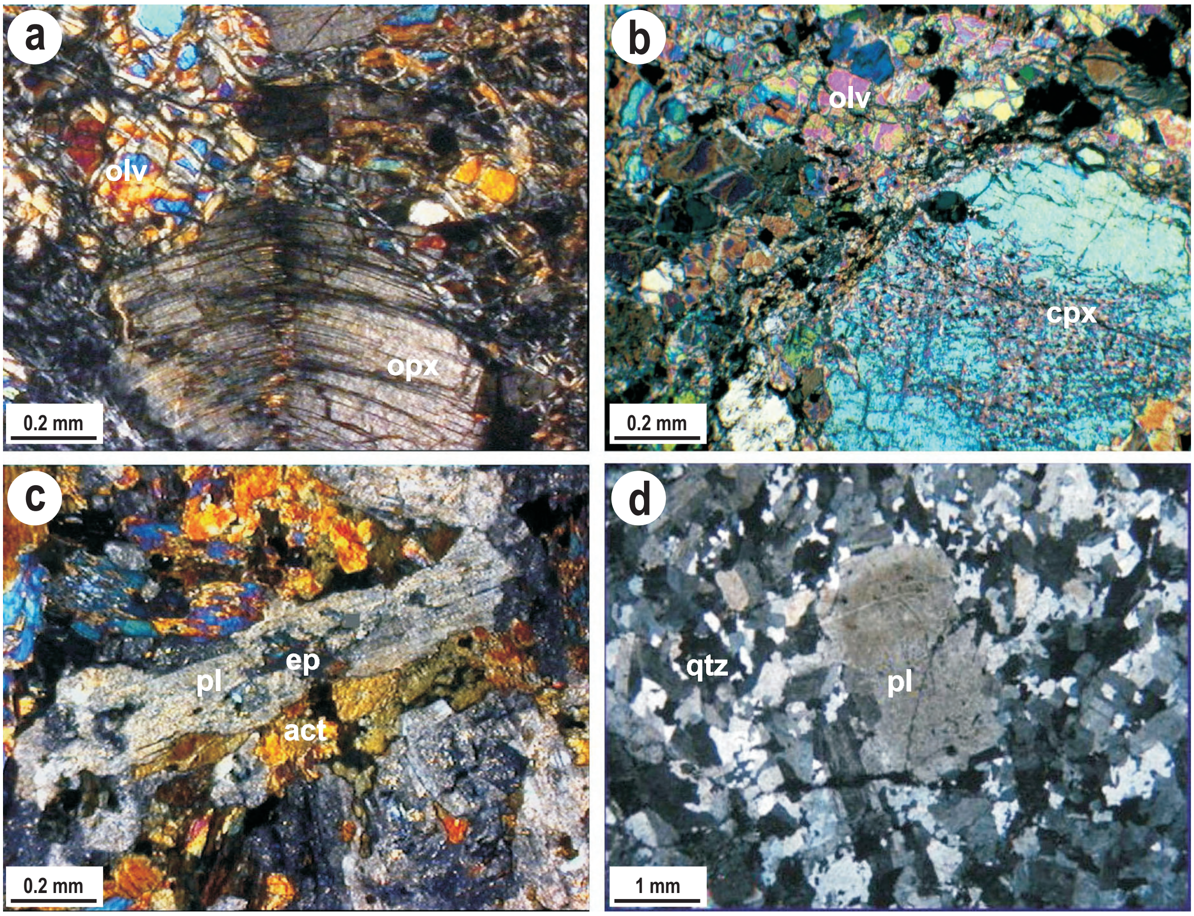


Figure 6. Selected thin section specimens from the Refahiye ophiolite: (a) clinopyroxene exsolution lamellae containing orthopyroxene in harzburgite; (b) mesocumulate texture showing wehrlite; (c) partially replaced primary plagioclase by secondary mineral assemblage as a result of hydrothermal ocean-floor metamorphism from the sheeted diabase dykes; (d) plagioclase microphenocrysts surrounded by a microcrystalline groundmass including albite and quartz from plagiogranite dyke (olv– olivine; opx– orthopyroxene; cpx– clinopyroxene; pl– plagioclase; cct– actinolite; ep– epidote; qtz– quartz).

of mafic minerals and pale feldspathic bands. Laminated and/or layered gabbros are comprised of millimetric–centimetric rhythmic intercalations of plagioclase (55–65%) and clinopyroxene (approximately 40%). The primary labradorite ($An_{54–60}$) plagioclases, with an average grain size of 0.6 mm, have been partly or totally sericitized. The clinopyroxene crystals, with an average grain size of 0.6–2 mm, are mostly uralitized.

The isotropic gabbros contain medium- to coarse-grained plagioclase and clinopyroxene, displaying poikilitic textures. The grain size varies between 0.2 mm and 1.5 cm. Secondary sericite, epidote and carbonates partly replace plagioclase, while clinopyroxene is progressively replaced by actinolite and green hornblende crystals beginning at the edges. As the grain size decreases, isotropic gabbros gradually grade into sheeted diabase dykes.

The sheeted diabase dykes display an intergranular and non-vesicular texture, and consist mainly of plagioclase and clinopyroxene, with a grain size varying between 0.2 mm and 0.6 mm. The primary minerals are partly or completely altered into albite, epidote, chlorite, sericite and actinolite, reflecting low-grade ocean floor metamorphism (Figure 6c).

The plagiogranites which cut the diabase dykes occur as plagioclase-phyric trondjhemite dykes, which are locally aphyric or contain plagioclase microphenocrysts. The plagiogranite dykes, which consist of approximately 30%

quartz, 55% plagioclase and 15% clinopyroxene, have generally undergone hydrothermal alteration. The plagioclase has been albitized and replaced by sericite, epidote and carbonate minerals. The relict clinopyroxene microphenocrysts have mostly been replaced by actinolite. Quartz and plagioclase have irregular boundaries within the microcrystalline matrix. Some actinolite needles can also be observed (Figure 6d).

The spilitic basalts, considered to be the upper units of the former oceanic crust, are observed as blocks in the ophiolitic mélange in tectonic contact with the Refahiye ophiolite. The primary mineralogical constitution and texture of these basalts, which have undergone intensive alteration, has been overprinted by secondary minerals. In the intersertal and amygdaloidal texture, albitized plagioclase laths, chloritized mafic minerals and opaque minerals were observed as xenomorph spots. Ellipsoidal voids were filled by secondary quartz and calcite.

## Analytical Method

49 samples of the ultramafic and mafic rock samples collected from NNE of Erzincan were analyzed for major element, trace element and REE contents. The results of 37 of these analyses were used in geochemical evaluation (Tables 1–3). Some analyses were performed at Keele University, England, using an ARL 8420 X-ray fluorescence spectrometer, calibrated against both international and internal Keele standards of appropriate composition (Floyd & Castillo 1992). Analytical methods and precision have also been described (Winchester *et al.* 1992). Some were analyzed for major and trace (including rare earth) elements at the ACT Analytical Laboratories Ltd., Canada. The total abundances of the major oxides and several minor elements were determined based on a 0.2 g sample analyzed by inductively coupled plasma (ICP) emission spectrometry following lithium metaborate/tetraborate fusion and dilute nitric acid digestion. Loss on ignition (LOI) was calculated as the weight difference after ignition at 1000 °C. Rare earth elements were determined by ICP mass spectrometry following lithium metaborate/tetraborate fusion and nitric acid digestion of a 0.2 g sample.

## Geochemistry

$SiO_2$ (33–52%) and MgO (20–49%) are the main chemical constituents of peridotites in the Refahiye ophiolite. The LOI value of these hydrothermally-altered mantle peridotites, varying between 9.5 and 16.0%, in particular reflects the widespread serpentinization of olivines and pyroxenes. The mafic rocks (gabbros and diabase dykes) were also affected by alteration, so their original major element chemistry was probably also altered. Thus $Na_2O + K_2O$ values range between 1% and 4.3%, with the $K_2O$ value much lower than that of $Na_2O$. The Na enhancement may result from spilitization following subjection of the mafic rocks to low-grade hydrothermal ocean floor metamorphism.

On an AFM diagram, the ultramafic and mafic cumulate rocks fall into the arc-related cumulate area, whereas the sheeted dykes and isotropic gabbros plot in the arc-related non-cumulate field (Figure 7). This shows that the ultramafic cumulates and the cumulate gabbros, formed by fractionation of primary melts through depleted mantle typically occurring at the base of the magma chamber. The clinopyroxene and plagioclase appear nearly simultaneously, forming gabbros interlayered with wehrlites. The sheeted dykes and isotropic gabbros represent crystallization that occurred at the top of magma chamber (Hopson *et al.* 1981). Therefore, the ultramafic-mafic rocks of the Refahiye ophiolite may be considered to be cogenetic. However, the isolated diabase dykes cutting the peridotites may represent fractional crystallization products from a co-magmatic source, as a result of the differentiation of the relict liquid phase, developed from the same magma. The plagiogranite dykes can be regarded as the products of the latest differentiation of this magma. Besides, the diabase dykes were determined to have formed in the same environment as the ophiolitic rocks and are also derived from the basaltic magma.

In addition to the alteration in the major element chemistry of the gabbroic cumulates, the isolated diabase dykes were affected by hydrothermal alteration, so that a wide scatter was observed in their LILE (K, Sr, Rb, Ba) contents. By contrast, the HFSE (Nb, Ti, Zr, Y) and LREE contents appear to have remained constant during the alteration, and so have been used as indicators in petrogenetic evaluation.

The cumulate gabbros have low $TiO_2$ (0.09–0.46%), Nb (0.21–3 ppm), Y (4–15 ppm) and Zr (59–25 ppm) values. Like the gabbros, the isolated diabase dykes also have low $TiO_2$ (0.1–1.13%), Nb (1.32–5 ppm), Y (6–3025 ppm) and Zr (6–83 63 ppm) values. The low Nb/Y

**Table 1.** The major, trace element and REE analyses of the mantle peridotites and ultramafic cumulates from the Refahiye Ophiolite.

| Lithology | MANTLE PERIDOTITES | | | | | | | ULTRAMAFIC CUMULATE | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hrz | Hrz | Du | Du | Du | Hrz | Du | Pyx | Whr | Whr | Wbs |
| Sample | E-9 | E-24 | E-26 | E-31 | E-50 | M-2 | ERZI-8 | ERZI-10 | E-6 | E-12 | E-19 |
| Oxide wt% | | | | | | | | | | | |
| $SiO_2$ | 40.84 | 40.78 | 38.18 | 33.14 | 41.37 | 40.94 | 37.81 | 50.05 | 48.26 | 42.87 | 52.02 |
| $TiO_2$ | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.11 | 0.06 | 0.09 | 0.35 | 0.08 | 0.09 |
| $Al_2O_3$ | 0.66 | 0.73 | 0.49 | 0.12 | 0.21 | 6.68 | 1.57 | 2.52 | 4.23 | 1.26 | 1.67 |
| $Fe_2O_3$ | 7.55 | 8.71 | 7.17 | 6.39 | 8.21 | 8.48 | 10.85 | 6.94 | 7.06 | 8.79 | 5.17 |
| MnO | 0.01 | 0.07 | 0.07 | 0.09 | 0.11 | 0.12 | 0.15 | 0.16 | 0.15 | 0.14 | 0.14 |
| MgO | 38.37 | 36.6 | 39.02 | 43.12 | 48.89 | 29.03 | 37.69 | 24.18 | 19.61 | 34.44 | 22.39 |
| CaO | 0.56 | 0.36 | 0.1 | 0.1 | 0.21 | 4.76 | 0.46 | 16.05 | 18.85 | 5.93 | 16.52 |
| $Na_2O$ | 0.05 | 0.03 | 0.05 | 0.04 | 0.04 | 0.56 | 0.1 | 0.13 | 0.33 | 0.12 | 0.23 |
| $K_2O$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.04 | 0.06 | 0.01 | 0.01 | 0.01 | 0.04 | 0.03 |
| $P_2O_5$ | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0 | 0 | 0 | 0.01 | 0.01 | 0.01 |
| LOI | 11.6 | 12.28 | 12.22 | 16.3 | 1.63 | 9.53 | 11.65 | 0.69 | 1.49 | 6.76 | 2.66 |
| Total | 99.76 | 99.6 | 100.3 | 99.32 | 100.7 | 100.27 | 100.35 | 100.82 | 100.33 | 100.4 | 100.9 |
| Trace ppm | | | | | | | | | | | |
| Cr | 1900 | 1970 | 3610 | 1320 | 1760 | 990 | 10570 | 3109 | 2540 | 2280 | 3400 |
| Cu | <10 | 30 | 20 | <10 | <10 | 25 | 8 | 33 | 20 | 90 | 300 |
| Ga | <1 | 1 | 1 | <1 | 1 | 6 | 2 | 5 | 6 | 2 | 3 |
| Ta | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | | | | 0.01 | 0.01 | 0.01 |
| Nb | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0 | 0 | 0 | 0.2 | 0.2 | 0.2 |
| Hf | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | | | | 0.4 | 0.2 | 0.1 |
| Ni | 1670 | 1800 | 1500 | 1780 | 2500 | 1508 | 1447 | 502 | 240 | 1020 | 560 |
| Pb | <5 | <5 | <5 | <5 | <5 | 0 | 2 | 3 | 8 | <5 | <5 |
| Rb | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 3 | 1 | 1 | 1 |
| Sr | 2 | 4 | 2 | 2 | 2 | 67 | 4 | 10 | 33 | 12 | 10 |
| Th | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 2 | 3 | 3 | 0.05 | 0.05 | 0.05 |
| U | 0.01 | 0.01 | 0.02 | 0.01 | 0.17 | | | | 0.02 | 0.01 | 0.01 |
| V | 43 | 23 | 19 | <5 | 8 | 57 | 97 | 132 | 234 | 61 | 107 |
| Y | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 3 | 3 | 7 | 8.5 | 2.5 | 3.5 |
| Zn | 40 | 50 | 50 | 30 | 40 | 43 | 56 | 45 | 40 | 50 | <30 |
| Zr | 1 | 1 | 2 | 2 | 2 | 11 | 8 | 9 | 6 | 4 | 3 |
| Ba | 5 | 3 | 5 | 3 | 3 | 25 | 4 | 12 | 8 | 4 | 6 |
| REE ppm | | | | | | | | | | | |
| La | 0.06 | 0.09 | 0.06 | 0.15 | 0.15 | 0 | 9 | 0 | 0.28 | 0.41 | 0.18 |
| Ce | 0.16 | 0.14 | 0.14 | 0.16 | 0.17 | 0 | 0 | 0 | 1.05 | 1.49 | 0.61 |
| Pr | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | | | | 0.21 | 0.23 | 0.1 |
| Nd | 0.05 | 0.05 | 0.05 | 0.05 | 0.1 | 8 | 2 | 1 | 1.59 | 1.42 | 0.71 |
| Sm | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | | | | 0.78 | 0.4 | 0.28 |
| Eu | 0.016 | 0.08 | 0.016 | 0.008 | 0.005 | | | | 0.346 | 0.129 | 0.124 |
| Gd | 0.02 | 0.01 | 0.02 | 0.02 | 0.01 | | | | 1.15 | 0.44 | 0.41 |
| Tb | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | | | | 0.24 | 0.08 | 0.09 |
| Dy | 0.03 | 0.04 | 0.04 | 0.04 | 0.02 | | | | 1.56 | 0.46 | 0.57 |
| Ho | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | | | | 0.32 | 0.09 | 0.12 |
| Er | 0.03 | 0.03 | 0.02 | 0.02 | 0.01 | | | | 0.95 | 0.25 | 0.35 |
| Tm | 0.006 | 0.007 | 0.005 | 0.005 | 0.005 | | | | 0.127 | 0.034 | 0.051 |
| Yb | 0.05 | 0.05 | 0.03 | 0.01 | 0.03 | | | | 0.72 | 0.22 | 0.32 |
| Lu | 0.007 | 0.008 | 0.003 | 0.002 | 0.005 | | | | 0.109 | 0.035 | 0.05 |

**Table 2.** The major, trace element and REE analyses of the gabbros and diabases from the Refahiye Ophiolite.

| Lithology | SHEETED DYKES | | | | | ISOLATED DIABASES | | | | CUMULATE GABBROS | | | | | ISOTROPIC GABBROS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | E-2 | E-4 | E-41 | E-43 | M-13 | D-8,9 | ER-3 | ASK-12 | ERZ-15 | ERZI-5 | M-11 | M-16 | ERZI-18 | ERZI-19 | ERZI-4 | ERZI-7 | M-20 | E-3 | E-14 |
| Oxide wt% | | | | | | | | | | | | | | | | | | | |
| $SiO_2$ | 50.59 | 52.11 | 51.14 | 51.18 | 56.51 | 46.83 | 47.33 | 50.26 | 49.39 | 50.49 | 49.95 | 49.8 | 49.09 | 50.61 | 46.79 | 51.94 | 52.08 | 47.34 | 48.96 |
| $TiO_2$ | 0.80 | 1.03 | 1.01 | 0.49 | 0.4 | 0.1 | 0.14 | 1.13 | 0.95 | 0.34 | 0.21 | 0.46 | 0.3 | 0.26 | 0.09 | 0.42 | 0.33 | 0.14 | 0.39 |
| $Al_2O_3$ | 14.83 | 15.4 | 14.28 | 14.52 | 14.53 | 19.75 | 23.74 | 16.06 | 17.28 | 12.54 | 14.2 | 13.81 | 16.96 | 15.51 | 20.53 | 15.85 | 17.02 | 24.5 | 21.89 |
| $Fe_2O_3$ | 11.57 | 11.16 | 13.99 | 12.04 | 9.23 | 6.45 | 5.4 | 11.61 | 10.4 | 10.57 | 9.26 | 10.27 | 9.49 | 9.09 | 5.88 | 9.42 | 8.56 | 4.53 | 5.41 |
| MnO | 0.19 | 0.20 | 0.22 | 0.19 | 0.17 | 0.09 | 0.08 | 0.18 | 0.15 | 0.18 | 0.14 | 0.17 | 0.15 | 0.13 | 0.09 | 0.14 | 0.13 | 0.09 | 0.09 |
| MgO | 6.54 | 6.3 | 4.74 | 5.84 | 5.96 | 8.44 | 5.41 | 6.48 | 5.89 | 11.64 | 10.97 | 11.43 | 9.57 | 9.82 | 8.53 | 8.38 | 7.8 | 5.13 | 4.75 |
| CaO | 9.23 | 8.52 | 7.41 | 7.41 | 9.04 | 14.96 | 15.32 | 9.75 | 10.22 | 10.3 | 12.86 | 10.78 | 11.54 | 12.71 | 16.66 | 11.44 | 11.22 | 15.03 | 10.62 |
| $Na_2O$ | 3.56 | 3.31 | 4.25 | 4.11 | 2.69 | 1.31 | 1.5 | 3.31 | 3.27 | 1.97 | 1.43 | 1.56 | 1.67 | 1.6 | 0.84 | 1.99 | 1.92 | 1.77 | 4.23 |
| $K_2O$ | 0.2 | 0.21 | 0.5 | 0.6 | 0.12 | 0.1 | 0.06 | 0.23 | 0.18 | 0.24 | 0.17 | 0.15 | 0.14 | 0.23 | 0.11 | 0.11 | 0.12 | 0.07 | 0.1 |
| $P_2O_5$ | 0.12 | 0.08 | 0.2 | 0.09 | 0.05 | 0 | 0 | 0.09 | 0.08 | 0.01 | 0 | 0.03 | 0.01 | 0 | 0 | 0.03 | 0.03 | 0.01 | 0.03 |
| LOI | 1.74 | 1.94 | 1.68 | 2.56 | 0.49 | 2.14 | 1.62 | 1.18 | 1.42 | 2.15 | 1.67 | 0.94 | 1.62 | 1.03 | 0.64 | 1.01 | 0.75 | 2.26 | 3.91 |
| Total | 99.37 | 100.6 | 99.4 | 99.05 | 99.19 | 100.17 | 100.6 | 100.31 | 99.25 | 100.43 | 100.86 | 99.4 | 100.54 | 100.99 | 100.16 | 100.73 | 99.96 | 100.9 | 100.4 |
| Trace ppm | | | | | | | | | | | | | | | | | | | |
| Cr | 100 | 40 | 30 | 50 | 181 | 185 | 127 | 206 | 82 | 652 | 499 | 263 | 263 | 182 | 409 | 332 | 105 | 40 | 30 |
| Cu | 60 | 40 | 60 | 40 | 37 | 28 | 19 | 44 | 56 | 53 | 27 | 52 | 70 | 22 | 48 | 24 | 17 | <10 | 40 |
| Ga | 17 | 18 | 21 | 16 | 13 | 10 | 14 | 17 | 17 | 10 | 12 | 11 | 14 | 12 | 10 | 13 | 17 | 17 | 17 |
| Ta | 0.12 | 0.05 | 0.21 | 0.09 | | | | | | | | | | | | | | 0.01 | 0.01 |
| Nb | 1.5 | 1.4 | 2.7 | 1.3 | 2 | 3 | 2 | 4 | 5 | 3 | 3 | 3 | 2 | 1 | 2 | 2 | 2 | 0.2 | 0.8 |
| Hf | 2.4 | 1.6 | 3.8 | 1.9 | | | | | | | | | | | | | | 0.2 | 0.5 |
| Ni | 50 | 30 | 30 | 30 | 37 | 45 | 17 | 35 | 27 | 104 | 81 | 99 | 79 | 72 | 59 | 38 | 31 | 20 | 30 |
| Pb | <5 | <5 | <5 | <5 | 1 | 4 | 3 | 0 | 2 | 6 | 1 | 1 | 3 | 4 | 0 | 1 | 2 | <5 | <5 |
| Rb | 2 | 4 | 5 | 6 | 4 | 4 | 3 | 5 | 3 | 5 | 6 | 5 | 4 | 5 | 3 | 5 | 2 | 1 | 1 |
| Sr | 194 | 145 | 147 | 171 | 94 | 162 | 324 | 349 | 287 | 109 | 135 | 92 | 157 | 133 | 140 | 166 | 197 | 342 | 162 |
| Th | 0.28 | 0.21 | 0.65 | 0.3 | 2 | 3 | 2 | 0 | 1 | 2 | 3 | 0 | 0 | 0 | 2 | 1 | 1 | 0.73 | 0.85 |
| U | 0.1 | 0.17 | 0.21 | 0.1 | | | | | | | | | | | | | | 0.07 | 0.04 |
| V | 369 | 307 | 397 | 349 | 128 | 102 | 80 | 306 | 263 | 240 | 181 | 181 | 173 | 204 | 85 | 307 | 167 | 128 | 178 |
| Y | 30 | 22.3 | 30 | 26.6 | 20 | 6 | 6 | 25 | 23 | 10 | 7 | 15 | 8 | 8 | 4 | 11 | 11 | 4 | 9.2 |
| Zn | 90 | 80 | 130 | 90 | 70 | 31 | 36 | 73 | 62 | 68 | 52 | 67 | 57 | 46 | 30 | 52 | 48 | 30 | 40 |
| Zr | 83 | 56 | 80 | 66 | 35 | 8 | 6 | 63 | 57 | 13 | 12 | 25 | 17 | 24 | 9 | 25 | 21 | 5 | 15 |
| Ba | 38 | 64 | 78 | 66 | 41 | 28 | 15 | 61 | 50 | 36 | 34 | 54 | 43 | 45 | 27 | 31 | 27 | 26 | 16 |
| REE ppm | | | | | | | | | | | | | | | | | | | |
| La | 4.37 | 2.33 | 6.80 | 3.33 | 2 | 1 | 4 | 0 | 1 | 4 | 1 | 9 | 0 | 5 | 0 | 4 | 0 | 0.93 | 1.09 |
| Ce | 12.4 | 6.65 | 16.70 | 9.88 | 0 | 0 | 0 | 0 | 0 | 0 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 2.04 | 2.82 |
| Pr | 1.67 | 0.98 | 2.49 | 1.37 | | | | | | | | | | | | | | 0.24 | 0.4 |
| Nd | 9.64 | 5.74 | 14.9 | 7.98 | 0 | 0 | 6 | 6 | 3 | 0 | 12 | 11 | 0 | 0 | 4 | 10 | 4 | 1.41 | 2.41 |
| Sm | 3.38 | 2.06 | 4.76 | 2.8 | | | | | | | | | | | | | | 0.46 | 0.88 |
| Eu | 1.23 | 0.861 | 1.75 | 1.11 | | | | | | | | | | | | | | 0.334 | 0.632 |
| Gd | 4.3 | 2.74 | 6.19 | 3.6 | | | | | | | | | | | | | | 0.58 | 1.23 |
| Tb | 0.91 | 0.58 | 1.15 | 0.7 | | | | | | | | | | | | | | 0.12 | 0.26 |
| Dy | 5.48 | 3.79 | 7.59 | 4.53 | | | | | | | | | | | | | | 0.73 | 1.59 |
| Ho | 1.13 | 0.77 | 1.58 | 0.93 | | | | | | | | | | | | | | 0.15 | 0.33 |
| Er | 3.27 | 2.26 | 4.59 | 2.75 | | | | | | | | | | | | | | 0.42 | 0.97 |
| Tm | 0.469 | 0.324 | 0.673 | 0.410 | | | | | | | | | | | | | | 0.059 | 0.14 |
| Yb | 3.05 | 2.1 | 4.36 | 2.61 | | | | | | | | | | | | | | 0.37 | 0.87 |
| Lu | 0.48 | 0.341 | 0.687 | 0.4 | | | | | | | | | | | | | | 0.06 | 0.137 |
| Nb/Y | 0.05 | 0.06 | 0.09 | 0.05 | 0.1 | 0.5 | 0.33 | 0.16 | 0.2 | 0.3 | 0.43 | 0.2 | 0.25 | 0.13 | 0.5 | 0.18 | 0.18 | 0.05 | 0.09 |
| Th/Y | 0.01 | 0.04 | 0.02 | 0.01 | 0.1 | 0.5 | 0.33 | 0.04 | 0.05 | 0.2 | 0.43 | 0.07 | 0.13 | 0.13 | 0.5 | 0.09 | 0.09 | 0.18 | 0.09 |
| Zr/Y | 2.77 | 2.50 | 2.70 | 2.40 | 1.75 | 1.33 | 1 | 2.52 | 2.48 | 1.3 | 1.71 | 1.66 | 2.13 | 3 | 2.25 | 2.27 | 1.91 | 1.25 | 1.63 |
| Ti/V | 13.0 | 19.52 | 15.25 | 8.42 | 18.73 | 5.88 | 10.48 | 22.13 | 21.65 | 8.49 | 6.95 | 15.23 | 10.4 | 7.64 | 6.75 | 8.2 | 11.84 | 7.02 | 13.10 |
| Ti/Zr | 57.78 | 107.0 | 75.69 | 44.52 | 68 | 75 | 140 | 107 | 99 | 158 | 104 | 110 | 105 | 65 | 60 | 100 | 94 | 172.6 | 155.9 |

Table 3. The major, trace element and REE analyses of the plagiogranites and basalts from the Refahiye Ophiolite.

| Lithology | PLAGIOGRANITES | | | | BASALTS | | |
|---|---|---|---|---|---|---|---|
| Sample | E-15 | E-42 | E-44 | E-46 | E-25a | E-25b | E-25c |
| Oxide wt% | | | | | | | |
| $SiO_2$ | 65.81 | 67.61 | 77.47 | 77.44 | 53.1 | 52.19 | 53.99 |
| $TiO_2$ | 0.69 | 0.45 | 0.17 | 0.14 | 1.47 | 1.45 | 1.47 |
| $Al_2O_3$ | 15.4 | 14.47 | 12.36 | 11.49 | 14.05 | 13.66 | 14.1 |
| $Fe_2O_3$ | 6.87 | 4.68 | 2.35 | 1.87 | 8.84 | 8.34 | 8.35 |
| MnO | 0.10 | 0.07 | 0.04 | 0.02 | 0.24 | 0.25 | 0.24 |
| MgO | 1.02 | 1.55 | 0.64 | 0.45 | 3.82 | 3.48 | 3.49 |
| CaO | 4.27 | 3.05 | 3.9 | 0.56 | 8.09 | 9.3 | 7.88 |
| $Na_2O$ | 5.51 | 6.99 | 3.5 | 5.2 | 4.78 | 4.74 | 4.97 |
| $K_2O$ | 0.31 | 0.18 | 0.13 | 0.29 | 0.22 | 0.2 | 0.2 |
| $P_2O_5$ | 0.21 | 0.08 | 0.06 | 0.03 | 0.13 | 0.12 | 0.12 |
| LOI | 0.6 | 1.23 | 0.31 | 0.82 | 5.99 | 6.73 | 5.81 |
| Total | 100.8 | 100.4 | 100.9 | 98.32 | 100.7 | 100.5 | 100.6 |
| Trace ppm | | | | | | | |
| Cr | 20 | 40 | 20 | 20 | 20 | 20 | 20 |
| Cu | 20 | <10 | 20 | 30 | 60 | 70 | 60 |
| Ga | 27 | 16 | 16 | 13 | 19 | 18 | 18 |
| Ta | 0.16 | 0.26 | 0.01 | 0.33 | 0.09 | 0.1 | 0.1 |
| Nb | 4.8 | 2.9 | 0.8 | 4.9 | 1.3 | 1.3 | 1.3 |
| Hf | 3.2 | 3.4 | 7.4 | 6.4 | 2.2 | 2.2 | 2.2 |
| Ni | 20 | 20 | 20 | 20 | 30 | 20 | 20 |
| Pb | <5 | <5 | <5 | <5 | <5 | <5 | <5 |
| Rb | 4 | 2 | 1 | 5 | 3 | 2 | 2 |
| Sr | 131 | 53 | 196 | 67 | 97 | 96 | 99 |
| Th | 0.61 | 2.23 | 0.19 | 4.28 | 0.35 | 0.34 | 0.34 |
| U | 0.21 | 0.8 | 0.14 | 1.3 | 1.73 | 1.46 | 1.58 |
| V | 12 | 62 | 41 | 18 | 388 | 383 | 390 |
| Y | 88.1 | 31.7 | 11.4 | 29.8 | 29.9 | 28.7 | 27.4 |
| Zn | 30 | 50 | <30 | <30 | 120 | 120 | 120 |
| Zr | 109 | 114 | 282 | 241 | 76 | 75 | 77 |
| Ba | 99 | 28 | 55 | 43 | 63 | 56 | 60 |
| REE ppm | | | | | | | |
| La | 15.2 | 7.28 | 3.14 | 7.65 | 3.56 | 3.43 | 3.28 |
| Ce | 41.5 | 18.2 | 6.39 | 17.7 | 10.4 | 10 | 9.65 |
| Pr | 5.8 | 2.13 | 0.72 | 2.01 | 1.42 | 1.38 | 1.3 |
| Nd | 31.8 | 11.3 | 3.8 | 9.73 | 8.88 | 8.56 | 8.26 |
| Sm | 10.1 | 3.29 | 1.16 | 2.79 | 2.96 | 2.88 | 2.78 |
| Eu | 2.52 | 0.796 | 0.731 | 0.515 | 1.14 | 1.13 | 1.09 |
| Gd | 12.2 | 4.11 | 1.53 | 3.23 | 3.92 | 3.83 | 3.69 |
| Tb | 2.42 | 0.77 | 0.28 | 0.67 | 0.75 | 0.74 | 0.71 |
| Dy | 15.3 | 5.14 | 1.8 | 4.69 | 4.97 | 4.86 | 4.57 |
| Ho | 3 | 1.11 | 0.38 | 1.03 | 1.03 | 1.01 | 0.94 |
| Er | 8.87 | 3.3 | 1.18 | 3.31 | 2.91 | 2.82 | 2.7 |
| Tm | 1.32 | 0.512 | 0.181 | 0.554 | 0.422 | 0.412 | 0.396 |
| Yb | 8.27 | 3.35 | 1.2 | 3.92 | 2.63 | 2.53 | 2.41 |
| Lu | 1.28 | 0.533 | 0.206 | 0.662 | 0.39 | 0.379 | 0.345 |

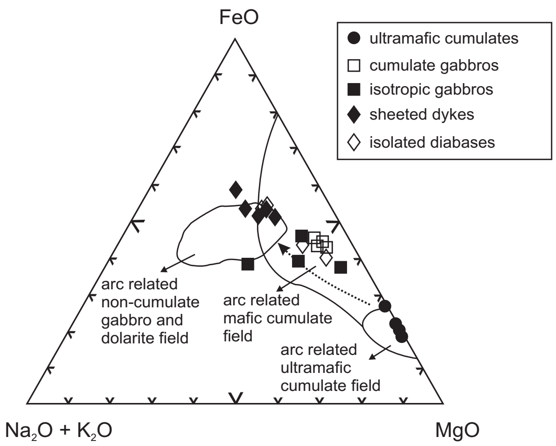


Figure 7. AFM compositions of ultramafic cumulates, cumulate gabbros and isolated diabases in the Refahiye ophiolite. Fields of cumulate and non-cumulate rocks are from Beard (1986). The dashed arrow indicates the ultramafic-mafic sequences resulted from fractional crystallization within magma chamber.

ratios in gabbros and diabases (0.051–0.5) indicate that they are subalkaline (Winchester & Floyd 1977), while the generally low Ti/V ratios (6.75–125.23 in gabbros; 5.88–22.13 in diabase dykes) are typical of island arc tholeiites (IAT) (Figure 6a). The Zr/Y ratio is 1.3–3.0 in gabbros and 1.0–2.78 in diabases: together with the low Zr this is typical of IAT. The Ti/Zr ratios in the gabbros and isolated diabase dykes range from 60.0 to 172.66 and the lower ratios suggest the presence of ultra-depleted (very low $TiO_2$, possibly boninitic) as well as depleted (low $TiO_2$) IAT magmas (Beccaluva *et al.* 1984). The Th/Y ratios of the mafic rocks (0.05–0.5) are higher than those in MORB (0.03) and indicate a magmatic source enriched by liquids derived from the slab (Pearce *et al.* 1987).

Figure 8 confirms that the mafic rocks, namely gabbros, sheeted dykes and isolated dykes, have IAT and possibly boninitic compositions, reflecting their formation in a subduction zone environment rather than at a mid-oceanic ridge spreading centre. On a $TiO_2$–Zr diagram (Capedri *et al.* 1980), gabbros mostly plot as having boninitic and/or IAT character, whereas the sheeted dykes show island arc affinities (Figure 9a). On a Ti/Cr–Ni diagram (Beccaluva *et al.* 1983), the low-Ti gabbros plot

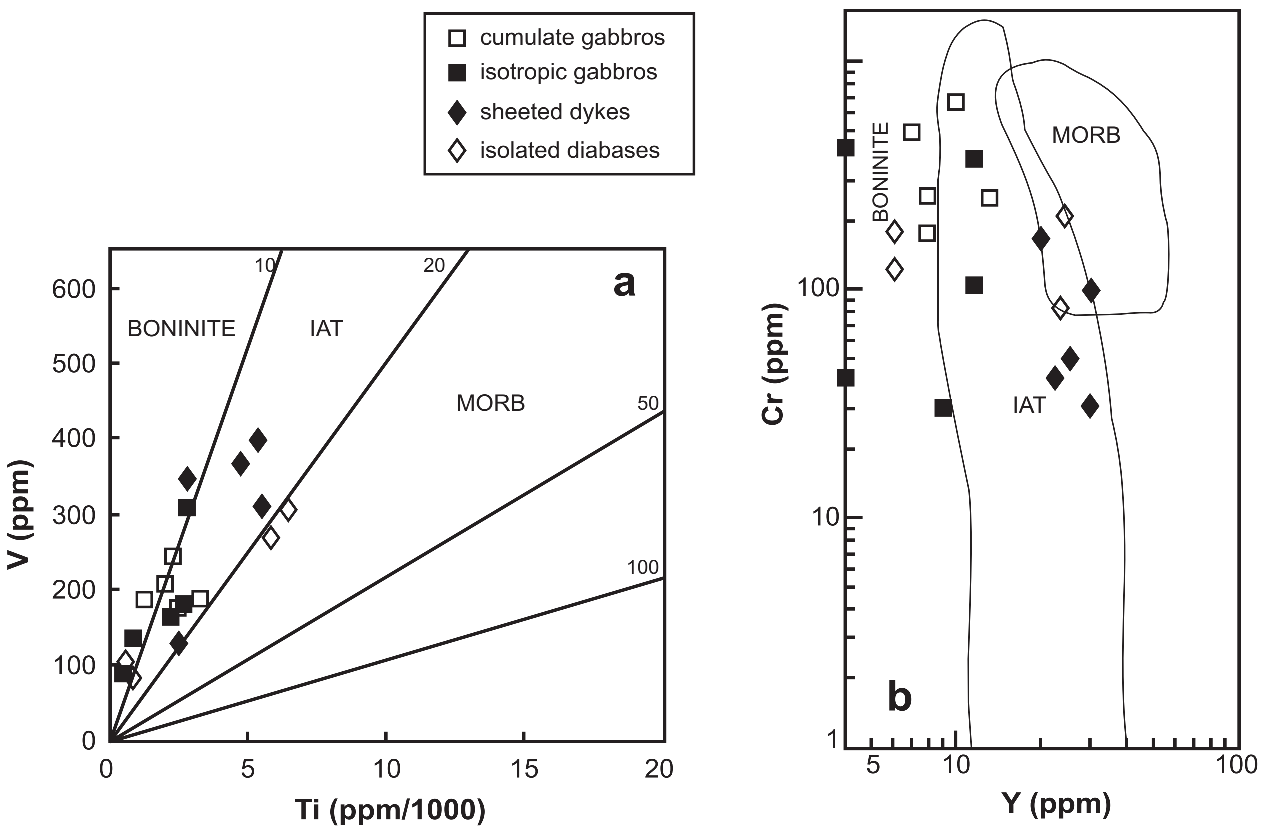


Figure 8. Petrogenetic discrimination diagrams for the Refahiye ophiolitic rocks: (a) Ti-V after Shervais (1982) and (b) Cr-Y after Pearce (1982).

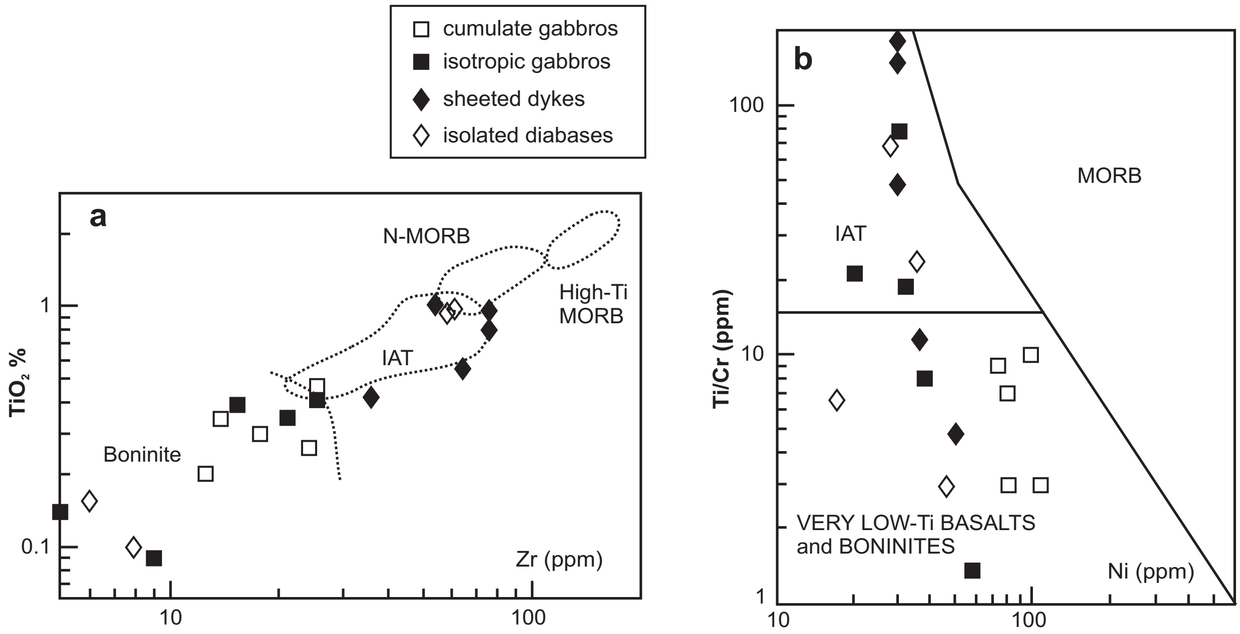


Figure 9. (a) $TiO_2$-Zr discrimination diagram (after Capedri *et al.* 1980) and (b) Ti/Cr-Ni discrimination diagram (after Beccaluva *et al.* 1983).

in the boninitic field. The sheeted dykes and isolated dykes, however, plot in both the boninitic field, and, with increased Ti, also in the IAT field (Figure 9b). Low-Ti ophiolites are widely considered to be generated in forearc regions of intraoceanic subduction-related settings (Crawford *et al.* 1981; Serri 1981).

Boninites, first described in the Bonin Islands by Kikuchi (1890) and Petersen (1891), are high-Mg, silica-saturated volcanic rocks (andesites, dacites). The boninite suite may be defined on a chemical basis: they have even lower $TiO_2$ (<0.5%) than IAT ($TiO_2$< 1%). While IAT shows LILE enrichment but depletion in the HFSE, boninites are variably enriched in LILE and are characterized by extreme depletion in Ti, Y, other HFSE, and HREE, thereby showing a U-shaped multi-element profile (Bloomer & Hawkins 1987). They seem to form from the remelting of overlying, previously-depleted refractory mantle in the presence of LILE enriched hydrous fluids in a suprasubductional tectonic setting (Crawford *et al.* 1981; Bloomer & Hawkins 1987). The gabbros of the Refahiye ophiolite also contain very low $TiO_2$ (0.09–0.46%) values and were probably derived from boninite-like magmas, whereas the low-$TiO_2$ sheeted dykes (0.4–1.01%) with island-arc affinities appear to have been derived from an enriched mantle source, with a subduction component.

On an MnO-$TiO_2$-$P_2O_5$ tectonic environment diagram (Mullen 1983), while the gabbros mostly cluster in the boninitic field, the isolated diabase dykes and sheeted dykes plot across both the boninitic and island arc tholeiitic (IAT) fields. A Ti-Zr diagram (Pearce & Cann 1973) also shows that the ophiolitic rocks plot in both boninite and IAT areas (Figure 10a, b), while all the mafic rocks plot as subduction-related magmas on a Zr-Th-Nb diagram (Figure 10c). These data suggest that the Refahiye ophiolite probably formed in an arc-forearc environment, similar to those proposed for the Greek and Albanian ophiolites in the Balkan Peninsula (Dilek *et al.* 2007).

On a multi-element spider diagram normalized against MORB, the LILE (Sr, K, Rb, Ba) contents of the gabbros and the diabase dykes are highly variable, because the mafic rocks underwent ocean floor metamorphism. Enrichment of Th, a relatively stable and reliable indicator among the LILE group, with respect to the other incompatible elements, indicates a subduction zone setting when the original magmas formed (Wood *et al.* 1979; Pearce 1983; Pearce *et al.* 1987). The depletion of HFSE compared to MORB (Saunders & Tarney 1984) also argues that these rocks were formed in an arc-related environment rather than at a mid-oceanic spreading ridge (Figure 11). On a spider diagram normalized to ocean

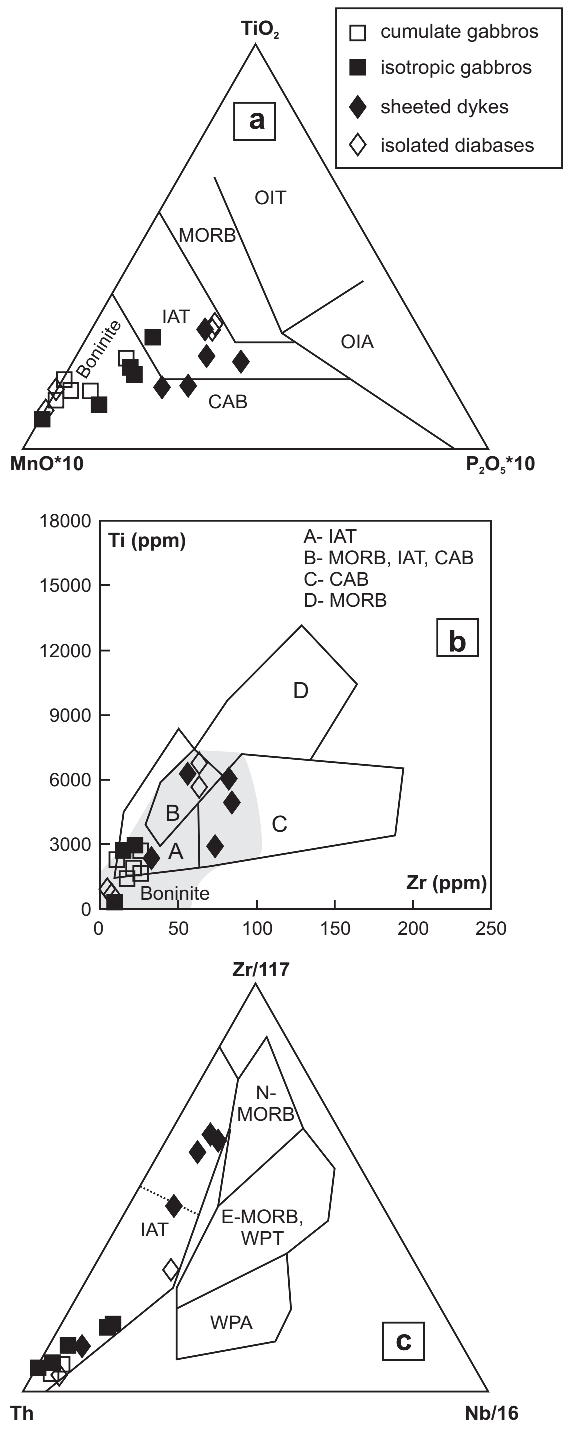


Figure 10. Tectonomagmatic discrimination diagrams for the gabbros and diabases of the Refahiye ophiolite: (a) $TiO_2$-$P_2O_5$-MnO ternary diagram, after Mullen (1983); (b) Ti-Zr diagram after Pearce & Cann (1973). The shaded field from Johnson & Fryer (1990); (c) Zr-Nb-Th ternary diagram, after Wood (1980).

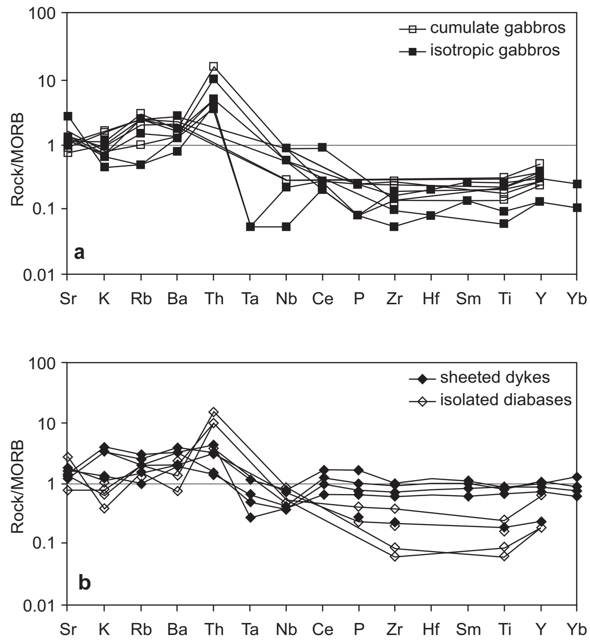


Figure 11. N-MORB normalized spider diagrams for the cumulate and isotropic gabbros (a) and sheeted dykes and isolated diabases (b) of the Refahiye ophiolite (normalizing values are from Pearce 1983).

ridge granites (ORG), the plagiogranites of the Refahiye ophiolite show enrichment in Th and depletion in Ta, Nb, Hf and Zr contents, similar to those of other Eastern Mediterranean ophiolites (Figure 12). On a MORB-normalized spider diagram, Th particularly exhibits positive anomalies in the three samples of basalts while Ta and Nb show negative anomalies, again reflecting IAT-like petrochemistry in a suprasubduction setting (Figure 13).

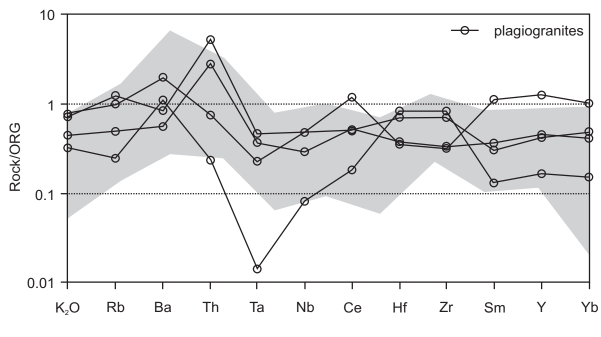


Figure 12. ORG normalized spider diagrams normalized by Pearce *et al.* (1984) for the plagiogranites from the Refahiye ophiolite. The shady field shows the plagiogranites of Eastern Mediterranean Ophiolites (after Sarıfakıoğlu 2006).

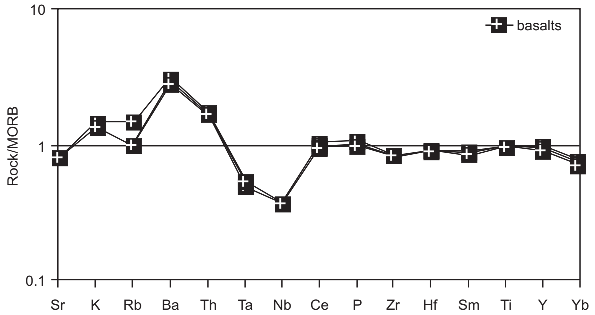


Figure 13. N-MORB normalized spider diagrams for the basalts of the Refahiye ophiolite (normalizing values are from Pearce 1983).

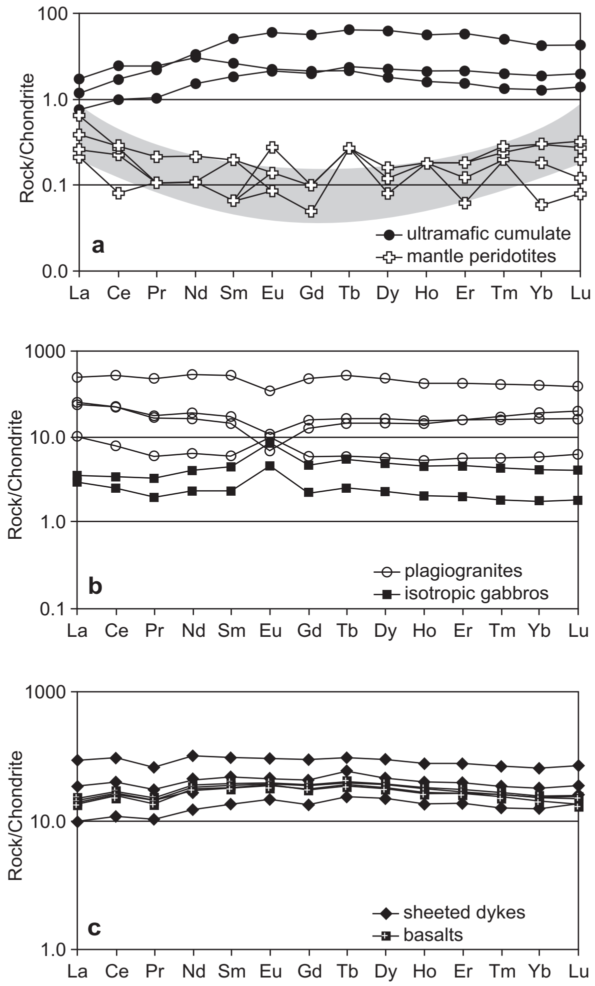


Figure 14. Chondrite normalized REE patterns of whole rock samples from the Refahiye ophiolite (normalizing values are from Sun & McDonough 1989). The shady field is from Pallister & Knight (1981).

The chondrite-normalized REE patterns of the mantle peridotites, ultramafic cumulates, isotropic gabbros, plagiogranites, sheeted dykes and basalts are presented in Figure 14. The mantle peridotites have very low REE concentrations (0.05–0.6×chondrite) producing U-shaped REE patterns (Figure 14a). Such patterns for peridotites are widely accepted as being typical of SSZ magmatism (Pallister & Knight 1981). The ultramafic cumulates show greater LREE and lesser HREE depletions, producing convex-upward patterns at ~1–6×chondrite. The isotropic gabbros show higher REE concentration levels (2–11×chondrite) and positive Eu anomalies, similar to those of the Semail (Oman) ophiolite. The plagiogranites have uniformly high abundance REE patterns (8–62×chondrite) but display negative Eu anomalies except for one sample (E-44). The REE patterns indicate that the plagiogranites and gabbros are cogenetic, also a characteristic of the Semail and Troodos ophiolites (Figure 14b). The basalt and dyke complex samples all show slightly LREE depleted patterns and cluster at 10–28×chondrite (Figure 14c). It is clearly seen that the REE contents of the peridotites, gabbros, plagiogranites, diabases and basalts correspond to their stratigraphic order in the ophiolite pseudostratigraphy.

The immobile element contents therefore imply that the main magmas comprising the ultramafic-mafic and leucocratic rocks of the Refahiye ophiolite have an IAT to possibly boninitic chemistry and were formed in an arc-forearc setting.

## Discussion and Results

In the Eastern Pontides, only a few tectonomagmatic zones can shed light on the tectonic evolution of the region. From north to south, these are (a) volcanic arc units that developed at the active continental margins, (b) forearc volcanosedimentary rocks, (c) metamorphic rocks of the Sakarya Zone, (d) ophiolites and (e) basins along the suture zone. The arc magmatism was initiated in the Late Cretaceous–Early Tertiary above the northerly dipping subduction zone of the northern (İzmir-Ankara-Erzincan) branch of the Neotethys Ocean beneath the Outer Pontides (Şengör & Yılmaz 1981; Yılmaz *et al.* 1998, 2000; Okay & Tüysüz 1999).

The İAESZ, represented by ophiolitic nappes regarded as the relicts of the northern branch of the Neotethys Ocean, crosses the study area. The Late Cretaceous Refahiye ophiolite, formed in a SSZ tectonic setting, was thrust in the Late Cretaceous both on to the Anatolide-Tauride Platform and, with backthrusting, also on to the Pontides. Most of the Refahiye ophiolite was thrust to the south over the Early Triassic–Campanian Munzur Limestone of the Anatolide–Tauride Platform on ophiolitic mélange and is overlain unconformably by upper Cretaceous–Eocene turbiditic flysch, including carbonates, clastic sediments and pyroclastic rocks formed in the forearc depositional basin. Ophiolitic rocks were also backthrust over the Pontide units to the north. The Refahiye opholite is also cut by the North Anatolian Fault trending NW–SE, near Erzincan. In the Refahiye ophiolite, as in other Neotethyan ophiolites in the İAESZ, mantle peridotites are overlain in turn by mafic-ultramafic cumulates, isotropic gabbros and sheeted dykes. As the pillow lavas are encountered only as blocks in the ophiolitic mélange, the ophiolitic slab studied displays a partly dismembered ophiolite pseudostratigraphy with a well-preserved inner structure. When the ophiolite slab was thrust on to the continental platform, the uppermost rocks of the ophiolite, namely the basalts, were shattered and formed much of the mélange.

Petrochemical data from the gabbros, diabase and basalts, which underwent oceanic low-grade hydrothermal alteration, display an irregular distribution of LILE (K, Sr, Rb, Ba) except for Th. While Th is enriched compared to MORB, the HFSE (Ti, Nb, Zr, Y) are depleted. The enrichment of LILE relative to HFSE has been generally interpreted as resulting from transport by hydrous fluids derived from the subducting slab (Stern *et al.* 1991). The plagiogranites exhibit similar geochemical features to those in other Eastern Mediteranean ophiolites. All this geochemical data suggests that mafic and leucocratic rocks of the Refahiye ophiolite formed in a subduction-related setting. The REE patterns of whole rock samples from the Refahiye ophiolite have a chemical composition indicating an arc-related tectonic setting rather than an oceanic spreading ridge. In addition, the presence of depleted peridotites (refractory peridotites with high MgO, Ni, Cr content and low REE contents) and the low to very low $TiO_2$ and Zr content of the basic rocks indicates that the Refahiye ophiolite has a depleted IAT or even boninitic character. Meijer (1980) listed the diagnostic chemical characteristics of boninites as high concentrations of refractory elements such as Mg, Ni, and Cr, and very low concentrations of high-field-strength (HFS) ions and REE. Boninitic lavas are regarded as derived from high degrees of melting of water-saturated (~20–35%) mantle harzburgites in intraoceanic forearc settings (Beccaluva & Serri 1988).

This work indicates for the first time that ophiolites within the İAESZ could contain not only IAT magmas but also boninitic magmas with exceptionally low $TiO_2$. Our stratigraphic and petrologic data indicate that the magmas in the Refahiye ophiolite were probably the product of the earliest phase of subduction-zone related forearc magmatism in a SSZ tectonic setting, resulting from intra-oceanic subduction in the northern branch of the Neotethyan Ocean.

The mantle peridotites (harzburgites and dunites) have strikingly low REE, and profiles are typically U-shaped. It has been suggested that these mantle peridotites represent the depleted residue of the partial melting event that produced the basaltic parent for the crustal suite. The isotropic gabbro and plagiogranite REE patterns show similar abundance levels but the REE patterns of the sheeted dykes and basalts are slightly less depleted than them. The various units of the ophiolite suite indicate that the crustal suite is cogenetic, produced by crystal fractionation of basaltic magma in an intra-oceanic basin (Pallister & Knight 1981). The Refahiye ophiolite may also be interpreted as a product of hydrous melting of a mixed SSZ peridotitic mantle in a SSZ forearc oceanic basin. Shervais (2001) stated that the presence of plagiogranites, considered to be the final fractionation product of the basaltic magma, indicates that the ophiolites formed in a suprasubduction zone setting.

Tüysüz & Dellaloğlu (1992) and Okay & Şahintürk (1998) stated that the ophiolitic nappes in the region are relicts of the northern branch of the Neotethys Ocean, in which an intra-oceanic ensimatic Cenomanian–Maastrichtian arc was formed, which then collided with the Pontides at the end of the Maastrichtian. The data obtained in this study indicates that the Refahiye ophiolite was formed in a suprasubductional tectonic setting, implying that it was a short-lived (5–10 Ma) compared to the probable age range of the Neotethys Ocean. Arc magmatism in the Outer Pontides resulting from subduction of the Neotethys Ocean below the Pontides, and the development of the SSZ ophiolites and ensimatic arc magmatism by intraoceanic subduction magmatism in the same ocean to the south, indicates that the Neotethys Ocean must have been consumed along at least two subduction zones (Figure 15).

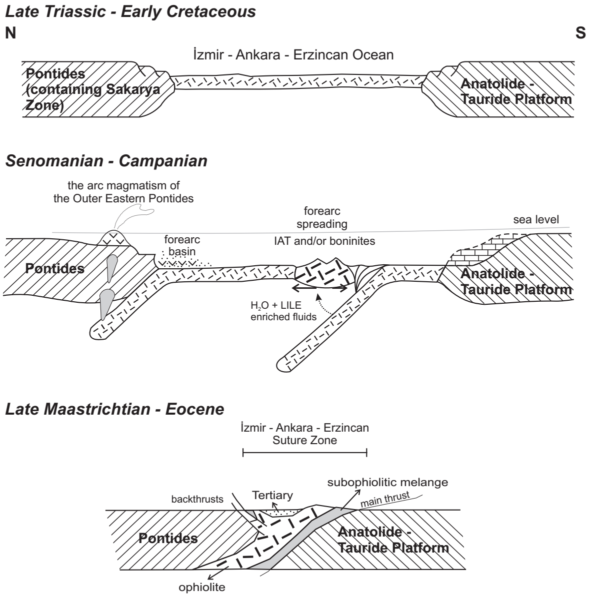


Figure 15. Model sections showing tectonic evolution of forearc ophiolites in the İAESZ (after Şengör & Yılmaz 1981; Tüysüz 1993; Okay *et al.* 2001).

In conclusion, the Refahiye ophiolite displays a similar tectonic setting to other Jurassic–Cretaceous Eastern Mediterranean ophiolites such as Mirdita (Albania), Pindos (Greece), Troodos (Cyprus), the Anatolide-Tauride (Turkey) and Semail (Oman) Ophiolites (Dilek & Flower 2003; Pe-Piper *et al.* 2004; Bağcı *et al.* 2005; Dilek *et al.* 2005, 2007; Özen *et al.* 2006; Sarıfakıoğlu 2006).

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