Geochemistry and Tectonic Environment of Diverse Magma Generations Forming the Crustal Units of the Kızıldağ (Hatay) Ophiolite, Southern Turkey

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Abstract: The Kızıldağ (Hatay) ophiolite is one of the best preserved Neotethyan oceanic lithospheric remnants in southern Turkey. It is represented by, from bottom to top, mantle tectonites, ultramafic to mafic cumulates, isotropic gabbros, sheeted dike complex, plagiogranites and extrusives (low-K tholeiites and boninites). The ultramafic to mafic cumulate rocks are composed of dunite, wehrlite, olivine gabbro, olivine gabbronorite and gabbro. The crystallization order of cumulus phases, and the presence of highly magnesian olivines and pyroxenes as well as highly calcic plagioclases in the cumulates, indicate a subduction-related tectonic environment and suggest derivation from an island arc tholeiitic magma. The isotropic gabbros are represented by gabbro, diorite and quartz diorite with granular, ophitic to micrographic textures. The sheeted dikes are characterized by diabase and microdiorite with ophitic to intersertal textures. The boninitic volcanics (so-called sakalavites) are basaltic in composition and exhibit hypocrystalline porphyric to hyalopilitic textures. All these rocks are tholeiitic in composition. New geochemical data presented in this paper from the isotropic gabbros, sheeted dikes and sakalavites suggest that there are two main types of parental basic magmas that form the crustal rocks of the Kızıldağ (Hatay) ophiolite. These are (i) IAT series comprising the Group I isotropic gabbros and sheeted dikes; (ii) Low-Ti boninitic series characterized by the Group II isotropic gabbros, sheeted dikes and sakalavites. The spatial and temporal relations of the IAT and boninitic magma types in the Kızıldağ ophiolite indicate that different magma sources were contemporaneously active in a fore-arc tectonic setting of the southern branch of Neotethys during the Late Cretaceous.

Key Words: suprasubduction zone, island arc tholeiite, boninite, fore-arc, Turkey

Kızıldağ (Hatay) Ofiyolitindeki Kabuk Birimlerini Oluşturan Farklı Magma Gelişimlerinin Jeokimyası ve Tektonik Ortamı, Güney Türkiye

Özet: Kızıldağ (Hatay) ofiyoliti, güney Türkiye'de en iyi korunmuş Neotetis okyanusal litosfer kalıntılarından birisi olup tabandan tavana doğru manto tektonitleri, ultramafik-mafik kümülatlar, izotrop gabrolar, levha dayk kompleksi, plajiyogranitler ve volkaniklerle (düşük-K toleyitler ve boninitler) temsil edilmektedir. Ultramafik ve mafik kümülatlar dunit, verlit, olivinli gabro, olivinli gabronorit ve gabro'dan oluşmaktadır. Kümülüs fazların kristallenme sırası, kümülatlardaki yüksek-Mg'lu olivin ve piroksenlerin varlığı ve yüksek-Ca'lu plajiyoklaslar dalma-batma ile ilişkili bir tektonik ortamı işaret etmekte olup, bu kayaçların adayayı toleyitik magmasından türediğini önermektedir. İzotropik gabrolar ofitik-mikrografik doku sunan gabro, diyorit ve kuvarslı diyoritler ile temsil edilmektedir. Levha daykları ise ofitik-intersertal dokulu olup diyabaz ve mikrodiyorit'lerden oluşmaktadır. Sakalavitler olarak isimlendirilen boninitik volkanikler bazaltik karakterli olup hypokristalen porfirik ve hiyalopilitik doku sergilemektedir. İzotropik gabrolar, levha daykları ve sakalavitlerden elde edilen yeni jeokimyasal veriler Kızıldağ (Hatay) ofiyolitinde okyanusal kabuk kayaçlarını oluşturan iki ana magmanın varlığına işaret etmektedir. Bunlar: (i) Grup I, izotrop gabro ve levha dayklarını oluşturan adayayı toleyitik serisi ve (ii) Grup II, izotrop gabrolar, levha daykları ve sakalavitleri oluşturan düşük-Ti boninitik seridir. Kızıldağ ofiyolitindeki boninitik ve ada yayı toleyitik magmatizmasının mekansal ve zamansal ilişkileri, farklı magma kaynaklarının Geç Kretase'de Neotetis okyanusunun güney kolundaki yay-önü tektonik ortamında eşzamanlı olarak aktif olduklarını işaret etmektedir.

Anahtar Sözcükler: dalma-batma zonu üstü, ada yayı toleyiti, boninit, yay-önü, Türkiye

Introduction

Suprasubduction zone tectonic settings include island arcs, fore-arc and back-arc basins for the generation of oceanic crust (ophiolite). Suprasubductional ophiolites (cf. Pearce *et al.* 1984) often contain a geochemical stratigraphy which includes island arc tholeiites (IAT), boninitic series volcanics as well as lavas transitional between IAT and mid-ocean ridge basalts (MORB) (Beccaluva *et al.* 1984, 2004, 2005; Malpas & Langdon 1984; Beccaluva & Serri 1988; Smellie *et al.* 1995; Meffre *et al.* 1996; Parlak 1996; Bedard *et al.* 1998; Bedard 1999; Parlak *et al.* 2000; Dilek & Flower 2003; Pearce 2003; Pe-Piper *et al.* 2004; Saccani & Photiades 2004, 2005; Rızaoğlu *et al.* 2006).

The Anatolian segment of the Alpine-Himalayan orogen comprises remnants of Neotethyan oceanic basins cropping out along E–W-trending tectonic zones between metamorphic massifs and/or platform carbonates (Şengör & Yılmaz 1981; Dilek *et al.* 1999; Robertson 2002) (Figure 1). The remnants of Neotethys, in a structurally descending order, are characterized by ophiolites,

metamorphic soles and ophiolitic mélanges. These ophiolites and related subduction-accretion units were generated during the closing stages of the Neotethyan oceanic basins in the Late Cretaceous (Dilek & Flower 2003). Well-preserved Neotethyan ophiolites in Turkey are of supra-subduction zone (SSZ) type (Parlak *et al.* 1996, 2000, 2002; Yalınız *et al.* 1996; Robertson 2002; Bağcı *et al.* 2005, 2006) and display a consistent sequence of events during their formation and emplacement.

The Kızıldağ (Hatay) ophiolite is situated in the peri-Arabian ophiolite belt that includes the Troodos (Cyprus) and Semail (Oman) ophiolites (Figure 1), which have been important in the evolution of ideas concerning the origin and significance of ophiolites and ophiolite-ocean crust analogy (Moores & Vine 1971; Gass & Smewing 1973; Panayioutou 1980; Coleman 1981; Lippard *et al.* 1986; Nicolas 1989; Dilek *et al.* 1990; Malpas *et al.* 1990; Dilek & Delaloye 1992; Dilek & Eddy 1992; Dilek & Thy 1998; Dilek 2003). Investigations in the Kızıldağ (Hatay) ophiolite covered seafloor spreading tectonics and
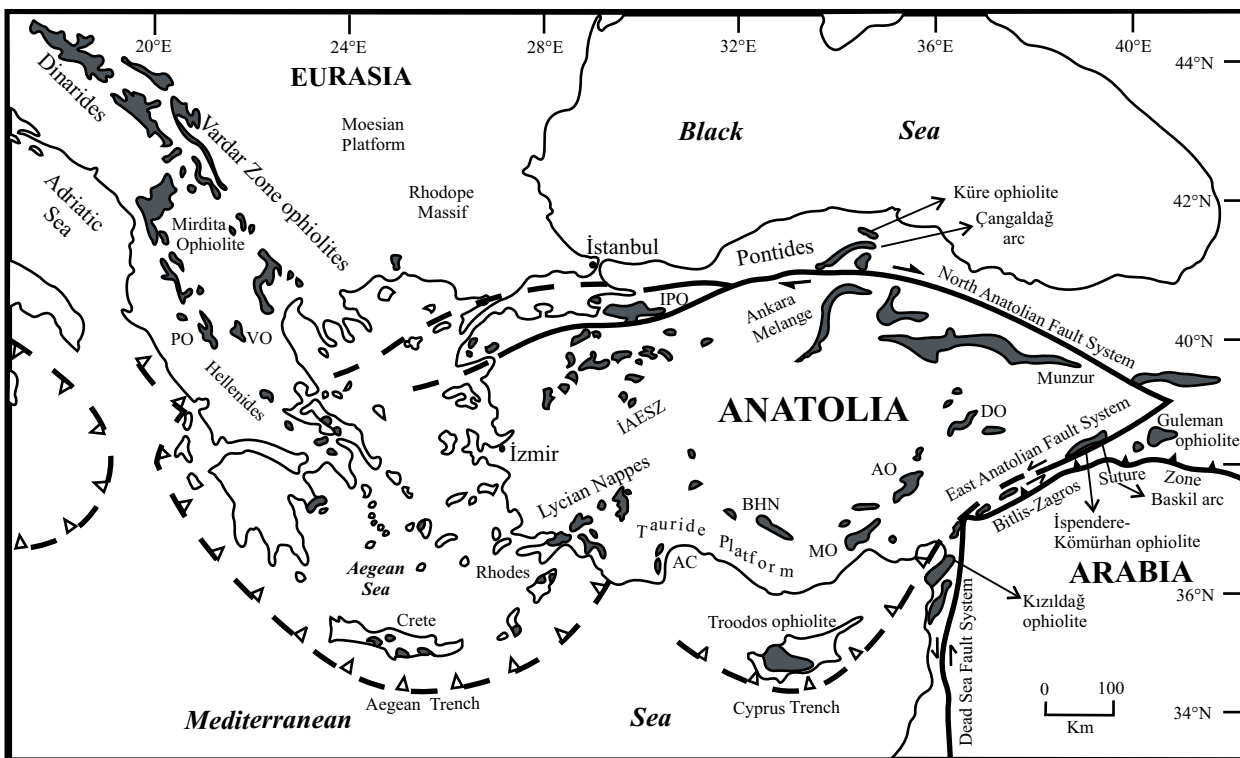

Figure 1. Distribution of Neotethyan ophiolites and major tectonic features in the eastern Mediterranean region (from Dilek & Flower 2003). AC– Antalya Complex; IPO– Intra Pontide Ophiolites; BHN– Beyşehir-Hoyran Nappes; İAESZ– İzmir-Ankara-Erzincan Suture Zone; MO– Mersin Ophiolite; PO– Pindos Ophiolite; VO– Vourinos Ophiolite; AO– Aladağ Ophiolite; DO– Divriği Ophiolite.
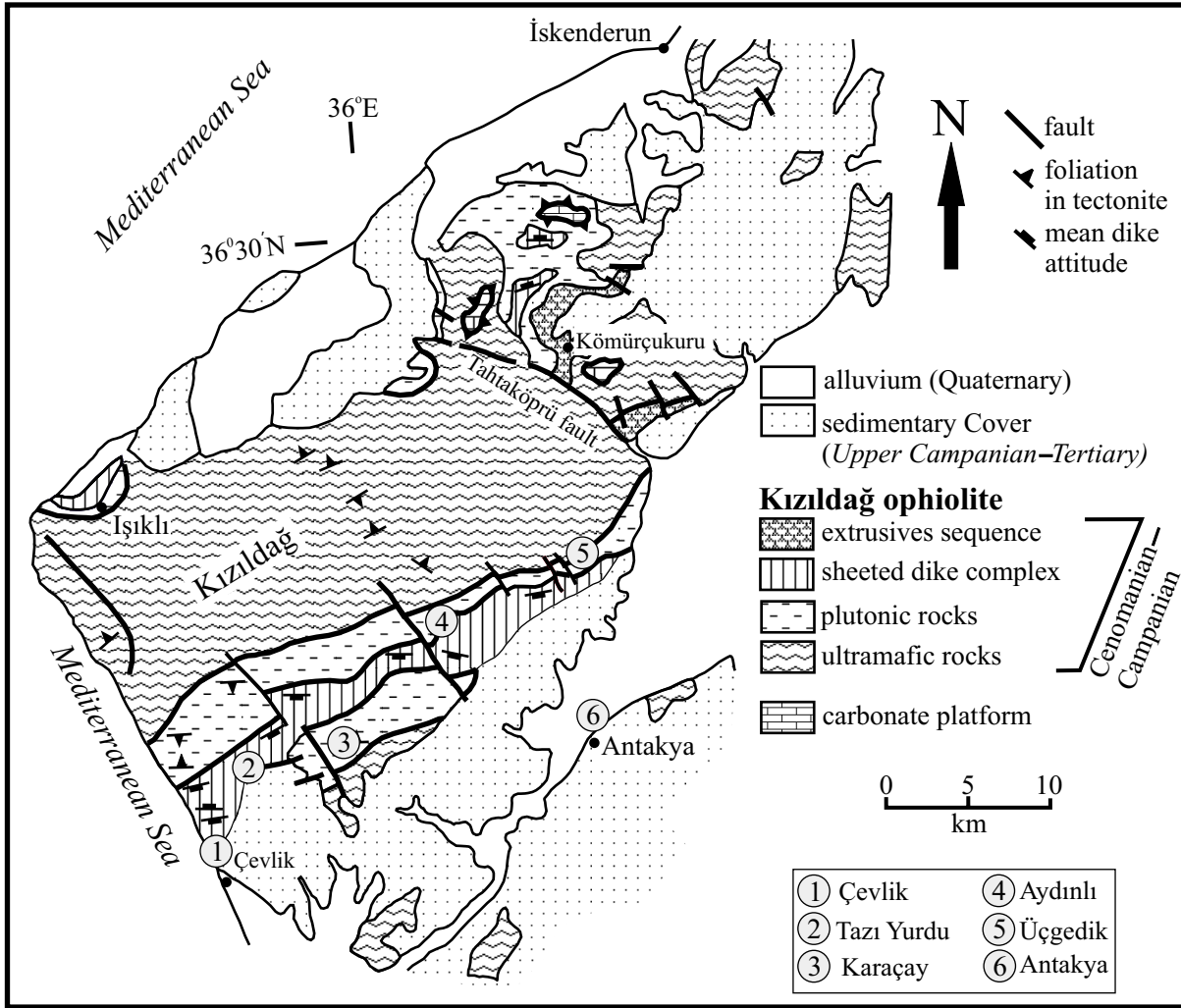
Figure 2. Geological map of the Kızıldağ ophiolite (from Selçuk 1981; Tekeli & Erendil 1984; Dilek & Thy 1998).

structure of oceanic crust as well as petrology of the plutonic and extrusive rocks (Dilek & Delaloye 1992; Dilek & Eddy 1992; Lytwyn & Casey 1993; Dilek & Thy 1998; Bağcı *et al.* 2005). Lytwyn & Casey (1993) showed the existence of boninites and island arc tholeiites from the volcanics and sheeted dikes of the Kızıldağ (Hatay) ophiolite and suggested that the Troodos and Kızıldağ (Hatay) ophiolites may be petrogenetically and tectonically related.

In this paper, new geochemical data from the isotropic gabbros and sakalavites (cf. Dubertret 1955), and complementary geochemical data for the sheeted dikes will be presented in order to demonstrate (a) the generation of voluminous boninitic and island arc

tholeiitic (IAT) magmatism that formed different parts of the oceanic crust (Kızıldağ ophiolite) during the development of the Late Cretaceous subduction/accretion system in southern Neotethys, (b) spatial and temporal interaction of these magmatic suites, and (c) to compare our results with those from other eastern Mediterranean ophiolites and modern analogues.

Regional Geology

The Kızıldağ ophiolite (Figure 2) in southern Turkey is 25 km wide, 45 km long, up to 7 km thick and covers an area of approximately 950 km^2 (Figure 2) (Tinkler *et al.* 1981; Tekeli *et al.* 1983). The Kızıldağ ophiolite thrust
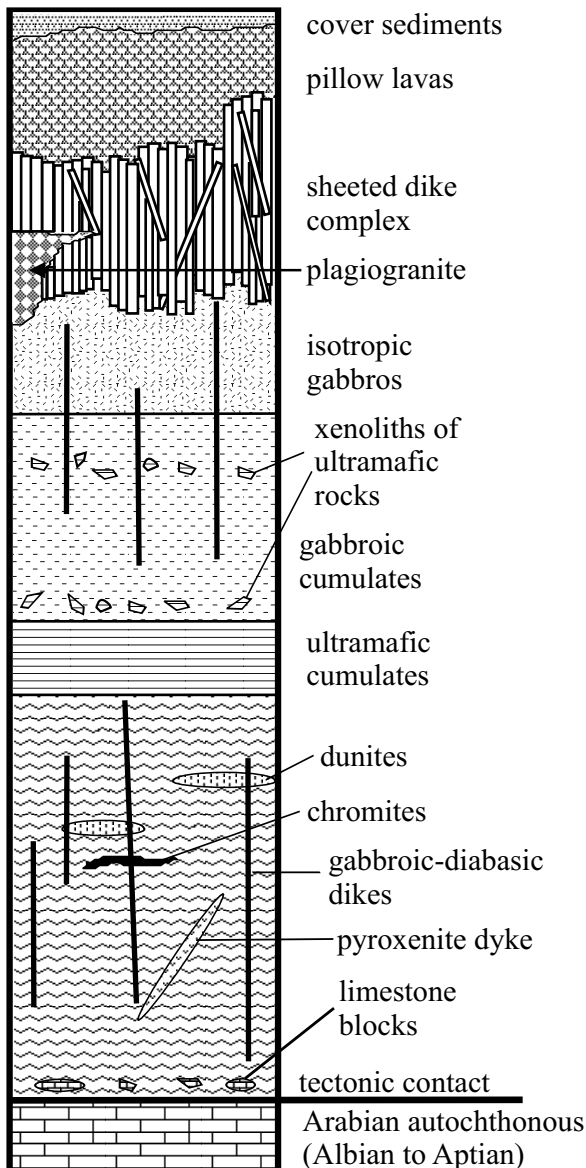
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Figure 3. Synthetic log of the Kızıldağ (Hatay) ophiolite (not to scale).

ultramafic to mafic cumulates, isotropic gabbro, sheeted dikes, plagiogranites and a volcanic complex (Figure 3). The mantle tectonites constitute the core of the ophiolite body and are represented primarily by harzburgite with local lenses and bands of dunite. The base of the serpentinized tectonites contains large blocks of limestones (10–20 m thick and 20–40 m long) near Kömürçukuru (Figures 2 & 3), which were incorporated into the peridotite during the emplacement of the ophiolite (Tinkler *et al.* 1981). The harzburgitic tectonites exceed 3 km in thickness and are intruded by pegmatitic gabbroic and pyroxenitic dikes (Figure 4a, b) (Tinkler *et al.* 1981; Tekeli *et al.* 1983; Erendil 1984; Dilek & Thy 1998). The cumulate rocks displaying a thickness from 165 to 700 m, are characterized by dunite, wehrlite, olivine gabbro, olivine gabbronorite and gabbro (Figure 4c). Near the top of the plutonic section, isotropic gabbros are more abundant, with a thickness of 2–2.5 km (Tinkler *et al.* 1981; Pişkin *et al.* 1990). They are represented by gabbro, diorite and quartz diorite rock assemblages. At the top, the isotropic gabbros grade into a well-developed sheeted dike complex containing several gabbro screens and lenses 50 to 70 cm in size (Erendil 1984; Tinkler *et al.* 1981; Dilek & Thy 1998) at the base (Figure 4d). The sheeted dikes start as isolated dikes at the basal contact with the isotropic gabbro, and are dominated by 100% dikes ranging in thickness from 2 cm to 2 meters. The best-preserved outcrops were observed north of Çevlik along the Mediterranean coastline. Some small outcrops of the sheeted dike complex are seen north of Kömürçukuru and Tahtaköprü (Figure 2). The sheeted dikes are oriented along a strike of E–W and display well-preserved chilled margins and cross-cutting relationships. Dilek & Thy (1998), based on cross-cutting relations, textural and compositional differences, showed that at least three main generations of dike intrusions exist in the sheeted dike complex (Figure 4e, f). The plagiogranite has an intrusive relationship with the upper part of the isotropic gabbros in the Karaçay valley and the sheeted dike complex in Çevlik village (Figure 4g). Two outcrops of the volcanic rocks are present in the Kızıldağ ophiolite. The first one is located in two areas, at or near Tahtaköprü and Kömürçukuru villages in the northern part of the massif (Figure 2). They tectonically overlie serpentinized peridotite in Tahtaköprü and isotropic gabbro in Kömürçukuru, respectively (Dilek & Thy 1998). The

sheets rest tectonically on the top of Arabian platform carbonates that are Early Cretaceous (Albian to Aptian) in age. The oldest transgressive sequence covering the ophiolitic rocks comprises conglomerate, sandstone and neritic to pelagic carbonates (Selçuk 1981; Tinkler *et al.* 1981; Delaloye & Wagner 1984) of Maastrichtian age. Therefore, the emplacement age of the Kızıldağ ophiolite is limited to the Late Cretaceous (pre-Maastrichtian). It displays a complete ophiolite assemblage that comprises, from bottom to top, depleted mantle tectonites,

Figure 4. Field views of the crustal rocks from the Kızıldağ (Hatay) ophiolite: **(a)** Pyroxenite dike in harzburgite; **(b)** pegmatitic gabbro veinlet in harzburgite; **(c)** ductilely deformed cumulate rocks; **(d)** isotrope gabbro-sheeted dike transition near Çevlik; **(e, f)** parallel to sub-parallel sheeted dikes and cross-cutting relations; **(g)** plagiogranite intruding the sheeted dikes and **(h)** pillow lavas surrounded by hyaloclastites in boninites. Pencil and hammer are 11 and 33 cm long, respectively. The coin and lense cap have diameters of 2.5 and 5.8 cm, respectively.

volcanic complex consists of pillow basalts, massive lavas and cross-cutting dikes and is 1.3 km thick, with an outcrop area of 5 km^2 (Tekeli *et al.* 1983; Erendil 1984). The lavas are interbedded with metalliferous umbers (Robertson 1986a). The second group of volcanic rocks is located 12 km southeast of the main body of the Kızıldağ ophiolite near Mount Silpius and is referred to as '*sakalavite*' by Dubertret (1955). It is 300 m thick and represented by hyaloclastites associated with boninitic egg-shaped micro pillow lavas, 4–5 cm to 20 cm long (Laurent *et al.* 1980; Robertson 1986b) (Figure 4h).

Petrography and Mineralogy

This section only summarizes the petrographic characteristics of the studied rocks because those of other rock units in the Kızıldağ (Hatay) ophiolite were already given elsewhere (Bağcı *et al.* 2005).

The boninitic volcanic rocks in the Kızıldağ (Hatay) ophiolite are called sakalavites (cf. Dubertret 1955). They exhibit hypocrystalline porphyric to hyalopilitic texture and are characterized by olivine (20 vol%), clinopyroxene (60–65 vol%), plagioclase (1–5 vol%) and chromite (1–3 vol%) in a glassy groundmass. Glass between the phenocrysts and pillows has been altered to montmorillonite or partly recrystallized to palagonite (Laurent *et al.* 1980). The olivine forms euhedral to subhedral phenocrysts up to 1.28 mm long. Occasionally completely fresh, they more often occur as skeletal forms (Figure 5a, b). Serpentine and iddingsite are the secondary phases. The olivine compositions were obtained by microprobe analyses and are presented in Table 1. The olivines are markedly less magnesian, varying from $Fo_{87.5}$ to $Fo_{89.5}$, than those from the mantle tectonite (Pişkin *et al.* 1990). A slight difference in Mg and Fe contents between the core and rim of individual grains is observed (Table 1). These values are similar to olivines from the ultramafic cumulates (Bağcı *et al.* 2005) and fall within the range of boninitic olivines from Troodos ophiolite Upper Pillow Lavas (Malpas & Langdon 1984), and Mariana trench boninites (Bloomer & Hawkins 1987). The clinopyroxenes differ texturally from olivines because the grains have developed forms and shapes indicative of rapid quenching (Figure 5c, d). They display stubby, swallow-tail and hourglass forms, ranging from 0.01 to 0.6 mm in length (Figure 5c, d). The clinopyroxene compositions were obtained by microprobe analyses and are presented in Table 1. They

are mainly calcic to subcalcic augite (Wo_{44-18}, En_{69-34}, Fs_{29-7}) in composition. They exhibit zoning, and have Mg-rich cores and Al_2O_3-, FeO- and CaO-rich rims (Table 1). The Ca-rich plagioclase (An_{83}) is represented by anhedral grains (0.05–0.18 mm) (Laurent *et al.* 1980). The chromite microphenocrysts, which are generally surrounded by olivine, occur as euhedral grains and have high Cr# (Cr/Cr+Al= 70) (Table 1), which is also typical of those found in boninites (Crawford *et al.* 1989).

The parallel- to subparallel-oriented dikes are dominated by diabase and quartz-microdiorite. The diabase exhibits intersertal, ophitic to subophitic textures (Figure 5e, f) and is characterized by euhedral to subhedral plagioclase (60–70 vol%) with a grain size of 0.03 to 0.9 mm, anhedral clinopyroxene (20–25 vol%) with a grain size of 0.18 to 2.17 mm and opaque minerals. The quartz microdiorite displays microgranular porphyric texture (Figure 5e, f) and is represented by subhedral plagioclase (An_{40-50}) (60–70 vol%) with a grain size of 0.15 to 2.1 mm, anhedral hornblende (15–20 vol%) with a grain size of 0.03 to 0.53 mm, anhedral quartz (5–10 vol%) with a grain size of 0.01 to 0.18 mm and opaque minerals. Epidote and chlorite are present as secondary phases.

The isotropic gabbros form the uppermost part of the plutonic section and are 2000 meters thick. They have transitional contacts with the cumulate rocks in the Çevlik, Karaçay, Aydınlı and Üçgedik regions (Figure 2). They exhibit light brown to green weathered surfaces and deep green to green fresh surfaces. The isotropic gabbroic rocks of the Kızıldağ (Hatay) ophiolite consist of gabbro, diorite and quartz diorite. The gabbro displays granular to ophitic textures (Figure 5g, h) and is characterized by prismatic plagioclase (55–60 vol%) with a grain size of 0.3 to 1.9 mm, subhedral clinopyroxene (30 vol%) with a grain size of 0.5 to 2.3 mm and opaque minerals. The diorite exhibits granular, ophitic to subophitic texture and is represented by euhedral to subhedral plagioclase (80 vol%) with a grain size of 0.4 to 1.6 mm, subhedral hornblende (10–15 vol%) with a grain size of 0.4 to 1.2 mm, clinopyroxene (1–5 vol%) and opaque minerals. The quartz diorite displays granular, ophitic and micrographic textures (Figure 5g, h). It consists of plagioclase laths (andesine) (60–70 vol%) with a grain size of 0.4 to 1.3 mm, subhedral to anhedral hornblende (15–20 vol%) with a grain size of 0.6 to 1.8 mm, anhedral clinopyroxene (~ 5 vol%) with
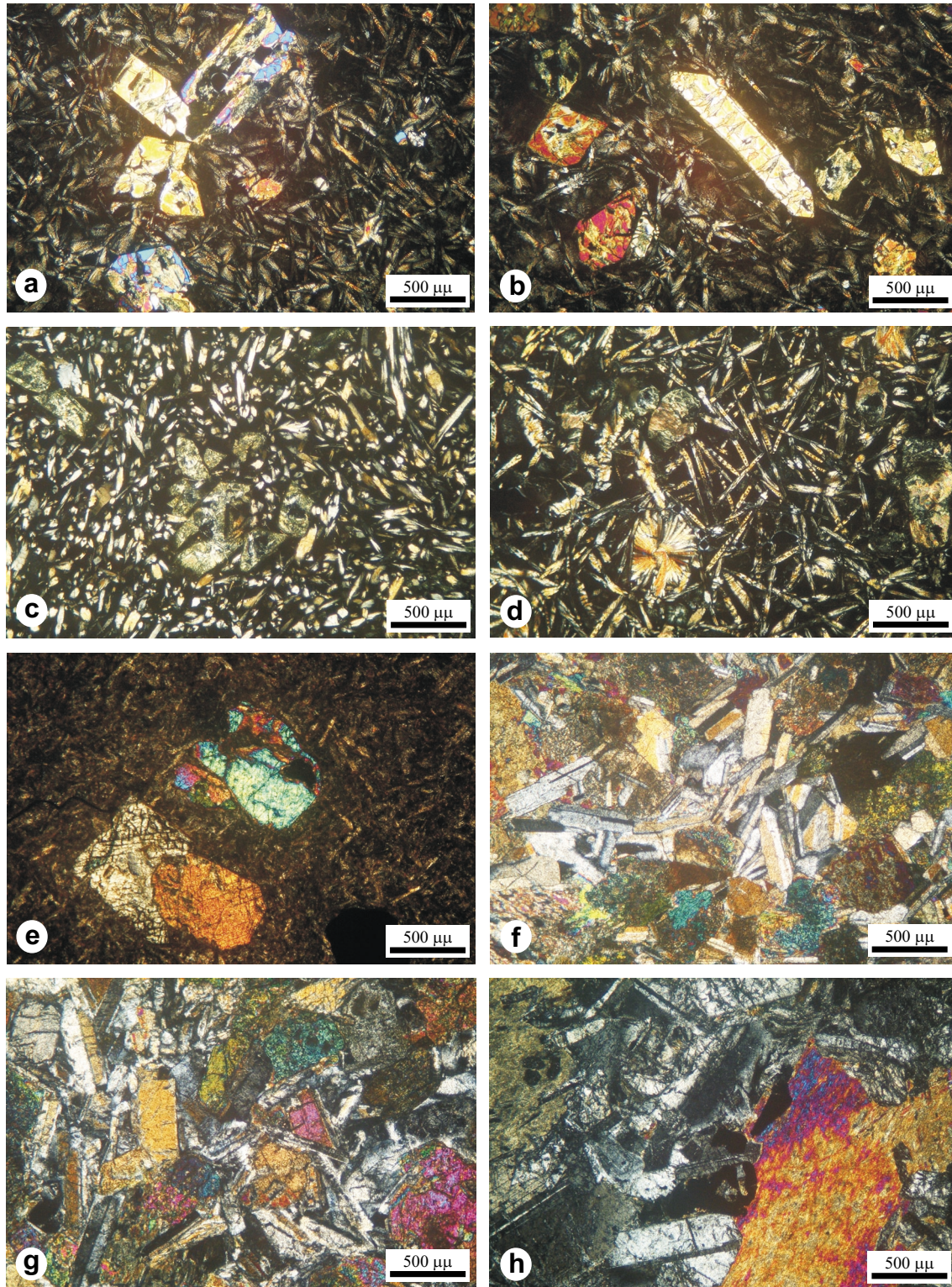
Figure 5. Petrographic views of the crustal rocks from the Kızıldağ (Hatay) ophiolite: (a, b) skeletal forms of the olivines in boninites; (c, d) stubby, swallowtail and hourglass shapes indicating of rapid quenching in boninitic lava; (e, f) microgranular to subophitic textures in sheeted dikes; (g, h) ophitic to granular textures in isotropic gabbros.

Table 1. Representative mineral chemistry data from the sakalavites in the Kızıldağ (Hatay) ophiolite.

Sample	Olivine				Pyroxene														Chromite	
	SKL2-1c	SKL2-8c	SKL16-5c	SKL16-5r	SKL2-1c	SKL2-7c	SKL2-11c	SKL2-14c	SKL14-1c	SKL14-6c	SKL14-6r	SKL14-9c	SKL14-9r	SKL16-5c	SKL16-6c	SKL16-6r	SKL16-8c	SKL16-11c	SKL2-1c	SKL2-2c
SiO₂	40.62	40.43	41.39	41.26	46.40	54.50	52.62	45.56	53.05	54.69	50.47	53.20	51.67	53.78	51.01	49.82	51.93	50.03	0.07	0.07
TiO₂	0.00	0.00	0.00	0.00	0.45	0.12	0.17	0.56	0.30	0.18	0.63	0.34	0.40	0.23	0.44	0.38	0.35	0.47	0.32	0.29
Al₂O₃	0.03	0.04	0.02	0.03	11.66	3.02	3.31	12.56	4.12	2.76	7.19	4.20	5.98	3.69	6.61	8.47	5.79	8.24	15.07	15.25
Cr₂O₃	0.06	0.08	0.08	0.08	0.02	0.40	0.70	0.05	0.65	1.12	0.05	0.51	0.05	0.65	0.14	0.07	0.12	0.03	50.15	49.28
FeO*	11.01	11.60	10.00	11.12	10.51	7.51	5.13	9.81	6.31	6.89	7.51	6.11	7.60	6.40	5.76	7.08	6.28	6.25	20.82	20.82
MnO	0.20	0.17	0.15	0.17	0.27	0.16	0.16	0.20	0.23	0.19	0.18	0.12	0.18	0.20	0.13	0.20	0.15	0.15	0.17	0.24
MgO	47.63	47.19	47.92	47.00	13.25	24.40	18.07	11.73	19.15	23.53	15.60	18.91	17.01	21.65	15.93	15.52	17.82	14.92	12.39	12.41
NiO	0.25	0.28	0.28	0.17	0.04	0.04	0.05	0.00	0.03	0.01	0.03	0.03	0.01	0.02	0.03	0.04	0.02	0.01	0.08	0.14
CaO	0.21	0.20	0.15	0.17	16.63	8.91	19.17	18.87	16.08	10.56	18.24	16.51	16.99	13.31	19.88	18.31	17.45	19.81	0.07	0.08
Na₂O	0.00	0.00	0.00	0.00	0.10	0.09	0.10	0.10	0.05	0.08	0.09	0.05	0.10	0.07	0.06	0.08	0.09	0.08	0.00	0.00
K₂O	0.00	0.00	0.01	0.00	0.00	0.02	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01
Total	100.00	100.00	100.00	100.00	99.33	99.18	99.49	99.44	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.14	98.60
Fo	88.52	87.88	89.52	88.28																
Fa	11.48	12.12	10.48	11.72																
En					42.40	69.50	51.90	37.95	55.70	67.06	47.24	55.18	50.66	62.00	47.52	47.37	52.46	45.57		
Fs					19.36	12.27	8.53	18.18	10.68	11.32	13.07	10.20	12.99	10.61	9.87	12.47	10.63	10.96		
Wo					38.24	18.23	39.57	43.87	33.62	21.62	39.69	34.62	36.35	27.39	42.61	40.15	36.91	43.46		
Mg#	88.52	87.88	89.52	88.28	69.20	81.73	85.04	68.06	80.16	81.51	75.31	79.53	76.36	82.25	80.01	77.25	80.48	77.44	51.48	51.51
Cr#																			69.07	68.44

a grain size of 0.2 to 0.8 mm, anhedral quartz (~10 vol%) and opaque minerals. Chlorite, albite, sericite, kaolinite, actinolite and epidote are the secondary phases in these rocks.

Analytical Method

A total of 67 samples (22 isotropic gabbros, 27 sheeted dykes and 18 boninitic volcanics) were analyzed for major and trace element contents. Major and trace element analyses were carried out at the University of Geneva (Switzerland). Major elements were determined by XRF spectrometry on glass beads fused from ignited powders to which $Li_2B_4O_7$ was added (1:5), in a gold-platinum crucible at 1150 °C. Trace elements were analysed on pressed powder pellets by the same method. A subset of 35 representative samples (14 isotropic gabbros, 15 sheeted dykes and 6 boninitic volcanics) were analysed by ICP-MS for trace elements (including REE) at Acme Analytical Laboratories and Actilabs-Activation Laboratories in Canada. A total of 3 representative polished sections from the boninitic volcanics were selected for electron microprobe analysis on a JEOL JXA-8600 at the Geology and Paleontology Department at Salzburg University (Austria). The analytical conditions for the elements were 13 s (10 s for Peak and 3 s for Background) of counting interval, beam current -20 nA and acceleration voltage -15 kV. The data reduction was done following the ZAF procedure. Fe^{+3} and Fe^{+2} were determined from stoichiometry of spinel using the equation of Droop (1987). The results of the analyses are presented in Tables 1 to 7.

Geochemistry

The major, trace and rare earth element contents of the isotropic gabbro, sheeted dike and boninitic volcanic (sakalavite) rocks are presented in Tables 2 to 7. The LOI values range up to 5.99% in isotropic gabbros, 6.43% in sheeted dikes and 13.38% in boninitic volcanics (sakalavite), reflecting variable secondary alteration indicated by the presence of secondary mineral phases (i.e. serpentine, epidote, kaolin, calcite, chlorite), as determined in the petrography section. The mobility of many elements during low-grade submarine alteration is well constrained (e.g., Hart *et al.* 1974; Humphris & Thompson 1978). For this reason, recourse is generally made to relatively immobile elements such as Ti, P, Zr, Y,

Nb and REE, and to a lesser extent Cr, Ni, Sc and V, to designate rock groups, petrogenetic trends and tectonic environments (Pearce & Cann 1973; Floyd & Winchester 1975; Winchester & Floyd 1977; Pearce & Norry 1979).

The Nb/Y ratios of the isotropic gabbro, sheeted dike, and sakalavite rocks range from 0.05 to 0.33, 0.04 to 0.31 and 0.15 to 0.42, respectively (Tables 2, 4 & 6). These indicate that the analysed rocks are derived from a tholeiitic magma source (Pearce 1982) (Figure 6a). The rock classification diagram for the rock units of the Kızıldağ (Hatay) ophiolite is based on ratio-ratio plot of immobile elements such as Zr/Ti versus Nb/Y (Pearce 1996). All the rocks from the isotropic gabbros, sheeted dikes and sakalavites plot in the basaltic field (Figure 6b).

The variations of some selected major and trace elements are presented in Figure 7. SiO_2, FeO, Y and V show positive correlations, whereas MgO, CaO/Al_2O_3, Cr and Ni exhibit negative correlations against Zr, consistent with a crystallization assemblage of olivine, clinopyroxene and plagioclase (Pearce & Norry 1979; Pearce 1982) (Figure 7). All the interelement relations and immobile trace element contents (Table 2 to 7) suggest that two geochemically distinct subgroups in the isotropic gabbro and two distinct subgroups in the sheeted dikes can be identified. The first geochemical group includes the Group I isotropic gabbros and sheeted dikes while the second group includes the Group II isotropic gabbros, sheeted dikes and sakalavites (Table 2 to 7). The first group is represented by high TiO_2 (0.43–1.06 wt%), Zr (24–54 ppm), Y (15–30 ppm), and V (169–399 ppm) and low MgO (3.88–9.60 wt%), Ni (27–67 ppm), and Cr (20–666 ppm) compared to the second group which is characterized by low TiO_2 (0.19–0.61 wt%), Zr (11–31 ppm), Y (9–23 ppm), and V (136–295 ppm) and high MgO (8.48–16.92 wt%), Ni (64–418 ppm), and Cr (54–1495 ppm) (Tables 2 to 7).

On the Al_2O_3/TiO_2 versus TiO_2 plot of the isotropic gabbros, sheeted dikes and sakalavites (Figure 8a), the first geochemical group (Group I isotropic gabbro and sheeted dike) is represented by low Al_2O_3/TiO_2 (14.45–34.61) and plots within the transitional field of mid ocean ridge basalt (MORB) and island arc tholeiite (IAT) whereas the second geochemical group has higher Al_2O_3/TiO_2 (23.81–83.8) contents and shares chemical affinity with both boninites and IAT (Figure 8a). The Zr versus TiO_2 plot of the isotropic gabbros, sheeted dikes and and sakalavites (Figure 8b) shows that the first

Table 2. Major and trace element contents of the isotropic gabbros from the Kızıldağ (Hatay) ophiolite.

Sample	IAT-type isotrope gabbro											Boninitic-type isotrope gabbro										
	K-6	KÇ-30	KÇ-34	KÇ-35	KÇ-36	KÇ-39	KÇ-41	KÇ-46	Ü-6	Ü-7	T-6	K-8	K 27	K 28	KÇ-28	KÇ-32	KÇ-33	KÇ-38	KÇ-40	KÇ-44	KÇ-45	KÇ-48
SiO_2	51.01	54.60	52.14	57.19	55.96	51.95	45.67	54.28	50.92	52.71	50.09	46.96	47.86	47.92	50.48	49.71	48.51	50.24	46.09	49.46	49.16	46.20
TiO_2	0.54	0.43	0.53	0.93	1.02	0.74	0.56	0.78	0.50	0.92	0.67	0.32	0.21	0.20	0.41	0.31	0.32	0.46	0.37	0.29	0.34	0.19
Al_2O_3	16.31	14.92	16.43	15.23	15.52	16.39	17.82	16.16	16.68	16.12	15.50	16.76	15.18	16.34	14.63	12.63	15.47	13.92	15.79	16.39	16.15	11.45
FeO*	8.37	6.90	7.65	9.65	10.15	9.21	7.38	9.89	6.02	10.18	9.66	5.94	5.00	5.19	7.08	8.44	6.63	9.60	5.63	5.43	6.41	8.96
MnO	0.16	0.11	0.10	0.08	0.08	0.10	0.12	0.13	0.11	0.11	0.10	0.10	0.11	0.11	0.14	0.13	0.12	0.18	0.09	0.11	0.13	0.15
MgO	7.96	8.03	7.86	4.84	5.21	6.81	9.46	5.65	7.86	5.45	7.43	10.51	10.74	9.91	9.52	13.96	10.62	11.20	12.00	9.48	9.40	16.92
CaO	9.02	9.18	10.46	5.60	4.50	10.63	12.04	7.91	11.74	8.19	10.06	13.66	16.67	16.10	10.54	9.82	13.69	9.34	12.14	12.67	13.77	12.03
Na_2O	3.53	3.05	2.44	4.06	4.68	2.18	1.13	2.80	2.84	3.95	3.15	1.63	1.10	1.20	2.58	1.30	1.41	1.86	1.38	2.37	1.57	0.38
K_2O	0.41	0.19	0.16	0.26	0.43	0.17	0.46	0.48	0.19	0.32	0.18	0.30	0.02	0.03	0.30	0.11	0.09	0.20	0.22	0.25	0.40	0.03
P_2O_5	0.04	0.05	0.04	0.10	0.09	0.05	0.03	0.07	0.05	0.08	0.05	0.03	0.01	0.01	0.02	0.02	0.03	0.01	0.03	0.02	0.03	0.02
LOI	2.57	2.01	1.55	1.62	2.05	1.18	4.44	1.55	2.44	1.64	2.45	3.20	2.51	2.48	3.45	3.01	1.71	2.54	5.99	2.58	1.98	2.85
Cr_2O_3	0.01	0.09	0.01	0.01	0.01	0.01	0.01	0.00	0.02	0.01	0.01	0.08	0.17	0.08	0.08	0.14	0.09	0.03	0.08	0.10	0.08	0.18
NiO	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.02	0.03	0.02	0.02	0.05	0.02	0.01	0.02	0.02	0.02	0.07
Total	99.93	99.57	99.38	99.57	99.69	99.42	99.13	99.70	99.37	99.69	99.35	99.50	99.61	99.57	99.25	99.61	98.71	99.58	99.82	99.17	99.44	99.42
Nb	2	3	2	6	5	2	2	3	1	3	2	1	1	1	2	4	1	3	1	2	1	3
Zr	24	40	32	51	54	37	24	40	31	39	32	18	11	11	16	16	20	23	15	18	20	14
Y	15	23	20	29	30	22	16	25	18	25	19	11	9	9	12	14	12	15	14	13	14	9
Sr	96	72	85	129	125	98	323	96	124	360	123	147	69	76	113	43	49	59	162	51	67	40
U	2	2	2	3	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Rb	5	4	4	5	5	5	7	6	4	4	4	6	4	4	5	5	4	4	4	5	6	5
Th	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Pb	7	9	8	7	6	9	7	10	5	6	8	7	8	8	6	13	9	10	7	4	7	13
Ga	14	15	15	18	18	15	17	19	15	18	16	11	10	10	12	11	12	13	12	12	13	8
Zn	113	47	34	19	21	22	28	30	43	43	48	27	75	191	64	46	42	51	37	47	55	58
Cu	8	8	5	5	2	6	7	6	7	11	6	20	103	193	8	21	52	14	5	62	164	96
Ni	50	91	57	15	23	31	47	18	80	25	54	125	143	127	114	303	149	74	114	106	120	418
Co	35	35	35	32	33	33	44	36	29	29	42	35	34	31	38	53	40	48	40	29	35	74
Cr	109	666	82	31	43	43	55	22	162	45	92	470	1082	484	902	718	459	232	754	619	477	1050
V	260	169	228	247	334	297	353	212	236	255	285	164	147	151	252	236	185	295	252	162	190	136
Ce	14	14	12	9	12	10	7	10	12	11	10	17	17	14	11	10	8	9	6	4	12	6
Nd	7	6	6	4	4	4	4	4	5	4	6	10	12	8	5	4	4	5	4	4	6	4
Ba	35	54	45	35	46	23	14	38	36	47	16	30	14	21	36	34	32	23	40	41	36	21
La	4	4	4	4	7	4	11	4	4	4	4	4	9	9	4	4	7	4	13	4	9	4
S	30	3	3	3	3	3	3	3	3	3	3	16	109	279	3	3	3	3	3	34	156	3
Hf	1	1	1	4	3	1	1	3	1	3	3	1	1	5	1	1	3	1	1	1	2	1
Sc	45	50	54	79	59	57	57	50	48	43	46	32	30	29	66	84	50	82	89	48	45	72
As	3	5	6	3	3	3	7	5	5	4	6	4	3	3	5	7	4	6	4	6	7	7

Total Fe is expressed as FeO

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

Sample	IAT-type isotrope gabbro							Boninitic-type isotrope gabbro						
	KC-30*	KC-35*	KC-39*	KC-41**	KC-46**	Ü-6*	Ü-7**	K-8**	K-27**	K-28*	KC-32**	KC-33**	KC-40*	KC-44**
Ba	19.00	7.1	11.70	4	25	8.70	32	5	< 3	5.6	3	6	3.2	12
Co	31.40	27.4	32.30	26	23	25.10	34	27	25	31.9	37	27	34.7	21
Cs	< 0.1	< .1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< .1	< 0.1	< 0.1	< .1	< 0.1
Ga	13.50	16.9	15.90	14	17	15.30	14	11	9	10.3	10	11	11.2	10
Hf	1.70	1.7	1.00	0.6	1.2	0.80	1.2	0.5	0.2	< .5	0.4	0.5	< .5	0.5
Nb	1.60	2.3	1.50	0.4	1.3	0.70	1.2	0.3	< 0.2	< .5	0.6	0.4	< .5	0.3
Rb	1.20	< .5	0.80	3	2	0.80	2	2	1	< .5	< 1	< 1	< .5	1
Sn	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	1
Sr	75.00	129.1	103.60	287	89	130.60	302	143	71	85.1	42	47	176.2	50
Ta	0.10	0.2	0.10	0.02	0.09	< .1	0.07	0.01	< 0.01	< .1	0.05	0.02	< .1	0.02
Th	0.60	0.5	0.30	0.09	0.2	0.20	0.2	0.09	< 0.05	< .1	0.09	0.12	0.1	0.07
U	0.10	0.1	< .1	0.03	0.07	< .1	0.07	0.03	0.01	< .1	0.04	0.04	0.1	0.03
V	164.00	245	301.00	268	188	201.00	267	153	155	156	198	171	198	136
W	< .1	0.2	0.10	< 0.5	< 0.5	< .1	< 0.5	< 0.5	< 0.5	< .1	< 0.5	< 0.5	< .1	< 0.5
Zr	43.20	54.3	30.70	20	36	24.30	35	17	8	4.3	12	15	11.2	14
Y	22.90	27.3	21.30	12.2	23.4	16.50	22.3	8.7	6.4	6.3	9.6	9.7	10.8	9.8
La	2.30	2.6	1.60	0.74	1.86	1.40	1.96	0.64	0.17	< .5	0.5	0.66	< .5	0.52
Ce	5.40	6.1	4.60	2.13	4.98	3.60	5.43	1.81	0.55	0.7	1.16	1.67	1.2	1.43
Pr	0.80	0.94	0.71	0.37	0.82	0.54	0.87	1.86	0.12	0.12	0.18	0.27	0.2	0.25
Nd	5.10	6.3	4.80	2.39	4.96	3.40	5.15	1.86	0.82	0.8	1.21	1.71	1.5	1.68
Sm	1.70	2	1.70	0.92	1.81	1.30	1.88	0.68	0.38	0.3	0.52	0.64	0.7	0.67
Eu	0.62	0.9	0.59	0.383	0.758	0.54	0.815	0.331	0.202	0.21	0.242	0.297	0.29	0.296
Gd	2.39	3.23	2.25	1.43	2.81	1.89	2.78	1.11	0.72	0.66	0.95	1.14	1.26	1.11
Tb	0.51	0.75	0.52	0.29	0.56	0.36	0.54	0.22	0.15	0.17	0.2	0.22	0.26	0.22
Dy	3.23	4.02	3.22	1.94	3.83	2.67	3.65	1.45	1.02	1	1.44	1.56	1.66	1.54
Ho	0.68	0.9	0.68	0.43	0.86	0.56	0.79	0.31	0.23	0.2	0.33	0.35	0.35	0.34
Er	2.28	2.83	2.06	1.36	2.66	1.75	2.4	0.95	0.69	0.7	1.06	1.11	1.07	1.05
Tm	0.33	0.48	0.30	0.207	0.407	0.25	0.355	0.142	0.103	0.11	0.164	0.17	0.18	0.161
Yb	2.33	2.98	2.06	1.31	2.59	1.58	2.21	0.91	0.63	0.59	1.09	1.07	1.11	1.03
Lu	0.31	0.45	0.30	0.191	0.391	0.26	0.326	0.138	0.091	0.09	0.167	0.153	0.21	0.151
Mo	2.50	0.9	1.50	< 2	< 2	1.20	< 2	< 2	< 2	0.6	< 2	< 2	0.2	< 2
Cu	8.30	2.3	3.20	< 10	< 10	4.80	10	20	80	163.5	20	50	2.8	250
Pb	0.10	< .1	<0.1	< 5	< 5	0.20	< 5	< 5	< 5	0.2	< 5	< 5	0.2	12
Zn	24.00	7	8.00	< 30	< 30	17.00	< 30	< 30	40	157	< 30	< 30	16	150
Ni	47.90	9.4	10.30	40	< 20	13.70	150	110	130	53.3	250	120	30.1	90
As	< .5	< .5	< .5	< 5	< 5	< .5	< 5	< 5	< 5	< .5	< 5	< 5	< .5	< 5
Cd	0.10	< .1	<0.1	1	1.1	0.10	1.2	1.3	1.3	1.7	1.1	1.1	0.1	1.1
Sb	< .1	< .1	< .1	< 0.2	< 0.2	< .1	< 0.2	< 0.2	< 0.2	< .1	< 0.2	0.4	< .1	< 0.2
Cr	n.a.	n.a.	n.a.	< 20	< 20	n.a.	30	380	900	n.a.	680	440	n.a.	480

na means not analysed

* analysed at Acme Analytical Laboratories Ltd

** analysed at Activation laboratories Ltd

geochemical group (Group I isotropic gabbro and sheeted dike) displays a positive coherent trend, whereas the second geochemical group has lower Zr and TiO_2 contents and is comparable to North Tonga boninites (Figure 8b), although lacking the characteristic Zr enrichment of many Tertiary boninite suites such as IBM fore-arc boninites and Hunter Ridge boninites (Figure 8b). Differences in terms of V and Ti contents of the both geochemical group can also be observed in Figure 8c. The first geochemical group shows close similarity to IAT or back-arc basin

Table 4. Major and trace element contents of the sheeted dikes from the Kızıldağ (Hatay) ophiolite.

Sample	IAT-type sheeted dikes															Boninitic-type sheeted dikes											
	AK-15	K-5	K-11	K-13	K-14	K-30	KÇ-29	KÇ-31	KÇ-37	KÇ-47	KÇ-51	KÇ-52	T-11	Ü-8	Ü-9	K-4	K-7	K-9	K-12	K-25A	K-29	K-33	KÇ-22	KÇ-25	KÇ-43	KÇ-49	T-10
SiO$_2$	51.36	49.64	58.89	50.90	53.07	51.28	50.56	54.43	55.21	54.35	52.08	52.14	54.57	53.37	53.39	49.65	49.77	51.34	51.22	49.78	49.89	46.83	50.35	51.92	51.65	52.17	48.94
TiO$_2$	0.71	0.75	0.97	0.73	0.92	0.87	0.82	0.71	1.03	1.04	0.68	0.67	0.69	0.77	1.06	0.58	0.51	0.45	0.48	0.56	0.28	0.47	0.61	0.41	0.51	0.40	0.50
Al$_2$O$_3$	15.27	15.15	14.49	15.55	15.76	15.55	15.11	15.00	14.99	15.08	16.24	16.14	15.59	15.51	15.67	14.58	15.57	15.48	13.32	15.60	14.14	14.37	14.55	13.29	15.03	13.96	16.44
FeO*	8.78	10.26	10.80	9.62	8.67	11.25	10.58	7.85	9.73	11.53	9.08	9.02	10.09	6.37	10.85	9.05	7.90	8.47	9.18	9.45	6.35	7.79	8.26	7.86	7.39	7.85	4.29
MnO	0.15	0.17	0.16	0.16	0.14	0.14	0.17	0.14	0.08	0.09	0.16	0.18	0.12	0.09	0.16	0.20	0.13	0.11	0.23	0.17	0.14	0.12	0.14	0.16	0.08	0.14	0.10
MgO	7.53	7.18	3.88	9.60	7.21	7.56	7.02	8.00	6.62	5.29	7.62	7.70	6.84	6.35	5.40	10.51	8.77	8.76	12.65	9.45	10.85	8.79	9.41	10.38	10.10	11.01	10.97
CaO	9.14	5.26	4.90	7.29	6.76	4.38	8.12	7.22	4.24	7.17	9.77	10.09	7.83	9.06	5.91	6.82	9.21	11.24	5.22	12.83	15.66	16.16	9.46	9.48	8.52	9.74	10.94
Na$_2$O	2.64	5.50	3.93	2.03	4.58	5.29	4.46	4.21	4.88	2.83	2.56	2.61	2.11	2.08	4.25	3.65	3.29	2.07	2.61	1.64	1.09	1.24	3.74	3.65	1.93	1.16	2.55
K$_2$O	0.42	0.52	0.54	0.76	0.35	0.31	0.03	0.15	0.25	0.89	0.22	0.14	0.13	0.22	0.32	0.55	0.17	0.27	0.38	0.03	0.07	0.06	0.02	0.03	0.82	0.38	0.69
P$_2$O$_5$	0.06	0.06	0.07	0.06	0.06	0.06	0.06	0.05	0.07	0.07	0.06	0.05	0.06	0.06	0.08	0.05	0.04	0.03	0.04	0.04	0.02	0.04	0.05	0.03	0.04	0.03	0.02
LOI	3.80	5.18	1.41	3.17	2.14	2.96	2.92	2.15	2.69	1.54	1.49	1.28	2.37	6.43	3.18	4.31	4.07	1.25	4.91	0.17	1.56	4.30	2.97	2.95	3.52	3.13	4.86
Cr$_2$O$_3$	0.03	0.01	0.00	0.01	0.00	0.00	0.05	0.02	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.05	0.03	0.05	0.10	0.06	0.07	0.06	0.07	0.03	0.03	0.07	0.01
NiO	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.02	0.01	0.02	0.03	0.02	0.02	0.02	0.03	0.01	0.01	0.02	0.01
Total	99.90	99.68	100.04	99.89	99.67	99.64	99.88	99.94	99.81	99.87	99.99	100.04	100.42	100.32	100.27	100.02	99.46	99.54	100.35	99.80	100.13	100.24	99.65	100.19	99.62	100.04	100.33
Nb	3	4	4	3	4	4	4	4	6	4	2	2	4	1	4	3	2	2	5	1	1	2	3	4	2	2	1
Zr	38	37	44	34	40	38	37	35	47	47	34	29	33	40	50	26	24	23	22	20	14	23	31	19	21	19	18
Y	18	20	26	20	23	22	21	19	25	25	19	19	21	22	25	18	16	15	16	17	11	15	17	13	18	14	16
Sr	112	62	382	81	98	85	67	106	99	112	80	83	65	53	150	122	156	69	108	55	55	116	68	101	117	37	178
U	2	2	2	2	2	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	3	3	2	2	2
Rb	6	7	6	7	6	5	4	4	5	7	5	5	4	5	5	6	4	5	4	4	4	4	4	4	8	7	10
Th	3	3	2	3	3	4	2	3	4	4	4	3	2	3	4	3	3	2	3	3	2	2	3	4	3	3	3
Pb	10	7	12	10	9	11	9	9	9	11	10	10	12	6	11	9	8	9	12	9	8	12	10	10	10	11	4
Ga	14	13	16	15	14	18	18	13	16	18	14	16	16	14	17	14	14	14	12	15	13	11	13	11	12	11	11
Zn	42	114	57	85	65	38	63	50	24	26	31	24	56	40	38	113	101	47	126	58	89	140	63	57	22	30	35
Cu	9	26	8	106	15	24	41	10	3	8	7	9	13	5	5	84	8	11	77	50	142	41	70	5	6	4	6
Ni	69	42	13	53	30	26	93	68	28	18	65	53	46	40	17	119	81	91	203	113	112	99	187	78	68	105	64
Co	38	34	30	39	37	45	42	35	37	33	41	38	42	36	38	37	38	36	50	41	32	42	43	36	39	39	21
Cr	200	66	23	464	49	27	576	104	314	30	338	145	568	33	20	282	220	345	532	405	487	448	1495	288	616	359	54
V	263	295	321	296	367	351	364	269	399	380	271	284	308	286	307	260	261	240	269	229	196	231	225	250	256	230	203
Ce	9	18	7	15	12	13	18	7	14	13	13	11	8	11	12	3	8	7	9	11	14	14	12	15	6	6	14
Nd	6	8	4	7	6	7	9	4	7	6	6	6	5	6	7	4	6	4	4	6	10	8	5	9	4	4	9
Ba	37	78	58	50	58	47	11	48	33	17	29	33	28	27	48	71	43	64	55	9	17	40	25	26	49	37	29
La	7	5	7	7	7	8	4	6	5	7	8	6	6	7	6	9	8	7	5	5	4	10	4	6	4	4	4
S	55	3	3	3	3	3	22	3	3	3	3	3	3	3	3	55	3	14	3	9	375	30	72	3	3	3	7
Hf	1	2	3	3	5	2	2	4	4	5	1	1	3	1	3	6	1	1	1	1	4	1	4	1	3	1	1
Sc	41	54	40	65	55	75	55	44	70	52	47	47	60	31	46	56	48	41	69	35	41	36	43	55	46	44	34
As	3	3	3	3	4	3	3	3	3	5	4	4	3	3	4	3	3	4	5	4	3	4	3	3	3	3	3

Ftotal Fe is expressed as FeO*

Table 5. Trace element and REE compositions of the subset of the sheeted dike samples analysed by ICP-MS.

Sample	IAT - type sheeted dike							Boninitic-type sheeted dike							
	K-5**	K-13**	K-14*	KC-29*	KC-37*	KC-51*	U-8**	K-4**	K-12**	K-25A**	K-29**	K-33*	KC-22**	KC-25*	KC-49**
Ba	34	12	20.60	3	4.80	12.6	< 3	25	11	9	4	31.8	< 3	5.70	4
Co	24	24	32.00	37.9	33.00	36.1	30	29	35	34	25	36.8	29	37.90	27
Cs	0.1	< 0.1	< 0.1	< .1	< 0.1	< .1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< .1	< 0.1	< 0.1	< 0.1
Ga	12	14	15.30	20.2	16.70	15.4	13	12	12	13	10	11.4	12	9.80	11
Hf	1.1	1	1.20	1.4	1.40	1.1	1.1	0.8	0.6	0.6	0.3	0.6	0.8	0.50	0.5
Nb	0.9	0.6	1.00	2.4	3.00	1	1.1	0.7	0.9	0.4	< 0.2	0.6	0.9	1.40	0.6
Rb	4	3	1.90	< .5	1.10	< .5	1	2	< 1	< 1	< 1	< .5	< 1	0.70	2
Sn	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sr	58	76	107.00	82.8	108.70	88	50	111	111	54	54	127.9	71	118.10	35
Ta	0.05	0.03	< .1	0.1	0.20	< .1	0.11	0.05	0.06	0.05	< 0.01	< .1	0.05	< .1	0.03
Th	0.18	0.16	0.50	0.5	1.10	< .1	0.19	0.16	0.17	0.06	< 0.05	< .1	0.18	0.30	0.14
U	0.07	0.05	0.20	< .1	0.40	< .1	0.06	0.06	0.06	0.02	0.02	< .1	0.06	< .1	0.03
V	243	247	312.00	325	339.00	250	286	209	218	228	200	201	198	217.00	185
W	< 0.5	< 0.5	0.20	0.6	0.30	0.1	8.7	< 0.5	< 0.5	< 0.5	< 0.5	< .1	< 0.5	0.10	< 0.5
Zr	32	30	35.80	31.8	44.50	27.4	33	23	21	17	10	15.9	25	13.20	17
Y	18.7	17.2	23.70	23.9	26.80	19	21.1	15.2	13.8	15.4	8.4	13.9	15.1	10.70	11
La	1.3	1.34	1.70	2.6	3.90	1.2	1.86	1.06	1.02	0.75	0.31	0.8	1.41	1.00	0.59
Ce	3.72	3.75	4.70	5.4	7.70	3.6	5.28	2.84	2.42	2.18	0.93	2.1	3.56	2.00	1.5
Pr	0.65	0.65	0.82	0.79	1.02	0.57	0.84	0.49	0.38	0.41	0.18	0.36	0.57	0.27	0.26
Nd	3.94	3.99	4.70	4.7	5.90	3.7	4.96	3.08	2.27	2.73	1.17	2.4	3.43	1.70	1.64
Sm	1.41	1.4	1.80	1.6	2.10	1.4	1.8	1.15	0.82	1.11	0.49	0.9	1.28	0.70	0.64
Eu	0.583	0.585	0.76	0.76	0.74	0.61	0.799	0.483	0.399	0.521	0.252	0.49	0.567	0.23	0.292
Gd	2.3	2.16	2.66	2.67	2.99	2.22	2.65	1.81	1.47	1.84	0.9	1.72	1.91	1.00	1.17
Tb	0.45	0.42	0.55	0.6	0.63	0.41	0.52	0.36	0.29	0.37	0.19	0.34	0.36	0.26	0.24
Dy	3.02	2.82	3.65	3.51	4.12	2.72	3.43	2.49	2.01	2.54	1.35	2.18	2.46	1.58	1.64
Ho	0.66	0.62	0.75	0.83	0.88	0.61	0.75	0.55	0.46	0.56	0.3	0.5	0.54	0.36	0.37
Er	2.05	1.92	2.58	2.37	2.55	1.87	2.28	1.72	1.45	1.76	0.95	1.39	1.66	1.22	1.18
Tm	0.315	0.291	0.34	0.38	0.38	0.3	0.347	0.262	0.229	0.266	0.149	0.23	0.249	0.17	0.184
Yb	2	1.84	2.40	2.55	2.88	2.02	2.21	1.66	1.45	1.67	0.94	1.47	1.58	1.49	1.2
Lu	0.291	0.265	0.34	0.39	0.39	0.25	0.332	0.233	0.208	0.24	0.129	0.2	0.23	0.18	0.182
Mo	< 2	< 2	0.90	0.5	1.20	0.2	< 2	< 2	< 2	< 2	< 2	0.7	< 2	0.60	< 2
Cu	30	100	13.40	65.7	2.10	3.1	10	90	100	40	100	30.2	70	2.50	< 10
Pb	< 5	< 5	0.10	0.1	0.10	0.3	< 5	< 5	< 5	< 5	< 5	1.8	< 5	0.20	< 5
Zn	60	40	49.00	38	15.00	12	30	60	100	60	50	126	30	34.00	< 30
Ni	30	30	9.70	62.4	16.30	16.1	40	100	180	100	100	38.2	130	52.40	90
As	< 5	< 5	< .5	< .5	< .5	< .5	< 5	< 5	28	< 5	< 5	< .5	< 5	< .5	< 5
Cd	1.2	0.8	0.40	0.1	0.10	0.1	1.3	1.3	0.8	1.3	1.4	0.5	1.4	0.10	1.4
Sb	< 0.2	< 0.2	< .1	< .1	< .1	< .1	< 0.2	0.5	1.2	< 0.2	< 0.2	1.7	< 0.2	< .1	< 0.2
Bi	< 0.1	< 0.1	< .1	< .1	< .1	< .1	< 0.1	< 0.1	0.2	< 0.1	< 0.1	< .1	< 0.1	< .1	< 0.1
Ag	< 0.5	< 0.5	< .1	< .1	< .1	< .1	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< .1	< 0.5	< .1	< 0.5
Cr	30	70	n.a.	n.a.	n.a.	n.a.	20	230	510	320	360	n.a.	340	n.a.	340

na means not analysed
* analysed at Acme Analytical Laboratories Ltd
** analysed at Activation laboratories Ltd

basalt (BABB), whereas the second geochemical group has very low Ti contents and overlaps with the boninite field (Figure 8c).

The chondrite normalized REE and N-MORB normalized spider diagrams for the first geochemical group (Group I isotropic gabbros and sheeted dikes) are presented in Figure 9. The REE concentrations vary from 3.12 to 20.05 X chondritic for isotropic gabbros and from 5.06 to 16.94 X chondritic for sheeted dikes. They have slightly LREE-depleted patterns (La_N/Yb_N= 0.41 to 0.71 for isotropic gabbros and La_N/Yb_N= 0.43 to 0.97) for sheeted dikes (Figure 9a, c). The spider diagrams of the first geochemical group exhibits such features as (a) enrichment in LIL (i.e. Cs, Rb, Ba, Th, K) elements, (b) positive Sr anomaly, (c) negative Nb and Ta anomalies and (d) flat and slightly depleted patterns of HFS elements relative to N-MORB (Figure 9b, d). Within the LIL element group Th is a relatively stable and reliable indicator, and

Table 6. Major and trace element contents of the sakalavites from the Kızıldağ (Hatay) ophiolite.

	Hyaloclastites									Pillows								
Sample	SKL 1	SKL 4	SKL 6	SKL 9	SKL 11	SKL 12	SKL 13	SKL 15	SKL 17	SKL 2	SKL 3	SKL 5	SKL 7	SKL 8	SKL 10	SKL 14	SKL 16	SKL 18
SiO_2	49.51	49.96	48.76	48.71	53.11	49.33	47.53	49.67	48.51	50.78	51.10	51.26	51.53	50.35	51.38	51.09	50.47	51.46
TiO_2	0.33	0.34	0.34	0.34	0.29	0.32	0.31	0.32	0.33	0.36	0.34	0.35	0.37	0.34	0.35	0.35	0.34	0.34
Al_2O_3	13.46	13.29	13.39	13.35	12.78	13.01	12.49	13.06	13.00	14.15	14.02	14.05	14.28	13.85	14.10	14.26	13.98	14.05
FeO^*	8.01	8.01	8.02	7.75	8.60	7.71	7.76	8.10	7.72	8.36	8.55	8.53	8.43	8.19	8.64	8.59	8.58	8.18
MnO	0.18	0.18	0.17	0.17	0.16	0.15	0.17	0.15	0.17	0.16	0.19	0.16	0.16	0.17	0.19	0.15	0.19	0.16
MgO	8.96	9.00	8.70	8.48	9.74	8.63	8.85	8.69	8.96	9.25	9.02	9.53	8.92	9.17	9.52	9.83	9.59	8.76
CaO	7.75	7.69	7.72	7.93	10.07	8.12	13.67	8.66	6.90	10.71	10.71	10.72	10.89	11.37	10.16	10.84	11.15	11.24
Na_2O	1.10	1.57	1.53	1.41	1.09	0.75	0.72	0.76	0.55	1.57	1.17	1.24	1.16	1.20	1.43	0.92	0.91	1.00
K_2O	0.32	0.24	0.29	0.26	0.55	0.30	0.30	0.25	0.27	0.24	0.18	0.19	0.15	0.18	0.26	0.21	0.30	0.14
P_2O_5	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.03
LOI	10.13	9.25	10.81	11.19	3.26	11.35	8.19	9.70	13.38	3.95	4.39	3.67	3.80	4.72	3.79	3.56	4.28	4.26
Cr_2O_3	0.08	0.08	0.08	0.08	0.13	0.09	0.08	0.09	0.10	0.09	0.10	0.09	0.09	0.08	0.10	0.08	0.09	0.10
NiO	0.04	0.03	0.04	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Toplam	99.88	99.66	99.87	99.71	99.84	99.81	100.12	99.51	99.95	99.66	99.81	99.85	99.83	99.69	99.97	99.93	99.94	99.76
Nb	4	4	4	4	4	4	2	5	4	2	3	2	3	3	3	3	3	4
Zr	18	18	18	18	15	18	18	19	18	19	18	19	20	19	17	19	17	20
Y	12	12	13	12	12	12	13	12	23	13	13	13	13	13	13	17	13	14
Sr	87	78	81	78	34	82	85	67	66	75	57	51	43	62	72	40	70	42
U	2	2	2	2	3	2	3	2	2	2	2	2	2	2	2	2	3	2
Rb	9	8	8	8	10	10	10	10	10	8	7	7	7	7	7	7	8	7
Th	3	4	2	3	3	3	4	3	3	3	3	4	4	3	3	3	4	2
Pb	11	12	13	10	12	12	9	12	10	12	11	12	11	11	12	13	12	10
Ga	12	12	11	11	10	11	11	11	11	11	11	12	13	11	12	13	12	12
Zn	62	60	81	62	63	58	53	58	58	62	64	65	65	60	65	64	66	61
Cu	87	85	90	90	33	88	97	93	88	92	101	97	106	91	98	94	103	107
Ni	224	207	235	210	232	202	166	184	230	176	202	215	181	203	215	215	200	175
Co	40	42	43	43	44	43	44	46	47	45	46	45	39	44	45	47	45	42
Cr	638	492	536	472	890	539	497	516	510	460	609	596	612	490	567	399	532	671
V	213	218	233	227	272	205	172	207	204	219	241	223	240	224	248	217	232	230
Ce	9	8	6	9	10	15	15	5	11	8	7	8	4	11	12	11	9	12
Nd	5	4	4	4	6	10	11	4	6	4	4	4	4	6	7	7	4	8
Ba	56	62	66	75	48	61	39	57	76	43	41	43	39	51	57	37	49	45
La	7	4	4	4	6	5	4	4	6	4	7	7	4	4	6	4	7	5
S	75	8	27	13	3	20	124	53	3	51	114	127	209	96	61	3	76	223
Hf	1	3	1	1	1	1	1	2	2	3	1	1	1	1	4	2	2	1
Sc	61	53	54	52	60	56	25	53	64	39	44	37	43	36	43	38	39	45
As	3	3	3	5	4	4	4	3	3	3	3	3	3	3	5	3	3	3

Total Fe is expressed as FeO

Table 7. Trace element and REE compositions of the subset of the sakalavite samples analysed by ICP-MS.

| Sample | Hyaloclastites | | Pillows | | | |
	SKL-1*	SKL-6*	SKL-3*	SKL-8*	SKL-10*	SKL-16*
Ba	20.60	26.4	21.9	19.1	28.30	21.30
Co	35.20	39.5	41.8	40.5	39.20	39.60
Cs	0.10	0.2	0.2	0.1	0.20	0.10
Ga	10.10	11.4	12.4	11.9	10.80	11.50
Hf	0.60	0.6	0.5	0.6	< 0.5	< 0.5
Nb	0.90	1.2	1	1.1	0.80	0.90
Rb	5.80	4.5	3.6	3.7	4.30	4.00
Sn	< 1	< 1	1	2	< 1	< 1
Sr	86.40	86.5	53.9	67.9	76.70	76.80
Ta	< .1	< .1	< .1	< .1	< .1	< .1
Th	< .1	< .1	0.1	0.1	0.10	< .1
U	< .1	< .1	< .1	< .1	< .1	< .1
V	177	212	242	226	230	224
W	< .1	0.2	0.2	0.2	0.10	0.10
Zr	10.40	13	10.9	11.4	10.20	9.90
Y	9.40	10.9	11.3	11.7	12.40	12.00
La	0.60	0.7	0.7	0.7	0.70	0.60
Ce	1.10	1.3	1.2	1.3	1.40	1.20
Pr	0.18	0.24	0.22	0.24	0.18	0.20
Nd	1.30	1.1	1.1	0.9	0.80	1.10
Sm	0.50	0.6	0.7	0.6	0.60	0.60
Eu	0.25	0.26	0.24	0.26	0.28	0.28
Gd	0.90	1.06	0.96	1.13	1.02	1.13
Tb	0.18	0.23	0.28	0.26	0.27	0.28
Dy	1.50	1.43	1.51	1.59	1.82	1.70
Ho	0.32	0.37	0.38	0.37	0.40	0.40
Er	0.94	1.04	1.1	1.24	1.30	1.20
Tm	0.14	0.18	0.21	0.2	0.19	0.20
Yb	1.08	1.23	1.3	1.46	1.46	1.30
Lu	0.15	0.19	0.23	0.19	0.22	0.19
Mo	0.50	1.3	2.3	0.8	0.80	0.60
Cu	55.70	62.3	40.5	45.1	61.50	65.30
Pb	0.40	6.2	0.3	0.4	0.80	0.50
Zn	35.00	90	18	18	24.00	29.00
Ni	180.10	170.4	134.6	144.7	141.60	149.30
As	< .5	0.8	< .5	< .5	< .5	< .5
Cd	0.10	0.2	< .1	0.1	0.10	0.10
Sb	< .1	2.2	< .1	< .1	< .1	0.10

* analysed at Acme Analytical Laboratories Ltd

its enrichment relative to other incompatible elements is taken to record the subduction zone component (Wood *et al.* 1979; Pearce 1983). Likewise, the negative Nb anomaly may indicate a subduction-related tectonic setting for the first geochemical group (Arculus & Powell 1986; Yogodzinski *et al.* 1993; Wallin & Metcalf 1998). The second geochemical group (Group II isotropic gabbros, sheeted dikes and sakalavites), however, differs

Figure 6. (a) Ti/Y vs Nb/Y (after Pearce 1982) and (b) Zr/Ti vs Nb/Y (after Pearce 1996) diagrams for the crustal rocks of the Kızıldağ (Hatay) ophiolite.

compositionally very similar to boninitic magmas found in the fore-arc regions of oceanic island arcs (Crawford *et al*. 1989; Falloon & Crawford 1991).

The Th/Yb versus Ta/Yb plot is included in the MORB-OIB array and thus discriminates between depleted mantle (MORB) and enriched mantle (intraplate) sources (Pearce 1982) (Figure 11). For subduction-related magmatic rocks, addition of a subduction chemical component by slab-derived fluids/melts results in an increase in Th/Yb in the mantle source as shown by the arrow in Figure 11. The data from the selected samples of the isotropic gabbros and sheeted dikes is consistent with derivation for a MORB-type depleted mantle source enriched by subduction zone fluids (Figure 11).

Petrogenesis

The first geochemical group (Group I isotropic gabbros, sheeted dikes) in the Kızıldağ (Hatay) ophiolite displays strong depletion of Nb (Ta) and enrichment of LIL elements. These rocks also exhibit parallel to slightly depleted HFS element patterns compared to N-MORB. Their negative Nb (Ta) and positive Th anomalies clearly indicate a suprasubduction zone tectonic environment. Similar flat to slightly LREE-depleted patterns have been found in island arc tholeiitic series, namely in Papua New Guinea, the Solomon Islands, Macquarie Island (Jakes & Gill 1970), and suprasubduction zone-type ophiolites of the eastern Mediterranean region (Alabaster *et al*. 1982; Meffre *et al*. 1996; Parlak 1996; Yalınız *et al*. 1996; Parlak *et al*. 2000; Al-Riyami *et al*. 2002; Beccaluva *et al*. 2004, 2005; Pe-Piper *et al*. 2004; Saccani & Photiades 2005; Rızaoğlu *et al*. 2006; Bağcı & Parlak 2007).

Experimental studies on boninite petrogenesis indicate that this magma type is generated from either a clinopyroxene-poor lherzolite or, more commonly, a harzburgite source at low pressures, probably less than 10 kbar for realistic H_2O contents in this magma (< 5 %) (Green 1976; Tatsumi 1982; Cawthorn & Davies 1983; Jenner 1983). A depleted or refractory magma source for the boninites is indicated by their low TiO_2 contents, which result in high CaO/TiO_2 and Al_2O_3/TiO_2 values and low Ti/V and Ti/Sc values (Crawford *et al*. 1989 and references therein). Based on the definition of Crawford *et al*. (1989), boninites are divided into two classes, low-Ca and high-Ca suites. The second geochemical group (Group II isotropic gabbros, sheeted dikes and

from the first geochemical group in both REE profiles and multi-element patterns (Figure 10). The REE concentrations vary from 0.71 to 8.27 X chondritic for isotropic gabbros, from 1.31 to 10.63 X chondritic for sheeted dikes and from 1.71 to 9.06 X chondritic for sakalavites. They exhibit spoon-shaped REE patterns typical of boninites (Figure 10), with La_N/Sm_N and Sm_N/Yb_N ratios ranging from 0.29 to 0.92 and from 0.46 to 0.90, respectively. The N-MORB normalized multi-element diagrams of the second geochemical group indicate that they are generally depleted in HFS and enriched in some of LIL elements (Cs, Rb, Ba, K) (Figure 10b, d, f). The REE and multi-element patterns indicate that the second geochemical group (Group II isotropic gabbros, sheeted dikes and sakalavites) are

Figure 7. Variations of selected major and trace element contents of the crustal rocks of the Kızıldağ (Hatay) ophiolite.

sakalavites) are basaltic in composition and have silica contents between 46.09 and 52.17 wt%. Their CaO/Al$_2$O$_3$ ratios and FeO contents vary from 0.39 to 1.12 and from 4.29 to 9.6 wt%, respectively. The total alkali contents are between 0.41 and 4.19 wt%. The

major element geochemistry of the second geochemical group (Group II isotropic gabbros, sheeted dikes and sakalavites) from the Kızıldağ (Hatay) ophiolite are very similar to high-Ca boninites and very comparable with the Upper Pillow Lava unit of the Troodos ophiolite
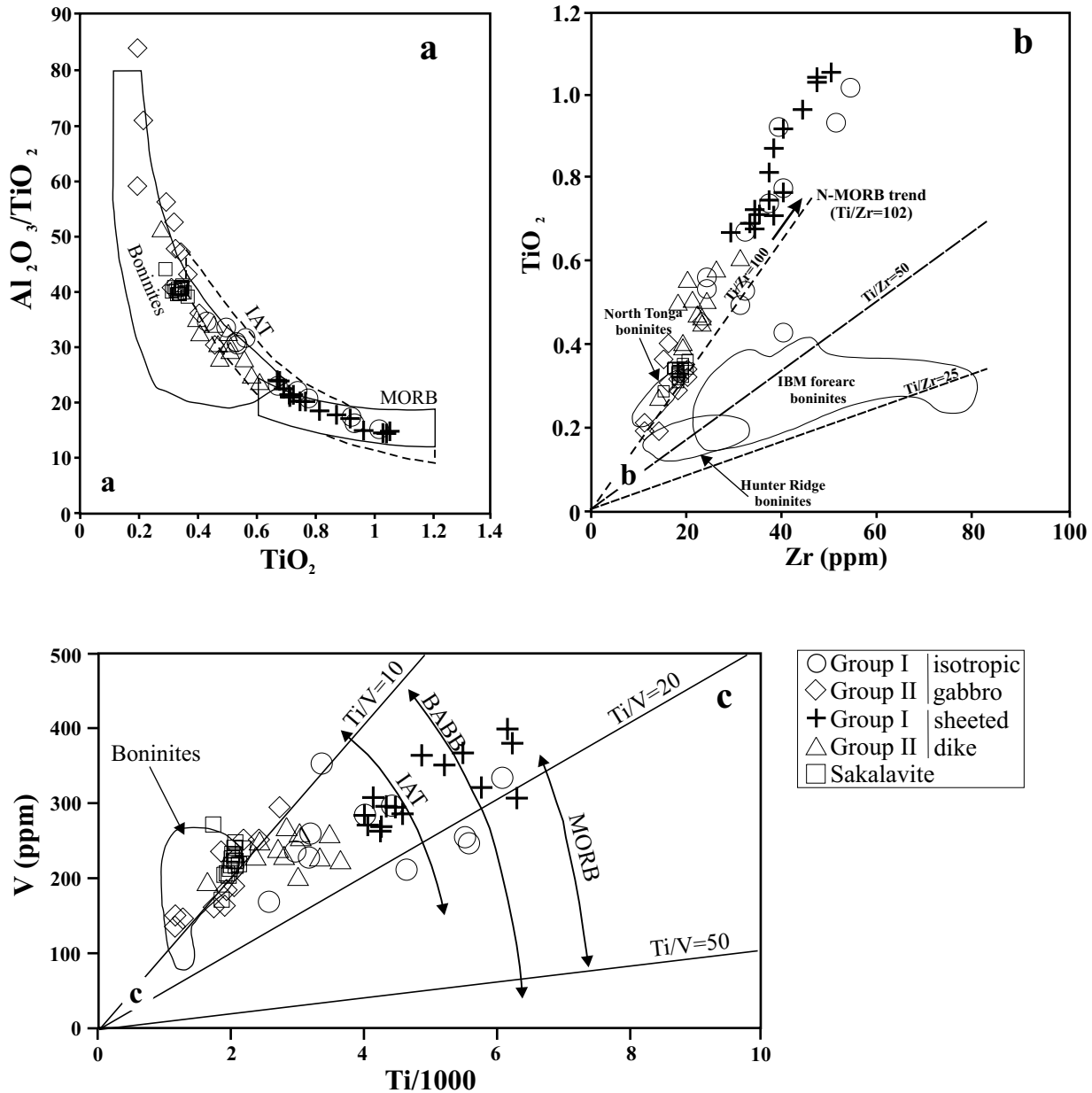
Figure 8. (a) Al_2O_3/TiO_2 vs TiO_2, (b) Zr vs TiO_2, and (c) V vs Ti variations for the crustal rocks of the Kızıldağ (Hatay) ophiolite. Data for Boninites, MORB and IAT from Hickey & Frey (1982); Crawford (1989). Ranges of Ti/V ratios for IAT, BAB and MORB from Shervais (1982). North Tonga from Falloon & Crawford (1991), IBM fore-arc from Arculus *et al.* (1992) and Wood *et al.* (1982), Hunter Ridge from Meffre *et al.* (1996).

(Crawford *et al.* 1989), as well as typical boninitic rocks from various ophiolitic complexes (Beccaluva *et al.* 1984, 2005; Malpas & Langdon 1984; Beccaluva & Serri 1988; Smellie *et al.* 1995; Meffre *et al.* 1996; Bedard *et al.* 1998; Bedard 1999; Pearce 2003; Pe-Piper *et al.* 2004; Saccani & Photiades 2004, 2005; Parlak 2006; Bağcı & Parlak 2007).

A Cr versus Y diagram for estimating the composition of mantle sources, and the degree of partial melting that generates different magma types (Pearce 1983) also plots the trend of N-MORB for comparison. On this diagram the studied rocks were clearly derived from an already-depleted lherzolitic to harzburgitic mantle composition (Figure 12). The first and second magma
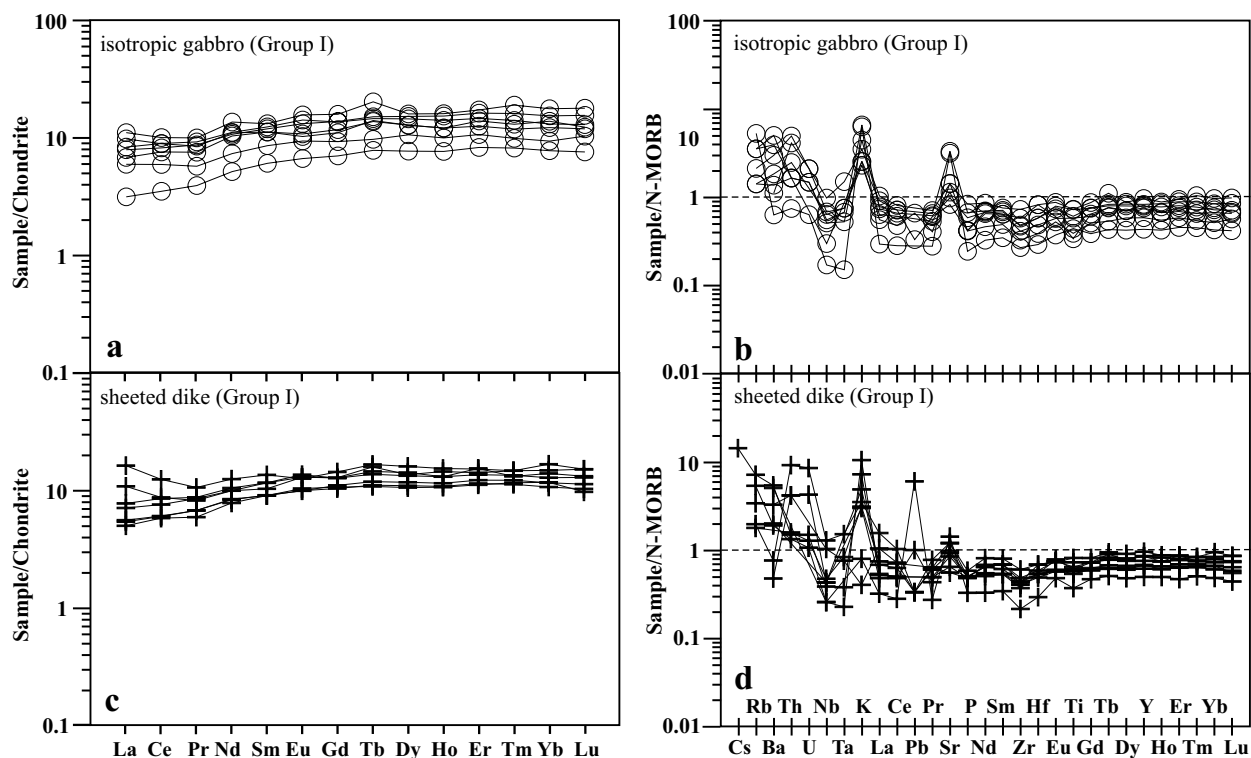
Figure 9. Chondrite-normalized REE (a, c) and N-MORB normalized spider diagrams (b, d) for the isotropic gabbroic and sheeted dike rocks from the Kızıldağ (Hatay) ophiolite (normalizing values are from Sun & McDonough 1989).

series (IAT and boninite) from the Kızıldağ (Hatay) ophiolite are plotted in Figure 12. The first geochemical group (Group I isotropic gabbros and sheeted dikes) have relatively higher REE contents, thus representing magmas generated from the less depleted mantle sources. These rocks may have been derived from approximately 12–17% partial melting from a mantle source that experienced previous MORB melt extraction at about 20% (M2) (Figure 12). In contrast, the second geochemical group (Group II isotropic gabbros, sheeted dikes and sakalavites) have progressively lower REE contents, which may result from the higher degrees of partial melting of same refractory mantle sources. Thus, this geochemical group may have been derived from approximately 17–25% partial melting of a M2 source (Figure 12).

Discussion and Conclusion

The south Neotethyan ophiolites formed around 90 Ma (Mukasa & Ludden 1987) in a suprasubduction zone

setting (Lytwyn & Casey 1993; Dilek & Thy 1998; Robertson 1986a, b, 2002; Parlak *et al.* 2004; Bağcı *et al.* 2005; Parlak 2006; Rızaoğlu *et al.* 2006). The southern branch of Neotethys comprises well-documented ophiolites such as the Tekirova (Antalya), Kızıldağ (Hatay), Göksun (Kahramanmaraş), İspendere (Malatya), Kömürhan-Guleman (Elazığ) in Turkey (Parlak *et al.* 2004; Bağcı *et al.* 2005; Rızaoğlu *et al.* 2006), the Troodos in Cyprus (Robertson 1998, 2000; Dilek & Flower 2003) and Baer-Bassit in Syria (Al-Riyami *et al.* 2002).

Modern boninites are mainly restricted to fore-arc environments (Cameron *et al.* 1979; Meijer *et al.* 1980; Hawkins *et al.* 1984; Murton 1989; Stern & Bloomer 1992). Rare examples of boninites have also been reported from the Lau back-arc basin (Falloon *et al.* 1992). Fore-arc regions in modern environments are characterized by significant extensional tectonism due to true seafloor-spreading (Meijer 1980; Bloomer & Hawkins 1983; Stern & Bloomer 1992; Taylor & Nesbitt 1994; Wessel *et al.* 1994). Boninitic lavas and intrusions
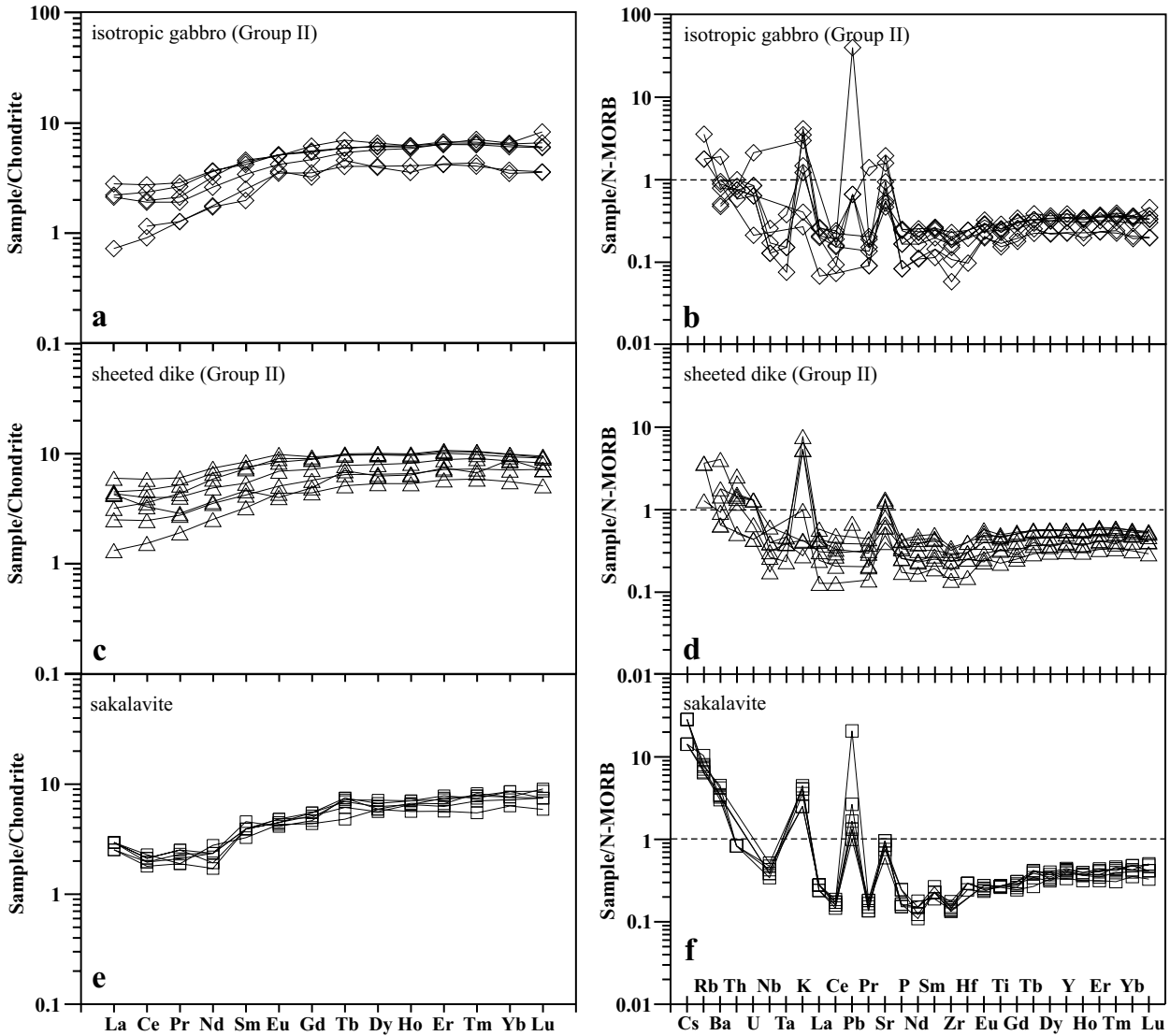
Figure 10. Chondrite-normalized REE (a, c, e) and N-MORB normalized spider diagrams (b, d, f) for the isotropic gabbros, sheeted dikes and sakalavites from the Kızıldağ (Hatay) ophiolite (normalizing values are from Sun & McDonough 1989).

have been reported from many ophiolite complexes (Bedard *et al.* 1998 and references therein).

Due to opening of the South Atlantic ocean at the end of the Early Cretaceous the southern branch of the Neotethyan ocean between the Eurasian and African plates started to close (Livermore & Smith 1984; Savostin *et al.* 1986; Dilek *et al.* 1990, 1999). Northward subduction occurred in the southern Neotethyan oceanic basin as a result of this convergent regime. Subduction-related ophiolites in the southern Neotethyan oceanic basin formed above this north-

dipping subduction zone (Dilek *et al.* 1999; Beyarslan & Bingöl 2000; Al-Riyami *et al.* 2002; Parlak *et al.* 2004; Bağcı *et al.* 2005, 2006; Rızaoğlu *et al.* 2006). These are, from west to east, Tekirova (Antalya), Troodos (Cyprus), Kızıldağ (Hatay), Baer-Bassit (Syria), Göksun (Kahramanmaraş), İspendere (Malatya), Kömürhan and Guleman (Elazığ).

The Kızıldağ ophiolite displays structural evidence for seafloor-spreading tectonics and associated structural, magmatic and hydrothermal processes (Erendil 1984; Robertson 1986a, b; Tekeli & Erendil 1986; Pişkin *et al.*
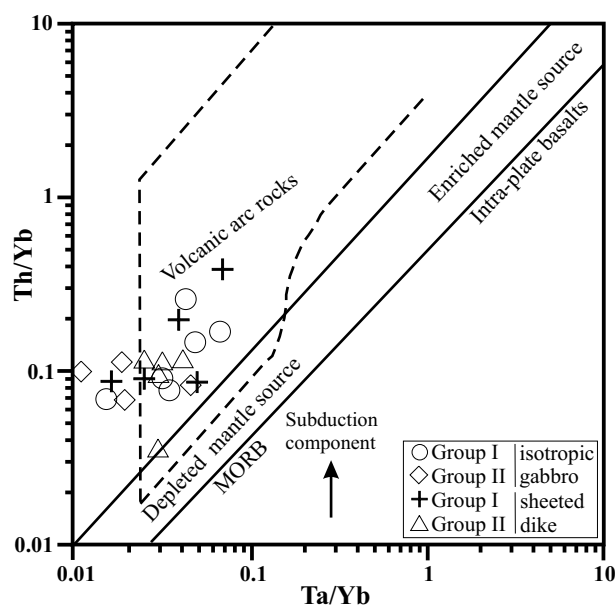
Figure 11. Ta/Yb vs Th/Yb diagram (after Pearce 1982) for the crustal rocks of the Kızıldağ (Hatay) ophiolite.

1990; Dilek *et al.* 1991; Dilek & Delaloye 1992; Dilek & Eddy 1992; Lytwyn & Casey 1993; Dilek & Thy 1998). Bağcı *et al.* (2005) presented detailed mineral chemistry data on the cumulate rocks of the Kızıldağ (Hatay) ophiolite and suggested its formation in a suprasubduction zone setting. New geochemical data presented in this paper from the isotropic gabbros, sheeted dikes and the volcanics (sakalavites) of the Kızıldağ (Hatay) ophiolite suggest that two main types of basic magmas formed the oceanic crust in the Late Cretaceous. These are (i) IAT series which can be referred to the Group I isotropic gabbros and sheeted dikes; (ii) Low-Ti boninitic series characterized by the Group II isotropic gabbros, sheeted dikes and sakalavites. The spatial and temporal relations of the boninitic magmatism relative to associated arc tholeiites in the Kızıldağ (Hatay) ophiolite is well constrained in this study. Tables 8 to 10 summarize the localities, geochemical affinities and spatial and temporal relations of the isotropic gabbros, sheeted dykes and sakalavites from the Kızıldağ ophiolite. In the Çevlik (Güvercinkayası burnu) region, the IAT-type sheeted dykes (K-11) were cut by plagiogranite which was in turn intruded by the boninitic-type sheeted dykes (K-9 and K-12) (Figure 13a, b). In the Karaçay valley, the boninitic-type dyke (KC-22) intruded the cumulate gabbro (Figure 13c) and in the same valley the boninitic
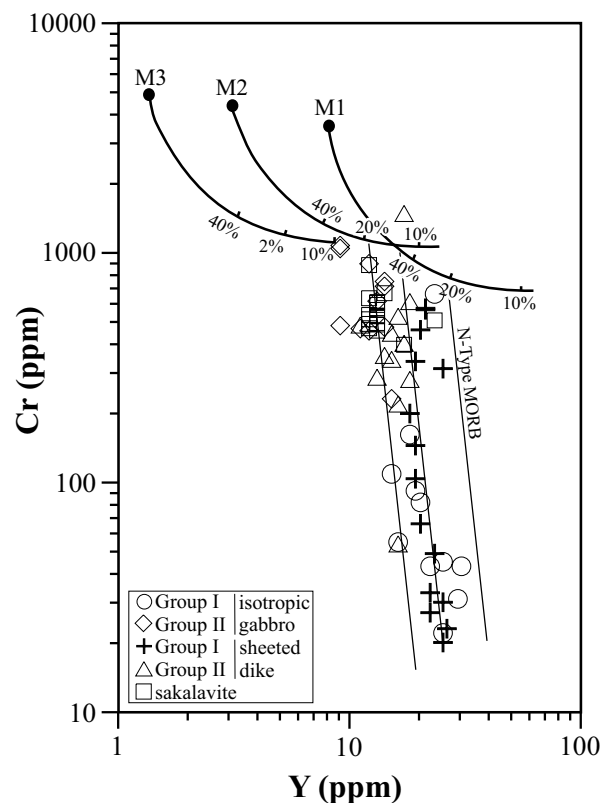
Figure 12. Cr vs Y diagram for the isotropic gabbros, sheeted dikes and sakalavites from the Kızıldağ (Hatay) ophiolite. Mantle source compositions and melting paths for incremental batch melting are from Murton (1989). M1– calculated mid-ocean ridge basalt (MORB) source; M2– residue after 20% MORB extraction; M3– residue after 12% melt extraction from M2.

type isotropic gabbro (KC-28) was cut by the IAT-type dyke (KC-29) (Figure 13d). Apart from these, there is plenty of field and geochemical evidence from different localities suggesting that IAT- and boninitic-type magmatism were contemporaneously active in forming the different parts of the crustal units of the Kızıldağ ophiolite in a fore-arc tectonic setting in the southern Neotethys ocean during the late Cretaceous (Tables 8 to 10).

In the Mariana fore-arc region, boninites overlie arc tholeiites (Wood *et al.* 1981; Hickey & Frey 1982). In Guam, arc tholeiites cap boninites (Reagan & Meijer 1984). In the Cape Vogel area, two boninite series of Paleocene age overlie island arc tholeiites (Jenner 1981; Walker & Cameron 1983). In the Troodos ophiolite, boninite magmatism (Upper Pillow Lava) occurred both contemporaneously and after emplacement of island arc

63
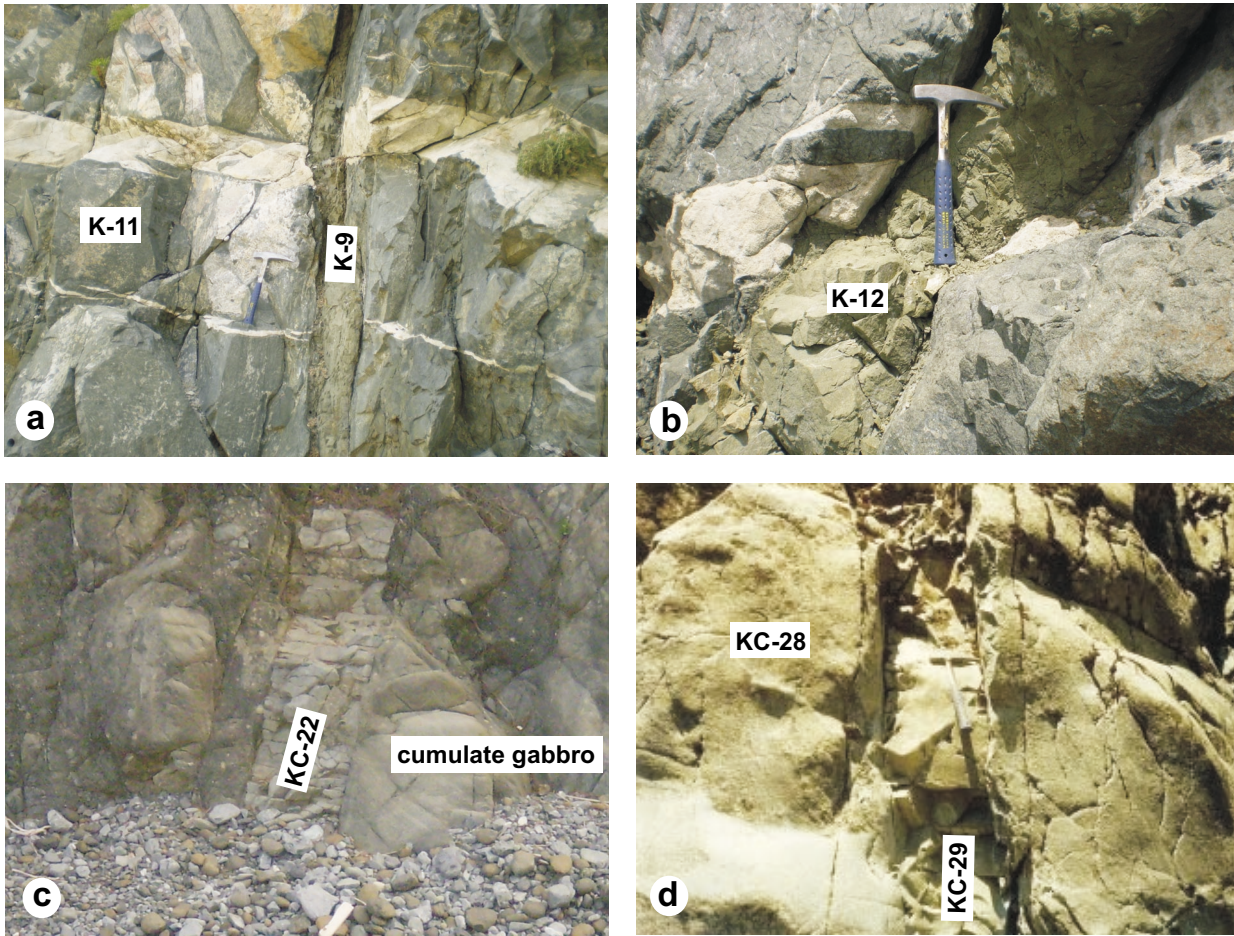
Figure 13. Cross-cutting relations between (a, b) plagiogranite and sheeted dykes, (c) dykes and cumulate gabbro, and (d) dyke and isotropic gabbro from the Kızıldağ (Hatay) ophiolite. Hammer is 33 cm long.

tholeiites (Lower Pillow Lava: Robinson *et al.* 1983; Beccaluva & Serri 1988). This situation seems to be site specific and indicates that distinctly different magma sources were contemporaneously active in a relatively restricted sector across an intraoceanic suprasubduction region. Boninites generally form early in the arc history but are often coincident with and/or follow generation of arc tholeiites (Lytwyn & Casey 1993). This may indicate progressive source depletion from island arc tholeiites to boninites with time.

In conclusion, new geological and geochemical data suggest that (i) the crustal units of the Kızıldağ (Hatay) ophiolite were fed by IAT and boninitic-type magmas and (ii) spatial and temporal relations suggest that these magmas were contemporaneously active in a fore-arc tectonic setting in the southern Neotethys ocean during the Late Cretaceous.

Table 8. Summary table for the isotropic gabbros.

Sample No	Rock type	Longitude/Latitude	Locality	Geochemical character	Spatial and temporal relations
K-6	Gabbro	35° 54′ 45,5″ E / 36° 07′ 58,9″ N	Çevlik, 25 m north of Güvercinkayası burnu	IAT type	Cut by boninitic dyke (K-7)
KÇ-30	Gabbro	35° 58′ 52,2″ E / 36° 11′ 36,7″ N	Karaçay valley	IAT type	
KÇ-34	Quartz diorite	35° 58′ 52,2″ E / 36° 11′ 36,7″ N	Karaçay valley	IAT type	
KÇ-35	Quartz diorite	35° 58′ 52,2″ E / 36° 11′ 36,7″ N	Karaçay valley	IAT type	
KÇ-36	Diorite	35° 58′ 51,3″ E / 36° 11′ 40,0″ N	Karaçay valley	IAT type	Cut by IAT-type dyke (KC-37)
KÇ-39	Quartz diorite	35° 58′ 43,6″ E / 36° 11′ 48,3″ N	Karaçay valley	IAT type	
KÇ-41	Diorite	35° 58′ 37,8″ E / 36° 11′ 53,3″ N	Karaçay valley	IAT type	
KÇ-46	Quartz diorite	35° 58′ 47,2″ E / 36° 11′ 57,9″ N	Karaçay valley	IAT type	Cut by IAT-type dyke (KC-47)
T-6	Diorite	35° 54′ 37,0″ E / 36° 12′ 30,9″ N	Tazı yurdu (Bakacak Tepe)	IAT type	
U-6	Diorite	35° 43′ 51,9″ E / 36° 18′ 56,8″ N	Üçgedik	IAT type	
U-7	Diorite	35° 43′ 52,9″ E / 36° 18′ 55,9″ N	Üçgedik	IAT type	Cut by IAT-type dyke (U-8)
K-8	Gabbro	35° 54′ 21,4″ E / 36° 8′ 37,7″ N	Çevlik, Karmuşun kayası	Boninitic-type	
K-27	Gabbro	35° 52′ 41,9″ E / 36° 10′ 41,7″ N	Çevlik, Ambardere	Boninitic-type	
K-28	Diorite	35° 52′ 51,2″ E / 36° 10′ 22,9″ N	Çevlik, Hırlavuk burnu	Boninitic-type	
KÇ-28	Gabbro	35° 58′ 52,9″ E / 36° 11′ 32,2″ N	Karaçay valley	Boninitic-type	Cut by IAT-type dyke (KC-29)
KÇ-32	Diorite	35° 58′ 52,2″ E / 36° 11′ 36,7″ N	Karaçay valley	Boninitic-type	
KÇ-33	Gabbro	35° 58′ 52,2″ E / 36° 11′ 36,7″ N	Karaçay valley	Boninitic-type	
KÇ-38	Diorite	35° 58′ 46,7″ E / 36° 11′ 44,9″ N	Karaçay valley	Boninitic-type	
KÇ-40	Gabbro	35° 58′ 39,7″ E / 36° 11′ 51,6″ N	Karaçay valley	Boninitic-type	
KÇ-44	Gabbro	35° 58′ 26,9″ E / 36° 11′ 57,6″ N	Karaçay valley	Boninitic-type	
KÇ-45	Gabbro	35° 58′ 26,9″ E / 36° 11′ 57,6″ N	Karaçay valley	Boninitic-type	
KÇ-48	Diorite	35° 58′ 21,1″ E / 36° 12′ 3,5″ N	Karaçay valley	Boninitic-type	Cut by boninitic dyke (KC-49)

Table 9. Summary table for the sheeted dykes.

Sample No	Rock type	Longitude/Latitude	Locality	Geochemical character	Spatial and temporal relations
AK-15	Diabase	35° 58' 26,9' E / 36° 11' 57,6" N	Aydınlı	IAT type	
K-5	Diabase	35° 54' 50,8' E / 36° 7' 54,8' N	Çevlik	IAT type	
K-11	Diabase	35° 54' 45,6' E / 36° 7' 48,4' N	Güvercinkayası burnu	IAT type	Cut by plagiogranite
K-13	Diabase	35° 54' 1,8' E / 36° 9' 16,3' N	Değirmendere (Çevlik)	IAT type	
K-14	Diabase	35° 53' 49,4' E / 36° 9' 32,0' N	Çevlik	IAT type	
K-30	Diabase	35° 53' 23,4' E / 36° 10' 0,2' N	Çevlik	IAT type	
KÇ-29	Diabase	35° 58' 53,0' E / 36° 11' 32,2' N	Karaçay	IAT type	Cutting the boninitic type isotropic gabbro (KC-28)
KÇ-31	Diabase	35° 58' 52,2' E / 36° 11' 36,7' N	Karaçay valley	IAT type	
KÇ-37	Diabase	35° 58' 51,3' E / 36° 11' 40,0' N	Karaçay valley	IAT type	Cutting the IAT-type isotropic gabbro (KC-36)
KÇ-47	Diabase	35° 58' 24,0' E / 36° 11' 58,5' N	Karaçay valley	IAT type	
KÇ-51	Diabase	35° 58' 21,1' E / 36° 12' 3,5' N	Karaçay valley	IAT type	Cut by IAT-type dyke (KÇ-52)
KÇ-52	Diabase	35° 58' 21,1" E / 36° 12' 3,5' N	Karaçay valley	IAT type	Cutting the IAT-type dyke (KÇ-51)
T-11	Diabase	35° 55' 58,9' E / 36° 11' 32,1" N	Tazı yurdu	IAT type	
U-8	Quartz microdiorite	35° 43' 52,9' E / 36° 18' 55,9' N	Üçgedik	IAT type	Cutting the IAT-type isotropic gabbro (U-7)
U-9	Diabase	35° 43' 54,8' E / 36° 18' 52,6' N	Üçgedik	IAT type	
K-4	Diabase	35° 54' 50,8' E / 36° 7' 54,8' N	Çevlik	Boninitic-type	Cutting the IAT type isotropic gabbro (K-6)
K-7	Diabase	35° 54' 43,3' E / 36° 8' 8,7' N	Çevlik	Boninitic-type	
K-9	Diabase	35° 54' 45,6' E / 36° 7' 48,4' N	Çevlik, Güvercinkayası burnu	Boninitic-type	Cutting the plagiogranite
K-12	Diabase	35° 54' 45,6' E / 36° 7' 48,4' N	Çevlik, Güvercinkayası burnu	Boninitic-type	Cutting the plagiogranite
K-25A	Diabase	35° 52' 28,3' E / 36° 10' 51,8' N	Çevlik, Şahanlıkkayası burnu	Boninitic-type	
K-29	Diabase	35° 53' 4,3' E / 36° 10' 51,7' N	Çevlik	Boninitic-type	
K-33	Diabase	35° 52' 28,3' E / 36° 10' 51,8' N	Çevlik	Boninitic-type	
KÇ-22	Diabase	35° 59' 7,9' E / 36° 11' 29,0' N	Karaçay valley	Boninitic-type	Cutting the mafic cumulates
KÇ-25	Diabase	35° 59' 5,8' E / 36° 11' 29,1' N	Karaçay valley	Boninitic-type	Cutting the mafic cumulates
KÇ-43	Diabase	35° 58' 30,9' E / 36° 11' 56,7' N	Karaçay valley	Boninitic-type	
KÇ-49	Diabase	35° 58' 21,1" E / 36° 12' 3,5' N	Karaçay valley	Boninitic-type	Cutting the boninitic type isotropic gabbro (KC-48)
T-10	Diabase	35° 55' 58,9' E / 36° 11' 32,1" N	Tazı yurdu	Boninitic-type	

Table 10. Summary table for the sakalavites.

Sample No	Rock type	Longitude/Latitude	Locality
SKL-1	Hyaloclastite	36° 10´ 49,5˝ E / 36° 10´ 22,3˝ N	Altunözü road section
SKL-2	Pillow lava	36° 10´ 49,5˝ E / 36° 10´ 22,3˝ N	Altunözü road section
SKL-3	Pillow lava	36° 10´ 49,1˝ E / 36° 10´ 22,1˝ N	Altunözü road section
SKL-4	Hyaloclastite	36° 10´ 49,7˝ E / 36° 10´ 21,4˝ N	Altunözü road section
SKL-5	Pillow lava	36° 10´ 49,7˝ E / 36° 10´ 21,4˝ N	Altunözü road section
SKL-6	Hyaloclastite	36° 10´ 50,6˝ E / 36° 10´ 20,8˝ N	Altunözü road section
SKL-7	Pillow lava	36° 10´ 51,2˝ E / 36° 10´ 20,8˝ N	Altunözü road section
SKL-8	Pillow lava	36° 10´ 51,8˝ E / 36° 10´ 20,1˝ N	Altunözü road section
SKL-9	Hyaloclastite	36° 10´ 52,2˝ E / 36° 10´ 19,5˝ N	Altunözü road section
SKL-10	Pillow lava	36° 10´ 52,2˝ E / 36° 10´ 19,0˝ N	Altunözü road section
SKL-11	Hyaloclastite	36° 10´ 53,0˝ E / 36° 10´ 18,3˝ N	Altunözü road section
SKL-12	Hyaloclastite	36° 10´ 53,0˝ E / 36° 10´ 18,3˝ N	Altunözü road section
SKL-13	Hyaloclastite	36° 10´ 52,6˝ E / 36° 10´ 17,6˝ N	Altunözü road section
SKL-14	Pillow lava	36° 10´ 52,8˝ E / 36° 10´ 17,2˝ N	Altunözü road section
SKL-15	Hyaloclastite	36° 10´ 53,0˝ E / 36° 10´ 17,1˝ N	Altunözü road section
SKL-16	Pillow lava	36° 10´ 53,4˝ E / 36° 10´ 16,9˝ N	Altunözü road section
SKL-17	Hyaloclastite	36° 10´ 53,5˝ E / 36° 10´ 16,5˝ N	Altunözü road section
SKL-18	Pillow lava	36° 10´ 54,0˝ E / 36° 10´ 14,6˝ N	Altunözü road section

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