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Petrological reconstruction of Triassic seamounts/oceanic islands within the Palaeotethys: Geochemical implications from the Karakaya subduction/accretion Complex, Northern Turkey

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ABSTRACT

Subduction/accretion complexes provide unique insight into the tectonic assembly of continental margins and oceanic basins, as they record the tectonic stacking and juxtaposition of materials derived from distinct tectonic environments. The Karakaya Complex, exposed throughout northern Turkey, is a good example of an ancient subduction/accretion complex that includes a number of pre-Liassic units that characterize the closure of Palaeotethys. Defining the components of this complex is of crucial importance to understanding the geodynamic evolution of Palaeotethys in the Eastern Mediterranean region. In this study, we explore the geochemistry of metabasic rocks within the Karakaya Complex, redefining and evaluating one of its main constituents, known as "the Nilüfer Unit". New geochemical results combined with previously published data suggest that the Nilüfer Unit is dominated by oceanic-island basalt (OIB)- and enriched mid-ocean ridge basalt (E-MORB)-type metabasic rocks which are variably enriched in the most highly incompatible elements relative to normal MORB (N-MORB). Associated alkaline OIB-type basalts are characterized by highly fractionated and variable rare earth element (REE) patterns ($[La/Yb]_N = 4.8–16.2$), suggesting melting across the garnet–spinel transition, derivation from a heterogeneous mantle source, and/or dynamic melting of a homogeneous source. Similar Nb/Y–Zr/Y systematics of spatially associated OIB- and E-MORB-type samples may indicate involvement of a shared enriched mantle source(s). Combining both geological and geochemical evidence, we suggest that the OIB- and E-MORB-type assemblages defining the Nilüfer Unit represent seamounts and oceanic islands formed on Palaeotethyan oceanic crust, which was finally incorporated into a forearc accretionary prism during latest Triassic and became a component of the Karakaya Complex.

1. Introduction

Subduction/accretion complexes are the tectonic environments most frequently associated with mélange formations (e.g. Raymond, 1984; Closs, 1984). A common feature of these complexes is the presence of high pressure/low temperature mineral assemblages which form in response to cold burial of subducting oceanic slab with associated sediments (Coleman and Lanphere, 1971; Saha et al., 2005). Ancient subduction/accretion complexes record important information about the geodynamic and geochemical evolution of the oceanic basins. Geochemical signatures of individual magmatic suites found within ancient complexes can provide substantial insights into the origin of subduction/accretion complexes worldwide. Individual magmatic suites thought to have formed in different tectonic settings could actually represent the products of the same magmatic event regardless of their metamorphic grade, if these suites can be shown to have similar geochemical signatures and ages of formation.

The northern margin of Turkey includes an ancient subduction/accretion complex that consists of distinct continental and oceanic blocks now juxtaposed chaotically. Formation of this subduction/accretion complex is linked to the demise of a Late Paleozoic–Early Mesozoic ocean known as Palaeotethys (e.g. Sengör and Yılmaz, 1981; Okay et al., 1996; Göncüoglu et al., 1997, 2000). The geodynamic reconstruction of Palaeotethys is questionable, since there is no broad agreement on the location of the suture zone and polarity of subduction, nor critically on the type of magmatism (Okay and Göncüoglu, 2004). There is however, a consensus that the Early Mesozoic Cimmeride Orogeny was responsible for the closure of the Paleozoic ocean, followed by the accretion of several oceanic and continental crustal fragments (Tekeli, 1981; Sengör et al., 1984). In this study, we use geochemical and paleontological data obtained on apparent relict blocks from the Cimmeride Orogeny in order to gain insight into the geodynamics of the Palaeotethyan region during Permo-Triassic time.

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The relicts of this subduction/accretion complex occupy a considerable portion of northern Turkey along an east–west trending belt. The resulting tectonic unit, known as the Karakaya Complex, forms the pre-Liassic basement of the Sakarya Zone (Okay, 1989) or of the Sakarya Composite Terrane (Göncüoglu et al., 1997) (Fig. 1). The Sakarya Composite Terrane includes a Variscan continental basement (Turhan et al., 2004), the Permo-Triassic Karakaya Complex and their Alpine cover. Recognizing and defining the elements of the Karakaya Complex is key to understanding the evolution of Palaeotethys in the Eastern Mediterranean region. The Karakaya Complex has been the subject of debate over many decades (e.g. Bingöl et al., 1973; Akyürek et al., 1984; Capan and Floyd, 1985; Kocyigit, 1987; Kocyigit et al., 1991; Okay et al., 1991; Altiner and Kocyigit, 1993; Ustaömer and Robertson, 1994, 1999; Pickett and Robertson, 1996, 2004; Göncüoglu et al., 2000; Genc, 2004; Sayit and Göncüoglu, 2009a, b). Central to this debate is the degree to which similarities among disparate units have been recognized, and have consequently been interpreted as portions of a single large accretionary complex.

The Karakaya Complex was originally defined by Bingöl et al. (1973) as the "Karakaya Formation", comprising pre-Liassic very low-grade metamorphic rock assemblages in Northwestern Anatolia. They interpreted these assemblages to have formed in a continental rift setting. In subsequent studies, similar pre-Liassic assemblages have extended the limits of the complex to the northeastern part of Turkey (Tekeli, 1981; Kocyigit, 1991; Okay, 1989). Some workers regard the Karakaya Complex as an "ophiolitic mélange" consisting of ophiolites, blueschist facies rocks as well as limestone blocks set in an intensely sheared matrix (Sengör et al., 1980; Sengör and Yılmaz, 1981). Ophiolitic assemblages, although rare, are described from the Küre region (Ustaömer and Robertson, 1994; Kozur et al., 2000), NW Anatolia and the Tokat region (Koçyiğit and Tokay, 1985; Genc, 1992; Rojay and Göncüoglu, 1997). Tekeli (1981) interpreted the Karakaya Complex as a Carboniferous-Triassic accretionary prism termed the North Anatolian Belt. Göncüoglu et al. (2000) suggested that the Karakaya Complex includes both marginal rift and mélange units juxtaposed during the final closure of Palaeotethys at the end of Triassic during the Cimmerian Orogeny. Sayit and Göncüoglu (2009b) emphasize that the pre-Liassic rock assemblages represent huge mélange and/or tectonostratigraphic units which have been assembled during closure of a Palaeotethyan oceanic realm. They interpret the Karakaya Complex as including a number of mélange units, both locally-derived and far-travelled blocks whose dimensions range from millimeter-scale fragments to masses of several kilometer scale. Some mélange units are megablocks within other mélange units. There is therefore little agreement the evolution of the Karakaya Complex (e.g. Altiner and Kocyigit, 1993; Genc and Yılmaz, 1995; Pickett and Robertson, 1996; Göncüoglu et al., 2000; Okay, 2000; Sayit and Göncüoglu, 2009a).

In this study, we evaluate and redefine one particular mélange unit known as "the Nilüfer Unit" that is dominated by OIB-and E-MORB-type metabasic rocks and discuss its tectonomagmatic origin on the basis of geological, petrographic and geochemical features. The "Nilüfer Unit" was initially defined by Okay et al. (1991) as a tectonic unit that includes mainly metabasalts and metatuffs alternating with minor phyllite and marble. However, metabasic rocks associated with oceanic metasediments are also commonly found as knockers within the metaclastic-dominated units of the Karakaya Complex (e.g. Çal and Hodul Units, defined by Okay et al., 1991). The origin of the metabasic rocks and their incorporation into the Karakaya Complex is a subject of controversy. Some studies suggest that they developed in a continental-rift setting that failed to mature into ocean-floor spreading (e.g. Bingöl et al., 1973; Akyürek et al., 1984; Kocyigit, 1987; Altiner and Kocyigit, 1993; Genc and Yılmaz, 1995). Alternatively, geochemical features of the associated volcanic units suggest they are relicts of a seamount and/or oceanic island (Capan and Floyd, 1985; Pickett and Robertson, 1996, 2004; Yaliniz and Göncüoglu, 2002), an oceanic plateau (Okay, 2000), a large igneous province (Genc, 2004) or mantle plume-related seamounts and/or oceanic islands associated with a spreading ridge (Sayit and Göncüoglu, 2009a). Another hypothesis is that these rock assemblages represent an intra-oceanic forearc/intra-arc sequence owing to their large distribution within the complex and the geochemical nature of the mafic rocks (Okay et al., 1996). As seen from these diverse interpretations, resolving the tectonomagmatic evolution of the Karakaya Complex is crucial to interpreting Palaeotethyan events. In the subsequent sections, we redefine and re-evaluate the Nilüfer Unit on the basis of geology, petrography and geochemistry, and then discuss its possible tectonic setting within the Palaeotethyan framework during Triassic time.

2. Geological features of the proposed Nilüfer Unit

2.1. Geology and tectonic setting of the Nilüfer Unit

During regional geological mapping in NW and N Anatolia, several authors (see Okay and Göncüoglu, 2004 for a review) recognized a number of mappable tectono-stratigraphic units within the Karakaya Complex. From these, the clastic-dominated units with metabasalt and limestone olistoliths (Çal, Hodul and Orhanlar Units of Okay et al., 1991) were considered as the Upper Karakaya Complex (e.g. Okay and Göncüoglu, 2004). They define the Nilüfer Unit as a separate tectonic package (Lower Karakaya Complex) comprising a strongly deformed low-grade metamorphic assemblage consisting mainly of metabasite, phyllite and marble. Our detailed work in NW Anatolia has shown that these basic volcanic rocks and associated sediments are not restricted to the Nilüfer Unit of Okay et al. (1991), but may be found in all previously defined units of the Karakaya Complex as blocks or tectonic slices (Sayit and Göncüoglu, 2009a,b). Hence, the metabasic rocks can be assembled and redefined by considering their age, lithology and geochemical characteristics rather than their structural setting and metamorphic grade. Consequently, our redefined Nilüfer Unit is characterized primarily by metabasaltic massive/pillow lava flows and pillow breccias, interbedded with volcaniclastics, mafic tuffs, neritic and pelagic limestones, and minor brick-red cherts and mudstones (e.g. Sayit and Göncüoglu, 2009a). The Nilüfer-type rock

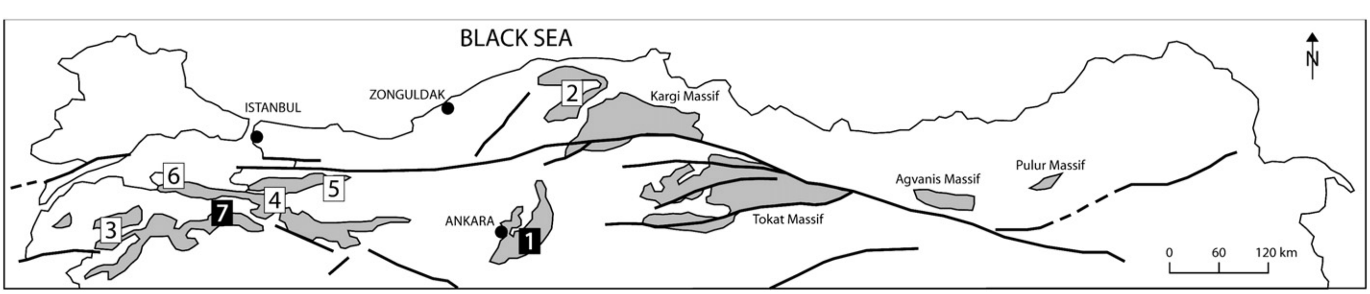

Fig. 1. Distribution of the Karakaya Complex in northern Turkey (modified from Göncüoglu et al., 1997). Marked study localities are: (1) Capan and Floyd (1985), Sayit and Göncüoglu (2009a), and this study; (2) Ustaömer and Robertson (1994); (3) Pickett and Robertson (1996, 2004), Sayit and Göncüoglu (2009a); (4) Genc (2004); (5) Sayit and Göncüoglu (2009a); (6) Genc (2004); (7) Genc (2004) and this study.

assemblages are prevalent throughout N, NW and Central Anatolia (Akyürek et al., 1984; Göncüoğlu et al., 1987; Kocyigit et al., 1991; Okay et al., 1991). An essential feature of this unit is the occurrence of basalt with associated carbonate and/or cherty rocks. In NW Anatolia, the unit is composed largely of metatuffs alternating with lesser phyllite and marble (Okay et al., 1991); similar assemblages can be found in eastern parts of the Karakaya Complex (Okay, 1984; Okay and Sahintürk, 1997). In this area, it comprises the originally defined Nilüfer Unit and Çal Unit (Okay et al., 1991), the Bahçecik Formation (Kocyigit et al., 1991) and part of the Ortaoba Unit (Pickett and Robertson, 1996). In Central Sakarya, the Tepeköy Metamorphic rocks described by Göncüoglu et al. (2000) lying within the lower slice of the Central Sakarya Basement are similar to the Nilüfer Unit although they include terrigenous material and metafelsic tuffs that are conspicuously absent elsewhere (Okay et al., 1996; Pickett and Robertson, 1996; Sayit and Göncüoglu, 2009a).

In Central Anatolia, the redefined Nilüfer Unit is represented by variably-sized metabasic blocks associated with limestones, set in a low-grade metaclastic matrix (Sayit and Göncüoglu, 2009a) and includes the Bahçecik Formation (Altiner and Kocyigit, 1993; Sayit and Göncüoglu, 2009a), Ortaköy Formation (Akyürek et al., 1984) and a part of the Eymir Complex (Kocyigit, 1992) or the Emir Formation (Akyürek et al., 1984). In the eastern parts of the Karakaya Complex, the limited available geochemical data reveal that the metabasites from the Pulur Complex display N-MORB-like characteristics (Topuz et al., 2004). Therefore, they differ from the counterparts in NW and Central Anatolia which display OIB- and E-MORB-like signatures; a detailed geochemical study is needed to further assess the origin of the Pulur Complex.

The age of the Nilüfer Unit is constrained by paleontological data. There is general agreement that the Karakaya Complex is overlain unconformably by Lower Jurassic clastic rocks thus limiting the uppermost age of the complex to latest Triassic (Kocyigit, 1987; Altiner et al., 1991; Okay et al., 1991; Kocyigit et al., 1991). The depositional age of the metaclastic rocks that include Nilüfer-type basalt olistoliths are dated as Late Triassic (Okay and Altiner, 2004), providing an indirect upper age limit for basic volcanism. Direct evidence comes from NW Anatolia, where an Early–Middle Triassic age is seen for conodont fauna found in marbles associated with metatuffs (Kaya and Mostler, 1992). Conodont-based ages suggesting a Ladinian(?)–Carnian (Late Triassic) interval have been reported from grey chert-bands associated with E-MORB-type Nilüfer metabasalts from the Ortaoba region (Sayit and Göncüoglu, 2009a). These ages are essentially consistent with the Middle–Late Triassic time frame indicated by the neritic limestones of the Nilüfer Unit in the Ankara region (Akyürek et al., 1984). A tighter constraint is provided from the Hasanoglan (Ankara) region by Altiner and Kocyigit (1993) who suggest a Late Anisian (Middle Triassic) age on the basis of foraminiferal fauna for the shallow-water limestones intercalated with pillow basalts. Another precise constraint from foraminifera found in the neritic limestones of the Imrahor (Ankara) region (Sayit and Göncüoglu, 2009a) constrains the age of basaltic volcanism to Middle Anisian (Middle Triassic). Taken together, these paleontological data imply that the basaltic magmatism characterizing the Nilüfer Unit has dominated the Middle–Late Triassic interval (Sayit and Göncüoglu, 2009a).

2.2. Petrographic features

It is important to note that all Nilüfer Unit samples include several secondary mineral phases reflecting low-grade metamorphism (e.g. Okay et al., 1991; Pickett and Robertson, 1996; Sayit and Göncüoglu, 2009a) although relict igneous textures can be still identified from several portions of the unit. The dominant primary phase characterizing these metabasic rocks is Ti-rich clinopyroxene (e.g. Okay et al., 1991; Sayit and Göncüoglu, 2009a). In OIB-type samples, the Ti-rich clinopyroxene generally appears to be Ti-augite with a pinkish color, whereas E-MORB-type samples are dominated by brownish titanium augite (Sayit and Göncüoglu, 2009a). The presence of abundant Ti-augite with subordinate kaersutitic amphibole and Fe–Ti oxides reflects the alkaline character of these metaigneous rocks. In the cases where metamorphism is intense, acicular actinolite can be observed replacing titaniferous clinopyroxene. Clinopyroxene sometimes appear to be in the form of calcite pseudomorphs in response to intense carbonatization. Chlorite and epidote are very common in these metabasic rocks. Plagioclase feldspar has albitic compositions due to low-grade alteration.

2.3. Geochemistry

The fundamental goal of this work is to determine the petrogenesis of OIB- and E-MORB-type metabasic rocks that represent the newly defined Nilüfer Unit. We integrate new geochemical results obtained from Central and NW Anatolia with published data to develop a robust characterization of Nilüfer-type magmatism during the Triassic. Of particular interest are the data of Capan and Floyd (1985), Pickett and Robertson (1996, 2004), Genc (2004), and Sayit and Göncüoglu (2009a). We also include supra-subduction zone-type extrusives from the Kure Complex (Ustaömer and Robertson, 1994) and supra-subduction zone-type metadiabases from the Eymir Complex (Sayit and Göncüoglu, 2009a) for comparative purposes, since these rocks do not represent Nilüfer-type magmatism.

2.3.1. Analytical techniques

All bulk rock analyses (except OR-49) were carried out at Duke University (North Carolina, USA; Table 1). Major and selected trace element concentrations were determined by direct current plasma spectroscopy (DCP) based on techniques modified after Klein et al. (1991). using a Fisons SpecterSpan 7 DCP equipped with a multielement cassette. Additional trace element abundances were determined by inductively-coupled plasma mass spectroscopy (ICP-MS) using a VG-Elemental PlasmaQuad3 applying modified techniques of Cheatham et al. (1993). Each sample was analyzed twice within a single run. Sample OR-49 was analyzed in the ACME Analytical Labs (Vancouver, Canada). Major elements as well as Ba and Sc abundances for this sample were determined by inductively coupled plasma atomic-emission spectrometry (ICP-AES) following a method of preparation based on a $LiBO_2$ fusion. Trace elements were determined by ICP-MS after acid decomposition with 5% HNO_3. Analytical precision based on replicates and analyses of natural and synthetic standards was generally better than 2% for most major and trace elements. All major element data were recalculated on a volatile-free basis for discussion and graphical presentation.

3. Results

In making petrogenetic interpretations, we use only elements known to be immobile under conditions of low-grade metamorphism because our samples have high and variable loss on ignition values (LOI ≤ 13.7 wt.%). The importance of this approach can be observed clearly when incompatible elements are plotted against Zr, a fluid-immobile element: large-ion lithophile elements (LILE) display extensive scatter indicating their mobility during metamorphic processes, whereas the coherent trends observed in high-field-strength elements (HFSE) and rare earth elements (REE) suggest that they represent near-original magmatic distributions (Fig. 3c).

The essential component of the newly defined Nilüfer Unit is variably metamorphosed alkaline metabasalt emplaced as flows and less common intrusives (Capan and Floyd, 1985; Pickett and Robertson, 1996, 2004; Genc, 2004; Sayit and Göncüoglu, 2009a, this study); we refer to these rock types as Group 1 (Fig. 2). The alkaline nature of this group is reflected in their high Ti contents (TiO_2 generally >2 wt.%), high Nb/Y (0.5–3.0) and low Zr/Nb values (1.0–11.3) (Figs. 2 and 3). In contrast, subordinate tholeiitic metabasic

Table 1
Chemical compositions of the metabasic rocks representing the Karakaya Complex. Fe_2O_3 is given as total Fe.

	Metabasalts															Metagabbros							
	Group 1												Group 2			Group 1						Group 2	
	OR-29	OR-47	OR-48	OR-58	OR-75	HS-62A	HS-62B	HS-88	GK-1	HC-2	ZT-3	NIL-12	OR-116	OR-33	GK-3	IM-24	OR-49	OR-98	OR-89	HS-89	HS-90	IM-28	OR-104
SiO_2	49.58	48.16	48.71	51.42	50.54	50.18	44.6	46.52	49.16	49.53	47.63	47.25	49.66	49.51	44.78	46.91	45.43	46.97	49.52	45.53	47.18	46.60	49.03
Al_2O_3	13.38	11.48	13.00	14.05	13.86	4.21	5.0	11.47	13.34	11.53	13.46	10.76	13.96	14.21	12.83	14.35	9.01	12.44	11.30	6.15	8.83	15.43	16.69
Fe_2O_3	12.50	12.23	11.92	11.33	10.46	9.42	14.5	10.39	10.50	9.39	11.09	13.75	11.84	12.74	13.01	13.39	11.11	12.85	11.06	11.78	9.95	12.49	10.95
MgO	5.67	10.65	11.67	6.55	6.18	22.31	29.1	7.91	7.53	7.23	9.61	14.81	8.71	8.88	8.81	12.37	16.58	13.54	9.09	21.27	9.79	9.06	8.89
CaO	11.75	12.29	8.56	8.60	11.72	10.63	5.3	17.28	11.98	15.74	9.31	7.58	9.59	8.57	16.20	7.23	9.67	9.54	14.53	11.71	19.73	11.94	9.64
Na_2O	4.57	3.33	2.52	4.59	5.02	0.43	0.2	3.24	2.70	3.62	2.92	2.25	4.28	2.96	2.27	3.08	0.81	2.09	3.11	0.22	1.98	2.75	3.51
K_2O	0.42	0.21	1.50	1.67	0.47	0.29		0.67	2.72	0.38	1.50	0.30	0.39	1.01	1.12	0.24	0.17	0.07	0.14	0.17	0.47	0.33	0.57
TiO_2	2.12	1.59	1.89	1.84	2.17	0.74	1.0	2.13	1.80	1.99	2.31	1.90	1.45	1.43	1.13	1.77	1.76	1.56	0.97	1.25	1.75	1.42	1.15
P_2O_5	0.24	0.17	0.23	0.25	0.42	0.13	0.1	0.33	0.31	0.30	0.34	0.25	0.14	0.15	0.10	0.25	0.18	0.23	0.11	0.17	0.18	0.09	0.13
MnO	0.13	0.17	0.17	0.15	0.16	0.14	0.2	0.17	0.15	0.15	0.19	0.19	0.18	0.17	0.17	0.21	0.15	0.22	0.16	0.15	0.15	0.17	0.16
Cr_2O_3																	0.154						
LOI	4.20	6.30	3.20	2.70	6.10	3.10	8.3	5.40	4.20	11.50	5.20	3.70	4.60	3.90	7.20	4.50	4.9	4.70	7.60	4.30	4.40	4.40	4.20
SUM	100.17	100.19	99.85	100.17	100.57	98.34	99.60	99.75	99.93	99.49	98.05	98.59	99.97	99.47	100.35	99.51	100.00	99.30	99.86	98.22	99.83	100.06	100.7
Ba	57	63	821	220	97	22	162	260	201	59	146	24	32	120	192	99	34	34	32	29	97	55	333
Co	65.7	73.8	73.2	85.5	44.8	68.3	103.9	61.8	43.5	55.0	87.0	84.9	84.1	74.6	75.0	65.4	65.5	64.0	95.2	90.5	61.4	55.9	54.4
Hf	3.4	2.6	3.3	2.7	4.4	1.4	1.4	3.7	3.8	3.4	2.3	1.6	1.8	2.0	1.5	2.9	3.3	2.6	1.4	1.8	1.9	2.0	1.1
Nb	20.5	13.2	17.7	23.5	53.3	16.6	17.0	43.2	39.1	17.5	19.6	17.4	8.4	7.8	4.8	35.3	14.2	31.3	12.4	23.3	25.4	6.0	9.3
Rb	5.0	2.6	20.4	23.3	4.3	1.1	5.7	6.3	27.9	1.1	26.5	1.0	2.8	21.8	18.6	2.2	2.5	86.3	82.7	0.8	2.9	3.2	5.5
Sr	221	205	168	131	162	52	51	484	379	284	173	45	150	118	400	197	30	135	353	48	270	170	535
Ta	1.28	0.82	1.08	1.39	3.07	0.96	1.31	2.63	2.28	1.09	1.27	1.15	0.55	0.52	0.31	2.09	0.9	1.86	0.71	1.43	1.56	0.37	0.58
Th	1.60	1.08	1.37	2.01	5.08	1.02	1.60	3.82	3.44	1.67	1.18	1.43	0.61	0.65	0.41	3.11	1.8	2.68	1.02	2.02	2.16	0.30	0.62
U	0.29	0.33	0.33	0.48	0.91	0.14	0.45	2.65	0.61	2.30	0.46	0.37	0.28	0.25	0.12	0.70	0.3	0.58	0.22	0.39	0.77	0.08	0.14
V	278	219	270	271	239	95	124	263	266	238	250	184	219	234	206	244	242	230	192	172	272	269	190
Zr	92	92	111	84	181	49	37	120	142	134	65	45	51	59	49	98	115	93	48	60	53	64	38
Y	22.5	18.1	24.0	20.5	28.8	7.3	13.0	21.6	24.9	23.7	22.1	15.1	16.7	18.6	16.1	23.4	18.5	20.3	14.2	12.5	16.7	18.5	15.6
Pb	1.5	0.6	0.9	1.3	2.1	1.9	0.5	2.7	13.9	1.2	1.4	0.7	0.7	0.5	1.1	1.7	2.2	1.4	2.3	0.5	2.6	0.7	0.6
Sc	30.8	27.1	33.6	30.2	21.1	20.2	23.0	34.9	24.3	25.3	23.6	22.2	24.3	26.6	23.0	27.5	31.0	26.0	27.7	45.9	53.0	37.9	22.7
Ni	184	590	336	74	78	800	1387	269	97	124	253	764	436	449	428	295	416	371	840	734	253	118	206
Cr	283	1025	639	114	93	1262	1269	668	171	192	557	1110	508	559	582	363		502	987	1918	766	254	507
La	15.21	10.51	13.20	17.82	33.62	4.44	11.60	31.41	27.62	14.58	13.12	14.22	5.50	5.94	4.04	21.97	10.4	19.22	9.08	10.37	18.86	4.27	6.62
Ce	35.35	24.21	31.77	36.75	66.64	14.26	25.95	62.60	53.08	32.64	32.74	33.76	14.37	14.76	10.17	45.59	24.9	38.12	18.33	27.60	38.89	11.40	15.32
Pr	4.97	3.33	4.47	4.63	8.05	2.20	3.19	7.72	6.49	4.51	4.64	4.72	2.13	2.14	1.42	5.70	3.44	4.63	2.28	3.80	4.90	1.68	2.09
Nd	20.79	14.02	18.62	17.61	29.11	9.14	12.59	28.07	24.04	18.80	19.83	19.56	9.59	9.92	6.89	21.65	16.2	17.31	9.29	15.04	18.69	8.53	9.08
Sm	5.10	3.66	4.58	4.16	5.81	1.98	2.79	5.58	5.02	4.48	4.89	4.47	2.78	2.92	2.16	4.65	3.7	3.74	2.28	3.18	4.06	2.65	2.41
Eu	1.62	1.23	1.49	1.38	1.64	0.57	0.58	1.75	1.58	1.44	1.62	1.30	0.92	0.94	0.82	1.50	1.16	1.33	0.80	1.00	1.28	1.03	0.91
Gd	5.18	3.85	5.01	4.47	5.66	1.85	2.75	5.26	5.01	4.78	5.15	4.35	3.32	3.38	2.79	4.84	3.89	4.04	2.60	2.91	4.03	3.27	2.87
Tb	0.83	0.61	0.81	0.71	0.92	0.28	0.44	0.81	0.80	0.79	0.80	0.67	0.56	0.58	0.49	0.78	0.66	0.66	0.43	0.46	0.63	0.55	0.49
Dy	4.77	3.72	4.73	4.22	5.32	1.56	2.57	4.48	4.77	4.60	4.70	3.62	3.38	3.71	3.08	4.63	3.76	3.93	2.79	2.54	3.40	3.50	2.96
Ho	0.85	0.70	0.88	0.77	1.01	0.27	0.46	0.79	0.91	0.85	0.84	0.61	0.63	0.72	0.59	0.88	0.7	0.74	0.55	0.46	0.62	0.67	0.58
Er	2.14	1.73	2.17	1.95	2.67	0.63	1.20	1.96	2.46	2.11	2.07	1.34	1.59	1.80	1.52	2.24	1.88	1.91	1.40	1.18	1.56	1.79	1.49
Tm																	0.25						
Yb	1.73	1.48	1.85	1.60	2.45	0.57	1.00	1.47	2.17	1.77	1.58	0.99	1.40	1.54	1.34	1.94	1.55	1.59	1.18	0.92	1.12	1.62	1.31
Lu	0.24	0.22	0.28	0.23	0.37	0.08	0.14	0.21	0.33	0.26	0.22	0.09	0.19	0.21	0.20	0.29	0.22	0.23	0.18	0.12	0.14	0.23	0.19

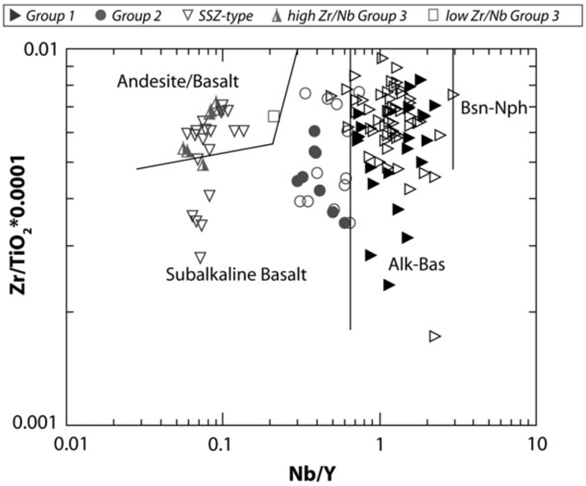

Fig. 2. Tectonomagmatic discrimination of representative metabasic rocks from the Karakaya Complex (after Winchester and Floyd, 1977). Closed triangles and circles (Groups 1 and 2, corresponding to OIB- and E-MORB-type, respectively) represent the new geochemical data, whereas the open symbols indicate equivalent geochemical types on the basis of data obtained from previous works. OIB- and E-MORB-type samples characterizing the newly defined Nilüfer Unit are from Capan and Floyd (1985), Pickett and Robertson (1996, 2004), Genc (2004) and Sayit and Göncüoglu (2009a). Group 3 samples are from the Nilüfer Unit of Genc (2004) and the Ortaoba Unit (Pickett and Robertson, 1996). Supra-subduction zone-type samples from the Kure Complex (Ustaömer and Robertson, 1994) and the Eymir Complex (Sayit and Göncüoglu, 2009a).

flows and intrusives (Genc, 2004; Sayit and Göncüoglu, 2009a, this study) have lower TiO_2 (~1.4 wt.%) and Nb/Y values (0.1–0.7); these rocks comprise two distinct groups (Fig. 2): one with Zr/Nb values between 4.1 and 14.0 (Group 2) and the other with Zr/Nb values between 14.2 and 36.3 (Group 3). Some Group 3 samples, specifically the Marmara Island samples of Genc (2004) and the Ortaoba samples of Pickett and Robertson (1996) plot within the field of supra-subduction zone-type samples from the Küre and Eymir Complexes (Fig. 3). A further subdivision within the Group 3 suite can be defined by three samples from Yenisehir (Genc, 2004) which have Zr/Nb values of 14 to 17 (Fig. 3).

The minor element geochemistry of the Group 1 suite is similar to that of oceanic-island basalt (OIB), displaying variable enrichment in immobile incompatible trace elements relative to normal mid-oceanic ridge basalt (N-MORB) (e.g. Weaver et al., 1986; Dupuy et al., 1988; Sun and McDonough, 1989) (Fig. 4). Samples in this group also have highly fractionated REE patterns with $(La/Yb)_N = 4.8–16.2$ (Fig. 5). The Group 1 suite is found throughout the studied region, from Ankara region to NW Anatolia (sites 1–7 except for 2; Fig. 1). Group 2 lavas have trace element abundances comparable to enriched mid-oceanic ridge basalt (E-MORB; e.g. Sun and McDonough, 1989; Hekinian et al., 1999) (Fig. 4). Although basalts of this group are less common than those of Group 1, the two types are found together consistently, suggesting a close link in their genesis. The geochemical character of the Group 3 suite is closely similar to supra-subduction zone-type magmas as indicated by high Zr/Nb and Ce/Nb as well as HFSE abundances similar to those of N-MORB. The supra-subduction zone-type signature of the Group 3 suite is particularly striking in the Ortaoba samples that display distinct negative Nb anomalies with moderate Th enrichment (Fig. 4).

4. Discussion

4.1. Petrogenesis of the metabasic rocks in the Karakaya Complex

The geochemical data presented here make it possible to assess the petrogenetic history of the Nilüfer Unit samples. Taken together, these metabasic rocks which are found within individual suites represent similar environments of melt generation and emplacement that coexist within the Karakaya Complex and thus provide significant insights into the origin of this major unit. Given the high LOI values of many Nilüfer samples, and the mobility observed among both major and highly incompatible trace elements, we address first the evidence for crustal contamination and subsequently use the immobile trace element abundances to constrain the tectonic settings of the individual mafic series.

4.1.1. Crustal contamination

Mafic magmas may interact with the continental crust to variable extents during transport, fractionation and storage through the process of assimilation (e.g. DePaolo, 1981; Hart et al., 1989). In the magmatic suites especially represented by porphyritic samples, the role of magma–crust interaction must be assessed in order to understand the impact of crustal contamination on the resulting trace element chemistry. We focus on the HFSE because of their immobility during alteration relative to the large-ion lithophile elements, even though the latter group is more sensitive to crustal inputs. Since Ti and Nb abundances are low in continental crust (e.g. Taylor and McLennan, 1995), magmas experiencing crustal contamination are in general expected to have lower Ti and Nb contents than those which pass through the crust unaffected. None of the Nilüfer samples has negative Ti anomalies (Fig. 4) and indeed the Group 1 samples display Ti/Y values between 409 and 830, much higher than that of the bulk continental crust (161.9; Taylor and McLennan, 1995). Among the Group 2 samples, Ti/Y values are somewhat lower (299–521) but do not require crustal contamination (e.g. Leeman and Hawkesworth, 1986). It is important to note in this context that the multi-element patterns from both Group 1 and 2 samples (Pickett and Robertson, 1996, 2004; Sayit and Göncüoglu, 2009a) lack negative Nb anomalies, supporting the idea that crustal contamination of these rocks is insignificant to their petrogenesis. Very high Zr/Nb values (33–36) of Group 3 samples may suggest involvement of a depleted source with or without a subduction component, rather than reflecting crustal contamination where the likely assimilants are characterized by low Zr/Nb values (e.g. Taylor and McLennan, 1995).

4.1.2. Evidence for source features and melt generation

Variations among HFSE are useful in determining geochemical features of the source regions for mafic volcanism. Variations in Nb/Y–Zr/Y values can distinguish between magmas derived from enriched (OIB or E-MORB) and depleted sources (N-MORB and subduction-related) (Fitton et al., 1997). All Group 1 and 2 samples plot within the field of lavas derived from enriched sources, whereas Group 3 samples appear to indicate involvement of depleted sources during their genesis (Fig. 6). Th/Y–Nb/Y values of Group 1 and 2 suites form an array which can be indicative of within-plate enrichment (Fig. 6). Group 2 samples are characterized by lower Th/Y and Nb/Y values than Group 1 lavas, which may reflect higher degrees of melting for generation of Group 2 suite provided that their sources were similar as indicated by Nb/Y–Zr/Y graph. This diagram further suggests a supra-subduction zone-affinity for the Ortaoba samples from the Group 3 suite.

Negative Nb and, to a lesser extent, Ta anomalies are observed among the Ortaoba samples of Group 3 suite; very similar to the Eymir metadiabases and the Küre lavas (Fig. 4). Negative Nb–Ta anomalies occur in some continental within-plate settings if the partial melts are generated in the region of subcontinental lithospheric mantle which has previously been fluxed by subduction components and/or the melts have been contaminated by continental crust on their way to the surface (e.g. Hawkesworth et al., 1992; Ellam and Cox, 1989; Peate et al., 1992). Negative Nb–Ta anomalies are also typical characteristics of subduction zones where mantle wedge is metasomatically modified through enrichment of large-ion-lithophile elements (LILE) and light rare earth elements (LREE) via fluids and melts

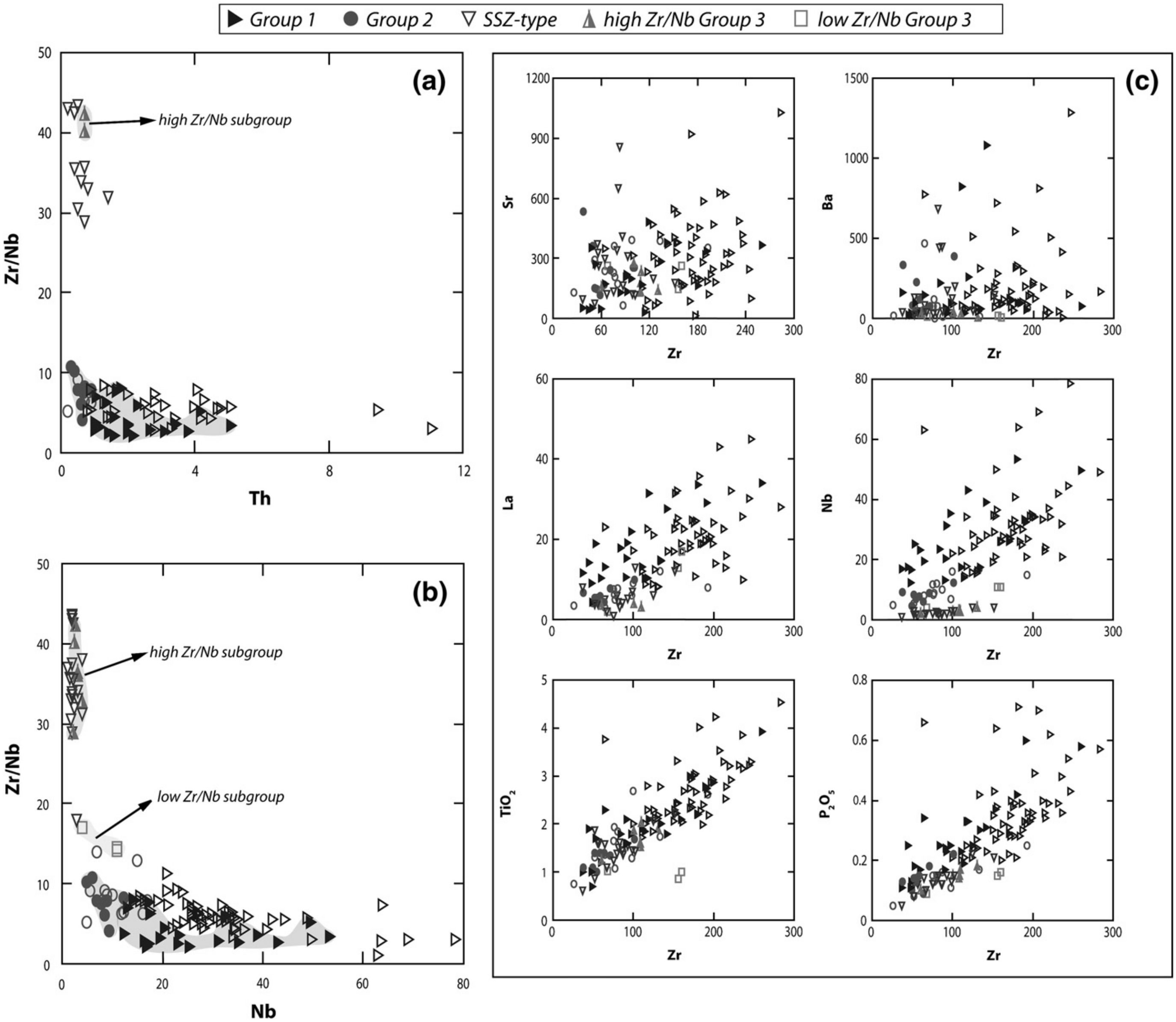

Fig. 3. Geochemical variations among Karakaya mafic lavas. Plot of Th (a) and Nb (b) against Zr/Nb. The new data as well as the subgroups of Group 3 suite are highlighted in order to provide a better comparison (c) Behavior of selected elements in the Karakaya suite indicating significant mobility has occurred in LIL elements (except Th) under low-grade alteration. HFSE and REE, on the other hand, remained as relatively immobile (same data sources as in Fig. 1).

generated by dehydration of the subducting oceanic slab (e.g. Gill, 1981; Hawkesworth et al., 1993; Woodhead et al., 1993). In this setting, Nb and Ta are retained in the slab presumably through the presence of a residual phase such as rutile and/or amphibole (e.g. Green, 1995; Ionov and Hofmann, 1995). Further, high Zr/Nb ratios are more typical for intra-oceanic arcs (Zr/Nb = 29–86, compiled from Elliott et al., 1997; Stern et al., 2006) than continental arcs (Aeolian arc, Zr/Nb = 8–18; De Astis et al., 1997), and oceanic within-plate magmas appear to be free from Nb–Ta anomalies (e.g. Weaver et al., 1986; Floyd, 1989; Sun and McDonough, 1989). For this reason, we do not agree with the interpretation of Pickett and Robertson (1996) who suggest a MORB-type setting for the Ortaoba basalts; rather, we infer an intra-oceanic supra-subduction zone-type environment (probably a back-arc setting considering the MORB-like HFSE distributions) for these lavas (Fig. 4b). Similarly, we suggest that the high Zr/Nb subgroup samples of Genc (2004) were generated either on a spreading ridge or above an intra-oceanic subduction zone. This interpretation is supported by multi-element patterns (Fig. 4), although further discrimination is not possible given the lack of Th in his dataset. We interpret the negative Nb anomalies coupled with variable Th enrichment observed in the Ortaoba basalts as the result of supra-subduction zone-enrichment rather than crustal contamination, noting that Th may become enriched in the mantle wedge during subduction, but it is immobile during the transport of aqueous fluids (e.g. Pearce and Peate, 1995).

The geochemical character of the basaltic rocks within the redefined Nilüfer Unit suggests that Karakaya magmatism in Central and NW Turkey is dominated by E-MORB and OIB-type basalts as indicated by the distinct enrichment in most incompatible elements relative to N-MORB. Several trace element ratios (e.g. Nb/La ~ 1.6, Nb/Y ~ 1.3, and Zr/Nb ~ 5.6) further imply involvement of one or more enriched sources in the generation of the Nilüfer metabasic rocks. We note that the Group 3 Ortaoba, Yenisehir and Marmara samples lack these characteristics and are not included in the newly defined Nilüfer Unit.

Variable REE patterns shown by the Group 1 suite may result from melting across spinel–garnet transition zone, or from a heterogeneous source, or alternatively may reflect dynamic melting of a homogeneous

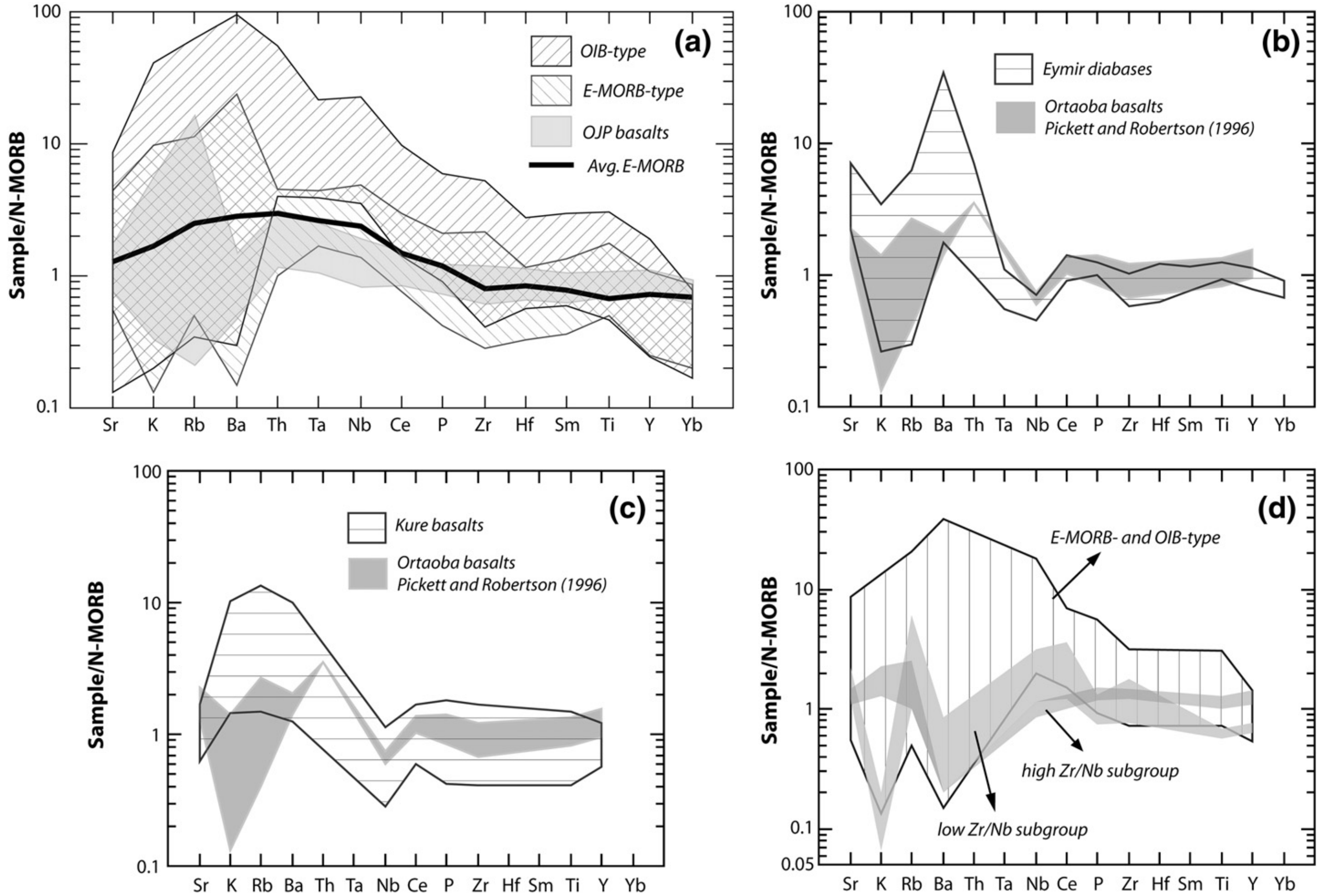

Fig. 4. a) N-MORB-normalized multi-element variation patterns of OIB- and E-MORB-type samples from the Karakaya Complex (data from Capan and Floyd, 1985; Pickett and Robertson, 1996, 2004; Genc, 2004; Sayit and Göncüoglu, 2009a and this study). Representative samples from the Ontong-Java Plateau (compiled from Mahoney et al., 1993; Fitton and Godard, 2004) are also shown for comparison. b) Comparison of the Ortaoba samples of Pickett and Robertson (1996) with the supra-subduction zone-type Eymir metadiabases and c) Küre lavas; d) Relative differences between the samples from the Nilüfer Unit of Genc (2004). Note that the Marmara island samples are characterized by the highest Zr/Nb ratios among three groups. Normalization values are from Pearce (1983). Average E-MORB concentration is from Sun and McDonough (1989).

source (e.g. Langmuir et al., 1977). High LREE/HREE values suggest that the OIB-type metabasic rocks within the Nilüfer Unit require substantial contributions from a garnet-bearing source (Sayit et al., 2008, 2009; Sayit and Göncüoglu, 2009a). The E-MORB-type samples, on the other hand, are dominated by melts from spinel-facies mantle as indicated by their less-fractionated REE patterns. Sayit and Göncüoglu (2009a) suggested that the E-MORB magmas (represented by their Imrahor and Ortaoba samples) may reflect mixing between melts of depleted spinel-lherzolite and OIB-type melts. However, given the overlap in Nb/Y–Zr/Y values among the OIB- and E-MORB-type samples we now exclude a depleted (N-MORB) mantle source as a potential component of the E-MORB-type samples. Large variations in La concentrations at a given

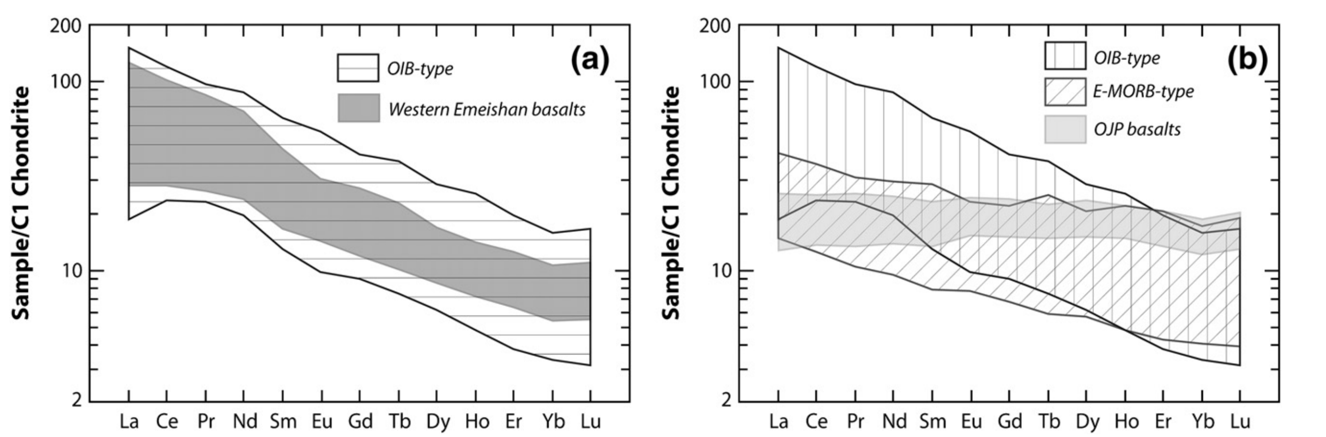

Fig. 5. a) Chondrite-normalized REE patterns of the OIB-type Karakaya samples (Sayit and Göncüoglu, 2009a; this study). Shown for comparison are selected picritic and basaltic lavas from the Western Emeishan Flood Basalt Province, China, which are interpreted to have been derived from a garnet-bearing source (Zhang et al., 2006); b) Comparison of the REE distributions of OIB- and E-MORB-type samples from the Karakaya Complex (Sayit and Göncüoglu, 2009a,this study) with those of Ontong-Java Plateau (Mahoney et al., 1993; Fitton and Godard, 2004). Normalization values from Sun and McDonough (1989).

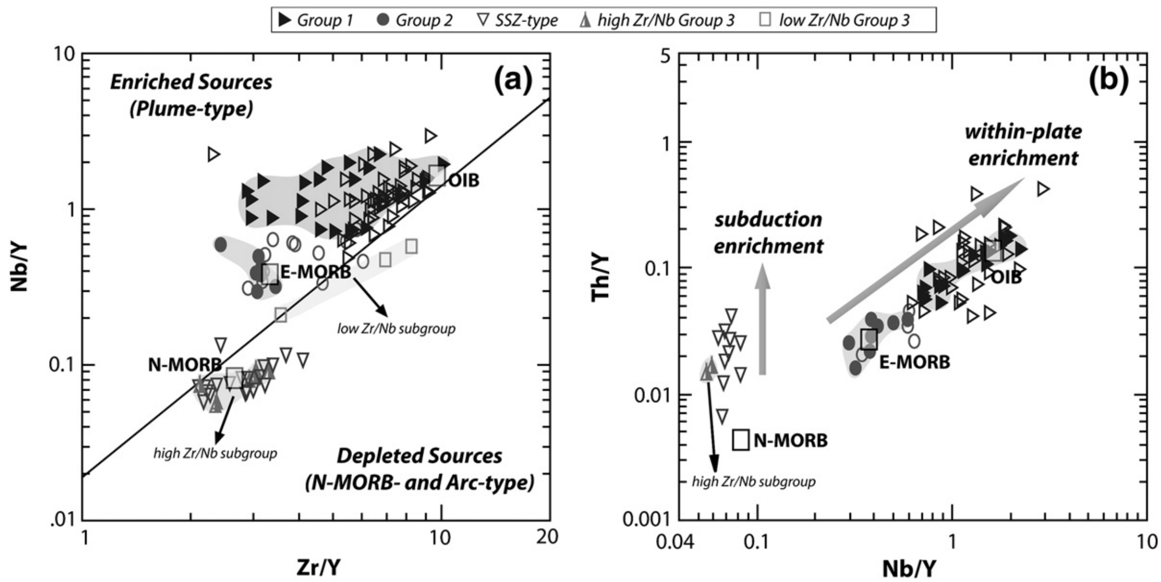

Fig. 6. Relative HFSE abundances in Karakaya samples (data sources as in Fig.1). a) Nb/Y–Zr/Y values of OIB- and E-MORB-type metabasalts plot on or above a line separating products of enriched and depleted sources (after Fitton et al., 1997). Supra-subduction zone-type samples plot within the field of N-MORB and arc-type lavas. b) OIB- and E-MORB-type samples show a positive correlation between Th/Y and Nb/Y interpreted as evidence for within-plate enrichment, whereas the supra-subduction zone-type samples display a range of Th/Y values at nearly constant Nb/Y. Average N-MORB, E-MORB and OIB compositions from Sun and McDonough (1989).

MgO of the studied rocks suggest that the REE abundances are mainly controlled by partial melting and/or source features, rather than post-emplacement element mobility.

4.2. Tectonic models for the origin of the Nilüfer Unit

Geodynamic models proposed previously for the origin of the Karakaya metabasic suites focus on two main processes: (1) subduction/accretion of the oceanic crust and (2) continental or back-arc rifting (see also Okay and Göncüoglu, 2004). In this section, we evaluate these models on the basis of all available geological and geochemical information to determine the origin of the Karakaya Complex.

Subduction/accretion scenarios require seamounts, oceanic islands and/or an oceanic plateau to be accreted during the closure of Palaeotethys (Capan and Floyd, 1985; Pickett and Robertson, 1996, 2004; Okay, 2000; Genc, 2004; Sayit and Göncüoglu, 2009a). After the oceanic plateau was proposed by Okay (2000) for his "Nilüfer Unit", Genc (2004) extended the boundaries of this unit suggesting that it represents the pieces of a large igneous province together with oceanic seamounts. Although the models differ in detail, both authors interpreted their Nilüfer Unit as an oceanic plateau. Such a tectonic setting is not supported by the geochemical data, however, as oceanic plateaus are dominated by basaltic rocks of tholeiitic character (e.g. Mahoney et al., 1993; Frey et al., 2000), whereas the Karakaya Complex is dominated by alkaline units (Capan and Floyd, 1985; Pickett and Robertson, 1996, 2004; Sayit and Göncüoglu, 2009a, this study). The Kerguelen Plateau, for example, is composed of tholeiitic basalts covering more than 85% of its surface (e.g. Condie, 2001). In addition, oceanic plateau basalts are characterized by generally flat REE and HFSE patterns (e.g. Kerr and Mahoney, 2007), which contrast with the OIB and E-MORB assemblages here (Groups 1 and 2) that display variable enrichment in LREE relative to HREE ($[La/Yb]_N = 2.1–16.2$) (Figs. 4 and 5).

The continental rift model (Bingöl et al., 1973; Sengör and Yılmaz, 1981; Kocyigit, 1987; Altiner and Kocyigit, 1993; Genc and Yılmaz, 1995) interprets the lithologies of the Karakaya Complex as the result of the opening of an E–W trending basin on the northern margin of the Tauride–Anatolide Platform via back-arc spreading. This tectonic model was developed primarily to explain the presence of exotic limestone blocks as well as volcano-sedimentary assemblages composed mainly of mafic lavas interbedded with limestone and chert, greywackes and arkosic sandstones (Bingöl et al., 1973). Göncüoglu et al. (2000) also suggest that some clastic-dominated units of the Karakaya Complex, e.g. Hodul Unit, rest disconformably on continental basement. There is no compelling geological or geochemical evidence to indicate that the Nilüfer Unit basalts were emplaced in a continental rift setting (Pickett and Robertson, 1996, 2004; Okay et al., 1996; Sayit and Göncüoglu, 2009a). Within the Nilüfer Unit, there is no field evidence of continental crustal material in primary contact with these OIB-type basalts. It is also significant in this context that the investigated basaltic samples characterizing the Nilüfer Unit display no geochemical evidence for either crustal contamination or derivation from a subduction-modified mantle (e.g. Ferrar Magmatic Province, Hergt et al., 1991). Hence, rift models with the involvement of continental crust do not appear to be suitable for the genesis of Nilüfer-type basalts considered in this study.

In contrast to the continental-rift and oceanic within-plate-related settings, Tekeli (1981) proposed that the basaltic rocks were generated in an arc-related setting and stated that the observed lithologies had been incorporated into an accretionary prism to form a tectonic mélange. Okay et al. (1996) suggested a similar model, arguing that the Nilüfer Unit was formed in an ensimatic forearc–intraarc basin. The paucity of supra-subduction zone-type mafic rocks relative to abundant E-MORB and OIB-type magmas within the Nilüfer Unit, however, reveals that these magmas cannot be generated in a supra-subduction zone setting.

As a working hypothesis, we suggest that during latest Permian, a mantle plume led to rifting on the northern margin of the Gondwana, forming a basin as represented by the rift succession observed in the Geyve region (Göncüoglu et al., 2000, 2004) (Fig. 7). During Early(?)–Middle Triassic, plume-related OIB- and E-MORB-type lavas erupted through the Palaeotethyan oceanic crust, creating seamount(s) and oceanic island(s) as represented by the Nilüfer Unit. During Latest Triassic, closure of Palaeotethys resulted in incorporation of seamounts/oceanic islands and rift-related assemblages that became further associated with clastic material derived from forearc region of the accretionary prism.

Mélanges are known to be profoundly associated with subduction/accretion complexes, though there are a number of other settings where these chaotic rock bodies can be generated (e.g. Raymond, 1984). The mélange units within the Karakaya Complex are clearly deformed in most places (e.g. Okay et al., 1991; Topuz et al., 2004;

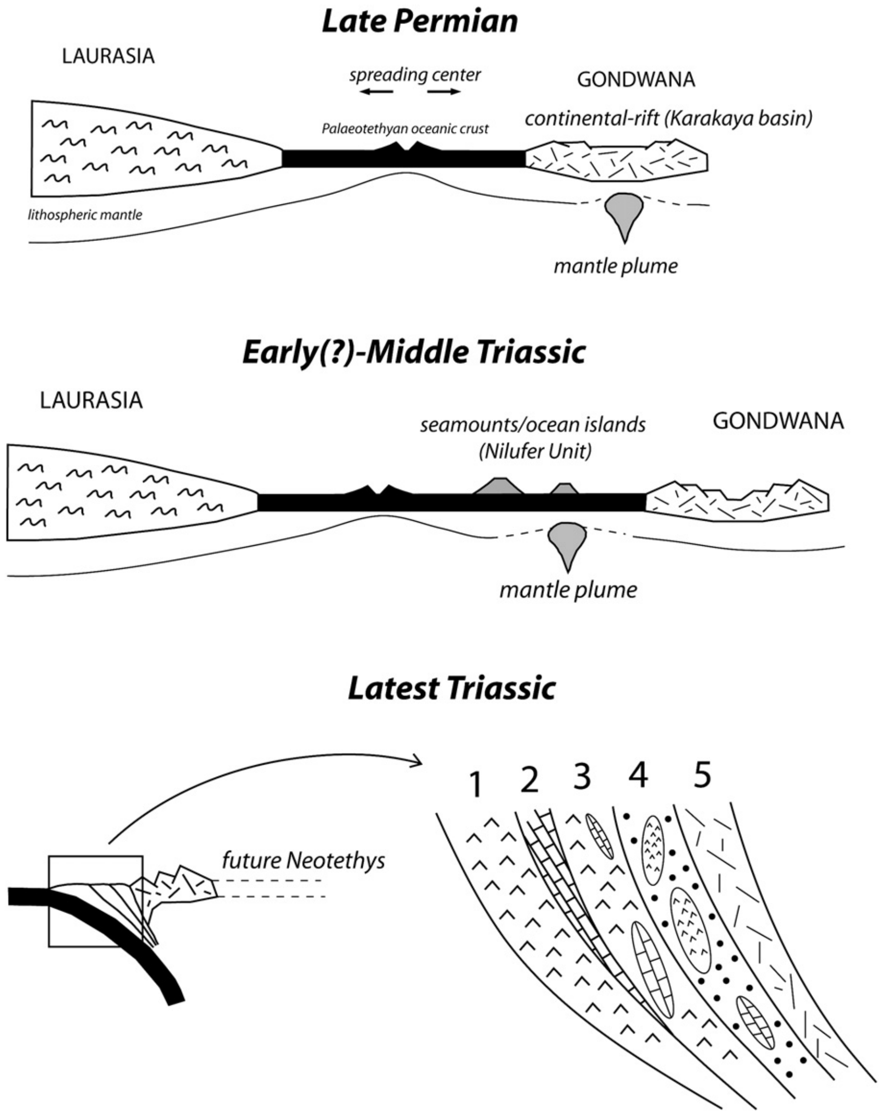

Fig. 7. Schematic model depicting geodynamic evolution of the Nilüfer Unit and the Karakaya rift basin during Permo-Triassic time and their incorporation in the subduction/accretion prism forming the final product "Karakaya Complex". (1) Nilüfer-type metabasic rocks; (2) Shallow-water (reefal) limestones associated with Nilüfer volcanics, (3) Nilüfer metabasalts with interbedded shallow/pelagic carbonates and cherts; (4) Nilüfer blocks embedded in forearc-derived metaclastics, (5) Continental rift succession.

Sayit and Göncüoglu, 2009a). Further, HP-greenschists and minor high pressure/low temperature metamorphic rocks such as blueschists and eclogites are commonly encountered all along the complex (e.g. Okay et al., 1991; Okay et al., 2002; Topuz et al., 2004). Intense deformation together with MP/LT–HP/LT metamorphism are typical features of mélanges generated in subduction/accretion complexes (e.g. Coleman and Lanphere, 1971; Saha et al., 2005).

5. Conclusions

We interpret the geochemical and geological evidence from several basaltic units within the Karakaya Complex to reflect a subduction–accretion environment where seamount(s) and ocean island(s) formed on the Paleotethyan oceanic crust became part of a forearc-accretionary prism during latest Triassic. These lithologies were imbricated tectonically with some continental rift assemblages along with the Variscan basement to form the Cimmerian part of the Sakarya Composite Terrane (Göncüoglu et al., 2000). The Nilüfer Unit (as defined by this study) became incorporated with forearc material, thus creating a huge mélange that covers northwestern and central Turkey. We find that Middle–Late Triassic OIB- and E-MORB-type Nilüfer basalts that make up a considerable part of the Karakaya Complex are variably enriched in terms of LREE relative to HREE. The OIB-type Nilüfer suite appears to have been formed largely by partial melting of a garnet-bearing source, whereas the E-MORB-type Nilüfer samples require greater contribution from the spinel–facies mantle (Sayit et al., 2008, 2009). The mafic rocks of the newly defined Nilüfer Unit do not represent rift or back-arc spreading where continental crust has been involved. They record oceanic islands and seamounts that formed on the Paleotethyan oceanic crust prior to accretion in a forearc setting; we find no compelling evidence for a large igneous province or plateau.

Such a model can explain both the presence of OIB-type and E-MORB-type meta-igneous rock assemblages together with sedimentary material observed within Karakaya Complex in NW and Central Anatolia. A more detailed picture of the evolution of the Karakaya Complex and hence the fate of the Palaeotethys can be revealed by the addition of isotopic geochemistry and also by enlarging the spatial limits of detailed geochemical studies within the Karakaya Complex.

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References

Akyürek, B., Bilginer, E., Akbas, B., Hepsen, N., Pehlivan, S., Sunu, O., Soysal, Y., Dager, Z., Catal, E., Sözeri, B., Yıldırım, H., Hakyemez, Y., 1984. Basic geological features of Ankara–Elmadag–Kalecik region. Jeoloji Mühendisligi 20, 31–46 (In Turkish with English abstract).
Altiner, D., Kocyigit, A., 1993. Third remark on the geology of the Karakaya basin. An Anisian megablock in northern central Anatolia: micropaleontologic, stratigraphic and tectonic implications for the rifting stage of Karakaya basin, Turkey. Revue de Palaeobiologie 12, 1–17.
Altiner, D., Kocyigit, A., Farinacci, A., Nicosia, U., Conti, M.A., 1991. Jurassic-Lower Cretaceous stratigraphy and paleogeographic evolution of the southern part of north-western Anatolia. Geologica Romana 27, 13–80.
Bingöl, E., Akyürek, B., Korkmazer, B., 1973. The geology of the Biga Peninsula and some features of the Karakaya Formation. Proceedings of the 50th Anniversary of the Turkish Republic Earth Science Congress. Mineral Research and Exploration Institute of Turkey (MTA) Publications, pp. 70–77 (in Turkish with English abstract).
Capan, U.Z., Floyd, P.A., 1985. Geochemical and petrographic features of metabasalts within units of Ankara mélange, Turkey. Ofioliti 10, 3–18.
Cheatham, M., Sangrey, W.F., White, W.M., 1993. Sources of error in external calibration ICP-MS analysis of geological samples and improved nonlinear drift correction procedure. Spectrochimica Acta 48B, E487–E506.
Closs, M., 1984. Flow mélanges and the structural evolution of accretionary wedges. In: Raymond, L.A. (Ed.), Mélanges: Their Nature, Origin, and Significance: Geological Society of America, Special Paper, 198, pp. 71–79.
Coleman, R.G., Lanphere, M.A., 1971. Distribution and age of high-grade blueschists, associated eclogites, and amphibolites from Oregon and California. Geological Society of America Bulletin 82, 2397–2412.
Condie, K.C., 2001. Mantle Plumes and Their Record in Earth History. Cambridge University Press.
De Astis, G., La Volpe, L., Peccerillo, A., Civetta, L., 1997. Volcanological and petrological evolution of Vulcano island (Aeolian Arc, southern Tyrrhenian Sea). Journal of Geophysical Research 102, 8021–8050.
DePaolo, D.J., 1981. Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. Earth and Planetary Science Letters 53, 189–202.
Dupuy, C., Barsczus, H.G., Liotard, J.M., Dostal, J., 1988. Trace element evidence for the origin of ocean island basalts: an example from the Austral Islands (French Polynesia). Contributions to Mineralogy and Petrology 98, 293–302.
Ellam, R.M., Cox, K.G., 1989. A Proterozoic lithospheric source for Karoo magmatism: evidence from the Nuanetsi picrites. Earth and Planetary Science Letters 92, 207–218.
Elliott, T., Plank, T., Zindler, A., White, W., Bourdon, B., 1997. Element transport from slab to volcanic front at the Mariana arc. Journal of Geophysical Research 102, 14991–15019.
Fitton, J.G., Saunders, A.G., Norry, M.J., Hardarson, B.S., Taylor, R.N., 1997. Thermal and chemical structure of the Iceland plume. Earth and Planetary Science Letters 153, 197–208.
Fitton, J.G., Godard, M., 2004. Origin and evolution of magmas on the Ontong Java Plateau. In: Fitton, J.G., Mahoney, J.J., Wallace, P.J., Saunders, A.D. (Eds.), Origin and Evolution of the Ontong Java Plateau, 229. Geological Society, London, pp. 151–178 (Special Publications).
Floyd, P.A., 1989. Geochemical features of intraplate oceanic plateau basalts. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in the Ocean Basins, vol. 42. Geological Society, London, pp. 215–230 (Special Publications).
Frey, F.A., Coffin, M.F., Wallace, P.J., et al., 2000. Origin and evolution of a submarine large igneous province: the Kerguelen Plateau and Broken Ridge, southern Indian Ocean. Earth and Planetary Science Letters 176, 73–89.
Genc, S., 1992. Geology of the Bursa region. International Symposium on the Geology of the Black Sea Region Guide Book, pp. 22–25.
Genc, S.C., 2004. A Triassic large igneous province in the Pontides, northern Turkey: geochemical data for its tectonic setting. Journal of Asian Earth Sciences 22, 503–516.
Genc, S.C., Yılmaz, Y., 1995. Evolution of the Triassic continental margin, northwest Anatolia. Tectonophysics 243, 193–207.
Gill, J.B., 1981. Orogenic Andesites and Plate Tectonics. Springer-Verlag, New York.
Göncüoglu, M.C., Dirik, K., Kozlu, H., 1997. Pre-Alpine and Alpine Terranes in Turkey: explanatory notes to the terrane map of Turkey. Annales Geologique de Pays Hellenique 37, 515–536.
Göncüoglu, M.C., Kuwahara, K., Tekin, K.U., Turhan, N., 2004. Upper Permian (Changxingian) radiolarian cherts within the clastic successions of the "Karakaya Complex" in NW Anatolia. Turkish Journal of Earth Sciences 13, 201–213.
Göncüoglu, M.C., Turhan, N., Sentürk, K., Özcan, A., Uysal, S., 2000. A geotraverse across NW Turkey: tectonic units of the Central Sakarya region and their tectonic evolution. In: Bozkurt, E., Winchester, J., Piper, J.A. (Eds.), Tectonics and magmatism in Turkey and the Surrounding Area, vol. 173. Geological Society, London, pp. 139–161 (Special Publications).
Göncüoğlu, M.C., Erendil, M., Tekeli, O., Aksay, A., Kuşçu, İ., Ürgün, B., 1987. Geology of the Armutlu Peninsula. IGCP Project No 5, Guide Book. Field Excursion along Western Anatolia, pp. 12–18.
Green, T.H., 1995. Significance of Nb/Ta as an indicator of geochemical processes in the crust–mantle system. Chemical Geology 120, 347–359.
Hart, W.K., Wolde, G.C., Walter, R.C., Mertzman, S.A., 1989. Basaltic volcanism in Ethiopia: constraints on continental rifting and mantle interactions. Journal of Geophysical Research 94, 7731–7748.
Hawkesworth, K., Gallagher, K., Hergt, J.M., McDermott, F., 1993. Mantle and slab contributions in arc magmas. Annual Review of Earth and Planetary Science 21, 175–204.
Hawkesworth, C.J., Gallagher, K., Kelly, S., Mantovani, M., Peate, D.W., Regelous, M., Rogers, N.W., 1992. Parana magmatism and the opening of South Atlantic. In: Storey, B.C., Alabaster, T., Pankhurst, R.J. (Eds.), Magmatism and the Causes of Continental Break-up, vol. 68. Geological Society, London, pp. 221–240 (Special Publications).
Hekinian, R., Stoffers, P., Ackermand, D., Revillon, S., Maia, M., Bohn, M., 1999. Ridge-hotspot interaction: the Pacific–Antarctic Ridge and the foundation seamounts. Marine Geology 160, 199–223.
Hergt, J.M., Peate, D.W., Hawkesworth, C.J., 1991. The petrogenesis of Mesozoic Gondwana low-Ti flood basalts. Earth and Planetary Science Letters 105, 134–148.
Ionov, D.A., Hofmann, A.W., 1995. Nb–Ta-rich mantle amphiboles and micas: implications for subduction-related metasomatic trace element fractionations. Earth and Planetary Science Letters 131, 341–356.
Kaya, O., Mostler, H., 1992. A Middle Triassic age for low-grade greenschist facies metamorphic sequence in Bergama (İzmir), western Turkey: the first paleontological age assignment and structural-stratigraphic implications. Newsletter for Stratigraphy 26, 1–17.
Kerr, A.C., Mahoney, J.J., 2007. Oceanic plateaus: problematic plumes, potential paradigms. Chemical Geology 241, 332–353.
Klein, E.M., Langmuir, C.L., Staudigel, H., 1991. Geochemistry of basalts from the Southeast Indian Ridge, 115°E–138°E. Journal of Geophysical Research 96, 2089–2107.
Kocyigit, A., 1987. Tectono-stratigraphy of the Hasanoglan (Ankara) region: evolution of the Karakaya orogen. Yerbilimleri 14, 269–293 (In Turkish with English abstract).
Kocyigit, A., 1991. First remark on the geology of Karakaya basin. Karakaya Orogen and pre-Jurassic nappes in eastern Pontides, Turkey. Geologica Romana 27, 2–11.
Kocyigit, A., 1992. Southward-vergent imbricate thrust zone in Yuvaköy: a record of the latest compressional event related to the collisional tectonic regime in Ankara-Erzincan Suture zone. TAPG Bull 4/I, 111–118.
Koçyiğit, A., and Tokay, M., 1985. Çatalçam (Zevker)-Erzincan arasında Kuzey Anadolu Fay Kuşağı'nın sismo-tektonik incelemesi: Fay Kuşağı'nın tektono-stratigrafisi, sistematiği ve Neotektonik özellikleri. Bayındırlık ve İskan Bakanlığı, Teknik Araş. Ve Uyg. Gn. Müd., Proje Kod no: 82-04-08-00-02, 101 pp (unpublished).
Kocyigit A, Kaymakcı N, Rojay B, Özcan E, Dirik K, Özcelik Y (1991) İnegöl-Bilecik-Bozüyük arasında kalan alanın jeolojik etüdü. Orta Dogu Teknik Üniversitesi-Türkiye Petrolleri Anonim Ortaklıgı projesi raporu, no: 90-03-09-01-05 (unpublished).
Kozur, H., Aydın, M., Demir, O., Yakar, H., Göncüoglu, M.C., Kuru, F., 2000. New stratigraphic and palaeogeographic results from the Palaeozoic and early Mesozoic of the Middle Pontides (northern Turkey) in the Azdavay, Devrekani, Küre and Inebolu areas: implications for the Carboniferous-Early Cretaceous geodynamic evolution and some related remarks to the Karakaya oceanic rift basin. Geologica Croatica 53, 209–268.
Langmuir, C.H., Bender, C.F., Bence, A.E., Hanson, G.N., Taylor, S.R., 1977. Petrogenesis of basalts from the Famous area: Mid-Atlantic Ridge. Earth and Planetary Science Letters 36, 133–156.
Leeman, W.P., Hawkesworth, C.J., 1986. Open magma systems: trace element and isotopic constraints. Journal of Geophysical Research 91, 5901–5912.
Mahoney, J.J., Storey, M., Duncan, R.A., Spencer, K.J., Pringle, M., 1993. Geochemistry and geochronology of Leg 130 basement lavas: nature and origin of the Ontong Java Plateau. In: Berger, W.H., Kroenke, L.W., Mayer, L.A., et al. (Eds.), Proc ODP Sci Results 130, College Station TX (Ocean Drilling Program), pp. 3–22.
Okay, A.I., 1984. The geology of Agvanis metamorphic rocks and neighboring formations. Mineral Research and Exploration Bulletin 99 (100), 16–36.
Okay, A.I., 1989. Tectonic units in the Pontides, northern Turkey. In: Sengör, A.M.C. (Ed.), Tectonic Evolution of the Tethyan Region. Kluwer Academic Publishers, USA, pp. 109–116.
Okay, A.I., 2000. Was the Late Triassic orogeny in Turkey caused by the collision of an oceanic plateau? In: Bozkurt, E., Winchester, J., Piper, J.A. (Eds.), Tectonics and magmatism in Turkey and the Surrounding Area, vol. 173. Geological Society, London, pp. 139–161 (Special Publications).
Okay, A.I., Sahintürk, Ö., 1997. Geology of the Eastern Pontides. In: Robinson, A. (Ed.) Regional and Petroleum Geology of the Black Sea and Surrounding Region. AAPG Memoir 68, 291–311
Okay, A.I., Altiner, D., 2004. Uppermost Triassic limestone in the Karakaya Complex-stratigraphic and tectonic significance. Turkish Journal of Earth Sciences 13, 187–199.
Okay, A.I., Göncüoglu, M.C., 2004. The Karakaya Complex: a review of data and concepts. Turkish Journal of Earth Sciences 13, 77–95.
Okay, A.I., Siyako, M., Bürkan, B.A., 1991. Geology and tectonic evolution of the Biga Peninsula, northwest Turkey. Bulletin of Technical University of Istanbul 44, 191–256.
Okay, A.İ., Monod, O., Monie, P., 2002. Triassic blueschists and eclogites from northwest Turkey: vestiges of the Paleo-Tethyan subduction. Lithos 64, 155–178.
Okay, A.I., Satır, M., Maluski, H., Siyako, M., Monie, P., Metzger, R., Akyüz, S., 1996. Paleo- and Neo-Tethyan events in northwest Turkey: geological and geochronological

constraints. In: Yin, A., Harrison, M. (Eds.), Tectonics of Asia. Cambridge University Press, pp. 420–441.
Pearce, J.A., Peate, D.W., 1995. Tectonic implications of the composition of volcanic arc magmas. Annual Review of Earth and Planetary Sciences 23, 251–285.
Peate, D.W., Hawkesworth, C.J., Mantovani, M.S.M., 1992. Chemical stratigraphy of the Parana lavas (South America): classification of magma types and their spatial distribution. Bulletin of Volcanology 55, 119–139.
Pickett, E.A., Robertson, A.H.F., 1996. Formation of the Late Paleozoic–Early Mesozoic Karakaya complex and related ophiolites in northwestern Turkey by Palaeotethyan subduction–accretion. Journal of the Geology Society, London 153, 995–1009.
Pickett, E.A., Robertson, A.H.F., 2004. Significance of the volcanogenic Nilüfer Unit and related components of the Triassic Karakaya Complex for Tethyan subduction/accretion processes in NW Turkey. Turkish Journal of Earth Sciences 13, 97–143.
Rojay, B., Göncüoglu, M.C., 1997. Tectonic setting of some pre-Liassic low grade metamorphics in northern Anatolia. Yerbilimleri 19, 109–118.
Raymond, L.A., 1984. Classification of mélanges. In: Raymond, L.A. (Ed.), Mélanges: Their nature, origin, and significance: Geological Society of America, Special Paper, vol. 198, pp. 7–20.
Saha, A., Basu, A.R., Wakabayashi, J., Wortman, G.L., 2005. Geochemical evidence for a subducted infant arc in Franciscan high-grade-metamorphic tectonic blocks. Geological Society of America Bulletin 117, 1318–1335.
Sayit, K., Göncüoglu, M.C., 2009a. Geochemistry of mafic rocks of the Karakaya Complex, Turkey: evidence for plume-involvement in the extensional oceanic regime during Middle-Late Triassic. International Journal of Earth Sciences 98, 367–385.
Sayit, K., Göncüoglu, M.C., 2009b. Geochemical characteristics of the basic volcanic rocks within the Karakaya Complex: a review. Yerbilimleri 30, 181–191.
Sayit, K., Göncüoglu, M.C., Furman, T., 2008. E-MORB- and OIB-type metabasalts from the Karakaya Complex: trace element evidence for melting across the spinel–garnet transition. Eos Transactions AGU 89 (53) (Fall Meeting Supplement, Abstract V43B-2163).
Sayit, K., Göncüoglu, M.C., Furman, T., 2009. Relict Seamounts within the Palaeotethyan Karakaya Complex, Turkey. Eos Transactions AGU 90 (52) (Fall Meeting Supplement, Abstract V51C-1706).
Sengör, A.M.C., Yılmaz, Y., 1981. Tethyan evolution of Turkey: a plate tectonics approach. Tectonophysics 75, 181–241.
Sengör, A.M.C., Yılmaz, Y., Ketin, I., 1980. Remnants of a pre-Late Jurassic ocean in northern Turkey: fragments of Permian-Triassic Paleo-Tethys. Geological Society of America Bulletin 91, 599–609.
Sengör, A.M.C., Yılmaz, Y., Sungurlu, O., 1984. Tectonics of the Mediterranean Cimmerides: nature and evolution of the western termination of Paleo-Tethys. In: Dixon, J.E., Robertson, A.H.F. (Eds.), The Geological Evolution of the Eastern Mediterranean, vol. 17. Geological Society, London, pp. 77–112 (Special Publications).
Stern, R.J., Kohut, E., Bloomer, S.H., Leybourne, M., Fouch, M., Vervoort, J., 2006. Subduction factory processes beneath the Guguan cross-chain, Mariana Arc: no role for sediments, are serpentinites important? Contributions to Mineralogy and Petrology 151, 202–221.
Sun, S.-S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (Eds.), Magmatism in the Ocean Basins. Geological Society, London (Special Publications).
Taylor, S.R., McLennan, S.M., 1995. The geochemical evolution of continental crust. Reviews of Geophysics 33, 241–265.
Tekeli, O., 1981. Subduction complex of pre-Jurassic age, northern Anatolia, Turkey. Geology 9, 68–72.
Topuz, G., Altherr, R., Satır, M., Schwarz, W.H., 2004. Low-grade metamorphic rocks from the Pulur complex, NE Turkey: implications for the pre-Liassic evolution of Eastern Pontides. International Journal of Earth Sciences 93, 72–91.
Turhan, N., Okuyucu, C., Göncüoglu, M.C., 2004. Autochthonous Upper Permian (Midian) carbonates in the Western Sakarya Composite Terrane, Geyve Area, Turkey: Preliminary data. Turkish Journal of Earth Sciences 13, 215–229.
Ustaömer, T., Robertson, A.H.F., 1994. Late Paleozoic marginal basin and subduction–accretion: the Paleotethyan Küre Complex, Central Pontides, northern Turkey. Journal of the Geology Society, London 151, 291–305.
Ustaömer, T., Robertson, A.H.F., 1999. Geochemical evidence used to test alternative plate tectonic models for the pre-Upper Jurassic (Palaeotethyan) units in the Central Pontides, N Turkey. Geological Journal 34, 25–53.
Weaver, B.L., Wood, D.A., Tarney, J., Joron, J.L., 1986. Role of subducted sediment in the genesis of ocean-island basalts: Geochemical evidence from South Atlantic Ocean islands. Geology 14, 275–278.
Woodhead, J., Eggins, S., Gamble, J., 1993. High field strength and transition element systematics in island arc and back-arc basin basalts: evidence for multi-phase melt extraction and a depleted mantle wedge. Earth and Planetary Science Letters 114, 491–504.
Yaliniz, M.K., Göncüoglu, M.C., 2002. Geochemistry and petrology of “Nilüfer-type” metabasic rocks of eastern Kozak Massif, NW Turkey. 1. International Symposium of Istanbul Technical University. The Faculty of Mines on Earth Sciences and Engineering, Istanbul, Abstracts. (pp 158).