BULLETIN OF THE MINERAL RESEARCH AND EXPLORATION

Foreign Edition 2013 146

CONTENTS

From Editor...

A New Age Finding In The Central Sakarya Region (NW Turkey)
.... M. Fuat UĞUZ 1

Description Of Two New Families, Three New Species and Re-Description Of Four known Genera And One Subfamily From The Larger Benthic Foraminifera Of Paleocene In Turkey
.... Ercüment SİREL 27

The Ostracod Fauna And Environmental Characteristics Of The Volcanosedimentary Yolüstü Formation In The Hınıs Region, Erzurum (Eastern Anatolia), Turkey
.... Ümit ŞAFAK 55

Petrogenetic Characteristics Of Oyaca – Kedikayası – Boyalık Adakites In SW Ankara (Central Anatolia, Turkey): Evidences For Slab Melt Metasomatism
.... Pınar ŞEN and Erdal ŞEN 81

Hydrogeochemical And Isotopic Investigation Of Nasrettin Hoca Springs, Eskisehir, Turkey
.... Mehmet ÇELİK, U. Erdem DOKUZ, P. Elif TÜRKÖZ, Özlem GÜLLÜ and Şebnem ARSLAN 93

Neogene Stratigraphy Of The Eskişehir Graben And The Investigation Of Coal Deposition By Seismic Reflection Method
.... İlker ŞENGÜLER and Erdener IZLADI 105

Notes to the authors 117

Bulletin of MTA (2013) 146 : 81-91

Bulletin of the
Mineral Research and Exploration

http://bulletin.mta.gov.tr

PETROGENETIC CHARACTERISTICS OF OYACA – KEDİKAYASI – BOYALIK ADAKITES IN SW ANKARA (CENTRAL ANATOLIA, TURKEY): EVIDENCE FOR SLAB MELT METASOMATISM

Pınar ŞEN [a,*] and Erdal ŞEN [b]

[a] *General Directorate of Mineral Research and Exploration (MTA), Department of Mineral Researches, 06520, Ankara, TURKEY*
[b] *Hacettepe University, Faculty of Engineering, Department of Geological Engineering, 06532, Beytepe-Ankara, TURKEY*

Key words:
Adakite,
Ankara,
partial melting,
petrogenetic modeling,
metasomatism

ABSTRACT

The Early Miocene Oyaca, Kedikayası and Boyalık dacites, situated approximately 50-60 km southwest of Ankara have affinities similar to adakitic rocks. They have porphyritic texture with a variable amount of plagioclase feldspar, hornblende and lesser biotite phenocrysts and a groundmass of plagioclase and quartz microcrysts. They have high Sr/Y (55-79 ppm) and (La/Yb)n (21-32 ppm) ratios, and low Y (10-19 ppm) and heavy rare earth element contents. According to their SiO_2 (62.3-69.70 % wt.) and MgO (0.62-2.23 % wt) contents, they are referred to as high silica adakites, indicating the effects of slab-derived melts in their genesis. The adakites in the study area are enriched in Large Ion Lithophile Elements (LILE) (e.g., Ba: 800-1395 ppm, Sr≥720 ppm) relative to High Field Strength Elements (HFSE) (e.g. Nb: 20-10 ppm, Ta: 0.8-1.2 ppm). Low Rb/Sr and high Ba/Sr ratios in these adakites indicate that they are resulted from an amphibole bearing mantle source, as amphiboles have low Rb concentrations. Thus, partial melting of an amphibole bearing mantle source would be responsible for low Rb concentrations). For that reason, non-modal partial melting calculations from a 13 % amphibole bearing garnet peridotite were carried out in order to determine the source features of adakites. The variations between La/Yb vs La and (Tb/Yb)n vs (La/Yb)n in partial melting studies demonstrate that the adakites in the study area were most probably derived from an amphibole bearing garnet peridotite mantle source via 5-10 % degrees of partial melting.

1. Introduction

1.1. The Aim of the Study

Most of the magmas of subduction zone are interpreted to have formed by the partial melting of metasomatised mantle wedge. However, recent studies have shown that these magmas could also be formed by the melting of subducting oceanic crust (Defant and Drummond, 1990; Stern and Kilian, 1996; Martin, 1999; Beate et al., 2001; Bourdon et al., 2002; Defant et al., 2002). Such sodic and felsic slab melts were named as adakite by Defant and Drummond (1990). Despite many investigations have been carried out about the adakite/adakitic magmatism in recent years, their genesis and evolutionary history are still discussed. It has been suggested by studies that adakite/adakitic rocks are the products of high pressure crystal fraction and assimilation of hydrous basaltic magmas (Macpherson et al., 2006) or low pressure crystal fraction and assimilation of basaltic magmas (Castillo et al., 1999; Castillo, 2006); crystal fractionation and/or differentiation of subduction-related magma in the crust-mantle transition zone (Eyuboğlu et al., 2011*a*); partial melts of subducted oceanic crust (Defant and Drummond, 1990; Stern and Kilian, 1996; Martin, 1999; Xu et al., 2000; Beate et al., 2001; Bourdon et al., 2002; Zhu et al., 2009); partial melts of thickened and delaminated mafic lower crust (Xu et al., 2002; Chung et al., 2003;

* *Corresponding author : P. ŞEN , pinarsen@mta.gov.tr*

Hou et al., 2004; Rollinson and Tarney, 2005; Wang et al., 2005; Wang et al., 2007*a, b;* Liu et al., 2008; Karslı et al., 2010; Eyüboğlu et al., 2012b) and the products generated by a slab window processes in a subduction-related setting (Eyüboğlu et al., 2011*b, c;* Eyüboğlu et al., 2012*a, b*). Extraordinary trace element characteristics as well high Mg, Ni and Cr contents in adakite and adakitic rocks are explained as metasomatism of mantle by slab melts (Sajona et al., 2000).

Adakite and adakitic rocks can form in different tectonical environments and by different processes. In this study, the Oyaca, Kedikayası and Boyalık dacites which was previously investigated by Bozkurt et al (1999) and Alıcı Şen (2009) are re-assessed geochemically and petrogenetically to determine whether these dacites were the products of adakitic magmatism or not. In doing so; major oxide and trace element data of Oyaca, Kedikayası and Boyalık dacites have been taken from Bozkurt et al. (1999) and Alıcı Şen (2009). With regard to the chemical composition of the dacitic samples, it is concluded that that they have features similar to adakites. During the evaluation studies, petrogenetic modeling studies have been used to address the question of which source is responsible for the genesis of these rocks. The study area is located among İzmir – Ankara – Erzincan Suture Zone (IAESZ), Sakarya Continent and Kırşehir Block (Figure 1). The early tectonic evolution of the Ankara region consists of the collision of Rhodopian – Pontide plates with the Kırşehir Metamorphic Massif to the south (Şengör and Yılmaz, 1981). The IAEZS is one of the main compressional paleotectonic structures in northern Anatolia. The İzmir – Ankara suture zone is the remnant of northern branch of the Neotethys ocean which, around Ankara, was closed in late Eocene (Görür et al., 1984; Koçyiğit, 1991; Koçyiğit et al., 1995; Bozkurt et al., 1999; Kaymakçı, 2000). Extensive Miocene volcanism has developed in Ankara and its surroundings after collision (Wilson et al., 1997; Tankut et al., 1998; Toprak and Türkecan, 1998; Varol et al., 2007; Varol et al., 2008; Koçyiğit et al., 2003; Temel et al., 2010). Geological units are ophiolitic mélange and Eocene flysch consisting the remnants of Neotethyan oceanic lithosphere, volcanic products and accretionary materials derived from the northern branch of Neotethys Ocean (Koçyiğit, 1991, Tüysüz and Yiğitbaş, 1994; Bozkurt et al., 1999). There is an intrusive contact relationship between Miocene volcanic units, and Eocene flysch and the ophiolitic mélange (Ünalan and Yüksel, 1985; Bozkurt et al., 1999; Şahin, 2007). The location of the study area in regional tectonical map and its simplified geological map are given in figure 1. Sedimentary (carbonate and clastics) and volcanic rocks are the most common rock types in the region.

The study area lies within IAESZ, between the Sakarya continent and the Kırşehir block, about 50-60 km SW of Ankara. The area is important to evaluate the volcanic evolutionary history of subduction, collision and the following post collisional processes. Besides; acidic rocks of Miocene Balkuyumcu volcanism located at 20 – 30 km NW of the study area as well show similar features to adakite (Varol et al., 2006; 2007). Therefore; these adakitic volcanisms in SW Ankara are important for the determination of genetic and evolutionary stages.

2. Petrographical and Geochemical Characteristics of the Oyaca – Kedikayası – Boyalık Dacites

Dacites in the study area have hypocrystalline porphyritic texture with variable amount of plagioclase feldspar, hornblende with lesser biotite phenocrysts. Oxides are common accessory minerals. The groundmass of the rock is mainly composed of plagioclase, quartz microlites, hornblende microcrysts and lesser amount of glass. Plagioclase microlites and hornblende microcrysts in the groundmass show preferred orientation and quartz microcrysts have rounded corners. Euhedral to subhedral plagioclase phenocrysts (2 – 4 mm) are the most common mineral, and zoning and twinning are typical. Although plagioclase phenocrysts are generally fresh, some have glass inclusions and argillic alteration through their fractures and rims. Hornblende phenocrysts, displaying significant pleochroism, are present as green elongate euhedral grains. Most of the hornblende phenocrysts are characterized by oxidized rims. Hornblende phenocrysts occasionally form cumulates. Biotite phenocrysts, which exist in minor amounts, generally show brownish pleochroism. Biotite phenocrysts, which display oxide replacement around their rims, have occasionally corroded texture.

Results of major oxide and trace element analyses taken from Bozkurt et al., (1990) and Alıcı Şen (2009) are given in table 1. Rocks with dacitic composition are calc-alkaline in character with high SiO_2 (% 62-70 wt.), Al_2O_3 (>% 15.50 wt.), Na_2O (>% 4.0 wt.), Sr (648-1026 ppm), Ba (648-1810 ppm), low TiO_2 (<% 0.90 wt.), K_20 (% 1.51-2.08 wt.), high field strength element (HFSE) (Nb: 20-10 ppm, Ta: 0.8-1.2 ppm), heavy rare earth element (HREE) [especially Yb (<1.70 ppm)] and Y contents. High Sr, low Y values and high

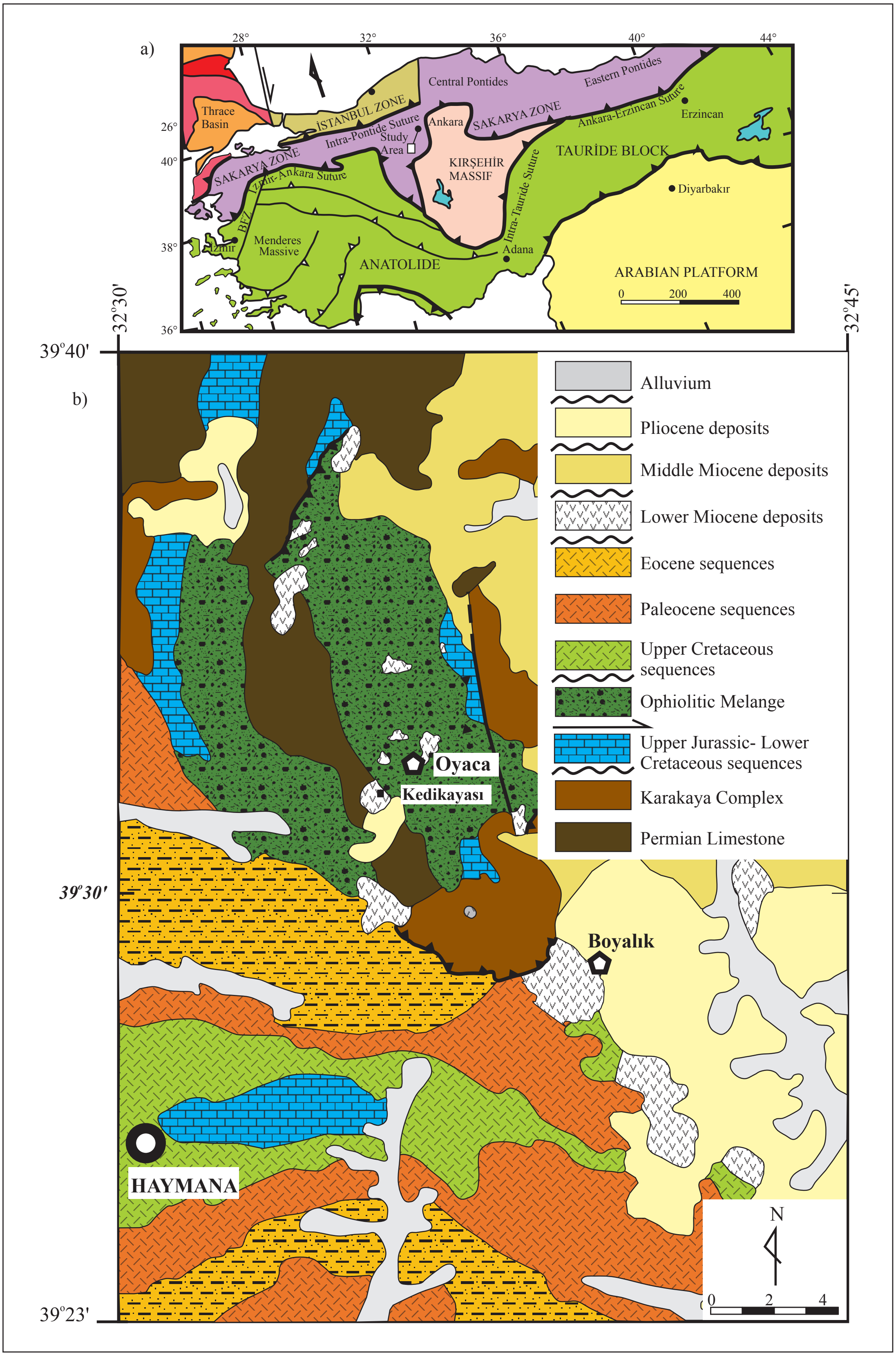


Figure 1-a) Tectonics of Turkey (Okay and Tüysüz, 1999); b) Simplified geological map of studied area and its surroundings (after 1/500.000 scaled map of MTA).

Table 1- Major-oxide, trace and rare earth element data of Oyaca, Kedikayası ve Boyalık adakites (data from Bozkurt et al., 1999 and Alıcı Şen, 2009).

	OYACA				KEDİKAYASI				BOYALIK							
	OY3	OY6	OY7	OY9	OY15	OY17	OY18	OY20	BY-06-1	BY-06-2	BY-06-3	BY-06-4	BY-06-5	BY-06-6	BY-06-13	BY-06-14
SiO_2 (wt. %)	66,12	64,54	62,3	65,43	65,18	63,42	64,46	65,4	64,77	66,51	66,20	66,19	65,50	69,68	63,44	63,03
MgO	1,13	1,85	1,74	1,62	1,78	2,23	1,68	0,68	1,69	1,45	1,77	0,62	1,58	0,50	1,27	0,97
CaO	4,11	5,18	5,73	5,27	4,37	4,84	4,52	4,28	6,52	4,95	4,85	5,27	4,93	3,67	5,08	4,86
MnO	0,06	0,06	0,09	0,06	0,07	0,12	0,07	0,05	0,11	0,07	0,06	0,06	0,04	0,00	0,02	0,02
TiO_2	0,49	0,47	0,59	0,47	0,5	0,54	0,57	0,48	0,59	0,51	0,48	0,54	0,44	0,46	0,83	0,86
FeO	2,55	2,60	3,05	2,42	2,86	3,01	2,79	2,34	2,88	2,74	2,76	2,53	2,17	1,74	2,71	2,63
Fe_2O_3	1,02	1,04	1,22	0,97	1,15	1,20	1,12	0,93	1,15	1,10	1,11	1,01	0,87	0,69	1,08	1,05
Na_2O	4,09	4,37	4,2	4,64	4,8	5,06	4,88	5,12	3,52	4,07	4,29	4,35	4,31	4,27	4,40	4,40
K_2O	1,61	1,51	1,52	1,63	2,08	1,87	1,91	1,99	2,16	1,77	1,62	2,04	1,65	1,74	1,77	1,76
Al_2O_3	16,16	15,67	15,41	16,02	16,14	16,28	16,66	16,88	16,80	16,17	16,42	17,10	16,67	17,10	17,44	17,61
P_2O_5	0,29	0,26	0,36	0,27	0,37	0,44	0,35	0,31	0,30	0,26	0,25	0,27	0,20	0,22	0,52	0,52
Total	97,63	97,55	96,21	98,8	99,3	99,01	99,01	98,46	100,51	99,61	99,81	99,97	98,35	100,08	98,58	97,72
Cr (ppm)	48	28	38	39	22	26	28	24	11,47	10,65	11,67	16,34	34,08	37,04	18,36	18,92
Ni	26	19	24	23	16	25	16	13	20,12	10,29	10,86	11,61	34,77	20,20	24,73	23,23
Zr	110	131	103	118	155	139	142	138	86,26	75,46	63,52	73,50	83,91	107,20	81,19	78,91
Rb	44	45	42	43	54	48	49	52	66,71	41,16	40,42	44,67	37,01	39,22	29,02	19,33
Sr	775	940	831	868	892	946	1007	1026	772,27	720,45	780,85	890,08	647,65	658,41	953,28	975,06
Y	14	15	15	11	17	15	17	13	12,15	11,20	10,48	14,03	10,47	10,64	16,76	18,64
Nb	16	15	17	15	18	19	17	20	10,49	12,83	11,82	12,80	11,05	11,84	17,91	17,78
Ba	938	1210	919	873	1332	1311	1295	1393	1810,82	948,08	951,41	1052,71	650,92	647,67	804,27	806,44
La	63	37	76	35,8	49	46,3	59	51	46,64	38,51	37,46	46,16	28,71	31,57	43,27	43,30
Ce	49	66	48	63,3	97	82	86	86,3	82,05	67,66	66,24	74,55	50,61	53,10	81,59	81,55
Pr		7,13		6,86		9		9,45	8,95	7,40	7,20	9,13	5,54	6,10	9,46	9,46
Nd	27	24,2	32	23,5	37	31,4	26	32,1	29,30	24,14	23,55	30,66	18,31	20,24	32,70	32,96
Sm		3,54		3,47		4,64		4,55	4,46	3,75	3,61	4,97	3,01	3,35	5,47	5,55
Eu		1,05		1,04		1,36		1,35	1,47	1,16	1,11	1,42	0,93	1,00	1,54	1,60
Tb		0,37		0,37		0,47		0,44	0,46	0,41	0,39	0,55	0,36	0,38	0,60	0,63
Gd		2,76		2,7		3,58		3,31	3,23	2,83	2,74	3,77	2,46	2,66	4,23	4,32
Dy		1,9		1,88		2,48		2,27	2,21	2,03	1,97	2,74	1,90	1,98	3,04	3,31
Ho		0,36		0,36		0,47		0,42	0,41	0,37	0,37	0,52	0,36	0,37	0,58	0,64
Er		0,95		0,97		1,24		1,13	1,10	1,01	1,02	1,42	0,99	0,99	1,52	1,78
Yb		0,93		0,94		1,19		1,08	0,98	0,90	0,93	1,33	0,91	0,89	1,41	1,68
Lu		0,15		0,15		0,19		0,16	0,14	0,12	0,15	0,20	0,14	0,14	0,21	0,26
Hf		1,47		1,71		1,42		1,24	0,86	0,84	1,71	1,31	2,21	1,94	2,36	2,33
Ta		0,86		0,85		1,1		1,18	0,72	0,91	0,84	0,89	0,82	0,80	1,11	1,11
Pb	21	31	19	20	36	27	28	32	21,18	21,81	18,04	21,71	23,53	18,82	21,19	22,20
Th	9	10,7	10	10,5	16	13,7	11	15,7	13,51	10,55	10,86	11,31	8,27	8,24	9,39	8,89
U		2,36		2,85		2,81		2,45	3,90	2,30	2,55	2,92	2,20	1,68	1,90	1,54

Sr/Y ratios are the general characteristics of adakitic rocks and reflect the features of high pressure and slab melting (Defant and Drummond, 1990; Martin et al., 2005). According to these criteria; Oyaca, Kedikayası and Boyalık dacites plot in the adakitic area in Sr/Y-Y and (La/Yb)n-(Yb)n diagrams with their high Sr/Y (55-79) and (La/Yb)n (21-32) (Thompson (1982) and low Y (10-19) and (Yb)n (5.2-6.4) contents (Figures 2 and 3). (Hereinafter "adakite" term will be used).

In the MgO-SiO_2 differentiation diagram (Figure 4) (Martin et al., 2005), all the samples plot in the high SiO2 adakite region, indicating the effects of slab-melting in the genesis of adakites (Martin et al., 2005).

Primitive mantle and Mid Ocean Ridge Basalts (MORB)-normalized spidergrams of the selected samples from Oyaca-Kedikayası-Boyalık adakites are illustrated in figure 5. The common features of

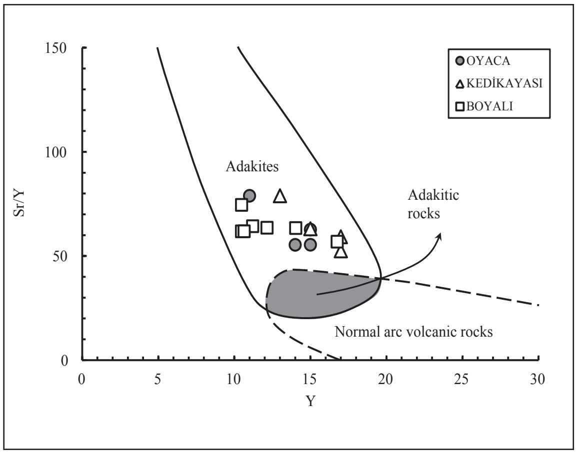


Figure 2- Sr/Y-Y discrimination diagram of studied adakites (Defant and Drummond, 1990).

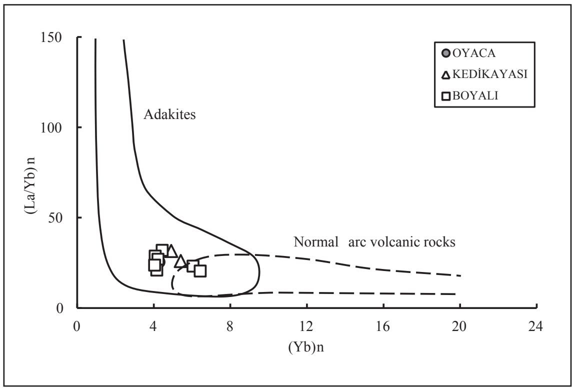


Figure 3- (La/Yb)n- (Yb)n discrimination diagram of studied adakites (Defant and Drummond, 1990). Values normalized to chondrite (Thompson, 1982).

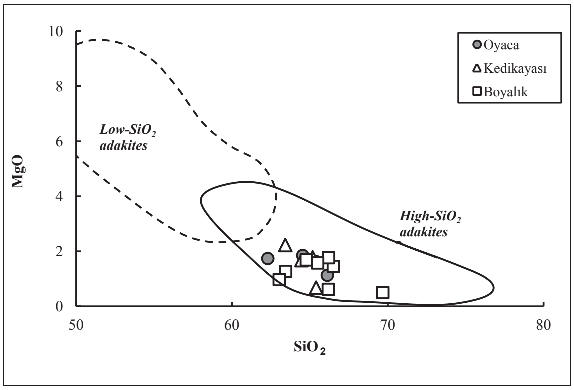
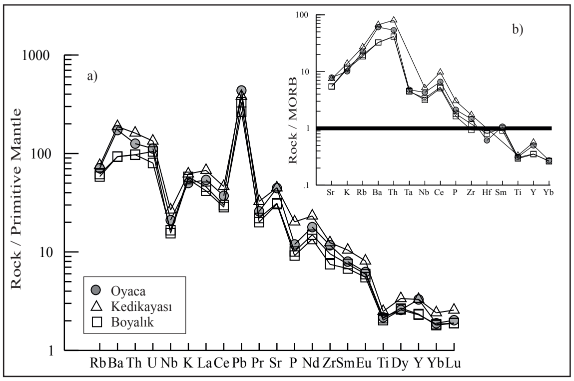


Figure 4- MgO-SiO_2 discrimination diagram of studied adakites.



Figurel 5-a) Primitive mantle (Sun and McDonough, 1989) and b) MORB (Pearce, 1983) normalized spider diagrams of the representative samples from studied adakites.

the samples are negative anomalies in Nb, Ta and Ti and positives anomalies in K, Th, Ba and Pb elements. Moreover, samples are enriched in large ion lithophile elements (LILE) but are depleted in Y and Yb relative to MORB.

Chondrite-normalized rare earth element (REE) spidergram (Nakamura, 1974) (Figure 6) demonstrate that the studied adakites are enriched in light rare earth elements (LREE) relative to heavy rare earth elements (HREE). High [(La/Yb)n: 21-32] ratio also indicates a significant LREE / HREE fractionation.

3. Source Characteristics and Petrogenetic Modelling

Adakites and adakitic rocks are represented by high concentrations of Al_2O_3 (≥%15), Na_2O (3.52-5.12), La/Yb, and low HFS (Nb, Ta) elements, and low Yb contents along with their high SiO_2 content (Richards and Kerrich, 2007; Eyüpoğlu et al., 2011*a, b, c;* Eyüboğlu, 2012*a, b*). High Sr, low Y and Yb

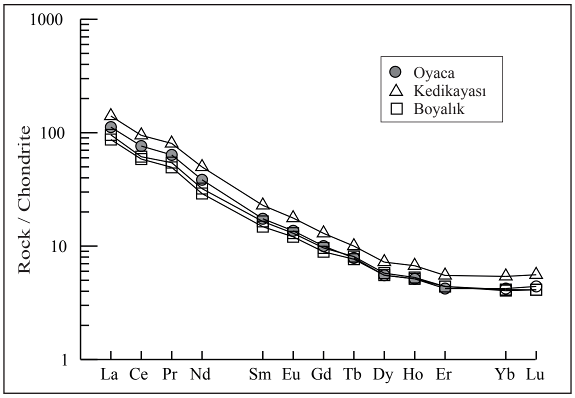


Figure 6- Chondrite-normalized rare earth element (Nakamura, 1974) spider diagrams for the representative samples from studied adakites.

values can be explained by the presence of plagioclase and/or garnet minerals in the source area. The degree of enrichment of Sr and Yb elements in the melt is controlled by the residual plagioclase and garnet phase in the basaltic source. The partition coefficient (Kd) of Sr element in plagioclase for basaltic melts is 1.83; however, Kd value of Y element in garnet is around 11.50 (Rollinson, 1993). Accordingly; in cases when plagioclase and garnet are residual phases, the enrichment level of Sr and Yb, respectively, will be low. The stability of plagioclase depends on the pressure. While the plagioclase mineral loses its stability under high pressure conditions, garnet becomes stable (Moyen, 2009). Therefore; under these conditions, while Sr becomes enriched in liquid phase, Yb becomes enriched in garnet phases. This explains the high Sr/Y ratios in adakites. High Sr and Sr/Y ratios combined with low Y and Yb contents can also be observed in asthenosphere derived magmatic rocks, but these rocks are generally represented by high Nb, Nb/Y (>1.5), Nb/La (>1.0) ratios (Edwards et al., 1991; Pearce, 1983; Jung and Hoernes, 2000). However; adakites are depleted in Nb, Ti and Ta. Thus, when the chondrite-normalized spider diagrams of the Oyaca, Kedikayası and Boyalık adakites are studied, positive anomalies in Ba, K and Th elements and negative anomalies in Nb, Ta and Ti elements are observed together with high Sr and low Y and Yb concentrations (Figure 5). Such geochemical features are characteristic for subduction zone magmatism, because phases such as sphene, rutile and perovskite are stable at 80 – 100 km depths in subduction zones. Elements such as, Nb, Ta and Ti in such conditions are retained in these stable phases, so the magmas becomes depleted in these elements (Saunders et al, 1980; Foley et al, 2000; Ringwood, 1990). Futhermore, high Ba/Nb (45-172) and Nb/La (≤0.41) ratios in Oyaca, Kedikayası and Boyalık adakites indicate that magmatic rocks in the study area were not derived directly from asthenospheric mantle, which suggests the presence of subduction signatures in the genesis of volcanism (Gill, 1981; Fitton et al., 1991; Wang et al., 2004).

In addition; Nb and Ta contents of the slab derived melts and fluids also presents differences among them because slab derived fluids are depleted in Nb and Ta with respect to slab-derived melts (Tatsumi et al., 1986; Tatsumi and Nakamura, 1986; Martin et al., 2005). Defant et al. (1992), Maury et al. (1996), Sajona et al. (1996) and Martin et al. (2005) claim that mantle wedge derived magmas which have been metasomatized by slab melts are high in Nb (7 ppm<Nb<20 ppm). Nb contents in Oyaca, Kedikayası and Boyalık adakites range between 11-20 ppm and relatively high Nb content reveals that adakites in the study area might have been derived from a mantle source which was enriched in slab melts.

Rb/Sr, Ba/Rb and K/Rb ratios are used to determine the presence of phlogopite and amphibole in the source region because while amphibole has high K and very low Rb contents, the phlogopite is enriched in Rb, Ba and K (Ionov and Hofmann, 1995; Martin et al., 2005). Accordingly; the melt of an amphibole bearing source is characterized by low Rb, Rb/Sr and high K/Rb , and the melt of a phlogopite bearing source has low K/Rb and high Rb/Sr ratios (Furman and Graham, 1999). Rogers et al. (1985), Calmus et al. (2003) and Martin et al. (2005) emphasize that the depletion in Rb in adakitic rocks is an indicator for the presence of metasomatic amphibole in peridotitic source. Moreover; the existence of amphibole and/or phlogopite in the source region can be related to metasomatised mantle as both minerals are metasomatic volatile bearing phases (Jiang et al., 2012). Adakites in the study area plot close to the amphibole bearing source in Rb/Sr – Ba/Rb diagram (Figure 7). In addition, the K/Rb ratio in adakites is used to determine the character of the source region. This ratio is approximately 1050 in low silica adakites but is around 350 in high silica adakites (Martin et al., 2005). The K/Rb ratio varies between 270 – 380 in Oyaca, Kedikayası and Boyalık adakites. This variation indicates that adakites in the study area have characteristics similar to high silica adakites that may have been derived from a metasomatic peridotite source, which interacted with slab melts. Therefore; as mentioned above, it is plausible that samples in the investigated area have not been derived from an asthenospheric source, but the source consists of subduction components.

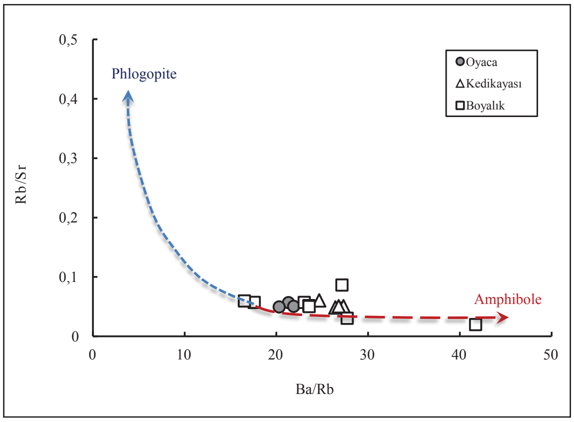


Figure 7- Rb/Sr - Ba/Rb discrimination diagram of studied adakites (Furman and Graham, 1999).

Low Nb/La and high Rb/Ba ratios also support the arguments mentioned above (Figure 8) since the low Nb/La ratio (<1) indicates the presence of subduction components at the magmatism. However, high Ba/Rb ratio occurs as a result of slab-melt or melting of subducting sediment (Wang et al., 2004). According to low Nb/La (≤0.41) and high Rb/Ba ratios in Oyaca, Kedikayası and Boyalık adakites, slab or sediment melting is likely during in their genesis (Figure 8).

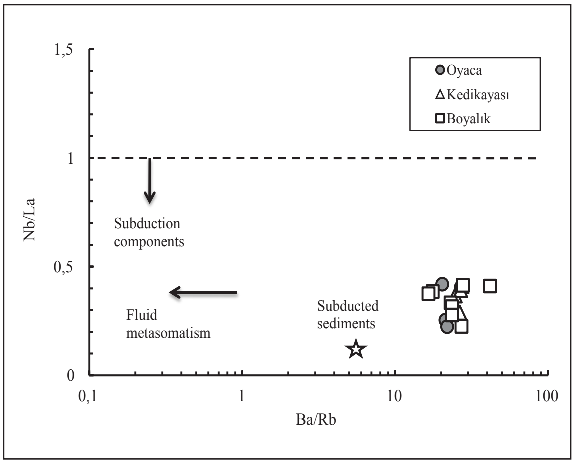


Figure 8-Nb/La - Ba/Rb discrimination diagram of studied adakites (Wang et al., 2004).

Low Rb/Sr (0.02-0.09) ratios and low % K2O (1.5 - 2.2) and high Mg # (31-57) values in Oyaca, Kedikayası and Boyalık adakites also indicate the interaction of slab melt / mantle peridotite, because low Rb/Sr (0.01-0.04) (Hou et al., 2004) and high Mg# values are encountered in the interaction of slab derived melt / mantle peridotite (Rapp et al., 1999; Hou et al., 2004). However, the processes such as lower crustal melting and/or crustal contamination are responsible for low MgO contents, Mg# values and high K_2O contents in adakites.

Consequently; the general opinion obtained from trace element geochemistry shows that adakites in the study area have an amphibole bearing metasomatized mantle source. Therefore; non-modal batch melting model of Shaw's (1970) was applied using rare earth element data. In the modeling, 13% amphibole bearing garnet peridotite [Sample no: MK5C, (Rampone and Morten, 2001)], which is the fragments of metasomatized mantle wedge, were used as initial composition. The melting model was calculated starting from this initial composition. Mineral / melt partition coefficient (Kd) values of rare earth elements are from Rollinson (1993) and Mc Kenzie and O'Nions (1991). La, Ce, Tb and Yb concentrations and modal mineralogy of amphibole – garnet peridotite (Xi), and the melting mode values (Pi) are from Rampone and Morten (2001) and Barry et al. (2003), respectively. Data used in the calculation of modeling are seen in table 2.

Table 2- Values used in non-modal batch melting model calculations.

	Amphibole-garnet peridotite	
	Source Mode (Xi)	Melt Mode (Pi)
Olivine	0,77	0,05
Orthopyroxene	0,05	0,05
Clinopyroxene	0,01	0,30
Amphibole	0,13	0,20
Garnet	0,04	0,40
	Bulk Partition Coefficient (D_0)	Melt Mode (P_0)
La	0,0110	0,0863
Ce	0,0193	0,1377
Tb	0,0973	0,5756
Yb	0,2760	1,1875
	Starting Composition Initial Concentration (C0)	
La	2,800	
Ce	5,250	
Tb	0,056	
Yb	0,230	

Rare earth element values of amphibole garnet-peridotite obtained from non-modal batch melting at different melting degrees (F %) are listed in table 3 and chondrite normalized spider diagram is illustrated in figure 9. According to this diagram, it is considered that Oyaca, Kedikayası and Boyalık adakites have been formed from a source represented by amphibole garnet peridotite via 5 -10 % F partial melting.

Similarly; La/Yb-La and (Tb/Yb)n-(La/Yb)n diagrams are shown in figure 10. La/Yb and Tb/Yb ratios change depending on the presence of garnet mineral. High La/Yb and Tb/Yb ratios indicate a residual garnet phase (Moufti et al., 2012) because,

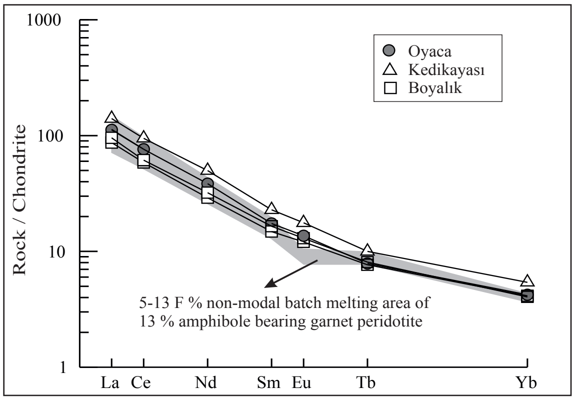


Figure 9- The comparison of Oyaca, Kedikayası and Boyalık adakites with data calculated from non-modal batch melting of 13 % amphibole bearing garnet peridotite at 5 and 13 % melting on a primitive-normalized REE spider diagram. (Chondrite-normalization data are from Nakamura (1974).

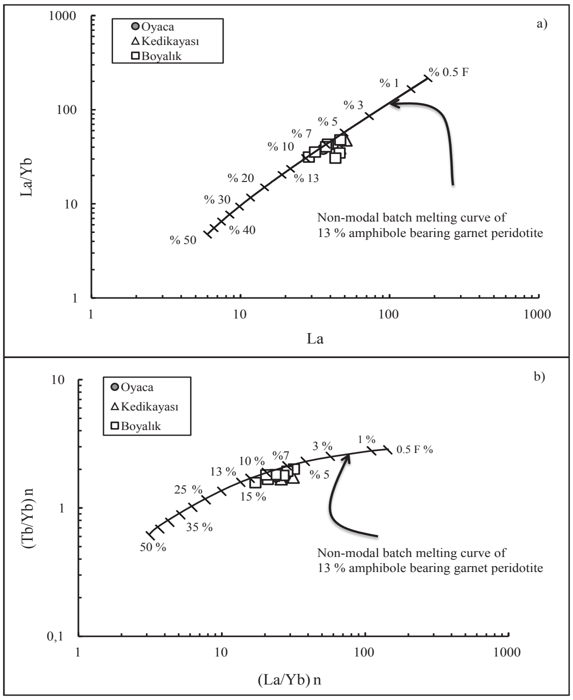


Figure 10- a) La/Yb-La and b) (Tb/Yb)n - (La/Yb)n diagrams for the Oyaca, Kedikayası and Boyalık adakites on non-modal batch melting models of amphibole bearing garnet peridotite. Ticks with a number represent the degree of partial melting. n denotes normalization to Chondrite of Thompson (1982).

as also mentioned above, Yb element exhibits a compatible behavior with garnet phase and is retained by garnet. It is observed that adakites in the study area plot on the amphibole bearing garnet peridotite melting curve.

Geochemical data and petrogenetic modeling studies show that Oyaca, Kedikayası and Boyalık adakites represent 5 -13 % partial melts from an amphibole bearing mantle source. Besides, the presence of amphibole minerals in samples also indicates that hydrous conditions were effective at the source of volcanism. It is considered that early Miocene Oyaca, Kedikayası and Boyalık adakites located in the post collisional environment were derived from an enriched peridotitic mantle source which was interacted with slab melts during previous subduction process.

4. Conclusions

In this study, it is determined that early Miocene dacitic rocks from the Oyaca, Kedikayası and Boyalık alkaline and calc alkaline magmatic suite are adakite in composition. Geochemical evaluations are consistent with the effects of subduction processes in the genesis of Oyaca, Kedikayası and Boyalık adakites. High silica, MgO and Nb contents indicate that slab derived melts had played an important role in the genesis of these rocks.High Ba / Rb ratio also indicates the presence of amphibole in their origin. Therefore; the studies of petrogenetic modeling were performed starting from an amphibole bearing peridotite source. The result of the modeling suggests that the adakites formed by 5-13 % partial melting of the amphibole bearing peridotite source.

Acknowledgments

We would like to thank to Prof. Erdin Bozkurt and Prof. Erkan Aydar for their supports during the reassessment of samples and to Prof. Güner Ünalan and Dr. Bahadır Şahin for their supportive criticisms and contributions. We are greatly indebted to Dr. Yavuz Hakyemez for his helps during the preparation of the geological map.

Received : 11.09.2012
Accepted : 28.01.2013
Published : June 2013

References

Alıcı Şen, P. 2009. Trace element modelling of the origin and evolution of the Oyaca-Boyalik volcanic rocks (NE of Haymana, Ankara, Turkey). *International Geology Review*, 51 (2),116-132.

Barry, T.L., Saunders, A.D., Kempton, P.D., Windley, B.F., Pringle, M.S. Dorjnamjaa, D., Saandar, S. 2003. Petrogenesis of Cenozoic basalts from Mongolia: evidence for the role of asthenospheric versus metasomatized lithospheric mantle sources. *Journal of Petrology* 44, 5–91.

Beate, B., Monzier, M., Spikings, R., Cotton, J., Silva, J., Bourdon, E., Eissen, J.P. 2001. Mio- Pliocene adakite generation related to flat subduction in southern Ecuador: the Quimsacocha volcanic center. Earth and Planetary Science Letters 192, 561-570.

Bourdon, E., Eissen, J.P., Monzier, M., Robin C., Martin H., Cotton J., Hall M.L. 2002. Adakite-like lavas from Antisana volcano (Ecuador): evidence for slab melt metasomatism beneath the Andean Northern Volcanic Zone. *Journal of Petrology*, 43, 199-217.

Bozkurt, E., Koçyiğit, A., Winchester J.A., Holland, G., Beyhan, A. 1999. Petrochemistry of the Oyaca-Kedikayası (Ankara) dacites as evidence for the post-collisional tectonic evolution of North-central anatolia. *Geological Journal* 34, 223-234.

Calmus, T., Aguillon-Robles, A., Maury, R.C., Bellon, H., Benoit, M., Cotten, J., Bourgois, J., Michaud, F. 2003. Spatial and temporal evolution of basalts and magnesian andesites (bbajaitesQ) from Baja California, Mexico: the role of slab melts. *Lithos* 66 (1–2), 77– 105.

Castillo, P.R., Janney, P.E., Solidum, R.U. 1999. Petrology and geochemistry of Camiguin island, southern Philippines: insights to the source of adakites and other lavas in a complex arc setting. *Contributions to Mineralogy and Petrology* 134, 33-51.

Castillo, P.R. 2006. An overview of adakite petrogenesis. Chinese Science Bulletin 51, 257-268.

Chung, S.L., Liu, D., Ji, J., Chu, M.F., Lee, H.Y., Wen, D.J., Lo, C.H., Lee, T.Y., Qian, Q., Zhang, Q. 2003. Adakites from continental collision zones: melting of thickened lower crust beneath southern Tibet. *Geology* 31, 1021-1024.

Defant, M.J., Drummond, M.S. 1990. Derivation of some modern arc magmas by melting of young subducted lithosphere. *Nature* 347, 662-665.

Defant, M.J., Jackson, T.E., Drummond, M.S., De Boer, J.Z., Bellon, H., Feigenson, M.D., Maury, R.C., Stewart, R.H. 1992. The geochemistry of young volcanism throughout western Panama and southeastern Costa Rica: an overview. *Journal of Geological Society* (London) 149, 569– 579.

Defant, M.J., Xu, J.F., Kepezhinskas, P., Wang, Q., Zhang, Q., Xiao, L. 2002. Adakites: some variations on a theme. *Acta Petrologica Sinica* 18, 129–142.

Edwards, C., Menzies, M., Thirwall, M. 1991. Evidence from Muriah, Indonesia, for the interplay of supra-subduction zone and intraplate processes in the genesis of potassic alkaline magmas. *Journal of Petrology* 32, 555-592.

Eyüboğlu, Y., Santosh, M., Chung, S.L. 2011*a*. Crystal fractionation of adakitic magmas in the crust-mantle transition zone: Petrology, geochemistry and U-Pb zircon chronology of the Seme adakites, Eastern Pontides, NE Turkey. *Lithos*, 121, 151-166.

Eyüboğlu, Y., Chung, S.L., Santosh, M., Dudas, F.O., Akaryali, E. 2011*b*. Transition from shoshonitic to adakitic magmatism in the Eastern Pontides, NE Turkey: Implications for slab window melting. *Gondwana Research*, 19, 413-429.

Eyüboğlu, Y., Santosh, M., Chung, S.L. 2011*c*. Petrochemistry and U-Pb zircon ages of adakitic intrusions from the Pulur Massif (Eastern Pontides, NE Turkey): implications for slab roll-back and ridge subduction associated with Cenozoic convergent tectonics in Eastern Mediterranean. *Journal of Geology*, v. 119, p. 394-417.

Eyüboğlu, Y., Santosh, .M., Dudas, F.O., Akaryalı, E., Chung, S.L., Akdağ, K., Bektaş, O. 2012*a*. The nature of transition from adakitic to non-adakitic magmatism in a slab-window setting: A synthesis from the Eastern Pontides, NE Turkey. *Geoscience Frontiers*, doi: 10.1016/jgsf.2012.10.001.

Eyüboğlu, Y, Santosh, M., Yi, K., Bektaş, O., Kwon, S. 2012*b*. Discovery of Miocene adakitic dacite from the Eastern Pontides Belt and revised geodynamic model for the late Cenozoic Evolution of eastern Mediterranean region. *Lithos,* 146-147, 218-232.

Fitton, J. G., James, D., Leeman, W. P. 1991. Basic magmatism associated with Late Cenozoic extension in the Western United States: compositional variations in space and time. *Journal of Geophysical Research*, 96, No: B8, 13693-13711.

Foley, S.F., Barth, M.G., Jenner, G.A. 2000. Rutile/melt partition coefficients for trace elements and an assessment of the influence of rutile on the trace element characteristics of subduction zone magmas. *Geochimica et Cosmochimica Acta* 64, 933–938.

Furman, T., Graham D. 1999. Erosion of lithospheric mantle beneath the East African Rift system: evidence from the Kivu volcanic province. *Lithos* 48, 237-262.

Gill, J.B. 1981. Orogenic andesites and Plate tectonics. *Springer - Verlag*, New York.

Görür, N., Oktay, P.Y., Seymen, I., Şengör, A.M.C. 1984. Palaeotectonic evolution of the Tuzgölü basin complex, central Turkey: sedimentary record of a Neotethyan closure. In: Dixon, J. E. and Robertson, A. H. F. (eds) The Geological Evolution of the Eastern Mediterranean. *Geological Society (London)*, Special Publications 17. 467-482.

Hou, Z.Q., Gao, Y.F., Qu, X.M., Rui, Z.Y., Mo, X.X. 2004. Origin of adakitic intrusives generated during mid-Miocene east-west extension in southern Tibet. *Earth and Planetary Science Letters* 220, 139-155.

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 Letter* 131 (3-4), 341-356.

Jiang, Y.-H., Liu, Z. Jia, R.-Y. Liao, S.-Y. Zhou, Q., Zhao, P. 2012. Miocene potassic granite–syenite association in western Tibetan Plateau: Implications for shoshonitic and high Ba–Sr granite genesis. *Lithos* 134-135, 146-162.

Jung, S., Hoernes, S. 2000. The major- and trace-element and isotope (Sr, Nd, O) geochemistry of Cenozoic alkaline rift-type volcanic rocks from the Rhön area (central Germany): petrology, mantle source characteristics and implications for asthenosphere-lithosphere interactions. *Journal of Volcanology and Geothermal Research* 99, 27-53.

Karslı, O., Dokuz, A., Uysal, İ., Aydın, F., Kandemir, R., Wijbrans, J. 2010. Generation of the Early Cenozoic adakitic volcanism by partial melting of mafic lower crust, Eastern Turkey: Implications for crustal thickening to delamination. *Lithos* 114, 109-120.

Kaymakçı, N. 2000. Tectonostratigraphical evolution of the Çankırı Basin (Central Anatolia, Turkey). Geological Survey Division, ITC-Enschede,The Netherland, PhD thesis, 245p.

Koçyiğit A. 1991. An example of an accretionary fore-arc basin from northern central Anatolia and its implications for the history of subduction of Neotethys in Turkey. *Geological Society of America Bulletin* 103, 22-36.

Koçyiğit A., Türkmenoğlu, A., Beyhan, A., Kaymakçı, N., Akyol, E. 1995. Post collisional tectonics of Eskişehir-Ankara-Çankırı segmants of the İzmir-Ankara-Erzincan suture zone (IAESZ): Ankara orogenic phase. *Turkish Association of Petroleum Geologists Bulletin* 6, 69-86.

Koçyiğit A., Winchester, A.J., Bozkurt, E., Holland, G. 2003. Saraçköy volcanic suite: implications for the subductional phase of arc evolution in the Galatean Arc Complex, Ankara, Turkey. *Geological Journal* 38, 1–14.

Liu, S., Hu, R-Z., Feng, C-X., Zhou, H-B., Li, C., Chi, X-G., Peng, J-T., Zhong, H., Qi, L., Qi, Y-Q., Wang, T. 2008. Cenozoic high Sr/Y volcanic rocks in the Qiangtang terrane, northern Tibet: geochemical and isotopic evidence for the origin of delaminated lower continental melts. *Geological Magazine* 145, 463-474.

Macpherson, C.G., Dreher S.T., Thirwall M.F. 2006. Adakites without slab melting: high pressure differentiation of island arc magma, Mindanao, the

Philippines. *Earth and Planetary Science Letters* 243, 581-593,.

Martin, H. 1999. The adakitic magmas: modern analogues of Archaean granitoids. *Lithos* 46 (3), 411– 429.

Martin, H., Smithies, R.H., Rapp, R., Moyen, J.F., Champion, D. 2005. An overview of adakite, tonalite-trondhjemite-granodiorite (TTG) and sanukitoid: relationships and some impplications for crustal evolution. *Lithos* 79, 1-24.

Maury, R.C., Sajona, F.G., Pubellier, M., Bellon, H., Defant, M.J. 1996. Fusion de la croute oceanique dans les zones de subduction/collision recentes: l'exemple de Mindanao (Philippines). *Bulletin de la Societe Geologique de France* 167 (5), 579– 595.

McKenzie, D.P., O'Nions, R.K. 1991. Partial melt distributions from inversion of rare earth element concentrations. *Journal of Petrology* 32, 1021-1091.

Moufti, M.R., Moghazi, A.M., Ali, K.A. 2012. Geochemistry and Sr–Nd–Pb isotopic composition of the Harrat Al-Madinah Volcanic Field, Saudi Arabia, *Gondwana Research* 21, 670-689.

Moyen, J., F. 2009. High Sr/Y ve La/Yb ratios: The meaning of the "adakitic signature". *Lithos* 112, 556–574.

Nakamura, N. 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. *Geochimica et Cosmochimica Acta* 38, 757-75.

Okay, A.İ., Tüysüz, O. 1999. Tethyan sutures of northern Turkey. In: Durand, B., Jolivet, L., Horvath, F., Seranne, M. (Eds.), The Mediterranean Basin: Tertiary Extension within the Alpine Orogen, 156. *Geological Society, Special Publications,* London, pp. 75– 515.

Pearce, J.A. 1983. The role of subcontinental lithosphere in magma genesis destructive plate margins. In: continental basalt and Mantle xenolits, C. J. Hawkesworth and M.J. Nory (eds) 230-249.

Rampone, E., Morten, L. 2001. Records of crustal metasomatism in the garnet peridotites of the Ulten zone (Upper Austroalpine, Eastern Alpes). *Journal of Petrology* 42(1), 201-219.

Rapp, P.R., Shimizu, N., Norman, M.D., Applegate, G.S. 1999. Reaction between slab-derived melt and peridotite in the mantle wedge: Experimental constrains at 3.8 GPa. *Chemical Geology* 160, 335-356.

Richards, J.P., Kerrich, R. 2007. Special paper: adakite-like rocks: their diverse origins and questionable role in metallogenesis. *Economic Geology* 102, 537–576.

Ringwood, A.E. 1990. Slab-Mantle interactions: Petrogenesis of intraplate magmas and structure of the upper mantle. *Chemical Geology*, 82, 187-207.

Rogers, G., Saunders, A.D., Terrell, D.J., Verma, S.P., Marriner, G.F. 1985. Geochemistry of Holocene volcanic rocks associated with ridge subduction in Baja California, Mexico. *Nature* 315, 389– 392.

Rollinson, H.R., Tarney, J. 2005. Adakites-the key to understanding LILE depletion in granulites. *Lithos*, 79, 61-81.

Rollinson, H.R. 1993. Using geochemical data: evaluation, presentation, interpretation. *Longman Scientific and Technical*, John Wiley and Sons, Inc., New York, 352p.

Sajona, F.G., Maury, R., Bellon, H., Cotten, J., Defant, M.J. 1996. High field strength element enrichment of Pliocene–Pleistocene island arc basalts, Zamboanga Peninsula, western Mindanao (Philippines). *Journal of Petrology* 37 (3), 693–726.

Sajona, F.G., Naury, R.C., Pubellier, M., Leterrier, J., Bellon, H., Cotton, J. 2000. Magmatic source enrichment by slab-derived melts in a young post-collision setting, central Mindanao (Philippines). *Lithos* 54, 173–206

Saunders, A.D., Tarney, J., Weawer S.D. 1980. Transverse geochemical variations across Antarctic Peninsula: implications for the genesis of calc-alkaline magmas. *Earth and Planetary Science Letters* 46, 344-360.

Shaw, D.M. 1970. Trace element fractionation during anatexis. *Geochimica et Cosmochimica Acta* 34, 237-243.

Stern C.R., Kilian R. 1996. Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Austral Volcanic Zone. *Contributions to Mineralogy and Petrology* 123, 263-281,

Sun, S.S., McDonough, W.F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D. and Norry, M.J. (eds.), Magmatism in ocean basins. *Geological Society* (London), Special Publication 42, 313-345.

Şahin, M. B. 2007. An important chabasite occurrence in central Anatolia and its mineralogical features. *Bulletin of the Mineral Research and Exploration* 135, 31-44.

Şengör, A.M.C., Yılmaz, Y. 1981. Tethyan evolution of Turkey: a plate tectonic approach. *Tectonophysics* 75, 181-241.

Tankut, A., Wilson, M., Yihunie, T. 1998. Geochemistry and tectonic setting of Tertiary volcanism in the Güvem Area, Anatolia, Turkey. *Journal of Volcanology and Geothermal Research* 85, 285-301.

Tatsumi, Y., Hamilton, D.L., Nesbitt, R.W. 1986. Chemical characteristics of fluid phase from the subducted lithosphere: evidence from high-presseure experiments and natural rocks. *Journal of Volcanology and Geothermal Researches* 29, 293-

309.

Tatsumi, Y., Nakamura, N. 1986. Composition of aqueous fluid from serpentinite in the subducted lithosphere. *Geochemical Journal* 20, 191– 196.

Temel., A., Yürür, T., Alıcı, P., Varol, E., Gourgaud, A., Bellon, H., Demirbağ, H. 2010. Alkaline series related to Early-Middle Miocene intra-continental rifting in a collision zone: An example from Polatlı, Central Anatolia, Turkey. *Journal of Asian Earth Science* 38, 289-306.

Thompson, R.N. 1982. British Tertiary volcanic province. *Scottish Journal of Geology*, 18, 49-107.

Toprak, V., Türkecan, A. 1998. Geology of the Galatean Volcanic Province, Turkey. In: *Third International Turkish Geology Symposium*, Excursion Guidebook.

Tüysüz, O., Yiğitbaş, E. 1994. The Karakaya basin: A Palaeotethyan marginal basin and its age of opening. *Acta Geologica Hungarica* 75, 181-241.

Ünalan, G., Yüksel V. 1985. Haymana-Polatlı Havzasının jeolojisi ve petrol olanakları. *Maden Tetkik ve Arama Genel Müdürlüğü* Rapor No: 7665, 59 s.

Varol, E., Temel, A., Gourgaud, A., Bellon, H. 2006. Orta Anadolu'da dalma-batma volkanizması için kanıt: Balkuyumcu yöresi adakit benzeri volkanizma. Evidence for slab-melt metasomatism in central Anatolia, Turkey: Adakite like volcanism from Balkuyumcu region). *59. Türkiye Jeoloji Kurultayı Bildiri özleri*,

Varol, E., Temel, A., Gourgaud, A., Bellon, H. 2007. Early Miocene 'adakite-like' volcanism in the Balkuyumcu region, central Anatolia, Turkey: petrology and geochemistry. *Journal of Asian Earth Sciences* 30, 613-628.

Varol, E., Temel, A., Gourgaud A. 2008. Textural and compositional evidences for magma mixing in the evolution of Çamlıdere volcanic rocks (Galatean Volcanic Province), Central Anatolia, Turkey. *Turkish Journal of Earth Sciences* 17, 709– 727.

Wang, K.-L., Chung, S.-L., O'Reilly, S. 2004. Geochemical Constraints for the Genesis of Post-collisional Magmatism and the Geodynamic Evolution of the Northern Taiwan Region. *Journal of Petrology* 45(5), 975-1011.

Wang, K., McDermott, F., Xu, J.-F., Bellon, H., Zhu, Y.-T. 2005. Cenozoic K-rich adakitic volcanic rocks in the Hohxil area, northern Tibet: Lower-crustal melting in an intracontinental setwting. *Geology* 33, 465-468.

Wang, K., Wyman, D.A., Xu, J., Jian, P., Zhao, Z., Li, C., Xu, W., Ma, J., He, B. 2007*a*. Early Cretaceous adakitic granites in the Northern Dabie Complex, central China: implications for partial melting and delamination of thickened lower crust. *Geochimica et Cosmochimica Acta* 71, 2609-2636.

Wang, K., Wyman, D.A., Xu, J., Zhao, Z., Jian, P., Zi, F. 2007*b*. Partial melting of thickened or delaminated lower crust in the middle of Eastern China: implication for Cu-Au mineralization. *Journal of Geology* 115, 149-161.

Wilson, M., Tankut, A., Güleç, N. 1997. Tertiary volcanism of the Galatia North west Central Anatolia, Turkey. *Lithos* 42, 105–121

Zamora, D. 2000. Fusion de la croute oceanique subductee: approche experimentale et geochimique. Universite Thesis Universite Blaise Pascal, Clermont-Ferrand, 314 pp.

Zhu, D.-C., Zhao, Z.-D., Pan, G.-T., Lee, H.-Y., Kanf, Z.-Q., Liao, Z.-L., Wang, L.-Q., Li, G.-M., Dong, G.-C., Liu, B. 2009. Early Cretaceous subduction-related adakite like rocks of the Gangdese Belt, southern Tibet: Products of slab melting and subsequent melt-peridotite interaction. *Journal of Asian Earth Science* 34, 298-309.

Xu, J.F., Wang, Q., Yu, X.Y. 2000. Geochemistry of high-Mg andesites and adakitic andesite from the Sanchazi block of the Mian-Lue ophiolitic melange in the Qinling Mountains, central China: Evidence of partial melting of the subducted Paleo-Tethyan crust. *Geochemical Journal* 34, 359-377.

Xu, J.F., Shinjio, R., Defant, M.,J., Wang, Q., Rapp, R.P. 2002. Origin of Mesozoic adakitic intrusive rocks in the Ningzhen area of east China: partial melting of delaminated lower continental crust. *Geology* 12, 1111-1114.