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TÜBİTAK

Geochemical Characteristics of Mafic and Intermediate Volcanic Rocks from the Hasandağ and Erciyes Volcanoes (Central Anatolia, Turkey)

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Abstract: Hasandağ and Erciyes stratovolcanoes, which are the two important stratovolcanoes in Central Anatolia, erupted volcanic products with both calc-alkaline and alkaline compositions, although the calc-alkaline activity is more widespread. There are three stages of geochemical evolution in the history of the Hasandağ stratovolcanic complex: (1) Keçikalesi tholeiitic volcanism, (2) Hasandağ calc-alkaline volcanism, and (3) Hasandağ alkaline volcanism. The geochemical evolution of Erciyes volcanic complex also exhibits three distinct evolutionary stages: (1) Koçdağ alkaline volcanism, (2) Koçdağ calc-alkaline volcanism and (3) Erciyes calc-alkaline volcanism. The volcanic rocks from both suites show enrichments in LREE relative to HREE. The rocks as a whole show enrichments in large ion lithophile elements (LILE) relative to high field strength elements (HFSE) in N-MORB normalized multi-element diagrams, although the thoeliitic and alkaline rocks have less pronounced effects of HFSE/LILE fractionation comparing to the calc-alkaline rocks.

Theoretical fractionation models obtained using the whole-rock trace element data indicate two distinct fractionation trends for the Hasandağ volcanism: amphibole and plagioclase fractionation for the tholeiitic and calc-alkaline rocks and plagioclase, pyroxene and amphibole fractionation for the alkaline rocks. The alkaline and calc-alkaline rocks of Erciyes volcanism, on the other hand, indicate similar fractionation trends that can be explained by plagioclase and amphibole fractionation. AFC modelling indicate that the effect of crustal contamination on parental melt compositions is less pronounced in the Erciyes volcanic rocks compared to the Hasandağ volcanic rocks. Theoretical melting trends obtained using the non-modal batch melting model indicate degree of melting between 8–9% for the Keçikalesi tholeiitic rocks, 4–5% for the Hasandağ alkaline rocks and 3–8% for the Koçdağ alkaline rocks. The modeling also shows that the Central Anatolian volcanic rocks were originated by variable degree melting of a mantle source with garnet+spinel lherzolite composition, although the effect of residual garnet in the source is more pronounced for the Hasandağ alkaline rocks. Geochemical modeling indicates that Central Anatolian volcanic rocks are likely to have originated by partial melting of a metasomatised lithospheric mantle. Delamination of TBL (termal boundary layer) may be considered as a potential mechanism that may cause thermal perturbation melting of continental lithospheric mantle. The distribution of volcanic centres along the region-scale strike-slip fault systems may also indicate additional effects of strike-slip faulting on melt production and eruption.

Key Words: Central Anatolia, collision volcanism, lithospheric delamination, Turkey

Hasandağ ve Erciyes Volkanlarının Mafik ve Ortaç Volkanik Kayaçlarının Jeokimyasal (Orta Anadolu, Türkiye)

Özet: Orta Anadolu'da iki önemli stratovolkan olan Hasandağ ve Erciyes stratovolkanları kalk-alkalen ve alkalen karakterli volkanizmalar olmasına rağmen, kalk-alkalen aktivite daha yaygındır. Hasandağ volkanik kompleksi jeokimyasal farklılıklarıyla Keçikalesi toleyitik, Hasandağ kalk-alkalen, Hasandağ alkalen volkanizması olmak üzere üç evrede gelişimini gerçekleşmiştir. Erciyes volkanik kompleksinin jeokimyasal gelişimi Koçdağ alkalen, Koçdağ kalk-alkalen, Erciyes kalk-alkalen volkanizması olmak üzere üç evredir. Volkanizmalara ait nadir toprak element (REE) içeriklerinde tüm ürünlerde, hafif nadir toprak elementler (LREE) ağır nadir toprak elementlere (HREE) göre göreceli bir zenginleşme göstermektedir. N-MORB'a göre normalize edilmiş çoklu element diyagramlarında tüm volkanik ürünlerde geniş iyonlu litofil (LIL) elementler ve hafif nadir toprak elementlerde (LREE) belirgin zenginleşme, Ta, Nb, Ti, Hf gibi kalıcılığı yüksek elementlerde (HFS) ise göreceli bir tüketilme görülmekle birlikte HFSE/LILE fraksiyonasyonunun etkileri kalk-alakali kayalarda daha yüksek ve toleyitik, alkali bileşimli kayalarda daha az oranlardadır.

Tüm kayaç iz element içerikleri kullanılarak yapılan teorik kristalizasyon modellemeleri ile elde edilen eğilim, Hasandağ toleyitik ve kalk-alkalen kayaçlarda amfibol, plajiyoklas; alkalen kayaçlarda plajiyoklas, piroksen, amfibol; Erciyes alkalen ve kalk-alkalen kayaçlarda ise plajiyoklas, piroksen ve amfibolun baskın olduğu fraksiyonel kristalizasyon ile açıklanabilir. AFC modellemelerine göre Erciyes volkanında kıta kirlemesinin etkisi Hasandağ'a göre daha azdır. Modal olmayan yığın ergime modeliyle hesaplanan ergime dereceleri Keçikalesi toleyitik kayaçlarında yaklaşık %8–9, Hasandağ alkalen kayaçlarında %4–5, Koçdağ alkalen kayaçlarında ise %3–8 arasındadır. Teorik ergime modelleri Orta Anadolu volkanik kayaçları için granat ve spinel-lerzolit bileşimli manto kaynaklarından türeyen değişen miktarlarda magma karışımını önerirken, Hasandağ alkalen kayaçlarında ergime sürecinde artık granat etkisi daha baskındır. Metasomatize olmuş litosferik mantodan türediği düşünülen Orta Anadolu volkanizması, termal sınır düzeyinin (TSD) deleminasyonu ile oluşan geniş çaplı termal düzensizlik sonucu kıta altı litosferik mantonun ergimesiyle açıklanabilir. Bölgedeki volkanizmanın doğrultu atımlı tektonizmanın bulunduğu kuşaklar boyunca görülmesi bu sistemin magma yükselimine olası katkı sağladığını göstermektedir.

Anahtar Sözcükler: Orta Anadolu, çarpışma volkanizması, litosferik delaminasyon, Türkiye

Introduction

Collision-related calc-alkaline and alkaline volcanisms are observed in the Hasandağ and Erciyes volcanoes, which are two important stratovolcanoes in the Central Anatolia, but calc-alkaline volcanism is more dominant. Tholeiitic rocks of small volumes comprise the first products of the Hasandağ volcanism. The plate boundaries between African, Arabian and Eurasian plates, which represent the western part of the Alpine-Himalayan belt, are irregular in the Mediterranean region (Jackson & McKenzie 1984). Aeolian and Aegean volcanic arcs were formed in the southern Italy and Aegean regions by subduction of the African plate under the Eurasian plate (Keller 1982). In addition, geologic and geomorphologic characteristics of other areas in the Aegean-Anatolian region are mainly shaped by the collision and post-collision tectonism (Notsu *et al.* 1995). In most collision zones (Himalaya and Anatolia), calc-alkaline and alkaline associations are found together that are closely associated chronologically and spatially (Pearce *et al.* 1990; Turner *et al.* 1996). Bonin (1990) who studied magmatic rocks in the Alps stated that magmatism changes from calc-alkaline to alkaline type due to decreasing water content; both types of volcanics are derived from almost the same source. The Central Anatolian volcanism also is characterized by products of calc-alkaline, alkaline and tholeiitic character which developed at various stages of volcanic activity and do not show any significant chronological and spatial systematic.

In this study we aimed to provide evidence for determining the petrogenetic processes that were effective during the formation and evolution of the volcanic suites. For this purpose, based on trace element data on volcanic rocks, a petrogenetic modeling was performed. During these studies, in order to determine crystallization processes of rocks, fractional crystallization and assimilation effects were examined and then possible source components of volcanoes were determined. This was followed by melting modelling studies to delineate percents of partial melting types which were effective during the magma generation processes.

Geological Setting

The Anatolian volcanism is one of the best examples of continental collision volcanism. With the opening of the Suez Gulf in the Oligocene, the Arabian plate was started to be separated from the African plate (McKenzie 1972; Cochran 1981; İzzeldin 1987; Bayer *et al.* 1988; Le Pichon & Gaulier 1988). Northerly movement of the Arabian plate during the middle–late Miocene resulted in continental collision which was responsible for shortening and thickening of the crust in the eastern Anatolia between the Eurasian and Arabian plates (Şengör 1980; Şengör & Yılmaz 1981; Fyitkas *et al.* 1984; Buket & Temel 1998; Temel *et al.* 1998; Yılmaz *et al.* 1998; Yürür & Chorowicz 1998). The continental collision gave rise to westward escape of the Anatolian block along North Anatolian Fault (NAF) and East Anatolian Fault (EAF) (McKenzie 1972; McKenzie & Yılmaz 1991). The shortening and thickening of the crust in the eastern Anatolia via Arabia-Eurasia collision and westward escape of the Anatolian block resulted in deformation of the Anatolian block (McKenzie & Yılmaz 1991; Lyberis *et al.* 1992). The volcanic activity in Central Anatolia is related to this deformation (McKenzie & Yılmaz 1991; Aydar *et al.* 1995). The Central Anatolian region in Turkey has been subjected to deformation and volcanism over the past 10 Ma (Innocenti *et al.* 1982; Şengör *et al.* 1985; Pasquare *et al.* 1988; Aydar 1992; Temel 1992; Aydar *et al.* 1993; Le Pennec *et al.* 1994). There are two major active fault systems in the Central Anatolian volcanism (Toprak & Göncüoğlu 1993). The first is the left-lateral Ecemiş fault zone and the right-lateral Tuz Gölü fault zone and the second is N60–70° E-trending normal faults that are consistent with main eruption centres as being parallel to the volcanic axis (Toprak & Göncüoğlu 1993). NE–SW-extending faults are central Kızılırmak and Niğde faults (Toprak 1994). Some of these faults are covered with young volcanic rocks.

Magmatic, metamorphic and ophiolithic rock assemblages in Central Anatolia form the crystalline basement complex. This complex is composed of ophiolithic units overlying Palaeozoic–Mesozoic medium- to high-grade metamorphic rocks and intrusive rocks cutting those units (Akıman *et al.* 1993 & Göncüoğlu *et al.* 1991b). There is no published geophyscial information regarding the thickness of crust and lithospheric mantle beneath Central Anatolia.

The products of the Hasandağ volcano (Figure 1), which is one of the important stratovolcanoes in the Central Anatolia, are composed of lava flows, lava domes and pyroclastic rocks. According to Aydar & Gourgaud (1998), volcanism was developed at four stages, namely,

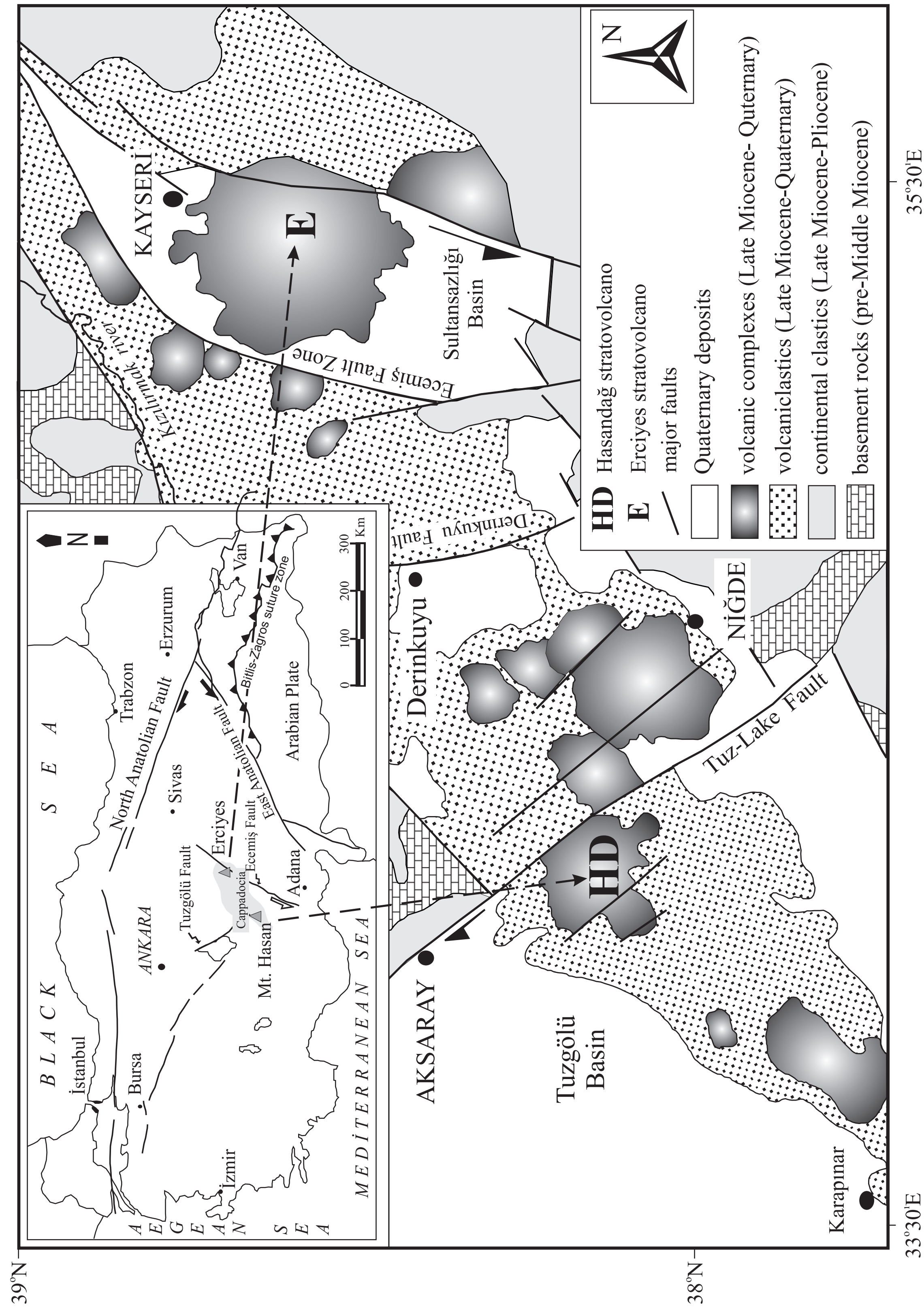


Figure 1. Map of Central Anatolia showing the location of 'the Cappadocian volcanic province' and distribution of volcanic products (modified from Toprak 1998).

Keçikalesi volcano (13 Ma), Palaeovolcano (7 Ma), Mesovolcano and Neovolcano.

The Keçikalesi tholeiitic volcanism is composed of lava flows of basalt and basaltic andesite and lesser amount of pyroclastic products while Hasandağ calc-alkaline volcanism is characterized mainly by andesite lava domes and dacite and rhyolite type lavas and widespread pyroclastic products. The latest stage of the Hasandağ volcanism is represented by basaltic alkaline volcanics and linear scoria cones (Aydar & Gourgaud 1998). Products of the Erciyes volcano are composed of lava flows, pyroclastics and some monogenic structures such as dome, cone and maar. The volcanism was developed in two stages as Koçdağ and Erciyes (Kürkçüoğlu *et al.* 1998). The products of the Koçdağ volcanism at the eastern part of the Erciyes stratovolcano are alkali basalts, andesitic lava flows, basaltic andesites and ignimbrites (Şen *et al.* 2003). Dark grey-black coloured basaltic rocks are monocrystalline and show flow structure. According to Ayrancı (1969), their age is 4.39±0.28 Ma. The Erciyes stratovolcano with an age ranging from 3 Ma to historical times displays a wide compositional spectrum from basalt to rhyodacite (Pasquare *et al.* 1988; Ayrancı 1991).

Analytical Methods

A total of 38 samples from lava and dome flows were collected for chemical analyses, 17 from the Hasandağ volcanism and 21 from the Erciyes volcanism. The rock samples were powdered at the Mineralogy-Petrography laboratories of the Geology Department in the Kocaeli University. The major and trace element analyses were conducted at the ALS Chemex (Toronto-Canada) analytical laboratory using ICP-MS and ICP-OES, respectively. Results of chemical analyses are shown in Table 1.

Geochemical Characteristics

Classification of Volcanic Rocks

The volcanic rocks in the region were classified using the classification scheme of Le Bas *et al.* (1986) based on the total alkali ($Na_2O + K_2O$) vs SiO_2 (TAS) diagram (Figure 2a). In this diagram, the dashed line separating the alkali and subalkali magma series was taken from Irvine & Baragar (1971).

Based on the Le Bas *et al.* (1986) diagram, Hasandağ alkaline rocks are basalt and trachybasalt while the Koçdağ alkaline rocks plot in the basalt field. Except for these two groups, all other rocks are below the subalkaline line. The Hasandağ calc-alkaline rocks are represented by basaltic trachyandesite, basaltic andesite and andesite while Keçikalesi tholeiitic rocks are represented by basaltic andesite. The Erciyes calc-alkaline rocks show a wide compositional spectrum from trachybasalt to dacite and calc-alkaline rocks of Koçdağ volcanics mostly plot in the andesite field.

Subalkali series are divided into several sub-groups based on K_2O and SiO_2 contents. This discrimination is shown in the Peccerillo & Taylor (1976) diagram (Figure 2b). It is shown in this diagram that samples plot in high K-calcalkaline series and calc-alkaline series. Moreover, in total alkali ($Na_2O + K_2O$)-total FeO-MgO triangular diagram (Figure 3) proposed by Irvine & Baragar (1971), subalkali series can be discriminated as calc-alkaline and tholeiitic types. In Figure 3 where subalkali samples are used, the Keçikalesi volcanic rock samples plot in tholeiitic field.

In the major oxide covariation diagrams, for all of samples, there is an increase in K_2O and a decrease in Fe_2O_3, MnO, CaO with increasing SiO_2 (Figure 4). There is also minor decrease in Al_2O_3 with SiO_2 although the distributions are rather scattered for most of the samples. Especially, the similar major oxide behaviour in calc-alkaline porphyric rocks is probably due to fractionation of plagioclase dominant mineral assemblages in the shallow depth of long-lived magma chambers. Consumption of CaO can be explained by crystallization of significant amount of plagioclase and clinopyroxene.

The high Fe_2O_3 and TiO_2 concentrations of Hasandağ and Erciyes alkaline rocks indicate that they are rich in iron. Especially, TiO_2 contents of Hasandağ and Erciyes alkaline rocks increase with SiO_2, while there is a negative trend in other rock groups. MnO, MgO and CaO concentrations of alkaline Hasandağ and Erciyes rock samples have high concentrations. There is an increase in MgO with increasing SiO_2 in the Hasandağ alkaline volcanism and this can be explained by the accumulation of forsteritic olivine which exists in the phenocrysts assemblages of these rocks.

Table 1. Whole-rock major and trace element data for the representative samples from Hasandağ* and Erciyes volcanoes. DL– Detection Limit, RSD– Relative Standart Deviation.

Sample No	H-26	H-80	H-36	H-20	H-7	H-4	H-42	H-75	H-15	H-14	H-2	H-72	H-70	H-43	H-49	H-62	H-64		
Locality	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ	Hasandağ		
Rock type	Basalt	B. Andesite	Andesite	Andesite	Andesite	Andesite	Basalt	Andesite	Andesite	Andesite	Andesite	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt		
Flow type	Lava flow	Lava flow	Dome flow	Dome flow	Lava flow	Lava flow	Lava flow	Dome flow	Dome flow	Dome flow	Dome flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow		
Latitude	38°03'32"	38°10'23"	38°01'06"	38°04'59"	38°11'26"	38°10'47"	38°13'52"	38°10'37"	38°05'54"	38°06'09"	38°08'26"	38°07'45"	38°07'35"	38°13'46"	38°14'21"	38°13'01"	38°14'38"		
Longitude	34°06'03"	34°05'35"	34°15'38"	34°09'51"	34°11'49"	34°05'40"	34°08'38"	34°03'44"	34°10'25"	34°10'24"	34°06'30"	34°04'03"	34°02'38"	34°08'32"	34°08'13"	34°04'25"	34°03'26"	DL	RSD (%)
SiO_2	55.12	53.33	60.10	60.50	57.71	61.09	54.23	56.02	60.70	61.29	60.30	47.96	52.34	48.36	48.66	48.26	49.05	0.01	0.10
TiO_2	0.91	1.01	0.76	0.58	0.77	0.72	1.10	0.80	0.70	0.70	0.69	1.26	0.88	1.20	1.16	1.19	1.36	0.01	0.80
Al_2O_3	17.10	16.65	15.50	16.00	16.40	15.65	15.60	15.60	16.30	16.05	16.15	17.40	17.25	16.55	15.95	16.55	16.10	0.01	0.90
Fe_2O_3	9.54	11.30	6.52	6.59	7.75	6.78	8.11	6.83	6.58	6.24	6.30	10.55	7.38	9.85	10.05	9.94	10.25	0.01	0.30
MnO	0.15	0.16	0.12	0.11	0.12	0.11	0.13	0.11	0.11	0.10	0.11	0.16	0.13	0.15	0.16	0.15	0.16	0.01	1.50
MgO	3.87	3.88	2.65	2.88	3.56	2.36	7.03	6.02	3.19	2.95	2.79	6.19	4.73	7.56	8.20	7.88	6.58	0.01	1.20
CaO	7.88	8.70	4.65	5.39	6.05	4.95	7.42	7.34	5.73	5.39	5.36	11.00	7.40	9.97	9.43	11.30	9.21	0.01	0.70
Na_2O	2.97	2.70	3.95	3.72	3.58	3.85	3.73	3.67	3.78	3.80	3.82	3.57	4.17	3.47	3.54	3.34	3.86	0.01	0.70
K_2O	1.12	1.04	2.25	1.98	1.99	2.33	1.74	1.68	1.93	1.98	2.01	0.96	1.27	1.18	1.18	0.95	1.48	0.01	0.50
P_2O_5	0.15	0.20	0.31	0.19	0.16	0.20	0.37	0.26	0.19	0.22	0.22	0.36	0.32	0.57	0.42	0.35	0.48	0.01	0.10
L.O.I	1.35	0.79	2.36	1.44	1.05	1.61	0.60	1.21	0.04	0.47	1.37	0.36	0.71	0.32	0.31	0.27	0.85	0.01	
Total	100.16	100.06	99.17	99.48	99.14	99.65	100.06	99.54	99.25	99.10	99.12	99.77	96.58	99.18	99.06	100.18	99.38		
Ppm																			
V	346.6	299.3	38.1	28.8	31.9	5.1	146.1	102.9	77.1	48.3	56.6	234.5	156.3	201.6	139.9	238.6	52.5	0.1	2.1
Co	34.8	50.7	31.0	38.4	49.0	34.2	42.7	37.9	32.7	32.1	30.7	54.4	33.1	52.6	60.4	52.3	63.4	0.1	0.8
Cu	104.9	150.2	63.8	72.0	115.2	76.1	65.8	52.5	61.7	56.6	49.4	99.8	60.7	85.4	100.8	85.4	114.2	0.1	1.5
Zn	99.3	100.8	65.8	61.7	65.1	69.9	81.3	67.9	65.8	59.2	55.5	92.6	75.1	89.5	85.4	90.5	83.3	0.1	1.5
Ga	22.6	21.6	20.8	20.5	22.4	21.7	20.8	20.0	21.6	20.6	20.6	21.8	19.9	21.0	19.9	20.8	20.2	0.1	1.6
Rb	38.9	39.5	70.8	62.5	59.5	67.8	44.9	50.3	63.9	66.1	64.2	19.6	23.5	25.9	23.3	19.0	30.4	0.1	0.8
Sr	396.1	403.2	374.7	392.0	497.9	411.3	609.9	566.1	408.3	398.1	397.1	671.0	619.1	676.1	665.9	656.7	705.6	0.1	1.4
Y	26.4	28.0	21.4	18.9	18.4	19.4	22.5	18.0	20.6	19.8	17.6	25.3	18.0	25.6	24.9	24.8	24.9	0.1	2.2
Zr	103.4	105.6	201.8	138.6	121.0	149.0	152.4	127.9	142.5	151.2	137.1	130.5	116.5	147.3	147.5	136.9	164.5	0.1	0.2
Nb	5.2	6.3	17.6	11.9	9.5	12.6	17.4	9.4	12.5	13.4	11.5	14.2	11.3	18.3	18.4	15.8	20.4	0.1	2.0
Cs	0.9	2.0	2.4	2.2	2.2	2.5	1.4	1.8	2.3	1.2	1.2	0.5	0.9	0.6	0.5	0.5	0.5	0.1	2.0
Ba	30.6	338.4	497.8	451.8	468.2	540.8	430.4	137.7	459.0	489.6	460.0	356.8	240.2	387.4	384.4	361.9	387.2	0.1	2.7
La	15.82	16.92	30.69	24.47	20.17	24.99	29.11	22.37	25.77	26.20	22.76	27.74	20.99	30.82	31.12	28.45	29.38	0.01	0.10
Ce	32.95	35.38	59.73	44.91	36.98	45.47	55.56	42.72	46.52	48.51	44.21	52.94	41.55	60.95	59.76	58.97	56.41	0.01	2.10
Pr	4.12	4.35	6.18	5.02	4.13	5.13	6.47	4.98	5.13	5.36	4.71	6.14	4.65	7.21	7.03	6.37	6.59	0.01	2.20
Nd	17.35	18.62	22.46	18.38	16.01	18.82	25.01	19.21	19.21	20.24	16.86	24.53	17.73	27.17	27.32	25.16	26.73	0.01	0.50
Sm	3.94	4.11	4.64	3.61	3.51	3.85	4.70	3.63	3.84	3.89	3.51	4.83	3.72	5.34	5.23	5.15	5.17	0.01	2.50
Eu	1.14	1.12	1.12	0.91	1.03	1.12	1.31	1.05	1.04	1.01	0.95	1.45	1.16	1.49	1.45	1.45	1.47	0.01	1.10
Gd	4.15	4.17	4.42	3.36	3.35	3.48	4.47	3.17	3.42	3.89	3.53	4.34	3.73	4.82	4.96	4.35	4.71	0.01	1.20
Tb	0.71	0.71	0.69	0.52	0.52	0.53	0.67	0.49	0.54	0.52	0.52	0.73	0.61	0.73	0.78	0.69	0.72	0.01	0.10
Dy	4.39	4.25	3.75	3.10	3.02	3.20	3.59	2.89	3.16	3.26	3.11	4.34	3.53	4.12	4.42	4.02	4.22	0.01	1.40
Ho	0.92	0.93	0.76	0.63	0.64	0.67	0.74	0.61	0.69	0.72	0.65	0.90	0.71	0.84	0.94	0.83	0.85	0.01	2.40
Er	2.48	2.49	2.03	1.69	1.79	1.91	1.92	1.68	1.98	2.03	1.79	2.32	1.92	2.25	2.56	2.16	2.15	0.01	0.10
Tm	0.35	0.38	0.31	0.26	0.26	0.28	0.27	0.24	0.29	0.29	0.27	0.32	0.27	0.31	0.37	0.30	0.31	0.01	2.70
Yb	2.34	2.49	2.14	1.71	1.71	1.82	1.90	1.62	1.78	1.83	1.79	2.11	1.78	2.07	2.51	2.01	2.01	0.01	0.80
Lu	0.37	0.38	0.39	0.27	0.27	0.28	0.29	0.25	0.29	0.27	0.28	0.29	0.27	0.31	0.36	0.30	0.30	0.01	0.10
Hf	3.94	3.34	6.90	4.35	4.34	4.34	4.23	4.99	4.97	4.35	4.88	4.12	4.92	4.56	4.41	4.12	4.78	0.01	5.20
Ta	0.53	0.51	1.04	0.86	0.74	0.86	1.08	0.67	0.84	0.85	0.83	0.92	0.76	1.02	1.14	1.09	1.24	0.01	1
Pb	11.17	7.23	16.53	10.33	13.47	11.37	7.28	10.25	11.37	12.40	27.90	10.63	10.33	10.33	7.48	7.21	7.23	0.01	2.80
Th	6.94	5.34	9.90	9.38	7.34	9.34	7.23	7.99	9.97	9.35	9.88	5.12	3.92	5.56	5.41	5.12	5.78	0.01	0.70
U	2.43	1.83	3.30	2.74	2.43	2.93	1.95	2.66	3.04	2.93	3.18	1.18	1.71	1.47	1.48	1.08	1.72	0.01	0.20

Table 1. (Continued)

Sample no	E-146	E-148	E-149	E-150	E-152	E-233	E-141	E-102-b	E-108	E-103	E-133	E-194	E-169	E-196	E-185	E-88	E-86	E-175	E-188
Locality	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes	Erciyes
Rock type	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Andesite	Andesite	Andesite	Andesite	Andesite	B.Andesite	Dasite	Basalt	Andesite	Andesite	Dasite	B.Andesite	Andesite
Flow Type	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Lava flow	Dome flow	Lava flow	Lava flow	Dome flow	Dome flow	Lava flow	Lava flow
Latitude	38°19'24"	38°19'46"	38°18'08"	38°17'36"	38°19'41"	38°17'36"	38°20'09"	38°34'20"	38°33'18"	38°32'55"	38°25'49"	38°36'00"	38°19'24"	38°27'17"	38°29'26"	38°39'22"	38°40'22"	38°24'20"	38°27'38"
Longitude	35°38'15"	35°38'03"	35°37'41"	35°38'10"	35°37'09"	35°38'10"	35°38'57"	35°39'04"	35°33'08"	35°32'17"	35°34'49"	35°16'26"	35°38'15"	35°21'41"	35°15'23"	35°33'43"	35°32'54"	35°27'51"	35°13'35"
Wt %																			
SiO_2	47.96	47.76	47.96	47.76	47.26	47.56	61.39	58.61	58.71	62.19	57.31	53.83	64.08	51.24	60.00	62.19	64.08	53.03	60.40
TiO_2	1.77	1.67	1.73	1.74	1.75	1.70	0.68	0.98	0.76	0.75	0.72	1.23	0.52	1.42	0.65	0.49	0.49	0.96	0.70
Al_2O_3	17.05	17.15	16.75	16.85	16.85	16.85	16.35	15.75	16.05	15.60	17.15	17.00	15.05	17.40	16.35	15.50	15.90	17.10	16.65
Fe_2O_3	12.45	11.65	11.90	12.25	12.15	11.75	5.35	7.17	6.31	5.31	6.79	7.92	4.73	8.78	5.93	4.40	4.73	7.67	5.96
MnO	0.19	0.17	0.18	0.19	0.18	0.18	0.08	0.10	0.15	0.09	0.10	0.12	0.08	0.13	0.10	0.07	0.08	0.12	0.09
MgO	6.28	6.79	6.78	6.52	6.59	6.75	2.71	3.12	3.46	2.04	4.34	4.29	2.17	5.59	3.15	2.01	1.91	6.14	3.08
CaO	8.56	8.90	8.75	8.55	8.49	8.74	4.85	5.19	5.72	4.04	7.33	6.49	4.32	7.41	5.81	4.70	4.63	8.17	5.84
Na_2O	3.93	3.80	3.79	3.92	3.86	3.81	4.06	4.01	3.43	3.77	3.36	3.96	3.76	3.92	3.61	3.74	3.85	3.52	3.95
K_2O	0.77	0.67	0.73	0.77	0.73	0.73	2.07	2.16	1.96	2.94	1.41	1.62	2.47	1.34	1.69	1.98	2.03	1.14	1.83
P_2O_5	0.40	0.36	0.39	0.42	0.39	0.35	0.21	0.24	0.19	0.20	0.18	0.39	0.22	0.39	0.18	0.14	0.14	0.36	0.16
L.O.I	0.43	0.07	0.40	0.36	1.45	1.47	1.32	2.65	2.67	2.79	0.50	2.78	2.29	2.28	1.75	2.90	1.29	1.13	1.07
Total	99.79	98.99	99.36	99.33	99.70	99.89	99.07	99.98	99.41	99.72	99.19	99.63	99.69	99.90	99.22	98.12	99.13	99.34	99.73
Ppm																			
V	171.8	237.6	271.5	174.9	210.9	228.3	115.2	60.7	65.8	45.3	93.6	126.5	23.7	129.6	46.3	80.2	13.4	148.1	66.9
Co	61.1	54.5	51.2	58.2	57.6	54.3	22.4	35.6	34.6	24.1	37.3	35.5	25.6	39.3	29.7	18.4	22.9	39.6	31.8
Cu	96.7	72.0	66.9	93.6	90.5	71.1	39.1	85.4	67.9	48.3	74.1	54.5	51.4	50.4	66.9	35.0	44.2	57.6	60.7
Zn	101.8	101.8	109.0	99.8	100.8	97.7	56.6	68.9	59.7	60.7	64.8	84.3	46.3	82.3	62.7	55.5	44.3	72.0	55.5
Ga	20.7	21.0	21.7	20.6	21.1	21.1	2.81	22.5	21.4	22.9	20.8	21.7	21.8	21.0	20.8	20.8	20.6	19.1	21.5
Rb	17.8	26.2	17.1	15.2	27.3	26.5	70.5	87.4	60.7	97.9	43.8	42.9	95.8	24.9	45.5	69.4	65.1	26.3	62.7
Sr	491.8	515.2	556.9	487.7	451.1	471.4	317.7	329.9	375.7	300.4	396.1	500.9	279.0	558.0	352.3	295.3	315.6	530.5	377.7
Y	29.5	27.6	31.2	29.0	28.5	28.0	19.2	28.3	20.7	32.2	18.6	22.9	21.3	22.5	18.2	20.2	19.6	18.2	18.4
Zr	204.1	185.5	199.2	199.7	194.7	194.5	202.8	229.6	179.0	260.6	131.0	167.5	148.2	188.5	152.0	165.5	153.0	133.5	153.5
Nb	14.2	11.2	12.4	13.1	12.2	12.2	11.5	14.2	12.5	14.7	10.4	18.4	12.6	18.3	11.4	10.5	10.1	16.3	9.4
Cs	0.4	1.1	0.5	0.3	0.5	0.6	2.5	2.9	0.9	3.3	1.4	1.3	3.4	0.6	1.7	2.5	1.0	1.0	2.3
Ba	193.4	222.8	148.7	299.5	271.9	303.6	400.7	380.3	378.2	432.4	321.0	376.2	518.3	333.2	303.6	353.7	373.1	323.0	342.4
La	19.73	17.63	20.92	19.64	18.63	19.12	20.97	33.99	22.93	29.41	19.86	24.85	26.72	22.57	20.64	22.63	23.36	25.54	19.46
Ce	42.87	37.72	45.58	42.64	40.88	40.12	41.19	55.92	45.55	57.24	39.14	49.31	48.65	47.89	41.55	45.28	46.82	48.65	39.43
Pr	5.11	4.65	5.49	5.24	5.04	4.79	4.59	6.13	5.03	6.75	4.51	5.43	5.15	5.56	4.59	5.03	5.14	5.13	4.35
Nd	21.16	20.11	22.67	21.88	20.59	19.16	16.97	23.37	18.97	25.81	16.48	20.26	18.28	21.37	16.87	18.88	18.93	17.98	16.49
Sm	5.12	4.83	5.61	5.31	4.91	4.89	3.61	5.52	3.94	5.03	3.59	4.26	3.81	4.71	3.61	4.07	3.81	3.68	3.54
Eu	1.72	1.52	1.80	1.68	1.57	1.47	0.99	1.13	1.12	1.24	1.02	1.24	0.96	1.45	0.99	0.91	0.89	1.08	0.98
Gd	5.34	4.91	5.43	5.15	5.12	4.71	3.44	5.49	3.89	5.31	3.24	4.26	3.83	4.58	3.64	3.62	3.72	3.38	3.35
Tb	0.89	0.80	0.91	0.84	0.87	0.78	0.57	0.92	0.62	0.86	0.53	0.67	0.59	0.72	0.59	0.62	0.61	0.56	0.53
Dy	5.56	4.83	5.37	5.03	5.24	4.71	3.42	4.95	3.64	4.77	3.20	3.78	3.51	4.31	3.41	3.58	3.34	3.29	3.22
Ho	1.19	1.04	1.15	1.06	1.08	1.02	0.74	1.04	0.75	1.02	0.68	0.84	0.75	0.89	0.72	0.76	0.72	0.72	0.69
Er	3.21	2.83	3.11	2.92	2.87	2.81	2.01	2.79	2.02	2.74	1.93	2.21	2.04	2.36	1.95	2.01	2.02	2.01	1.87
Tm	0.47	0.43	0.45	0.43	0.41	0.41	0.29	0.39	0.29	0.39	0.28	0.31	0.31	0.34	0.28	0.29	0.29	0.29	0.28
Yb	3.18	2.76	2.98	2.87	2.68	2.65	1.93	2.51	1.91	2.70	1.79	2.31	2.01	2.32	1.88	1.99	1.98	1.87	1.80
Lu	0.49	0.43	0.44	0.44	0.41	0.39	0.29	0.39	0.29	0.46	0.28	0.30	0.30	0.38	0.29	0.31	0.30	0.29	0.28
Hf	5.25	5.32	5.49	5.33	5.85	5.94	6.18	7.76	6.64	7.89	4.98	5.83	5.81	5.71	5.60	5.82	5.71	4.62	5.20
Ta	0.93	0.75	0.83	0.82	0.82	0.84	0.86	0.95	0.88	0.93	0.73	1.02	0.82	1.12	0.83	0.73	0.72	1.01	0.75
Pb	5.17	5.11	5.17	7.23	5.17	10.33	11.37	13.45	9.63	13.43	9.30	9.32	12.40	11.37	10.33	13.57	13.43	7.23	9.30
Th	2.25	2.88	2.49	2.33	2.85	2.94	11.18	15.76	9.64	14.89	7.98	4.83	14.81	4.71	6.60	10.82	10.71	6.62	10.20
U	0.67	0.71	0.82	0.82	1.07	1.12	3.32	5.00	3.13	4.89	2.45	2.05	5.04	1.47	2.40	3.25	3.37	2.01	3.23

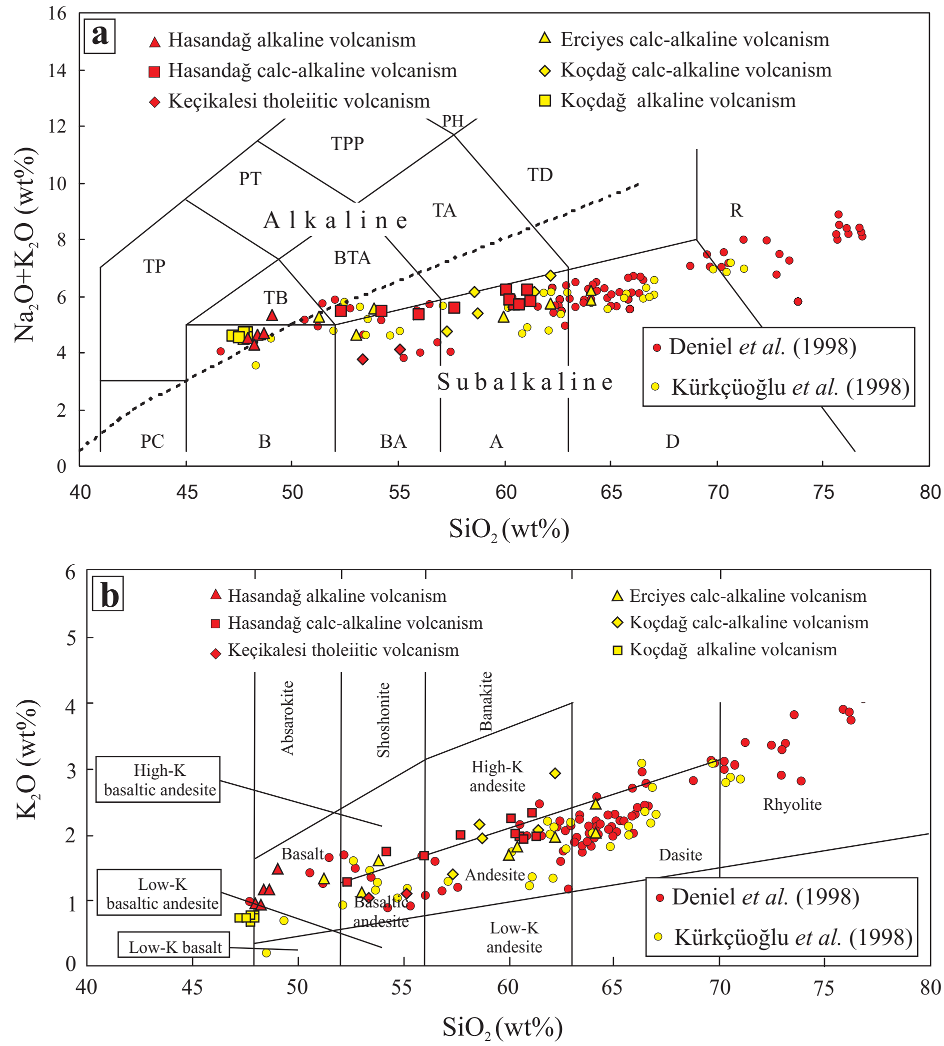


Figure 2. Classification of the volcanic rocks from Central Anatolia. (a) TAS diagram of Le Bas *et al.* (1986). Key to abbreviations: PC– picrobasalt; B– basalt; BA– basaltic andesite; A– andesite; D– dacite; R– rhyolite; TB– trachybasalt; BTA– basaltic trachyandesite; TA– trachyandesite; T– trachyte; TD– trachydacite; BS– basanite; TP– tephrite; TPPH– tephriphonolite; PHTP– phonotephrite; PH– phonolite; F– foidite. (b) K_2O vs SiO_2 diagram of Peccerillo & Taylor (1976). Data from Deniel *et al.* (1998) and Kürkçüoğlu *et al.* (1998) are also plotted for comparison.

Trace Element Characteristics

In trace element diagrams an increase is observed in Rb and Ba concentrations with increasing SiO_2 for all of the samples but there is not a prominent trend defined for the rest of the elements (Figure 5). However, concentrations of Rb, Zr and Nb indicate positive correlations with silica contents of the rocks when the Hasandağ and Erciyes alkaline samples are examined separately. Also, for the Hasandağ calc-alkaline rocks there is an increasing trend in Nb, Sr, Zr and Y with increasing SiO_2 contents for the samples with over 60% SiO_2. Similar trends are also observed for Rb, Ba, Th in this rock suite.

Rare Earth Element Characteristics

Chondrite normalized rare earth element diagrams were prepared separately for the Hasandağ and Erciyes volcanic rocks (Figures 6a, b). These diagrams were used to

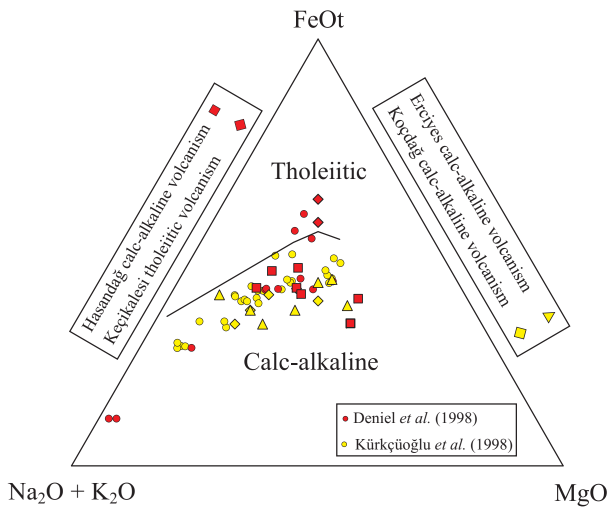


Figure 3. Distrubution of the samples from the Central Anatolian volcanic rocks on Irvine & Baragar (1971) AFM diagram. Data from Deniel *et al.* (1998) and Kürkçüoğlu *et al.* (1998) are also plotted for comparison.

compare the composition of rock samples of present study with average OIB and MORB compositions of Sun & McDonough (1989). In addition to rock samples, OIB and MORB compositions were also normalized to chondrite values of Boynton (1984). In these diagrams, one or two samples were used for each rock group. Symbols and SiO_2 contents of these patterns are shown in the same figures. In samples from the Hasandağ stratovolcano, light rare earth element patterns are flat and show sub-parallel trends and they are more enriched with respect to heavy rare earth elements (Figure 6a). There is a negative Eu anomaly in a sample with SiO_2 content of 60.1% from the Hasandağ calc-alkaline volcanism (Figure 6a). Rare earth element patterns of the Erciyes stratovolcano closely resemble those of Hasandağ samples (Figure 6b). In this diagram, negative Eu anomalies are noticeable in samples from the Koçdağ calc-alkaline volcanics. The most negative Eu anomalies are the product of plagioclase fractionation.

LREE enrichment in REE patterns of samples from the Hasandağ and Erciyes stratovolcanoes could be originated from a low-degree partial melting or due to contributions from subducting slab or crustal components.

Multi Element Characteristics

N-type MORB normalized multi-element diagrams for the Hasandağ and Erciyes volcanisms are shown in Figure 7a and b, respectively. In multi-element diagram of the Hasandağ strato volcano, there is significant enrichment of large ion lithophile elements (LIL) (e.g., Rb, Ba, Th, U and K) and light rare earth elements and a relative depletion of high field strength elements (HFS) (e.g., Ta, Nb, Ti and Hf) and heavy rare earth elements (HREE).

In comparison to other rock suites, concentrations of large ion lithophile elements (LIL) such as Rb, Ba, Th, U and K in samples from the Hasandağ alkaline volcanism display variable depletion trends. In addition, they display Ta and Nb negative anomalies smaller than the other rock groups, suggesting that the source of the Hasandağ alkaline lavas is different from those of the other rock groups. This may indicate that the source of the Hasandağ alkaline rocks contained less significant subduction component when compared to the other rock groups or that their derivative melts have not been significantly affected by subsequent crustal contamination. These rocks are significantly enriched in large ion lithophile elements (LIL) and high field strength elements (HFS; Ta, Nb, Zr) in comparison to mid-ocean ridge basalts (N-MORB) and this can be explained by different mechanisms: (1) enrichment of lithospheric mantle source with small melts fractions derived from asthenosphere; (2) melting of lithospheric source which is depleted in large ion lithophile elements (LIL) and light rare earth elements (LREE) by previous melting events and formation of tholeiitic and calc-alkaline magmas; (3) low-degree partial melting of the asthenospheric mantle source. In some samples of the Keçikalesi tholeiitic volcanism and Hasandağ calc-alkaline volcanism, depletion in Ta, Nb and P is much more than that of other rock suites. These negative Ta and Nb anomalies resemble subduction-related active continental margins and enrichment in large ion lithophile elements (LIL) can be explained by metasomatism in the mantle source with effect of subduction component (Pearce 1983).

Patterns in multi-element variation diagram for the Erciyes stratovolcano are similar to those of the Hasandağ stratovolcano. In this diagram, concentrations of large ion lithophile elements (LIL) (Th, U and K) in samples of the Koçdağ and Erciyes calc-alkaline volcanism are significantly enriched in comparison to other samples. Depletion of Hf and Ti with respect to other high field strength elements (HFS) is attributed to mantle enrichment due to intra-continental processes or derivation from a source with low-degree partial melts.

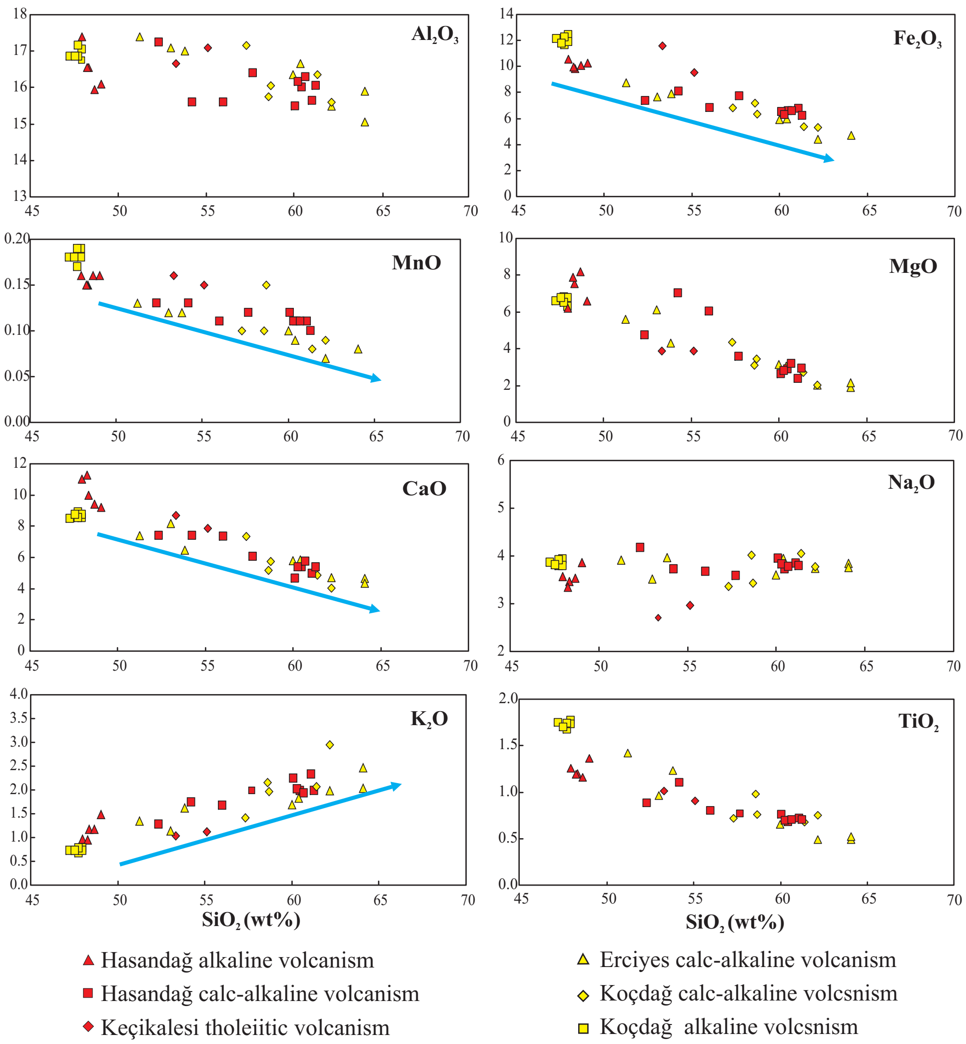


Figure 4. Major element variation of the Central Anatolian volcanic rocks.

Post-collisional within plate origin is also reported in previous works (Kürkçüoğlu *et al.* 1998).

Concentrations of large ion lithophile elements (LIL) (Rb, Ba, Th, U and K) in samples of the Koçdağ alkaline volcanism are relatively less enriched compared to those in other rock suites. However, Ta and Nb display negative anomalies. These patterns are similar to those of the Hasandağ alkaline volcanism and can be evaluated in the same way.

Trace Element Ratios

Diagrams where Th/Yb and Ta/Yb trace element ratios are used can determine fractional crystallization and/or partial melting. This diagram proposed by Pearce (1983) makes a distinction between rocks derived from regular mantle such as ocean island basalts (OIB) or mid-ocean ridge basalts (MORB) which generally lie on a diagonal line of mantle array, and rocks derived from mantle which is enriched via subduction process or rocks affected by the crustal contamination.

The deviation observed along the diagonal mantle array for all the samples from the Hasandağ and Erciyes stratovolcanoes could be explained with subduction-related metasomatism or mantle-derived melts that are significantly modified by the crustal melts (Figure 8). The trend of samples from the Hasandağ alkaline volcanism is almost parallel to that diagonal mantle array. Although

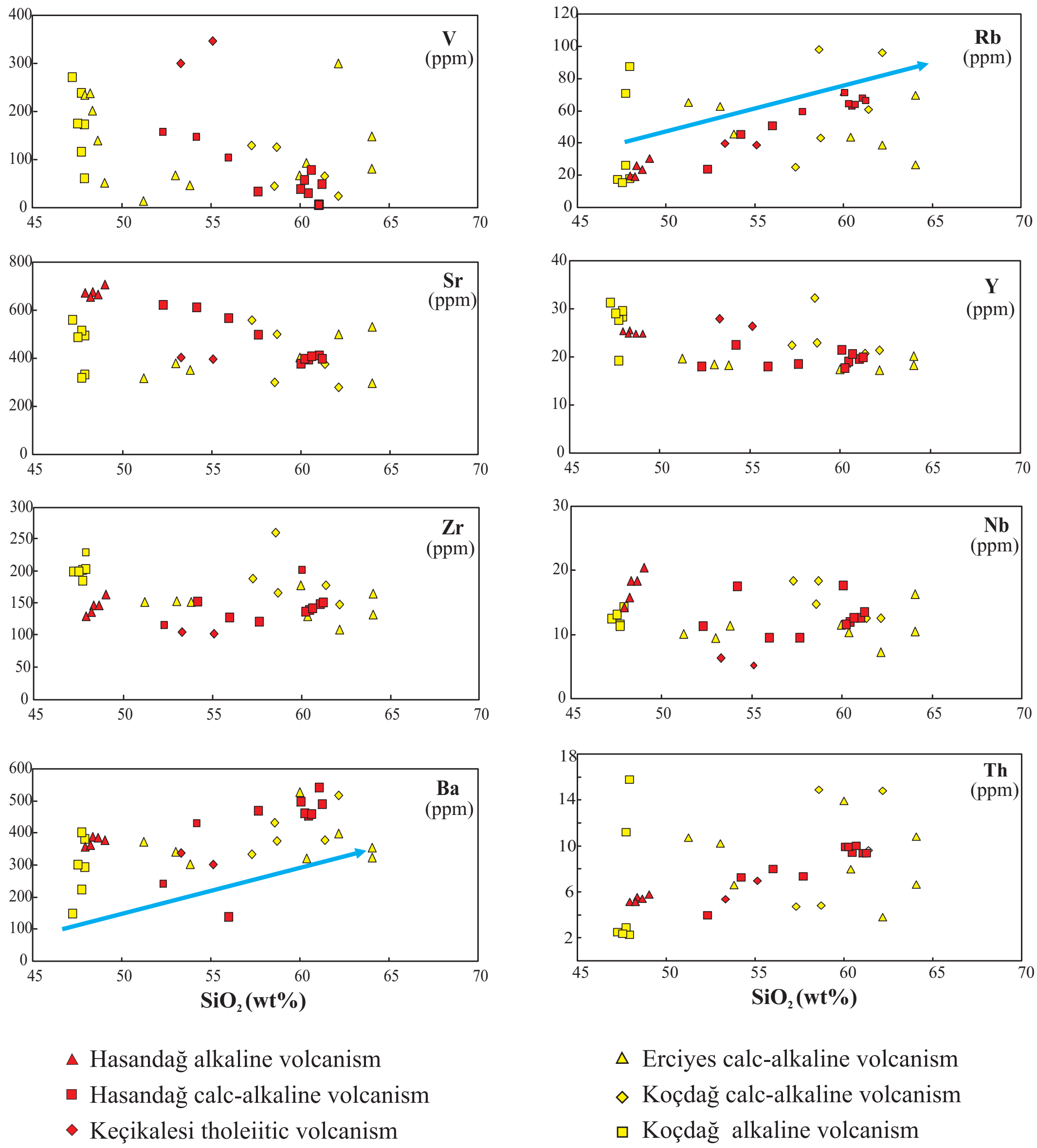


Figure 5. Trace element variation of the Central Anatolian volcanic rocks.

this does not rule out variable effect of crustal contamination, the relative enrichment of LILEs observed even in the least modified mafic compositions suggests a subduction influence in the source of Hasandağ alkaline volcanics. The effect of subduction modified mantle source is also observed in the alkaline series of Erciyes volcanism but the effect of crustal contamination is less pronounced.

Petrogenetic Modeling

Interpretation of Crystallization Process in Volcanic Rocks

Changes in trace element concentrations can be modelled using binary vector diagrams which show direction and amount of variation occurring as a result of certain processes. The mineral vectors used in modeling

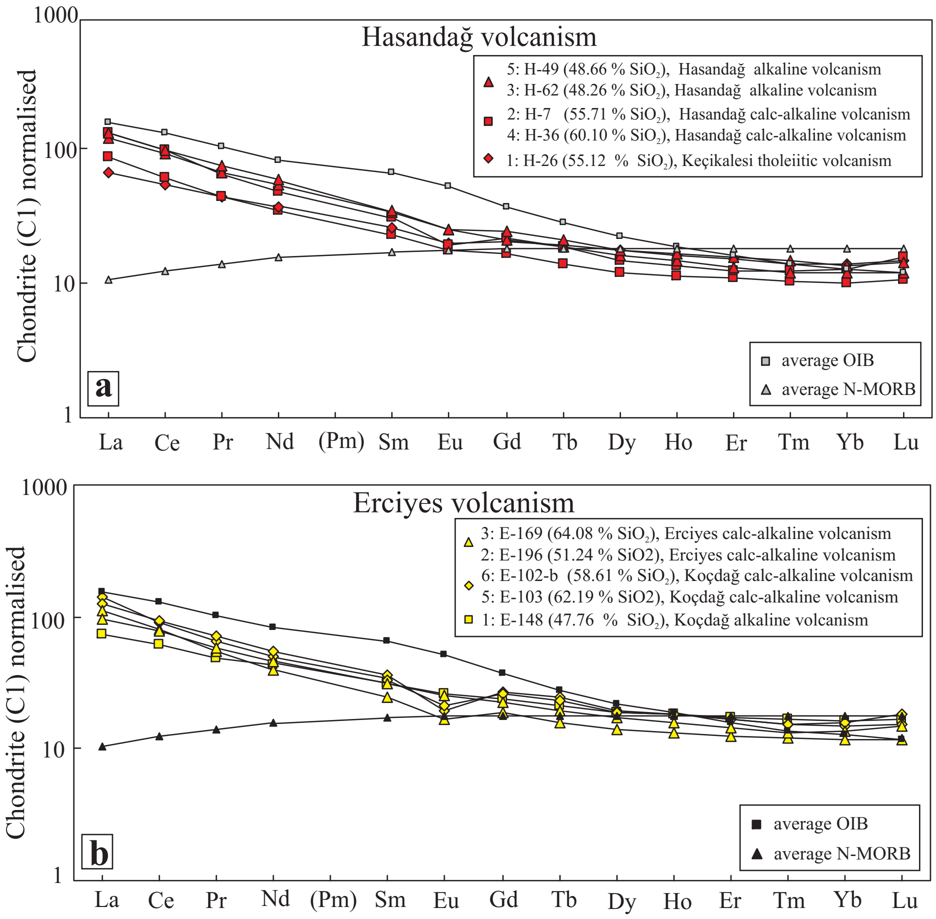


Figure 6. Chondrite-normalised REE element patterns for the Central Anatolian volcanic rocks. Chondrite normalising values are from Boynton (1984).

represent the compositions arising from fractionation of any mineral phase or assemblage. Theoretically, the fractionation trends are computed using the 'Rayleigh' equation.

The mineral vectors used in modeling were formed with computer software by Keskin (2002). In fractional crystallization modeling, Rb and Th were used as the fractionation index since they are incompatible elements. Other elements used in diagrams include Y and Sm. Yttrium was used to examine the fractionation effect during the formation of the volcanic rocks. As known, yttrium has a high distribution coefficient in garnet and amphibole. Samarium was used for discrimination of anhydrous and hydrous crystallization assemblages.

In general, two different trends are found in rock suites of the Hasandağ stratovolcanism (Figure 9). Fractionation effects of amphibole and plagioclase are very distinct in the Hasandağ calc-alkaline rocks (Figure 9a–c).

The Hasandağ alkaline rocks, which are the youngest products of volcanism, are conformable with trend no. 2 in Figure 9 and also mineral assemblages ($plag_{[\%50]}$ + $amp_{[\%30]}$ + $cpx_{[\%10]}$ + $opx_{[\%10]}$) determined in petrographic studies (Figure 9a–c). The phenocrystal assemblage in these rocks are composed of olivine, plagioclase and clinopyroxene and do not contain amphibole. This can be attributed to earlier amphibole fractionation and depletion of Y($^{amp\text{-}liquid}Kd_Y \approx 1.1$) and Sm($^{amp\text{-}liquid}Kd_{Sm} \approx 2.3$) elements in magmas. Previous studies report the presence of little garnet in these rocks (Aydar *et al.* 1995; Aydar & Gourgaud 2002). However, in trace element modeling, no garnet fractionation was observed that could affect the

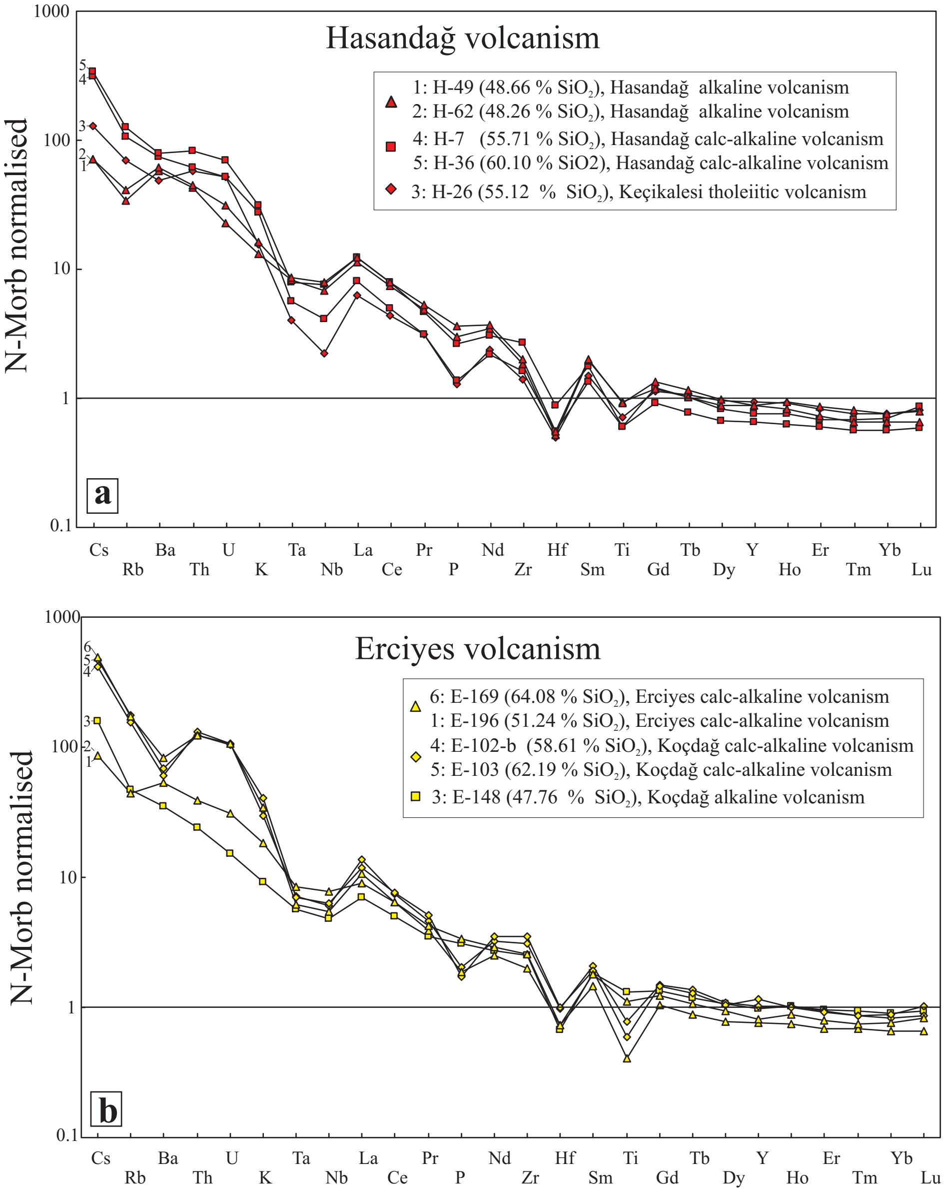


Figure 7. N-MORB normalised multi-element patterns for the Central Anatolian volcanic rocks. N-MORB normalising values are from Sun & McDonough (1989).

trace element concentrations. The presence of pyroxene and plagioclase is supported by decreasing Y ($^{cpx\text{-}liquid}Kd_Y \approx 1.2$, $^{plg\text{-}liquid}Kd_Y \approx 0.15$) contents vs Th. Fractionation trends of rock suites from the Erciyes strato volcano are quite similar and consistent with petrographically proposed fractionation trends ($plg_{[\%50]}+amp_{[\%50]}$) (Figure 10a–c).

Assimilation-fractional Crystallization Effect

As a result of heat transfer from hot magma to the cold crust, magmas, which are undergone fractional crystallization and assimilated around the crust, are very common (De Paolo 1981; Spera & Bohrson 2001; Thompson *et al.* 2002; Kuritani *et al.* 2005). Most of large-volume continental silicic magmas are combination of continental rocks and mantle-derived basaltic melts (De

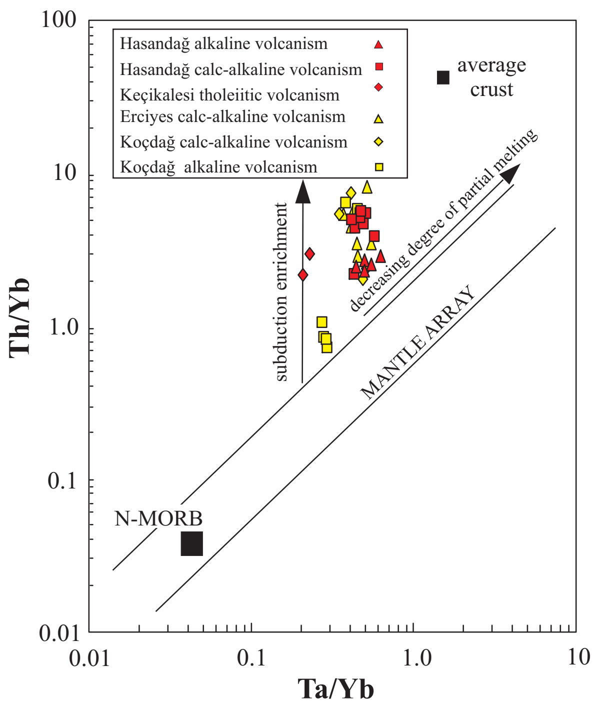


Figure 8. Th/Yb against Ta/Yb log±log diagram (after Pearce 1983) for the Central Anatolian volcanic rocks. Average OIB and MORB values used for comparasion are from Sun & McDonught (1989).

Paolo *et al.* 1992). Although physical mixing formed by hybridization is preserved in xenoliths and xenocrysts, most workers state that chemical evidence (particularly radiogenic isotopes) are important for mixing between magmas with contrasting geochemical compositions (Beard *et al.* 2005). By the early 1970's it was recognized that isotopic variations in the Sierra Nevada batholith, for example, correlated with the character of the basemenet and, implicitly, required mixing of crustal- and mantle-derived melts (Kistler 1974). Recent geochemical works indicated that fractional crystallization and assimilation are the most important processes for differentiation of volcanic rocks (De Paolo 1981; Spera & Bohrson 2001). Mantle-derived magmas are subjected to contamination when they rise through the thick crust and therefore, are affected by the contamination with certain degree.

In order to examine the effects of magma mingling and assimilation processes in rocks of the Hasandağ and Erciyes stratovolcanoes, theoretical AFC models (De Paolo 1981) were used that are based on trace element chemistry. In the modeling, 'r' value (the ratio of assimilation to fractional crystallization) was used as the AFC numeric index.

Since mantle xenoliths are absent in rocks of the Hasandağ and Erciyes stratovolcanoes, alkaline rocks comprising the most primitive rocks in the region were used in studies regarding end-member of the mantle source. The average crust values provided by Taylor & McLennan (1985) were used as the crust composition.

Distribution coefficients (D) used in AFC modeling were computed from mineral/melt distribution coefficients (Kd) which were used in previous fractional crystallization modeling (Keskin 1994; Keskin *et al.* 1998). AFC vectors for the Hasandağ and Erciyes stratovolcanoes were separately computed. All distribution coefficients were calculated considering fractional assemblages of ($plg_{[50\%]}$+$amp_{[50\%]}$) for the Hasandağ stratovolcano and ($plg_{[505\%]}$+$amp_{[50\%]}$) for the Erciyes stratovolcano.

Assimilation and fractional crystallization effects of all the rock samples from the Hasandağ and Erciyes stratovolcanoes were studied on the Rb vs Rb/Th diagrams. In the AFC modeling, Rb/Th ratio was used since Rb and Th are not affected significantly by crystallizing phases. Rb/Th ratio of the crust is higher than basaltic lavas and increases in this ratio may be possible reflections of the crustal assimilation. Rubidium was used as the fractionation index. Rb is strongly retained in biotite which is not involved significantly in the crystallization assemblages of volcanic rock suites except for some high silica rocks. Calculated theoretical curves were included to the Rb vs Rb/Th diagrams. In this modeling, due to potential variations in distribution coefficient values during the course of fractional crystallization and uncertainties in end-member compositions, 'r' values represent rather broad approximations. However, r values significantly reflect the most primitive composition of rocks and AFC effects between the rocks. Similar trends and assimilation ratios are also reported by Keskin *et al.* (1998) for the East Anatolian post-collisional volcanic rocks.

As shown from the diagram, the Hasandağ alkaline rocks is the group which is the least contaminated by the crust. This rock group is found between r= 0.01 and 0.2 theoretical curves. Most of the Keçikalesi tholeiitic and Hasandağ calc-alkaline rock samples are observed at r= 0.2–0.3 while a few samples are at r>0.4 (Figure 11a).

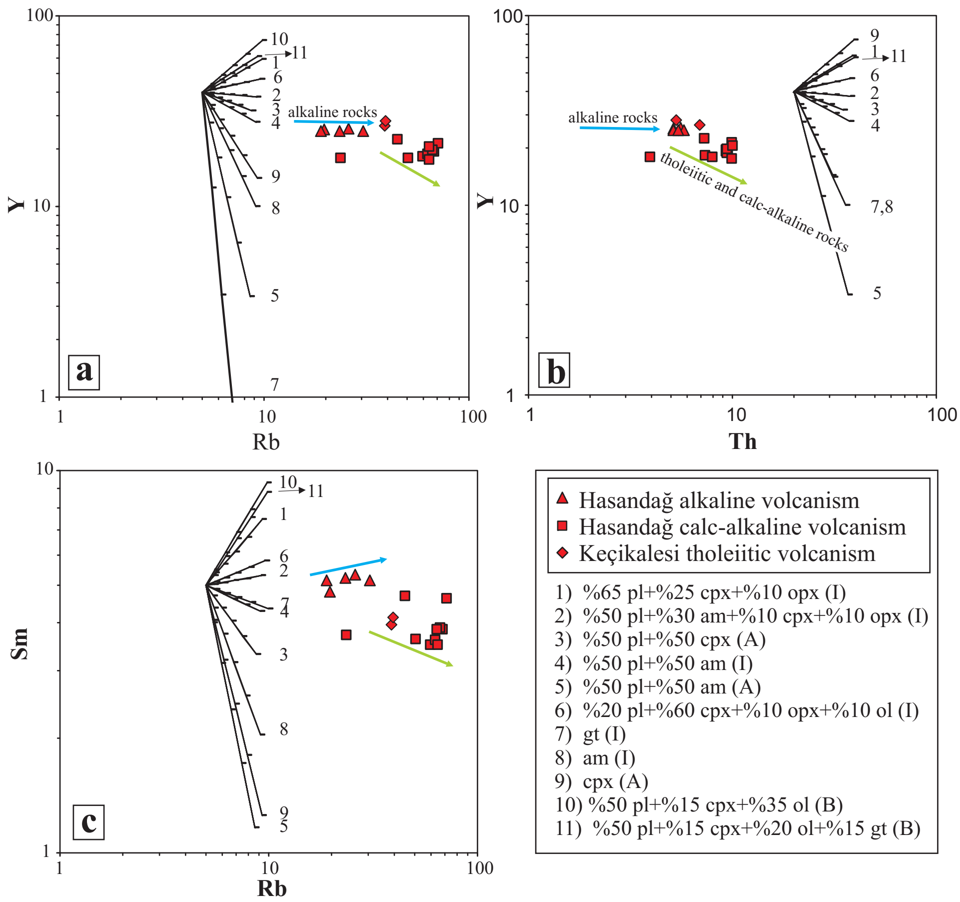


Figure 9. Trace-element diagrams used to study the petrogenesis of the Hasandağ strato volcanic rocks. Diagram showing theoretical Rayleigh fractionation vectors for 50% crystallisation of the phase combinations indicated in the inset (a– logRb–logY; b– logTh–logY; c– logRb–logSm). Thick marks on each vector correspond to 5% crystallization intervals am– amphibole; pl– plagioclase; ol– olivine; cpx– clinopyroxene; opx– orthopyroxene; gt– garnet; B– basic; I– intermediate; A– acidic; numbers refer to phase proportions.

AFC effects on samples from the Erciyes stratovolcano are examined in Figure 11b. In this diagram, the Koçdağ alkaline rocks that comprise the most primitive rocks of volcanism are found between theoretical vectors of r= 0.01 and 0.1. All the calc-alkaline rocks are found between similar vectors. In diagram, Rb/Th ratios span a rather narrow range particularly for the Koçdağ alkaline and Erciyes calc-alkaline rocks, although there is a significant increase in Rb concentrations indicating that fractional crystallization was an effective process during the magmatic evolution.

Mantle-melting Modeling

In mantle melting modeling, non-modal batch melting equations of Shaw (1970) were used. REE abundances and their ratios were used for limiting the source characteristics of magmas. Distribution coefficients of REE were taken from McKenzie and O'Nions (1991, 1995). Values proposed by Kostopoulos & James (1992) were utilized for the modal mineralogies and melting ratios.

In the modeling, we first attempted to test whether the trace element composition of depleted MORB mantle

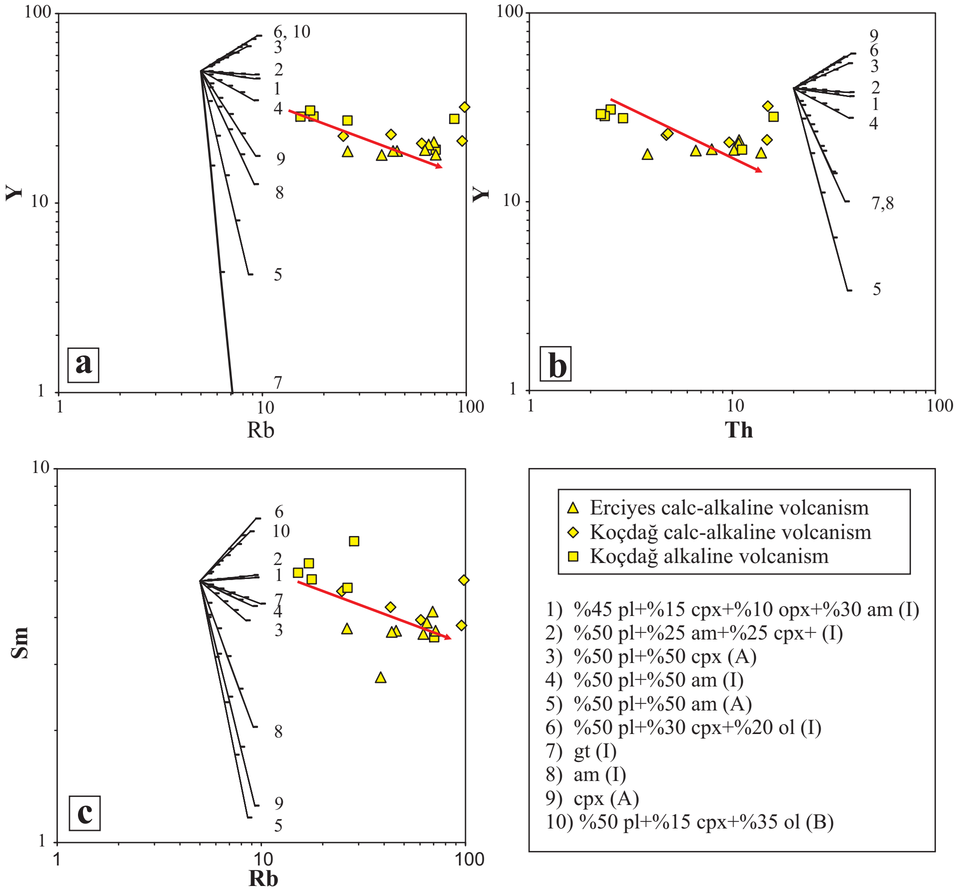


Figure 10. Trace-element diagrams used to study the petrogenesis of the Erciyes strato volcanic rocks. Diagram showing theoretical Rayleigh fractionation vectors for 50% crystallisation of the phase combinations indicated in the inset (a– logRb–logY; b– logTh–logY; c– logRb–logSm). Thick marks on each vector correspond to 5% crystallization intervals am– amphibole; pl– plagioclase; ol– olivine; cpx– clinopyroxene; opx– orthopyroxene; gt– garnet; B– basic; I– intermediate; A– acidic; numbers refer to phase proportions.

(DMM) can be a suitable source for the Central Anatolian volcanic rocks. DMM was assumed to represent the asthenospheric mantle circulation which is characterized by a theoretical depleted MORB source proposed by McKenzie and O'Nions (1991, 1995). Since the mantle source mineralogy is not accurately known, the modelling was based on a mixture of three different source compositions; garnet lherzolite, spinel lherzolite and garnet-spinel lherzolite (50%: 50%). In the modelings, priority was given to incompatible element concentrations (LRE) which are not significantly affected by changes in the source mineralogy.

Theoretic melting curves in the La-Ce, La-La/Nd and La/Ce-La/Yb diagrams are computed based on the batch melting modeling (Figure 12). Melting degrees and source compositions used in calculations are shown on the melting curves. As shown from diagrams in Figure 12, melting degrees of the Keçikalesi tholeiitic rocks, the Hasandağ alkaline rocks and Koçdağ alkaline rocks are 8–9%, 4–5% and 3–8%, respectively.

In order to determine the source mineralogy, La-La/Sm and La/Sm-Sm/Yb diagrams (MREE/HREE and LREE/MREE ratios are considered) were used (Figure 13). Since La and Sm are not significantly affected by changes in the source mineralogy, they may be very useful for determination of bulk chemical composition of the source (Aldanmaz *et al.* 2000). These diagrams were used to distinguish the melting of garnet-lherzolite and spinel-

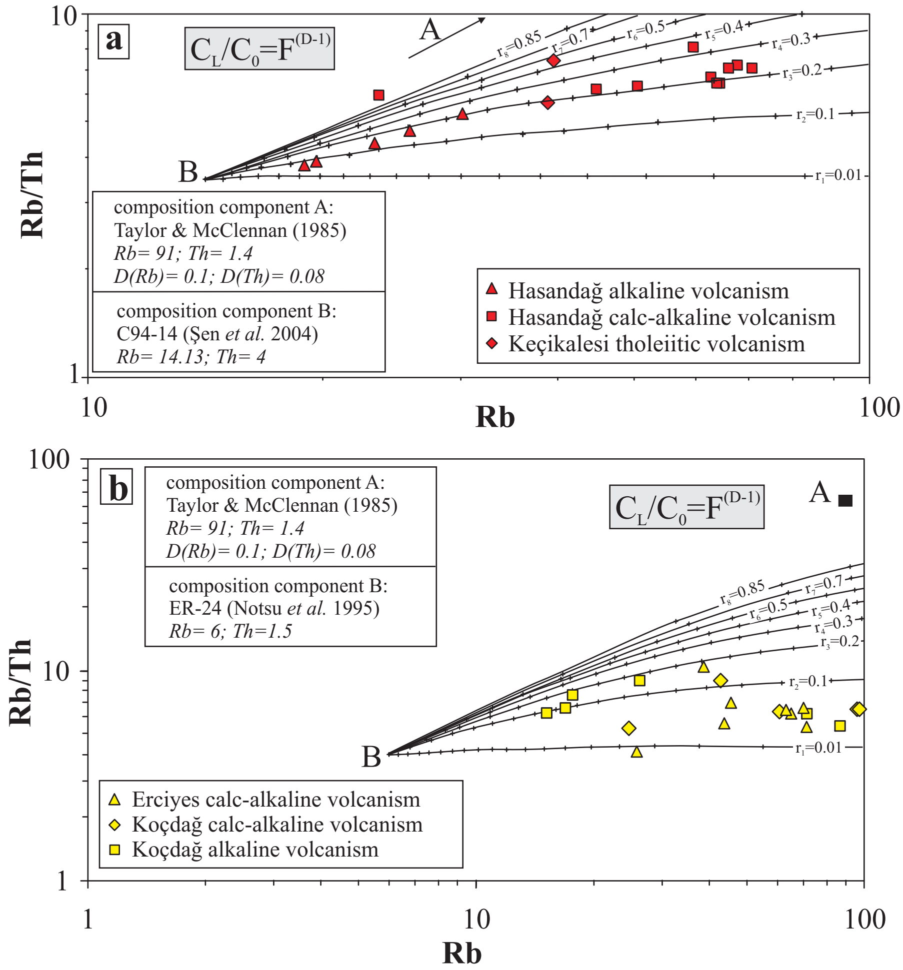


Figure 11. Rb/Th vs Rb diagram for the Central Anatolian volcanc rocks showing the results of AFC (assimilation-fractional crystallization modelling) as discussed in the text.

lherzolite sources. Melting of spinel-lherzolite source causes only a small change in La/Sm ratio of the melt, because none of these elements is fractionated by spinel facies melting. Likewise, only a small change occurs in Sm/Ym ratio of the melt. Therefore spinel-lherzolite melting is observed as a horizontal trend. Melting of garnet-lherzolite source, on the other hand, produces melt with La/Sm ratio higher than the mantle array and the melt fraction produced from such a source will be displaced from the mantle array towards higher La/Sm and Sm/Yb ratios on a La/Sm-Sm/Yb diagram. The results are given in Table 2, together with estimated mantle source composition for the Central Anatolian volcanic rocks.

C1 chondrite-normalized REE diagram including depleted MORB mantle (DMM), primordial mantle (PM) and estimated using the above approach Central Anatolian mantle is shown in Figure 14. As shown from this figure, the computed Central Anatolian mantle composition is more enriched in LREE's with respect to DMM and PM. In addition, LREE concentrations are not affected by garnet or spinel lherzolite source while M-HREE concentrations are significantly affected by the source mineralogy. Figure 14 indicates that the mantle sourcing the Central Anatolian volcanic rocks is represented by a source with garnet + spinel lherzolite composition and the abundance of garnet component is more pronounced for the Hasandağ alkaline rocks.

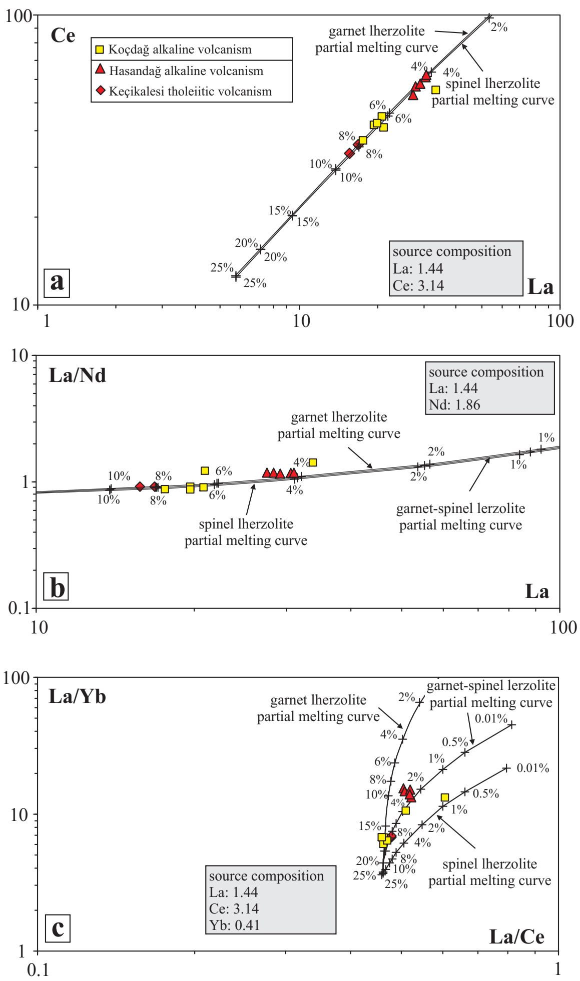


Figure 12. Plots of (a) Ce and (b) La/Nd against La shows melting curves obtained using the non-modal batch melting equations (Shaw 1970) and data from Central Anatolian rocks. The absolute abundances of plotted incompatible elements are unaffected by the mantle mineralogy, therefore the sole control is the bulk chemical composition of the source. (c) Variation of La/Yb vs La/Ce showing melting curves obtained using non-modal batch melting equations for varying proportions of source mineralogy. The points on the curves represent degree of partial melting. Mineral/matrix partition coefficients are from the compilation of McKenzie & O'Nions (1991, 1995).

Source Characteristics and Melting Mechanisms

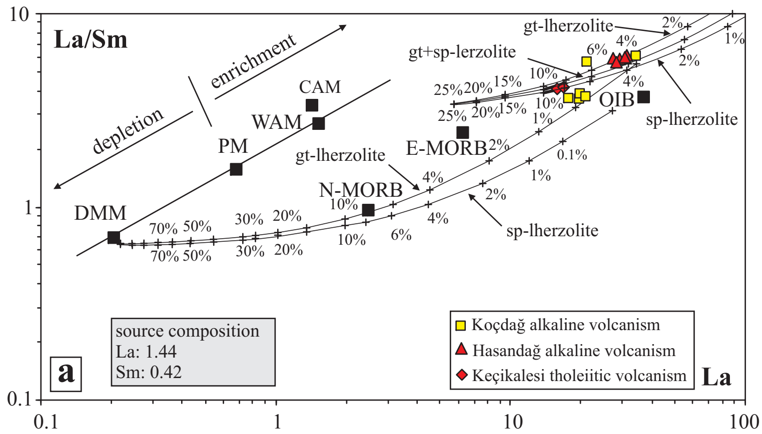
The Central Anatolian volcanism is characterized by calc-alkaline, alkaline and tholeiitic type volcanic rocks which were formed at various stages of volcanic activity and do not show any systematic relationships. Based on geochemical characteristics, the Central Anatolian calc-alkaline and tholeiitic volcanism is reported to be similar to Andean basalts (Hickey *et al.* 1986), basaltic rocks from the Dikili-Ayvalık-Bergama area (Aldanmaz *et al.* 2000) and Big Pine volcanic rocks (Ormerod *et al.* 1991) which are generally derived from lithospheric mantle enriched in subduction components (Şen *et al.* 2004). The alkaline rocks resemble within plate oceanic island basalt (OIB) and to some extent they also indicate mantle source with a subduction component.

The Central Anatolian Quaternary volcanism is mainly related to an extensional tectonism without an active subduction process (Deniel *et al.* 1998; Şen *et al.* 2004). As mentioned previously, considering the trace element content of volcanic rocks in MORB normalized multi-element diagrams, LIL element concentrations are significantly enriched with respect to HFS elements which can be attributed to either the addition of subduction component to the source or crustal contamination on mantle-derived primary magmas.

As shown from the Th/Yb-Ta/Yb diagram, most of samples have compositions indicative of derivation from subduction modified source and resulting melts possibly modified further by crustal contamination. Alkaline rocks seem to be less affected from these processes. In addition, low Zr/Nb (Hasandağ alkaline rocks: 8–10, Erciyes alkaline rocks: 14–17) and high La/Yb (Hasandağ alkaline rocks: 13–15, Erciyes alkaline rocks: 6–14) ratios observed in alkaline rocks of the Hasandağ and Erciyes stratovolcanoes may indicate derivation from a mantle source similar to those of alkaline OIB magmas. In formation of calc-alkaline series, a combination of assimilation and fractional crystallization processes are effective.

Alkaline rocks of the Hasandağ stratovolcano are characterized by low Sr isotopic ratios and the crust contribution is decreased in time (Deniel *et al.* 1998). Alkaline rocks of the Erciyes stratovolcano have been reported to have $^{87}Sr/^{86}Sr$ ratios higher than the typical MORB but significantly lower than the chondritic silicate earth compositions and this may indicate the presence of an OIB source in the development of this magma (Kürkçüoğlu *et al.* 1998).

Hofmann & White (1982) state that enriched isotope compositions of oceanic island basalts is due to old crust material sent back to the mantle. On the other hand, McKenzie and O'Nions (1983) suggest that lower parts of the lithosphere thickening in the orogenic belts are detached in time and separated from the lithosphere and



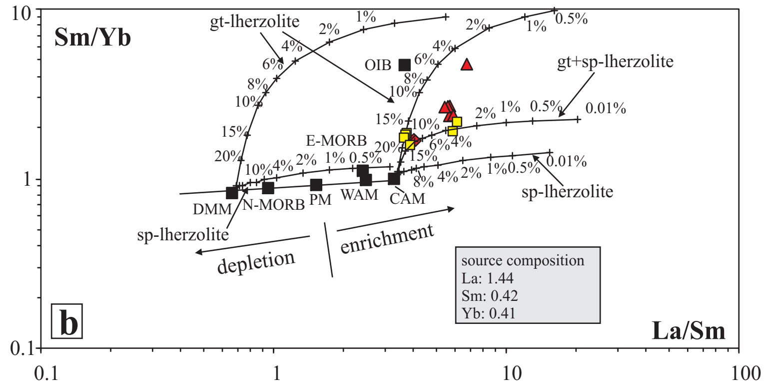


Figure 13. Plots of La/Sm vs La and Sm/Yb vs La/Sm showing melt curves (or lines) obtained using the non-modal batch melting equations of Shaw (1970). Melt curves are drawn for spinel-lherzolite (with mode and melt mode of $ol_{0.578} + opx_{0.270} + cpx_{0.119} + sp_{0.033}$ and $ol_{0.10} + opx_{0.270} + cpx_{0.50} + sp_{0.13}$) and for garnet-lherzolite (with mode and melt mode of $ol_{0.598} + opx_{0.211} + cpx_{0.076} + gt_{0.115}$ and $ol_{0.05} + opx_{0.20} + cpx_{0.30} + gt_{0.45}$; respectively; Kostopoulos & James 1992). Mineral/matrix partition coefficients and DMM are from the compilation of McKenzie & O'Nions (1991, 1995); PM, N-MORB and E-MORB compositions are from Sun & McDonough (1989). Western Anatolian Mantle (WAM) composition is from Aldanmaz *et al.* (2000). The heavy line represents the mantle array defined using DMM and PM compositions. Solid curves (or lines) are the melting trends from DMM and Central Anatolian Mantle (CAM), respectively. Tick marks on each curve (or line) correspond to degrees of partial melting for a given mantle source.

added to convectional currents in the asthenosphere and, they rise as plumes in certain places thus forming the source of oceanic island basalts.

McKenzie (1989) defined the continental basaltic magmas as those derived probably from the metasomatized subcontinental lithospheric mantle (SCLM). He also described melts that are significantly enriched in incompatible elements and volatiles and also upward migration of such melts which may result in metasomatism at the base of SCLM and the combination of low-degree partial melt of the asthenospheric mantle material under the continents. Anderson (1994) proposed convective mantle that is represented by trace element and isotope characteristics (like DMM) depleted prior to

Table 2. Mantle source compositions for the central Anatolian volcanic rocks. Trace element concentrations were estimated using three different mineral modes as garnet-lherzolite, spinel–lherzolite and garnet+spinel-lherzolite (50%– 50%).

(F) Degree of partial melting	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
	Estimation of mantle source composition of the Central Anatolia suite													
	1.44	3.14	0.40	1.86	0.42	0.14	0.50	0.09	0.61	0.13	0.40	0.06	0.41	0.06
	Concentration of trace element in tle liquid (garnet-lherzolite)													
0.25	5.76	12.52	1.59	7.41	1.68	0.58	1.96	0.35	2.40	0.53	1.54	0.23	1.54	0.23
0.20	7.15	15.48	1.95	9.01	2.01	0.68	2.27	0.40	2.62	0.55	1.55	0.22	1.32	0.18
0.15	9.45	20.29	2.52	11.50	2.49	0.82	2.68	0.45	2.87	0.58	1.55	0.20	1.15	0.14
0.10	13.90	29.40	3.57	15.88	3.28	1.04	3.28	0.53	3.18	0.61	1.55	0.19	1.02	0.12
0.08	17.13	35.85	4.28	18.74	3.76	1.17	3.60	0.57	3.32	0.62	1.55	0.18	0.98	0.11
0.06	22.32	45.91	5.34	22.85	4.40	1.33	4.00	0.61	3.48	0.63	1.55	0.18	0.94	0.11
0.04	32.01	63.84	7.11	29.26	5.30	1.55	4.48	0.66	3.65	0.64	1.55	0.17	0.90	0.10
0.02	56.59	104.71	10.62	40.68	6.65	1.84	5.11	0.72	3.84	0.66	1.55	0.17	0.87	0.10
0.01	91.87	154.01	14.09	50.55	7.64	2.04	5.49	0.75	3.95	0.66	1.55	0.17	0.85	0.10
0.005	133.46	201.42	16.85	57.53	8.24	2.15	5.70	0.77	4.00	0.67	1.55	0.17	0.84	0.09
0.0001	239.93	288.47	20.85	66.53	8.94	2.28	5.93	0.79	4.05	0.67	1.55	0.17	0.84	0.09
	Concentration of trace element in tle liquid (spinel-lherzolite)													
0.25	5.76	12.55	1.60	7.45	1.70	0.58	1.98	0.36	2.44	0.54	1.58	0.24	1.60	0.24
0.2	7.15	15.49	1.96	9.07	2.05	0.70	2.38	0.43	2.92	0.65	1.89	0.29	1.91	0.28
0.15	9.42	20.21	2.53	11.57	2.59	0.87	2.98	0.54	3.63	0.81	2.36	0.36	2.37	0.35
0.1	13.79	29.10	3.57	15.98	3.51	1.16	3.98	0.71	4.79	1.07	3.12	0.48	3.13	0.46
0.08	16.93	35.30	4.27	18.86	4.10	1.34	4.60	0.82	5.49	1.23	3.59	0.55	3.59	0.53
0.06	21.93	44.87	5.32	23.00	4.92	1.59	5.45	0.97	6.44	1.44	4.23	0.64	4.21	0.61
0.04	31.11	61.55	7.04	29.47	6.15	1.94	6.68	1.18	7.77	1.75	5.13	0.77	5.08	0.74
0.02	53.53	97.97	10.43	41.00	8.19	2.50	8.62	1.51	9.82	2.23	6.52	0.98	6.41	0.92
0.01	83.69	139.14	13.72	50.98	9.83	2.92	10.08	1.76	11.30	2.57	7.55	1.13	7.37	1.05
0.005	116.51	176.15	16.30	58.04	10.92	3.19	11.02	1.91	12.22	2.79	8.20	1.23	7.97	1.13
0.0001	189.22	238.27	19.98	67.16	12.25	3.50	12.12	2.10	13.28	3.04	8.94	1.33	8.66	1.22
	Concentration of trace element in tle liquid (spinel+gt-lherzolite)													
0.25	5.76	12.54	1.59	7.43	1.69	0.58	1.97	0.36	2.42	0.54	1.56	0.24	1.57	0.23
0.2	7.15	15.49	1.95	9.04	2.03	0.69	2.32	0.41	2.77	0.60	1.72	0.25	1.61	0.23
0.15	9.43	20.25	2.53	11.54	2.54	0.85	2.83	0.50	3.25	0.69	1.95	0.28	1.76	0.25
0.1	13.84	29.25	3.57	15.93	3.40	1.10	3.63	0.62	3.99	0.84	2.34	0.33	2.08	0.29
0.08	17.03	35.58	4.28	18.80	3.93	1.26	4.10	0.69	4.41	0.92	2.57	0.36	2.28	0.32
0.06	22.12	45.39	5.33	22.92	4.66	1.46	4.72	0.79	4.96	1.04	2.89	0.41	2.57	0.36
0.04	31.56	62.69	7.08	29.37	5.72	1.74	5.58	0.92	5.71	1.20	3.34	0.47	2.99	0.42
0.02	55.06	101.34	10.52	40.84	7.42	2.17	6.86	1.12	6.83	1.44	4.04	0.58	3.64	0.51
0.01	87.78	146.57	13.91	50.77	8.73	2.48	7.79	1.26	7.62	1.62	4.55	0.65	4.11	0.57
0.005	124.99	188.79	16.58	57.78	9.58	2.67	8.36	1.34	8.11	1.73	4.87	0.70	4.41	0.61
0.0001	214.58	263.37	20.41	66.84	10.59	2.89	9.03	1.44	8.67	1.86	5.25	0.75	4.75	0.66

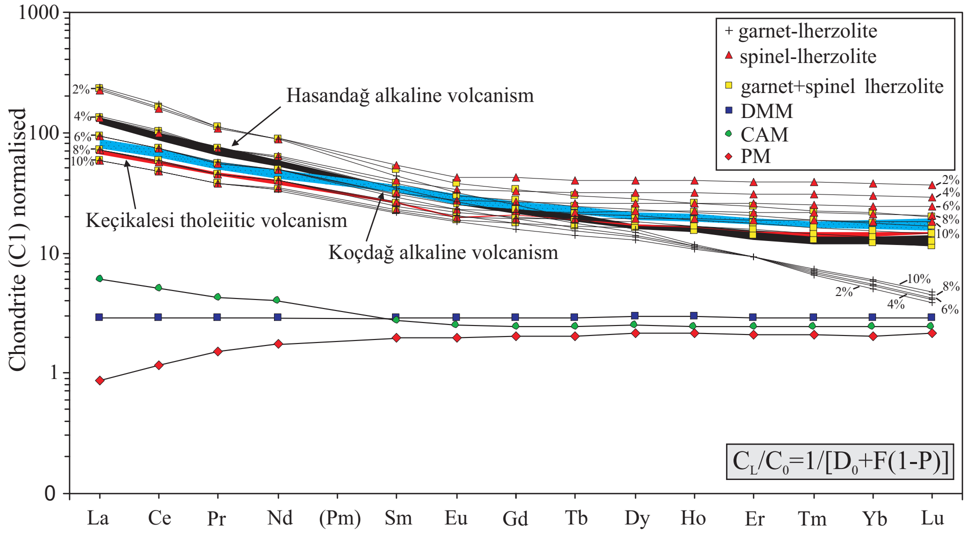


Figure 14. Chondrite (C1) normalised REE patterns showing the compositions of modelled batch melts produced by melting of a CAM source with mineral proportions of garnet-lherzollite, spinel-lherzolite and garnet (%50) + spinel (%50) lherzolite. The modal mineral proportions and distribution coefficients used same as figure 13. Normalised values are srom Boynton (1984) and the batch melting equation is from Shaw (1970).

ascension and interacted at the beginning with shallow and enriched mantle. This portion proposed by Anderson (1994) is below the thermal boundary layer or within the asthenosphere. The same author also states that enriched part of the shallow mantle may correspond to chemical characteristics of a source region similar to continental basaltic or OIB magmatism. In order to explain composition of all oceanic and continental within plate basic volcanics which necessitate an enriched source, McKenzie and O'Nions (1995) proved that SCLM could be enriched and remelted afterwards.

No evidence was found for spatial and chronologic systematic variation of the source component and the magmatism sourcing alkaline and calc-alkaline volcanics in the Central Anatolia. Therefore, it is thought that alkaline and calc-alkaline magmatic products were represented by magmas derived from a heterogeneous mantle source with melts of varying rates and affected from crustal contamination at varying rates.

In order to examine melting mechanisms which gave rise to generation of Central Anatolian post-collisional volcanism, P-T diagram of Pearce *et al.* (1990) proposed for the Eastern Anatolia was taken into consideration. Pearce *et al.* (1990) state that a typical non-cratonic continental lithosphere has a mechanical boundary layer (MBL) of varying thickness and is separated from the convective asthenosphere with a thermal boundary layer (TBL). Bailey (1987) suggests that geothermal gradient of MBL cuts the lithospheric solidus which is metasomatized by small melt pockets ascending from asthenosphere to the lithosphere and it is metasomatized in lower parts of the region.

The potential mechanisms of magma generation in the (subduction component bearing) heterogeneously enriched mantle source of the Central Anatolian volcanism may include: (a) mantle-plume, (b) slab break-off, (c) extension and associated strike-slip faulting, and (d) lithospheric delamination and associated orogenic collapse. These possible options are discussed below.

(a) Melting of lithospheric mantle as a result of thermal perturbation in association with ascending mantle plume or asthenospheric mantle may give rise to formation of widespread volcanism in the Central Anatolia. It was proposed by McKenzie & Bickle (1988) that asthenosphere could start to melt at a potential temperature of 1280 °C and at an initial depth of 50 km under a stress factor of 2.5. Under hot mantle conditions, mantle plume can also start melting at great depths without substantial stress (at 100 km, potential temperature is 1480 °C) and affects the regional topography. The typical mantle plume is described by White and McKenzie (1989) as a spreading center (limited to 150–200 km) forming a mushroom-shaped hot spot with a diameter of 1000–2000 km that dynamically uplifts an area of 1000–2000 km in diameter. There is no regional stress evidence that could be associated with a mantle plume responsible for the post-collisional Central Anatolian volcanism and there are no topographic indicators necessary for such a mantle plume either.

(b) Melting of lithospheric mantle due to thermal perturbation arising from ascending asthenospheric mantle by slab breakoff could be an alternative mechanism for the source of Central Anatolia volcanism. According to Davies and Von Blanckenburg (1995), slab breakoff is very common for many orogenic belts and it explains the coexistence of ultra-high pressure metamorphics and mantle-derived magmatism. Slab should be separated at the early stages of continental collision (Davies & Von Blanckenburg 1995; Wong A Ton & Wortel 1997). This is due to decrease in subduction rate by the positive lifting power of continental lithosphere intruded into the subduction zone (Gerya *et al.* 2004).

In contrast to previously proposed several models for the Eastern Anatolia, Şengör *et al.* (2003) and Keskin (2003, 2007) suggested the model of slab breakoff and steepening under widely spread subduction accretionary complex. In the model proposed by Davies & Von Blanckenburg (1995), if the subduction rate is 1 cm/year, the breakoff was stated to occur at a depth of 50–120 km. The volcanism was thought to start as a result of release of this substantial load and upwelling of less dense asthenospheric mantle. Unlike the model of 'original slab breakoff' proposed by Davies & Von Blanckenburg (1995), Keskin (2003), Şengör *et al.* (2003) suggest a new model where subducting oceanic lithosphere beneath the accretionary prism gets steepened and eventually detached from the continental lithosphere. According to these workers, the melting occurs in the asthenospheric mantle and eventually volcanic activity spreads in a large area apart from the suture zone.

Under the light of above information, a similar mechanism can be discussed for Central Anatolia considering its closeness to Eastern Anatolia and similar geochemical characteristics of the two regions. Given the distance of the volcanic centres to any possible subduction zone in this region, however, the volcanism in Central Anatolia is unlikely to be directly affected by the subduction process that resulted in formation of the Eastern Anatolia collision system. One can infer that the closure of inner-Tauride Ocean could be a possible subduction. Geochemical characteristics of Paleocene–Eocene volcanic and intrusive products in the region and their radiometric ages may indicate that these volcanics are cogenetically formed (Gürer & Aldanmaz 2002). In most of previous works, these events are evaluated in the concept of arc magmatism associated with closure of the inner-Tauride Ocean (Şengör &Yılmaz 1981; Görür *et al.* 1984; Gökten & Floyd 1987; Erdoğan *et al.* 1996). More recent studies, however, showed that the regional magmatic activity took place in a post-collisional environment and may have an intra-plate character (Gürer & Aldanmaz 2002). This is evident from the temporal evolution of the activity that changes from a syn-collisional episode (e.g., S-type, peraluminous granites) through a post-collisional, calc-alkaline episode (e.g., I-type, high-K, metaluminous granites) to a post-collisional, within-plate alkaline episode (e.g. A-type, peralkaline granites) (e.g., Göncüoğlu & Türeli 1993; İlbeyli & Pearce 1997; Boztuğ 2000, 2008; Köksal & Göncüoğlu 2008).

The age of tholeiitic volcanism of the Hasandağ strato volcano ranges from 12.4±0.6 to 13.7±0.3 Ma (Besang *et al.* 1977) and alkaline type latest products are dated as 34000±7000 years (Aydar 1992). Alkaline rocks as the first products of the Erciyes stratovolcano are of 4.39±0.28 Ma old (Ayrancı 1969). Since the volcanism in both regions is not a subduction-type volcanism related to the closure of inner-Tauride Ocean and the subsequent slab breakoff event is not evidenced by significant chronological and spatial systematic, this model is not suitable one. In addition, considering the alkaline lavas of varying ages, the presence of a heterogeneous mantle source is reasonable.

(c) Another alternative mechanism is that regional extension developing in association with strike-slip faults and the melting of mantle lithosphere due to thermal perturbation could be related to tectonic regime in the Central Anatolia. Formation of lithospheric melting in continental extensional environments is studied by several workers (Latin *et al.* 1989; Hawkesworth & Norry 1982; Menzies & Hawkesworth 1987). Lithospheric thermal perturbation arising from upwelling of hot asthenosphere is the reason for lithospheric extension necessary for the melting of lithospheric mantle material (Dixon *et al.* 1981) or the position of solidus above the metasomatized level. Since melting point of these rocks will be lower in metasomatized mantle conditions, small thermal irregularities could be sufficient for starting of melting. Thus, even small-size extensions can trigger volcanism.

The magma generation in pull-apart basins in association with N–S-trending fractures and strike-slip regimes in the Eastern Anatolia is attributed to fast lithospheric extension and small-scale delamination under the pull-apart basins (Dewey *et al.* 1986). Although Pearce *et al.* (1990) suggest that delamination process is the dominant mechanism for widespread magma generation in the same region they also state that other mechanisms such as formation of pull-apart basins accompany these processes. Cooper *et al.* (2002) proposed that mantle upwelling and melting under the strike-slip fault systems could be the origin of mafic magmas in northwest Tibet. Likewise, Aldanmaz *et al.* (2005, 2006) mention partial effect of strike-slip faults in generation of alkaline volcanics in NW Turkey.

The first group of active fault systems extending through the Central Anatolian volcanism is left-lateral Ecemiş fault zone and right-lateral Tuz Gölü fault zone and the second is N60–70° E-trending normal faults that are parallel to the volcanic axis and concordant with the main eruption centres (Toprak & Göncüoğlu 1993). The Erciyes basin is a pull-apart basin with an important strike-slip component (Koçyiğit & Beyhan 1998). Due to lateral stress arising from transtensional tectonic regime in the Central Anatolia coupled with regional extension, formation of thermal perturbation in the mantle lithosphere could be a possible mechanism. In addition, as mentioned previously, little effect of AFC on the Erciyes strato volcano could be explained with crustal thinning as a result of extensional tectonism in the region associated with pull-apart basin.

(d) Another alternative mechanism could be thermal perturbation and melting triggered by lithospheric delamination and associated orogenic collapse following the post-collisional lithospheric thickening. Thermal perturbation and melting arising from lithospheric delamination could be the reason of volcanism in the Central Anatolia. Although thermal perturbation in association with strike-slip faults in lithosphere can be thought as the mechanism to start melting, delamination of thermal boundary layer (TBL) could be proposed as the more efficient mechanism (Pearce *et al.* 1990). In general, one of the fundamental consequences of the lithospheric delamination is the collapse event associated with rapid uplifting and extensional system which occurs as a result of isostatic replacing of relatively dense (cold) lithospheric mantle by the less dense (hot) asthenospheric mantle (Dewey 1988; England & Houseman 1998; Nelson 1992; Platt & England 1993). Thickening TBL is denser and colder than the surrounding medium and since thickened levels of metasomatized lithosphere are in close contact with the asthenosphere, they are convectively replaced by the asthenosphere (Houseman *et al.* 1981; England & Houseman 1998). Due to thermal perturbation arising from direct contact between metasomatized mantle lithosphere and hot asthenosphere, delamination of TBL could result in melting of metasomatized mantle lithosphere.

Pearce *et al.* (1990) stated that the close contact between thickened metasomatized lithospheric mantle and asthenosphere is an effective mechanism for collisional magma generation developed in the Eastern Anatolia. While delaminated block of the mantle lithosphere sinks into the asthenosphere, increasing melting may release water (Elkins-Tanton 2004). These two mechanisms play an important role in formation of common partial melt in the mantle and can produce widespread volcanism in the region.

As a result, delamination of TBL and associated substantial thermal perturbation could be alternative models that facilitate melting of continental lithosphere responsible for initiation of Central Anatolia volcanism. In addition, the close association of volcanism with the strike-slip tectonism in the region indicates that this system possibly contributes to the magma rising.

Conclusion

The Hasandağ and Erciyes stratovolcanoes represented by widespread calc-alkaline volcanism are two important members of collisional volcanism in the Central Anatolia. The calc-alkaline products are accompanied by tholeiitic and alkaline rocks in the Hasandağ volcano and by alkaline rocks in the Erciyes stratovolcano. Rocks of both volcanisms show a wide composition spectrum from basalt to rhyolite.

In the chondrite normalized diagrams the rocks from the Hasandağ and Erciyes stratovolcanoes, display uniform and sub-parallel light rare earth element patterns and show relatively enrichment in LREE. In the multi-element diagram normalized to N-MORB, tholeiitic and calc-alkaline rocks of the Hasandağ strato volcano show a significant enrichment in LIL elements (Rb, Ba, Th, U and K) and LREE's and relatively depletion in HFS elements (Ta, Nb, Ti and Hf). In the calc-alkaline rocks of the Erciyes stratovolcano that are characterized by similar patterns, LIL elements such as Th, U and K as well as LREE's also show a distinct enrichment. In the alkaline rocks of the both stratovolcanoes, LIL elements are in lower concentrations in comparison to other rock groups and they do not have negative Ta and Nb anomalies indicating that alkaline rocks are derived from a different source. In MORB normalized multi-element diagrams of the same rocks, it was observed that LIL elements are significantly enriched compared to HFS elements. This enrichment may be attributed to the effect of subduction component in the source region or crustal contamination. Depletion of Hf and Ti with respect to other HFS elements can be explained with mantle enrichment in intracontinental processes or derivation from a source with small degree partial melts.

According to fractionation vectors constructed on the basis of variations in trace element concentrations, rocks of the Hasandağ volcanism generally display two different trends. Tholeiitic and calc-alkaline rocks are modified by fractionation of amphibole and plagioclase while alkaline rocks are represented by fractionation effects of plagioclase, pyroxene and amphibole minerals. In alkaline and calc-alkaline rocks of the Erciyes volcano, fractionation trends are similar and conformable with those of plagioclase and amphibole.

Theoretically constructed AFC modelings show that Hasandağ alkaline rocks are less affected from the crustal contamination in comparison to tholeiitic and calc-alkaline rocks. However, in alkaline and calc-alkaline rocks of the Erciyes volcano which display similar AFC trends, the effect of crustal contamination is less than that of Hasandağ volcanics.

According to theoretical melting curves calculated with non-modal batch melting model, the melting degrees of Hasandağ and Erciyes volcanic rocks are 8–9% for the Keçikalesi tholeiitic rocks, 4–5% for the Hasandağ alkaline rocks and 3–8% for the Koçdağ alkaline rocks. The Central Anatolian volcanic rocks are generated by a mantle source of garnet + spinel lherzolite composition while Hasandağ alkaline rocks are dominated by the garnet composition. The calculated Central Anatolian mantle composition is more enriched in LREE's in comparison to DMM and PM.

Accordingly, it is believed that alkaline and calc-alkaline magmatic products were generated from a heterogeneous mantle source under varying melting conditions and affected by the crustal contamination at varying degrees.

Considering its geochemical characteristics, the Central Anatolian volcanism seems to be derived from a lithospheric mantle that is enriched in subduction components. Solutions which are strongly enriched by incompatible elements and volatiles result in metasomatism at the base of continental lithosphere. TBL which is thickened by lithospheric thickening in association with collisional tectonism is denser and colder than its environs. When thickened levels of metasomitized lithosphere are in close contact with asthenosphere, it can be convectively replaced by the asthenosphere. Delamination of TBL may result in melting due to thermal perturbation arising from direct contingence of metasomitized mantle lithosphere to hot asthenosphere. Hence, the Central Anatolian volcanism can be generated by melting of continental lithosphere as a result of a substantial thermal perturbation occurring by delamination of TBL. In addition, the observation that volcanism is closely associated with strike-slip tectonism in the region may indicate that this system possibly contributes to the magma rising. The mechanism suggested for the melt generation is rather similar to that proposed by Pearce *et al.* (1990) and Keskin *et al.* (1998) for the east Anatolian and by the Aldanmaz *et al.* (2000) for the west Anatolian volcanisms.

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