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Petrogenetic modelling of Quaternary post-collisional volcanism: a case study of central and eastern Anatolia

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Abstract – Extensive continental collision-related volcanism occurred in Turkey during Neogene–Quaternary times. In central Anatolia, calc-alkaline to alkaline volcanism began in the Middle–Late Miocene. Here we report trace elemental and isotopic data from Quaternary age samples from central and eastern Anatolia. Most mafic lavas from central Anatolia are basalt and basaltic andesite, with lesser amounts of basaltic trachyandesite and andesite. All magma types exhibit enrichment in LILE (Sr, Rb, Ba and Pb) relative to HFSE (Nb, Ta). Trace element patterns are characteristic of continental margin volcanism with high Ba/Nb and Th/Nb ratios. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios of central Anatolian lavas range between 0.704105–0.705619 and 0.512604–0.512849, respectively. The Quaternary alkaline volcanism of eastern Anatolia has been closely linked to the collision between the Arabian and Eurasian plates. Karacadağ and Tendürek volcanic rocks are represented by alkali basalts and basaltic trachyandesites, respectively. As expected from their alkaline nature, they contain high abundances of LIL elements, but Tendürek lavas also show depletion in Nb and Ta, indicating the role of crustal contamination in the evolution of these magmas. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of the Karacadağ and Tendürek lavas range from 0.703512 to 0.704466; 0.512742 to 0.512883 and 0.705743 to 0.705889 and 0.512676, respectively. Petrogenetic modelling has been used to constrain source characteristics for the central and eastern Anatolian volcanic rocks. Trace element ratio plots and REE modelling indicate that the central Anatolian volcanism was generated from a lithospheric mantle source that recorded the previous subduction events between Afro-Arabian and Eurasian plates during Eocene to Miocene times. In contrast, The Karacadağ alkaline basaltic volcanism on the Arabian foreland is derived from an OIB-like mantle source with limited crustal contamination. Tendürek volcanism, located on thickened crust, north of the Bitlis thrust zone, derived from the lithospheric mantle via small degrees (1.5 %) of partial melting.

Keywords: geochemistry, Quaternary, volcanism, basaltic composition, Turkey.

1. Introduction

Northward motion of the Afro-Arabian plate caused subduction during Eocene to Miocene times, followed by continental collision between the Eurasian and Arabian plates during the Middle to Late Miocene. The continental collision was accommodated by crustal shortening and thickening in eastern Anatolia (Şengör, 1980; Şengör & Yilmaz, 1981; Fytikas *et al*. 1984; Buket & Temel, 1998; Temel *et al*. 1998; Yilmaz, Güner & Şaroğlu, 1998; Yürür & Chorowicz, 1998), with a N–S-directed compressional regime that continues today. The thickness of the crust is about 45–50 km in eastern Anatolia (Şengör, 1980; Yilmaz, 1990). As a result of this collisional event, the Anatolian block began to move westward along two strike-slip faults, the North Anatolian and East Anatolian faults (Fig. 1) (Şengör, 1980; Lyberis *et al*. 1992). This movement is the main cause of internal deformation within the Anatolian block, with pull-apart basins and thrust faults (Şengör, Görür & Şaroğlu, 1985).

Widespread volcanism occurred in Anatolia from Neogene to Quaternary times as a consequence of plate convergence and continental collision (Le Pennec *et al*. 1994; Pearce *et al*. 1990). Collision volcanism in eastern Anatolia began in the Late Miocene (Pearce *et al*. 1990). North of the Bitlis suture zone, volcanism developed on thickened crust, while south of the Bitlis suture zone, foreland volcanism (e.g. Karacadağ volcano) developed on the thin crust of the Arabian plate (Notsu *et al*. 1995) (Fig. 1). The central Anatolian volcanism of Late Miocene to Quaternary age has been interpreted as arc volcanism related to continental collision between the Afro-Arabian and Eurasian plates (Pasquare *et al*. 1988) (Fig. 1). However, Lyberis *et al*. (1992) proposed that the subducted African slab did not reach central Anatolia and thus cannot be directly responsible for generating the calc-alkaline

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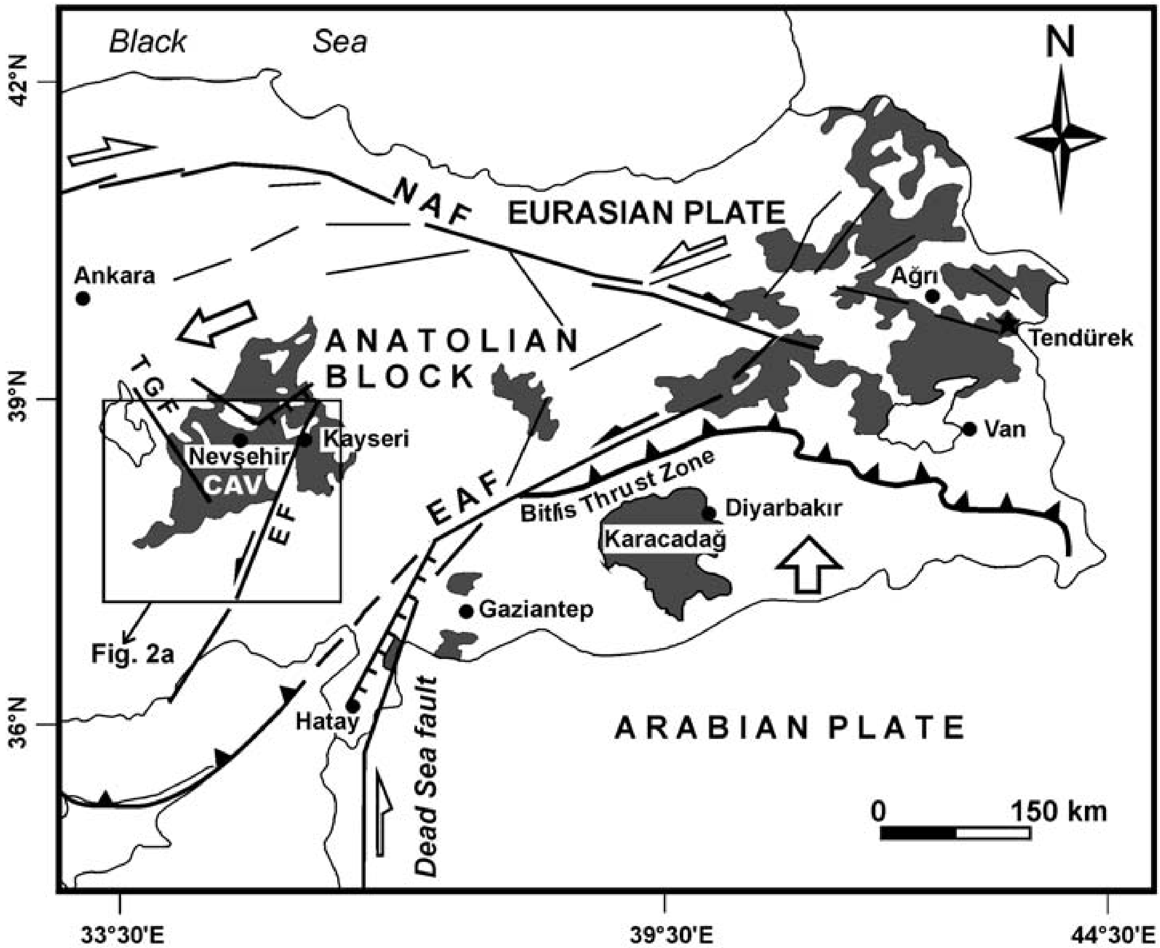

Figure 1. Distribution of Neogene–Quaternary volcanism in central and eastern Anatolia (modified from Temel, Gündoğdu & Gourgaud, 1998) and the location of central Anatolian Volcanism and Karacadağ and Tendürek volcanoes. Box shows area of Figure 2a. CAV: Central Anatolian Volcanism; EAF: East Anatolian Fault; EF: Ecemiş Fault; NAF: North Anatolian Fault; TGF: Tuz Gölü Fault.

volcanism in this area (Aydar *et al*. 1995; Deniel, Aydar & Gourgaud, 1998). Recent studies show that, since Late Miocene times, the transitional alkaline–calc-alkaline volcanism (Aydar *et al*. 1994) is related to an extensional regime (Toprak & Göncüoğlu, 1993; Kürkcüoğlu *et al*. 1998; B. Kürkcüoğlu, unpub. Ph.D. thesis, Hacettepe Univ. 2000; Kürkcüoğlu *et al*. 2001), but the volcanic rocks have retained signatures of earlier subduction (K. Olanca, unpub. Ph.D. thesis, Univ. Blaise Pascal, 1994; Deniel, Aydar & Gourgaud, 1998; Alici, Temel & Gourgaud, 2002). Furthermore, Dirik (2001) and Dirik & Göncüoğlu (1996) suggested that Late Miocene to Quaternary volcanic activity in central Anatolia developed under an extensional regime. These studies also demonstrated that central Anatolia has been affected by a transtensional regime since Late Pliocene times.

The sources of magmas in extensional and collisional volcanism are still controversial. In particular, is the source of within-plate basaltic magmas in an extensional setting the lithosphere, convecting asthenosphere or both? It is has often been argued that if the continental basalts are similar to ocean island basalts (OIB) in both incompatible trace element patterns and isotopic compositions, then they probably originate from the asthenosphere (Fitton & Dunlop, 1985; Kempton *et al*. 1991) However, direct melting of the continental lithospheric mantle has been involved in the genesis of continental basaltic volcanism in extensional settings (McKenzie & O'Nions, 1983; McKenzie, 1989; Menzies, 1992).

The present study of the lavas of central (Erciyes stratovolcano and the dispersed activity of Derinkuyu, Hasandağ and Karapinar) and eastern Anatolia (Karacadağ and Tendürek shield volcanoes) focuses on their geochemistry. Rare earth element (REE) petrogenetic modelling is applied to constrain the source characteristics of the mafic magmas in extensional and collisional settings.

2. Samples and analytical techniques

Volcanic samples were collected from Quaternary volcanoes of central and eastern Anatolia (Figs 1, 2).

In central Anatolia, Plio-Quaternary volcanism is represented by two large stratovolcanoes (Erciyes Dağ

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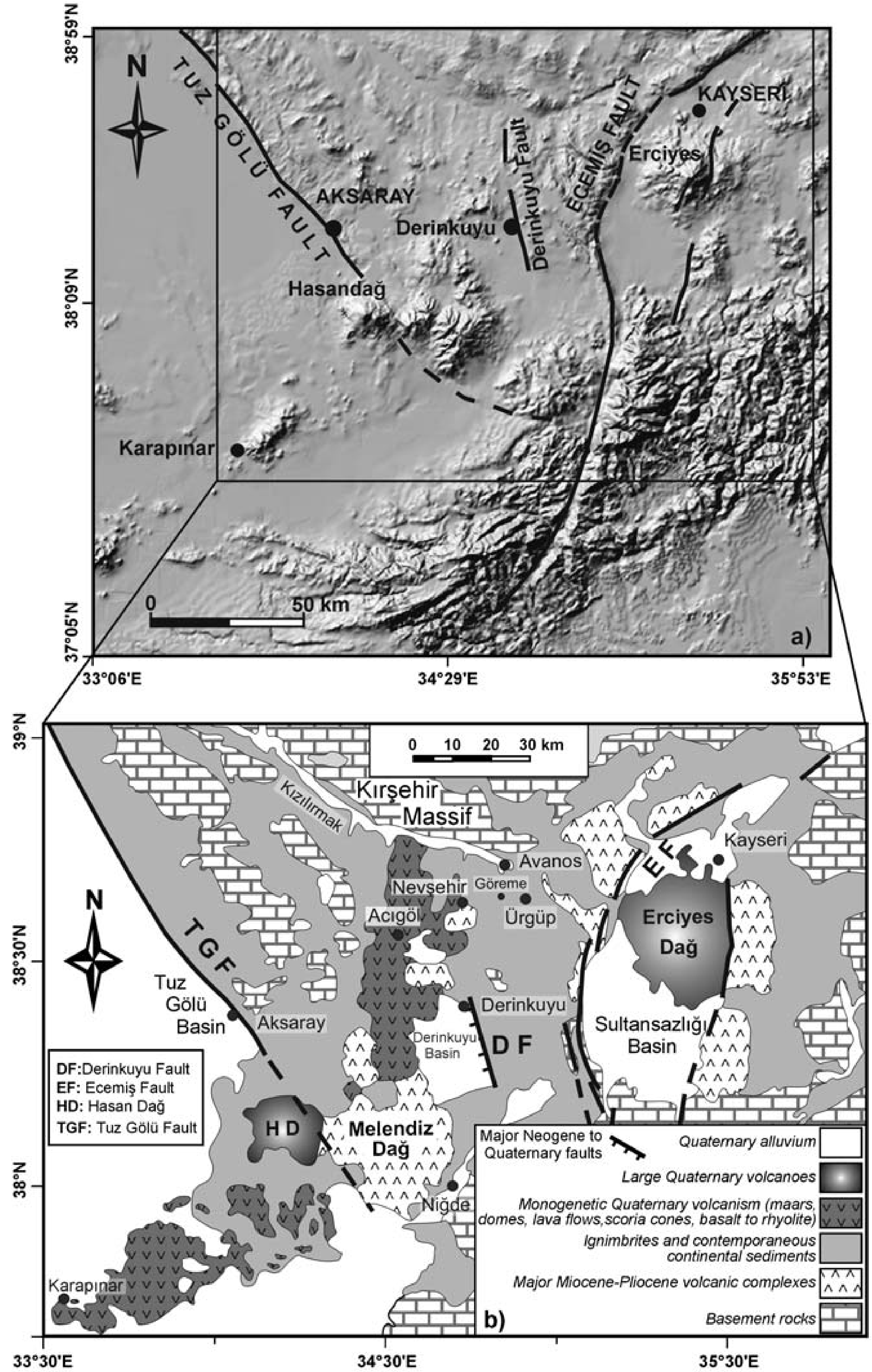

Figure 2. (a) Location map of the Erciyes, Derinkuyu, Hasandağ and Karapinar volcanic fields on an illuminated digital elevation model (DEM). The DEM is artificially illuminated from the northwest with a zenith angle of 45°. Vertical exaggeration is 0.005. Major tectonic structures from Pasquare *et al*. (1988); Toprak & Göncüoğlu (1993); Temel *et al*. (1998). Box shows area of (b) generalized geological sketch map of the study area (modified from Pasquare *et al*. 1988; Le Pennec *et al*. 1994 and Temel *et al*. 1998).

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Table 1. Major-oxide, trace, rare earth element and Sr–Nd isotope analysis of representative volcanic rocks from central and eastern Anatolia

	Central Anatolian volcanic rocks										
	Karapınar		Hasandağ								
Sample	C94-1	C94-2	C94-4	C94-5	C94-6	C94-7	C94-8(1)	C94-8(2)	C94-9	C94-10	C94-11
SiO_2 (wt %)	52.50	48.80	48.08	49.57	47.79	48.87	51.11	51.28	50.01	49.50	48.25
Al_2O_3	15.82	16.97	16.28	16.37	15.92	15.68	16.72	16.86	16.68	16.00	16.52
Fe_2O_3	7.91	8.48	9.20	9.32	8.86	8.42	8.74	8.77	8.91	9.05	9.51
MnO	0.13	0.13	0.16	0.15	0.15	0.14	0.14	0.14	0.14	0.15	0.16
MgO	7.21	7.21	8.08	7.75	8.94	9.22	6.33	6.42	7.12	8.40	7.28
CaO	8.69	11.72	10.70	8.89	10.66	10.59	8.04	8.12	8.85	9.75	11.29
Na_2O	3.33	3.09	3.06	3.07	3.17	3.73	3.79	3.81	3.40	3.29	3.17
K_2O	1.38	0.92	0.77	1.04	0.91	0.77	1.53	1.53	1.41	1.11	0.93
TiO_2	0.95	1.07	1.13	1.48	1.14	0.91	1.51	1.49	1.45	1.20	1.27
P_2O_5	0.31	0.23	0.38	0.36	0.39	0.29	0.43	0.45	0.43	0.40	0.36
LOI	0.18	0.26	0.47	0.13	0.51	0.30	−0.03	−0.15	0.09	−0.26	0.06
Total	98.41	98.88	98.31	98.13	98.44	98.92	98.31	98.72	98.50	98.58	98.79
Rb (ppm)	31.55	19.86	–	14.10	–	–	–	–	–	–	–
Sr	545.93	548.67	–	486.42	–	–	–	–	–	–	–
Y	16.84	16.08	–	19.00	–	–	–	–	–	–	–
Zr	120.84	84.73	–	142.92	–	–	–	–	–	–	–
Nb	11.56	6.18	–	12.90	–	–	–	–	–	–	–
Ba	486.56	246.93	–	226.35	–	–	–	–	–	–	–
La	39.84	18.28	–	21.42	–	–	–	–	–	–	–
Ce	72.83	39.80	–	45.43	–	–	–	–	–	–	–
Pr	7.49	4.74	–	5.30	–	–	–	–	–	–	–
Nd	25.18	18.00	–	19.56	–	–	–	–	–	–	–
Sm	4.51	3.75	–	4.27	–	–	–	–	–	–	–
Eu	1.64	1.43	–	1.71	–	–	–	–	–	–	–
Gd	5.76	4.59	–	5.45	–	–	–	–	–	–	–
Dy	3.49	3.49	–	4.33	–	–	–	–	–	–	–
Ho	0.64	0.65	–	0.80	–	–	–	–	–	–	–
Er	1.72	1.86	–	2.22	–	–	–	–	–	–	–
Tm	0.27	0.29	–	0.33	–	–	–	–	–	–	–
Yb	1.86	1.78	–	2.16	–	–	–	–	–	–	–
Lu	0.28	0.28	–	0.33	–	–	–	–	–	–	–
Hf	2.50	2.05	–	3.14	–	–	–	–	–	–	–
Ta	0.99	0.85	–	1.08	–	–	–	–	–	–	–
Pb	7.84	5.77	–	4.28	–	–	–	–	–	–	–
Th	11.08	3.26	–	3.35	–	–	–	–	–	–	–
U	2.56	1.14	–	0.76	–	–	–	–	–	–	–
$^{87}Sr/^{86}Sr$	0.705619 ± 11	0.70516 ± 12	–	0.704105 ± 12	–	–	–	–	–	–	–
$^{143}Nd/^{144}Nd$	0.512604 ± 7	0.512654 ± 12	–	0.512819 ± 6	–	–	–	–	–	–	–

and Hasandağ) and also by scoria cones, maars, lava flows and domes (Fig. 2) (Şen *et al.* 2003). Rock samples for this study were collected from selected Quaternary basaltic vents of the Erciyes and Hasandağ stratovolcanoes and from the monogenetic volcanic centres of the Karapinar and Derinkuyu areas.

In eastern Anatolia, rock samples were collected from the Tendürek and Karacadağ shield volcanoes. The K–Ar ages of Tendürek and Karacadağ volcanic rocks are 0.40 ± 0.02–0.013 ± 0.002 Ma and 1.93 ± 0.14–0.10 ± 0.01 Ma, respectively (Notsu *et al.* 1995).

Analysis of major elements was carried out by X-ray fluorescence (XRF) at Hacettepe University of Ankara, using a Philips model PW 1480 spectrometer. All samples were crushed in agate because tungsten carbide crushing vessels are a well-known source of Ta contamination. Major elements were analysed on fused discs and trace elements on pressed pellets. For major oxide analyses, 0.75 g of powdered sample was mixed with 4.5 g of anhydrous lithium tetraborate ($Li_2B_4O_7$). The mixture was fused at 1050 °C in an electric furnace to obtain a glass disc, which was then used directly for the measurements. Loss on Ignition (LOI) was determined by heating the sample for 2 h at 1000 °C in an electric furnace. The spectrometers were calibrated using international standards (USGS and GEOSTANDARDS) to ensure accurate data.

Sr and Nd isotopic composition analyses were performed using a VG 54E mass spectrometer in the double collection mode, at the Université Blaise Pascal, Clermont-Ferrand, France. The $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$, and $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. Over the period of measurements, replicate analyses of standards gave, for the National Bureau of Standards NBS 987, $^{87}Sr/^{86}Sr = 0.710245 \pm 12$ (2σ), and for AMES, $^{143}Nd/^{144}Nd = 0.511968 \pm 6$ (2σ).

Trace and rare earth element analyses of whole rock samples were determined by solution ICP-MS at

Table 1. *(Contd.)*

Central Anatolian volcanic rocks										
Hasandağ					Erciyes					
C94-12	C94-13	C94-14	C94-15(1)	C94-15(2)	C94-17	C94-18	C94-19	C94-21	C94-22	C94-23
50.50	46.55	48.75	55.75	55.15	54.03	53.84	55.10	51.46	51.57	52.82
15.73	14.97	15.92	16.70	17.00	16.92	17.03	17.14	17.04	17.14	17.31
8.30	9.05	9.50	7.24	7.45	6.95	7.06	7.05	8.70	8.76	8.26
0.13	0.15	0.15	0.12	0.13	0.11	0.11	0.11	0.14	0.14	0.13
8.38	9.79	8.58	3.73	3.90	5.75	5.98	5.30	5.61	5.67	5.45
9.34	12.18	9.32	7.34	7.54	8.10	8.31	7.86	7.86	7.88	7.54
3.53	3.01	3.46	3.50	3.88	3.30	3.22	3.37	3.83	3.75	2.75
1.18	0.74	1.03	2.12	1.78	1.21	1.27	1.28	1.60	1.59	1.54
1.25	1.09	1.52	1.23	1.27	0.97	0.98	1.03	1.44	1.45	1.47
0.27	0.41	0.41	0.29	0.31	0.34	0.34	0.31	0.51	0.52	0.39
0.24	0.79	0.19	0.38	0.21	1.53	0.25	−0.14	−0.06	−0.11	−0.24
98.85	98.73	98.83	98.40	98.63	99.21	98.39	98.41	98.14	98.36	97.42
22.21	12.20	14.13	40.97	–	–	22.84	–	–	25.22	–
496.39	574.62	569.81	472.62	–	–	425.48	–	–	435.96	–
16.62	16.00	19.30	18.13	–	–	14.11	–	–	19.63	–
117.41	88.82	142.99	142.75	–	–	112.42	–	–	173.23	–
10.50	13.54	13.75	12.76	–	–	14.97	–	–	20.41	–
299.74	416.47	235.24	429.42	–	–	372.17	–	–	384.93	–
20.89	30.52	24.58	28.30	–	–	28.72	–	–	30.55	–
42.26	58.17	52.36	54.89	–	–	52.79	–	–	64.13	–
4.86	6.21	6.21	6.02	–	–	5.48	–	–	7.16	–
17.49	20.97	23.26	20.49	–	–	17.82	–	–	24.58	–
3.66	3.91	4.83	4.00	–	–	3.49	–	–	4.92	–
1.46	1.60	1.84	1.71	–	–	1.35	–	–	1.81	–
4.49	5.17	5.98	5.53	–	–	4.91	–	–	6.12	–
3.48	3.80	4.61	4.27	–	–	3.20	–	–	4.35	–
0.67	0.63	0.82	0.78	–	–	0.57	–	–	0.78	–
1.89	1.77	2.29	2.19	–	–	1.56	–	–	2.23	–
0.28	0.26	0.34	0.33	–	–	0.24	–	–	0.32	–
1.83	1.76	2.12	2.08	–	–	1.49	–	–	2.12	–
0.30	0.26	0.33	0.33	–	–	0.24	–	–	0.33	–
2.48	2.00	3.23	3.53	–	–	2.45	–	–	3.61	–
1.06	0.91	1.20	1.20	–	–	1.18	–	–	1.66	–
4.64	5.37	4.33	10.52	–	–	7.76	–	–	7.08	–
4.21	4.99	4.93	10.88	–	–	7.07	–	–	3.99	–
1.32	1.14	1.15	2.48	–	–	1.91	–	–	1.17	–
0.704383 ± 10	0.704878 ± 14	0.704147 ± 13	0.704567 ± 11	–	–	0.705168 ± 14	–	–	0.704597 ± 16	–
0.512795 ± 6	0.512681 ± 6	0.512849 ± 5	0.512725 ± 6	–	–	0.51266 ± 7	–	–	0.512712 ± 8	–

the Université Blaise Pascal, Clermont-Ferrand, France on a VG Elemental PQ2 instrument. The analytical technique largely followed that described by Ionov, Savoyant & Dupuy (1992) and Ionov & Harmer (2002). One hundred milligrams of whole rock powdered samples were dissolved in $HF–HNO_3–HClO_4$ mixture, evaporated to incipient dryness, then evaporated twice at about 140 °C with 0.25 ml of $HClO_4$ to destroy insoluble flourides. The dry sample was taken up for analysis in 2 % HNO_3 with a small amount of HCl. Attempts to use pure 2 % HNO_3 for sample take-up failed because of formation of dark precipitates from an initially clear solution, but the addition of several drops of HCl produced clear, stable solutions, possibly due to cation complexing with Cl^-. Composite synthetic pure element solutions were used as external standards. In and Bi were added to both sample and external standard solutions as internal standards. The BHVO-1 reference sample was analysed as an unknown for quality control.

3. Geochemical characteristics of the volcanic rocks

Major oxide, trace and rare earth element data and Sr–Nd isotopic compositions of representative samples from central and eastern Anatolia are listed in Table 1. In a total alkali versus silica diagram (Fig. 3), central Anatolian volcanic rocks exhibit calc-alkaline to alkaline transitional characteristics and are generally basalt, basaltic andesite and basaltic trachyandesite (Fig. 3a). Karacadağ and Tendürek samples exhibit alkaline trends, ranging in composition from basalt to basaltic trachyandesite, respectively (Fig. 3b).

Mid-Ocean Ridge Basalt (MORB)-normalized (Pearce, 1983) spidergrams of central and eastern Anatolia are shown in Figure 4a–d. Features common to all samples from central Anatolia are the enrichment in some incompatible elements, such as Ba, Rb, Th, Pb and Sr, high large ion lithophile element (LILE)/high field strength element (HFSE) ratios and depletion in Nb and Ta. Typical features including enrichment

Table 1. *(Contd.)*

	Central Anatolian volcanic rocks							Eastern Anatolian volcanic rocks			
	Erciyes				Derinkuyu			Karacadağ			
Sample	C94-24	C94-25	C94-26	C94-30	C94-31	C94-16(1)	C94-16(2)	ZV-1	ZV-2	ZV-3	ZV-4
SiO_2 (wt %)	52.12	52.36	54.97	51.16	57.64	54.87	54.57	46.80	46.63	48.51	45.11
Al_2O_3	17.37	16.94	17.86	16.57	17.30	16.38	16.32	14.64	14.26	15.08	13.73
Fe_2O_3	8.34	8.04	6.79	9.26	6.44	6.94	7.09	13.05	13.54	12.20	15.15
MnO	0.13	0.13	0.11	0.15	0.11	0.11	0.11	0.16	0.17	0.16	0.19
MgO	5.74	5.87	4.79	6.38	3.51	6.12	6.24	7.31	8.08	6.21	8.83
CaO	7.77	7.70	7.81	8.64	6.91	8.01	7.91	10.46	9.68	7.33	9.48
Na_2O	3.71	3.67	3.25	3.37	3.25	2.97	3.21	2.84	2.61	3.60	2.93
K_2O	1.44	1.45	1.19	1.01	1.72	1.27	1.25	0.85	0.83	1.50	0.88
TiO_2	1.49	1.42	0.94	1.59	0.91	0.84	0.85	2.33	2.48	2.07	2.65
P_2O_5	0.39	0.32	0.30	0.46	0.23	0.24	0.24	0.20	0.22	0.58	0.40
LOI	−0.19	−0.03	0.19	−0.22	0.32	0.60	−0.19	0.79	0.68	1.24	−0.32
Total	98.31	97.87	98.20	98.37	98.34	98.35	97.61	99.43	99.17	98.48	99.03
Rb (ppm)	20.66	–	22.64	13.67	32.62	–	32.96	12.02	–	–	9.44
Sr	419.59	–	382.21	418.67	324.51	–	355.55	355.89	–	–	509.36
Y	17.85	–	14.14	21.87	16.83	–	12.98	14.46	–	–	16.25
Zr	158.07	–	118.80	175.50	131.59	–	112.46	102.17	–	–	135.58
Nb	15.88	–	12.59	13.47	9.79	–	9.69	15.48	–	–	20.36
Ba	295.67	–	277.19	207.54	353.30	–	319.65	142.92	–	–	126.45
La	23.68	–	23.99	23.89	24.12	–	24.02	12.47	–	–	20.61
Ce	49.75	–	47.28	51.96	48.20	–	45.75	28.70	–	–	45.09
Pr	5.62	–	5.11	6.13	5.37	–	4.79	3.69	–	–	5.42
Nd	20.21	–	17.23	22.52	18.36	–	16.13	15.50	–	–	21.67
Sm	4.19	–	3.48	5.05	3.89	–	3.10	4.04	–	–	5.27
Eu	1.55	–	1.24	1.76	1.37	–	1.36	1.49	–	–	2.03
Gd	5.15	–	4.27	5.87	4.68	–	4.63	4.53	–	–	6.35
Dy	3.93	–	3.07	4.56	3.48	–	3.25	3.55	–	–	4.25
Ho	0.72	–	0.51	0.86	0.65	–	0.56	0.61	–	–	0.69
Er	2.01	–	1.54	2.37	1.92	–	1.62	1.59	–	–	1.77
Tm	0.29	–	0.22	0.37	0.30	–	0.24	0.22	–	–	0.24
Yb	1.93	–	1.45	2.39	1.93	–	1.45	1.33	–	–	1.40
Lu	0.30	–	0.24	0.36	0.29	–	0.23	0.20	–	–	0.19
Hf	3.48	–	2.49	3.70	3.22	–	2.83	2.52	–	–	3.25
Ta	1.25	–	1.00	1.13	1.15	–	1.30	1.36	–	–	1.25
Pb	6.73	–	7.50	4.84	8.92	–	10.76	2.09	–	–	1.57
Th	3.91	–	5.38	3.61	6.68	–	7.75	1.71	–	–	1.81
U	1.08	–	1.53	1.03	1.70	–	2.06	0.22	–	–	0.65
$^{87}Sr/^{86}Sr$	0.704351 ± 12	–	0.704906 ± 15	0.704597 ± 11	0.705179 ± 18	–	0.705052 ± 14	0.704466 ± 12	–	–	0.703512 ± 13
$^{143}Nd/^{144}Nd$	0.512735 ± 7	–	0.512685 ± 6	0.512755 ± 6	0.512615 ± 7	–	0.51262 ± 7	0.512742 ± 6	–	–	0.512883 ± 6

in Ba, Th and Pb and depletion in Nb, Ti and Ta are characteristic of subduction-related magmas (Fitton *et al*. 1988; Saunders, Tarney & Weaver, 1980; Saunders, Norry & Tarney, 1988). However, Nb and Ta are also highly sensitive to crustal contamination. Mantle-derived magmas, which might be contaminated by continental crustal rocks during their ascent to the surface, exhibit marked Nb and Ta negative anomalies (Thompson *et al*. 1983; Wilson, 1989; Alici *et al*. 2001) in spidergrams. Therefore, the MORB-normalized patterns of the central Anatolian lavas were compared with those of Andean volcanism, typical of active continental margins (Fig. 4e). Comparison reveals that the diagram patterns show certain similarities both in the abundance of some trace elements and in the shape of the pattern. However, enrichment levels in Th in central Anatolian mafic lavas (especially in Karapinar (Fig. 4a) and Derinkuyu (Fig. 4b)) are much higher than in Andean basalts. Similarly, the depletion in Nb in Andean magmas is higher than in those of central Anatolia (especially in Erciyes and Hasandağ). Furthermore, Ba/Ta and Ba/Nb ratios can be used to distinguish the tectonic affinity of basaltic magmas (Gill, 1981, p. 138; Fitton *et al*. 1988). High Ba/Ta (>450) and Ba/Nb (>28) ratios are the most striking features of subduction-related magmas (Gill, 1981, p. 138; Fitton *et al*. 1988). Ba/Nb ratios of the central Anatolian volcanic rocks are variable, ranging from 40 to 42 in Karapinar, 33 to 36 in Derinkuyu, 15–25 in Erciyes, and 17–34 in Hasandağ lavas. These variations may be attributed to the decreasing role of the subducted component in Erciyes and Hasandağ. Additionally, Nb/Ta values in central Anatolian lavas are also variable. Karapinar and Derinkuyu lavas have lower Nb/Ta values (7–12) than Erciyes and Hasandağ lavas (10–15), but in general, all of the central Anatolian lavas have chondritic Nb/Ta (10–17) values. Nb/Ta values lower than those for chondrites have also

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Table 1. *(Contd.)*

Eastern Anatolian volcanic rocks										
Karacadağ								Tendürek		
ZV-5	ZV-6	MA-7	MA-8	D1	D2	D3	D4	28	31	AN-G$^{\phi}$
46.52	45.14	45.66	46.93	46.22	47.48	46.04	46.66	53.50	51.00	46.51
14.08	15.73	13.69	13.45	13.63	14.71	13.95	14.06	17.20	17.14	29.93
13.51	15.28	15.11	14.38	15.15	13.76	15.35	13.37	9.96	11.20	3.34
0.18	0.19	0.18	0.17	0.18	0.18	0.18	0.17	0.19	0.19	0.045
8.46	5.55	7.87	7.62	9.46	7.87	9.73	8.34	2.88	4.10	1.80
9.69	6.88	7.86	8.25	9.17	9.29	9.36	9.60	6.24	7.35	16.18
2.67	2.10	2.47	3.27	3.34	3.04	3.29	2.74	5.31	5.22	1.65
1.00	1.18	1.47	1.37	0.94	1.25	0.85	1.24	2.13	1.65	0.13
2.48	2.92	2.74	2.52	3.06	2.89	2.59	2.80	1.52	1.87	0.23
0.32	0.40	0.65	0.64	0.43	0.40	0.39	0.43	–	–	0.01
0.45	3.34	1.15	0.28	−0.84	−0.24	−0.87	1.33	0.33	0.08	–
99.37	98.71	98.83	98.87	100.74	100.63	100.86	100.74	99.26	99.80	99.82
										BHVO-1*
–	–	–	19.37	–	–	–	18.12	36.77	22.79	9.68
–	–	–	668.61	–	–	–	756.32	524.75	503.81	364.10
–	–	–	17.67	–	–	–	16.43	33.60	27.86	20.60
–	–	–	190.74	–	–	–	157.10	342.25	246.24	144.08
–	–	–	27.69	–	–	–	21.73	33.17	26.20	17.50
–	–	–	211.31	–	–	–	187.29	546.11	454.74	126.91
–	–	–	35.87	–	–	–	23.14	57.01	44.24	16.97
–	–	–	76.44	–	–	–	51.30	115.01	90.15	41.77
–	–	–	9.16	–	–	–	6.25	13.18	10.48	5.67
–	–	–	34.54	–	–	–	24.63	46.63	37.74	24.00
–	–	–	7.34	–	–	–	5.46	8.92	7.37	5.95
–	–	–	2.63	–	–	–	2.12	3.08	2.54	2.31
–	–	–	8.98	–	–	–	6.81	11.50	9.11	7.16
–	–	–	5.09	–	–	–	4.64	7.74	6.06	5.37
–	–	–	0.76	–	–	–	0.74	1.40	1.10	0.87
–	–	–	1.69	–	–	–	1.75	3.86	3.11	2.32
–	–	–	0.25	–	–	–	0.26	0.62	0.48	0.32
–	–	–	1.43	–	–	–	1.46	3.91	2.94	1.97
–	–	–	0.21	–	–	–	0.21	0.61	0.49	0.28
–	–	–	4.41	–	–	–	3.87	6.95	5.03	3.68
–	–	–	1.48	–	–	–	1.11	1.51	1.10	1.10
–	–	–	3.24	–	–	–	3.39	15.40	11.30	1.82
–	–	–	3.69	–	–	–	2.61	6.45	5.13	1.31
–	–	–	1.42	–	–	–	0.85	1.95	1.63	0.52
–	–	–	0.703822 ± 13	–	–	–	0.705249 ± 11	0.705889 ± 12	0.705743 ± 11	–
–	–	–	0.512871 ± 7	–	–	–	–	0.512676 ± 6	0.512676 ± 6	–

Total iron is expressed as Fe_2O_3 ; wt %: weight percent; LOI: Loss on Ignition; $^{\phi}$AN-G and *BHVO-1 (International rock standards)

been reported for MORB and island arc volcanic rocks (Plank & White, 1995). Stolz *et al*. (1996) suggest that chondritic Nb/Ta values were derived from a mantle that had been modified by addition of LILE-enriched and HFSE-poor fluid derived from the subducted slab. According to this criterion, low Nb/Ta ratios in central Anatolian lavas may be due to effects of subduction components.

Karacadağ basalts exhibit 'humped' patterns, being enriched in both LIL elements, Sr, K, Rb, Ba, and light rare earth elements (LREE) and only slightly depleted in Ta and Nb (Fig. 5a). This may be considered as an OIB-like mantle source with an insignificant subduction component and/or crustal contamination in the evolution of Karacadağ basalts. Furthermore, the significant depletion in Y and heavy rare earth elements (HREE) in the Karacadağ basalts may indicate a residual garnet signature during partial melting, also suggesting an OIB-like mantle source.

Tendürek lavas also show 'humped' patterns but the depletion in Nb and Ta relative to Ba and Th is significant (Fig. 5b). Depletion in Nb and Ta relative to Ba and Th may be attributed to either subduction or crustal contamination. Tendürek lavas have Ba/Nb (16–17) and Ba/Ta (362–413) ratios, indicative of an insignificant subduction component. Nb/Ta ratios of Karacadağ and Tendürek lavas range between 16–19 and 22–24, respectively. As mentioned above, these relatively higher Nb/Ta ratios imply that the source regions of Karacadağ and Tendürek lavas do not have subduction signatures. Moreover, Haase, Mühe & Stoffers (2000) show that a high Nb/La (> 1) ratio is characteristic of uncontaminated mantle-derived magmas. According to this proposal, the low Nb/La (< 0.6) ratios in Tendürek magmas imply that crustal

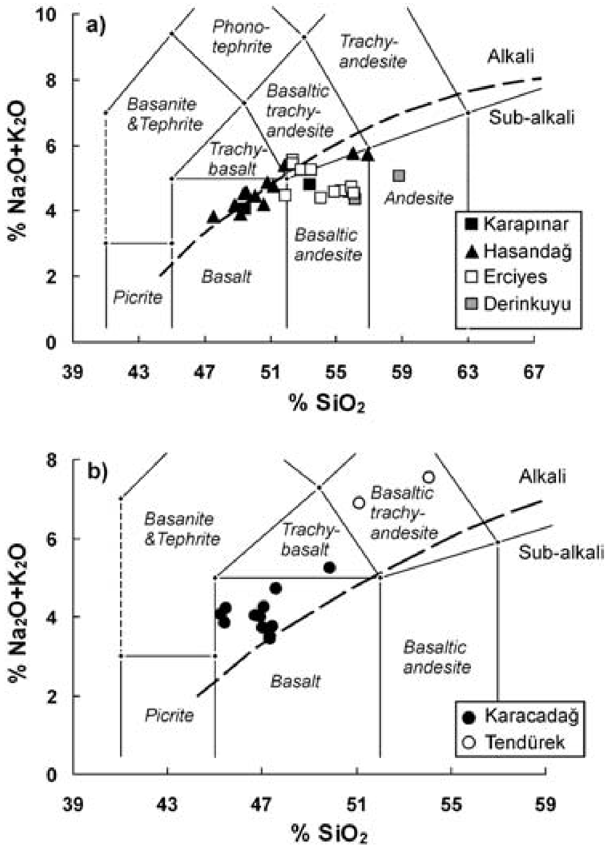

Figure 3. Total alkali v. silica diagram of (a) central Anatolian and (b) eastern Anatolian volcanic rocks (Le Bas *et al*. 1986). The alkaline–subalkaline dividing line is from Miyashiro (1978).

contamination was responsible for the variations in Ba, Nb and Ta. Karacadağ basalts have lower Ba/Nb (6–9) and relatively higher Nb/La (0.8–1.2) ratios than Tendürek, so the mantle source of the Karacadağ basalts lacks a subduction component and the magmas have undergone minor crustal contamination.

Rare earth element patterns for the selected samples from central Anatolian lavas (Fig. 6a) exhibit light REE (LREE) enrichment relative to chondrites (Nakamura, 1974). All samples are characterized by significant flattening of REE patterns from Dy to Lu relative to the LREE. The abundances of LREE are variable ($La_N = 55$–120), thus there is a range in LREE/HREE ratios and the $(La/Yb)_N$ ratio varies from 7 to 14. As can be seen in the spidergrams, notable features common to all of the central Anatolian lavas are the enrichment in LREE relative to the HREE.

Chondrite-normalized REE patterns of eastern Anatolian lavas are illustrated in Figure 6b. It is clear from this figure that Tendürek lavas are enriched in both LREE and HREE relative to Karacadağ lavas. Tendürek lavas exhibit flattening of REE patterns from Dy to Lu relative to the LREE. Both Tendürek and Karacadağ lavas show slight enrichment in LREE relative to HREE.

Sr–Nd isotopic compositions of volcanic rocks from central and eastern Anatolia are listed in Table 1. The plot of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ is shown in Figure 7. Central Anatolian and Karacadağ basalts have Sr–Nd isotopic compositions situated in the mantle array. These Sr–Nd isotopic compositions were compared with a selection of volcanic suites worldwide. Isotopic compositions of the central Anatolian volcanic rocks range from isotopically depleted mantle (DM) to enriched mantle similar to the source of Kerguelen (Gautier *et al*. 1990) and Society Island lavas (Devey *et al*. 1990), which are represented by EMI and EMII components in their source, respectively (Zindler & Hart, 1986).

Sr–Nd isotopic compositions of the Karacadağ and Tendürek volcanic rocks range from 0.703510 to 0.704466, 0.512742 to 0.512880 and 0.705743 to 0.705889 and 0.512676, respectively. Karacadağ alkali basalts plot in the depleted quadrant of the mantle array, whereas Tendürek basaltic trachyandesites plot in the enriched quadrant (Fig. 7). The role of crustal contamination is minimal and/or negligible in the Karacadağ basalts, due to the location of this volcanism in the thin crust of the Arabian foreland (Notsu *et al*. 1995). Conversely, contamination by continental crust is clearly significant in the Tendürek volcanic rocks, because they have passed through thickened crust (Pearce *et al*. 1990).

4. Discussion

4.a. Source characteristics

Trace element data suggest the existence of a subduction component in the central Anatolian lavas and crustal components in the eastern Anatolian lavas. As is often the case for volcanism that developed in a continental collisional setting, evidence of crustal contamination can often be found. Quaternary central Anatolian basaltic volcanism has developed in the absence of active subduction, but nevertheless exhibits subduction signatures, despite having been erupted in an extensional setting that had existed since Late Miocene times. Therefore, we attempt here to constrain the source characteristics of the magmas by trace element ratio diagrams. They are compared with extension-related volcanic rocks from western turkey (Late Miocene Ezine–Gülpinar–Ayvacik (EGA) basanites and Middle Miocene Dikili–Ayvalik–Bergama (DAB) basaltic volcanic rocks), southeastern Turkey (Karasu Valley Alkali Basalts (KVAB)), the Big Pine volcanic field (California) and subduction-related volcanic rocks from the Andes. Aldanmaz *et al*. (2000) have shown that Late Miocene Ezine–Gülpinar–Ayvacik (EGA) basanites from western Turkey formed by partial melting of a garnet-bearing lherzolite source, consistent with an origin by decompression melting of an OIB-like asthenospheric mantle. In contrast, Middle

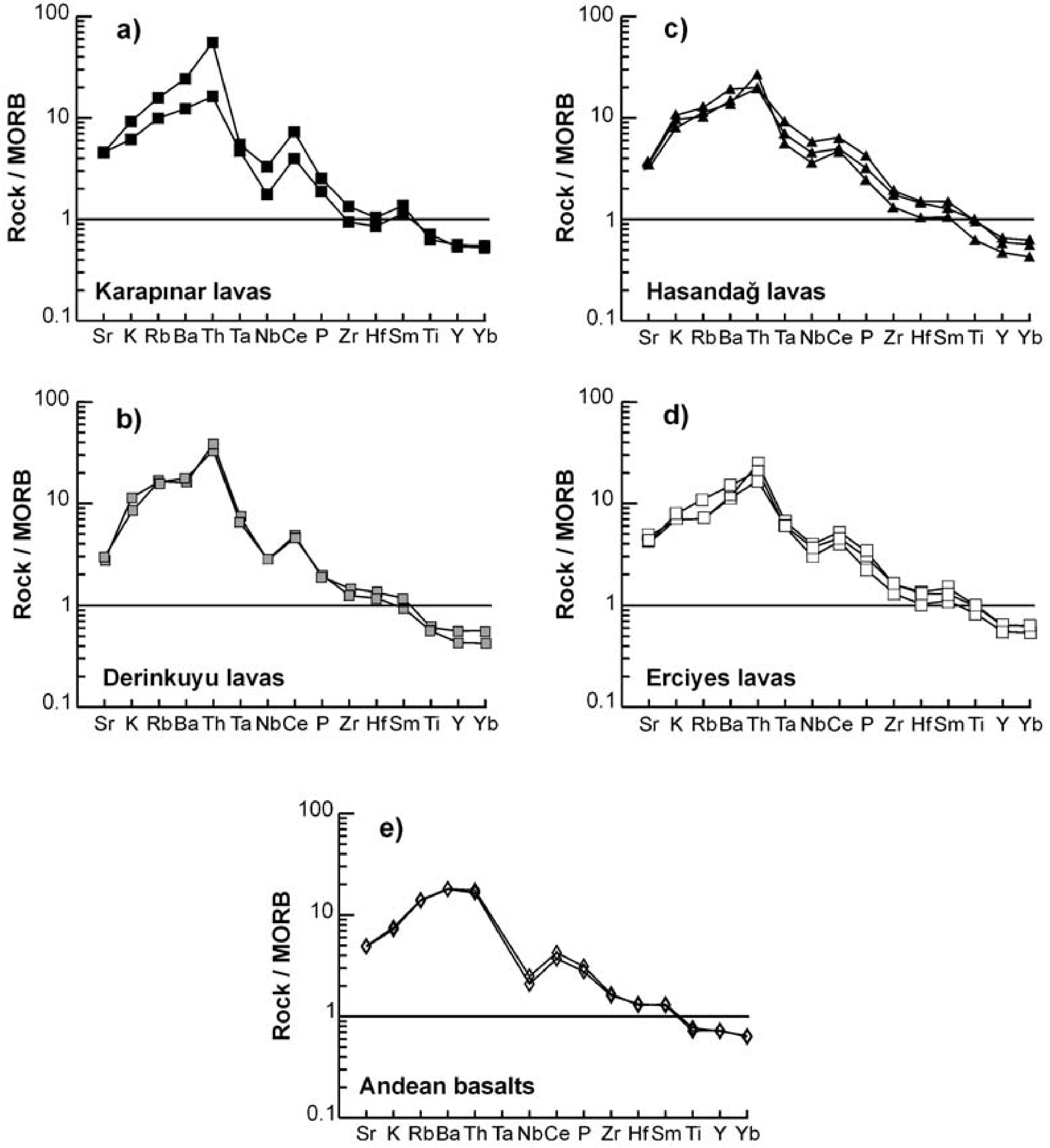

Figure 4. MORB-normalized (Pearce, 1983) incompatible trace element patterns for the representative samples of central Anatolian lavas.

Miocene Dikili–Ayvalik–Bergama (DAB) basaltic volcanic rocks from the same region were derived from a lithospheric mantle source carrying previous subduction components. Karasu Valley alkali basalts (KVAB), which are located at the northern segment of the Dead Sea rift system, were derived from an OIB-like asthenospheric mantle with no and/or negligible crustal contamination (Alici *et al*. 2001).

The Th/Y versus Nb/Y diagram (Fig. 8) has been used to distinguish basaltic rocks from within-plate source regions from those from subduction-related source regions (Deniel, Aydar & Gourgaud, 1998; Seyitoğlu *et al*. 1997). Nb/Y and Th/Y ratios may be useful in assessing the role of source heterogeneities and crustal contamination (Pearce, 1983). Mantle that has been enriched by subduction components and/or crustal components will shift to higher Th/Y ratios with respect to Nb/Y, whereas mantle that had been previously enriched by a small volume of partial melt will be displaced along the melt enrichment and

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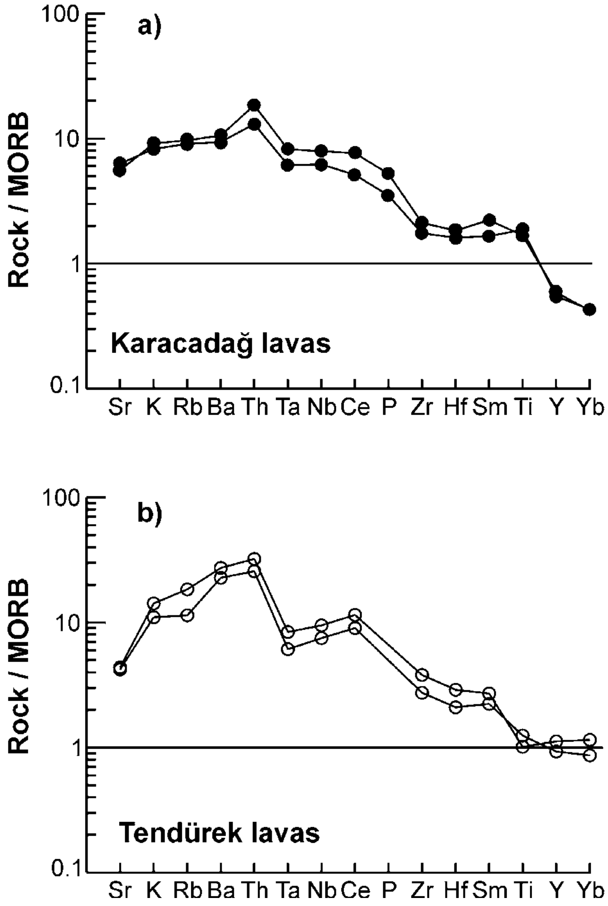

Figure 5. MORB-normalized (Pearce, 1983) incompatible trace element patterns for the representative samples from eastern Anatolian lavas of (a) Karacadağ, (b) Tendürek lavas.

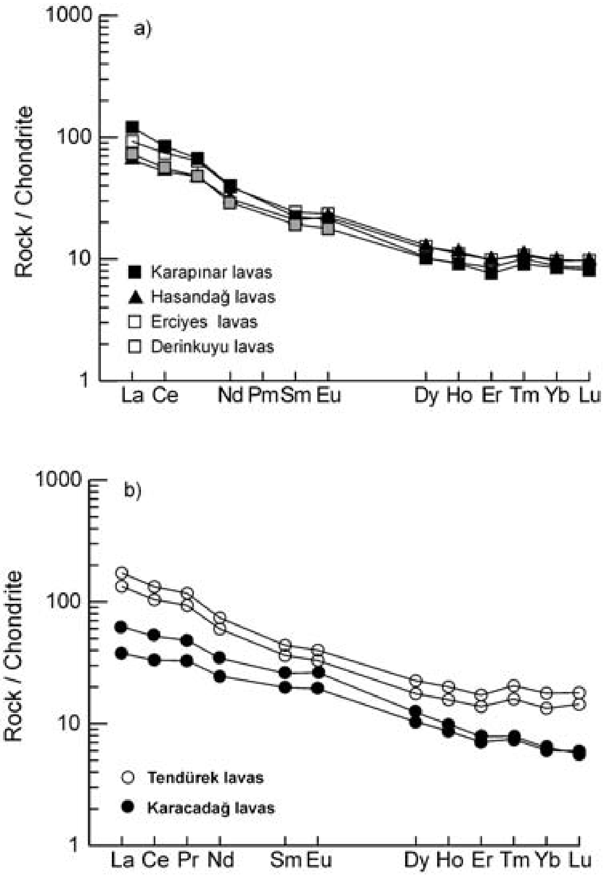

Figure 6. Chondrite-normalized (Nakamura, 1974) rare earth element patterns for representative samples of (a) central Anatolian, and (b) eastern Anatolian lavas.

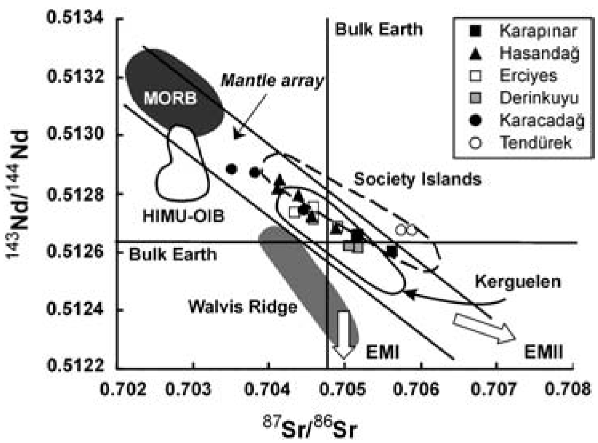

Figure 7. $^{143}Nd/^{144}Nd$ v. $^{87}Sr/^{86}Sr$ isotope diagram showing representative samples from central Anatolian and eastern Anatolian lavas. Selected suites from other parts of the world are also shown. Data sources: Richardson *et al.* (1982); Ito, White & Göpel (1987); Chaffey, Cliff & Wilson (1989); Gautier *et al.* (1990); Devey *et al.* (1990). Mantle array and Bulk Earth from Wasserburg *et al.* (1981) and Faure (1986). EMI and EMII from Zindler & Hart (1986).

within-plate trend in the direction of high Th/Y and Nb/Y ratios.

Figure 8 further illustrates the HFSE depletion of the Karapinar and Derinkuyu lavas compared to Hasandağ and Erciyes lavas. Despite these variable levels of depletion, all of the central Anatolian volcanic rocks have generally low Nb/Y and Th/Nb ratios. In addition, most of the central Anatolian volcanic rocks are shifted towards the direction of subduction zone enrichment, while the majority of samples from the Erciyes and Hasandağ lavas are displaced along the melt enrichment and within-plate trend. The range of Th/Y and Nb/Y in the Derinkuyu and Karapinar lavas is almost identical to lavas from Dikili–Ayvalik–Bergama (DAB), which are thought to be derived from a lithospheric mantle source carrying an earlier subduction component (Aldanmaz *et al.* 2000). Some of the Hasandağ and Erciyes samples plot close to the field of Big Pine lavas, which were also derived from a lithospheric mantle enriched by fluids released by previous subduction events (Ormerod, Rogers & Hawkesworth, 1991). According to this diagram, many of the central Anatolian lavas exhibit subduction signatures. However, from the Late Miocene onwards, their eruption took place in an extensional setting (Toprak & Göncüoğlu, 1993). Therefore, we suggest that their subduction-related characteristics are inherited from an

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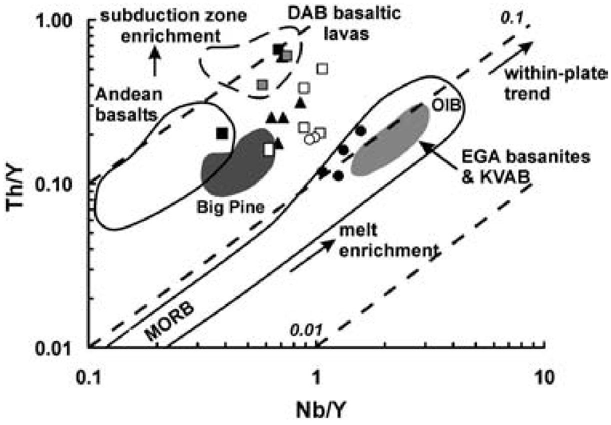

Figure 8. Th/Y v. Nb/Y diagram showing the central and eastern Anatolian volcanic rocks. DAB: Dikili-Ayvalik-Bergama; EGA: Ezine-Gülpinar-Ayvacik; KVAB: Karasu Valley Alkali Basalts. Data sources: Hickey *et al*. (1986); Ormerod, Rogers & Hawkesworth (1991); Hoernle, Tilton & Schmincke (1991); Hoernle & Schmincke (1993); Thirlwall *et al*. (1997); Norman & Garcia (1999); Aldanmaz *et al*. (2000); Alici *et al*. (2001). Symbols as in Figure 3.

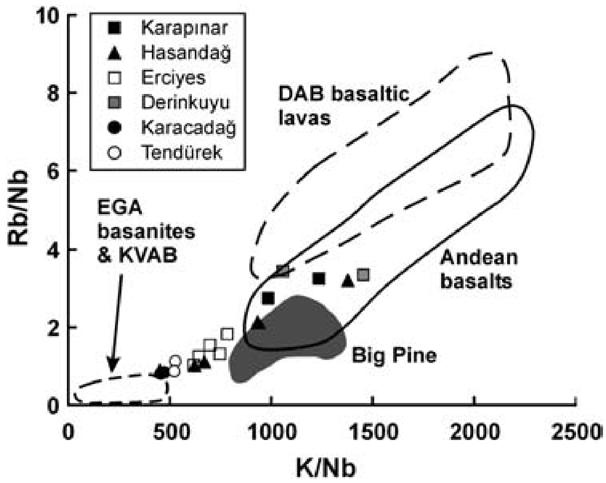

Figure 9. K/Nb v. Rb/Nb diagram showing the central and eastern Anatolian volcanic rocks. DAB: Dikili-Ayvalik-Bergama; EGA: Ezine-Gülpinar-Ayvacik; KVAB: Karasu Valley Alkali Basalts. Data sources: Hickey *et al*. (1986); Ormerod, Rogers & Hawkesworth (1991); Aldanmaz *et al*. (2000); Alici *et al*. (2001).

earlier subduction event. This is also supported by the variations in high Ba/Nb and Ba/Ta ratios as discussed above.

It is apparent from Figure 8 that the Karacadağ basalts plot within the OIB field and they also plot close to the EGA basanites (Aldanmaz *et al*. 2000) and KVAB (Alici *et al*. 2001). There seems to be no or negligible crustal involvement in the evolution of Karacadağ basalts. The Tendürek samples are slightly shifted from the OIB field in the direction of low Nb/Y, indicating the possible role of crustal contamination in their evolution.

Figure 9 displays the K/Nb versus Rb/Nb diagram for central and eastern Anatolian volcanism. All of the samples exhibit linear trends from Karacadağ lavas to Derinkuyu lavas. This may indicate the existence of two distinct mantle sources (Wilson & Downes, 1991; Jung & Masberg, 1998). The asthenospheric component is represented by low Rb/Nb and K/Nb such as EGA basanites and KVAB, whereas a lithospheric component, retaining subduction signatures, is represented by high Rb/Nb and K/Nb as in the Andean basalts, Big Pine and DAB basaltic volcanic rocks.

Comparison with selected volcanic provinces from around the world reveals that Derinkuyu and Karapinar lavas plot within the field of Andean basalts (Hickey *et al*. 1986) having high Rb/Nb and K/Nb ratios. Erciyes and Hasandağ samples fall between the field of EGA basanites and KVAB (Aldanmaz *et al*. 2000; Alici *et al*. 2001), and Big Pine (Ormerod, Rogers & Hawkesworth, 1991). This implies a tendency towards within-plate enrichment with decreasing effects of subduction components. Karacadağ basalts overlap the field of EGA basanites and KVAB whose source components are considered to be an OIB-like asthenospheric mantle (Aldanmaz *et al*. 2000; Alici *et al*. 2001). Tendürek lavas have Rb/Nb and K/Nb ratios higher than Karacadağ basalts but lower than central Anatolian lavas. This may indicate that the source regions of Tendürek volcanism did not carry any subduction signatures.

Figure 10 displays La/Nb versus $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ variations in the central and eastern Anatolian lavas. The good negative correlation between La/Nb and $^{143}Nd/^{144}Nd$ suggests that the depletion in Nb has been inherited from the sub-continental lithospheric mantle enriched by subduction components (except Nb and Ta) during successive subduction episodes over long periods of time (Fitton *et al*. 1988). According to this criterion, it is clear from Figure 10a that the negative variation between La/Nb and $^{143}Nd/^{144}Nd$ and positive variation between La/Nb and $^{87}Sr/^{86}Sr$ (Fig. 10a, inset) in central Anatolian lavas indicate that the depletion in Nb can be the result of the lithospheric mantle retaining earlier subduction components although they were erupted in an extensional setting. However, in eastern Anatiolan lavas, La/Nb ratios do not show a systematic relationship with $^{143}Nd/^{144}Nd$ (Fig. 10b) and $^{87}Sr/^{86}Sr$ (Fig. 10b, inset), indicating that depletion in Nb in Tendürek lavas is not due to subduction processes. The lack of any systematic relationship between La/Nb and $^{143}Nd/^{144}Nd$ in eastern Anatolian lavas thus suggests that Tendürek lavas are not affected by subduction components but their low Nb concentrations relative to the Karacadağ lavas can be the result of crustal contamination.

Consequently, the trace element characteristics of central Anatolian volcanism generally resemble those of lavas generated from lithospheric mantle enriched by subduction components (such as Andean basalts, DAB

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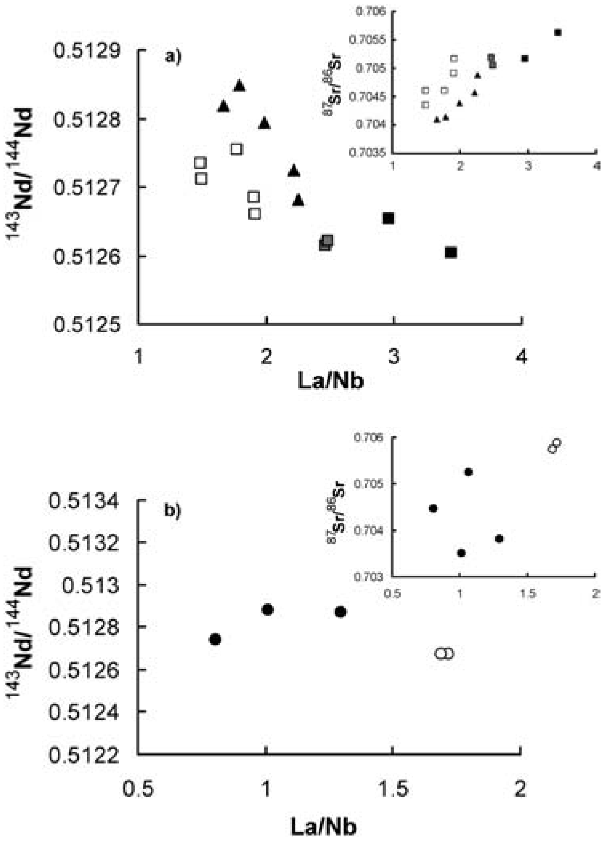

Figure 10. La/Nb v. $^{143}Nd/^{144}Nd$ diagrams showing the (a) central and (b) eastern Anatolian volcanic rocks. Insets show La/Nb v. $^{87}Sr/^{86}Sr$ plots of (a) central and (b) eastern Anatolian volcanic rocks. Symbols as in Figure 3

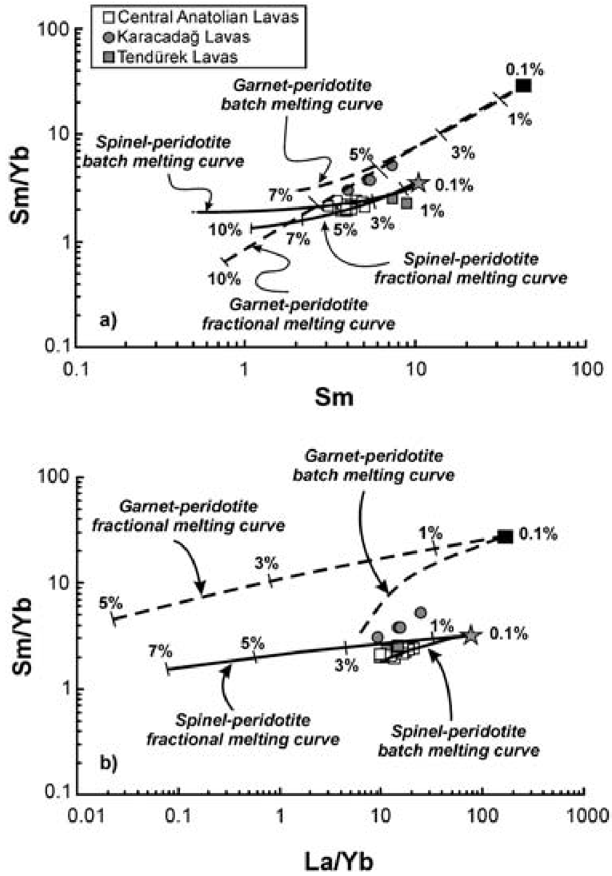

Figure 11. (a) Sm/Yb–Sm and (b) Sm/Yb–La/Yb diagrams showing the melt curves obtained from fractional and batch melting equations of Shaw (1970). La, Sm and Yb concentrations of the spinel and garnet peridotite are from McDonough (1990) and Sen & Leeman (1991), respectively. Bulk partition coefficients are taken from Tables 2 and 3. Solid square and grey star represent starting compositions of garnet and spinel peridotite at 0.1 % F, respectively.

basaltic lavas and Big Pine volcanic rocks). Therefore, we propose that the central Anatolian magmas were generated from a lithospheric mantle enriched by subduction-related processes, responsible for low Nb and Ta, high Rb/Nb, K/Nb, Ba/Nb, Ba, Th and Pb contents. The effects of the subduction components, however, decrease slightly in the Erciyes and Hasandağ lavas. Karacadağ basalts were derived from an OIB-like mantle source with no subduction signatures and they also did not experience crustal contamination. Trace element ratio–ratio plots have shown that enrichment in LIL elements relative to HFSE, and Nb and Ta negative anomalies in Tendürek lavas result from the involvement of crustal materials rather than subduction components as discussed above. This is also apparent from the low Ba/Nb (16–17) and Ba/Ta (362–413) ratios.

4.b. Petrogenetic modelling

4.b.1. Determination of source characteristics with REE modelling: Sm/Yb–Sm and Sm/Yb–La/Yb plots

In Figure 11a, b, REE modelling of central and eastern Anatolian volcanism was carried out to evaluate the source characteristics of the alkaline and calc-alkaline volcanism. The modelling uses Shaw's (1970) fractional and batch melting equations. La, Sm and Yb concentrations, mineral/melt (K_d) and bulk (D_0) partition coefficients and modal mineralogy of the spinel and garnet peridotite are reported in Tables 2 and 3.

In Figure 11a, garnet-dependent ratios of Sm/Yb are plotted against Sm. The Sm/Yb ratio depends on the proportion of garnet and may be used to determine the source mineralogy of the volcanic rocks, since Yb is compatible in garnet. It is clear in Figure 11a that the Karacadağ alkaline basalts are displaced from the spinel-peridotite melting curve to higher Sm/Yb ratios and plot close to the melting curve of garnet-peridotite. This implies a residual garnet signature in their source regions. The modelling demonstrates that variable degrees of partial melting of spinel-peridotite source are insufficient to explain the genesis of the Karacadağ alkaline basalts. On the other hand, Tendürek and central Anatolian lavas are significantly concentrated on the melting curve drawn for

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Table 2. Data used in the batch and fractional melting calculations of spinel-peridotite

	Spinel-peridotite composition (K_d) Initial concentration Co (ppm)	Mineral/melt partition coefficients				Bulk partititon coefficients (D_0) (66 % ol, 24 % opx, 8 % cpx, 2 % spinel)
		olivine	opx	cpx	spinel	
La	2.6	0.0067	–	0.056	0.01	0.0091
Sm	0.47	0.007	0.05	0.45	0.01	0.0448
Yb	0.26	0.014	0.34	0.542	0.01	0.08

La, Sm and Yb concentrations are from McDonough (1990), modal mineralogy of the spinel-peridotite are from Wilson (1989) and mineral/melt partition coefficients of the basaltic melts are from Fujimaki, Tatsumoto & Aoki (1984); McKenzie & O'Nions (1991); Rollinson (1993, p. 108).
Abbrevations: Concent: Concentration; opx: orthopyroxene; cpx: clinopyroxene; ol: olivine

Table 3. Data used in the batch and fractional melting calculations of garnet-peridotite

	Garnet-peridotite composition (K_d) Initial concentration Co (ppm)	Mineral/melt partition coefficients				Bulk partititon coefficients (D_0) (63 % ol, 30 % opx, 2 % cpx, 5 % garnet)
		olivine	opx	cpx	garnet	
La	1.73	0.0067	–	0.056	0.0016	0.0054
Sm	1.12	0.007	0.05	0.45	0.217	0.0253
Yb	0.51	0.014	0.34	0.542	6.167	0.3348

La, Sm and Yb concentrations are from Sen & Leeman (1991), modal mineralogy of the garnet-peridotite are from Wilson (1989) and mineral/melt partition coefficients of the basaltic melts are from Irving & Frey (1978); Fujimaki, Tatsumoto & Aoki (1984); Rollinson (1993, p. 108).
Abbrevations: opx – orthopyroxene; cpx – clinopyroxene; ol – olivine

spinel-peridotite. Similarly, the Sm/Yb versus La/Yb diagram (Fig. 11b) has also been used to determine the source characteristics of both the central and eastern Anatolian volcanism. Central Anatolian and Tendürek lavas are clearly linked to the spinel-peridotite melting curve in Figure 11b. In contrast, Karacadağ basalts plot close to the garnet-peridotite melting curve, indicating an OIB-like mantle source with residual garnet signatures. Consequently, Figure 11 shows that variable degrees of partial melting of a garnet-peridotite source cannot explain the composition of the central Anatolian and Tendürek lavas.

4.b.2. Trace element modelling of Tendürek volcanism

In the above sections, the lithospheric mantle source can account for the observed geochemical characteristics of the alkaline Tendürek lavas. Thus, fractional melting modelling was performed using the average trace element concentrations of the spinel-peridotite sample of McDonough (1990). Trace element contents, bulk distribution coefficients and results obtained from the calculations of 1.5 % fractional melting of the spinel-peridotite are reported in Table 4. The results obtained from a 1.5 % degree of partial melting modelling were compared to the Tendürek samples on the MORB-normalized spidergram (Fig. 12). It is clear in Figure 12 that the trace element pattern obtained from the 1.5 % fractional melting of the spinel-peridotite sample resembles those from the Tendürek lavas. However, Ta and Nb negative anomalies are clearly significant in Tendürek, since they are related to crustal contamination processes.

Table 4. Data obtained from the 1.5 % fractional melting calculations of the spinel peridotite (McDonough, 1990) end-member

	Starting composition (66 % ol; 24 % opx; 8 % cpx; 2 % sp) Spinel-peridotite	Bulk partition coefficients D_0	Calculated composition assuming fractional melting 1.5 % F
La	2.6	0.0091	55.1
Ce	6.29	0.029	130.79
Nd	2.67	0.076	29.31
Sm	0.47	0.0448	7.6
Eu	0.16	0.065	1.98
Dy	0.51	0.052	7.44
Yb	0.26	0.080	2.73
Lu	0.043	0.055	0.6
Ba	33	0.035	621.9
Sr	49	0.152	297.2
Rb	1.9	0.0107	43.9
K	448.2	0.02	10686
Ta	0.4	0.027	8.59
Nb	4.8	0.0074	85.42
Zr	21	0.042	354.11
U	0.12	0.006	1.63
Y	4.4	0.1231	32.1

Modal mineralogy of the spinel-peridotite as in Table 2. The mineral/melt partition coefficients of the basaltic melts are from Fujimaki, Tatsumoto & Aoki (1984); McKenzie & O'Nions (1991); Rollinson (1993, p. 108).
Abbrevations: ol – olivine; opx – orthopyroxene; cpx – clinopyroxene; sp – spinel

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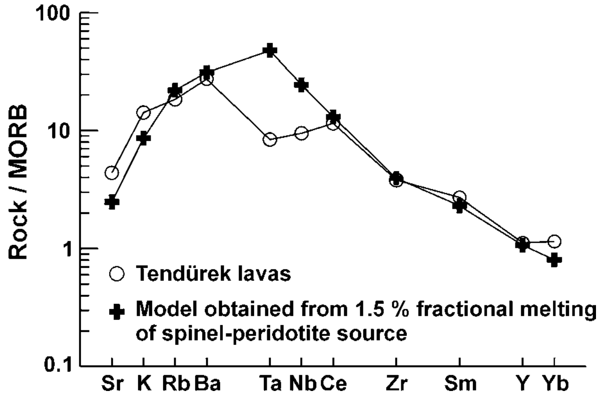

Figure 12. MORB-normalized (Pearce, 1983) spidergrams calculated from the spinel-peridotite sample (McDonough, 1990) at 1.5 % fractional melting, comparing with the representative sample from Tendürek lavas. Trace element concentrations and bulk partition coefficient (D_0) of spinel-peridotite are taken from Table 4. Modal mineralogy of the spinel-peridotite as in Table 2.

5. Conclusions

Quaternary basaltic volcanic rocks in central Anatolia exhibit transitional calc-alkaline to alkaline and calc-alkaline characteristics, with significant enrichment in LILE (Ba, Rb, Pb and Sr) relative to the HFSE (Nb and Ta). Furthermore, most of the central Anatolian volcanic rocks exhibit high Ba/Nb (> 28) ratios, which are a typical feature of subduction-related magmas.

Quaternary basaltic volcanism in central Anatolia was related to extensional tectonics and developed in the absence of active subduction. However, the geochemical data are consistent with derivation of magmas from a mantle source modified by subduction processes. Thus, we consider that the lithospheric mantle beneath central Anatolia carries an earlier subduction component. Its subduction-related geochemical features are inherited from an enriched lithospheric mantle which retains earlier subduction signatures. This enrichment probably occurred with fluids released from the northward subduction between the Afro-Arabian and the Eurasian plates during Eocene to Miocene times (Deniel, Aydar & Gourgaud, 1998).

In contrast, Quaternary volcanism in eastern Anatolia is related to the continental collision between the Arabian and Eurasian plates during the Late Miocene. Karacadağ Arabian foreland volcanism is characterized by alkali basalts. Volcanic rocks of the Tendürek region, situated to the north of the Bitlis suture zone on the thickened crust, are basaltic trachyandesite in composition and characterized by enrichment in LILE and LREE and depletion in HFSE (such as Nb and Ta). Isotope and trace element systematics indicate that basalts from Karacadağ were inherited from an OIB-like mantle source. Tendürek alkaline volcanic rocks were derived from a lithospheric mantle source via a small degree (1.5 %) of partial melting. Karacadağ basalts have undergone only minor and/or negligible crustal contamination during their ascent to the surface, whereas Tendürek lavas display significant effects of crustal contamination.

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Appendix 1. Location and description of the rock samples

Sample no.	Location	Description
Central Anatolian volcanic rocks		
Karapınar		
C94-1	N 37°42′52″; E 033°34′43″	Lava flow
C94-2	N 37°42′32″; E 033°40′14″	Bomb (maar)
Hasandağ		
C94-4	N 37°58′39″; E 033°56′52″	Lava (cinder cone)
C94-5	N 37°58′53″; E 034°07′01″	Lava (cinder cone)
C94-6	N 37°51′00″; E 034°06′09″	Lava (cinder cone)
C94-7	N 37°50′53″; E 034°11′06″	Lava (cinder cone)
C94-8 (1)	N 38°15′11″; E 034°04′11″	Lava (cinder cone)
C94-8 (2)	N 38°15′11″; E 034°04′11″	Lava (cinder cone)
C94-9	N 38°15′11″; E 034°04′11″	Lava flow
C94-10	N 38°14′33″; E 034°07′48″	Lava flow
C94-11	N 38°11′54″; E 034°07′40″	Lava flow
C94-12	N 37°54′57″; E 034°12′42″	Lava (cinder cone)
C94-13	N 37°51′47″; E 034°18′04″	Lava flow
C94-14	N 37°51′31″; E 034°18′26″	Lava (cinder cone)
C94-15 (1)	N 37°58′51″; E 034°15′15″	Lava flow
C94-15 (2)	N 37°58′51″; E 034°15′15″	Lava flow
Erciyes		
C94-17	N 38°25′47″; E 035°25′43″	Lava (cinder cone)
C94-18	N 38°24′24″; E 035°27′23″	Lava flow
C94-19	N 38°27′25″; E 035°27′36″	Bomb (cinder cone)
C94-21	N 38°35′21″; E 035°19′16″	Lava flow
C94-22	N 38°35′20″; E 035°19′26″	Lava (cinder cone)
C94-23	N 38°36′08″; E 035°17′23″	Lava (cinder cone)
C94-24	N 38°35′17″; E 035°18′55″	Lava flow
C94-25	N 38°35′35″; E 035°18′28″	Bomb (cinder cone)
C94-26	N 38°32′08″; E 035°19′39″	Lava flow
C94-30	N 38°36′07″; E 035°25′54″	Lava flow
Derinkuyu		
C94-31	N 38°24′58″; E 034°37′46″	Lava flow
C94-16 (1)	N 38°22′59″; E 034°33′58″	Lava flow
C94-16 (2)	N 38°22′59″; E 034°33′58″	Lava flow
Eastern Anatolian volcanic rocks		
Karacadağ		
ZV-1	N 37°39′46″; E 039°14′52″	Lava flow
ZV-2	N 37°39′59″; E 039°14′38″	Lava flow
ZV-3	N 37°39′43″; E 039°14′23″	Lava flow
ZV-4	N 37°39′14″; E 039°13′44″	Lava flow
ZV-5	N 37°38′51″; E 039°13′12″	Lava flow
ZV-6	N 37°38′51″; E 039°13′12″	Lava flow
MA-7	N 37°59′30″; E 040°09′13″	Lava flow
MA-8	N 37°58′58″; E 040°09′21″	Lava flow
Tendürek		
28	N 39°28′06″; E 044°06′34″	Lava flow
31	N 39°14′13″; E 044°00′38″	Lava flow

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Appendix 2. Petrographical determinations of selected samples from central and eastern Anatolia

Location	Phenocrysts	Mineral texture	Groundmass	Miscellaneous
Central Anatolia				
Erciyes				
C94-18	pl ≫ cpx	Embayed pl and zoned cpx	pl ≫ cpx, hypocrystalline (crystals > glass)	Glass inclusions in pl (honeycomb texture)
C94-19	ol > cpx	curved ol	pl ≫ cpx > ol, hypocrystalline (crystals > glass)	
C94-20	pl > ol	curved ol and zoned pl	pl > cpx > ol, hypocrystalline (crystals > glass)	
C94-23	ol	curved ol	pl ≫ ol, hypocrystalline (crystals > glass)	
C94-29	ol ≫ pl > cpx	curved and embayed ol	pl ≫ ol > cpx, hypocrystalline (crystals > glass)	rarely iddingisite rims on ol
Derinkuyu				
C94-16(1)	ol > cpx	curved ol	pl ≫ cpx > ol, hypocrystalline (crystals > glass)	
C94-16(2)	ol > cpx	curved and embayed ol	pl ≫ cpx, hypocrystalline (crystals > glass)	
C94-31	pl > ol	zoned and embayed pl	pl ≫ cpx > ol, hypocrystalline trachytic texture (crystals > glass)	glass inclusions in pl (honeycomb texture)
Hasandağ				
C94-12	pl > ol > cpx	embayed and curved ol	pl ≫ cpx > ol, hypocrystalline, (crystals > glass)	rarely iddingisitized, glass inclusion in pl (honeycomb texture) and zoned pl
C94-14	pl > ol > cpx	embayed and curved ol, zoned and curved cpx	pl ≫ cpx > ol, hypocrystalline, (crystals > glass)	cumulate ol + cpx
C94-5	pl > ol	embayed and curved ol, prismatic and clean (fresh) pl	pl ≫ ol > cpx + opaque min, hypocrystalline, (crystals > glass)	
C94-13	pl > cpx > ol	pale green zoned cpx, embayed ol	cpx > pl > ol, subophitic texture, no glass	rarely iddingisitized, vesicular basalt
C94-15	pl ≫ cpx > ol	curved ol, zoned cpx	pl > cpx > ol, (crystals > glass)	glass inclusion in pl (dusty zone and honeycomb texture)
Karapınar				
C94-2	cpx > pl > ol	pale green, zoned cpx, curved ol	pl > cpx > ol, hypocrystalline (glass > crystals)	
C94-1	pl > ol > cpx	zoned cpx, curved ol	pl > cpx > ol, hypocrystalline (glass > crystals)	glass inclusions in pl (honeycomb texture, dusty zone)
Eastern Anatolia				
Tendürek				
31	pl ≫ cpx	cumulated cpx + pl, curved and pale green cpx	pl ≫ cpx > ol + opaque min, hypocrystalline (crystals ≫ glass)	
Karacadağ				
D1	ol ≫ pl ± opaque min.	euhedral, embayed and curved ol	pl > cpx ≫ ol + opaque min., holocrystalline sub-ophitic texture	rarely iddingisite rims on ol
D3	pl > cpx > ol + opaque min.	pale brown, zoned cpx, euhedral and rarely embayed, curved ol	pl > cpx ≫ ol + opaque min., holocrystalline sub-ophitic texture	rarely iddingisite rims on ol
D4	ol > pl > cpx + opaque min + secondary chlorite	pale brown, zoned cpx, euhedral and rarely embayed, curved ol	pl > cpx ≫ ol + opaque min., holocrystalline sub-ophitic texture	rarely serpentinized ol
ZV-4	pl > cpx > ol	pale brown, zoned cpx, embayed ol	cpx > pl > ol, subophitic texture, no glass	rarely iddingisitized, non-vesicular

Abbreviations: cpx: clinopyroxene; pl: plagioclase; ol: olivine