

Early Miocene adakite-like volcanism in the Balkuyumcu region, central Anatolia, Turkey: Petrology and geochemistry

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Abstract

The Balkuyumcu region, located in the southwestern part of Ankara in the Izmir-Ankara suture zone (central Anatolia, Turkey), consists of basic andesitic, andesitic, dacitic and rhyolitic rocks extruded during the Early Miocene (20–22 Ma) as a result of post-collisional volcanism. Balkuyumcu volcanic rocks can be divided into two groups on the basis of their mineralogy and composition: The basic andesitic (BA) and andesitic, dacitic and rhyolitic (ADR) groups. The ADR and BA group of rocks have adakite-like and calc-alkaline characteristics, respectively. The ADR group has higher SiO₂ content, Sr/Y and La/Yb ratios and low MgO, Mg#, Y and Yb contents than the BA group. Both groups have nearly the same Sr, Nd isotopic compositions and display similar normalized multi-element patterns with enrichments in LILE and LREE, depletions in Nb, Ti, Zr, P and a lack of Eu anomalies. Major, trace element and Sr, Nd isotopic data indicate that both groups of rocks were derived from the same source but affected by different magmatic processes during ascent. The adakite-like rocks may have been produced by partial melting of thickened lower continental crust. Fractional crystallization also played a major role in their formation. However, the BA group rocks were derived from partial melting of lower continental crust that was probably delaminated. These rocks appear to have had limited interaction with mantle peridotite during ascent to the surface. © 2007 Elsevier Ltd. All rights reserved.

Keywords: Balkuyumcu; Adakite-like; Calc-alkaline; Lower crust; Delaminated lower crust

1. Introduction

Adakites form suites of intermediate to felsic rocks with compositions ranging from andesite to dacite and rhyolite (Defant and Drummond, 1990; Martin, 1999). Defant and Drummond (1990) interpreted that adakites are derived by partial melting of young (<20 Ma), hot subducting slab that extends down to the amphibolite–eclogite transition zone. Other models for generation of adakitic rocks include, partial melting of thickened mafic lower crust (Atherton and Petford, 1993), assimilation–fractional crystallization processes (Castillo et al., 1999), partial melting of delaminated lower continental crust (Xu et al., 2002, 2006) and partial

melting of underplated basaltic lower crust (Rapp et al., 2002). Adakitic magmas are encountered in active continental margins (Atherton and Petford, 1993) and collision zones (Xu et al., 2002). The mineralogical phases present in these rocks are mainly zoned plagioclase, hornblende and biotite. Pyroxenes are rare but may also be present in more mafic suites. These unusual volcanic rocks are characterized by SiO₂ > 56 wt%, Al₂O₃ > 15 wt%, high Na₂O contents (3.5 wt% ≤ Na₂O ≤ 7.5 wt%), high Mg# (~0.51), low K₂O/Na₂O ratio (~0.42), high Sr content (>300 ppm), high LILE (>400–3000 ppm) and low HREE contents (e.g. Yb ≤ 1.8 ppm, Y ≤ 18 ppm) (Defant and Drummond, 1990; Martin, 1999). Primitive mantle normalized multi-element and chondrite-normalized rare earth element patterns in adakites display a characteristic U-shape, positive Sr peaks and absence of significant Eu anomalies.

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The Balkuyumcu region (central Anatolia, Turkey, Fig. 1a and b) is one of a few sites where adakitic rocks in Turkey have been reported (Topuz et al., 2005). Since previous studies at the site provided insufficient geochemical and geochronological data (Lünel, 1987), we here report new major and trace element, radiogenic isotope (Sr, Nd) data and K–Ar ages from selected samples in order to identify the formation, magmatic evolution and origin of these volcanic rocks.

2. Geological setting

Located 30 km to the southwest of Ankara, the study area is a part of the Izmir-Ankara suture zone that formed by collision of the Sakarya block to the northwest with the Kırşehir block to the east-southeast (see Fig. 1a). The

suture zone is a product of closure of the northern branch of Neotethys during the Late Cretaceous when northward motion of the Anatolide–Tauride platform resulted in subduction under the Pontides platform to the north. The collision resulting from closure continued during Late Paleocene to Eocene times (Görür et al., 1984; Şengör and Yılmaz, 1981; Koçyiğit, 1991; Koçyiğit et al., 1995; Koçyiğit et al., 2003). While the magmatism associated with collision and post-collision processes have alkaline and calc-alkaline characteristics, almost all sites in the Ankara province (Lünel, 1987; Wilson et al., 1997; Tankut et al., 1998; Bozkurt et al., 1999; Koçyiğit et al., 2003) and Balkuyumcu region constitute a unique area where adakite-like rocks have also been observed. Other examples of similar rocks (e.g. Topuz et al., 2005) are observed 600 km northeast of the Balkuyumcu region.

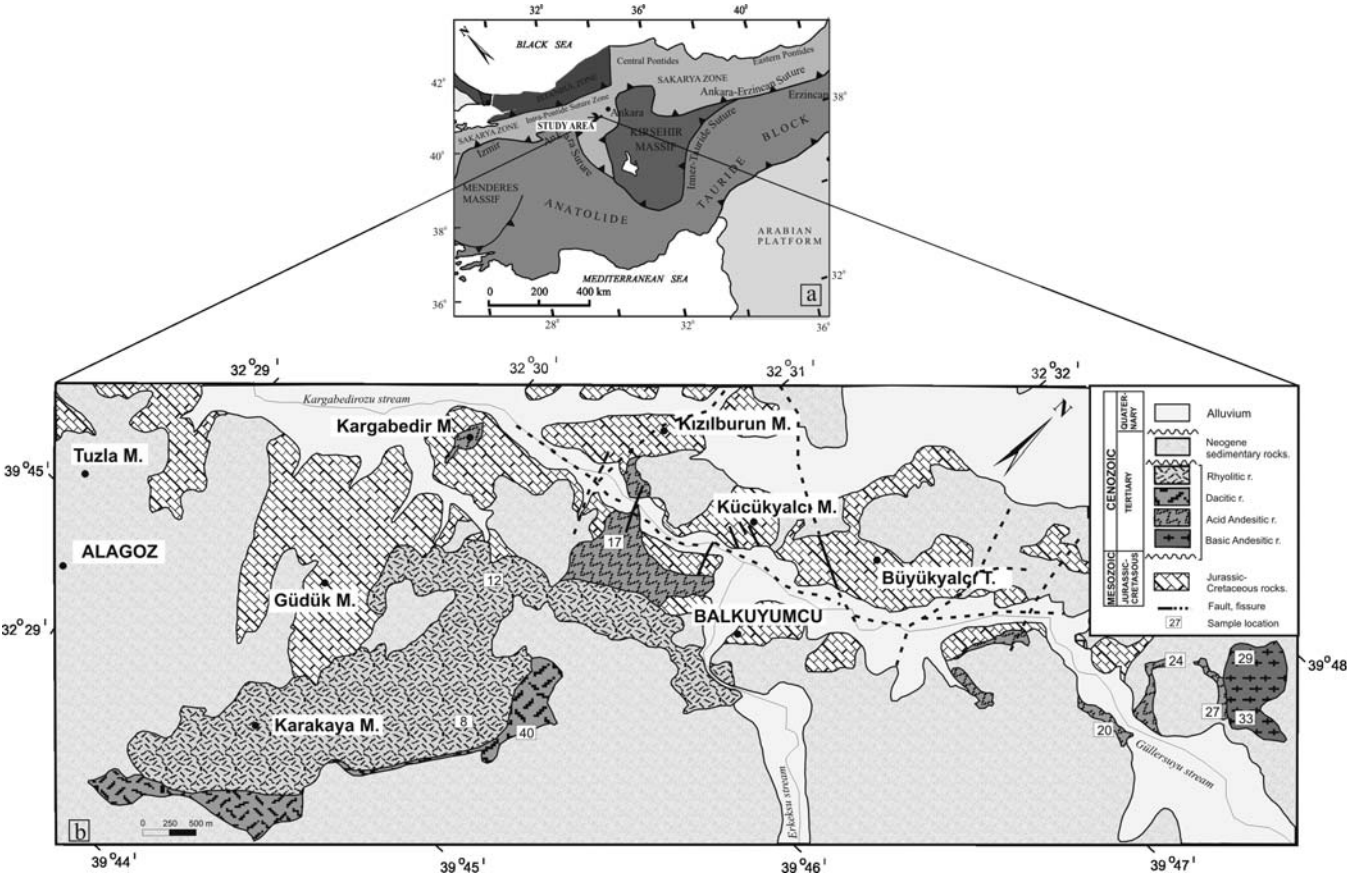


Fig. 1. (a) Simplified tectonic map of Turkey (after Okay and Tüysüz, 1999), (b) Simplified geological map of the Balkuyumcu area (modified from Lünel, 1987).

Table 1
K–Ar age data of Balkuyumcu volcanic rocks

Sample code	Age ± error (My) at ±1 s level	K ₂ O (wt%)	Weight (g)	⁴⁰ Ar ^{ast} /g (10 ^{−7} cm ³)	⁴⁰ Ar ^{ast} (%)	³⁶ Ar _{Exp} (10 ^{−9} cm ³)
KB 99-40	20 ± 0.3	2.57	0.7031	16.64	76.8	1.2
KB 99-33	20.3 ± 0.3	2.16	0.8330	14.21	76.1	1.26
KB 96-5	21.5 ± 0.4	2.34	0.8240	16.33	73.9	1.61

Table 2
Representative microprobe analyses of plagioclase crystals from Balkuyumeu volcanic rocks (r, rim; c, center)

	Basic andesite												Acid andesite											
	99-33						99-29						99-24						99-27					
	#19r→	#20c	#29r→	#30c	#1c→	#2r	#24c→	#25r	#69c→	#70r	#10c→	#11r	#23c→	#24r	#33c→	#34r	#57c→	#58r	#123c→	#124r	#125c→	#126r		
SiO ₂	60.77	60.77	55.28	55.22	55.33	54.64	56.82	60.63	55.01	53.81	55.42	56.77	56.20	55.54	55.80	53.97	56.36	53.61	57.97	60.62	54.83	55.23		
Al ₂ O ₃	24.53	25.05	28.10	27.88	28.12	28.27	26.15	24.37	27.15	28.23	27.13	27.60	27.52	28.10	27.64	28.63	28.05	29.47	26.54	24.75	28.19	28.66		
FeO _i	0.08	0.09	0.62	0.47	0.77	0.94	0.85	0.76	0.34	0.48	0.54	0.41	0.40	0.60	0.29	0.46	0.29	0.43	0.21	0.17	0.55	0.60		
CaO	6.34	6.56	10.65	10.70	10.94	11.37	8.33	6.14	10.33	11.72	9.91	9.88	10.02	10.66	10.30	11.67	10.47	12.14	8.72	6.84	11.45	11.10		
Na ₂ O	7.23	7.18	5.24	5.28	5.19	5.29	6.70	8.10	5.59	4.86	5.40	5.71	5.99	5.56	5.78	5.08	5.95	4.96	6.80	7.79	5.09	5.23		
K ₂ O	1.50	1.37	0.52	0.48	0.35	0.32	0.41	1.03	0.28	0.19	0.35	0.31	0.33	0.39	0.28	0.21	0.26	0.22	0.29	0.38	0.23	0.35		
Total	100.44	101.02	100.40	100.02	100.70	100.82	99.26	101.02	98.70	99.29	98.74	100.68	100.47	100.85	100.08	100.01	101.39	100.82	100.53	100.55	100.33	101.17		
Si	2.70	2.69	2.49	2.49	2.48	2.45	2.56	2.67	2.51	2.45	2.53	2.54	2.51	2.48	2.51	2.43	2.50	2.40	2.58	2.69	2.47	2.46		
Al ₂ O ₃	1.29	1.31	1.49	1.48	1.49	1.49	1.39	1.26	1.46	1.52	1.46	1.46	1.45	1.48	1.46	1.52	1.47	1.56	1.39	1.29	1.50	1.51		
Fe ³⁺	0.00	0.00	0.02	0.02	0.01	0.04	0.03	0.03	0.01	0.02	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.02	0.02		
Ca	0.30	0.31	0.51	0.52	0.53	0.55	0.40	0.29	0.51	0.57	0.49	0.47	0.48	0.51	0.50	0.56	0.50	0.58	0.42	0.33	0.55	0.53		
Na	0.62	0.62	0.46	0.46	0.45	0.46	0.59	0.69	0.49	0.43	0.48	0.50	0.52	0.48	0.50	0.44	0.51	0.43	0.59	0.67	0.44	0.45		
K	0.09	0.08	0.03	0.03	0.02	0.02	0.02	0.06	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.02		
Total	5.00	5.00	5.00	4.99	4.97	4.99	4.99	5.00	5.00	5.00	4.97	4.98	5.00	5.00	5.00	4.99	5.00	5.00	5.00	5.00	5.00	5.00		
Ab	61.68	61.32	45.70	45.92	45.24	44.91	57.86	66.57	48.67	42.39	48.63	50.20	50.98	47.53	49.61	43.53	49.95	41.95	57.51	65.85	44.00	45.06		
An	29.90	31.01	51.30	51.39	52.76	53.33	39.76	27.84	49.75	56.52	49.34	47.97	47.15	50.30	48.82	55.29	48.58	56.78	40.82	31.99	54.71	52.94		
Or	8.42	7.68	3.00	2.68	2.01	1.76	2.37	5.59	1.58	1.09	2.03	1.83	1.87	2.17	1.57	1.18	1.47	1.27	1.67	2.17	1.29	1.99		

	Dacite												Acid andesite											
	99-17						99-8						99-42						99-40					
	#26r→	#27c	#42r→	#43c	#49r→	#50c	#77c→	#78r	#79c→	#80r	#112c	#36c→	#37r	#46c→	#47r	#50c→	#51r	#71c→	#72r	#81c→	#82r	#3c→	#4r	#58r
SiO ₂	59.05	57.90	54.54	56.52	56.06	54.92	59.59	60.94	59.71	57.39	55.37	57.35	58.15	59.19	60.39	62.94	59.71	61.94	63.22	58.69	57.51	57.49	58.31	60.39
Al ₂ O ₃	24.52	25.81	27.02	26.08	26.30	27.30	23.78	23.38	24.69	25.48	27.35	26.54	26.59	25.61	24.86	23.55	25.82	24.24	23.56	25.67	25.93	26.96	26.74	24.32
FeO _i	0.08	0.14	0.41	0.26	0.60	0.54	0.21	0.10	0.18	0.18	0.26	0.30	0.40	0.13	0.13	0.11	0.07	0.09	0.13	0.19	0.30	0.18	0.21	0.23
CaO	6.79	8.24	10.37	8.86	9.23	10.56	5.98	5.39	6.92	7.97	10.08	8.92	8.89	7.29	6.52	4.97	7.81	5.70	5.04	7.68	8.23	8.85	8.34	6.46
Na ₂ O	7.53	6.83	5.52	6.50	6.09	5.47	8.16	8.42	7.46	6.89	5.79	6.38	6.38	7.60	8.01	8.67	7.14	8.34	8.48	6.83	6.78	6.73	6.59	7.75
K ₂ O	0.61	0.26	0.42	0.33	0.46	0.42	0.37	0.68	0.43	0.41	0.40	0.35	0.39	0.34	0.32	0.63	0.35	0.47	0.54	0.63	0.48	0.21	0.47	0.52
Total	98.59	99.17	98.26	98.56	98.74	99.20	98.08	98.91	99.38	98.32	99.26	99.83	100.80	100.16	100.23	100.9	100.9	100.79	100.97	99.69	99.22	100.41	100.66	99.67
Si	2.67	2.61	2.50	2.57	2.55	2.49	2.70	2.73	2.68	2.61	2.51	2.58	2.59	2.63	2.68	2.77	2.65	2.73	2.78	2.63	2.59	2.56	2.60	2.70
Al ₂ O ₃	1.31	1.37	1.46	1.40	1.41	1.46	1.27	1.24	1.31	1.37	1.46	1.41	1.40	1.34	1.30	1.22	1.35	1.26	1.22	1.36	1.38	1.42	1.40	1.28
Fe ³⁺	0.00	0.01	0.02	0.01	0.02	0.02	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01
Ca	0.33	0.40	0.51	0.43	0.45	0.51	0.29	0.26	0.33	0.39	0.49	0.43	0.42	0.35	0.31	0.23	0.35	0.27	0.24	0.37	0.40	0.42	0.40	0.31
Na	0.66	0.60	0.49	0.57	0.54	0.48	0.72	0.73	0.65	0.61	0.51	0.56	0.55	0.66	0.69	0.74	0.64	0.71	0.72	0.59	0.59	0.58	0.57	0.67
K	0.04	0.02	0.02	0.02	0.03	0.02	0.02	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.02	0.03	0.03	0.04	0.03	0.01	0.03	0.03
Total	5.00	5.00	5.00	5.00	5.00	4.99	5.00	5.00	5.00	5.00	5.00	5.00	4.98	5.00	5.00	5.00	5.00	5.00	5.00	4.99	5.00	5.00	4.99	5.00
Ab	64.42	59.11	47.90	56.01	52.96	47.30	69.72	71.04	64.51	59.57	49.80	55.28	55.27	64.15	67.72	73.24	63.94	70.63	72.96	59.46	58.31	57.24	57.24	66.37
An	32.16	39.41	49.76	42.13	44.38	50.34	28.24	25.17	33.10	38.08	47.94	42.73	42.53	33.99	30.51	23.19	34.47	26.69	24.02	36.94	39.04	41.58	40.04	30.66
Or	3.42	1.49	2.35	1.86	2.66	2.36	2.04	3.79	2.39	2.36	2.25	1.99	2.21	1.86	1.77	3.568	1.598	2.68	3.03	3.60	2.65	1.18	2.72	2.97

(continued on next page)

Table 2 (continued)

Rhyolite																				
99-15										99-12						99-18				
#57r→	#58c	#65r→	#66c	#13r→	#14c	#22c→	#23r	#29c→	#30r	#38c→	#39r	#57c→	#58r	#80c→	#81r	#94c→	#95r	#111c→	#112r	
SiO ₂	59.92	58.97	62.16	62.31	59.83	62.51	62.90	60.94	59.41	57.90	61.36	60.93	61.31	60.39	62.13	59.21	61.80	62.64	58.29	62.53
Al ₂ O ₃	25.32	25.69	24.10	24.12	24.75	23.49	23.36	23.73	25.37	25.95	24.08	24.47	22.98	24.32	24.24	25.71	23.83	23.71	25.68	23.73
FeO _t	0.25	0.11	0.13	0.09	0.07	0.05	0.12	0.16	0.13	0.11	0.13	0.17	0.15	0.23	0.21	0.18	0.13	0.08	0.10	0.04
CaO	7.28	7.80	5.99	5.47	6.81	5.11	4.91	5.71	7.34	8.05	5.46	6.31	4.72	6.46	5.71	7.93	5.35	5.06	7.82	5.46
Na ₂ O	7.55	7.48	8.22	8.56	7.84	8.88	8.91	8.39	7.63	7.17	8.24	7.76	8.91	7.75	8.38	6.94	8.73	8.73	7.11	8.51
K ₂ O	0.35	0.35	0.43	0.44	0.34	0.45	0.51	0.53	0.26	0.32	0.45	0.53	0.53	0.52	0.45	0.30	0.40	0.41	0.27	0.43
Total	100.66	100.38	101.02	100.99	99.63	100.48	100.71	99.46	100.14	99.50	99.72	100.17	98.59	99.67	101.11	100.28	100.24	100.64	99.27	100.69
Si	2.65	2.62	2.74	2.74	2.67	2.75	2.77	2.72	2.64	2.60	2.73	2.71	2.75	2.70	2.73	2.64	2.73	2.76	2.62	2.76
Altot	1.32	1.34	1.25	1.25	1.30	1.22	1.21	1.25	1.33	1.37	1.26	1.28	1.21	1.28	1.26	1.35	1.24	1.23	1.36	1.23
Fe ³⁺	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.00
Ca	0.35	0.37	0.28	0.26	0.33	0.24	0.23	0.27	0.35	0.39	0.26	0.30	0.23	0.31	0.27	0.38	0.25	0.24	0.38	0.26
Na	0.65	0.64	0.70	0.73	0.68	0.76	0.76	0.73	0.66	0.62	0.71	0.67	0.77	0.67	0.71	0.60	0.75	0.75	0.62	0.73
K	0.02	0.02	0.02	0.03	0.02	0.03	0.03	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02
Total	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	4.99	5.00	5.00	5.00	4.99	5.00	5.00	5.00	5.00
Ab	63.97	62.19	69.64	72.11	66.31	74.02	74.58	70.53	64.38	60.60	71.31	66.87	75.15	66.37	70.80	60.28	73.05	73.98	61.20	72.05
An	34.06	35.88	27.98	25.42	31.84	23.54	22.67	26.56	34.15	37.65	26.08	30.13	21.94	30.66	26.71	38.01	24.71	23.73	37.22	25.57
Or	1.97	1.93	2.38	2.47	1.86	2.44	2.75	2.92	1.47	1.75	2.61	3.00	2.91	2.97	2.48	1.71	2.25	2.28	1.58	2.38

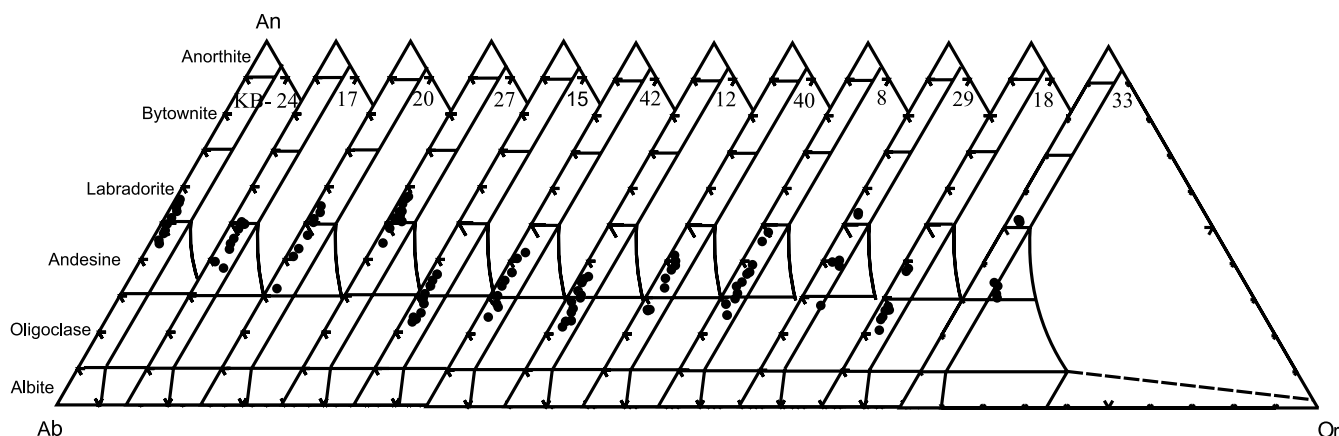


Fig. 2. Plot of plagioclase composition in the Ab–An–Or diagram (Basic andesitic volcanics: 99-33, 99-29; Acid andesitic volcanics: 99-24, 99-27, 99-20, 99-17; Dacitic volcanics: 99-42, 99-40, 99-8; Rhyolitic volcanics: 99-15, 99-12, 99-18).

Table 3

Representative microprobe analyses of pyroxene crystals from Balkuyumcu volcanic rocks (r, rim; c, center)

	Basic andesite															
	99-33								99-29							
	#5r→	#6c	#7r→	#8c	#21r→	#22c	#35r→	#36c	#12c→	#13r	#17c→	#18r	#19c→	#20r	#21c→	#22r
SiO ₂	49.44	52.49	51.21	50.36	50.52	51.53	52.05	51.94	52.37	52.06	51.41	51.38	50.18	50.86	50.59	50.85
TiO ₂	1.26	0.48	0.83	0.93	1.01	0.72	0.53	0.71	0.49	0.64	0.75	0.85	1.08	0.71	0.93	0.9
Al ₂ O ₃	4.49	2.38	4.91	5.13	4.49	4.32	2.73	3.90	3.75	2.87	4.71	5.01	6.09	4.62	5.2	4.14
FeO	7.82	7.53	5.91	6.25	7.23	5.71	6.83	6.00	3.27	6.3	3.99	5.21	5.93	4.82	5.64	6.17
MnO	0.28	0.15	0.17	0.12	0.19	0.17	0.25	0.15	0.16	0.16	0.1	0.16	0.19	0.23	0.2	0.14
MgO	14.25	15.86	15.40	15.68	15.00	15.66	17.04	16.28	16.00	16.46	15.19	15.45	15.25	15.01	14.6	15.84
CaO	21.25	20.57	21.24	20.89	21.04	21.66	19.69	21.13	21.12	21.08	21.51	21.23	20.11	21.1	20.73	21.26
Na ₂ O	0.58	0.57	0.67	0.65	0.57	0.64	0.53	0.67	0.64	0.41	0.69	0.61	0.69	0.67	0.68	0.47
Total	98.79	99.44	99.67	99.36	99.49	99.77	99.12	100.12	97.16	99.57	97.66	99.29	98.83	97.35	97.89	99.30
Si	1.84	1.93	1.86	1.84	1.86	1.87	1.91	1.88	1.91	1.91	1.88	1.87	1.84	1.88	1.87	1.87
Ti	0.04	0.01	0.02	0.03	0.03	0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.03	0.02	0.03	0.02
Al	0.20	0.10	0.21	0.22	0.19	0.18	0.12	0.17	0.16	0.12	0.20	0.22	0.26	0.20	0.23	0.18
Fe ²⁺	0.24	0.23	0.18	0.19	0.22	0.17	0.21	0.18	0.10	0.19	0.12	0.16	0.18	0.15	0.17	0.19
Mn	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00
Mg	0.79	0.87	0.84	0.85	0.82	0.85	0.93	0.88	0.87	0.90	0.83	0.84	0.83	0.83	0.80	0.87
Ca	0.85	0.81	0.83	0.82	0.83	0.84	0.77	0.82	0.83	0.83	0.84	0.83	0.79	0.83	0.82	0.84
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.03	0.05	0.04	0.05	0.05	0.05	0.03
Total	3.96	3.96	3.95	3.95	3.96	3.95	3.96	3.95	3.93	4.01	3.96	3.99	4.00	3.96	3.97	4.01
Wo	0.45	0.42	0.45	0.44	0.44	0.45	0.40	0.44	0.46	0.43	0.47	0.45	0.44	0.46	0.46	0.44
En	0.42	0.45	0.45	0.46	0.44	0.45	0.49	0.47	0.48	0.47	0.46	0.46	0.46	0.46	0.45	0.46
Fs	0.13	0.12	0.10	0.10	0.12	0.09	0.11	0.10	0.06	0.10	0.07	0.09	0.10	0.08	0.10	0.10
Mg#	0.76	0.79	0.82	0.82	0.79	0.83	0.82	0.83	0.90	0.82	0.87	0.84	0.82	0.85	0.82	0.82

The Balkuyumcu volcanic complex consists of a plug dome (Kargabedir Tepe) and lava flows with compositions ranging from basic andesite to rhyolite (Fig. 1b). Lava flows spread from N/NE to S/SW in the area and unconformably overlay Jurassic–Cretaceous limestones, sandstones and other sedimentary rocks.

3. Analytical techniques

K–Ar analyses of 3 samples were carried out at the University of Bretagne Occidentale (France) (Table 1). Datings

were performed on whole-rock samples. After crushing and sieving, the rock fraction of 0.15–0.30 mm sizes were cleaned with distilled water and then retained for analytical purposes: (i) one aliquot was powdered for K analysis by atomic absorption after the HF chemical attack, and (ii) 0.5–0.15 mm grains were used for argon isotopic analysis. Argon was extracted under high vacuum by induction heating of a molybdenum crucible containing the sample grains. Gases were cleaned on two titanium sponge furnaces and finally purified by using two Al–Zr SAES getters. The isotopic dilution method was applied using a ³⁸Ar

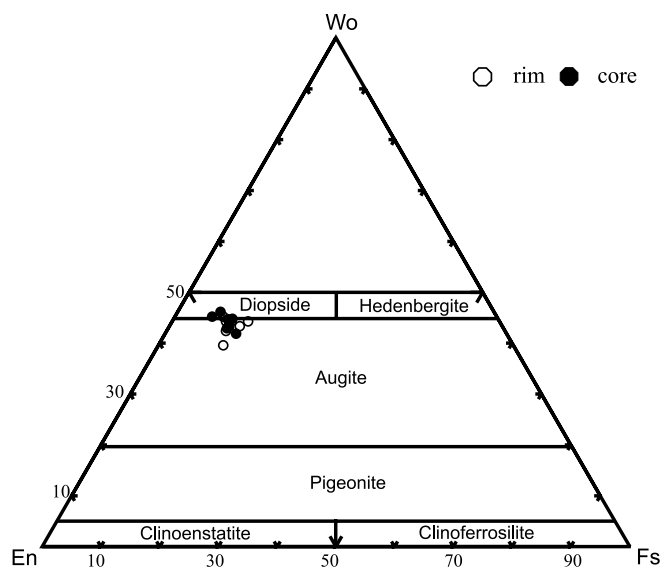


Fig. 3. Plot of clinopyroxene composition in the Wo–En–Fs diagram (after Morimoto, 1989).

spike, buried as ions in aluminium targets, according to the original procedure described by Bellon et al. (1981). The isotopic composition of argon and concentration of radiogenic ^{40}Ar were determined using a 180° -geometry stainless steel mass spectrometer equipped with a 642 Keithley amplifier. Ages were calculated using the constants recommended by Steiger and Jäger (1977) and listed with their respective characteristic parameters in Table 1. Errors at ± 1 sigma level were calculated following the equation of Mahood and Drake (1982).

We determined mineral compositions using a Cameca-SX 100 electron microprobe at Blaise-Pascal University (France). Counting times for the individual elements and the sample current were 10 s and 10–12 nA, respectively.

Major elements were determined using a Philips PW 1480 X-ray fluorescence spectrometer at Hacettepe University (Turkey). The trace element (Rb, Sr, Zr, Nb, Ba, Hf, Ta, Pb, Th, U) and the rare earth element (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) abundances were obtained by Fison Instruments ICP-MS (PQ2⁺) at Blaise-Pascal University (France).

For isotopic analyses, sample powders (~150 mg) were washed in cold 2 N HCL for 24 h prior to dissolution in HF. Sr and Nd were sequentially separated using standard ion-exchange techniques. Radiogenic isotope compositions ($^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$) were determined on a VG54E mass spectrometer at Blaise-Pascal University (France). The $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively.

4. Petrography and mineral chemistry

Balkuyumcu volcanic rocks have compositions ranging from basic andesite to rhyolite. Basic rocks exhibit por-

phyritic textures mainly with dominant plagioclase and amphibole phenocrysts. Rare clinopyroxene and biotite phenocrysts are set in a matrix of plagioclase, amphibole microlites and opaque minerals. No orthopyroxene was found. Plagioclase phenocrysts in the basic rocks are labradorite and andesine in composition (An_{28} to An_{53}) (Table 2, Fig. 2). Most of the phenocrysts display normal, reverse and oscillatory zoning as marks of disequilibrium during their crystallization. Other disequilibrium clues such as glass inclusions with typical ‘honeycomb texture’ (Kawamoto, 1992) are also observed. Some plagioclase phenocrysts are embayed and resorbed. Pyroxene phenocrysts are Ca–Mg–Fe clinopyroxenes (nomenclature from Morimoto (1989)). They are only observed in the mafic rocks. The composition of clinopyroxene phenocrysts ranges from En_{42} to En_{49} , Wo_{40} to Wo_{47} . Mg numbers are in the range of 76–90 (Table 3). Clinopyroxenes are augite and diopside (Fig. 3). Both reverse and normal zoning are observed in clinopyroxene phenocrysts. Biotite phenocrysts are present in the basic rocks and are usually rimmed by oxide minerals (Table 5). Accessory minerals such as ilmenite (Table 6) commonly occur as rounded crystals in the groundmass, or as inclusions within pyroxene and plagioclase phenocrysts.

Andesitic rocks are also porphyritic with fluidal textures. Phenocrysts of zoned plagioclase, altered amphibole and scattered biotite are set in a matrix of feldspar, amphibole, biotite, opaque microlites and brown glass. Plagioclase phenocrysts have labradorite–andesine compositions (An_{32} to An_{57}) (Table 2, Fig. 3) and display complex normal and reverse zonation. They commonly exhibit multiple disequilibrium textures such as embayment and sieved-textures, while the outer parts of phenocrysts commonly show oscillatory zoning. All amphibole phenocrysts are calcic amphiboles (nomenclature from Leake et al. (1997)) of pargasite type (Table 4, Fig. 4), and commonly occur with opaque rims that probably formed during magma ascent. Rounded Ti-magnetite and ilmenite microcrysts commonly occur in the matrix of andesitic rocks (Table 6).

Dacitic and rhyolitic rocks exhibit porphyritic textures with phenocrysts of plagioclase and oxidized amphibole. Biotite microphenocrysts and trace quartz are common in some rhyolitic samples. Ti-magnetite, ilmenite and hematite occur as accessory minerals. These phases are enclosed in a microlitic matrix of plagioclase, amphibole, biotite, quartz, oxides and clear glass. Plagioclase range from andesine to oligoclase (An_{22} to An_{48}) in composition (Table 2, Fig. 2). In addition to the normal zonation, disequilibrium textures such as oscillatory and reverse zonations are also present. These textures provide evidence of magma mixing and/or interaction of chemically different magmas during formation of Balkuyumcu volcanic rocks. Amphibole phenocrysts are largely oxidized. The rare fresh amphiboles are pargasite and ferro-pargasite (Fig. 4). The Mg numbers of amphibole phenocrysts range from 44 to 71 (Table 4). Only one dacitic sample contains biotite phenocrysts, Ti-magnetite, ilmenite and hematite.

Table 4
Representative microprobe analyses of amphibole crystals from Balkuyumcu volcanic rocks (r: rim; c: center)

	Acid Andesite										Dacite									
	Acid Andesite					Acid Andesite					Dacite					Dacite				
	99-24					99-27					99-42					99-42				
	#64c→	#65r	#67c→	#68r	#15c→	#16r	#17c→	#18r	#43c→	#44r	#66c→	#67r	#32c→	#33r	#38c→	#39r	#57c→	#58r		
SiO ₂	41.52	41.58	42.39	41.07	42.31	42.10	41.70	42.91	41.32	41.03	42.61	42.65	42.67	40.61	42.37	40.68	39.13	41.19		
Al ₂ O ₃	12.35	12.45	12.57	12.79	13.57	13.39	13.78	13.14	13.56	13.97	13.35	13.27	13.18	13.83	13.10	14.18	14.34	13.27		
FeO _t	9.89	9.44	10.41	11.67	10.24	11.78	13.33	10.12	16.24	14.91	11.45	10.61	10.20	14.83	12.50	14.63	16.83	15.61		
MgO	14.86	15.03	14.72	13.75	14.45	13.43	12.49	14.51	11.31	12.28	14.39	15.01	14.50	11.53	13.22	11.44	10.07	11.20		
CaO	11.26	11.19	10.94	10.79	11.45	11.07	11.20	11.51	10.78	11.14	11.36	11.5	10.97	11.13	11.08	11.15	11.08	11.09		
Na ₂ O	2.66	2.74	2.64	2.58	2.76	2.75	2.67	2.72	2.66	2.62	2.69	2.73	2.70	2.75	2.67	2.59	2.57	2.58		
K ₂ O	0.80	0.93	0.79	0.79	0.86	0.75	0.83	0.83	0.83	0.8	0.85	0.95	0.83	0.83	0.78	0.74	0.83	0.58		
TiO ₂	3.03	3.01	2.64	2.52	2.58	2.54	2.55	2.63	2.59	2.65	2.61	2.71	2.53	2.53	2.20	2.58	1.88	2.32		
MnO	0.11	0.18	0.15	0.18	0.13	0.10	0.19	0.14	0.22	0.24	0.13	0.18	0.10	0.20	0.19	0.21	0.17	0.31		
Total	96.50	96.56	97.27	96.20	98.34	97.91	98.74	98.50	99.51	99.64	99.44	99.61	97.69	98.24	98.11	98.20	96.89	98.13		
Si	6.17	6.18	6.25	6.16	6.18	6.22	6.14	6.25	6.15	6.05	6.20	6.18	6.27	6.06	6.25	6.06	5.96	6.15		
Al	2.16	2.18	2.18	2.26	2.34	2.33	2.39	2.26	2.38	2.43	2.29	2.26	2.28	2.43	2.28	2.49	2.57	2.33		
Al ^{IV}	1.83	1.82	1.75	1.84	1.82	1.78	1.86	1.75	1.85	1.95	1.80	1.82	1.73	1.94	1.75	1.94	2.04	1.85		
Al ^{VI}	0.33	0.36	0.44	0.42	0.52	0.54	0.54	0.51	0.53	0.48	0.49	0.44	0.55	0.50	0.53	0.55	0.53	0.49		
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00		
Fe ²⁺	1.23	1.17	1.28	1.46	1.25	1.45	1.64	1.23	1.93	1.74	1.32	1.22	1.25	1.85	1.54	1.82	1.98	1.95		
Mg	3.29	3.33	3.24	3.07	3.14	2.96	2.74	3.15	2.51	2.70	3.12	3.24	3.18	2.57	2.91	2.54	2.29	2.49		
Ca	1.79	1.78	1.73	1.73	1.79	1.75	1.77	1.80	1.72	1.76	1.77	1.78	1.73	1.78	1.75	1.78	1.81	1.77		
Na	0.77	0.79	0.75	0.75	0.78	0.79	0.76	0.77	0.77	0.75	0.76	0.77	0.77	0.80	0.77	0.75	0.76	0.75		
K	0.15	0.18	0.15	0.15	0.16	0.14	0.16	0.15	0.16	0.15	0.16	0.18	0.16	0.16	0.15	0.14	0.16	0.11		
Ti	0.34	0.34	0.29	0.28	0.28	0.28	0.28	0.29	0.29	0.29	0.29	0.30	0.28	0.28	0.24	0.29	0.22	0.26		
Mn	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.03	0.03	0.02	0.02	0.01	0.03	0.02	0.03	0.02	0.04		
Total	18.08	18.14	18.08	18.16	18.28	18.26	18.31	18.18	18.31	18.33	18.21	18.21	18.21	18.39	18.19	18.38	18.49	18.19		
Mg#	72.80	73.95	71.59	67.74	71.55	67.02	62.55	71.87	56.53	60.75	70.23	72.69	71.71	58.09	65.34	58.21	51.62	56.11		
Ca _B	1.79	1.78	1.73	1.73	1.79	1.75	1.77	1.80	1.72	1.76	1.77	1.78	1.73	1.78	1.75	1.78	1.81	1.77		
(Na+K) _A	0.92	0.97	0.90	0.90	0.94	0.93	0.92	0.92	0.93	0.90	0.92	0.94	0.92	0.95	0.91	0.89	0.92	0.86		
Mg/(Mg+Fe ²⁺)	0.73	0.74	0.72	0.68	0.72	0.67	0.63	0.72	0.57	0.61	0.70	0.73	0.72	0.58	0.65	0.58	0.54	0.56		

(continued on next page)

Table 4 (continued)

	Dacite				Rhyolite				Rhyolite									
	99-40				99-18				99-15									
	#77c→	#78r	#85c→	#86r	#92c→	#93r	#84c→	#85r	#86c→	#87r	#50r→	#51c	#59r→	#60c	#67r→	#68c	#76c→	#77r
SiO ₂	40.69	40.43	41.16	40.14	41.83	40.96	42.78	41.59	43.93	43.25	42.74	42.59	43.42	42.90	42.52	43.81	43.04	42.81
Al ₂ O ₃	14.00	13.62	13.21	13.57	13.34	13.58	11.68	12.4	12.16	12	11.69	12.00	11.98	12.01	12.02	11.78	11.49	12.09
FeO _t	12.79	14.05	12.45	14.95	11.18	13.72	19.49	20.63	15.75	19.3	18.62	20.04	17.20	18.53	19.09	16.11	16.96	18.36
MgO	12.30	11.55	13.22	11.19	13.74	12.09	9.85	8.86	12.18	10.17	9.71	9.18	10.85	9.55	9.83	11.40	11.66	11.25
CaO	11.29	11.06	10.97	10.82	11.47	10.78	10.69	11	11.16	10.71	10.73	10.92	10.42	10.73	10.54	10.72	10.65	9.81
Na ₂ O	2.65	2.57	2.66	2.67	2.70	3.07	2.03	2.08	2.3	2.1	1.89	2.04	2.17	2.21	2.13	2.27	2.3	2.25
K ₂ O	0.76	0.80	0.73	0.80	0.82	0.71	0.72	0.97	0.6	0.73	0.75	0.91	0.57	0.81	0.91	0.72	0.58	0.68
TiO ₂	2.48	2.31	2.38	2.62	2.48	2.50	1.1	1.07	1.73	1.11	0.96	1.02	1.32	1.13	1.18	1.74	1.94	1.43
MnO	0.20	0.21	0.19	0.24	0.15	0.18	0.62	0.62	0.3	0.62	0.67	0.62	0.46	0.66	0.57	0.41	0.3	0.58
Total	97.14	96.61	96.95	96.98	97.71	97.60	98.96	99.22	100.1	99.99	97.77	99.31	98.39	98.53	98.79	98.95	98.92	99.26
Si	6.08	6.11	6.14	6.08	6.17	6.14	6.44	6.30	6.43	6.44	6.45	6.38	6.47	6.45	6.38	6.49	6.22	6.41
Al	2.47	2.43	2.32	2.42	2.32	2.40	2.07	2.21	2.10	2.11	2.08	2.12	2.10	2.13	2.13	2.06	2.28	2.10
Al ^{IV}	1.92	1.89	1.86	1.92	1.83	1.86	1.56	1.71	1.57	1.56	1.55	1.63	1.53	1.55	1.62	1.51	1.78	1.59
Al ^{VI}	0.55	0.54	0.46	0.50	0.49	0.54	0.52	0.51	0.53	0.55	0.53	0.49	0.57	0.58	0.50	0.54	0.50	0.52
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.16	0.00	0.02	0.10	0.13	0.00	0.00	0.05	0.00	0.00	0.01
Fe ²⁺	1.60	1.78	1.55	1.89	1.38	1.72	2.28	2.35	1.84	2.27	2.25	2.38	2.14	2.33	2.34	1.99	2.16	2.27
Mg	2.74	2.60	2.94	2.52	3.02	2.70	2.21	2.00	2.66	2.26	2.19	2.05	2.41	2.14	2.20	2.52	2.25	2.26
Ca	1.81	1.79	1.75	1.76	1.81	1.73	1.73	1.78	1.75	1.71	1.74	1.75	1.66	1.73	1.69	1.70	1.79	1.72
Na	0.77	0.75	0.77	0.78	0.77	0.89	0.59	0.61	0.65	0.61	0.55	0.59	0.63	0.65	0.62	0.65	0.71	0.64
K	0.14	0.15	0.14	0.15	0.15	0.14	0.14	0.19	0.11	0.14	0.14	0.17	0.11	0.16	0.17	0.14	0.15	0.13
Ti	0.28	0.26	0.27	0.30	0.28	0.28	0.13	0.12	0.19	0.12	0.11	0.12	0.15	0.13	0.13	0.19	0.25	0.14
Mn	0.02	0.03	0.02	0.03	0.02	0.02	0.08	0.08	0.04	0.08	0.09	0.08	0.06	0.08	0.07	0.05	0.04	0.07
Total	18.38	18.33	18.23	18.36	18.25	18.43	17.81	18.01	17.86	17.85	17.78	17.88	17.83	17.93	17.91	17.84	18.15	17.87
Mg#	63.16	59.44	65.42	57.15	68.67	61.09	48.56	44.35	59.07	49.67	48.18	44.94	52.93	47.87	47.86	55.78	51.02	49.77
Ca _B	1.81	1.79	1.75	1.76	1.81	1.73	1.73	1.78	1.75	1.71	1.74	1.75	1.66	1.73	1.69	1.70	1.79	1.72
(Na+K) _A	0.97	0.91	0.91	0.91	0.94	0.93	0.73	0.80	0.76	0.75	0.70	0.77	0.73	0.80	0.79	0.79	0.87	0.78
Mg/(Mg+Fe ²⁺)	0.63	0.59	0.65	0.57	0.69	0.61	0.49	0.46	0.59	0.50	0.49	0.46	0.53	0.48	0.48	0.56	0.51	0.50

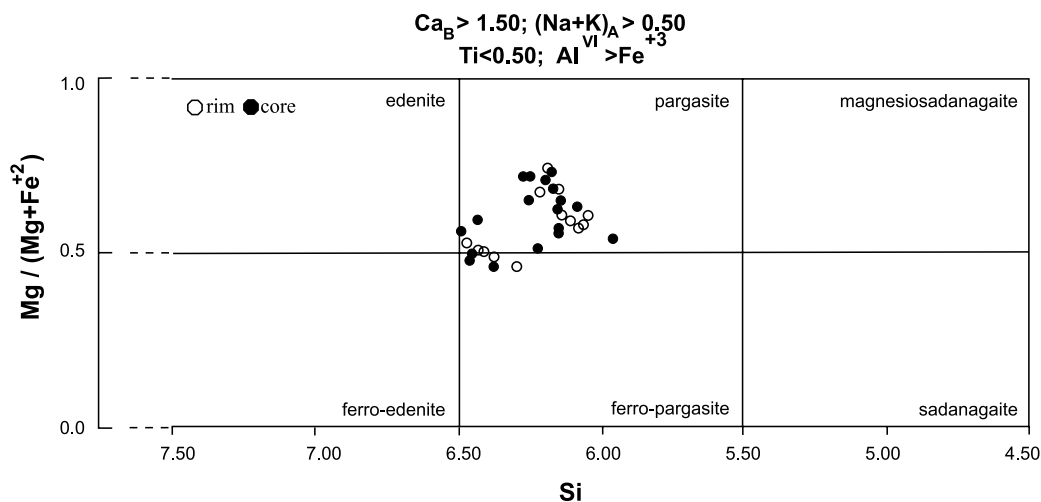


Fig. 4. Plot of amphibole compositions (after Leake et al., 1997).

Table 5
Representative microprobe analyses of mica crystals (r, rim; c, center)

	Basic andesite 99-33						Rhyolite 99-15			
	#1k→	#2m	#25k→	#26m	#40k→	#41m	#70m→	#71k	#16k→	#17m
SiO ₂	40.60	41.14	39.92	40.67	40.11	41.10	36.92	37.90	35.87	37.22
TiO ₂	5.98	5.35	5.96	5.37	6.03	5.26	3.25	3.05	2.74	2.49
Al ₂ O ₃	11.63	11.63	11.49	11.65	11.72	11.37	15.95	16.42	15.44	17.79
Fe ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO	6.56	6.57	6.56	6.44	6.77	6.29	19.00	17.79	19.81	17.91
MnO	0.09	0.03	0.08	0.09	0.10	0.05	0.18	0.24	0.26	0.19
MgO	20.63	20.84	20.10	20.70	20.17	20.69	11.13	11.52	11.59	10.91
CaO	0.10	0.08	0.01	0.03	0.02	0.00	0.00	0.06	0.00	0.00
Na ₂ O	0.95	1.09	1.07	1.06	0.98	1.09	0.77	0.66	0.59	0.72
K ₂ O	9.01	9.03	9.34	9.02	9.27	9.31	8.47	8.64	9.03	8.37
Total	95.55	95.80	94.55	95.04	95.21	95.15	95.69	96.30	95.33	95.60
Si	2.99	3.02	2.99	3.00	2.98	3.04	2.85	2.89	2.78	2.85
Ti	0.33	0.30	0.34	0.30	0.34	0.29	0.19	0.17	0.16	0.14
Al	1.01	1.00	1.01	1.01	1.03	0.99	1.45	1.48	1.41	1.60
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	0.40	0.40	0.41	0.40	0.42	0.39	1.22	1.13	1.29	1.15
Mn	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.02	0.02	0.01
Mg	2.26	2.28	2.24	2.28	2.23	2.28	1.28	1.31	1.34	1.24
Ca	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.14	0.15	0.16	0.15	0.14	0.16	0.12	0.10	0.09	0.11
K	0.85	0.84	0.89	0.85	0.88	0.88	0.83	0.84	0.89	0.82
Total	7.99	8.00	8.05	8.00	8.02	8.03	7.95	7.94	7.98	7.92
FM	15.15	15.03	15.48	14.87	15.85	14.56	48.91	46.42	48.94	47.94

5. Geochemistry

5.1. Major and trace element variations

Major element compositions determined from 52 samples are given in Table 7. All major element contents were recalculated on a water-free basis. The SiO₂ and MgO contents of Balkuyumcu lavas range from 50% to 70% and

from 0.2% to 2.58%, respectively. The K₂O–SiO₂ diagram demonstrates that Balkuyumcu volcanic rocks, having medium-high K contents, show variations from basic andesite to rhyolite (Fig. 5). The ADR and BA groups are easily identified by geochemical properties and different mineral assemblages. The BA group (BA) consists of calc-alkali basic andesite rocks while the ADR group (ADR) include adakite-like andesitic–dacitic–rhyolitic rocks

Table 6
Representative microprobe analyses of oxides (m, microlite)

	Ti-magnetite					Ilmenite						Hematite			
	Acid andesite 99-17		Dacite 99-40	Rhyolite 99-15		Basic andesite 99-33		Acid andesite 99-24		Rhyolite 99-15		Rhyolite 99-15			
	#41m	#46m	#1m	#54m	#55m	#9m	#10m	#40m	#87m	#5m	#18m	#63m	#69m	#80m	#20m
SiO ₂	0.13	0.13	0.39	1.08	0.25	0.06	0.07	0.05	0.06	0.03	0.04	0.77	1.34	0.26	0.46
TiO ₂	6.45	5.76	2.17	1.04	1.69	35.08	43.88	52.72	38.62	26.42	26.80	0.59	1.66	3.67	2.61
Al ₂ O ₃	1.64	0.28	4.16	2.81	7.91	0.15	0.16	0.05	0.16	0.47	0.39	4.32	6.42	1.23	6.57
Fe ₂ O ₃	52.34	55.12	58.54	62.30	55.37	30.59	19.98	0.00	26.31	48.74	48.82	91.21	86.27	90.23	80.70
FeO	29.56	29.26	28.84	27.14	27.59	26.18	31.28	37.43	30.41	21.60	20.87	0.00	0.00	1.99	0.00
MnO	0.61	1.08	1.09	1.56	1.18	0.74	0.95	2.36	0.92	0.62	0.77	1.33	1.16	0.61	3.85
MgO	3.45	2.85	2.12	2.82	2.88	2.47	3.96	3.93	1.77	0.86	1.33	1.42	2.39	0.35	2.92
CaO	0.12	0.02	0.07	0.02	0.03	0.10	0.16	0.05	0.02	0.03	0.00	0.06	0.01	0.16	0.03
Total	94.30	94.50	97.38	98.77	96.90	95.37	100.44	96.59	98.27	98.77	99.02	99.70	99.25	98.50	97.14
Si	0.01	0.01	0.01	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.03	0.01	0.01
Ti	0.19	0.17	0.06	0.03	0.05	0.69	0.81	1.00	0.74	0.52	0.52	0.01	0.03	0.07	0.05
Al	0.08	0.01	0.19	0.12	0.35	0.00	0.00	0.00	0.00	0.01	0.01	0.13	0.19	0.04	0.20
Fe ³⁺	1.54	1.64	1.66	1.75	1.54	0.61	0.37	0.00	0.51	0.95	0.95	1.75	1.63	1.80	1.55
Fe ²⁺	0.96	0.97	0.91	0.85	0.85	0.58	0.64	0.79	0.65	0.47	0.45	0.00	0.00	0.04	0.00
Mn	0.02	0.04	0.03	0.05	0.04	0.02	0.02	0.05	0.02	0.01	0.02	0.03	0.02	0.01	0.08
Mg	0.20	0.17	0.12	0.16	0.16	0.10	0.15	0.15	0.07	0.03	0.05	0.05	0.09	0.01	0.11
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	3.00	3.00	2.99	2.99	3.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

(Fig. 6a and b). The BA group volcanic rocks have lower SiO₂ and higher MgO, Mg# and Y contents than those of ADR group rocks. Harker diagrams, displaying selected major elements, show that in BA group rocks, the MgO and CaO are positively correlated with SiO₂ while Al₂O₃, Fe₂O₃, MnO, TiO₂, P₂O₅, Na₂O and K₂O are inversely correlated. In the ADR group rocks, Al₂O₃, MgO, CaO, Fe₂O₃, MnO, TiO₂, P₂O₅, Na₂O contents decrease and K₂O contents increase with increasing SiO₂ content (Fig. 7).

All trace elements increase with increasing SiO₂ content in BA group rocks, while only Rb and Pb contents have a positive correlation with SiO₂ in the ADR group rocks (Fig. 8). In both groups, samples have high Sr and Ba contents but generally low Y and Yb contents. The incompatible trace element and rare earth element data are illustrated on primitive mantle (Sun and McDonough, 1989) and chondrite normalized (Nakamura, 1974) multi-element variation diagrams (Fig. 9a and b). In these diagrams, all samples of both groups show LILE and LREE enriched normalized trace element patterns with negative Nb, Ti, Zr, P and negligible Eu anomalies (Fig. 9a and b). All samples show element concentrations similar to those of typical adakites such as from Costa Rica (Defant et al., 1992).

5.2. Sr, Nd isotope variations

The (⁸⁷Sr/⁸⁶Sr)_i and (¹⁴³Nd/¹⁴⁴Nd)_i ratios of selected samples range between 0.70510–0.70536 and 0.51263–0.51278, respectively (Table 7). Graphs of ⁸⁷Sr/⁸⁶Sr versus

SiO₂, MgO and Rb/Sr indicate the dominance of fractional crystallization while assimilation–fractional crystallization (AFC) seems to have contributed slightly to magma evolution during ascent (Fig. 10a, b and c). The clustering of Balkuyumcu volcanic rocks in a narrow zone on the isotopic ratio graph implies a common parental magma source. In the Sr–Nd isotope ratios diagram (Fig. 11), the ADR rock group plot as a dense cluster while BA rocks are offset slightly from the former due to an increase in ¹⁴³Nd/¹⁴⁴Nd ratios. Both groups plot along the mantle array and fall into the fields of Galatia and Cappadocia volcanic provinces (Wilson et al., 1997; Temel et al., 1998). Wilson et al. (1997) argue that Galatian volcanic rocks were derived from an enriched lithospheric mantle source of post-collisional origin. For Cappadocia volcanic rocks, Temel et al. (1998) suggest collision-related mechanism that includes fractional crystallization of mantle-derived magma. Balkuyumcu rocks have isotopic ratios that seem to be more closely associated with rocks of the Galatia province that are closer (i.e. 80 km) to the study area compared to Cappadocia province rocks.

6. Discussion

6.1. Effective processes in the evolution of Balkuyumcu volcanic rocks

The Balkuyumcu volcanic rocks form two distinct groups, as BA and ADR in terms of mineral assemblage and geochemistry. The BA group rocks have clinopyroxene minerals that are lacking in ADR group rocks. Both

Table 7
Major, trace, rare earth elements and $^{87}\text{Sr}/^{86}\text{Sr}$ – $^{143}\text{Nd}/^{144}\text{Nd}$ contents of selected volcanic rocks from the Balkuymcu region

Sample no.	Basic andesite						Acid andesite						Dacite												
	99-28	99-29	99-30	99-31	99-32	99-33	99-16	99-17	99-19	99-20	99-21	99-22	99-23	99-26	99-34	99-35	99-24	99-25	99-27	99-36	99-44	99-45	99-7	99-8	99-10
SiO ₂ (%)	52.09	53.46	51.77	52.98	51.03	49.99	60.39	60.05	57.33	57.19	56.65	56.62	58.50	56.86	56.61	56.48	57.80	58.52	56.81	60.43	59.89	60.04	67.41	66.54	66.69
MgO	2.21	1.79	2.37	2.22	2.08	2.54	0.99	1.14	1.26	2.58	1.74	2.45	1.40	2.40	1.50	2.13	1.93	1.23	1.85	0.91	0.71	1.04	0.58	0.20	0.68
Al ₂ O ₃	17.14	17.81	17.14	17.44	16.73	16.55	17.93	17.90	17.66	17.44	17.71	17.56	17.76	17.80	18.11	17.79	17.62	17.52	17.60	17.69	17.28	17.44	15.65	16.20	15.79
Fe ₂ O ₃	7.20	7.47	7.20	7.34	6.92	7.00	5.02	5.03	5.93	5.83	5.86	5.85	5.23	5.81	6.29	6.05	5.68	5.21	5.66	5.02	4.73	5.06	2.47	3.01	2.58
MnO	0.13	0.16	0.15	0.13	0.13	0.11	0.11	0.10	0.10	0.11	0.10	0.11	0.09	0.11	0.12	0.10	0.11	0.10	0.11	0.11	0.09	0.12	0.07	0.06	0.07
CaO	8.25	6.65	8.41	7.39	9.29	9.92	4.66	4.88	6.08	6.26	6.56	6.54	5.83	6.33	6.24	6.27	5.99	5.54	6.11	5.00	5.28	5.08	3.05	3.04	3.07
Na ₂ O	4.41	4.57	4.32	4.50	4.39	4.18	4.65	4.65	4.62	4.55	4.57	4.47	4.33	4.46	4.74	4.55	3.86	3.72	3.78	4.25	4.16	4.22	4.19	4.42	4.06
K ₂ O	2.25	2.33	2.23	2.26	2.21	2.18	2.32	2.34	2.31	2.09	1.99	2.02	2.10	2.00	2.34	2.32	2.14	2.19	1.76	2.30	2.22	2.29	2.50	2.40	2.43
TiO ₂	1.18	1.23	1.18	1.20	1.12	1.13	0.66	0.66	0.87	0.85	0.84	0.86	0.72	0.84	0.92	0.91	0.81	0.72	0.80	0.67	0.62	0.68	0.27	0.35	0.29
P ₂ O ₅	0.87	0.89	0.90	0.92	0.84	0.85	0.54	0.54	0.73	0.69	0.74	0.72	0.60	0.70	0.76	0.78	0.68	0.60	0.66	0.52	0.47	0.55	0.14	0.21	0.17
LOI	2.25	1.43	2.40	1.41	3.16	3.68	1.17	0.92	1.43	0.70	1.55	1.34	2.32	1.10	0.43	0.53	1.51	2.02	1.86	0.79	1.15	1.02	2.04	1.31	2.39
Mg#	37.83	32.21	39.49	37.49	37.34	41.84	28.11	31.01	29.64	46.74	37.06	45.37	34.67	45.03	32.10	41.11	40.25	31.89	39.32	26.44	22.94	28.95	31.77	11.64	34.32
Total	97.99	97.79	98.05	97.78	97.89	98.13	98.43	98.22	98.33	98.28	98.31	98.53	98.88	98.43	98.07	97.92	97.61	97.37	97.00	97.70	96.59	97.52	98.38	97.76	98.23
Rb (ppm)	45.22					42.27		55.87		46.03							51.72		45.35					70.56	
Sr	1328.85					1245.10		1210.95		1233.30							1257.50		1249.55					822.44	
Y	20.65					19.72		15.01		17.31							16.41		16.26					10.25	
Zr	148.26					98.20		117.50		164.97							170.33		168.52					94.44	
Nb	28.70					22.53		22.53		23.33							21.42		22.47					19.28	
Ba	1425.45					994.00		1195.85		1040.55							1156.80		1115.05					1248.50	
Hf	3.91					2.85		3.29		4.13							4.08		4.07					2.58	
Ta	1.68					1.46		1.33		1.53							1.40		1.36					1.27	
Pb	18.31					15.14		24.13		18.45							24.35		23.19					30.10	
Th	9.03					7.35		10.88		11.20							11.00		11.01					11.69	
U	2.25					1.78		2.32		2.95							2.85		2.46					3.28	
La	64.42					59.56		63.05		60.81							61.83		61.46					47.94	
Ce	126.62					117.09		119.49		116.32							119.57		118.17					85.99	
Pr	13.86					12.70		12.47		12.46							12.68		12.57					8.73	
Nd	50.21					46.36		43.34		44.47							44.84		44.69					29.15	
Sm	7.67					7.02		6.14		6.58							6.42		6.41					3.99	
Eu	2.35					2.09		1.79		1.93							1.90		1.88					1.23	
Gd	6.82					6.22		5.17		5.62							5.55		5.45					3.45	
Tb	0.83					0.74		0.58		0.67							0.63		0.62					0.39	
Dy	4.45					4.03		3.02		3.61							3.38		3.33					2.04	
Ho	0.83					0.74		0.54		0.69							0.61		0.61					0.37	
Er	2.23					1.99		1.49		1.89							1.68		1.67					1.02	
Tm	0.36					0.31		0.23		0.31							0.26		0.26					0.16	
Yb	2.14					1.90		1.46		1.90							1.71		1.68					1.05	
Lu	0.35					0.30		0.24		0.32							0.27		0.28					0.17	
Sr/Y	64.35					63.14		80.68		71.24							76.65		76.85					80.23	
(La/Yb) _N	20.13					20.96		28.88		21.40							24.18		24.46					30.53	
Yb _N	9.73					8.64		6.64		8.64							7.77		7.64					4.77	
(⁸⁷ Sr/ ⁸⁶ Sr) _h	0.705150					0.705100		0.705180		0.705180							0.705160		0.705160					0.705230	
(¹⁴³ Nd/ ¹⁴⁴ Nd) _h	0.512690					0.512780		0.512660		0.512680							0.512690		0.512640					0.512660	

(continued on next page)

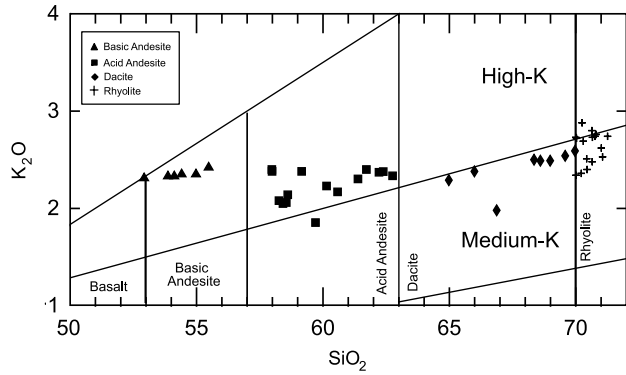


Fig. 5. K_2O – SiO_2 classification diagram. Fields and nomenclature after Peccerillo and Taylor (1976).

groups display similar normalized trace element patterns and Sr and Nd isotopic compositions. Furthermore, compared to the ADR group, the BA group has lower SiO_2 (50–54 wt%) content, higher MgO (1.78–2.54 wt%), Mg# (0.3–0.4), Y (9–17 ppm) and Yb (0.9–1.9 ppm) contents and lower Sr/Y and La/Yb ratios. These differences are interpreted as an indication of different petrogenetic processes that affected BA and ADR magmas during ascent to the surface. Major and trace element distribution trends indicate that fractional crystallization was not effective in the formation of BA group rocks. If these processes were effective, some typical trends, such as decreasing of Al_2O_3 , Fe_2O_3 , MnO and TiO_2 with increasing SiO_2 , should be observed in Fig. 7. The decrease in MgO and CaO contents with increasing SiO_2 (Fig. 7) appears to be related to fractionation of pyroxene and/or plagioclase. If fractionation of plagioclase occurred, this should have caused negative Eu and Sr anomalies in spider diagrams. However, the observed positive Sr and slightly positive Eu anomalies indicate an absence of residual plagioclase or lack of important plagioclase fractionation. These properties suggest that only fractionation of pyroxene played an impor-

tant role in the formation of these BA group rocks. Disequilibrium textures and complexly zoned minerals in many BA group volcanic rocks support the interaction of different magmas. Because orthopyroxene minerals are lacking, a limited interaction with mantle peridotite seems likely (Rapp et al., 1999).

The ADR samples have similar features to those of modern adakitic rocks of andesite, dacite and rhyolite composition. Their SiO_2 wt% range from 57 to 70. They have $Al_2O_3 > 15$ wt%, low MgO wt% (0.20–2.58), Mg# (0.11–0.45), Y (9–15 ppm) and Yb (0.9–1.5 ppm), elevated Sr (700–1500 ppm) contents and high Sr/Y and $(La/Yb)_N$ ratios (see Fig. 6a and b). They show LILE and LREE enriched normalized multi-element patterns, U-shaped chondrite-normalized REE patterns and negative Nb, Ti, P and negligible Eu anomalies (Fig. 9a and b). These characteristics are consistent with ratios obtained from rocks having adakitic characteristics (e.g. Defant and Drummond, 1990; Martin, 1999).

As for the source of Balkuyumcu adakitic rocks, the geodynamic evolution of the study area and vicinity is considered. K–Ar ages of Balkuyumcu volcanic rocks range between 20 and 22 Ma, but no evidence for an synchronous active subduction event has been reported in and around the study area for this time period (e.g. Şengör and Yılmaz, 1981; Koçyiğit, 1991; Koçyiğit et al., 1995, 2003; Göncüoğlu et al., 2000). The Sakarya, Kırşehir and Menderes blocks collided well before the formation of these rocks. Thus, a subduction related source for Balkuyumcu volcanic rocks seems unlikely. Beyond this, if these rocks were formed by AFC processes (e.g. Castillo et al., 1999), the BA group rocks would have had consistent trends with ADR group rocks. However, Harker diagrams clearly show that the ADR group did not formed from the BA group of calc-alkaline rocks by normal differentiation processes. Eclogitization associated with thickened crust due to colliding blocks, and partial melting of thickened lower

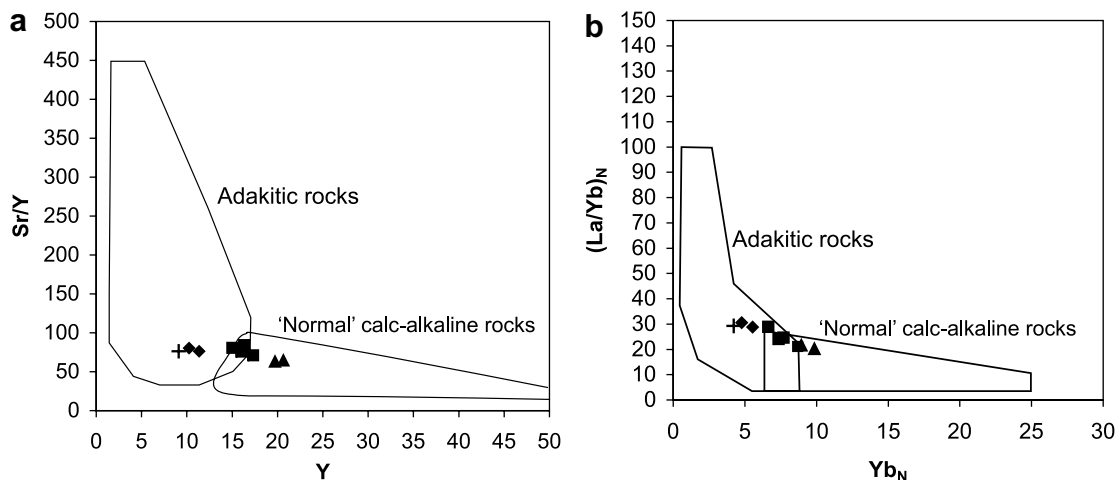


Fig. 6. Discrimination diagrams between adakites and 'normal' calc-alkaline rocks, (a) Y vs Sr/Y (after Defant and Drummond, 1990), (b) Yb_N vs $(La/Yb)_N$ (after Martin, 1999). Symbols same as in Fig. 5.

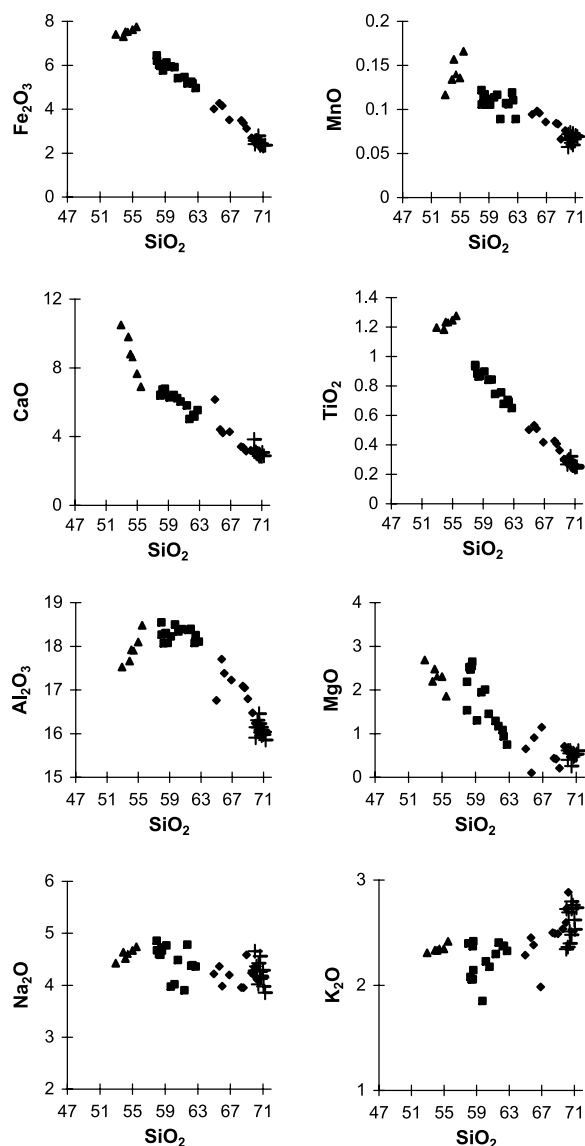


Fig. 7. Harker variation diagrams (SiO_2 vs selected major elements) for Balkuyumcu volcanic rocks. Symbols same as in Fig. 5.

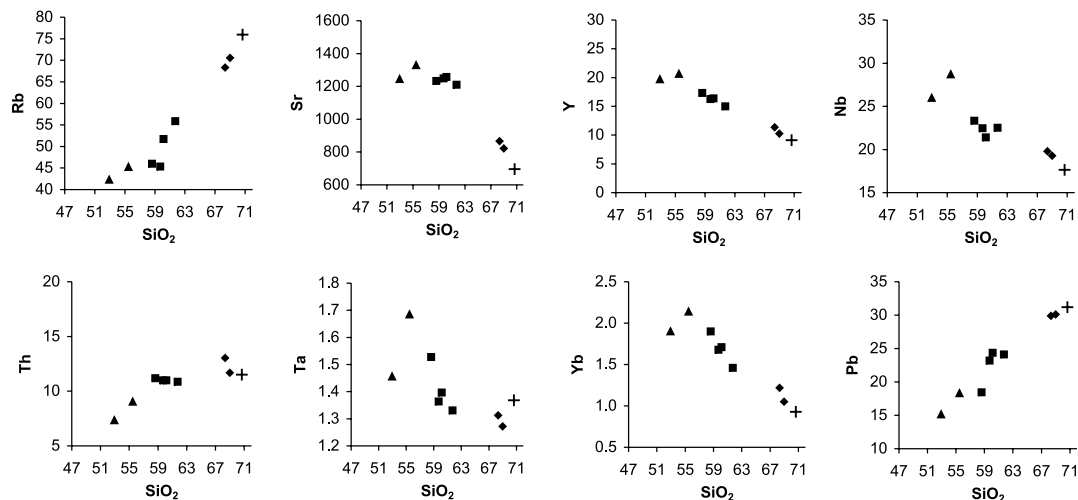


Fig. 8. Harker variation diagrams (SiO_2 vs selected trace elements) for Balkuyumcu volcanic rocks. Symbols same as in Fig. 5.

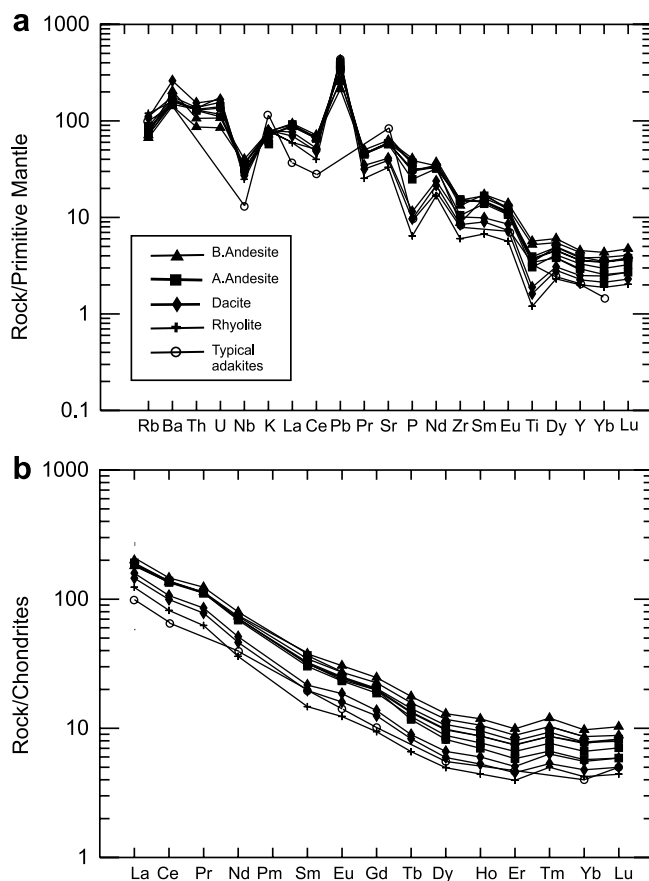


Fig. 9. (a) Primitive mantle and (b) Chondrite-normalized spider plots (after Sun and McDonough, 1989; Nakamura, 1974, respectively) of selected samples from the Balkuyumcu region (typical adakite data are from Defant et al., 1992).

crust is another possibility regarding formation of these adakite-like rocks. Partial melting resulting from thickened lower crust, with garnet $\pm$ amphibole as the residual phase and loss of plagioclase in the source, could form ADR group rocks that would have high Sr/Y, La/Yb ratios

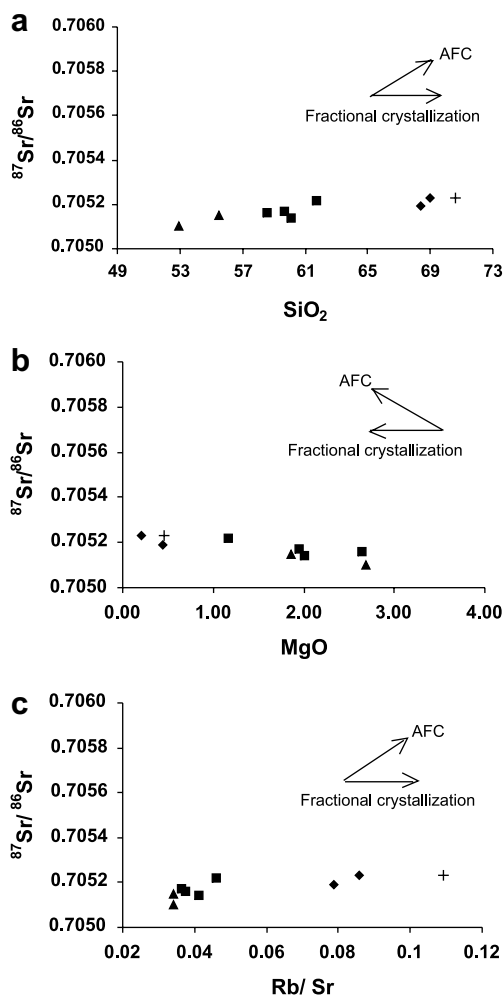


Fig. 10. Diagrams of (a) $^{87}\text{Sr}/^{86}\text{Sr}$ – SiO_2 , (b) $^{87}\text{Sr}/^{86}\text{Sr}$ – MgO and (c) $^{87}\text{Sr}/^{86}\text{Sr}$ – Rb/Sr . Symbols as in Fig. 5.

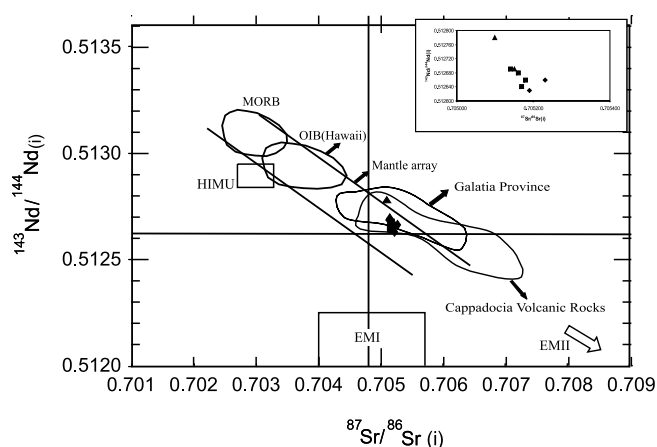


Fig. 11. $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$ diagram of different volcanic environments and of Balkuyumcu volcanic rocks (references from Chen and Frey, 1985; Temel et al., 1998; Wilson et al., 1997; HIMU, EMI, EMII from Zindler and Hart, 1986). Symbols same as in Fig. 5.

and low MgO , $\text{Mg\#}$, Y and Yb concentrations. Diagrams for determination of effective processes after partial melting of lower crust as a probable source for ADR group rocks,

display clear trends of fractional crystallization. The effect of AFC on the ADR group seems to be very weak (see Fig. 10). The similarity between multi-element abundance patterns (Fig. 9a and b) and Sr/Nd ratios (Fig. 11) for BA and ADR group rocks are interpreted as a clear indication of a common parental magma that was subjected to different differentiation processes during ascent.

6.2. The source of the magma

It is thought that ADR group rocks formed from thickening of mafic lower crust (underplated basaltic lower crust) or partial melting of delaminated lower continental crust after collision. Low MgO contents and $\text{Mg\#}$ for rocks in this group are similar to the experimental melts of Rapp and Watson (1995). This also supports a lower crustal source and less interaction with mantle peridotite. Therefore, a fractional crystallization of magma formed by partial melting of thickened and eclogitized lower continental crust with negligible interaction with mantle rocks, appear to be a most plausible generation model for adakite-like rocks of the Balkuyumcu region. On the other hand, higher contents of MgO and $\text{Mg\#}$ indicate that BA group rocks seem to have been derived by partial melting of delaminated lower continental crust. Limited interaction of this magma occurred with mantle peridotite during ascent. Fractional crystallization was not a major petrogenetic process for BA group rocks.

7. Conclusions

Balkuyumcu volcanic rocks constitute two distinct groups (BA and ADR) exhibiting calc-alkaline and adakite-like characteristics. These volcanic rocks were emplaced during the Early Miocene (20–22 Ma) within the Izmir–Ankara suture zone, after collision between the Pontides and the Anatolide–Tauride platforms. The BA group rocks have lower SiO_2 , higher MgO , $\text{Mg\#}$, Y and Yb contents, and lower Sr/Y and La/Yb ratios compared to ADR group rocks. These characteristics suggest that the adakite-like ADR group rocks were formed by partial melting of thickened and eclogitized lower crust after collision, followed by fractional crystallization. It is inferred that BA group rocks, with calc-alkaline characteristics, developed through melting of delaminated lower crust that had limited interaction with mantle peridotite.

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