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# Contemporaneous Late Cretaceous Calc-alkaline and Alkaline Magmatism in Central Anatolia, Turkey: Oxygen Isotope Constraints on Petrogenesis

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**Abstract:** A wide variety of rock types were produced by the latest Cretaceous magmatism in the Central Anatolian Crystalline Complex. These rocks can be divided into three distinct units: (i) calc-alkaline, (ii) subalkaline/transitional, and (iii) alkaline. The calc-alkaline rocks are mainly metaluminous (I-type) ranging from monzodiorite to granite. The subalkaline/transitional rocks are also metaluminous (I-type) ranging from monzonite to granite. The alkaline rocks are mainly peralkaline (A-type), ranging from feldspathoid-bearing monzosyenite to granite. Whole-rock oxygen isotope data from the complex have a considerable range of  $\delta^{18}\text{O}$  values between 6.5‰ and 14.8‰. Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios, and both ratios versus  $\delta^{18}\text{O}$  values diagrams show that the intrusive rocks are derived from a subduction-modified mantle and also have experienced fractional crystallisation coupled with crustal assimilation. Delamination of a thermal boundary layer, and/or slab breakoff is the likely mechanisms for the initiation of the diverse magmatism in the complex.

**Key Words:** I-type granite, A-type granite, oxygen isotope, Kaman-Kırşehir region, central Anatolia, Turkey

## Orta Anadolu'da Eş zamanlı Geç Kretase Kalkalken ve Alkalen Magmatizma (Türkiye): Petrojenizde Oksijen İzotop Kısıtlamaları

**Özet:** Orta Anadolu Kristalen Kompleksi içerisinde yeralan farklı türdeki kayaç tipleri geç Kretase magmatizması ile üretilmiştir. Bu kayaçlar üç farklı birime ayırt edilmiştir: (i) kalkalkalen, (ii) yarıalkalen/geçişli, ve (iii) alkalen. Kalkalkalen kayaçlar genelde metalüminüs (I-tip) olup, bileşimleri monzodiyoritden granite kadar değişir. Yarıalkalen/geçişli kayaçlar da metalüminüs (I-tip) olup, bileşimleri monzonitden granite kadar değişir. Alkalen kayaçlar genelde peralkalen (A-tip) olup, bileşimleri feldispatoyidli monzosiyenitden granite kadar değişir. Kompleksdeki tüm kaya oksijen izotop verileri 6.5‰ ve 14.8‰ arasında önemli oranlardaki  $\delta^{18}\text{O}$  değerlerine sahiptir. İlkel  $^{87}\text{Sr}/^{86}\text{Sr}$ - $^{143}\text{Nd}/^{144}\text{Nd}$  oranları, ve her iki oran- $\delta^{18}\text{O}$  diyagramları göstermektedir ki intrüvizif kayaçlar dalma-batma ile değişikliğe uğramış mantodan türemiş ve ayrıca fraksiyonel kristalleşme ve kabuksal kirlenme geçirmiştir. Kompleks de farklı magmatizmaların başlangıcı için uygun mekanizmalar ya termal sınır tabakasının delaminasyonu ya da dalmakta olan levhanın (kırılıp?) yok edilmesidir (slab breakoff).

**Anahtar Sözcükler:** I-tipi granit, A-tipi granit, oksijen izotop, Kaman-Kırşehir bölgesi, Orta Anadolu, Türkiye

## Introduction

The Alpine-Mediterranean region is one of the most complex geodynamic settings on Earth. In this

region, subduction, collision and extension have occurred, associated with the formation of a wide variety of igneous rocks during pre-Tertiary, Tertiary

(subject of this study) and Quaternary times (Şengör & Yılmaz 1981). The large compositional diversity is caused by (1) different source compositions, (2) variable melting conditions, (3) complex chemical and physical interactions between mafic and felsic magmas, and (4) crustal contamination. Interpretation of results from petrogenetic studies in this region not only provides constraints on the geodynamic processes, but also reveals changes in magma source regions. One of the principal features of collision-related magmatism is its subduction-related geochemical characteristics, despite subduction processes having been terminated as a result of continental collision. The subduction-related signatures of these magmatic rocks are mainly attributed to metasomatism by slab-derived fluids of the mantle lithosphere prior to collision (e.g., Pearce *et al.* 1990; Platt & England 1993; Turner *et al.* 1996). Thus, the geochemical characteristics of collision-related magmatism allow the evaluation of subduction-related metasomatism of their mantle source.

Oxygen isotopes provide a tracer of subducted materials that were once part of the continental crust. The oxygen isotope composition is particularly useful because one can use simply binary mixing equations to perform calculations.

Intrusive rocks are abundant in the central Anatolian region and reveal a wide range of fabrics, mineral assemblages and compositions. The  $\delta^{18}\text{O}$  values of the central Anatolian intrusive rocks are scarce (e.g., Tatar & Boztuğ 2005; Önal *et al.* 2005; Boztuğ & Arehart 2007; Boztuğ *et al.* 2007a). In this paper, we present new oxygen isotope data from the key plutons in central Anatolia to establish the compositional differences of the magma sources and the processes responsible for the generation of this wide variety of magmas. The combination of oxygen isotope data with existing whole-rock, Sr, Nd geochemistry and geochronologic data also have been used in the paper to obtain a petrogenetic model for the diverse magmatism in the complex.

## Geological Background

The Central Anatolian Crystalline Complex is made up of several metamorphic massifs (Akdağmadeni, Kırşehir, Niğde), numerous granitic to syenitic

plutons and dismembered ophiolites, and Tertiary volcanic and sedimentary rocks that unconformably overlie the crystalline rocks (Göncüoğlu *et al.* 1991) (Figure 1). The massifs constitute the nucleus of the complex and consist of gneisses, schists, amphibolites and marbles displaying different *P-T-t* trajectories (e.g., Whitney *et al.* 2001). Studies concerning the ages of the main metamorphic events suggest a Late Cretaceous age (Late Campanian–Early Maastrichtian) (Whitney *et al.* 2003; Whitney & Hamilton 2004).

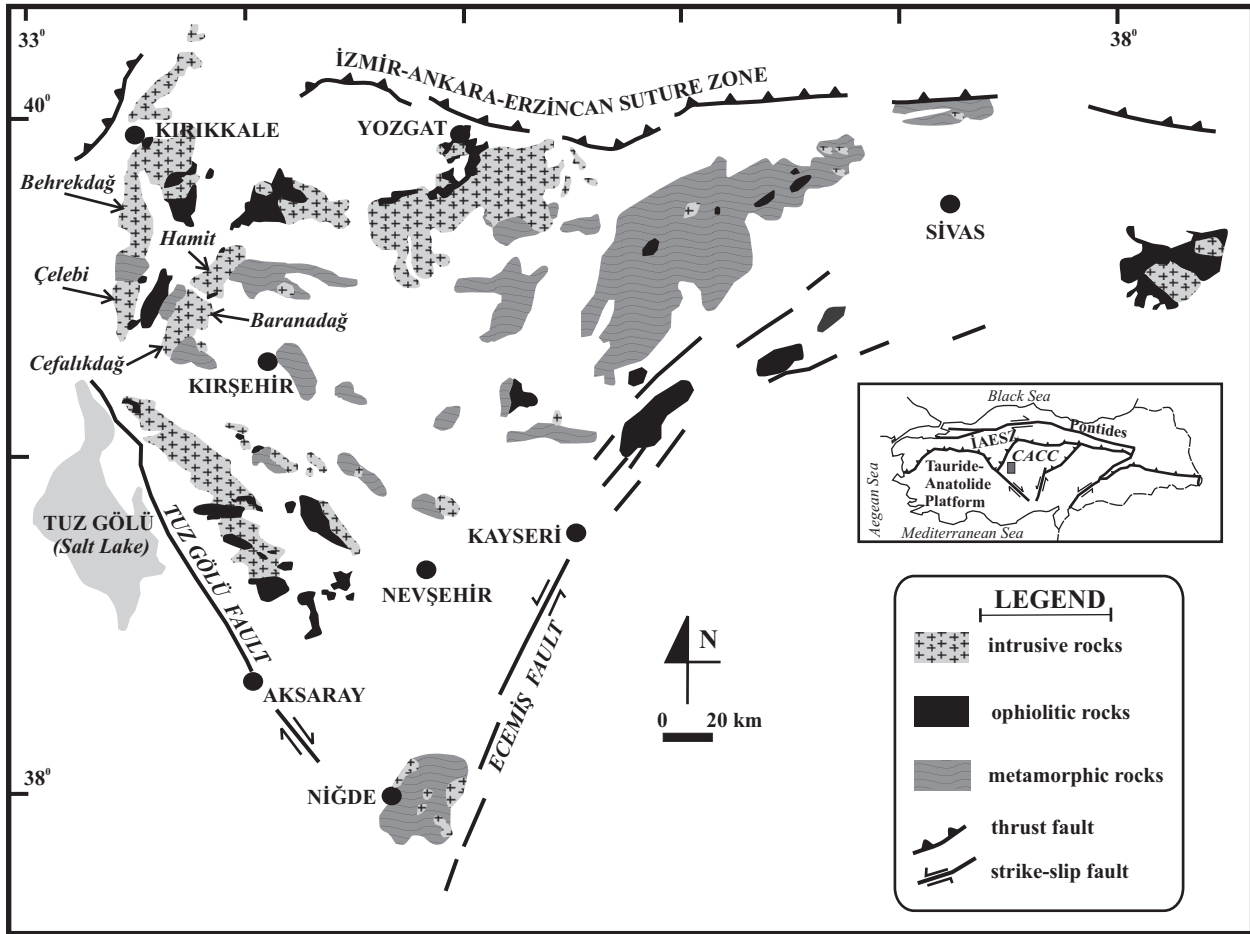
Ophiolitic rocks occur in thrust sheets over the massifs and represent dismembered remnants of the Neo-Tethyan oceanic lithosphere. Ophiolitic assemblages in the eastern part of the complex (Figure 1) are composed mainly of serpentinised peridotites with a significant listwaenite occurrence along their sheared contacts with the metamorphic massifs (e.g., Boztuğ *et al.* 1997), whereas those exposed in the west consist essentially of gabbro, diabase and individual basaltic dykes (e.g., Yalınız & Göncüoğlu 1998). Most ophiolitic rocks are Late Cretaceous (excluding metamorphosed equivalents) and of supra-subduction type, derived from the closure of the northern branch of the Neo-Tethyan Ocean (e.g. Yalınız *et al.* 1996).

Although the crystallisation ages for the central Anatolian intrusive rocks are still debated, radiogenic age determinations mainly indicate Late Cretaceous–Palaeocene ages (e.g., Whitney *et al.* 2003; İlbeyli *et al.* 2004; Köksal *et al.* 2004; Boztuğ & Jonckheere 2007; Boztuğ *et al.* 2007b; Boztuğ & Harlavan 2008; Boztuğ *et al.* 2009a, b).

## Petrology and Petrochemistry

Summaries of the field, petrographic, mineralogical and geochemical characteristics of the intrusive rocks from the Central Anatolian Crystalline Complex are presented in Table 1. The magmatic activity in the complex began during the Late Cretaceous and created both calc-alkaline and alkaline products (e.g., İlbeyli 2004, 2005; İlbeyli *et al.* 2004; Boztuğ & Arehart 2007) (Figure 2) (Table 1).

Samples from the Behrekdağ, Cefalıkdağ, and Çelebi intrusions have been chosen as



**Figure 1.** Geological setting of the Central Anatolian Crystalline Complex (modified from Bingöl 1989). Abbreviations: CACC– Central Anatolian Crystalline Complex, İAESZ– İzmir-Ankara-Erzincan Suture Zone.

representatives of the calc-alkaline rocks, samples from the Baranadağ intrusion are representative of the subalkaline/transitional rocks and samples from the Hamit intrusion are representative of the alkaline rocks (Figure 1). Details of the geological setting, mineralogical and geochemical characteristics and geochronological data of these intrusive rocks can be found in İlbeylı (2004, 2005) and İlbeylı *et al.* (2004), and are summarised in Table 1.

### Analytical Methods

Ten samples were selected for oxygen isotope analyses. Inclusions such as mafic enclaves and xenoliths were removed from the samples. Oxygen isotope ratios were measured at the Scottish

Universities Environment and Research Centre, United Kingdom. Oxygen was extracted by reacting 1–2 mg of sample with purified chlorine trifluoride in a laser fluorination system, based on Sharp (1990). The oxygen was converted to CO<sub>2</sub> by reaction on a hot graphite rod, and its isotopic composition was analysed on a VG PRISM III mass spectrometer. All oxygen ratios are in the standard per mil notation relative to VSMOW (Vienna Standard Mean Ocean Water). Multiple analyses of NBS 28 reference sample quartz give a mean value of 9.6‰. An accepted value for this reference sample is 9.84‰ (Coplen *et al.* 1983). Precision estimated through regular analysis of internal quartz standard (SES at 10.2‰) was 0.2‰ (1σ).

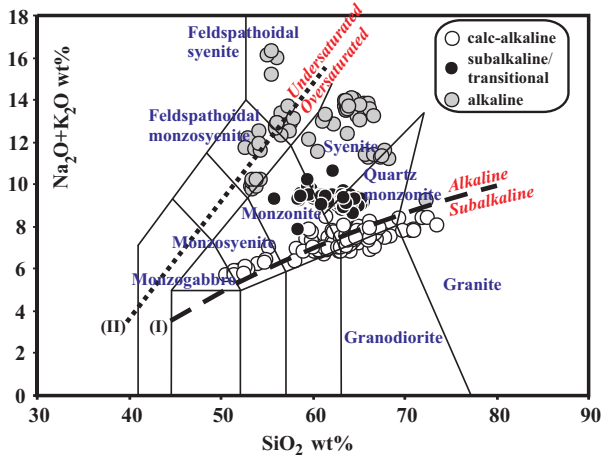
Table 1. Classification of the central Anatolian intrusive rocks on the basis of their field, petrography, mineralogy and major element geochemistry.

Pluton	Behrekdağ, Cefalıkdag, Çelebi	Baranadağ	Hamit
Age	Late Cretaceous to Palaeocene	Late Cretaceous to Palaeocene	Late Cretaceous to Palaeocene
Mineral composition	Ksp+Pl (albite to andesine) +Qtz+Amp (edenite, magnesio-hornblende)+Bt±Cpx (salite)	Ksp+Pl (oligoclase to andesine) +Qtz+Amp (edenite, magnesio-hastingsite)+Bt±Cpx (salite)	Ksp+Pl (albite to labradorite) ±Qtz±Amp (edenite, hastingsite) ±Bt±Cpx (salite)±Ne±Grt (melanite)
Grain size	fine- through medium- to porphyritic with feldspar (up to 15 cm across)	coarse- to porphyritic with feldspar (up to 5 cm across)	fine- to porphyritic with alkali feldspar (up to 3.5 cm across)
Texture	allotriomorphic to porphyritic	allotriomorphic to porphyritic	hypidiomorphic to porphyritic
Accessory phases	titanite, opaques, apatite, zircon, allanite	titanite, opaques, apatite, zircon, allanite	titanite, opaques, apatite, zircon, fluorite
Alteration	sericite, chlorite, calcite, epidote	sericite, chlorite, calcite	cancrinite, gieseckite, garnet, sericite, chlorite, epidote
Rock type (see Figure 2)	mzdi, qmzdi, mz, qmz, grd, gr	mz, qmz	feldspathoid-bearing (nepheline, pseudoleucite) sy ( <i>the least silicic</i> ); feldspathoid-free (mz, qmz, sy, ksp <sub>sy</sub> , qsy) ( <i>the most silicic</i> )
K <sub>2</sub> O composition	high-K to shoshonite	high-K to shoshonite	high-K to shoshonite
Shand's index	metaluminous / peraluminous	metaluminous	mostly peralkaline

Table 1. Continued.

Pluton	Behrekdağ, Cefalıkdağ, Çelebi	Baranadağ	Hamit
<b>Alkali-lime index</b>	calc-alkalic	alkali-calcic	alkalic
<b>Rare earth element patterns (Chondrite-normalised, Boynton 1984)</b>	all LREE-enriched with small to moderate negative Eu anomalies	all LREE-enriched with small to moderate negative Eu anomalies	all LREE-enriched with small to moderate negative Eu anomalies
<b>Multi-element patterns (ORG-normalised, Pearce <i>et al.</i> 1984)</b>	enrichment in the LILE (K, Rb, Ba, Th) and the LREE (Ce) relative to the HFSE (Ta, Nb, Hf, Zr, Sm, Y, Yb).	enrichment in the LILE and the LREE relative to the HFSE	enrichment in the LILE and the LREE relative to the HFSE
<b>Tectonic discrimination diagrams (Pearce <i>et al.</i> 1984)</b>	fall into the VAG (volcanic arc granite) and syn-COLG (syn-collisional granite) fields	plot between the VAG and syn-COLG and WPG (within plate granite) fields.	fall in the WPG field
<b>Granite type</b>	<b>CALC-ALKALINE</b> I- / S- (the least silicic-I) (the most silicics)	<b>SUBALKALINE / TRANSITIONAL</b> I- / A-	<b>ALKALINE</b> A- (the most silicic-S)
<b>References</b>	İlbeyli <i>et al.</i> (2004) İlbeyli (2005)	İlbeyli <i>et al.</i> (2004) İlbeyli (2005)	İlbeyli <i>et al.</i> (2004) İlbeyli (2004, 2005)

Abbreviations: Ksp- alkali feldspar, Pl- plagioclase, Qtz- quartz, Amp- amphibole, Bt- biotite, Cpx- clinopyroxene, Ne- nepheline, Grt- garnet; mzd- monzodiorite, qmzd- quartz monzodiorite, mz- monzonite, qmz- quartz monzonite, grd- granodiorite, gr- granite, sy- syenite, kpsy- alkali feldspar syenite, qsy- quartz syenite.



**Figure 2.** Classification of the central Anatolian plutonic rocks (Middlemost 1994) using the total alkali-silica diagram. Line (I) separates the alkaline and subalkaline field of Miyashiro (1978) and line (II) separates the alkaline oversaturated and undersaturated series (Giret & Lameyre 1980).

The full data set is given in Table 2. Major, trace element and radiogenic isotope data of these rock samples are also presented in Table 3.

### Oxygen Isotope Geochemistry

Whole-rock oxygen isotope data from the Central Anatolian Crystalline Complex have a large range of  $\delta^{18}\text{O}$  values between 6.5‰ and 14.8‰ (Figure 3)

(Table 2). The calc-alkaline rocks have  $\delta^{18}\text{O}$  values ranging from 8.4‰ to 11.1‰ (Figure 3). The subalkaline/transitional rock has only one analysis, which has a  $\delta^{18}\text{O}$  value of 8.3‰ (Figure 3).

The lowest  $\delta^{18}\text{O}$  (6.5‰) value is represented by the feldspathoid-bearing rock (sample N33) and the highest value (12.1‰) belongs to the feldspathoid-free rock (sample N290) of the alkaline samples (Figure 3) (Table 2). A metasedimentary rock (sample C-2) from central Anatolia has a  $\delta^{18}\text{O}$  value 14.8‰. Typical oxygen isotopic compositions for MORB (mid ocean ridge basalt) are between 5.2‰ and 6.4‰ (Eiler *et al.* 2000). I-type granitoids have  $\delta^{18}\text{O}$  values of 6 to 10‰, whereas S-type granitoids display higher  $\delta^{18}\text{O}$  values of 10 to 15‰ (Harris *et al.* 1997) and A-type granitoids have  $\delta^{18}\text{O}$  values of 6 to 8‰ (Whalen *et al.* 1996).

Oxygen isotope ratios were analysed on mineral separates (e.g., zircon) in preference to whole-rock samples because the latter is susceptible to changes in  $\delta^{18}\text{O}$  values resulted by later hydrothermal alteration (e.g., Valley *et al.* 1994; King *et al.* 1998; Monani & Valley 2001). Although alteration at surface temperatures causes an increase in  $\delta^{18}\text{O}$  values, meteoric alteration in continental systems lowers  $\delta^{18}\text{O}$  values (e.g., Gregory & Criss 1986; Larson & Taylor 1986; Criss *et al.* 1987; Taylor 1997; Jung *et al.* 2007).

**Table 2.** O isotope data of the intrusive rocks from the Central Anatolian Crystalline Complex.  $\delta^{18}\text{O}$  values reported in per mil relative to VSMOW.

Pluton / Area	Characteristics	Rock unit	Sample no	$\delta^{18}\text{O}$ , per mil
Behrekdağ	calc-alkaline	quartz monzonite	N2	10.3
Cefalıkdag	calc-alkaline	quartz monzodiorite	N78	9.4
		quartz monzonite	N20	9.9
		granite	N395	11.1
Çelebi	calc-alkaline	quartz monzonite	N75	8.4
Baranadağ	subalkaline/transitional	monzonite	N26	8.3
Hamit	alkaline	nepheline syenite	N33	6.5
		nepheline syenite	N285	7.6
		quartz syenite	N290	12.1
Central Anatolia (Kırşehir)		metasediment	C-2	14.8

**Table 3.** XRF-major element (wt%), trace element (ppm) and ICP-MS-rare earth elements (ppm) analyses of the representative samples from the central Anatolian intrusive rocks (İlbeyli 1999, 2005; İlbeyli et al. 2004).

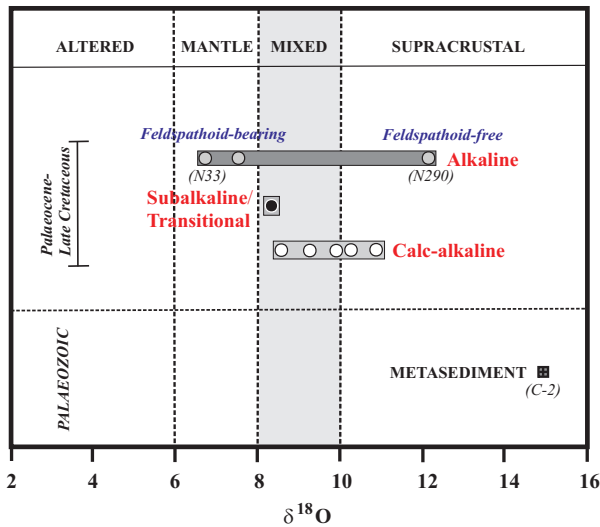
Pluton / Area Sample no Rock unit	Behrekdağ		Çefalıkdağ		Çelebi		Baranadağ		Hamit		Kırşehir		C-2 metapelite
	N2 qmz	N78 qmzd	N20 qmz	N395 gr	N75 qmz	N26 mz	N33 nesy	N285 nesy	N290 qsy	N490 metagreywacke			
SiO <sub>2</sub>	60.11	53.86	61.82	71.53	65.07	58.44	53.32	56.09	66.78	74.96	77.52		
TiO <sub>2</sub>	0.61	0.85	0.61	0.20	0.39	0.59	0.72	0.51	0.28	0.17	0.39		
Al <sub>2</sub> O <sub>3</sub>	16.49	17.70	16.36	14.37	15.81	17.62	18.09	20.42	17.32	12.52	11.21		
Fe <sub>2</sub> O <sub>3</sub>	6.04	8.22	5.77	1.98	4.34	5.42	6.49	4.44	1.79	1.61	3.87		
MnO	0.12	0.15	0.12	0.05	0.09	0.13	0.15	0.12	0.05	0.02	0.06		
MgO	2.42	3.74	2.52	0.61	1.46	1.85	2.97	1.08	0.29	0.71	2.10		
CaO	6.38	8.22	5.14	1.97	4.33	5.95	7.01	3.59	1.59	1.57	0.45		
Na <sub>2</sub> O	2.94	2.99	2.99	2.82	3.13	3.73	3.37	4.93	4.29	2.14	0.74		
K <sub>2</sub> O	3.89	3.23	4.19	5.37	4.54	5.52	6.71	7.99	7.30	5.58	2.84		
P <sub>2</sub> O <sub>5</sub>	0.18	0.27	0.19	0.06	0.14	0.24	0.42	0.25	0.04	0.03	0.07		
L.O.I	0.37	0.78	0.51	0.79	0.54	0.58	1.05	0.77	0.64	1.12	2.57		
TOTAL	99.18	99.24	99.71	98.96	99.30	99.48	99.25	99.42	99.72	99.32	99.25		
Sc	15	23	13	4	9	12	8	3	1.8	4.7	16		
Cr	28	35	22		7	5	40	21	3.0	4.6	323		
V	91	144	93	12	63	102	123	52	24.5	18.7	45		
Ni	12	16	9	2	9	14	15	5	1.4	0.9	7		
Co	13	24	14	2	10	12	13	7	10.5	2.0	85		
Cu	12	24	2		1		34	25	2.7	19.9	13		
Zn	78	95	81	38	55	91	108	96	26.7	11.9	56		
Ga	16	23	20	15	19	22	26	20	19.7	11.9	15		
Rb	132	87	142	171	185	193	226	256	368.8	261.6	135		
Sr	548	903	510	331	456	911	1294	1391	240.4	84.5	50		
Y	26	26	30	1.9	28	36	40	33	40.4	20.7	28		
Zr	177	187	176	127	145	277	369	375	316.1	124.2	165		
Nb	14	18	16	10	14	26	28	35	35.2	13.5	11		
Ba	1042	1435	961	686	788	933	1248	1345	308.8	662.1	413		
La	56.60	43.64	59.18	25.27	49.86	89.24	112.68	103.84	117.64	25.51	28.67		
Ce	95.69	82.10	103.27	45.19	91.06	157.48	208.86	160.73	177.54	47.66	56.06		



Table 3. Continued.

Sample no Rock unit	Behrekdağ		Cefalikdağ		Çelebi		Baranadağ		Hamit		Kırşehir		
	N2 qmz	N78 qmzd	N20 qmz	N395 gr	N75 qmz	N26 mz	N33 nesy	N285 nesy	N290 qsy	N490 metagreywacke	C-2 metapelite		
Pr	10.59	10.04	12.05	5.00	10.53	17.75	23.03	19.71	15.80	5.60	6.90		
Nd	35.59	38.40	42.19	16.50	36.35	60.12	76.77	66.56	45.68	19.98	25.98		
Sm	5.84	7.20	7.14	2.50	6.04	9.90	13.57	10.00	6.11	3.97	5.25		
Eu	1.37	1.83	1.40	0.88	1.17	2.01	2.89	2.27	1.00	0.41	0.68		
Gd	4.59	5.96	5.61	1.57	4.36	6.39	9.58	6.72	3.92	3.46	4.37		
Tb	0.73	0.85	0.88	0.22	0.69	1.01	1.00	0.86	0.62	0.60	0.77		
Dy	3.98	4.67	4.86	1.18	3.78	5.20	5.16	4.12	3.21	3.81	4.56		
Ho	0.79	0.89	0.94	0.23	0.78	0.97	0.83	0.74	0.63	0.82	0.94		
Er	2.14	2.42	2.68	0.60	2.10	2.60	2.14	1.94	1.89	2.19	2.34		
Tm	0.36	0.34	0.44	0.11	0.36	0.43	0.32	0.31	0.34	0.39	0.42		
Yb	2.18	2.14	2.74	0.68	2.31	2.64	2.25	1.92	2.27	2.41	2.62		
Lu	0.36	0.34	0.45	0.12	0.39	0.42	0.32	0.29	0.37	0.37	0.39		
Hf	5.16	5.43	5.82	3.21	4.38	6.91	7.32	7.39	7.30	3.51	4.55		
Ta	0.96	0.85	1.32	0.28	1.49	1.74	2.13	2.62	1.94	0.65	1.00		
Pb	41.74	34.08	43.19	37.72	47.55	38.69	51.51	72.67	67.57	34.23	13.04		
Th	22.34	11.17	23.23	14.88	36.89	30.19	50.91	62.00	106.99	21.40	11.06		
U	4.48	3.08	5.07	2.90	5.69	5.29	13.72	18.15	13.24	3.06	3.33		
$^{87}\text{Sr}/^{86}\text{Sr} (\pm 1\sigma)$	0.71004±11	0.70972±09	0.71002±08	0.71087±19	0.71028±35	0.70873±11	0.70875±12	0.70876±11	0.71275±09				
(meas)													
$^{87}\text{Sr}/^{86}\text{Sr}_i$	0.70923	0.70943	0.70924	0.70964	0.70900	0.70804	0.70826	0.70822	0.70838				
$\epsilon\text{Sr} (70 \text{ Ma})$	68.571	68.4	74	64.7	51.6	54.6	54	56.3					
$^{143}\text{Nd}/^{144}\text{Nd} (\pm 1\sigma)$	0.512263±4	0.512256±5	0.512295±5	0.512300±5	0.512298±5	0.512324±5	0.512349±5	0.512348±5	0.512307±5				
(meas)													
$^{143}\text{Nd}/^{144}\text{Nd}_i$	0.51220	0.51221	0.51225	0.51226	0.51225	0.51227	0.51230	0.51230	0.51223				
$\epsilon\text{Nd} (70 \text{ Ma})$	-6.3	-6.7	-5.9	-5.7	-5.5	-5.2	-4.8	-4.8	-5.5				

Abbreviations: qmz– quartz monzonite, qmzd– quartz monzodiorite, gr– granite, mz– monzonite, nes– nepheline syenite, qsy– quartz syenite.



**Figure 3.**  $\delta^{18}\text{O}$  values of the intrusive rocks and crust (metasediment) from central Anatolia. Dividing lines between altered, mantle, mixed and supracrustal rocks are taken from Whalen *et al.* (1996).

The values obtained for the central Anatolian intrusive rocks may represent primary values or may result from hydrothermal alteration that changes  $\delta^{18}\text{O}$  values. Field evidence and petrographic observations of the central Anatolian intrusive rocks suggest that hydrous alteration was limited. Since the representative intrusive rocks have fresh and unaltered appearances in the field, most whole-rock loss-on-ignition (LOI) values are less than 1 wt%, and only one sample (N33) has a value of 1.05 wt% LOI (Figure 4) (Table 4). This could indicate limited amounts of volatiles in the samples.

Hydrous alteration under oxidising conditions results in enrichment of the whole-rock  $\text{Fe}^{3+}/\text{Fe}^{2+}$  ratio (Jung *et al.* 2007). The  $\text{Fe}^{3+}/\text{Fe}^{2+}$  ratios also correlate positively with the LOI values during these conditions (Jung *et al.* 2007). The  $\text{Fe}^{3+}/\text{Fe}^{2+}$  ratio vs LOI,  $\text{Fe}^{3+}/\text{Fe}^{2+}$  ratio vs  $\delta^{18}\text{O}$  and  $\delta^{18}\text{O}$  vs LOI may provide an indication of the extent to which such alteration influenced the stable isotope chemistry of the rocks analysed (Figure 4). There is a lack of positive correlation between  $\text{Fe}^{3+}/\text{Fe}^{2+}$  and LOI for the intrusive rocks (Figure 4a), indicating that they are not altered. The  $\text{Fe}^{3+}/\text{Fe}^{2+}$  ratios vs  $\delta^{18}\text{O}$  values (Figure 4b) show that there is also no correlation between  $\text{Fe}^{3+}/\text{Fe}^{2+}$  and  $\delta^{18}\text{O}$ . The  $\delta^{18}\text{O}$  values display

negative trends with LOI for the calc-alkaline and alkaline rocks (Figure 4c). Although some meteoric alteration is probable in the alkaline rocks, the correlations (Figure 4) could suggest that the alteration was not important to any considerable extent. The positive correlation of  $\delta^{18}\text{O}$  values with initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios (largely insensitive with respect to hydrous alteration; Jung *et al.* 2007) for the intrusive rocks reveals that they are not altered (see below Figure 7: inset figures). Therefore we can assume that the  $\delta^{18}\text{O}$  values of the intrusive rocks could be primary.

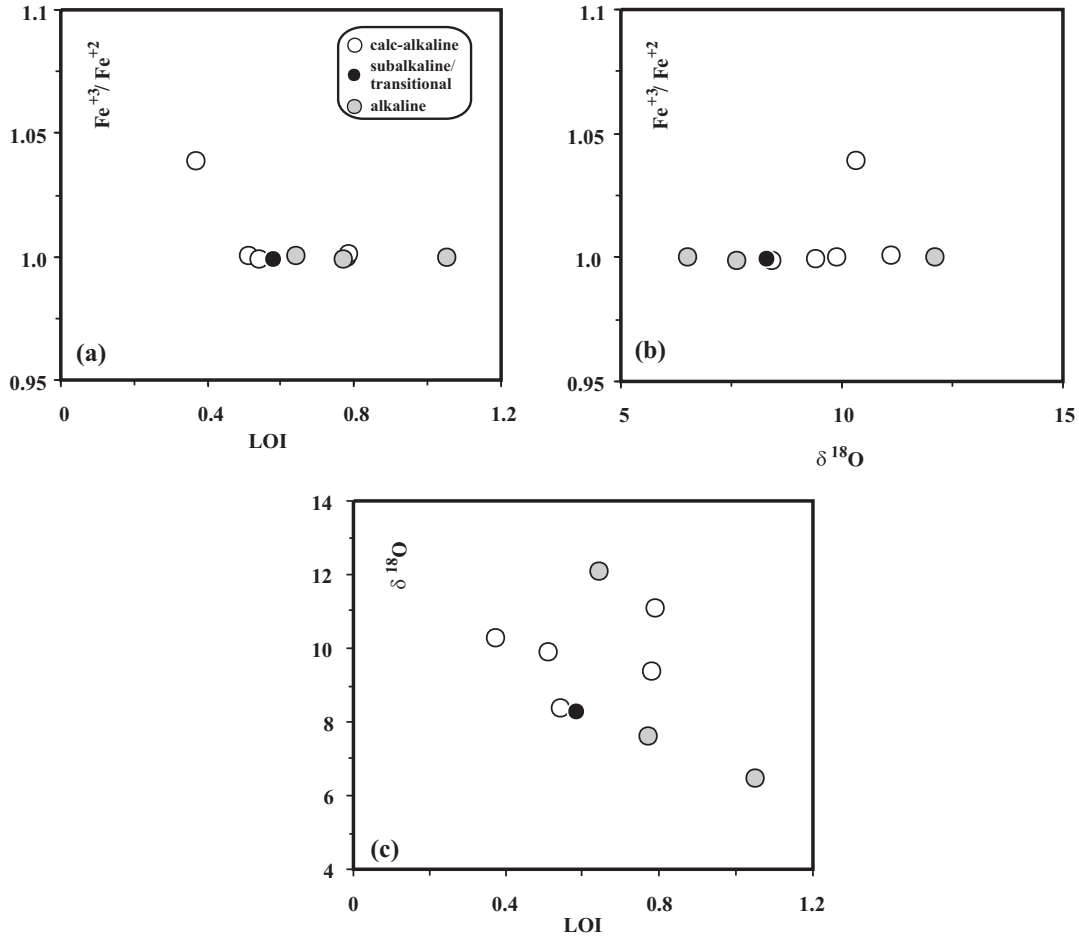
## Discussion

The central Anatolian intrusive rocks are enriched in LILE relative to HFSE (İlbeyli *et al.* 2004). In addition, they are radiogenic in terms of Sr, and unradiogenic in terms of Nd isotope ratios (İlbeyli *et al.* 2004). These features could be related to combined crustal assimilation and fractional crystallisation (AFC) (e.g., Hildreth & Moorbath 1988) or to mantle source enrichment by recycling of crustal material (e.g., Gill 1981; Sun & McDonough 1989).

Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the plutonic rocks are plotted against initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios (Figure 5) to reveal AFC or source enrichment processes in the origin of central Anatolian intrusive rocks. All rock types plot in the high initial  $^{87}\text{Sr}/^{86}\text{Sr}$  and low initial  $^{143}\text{Nd}/^{144}\text{Nd}$  quadrant in the range characteristic of continental crustal sources or mantle sources with large continental crustal components (Figure 5a).

Calculation of AFC curves are model-dependent, since they require presumptions about the fractionating mineral assemblages and mineral-melt partition coefficients, the concentrations of the chosen trace elements in the starting melt and the contaminant(s) as well as the ratio of assimilation to fractional crystallisation (Jung *et al.* 2004).

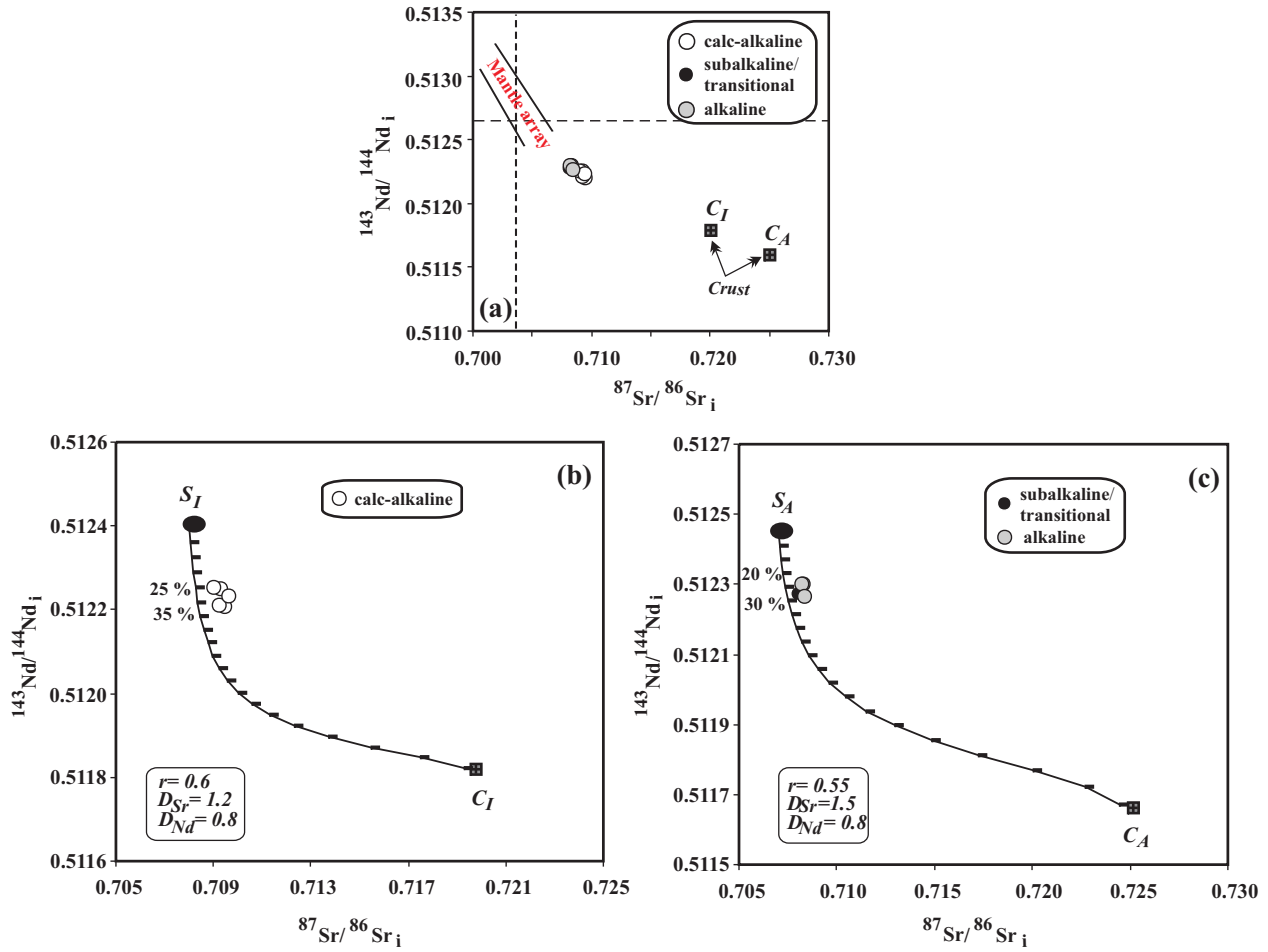
Estimation of the compositions of possible source component(s) and also crustal contaminant(s) is a very difficult problem for the central Anatolian intrusive rocks, as there are no rock samples that can be taken as representative of a parental magma(s) (see Discussion section; İlbeyli 2005). Therefore, the chosen values for the parental magmas are close to



**Figure 4.** (a) Fe<sup>3+</sup>/Fe<sup>2+</sup> versus LOI; (b) Fe<sup>3+</sup>/Fe<sup>2+</sup> versus δ<sup>18</sup>O; and (c) δ<sup>18</sup>O versus LOI diagrams for the central Anatolian intrusive rocks.

**Table 4.** Loss-on-ignition (LOI), Fe<sub>2</sub>O<sub>3</sub> and FeO values and Fe<sup>3+</sup>/Fe<sup>2+</sup> ratios of the intrusive rocks from the Central Anatolian Crystalline Complex.

Pluton	Sample no	LOI (wt%)	Fe <sub>2</sub> O <sub>3</sub> (total) (wt%)	FeO (wt%)	Fe <sup>3+</sup> / Fe <sup>2+</sup>
Behrekdağ	N2	0.37	6.04	5.23	1.04
Cefalıkdağ	N78	0.78	8.22	7.40	0.99
	N20	0.51	5.77	5.19	1.00
	N395	0.79	1.98	1.78	1.00
Çelebi	N75	0.54	4.34	3.91	0.99
Baranadağ	N26	0.58	5.42	4.88	1.00
Hamit	N33	1.05	6.49	5.84	1.00
	N285	0.77	4.44	4.00	1.00
	N290	0.64	1.79	1.61	0.99



**Figure 5.** (a)  $^{143}\text{Nd}/^{144}\text{Nd}_i$  versus  $^{87}\text{Sr}/^{86}\text{Sr}_i$  diagram for the central Anatolian plutonic rocks and hypothetical basement samples. The mantle array is after DePaolo (1988); (b)  $^{143}\text{Nd}/^{144}\text{Nd}_i$  versus  $^{87}\text{Sr}/^{86}\text{Sr}_i$  plot showing AFC model for the calc-alkaline intrusive rocks; and (c)  $^{143}\text{Nd}/^{144}\text{Nd}_i$  versus  $^{87}\text{Sr}/^{86}\text{Sr}_i$  plot displaying AFC model for the subalkaline/transitional and alkaline intrusive rocks. Tick marks on each curve represent 5% crystallisation intervals (F). In this model, crystallisation ends after F reaches 0.05. Tick marks on the AFC curves represent the ratio of the final mass of magma to the initial mass of magma. Abbreviations: D- the bulk partition coefficient, F- the fraction of melt remaining, r- the ratio of the rate of assimilation to the rate of fractional crystallisation,  $S_I$ - source for the calc-alkaline rocks,  $C_I$ - crust for the calc-alkaline rocks,  $S_A$ - source for the subalkaline/transitional and alkaline rocks,  $C_A$ - crust for the subalkaline/transitional and alkaline rocks. Assumed mantle and crustal end-member compositions are given in Table 5.

those of the least acidic samples for the calc-alkaline (source I-  $S_I$ ) and alkaline intrusive rocks (source A-  $S_A$ ) (Table 5). Two metamorphic samples (C-2 and N490) from the Central Anatolian Crystalline Complex are used as the crustal components [crust I-  $C_I$  (sample no. C-2) for the calc-alkaline samples and crust A-  $C_A$  (sample no. N490) for the alkaline samples] (Figure 5, Table 5). Unfortunately, there is also insufficient Sr-Nd isotope data to define crustal

end-member compositions of the complex, so possible Sr and Nd isotope compositions for C-2 and N490 are assumed (Table 5). O isotope composition is available only for C-2 (Table 2).

The AFC modelling has been conducted using the AFC equations of DePaolo (1981), the bulk partition coefficient (D) and the ratio of the rate of assimilation to the rate of fractional crystallisation

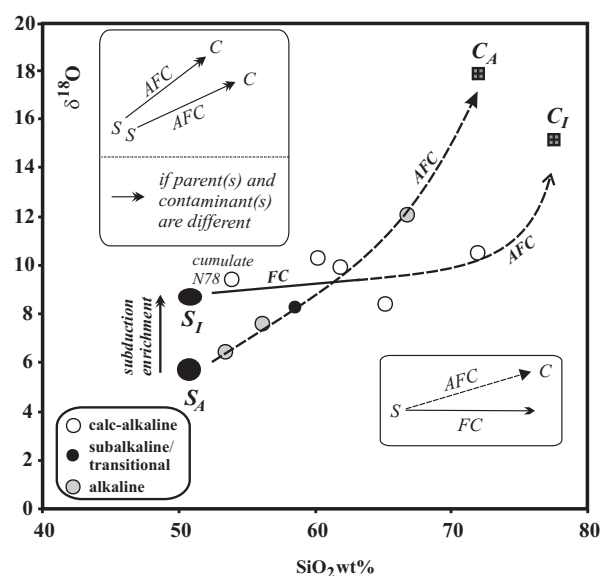
**Table 5.** Table showing possible parental magmas and contaminants for the central Anatolian intrusive rocks used in the petrogenetic modelling.

	Source I ( $S_I$ ) for the calc-alkaline rocks	Crust I ( $C_I$ ) for the calc-alkaline rocks (sample no: C-2)	Source A ( $S_A$ ) for the subalkaline/transitional & alkaline rocks	Crust A ( $C_A$ ) for the subalkaline/transitional & alkaline rocks (sample no: N490)
$^{87}\text{Sr}/^{86}\text{Sr}_i$	0.7080	0.7200	0.7070	0.7250
Sr ppm	1000	50	1400	85
$^{143}\text{Nd}/^{144}\text{Nd}_i$	0.51240	0.51180	0.51245	0.51160
Nd ppm	30	26	25	19
$\delta^{18}\text{O}$ per mil	7	14.8	5.7	18

( $r$ ) presented in Figure 5. All models use  $D_{\text{Sr}}$  of 1.2 (for the calc-alkaline rocks) – 1.5 (for the alkaline rocks) and  $D_{\text{Nd}}$  of 0.8 (for both rock types), values broadly consistent with the observed geochemical behaviour of Sr and Nd in these rocks. The modelled AFC mixing curves pass close to the plutonic rocks (Figure 5b, c). Between ~25% and ~35% upper crustal contaminant is required in the AFC modelling for the calc-alkaline rocks, whereas between ~22% and ~30% upper crustal contaminant is required in the AFC modelling for the alkaline rocks (Figure 5b, c). Such rates make assimilation acceptable because at upper crustal levels higher rates would not be possible (DePaolo 1981).

In terms of determining source(s) of contamination, oxygen isotopes also provide a potentially powerful tool because many components that can be present in the crust have differing  $\delta^{18}\text{O}$  values (e.g., James 1981; Bacon *et al.* 1989; Feeley & Sharp 1995; Macpherson *et al.* 1998). The upper portion of ocean crust is shifted in  $\delta^{18}\text{O}/\delta^{16}\text{O}$  because of low-temperature hydrothermal alteration and also the presence of high  $\delta^{18}\text{O}$  sediments, and thus metasomatising fluids are high in  $\delta^{18}\text{O}$  (Eiler *et al.* 1998; Eiler 2001).  $\delta^{18}\text{O}$  values can also be shifted by assimilation or remelting of altered igneous rocks (Valley *et al.* 2005).

The  $\delta^{18}\text{O}$  values of the central Anatolian plutonic rocks are plotted against  $\text{SiO}_2$  (Figure 6). The intrusive rocks align along two different trends starting from two different hypothetical parental magma compositions (i.e. source  $S_I$  and source  $S_A$ )



**Figure 6.**  $\delta^{18}\text{O}$  values versus silica plot for the central Anatolian intrusive rocks. Abbreviations: S– source, C– crust,  $S_I$ – source for the calc-alkaline rocks,  $C_I$ – crust for the calc-alkaline rocks,  $S_A$ – source for the subalkaline/transitional and alkaline rocks,  $C_A$ – crust for the subalkaline/transitional and alkaline rocks, FC– fractional crystallisation, AFC– fractional crystallisation coupled with crustal assimilation.

and, crossing from each other, heading toward two separate crustal compositions (i.e. crust  $C_I$  and crust  $C_A$ ) (Figure 6). Two contrasting groups in the central Anatolian plutonic rocks can be also displayed in initial  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios vs  $\text{SiO}_2$  diagrams (see figure 8 in İlbeyli *et al.* 2004).

The calc-alkaline rock samples are characterised by slightly higher  $\delta^{18}\text{O}$  values than the alkaline rock samples (Figure 6). The contaminants have also higher  $\delta^{18}\text{O}$  values (14.8–18‰) (Table 5) than the calc-alkaline and alkaline samples. Fractional crystallisation (FC) has little effect ( $\leq 1\%$ ) on  $\delta^{18}\text{O}$  values (Sheppard & Harris 1985), therefore oxygen isotopes are a powerful indicator of source composition and/or degree of crustal contamination. The trend for the calc-alkaline rocks indicates that the rocks have undergone mainly FC and only AFC in the latest stages. On the other hand, the  $\delta^{18}\text{O}$  values of the alkaline rock samples (including the subalkaline/transitional sample) show a well-defined positive correlation with silica (Figure 6). This indicates that the evolution of the alkaline samples is governed by AFC processes and probably also some alteration processes. The higher  $\delta^{18}\text{O}$  values of the calc-alkaline rocks suggest a mantle source which is more enriched in subduction components than the source of alkaline rocks (Figure 6).

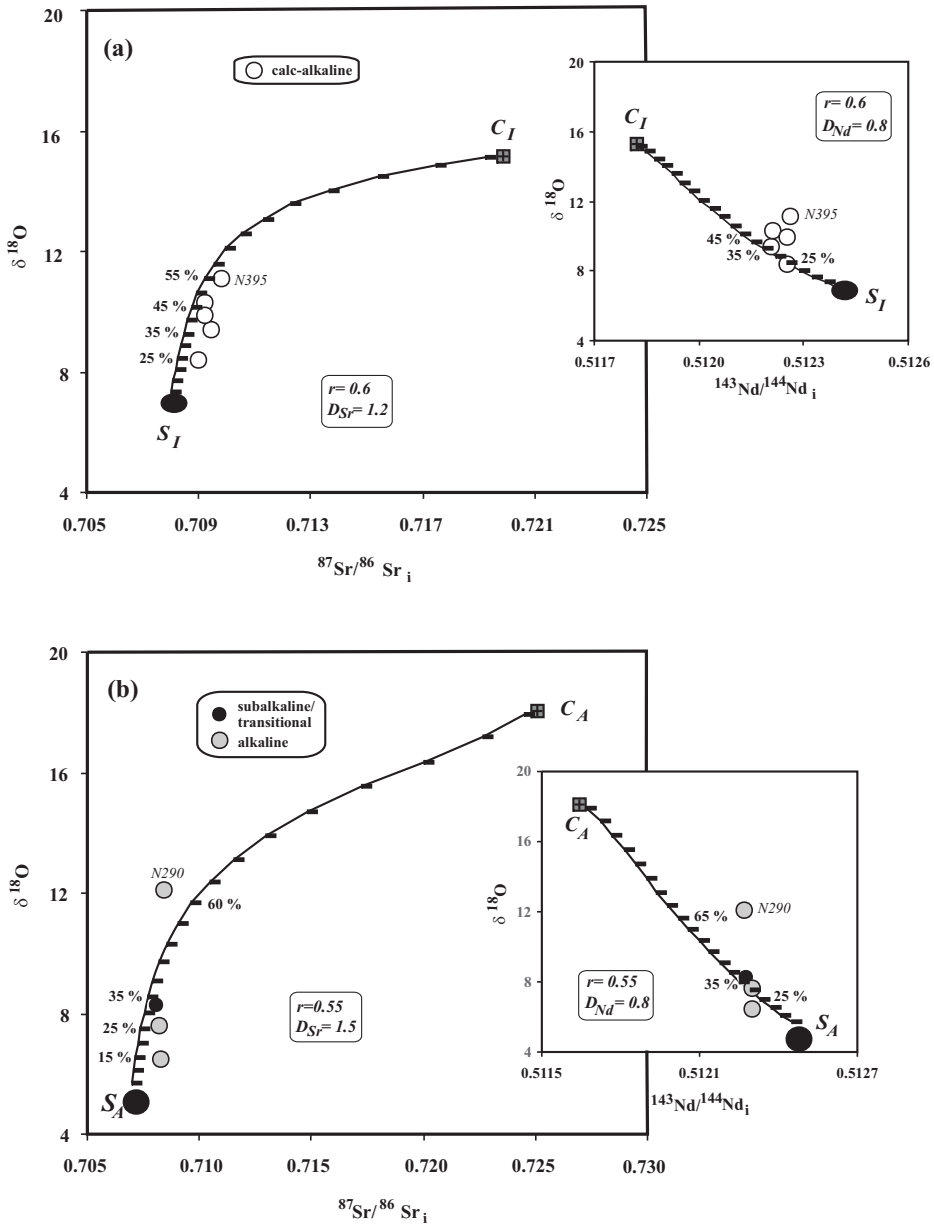
The distinction between source contamination and crustal assimilation can be identified using O-Sr isotopic modelling (e.g., James 1981; Taylor 1986; Ellam & Harmon 1990). Oxygen isotope enrichment is a sensitive indicator of crustal contamination, whereas Sr isotopes can be either sensitive or insensitive to contamination (e.g., Davidson *et al.* 1990; Ellam & Harmon 1990; Mason *et al.* 1996).

The  $\delta^{18}\text{O}$  values are plotted against initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (Figure 7) to better define the process(es) causing the formation of the two trends in Figure 6 for the central Anatolian plutonic rocks. Initial  $^{143}\text{Nd}/^{144}\text{Nd}$  vs  $\delta^{18}\text{O}$  values are also plotted in Figure 7 as inset figures. Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios increase with increasing  $\delta^{18}\text{O}$  values, whereas initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios decrease with  $\delta^{18}\text{O}$  values. We also plot theoretical trends that reflect AFC mixing models (Figure 7). The crustal material underlying the alkaline rocks is much more radiogenic in terms of Sr, and unradiogenic in terms of Nd than the one that underlies the calc-alkaline rocks (Figure 7). The calc-alkaline and alkaline samples (including one subalkaline/transitional) plot around or close to the modelled AFC trends. Between ~25% and ~55% upper crustal contaminant is required in the AFC modelling for the calc-alkaline rocks, whereas

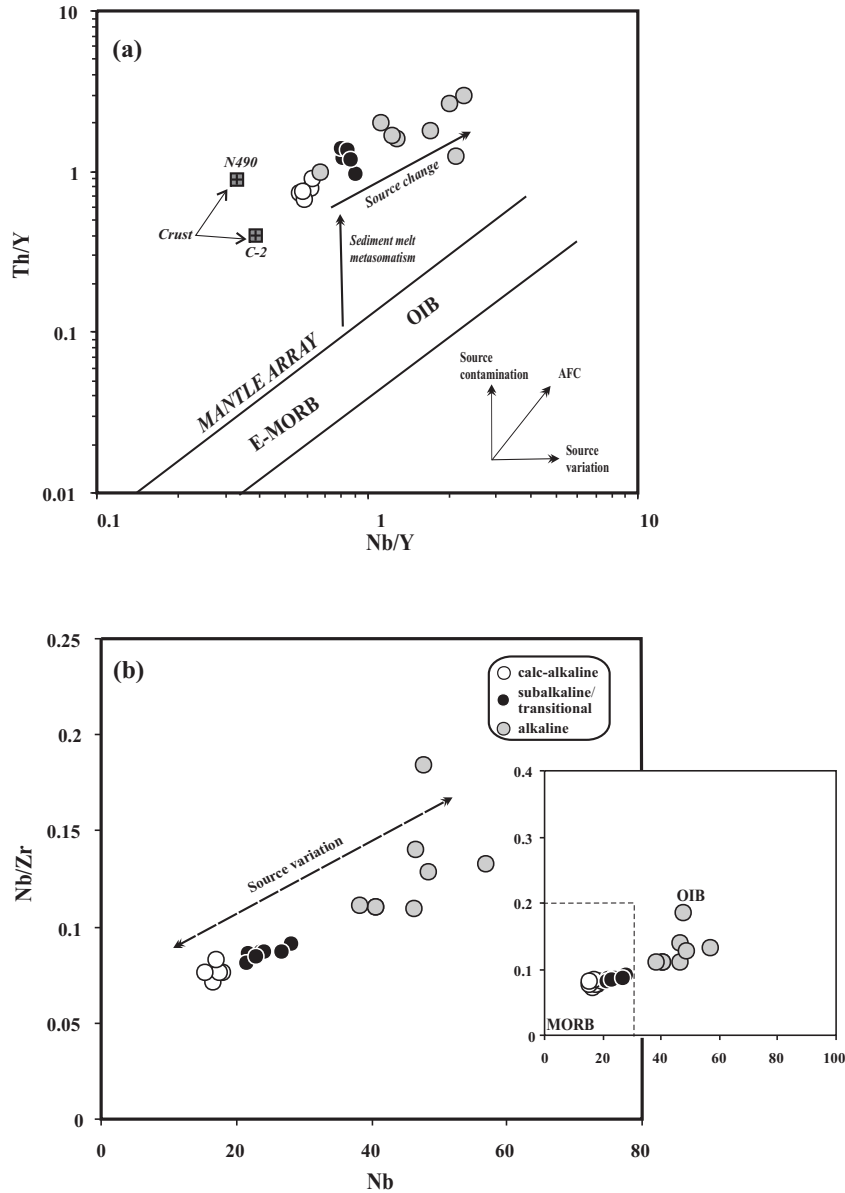
between ~15% and ~65% upper crustal contaminant is required in the AFC modelling for the alkaline rocks (Figure 7). The most silicic calc-alkaline (N395) and alkaline (N290) samples have higher assimilation (~55% for Sr; ~50% for Nd; the former) (~60% for Sr; ~65% for Nd; the latter) than the other calc-alkaline and alkaline samples.

The main variations shown by isotope data (Sr, Nd, O) (Figures 5–7) for the central Anatolian plutonic rocks can be also seen in plots of Th/Y vs Nb/Y and Nb/Zr vs Nb (Figure 8). The former plot (Figure 8a) shows that all intrusive rocks form trends that run parallel to the mantle array but are displaced towards higher Nb/Y ratios, indicating either derivation from an enriched mantle source to which subduction component had been added, or AFC, or both (İlbeyli *et al.* 2004). The Th/Y and Nb/Y ratios increase from the calc-alkaline through the subalkaline/transitional and alkaline plutonic rocks (Figure 8a). The high Nb/Y ratio of the alkaline rocks can be explained by derivation from more enrichment in a within-plate component than that of the calc-alkaline plutonic rocks. The central Anatolian plutonic rocks do not form a trend from the mantle array to the crust (Figure 8a), so AFC is not likely to have been the only process for the generation of the plutonic rocks.

Ratios of HFSE (e.g., Nb, Zr) can give useful information about magma source composition (e.g., Davidson 1996; Singer *et al.* 1996). Nb and Zr are mainly mantle-derived and strongly fractionated during melting or magma-mixing (e.g., Thirlwall *et al.* 1994; Davidson 1996). The Nb/Zr ratios are not affected by FC and crustal contamination (e.g., Seghedi *et al.* 2004). Different Nb/Zr ratios are interpreted in terms of variations in source composition and/or changes in degree of partial melting of the mantle (e.g., Thirlwall *et al.* 1994; Singer *et al.* 1996). In Figure 8b, the Nb/Zr ratios and Y increase from the calc-alkaline through the subalkaline/transitional to the alkaline plutonic rocks. The calc-alkaline rocks are closer to a MORB-like source comparable to that of the subalkaline/transitional and alkaline rocks. However, the alkaline rocks are closer to an OIB-like source (Figure 8b). Figure 8 shows that the alkaline rocks are more enriched in a within-plate component than the calc-alkaline plutonic rocks (Figure 8b).



**Figure 7.** (a)  $\delta^{18}\text{O}$  values versus  $^{87}\text{Sr}/^{86}\text{Sr}_i$  diagram showing the results of AFC for the calc-alkaline intrusive rocks (inset figure:  $\delta^{18}\text{O}$  vs  $^{143}\text{Nd}/^{144}\text{Nd}_i$ ); (b)  $\delta^{18}\text{O}$  values versus  $^{87}\text{Sr}/^{86}\text{Sr}_i$  diagram displaying the results of AFC for the subalkaline/transitional and alkaline rocks (inset figure:  $\delta^{18}\text{O}$  vs  $^{143}\text{Nd}/^{144}\text{Nd}_i$ ). Tick marks on each curve represent 5% crystallisation intervals. In this model, crystallisation ends after F reaches 0.05. Tick marks on the AFC curves represent the ratio of the final mass of magma to the initial mass of magma. Abbreviations: D– the bulk partition coefficient, F– the fraction of melt remaining, r– the ratio of the rate of assimilation to the rate of fractional crystallisation,  $S_I$ – source for the calc-alkaline rocks,  $C_I$ – crust for the calc-alkaline rocks,  $S_A$ – source for the subalkaline/transitional and alkaline rocks,  $C_A$ – crust for the subalkaline/transitional and alkaline rocks.



**Figure 8.** (a) Th/Y versus Nb/Y diagram for basic and intermediate intrusive rocks (samples <63% SiO<sub>2</sub> are plotted) (after Seghedi *et al.* 2004). (b) Nb/Zr versus Nb diagram for basic and intermediate intrusive rocks (after Seghedi *et al.* 2004). MORB and OIB values after Sun & McDonough (1989).

Based on the Sr-Nd-O data, it seems possible that the central Anatolian magmas were derived from a source composed of two distinct mantle and crustal components. The variations (Figures 5–8) shown by the calc-alkaline intrusive rocks could suggest that they are derived from a mantle source containing

subduction components, and later experienced assimilation and fractional crystallisation processes. In contrast, the subalkaline/transitional and alkaline intrusive rocks could be derived from a more-enriched mantle source compared to the calc-alkaline intrusive rocks. These assumptions are in



general agreement with the interpretation, based on initial  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  data, that the coexistence of calc-alkaline and alkaline magmatism in the complex may be explained by pre-collision differences in their mantle source regions (İlbeyli *et al.* 2004; İlbeyli 2005).

#### *Mechanism of Melt Genesis*

Slab detachment has been increasingly recognised in many collision-related systems (e.g., Pearce *et al.* 1990). Lithospheric thinning through delamination is induced by thermal and mechanical instability of the continental lithosphere. Rapid unroofing by isostasy is accompanied by hot asthenospheric upwelling and magmatic underplating. For the central Anatolian intrusive rocks, which are interpreted to have been derived from a subduction-modified mantle source(s), the likely mechanisms for magma generation are either lithospheric extension or uplift; or melting of mantle lithosphere by the perturbation of the geotherm due to delamination of the thermal boundary layer, or slab detachment. Perturbation of subduction-metasomatised lithosphere by either delamination of the thermal boundary layer or slab detachment may have generated the primary magmas for the central Anatolian plutonic rocks (İlbeyli *et al.* 2004). Both processes would lead to conductive heating of enriched mantle. This may have assisted or initiated the orogenic collapse that followed collision and uplift. A similar mechanism was also suggested for the origin of the east-central Anatolian intrusive rocks (Özgenç & İlbeyli 2009). This mechanism was also noted for the generation of the central Anatolian intrusive rocks (İlbeyli & Pearce 1997; Aydın *et al.* 1997; Boztuğ 1998).

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#### Conclusions

The intrusive rocks of the Central Anatolian Crystalline Complex can be divided into three groups on the basis of their field, petrographic, major-trace element and isotopic characteristics. These are: (i) calc-alkaline, (ii) subalkaline/transitional, and (iii) alkaline. These intrusive rocks cover a petrological range from monzodiorite through quartz monzonite to syenite/granite. Whole-rock oxygen isotope data from the complex have a range of  $\delta^{18}\text{O}$  values from 6.5‰ to 14.8‰.

The oxygen isotope values show that the intrusive rocks originated from a mantle source containing large subduction components, although a within-plate component is also present in the source of alkaline rocks. All rock types have experienced crustal assimilation and fractional crystallisation. In the region, the coexistence of calc-alkaline and alkaline magmatism could be attributed to mantle source heterogeneity before collision. Delamination of the thermal boundary layer, and/or slab breakoff is the likely mechanisms for the initiation of the diverse magmatism in the complex.

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