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Sr and Nd Isotopic Characteristics of Some S-, I- and A-type Granitoids from Central Anatolia

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Abstract: The petrogenesis of some Late Cretaceous S-, I- and A-type granitoids in the Aksaray and Kırşehir regions of Central Anatolia is investigated by means of whole-rock Sr and Nd isotope data with supplementary field, petrographic, and whole-rock geochemical studies.

The S-type Central Anatolian granitoids (Sinandı and Namlıkışla) have calc-alkaline peraluminous characteristics and show LILE and LREE enrichment. The I-type Central Anatolian granitoids (Borucu, Terlemez, Hisarkaya, Baranadağ), on the other hand, are calc-alkaline (excepting the alkaline Baranadağ sample) and metaluminous or slightly peraluminous with LILE and LREE enriched patterns and variable Eu-anomalies. Additionally, the A-type Çamsarı granitoid is alkaline and metaluminous with the highest LREE contents.

Isotope data from the I-type Central Anatolian granitoids ($^{87}Sr/^{86}Sr_{(i)}$: 0.7078–0.7109; εNd: -5.4 to -7.9), and the A-type Çamsarı granitoid ($^{87}Sr/^{86}Sr_{(i)}$: 0.7082; εNd: -7.1) are similar. The S-type Central Anatolian granitoids, on the other hand, have more radiogenic initial Sr isotopic ratios ($^{87}Sr/^{86}Sr_{(i)}$: 0.7128–0.7152) and lower εNd values (-9.1 to -9.7) than the I- and A-type granitoids from Central Anatolia.

When combined with the available petrological and age data, the isotope data presented in this study support the suggestion of collisional S-type granitic associations, and younger post-collisional and subsequent extensional I- and A-type magmatism in Central Anatolia. Sr and Nd isotope data infer that the I- and A-type Central Anatolian granitoids have hybrid and heterogeneous sources, while in the A-type granitoids a mantle component is likely to be dominant. Moreover, the S-type Central Anatolian granitoids were possibly derived from crustal, or crustal-dominated sources. Furthermore, the increase of $^{87}Sr/^{86}Sr_{(i)}$ and decrease of εNd values observed from S-type granitoids to I- and A-type magmatic rocks is either related to distinct source characteristics or to isotopic mixing between mantle and crustal sources through time.

Key Words: Sr–Nd isotope geochemistry, Central Anatolia, granitoid

Bazı S-, I- ve A-tipi Orta Anadolu Granitoyidlerinin Sr ve Nd İzotopik Özellikleri

Özet: Orta Anadolu'da, Aksaray ve Kırşehir yörelerindeki bazı Geç Kretase yaşlı S-, I- ve A-tipi granitoyidlerin petrojenezi, tüm-kayaç Sr ve Nd izotop verileri ve tamamlayıcı arazi, petrografi ve tüm-kayaç jeokimyası verilerine dayanarak irdelenmiştir.

S-tipi Orta Anadolu granitoyidleri (Sinandı ve Namlıkışla) kalk-alkalen peralüminalı karaktere sahip olup, LILE ve LREE zenginleşmesi göstermektedir. Buna karşın I-tipi Orta Anadolu granitoyidleri (Borucu, Terlemez, Hisarkaya, Baranadağ) kalk-alkalen (alkalen Baranadağ örneği dışında) metaaluminalı veya zayıf peraluminalı olup, LILE ve LREE'ce zengin dağılımlar ve farklılaşan Eu-anomalisi sunmaktadır. Ayrıca A-tipi Çamsarı granitoyidi alkalen metaaluminalı olup en yüksek LREE içeriklerine sahiptir.

I-tipi Orta Anadolu granitoyidleri ($^{87}Sr/^{86}Sr_{(i)}$: 0.7078–0.7109; εNd: -5.4'ten -7.9'a) ve A-tipi Çamsarı granitoyidi ($^{87}Sr/^{86}Sr_{(i)}$: 0.7082; εNd: -7.1) benzer izotop verilerine sahiptir. Buna karşın S-tipi Orta Anadolu Granitoyidleri Orta Anadolu'daki I- ve A-tipi granitoyidlerden daha radyojenik ilksel Sr izotop oranlarına ($^{87}Sr/^{86}Sr_{(i)}$: 0.7128–0.7152) ve daha düşük εNd (-9.1'den -9.7'e) değerlerine sahiptir.

Mevcut petroloji ve yaş verileriyle birleştirildiğinde, bu çalışmada sunulan izotop verileri Orta Anadolu'daki çarpışma ile ilgili S-tipi granitik birlikler ve nispeten genç I- ve A-tipi magmatizma önerisini desteklemektedir. Sr ve Nd izotop verileri I- ve A-tipi Orta Anadolu granitoyidlerinin, A-tipinde manto bileşeni daha baskın olmak üzere, hibrid ve heterojen kaynaklara sahip olduğunu önermektedir. Buna ek olarak, S-tipi Orta Anadolu granitoyidleri muhtemelen kıtasal, veya baskın kıtasal kökenli magmatik kaynaklardan oluşmuştur. Ayrıca, S-tipi granitoyidlerden I- ve A-tipi magmatik kayaçlara doğru gözlenen $^{87}Sr/^{86}Sr_{(i)}$ değerlerindeki artış ve εNd değerlerindeki yükseliş, farklı kaynak özelliklerinden veya manto ve kıtasal kaynakların zaman içerisinde izotopik olarak karışması ile bağlantılı olabilir.

Anahtar Sözcükler: Sr–Nd izotop jeokimyası, Orta Anadolu, granitoyid

Introduction

Strontium and neodymium isotopes are useful tools for determining the origin of, and processes encountered during the evolution of rocks (e.g., Zindler & Hart 1986). When combined with information from field, petrographic and whole-rock geochemical studies, Sr and Nd isotope ratios provide important data for the evaluation of petrological problems related to magmatic, metamorphic and sedimentary systems (e.g., DePaolo 1981; Zindler & Hart 1986; Halliday *et al.* 1988; Jung *et al.* 2002).

The petrology of the Central Anatolian granitoids, particularly investigations of mantle and crustal contributions during their petrogenesis, has been the subject of numerous studies. These granitoids were investigated in terms of their geology, mineralogy, mineral chemistry and whole-rock chemistry. However, there is only limited isotope data available for the granitoids from Central Anatolia (e.g., Göncüoğlu 1986; Güleç 1994; Göncüoğlu & Türeli 1994; İlbeyli *et al.* 2004; Boztuğ *et al.* 2007a). Hence, the complex petrology of the Central Anatolian granitoids needs to be clarified by further, more detailed isotope studies.

S-, I- and A-type granitoid associations are well exposed in Central Anatolia (e.g., Akıman *et al.* 1993; Göncüoğlu & Türeli 1994; Aydın *et al.* 1998; Boztuğ 2000; Düzgören-Aydın *et al.* 2001). We have studied seven granitoids (Borucu, Hisarkaya, Sinandı, Terlemez, Namlıkışla, Baranadağ and Çamsarı) from magmatic suites in the Aksaray and Kırşehir regions for Sr and Nd whole rock isotope data.

These are the first Sr and Nd whole-rock isotope data produced from the Radiogenic Isotope Laboratory, Middle East Technical University (METU) Central Laboratory. We aim to constrain the petrological characteristics of the granitic rocks within the Central Anatolia using these new isotope data, in conjunction with field, petrographical and whole-rock geochemical studies.

Regional Geology

The Central Anatolian Crystalline Complex comprises Precambrian, Palaeozoic and Mesozoic metamorphic rocks, consisting of gneisses, schists, calc-schists, phyllites, with marbles as the oldest lithologies (e.g., Göncüoğlu *et al.* 1991) (Figure 1). Supra-subduction-zone type ophiolitic rocks have been thrust over these metamorphic rocks (e.g., Göncüoğlu *et al.* 1993; Yalınız *et al.* 1996, 1999). Collisional to post-collisional S-, I- and A-type granitoids yielding Late Cretaceous ages (e.g., Göncüoğlu 1986; Yalınız *et al.* 1999; İlbeyli *et al.* 2004; Kadıoğlu *et al.* 2006) intrude this succession. Evolved I-type and A-type Central Anatolian granitoids postdate the Alpine thickening within the passive margin of the Tauride-Anatolide Platform in Central Anatolia (e.g., Köksal *et al.* 2004), and the A-type granitoids and their extrusive equivalents mark the subsequent extensional magmatic episode in the Central Anatolian Crystalline Complex (e.g., Göncüoğlu *et al.* 1997; Köksal *et al.* 2001; Alpaslan *et al.* 2004). Cover units in the Central Anatolian Crystalline Complex are latest Cretaceous clastics, Paleocene–Eocene volcanic, volcanoclastic, and carbonate rocks, Oligocene–Miocene evaporites and continental clastic rocks, and Upper Miocene–Pliocene continental clastic, volcanoclastic, and volcanic rocks (e.g., Göncüoğlu *et al.* 1991).

Analytical Methods

Isotopic analyses were performed at the Radiogenic Isotope Laboratory of METU Central Laboratory, in a similar manner to the analytical procedures described by Romer *et al.* (2001). Isotope ratios were measured using a Triton Multi-Collector Thermal Ionization Mass Spectrometer. The long-term average of the Sr SRM 987 standard obtained in our laboratory, 0.710242 ± 9 ($2\delta_{stdev}$, n=16), is within the error of its commonly accepted value (i.e. 0.710240 ± 20) and the obtained values gained in other international laboratories, e.g., 0.710249 ± 4 ($2\delta_{stdev}$, n=12) at GFZ-Potsdam (Germany) (e.g., Romer *et al.* 2001); 0.710246 ± 21 ($2\delta_{stdev}$, n=58) at Royal Holloway, University of London (U.K.) (e.g., Tribuzio *et al.* 2004); 0.710259 ± 12 ($2\delta_{stdev}$, n=28) at the University of Tübingen (Germany) (e.g., Shang *et al.* 2004). Moreover, the laboratory mean acquired in our laboratory for the Nd La Jolla standard (cf. Lugmair & Carlson 1978) is 0.511848 ± 5 ($2\delta_{stdev}$, n=22), a value within the generally accepted window of Nd La Jolla values (i.e. 0.511850 ± 10) and also within the error of the values gained in other international laboratories, e.g., 0.511850 ± 4 ($2\delta_{stdev}$, n=14) at GFZ-Potsdam (Germany) (e.g., Romer *et al.* 2001); 0.511845 ± 11 ($2\delta_{stdev}$, n=123) at GEOMAR (Germany) (e.g., Baranov *et al.* 2002); 0.511860 ± 15 ($2\delta_{stdev}$, n=9) at McMaster University (Canada) (e.g., Thompson *et al.* 2005);

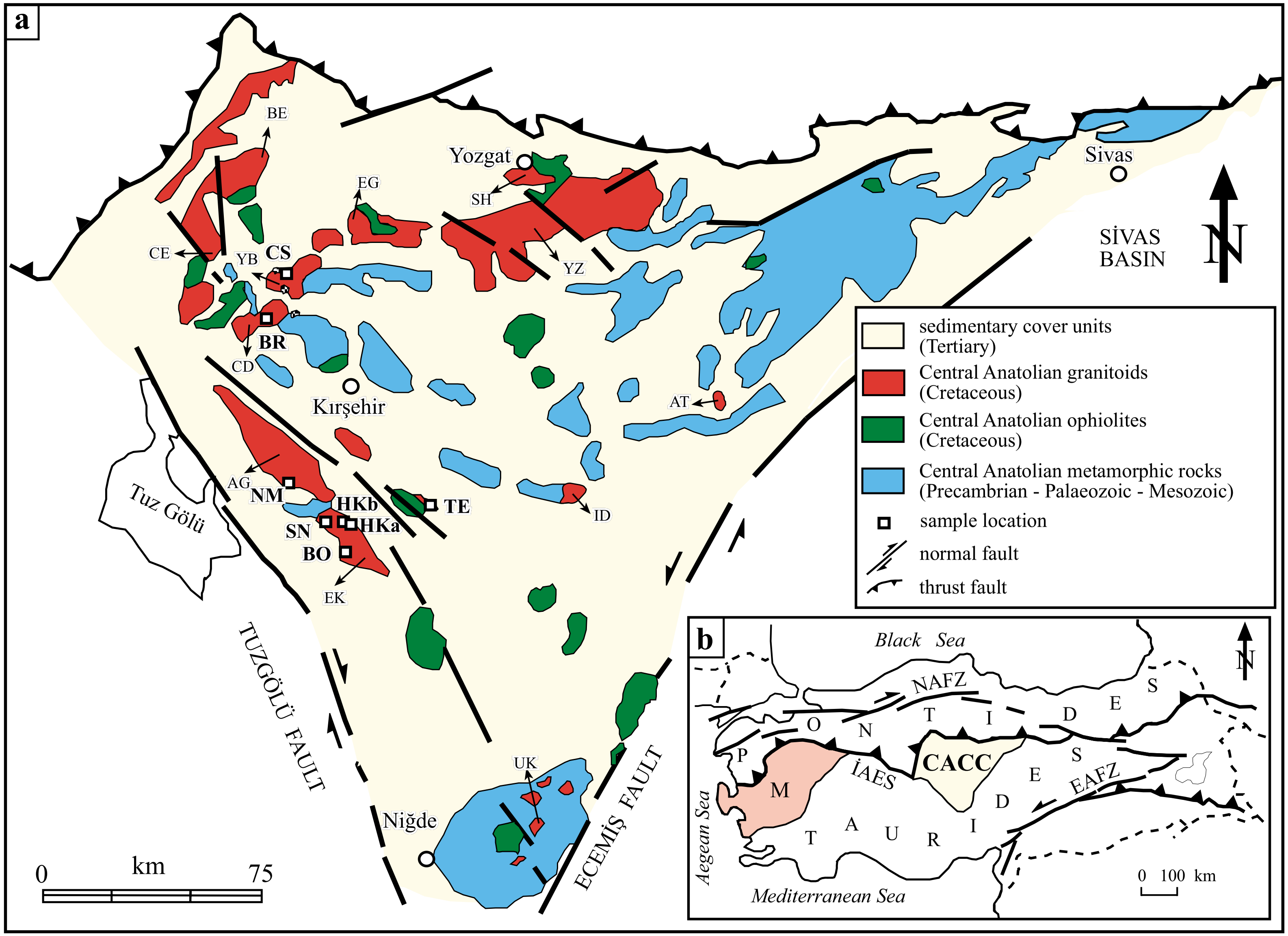

Figure 1. (a) Simplified geological map of the Central Anatolian Crystalline Complex and sample locations (modified after Düzgören-Aydın *et al.* 2001; Köksal *et al.* 2004). *I-type Central Anatolian granitoids*: BO– Borucu, BR– Baranadağ, CD– Cefalıkdağ, AG– Ağaçören Igneous Suite, TE– Terlemez, EK– Ekecikdağ Igneous Suite, HK– Hisarkaya, CE– Çelebi, BE– Behrekdağ, YZ– Yozgat; *S-type Central Anatolian granitoids*: SN– Sinandı, NM– Namlıkışla, UK– Üçkapılı, SH– Sarıhacılı; *A-type Central Anatolian granitoids*: CS– Çamsarı, EG– Eğrialan, ID– İdişdağ, AT– Atdere. (b) Locations of main tectonic units and the structure belts in Turkey (from Köksal *et al.* 2004). M– Menderes Massif, IAES– İzmir-Ankara-Erzincan Suture Zone, NAFZ– North Anatolian Fault Zone, EAFZ– East Anatolian Fault Zone.

0.511854 ± 18 ($2\delta_{stdev}$, n=30) at Max–Planck–Institut für Chemie in Mainz (Germany) (e.g., Puchtel *et al.* 2007); 0.511849 ± 10 ($2\delta_{stdev}$, n=5) at the University of Maryland (U.S.A.) (e.g., Terakado & Walker 2005).

Rock samples with a mass of at least 5 kg from each unit were crushed, ground to a powder and sieved to <63 µm size and homogenized in the sample preparation section of the METU Central Laboratory. Sr and Nd isotope geochemistry was done at the Clean Laboratory (including one Class 1000 and two Class 100 clean rooms) in the METU Central Laboratory.

Powdered samples (ca. 80 mg) were weighed and transferred into teflon perfluoroalkoxy vials. Samples were leached with 4 ml of 52% HF for four days at 160 °C on the hot plate. Digested samples were dried and then dissolved overnight in 4 ml 6 N HCl at 160 °C on the hot plate. Leaching and drying were done on teflon hot plates within laminar flow hotboxes.

Sr was separated in 2.5 N HCl medium using 12 ml Bio Rad poly-propylene columns with 2 ml Bio Rad AG50 W-X12, 100–200 mesh resin. Sr was loaded on single Re-filaments with Ta-activator and 0.005 N H_3PO_4 and its isotopic composition was determined by using static multi-collection. Analytical uncertainties are given at $2\delta_m$ level. $^{87}Sr/^{86}Sr$ data are normalized with $^{86}Sr/^{88}Sr$= 0.1194. During the course of the measurement Sr standard NIST SRM 987 was measured as 0.710247 ± 10 (n= 3) that is within the error of the accepted value of this standard.

A REE fraction was collected from the cation exchange columns with 6 N HCl after Sr was separated. Nd was separated from the REE fraction in a 0.022 N HCl medium using 12 ml Bio Rad poly-propylene columns with 2 ml biobeads (Bio Rad) coated with HDEHP (bis-ethyexyl phosphate). Nd was loaded on double Re-filaments with 0.005 N H_3PO_4 and its isotopic composition was determined by using static multi-collection. $^{143}Nd/^{144}Nd$ data are normalized to $^{146}Nd/^{144}Nd$= 0.7219. Measurement of the Nd La Jolla standard gave a value of 0.511846 ± 5 (n= 3) that is within the accepted error range for this standard. No corrections were applied to Nd and Sr isotopic compositions for instrumental bias.

As a quality check of the Sr and Nd analyses (from sample preparation to measurement) a selection of U.S. Geological Survey rock standards (i.e. BCR-1, G-2, GSP-1 and AGV-1) were chemically treated and measured using the same procedures above. Data obtained from these USGS reference materials are presented in Table 1. Also shown in Table 1 are the preferred values of GeoRem (http://georem.mpch-mainz.gwdg.de/), which is the Max-Planck-Institute database for geological and environmental reference materials including those of the USGS, and published data obtained by some comprehensive isotopic studies (e.g., Raczek *et al.* 2003; Weis *et al.* 2006) for correlation with our data. Most of the isotope ratio data of the Radiogenic Isotope Laboratory of METU are within the error of the preferred and/or published data.

Geological and Petrological Characteristics

In this study, we sampled the Borucu granodiorite-monzogranite, the Hisarkaya porphyritic granite, i.e. samples Hisarkaya(a) and Hisarkaya(b), the Sinandı

Table 1. Results of Sr and Nd isotope ratio analyses of some USGS standards and data from GeoRem.

USGS Std.	$^{87}Sr/^{86}Sr$ METU-Radiogenic Isotope Lab. Data	$^{87}Sr/^{86}Sr$ Preferred and/or Published Data	$^{143}Nd/^{144}Nd$ METU-Radiogenic Isotope Lab. Data	$^{143}Nd/^{144}Nd$ Preferred and/or Published Data
BCR-1	0.705027 ± 5 (n= 3)	0.705020 ± 40 (GeoRem preferred value)	0.512644 ± 1 (n= 2)	0.512640 ± 20 (GeoRem preferred value)
G-2	0.709776 ± 11 (n= 3)	0.709770 ± 14 (Weis *et al.* 2006)	0.512216 ± 1 (n= 2)	0.512228 ± 6 (Weis *et al.* 2006)
GSP-1	0.768798 ± 9 (n= 3)	0.767310 ± 34 (Raczek *et al.* 2003)	0.511388 ± 2 (n= 3)	0.511373 ± 38 (Raczek *et al.* 2003)
AGV-1	0.703985 ± 45 (n= 4)	0.703999 ± 60 (GeoRem preferred value)	0.512747 ± 10 (n= 2)	0.512790 ± 20 (GeoRem preferred value)

microgranite from the Ekecikdağ area (Aksaray), the Namlıkışla biotite-granite from the Ağaçören area (Aksaray), the Terlemez quartz monzonite from the Terlemez area (Aksaray), the Baranadağ quartz-monzonite and the Çamsarı quartz syenite from the Baranadağ area (Kırşehir) (Figure 1).

Geological and geochemical features of these granitoids have been reported in detail in previous studies (e.g., Türeli *et al.* 1993; Göncüoğlu & Türeli 1994; Otlu & Boztuğ 1998; Aydın & Önen 1999; Boztuğ 1998, 2000; Güleç & Kadıoğlu 1998; Kadıoğlu & Güleç 1999; Yalınız *et al.* 1999; Düzgören-Aydın *et al.* 2001; Kadıoğlu *et al.* 2003, 2006; İlbeyli *et al.* 2004; Köksal *et al.* 2004). Ophiolitic rocks overthrust the metamorphic basement rocks and the granitoids concerned intrude both ophiolitic and metamorphic rocks (e.g., Göncüoğlu & Türeli 1994; Yalınız *et al.* 1999).

The Borucu, Terlemez, and Hisarkaya granitoids can be described as I-type (i.e. those derived by melting of meta-igneous crust; e.g., Chappell *et al.* 1987) based on their geological and petrological features, whereas the Sinandı and Namlıkışla granitoids have S-type characteristics (i.e. those derived from sedimentary protoliths; e.g., Chappell & White 1974). The Çamsarı granitoid, on the other hand, has an A-type character (i.e. alkaline, anhydrous and/or anorogenic; e.g., Loiselle & Wones 1979; Collins *et al.* 1982; Whalen *et al.* 1987; or post-orogenic, e.g., Bonin *et al.* 1998) while the Baranadağ granitoid is defined either as evolved I-type (e.g., Köksal *et al.* 2004) or as transitional from I- to A-type (e.g., İlbeyli *et al.* 2004).

The Borucu, Terlemez, Hisarkaya and Baranadağ granitoids contain orthoclase, plagioclase, quartz ± microcline ± hornblende ± biotite ± clinopyroxene ± chlorite with accessory zircon, apatite, titanite, allanite, and opaque minerals (e.g., Göncüoğlu & Türeli 1994; Otlu & Boztuğ 1998; Yalınız *et al.* 1999; İlbeyli *et al.* 2004; İlbeyli 2005). Extensive mafic microgranular enclaves in these granitoids infer magma mingling processes (e.g., Güleç & Kadıoğlu 1998; Kadıoğlu & Güleç 1999). The S-type Sinandı and Namlıkışla granitoids consist of biotite (occasionally chloritized), muscovite, orthoclase, quartz, plagioclase ± garnet and accessory zircon, epidote, apatite and opaque minerals, and only a few mafic enclaves compared to the I-type Central Anatolian granitoids (e.g., Türeli 1991; Kadıoğlu 1996; Köksal *et al.* 2007). Moreover, the A-type Çamsarı granitoid contains orthoclase, quartz, plagioclase (An_{21} to An_0) ± hornblende ± biotite ± clinopyroxene (hedenbergite), accessory fluorite, titanite, zircon, apatite, and opaque minerals, and has no mafic enclaves (e.g., Köksal *et al.* 2004).

Representative whole-rock geochemical data, including rare earth elements (REE), obtained from the granitoids in this study are given in Table 2. The granitoids are calc-alkaline in general, except for the Çamsarı and Baranadağ granitoids, which show an alkaline character based on the classifications of Irvine & Baragar (1971). The Çamsarı granitoid shows characteristic geochemical features of the A-type granitoids, e.g. enrichment in Zr, Nb, Y and Ga, and REE (except Eu) and depletion of Ba, and Sr (Table 2) (e.g., Köksal *et al.* 2004; Whalen *et al.* 1987). The S-type Sinandı and Namlıkışla granitoids are peraluminous, whereas the I- and A-type ones are metaluminous, except the Hisarkaya samples, which have a slightly peraluminous composition (Figure 2).

On an ocean-ridge granite normalized multi-element variation diagram (Figure 3), patterns of these granitoids resemble those of collisional granitoids, i.e. in showing LILE enrichment and HFSE, HREE depletion (cf. Pearce *et al.* 1984).

Chondrite-normalized REE patterns of the investigated granitoids have steep LREE-enriched and almost flat HREE patterns (Figure 4). The Çamsarı and Baranadağ granitoids differ from the others in being more enriched in LREE and MREE, while the Hisarkaya granitoid has lower LREE and MREE and higher HREE contents compared to the other samples, possibly due to the fractionation of hornblende. All granitoid types have negative Eu-anomalies $[(Eu/Eu^*)_N]$, and the Hisarkaya granitoid has more pronounced Eu-anomalies (0.31–0.54) than the other granitoids (0.67–0.73 for other I-type samples, 0.59–0.63 for S-type samples, 0.62 for the A-type Çamsarı granitoid) (Figure 4).

Radiometric age constraints for these granitoids are based on different whole-rock and mineral isotope data. K-Ar hornblende and K-feldspar ages for the Terlemez granitoid range from 81.5 ± 1.9 (interpreted as the date of intrusion) to 67.1 ± 1.3 Ma (interpreted as a cooling age) (Yalınız *et al.* 1999). Depending on the U-Pb titanite age data, Köksal *et al.* (2004) indicated that both the post-collisional evolved I-type Baranadağ and the A-type

Table 2. Geochemical analyses[1] from the granitoids concerned.

Sample ▶	Borucu	Hisarkaya(a)	Hisarkaya(b)	Sinandı	Terlemez	Namlıkışla	Baranadağ	Çamsarı
Element ▼								
SiO_2	68.5	71.0	75.1	69.9	65.6	66.5	59.6	63.7
Al_2O_3	14.7	15.0	13.0	14.8	15.4	15.2	17.3	18.1
$Fe_2O_3^{tot}$	3.58	2.06	1.41	3.04	4.33	5.14	4.98	2.63
MgO	1.26	0.51	0.23	0.79	1.20	2.29	1.54	0.28
CaO	3.26	1.95	0.92	2.91	4.42	3.11	4.87	1.74
Na_2O	2.83	3.55	3.10	2.76	2.84	2.17	3.49	4.77
K_2O	4.02	5.09	5.37	3.89	4.12	3.81	6.35	7.95
TiO_2	0.34	0.17	0.10	0.40	0.60	0.63	0.53	0.35
P_2O_5	0.05	0.02	< .01	0.13	0.14	0.12	0.24	< .01
MnO	0.06	0.08	0.07	0.06	0.08	0.09	0.10	0.06
LOI	1.1	0.6	0.6	1.4	1.1	1.2	0.8	0.6
TOTAL	99.8	100.2	100.0	100.2	100.0	100.4	99.9	100.2
Ba	369	435	290	755	904	648	1114	261
Sc	7	3	2	7	5	14	6	1
Co	8	3	2	4	6	13	10	3
Cs	10.4	6.8	34.3	4.2	7.3	6.0	9.3	14.8
Ga	17	17	15	19	25	22	20	22
Hf	4.7	3.0	3.4	4.7	6.8	5.6	7.6	10.3
Nb	10	14	19	12	19	12	24	47
Rb	171	266	382	128	175	145	233	335
Sn	6	3	3	2	3	3	5	3
Sr	137	119	47	226	634	183	1014	309
Ta	1.0	1.8	3.3	1.0	1.3	0.8	1.3	2.0
Th	25	32	35	13	22	16	27	59
U	6.3	8.9	10.2	2.6	3.6	2.0	6.8	12.5
V	47	24	14	21	53	95	97	40
Zr	133	87	73	160	223	182	275	518
Y	20	23	30	25	21	23	29	24
Cu	22	15	9	7	15	34	19	14
Pb	8.3	6.0	6.9	3.5	9.4	6.1	6.8	29.2
Zn	32	33	21	62	49	83	47	31
Ni	24	24	13	11	25	45	28	22
La	30	23	25	38	52	42	75	148
Ce	62	42	43	72	99	82	151	248
Pr	6.1	3.9	4.0	7.2	9.4	8.2	14.3	18.3
Nd	22.9	14.5	15.3	30.1	37.3	35.3	57.3	58.5
Sm	4.0	3.1	2.9	6.2	6.8	6.6	9.5	7.5
Eu	0.8	0.5	0.3	1.2	1.3	1.2	2.0	1.4
Gd	3.24	2.54	2.96	5.36	5.21	5.78	7.26	6.32
Tb	0.56	0.53	0.59	0.77	0.71	0.79	0.94	0.71
Dy	3.1	3.4	4.0	4.4	3.5	4.0	5.0	3.9
Ho	0.67	0.63	0.81	0.79	0.68	0.75	0.79	0.66
Er	2.1	2.3	3.1	2.1	2.0	2.1	2.4	2.2
Tm	0.28	0.34	0.62	0.28	0.28	0.30	0.32	0.29
Yb	2.2	2.6	4.1	2.2	2.2	2.4	2.5	2.4
Lu	0.30	0.45	0.68	0.35	0.31	0.37	0.36	0.37

[1] Geochemical analyses were performed in ACME Analytical Laboratories Ltd. (Canada). Major elements, Ba, and Sc were measured by ICP-AES. Trace elements excluding Ba and Sc were measured by ICP-MS, and LOI is Loss of Ignition; tot: total Fe as Fe_2O_3 ; major elements in wt%; trace elements in ppm. Geochemical data from the Baranadağ, Terlemez, Çamsarı, Hisarkaya(a), and Hisarkaya(b) granitoids are from Köksal *et al.* (2008), and those from the Sinandı, Namlıkışla and Borucu granitoids are from this study.

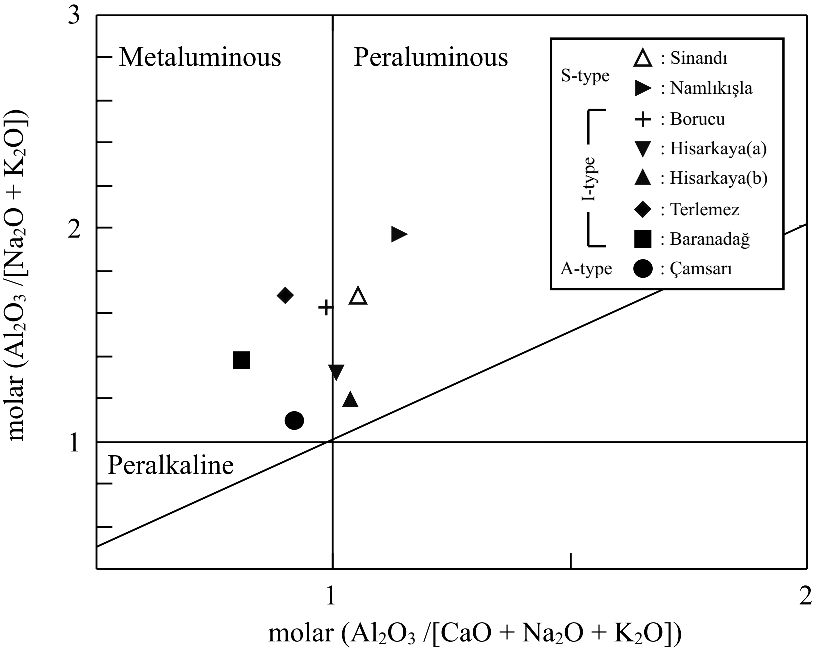

Figure 2. Plot of Shand index for the Central Anatolian granitoid samples: discrimination fields are from Maniar & Piccoli (1989).

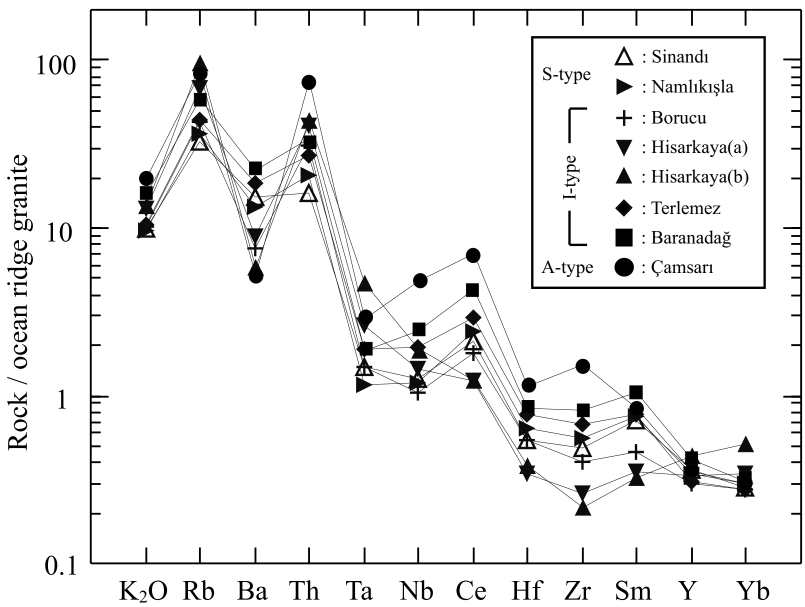

Figure 3. Ocean-ridge granite-normalized (after Pearce *et al.* 1984) multi-element variation plots of the Central Anatolian granitoids samples.

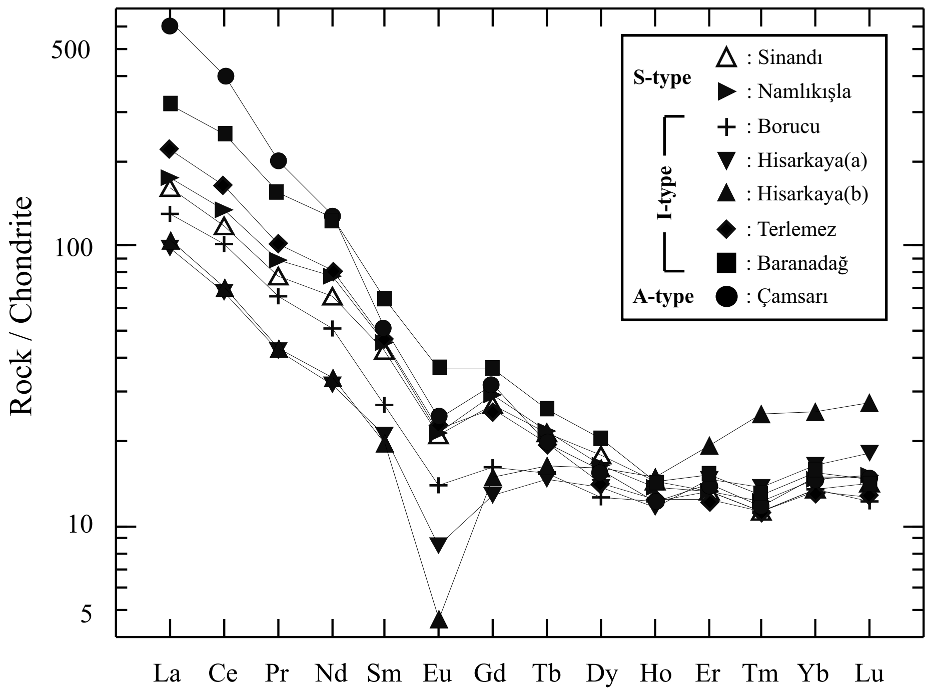

Figure 4. Chondrite-normalized (after McDonough & Sun 1995) rare earth element patterns for the Central Anatolian granitoids samples.

Çamsarı granitoids were emplaced in the Campanian (e.g., 74.0 ± 2.8 Ma and 74.1 ± 0.7 Ma, respectively). Similarly, İlbeyli *et al.* (2004) determined the age of the Baranadağ granitoid as 76.4 ± 1.3 Ma by the K/Ar method on hornblende. The cooling age of the Namlıkışla granitoid was determined as 77.7 ± 0.3 Ma ($^{40}Ar/^{39}Ar$ biotite age) by Kadıoğlu *et al.* (2006). Accordingly, LA-SF-ICP-MS analyses on rims and/or outer zones of zircons yielded U-Pb ages for the S-type Namlıkışla and Sinandı granitoids of 81.5 ± 0.84 Ma and 83.8 ± 0.95 Ma, respectively, with inherited cores yielding Jurassic to Proterozoic ages (Köksal *et al.* 2007).

In summary, the characteristics of the granitoids suggest that there are S-, I- and A-type granitoids in the Aksaray and Kırşehir regions and there are petrographical, geochemical and geochronological differences between them.

Sr and Nd Isotope Geochemistry

Previously published Sr and Nd isotope data for the Central Anatolian granitoids are shown in Table 3. Data from the I-type granitoids reveal a limited range (initial $^{87}Sr/^{86}Sr$ ratio varies from 0.7080 to 0.7097; εNd values ranges from -5.2 to -7.1), while A-type granitoids display wide a range but relatively lower $^{87}Sr/^{86}Sr_{(i)}$ (0.7042–0.7100) and higher εNd (-6.5 to 1.2) data. The lowest initial $^{87}Sr/^{86}Sr$ datum was presented by Boztuğ *et al.* (2007a) as 0.7042 from the A-type Dumluca granitoid (Sivas).

The S-type Üçkapılı granitoid, however, has higher $^{87}Sr/^{86}Sr_{(i)}$ ratio (0.7104), and the Hisarkaya granitoid has a εNd value of -6.1. Additionally, sodic alkaline volcanic rocks from the Ulukışla (Niğde) area, related to post-collisional extension of Late Cretaceous to Early Tertiary age show relatively low $^{87}Sr/^{86}Sr_{(i)}$ ratios (0.7070 to 0.7074) and εNd values (-4.1 to -5.5) (Alpaslan *et al.* 2004). Moreover ultrapotassic volcanic rocks from the same area reveal higher $^{87}Sr/^{86}Sr_{(i)}$ (0.7079 to 0.7092) but lower εNd data (-6.5 to -9.1) (Alpaslan *et al.* 2006).

Results of Sr and Nd isotope analyses performed in the METU Central Laboratory are presented in Tables 4 and 5, respectively. The isotopic composition of the

Table 3. Previous Sr and Nd isotope data from magmatic rocks in Central Anatolia.

Name of Intrusion	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr_{(i)}$	$^{143}Nd/^{144}Nd$	εNd	Authors
Üçkapılı granitoid (S-type)	0.71336 – 0.72212	0.71040[2]	–	–	Göncüoğlu (1986)
Borucu granitoid [1] (I-type)	0.715459 – 0.715723	–	0.512274 – 0.512325	-6.1 to -7.1	Göncüoğlu & Türeli (1994)
Hisarkaya granitoid[1] (I-type)	0.722029 ± 37	–	0.512329	-6.1	Göncüoğlu & Türeli (1994)
Yenişabanlı granitoid (Ağaçören) (I-type)	0.711245 – 0.712702	0.70862[2]	–	–	Güleç (1994)
Behrekdağ granitoid (I-type)	0.71004 ± 11	0.70923	0.512263 ± 4	-6.3	İlbeyli *et al.* (2004)
Cefalıkdağ granitoid (I-type)	0.70972 – 0.71087	0.70924 – 0.70964	0.512256 – 0.512300	-5.7 to -6.7	İlbeyli *et al.* (2004)
Cefalıkdağ granitoid (I-type)	0.709300 – 0.710700	0.70867[2]	–	–	Ataman (1972)
Çelebi granitoid (I-type)	0.71028 ± 35	0.70896	0.512298 ± 5	-5.5	İlbeyli *et al.* (2004)
Baranadağ granitoid (I-type)	0.70873 ± 11	0.70804	0.512324 ± 5	-5.2	İlbeyli *et al.* (2004)
Bayındır syenitoid (A-type)	–	0.70850	–	–	Gündoğdu *et al.* (1988)
Murmano granitoid (A-type)	0.70625 – 0.71113	0.7058 – 0.7068	–	–	Zeck & Ünlü (1987)
Murmano granitoid (A-type)	0.712666 (felsic)	0.7100	0.512255	-6.5	Boztuğ *et al.* (2007a)
	0.70627 (mafic)	0.7061	0.51247	-2.3	
Dumluca granitoid (A-type)	0.70963 (felsic)	0.70721	0.512445	-2.9	Boztuğ *et al.* (2007a)
	0.70456 (mafic)	0.70424	0.512665	-1.2	
Amit granitoid (A-type)	0.70875 – 0.71275	0.70822 – 0.70838	0.512307 – 0.512349	-4.8 to -5.5	İlbeyli *et al.* (2004)
Ulukışla sodic alkaline volcanic rocks	0.707242 – 0.707712	0.70704 – 0.70740	0.512279 – 0.512350	-4.1 to -5.5	Alpaslan *et al.* (2004)
Ulukışla ultrapotassic volcanic rocks	0.708264 – 0.709514	0.70798 – 0.70917	0.512109 – 0.512231	-6.5 to -9.1	Alpaslan *et al.* (2006)

[1] Initial Sr isotope ratio could not be calculated due to lack of Rb and Sr concentration data from the analysed samples

[2] Initial Sr isotope ratio is determined from the isochron

Table 4. Sr isotope data (from the Central Anatolian granitoids) obtained at the Radiogenic Isotope Laboratory of METU Central Laboratory.

Granitoid	$^{87}Sr/^{86}Sr$	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr_{(i)}$
Borucu	0.715323 ± 10	171.3	136.9	0.710891
Hisarkaya(a)	0.716245 ± 7	266.0	118.7	0.708687
Hisarkaya(b)	0.735422 ± 10	382.2	46.7	0.707818
Sinandı	0.714717 ± 12	127.5	226.1	0.712827
Terlemez	0.709462 ± 9	175.3	633.5	0.708608
Namlıkışla	0.717904 ± 9	144.8	182.5	0.715168
Baranadağ	0.709029 ± 12	233.1	1013.9	0.708329
Çamsarı	0.711517 ± 11	334.8	308.9	0.708218

$^{87}Sr/^{86}Sr_{(i)}$ was calculated for 74 Ma for the Baranadağ and the Çamsarı granitoids (e.g., Köksal *et al.* 2004), for 81.5 Ma for the Namlıkışla granitoid and 83.8 Ma for the Sinandı granitoid (e.g., Köksal *et al.* 2007) using $^{87}Rb = 1.42E\text{-}11y^{-1}$. Age data used in calculation of initial isotope values for other granitoids based on preliminary results of our LA-SF-ICP-MS U-Pb zircon studies, which reveal ca. 75 Ma for the Terlemez, ca. 82 Ma for the Hisarkaya, and ca. 86 Ma for the Borucu granitoids.

Table 5. Nd isotope data (from the Central Anatolian granitoids) obtained at the Radiogenic Isotope Laboratory of METU Central Laboratory.

Granitoid	$^{143}Nd/^{144}Nd$	Nd (ppm)	Sm (ppm)	$^{143}Nd/^{144}Nd_{(i)}$	$\varepsilon Nd_{(i)}$
Borucu	0.512181 ± 4	22.9	4.0	0.512130	-7.9
Hisarkaya(a)	0.512277 ± 3	14.5	3.1	0.512214	-6.3
Hisarkaya(b)	0.512252 ± 3	15.3	2.9	0.512197	-6.7
Sinandı	0.512131 ± 3	30.1	6.2	0.512082	-9.1
Terlemez	0.512227 ± 3	37.3	6.8	0.512184	-7.2
Namlıkışla	0.512093 ± 13	35.3	6.6	0.512049	-9.7
Baranadağ	0.512317 ± 2	57.3	9.5	0.512268	-5.4
Çamsarı	0.512215 ± 3	58.5	7.5	0.512177	-7.1

$\varepsilon Nd_{(i)}$ was calculated for the ages mentioned in Table 4 using $\lambda^{147}Sm = 6.54E\text{-}12y^{-1}$, $(^{147}Sm/^{144}Nd)^0_{CHUR} = 0.1967$, and $(^{143}Nd/^{144}Nd)^0_{CHUR} = 0.512638$

Baranadağ granitoid is very close that is obtained by İlbeyli *et al.* (2004) from the same granitoid. The I-type Borucu granitoid displays remarkably high initial Sr but low Nd isotope data compared to the other I-type granitoids. $^{87}Sr/^{86}Sr_{(i)}$ ratios of the S-type Central Anatolian granitoids, especially Sinandı and Namlıkışla, are considerably higher than those of the I- and A-type granitoids. These samples also show lower εNd values than the I- and A-type granitoids. The Terlemez and Çamsarı granitoids display similar $^{87}Sr/^{86}Sr_{(i)}$ and εNd data to the other I- and A-type granitoids.

Initial Sr and Nd isotope data from the granitoid samples are plotted in Figure 5, together with previous data from other magmatic rocks in Central Anatolia. Also shown for comparison are fields for I- and S-type granitoids of the Lachlan Fold Belt (Eastern Australia), and oceanic basalt suites with mantle components, i.e. HIMU, EM I, EM II, PREMA.

The S-type Central Anatolian granitoids display higher $^{87}Sr/^{86}Sr_{(i)}$ and lower εNd with respect to the I- and A-type granitoids (Figure 5) and plot in the field of the S-type Lachlan granitoids. The I- and A-type granitoids, including the previous data, fall into the field of the I-type Lachlan granitoids. Despite its more radiogenic Sr compositions the Borucu granitoid also plots in the field of the I-type granitoids.

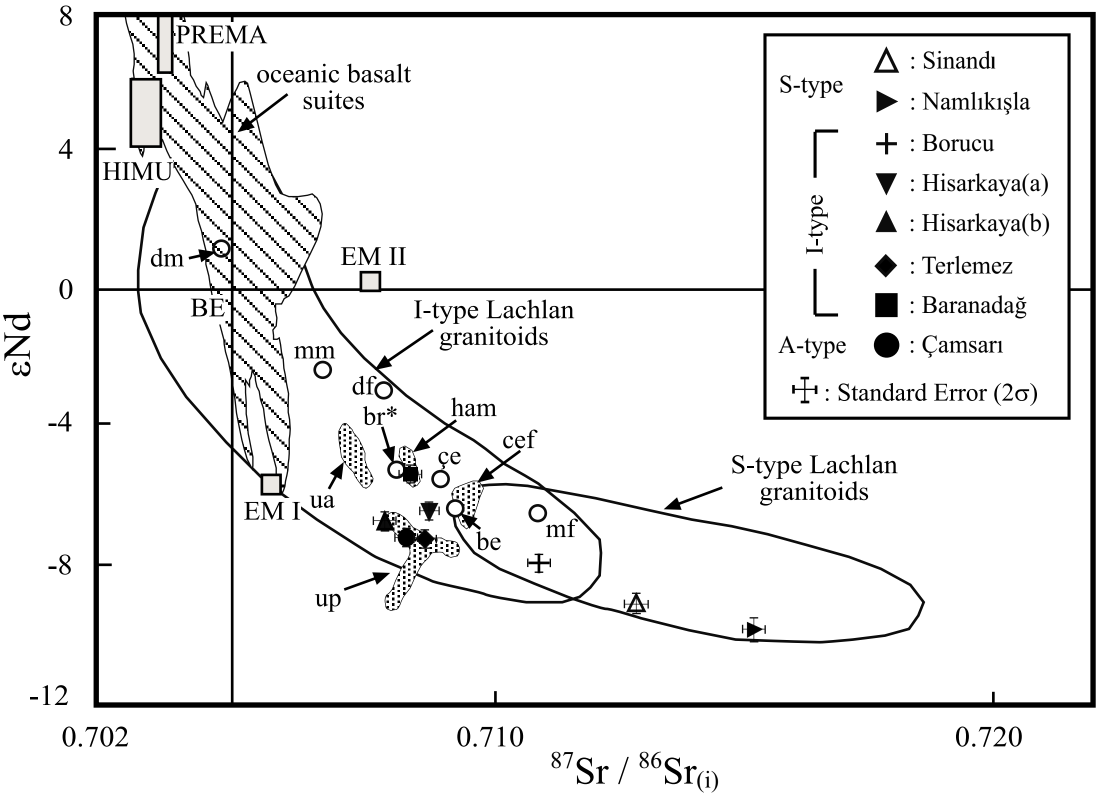

Figure 5. $^{87}Sr/^{86}Sr_{(i)}$ – εNd diagram for Central Anatolian granitoid samples. Other isotope data (shaded areas and open circles): ua– Ulukışla sodic alkaline volcanic rocks (Alpaslan *et al.* 2004); up– Ulukışla ultrapotassic volcanic rocks (Alpaslan *et al.* 2006); previous isotope data of Central Anatolian granitoids: br*– Baranadağ, çe– Çelebi, cef– Cefalıkdağ, be– Behrekdağ, ham– Hamit granitoids are from İlbeyli *et al.* (2004); df– Dumluca (felsic) granitoid, dm– Dumluca (mafic) granitoid, mf– Murmano (felsic) granitoid, mm– Murmano (mafic) granitoid are from Boztuğ *et al.* (2007a). Mantle components (BE– bulk silicate earth; EM I– Rb-enriched mantle 1; EM II– Rb-enriched mantle 2; HIMU– mantle component markedly enriched in U and Th relative to Pb; PREMA– prevalent mantle) and field for oceanic basalt suites are from Zindler & Hart (1986) and Hart (1988). Fields for I- and S-type granitoids from the Lachlan fold belt (after Keay *et al.* 1997) are also shown for comparison.

Discussion

Late Cretaceous granitoids in Central Anatolia reveal complex geochemical characteristics affected by previous subduction and subsequent collisional events due to closure of the Neotethyan Ocean (e.g., Göncüoğlu *et al.* 1991). The source regions of these granitoids cannot therefore be portrayed by simple geochemical models.

The $^{87}Sr/^{86}Sr_{(i)}$ - εNd diagram (Figure 5) shows that the present samples have a much larger crustal contribution than the oceanic basalt suites described by Zindler & Hart (1986). Moreover, the A-type Central Anatolian granitoids, in common with the Baranadağ granitoid, the Late Cretaceous–Early Tertiary Ulukışla volcanic rocks (Alpaslan *et al.* 2004, 2006), and granitoids from the Murmano and Dumluca plutons (Boztuğ *et al.* 2007a), can be differentiated from the I-type granitoids because they have compositions closer to the enriched mantle components, EM I and EM II. One noteworthy sample from the A-type Dumluca granitoid (mafic sample) (Boztuğ *et al.* 2007a) differs from the other A-type granitoids in the Central Anatolia with its high εNd and low $^{87}Sr/^{86}Sr_{(i)}$ values, suggesting a greater mantle contribution. We present in this research the first combined Sr and Nd data from the S-type granitoids from Central Anatolia (e.g., Table 2). The most significant isotopic characteristics of the S-type Sinandı and

Namlıkışla granitoids are their higher initial Sr and lower εNd isotope data than the Central Anatolian I- and A-type granitoids (Figure 5).

Isotopic data from the S- and I-type Central Anatolian Granitoids fall into the fields of isotopic data from the S- and I-type Lachlan Fold Belt granitoids, respectively (Figure 5). From this diagram it can be deduced that the Sr and Nd isotopic compositions of the S-type Sinandı and Namlıkışla granitoids are within the same compositional range as the S-type granitoids from the Lachlan Fold Belt. Similarly the I-type Central Anatolian granitoids (also some A-type granitoids) have Sr and Nd isotope data comparable to those of the I-type granitoids of the Lachlan Fold Belt. Continuing discussion about the Lachlan fold belt, i.e. discrete sources for S- and I-types or restite model (e.g., Chappell & White 1974; Chappell *et al.* 1999) or mixing of crust-mantle sources for both S- and I-type granitoids (e.g., Gray 1984; Keay *et al.* 1997), still questions the origin of the different granitoid types. Correspondingly, Maas *et al.* (2001) inferred involvement of mantle-derived magmas in the genesis of the S-type granitoids from the Lachlan Fold Belt, while Kemp *et al.* (2007) suggested the I-type granitoid from this area was formed by the reworking of sedimentary materials by mantle-like magmas.

The origin of different Central Anatolian granitoid types also remains enigmatic. The I- and A-type granitoids in Central Anatolia are accepted to be formed in post-collisional and subsequent extensional environments (e.g., Akıman *et al.* 1993; Aydın *et al.* 1998; Boztuğ 1998, 2000; Düzgören-Aydın *et al.* 2001), and their geochemical and isotopic differences are related to source heterogeneities and variable contributions of mantle and crustal material (e.g., Köksal *et al.* 2004; İlbeyli *et al.* 2004). Güleç & Kadıoğlu (1998) demonstrated the involvement of upper crustal and mantle sources in the petrogenesis of I-type granitic rocks from the Ağaçören area by using Sr-isotope data. Their model for the origin of the granitoids invokes involvement of an upper crustal melt and a subduction-modified upper mantle-derived melt with an isotope signature typical of MORB. Mafic microgranular enclaves found in the granitoids provide evidence for magma mingling (Güleç & Kadıoğlu 1998). The Sr and Nd isotope data of İlbeyli *et al.* (2004) also infers sourcing from enriched mantle with a subduction component inherited from pre-collisional subduction for the I-type granitoids in Central Anatolia. It is suggested that this mantle-derived mafic magma underplated the lower crust as a result of lithospheric delamination or slab break-off processes following crustal thickening (e.g., Aydın *et al.* 1997, 1998; Boztuğ 1998, Düzgören-Aydın *et al.* 2001; İlbeyli *et al.* 2004; İlbeyli 2005; Boztuğ *et al.* 2007a, b).

Boztuğ *et al.* (2007a) suggest the association of two discrete, but coeval magma sources for the A-type Dumluca and Murmano granitoids in the east of Central Anatolia. They infer that these two sources were (1) mafic magma derived from an EM II type of enriched mantle source, probably an enriched lithospheric mantle source that was metasomatized by subduction-derived fluids above a supra-subduction zone, and (2) hybrid felsic magmas resulted from mixing of mantle-derived and crustal-derived melts. Köksal *et al.* (2004) suggested that a subcontinental lithosphere enriched from dehydration and melting of sediments and/or basaltic crust of the subducted slab was the source of the A-type Çamsarı and evolved I-type Baranadağ granitoids. Our data on isotopic compositions, together with previous information, however, infer similar sources for I- and A-type granitoids. Crustal components exist for both types; although the A-type Central Anatolian granitoids are likely to have had a more enriched mantle component compared to the I-type granitoids as proposed by İlbeyli *et al.* (2004).

The heterogeneous isotopic compositions with elevated initial $^{87}Sr/^{86}Sr$ and low εNd data, as observed for the S-type granitoids in this study, are characteristic of granitoids that include a crustal component, or formed by remelting of crustal rocks (e.g., Elburg & Foden 1999). Accordingly, the S-type granitoids in Central Anatolia are described as having syn-collisional characteristics (e.g., Akıman *et al.* 1993; Aydın *et al.* 1998; Boztuğ 1998, 2000) and are assumed to be formed by partial melting of shortened and thickened crust (e.g., Akıman *et al.* 1993; Aydın *et al.* 1998; Boztuğ 2000), and were either derived from granitic melts generated at the thermal peak of a regional progressive metamorphism (e.g., Boztuğ 2000) or from partial melting of an upper crustal sedimentary protolith by, with or without intrusion of mantle-derived mafic melts (e.g., Aydın *et al.* 1998). Düzgören-Aydın *et al.* (2001) on the other hand, described these granitoids as formed in the early stages of post-collisional magmatism by partial melting of lower continental crust. Tatar & Boztuğ

(2005) proposed that the formation of the S-type Danacıobası biotite leucogranite (from the Behrekdağ pluton), resulted from dehydration and partial melting of high-grade metasediments of the Central Anatolian Crystalline Complex during peak regional metamorphic conditions induced by crustal thickening. Similarly, Göncüoğlu (1986), using Sr-isotope data, implied that the S-type Üçkapılı granitoid formed as a result of partial melting of semipelitic rocks from the lower parts of the Niğde group, while Whitney *et al.* (2003) suggested that it formed by melting of the middle crust during prograde metamorphism and/or initial decompression accompanied by removal of upper crustal rocks. Moreover, based on Late Neoproterozoic through Early Palaeozoic, Triassic, and Jurassic U-Pb SHRIMP ages obtained from zircon cores from this S-type granitoid, Whitney *et al.* (2003) suggested an Afro-Arabian (Gondwanan) basement or sediments derived from it as the magma source, confirming the idea of Göncüoğlu (1982).

The presence of a few mafic microgranular enclaves in the S-type granitoids, although less abundant than the I-type Central Anatolian granitoids (e.g., Göncüoğlu & Türeli 1994 and this study) suggests the existence of some mantle input at least for some of the S-type Central Anatolian granitoids. Similarly, Maas *et al.* (2001) proposed that the S-type Deddick granitoid from the Lachlan Fold Belt was not only derived from turbidites having contributions from volcano-sedimentary sequences, but also from contemporaneous, mantle-derived magmas. In addition, the co-existence of the S- and I-type granitoids in some magmatic suites in the Central Anatolia (i.e. Ekecikdağ: Göncüoğlu & Türeli 1994; Ağaçören: Güleç & Kadıoğlu 1998 and this study; Felahiye: Boztuğ *et al.* 2003; Behrekdağ: Tatar & Boztuğ 2005) is significant.

The I- and A-type granitoids were generally dated as Campanian (e.g., Ataman 1972; İlbeyli *et al.* 2004; Köksal *et al.* 2004; Boztuğ *et al.* 2007b), while post-collisional extension related volcanic rocks (e.g., Karahıdır, Ulukışla), possibly petrogenetically linked with the A-type magmatism, are assumed to have formed in Late Cretaceous to Early Tertiary (e.g., Köksal *et al.* 2001; Alpaslan *et al.* 2004, 2006) (according to the geologic time scale of the International Union of Geological Sciences, Gradstein *et al.* 2005). S-type Central Anatolian granitoids, however, are commonly older than the I- and A-type granitoids (i.e. Santonian age; e.g. Göncüoğlu 1986; Whitney *et al.* 2003; Boztuğ *et al.* 2007b; Köksal *et al.* 2007).

From the Nd and Sr isotope data (Figure 5) and from the available age information we can suggest that there is an isotopic difference between the Santonian S-type magmatism stage and the Campanian I- and A-type magmatism period. This phenomenon can be elucidated by (1) distinct sources for the S-type Central Anatolian granitoids and I- and A-type granitoids, i.e., crustal source for S-type granitoids, hybrid source for I- and A-type granitoids, or (2) a varying degree of mixing of mantle and crustal components (with an increasing mantle component or decreasing crustal contribution) through time, deduced from decreasing $^{87}Sr/^{86}Sr_{(i)}$ and increasing εNd values.

Because of the lack of Sr and Nd isotope data from potential sedimentary sources we cannot identify the crustal component on the isotope diagram, i.e. Figure 5. Nevertheless, considering the isotopic data of the S-type Sinandı and Namlıkışla granitoids, the possible crustal end member is thought to have $^{87}Sr/^{86}Sr_{(i)}$ ratio > 0.715 and εNd value < -9.7. Further and detailed isotopic studies from granitic rocks in the Central Anatolia will provide a basis for the petrogenetic models portraying the isotopic evolution of the magmatism as in the case of Lachlan Fold Belt granitoids (e.g., Gray 1984; Keay *et al.* 1997; Maas *et al.* 2001; Kemp *et al.* 2007).

Conclusions

To study the source characteristics of the Central Anatolian granitoids, samples from seven granitoid bodies from Aksaray and Kırşehir were investigated for their Sr and Nd isotopic characteristics. The Sr and Nd isotope data presented in this research are the first results obtained from the Radiogenic Isotope Laboratory of METU Central Laboratory, applying the analytical methods mentioned in the text.

Nd and Sr whole-rock isotope data presented here imply that there is an apparent isotope geochemical difference between the S-type granitoids in the Central Anatolia and the I- and A-type granitoids. Considering the existing isotopic difference, combined with the petrological and geochronological background, it can be suggested that the mantle input increased through time during the genesis of the Central Anatolian granitoids. The S-type granitoids in Central Anatolia have crustal, or crustal-dominant, magmatic sources, while the I- and A-type granitoids are commonly attributed to melting of hybrid and heterogeneous sources: in the latter a mantle component is considered dominant. Whether the S-type magmatism had distinct sources from the I- and A-type magmatism, or if there was isotopic mixing between crustal and mantle sources with proportions varying through time is, however, difficult to interpret from the limited available data.

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