Geochemical and Isotopic Constraints on Petrogenesis of the Beypazarı Granitoid, NW Ankara, Western Central Anatolia, Turkey

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Abstract: The Upper Cretaceous Beypazarı granitoid of the western Ankara, Turkey, is composed of two different units, on the basis of petrography and geochemical composition; these are granodiorite and diorite. The granitoid is subalkaline, belonging to the high-K calc-alkaline I-type granite series, which have relatively low initial $^{87}Sr/^{86}Sr$ ratios (0.7053–0.7070). All these characteristics, combined with major, trace element geochemical data as well as mineralogical and textural evidence, reveal that the Beypazarı granitoid formed in a volcanic arc setting and was derived from a subduction-modified and metasomatized mantle-sourced magma, with its crustal and mantle components contaminated by interaction with the upper crust. The rocks have $\varepsilon Nd_{(75Ma)}$ values ranging from –5.5 to –2.0. These characteristics also indicate that a crustal component played a very important role in their petrogenesis.

The moderately evolved granitoid stock cropping out near Beypazarı, Ankara, was studied using the oxygen and hydrogen isotope geochemistry of whole rock, quartz and silicate minerals. $\delta^{18}O$ values of the Beypazarı granitoid are consistently higher than those of normal I-type granites. This is consistent with field observations, petrographic and whole-rock geochemical data, which indicate that the Beypazarı granitoid has significant crustal components. However, the $\delta^{18}O$ relationships among minerals indicate a very minor influence of hydrothermal processes in sub-solidus conditions. The oxygen isotope systematics of the Beypazarı granitoid samples results from the activity of high-$\delta^{18}O$ fluids (magmatic water), with no major involvement of low-$\delta^{18}O$ fluids (meteoric water) evident. The analysed four quartz-feldspar pairs have values of $\Delta_{qtz-fsp}$ between 0.5–2.0, which are consistent with equilibrium under close-system conditions. No stable isotope evidence was found to suggest that extensive interaction of granitoids with hydrothermal fluids occurred and this is consistent with the lack of large-scale base-metal mineralization.

Key Words: Beypazarı granitoid, Upper Cretaceous, oxygen and hydrogen isotopes, crustal contamination, western-central Anatolia, Turkey

Beypazarı Granitoyidinin (KB Ankara, Batı-Orta Anadolu, Türkiye) Petrojenezi Üzerine Jeokimyasal ve İzotopik Sınırlamalar

Özet: Ankara (Türkiye) batısında yer alan Geç Kretase yaşlı Beypazarı granitoyidi, petrografi ve jeokimyasal bileşimine dayanarak, granodiyorit ve diyorit olmak üzere iki farklı birime ayrılmıştır. Granitoyid subalkalin özellikte ve yüksek-K'lu seriye aittir. Granitoyidin bileşimi granitten diyorite değişim sunmaktadır. Bu kayaçlar göreceli olarak düşük $^{87}Sr/^{86}Sr$ (0.7053–0.7070) oranına sahiptir. Mineralojik ve dokusal veriler, ve ana ve iz element jeokimyası ile birlikte, tüm bu karakteristik özellikler, Beypazarı granitoyidiinin üst kabuk etkileşimi ile kirlenmiş manto ve kabuk bileşenlerine sahip, hibrid bir kaynaktan, magmatik bir yay ortam içinde oluştuğuna işaret etmektedir. Bu kayaçlar –5.5'den –2.0'a değişen aralıkta $\varepsilon Nd_{(75Ma)}$ değerlerine sahiptir. Bu karakteristikler aynı zamanda, kabuk bileşeninin Beypazarı granitoyidinin petrojenezinde önemli bir rol oynadığına işaret etmektedir.

Beypazarı (Ankara) yakınında yüzlek veren, orta derecede evrim geçirmiş granitoyid stoğunun, toplam kayaç, kuvars ve silikat minerallerinin oksijen ve hidrojen izotop jeokimyası çalışılmıştır. Beypazarı granitoyidinin $\delta^{18}O$ değerleri normal I-tipi granitler için tanımlanan değerlerden daha yüksektir. Bu durum, Beypazarı granitoyidinin önemli bir kabuk bileşenine sahip olduğuna işaret eden arazi gözlemleri, petrografik ve tüm-kayaç jeokimyasal veriler ile uyum içindedir. Bununla birlikte, mineraller arasındaki $\delta^{18}O$ ilişkileri yarı-katı koşullarda herhangi bir hidrotermal proses girişine işaret etmemektedir. Beypazarı granitoyid örneklerine ait oksijen izotop sistematikleri, düşük-$\delta^{18}O$ akışkanlarının (meteorik su) belirgin bir girişi olmaksızın, yüksek $\delta^{18}O$ değerlerine sahip akışkanların (magmatik su) aktivitesini sonuçlamaktadır. Analizi yapılan dört kuvars-feldispat çifti 0.5–2.0 arasında $\Delta_{qtz-feld}$ değerlerine sahiptir,

bu da kapalı sistem koşulları altında denge kavramı ile uyumludur. Sonuçta, granitoyidlerin hidrotermal akışkanlarla yaygın etkileşimini gösteren herhangi bir duraylı izotop verisi bulunmamaktadır ve bu sonuç bölgede büyük ölçekli baz metal mineralizasyonunun olmaması ile uyumludur.

Anahtar Sözcükler: Beypazarı granitoyidi, Üst Kretase, oksijen ve hidrojen izotopları, kabuk kirlenmesi, batı-orta Anadolu, Türkiye

Introduction

The numerous granitoids and volcanic rocks in the Sakarya Zone, western-central Anatolia, were formed from partial melts that were developed by the closing of the Tethyan Ocean during the Late Cretaceous period (Şengör & Yılmaz 1981; Okay *et al.* 2001). The Beypazarı granitoid, located south of the Kirmir stream, west of Ankara city, Turkey, is a well-known example of a subduction-derived magma from a metasomatized mantle source with considerable crustal contribution (Figure 1; Helvacı & Bozkurt 1994; Kadıoğlu & Zoroğlu 2008). According to Helvacı & Bozkurt (1994), the initial $^{87}Sr/^{86}Sr$ ratios, ranging between 0.706 and 0.707 indicate that the Beypazarı granitoids were formed by anatexis of older continental crust, and were shallowly intruded in the region probably during the Late Cretaceous.

The granitodic body represents one of the best exposed of the intrusive bodies in the Central Sakarya Terrane that played a significant role during the Tethyan evolution of the eastern Mediterranean region. The granitoid intruded the Tepeköy metamorphic rocks of the Central Sakarya Terrane, consisting of calc-alkaline felsic and mafic rocks (Çoğulu 1967).

The geodynamic scenario commonly accepted by Şengör & Yılmaz (1981) and Göncüoğlu (1997) is that the İzmir-Ankara-Erzincan Ocean had closed by northward subduction. If this interpretation is valid, the studied area must be located at the active margin of the İzmir-Ankara-Erzincan Ocean, above the northward subducting oceanic lithosphere (Billur 2004). This would explain the magmatic arc character of the Beypazarı granitoid, possibly generated by the north-dipping subduction of the northern branch of the Neo-Tethys ocean under the Sakarya Continent (Billur 2004). In this model, the melting started in the upper mantle above the subducting slab, but was followed by melting of the lower crust and finally the upper crust, resulting in the formation of the Beypazarı granitoid (Billur 2004).

This paper focuses on the origin of the granitoids, using detailed geochemical and Nd-, Sr- and O-isotopic analyses to further constrain their petrogenesis. The tectonic setting of the rocks is also discussed.

Stable isotopes are important tools for petrogenetic processes as they are good indicators of granite source materials, also providing valuable information about cooling history and sub-solidus fluid interaction processes (e.g., Taylor & Sheppard 1986). The entire magmatic system of Beypazarı shows only minor obvious effects of post-magmatic processes, and no extensive meteoric-hydrothermal alteration (no extensive alteration of feldspar or micas, see Helvacı & Bozkurt 1994, for detailed petrologic characteristics of the Beypazarı granitoid). The system is therefore suitable for the study of the $\delta^{18}O$ and δD systematics of the individual igneous rock types. The present paper is the first report of the oxygen and hydrogen isotopic study of the Beypazarı granitoid. The locations from which samples were collected are shown on a simplified geological map of the Beypazarı granitoid in Figure 1 (Helvacı & İnci 1989).

Petrography and Field Relations

The Beypazarı granitoid comprises the various felsic intrusive rocks outcrops within the Central Sakarya Terrane intruded into metamorphic rocks and Tethyan ophiolites. The samples from twelve localities chosen for this study are derived from four exposures, located at Beypazarı, Oymaağaç, Tahir, Kırbaşı and Yalnızçam (Figure 1). The oldest rocks in this region are the Tepeköy metamorphic units (Billur 2004), which are part of the Central Sakarya unit of the Sakarya Composite Terrane. The Central Sakarya Terrane contains three metamorphic units (Göncüoğlu *et al.* 2000), the Söğüt metamorphics, the Tepeköy metamorphics and the Soğukkuyu
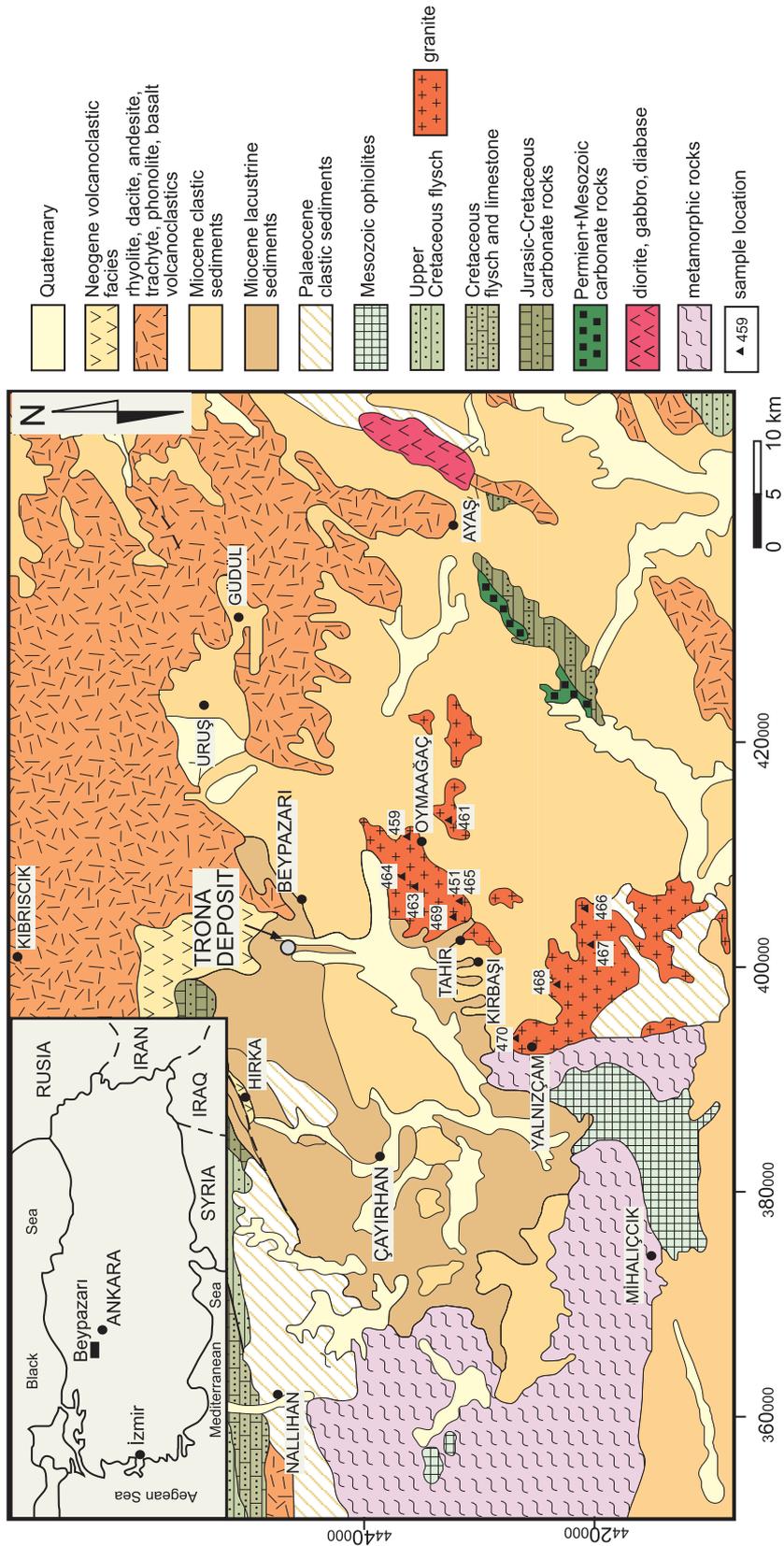
Figure 1. Geological map showing location of the Beypazarı granitoid (modified from Helvacı & İnci 1989).

metamorphics. The Söğüt metamorphics are composed of paragneisses, intruded by many plutonic rocks of granitic-dioritic composition (Yılmaz 1981). The variety of the metamorphic rock types in the Söğüt metamorphics, the presence of ophiolitic assemblages and the geochemical characteristics of the granitoids intruding them, strongly suggest a Late Palaeozoic island-arc tectonic setting (Göncüoğlu *et al.* 2000). The Tepeköy metamorphics are composed of metabasic rocks, metatuffs, metafelsic rocks, black phyllites, metagreywackes, metasandstones and recrystallized pelagic limestone with metaradiolarite interlayers (Billur 2004). They are unconformably overlain by basal clastic rocks of the Soğukkuyu metamorphics containing pebbles of the Tepeköy metamorphics. The Soğukkuyu metamorphics unconformably overlie the Söğüt and the Tepeköy metamorphics (Göncüoğlu *et al.* 2000). The rock units and their relations suggest that the Soğukkuyu metamorphics were deposited in a rifted basin, which probably opened on the accreted Söğüt and Tepeköy units and their Permian carbonate cover. Regionally, all these metamorphic rocks correspond to the Karakaya Nappe of Koçyiğit (1987) and Koçyiğit *et al.* (1991), which is mainly Late Triassic in age (Billur 2004).

Two sedimentary basins (Beypazarı and Kırbaşı) initially evolved as peripheral foreland and/or forearc basins in the Miocene time. The west and north part of the BG is bounded by the branch of Tethyan ophiolites.

The Beypazarı granitoid is dominantly granodiorite in composition. It consists principally of quartz, plagioclase, orthoclase. Plagioclase and orthoclase are sericitized, whereas biotite is chloritized. Amphibole, biotite, chlorite, zircon, titanite, apatite and rare opaque minerals are accessory phases. The main mafic phases are typical of granitoids with igneous (I-type) rock sources. The Beypazarı granitoid mostly has holocrystalline, hypidiomorphic and, less commonly, myrmekitic and allotriomorphic textures (Helvacı & Bozkurt 1994). Around the Kapullu fault, which has a strike of N55°–72°E and dips 78° to the SE, within the Beypazarı granitoid, porphyroclastic, mortar and cataclastic textures were found to be common along the fault zone and a holocrystalline granular texture

is dominant in distal parts of the fault (Diker *et al.* 2006).

Mafic enclaves were observed within the granitoid. These enclaves can be divided genetically into three different types based on field observation, their textural features and mineralogical compositions (Kadıoğlu & Zoroğlu 2008). The first type comprises diorite to monzodioritic enclaves mostly with subophitic texture, interpreted as magma mixing/mingling enclaves in origin (Kadıoğlu & Zoroğlu 2008). The second type comprises enclaves with cumulate texture, representing a segregation of mafic minerals from early crystallization processes. The third type consists of xenolithic enclaves with metamorphic textures. These enclaves are metapelitic at the contact with the host rock as a product of contact metamorphism and amphibolitic at the core resulting from high temperature metamorphism (Kadıoğlu & Zoroğlu 2008).

Analytical Techniques

12 samples of 5–7 kg were crushed in a jaw crusher and powdered in an agate mill to avoid contamination. Major and trace element abundances were determined by wavelength-dispersive X-ray fluorescence (WDS-XRF) spectrometry (Bruker AXS S4 Pioneer) at the University of Tübingen. Loss on ignition (LOI) was calculated after heating the sample powder to 1000°C for 1 h. Major and trace element analyses were performed on fused glass discs, which were made from whole-rock powder mixed with $Li_2B_2O_7$ (1:5) and fused at 1150°C. Total iron concentration is expressed as Fe_2O_3. Relative analytical uncertainties range from ±1% to 8% and 5% to 13% for major and trace elements, respectively, depending on the concentration level.

Radiogenic Isotope Analyses

For determination of Sr and Nd isotopic ratios, approximetaly 50 mg of whole-rock powdered samples were used. The samples were decomposed in a mixture of $HF-HClO_4$ in Teflon beakers in steel jacket bombs at 180°C for six days to ensure the decomposition of refractory phases. Sr and Nd were separated by conventional ion exchange techniques and their isotopic compositions were measured

on a single W filament and double Re filament configuration, respectively. A detailed description of the analytical procedures is outlined in Hegner *et al.* (1995). Isotopic compositions were measured on a Finnigan-MAT 262 multicollector mass spectrometer at the University of Tübingen using a static mode for both Sr and Nd. The isotopic ratios were corrected for mass fractionation by normalizing to $^{86}Sr/^{88}Sr= 0.1194$ and $^{146}Nd/^{144}Nd= 0.7219$. Total procedure blanks are <200 pg for Sr and <50 pg for Nd. During the course of this study, four analyses of standard NBS 987 yielded a mean value of $^{87}Sr/^{86}Sr$ 0.710257±10 (2σ). Measurements of the Ames Nd Standard yielded a mean value of $^{143}Nd/^{144}Nd=$ 0.512129±10 (2σ, n= 5). $^{87}Rb/^{86}Sr$ ratios for whole-rock samples were calculated based on the measured $^{87}Sr/^{86}Sr$ ratios and the Rb and Sr concentrations determined by XRF.

Stable Isotope Analyses

12 whole rock H-and O-isotope analyses of the Beypazarı granitoid have been performed and from those 4 selected samples of mineral separates (quartz, feldspar, hornblende, biotite, magnetite, apatite and titanite) were analyzed. To study the Beypazarı granitoid, monominerallic samples were prepared using standard magnetic and heavy liquid techniques (Zussman 1977). Grains of feldspars and micas showing signs of alteration or mineral intergrowths were discarded. Finally, pure samples for isotopic analysis were separated by handpicking.

The oxygen isotope compositions (^{18}O, ^{16}O) of the whole-rock samples were determined using a modified version of the conventional method after Clayton & Mayeda (1963), with ClF3 as a reagent and converting the liberated oxygen to CO_2 before mass spectrometric analyses. Oxygen was extracted from approximately 10 mg of dried whole – rock powder at 550°C using ClF3 as a reagent following the method of Clayton & Mayeda (1963). Quantitative oxygen yields were between 95 and 100%. The oxygen was converted to CO_2 using a graphite rod heated by a Pt coil. CO_2 was analyzed for its $^{18}O/^{16}O$ ratios with a Finnigan Mat 252 gas source mass spectrometer. The isotopic ratios are reported in the δ-notation relative to Vienna standard mean ocean water (V-SMOW). All analyses have been duplicated with an analytical

precision of between ±0.1–0.2 per mil. The analyses of NBS-28 standard quartz were +9.7±0.1 per mil (2 sigma) and all data have been normalized to NBS-28 = +9.7 per mil.

The oxygen isotope compositions of handpicked mineral separates were measured using a method similar to that described by Sharp (1990) and Rumble & Hoering (1994). Between 0.5 to 2 mg of sample was loaded onto a small Pt-sample holder and evacuated to about 10^{-6} mbar. After prefluorination of the sample chamber overnight, the samples were heated with a CO_2-laser in 50 mbars of pure F_2. Excess F_2 was separated from the O_2 produced by conversion to Cl_2 using KCl held at 150°C. The extracted O_2 was collected on a molecular sieve (13X) and subsequently expanded and analyzed using a Finnigan MAT 252 isotope ratio mass spectrometer at Tübingen University, Germany. Analytical results are reported in the normal d notation, relative to Vienna Standard Mean Ocean Water for oxygen (V-SMOW, Kendall *et al.* 1995). The reproducibility is better than ±0.1‰. The mean value for the NBS-28 standard obtained during the present study was +9.64 ‰.

The hydrogen isotope compositions (D/H) of the hydrous samples were measured using the closed tube technique described by Vennemann & O'Neil (1993). This closed tube technique involves quantitative reduction of the H_2O in hydrous minerals by a Zn reagent where sample and Zn are inserted into quartz tubes and, after evacuation, are heated to 1200°C in a resistance furnace. Samples are heated in the quartz tube to extract water. The water and any H_2 gas produced are then passed over hot CuO to oxidize the H_2 and all water is collected in a glass-tube containing zinc. Zinc and water are reacted for 10 min at 500°C to quantitatively convert all water to H_2 gas for mass spectrometric analysis.

Results

Major and Trace Element Geochemistry

Samples collected from the Beypazarı granitoid were analyzed for both major and trace element contents. The results of geochemical analyses are listed in Table 1.

In terms of major elements, all values from the Beypazarı granitoid plot as calc-alkaline (Figure 2a)

Table 1. Major- and trace-element compositions of the Beypazarı granitoid.

Sample	06-451	06-465	06-466	06-467	06-468	06-470	06-459	06-461	06-463	06-464	06-469
		Yalnızçam diorite						Tahir quartz diorite			
(%) SiO_2	61.42	54.18	55.97	61.16	61.30	61.17	64.24	63.73	62.74	64.39	65.39
TiO_2	0.62	0.78	0.77	0.55	0.59	0.61	0.40	0.49	0.51	0.43	0.41
Al_2O_3	16.67	17.63	16.67	17.29	16.27	16.24	16.79	15.87	16.25	16.58	15.75
Fe_2O_3	6.33	8.93	8.23	5.66	6.23	6.34	3.90	5.16	5.25	4.04	3.82
MnO	0.13	0.22	0.19	0.11	0.12	0.12	0.12	0.11	0.12	0.11	0.10
MgO	2.67	3.78	3.97	2.49	2.93	2.77	1.21	1.88	1.60	1.33	1.36
CaO	5.85	7.30	6.50	5.67	5.25	5.58	4.49	4.96	5.46	4.70	4.44
Na_2O	2.86	3.35	3.32	3.01	2.77	2.78	3.51	3.16	3.69	3.54	3.27
K_2O	3.09	2.16	2.79	3.29	3.52	3.45	4.59	3.93	3.24	4.01	4.65
P_2O_5	0.17	0.21	0.17	0.14	0.16	0.16	0.17	0.19	0.19	0.17	0.17
LOI	0.52	1.06	1.24	0.73	1.01	0.63	0.55	0.60	0.81	0.54	0.37
Sum	100.51	99.74	99.99	100.27	100.32	100.03	100.16	100.24	100.03	100.00	99.89
(ppm) Ba	638	445	576	659	645	694	678	548	398	527	474
Co	7	11	12	5	6	5	0	2	1	0	0
Cr	7	7	4	7	5	12	0	0	0	0	0
Ni	45	36	36	37	44	38	24	40	29	26	24
Rb	100	96	97	102	111	112	154	144	121	140	180
Sr	399	346	333	399	358	367	641	481	585	605	537
V	134	173	187	116	135	133	74	99	98	74	76
Y	23	31	44	21	25	27	16	20	22	19	15
Zn	55	84	84	58	57	63	37	33	32	30	20
Zr	149	111	146	148	171	156	136	152	151	148	111
Ce	67	76	83	69	77	60	67	67	81	69	62
Eu	1.3	1.3	1.3	1.2	1.2	1.2	1.6	1.2	1.6	1.6	1.3
La	33	30	39	30	41	25	53	49	62	54	52
Nb	0	0	11	0	0	0	0	0	0	0	0
Nd	22	37	34	24	21	32	30	25	26	35	29
Sm	4.7	4.9	6.2	4.1	5.0	4.6	3.9	3.2	4.4	5.0	3.4
Yb	1.9	2.8	4.0	1.8	2.1	2.3	1.4	1.7	1.9	1.6	1.4

and subalkaline (Figure 2b) rocks in the classification scheme of Irvine & Baragar (1971). On the Na_2O+K_2O vs SiO_2 diagram of Cox *et al.* (1979) (Figure 2b), the samples fall in the quartz-diorite, syeno-diorite and diorite fields. The ACNK vs ANK diagram (Maniar & Piccoli 1989) defines the rocks as metaluminous to slightly peraluminous, and of I-type character (Figure 2c). The K_2O-SiO_2 plot further shows almost all samples to have high-K affiliation (Figure 3f).

Major and trace element variations are illustrated in Harker diagrams in Figures 3 and 4. The samples exhibit a wide range in SiO_2 content from approximately 54 to 65 wt% for the Beypazarı granitoid. TiO_2, Al_2O_3, Fe_2O_3, MgO and CaO abundances decrease with increasing SiO_2, whereas K_2O increases and Na_2O remains nearly constant. The trace elements (Figure 4) exhibit considerably more scatter than the major elements, particular Ba and Zr. However, Sr and Rb define a positive correlation with increasing SiO_2 content.

K/Rb ratios are particularly useful in the evaluation of highly fractionated melts. In the K/Rb-SiO_2 diagram, there is a progressive decrease in K/Rb values with a granite evaluation (Figure 5a, b). This diagram shows that the Beypazarı granitoid is similar to I-type granites from continental margins (Figure 5c) and was derived from moderately evolved melts (Figure 5d).

The trace element data are used in the discrimination of tectonic or geologic provinces associated with particular magma types (e.g., Pearce *et al.* 1984). In the Rb vs Y+Nb and Rb/Zr-Y (Figure 6a, b) diagrams, values from the Beypazarı granitoid plot in the VAG field and also range from oceanic to continental setting arc granites (Förster *et al.* 1997) and normal continental arc setting (Brown *et al.* 1984), respectively.

Rare Earth Element Geochemistry

The chondrite-normalized REE pattern (Figure 7) shows that all analyzed Beypazarı samples are characterized by fractionation between the light and heavy REE. The Beypazarı granitoid is enriched in LREE and has a horizontal normalized pattern for the HREE. The previous ICP data of Billur (2004) had smaller negative Eu anomalies (Figure 7a, grey field). Note that the new geochemical data are consistent

with the general pattern (Billur 2004; Kadıoğlu & Zoroğlu 2008): namely LREE enrichment, a small negative Eu anomaly and flat and low HREE.

Trace element patterns give information about source and magmatic processes. Differences in element patterns are important since mobile incompatible elements (Sr, K, Ba, Rb) enter melts and immobile compatibles are kept in the subducting slab (Billur 2004). Spider diagrams for ocean-ridge granitoids (ORG) give a flat pattern close to unity (Pearce *et al.* 1984). However, spider diagram profiles for volcanic arc granites (VAG) are sloping due to enrichment in LILE (K, Rb, Ba) and Th relative to HFSE (Ta, Zr, Y, Yb). Little enrichment in Rb is observed and continental margin granitoids are more enriched in LILE than island arc granitoids (Billur 2004). A slightly inclined pattern, however, indicates within plate granitoids (WPG), and depletion in Ba indicates a mantle source. A crustal source is suggested by the gently sloping profile between Ba, Ta, Th, unlike other granites. As with VAG, collisional granites (COLG) have a sloping profile and in syn-collision granites (SYN-COLG) exceptionally high Rb. Ocean-ridge granite (ORG)-normalized patterns for the Beypazarı granitoid are characterized by K_2O, Rb and Ba enrichment and Zr and Y depletion (Figure 8a), indicating crustal interaction (Pearce *et al.* 1984). Comparison of the Beypazarı granitoid trace element contents with those of the lower and upper crust (Wilson 1989) shows that the Beypazarı granitoid is fairly similar to the upper crust (Figure 8a, b), in the enrichment of LIL elements compared to HFS elements. The patterns resemble those of rock units formed by subduction and/or collision tectonics. These features indicate a mantle source, enriched by subduction processes (e.g., Pearce *et al.* 1984; Rogers *et al.* 1985; Harris *et al.* 1986). Therefore, the trace element and REE patterns of the Beypazarı granitoid are comparable with volcanic arc granites, formed in a transitional setting between oceanic and continental.

Nd-Sr Isotopic Ratios

Selected samples were analysed for Sr and Nd isotope composition. The data are given in Table 2 and Figure 9. Nd isotopic compositions were calculated for the 75 Ma age of the Beypazarı granitoid obtained
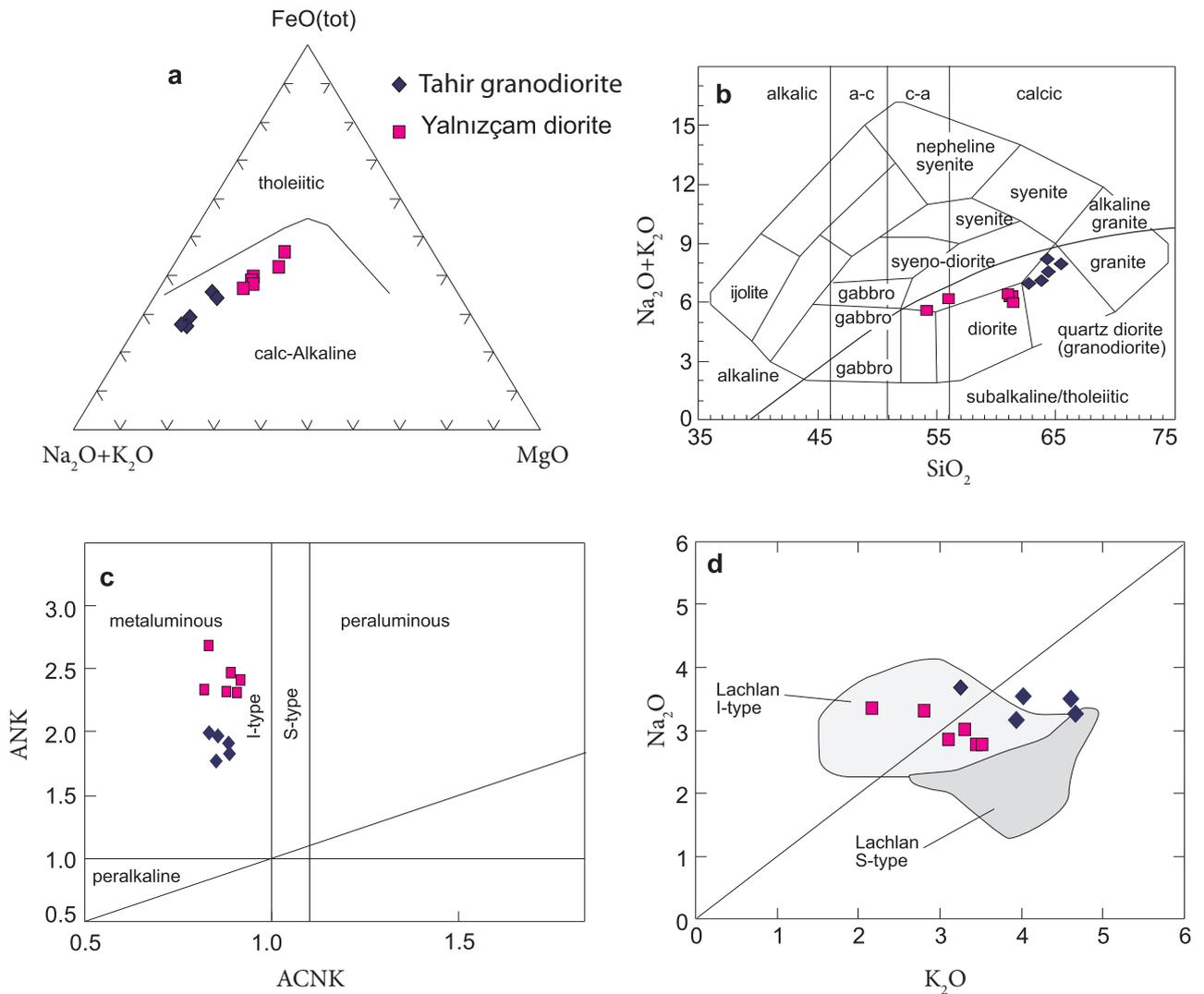
Figure 2. C lassification of (**a**) calc-alkaline, (**b**) subalkaline (Cox *et al.* 1979), (**c**) Al-saturation index (Peacock 1931) and (**d**) Na_2O-K_2O diagrams for the Beypazarı granitoid.

from conventional K-Ar dating of hornblende and biotite (unpublished data) and interpreted as the emplacement age of the granitoid. Figure 9a shows the variation of initial $^{143}Nd/^{144}Nd$ with initial $^{87}Sr/^{86}Sr$ (Sr_i) isotopic ratios. The Beypazarı granitoid has a pronounced negative correlation between both parameters, whereby $^{143}Nd/^{144}Nd_{(i)}$ values decrease with increasing Sr_i values. Note that the Tahir quartz-diorite samples have higher $^{143}Nd/^{144}Nd_{(i)}$ with slightly decreasing Sr_i, than the Yalnızçam diorite samples, which have higher Sr isotope ratios than the Tahir quartz-diorite samples. However, in the $\delta^{18}O$ vs $^{87}Sr/^{86}Sr$ (Sr_i) (Figure 9c) diagram, values from the Beypazarı granitoid have a negative trend, whereas in

the $\delta^{18}O$ vs $\varepsilon Nd_{(75Ma)}$ diagram, the Beypazarı granitoid has a pronounced positive correlation between both parameters, whereby $\varepsilon Nd_{(T)}$ values increase with decreasing $\delta^{18}O$ values (Figure 9d). Note that the Tahir quartz-diorite samples (Figure 9c) have higher $\delta^{18}O$ with lower Sr_i, than the Yalnızçam diorite samples. The Tahir quartz-diorite also has higher $\varepsilon Nd_{(T)}$ values than the Yalnızçam diorite samples (Figure 9d).

Oxygen Isotope Geochemistry

Oxygen and hydrogen isotope analyses of the Beypazarı granitoid reported here (Table 3) were
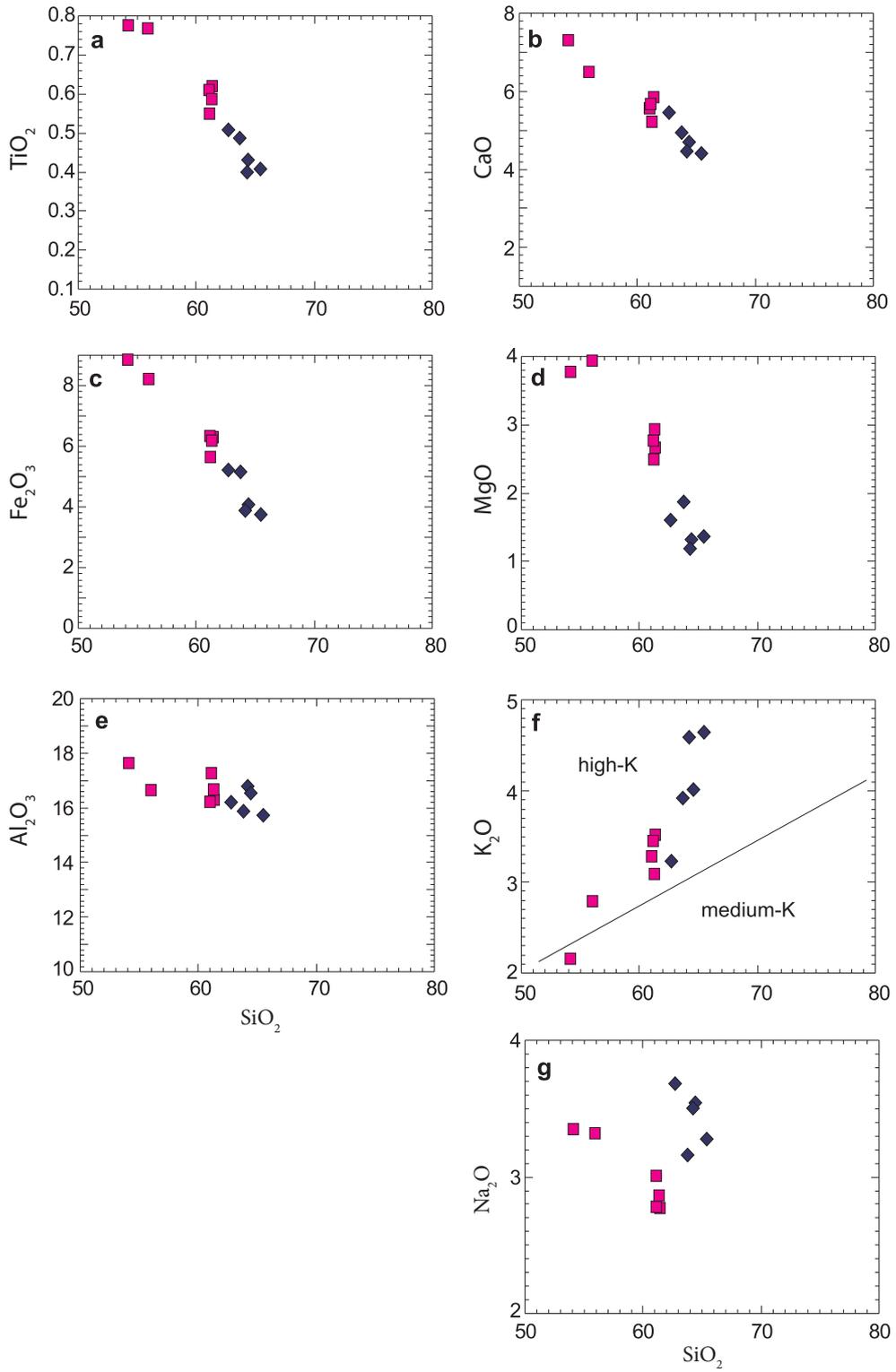
Figure 3. Selected Harker variation diagrams of major elements for the Beypazarı granitoid. The K₂O-SiO₂ diagram (Figure 3f) is after Le Maitre (1989), with lines separating medium-K and high-K granites.
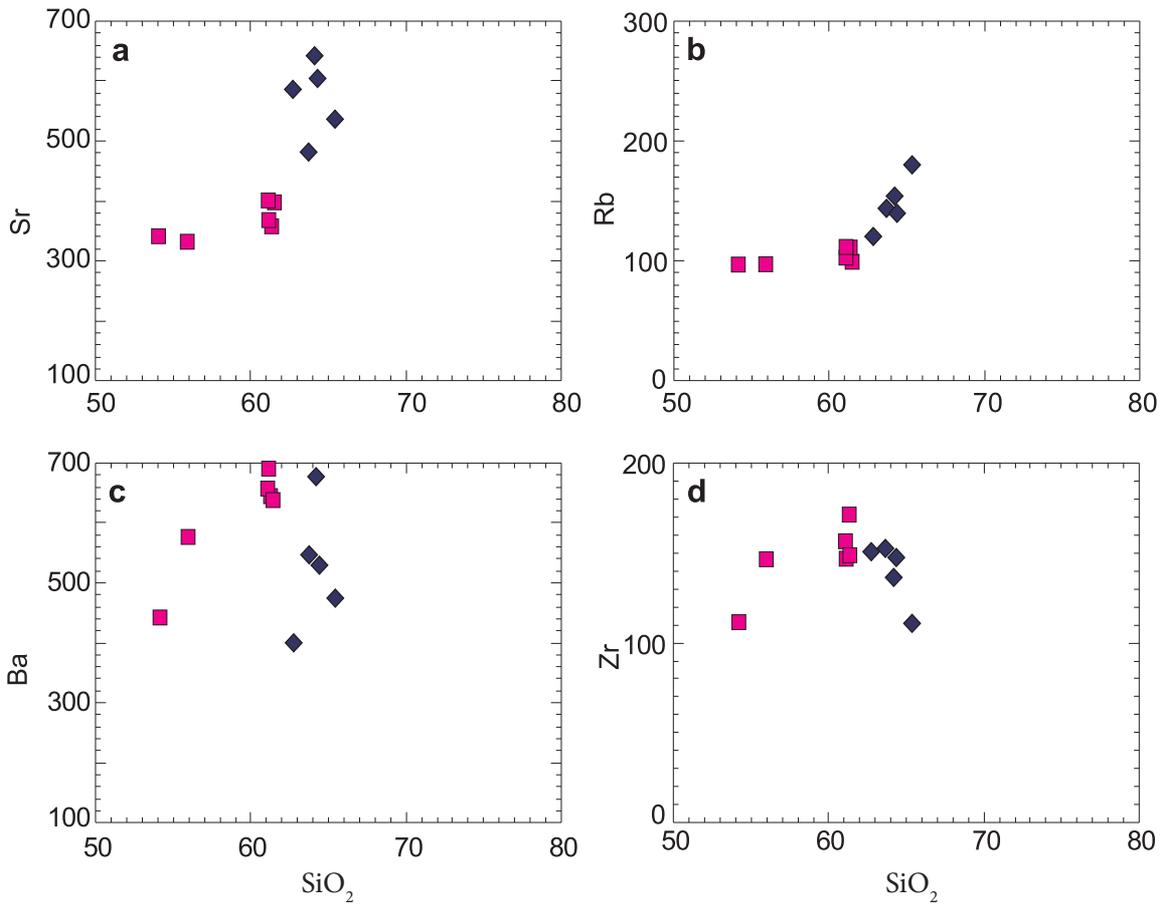
Figure 4. Selected Harker variation diagrams of trace elements for the Beypazarı granitoid.

performed on mineral separates (quartz, K-feldspar, hornblende, biotite, apatite, titanite and magnetite) and whole-rock samples. Granitic rocks have generally been subdivided into three groups: (1) normal ^{18}O-granitic rocks with δ^{18}O-values between 6–10‰, (2) high ^{18}O-granitic rocks with δ^{18}O-values >10‰, and (3) low ^{18}O-granitic rocks with δ^{18}O-values <6‰ (Taylor 1977, 1978). The oxygen isotope geochemical data for various lithological units of the Beypazarı batholith are presented in Table 3. All have relatively high δ^{18}O values (average 10.2‰). The δ^{18}O data for the Beypazarı granitoid plot close to the lower end of 'high δ^{18}O granite range. These I-type granites are classified as relatively high ^{18}O granitic rocks based on the classification of Taylor (1978, 1980) because they have δ^{18}O values greater than 10‰. These high δ^{18}O values suggest a crustal contribution in the infracrustal (i.e. lower crust) hybrid magma

source of these I-type granites (Boztuğ *et al.* 2007). A slight positive correlation between δ^{18}O values and SiO$_2$ is evident in the Beypazarı samples (Figure 10). They also plot above the boundary line between the magnetite- and ilmenite-series granitoids of southwest Japan, and in the magnetite-series field (see Ishihara & Matsuhisa 2002).

However, only one granitoid sample with a very low δ^{18}O value (06-451) shows a smaller δ^{18}O$_{fsp}$ and δ^{18}O$_{whole-rock}$ values (9.9 and 9.8 per mil, respectively) than all the others (10.6 to 10.7 per mil and 10.1 to 11.0 per mil, respectively), while their δ^{18}O$_{qtz}$ values are the same. Thus it appears that the lower whole rock oxygen isotope values (<10 permil) are probably related to a slight alteration (of the feldspars). The measured δ^{18}O$_{whole-rock}$ and dD$_{whole-rock}$, and the calculated δ^{18}O$_{H2O}$ and dD$_{H2O}$ values of the fluids from the minerals are plotted on Figure 11. Note that the
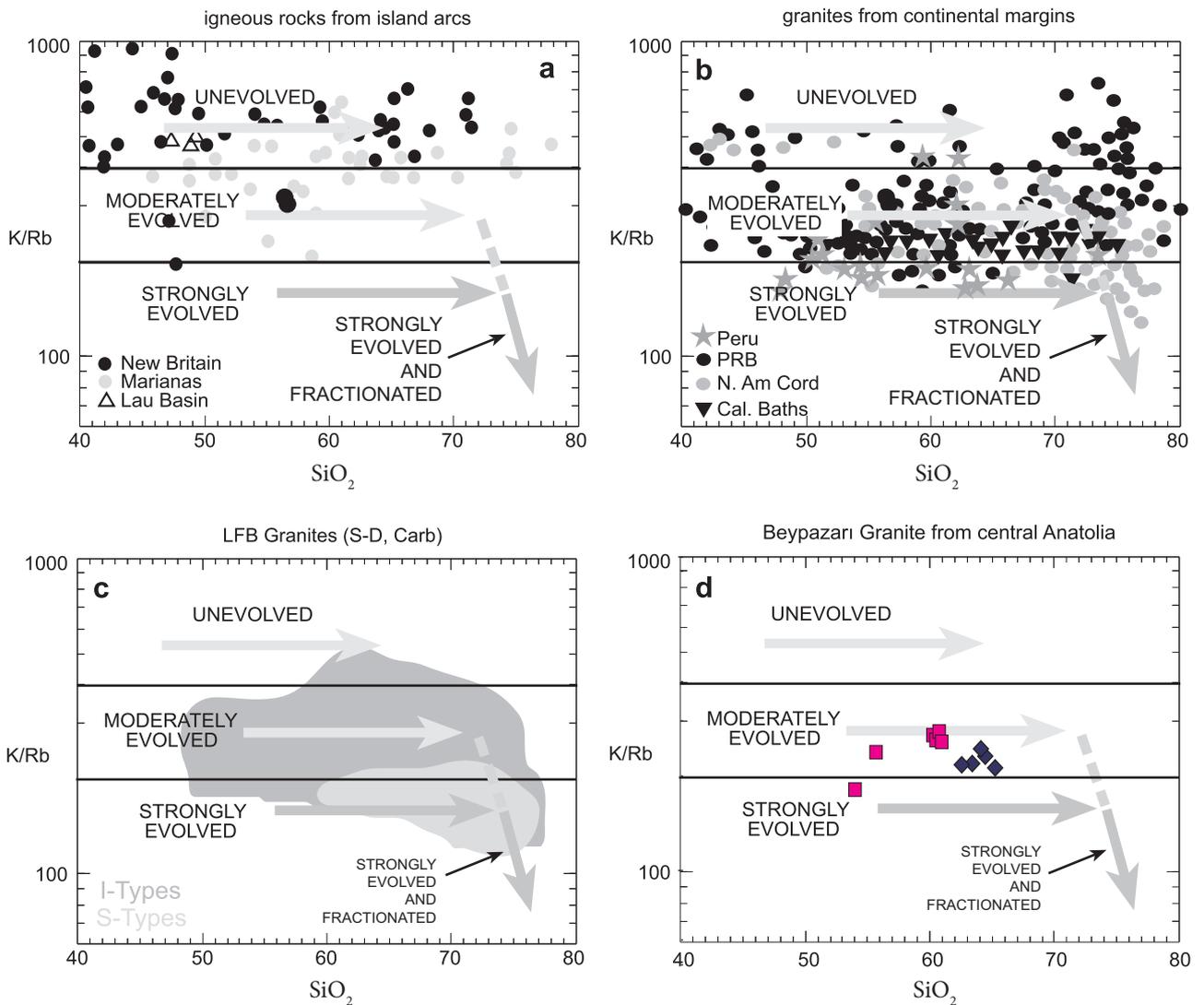
Figure 5. K/Rb classification scheme showing classification fields/typical trends for **(a)** igneous rocks from island arcs, **(b)** granites from continental margins, **(c)** I- and S-type granites (all data from Blevin 2004) and **(d)** the Beypazarı granitoid.

Beypazarı rocks studied here show no mineralogical evidence for extensive meteoric low-temperature alteration. This is confirmed for the hornblende and biotite samples by their oxygen and hydrogen isotope compositions, as measured in this study (Figure 11).

Mineral-mineral Fractionation – The $\delta^{18}O$ values for the analysed minerals are relatively high compared to the general range of granitic rocks, although the order of enrichment of ^{18}O quartz > K-feldspar > hornblende > apatite > biotite > magnetite is preserved in most cases. Under

equilibrium conditions, the O-isotope fractionation between quartz and constituent minerals (e.g., $\Delta_{qtz-fsp}$) should fall in the range of 0.5–2.0‰ at magmatic temperatures (Chiba *et al.* 1989). The analysis of quartz-feldspar oxygen isotope fractionation most often chosen for felsic igneous rocks is applicable here. The average $\Delta_{qtz-fsp}$ observed in the Beypazarı granitoid ranges from 1.1 to 1.9‰, indicating that the O-isotopes are in equilibrium in these samples. These isotopic characteristics demonstrate that the Beypazarı granitoid has not experienced post-emplacement open-system hydrothermal alteration.

◆ Tahir granodiorite
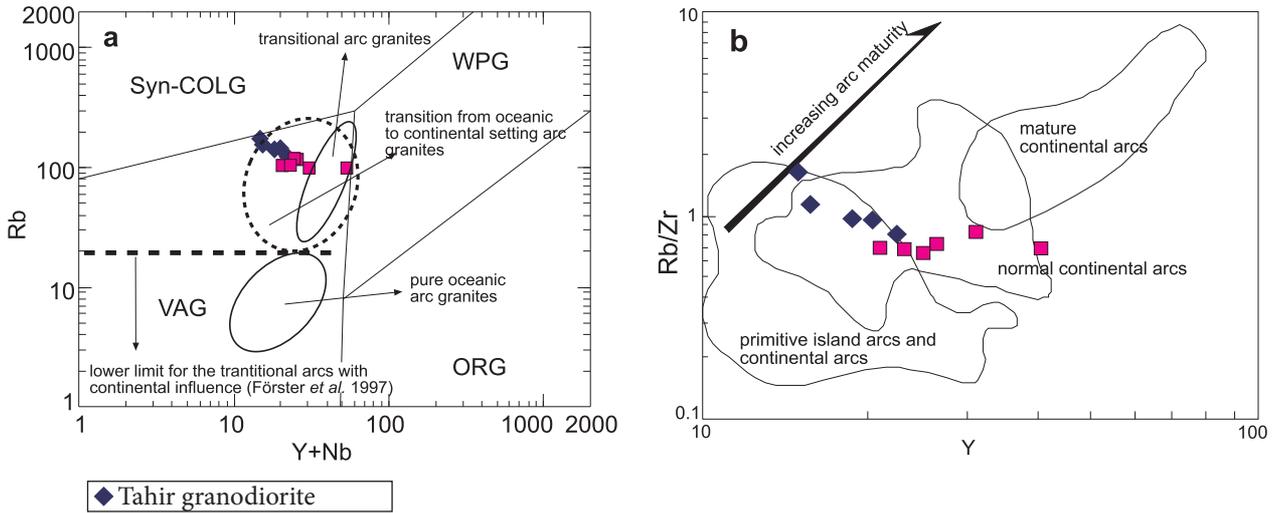
Figure 6. (a) Rb vs (Y+Nb) granitoid diagram discriminating the magma characteristics of the Beypazarı granitoid (field boundaries and nomenclature after Pearce *et al.* 1984). (b) Rb/Zr vs Y granitoid diagram to discriminate the magma characteristics of the Beypazarı granitoid (field boundaries after Brown *et al.* 1984).
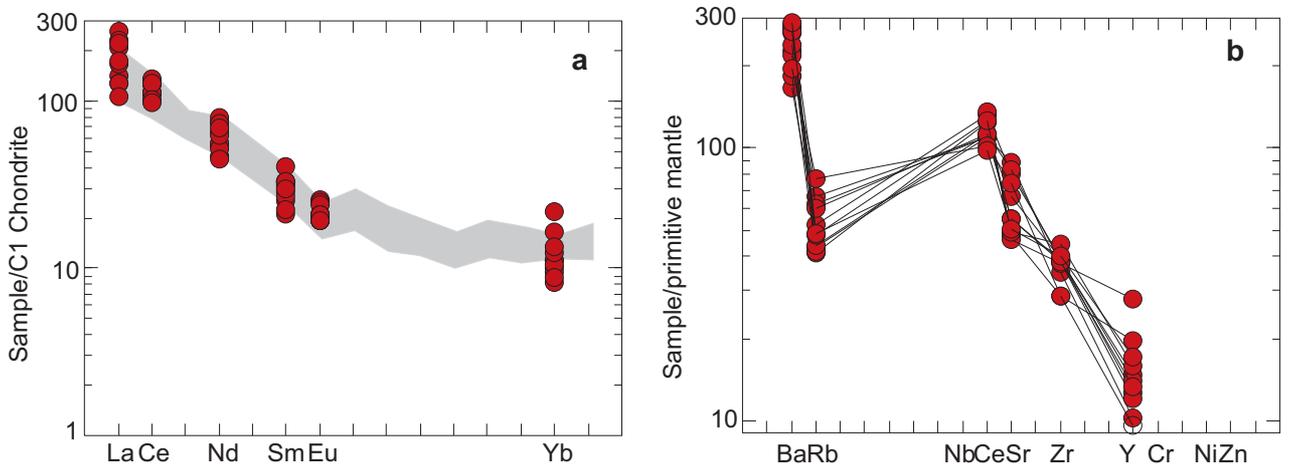

Figure 7. Primitive-mantle-normalized trace element abundances (normalizing values from Taylor & McLennan 1985) for the Beypazarı granitoid (grey field from Billur 2004).

Oxygen isotope results for quartz-feldspar pairs from the Beypazarı granitoid plotted in Figure 12, show that minerals from the unaltered pluton typically have quartz-feldspar fractionations of 0.5 to 2.0‰ (Pollard *et al.* 1991). Granites which exchanged oxygen isotopes with meteoric waters usually have larger fractionations due to lowering of $\delta^{18}O_{feldspar}$ during subsolidus reactions with meteoric hydrothermal fluids (Taylor 1979). In Figure 12,

following Gregory & Criss (1986) and Gregory *et al.* (1989), two diagonal lines denote the probable equilibrium isotopic fractionation between quartz and feldspar at magmatic temperatures. Data points for Beypazarı are similar to those of the Yiershi pluton, NE China (Wu *et al.* 2003) and fall in the equilibrium range.

According to Žak *et al.* (2005), the following conditions must be fulfilled to apply oxygen isotope
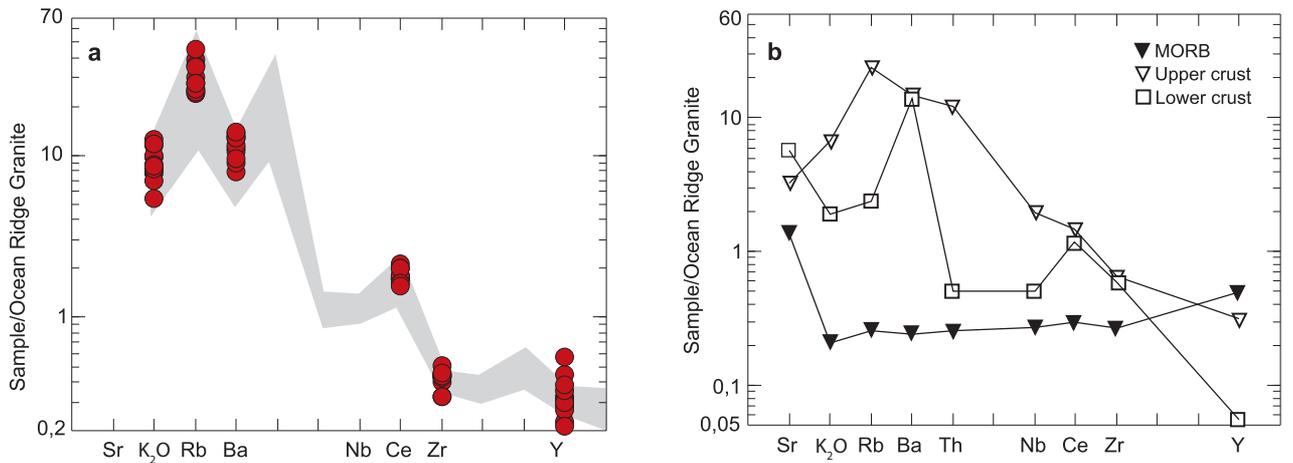
Figure 8. Ocean ridge granite (ORG)-normalized spider diagrams for **(a)** the Beypazarı granitoid (filled red circles) (grey field from Billur 2004); **(b)** MORB, upper crust and lower crust, for comparison. The normalizing values are from Pearce *et al.* (1984).

Table 2. Nd and Sr radiogenic isotope data of the Beypazarı granitoid.

Sample	Age	Sr	Nd	$^{87}Rb/^{86}Sr$	$^{87}/^{86}Sr$	$^{87}/^{86}Sr$ (i)	$^{147}Sm/^{144}Nd$	$^{143}/^{144}Nd$	$^{143}/^{144}Nd$(i)	eNd(T)	eNd(0)
06-451	75	399	22	0.7251	0.707809	0.70704	0.1297	0.512321	0.512257	−5.5	−6.2
06-459	75	641	30	0.6950	0.706211	0.70547	0.0789	0.512469	0.512430	−2.2	−3.3
06-461	75	481	25	0.8420	0.706837	0.70594	0.0777	0.512437	0.512399	−2.8	−3.9
06-463	75	585	26	0.5983	0.706225	0.70559	0.1028	0.512469	0.512419	−2.4	−3.3
06-464	75	605	35	0.6694	0.706203	0.70549	0.0867	0.512480	0.512437	−2.0	−3.1
06-465	75	346	37	0.8028	0.707818	0.70696	0.0804	0.512367	0.512328	−4.2	−5.3
06-466	75	333	34	0.8428	0.707699	0.70680	0.1107	0.512356	0.512302	−4.7	−5.5
06-467	75	399	24	0.7396	0.707687	0.70690	0.1037	0.512342	0.512291	−4.9	−5.8
06-468	75	358	21	0.8971	0.707899	0.70694	0.1446	0.512345	0.512274	−5.2	−5.7
06-469	75	537	29	0.9697	0.706328	0.70529	0.0712	0.512472	0.512437	−2.0	−3.2
06-470	75	367	32	0.8830	0.707845	0.70690	0.0873	0.512349	0.512306	−4.6	−5.6

thermometers in order to estimate the magmatic crystallization temperatures of a mineral pair; (1) an exchange of oxygen isotopes must have occurred between the two mineral phases at some stage during their common history (usually via a fluid phase), leading to isotopic equilibrium; (2) the isotopic equilibrium between the phases must be frozen in order to preserve the isotopic signal; (3) the isotopic composition of the minerals must not have been changed by later processes.

The $\Delta_{qtz\text{-}fsp}$ observed in the Beypazarı granitoid ranges from 1.1 to 1.9‰ and yields a temperature range from 481±5 to 675±10°C, using the equation of Matsuhisa *et al.* (1979) for $\alpha_{qtz\text{-}fsp}$ (T) (Table 3, Figure
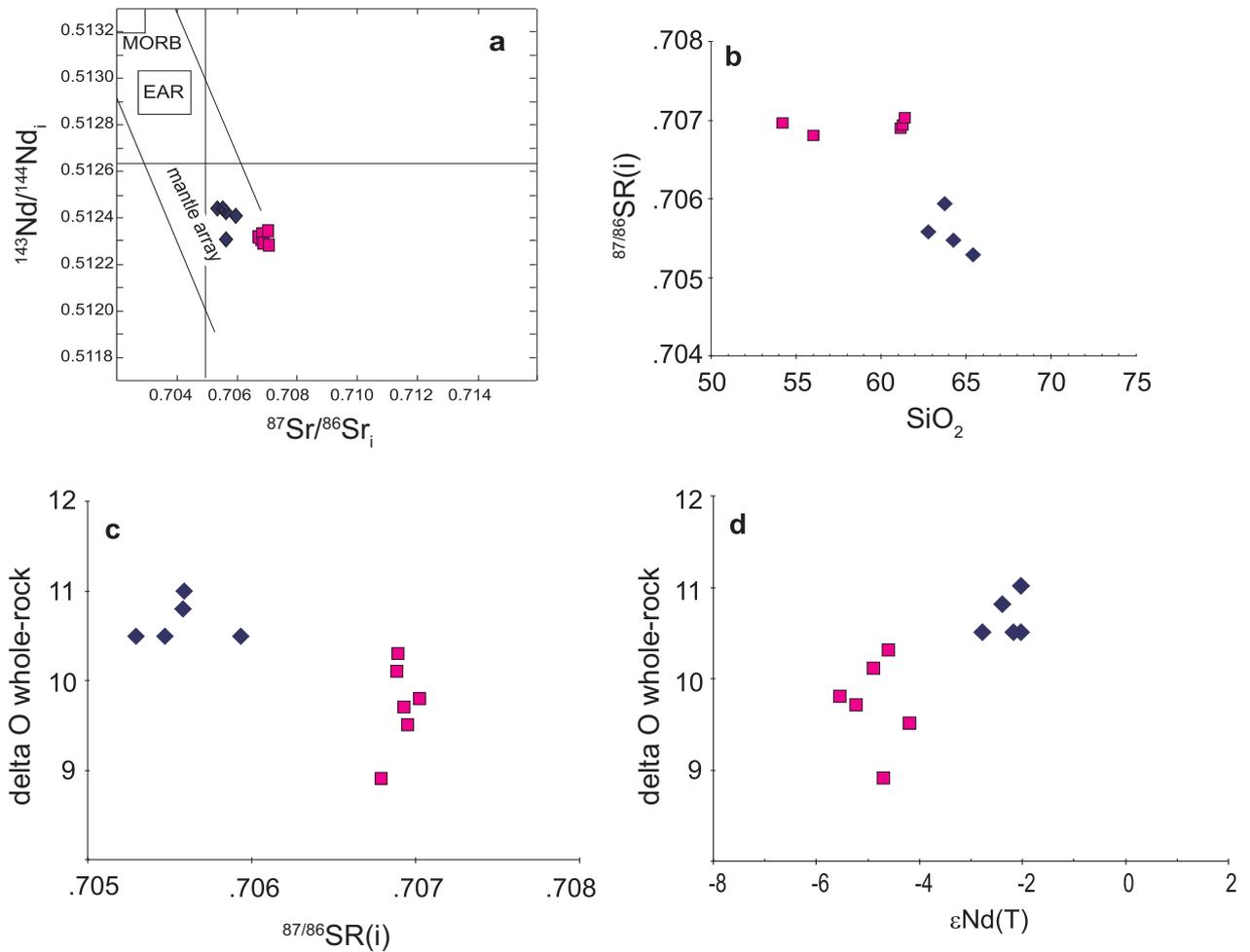
Figure 9. Nd and Sr isotopic compositions of samples from the Beypazarı granitoid; **(a)** $\varepsilon Nd_{(T)}$ values vs initial $^{87}Sr/^{86}Sr$ (Sr_i) isotopic ratios; **(b)** initial $^{87}Sr/^{86}Sr$ (Sr_i) isotopic ratios vs SiO_2; **(c)** delta O whole-rock values vs $^{87}Sr/^{86}Sr$ (Sri); and **(d)** delta O whole-rock values vs $\varepsilon Nd_{(T)}$ values.

13a). The quartz-feldspar pairs clearly do not reflect real crystallization temperatures in most cases, but closure temperatures of isotope exchange (Žak *et al.* 2005). A quartz-feldspar pair from the altered Podlesí granite (Krušné hory Mts., Czech Republic) shows lower $\delta^{18}O$ values for both quartz and feldspar, with a $\Delta^{18}O_{qtz-fsp}$ of 2.1‰, corresponding to a temperature of ~400°C (Žak *et al.* 2005). Only one sample (06-451) from the Beypazarı granitoid has lower $\Delta^{18}O_{qtz-fsp}$ of 1.9‰, corresponding to a temperature of ~481°C.

The observed $\Delta^{18}O_{qtz-bio}$ values, in samples 06-451, 06-467 and 06-470, range from 4.2 to 6.0‰ (Figure 13b). Oxygen isotope fractionations between quartz and biotite yield a temperature of 375±15 to 540±25°C, using the equation of Zheng

(1993) for $\alpha_{qtz-bio}$ (T). This range does not reflect real crystallization temperatures. This temperature range suggests re-equilibration below the solidus temperature. However, the $\Delta_{qtz-amph}$ and $\Delta_{qtz-mag}$ observed in the Beypazarı granitoid range from 3.5 to 3.9‰ and 7.2 to 8.4‰ and yield temperatures ranging from 550±25 to 605±30°C and 595±10 to 660±15°C, respectively. In theory, the $\delta^{18}O$ value of the fresh rock (and hence δ_{magma}) can be calculated from the mineral $\delta^{18}O$ values and modal proportions, provided that oxygen isotope data are available for all of the constituent minerals (Harris *et al.* 1997). Therefore, we can calculate the oxygen isotope composition of the fluid in equilibrium with these minerals and obtain $\delta^{18}O_{magma} = 7.7$ to 10.6‰ (Table 3).

Table 3. Stable isotope ratios for the whole-rocks and the single minerals from the Beypazarı granitoid.

| Sample Number	Coordinates of Samples	Mineral	δD (‰)	δ¹⁸O (‰)	Pair	Δ_{Q-X} (‰)	T (°C)	δ¹⁸O$_{magma}$ (‰)	δD$_{magma}$ (‰)
			(Measured)				(Calculated)		
06-451	0401199 E°/ 4426702 N°	Whole-rock	−60.1	9.8					
		Quartz		11.8					
		K-feldspar		9.9	Qtz-Feld	1.9	481±5	8.3	
		Hornblende	−46.0	8.3	Qtz-Hbl	3.5	605±30	10.6	−22.9
		Biotite	−60.2	5.8	Qtz-Bt	6.0	375±15	7.7	−9.8
		Magnetite		4.6	Qtz-Mag	7.2	660±15	10.6	
06-459	0416416 E°/ 4435610 N°	Whole-rock	−47.5	10.5					
06-461	0413969 E°/ 4432154 N°	Whole-rock	−45.1	10.5					
		Quartz		11.8					
		Apatite		7.6					
		K-feldspar		10.7	Qtz-Feld	1.1	675±10	10.1	
		Hornblende	−51.4	8.1	Qtz-Hbl	3.7	575±30	10.4	−26.1
		Titanite		6.6	Qtz-Ti	5.2	455±15	9.1	
		Magnetite		3.4	Qtz-Mag	8.4	595±10	9.9	
06-463	0410473 E°/ 4435001 N°	Whole-rock	−61.2	10.8					
06-464	0410795 E°/ 4435572 N°	Whole-rock	−56.0	11.0					
06-465	0401199 E°/ 4426702 N°	Whole-rock	−56.6	9.5					
06-466	0399257 E°/ 4420165 N°	Whole-rock	−46.6	8.9					
06-467	0399033 E°/ 4417249 N°	Whole-rock	−67.0	10.1					
		Quartz		11.7					
		Apatite		6.9					
		K-feldspar		10.6	Qtz-Feld	1.1	675±10	10.0	
		Hornblende	−48.0	7.9	Qtz-Hbl	3.8	565±25	10.2	−21.9
		Biotite	−54.5	5.9	Qtz-Bt	5.8	390±15	7.9	−6.5
		Magnetite		4.4	Qtz-Mag	7.3	655±15	10.5	
06-468	0397187 E°/ 4419216 N°	Whole-rock	−63.6	9.7					
06-469	0405174 E°/ 4432080 N°	Whole-rock	−66.0	10.5					
		Hornblende	−59.5						
06-470	0393289 E°/ 4424995 N°	Whole-rock	−75.4	10.3					
		Quartz		11.6					
		Apatite		7.5					
		K-feldspar		10.5	Qtz-Feld	1.1	675±10	9.9	
		Hornblende	−68.4	7.7	Qtz-Hbl	3.9	550±25	9.9	−41.0
		Biotite	−65.8	7.4	Qtz-Bt	4.2	540±25	9.9	−34.8
		Magnetite		4.2	Qtz-Mag	7.4	650±10	10.4	
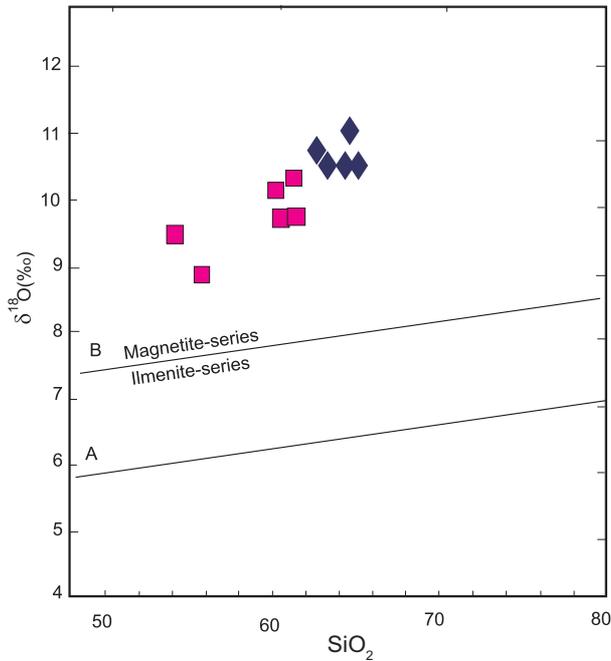
Figure 10. $\delta^{18}O_{whole-rock}$(‰) vs SiO_2 for the Beypazarı granitoid. Line A, tholeiitic trend of volcanic rocks in the Hachijo-jima (Matsuhisa 1979). Line B, boundary line between the magnetite-series and ilmenite-series granitoids of Southwest Japan (see Ishihara & Matsuhisa 2002).

Estimation of the $\delta^{18}O$ Value of the Original Magmas (δ_{magma})

Generally oxygen isotope ratios of whole-rock samples are vulnerable to effects of post-crystallization, sub-solidus alteration. For some granites, little or no interaction with external fluids seems to have taken place (e.g., the Berridale batholith in eastern Australia, O'Neil & Chappell 1977; Manaslu granite, Himalaya, France-Lonard *et al.* 1988) and the whole-rock oxygen isotope ratios probably reflect quite closely the original magma values. Other granites have been subjected to extensive exchange with external fluids which has shifted the original magmatic $\delta^{18}O$ values. Some Pyrenean Hercynian granites (Wickham & Taylor 1987), the Idaho batholith, many other Tertiary batholiths of the western USA (Criss *et al.* 1991) and some Caledonian granites of Britain (Harmon 1984) fall into this category.

In this section, the $\delta^{18}O$ value for the original magma (δ_{magma}) has been calculated from the $\delta^{18}O$ values of quartz (and consistuent minerals). In slowly cooled coarse-grained rocks (e.g., the Cape granites, Harris *et al.* 1997), the difference between the $\delta^{18}O$ value of quartz and δ_{magma} is not only dependent on
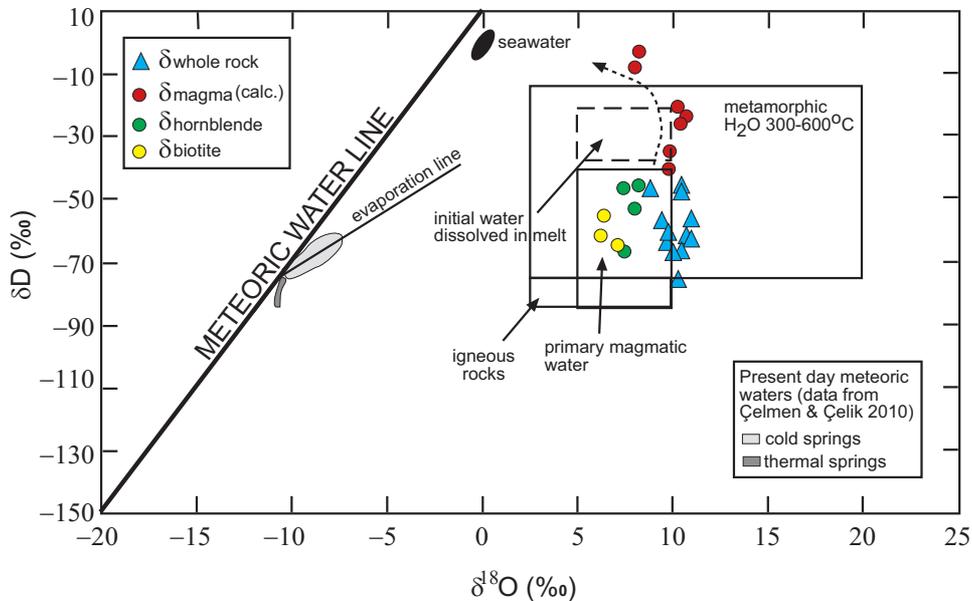

Figure 11. Measured and calculated $\delta^{18}O$ vs dD compositions for the Beypazarı granitoid. Fields for seawater, meteoric waters, primary magmatic waters and metamorphic waters (Sheppard 1986) are shown for comparison.
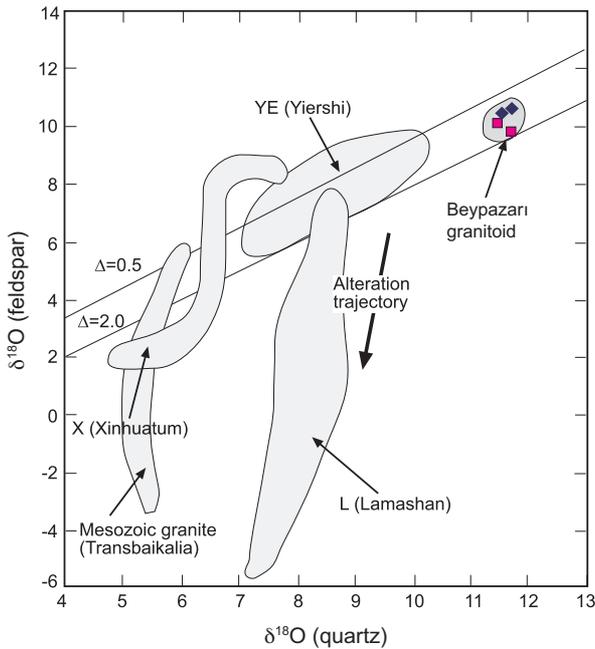
Figure 12. Feldspar $\delta^{18}O$ vs quartz $\delta^{18}O$ diagram. Two lines with constant $\Delta_{qtz-feld}$ values represent possible isotopic fractionation between quartz and feldspar at magmatic temperatures. The data for the rocks from Transbaikalia and Yiershi, Xinhuatun, Lamashan are from Wickham *et al.* (1996) and Wu *et al.* (2003) respectively.

$\Delta_{qtz-melt}$, but is also dependent on grain-size, the rate of cooling, and the temperature of closure of the mineral to oxygen diffusion (e.g., Giletti 1986; Jenkin *et al.* 1991). Larger grain size generally results from slower cooling, which in turn means that oxygen diffusion and re-equilibrium continues for a greater period of time. The difference between the $\delta^{18}O$ value of quartz and the other constituent minerals in a slowly cooled rock will be larger than for a more rapidly cooled rock. To correct for these 'closure' effects $\Delta_{quartz-magma}$ was assumed to be +1‰ in the quartz porphyries (e.g., Taylor & Sheppard 1986) and +2‰ in the remaining granites, which are relatively coarse-grained (see Giletti 1986). The average $\Delta_{qtz-fsp}$ observed in the Beypazarı granitoid is +1.3‰ (range 1.1 to 1.9‰, Table 3). The whole rock $\delta^{18}O$ of the Beypazarı granitoid and granite magma (δ_{magma} calculated from quartz and constituent minerals $\delta^{18}O$ values) are presented in Figure 14. The $\delta^{18}O$ values calculated for the granite magmas range from 7.7 to 10.6‰.
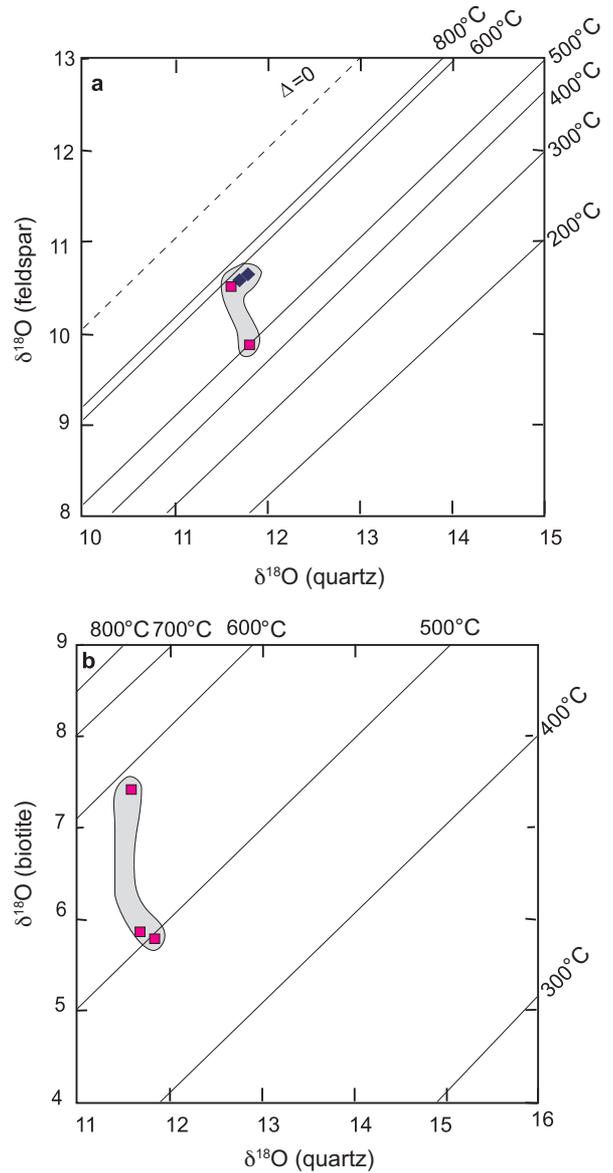
Figure 13. Oxygen isotope data of **(a)** quartz-feldspar and **(b)** quartz-biotite pairs for the Beypazarı granitoid. Isotherms are based on the formula of Bottinga & Javoy (1975).

The variation of quartz $\delta^{18}O$ value with selected major element oxides from the Beypazarı granitoid (Figure 15) displays generally weak correlations: quartz $\delta^{18}O$ values exhibit weak positive correlations with SiO_2 (r= 0.5898) and Na_2O (r= 0.5909) while there is a weak negative correlation of $\delta^{18}O$ value with Al_2O_3 (r= –0.1252) and Fe_2O_3 (r= –0.4368). The overall poor correlation of oxygen isotope variations
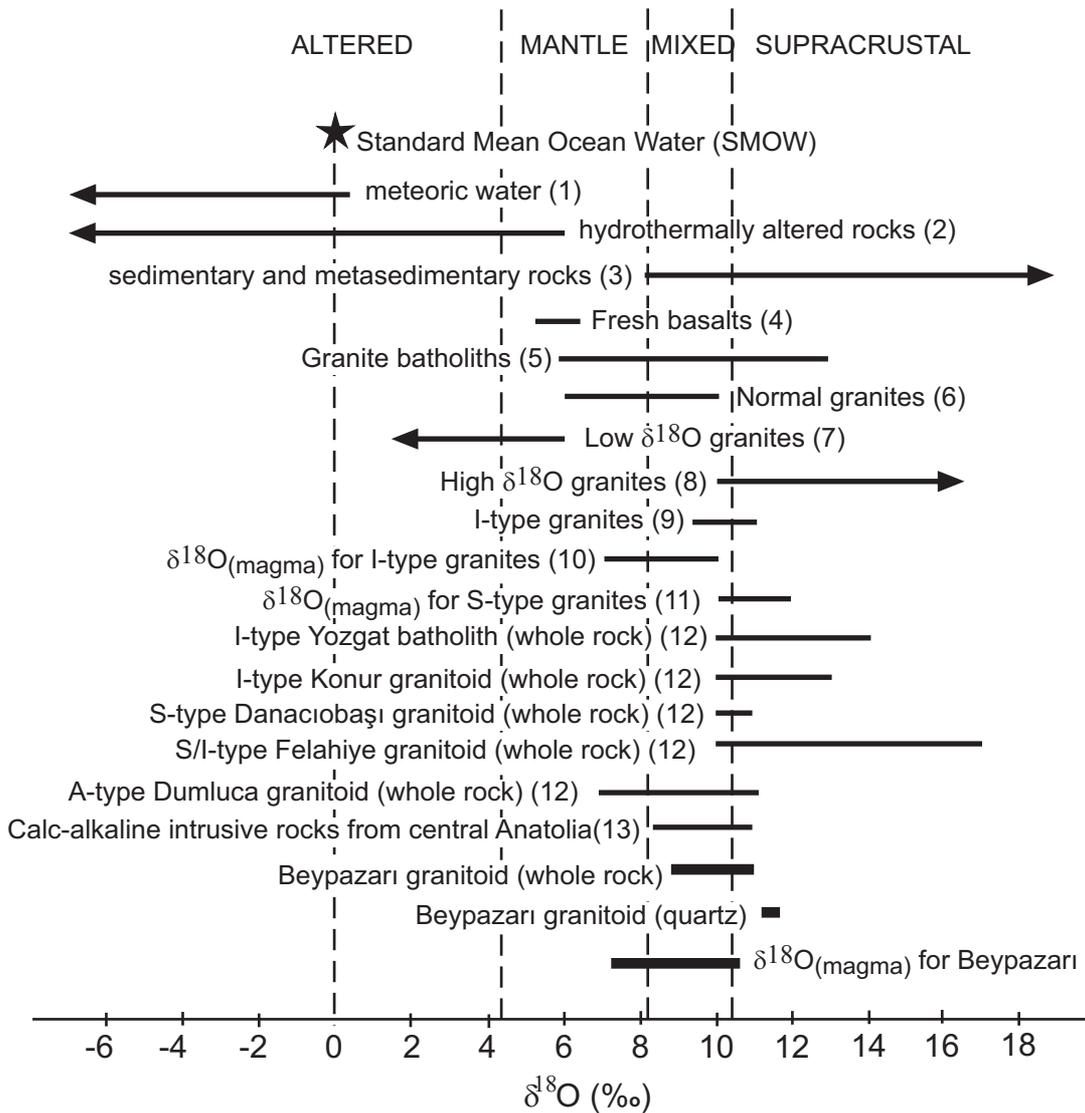
Figure 14. Oxygen-isotopic composition of the Beypazarı granitoid compared to those of typical terrestrial materials, granitoids and some S-I-A type granites from published literature data from central Anatolia. 1– Craig (1961); 2– Ohmoto (1986); 3, 4 and 5– Taylor & Sheppard (1986); 6, 7 and 8– Taylor (1978); 9, 10 and 11– Harris *et al.* (1997); 12– Boztuğ & Arehart (2007); and 13– İlbeyli *et al.* (2009). Dividing lines between altered, mixed, mantle and supracrustal rocks are taken from Whalen *et al.* (1996).

with major elements probably results from the combination of several processes, such as differences in source composition, crystal fractionation, and crustal contamination (Harris *et al.* 1997). Of these processes, crystal fractionation has little effect (≤ 1‰) on $\delta^{18}O$ values (e.g., Sheppard & Harris 1985), which is why oxygen isotopes are a powerful indicator of source composition and/or degree of crustal contamination (Harris *et al.* 1997).

Hydrogen Isotopes

Samples from the Beypazarı granitoid (Table 3) have whole rock δD values ranging from –75.4 to –45.1‰, with a mean value of –59.0. The biotite and hornblende from the Beypazarı granitoid have δD values which range from –65.8 to –54.5‰ and –68.4 to –46.0 respectively. In two samples (06-467 and 06-470), $\delta D_{whole-rock}$ values (–67.0 and –75.4
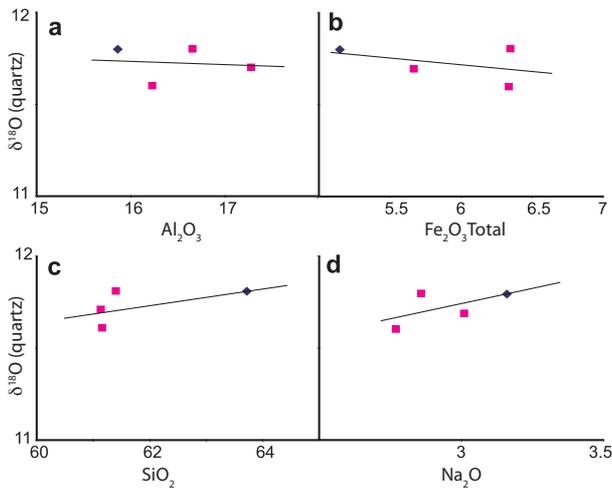
Figure 15. δ¹⁸O of quartz separated from the Beypazarı granitoid vs SiO_2, Al_2O_3, Fe_2O_3 and Na_2O content.

permil, respectively) are not consistent with the sum of the separated mineral analyses of hornblende and/or biotite (−51.2 and 67.1 per mil, respectively). The reason for these discrepancies is that there are hydrous mineral present, e.g., some sericite, in feldspars. The D/H ratios of the granite magma have been calculated from those of biotite and hornblende, using the equations from Suzuoki & Epstein (1976) and Graham *et al.* (1984). However, the D/H ratios of the granite magma have been estimated from those of the biotite, using a value of $\Delta_{\text{biotite-magma}}$ of −30‰ (Suzuoki & Epstein 1976) which corresponds to a temperature of about 800°C for the Fe/Mg ratio observed.

δD Values of Original Magmas

The factors which determine the final δD value of minerals are (France-Lanord *et al.* 1988) (1) the chemical composition of the minerals; (2) the temperature of crystallization; and (3) the δD value of the hydrogen present, which could include water dissolved in the magma, exsolved magmatic water and/or circulating meteoric waters. Degassing of water from magmas leads to a progressive decrease in δD value of the remaining melt (Taylor *et al.* 1983; France-Lanord *et al.* 1988). The Beypazarı granitoid has low LOI, between 0.37 and 1.24 (mean 0.72 wt%), which means that it presumably suffered

extensive degassing of water during crystallization, with resulting shifts to lower magma δD value as crystallization proceeded (Harris *et al.* 1997).

Discussion

Petrogenetic Considerations

Petrogenetic models for the origin of felsic arc magmas fall into two broad categories (Thuy *et al.* 2004). Firstly, felsic arc magmas are derived from basaltic parent magmas by assimilation and fractional crystallization or AFC processes (e.g., Grove & Donelly-Nolan 1986; Bacon & Druitt 1988). The second model is that basaltic magmas provide heat for the partial melting of crustal rocks (e.g., Bullen & Clynne 1990; Roberts & Clemens 1993; Tepper *et al.* 1993; Guffanti *et al.* 1996). The first model is considered to be unlikely, because volcanic and granitoid rocks of the Beypazarı province are voluminous and none are of basaltic composition (all samples have SiO_2 content >56%, Figure 4). Such voluminous felsic magmas could not be generated by differentiation of mantle-derived mafic magmas (Thuy *et al.* 2004). Furthermore, the rock compositions do not represent a fractionation sequence from basalt to granodiorite or leucogranite. Rocks for all four subunits show quite significant variations in initial Sr-isotope ratios and δ¹⁸O values with SiO_2 (Figures 9b & 10), which does not support derivation from mafic magmas through AFC processes.

Fractional Crystallization

Increasing SiO_2, K_2O, Rb, and decreasing TiO_2, Fe_2O_3, CaO, MgO and Al_2O_3 contents shown in the Beypazarı granitoid are compatible with its evolution through fractional crystallization processes (Figures 3 & 4). On a K_2O-SiO_2 diagram (Figure 3f), samples display a positive trend, indicating that K_2O is reflecting fractionation. Decrease in TiO_2 with increasing SiO_2 content is attributed to fractionation of titanite. The fractionation of accessory phases such as zircon and titanite may account for depletion of zirconium and yttrium. A Na_2O-SiO_2 diagram (Figure 3g) does not give any specific trend: only a slight decrease in Na_2O content occurs with increasing silica content. Since Na is present in plagioclase, it should have

increased with silica (Billur 2004). This opposite trend may occur because of two reasons: either Na_2O is controlled by hornblende rather than plagioclase, or plagioclase crystallized in the early stages, whereas in the late stages K-feldspar crystallized, rather than plagioclase (Yohannes 1993). The Beypazarı samples display moderate concave upward REE patterns and relative depletion of middle REE with respect to HREE (Figure 7a), which can be attributed to fractionation of hornblende and/or titanite (e.g., Romick *et al.* 1992; Hoskin *et al.* 2000). The Beypazarı granites have high SiO_2 contents, indicating that parental magmas for the Beypazarı granites have experienced extensive magmatic differentiation (Whalen *et al.* 1987).

Nature of Parental Magmas and Potential Sources

The Beypazarı granitoid is a high-K calc-alkaline rock, characterized by pronounced negative Ba, Sr and Nb anomalies and Rb, K and La enrichment. These features are compatible with those of typical crustal melts, e.g., granitoids of the Lachlan fold belt (Chappell & White 1992), or Himalayan leucogranites (Harris *et al.* 1986; Searle & Fryer 1986), so its derivation from crustal sources is indicated. The heterogeneity of initial Sr and Nd isotope values are also consistent with this interpretation. Compositional differences of magmas produced by partial melting under variable melting conditions of different crustal source rocks such as amphibolites, gneisses, metagreywackes and metapelites, may be visualized in terms of major oxide ratios (Thuy *et al.* 2004). Partial melts originating from mafic source rocks, for example, have lower $Al_2O_3/(FeO_{tot}+MgO+TiO_2)$ and $(Na_2O+K_2O)/(FeO_{tot}+MgO+TiO_2)$ than those derived from metapelites (Figure 16). The Beypazarı rocks have lower values of $Al_2O_3/(FeO_{tot}+MgO+TiO_2)$, $(Na_2O+K_2O)/(FeO_{tot}+MgO+TiO_2)$ and a rather high range of $(CaO)/(FeO_{tot}+MgO+TiO_2)$ ratios. This chemistry precludes a derivation from felsic pelite and metagreywacke rocks. Instead, the Beypazarı magmas were generated by partial melting of alkaline mafic lower crustal source rocks. On the Na_2O-K_2O diagram (Figure 2d), the Beypazarı samples plot in the field outlined for typical I-type granite of the Lachlan fold belt (White & Chappell 1983).
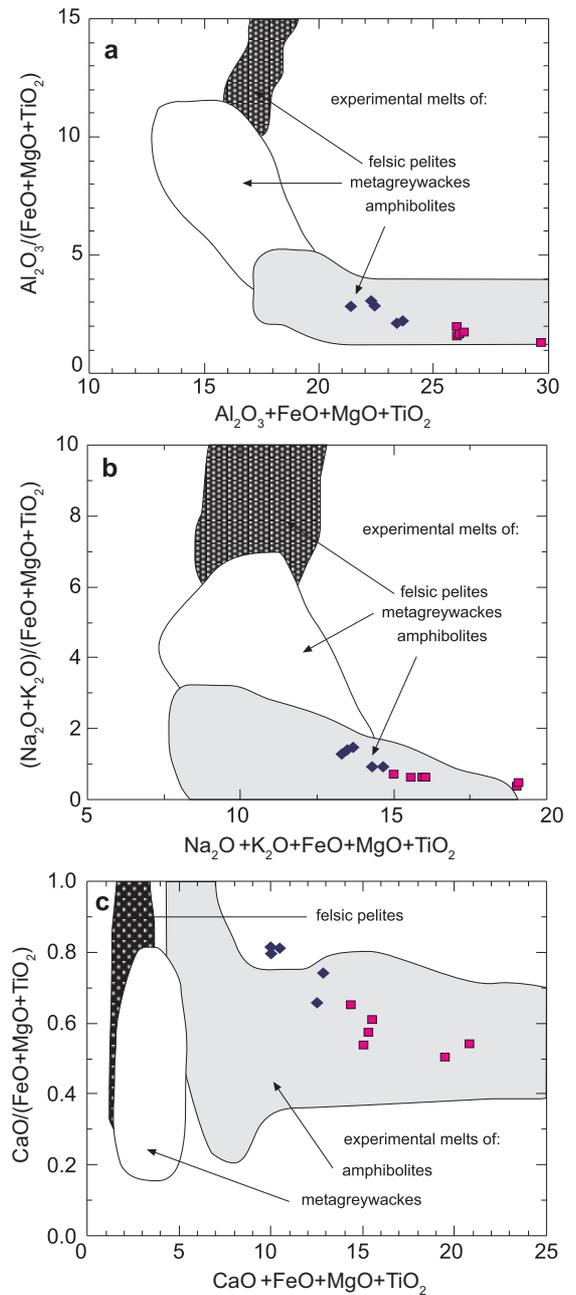
Figure 16. **(a–c)** Plots show compositional fields of experimental melts derived from partial melting of felsic pelites, metagreywackes and amphibolites (Patiño Douce 1999) and compositions of studied samples.

Stable Isotopic Relationships Between Rock-forming Minerals

The observed $\delta^{18}O$ data for quartz and silicate minerals are the result of the combined effects of magmatic evolution and post-magmatic

hydrothermal events (Žak *et al.* 2005). The existence of oxygen isotope equilibrium between coexisting minerals can be evaluated by the use of d-d plots (Gregory & Criss 1986; Gregory *et al.* 1989). In the d-d diagrams (Figure 12), the data from the Beypazarı granitoid samples show a relatively constant per mil difference (Δ) between the two minerals, indicating constant temperature crystallization of minerals from magmas of different $^{18}O/^{16}O$ ratios (Harris *et al.* 1997). Of the common rock-forming minerals in granitic rocks, the feldspars are usually the most sensitive to later isotope exchange. In the Beypazarı stock, the direct sub-solidus oxygen isotope exchange between minerals was probably very limited. The $\delta^{18}O$ values of feldspar and quartz, and biotite and quartz are generally well correlated for the Beypazarı granitoid (Figure 13). The observed narrow range of Δ_{qtz-bt} and $\Delta_{qtz-fsp}$ values is the result of isotope exchange between minerals and high-$\delta^{18}O$ magmatic fluids at sub-magmatic temperatures in a system open to fluid phases, and indicates that there was no infiltration of external fluids with slightly lower $\delta^{18}O$ (Žak *et al.* 2005). Figure 13a, b does not show the Beypazarı granitoid having the steep positively sloping data arrays expected for hydrothermal alteration, suggested that exchange with external hydrothermal fluids was not important.

The Origin of High $\delta^{18}O$ Magmas

Based on material-balance calculations, Taylor & Sheppard (1986) concluded that during magma differentiation the $\delta^{18}O$ of the melt usually increases slightly (bulk cumulates are usually slightly lower in $\delta^{18}O$ than the residual silicate melt). The calculations of Zhao & Zheng (2003) verified the following sequence of ^{18}O enrichment: felsic rocks>intermediate rocks>mafic rocks>ultramafic rocks. Nevertheless, the bulk $\delta^{18}O$ value of a melt does not usually change by more than 0.2 to 0.8‰ during magmatic differentiation. Based on the increment method model calculation, Zhao & Zheng (2003) concluded that for common magmatic rocks there is negligible oxygen isotope fractionation between the melt and the rock of the same composition.

The measured $\delta^{18}O$ whole-rock values of the Beypazarı granite samples (Table 3) range between 8.9 to 11.0‰ (VSMOW). Harris *et al.* (1997) distinguished between S- and I-type (or A-type) granites using the $\delta^{18}O$ data from quartz, as this mineral is relatively insensitive to later alterations. The observed quartz $\delta^{18}O$ values from the Beypazarı granitoid range from 11.6 to 11.8‰ (Table 3), which is within the range of I- type, high ^{18}O-granites. Boztuğ & Arehart (2007) found different $\delta^{18}O$ for the Yozgat batholith granites in central Anatolia. The Beypazarı granitoid is similar to the Yozgat batholith. Both granites are fractionated and represent similar genetic types from the perspective of granite geochemistry. Boztuğ & Arehart (2007) found practically identical $\delta^{18}O$ whole-rock values between 11.8 and 13.6‰ (SMOW) for the Yozgat batholith granites.

High-$\delta^{18}O$ magmas are usually interpreted as having a crustal origin (Sheppard 1986; Taylor & Sheppard 1986). A crustal origin for the Beypazarı granitoid melts is further supported by their high initial $^{87}Sr/^{86}Sr$ ratio of ~0.707.

Tectonic Setting

The Beypazarı granitoids are high-K, calc-alkaline rocks enriched in LILE (such as Rb) with respect to the HFSE (especially Nb) (Figure 7). Magmas with these chemical features are generally believed to be generated in subduction-related environments (e.g., Floyd & Winchester 1975; Rogers & Hawkesworth 1989; Sajona *et al.* 1996). The trace element data could be used in the discrimination of tectonic or geological provinces associated with particular magma types (Pearce *et al.* 1984). In the Rb-Y+Nb diagram, values from the Beypazarı granitoid plot in the VAG field and also in transition zone from an oceanic to continental setting of granites (Förster *et al.* 1997) (Figure 6). These VAGs belong to the group of 'active continental margin' rocks (Group C after Pearce *et al.* 1984). They contain biotite and hornblende, are metaluminous to weakly peraluminous and have the characteristics of I-type granites (Figure 2c) (White & Chappell 1983; Chappell & White 1992). Further argument in favour of volcanic arc characteristics for the Beypazarı granitoids comes from their low Rb/Zr values (<1.6 in almost all samples) which are compatible with volcanic arc settings (Harris *et al.* 1986). Note that trace element compositions of magmas are also dependent on protolith composition, and therefore, may not necessarily indicate the tectonic setting of

magma formation (e.g., Roberts & Clemens 1993). However, the spatial and temporal relationship of the Beypazarı granitoids, in conjuction with their geochemical and mineralogical data, indicates a subduction-related origin.

Conclusion

The Beypazarı granitoids have I-type characteristics and belong to the high-K calc-alkaline series and occur as two different rock-types in the area, namely the Tahir quartz-diorite and the Yalnızçam diorite. The geochemical and isotopic compositions of the Beypazarı granitoids indicate derivation by dehydration melting of alkaline mafic lower crustal source rocks.

The major and trace element compositions of the Beypazarı granitoids indicate that they are continental arc subduction-related products. Based on the available data, the Beypazarı granitoids were derived primarily from reworked continental crust (from a subduction modified magma and metasomatized mantle source with considerable crustal contribution).

The oxygen isotope systematics of the Beypazarı granitoid samples results from the activity of high-δ^{18}O fluids (magmatic water) while no major involvement of low-δ^{18}O fluids (meteoric water) is evident. No stable isotope evidence was found to suggest that extensive interaction of granites with hydrothermal fluids occurred and this is consistent with the lack of large-scale base-metal mineralization. High-δ^{18}O magmas are usually interpreted as having a crustal origin. High δ^{18}O values in S-type granites are traditionally interpreted as indicating isotopic inheritance from the metasedimentary source rocks. But, for the Beypazarı granitoid, mainly amphibolitic rocks were melted. So fluid-rock interaction has probably changed the oxygen isotope composition of the amphibolitic protoliths, and low-T oceanic alteration is the most probable mechanism to produce the high $\delta^{18}O_{magma}$ in mafic protoliths.

Acknowledgements

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