Mantle Source Characteristics of Alkali Basalts and Basanites in an Extensional Intracontinental Plate Setting, Western Anatolia, Turkey: Implications for Multi-stage Melting

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Abstract

The alkaline volcanic province of Western Anatolia is characterized by intra-continental plate alkali olivine basalts and basanites extruded along localized extensional basins during Late Miocene (<11 Ma) to Quaternary (>0.13 Ma) time. The rocks are characterized by low \(^{87}\)Sr/\(^{86}\)Sr (0.70311–0.70325) and high \(^{143}\)Nd/\(^{144}\)Nd (0.51293–0.51298) ratios; they have OIB-like trace-element patterns characterized by enrichment in LILE, HFSE, and L-MREE, and a slight depletion in HREE relative to N-MORB. Trace-element modeling indicates that the mafic magmas formed by variable degrees (–2% –10%) of partial melting of an isotopically homogenous garnet-bearing mantle source. The degree of melting decreased progressively from early-formed alkali olivine basalts to later basanites. Major- and trace-element systematics reveal two distinct depth ranges of melt segregation from the source mantle: (1) garnet and spinel + garnet stability zone for the Late Miocene rocks; and (2) spinel and spinel + garnet stability zone for the Quaternary rocks. Source concentrations, calculated using an inverse numerical method, show that the mantle from which the alkaline magmas were generated was enriched in all incompatible elements (e.g., LILE, HFSE, and L-MREE) relative to depleted MORB mantle (DMM) and primitive mantle (PM) compositions. The isotopically depleted nature of the alkaline rocks relative to bulk silicate earth (BSE) further indicates that this enrichment is a recent event related to small-degree, multi-stage melting processes that involve local metasomatism of the mantle.

Introduction

Basaltic magmas in intra-continental extensional settings are generally inferred to form by pressure-release partial melting of an upwelling mantle plume or mantle asthenosphere close to the base of the subcontinental mantle lithosphere (e.g., White and McKenzie, 1989). Alternatively, small volumes of primary melts may originate by direct melting of mantle lithosphere as a consequence of thermal perturbation. Trace-element and isotopic studies of primary basaltic magmas erupted within continental environments record geochemical fingerprints and the evolutionary history of the source reservoirs from which they came.

The Late Miocene–Quaternary alkaline volcanic province of Western Anatolia comprises a series of scattered outcrops of mafic lavas extruded along localized extensional basins (Fig. 1). In recent years, a number of attempts have been made to provide constraints on the genesis of the alkaline magmatism in the area. The common belief is that the formation of these volcanics is related to late-stage extension reflecting lithospheric thickening followed by orogenic collapse and lithospheric spreading (e.g., Seyitoğlu et al., 1997; Aldanmaz et al., 2000). However, identification of the source region and its characteristics is still controversial. McKenzie and O’Nions (1995) used REE data to propose that extensional basic volcanic rocks of Western Anatolia represented melts generated within the mantle lithosphere that had previously been enriched by melt fractions from the asthenosphere. Controversially, Aldanmaz et al. (2000) used trace-element and isotope data to propose that subduction-modified mantle lithosphere is unlikely to have been involved in the genesis of the alkaline magmas of Western Anatolia, and thus they suggested a mantle asthenospheric source.

This work presents a new temporally controlled geochemical data set for the lava sequences of the basic alkaline suite of Western Anatolia, and suggests a modeled basis for alkaline suite genesis in an attempt to document: (1) the characteristics of
the mantle source in terms of mineralogy and chemical composition; (2) the melting processes that formed the alkaline magmas; and (3) the possible effects of shallow-level processes such as fractional crystallization and crustal contamination on mantle-derived (primary) magma(s).

Geological Setting and the Distribution of the Volcanic Rocks

The neotectonic evolution of Anatolia has been dominated by the collision of the African and Arabian plates with the Eurasian plate along the Izmir-
Ankara suture zone to the west and along the Bitlis-Zagros suture zone to the east (Dewey et al., 1986). The main collision that took place between the Anatolian and Arabian plates along the Bitlis-Zagros suture zone led to major crustal shortening and uplift in Eastern Anatolia and caused the westward escape of the wedge-shaped Anatolian microplate by right-lateral strike-slip along the North Anatolian fault (NAF) and left-lateral strike-slip along the East Anatolian fault (EAF). The effect of the major, dextral, E-W–trending strike-slip activity along the NAF was that the movement of the Anatolian plate relative to the Pontides changed from westward to southwestward (Fig. 1). This generated small pull-apart basins related to NE-SW–trending strike-slip faulting in the northern part of Western Anatolia (the Biga Peninsula) and E-W–trending normal faults with significant strike-slip movements linked to graben formation in the central and southern parts of Western Anatolia during Late Miocene–Quaternary time.

The geological and seismological analyses of Zanchi and Angelier (1993) show that the Quaternary stress regime of Western Anatolia is dominantly extensional in association with NNE-SSW- and NE-SW–trending normal faults. Although strike-slip mechanisms are subordinate in the south, there is an increase of strike-slip faulting from south to north, toward the Biga Peninsula.

Alkaline volcanic rocks in the area are exposed in two different localities: (1) the Biga Peninsula, between the towns of Ayvacik and Çanakkale to the north; and (2) the Kula volcanic area to the south (Fig. 1A). In the Biga Peninsula, the volcanic field comprises a number of subhorizontal lava flows lying in the localized extensional basins formed by strike-slip movements related to the activation of the North Anatolian Fault. From the distribution of the eruption centers, a predominant N-S volcanic trend is recognized (Fig. 1B). The rocks in this area are mainly fine-grained olivine-phyric or aphyric basalts and basanites. The published radiometric dates (K-Ar) show that the alkaline volcanic activity lasted from 11.0 ± 0.4 Ma to 8.3 ± 0.3 Ma (Erkan et al., 1995; Aldanmaz et al., 2000).

In the Kula volcanic field, volcanic activity formed a number of small cinder cones with lava flows and tephra deposits. The volcanic field comprises more than 100 eruption centers including parasitic cones, main craters, and vents from which the pyroclastic materials and lavas were ejected. Cinder cones are generally <1 km in basal diameter and <100 m high, indicating a low flow rate to the surface. The cones consist of thin (~50 cm thick) lava sheets interleaved with conical layers of scoria. Lavas erupted along NNW-SSE–trending normal faults bordering one of the active normal faulting grabens of Western Anatolia known as the Alasehir graben (Fig. 1C). The volcanic field lies to the north of the graben. Richardson-Bunbury (1996) reported Ar-Ar ages of between 1.94 ± 0.16 and 0.13 ± 0.05 Ma for the Kula lavas.

**Analytical Techniques**

Rock powders were prepared by removing the altered surfaces, crushing, and then grinding in an agate ball mill. Major and selected trace-element abundances of a total of 23 samples from the Biga Peninsula were measured on fused discs and pressed powder pellets, respectively, using an automated Philips PW1400 XRF spectrometer with a rhodium anode tube at the University of Durham. Loss on ignition (L.O.I.) was determined by heating a separate aliquot of rock powder at 900°C for ≥2 hr.

A subset of 12 samples was dissolved and analyzed by ICP-MS at the University of Durham for a total of 36 minor and trace elements. Errors and analytical precision are given in Peate et al. (1997).

The Kula samples, together with an additional set of 11 samples from the Biga Peninsula, were analyzed at the ACME analytical laboratories at Vancouver. Rock powders were fused and then dissolved to prepare the solutions from which the major- and trace-element abundances were determined using ICP-AES and ICP-MS, respectively. Major- and trace-element data are given in Table 1.

**Petrography**

Rocks from the Biga Peninsula consist mainly of olivine, clinopyroxene, and plagioclase phenocrysts in a microcrystalline to glassy groundmass. Phenocryst contents are variable, generally ranging from <3 (aphyric) to 20% (weakly porphyritic), although the majority of the rocks are aphyric. Olivine phenocrysts (Fo_{73-86}) are commonly subhedral and their abundances range between 40 and 70% of the total phenocrysts. Clinopyroxene phenocrysts generally display glomeroporphyric textures, forming spherulite shapes with clustered crystals radiating outwards from early-formed olivine crystals. Plagioclase (An_{73-93}) occurs as a phenocryst phase in only the least basic samples, and its abundance only rarely
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**ALKALI BASALTS AND BASANITES**

**Table continues**
OLIVINE PHENOCRYSTS

The Kula samples are petrographically similar to those from the Biga Peninsula. However, unlike the Kula rocks, most of which have been found to be more abundant than augite.

**Major and Trace Elements**

The lavas all plot in the alkaline field of Irvine and Baragar (1971) and also classify as basanite, basalt, and trachybasalt on a total alkalis (K₂O + Na₂O) versus silica (SiO₂) classification diagram of Le Bas et al. (1986) (Fig. 2). The rocks are silica undersaturated, mafic (MgO = 5.90–9.62 wt%) and sodic (Na₂O/K₂O = 1.74–3.50) in character. They have moderate CaO (7.68–12.11 wt%) and high Al₂O₃ (12.49–18.57 wt%) contents and their Cr and Ni concentrations range from 64.3 to 301.2 ppm and from 53.1 to 183.3 ppm respectively.

The rocks display almost straight and subparallel chondrite (C1)–normalized REE patterns with nearly constant concentration ratios. Absolute REE abundances decrease with increasing SiO₂ content (Fig. 3A). The rocks are all enriched in large-ion lithophile elements (LILE), high-field-strength elements (HFSE), and light to medium rare earth elements (L-MREE) and slightly depleted in heavy rare-earth elements (HREE) relative to normal mid-oceanic ridge basalt (N-MORB) normalizing values (Fig. 3B). Incompatible-element concentrations correlate with both silica and age (e.g., stratigraphic position of the lavas). Almost all incompatible-element concentrations increase with decreasing SiO₂ contents toward the top of the lava sequences (shown as the inset in Fig. 3A). This chemical trend cannot be explained by fractional crystallization, as compatible major-element concentrations such as MgO do not vary systematically with respect to lava stratigraphy. This overall chemical trend is accompanied by a lithologic shift from alkali basalts to basalts, suggesting a long-term trend of progressively lower degrees of melting through multiple eruptive episodes.

No samples show negative Ta or Nb anomalies, indicating derivation from a mantle source(s) with no subduction component and an ascent of primary melt(s) with no significant crustal contamination. Negative Rb, K, and Ti anomalies may, however, be explained by existence of hydrous mineral phase(s) (e.g., phlogopite and/or amphibole) in the source region and/or in the fractionating assemblage of the alkaline magma(s) (Fig. 3B).

**Sr-Nd Isotopes**

Previously reported Nd and Sr isotopic ratios for the Western Anatolian alkaline rocks are plotted on an ⁸⁷Sr/⁸⁶Sr versus ¹⁴³Nd/¹⁴⁴Nd diagram in Figure 4. The rocks are characterized by low ⁸⁷Sr/⁸⁶Sr (0.703108–0.703253) and high ¹⁴³Nd/¹⁴⁴Nd (0.512929–0.512978) (€Nd = +5.49 to +6.51) ratios.
The alkaline lavas display very similar isotopic ratios regardless of their petrographic type (e.g., alkaline olivine basalt or basanite) and age (e.g., the Late Miocene or Quaternary), indicating that the mantle source of the alkaline magmas remained isotopically homogenous during the formation of the entire suite. Thus, the Western Anatolian alkaline lavas can be considered cogenetic in a broad sense, referring to their derivation from a single homogenous mantle source. The rocks have nearly constant $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios for a range in $\text{SiO}_2$ content from 41.8 to 50.0 wt%. This can be...
explained either by variable degrees of partial melting of an isotopically homogeneous source, or by fractional crystallization of an isotopically homogeneous parent magma. Contamination by continental crust is clearly insignificant for these mafic alkaline rocks. The $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ diagram shows that the samples all plot within the mantle array, and extend from MORB-like compositions toward the bulk silicate earth (BSE) (Fig. 4). The alkaline samples are all LREE-enriched relative to average N-MORB and BSE values, with $^{147}\text{Sm}/^{144}\text{Nd}$ ratios ranging from 0.104 to 0.142, and thus plot to the left of a 4.55 Ga geochron on a $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{147}\text{Sm}/^{144}\text{Nd}$ diagram (Fig. 5). However, the samples have present-day $^{143}\text{Nd}/^{144}\text{Nd}$ ratios greater than BSE, reflecting significant periods of evolution in LREE-depleted reservoirs (e.g. Nd/Sm $< [\text{Nd/Sm}]_{\text{BSE}}$).

**Petrogenesis**

The principal objective here is to examine the melting processes in order to: (1) characterize the mineralogy and composition of the mantle source(s); and (2) define the degree of partial melting. The Western Anatolian alkaline suite provides a good opportunity for using basalt data to define the mantle source characteristics because each of the individual lava piles erupted continuously during a short interval within a small geographic region, providing a detailed geochemical data set on temporally controlled sequences of cogenetic magmas. Moreover, although some have been affected by fractional crystallization, most of the rocks in the alkaline suite fulfill several criteria for near-primary magmas—i.e., liquids generated by partial melting of a mantle source with little or no subsequent compositional modification (e.g. crustal contamination). Specifically, well-developed correlation of highly incompatible elements and the isotopically homogeneous nature of the alkaline rocks enable us to use the rock compositions for modeling the source-region characteristics and melting processes.

However, the task of examining the degree of melting and source composition using the rock compositions requires caution because: (1) trace-element variations in mantle-derived magmas can be interpreted as resulting from variations in the degree of partial melting of a single source or compositional variation between two or more mantle sources, or both; and (2) mantle trace-element signatures can be modified by shallow-level processes in low-pressure magma storage areas such as fractional crystallization, and mixing and accumulation of time-integrated melt batches. These processes may obscure the geochemical signatures of primary melts. Thus it is essential to evaluate the possible roles of these processes and remove any such effects.

**Fig. 4.** The Nd-Sr isotope covariation shows that the Late Miocene–Quaternary alkaline rocks from Western Anatolia plot in the mantle array, extending from MORB-like compositions toward bulk earth. MORB compositions are from Zindler and Hart (1986); BSE (bulk silicate earth) composition is from Hart et al. (1992). Nd-Sr isotopes are from Güleç (1991) and Ercan et al. (1995) for the Kula rocks and from Genç (1988) and Aldanmaz et al. (2000) for the Biga Peninsula rocks.
from the primary melt compositions before considering any qualitative or quantitative modeling.

**Fractionation correction and primary melt compositions**

In order to apply the melt modeling to evaluate the nature of the source for the alkaline magmas, it is essential either to use only analyses of primary liquids or to be able to determine the compositions of the primary melts. Two criteria can potentially be used for identifying primary melts: (1) high concentrations of compatible trace elements (e.g., Ni, Cr, V, Sc); and (2) Mg# in the range 68–76 (e.g., Frey et al., 1978) or Fe/Mg ratios within a range that is in equilibrium with mantle olivine (e.g., Fo91; Albarède, 1992). Major- and trace-element data show that none of the alkaline rocks from the Western Anatolian suite represent primary melts, as their Ni and Cr contents are too low and Fe/Mg ratios are too high to be in equilibrium with mantle olivine. Existence of olivine and clinopyroxene phenocrysts in most of the rocks further indicates that the separation of these phases may have had an effect on trace element abundances for which a correction must be made.

An attempt has thus been made here to remove the fractionation effects by adding the fractionated mineral phases back into the magma to attain the primary melt composition(s). The variation in the compatible trace element concentrations provides constraints on the fractionation of ferromagnesian phases. In the case of Western Anatolian alkaline rocks, Cr contents decrease with decreasing Ni, but V and Sc abundances remain almost constant. This may imply that fractionation of clinopyroxene is limited as V and Sc partition favorably into clinopyroxene. Thus, olivine fractionation appears to be the only significant modification of the primary magma. The effect of olivine separation has been corrected using the olivine control lines (Fig. 6) and the composition of the corresponding melts obtained by redissolving olivine until the melt is in equilibrium with olivine Fo91 (see Albarède, 1992 for details on the method). Having estimated the proportions of the mineral phases that have been removed from the primary melt(s) to produce the observed melt (taken

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**FIG. 5.** Plot of $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{147}\text{Sm}/^{144}\text{Nd}$ showing the isotopically depleted and LREE-enriched nature of the Western Anatolian alkaline rocks. The heavy lines represent the mantle trends drawn for 4.5 Ga, 2.0 Ga, and 1.0 Ga from the hypothetical bulk silicate earth (BSE; Hart et al., 1992) composition.
here as the rock compositions), trace element concentrations of each primary melt were estimated from the observed melt using the Rayleigh fractionation law. The F value (mass fraction of liquid) for each sample was calculated using Fe/Mg ratios of the samples and the olivine control line. The fractionation-corrected data set for the elements that are used for the melt modeling is given in Table 1.

Cogenetic nature of the magmas

Most of the melt modeling is based on the assumption that the primary melts from which the examined rock samples were derived are cogenetic. The method of Minster and Allègre (1978) with equations deduced from the simple batch-melting model of Shaw (1970) was used to examine whether the primary melts that formed the alkaline rocks of Western Anatolia are cogenetic. If a set of samples is produced by different degrees of melting of identical batches of source material, this set will form a linear array on a plot of C/H against C/H (C/H and C/H are concentration of highly incompatible and less incompatible elements respectively). Samples that have been affected by other processes such as mixing of variable magma batches or melts from two or more geochemically distinct sources will deviate from the array and will cause scatter. Fractional crystallization will also cause deviations from the array unless the degree of fractionation (or the mass fraction of liquid) and the fractionating phases are unrealistically identical for each sample.

Figure 7 shows that the plot of La/Nd versus La form linear arrays indicating that the alkaline rocks formed by variable degrees of partial melting from a single mantle source and that the magmas were not affected by any significant mixing and/or fractional crystallization. Furthermore, in addition to the isotopically homogenous nature of the alkaline samples and the excellent linear correlation between highly incompatible element concentrations, all highly incompatible elements have nearly constant concentration ratios for the entire suite, indicating that the rocks are cogenetic.

Partial melting variations and the source mineralogy

Although the effects of fractional crystallization on primary magma compositions can be very difficult to distinguish from those of partial melting, the use of highly incompatible to not so highly incompatible element ratios (e.g., La/Yb and Zr/Nb) may still be helpful. An La/Yb versus Zr/Nb ratio plot was used to define the source characteristics of the Western Anatolian alkaline magma(s) in terms of the degree of source enrichment (e.g., relative to PM) and the source mineralogy.

The rationale for the use of an La/Yb versus Zr/Nb plot is threefold. First, the ratio of Zr/Nb is not affected significantly by fractional crystallization of the mantle phases, and hence it can distinguish the effects of partial melting from those of fractional crystallization. Fractional crystallization of predominantly olivine + clinopyroxene can only generate small changes in these ratios. Crystallization of clinopyroxene, for example, is the most effective in fractionating Zr/Nb ratios (with DZr/DNb ~5–6), yet even 50% fractionation of clinopyroxene from a liquid with Zr/Nb = 10 would only lower Zr/Nb to 9.1. A variable degree of partial melting from a single source, on the other hand, may create large variations in the Zr/Nb ratio.

Second, because the ratio of Zr/Nb is not affected significantly by variations in the source mineralogy, it can be used to examine the enrichment level of the source mantle. Partial melting from a hypothetical PM composition, for example, would be expected to leave a mantle residue with Zr/Nb ratio higher than that of PM (e.g., DMM-like mantle). The lower Zr/Nb ratios (with respect to PM) on the mantle array, however, should be a consequence of multi-stage melting processes that pro-
duce additional small melt fractions with significantly low Zr/Nb ratios.

Third, the garnet-dependent ratio La/Yb can distinguish between melting of garnet- and spinel-lherzolite sources. Basaltic magmas derived from the mantle asthenosphere (e.g., DMM-like), or primitive sources (e.g., plume asthenosphere) all lie within or close to the diagonal mantle array if the source mantle that undergoes partial melting is a spinel-lherzolite. In contrast, small or moderate partial melting of a garnet-lherzolite source (from DMM- or PM-like mantles) produces melt with significantly higher La/Yb ratios than that of spinel-lherzolite melting inasmuch as Yb is compatible with garnet but not with clinopyroxene. In consequence, the garnet-lherzolite melting trend is displaced from the mantle array to higher La/Yb ratios on an La/Yb versus Zr/Nb diagram. Mixing between spinel- and garnet-lherzolite sources also creates a melting trend displaced from the mantle array.

Figures 8 and 9 exhibit modeled trace-element abundances and ratios to constrain the source characteristics of the alkaline magma(s) in terms of the above characteristics. The modeling uses the non-modal batch melting equations of Shaw (1970) and the REE partition coefficient compilation of McKenzie and O’Nions (1991, 1995). Two different reference compositions have been used to define the likely mantle array: (1) depleted MORB mantle (DMM), which is assumed here to represent the convecting mantle asthenosphere with the composition of the hypothetical depleted MORB source (McKenzie and O’Nions, 1991); and (2) primitive mantle (PM; Sun and McDonough, 1989), which is representative of the initial mantle composition prior to MORB formation and depletion (Aldanmaz et al., 2000).

Figure 8 shows that the ratios of La/Yb and Zr/Nb vary widely in the Western Anatolian alkaline samples, and increasing Zr/Nb ratios are accompanied by decreasing La/Yb. The significantly large range of Zr/Nb ratios (from 2.1 to 6.1) of the alkaline samples cannot possibly be explained by fractional crystallization for the reasons explained above. Given that the rocks are cogenetic, evident from the isotope data and trace element modeling, a possible long-lived mantle heterogeneity also cannot explain the observed Zr/Nb ratios.

Variable degrees of partial melting is thus clearly the simplest, and perhaps the only, explanation to account for the variation in highly incompatible to not so highly incompatible element ratios that are not associated with isotopic variability, with samples representing a smaller degree of partial melting having higher incompatible-element concentrations and highly incompatible to not so highly incompatible ratios (e.g., Nb/Zr and La/Yb).

The modeling in Figure 8 shows that the alkaline rocks from both the Biga Peninsula and the Kula volcanic field have La/Yb ratios greater and Zr/Nb ratios smaller than those that could be generated by direct melting of DMM and/or PM, even when the degree of partial melting is unrealistically small (0.1%). Thus, it can be argued that the one-stage melting of DMM or PM cannot produce magma with incompatible-element ratios similar to those of the alkaline rocks of Western Anatolia. Clearly, a mantle source that has been enriched in highly incom-
Alkaline basalts and basanites

The relative overabundance of incompatible elements with respect to DMM is required to produce the alkaline rocks. This enrichment is presumed to result from the source composition, which has been inferred to be a garnet peridotite (Gurnis et al., 1985). The melt curves for garnet-lherzolite and spinel-lherzolite are shown in Figure 8, which indicates the presence of garnet residue in the source region. Rocks from the Kula volcanic field, on the other hand, plot closer to the mantle array and follow the melting trajectory drawn for spinel-lherzolite melt source when the mantle trace-element composition is considered the same as that of the Biga Peninsula suite. The possible options to explain this difference between the two suites are: (1) different depths of melt segregation; and/or (2) different source trace-element compositions.

The empirical relationship proposed by Albarède et al. (1992) has also been applied to estimate the pressure at which magmas segregate from their source mantle. The results point mostly to the garnet stability field (garnet and overlap into the spinel stability field) for the Biga Peninsula samples and to the spinel stability field (spinel and overlap into the

FIG. 8. Plots of La/Yb versus Zr/Nb showing melt curves (or lines) obtained using the non-modal batch melting equations of Shaw (1970). Melt curves are drawn for spinel-lherzolite (with mode and melt mode of ol + opx + cpx + sp, respectively; Kinzler, 1997) and for garnet-lherzolite (with mode and melt mode of ol + opx + cpx + gt, respectively; Walter, 1998). Mineral/matrix partition coefficients and DMM are from the compilation of McKenzie and O’Nions (1991, 1995); PM, N-MORB, and E-MORB compositions are from Sun and McDonough (1989). WAM represents the Western Anatolian Mantle defined by the dynamic melt inversion method of Zou (1998). The modeling uses the enrichment ratios of two different incompatible elements between two different but cognate primary magmas and the parameters proposed by Zou and Zindler (1996) and Zou (1998). The heavy line represents the mantle array defined using DMM and PM compositions. The melting trends from DMM and WAM compositions are shown by solid curves (or lines), whereas the dashed curves (or lines) represent the melting trends from PM. Thick marks on each curve (or line) correspond to degrees of partial melting for a given mantle source. The inset diagram shows the depths of melt segregation (from the mantle source) for individual samples. The estimates have been obtained from the fractionation-corrected data using the empirical relationship proposed by Albarède (1992).
garnet stability field) for the Kula samples (shown as an inset in Fig. 8), confirming the interpretation from the trace-element modeling that the depth of melt segregation for the Kula rocks is, in general, shallower than that of the Biga Peninsula samples.

In order to calculate the degree of partial melting variations within the alkaline suite more accurately, La/Sm was plotted against La (Fig. 9). Neither of these elements is affected significantly by the source mineralogy, and thus provide information on the degree of partial melting from a given mantle source composition. Partial melting trajectories drawn using the model mantle source of WAM give degrees of partial melting between ~2% and ~10% for the Western Anatolian rocks.

**Characteristics of the Mantle Source**

The relative source concentrations, calculated using an inverse numerical method presented above, show that the model mantle source from which the alkaline magmas were derived was enriched in all highly (and moderately) incompatible elements relative to DMM and PM. The degree of enrichment, as observed in many OIB settings, increases systematically in order of increasing incompatibility, resulting in light over heavy REE and highly incompatible over not so highly incompatible element enrichments compared to DMM and/or PM compositions (e.g., Nd/Sm > [Nd/Sm]DMM-PM and Nb/Zr > [Nb/Zr]DMM-PM). In contrast, the Nd isotope ratios of the alkaline rocks are characterized by positive $\varepsilon_{Nd}$ (+6.51 to +5.49) values, indicating a source significantly depleted relative to BSE (e.g., Nd/Sm < [Nd/Sm]BSE). Thus, it could be argued that the enrichment in highly incompatible over less incompatible elements cannot be a long-term source characteristic and requires explanation by some other process(es) that did not affect the isotopic composition of the source mantle and that of the resulting melt batches. In other words, the enrichment is likely to be a consequence of a recent event that affected only the composition of the melted magma batches during and/or after melt segregation from the source mantle. The possible options to explain incompatible-element enrichment in association with depleted isotopic signatures are: (1) mixing of melts from two or more geochemically distinct end members; (2) reactive melt transport through ion-exchange chromatography or zone refining; and (3) metasomatism of the mantle source by small-degree partial melts or hydrous fluids.

**Melt mixing**

Mixing of melts formed by variable degrees of melting of two or more mantle end members with different trace-element and isotope compositions is
often invoked to explain the isotopically depleted (relative to BSE), but LREE-enriched nature of OIB-type alkaline suites. In this context, the most likely mantle source end members are presumed to be plume components, asthenospheric and lithospheric mantle sources. The processes of mixing melts from two or more compositionally distinct end-member models generally involve either the addition of incompatible element–enriched plume-derived melts or fluids to a depleted (e.g., DMM-like) mantle source prior to magma generation or, alternatively, addition of incompatible element–depleted mantle-derived melts or fluids to an enriched lithospheric mantle source. Although postulated involvement of two or more distinct sources in OIB-type magma genesis is very common in conventional geochemical wisdom, it seems rather improbable for the Western Anatolian suite. First, there is no mantle plume signature in Western Anatolia for the reasons discussed by McKenzie and O’Nions (1995). Second, involvement of melts from mantle lithosphere (taken here as the non-convecting part of the mantle) in the genesis of the Western Anatolian alkaline magmas is subject to a recent study by Aldanmaz et al. (2000) who demonstrated that the mantle lithosphere beneath Western Anatolia is subduction-modified, and is unlikely to produce magmas with trace-element and isotope compositions similar to those of the Western Anatolian alkaline suite. Furthermore, in addition to their isotopic homogeneity, the alkaline rocks that formed over a significant period of time from the Late Miocene to Quaternary have nearly constant incompatible-element concentration ratios for the entire suite, reflecting melt generation from a homogeneous, single mantle source.

**Reactive melt transport**

Another possible option to explain the highly incompatible over less incompatible element enrichment might be that the trace-element concentrations are partly controlled by reactive melt transport during melting and ascent of magma(s). Several studies regarding the source-region characteristics of primitive, mantle-derived magmas have recognized the theoretical potential for melt-mantle reaction. Such reaction may take place as a consequence of either ion exchange chromatography caused by percolation through partially molten mantle (e.g., Navon and Stolper, 1987; Vasseur et al., 1991; Iwamori, 1993) or zone refining (e.g., Harris, 1957; Alibert et al., 1983). It has been argued that the rate of interaction during melt-mantle reaction is faster in the highly incompatible mantle reaction is faster in the highly incompatible elements than the less incompatible elements and, as a result, the abundance ratios of elements of different compatibilities can vary considerably with time. Thus, it could be argued that the alkali basic magma(s) might have reacted with large volumes of solid mantle during melt migration and ascent, preferentially leaching incompatible elements from the surrounding mantle. This process would then increase the ratios of highly incompatible to less incompatible elements in the resulting magma batches (relative to the original parental melt composition) without affecting their isotopic ratios significantly, and could potentially produce the trace-element and isotopic characteristics observed in many OIB-type alkaline suites in a broad sense.

However, the difficulty with applying this model to the Western Anatolian suite is that the alkaline lavas show a temporal compositional trend of increasing incompatible elements over time. This is the opposite of what we would expect if the composition of the alkaline magmas were modified via reactive melt transport. As shown by Reiners (1998), the composition of the leading melt batch through a column of refractive mantle will be shifted toward the composition of an incipient partial melt of the mantle matrix as the first melt to emerge from the column reacts with the largest volume of mantle matrix, resulting in strongest incompatible-element enrichment in the melt. Successive melts migrating through and emerging from the columns will then show a temporal compositional trend that reflects the exhaustion of the reactive capacity of the mantle. Thus, these effects should result in an enrichment in incompatible elements relative to the original input melt, and a temporal compositional trend of decreasing incompatible elements in erupted melt batches with time. Eventually, element concentrations should return to the original parental melt concentrations in order of increasing compatibility (Navon and Stolper, 1987; Reiners, 1998). Thus, enrichment in highly incompatible over less incompatible elements seems unlikely to be explained solely by reaction between melt and the source matrix, although this process may have had a partial effect on the composition of the resulting melt(s).

**Metasomatism of the mantle source**

An alternative, and perhaps more likely, mechanism to explain the highly incompatible element
enriched nature of the alkaline magma(s) is that the local mantle source region may have been metasomatized by melt fractions (or fluids) generated from the same source by small-degree partial melting. Zou and Zindler (1996) described an autometasomatic event as a process related to the release of volatile-rich metasomatising agents (melts and/or fluids) in the subsolidus peridotite during or shortly before melting—i.e., a metasomatic event resulting from the addition of either a small volume of hydrous melt or a metasomatic fluid derived from the same mantle source as the alkaline magma.

One possible indication of a melt or fluid metasomatism in the mantle source region may be the existence of hydrous mineral phases. One of the most striking features of the Western Anatolian alkaline rocks is that, unlike all other incompatible elements, the abundances of K and Rb (and Ti) are weakly correlated with the highly incompatible elements (e.g., P, Th, and LREE). As shown by the N-MORB normalized plots, there is also a considerable relative depletion (or negative anomalies) in the abundances of K, Rb, and Ti in the most basic samples (Fig. 3A). These negative anomalies are observed even in the freshest samples, and are not associated with a similar behavior of Ba (also a mobile element), implying that alteration is not the main cause of such depletion. Furthermore, this depletion correlates with the degree of partial melting and, as shown in the Ti/Ti* versus La plots (inset in Fig. 3B), it decreases gradually toward the least basic sample (the product of the greatest degree of melting), suggesting a correlation between the extent of source metasomatism and the degree of partial melting. The most likely explanation for such a systematic depletion is thus the presence of a residual Rb, K, and Ti retaining phase in the source region (e.g., phlogopite and/or amphibole).

Most studies regarding the source characteristics of OIB-type alkaline magmas assume that trace-element and/or petrographic evidence for hydrous phases such as amphibole or phlogopite require their presence in the original, pre-melting, solid mantle source. Thus, in the conventional context of single-stage melting and instantaneous melt extraction, the plausible explanation would be that the original mantle source contained the inferred hydrous minerals as residual phases.

However, long-term existence of amphibole or phlogopite in a steady-state solid mantle does not seem to be logical, inasmuch as these phases are not particularly common primary mantle minerals. The question should thus be addressed to the possibility of whether these phases may be products of metasomatic (e.g., fluid- and/or melt-mantle) reaction, in which case their existence may not require unusual mantle source characteristics. This may be particularly important in cases where stability of the inferred hydrous phases is limited to the non-conveeting (lithospheric) mantle, whereas the other geochemical signatures suggest melt segregation at greater depths within the convecting (asthenospheric) mantle. Reaction of small-degree mantle melts or hydrous fluids with dry peridotite may cause precipitation of hydrous phases not initially present in the melt source or the peridotite. It is well known that metasomatic effects on mantle peridotites, possibly caused by hydrous fluid or small-degree melt percolation, include precipitation of trace phases uncommon in typical depleted-mantle rocks (e.g., dry peridotite) such as amphibole and phlogopite (Roden and Murthy, 1985; Bodinier et al., 1990; Sen and Dunn, 1994; Zanetti et al., 1996; Yaxley et al. 1998). The hydrous fluid or melt may therefore be considered to have permitted amphibole to form at the expense of clinopyroxene. Precipitation of hydrous mineral phases as a consequence of small-degree hydrous melt-mantle reactions will also have a strong effect on the trace-element composition of derivative primary melts. Starting with an LREE-depleted mantle (e.g., DMM type), an autometasomatic fluid (or melt) is derived that metasomatizes and enriches local regions of this mantle. This fluid (or melt) is probably generated under garnet-bearing peridotite-facies conditions, reflecting the necessity to provide the light over heavy REE (or highly incompatible over not so highly incompatible element) enrichments in the fluid.

This model would then require a multi-stage melting process (as also shown in Fig. 3). The first stage is the generation of a highly incompatible element enriched metasomatic component. This early-formed fluid or melt produced in the peripheral regions of a melting zone will react with the local mantle to produce a second-stage source that will undergo greater extents of melting to produce melts with isotopically depleted affinities in association with strong LREE-enrichments. It could therefore be argued that the concentration of the source used for partial melting modeling (WAM in Figs. 8 and 9) only represents the mantle source that has already been modified by earlier metasomatic events. The original source composition prior to the melt or fluid
metasomatism may have been similar to that of DMM (or PM). This mechanism may also explain compositional differences between OIB-type magmas (the products of mainly small-degree melting processes) and MORB-type magmas (the products of a greater degree of melting processes).

Conclusions

The Late Miocene–Quaternary mafic alkaline suite of Western Anatolia comprises a series of scattered outcrops of lava flows formed within localized extensional zones. The alkaline rocks are mostly classified as basalt, basanite, and trachybasalt, with silica contents ranging from 42 to 50 wt%. In general, they show OIB-like trace-element patterns characterized by enrichment in LILE, HFSE, LREE, and MREE, and a slight depletion in HREE relative to N-MORB.

Major- and trace-element systematics reveal two distinct depth ranges of melt segregation from the source mantle: (1) predominantly garnet (and spinel + garnet) stability zone for the Late Miocene rocks; and (2) predominantly spinel (and spinel + garnet) stability zone for the Quaternary rocks. The alkaline magmas are shown to have been generated by variable degrees of partial melting (~2% to ~10%) of an isotopically homogeneous, single mantle source enriched in incompatible elements relative to DMM and PM compositions. The isotopically depleted nature (relative to BSE) of the rocks further suggests that this enrichment is not a long-term source characteristic and is likely to have been a recent event.

The alkaline lavas that formed over a significant period of time from the Late Miocene to Quaternary have nearly constant Sr and Nd isotopes and incompatible-element concentration ratios for the entire suite. These characteristics indicate melt generation from a homogeneous, single mantle source, and preclude mixing of melts from two or more compositionally distinct mantle sources as the origin of the incompatible-element enrichments of the alkaline magmas.

Because the alkaline lavas demonstrate a systematic temporal compositional trend of increasing incompatible-element concentrations with time within the individual eruptive sequences, the recent incompatible-element enrichments cannot be attributed to any possible reactive melt transport during melting and ascent of magmas. Trace-element and isotopic characteristics show that the simplest, and most likely, explanation is that the alkaline lavas are the products of integrated (multi-stage) melting processes that initially produced small-volume melts and/or hydrous fluids that metasomatized (and enriched) the local (originally depleted) mantle regions and caused precipitation of hydrous mineral phases (amphibole in particular at the expense of clinopyroxene).

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