# *Shallow convective mantle origin for the OIB-type, mid-plate lavas of western Turkey: Implications for fertility anomaly zones in the upper mantle*

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## *Abstract*

*Western Turkey contains a number of intra-continental alkaline volcanic eruption sequences along localized extensional basins that developed in relation to Late Cenozoic extensional processes. The volcanic suites are small-volume alkaline olivine basalts and basanites with compositions representative of mantle-derived primary (or near-primary) melts. The rocks have near-uniform radiogenic isotopic ratios ($^{87}Sr/^{86}Sr$= 0.70299-70354 and $^{143}Nd/^{144}Nd$= 0.51281-0.51301) and are characterized by OIB-type trace-element patterns with significant enrichment in LILE, HFSE and L-MREE, and slight depletion in HREE, relative to N-MORB. Systematic changes in melt chemistry with time do not reflect fractional crystallization nor can they be explained by variable proportions of mixing between melts produced by different degrees of partial melting of two (or more) compositionally distinct sources in the mantle. Instead, the observed trends are consistent with a progressive decrease in degree of melting and systematic mixing between increments of melt derived from the same source but probably at different depths. Incompatible-trace-element modeling of fractionation-corrected data indicates that mafic alkaline magmas formed by variable degrees of incremental partial melting of a single, convective mantle domain that is enriched in all incompatible elements (e.g. LILE, HFSE and L-MREE) relative to compositions of hypothetical geochemical reservoirs such as Depleted MORB Mantle (DMM) or Primitive Mantle (PM).*

*The calculations, based on the melt products of experimental phase equilibria, show that the compositions of the primary magmas precipitating the most magnesian olivine phenocrysts of the alkaline melts reveal anhydrous liquidus temperatures that range from about 1320°C to 1410°C. Projection along the solid-state adiabat to one atmosphere reveals a mantle potential temperature Tp ~1300°C which is inconsistent with melt generation by either deep-seated thermal anomalies associated with mantle plumes (which require Tp >1450°C) or by melting of thermally perturbed (wet) mantle lithosphere, but are consistent with the adiabatic upwelling of normal-temperature mantle asthenosphere.*

## Introduction

Mantle melting linked to either actively upwelling plumes or convectively upwelling hot mantle materials is widely believed to be responsible for the genesis of the considerable volume of primary basaltic magma that constitutes the mafic volcanic suites of oceanic islands and intra-continental extensional settings (*e.g.*, *McKenzie & Bickle*, 1988). Many recent papers have alternatively linked the origin of small volumes of primary melt to direct melting of thermally perturbed mantle lithosphere. Models of melt generation from chemically distinct parts of mantle domains have been developed (*Meibom & Anderson*, 2003; *Foulger & Anderson*, 2005; *Foulger et al.*, 2005). The primary melt products of adiabatic decompression melting in the upper mantle preserve information on the composition of the mantle and the mechanisms and extents of melt extraction.

In western Turkey, Late Miocene to Quaternary volcanic activity (11 to 0.13 Ma; *Aldanmaz*, 2002; *Aldanmaz et al.*, 2006) produced a series of scattered outcrops of silica-undersaturated, mafic alkaline lava flows along localized extensional zones (Figure 1). Many recent studies have suggested that this alkaline magmatism is related to the late-stage extension that occurred as a consequence of post-collisional strike-slip and extensional faulting (*e.g., Aldanmaz et al.*, 2000 and references therein).

*Figure 1: (a) Satellite map of western Turkey. (b) Map showing the plate reconstruction of the eastern Mediterranean and the area of volcanism in western Turkey (shaded).*

In recent years, attempts have been made to constrain the melt generation processes that produce the alkaline magmas of western Turkey. Some researchers have proposed mixing of melts from discrete mantle components, a model which is invoked to explain the formation of many OIB-type (both oceanic and continental) alkaline suites elsewhere. These studies mainly used trace-element and isotopic data to propose that the extensional mafic volcanic rocks of western Turkey were derived from melts generated within mantle lithosphere that had previously been enriched by melt fractions from the mantle asthenosphere (*e.g., McKenzie & O'Nions*, 1995; *Alici et al.*, 2002; Editor's note: see also The Metasomatic Alternative). However, other studies (*e.g., Aldanmaz et al.*, 2000), having constrained the likely compositions of the variable mantle regions beneath western Turkey, demonstrated the improbability of mantle lithosphere source involvement in the genesis of the alkaline magmas. Instead, a well-mixed, homogeneous convecting upper mantle was proposed as the main source.

This webpage presents the geochemical characteristics of the primitive alkaline volcanic rocks from western Turkey in order to provide insights into the nature and characteristics of the mantle source. Models involving contributions from lithologically and chemically discrete mantle components are also evaluated. Western Turkey is a good place to study the characteristics of the source mantle because the erupted basalts are relatively free from the complicating effects of mantle lithosphere or crustal interactions and several lavas have bulk compositions that may approximate primary melts. Chemical data from these rocks may thus provide the essential evidence to constrain the nature of the melting and characteristics of the mantle source.

## Geological setting

Western Turkey is an active continental extensional shear zone influenced largely by forces related to both post-orogenic Aegean extension and strike-slip faulting consequential to westward motion of the Anatolian plate (Figure 1). Extension-related tectonic and magmatic activity occurred along with lithospheric thinning and asthenospheric upwelling (*Aldanmaz et al.*, 2005; 2006; Editor's note: see also Slab breakoff, Anatolia). Alkali basalts with primary compositions occur at several localities and have been used to document mantle melting episodes from the Late Miocene to Quaternary. Compositional variation in basalts throughout the lava sequences is limited as the rocks are generally alkaline basalts and basanites occurring as lava flows with OIB-type (or mid-plate) major-trace-element and radiogenic-isotope signatures (*Aldanmaz et al.*, 2000; 2005).

## Whole-rock geochemistry

### *Major and trace elements*

The lavas comprise a strongly alkaline series of silica-undersaturated ($SiO_2$= 42-50 wt.%), sodium-rich and high magnesian (MgO= 6-14 wt.%) type. The more magnesian samples have Mg# >0.70, are saturated with olivine in the range $Fo_{89-92}$, and could be in equilibrium with mantle olivine. They have almost straight, sub-parallel chondrite (CI)-normalized REE patterns with near-constant concentration ratios and absolute REE abundances decrease with increasing silica content through the eruptive sequences (Figure 2a). All samples show LREE enriched patterns on chondrite-normalized REE plots. The lavas also have all the classic enrichments in LILE, HFSE and L-MREE and slight depletion in HREE (*e.g.,* relative to average N-MORB) that characterize OIB-type basalts from intra-plate continental and oceanic settings (Figure 2b). They also display prominent negative Rb, K and Ti anomalies, which is also a common feature for the majority of mid-plate basalts.

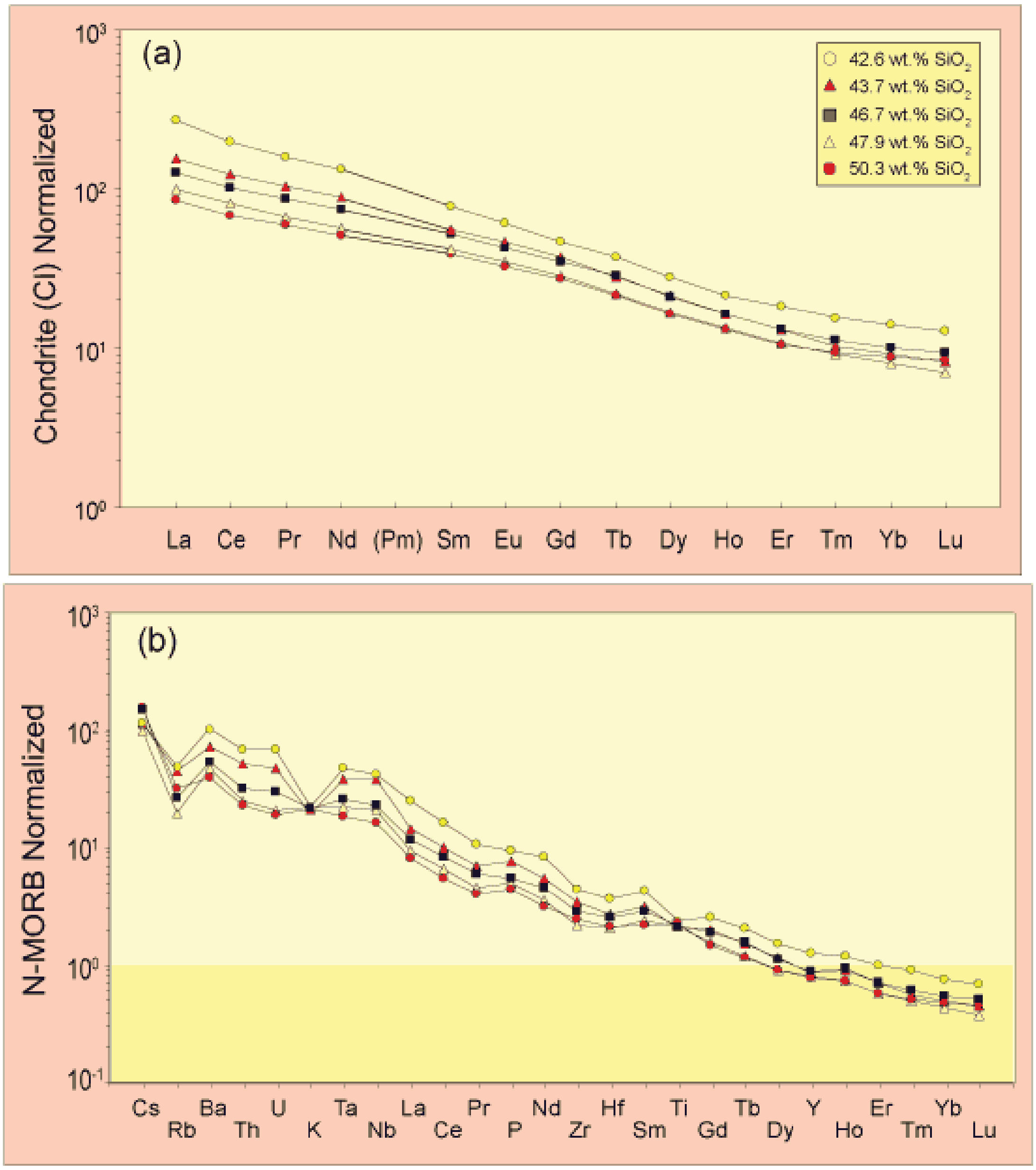


*Figure 2. (a) Chondrite- (b) N-MORB-normalized trace-element patterns for the alkaline volcanic rocks from western Turkey. Chondrite and N-MORB normalizing values are from Boynton (1984) and Sun & McDonough (1989), respectively.*

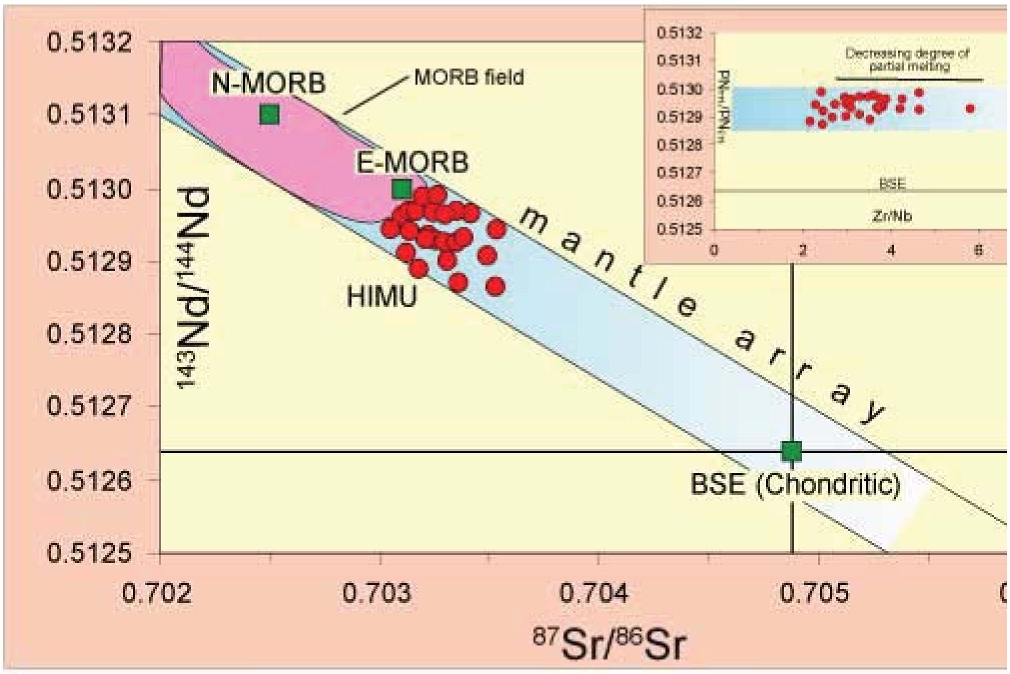
There are no significant differences in trace-element ratios between the primary and slightly evolved lavas, indicating that differentiation played only a minor role. Incompatible-element concentrations correlate with both silica and age; in the individual eruptive sequences almost all incompatible-element concentrations increase with decreasing silica contents towards the top of the sequences. This trend cannot be explained by fractional crystallization, as compatible major-element concentrations such as MgO do not vary systematically with stratigraphic height. The largely primitive compositions of the alkaline magmas also preclude a significant role for fractional crystallization in generating the compositional trends. Moreover, $SiO_2$ is negatively correlated with incompatible elements in all sequences, the opposite of what would be expected from fractional crystallization of olivine and pyroxene. This overall chemical trend is accompanied by a lithologic shift from alkali basalts to basanites, suggesting a long-term trend of progressively lower degrees of melting through multiple eruptive episodes. Thus, much of the correlated variation in the major and trace elements with stratigraphy is likely to result from variation in the degree of melting rather than fractional crystallization.

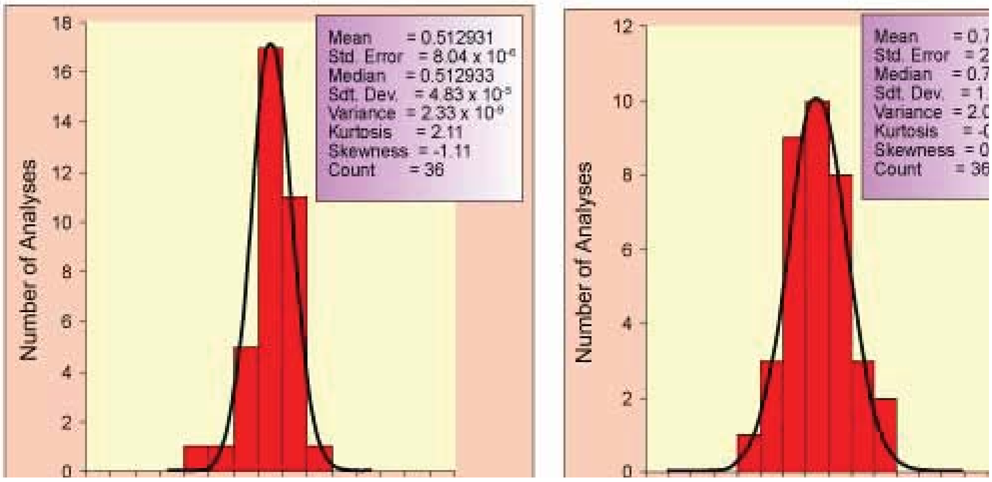
### *Isotope ratios*

The lavas are young, with insignificant radiogenic in-growth, indicating that their isotopic compositions represent the composition of their sources. The rocks are characterized by low $^{87}Sr/^{86}Sr$ (0.70299-70354) and high $^{143}Nd/^{144}Nd$ (0.51281-0.51301) ratios, typical of what is usually seen in OIB-type rocks from oceanic and continental settings. They have a restricted range of isotopic ratios throughout the lava sequences, indicating that the mantle source remained isotopically homogeneous during the formation of the entire suite from the Late Miocene to the Quaternary. The rocks can therefore be considered cogenetic in a broad sense referring to their derivation from a single, homogeneous mantle domain. They have near-constant $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios for a relatively large range in $SiO_2$ content from 42 to 50 wt.%. This could be explained by fractional crystallization from an isotopically homogeneous parent magma. However, systematic change and relatively large variation in ratios of certain trace elements, such as Zr/Nb, are not reflected in variations in the isotopic ratios, supporting a model of melt generation by variable degrees of partial melting of an isotopically homogeneous mantle source. Despite their LREE-enriched nature, the rocks have present-day $^{143}Nd/^{144}Nd$ ratios greater than the hypothetical bulk silicate Earth (BSE), reflecting significant periods of evolution in LREE-depleted reservoirs, *i.e.* the rocks plot within the depleted quadrant of mantle array on a $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ diagram, and display significant depletions in isotopic ratios with respect to the BSE (Figure 3a).

The statistical distribution of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotope data mostly show narrow, normal distributions for both isotope ratios (Figure 3b). This also suggests that the source mantle from which the alkaline magmas were formed was not chemically heterogeneous and that the contribution from lithological outliers (*e.g.,* a possible sub-reservoir) was insignificant.

*Figure 3 (Overleaf). (a) The Nd-Sr isotopic covariation shows that all the Late Miocene to Quaternary mafic alkaline volcanics from western Turkey plot in the mantle array extending from MORB-like compositions toward BSE, and display close similarities to HIMU. Data plotted are from Aldanmaz et al. (2000; 2006), Alici et al. (2002), Aldanmaz (2002) and references therein. Inset diagram shows the variation of* $^{143}Nd/^{144}Nd$ *ratios with changing Zr/Nb ratios throughout the sequences. (b) Sr and Nd isotopic distributions representing the entire volume of the alkaline volcanic rocks, along with the statistical parameters derived from each distribution. Solid lines denote the fitted normal distributions. Click here or on Figure for enlargement.*





## Inferring the nature of mantle source

Geochemistry suggests that the alkaline lavas of western Turkey originated from a mantle source that was enriched in all highly and moderately incompatible elements relative to hypothetical reservoirs such as DMM (considered to be the source of mid-ocean ridge basalts) and PM (considered as the source of mid-plate, OIB-type basalts) (Figure 4a-b). The degree of enrichment in the lavas from western Turkey, 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 the DMM and/or PM compositions. The isotopic results, however, incongruently reveal an isotopically depleted (*e.g.,* relative to BSE) mantle source, emphasizing that the postulated enrichment of the lavas is a recent (possibly process-related) event and not a long-term source characteristic.

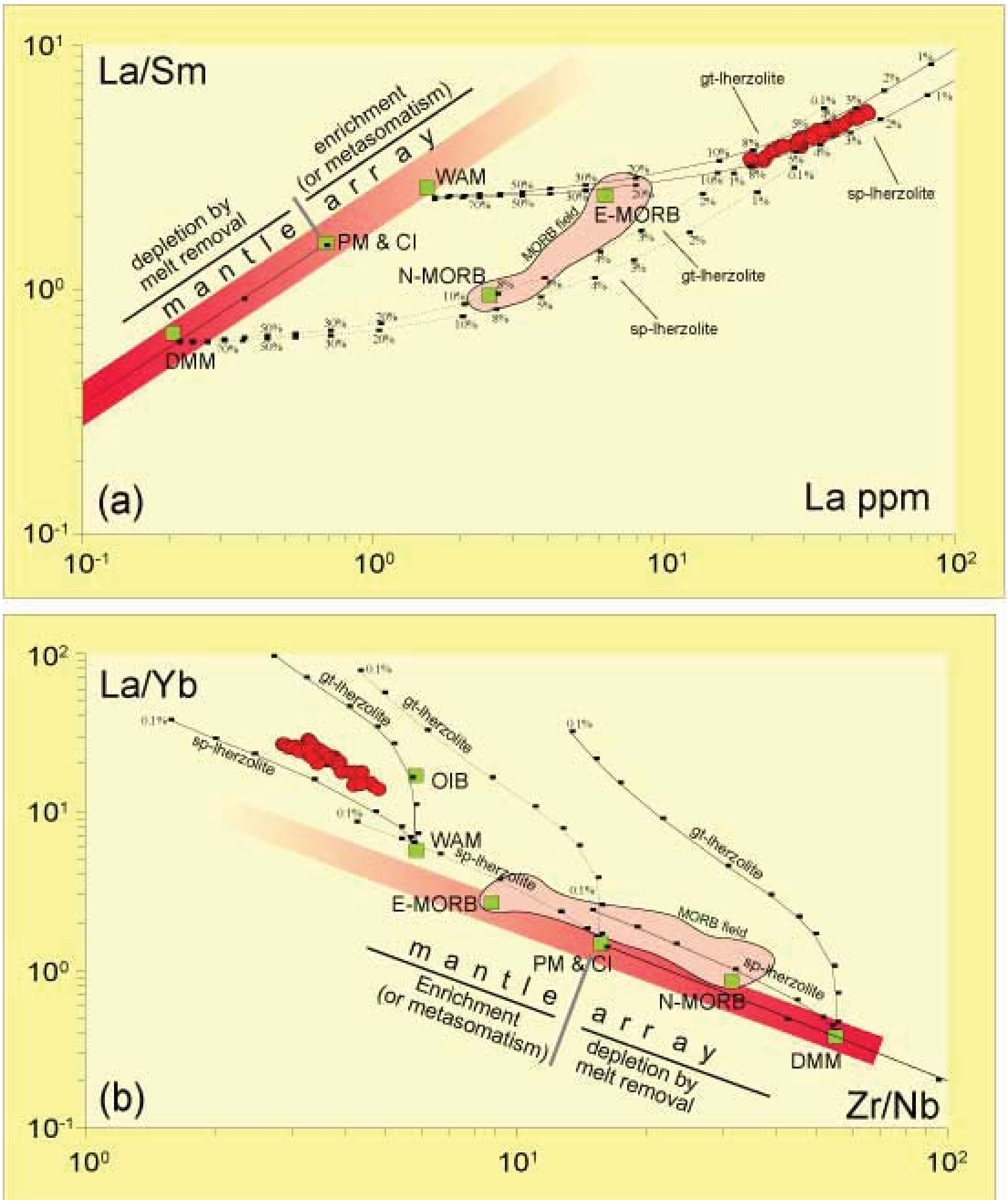


*Figure 4. (a) – (b) Plots of La vs. La/Sm and La/Yb vs. Zr/Nb showing melting trajectories obtained using the nonmodal batch melting. Melt curves are drawn for both spinel-lherzolite and for garnet-lherzolite. WAM represents the Western Anatolian Mantle defined in Aldanmaz et al. (2000). The heavy line represents the mantle array defined using melt-residual compositional trends from DMM and PM compositions. Mantle depletion and enrichment trends are defined by melt extraction from the mantle (towards the residue) and melt addition to the mantle (or influx of material from outside the mantle prior to solid-state mixing and homogenization) respectively. Thick marks on each curve correspond to degrees of partial melting for a given mantle source. Click here or on Figure for enlargement.*

Recent enrichment, *i.e.* enrichment in more-incompatible relative to less-incompatible elements during and/or after melt segregation from the mantle, is a common feature of the majority of OIB lavas and could be attributed to a number of processes, including:

1. mixing of melts from two or more chemically (or lithologically) distinct end-members

(usually requiring the involvement of either enriched deep-plume upwellings, an enriched mantle lithospheric source, or enriched pyroxenitic vein components); and

2. metasomatic reactions associated with extensive porous flow (usually requiring involvement of the lithospheric portion of the upper mantle in melt generation). These possible options are discussed below for the alkaline rocks of western Turkey.

### *Mixing melts from chemically distinct mantle sources and potential end-members*

Systematically changing the proportions of mixing between melts produced by variable degrees of partial melting of at least two compositionally distinct sources in the mantle is often invoked to explain both the isotopically depleted (*e.g.,* relative to BSE), but LREE-enriched nature of many OIB-type alkaline suites and the quasi-linear patterns in highly incompatible elements observed in OIB-type rocks. Several recent studies of trace-element and isotope compositional variations of mid-plate basalts have suggested binary mixing as the dominant source of chemical variation in alkali primary suites (*e.g., Class & Goldstein*, 1997; *Kamber & Collerson*, 2000; *Lassiter et al.*, 2000). In this context, the most likely hypothetical end-member reservoirs are presumed to be located in rheologically distinct (but accessible by surface volcanoes?) parts of the mantle, including plume components (*e.g.,* originating from below the convectively stirred upper mantle), and convective and conductive upper-mantle sources. The processes of mixing melts from two or more compositionally distinct end-members 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 melt generation or, alternatively, addition of incompatible-element-depleted mantle-derived melts to an enriched conductive mantle source. Thus, several recent studies regarding OIB-type magma genesis assume that the lavas are pooled and mixed melts and that the magma generation is related to either a plume origin or involvement of melts from conductive mantle or both (*e.g., Lassiter et al.*, 2000; *Lundstrom et al.*, 2003).

### *Mantle plume origin*

The plume hypothesis (in the sense of deep-seated thermal anomalies), assumes (perhaps unrealistically) that the convecting upper mantle is cold, dry and significantly subsolidus, and generally attributes magma generation to temperatures of approximately 250-300°C above the ambient mantle temperature to achieve sufficient melt for intra-plate basalt provinces (despite the volatile-rich nature of most intra-plate sources). This hypothesis also assumes (again, perhaps unrealistically) that the composition of the DMM is representative of the entire convecting upper mantle, and invokes deeper, more enriched mantle sources to produce melts with OIB geochemical signatures.

There are, however, numerous problems reconciling the observations with a plume model in the OIB-type alkaline suite of western Turkey. Extensional stress associated with lithospheric uplift, for instance, should be at a maximum above a plume apex, which in turn would be expected to result in uplift and doming. This is, however, not observed in the alkaline field of western Turkey, nor is there any evidence for locally elevated temperatures. In fact, the evidence from surface heat flow measurements and mineral equilibrium constraints (*Aldanmaz et al.*, 2005) suggests that the thermal gradient in western Turkey is not anomalously high. The bulk chemistry of undifferentiated (or fractionation corrected) alkaline magma compositions from western Turkey provides evidence for “primary melts” with 11-16 wt% MgO and liquidus temperatures ranging from 1290°C to 1410°C (see *Aldanmaz et al.*, 2005 for details). Combining these results with information on the depth of melt extraction (Figure 5) implies that the mantle region which melted to produce the alkaline primary compositions has a potential temperature of ~1300°C, a value significantly lower than suggested to be associated with mantle plumes (>1450°C; *McKenzie & Bickle*, 1988). It is therefore difficult to attribute mantle melting in this region to plume-related thermal anomalies. In addition, the radial thermal and stress perturbations expected from an adiabatically upwelling mantle plume are inconsistent with the linear distributions of the volcanic centers as well as the planar geometry of normal and strike-slip faulting in western Turkey, to which the small volume and episodic alkaline magma generation is mostly related (*e.g., Aldanmaz et al.*, 2005; 2006).

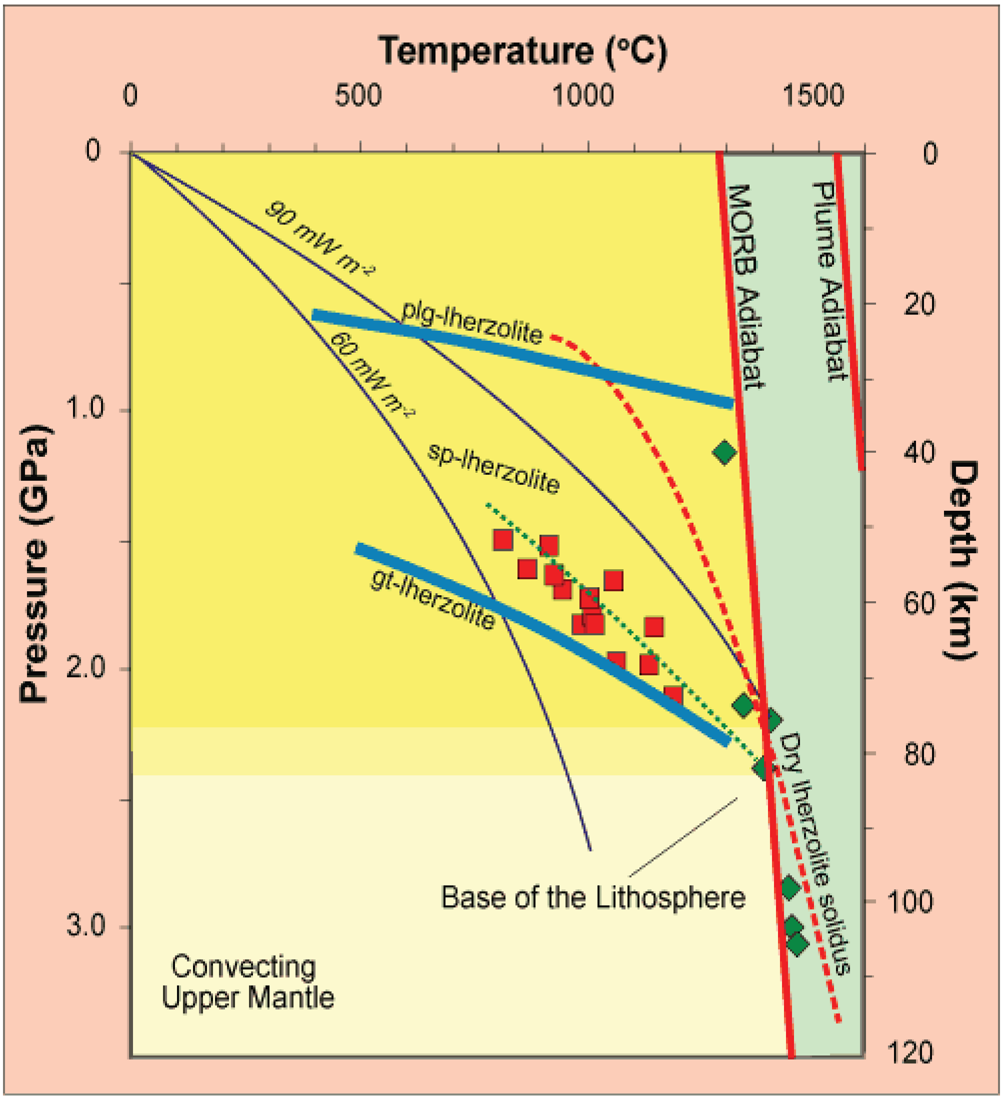


*Figure 5. Thermal structure of the northern part of western Turkey inferred from mantle-derived ultramafic nodules and alkali primary melts. Squares represent coarse, shallow xenoliths along which the inferred (and laterally averaged) regional geotherm was determined (dashed line). Closed diamonds represent alkaline primary melts along which the inferred ambient mantle geotherm was determined. The MORB adiabat and the plume adiabat have potential temperatures (Tp) of 1280°C and 1540°C respectively. Dry peridotite solidus shown as dashed curve are from Herzberg et al. (2000). Conductive Continental Geotherm curves are from Pollack & Chapman (1977).*

Furthermore, for the case of western Turkish alkaline suites there is no clear indication of a change in depth, *i.e.* from garnet- to spinel-facies mantle, as might be expected for an actively upwelling mantle plume. Nor is there any dramatic change in the degree of partial melting, also expected for a mantle plume, that would potentially include large degrees of partial melting. The alkaline lavas from western Turkey display a trend of significant enrichment in incompatible trace elements and a gradual decrease in silica content with decreasing eruption age. Such a compositional trend can be interpreted in terms of progressively increasing depth of melting coupled with decreasing degree of melting in a compositionally uniform source. This is inconsistent with the plume hypothesis.

### *Lithospheric mantle origin*

Involvement of melts from the conductive mantle in the genesis of OIB-type magmas is usually considered to be a common process owing partly to the ability of the conductive mantle to remain isolated from mantle convection for periods of time geologically reasonable to create the anomalous isotopic signatures of most OIB magmas compared to MORB. The existence of residual hydrous minerals such as amphibole or phlogopite (evident from the classic negative K and Rb anomalies in most OIBs) is another reason why many researchers believe that involvement of conductive mantle-derived melt in OIB genesis is inevitable (*e.g., Class & Goldstein*, 1997). Melt derivation from conductive mantle for the alkaline magmas of western Turkey is unlikely however; as noted by *Aldanmaz et al.* (2000), the mantle lithosphere beneath western Turkey is subduction-modified, and any model involving melts from such a source would produce magmas with significant arc signatures (*e.g.,* selective enrichment in fluid-soluble LILE relative to the insoluble HFSE). However, neither the lavas of western Turkey nor OIB-type magmas in general display such selective enrichments. Many oceanic and continental alkaline primary suites worldwide are characterized by "non-selective enrichment" in both HFSE and LILE (relative to N-MORB), supporting a source of melt from a homogeneous, possibly convective, region.

The prominent negative anomalies in K, Rb and Ti (both in western Turkish lavas and OIB-type lavas) can most likely be explained by buffering against a K-bearing (hydrous) phase (*e.g.,* phlogopite and/or amphibole) in the mantle source region. Although some argue against the possibility of long-term stability of the inferred hydrous minerals in a steady-state convecting system (because these phases are not particularly common primary mantle minerals), the existence of such phases can be attributed to the metasomatizing effects of melts during (or shortly after) melt generation and should not necessarily be interpreted as a long-term source characteristic.

For the case of the alkaline rocks from western Turkey, the presence of the inferred hydrous phases in the original, pre-melting, solid mantle is also inconsistent with the temporal compositional trend of the lavas because, irrespective of the nature of the mantle region, the time-integrated fusion of these hydrous phases would be expected to lower the hydrous character of the magmas as melting precedes, which is not the case here. The most likely explanation is therefore that the inferred hydrous minerals are not primary phases in the source mantle and might instead be the short-lived products of metasomatic reaction during melting and melt migration through intergranular channels. Supporting evidence for melt metasomatism may be that the depletion in Rb, K and Ti correlates with both time and degree of partial melting (but not with the isotopic ratios) and, as shown in K/K* vs. La plots (Figure 6), the degree of depletion increases gradually with time towards the most primitive sample (the product of the smallest degree of melting with the greatest liquidus temperature) implying a time-integrated increase in the extent of source metasomatism.

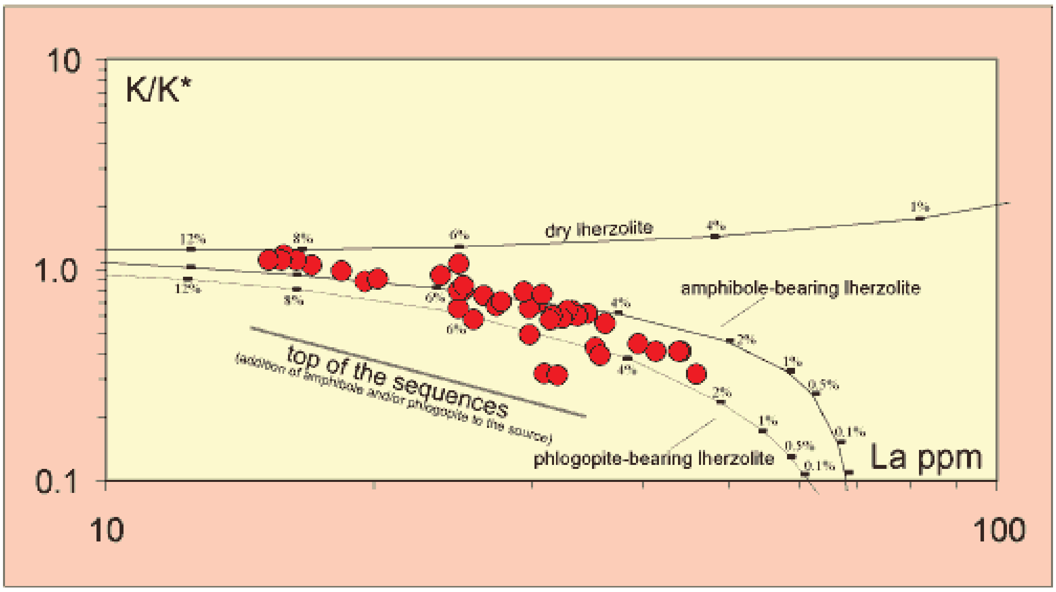


*Figure 6. Covariation of K/K* (taken as K negative anomalies) with changing La contents of the rocks. K* has been taken as extrapolated K calculated using normalized concentrations of Th, K, Nb. Melt trajectories are drawn for (1) dry lherzolite ($ol_{0.530}$+$opx_{0.270}$+$cpx_{0.170}$+$sp_{0.030}$); (2) amphibole-bearing lherzolite ($ol_{0.558}$+$opx_{0.201}$+$cpx_{0.076}$+$sp_{0.115}$+$amp_{0.050}$); and (3) phlogopite-bearing lherzolite ($ol_{0.558}$+$opx_{0.201}$+$cpx_{0.076}$+$sp_{0.115}$+$amp_{0.050}$) sources using non-modal batch partial melting. Melting of amphibole- and phlogopite-bearing lherzolites is assumed to initiate in adry condition but to continue with addition of the inferred hydrous phases by up to 5%.*

This type of metasomatism can also be considered effective in modifying the composition of the resultant melts, because elements move through porous peridotites with a diffusive velocity inversely proportional to their solid/melt partition coefficients (*e.g., Takazawa et al.*, 1992). Under certain conditions, infiltrating melts can be equilibrated with incompatible elements in mantle peridotites during melt migration and ascent, preferentially leaching incompatible elements from the mantle peridotites. This type of melt-rock interaction produces magma batches with high ratios of highly incompatible to less incompatible elements relative to the original parental melt composition.

### *Convective mantle origin*

Incompatible-trace-element ratios and isotopic constraints provide the most compelling evidence against melt generation by mixing melts from multiple source components in the genesis of western Turkish alkaline lavas. Rocks that formed over a significant period of time have near-constant Sr and Nd isotopic ratios and incompatible-element-concentration ratios for the entire suite, indicating that melt generation probably took place under conditions of significant chemical homogeneity, probably within a single mantle domain. Therefore, any model proposed to account for the composition of the alkaline magmas from western Turkey should be able to describe melt generation within a well-homogenized system with no contribution from a source that was selectively enriched in mobile incompatible elements. The best site for this homogenization, which might possibly require pre-melting and mixing of discrete mantle lithologies created by plate-recycling processes or delamination would be a sub-lithospheric, convecting *(i.e.* efficiently stirred, homogeneous) system (*e.g., Hofmann*, 1997; *van Keken et al.*, 2002; *Kellogg et al.*, 2002; Editor's note: see also Lower crust recycling and Gravitational instability ).

The inferred mantle source seems to represent a part of the uppermost convecting system that shows remarkable differences in terms of geochemical characteristics compared to the MORB source which is usually considered the sole representative of the uppermost convecting mantle. This can most likely be explained by the existence of self-mixed and chemically homogeneous mantle domains (*e.g.,* created by plate recycling and subsequent mixing-homogenization processes) within the convectively stirred upper mantle.

If interpreted in a regional context, the western Turkish alkaline lavas exhibit strong similarities in terms of trace-element and isotopic compositions with coeval widespread alkaline magmatism formed in very similar geological settings throughout a magmatic belt extending from the central east Atlantic through southern, northern and eastern Europe to the western Mediterranean (the so-called "European Volcanic Province" (EVP); *Wilson et al.*, 1995). In particular, geochemical characteristics of the western Turkish alkaline rocks are almost identical to the HIMU end-member of the EVP volcanism, which is referred to in the literature as to the lower-velocity-component (LVC; *Hoernle et al.*, 1995) or the European Asthenospheric Reservoir (EAR; *Wilson et al.*, 1995). The existence of this component has been attributed to a number of processes including;

1. plume activity from lower mantle in the central Atlantic and sublithospheric channeling throughout North Africa and Europe (*Oyarzun et al.*, 1997);
2. plume-like smaller-scale diapiric upwellings from deeper sources (*Wilson et al.*, 1995).

However, a deep, lower-mantle source for this component seems unlikely because of the thermal and compositional constraints outlined above. This component seems to be the hallmark of mid-plate basalts that characterize a tectonic regime dominated by plate convergence and collision followed by later-stage extension (i.e. the convergence zone between the European and African plates). It is thus likely to represent compositional, rather than thermal, anomaly zones within the shallow convective mantle – partially molten, shallow fertility anomaly zones. (Editor's note: see also Paraná basalts).

## **Summary**

Geochemical evidence indicates that, on average, the alkaline lavas of western Turkey were generated by variable degrees of partial melting of an isotopically homogeneous, single mantle domain enriched in incompatible elements relative to hypothetical DMM and PM. The lavas have a temporal compositional trend indicating a progressively decreasing degree of melting of a compositionally uniform source with a potential temperature of ~1300°C. This, along with the other geochemical signatures of the lavas (*e.g.,* constraints on melt contribution from the conductive mantle), suggests that melting probably occurred within the shallow convecting system.

The alkaline lavas have near-constant Sr and Nd isotope ratios for the entire suite and systematic change in incompatible trace element compositions (and ratios) of the lavas is not reflected in the isotopic ratios, suggesting that the temporal compositional trends are not caused by source variations. Instead, the trends may be a function of pressure and degree of melting, implying that parts of the isotopically homogeneous (and a single) source are sampled systematically as a function of pressure and degree of melting.

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