Melt equilibration depths as sensors of lithospheric thickness during Eurasia-Arabia collision and the uplift of the Anatolian Plateau

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ABSTRACT

A co-investigation of mantle melting conditions and seismic structure revealed an evolutionary record of mantle dynamics accompanying the transition from subduction to collision along the Africa-Eurasia margin and the >1 km uplift of the Anatolian Plateau. New 40Ar/39Ar dates of volcanic rocks from the Eastern Taurides (southeast Turkey) considerably expand the known spatial extent of Miocene-aged mafic volcanism following a magmatic lull over much of Anatolia that ended at ca. 20 Ma. Melt equilibration depths for these chemically diverse basalts are interpreted to indicate that early to middle Miocene lithospheric thickness in the region varied from ~50 km or less near the Bitlis suture zone to ~80 km near the Inner Tauride suture zone. This southward-tapering lithospheric base could have been the former interface between the subducted (and now detached) portion of the Arabian plate and the overriding Eurasian plate, and/or a reflection of mantle weakening associated with greater mantle hydration trenchward prior to collision. Asthenospheric upwelling driven by slab tearing and foundering along this former interface, possibly accompanied by convective removal of the lithosphere, could have led to renewed volcanic activity after 20 Ma. Melt equilibration depths for late Miocene and Pliocene basalts together with seismic imaging of the present lithosphere indicate that relatively invariant lithospheric thicknesses of 60–70 km have persisted since the middle Miocene. Thus, no evidence is found for large-scale (tens of kilometers) Miocene delamination of the lower lithosphere from the overriding plate, which has been proposed elsewhere to account for late Miocene and younger uplift of Anatolia.

INTRODUCTION

Hallmarks of continental collision include lithospheric thickening and shortening, uplift and exhumation of crust, slab breakoff, diffuse volcanism, and possible delamination (van Hunen and Miller, 2015). In southeastern Anatolia, subduction of oceanic lithosphere transitioned to that of buoyant attenuated continental lithosphere in the middle to late Eocene (“soft” collision), with arrival of more typical Arabian lithosphere at the trench in the early Miocene (Ballato et al., 2011; Darin et al., 2018, and references therein). A magmatic lull was terminated by a flare-up ca. 20 Ma (Schleiffarth et al., 2018), possibly triggered by upwelling asthenosphere associated with rollback and breakoff of the subducted portion of the Arabian plate (e.g., Keskin, 2003) and/or asthenosphere heating of delaminated or otherwise thinned lithospheric mantle beneath the overriding Eurasian plate (e.g., Pearce et al., 1990). Upwelling asthenosphere could be dynamically supporting the Anatolian Plateau at >1 km elevation, since its thin lithosphere (≤60 km; Angus et al., 2006; Delph et al., 2017) should result in lower elevations if the lithosphere is in isostatic balance (Boschi et al., 2010; Uluocak et al., 2016). However, uplift of the Anatolian Plateau interior began no earlier than ca. 11 Ma (Meijers et al., 2018a, and references therein). These events should have been contemporaneous, since slab rollback and breakoff and/or delamination of mantle lithosphere are anticipated consequences of continental collision (van Hunen and Miller, 2015), and associated asthenospheric upwelling due to mantle reorganization could lead to mantle melting and isostatic— and possibly dynamic— support of a relatively high plateau (Keskin, 2003; Şengör et al., 2003; McNab et al., 2018).

Melting conditions for mafic volcanic rocks in the Eastern Tauride region (Fig. 1) combined with seismic imaging (Fig. 2) provide windows into mantle evolution in response to collision and uplift of the Anatolian Plateau. Here, we considered mantle depths of melt equilibration for relatively Mg-rich lavas as paleoproxies for the lithosphere-asthenosphere boundary (LAB) and compared them to seismic images of modern-day upper-mantle architecture, leading us to propose that relatively thin lithosphere has characterized much of this region from the early Miocene to present. Slab breaks/tears and/or small-scale convective removal of the Anatolian lithosphere likely accompanied melting but do not appear to explain late Miocene uplift of the Anatolian Plateau.

PROTRACTED MAFIC VOLCANISM IN THE EASTERN TAURIDES

Most Eastern Tauride volcanic rocks reside on the Anatolide-Tauride block, which, in this area, consists of variably metamorphosed Paleozoic–Mesozoic sediments and Neoproterozoic–Cambrian crystalline basement, bounded by the Arabian plate along the Bitlis suture to the south (e.g., Robertson et al., 2012). New 40Ar/39Ar analyses and bulk chemical compositions were obtained along a broadly northwest-southeast–trending transect (Fig. 1). The 40Ar/39Ar analyses were
Figure 1. (A) Study region. Brown shading shows location of the Anatolian Plateau. (B) Locations and (C) Ar/Ar dates for Neogene volcanic deposits in the Eastern Taurides of Turkey. Volcanic fields are distinguished as early to middle Miocene (green), late Miocene (dark blue), and Pliocene (light blue). Sedimentary basins (orange fields) are named by cities denoted within them. Main tectonic features include: ITS—Inner Tauride suture (stippled area shows uncertainty in location); BS—Bills suture zone; MOFZ—Malatya-Ovacık fault zone; CAFZ and NAFZ—Central and Northern Anatolian fault zones, respectively. Age distribution plots (right-hand side) are keyed to locations in B, and bars represent dates and their 2σ uncertainty. New Ar/Ar dates (colored symbols) and existing dates (gray symbols) are listed in the Data Repository (see footnote 1). MSWD—mean square of weighted deviates. Lowermost section of C is a population density plot for all early to middle Miocene dates.

Figure 2. Comparison of (A) chondrite-normalized Dy/Yb in early—middle Miocene Eastern Tauride–Kırşehir (ETK) region and transitional to subalkaline in the southern ETK region, a variation that could indicate a southward decrease in melt derivation depths. Compiled data (McNab et al., 2018) show that ratios between middle and heavy rare earth elements decrease southward along the ETK transect (Fig. 2A), consistent with greater dilution of garnet signatures by shallower melt generation.

We applied the olivine-orthopyroxene-melt barometer calibration of Plank and Forsyth (2016) to projected primary magma compositions for Mg-rich ETK mafic lavas (Item DR2), assuming a Fo0.55, FeO/ΣFe = 0.2, and H2O/Ce = 200 in melts (Reid et al., 2017). Corresponding melt equilibration depths for early and middle Miocene basalts increase from ~80 km (and ~100 km for basanites) in the northern ETK (cf. Kürkçüoğlu et al., 2015) to ~50 km in the southern ETK (Fig. 2). This range is considerably larger than the ±8 km depth uncertainty extrapolated from barometer uncertainty (Plank and Forsyth, 2016). Lateral variations in mantle conditions of ~±1 in Fo content (reasonable) or ~±0.1 in FeO/ΣFe (extreme) could double this uncertainty: increasing H2O produces a negligible depth decrease. Melts equilibration depths for the ca. 11 Ma and ca. 5 Ma basalts are indistinguishable from each other at ~62 km, and from values for nearby older lavas (Fig. 2).

PRESENT-DAY MANTLE STRUCTURE

The evolution of mantle conditions captured by ETK barometry is compared to a snapshot of present-day crust and upper-mantle structure provided by seismic imaging in Figure 2.

conducted on fine-grained and massive samples, as described by Meijers et al. (2018b). Early to middle Miocene volcanism (ca. 18–14 Ma) occurred in four areas distributed across the Eastern Taurides and into the Kırşehir block (Fig. 1; Table DR1 in the GSA Data Repository). Dates obtained for volcanic rocks near the Inner Tauride suture and in the Arguvan region (10.9 Ma) are considerably older than the Pliocene ages inferred for them in previous geochemical investigations (Parlak et al., 2001; EKici et al., 2007; Kürkçüoğlu et al., 2015). The youngest dates (ca. 5.4–4.7 Ma; see also Meijers et al., 2018b) span those reported previously for lavas in locations distributed over ~2000 km2 in the Kangal Basin (Platzman et al., 1998).

GSA Data Repository item 2019335, description of previously published seismic methods, and Tables DR1 and DR2 summarizing new and published regional geochronology and geochemistry on mafic volcanic rocks, is available online at http://www.geosociety.org/daterepository/2019/, or on request from editing@geosociety.org.
A high-resolution model of the shear-wave velocity structure down to ~150 km below the ETK was obtained by a joint inversion of P-wave receiver functions (Abgarmi et al., 2017) and Rayleigh-wave dispersion data derived from ambient noise cross-correlations and earthquakes (Delph et al., 2017). Shear wave velocities of >4.4 km/s were resolved in the uppermost 15 km (southern ETK) to 35 km (northern ETK) of the mantle, consistent with expected velocities for mantle lithosphere (item DR1; Fig. 2). The exception is ~40 km north of the Malatya-Ovacık fault zone (MOFZ; Fig. 2), where the Vs immediately below the Moho is <4.3 km/s. As observed throughout Central Anatolia (Delph et al., 2017), lithospheric thickness is relatively thin, deepening from ~60 km thick under most of the study area to ~70 km near the Inner Tauride suture. Overall, except to the north of the Inner Tauride suture, the present-day LAB depths correspond to the melt equilibration depths obtained for early to middle Miocene, late Miocene, and Pliocene basalts (Fig. 2).

**INSIGHTS INTO UPPER-MANTLE DYNAMICS FROM MELTING CONDITIONS**

**Melt Equilibration Depths as Proxies for the Paleolab**

New and published ⁴⁰Ar/³⁹Ar and geochemical data (Table DR2) show that chemically diverse mafic lavas of Miocene age are distributed over >15,000 km² in the Eastern Tauride region. This magmatic activity, concentrated between 18 and 14 Ma (Fig. 1), followed an ~20 m.y. magmatic lull in Central and Eastern Anatolia (Schleiffarth et al., 2018) and was contemporaneous with final Arabia-Eurasia collision, slab breakoff, and/or lithosphere delamination (Keskin, 2003; Şengör et al., 2003; Okay et al., 2010; Bartol and Govers, 2014; Göğüş et al., 2017). We hypothesize that the variation in melt equilibration depths obtained for ETK basalts records the maximum distribution and evolution of lithospheric thickness and, in turn, provides insights into the settings for magmatism during and after continental collision.

Equating melt equilibration depths with paleolab depths has support from investigations of Quaternary-aged basalts (Plank and Forsyth, 2016; Reid et al., 2017), where mean melt equilibration depths are mostly within 5 km of seismically delimited LAB depths. Extraction of melts should be favored when melts encounter the rheological boundary represented by the lithospheric lid, but average melt equilibration conditions could be skewed to greater depths if some melts (e.g., basanites) were extracted along an adiabat (Plank and Forsyth, 2016). For the basalts at least, similar ranges in Sr and Nd isotopes between ETK volcanic areas (see compilation in McNab, 2018) appear to require contributions from lithospheric as well as sublithospheric sources. Accordingly, we infer that the lithosphere in the early to middle Miocene in the region of the ETK transect varied in thickness from ~50 km near the Bitlis suture between Arabia and Anatolia to ~80 km to the north of the Inner Tauride suture between the Eastern Tauride and Kırşehir crystalline blocks. Basalt-estimated lithospheric thicknesses in late Miocene and Pliocene times along and near the transect are similar to those estimated for earlier Miocene times, and to the region’s present-day thickness (Fig. 2). Thus, the lithosphere in much of the ETK region could have been relatively thin (mostly <60–70 km) since early Miocene time (e.g., Kocaarslan and Ersoy, 2018).

The inferred early-middle Miocene northward-dipping LAB could represent a vestige of the former interface between the overriding Anatolian portion of the Eurasian plate and the Bitlis slab at the leading edge of the Arabian plate. The timing of Bitlis slab breakoff is poorly constrained, but seismic images show that slab fragments now reside within or below the mantle transition zone (Fig. 3; Portner et al., 2018). Early-middle Miocene slab rollback and/or breakoff along with shallow LAB depths would have enabled hot asthenosphere (mantle potential temperature, $T_p >$ 1380 °C; Reid et al., 2017; McNab et al., 2018) to ascend and melt in response to Bitlis slab tearing and retreat, with variations in melt compositions determined largely by the extent of mantle ascent. Alternatively, or additionally, trenchward variations in the extent of mantle hydration could have preferentially weakened the mantle under the southern ETK, leading to greater lithospheric removal associated with small-scale convection (Kaisianiem et al., 2014). In this case, the inferred LAB depths may reflect more localized effects of erosion at the base of the lithosphere (Plank and Forsyth, 2016). Last, if lithospheric removal occurred in conjunction with rollback of the Bitlis slab (e.g., Bartol and Govers, 2014), lateral variations in the extent of mantle hydration could have localized the décollement within rather than above the Eastern Tauride mantle lithosphere.

**ETK Magmatism and Lithospheric Dynamics**

Southwestward rollback of the Cyprus slab may have initiated below the ETK and may account for the southwest expansion of Central Anatolian volcanism (Delph et al., 2017; Schleiffarth et al., 2018). The ETK region is located just east of the tomographically imaged edge of the Cyprus slab (Biryol et al., 2011; Portner et al., 2018) and north of the Arabian plate, which may represent the relict boundary of a vertical slab tear. In this scenario, early Miocene ETK volcanism represents the initial stages of slab tearing in the once-continuous subducting Neotethyan lithosphere. The tear would have led to effective decoupling of the Miocene to recent evolution of the Cyprus and Bitlis slabs and associated overriding lithosphere (Fig. 3; Schleiffarth et al., 2018). Volcanism to the east of the ETK is mostly younger than 7 Ma and has...
elsewhere been linked to slab breakoff (Keskin, 2003; Şengör et al., 2003); however, we interpret small-scale delamination as the impetus for mantle melting there (Pearce et al., 1990; Kaislanemi et al., 2014) and hypothesize an earlier demise of the slab based on the absence of slab fragments in the upper mantle (Fig. 3).

Onset of magmatism in the ETK region apparently preceded >1 km uplift of the Anatolian Plateau, including that documented regionally, by almost 10 m.y. (Meijers et al., 2018a). Some possible explanations for this delay include viscous coupling between delaminated and overriding lithosphere (Bartol and Govers, 2014), or the possibility that the thin lithosphere of Anatolia did not develop until the late Miocene (e.g., Göğüş et al., 2017); reexamination of both scenarios is required in light of our results. Early to middle Miocene fountaining of the Bitlis slab could have simultaneously led to extension in the ETK blocks and mantle melting, yet limited the extent of crustal uplift (Göğüş, 2015). Associated lavas investigated here largely occur in basins containing terrestrial sedimentary units; extensional and contractional tectonic settings for these have both been proposed (summarized by Darin et al., 2018).

Deposition near sea level is indicated by the local presence of Langhian Stage marine deposits (Poisson et al., 2016), and by the oxygen isotope signatures of lacustrine sediments interbedded with the Gürün basalts (Meijers et al., 2018a).

Following mid-Miocene volcanism, lithospheric thickness under the Eastern Taurides apparently persisted at ~60–70 km, based on equilibrium depths for late Miocene and Pliocene basalts and seismic imaging of the LAB. Under the Kışırhîr block to the north, the apparent ~20 km decrease in equilibrium depths since the middle Miocene (Fig. 2) is permissive of lithospheric removal. Elsewhere, early to middle Miocene removal of melt and volatiles could have strengthened the residual mantle (Dagsputa et al., 2007) and made the base of the lithosphere relatively refractory, possibly resulting in little net lithospheric thinning (Kaislanemi et al., 2014). Instead, some lithospheric thickening probably accompanied an episode of contraction in late Miocene time, with crustal thickening associated with plate convergence on the order of 3–8 km (Bartol and Govers, 2014). If horizontal shortening also applied to the mantle lithosphere, lithospheric removal in the range of 5–15 km in conjunction with late Miocene and Pliocene mantle melting is permitted by our results but by no means required. The inferred northward increase in LAB depth would have also enhanced the likelihood of edge-driven small-scale convection and melting under the ETK. Lithosphere delamination and mantle melting, along with crustal uplift, may have been cyclical as a result, with delamination and melting in the late Miocene–early Pliocene accompanying the best-documented phase of Anatolian Plateau uplift.

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REFERENCES CITED


