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East Anatolian plateau constructed over a continental basement: No evidence for the East Anatolian accretionary complex

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ABSTRACT

The East Anatolian plateau (Turkey) is extensively covered by Neogene to Quaternary volcanic-sedimentary rocks, and is characterized by an attenuated lithospheric mantle. Its pre-Neogene basement is commonly considered to consist entirely of Late Cretaceous to Oligocene oceanic accretionary complexes, formed at the junction of several continental blocks. Here we report on three main exposures of the pre-Neogene basement in this region. The exposed areas consist mainly of amphibolite- to granulite-facies metamorphic rocks, including marble, amphibolite, metapelite, metagranite, and metaquartzite. An upper amphibolite– to granulite-facies domain is equilibrated at ~0.7 GPa and ~800 °C at 83 ± 2 Ma (2σ). U-Pb dating of magmatic zircons from the metagranite yielded a Late Ordovician–early Silurian protolith age (444 ± 9 Ma, 2σ). The detrital zircons from one metaquartzite point to a Neoproterozoic–early Paleozoic provenance. Ophiolitic rocks tectonically sit on the metamorphic rocks. Both the metamorphic and ophiolitic rocks are in turn unconformably covered by lower Maastrichtian clastic rocks and reefal limestones, suggesting that the whole exhumation process and juxtaposition with the ophiolitic rocks had occurred by the early Maastrichtian. Several lines of evidence, such as (1) the absence of any indication of a former high-pressure metamorphism in the metamorphic rocks, (2) the allochthonous nature of the ophiolitic rocks, (3) the presence of metagranite with a Late Ordovician–early Silurian protolith age, and (4) the Neoproterozoic–early Paleozoic provenance of detrital zircons in the metaquartzite (in contrast to the dominance of late Paleozoic–Mesozoic crystalline rocks in the adjacent continental blocks) indicate a substantial component of continental basement beneath the Neogene to Quaternary cover. Thus, the loss of the lithospheric mantle probably resulted from lithospheric foundering processes beneath the plateau, rather than just slab steepening and break-off.

INTRODUCTION

Continental collision is commonly succeeded by a series of plate-mantle interactions including slab steepening, slab break-off, formation of slab windows, and lithospheric foundering (van Hunen and Miller, 2015). Docking of continental blocks, ophiolite obduction, and accretion of intraoceanic arcs before final collision lead to complexities in mantle structure. A combination of field geological and seismic studies is crucial in understanding the plate-mantle interactions. Within the Tethyan belt, the East Anatolian plateau (Turkey) is characterized by (1) an extensive volcanic and sedimentary cover of Neogene to Quaternary age, (2) crustal thicknesses of 42–50 km, and (3) attenuated or absent lithospheric mantle (Fig. 1) (Zor et al., 2003; Şengör et al., 2003; Angus et al., 2006). The Neogene to Quaternary volcanic rocks display calc-alkaline, alkaline, and peralkaline basaltic to rhyolitic compositions with variable amounts of crustal contamination (Pearce et al., 1990; Keskin, 2003). The pre-Neogene basement has been interpreted as consisting largely of accretionary complexes (East Anatolian accretionary complex, an ~380 × ~130 km region), formed at the junction of several crustal blocks with irregular margins, similar to the Makran accretionary wedge in Iran (Şengör and Yılmaz, 1981; Şengör et al., 2003). This interpretation, which was brought into question by Yılmaz et al. (2010), found widespread acceptance, and has been invoked to explain the attenuated or absent lithospheric mantle and the source of the widespread young volcanism by slab steepening and subsequent break-off (Keskin, 2003; Angus et al., 2006; Şengör et al., 2008; Skobeltsyn et al., 2014).

We present field geological, petrological, and geochronological data on three isolated basement inliers from the East Anatolian plateau (Fig. 1). Our data consistently indicate that these areas are characterized by continental rock assemblages that underwent high-temperature–medium-pressure metamorphism at middle- to lower-crustal depths during the Late Cretaceous.

GEOLOGICAL FRAMEWORK

The East Anatolian plateau is bounded by two Neo-Tethyan sutures, the İzmir-Ankara-Erzincan suture in the north and the Bitlis-Zagros suture in the south (Fig. 1). The northern ocean closed by the middle Eocene, and the southern one during the Oligocene–early Miocene (Okay et al., 2010). The emergence of the plateau above sea level took place after the Burdigalian (ca. 15 Ma), as deduced from the ages of the youngest marine sedimentary sequences in the region (Yılmaz et al., 1988). The formation of the plateau is ascribed to the ongoing convergence after the continental collision along the Bitlis-Zagros suture. The crustal seismicity in the plateau is related predominantly to strike-slip and subordinately to reverse faulting at shallower depths (Örgülü et al., 2003). The tomographic images of the upper mantle reveal the presence of high-velocity domains within widespread low-velocity ones, which are interpreted as parts of the detached slab (Skobeltsyn et al., 2014).

The East Anatolian plateau is located at the meeting point of several continental blocks: the Eastern Pontides in the north, the Bitlis massif in the south, the Menderes-Taurus block to the west, and the northwest Iranian block to the east (Fig. 1). The Eastern Pontides represent a Jurassic–Cretaceous submarine magmatic arc constructed on (1) Carboniferous high-temperature–low-pressure metamorphic rocks and granitoids, and (2) Permian–Triassic accretionary complexes. Its southern margin grew by accretionary processes from Permian–Triassic to end-Mesozoic time with intermittent subduction erosion and collision of intraoceanic arcs (Topuz et al., 2013; Okay and Nikishin, 2015). The Bitlis massif is made up of Late Cretaceous greenschist- to amphibolite-facies continental rock assemblages with locally preserved kyanite-eclogite and blueschist (Oberhänsli et al., 2010). The exact location of the Bitlis-Zagros suture in southeast Turkey is controversial—in particular,

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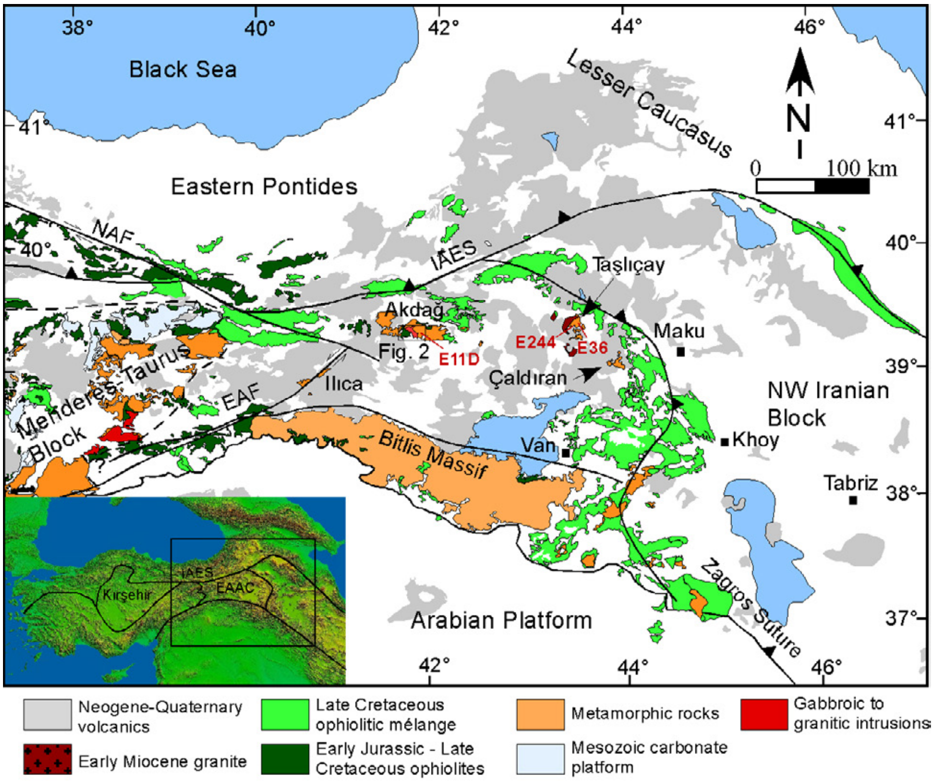

Figure 1. Distribution of Neogene to Quaternary volcanic rocks, ophiolitic rocks, and main basement exposures in Eastern Anatolia and adjacent areas (Turkey). Red labels indicate sample locations. Inset shows present-day topography together with Neo-Tethyan sutures. EAAC—so-called East Anatolian accretionary complex; IAES—İzmir-Ankara-Erzincan suture; NAF—North Anatolian fault; EAF—East Anatolian fault.

whether it is north or south of the Bitlis massif or on both sides (Şengör et al., 2008; Okay et al., 2010; Robertson et al., 2013). Because the massif comprises continental rock assemblages with locally preserved high-pressure mineral assemblages indicative of a subduction regime, there should be at least one paleo–ocean basin that originally lay to the north of the massif. The Menderes-Taurus block is characterized by continuous carbonate deposition from Permian to Late Cretaceous time with some Triassic basic to acidic magmatism (Fig. DR1 in the GSA Data Repository[1]) (Özgül and Turşucu, 1984). Robertson et al. (2013) regarded the Menderes-Taurus block as a collage of several microcontinental fragments separated by Mesozoic oceanic basins. Its northern, leading edge was subjected to ophiolite obduction before the middle Campanian (Özgül and Turşucu, 1984). In contrast to the Menderes-Taurus block, the northwest Iranian block is characterized by Triassic carbonate deposition that is unconformably overlain by a Jurassic–Cretaceous arc sequence (Fig. DR1) (Hassanzadeh and Wernicke, 2016). The relationship between the Menderes-Taurus and the northwest Iranian blocks and their exact boundaries are controversial.

The pre-Neogene basement of the East Anatolian plateau crops out mainly in four areas that include the Ilıca, Akdağ, Taşlıçay, and Çaldıran inliers (Fig. 1). Here we focus on the three largest ones: the Taşlıçay, Akdağ, and Ilıca inliers.

THE TAŞLIÇAY, AKDAĞ, AND ILICA INLIERS

The Taşlıçay metamorphic rocks, with a 30 km by 20 km area of exposure, comprise amphibolite-facies metagranite, metapelite, quartzite, marble, calc-silicate gneiss, and rare amphibolite (Fig. 1). They are tectonically overlain by Late Cretaceous ophiolitic mélange along their northwestern edge, and intruded by early Miocene granitic bodies. The metagranite is composed of K-feldspar, plagioclase, quartz, biotite, ± amphibole, and accessory phases such as zircon, apatite, and ± allanite. The metapelite contains garnet, sillimanite, plagioclase, biotite, quartz, and K-feldspar.

The Akdağ area, 60 km long and 20 km wide, is located ~50 km to the south of the İzmir-Ankara-Erzincan suture and includes metamorphic, intrusive, and ophiolitic rocks that are unconformably overlain by lower Maastrichtian conglomerate and reefal limestone (Fig. 2). The basal conglomerate contains well-rounded pebbles derived from both metamorphic and ophiolitic rocks. All of these units are unconformably overlain by a middle Eocene to lower Miocene sedimentary succession. The metamorphic rocks are complexly folded and made up of marble (~80% of the outcrop area), amphibolite, calcsilicate gneiss, and restitic to migmatitic metapelite. Restitic and migmatitic metapelites contain garnet + sillimanite + biotite ± cordierite ± spinel ± K-feldspar ± plagioclase, suggesting upper amphibolite– to granulite-facies conditions. The metamorphic rocks are intruded by subduction-related gabbro, quartz monzonite and tonalite with U-Pb zircon ages of ca. 85 Ma (our data). A relatively intact ophiolite, represented by a crustal section consisting of cumulate gabbro/peridotite and diabase, rests tectonically above the crystalline complex (Fig. 2). It lacks penetrative ductile deformation and shows traces of hydrothermal alteration.

The metamorphic rocks in the Ilıca area form two isolated exposures (10 × 5 km and 3 × 13 km) along the East Anatolian fault, which offsets them by ~20 km (Fig. 1). They are made up of a coherent sequence of marble (~80% of outcrop area) and subordinate phyllite and metabasite. The metabasites contain hornblende with local actinolitic cores, plagioclase (An_{16-18}) with albitic cores, titanite, epidote, and chlorite, suggesting uppermost greenschist– to lowest amphibolite–facies conditions.

METAMORPHIC CONDITIONS

We estimate pressure-temperature conditions in the Akdağ area using a combination of trace element and conventional geothermobarometers. Mineral compositions and trace element compositions were determined by electron microprobe at the Institute of Earth and Environmental Sciences (Potsdam, Germany), and by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the Institute of Earth Sciences (Gothenburg, Sweden). The analytical procedures and data are given in the Data Repository (Tables DR1–DR2).

Sample E11D is a restitic metapelite, consisting of garnet + sillimanite + spinel + plagioclase ± biotite ± quartz ± K-feldspar and accessory phases including rutile, zircon, and apatite. Rutile is confined to inclusions (20–80 μm) in the garnet. Zircon occurs as rounded grains (30–120 μm) with unzoned internal structure (Fig. DR2a). They are compositionally characterized by (1) very low Th/U ratios (0.02–0.04), comparable with those of metamorphic zircons (Rubatto, 2002), and (2) a lack of fractionation between middle and heavy rare earth elements (chondrite-normalized Lu/Gd = 0.79–3.14) and a pronounced negative Eu anomaly (Eu/Eu* =

[1]GSA Data Repository item 2017259, analytical procedures; Table DR1 (Trace element compositions of zircons and ruiles); Table DR2 (Electron microprobe mineral analyses); Table DR3 (LA-ICP-MS U-Pb data); Figure DR1 (Columnar sections); Figure DR2 (Rare earth element patterns and U-Pb age plots), is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

0.49–0.83), suggestive of growth in the presence of garnet and plagioclase.

Zircon Ti concentrations are in the range of 11–26 ppm, yielding Ti-in-zircon temperatures of 761–831 °C, after Watson et al. (2006). Zr contents of rutile are 1243–2036 ppm, recording Zr-in-rutile temperatures of 775–830 °C at an assumed pressure of 0.7 GPa, using the calibration of Tomkins et al. (2007). The plagioclase-garnet-Al_2SiO_5-quartz geobarometer of Koziol and Newton (1988) yields pressures of 0.7 GPa at temperatures of 760–830 °C. Thus, metamorphic conditions are ~800 °C and 0.7 GPa. Whereas the Taşlıçay metamorphic rocks were probably subjected to comparable metamorphic conditions based on the similar mineral assemblages, the Ilıca metamorphics were metamorphosed at substantially lower temperatures (e.g., 450–500 °C).

GEOCHRONOLOGY

We performed LA-ICP-MS U-Pb dating on both zircon and rutile at the Institute of Earth Sciences (Gothenburg). The analytical procedures and data are given in Table DR3.

In the Taşlıçay area, zircons from a metagranite (sample E36) are characterized by (1) prismatic grains (120–180 µm) with oscillatory and sector zoning, (2) elevated Th/U ratios (0.35–0.62) and Eu anomalies (Eu/Eu* = 0.05–0.15), and (3) chondrite-normalized Lu/Gd values of 14–18, characteristic of zircons grown from a melt phase. Thirteen grains yielded a concordia age of 447 ± 10 Ma (2σ, Late Ordovician–early Silurian) (Figs. DR2b and DR2c), interpreted as the intrusive age of the protolith. The zircons in the metaquartzite (sample E244) are represented by subrounded to rounded detrital grains with mainly oscillatory zoning. Concordant zircon grains yielded $^{206}Pb/^{238}U$ ages ranging mainly from 455 to 953 Ma, pointing to a Neoproterozoic–early Paleozoic crystalline provenance (Fig. DR2d). Because the Late Ordovician to early Silurian metagranite is intrusive into the metaquartzite (sample E36), the protolith of the quartzite must be of Middle to Late Ordovician age.

In the Akdağ area, both morphological and geochemical features of zircons from sample E11D suggest metamorphic growth. Seven grains of zircon and eight grains of rutile from sample E11D define concordia ages of 83 ± 2 and 78 ± 3 Ma (2σ), respectively (Figs. DR2e and DR2f), indicating that high-temperature–medium-pressure metamorphism occurred during the Santonian to Campanian.

DISCUSSION AND CONCLUSION

The presence of continental basement rocks beneath the Neogene to Quaternary cover is evidenced by several criteria, including (1) high-temperature–medium-pressure metamorphism without any indication of former high-pressure metamorphism, (2) the presence of metagranite with a Late Ordovician–early Silurian protolith age intruding into a metasedimentary sequence of early Paleozoic protolith age, and (3) the allochthonous nature of the ophiolitic rocks. Within the limited basement exposures there is no indication of (1) major strike-slip faulting that might have interposed the continental fragments with the oceanic accretionary complexes, as in the Altaic orogenic collage (Şengör et al., 1993), or (2) the presence of multiple continental fragments separated by oceanic accretionary complexes (Robertson et al., 2013). Rather, we interpret the ~250-km-long basement inliers as a more or less continuous continental substrate to the allochthonous ophiolitic rocks.

The peak (or close-to-peak) condition of the metamorphism is concurrent with the emplacement of voluminous subduction-related intrusions in the Akdağ area. The metamorphism and coeval magmatism can be regarded as the middle- to lower-crustal root of the Late Cretaceous magmatic arc that developed due to northward subduction along the Bitlis-Zagros suture. The geochronological data together with the field relations require that the exhumation of the metamorphic rocks at the Earth's surface from depths of ~25 km occurred in a very short time span between ~83 and ~71 Ma in an extensional setting (our unpublished data).

The coherent metamorphic sequences in both the Akdağ and Ilıca inliers are dominated by marble with minor clastic and basic rocks at the lower structural levels, resembling the typical Mesozoic stratigraphy of the Menderes-Taurus block (Fig. DR1). The presence of the metagranite with a Late Ordovician–early Silurian protolith age and a lower Paleozoic quartzite

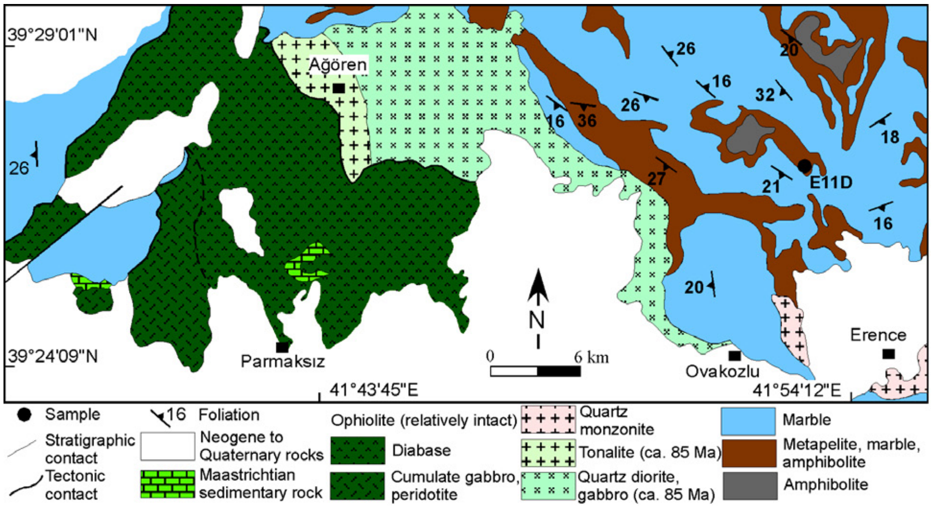

Figure 2. General geological map of Akdağ area, Turkey (modified after Yılmaz et al., 1988).

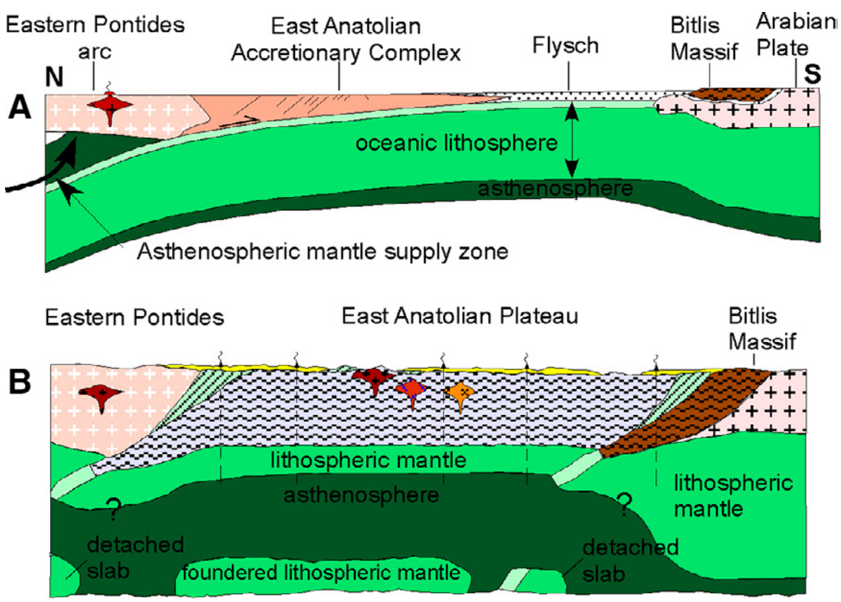

Figure 3. Simplified and schematized north-south cross sections across the East Anatolian plateau (Turkey), after Şengör et al. (2008) (A) and this study (B).

imply that the Taşlıçay metamorphic rocks represent a lower Paleozoic sequence. Ordovician granites and lower Paleozoic quartzites have also been described from the Menderes-Taurus block (Özgül, 1976; Okay et al., 2008), suggesting that the basement of the East Anatolian plateau probably represents the eastward extension of the Menderes-Taurus block.

The eastern margin of the East Anatolian plateau is marked by large tracts of ophiolite and oceanic accretionary complexes along a north-south transect up to the Bitlis-Zagros suture (Fig. 1) that are commonly regarded by Iranian geologists as parts of the back-arc ophiolites separating the Urumieh-Dokhtar arc and the Sanandaj-Sirjan zone (Hassanzadeh and Wernicke, 2016). The northwest Iranian block differs from the Menderes-Taurus block due to the presence of Late Triassic–Early Jurassic and Late Jurassic–Early Cretaceous unconformities, and to Jurassic arc magmatism (Fig. DR1), implying that they represent different continental blocks. Thus, these ophiolitic rocks are best interpreted as vestiges of the oceanic seaway separating the two continental blocks.

The presence of a continental basement beneath the young cover requires that the loss of the lithospheric mantle from beneath the East Anatolian plateau may have resulted from other processes of lithospheric foundering (Fig. 3) (Göğüş and Pysklywec, 2008). Some tomographic models reveal the presence of a single high-velocity anomaly in the center of the plateau at a depth range of 120–210 km, and two detached slab-like high-velocity anomalies, one beneath the İzmir-Ankara-Erzincan suture and the other beneath the Bitlis-Zagros suture (Skobeltsyn et al., 2014). The central high-velocity anomaly could represent the foundered part of the East Anatolian continental lithospheric mantle. The East Anatolian plateau can be compared with the Sierra Nevada (California, USA) and the eastern part of the North China craton in terms of the attenuated lithospheric mantle (Lee, 2014).

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