Lithospheric structure of the Arabia-Eurasia collision zone in eastern Anatolia: Magnetotelluric evidence for widespread weakening by fluids?

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ABSTRACT

Eastern Anatolia is the location of a young continent-continent collision between the Arabian and Eurasian plates. Long-period magnetotelluric data have been used to image the electrical resistivity of the crust and upper mantle in this region. The Anatolian block is being extruded to the west and is characterized by a low-resistivity (fluid rich) lower crust underlain by relatively normal upper mantle structure. The Anatolian Plateau has a lower crust that contains pockets of very low resistivity that may indicate local accumulations of melt. This is underlain by an upper mantle with an anomalously low resistivity that can be accounted for by an asthenosphere containing a few percent partial melt. The presence of fluids may weaken the crust and mantle sufficiently to permit lateral flow, and may also allow a decoupling of the upper and lower portions of the lithosphere. The lithospheric structure of the Anatolian Plateau is similar to that of the northern Tibetan Plateau, with zones of elevated fluid content. However, low resistivity in the Anatolian crust is found in isolated pockets, rather than the widespread regions observed in Tibet.

Keywords: continent-continent collision, plate tectonics, rheology, orogenesis.

INTRODUCTION

Continent-continent collision is a fundamental tectonic process that has shaped the evolution of the Earth's surface. A series of these collisions have occurred in the Alpine-Himalaya mountain belt and produced high-elevation plateaux. The Tibetan Plateau is the largest of these, and geophysical studies have shown that fluids are widespread in the crust (Unsworth et al., 2005). The eastern Anatolian–Iranian plateau is the second largest and was formed by the convergence of the Arabian and Eurasian plates over the past 13 m.y. (Şengör and Kidd, 1979; Dewey et al., 1986). Passive seismic data have shown that crustal thickness increases from 40 to 50 km from south to north (Zor et al., 2003). Low seismic velocities in the upper mantle (Al-Lazki et al., 2004; Gök et al., 2003) and the absence of subcrustal earthquakes (Turkelli et al., 2003) suggest that the lithospheric mantle is either very thin or completely absent, the high elevation being supported dynamically by hot asthenosphere, rather than a thickened crust (Şengör et al., 2003; Keskin, 2003). Deep-sounding magnetotelluric (MT) data complement seismic studies of the lithosphere since they determine the resistivity of the crust and upper mantle, which is sensitive to the in situ temperature and fluid content (Xu et al., 2000; Partzsch et al., 2000). Here we present the first deep-sounding MT data collected in eastern Anatolia.

GEOLOGICAL SETTING AND TECTONIC MODELS

The Tertiary history of eastern Anatolia was dominated by closure of the Tethyan Ocean, with subduction occurring beneath the Bitlis and Pontide arcs (Barazangi et al., 2006). Much of the study area is covered by postcollisional volcanic rocks. The oldest volcanic centers in the northeast exhibit a subduction zone signature and volcanism becomes younger to the south, with the composition changing to an intraplate signature (Keskin et al., 1998; Pearce et al., 1990). Active underthrusting occurs along the Bitlis suture zone, and the Anatolian block moves westward along the North Anatolian fault and the East Anatolian fault with minimal fault-normal convergence (Reilinger et al., 2006). East of the Karlıova triple junction, convergence is accommodated through crustal thickening (Şengör and Yılmaz, 1981).

A range of geodynamic models has been proposed for the evolution of this collision zone. After the closure of the Tethyan Ocean the style of deformation changed, because continental crust is too buoyant to be subducted. Some models suggest that the Anatolian Plateau was formed by a combination of crustal thickening and the escape of the Anatolian block (Dewey et al., 1986; McKenzie, 1972). These models predict a crustal thickness of 55 km on the basis of isostasy and the negative gravity anomaly (Şengör, 1980). However seismic studies indicate a crustal thickness of 45 km and show that the plateau is isostatically undercompensated (Zor et al., 2003). In addition, these models cannot explain the widespread distribution of extrusive volcanic rocks in eastern Anatolia. An alternative class of models invokes slab breakoff followed by lithospheric delamination and development of asthenosphere at a depth of <100 km (Keskin et al., 1998; Pearce et al., 1990; Innocenti et al., 1982). These models can explain temporal and spatial changes in volcanism (Keskin, 2003; Pearce et al., 1990) and account for high upper mantle temperatures that may have contributed to the uplift of the Anatolian Plateau (Şengör et al., 2003, Keskin, 2003). Seismic studies support models with a shallow asthenosphere (Turkelli et al., 2003). MT exploration can detect the presence of crustal fluids such as partial melt and image the geometry of the asthenosphere. Electrical resistivity measurements can also be related to subsurface rheology and constrain geodynamic modeling (Unsworth et al., 2005).

MT DATA COLLECTION AND ANALYSIS

MT data were collected in eastern Anatolia in 2005 (Fig. 1). Variations of the Earth's natural electromagnetic field were recorded at each location and analyzed to give estimates of the magnetotelluric impedance (Egbert, 1997). Geoelectric strike directions were computed using both tensor decomposition (McNeice and Jones, 2001) and induction vectors (see the GSA Data Repository[1]). Data at a significant number of the stations exhibit two-dimensional (2-D) behavior with the strike direction approximately parallel to the major tectonic boundaries. However, on the western profiles, there are indications of 3-D behavior that could invalidate a 2-D approach, and a careful analysis was used to ensure that the 2-D models were not influenced by these effects (see the Data Repository).

The MT data show smooth variations from site to site, indicating that the data were not spatially aliased (Fig. DR3; see footnote 1). Some static shifts are observed, but were removed during the MT inversion. A distinctive change in the MT data is observed across the Bitlis suture zone. To the south, the apparent resistivity curves increase at a long period (100–10,000 s). To the north, the apparent resistivity has a lower value at long periods, implying lower resistivity values at depth compared to the Arabian plate (Fig. 2). The MT data were converted into a resistivity model using the inversion algorithm of Rodi and Mackie (2001). Resistivity models were chosen that fit the measured data and that were also as spatially smooth as possible (Fig. 3). Because

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[1] GSA Data Repository item 2008150, additional details about the data and analysis, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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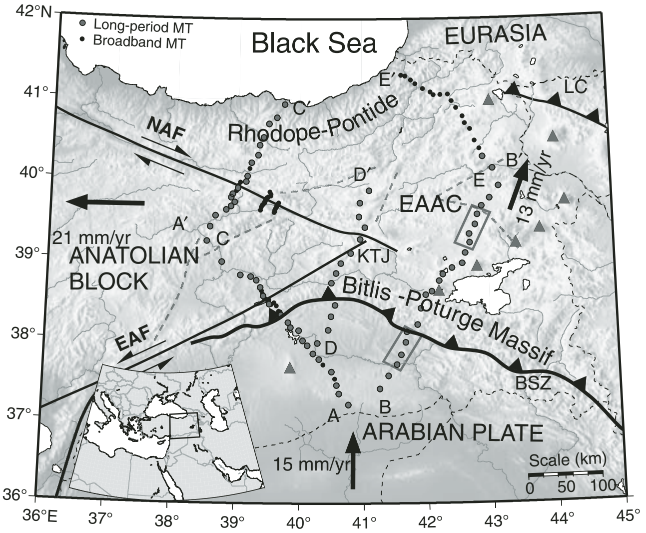

Figure 1. Tectonic setting of eastern Anatolia. Gray and black dots represent long-period and broadband magnetotelluric (MT) stations, respectively. Plate motions are from Reilinger et al. (2006). BSZ—Bitlis suture zone; KTJ—Karlıova triple junction; NAF—North Anatolian fault; EAF—East Anatolian fault; LC—Lesser Caucasus; EAAC—Eastern Anatolia accretionary complex. Triangles show volcanoes.

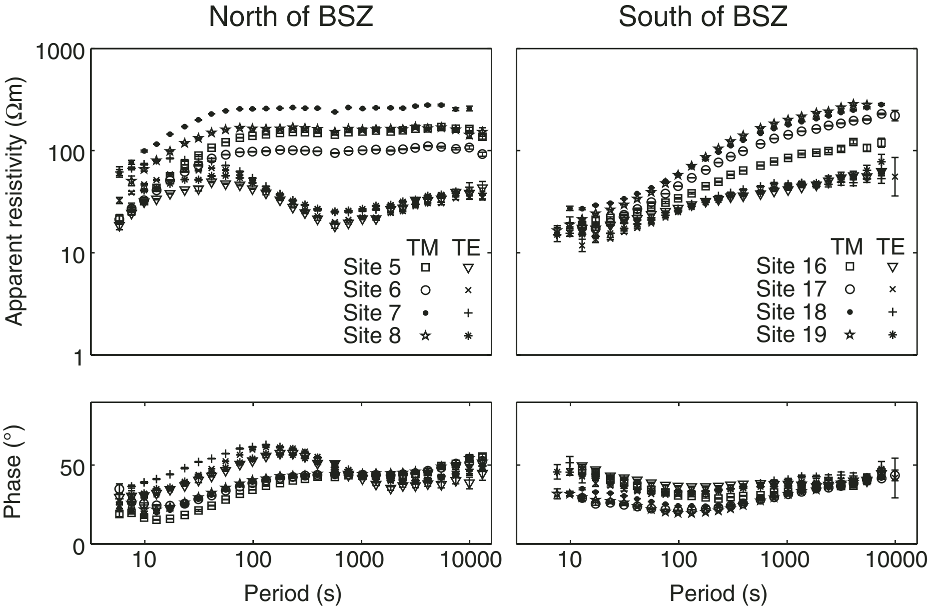

Figure 2. Selected apparent resistivity and phase curves from B-B′ profile. TM—transverse magnetic mode; TE—transverse electric mode. Left panel shows stations in the box (Fig. 1) on Eurasian plate. Right panel shows stations in box (Fig. 1) on Arabian plate. BSZ—Bitlis suture zone.

there are indications of 3-D behavior in some data, a range of inversions was undertaken to investigate the validity of the 2-D models (see Fig. DR5).

INTERPRETATION AND DISCUSSION

Arabian Plate

The sedimentary basin in the Arabian foreland produces the low-resistivity upper crust to a depth of 5 km. South of the Bitlis suture zone, the lower crust exhibits a high electrical resistivity on profiles A-A′, B-B′, and D-D′. A low-resistivity structure (b in Fig. 3) may be related to intraplate volcanism that is localized at Karacadağ volcano, whose 1.9–0.1 Ma lavas exhibit a mantle origin (Pearce et al., 1990; Notsu et al., 1995).

Lithospheric Structure of the Anatolian Block

Profiles A-A′ and C-C′ traverse the region where the Anatolian block is extruded to the west. A zone of lower crustal low resistivity (10–20 Ωm) is localized beneath the Anatolian block, bounded by the North Anatolian fault and East Anatolian fault (a2 in Fig. 3). Low resistivities in the lower crust are widely observed in many tectonic settings and have been attributed to partial melts, aqueous fluids, or graphite films (Brown, 1994). Graphitic conductors can perhaps be excluded in Anatolia since interconnection of graphite is unlikely to be preserved in a high-temperature regime. Aqueous fluids and/or partial melting can provide a single explanation of both the observed low velocity and resistivity. Aqueous fluids at mid-crustal depths could be supplied by the subducting plate or derived from metamorphic reactions in a thickened crust (Vanyan and Gliko, 1999; Wannamaker et al., 2002).

Lithospheric Structure of the Anatolian Plateau

Profiles B-B′ and E-E′ are located where direct convergence occurs between the Arabian and Eurasian plates. The lower crustal resistivity in this region is lower than to the west of the Karlıova triple junction and shows significant horizontal variability. Localized pockets have resistivities of ~3 Ωm and require 3%–10% partial melt to explain the observed resistivity values (see Fig. DR7). Crustal resistivity between these pockets is ~30 Ωm and can be accounted for with <1% melt. Passive seismic data show that a crustal low-velocity zone is not observed across the entire Anatolian Plateau (Angus et al., 2006). Low velocities are locally observed in a series of discrete pockets, which are inferred to represent accumulations of magma (Angus et al., 2006).

The resistivity of the upper mantle decreases from 300 Ωm in the Arabian plate and Anatolian block (e in Fig. 3) to ~30 Ωm beneath the Anatolian Plateau (f in Fig. 3). This upper mantle resistivity is anomalously low compared to the values of 100–10,000 Ωm observed in stable regions (Xu et al., 2000). This value can be explained with a fluid fraction ~1% (see Fig. DR7). Interconnection is required for a fluid to influence electric and mechanical properties, but this can occur at quite low fluid fractions (Rosenberg and Handy, 2005). Low P wave velocities in the upper mantle beneath the Anatolian Plateau and blockage of upper mantle S waves have also been attributed to partial melting (Gök et al., 2003; Al-Lazki et al., 2004). Additional evidence for a shallow asthenosphere comes from the absence of subcrustal earthquakes (Turkelli et al., 2003) and regional velocity models (Piromallo and Morelli, 2003; Maggi and Priestley, 2005). The seismic and electrical properties of the upper mantle are mutually consistent; zones of elevated fluid content exhibit both low electrical resistivity and seismic velocity (Fig. 4). Very low Pn velocities (~7.6 km/s) are observed beneath the Lesser Caucasus and north of the Karlıova triple junction, the same regions with the lowest resistivities. Heat flow values >80 mW/m^2 are reported on the Anatolian Plateau and are consistent with a shallow asthenosphere (Tezcan, 1995).

IMPLICATIONS FOR DYNAMICS OF ARABIA-EURASIA COLLISION

The electrical resistivity images derived from MT data can be used to infer subsurface rheology. This is because fluids reduce both the mechanical strength and electrical resistivity of

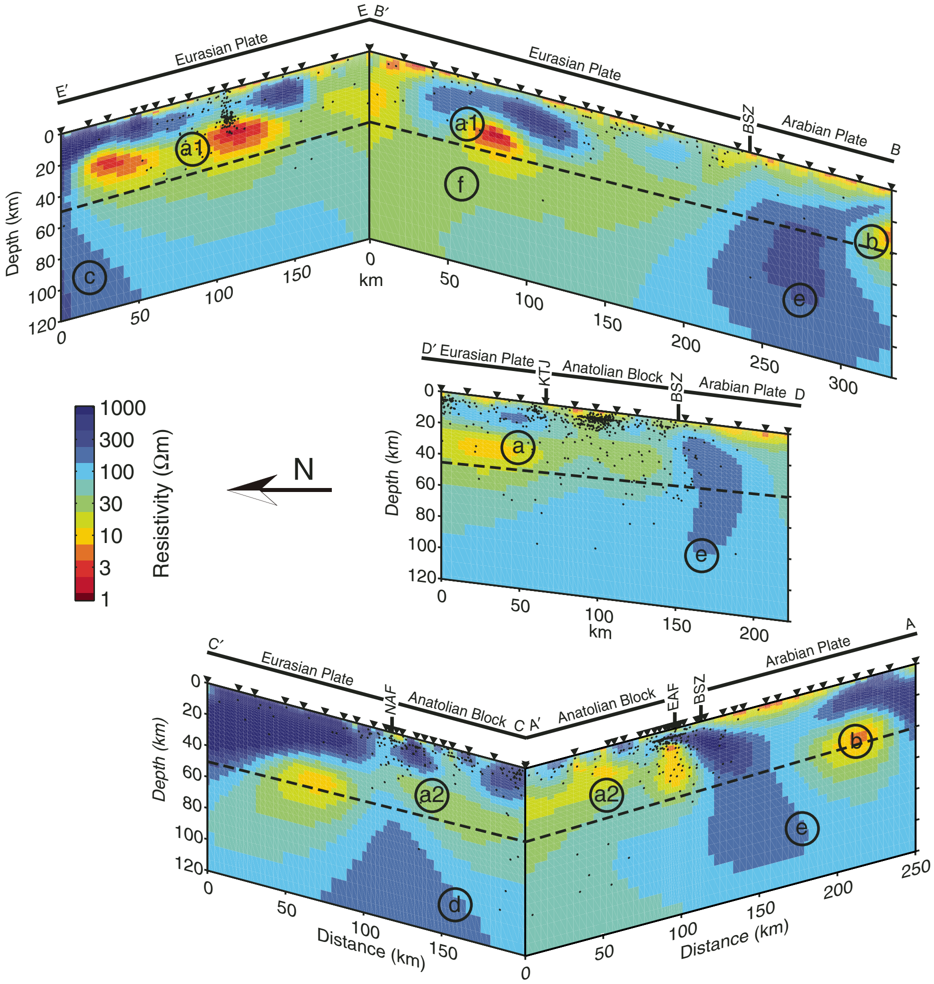

Figure 3. Two-dimensional resistivity models derived by inverting magnetotelluric (MT) data. Black triangles represent MT stations; small dots show U.S. Geological Survey earthquake locations from 1960 to 2004, and include those of Turkelli et al. (2003). Dashed line represents approximate Moho depth (Zor et al., 2003). Main geoelectric features are shown as numbers and explained in text. Adjacent stations are projected onto profiles perpendicular to strike directions, calculated to be N75°E, N105°E, N102°E, N90°E, and N45°E for profiles A, B, C, D, and E, respectively. Cluster of events on profile E-E′ are aftershocks of Şenkaya earthquake. BSZ—Bitlis suture zone; KTJ— Karlıova triple junction; NAF—North Anatolian fault; EAF—East Anatolian fault.

a rock (Unsworth et al., 2005). Regions with a low fluid content will be strong and highly resistive while regions with significant fluid content will have a lower resistivity and be weaker. In first-order terms, the lithosphere adjacent to the Black Sea and in the Arabian plate appears to be strong, while lithosphere beneath the Anatolian block and eastern Anatolia is weaker. The crustal low-resistivity zone beneath the Anatolian block and plateau is bounded by the North Anatolian fault and East Anatolian fault in the west, and the Rhodope-Pontide massif and Bitlis suture zone in the east. The top of this low-resistivity layer defines the base of the seismogenic zone, as shown by the earthquake hypocenters in Figure 3. The degree of crustal melting inferred beneath the Anatolian Plateau is sufficient to produce the reduction in strength needed to permit localized crustal flow (Rosenberg and Handy, 2005).

The upper mantle also appears to be anomalous beneath the Anatolian Plateau. The presence of a shallow asthenosphere and fluid-rich lower crust indicates zones of weakness that may represent the locations of the most active deformation as defined by geodetic data (Reilinger et al., 2006). The low-resistivity layer detected by the MT data could represent a weak layer that decouples the crust and upper mantle.

It is important to consider the question of cause and effect when discussing the relationship of fluids and deformation. It is possible that (1) fluids are controlling the observed deformation through weakening the lithosphere, or (2) the deformation produces zones of enhanced fluid content through maintaining a network of interconnected cracks. Both scenarios are possible in different tectonic settings. In terms of the widespread lower crustal conductors beneath the Anatolian block and plateau, either scenario

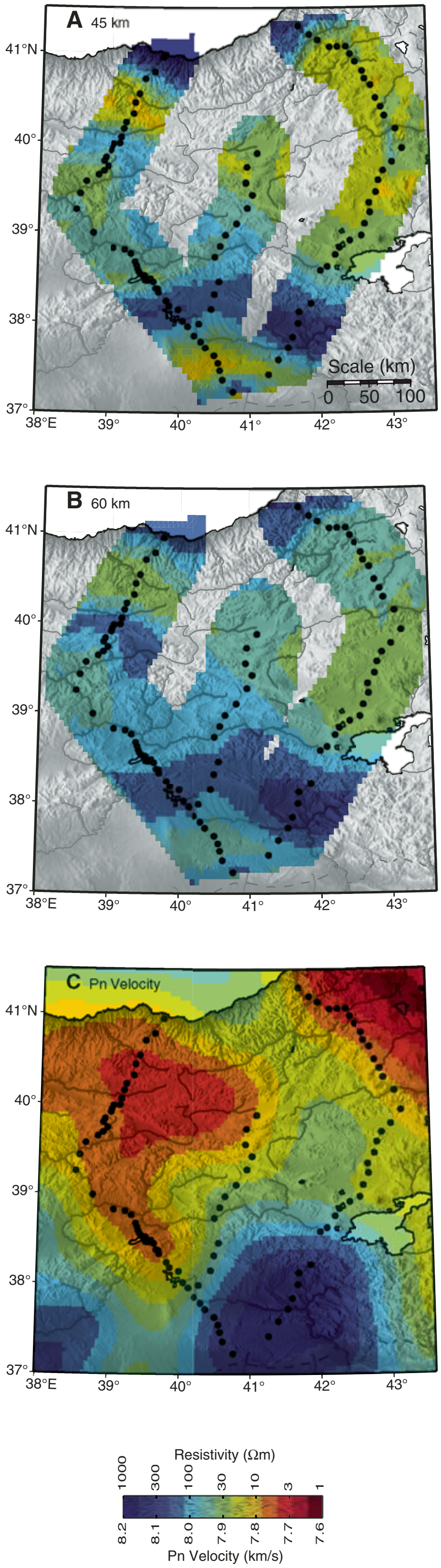

Figure 4. A: Depth slice of electrical resistivity at 45 km. B: Depth slice of electrical resistivity at 60 km. C: Pn seismic velocity in upper mantle (from Al-Lazki et al., 2004). Magnetotelluric (MT) data are interpolated between profiles to distance that reflects region imaged by each station. MT station locations are shown for comparison.

could be possible. The vertical low-resistivity zone associated with the East Anatolian fault on A-A′ could be an example of possibility 2. The zone of low resistivity in the asthenosphere beneath the Anatolian Plateau could be an example of possibility 1, with the melt produced by delamination and localized upper mantle convection (Pearce et al., 1990), which allow deformation to occur.

The geoelectric structures beneath eastern Anatolia and Tibet show some important similarities and differences. Eastern Anatolia and the northern Tibetan Plateau both exhibit unusually low resistivities in the upper mantle. This indicates the presence of a shallow asthenosphere with a melt fraction of ~1%. The very low-resistivity layers in the middle and lower crust of both orogens suggest the presence of a few percent melt. However, the mid-crustal low-resistivity layer in Tibet appears to be spatially continuous, while it exhibits significant lateral variation beneath eastern Anatolia. In both locations, the regions of lowest resistivity likely represent zones of deformation. It should be noted that in southern Tibet the MT profiles are parallel to the inferred flow direction, while in eastern Anatolia, the profiles are orthogonal to crustal flow in an east-west direction.

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