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Crustal structure of the North Anatolian and East Anatolian Fault Systems from magnetotelluric data

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ABSTRACT

Magnetotelluric (MT) studies can map subsurface resistivity structure and have located zones of low resistivity (high conductivity) within major strike-slip fault zones worldwide which have been interpreted as regions of elevated fluid content. This study describes MT data from the eastern part of the North Anatolian and the East Anatolian Fault Systems (NAFS and EAFS) and presents the results of the first MT studies of these faults. The inversion of the MT data produced 2-D resistivity models which showed that both fault systems are underlain by a broad low resistivity zone that extended into the lower crust. However, the resistivity beneath the East Anatolian Fault System was much lower than beneath the eastern part of the North Anatolian Fault System. These conductors begin at a depth of 10 km – not at the surface as on the central San Andreas Fault (SAFS). This difference is interpreted as being due to the fact that the EAFS and NAFS are young fault systems characterized in the upper crust by multiple fault traces – as opposed to the SAFS that has evolved into a single through going fault. Different stages of the seismic cycle may also influence the resistivity structure, although this is difficult to constrain without knowledge of time variations in resistivity structure at each location.

1. Introduction

Transform faults represent one of the three classes of plate boundaries and pose a significant seismic hazard, as evidenced by recent earthquakes on the North Anatolian, San Andreas, and other faults (Barka and Kadinsky-Cade, 1988; Fuenzalida et al., 1997; Barka et al., 2002; Toppozada and Branum, 2002). Strike-slip faults exhibit a wide variability in their seismogenic behavior. Some faults are characterized by segments that exhibit continuous creep, with adjacent segments locked and rupturing during major earthquakes. The physical cause of these variations in behavior is not well understood. The structure of strike-slip faults in the ductile lower crust is also an ongoing research question (Becken et al., 2008). Geological studies of exhumed faults and shear zones suggest that the zone of deformation broadens with depth (Sibson, 1977; Hanmer, 1988). Geophysical studies of the lower crust beneath shear zones are limited in number, but indicate that fluid composition is an important parameter that may influence the style of deformation (Bedrosian et al., 2004). Deformation in the ductile lower crust is influenced by fluids and laboratory studies suggest that deformation in the ductile part of the crust may occur by creep processes that are enhanced by the presence of water (Tullis et al., 1996). It has also been proposed that in the brittle upper crust, the behavior of seismogenic faults may be controlled by spatial and temporal variations in fluid content (Byerlee, 1993; Sleep and Blanpied, 1992). Over-pressured fluids in the fault-zone may trigger earthquakes through reducing the effective normal stress and thereby lowering the shear stress needed for failure (Sleep and Blanpied, 1992). A related observation is that strike-slip faults are often observed to be mechanically weak. For example, the San Andreas Fault System (SAFS) appears to move with a shear stress of just 10–20 MPa, that corresponds to a coefficient of friction in the range 0.1–0.2 (Zoback et al., 1987; Mount and Suppe, 1987). Similar values (0.05–0.2) have been reported on the NAFS based on geodetic data (Provost et al., 2003). These frictional values are significantly lower than those obtained in laboratory studies of rock friction (Byerlee, 1978; Sibson, 1974) and are consistent with the low values of frictional heat generation reported from the San Andreas Fault by Williams et al. (2004).

A key question that arises in this debate is how the amount of fluid and type of deformation are related in strike-slip faults. It is possible that either (a) an increase in the amount of fluid causes a fault to weaken and rupture, or (b) that the amount of fluid is

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the result of elevated porosity caused by deformation. This question can be addressed by mapping the subsurface distribution of fluids within major strike-slip faults using surface based geophysical studies. Electromagnetic (EM) methods are effective in this regard because they image subsurface resistivity – a rock property that is largely controlled in the upper crust by the amount, salinity and geometry of the pore fluids. In this context, magnetotellurics (MT) is the most useful because it can image the entire crust using natural EM signals, without the need for a transmitter. Depth sounding in MT is achieved through the skin-depth phenomenon that gives a penetration depth that is inversely related to the signal frequency (Vozoff, 1991).

A number of MT surveys have been used to study the fluid distribution within active strike-slip fault zones. Studies of the San Andreas Fault (SAF) in California revealed that some fault segments are characterized by a zone of low resistivity (elevated conductivity). At Parkfield, the SAF is in transition from creeping to locked and the conductor extends from the surface to a depth of 2–3 km (Unsworth et al., 1997). The conductor extends to mid-crustal depths at Hollister where the fault creeps at 10–15 mm/yr (Burford and Harsh, 1980; Evans et al., 1981; Bedrosian et al., 2002). A small fault-zone conductor was observed on the locked Carrizo segment (Unsworth et al., 1999; Mackie et al., 1997). Deeper fault zone structure of the SAF was investigated with the longer profile and 3-D array of Becken et al. (2008) and showed a continuous zone of low resistivity extending through the entire crust.

In northwest Turkey, a number of MT studies have investigated the resistivity structure of the North Anatolian Fault close to the ruptures of the İzmit and Düzce earthquakes and revealed deeper zones of low resistivity in the mid-crust (Tank et al., 2005; Kaya et al., 2009). More recent studies have used seafloor MT to study the fault strand of the NAF under the Sea of Marmara (Kaya et al., 2013). In China, a number of MT studies have investigated the Kunlun and Altyn Tagh Faults which are major strike-slip faults associated with the northern margin of India–Asia collision (Unsworth et al., 2004; Le Pape et al., 2012; Zhang et al., 2015). Bai et al. (2010) described major conductors in the mid-crust that were coincident with major shear zones in southwest China over horizontal distances of hundreds of kilometers. The Alpine Fault in New Zealand was studied with MT by Wannamaker et al. (2002). These studies have detected conductors in two distinct tectonic environments. To make a clear distinction between these, separate abbreviations are used in this paper:

(1) Shallow conductors associated with the damage zone of a fault, and caused by groundwater present in regions of elevated porosity, and perhaps supplemented with clay mineralization. These are termed damage zone conductors (DZC).
(2) Deeper conductors in the mid-crust, generally extending across the brittle–ductile transition are called crustal fault-zone conductors (CFZC).

The object of this paper is to present new images of the electrical resistivity structure of the major strike-slip faults in Eastern Anatolia, with the goal of being able to relate the electrical resistivity structure to the style of deformation. The NAFS and EAFS are relatively young strike-slip faults that have relatively small offsets and have not yet developed into mature strike-slip fault zones. Studying faults at an early stage of development allows the opportunity to address the question of how the structure of fault zones evolves over time.

2. Tectonic setting and previous studies

The tectonics of Eastern Anatolia is dominated by the ongoing collision of the Eurasian and Arabian Plates (Fig. 1). Convergence in the Eocene was initially accommodated by shortening and thickening of the Arabian continental margin (Hempton, 1985; Şengör et al., 1985). The NAFS and EAFS subsequently developed to accommodate the westward motion of the Anatolian block towards the Aegean arc (Burke and Sengör, 1986). Forces generated by trench rollback and the southward migration at the Aegean arc contribute to the westward motion of the Anatolian block along the large-scale strike slip fault systems (Reilinger et al., 2006). Today, the Arabian Plate moves northward at a velocity of 15 mm/yr and only 10% of this convergence is accommodated by lithospheric shortening with the remainder of the convergence accommodated by strike-slip motion on the NAFS and EAFS (Reilinger et al., 2006). Recent studies have shown that the present day driving force for the westward movement of the Anatolian plate is primarily derived from the Aegean subduction, with only a small component

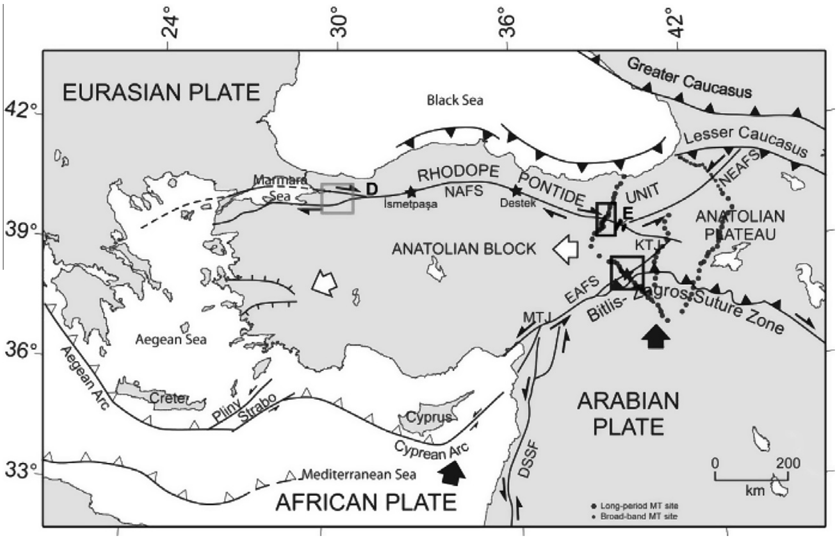

Fig. 1. Simplified tectonic map of Turkey and surroundings (modified from Şengör et al., 1985; Barka, 1992). Black rectangles indicate the areas studied with MT data in this paper. The gray rectangle, east of the Marmara Sea, shows the survey area of Tank et al. (2005). Star symbols show the location of previously reported creep on the NAF and EAF. Filled circles show MT sites (Türkoğlu et al., 2008) NAFS: North Anatolian Fault System. NEAFS: North East Anatolian Fault System. EAFS: East Anatolian Fault System. DSFS: Dead Sea Fault System. KTJ: Karlıova Triple Junction. MTJ: Maraş Triple Junction. D: Düzce. E: Erzincan.