Contribution to the seismotectonics of Eastern Turkey from moderate and small size events

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[1] Source properties of small-to-moderate magnitude events in eastern Turkey were studied using high quality waveform data produced by the Eastern Turkey Seismic Experiment (ETSE). A data set of fault plane solutions was obtained for 134 earthquakes using the regional moment tensor inversion technique for 34 events with magnitude 3.7 and above, and first motion analysis for 115 earthquakes with magnitude 3.0 and higher (for 15 events both techniques were used). Most of the events studied had strike slip mechanisms in agreement with nearby local fault structures. Reverse mechanisms were more scarce and were restricted to certain areas, such as in the eastern Anatolian plateau and southwest of the Karliova junction along the Arabian plate boundary. Our results indicate a difference in the deformational style east and west of the Karliova junction which results in internal deformation in the east and westward extrusion of the Anatolian plate with no or very little internal deformation in the west. Our results also suggest that in eastern Turkey, most of the collision is taken up by strike slip faults of varying types and sizes, suggesting that the northward convergence of Arabia is being accommodated by escape tectonics. Compressive features, such as thrust faulting, which were obviously the primary faulting during the earliest stages of continental collision, are still active but are of lesser importance. *INDEX TERMS:* 7205 Seismology: Continental crust (1242); 7215 Seismology: Earthquake parameters; 7230 Seismology: Seismicity and seismotectonics; 8102 Tectonophysics: Continental contractional orogenic belts; 8107 Tectonophysics: Continental neotectonics. **Citation:** Örgülü, G., M. Aktar, N. Türkelli, E. Sandvol, and M. Barazangi, Contribution to the seismotectonics of Eastern Turkey from moderate and small size events, *Geophys. Res. Lett.*, *30*(24), 8040, doi:10.1029/2003GL018258, 2003.

1. Introduction

[2] Eastern Turkey is an intensely deformed high plateau, located behind the collision zone of the Arabian and Eurasian plates (Figure 1) that is part of the Alpine-Himalayan mountain belt. The existence of a conjugate strike slip fault system adjacent to thrust faults and widespread young volcanism have raised a particular interest in the complex evolution of the Anatolian plateau and surrounding regions. It is widely recognized that, starting from Late Miocene, the compressional character of the collision zone was reshaped by the genesis of the new major transform structures (i.e., the North Anatolian Fault System and the East Anatolian Fault System), due to the initiation of tectonic escape in addition to the already existing contraction [*Sengör et al.*, 1985; *Yilmaz et al.*, 1987; *Kocyigit et al.*, 2001; *McClusky et al.*, 2000]. Eastern Turkey is extremely seismically active as shown by fault plane solutions of large earthquakes of the last 27 years given by the Harvard CMT catalogue (Figure 1), whose moment magnitudes range from 5.1 to 7.0. It is clear from Figure 1 that strike slip faulting is the most common faulting type in eastern Turkey. Only a limited number of localized normal or reverse fault plane solutions have been observed. The recent Eastern Turkey Seismic Experiment (ETSE) PASSCAL seismic array significantly improved the station coverage in order to provide evidence of the ongoing seismic deformation. In this study we present 38 selected and representative source mechanisms of 134 such earthquakes (M 3 to 5.5) that were recorded by ETSE (Figures 2 and 3) Table 1.

2. Data and Method

[3] We have used broadband waveform data collected by the Eastern Turkey Seismic Experiment (ETSE). The experiment included 29 broadband stations that operated for 21 months in a triangular pattern covering most of Eastern Turkey (Figure 1). The accuracy of the location is a critical factor for reliably identifying faulting parameters. Special care was taken in locating the events that were selected for the waveform modeling and the first motion analysis. All *P* and *S* phases were manually picked. The HYPOINVERSE algorithm [*Klein*, 1984] was applied using a 1 D crustal model obtained from a grid search approach for well-located events within the ETSE array [Table 1, *Türkelli et al.*, 2003]. The majority of the events were recorded on the average by 16 stations. The RMS error is of the order of 0.5 sec and the azimuthal gap of about 105°. The final locations of the events in this study had, on average horizontal errors between 3 and 5 km and vertical errors of about 5 to 9 km. Figure 1 shows the epicenter distribution of earthquakes that were selected for source mechanism studies.

[4] In this study we have used the Regional Moment Tensor (RMT) inversion method [*Dreger and Helmberger*, 1993; *Pasyanos et al.*, 1996] for 34 larger events ($M_w \geq 3.7$), and/or the first motion analysis for 115 smaller events ($M \geq 3.0$). We used both techniques for 15 events. The RMT method provides a more robust estimation of source properties. In this approach, synthetic seismograms were generated using frequency-wavenumber (f–k) integration

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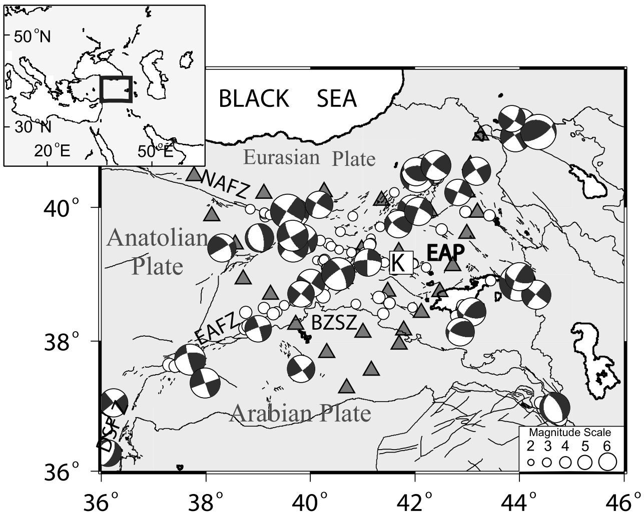

Figure 1. Map of major tectonic boundaries in eastern Turkey with the locations of events (open circles) used for source mechanism studies. The locations of broadband stations deployed during the Eastern Turkey Seismic Experiment are shown by solid triangles. Beach balls indicate fault plane solutions of large earthquakes from the Harvard CMT catalogue. Labels indicate the Karliova Junction (K), North Anatolian Fault Zone (NAFZ), East Anatolian Fault Zone (EAFZ), Bitlis-Zagros Suture Zone (BZSZ), East Anatolian Plateau (EAP), and Dead Sea Fault Zone (DSFZ).

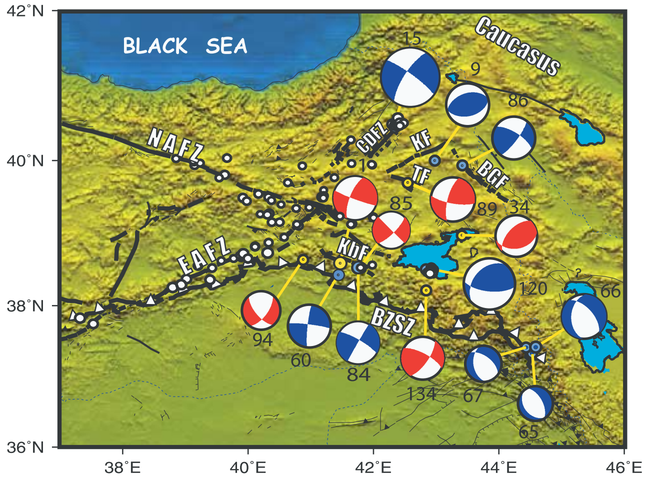

Figure 3. Fault plane solutions obtained from the moment tensor inversion (blue) and first motion analysis (red), for selected events in the Eastern Anatolian Plateau and on its borders, east of Karliova. Çobandede Fault Zone (ÇDFZ), Kagizman Fault (KF), Tutak Fault (TF), Balik Gölü Fault (BGF), Kavakbasi Fault (KbF). See Figure 1 for fault zone abbreviations. (lower hemisphere projection).

[*Saika*, 1994]. Previous studies have shown that the RMT method performs remarkably well even if only a few broadband stations are available [*Dreger and Helmberger*, 1993; *Pasyanos et al.*, 1996]. Our RMT solutions are based on data from an average of 6 stations. We used first motion analysis for the events that were generally smaller in magnitude, and therefore not suitable for the RMT approach. In this approach only the events located inside the network were analyzed in order to secure good azimuthal coverage. The FPFIT algorithm [*Reasenberg and Oppenheimer*, 1985] was used for the first motion analysis. Events with fewer than 10 polarity readings were discarded. Details of the focal parameters and hypocentral locations to the selected earthquakes are given as auxiliary material (Table 2)[1].

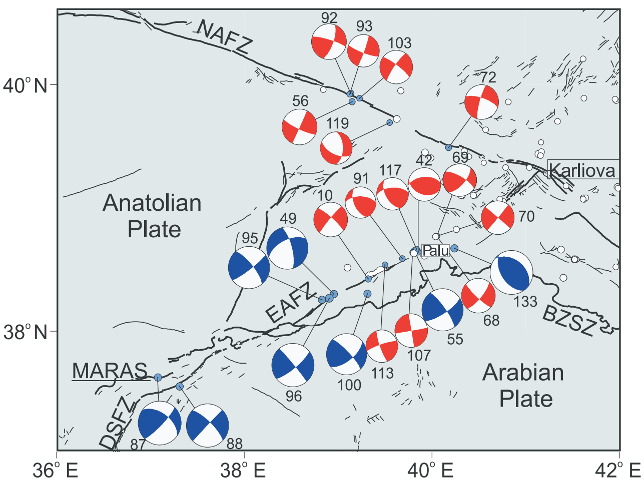

Figure 2. Fault plane solutions obtained from the moment tensor inversion (blue) and first motion analysis (red), for selected events along the escape structures to the west of Karliova, namely the North and East Anatolian Fault Zones. Close and open circles indicate locations of all earthquakes in the region used in our interpretation. See Figure 1 for fault zone abbreviations. (lower hemisphere projection). The adjacent numbers indicate the event number given in the auxiliary material (Table 2)[1].

3. Earthquake Source Parameters

[5] The study area covers two major tectonic domains extending on either side of the Karliova junction (marked as K in Figure 1). To the west we observe the Anatolian plate escaping westward via two main intracontinental transform structures, the North Anatolian Fault Zone (NAFZ) and the East Anatolian Fault Zone (EAFZ). To the east of the Karliova junction, the East Anatolian Plateau (EAP) appears as an internal deformation zone characterized by NW and NE-trending active strike slip faults. The distribution of earthquakes recorded during the ETSE experiment outlines these major tectonic domains. Both the NAFZ and the EAFZ are marked by epicenters that are aligned along the main fault zones or are in close vicinity.

[6] The NAFZ is a 1300 km long dextral strike-slip fault, with a slip rate of 1.3 cm/year [*Kocyigit et al.*, 2001]. It has been well studied due to the very destructive earthquakes along the NAFZ during the last century [*Sengör et al.*, 1985; *Barka*, 1996]. Figure 2 shows fault plane solutions for selected events, which have pure strike slip mechanisms, in agreement with the general character of the NAFZ. In

[1]Auxiliary material is available at ftp://ftp/agu.org/apend/gl/2003GL018258.

Table 1. Velocity Model Obtained From a Grid Search Approach for Well-Located Events [after *Türkelli et al.*, 2003]

Depth (km)	V_p (km/s)	ρ (g/cm3)
0	4.93	2.4
2	6.30	2.6
42	7.69	3.0

addition we observe that one event is a normal fault and is likely to be related to a local structure.

[7] The EAFZ is a sinistral strike slip transform fault that marks the boundary of the Arabian plate and Anatolian plate [*Arpat and Saroglu*, 1972]. It extends 600 km from the Karliova basin, where it meets the NAFZ, to the city of Maras in the southwest, where it joins the Dead Sea Fault Zone (DSFZ) (Figure 2). A relatively small number of large earthquakes have occurred along the EAFZ during the last century, and past derived faulting mechanisms have supported the sinistral transform motion also with reverse component [*Jackson and McKenzie*, 1984; *Taymaz et al.*, 1991].

[8] Fault plane solutions were estimated for 17 events that occurred on and near the EAFZ (Figure 2). The fault plane solutions extending from southwest of the Karliova junction give strike slip source mechanisms, whose northeast trending nodal planes are predominantly compatible with the main trend of the EAFZ. Based upon the alignment of the epicenters, which show nearly identical source mechanism solutions, we infer that they are left lateral strike slip earthquakes. At only one location, near Palu (at 38.7°N, 39.9°E; see Figure 2), did we observe a limited number of reverse mechanisms that are consistent with local compressive structures [*E. Arpat*, 2002, personal communication]. We conclude that the overall character of the EAFZ reflects a pure lateral motion.

[9] East of the Karliova junction, deformation is accommodated by a set of conjugate strike slip faults, dextral faults trending SE, and sinistral faults trending NW, plus a few minor thrust and normal faults. The Bitlis-Zagros Suture (BZSZ) marks the southern boundary of this deformation zone and shows limited seismic activity. None of the events recorded along this frontal region gave thrust focal mechanisms (Figure 3). Strike slip focal mechanisms that were found, are presumably right lateral referring to local unmapped fault trends formed in the frontal region of the BZSZ. Normal mechanisms are also recorded and may be associated with local trans-tensional features, scattered across most parts of the EAP.

[10] A number of large destructive earthquakes and active faults have been used to characterize the deformation of the EAP [*Jackson and McKenzie*, 1984]. We also observe a second order coexisting compressional deformation regime that occasionally generates large reverse mechanisms such as the Lice Earthquake (6 December 1975, Ms 6.7). This event is not a part of the Harvard CMT catalog. In this study we located many events in the central part of the EAP and demonstrated that the seismic deformation is distributed throughout the EAP (Figure 3). We observed strike slip source mechanisms which give evidence for the shearing process. These events are located along the Kavakbasi Fault (KbF), Balik Gölü Fault (BGF) and Tutak Fault (TF) which are mapped as dextral faults [*Bozkurt*, 2001; *Kocyigit et al.*, 2001]. Three events have reverse mechanism and provide further evidence of N-S compressive deformation. These events occurred on previously unidentified thrust faults, where geomorphic expressions are not clearly observed in the field.

[11] The N-NW boundary of the EAP is characterized by a diffuse zone of sub-parallel sinistral strike-slip faults, trending NE, extending in a discontinuous manner from Karliova to the thrust structures of the Caucasus in the north (Figure 3). The Senkaya earthquake (3 December 1999, M_w 5.5), which is the largest magnitude event recorded during the total duration of ETSE, occurred in this diffuse boundary zone. It ruptured the northern end of the Çobandede fault zone [*Kocyigit et al.*, 2001], which is a 4 to 6 km wide and 130 km long dominantly northeast trending sinistral shear zone with conjugate northwest trending strike slip faults [*Sengör et al.*, 1985; *Barka et al.*, 1983]. The moment tensor solution of the Senkaya earthquake indicates a strike slip source mechanism (Figures 3 and 4). We infer that the northeast striking nodal plane is the fault plane in accordance with the major trends along the Çobandede shear zone. The source mechanism of the Senkaya earthquake was well constrained using data from 9 broadband stations, including two IRIS/GSN stations, GNI and KIV, which were added to reduce the azimuthal gap in the northeast quadrant (Figures 4a and 4b). The inversion solution provides a good match between observed and synthetic seismograms. We note that long period excitations of BNGL, HRPT and HAMR stations on the radial and vertical components are weak since they are located near the nodal planes. The variation in the waveform fits relative to the hypocentral depth is shown as a function of double couple (DC) and variance reduction (VR) percentages (Figure 4c). The fault plane solution is stable over a wide range of source depths, but maximum VR and DC percentages indicate that the earthquake occurred at a shallow depth of 6 km.

4. Conclusions

[12] A close look at the earthquake activity in eastern Turkey, during the 14 months period from November 1999

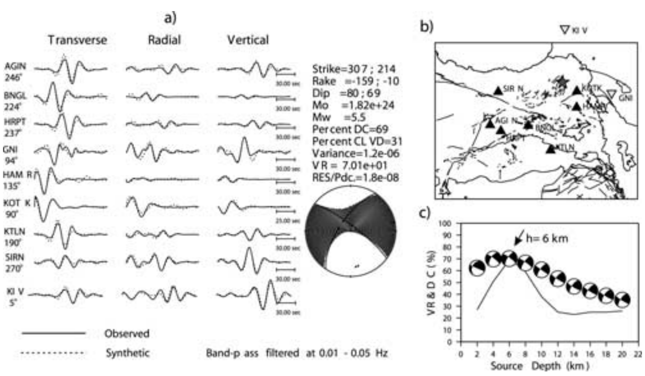

Figure 4. The Moment Tensor Solution for the Senkaya earthquake (3 December 1999, M_w 5.5). (a) Waveform comparison of observed and synthetic seismograms. (b) Location map of broadband stations used in this analysis (epicenter represented by star). (c) The variance of double couple (DC, represented by solid curve) and variance reduction (VR, represented by beach balls) percentages as a function of depth.

to December 2000, has revealed many detailed aspects of the ongoing continental collision process. We note that the events recorded, in spite of their relatively small magnitudes, provide a coherent picture of the deformation currently taking place in eastern Turkey. The fault plane solutions that we observed are in agreement with the general characteristics given by the CMT solutions. Deformational domains east and west of the Karliova junction can be clearly distinguished by their inherently different seismogenic behavior. West of Karliova, the Anatolian plate is escaping westward with no or very little internal deformation. Most of the seismic activity occurs along the bordering transform structures, namely on the EAFZ and NAFZ, and marks the pure strike slip mechanism as the governing type of motion. Thrust focal mechanisms are only observed along one small part of the Eurasian-Arabian plate boundary near Palu in the southwest of the Karliova junction.

[13] East of the Karliova junction, the EAP presents a totally different deformational style, where translational movement is replaced by internal deformation. Large number of NE and NW trending conjugate fault systems, strike slip in character and often of limited size, translate the shearing action towards the inner parts of the plateau. Normal mechanisms are recorded along the eastern extension of the BZSZ and are possibly related to geometrical discontinuities along strike slip faults such as transtensional step-overs. Some compressional features, namely reverse faults, are also present but less frequent. This would indicate that the present day seismogenic deformational setting is dominated by escape tectonics that has gradually taken the place of horizontal shortening that presumably dominated during Miocene times [*Kocyigit et al.*, 2001].

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