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Contribution to the Seismotectonics of the Eastern Anatolian Plateau from Moderate and Small Size Events

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Abstract. Source properties of low-to-moderate magnitude events in Eastern Turkey were studied in detail using high quality waveform data from temporary broadband network recorded by the Eastern Turkey Seismic Experiment (ETSE). A data set of fault plane solutions was obtained for 134 earthquakes using regional moment tensor inversion technique for 34 events with magnitude 3.7 and above, and the first motion analysis for 115 earthquakes with magnitude 3.0 or above. 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 SW of the Karlıova junction along the Arabian Plate boundary and also in the Eastern Anatolian Plateau. Normal source mechanisms were also limited in number and seemingly connected to local structures such as trans-tensional steps along major strike slip faults. Our results 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.

Introduction

Eastern Turkey is an intensely deformed high plateau, located at the collision point of 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 of both calc-alcaline and alkaline type have raised a particular interest on 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 (e.g. North Anatolian Fault System and East Anatolian Fault System), due to the initiation of tectonic escape in addition to the already existing contraction (*Şengör et al.,* 1985; *Yılmaz et al.,* 1987; *Koçyiğit et al.,* 2001). Eastern Turkey is extremely seismically active as shown by fault plane solutions of large earthquakes of the last 27 years given by Harvard CMT catalogue (Figure 1), whose moment magnitudes vary between 5.1 and 7.0. The CMT solutions have revealed the outlines of both major tectonic structures and surroundings. It is clear from Figure 1 that strike slip faulting is the most common faulting type in eastern Turkey. Only a limited number of normal or reverse fault plane solutions have been observed and they are restricted to certain particular locations, which are relatively closer to the local extensional or compressional structures. A large number of low to moderate size events still remain uninvestigated mainly due to the lack of a high quality local seismic network. The Eastern Turkey Seismic Experiment (ETSE) PASSCAL seismic array significantly improved the station coverage in order to provide evidence of the ongoing seismic activity. In this study we present selected source mechanisms of 134 such earthquakes (M 3 to 5.5) that were recorded by ETSE.

Data and Method

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 instrumentation was provided by PASSCAL and included 28 STS2 sensors and one Guralp CMG-3T sensor; data were recorded continuously at 24 bits and 40 samples/sec, using REFTEK data acquisition systems.

The accuracy of the location is a critical factor for reliably identifying faulting parameters. Special care is taken for locating the events that were selected for the waveform modeling and the first motion analysis. All *P* and *S* phases were picked. HYPOINVERSE algorithm (*Klein*, 1984) was applied using 1 D crustal model obtained from a grid search approach for well-located events within the ETSE array (Table 1, *Türkelli et al.,* 2003, this issue). The majority of the events are observed on the average by 16 stations, each having three-component sensors. 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 have a horizontal and vertical error of about 5 and 9 km respectively. Figure 1 shows the epicenter distribution of earthquakes that were selected for source mechanism studies.

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 ($M \geq 3.0$). The RMT method provides a more robust estimation of source properties. In this approach, synthetic seismograms were generated using frequency-wavenumber (f-k) integration technique (*Bouchon*, 1981; *Fuchs and Muller,* 1971; *Saika,* 1994). The inversion procedure is based on full waveform comparison of observed and synthetic displacement data at long periods (20 -100 s) using all three components. 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; *Örgülü,* 2001). Our RMT solutions are based on data from an average of 6 stations. We used the first motion analysis for the events that were generally smaller in magnitude, 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 less than 10 polarity readings were discarded. In total we retrieved the source mechanisms of 134 earthquakes from November 1999 through the end of December 2000 that occurred in the study area. This study presents selected examples of these fault plane solutions. Details of the focal parameters and hypocentral locations to the selected earthquakes are given in Table 2 (Auxiliary material is available at ftp://ftp/agu.org/apend/gl/2003GL018258.).

Earthquake Source Parameters

The study area covers two major tectonic domains extending on either side of Karlıova 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 Karlıova 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 observation period to first order outline these major tectonic domains. Both the NAFZ and the EAFZ are marked by epicenters that are aligned along the main faults zones or are in close vicinity. This alignment is not clearly observed along the boundaries of the EAP, where the northward convergence of the Arabian plate is taken up within the Anatolian plateau. For the sake of clarity, we examine the two domains separately. First, the events along the NAFZ and EAFZ are investigated, and then we will focus on the events scattered in and on the periphery of the deforming EAP.

The NAFZ is a 1300 km long dextral strike-slip fault, with a slip rate of 1.3 cm/year (*Koçyiğit et al.,* 2001). It has been intensively studied due to the very destructive earthquakes along the NAFZ during the last century (*Şengör et al.,* 1985; *Barka,* 1996). A relatively low number of events were observed along the NAFZ during the operation of the temporary network. 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 addition we observe that one event is a normal fault and is likely to be related to a local structure.

The EAFZ is a sinistral strike slip transform fault that marks the boundary of the Arabian Plate and Anatolian Plate (*Arpat and Şaroğlu*, 1972). It extends 600 km from Karlıova basin, where it meets the NAFZ, to the city of Maraş in the southwest, where it joins the Dead Sea Fault Zone (DSFZ) (Figure 2). A relatively small number of large earthquakes has 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).

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 Karlıova 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 shows nearly identical source mechanism solutions, we infer that they are left lateral strike slip earthquakes. The consistency of the sinistral motion along the total length of the EAFZ provides a striking evidence for the intracontinental transform character. Only at one particular location, situated near Palu (at 38.7° N, 39.9° E, see Figure 2), we observed reverse component in addition to the strike slip or even purely reverse mechanisms. Thrust faults are clearly observed both in field studies and in the inspection of areal photographs (*E. Arpat*, 2002, personal communication). This area may well be associated with compressional deformation of a local character. We conclude that although a local compressional zone may exist, the overall character of the boundary between the Arabian Plate and Anatolian Plate reflects a pure lateral motion.

East of the Karlıova junction, the EAP is a wedge like zone of intense deformation, characterized by a complex network of active dextral to sinistral strike slip faults, trending both NE and NW. The Bitlis-Zagros Suture 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 BZSZ. Normal mechanisms are also recorded and maybe associated with local trans-tensional features, scattered across most parts of the EAP.

A number of large destructive earthquakes and active faults have been used to characterize the deformation of the EAP (*Jackson and McKenzie*, 1984). Most of this deformation is taken up by pure shear, along conjugate strike-slip faults trending NE and NW. We also observe a second order coexisting compressional deformation regime that occasionally generates large reverse mechanisms such as Lice Earthquake (6 December 1975, Ms 6.7 not included in the Harvard CMT catalogue and does not appear in Figure 1). 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). There are two events that have strike slip character and give evidence for the shearing process. They are located on the Balık Gölü Fault (BGF) and Tutak Fault (TF) respectively that have a dextral strike slip motion clearly seen from morphological evidence (*Bozkurt*, 2001; *Koçyiğit et al.,* 2001). We also observed strike slip source mechanisms located along the Kavakbaşı Fault, which is mapped as a dextral fault (*Bozkurt,* 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.

The N-NW boundary of the EAP is characterized by a diffuse zone of sub-parallel faults, trending NE, extending in a discontinuous manner from Karlıova to the thrust structures of Caucasus in the north (Figure 3). The Şenkaya 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 (*Koçyiğit et al.,* 2001), which is a 4 to 6 km wide and a 130 km long dominantly northeast trending sinistral shear zone with conjugate northwest trending strike slip faults (*Şengör et al.,* 1985; *Barka et al.,* 1983). The recent destructive Horasan-Narman Earthquake (30 October 1983, M_w 6.8) had ruptured the same fault zone south of the Şenkaya earthquake (*Eyidoğan et al.*, 1999). The moment tensor solution of the Şenkaya earthquake indicates a strike slip source mechanism (Figures 3 and 4). We infer that northeast striking nodal plane is the fault plane in accordance with the major trends along the Çobandede shear zone. The source mechanism of the Şenkaya 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 (Figure 4a, b). 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.

Conclusions

A close look at the earthquake activity in Eastern Turkey, during the 14 months period from November 1999 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 low magnitudes, provide a coherent picture of the deformation currently taking place in Eastern Turkey. The fault plane solutions that we observed during the ETSE experiment are in agreement with the general characteristics given by the CMT solutions. Domains situated on both sides, East and West of Karlıova need to be clearly distinguished by their inherently different seismic behavior. West of Karlıova, 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 Karlıova junction.

East of the Karlıova junction, the EAP presents a totally different deformational style, where translational movement is substituted 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 have a local character possibly related to geometrical discontinuities along strike slip faults such as trans-tensional step-overs. Some compressional features, namely reverse faults, are also present but less frequent. This means that the present day seismogenic deformation is dominated by shear and translation gradually taking place over the compression and subsequent crustal shortening (*Koçyiğit et al.,* 2001).

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Figure Captions

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. Karlıova Junction (K), North Anatloian Fault Zone (NAFZ), East Anatolian Fault Zone (EAFZ), Bitlis-Zagros Suture Zone (BZSZ), East Anatolian Plateau (EAP), Dead Sea Fault Zone (DSFZ) etc.

Figure 2. Fault plane solutions obtained from the moment tensor inversion (black) and first motion analysis (grey), for selected events along the escape structures to the west of Karlıova, namely the North and East Anatolian Fault Zones. See Figure 1 for fault zone abbreviations. (lower hemisphere projection).

Figure 3. Fault plane solutions obtained from the moment tensor inversion (black) and first motion analysis (grey), for selected events distributed in Eastern Anatolian Plateau and on its borders, east of Karlıova. Çobandede Fault Zone (ÇDFZ), Kağızman Fault (KF), Tutak Fault (TF), Balık Gölü Fault (BGF), Kavakbaşı Fault (KbF). See Figure 1 for fault zone abbreviations. (lower hemisphere projection).

Figure 4. Moment Tensor Solution of the Şenkaya 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) Variance of double couple (DC) and variance reduction (VR) percentages as a function of source depth.

Table 1. Velocity model obtained from a grid search approach for well-located events (after Turkelli 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

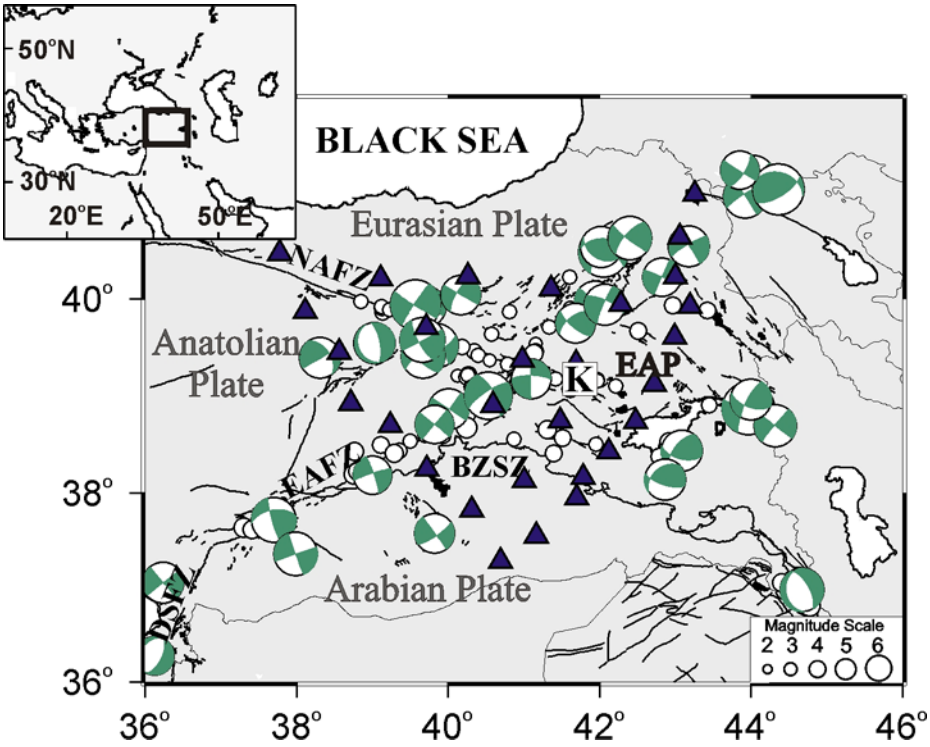

Figure 1

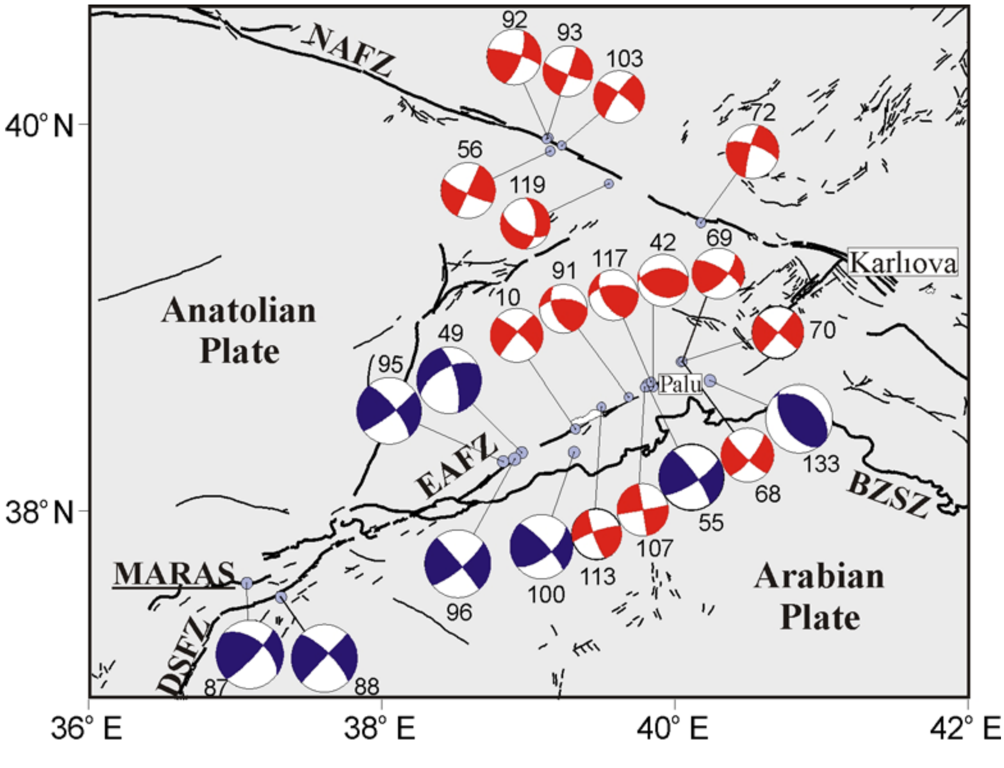

Figure 2

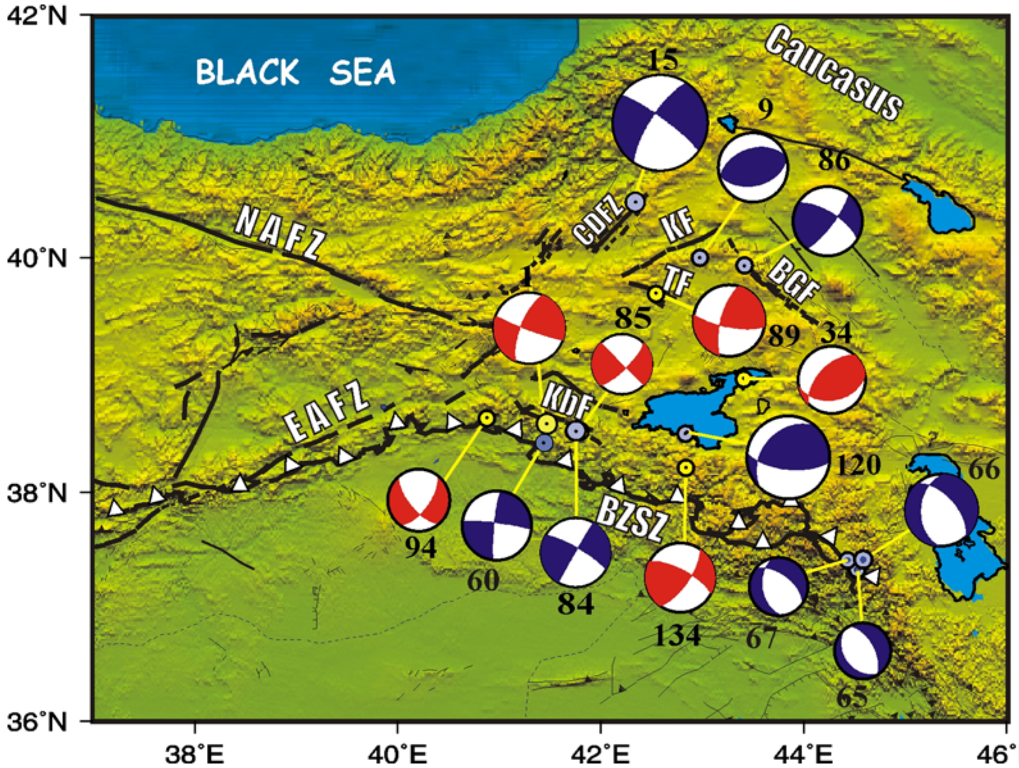

Figure 3

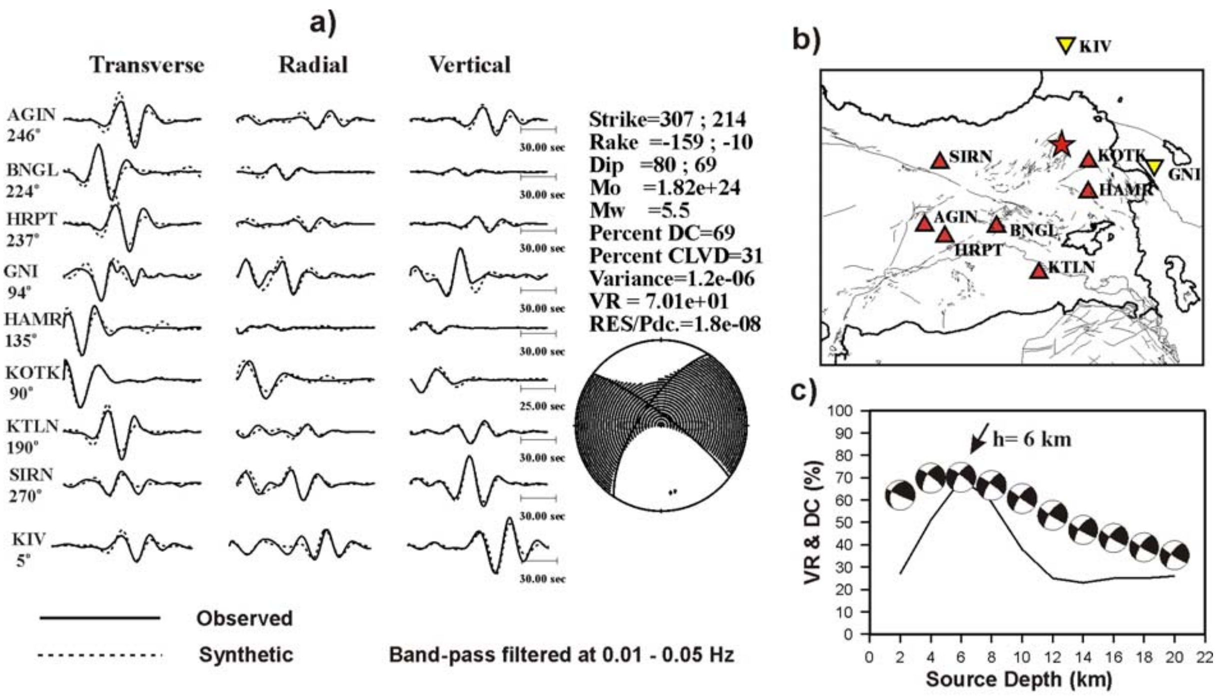

Figure 4