Published as:
Turkelli, N., Sandvol, E., Zor, E., Gok, R., Bekler, T., Al-Lazki, A., Karabulut, H., Kuleli, S., Eken, T., Gurbuz, C., Bayraktutan, S., Seber, D., and Barazangi, M. Seismogenic zones in Eastern Turkey, *Geophys. Res. Lett., 30(24)*, 2003.

Seismogenic zones in Eastern Turkey

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Abstract. A 29-station temporary broadband PASSCAL network was operated from late October 1999 to August 2001 in eastern Turkey in order to decipher the geodynamics of one of the youngest continent-continent collision zones in the world. This paper focuses on the hypocentral distribution of local earthquakes located during the operation of the network and provides new insights into the active faulting in the Anatolian Plateau. A total of 1165 earthquakes were located and classified into four different categories based on the reliability of the locations based on the data coverage. The accuracy of the locations ranked in the best two categories is estimated to be less than 10 km. The results show that seismic activity in Eastern Turkey is higher than previously documented and there were no subcrustal earthquakes beneath the Arabian-Eurasian collision zone or beneath the Anatolian plateau during our deployment. This result suggests no or very little underthrusting of the Arabian plate beneath Eurasia. Our results also suggest that the North Anatolian Fault zone extends farther toward the southeast, well beyond the Karliova triple junction, and that a number of unmapped active, seismogenic faults exist in the region. We observe a possible difference in the seismogenic thickness of the East Anatolian fault zone (EAFZ) and the North Anatolian fault zone (NAFZ).

Introduction and Tectonic Setting

A PASSCAL broadband network was installed for about 21 months in one of the youngest continent-continent collision zones on earth, where the Arabian plate collides with the Eurasian plate to form the Turkish-Iranian plateau, causing movement along the North and East Anatolian fault zones (Figure 1a). The East Anatolian plateau is about 2 km of average elevation and in many respects it can be thought of as a younger version of the Tibetan plateau (Figure 1a; Sengor and Kidd, 1979; Dewey et al., 1986; Barazangi, 1989). The Bitlis suture/thrust zone and the East Anatolian fault system (EAF) mark a distributed, irregular, and young continental collision zone. The northward motion of the Arabian plate relative to Eurasia causes lateral movement and rotation of the Anatolian block to the west, as evidenced by the right-lateral strike-slip movement along the North Anatolian fault system (NAF) (Sengor, 1979; Dewey and Sengor, 1979; McClusky et al., 2000) and the left lateral strike-slip movement along the EAF (Fig. 1a) (McKenzie, 1972; Jackson and McKenzie, 1988). The Anatolian block is escaping westward due, in part, to the northward motion of the Arabian plate. The NAF and EAF have been active since the Miocene (e.g., Allen, 1975; Ambraseys 1970; Barka and Kadinsky-Cade, 1988) and are associated with large pull apart basins, such as the Karliova Basin located at the junction of these two fault systems (Hempton, 1985). The area to the east of Karliova triple junction is characterized by a N-S compressional tectonic regime and conjugate strike slip faults of dextral and sinistral character, mostly paralleling the NAF and EAF which are the dominant structural elements of the region (Fig. 1b).

A number of geodynamic models have been proposed to explain the Arabia/Anatolia continental collision zone: (a) continental subduction (Rotstein and

Kafka, 1982), (b) the Arabian plate convergence being accommodated entirely by microplate escape (McKenzie, 1976**;** Sengor and Kidd, 1979; Jackson and McKenzie, 1988), (c) lithospheric thickening (Dewey et al., 1986), and (d) lithospheric delamination (Pearce et al., 1990). It may be that a combination of these processes is taking place. Rotstein and Kafka (1982) have suggested that the Arabian lithospheric plate is being subducted beneath the Eurasian plate at the Bitlis thrust zone based on the presence of apparently subcrustal earthquakes. However, the reliability of these hypocentral solutions is unclear because there are no nearby stations used for the depth calculation. In this paper we provide an accurate documentation of earthquake hypocenters in the region and provide additional constraints for the proposed geodynamic models.

Because of the relative lack of seismic instrumentation in the region prior to our deployment, the seismic activity could not be monitored well and earthquakes with magnitudes less than 4.0 were nearly impossible to accurately locate. In particular, the hypocenter depths were inaccurate. Therefore, the current seismic maps do not show the real picture of seismicity and many events are not clearly associated with mapped active faults.

Data and Analysis

Seismic waveform data from a temporary 29-station broadband PASSCAL network were collected in eastern Turkey from late October 1999 to August 2001 (Fig.1b). The distribution of the seismic stations is such that the network would provide good location of not only any micro-earthquake within the network but also any of the subcrustal earthquakes that are reported to occur in this region. The network consisted of two main transects: an eastern linear array of twelve stations and a western array of eight stations. The interior of the V shape formed by the two transects is filled with nine stations spaced approximately 100 km apart. The average station separation was approximately 50 km for the western line and 30 km for the eastern line. Each broadband station was equipped with a Streckeisen STS-1 seismometer, a REFTEK 72A recorder with a 4 GB field disk, and solar panels, except for station EZRM. A Guralp CMG-3T seismometer was used at EZRM. We recorded 24 bit broadband data continuously at 40 sps (samples per second), which provided high enough sampling resolution for accurate event locations. An automated network triggering algorithm based on STA (short term averaging) and LTA (long term averaging) was used to detect the events. To set the values of STA, LTA and their ratio, STA/LTA, the aftershocks of the Senkaya earthquake, which occurred in the northeastern corner of the Anatolian plateau in the beginning of the experiment, were used. By taking into consideration the seismic noise level at the sites, proper values of 10 sec., 50 sec. and 1.70 for STA, LTA and STA/LTA, respectively, were obtained. We also applied a band-pass frequency filter between 0.5 and 2.0 Hz.

During the experiment, approximately 10 events per day were detected and a total of 1165 local earthquakes (Fig. 2) were located. Furthermore, two moderate size earthquakes ($M \approx 5.5$) near Senkaya and in Lake Van occurred during the deployment of The Eastern Turkey Seismic Experiment (ETSE). Arrival times of both Pg and Sg or Pn and Sn phases were obtained by visual inspection. Those phases were manually picked with a clear S-wave arrival which was not always apparent due to the very high attenuation in this region (Gok et al., 2003).

In order to determine the optimal velocity for location, a grid search technique was employed. To invert the optimal velocity model we selected only the best located events whose locations would largely be insensitive to the velocity model, thereby allowing us to determine the optimal 1-D model for Eastern Turkey. We used a grid search approach and phase data from 66 very well located events evenly distributed throughout the Anatolian plateau. The resulting velocity model (Table 1) was used in the HYPOCENTER locating program (Lienert and Havskov, 1995). In addition, the hypocentral locations and the crustal model were tested and calibrated by a 12-ton controlled source explosion that took place in Eastern Turkey on June 5, 2001 (Gurbuz et al., 2003). Average crustal structure and site correction terms for the stations have been obtained by using the travel-time data of the explosion. We found that for near-surface events, the ETSE network is able to locate events within 2-3 km of the true epicenter even when not using optimal velocity models.

All hypocenter locations were classified into four different categories based on the reliability of the locations as shown in Table 2. We used four parametric values of the output of the hypocenter location program to determine the quality of the location. The parameters are: number of stations, root mean square (rms), epicentral distance to the nearest station, and azimuthal gap. Owing to their presence inside the network, only events in class A and class B were taken into consideration for the analysis and interpretation of this research (Fig. 3).

Results

A comparison among event locations based on the ETSE, Kandilli Observatory and Earthquake Research Institute (KOERI), and the Preliminary Determination of Epicenters (PDE) of the US Geological Survey showed that there is a significant difference in epicentral location, depth, and the number of located events in the region among these three sources. For example, we located 101 ETSE events between October 29 and November 31, 1999 while KOERI and PDE reported 42 and 8 events, respectively. The eight PDE locations and the ETSE locations had an average difference in epicentral location of 12 km where all but one of the PDE hypocentral depths were fixed to 10 km. The one PDE event that did not have fixed depth was within 2 km deeper than the ETSE hypocentral depth solution. We also recorded a Mw 5.5 earthquake that occurred along the southern portion of LakeVan (Figure 1). The hypocentral depth for this even was 23 km depth, however, thePDE reported a depth of 65 km.

In general, the distribution of the epicenters in class A and class B correlate well with mapped surface faults. It should be noted, however, that we observed seismic activity in regions where no surface faults have been mapped. There has been no surface faulting in the area NE of the Karliova junction and yet we observed a large number of small to moderate size events in the region. In order to understand the hypocentral distribution of earthquakes on NAF, EAF, the Bitlis suture zone, and near the Karliova Junction, we displayed them in two cross sections that are orthogonal to both fault zones (Figure 4). Eighty percent of the hypocenters in class A and B are located in the upper 10 km of the crust. During the entire period of the experiment only one earthquake on the NAF occurred in the 20-30 km depth range and seven in the 10-20 km range; the rest (38 events) occurred in the 0-10 km depth range (Fig. 4). The depth distribution of seismic events in other regions appear to be similar. The EAFZ, however, has the greatest number of seismic events in the 10-30 km depth range (22 in the 10-20 km bin and 35 in the 20-30 km bin), and those events are concentrated in the middle portion of the EAFZ in and around Lake Hazar. Of the class A and B events, only one depth value in the entire region exceeded 30 km depth. This event has a reasonably well constrained hypocentral depth with The vast majority of our well-constrained hypocentral depths are less than 20 km. This result strongly implies that there is no continental underthrusting/subduction of Arabia beneath Eurasia. In fact this suggests that only the upper crust in Anatolia is seismogenic which is consistent with similar results in other continental plateaus (e.g. Maggi et al., 1999).

Seismicity patterns from prior earthquake catalogs in eastern Turkey have shown a relatively even distribution of events throughout the eastern Anatolian plateau with little or no correspondence between mapped surface faults and the location of earthquakes. This is almost certainly a result of poor earthquake location resolution. The ETSE network did not detect any seismic activity in the Erzincan basin (near the town of Uzumlu; station UZML) (Fig 4a). This observation supports the idea that the NAFZ extends toward the SE (in the direction of Lake Van) via the Karliova triple junction as shown in Fig 2, Fig 3 and Fig 4. This apparent continuation of the NAFZ is also consistent with many of the strike slip focal mechanisms found along the zone between the Karliova triple junction and Lake Van.

Discussion and Conclusions

Our study shows that the seismic activity in Eastern Turkey is higher than previously observed and we have significantly improved the accuracy of hypocenter locations in the region. Correlation of epicenters and mapped surface faults is good along the NAFZ and EAFZ (Figure 3). 90% of the epicenters within 100 km of the EAFZ fall within 10 km of the mapped fault zone. Along the NAFZ the correlation is less good where approximately 50% of the epicenter fall within 10 km of mapped surface faults. Seismic activity east of the Karliova triple junction suggests possible unmapped faults. Our results also show that the NAFZ extends to the SE direction to the east of the Karliova junction. Most of the seismic activity seem to occur in the upper crust (in the first 10 km). However, the EAFZ, the Bitlis suture zone, the Karliova junction area and the area east of Karliova have some hypocenters which may originate in the lower crust (h>20 km) as well. This may suggest that the EAFZ and Bitlis suture are seismogenically thicker than the NAFZ.

We observe no subcrustal events in the northern Arabian plate or within the Anatolian or Eurasian plate. This observation essentially rules out any standard underthrusting/subduction of the Arabian lithosphere beneath Eurasia. This result is also consistent with the observations of Al-Lazki et al. (2003) and Zor et al. (2003).

A continuous band of seismicity stretches from the commonly defined easternmost extent of the NAFZ (Karliova) to Lave Van. This observation may suggest that the NAFZ continues all of the way to the Main Recent Fault in northwestern Iran (Zagros Mountain). This is consistent with the observation of Talebian and Jackson, (2002) that the Main Recent Fault in northwestern Iran and the NAFZ combine to form a nearly continuous band of right lateral shear on the margin of the Arabian and Eurasian plates.

Acknowledgements

We thank all Turkish officials and local people for their enormous help in this project. The ETSE study was partially supported by the National Science Foundation under Grant No EAR-984780. Additional support was provided by the Bogazici University Research Fund under Grant No 99T206. Equipment was provided by the IRIS-PASSCAL Instrumentation Center.

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Table 1. 1-D Velocity Model Obtained by Using the Grid Search Technique.

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

Table 2. Criteria for location quality classifications.

	Class A	Class B	Class C	Class D
Number of Stat.	>15	>10	>6	Everything else
RMS	=<1.0	=<1.0	=<1.5	
Nearest Station	<50 km	100 km	150 km	
Azimuthal Gap	$<100^0$	$<180^0$	$<250^0$	

Figure Captions

Figure 1. (a) Map showing tectonic boundaries and plates motion in eastern Turkey and surrounding regions. High topography in Eastern Turkey and Zagros thrust zones is shaded. NAF: North Anatolian Fault, EAF: East Anatolian Fault (after Seber et al., 1997). Arrows indicate direction of plate motion. (b) Active fault map of Eastern Turkey (modified after Saroglu et al., 1992) and the seismic station distribution of the ETSE network. Solid triangles represent seismic stations. The two shaded areas are the locations of two moderate-sized earthquakes, determined by ETSE, KOERI and USGS respectively.

Figure 2. Map showing earthquake locations in Eastern Turkey based on the ETSE data for the period October 1999-August 2001. All hypocenter locations were classified into four different categories based on the reliability of the locations which are shown by solid dots in red, yellow green and gray.

Figure 3. Map showing the hypocenter depth distribution of the well-located events inside the ETSE network (class A and class B events only).

Figure 4. Two cross sections taken across the North Anatolian Fault (top panel) and East Anatolian Fault (bottom panel). The locations of the cross sections are shown on Figure 3.

Figure 1a

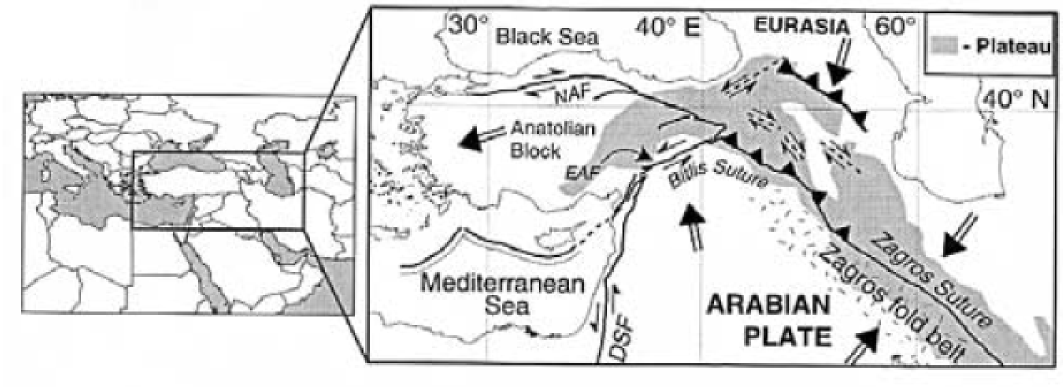


Figure 1b

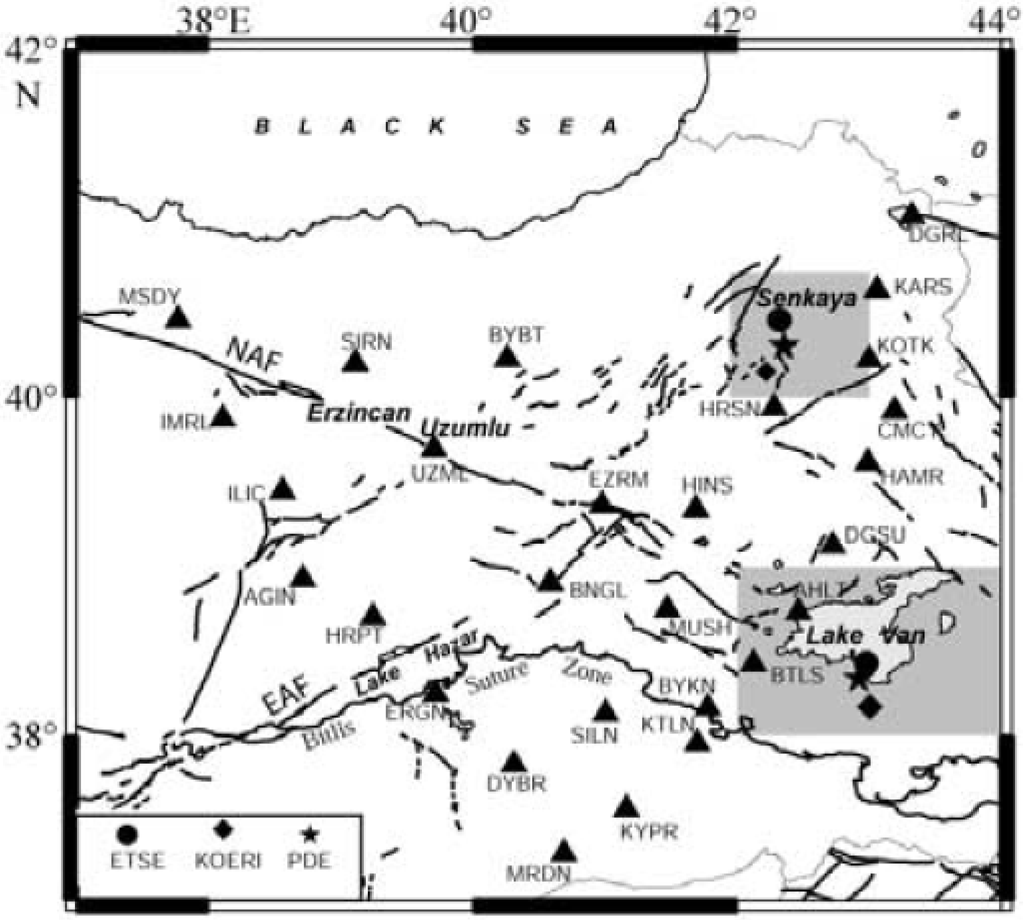


Figure 2

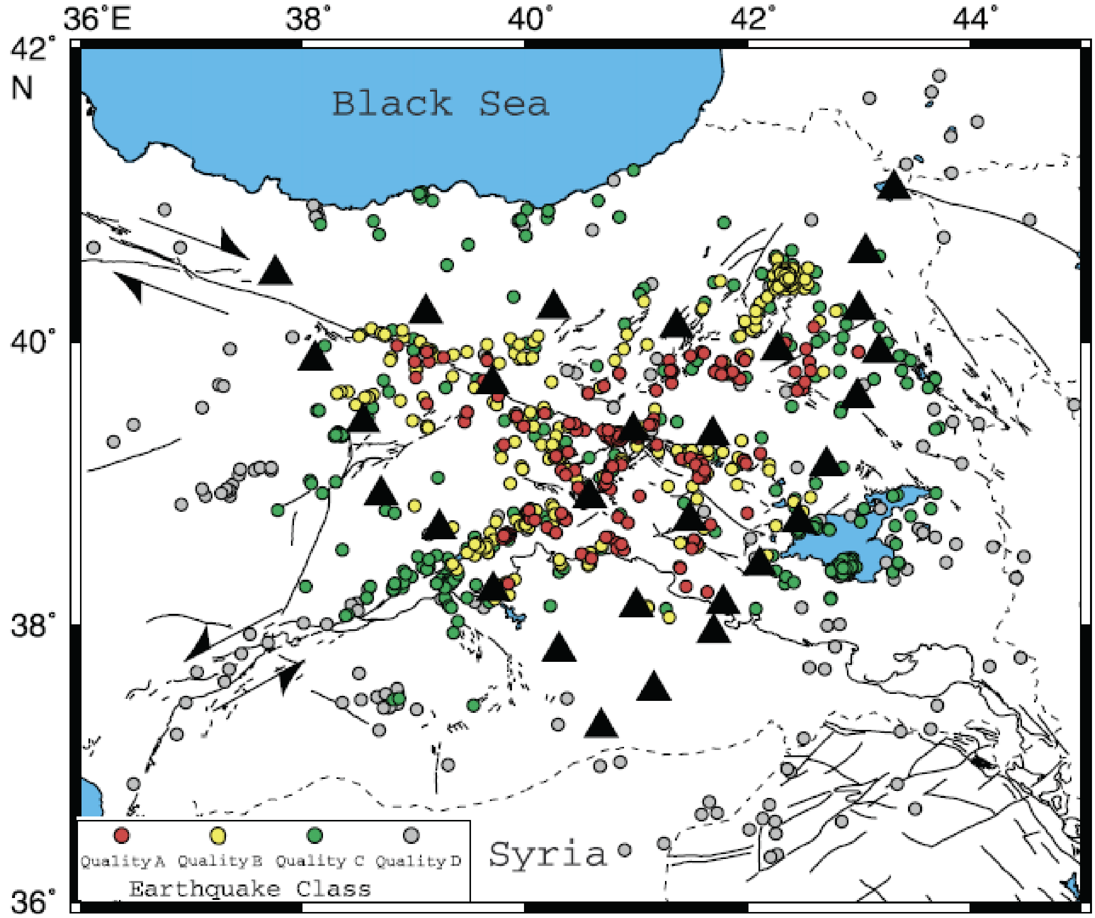


Figure 3

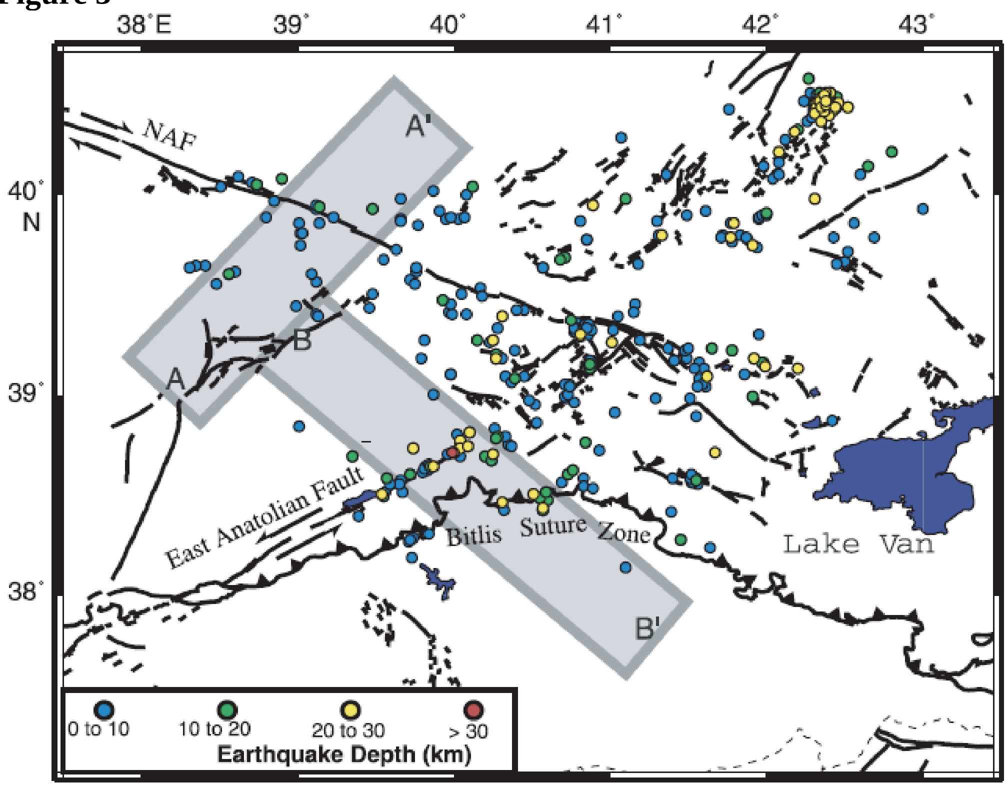
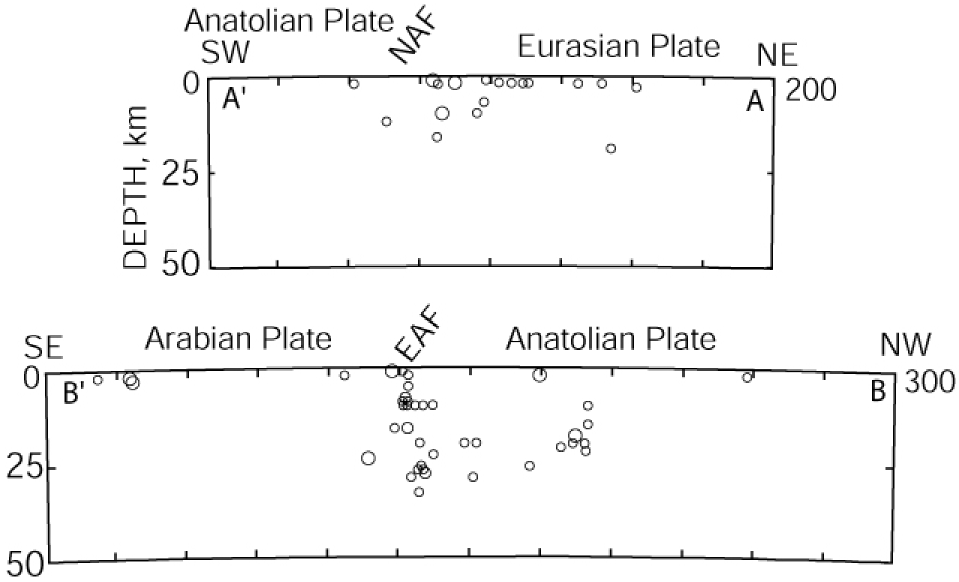


Figure 4


Anatolian Plate
SW
NAF
Eurasian Plate
NE
0
A'
A
200
DEPTH, km
25
50
SE
Arabian Plate
EAF
Anatolian Plate
NW
0
B'
B
300
25
50