Bulut, F., Bohnhoff, M., Aktar, M., Dresen, G. (2007): Characterization of aftershock-fault plane orientations of the 1999 Izmit (Turkey) earthquake using high-resolution aftershock locations. - Geophysical Research Letters, 34, L20306, 1-4

DOI: 10.1029/2007GL031154.

**Formatiert:** Nummerierung: Jede Seite neubeginnen

# Characterization of aftershock-fault plane orientations of 1999 Izmit (Turkey) earthquake using high-resolution aftershock locations

Fatih Bulut, Marco Bohnhoff, Mustafa Aktar and Georg Dresen

## Abstract

Joint inversion for hypocentral parameters and the velocity field is nowadays a state of the art tool to obtain high-resolution images of seismically active regions. In this study, we focus on the location accuracy of aftershocks of the 1999 Mw=7.4 İzmit (NW Turkey) earthquake. We obtained a new velocity model for the region, and depicted its improvement on absolute locations in terms of uncertainty and misfit. Two well-developed aftershock clusters located in the Akyazı area and Karadere-Düzce region, were analyzed in detail based on a waveform cross-correlation approach that allowed improving the location accuracy by a factor of 6. Relocation results reveal that hypocenters form narrow planes of activity that can be correlated with focal mechanisms of the larger aftershocks as well as nearby clouds of activity with no internal structure down to the resolved scale of ~300 m.

## 1. Introduction and data base

On 17 August 1999 a Mw=7.4 earthquake occurred at the Izmit segment of the North Anatolian Fault Zone (NAFZ) in NW Turkey. The hypocenter was located at 40.75°N, 29.86°E at 17 km depth (see Figure 1a). The mainshock ruptured a roughly 140 km long section of the NAFZ extending from the easternmost Sea of Marmara in the West to near the city of Düzce in the East (e.g. Barka et al., [2002]). Several studies have been carried out to examine the aftershock activity along the rupture zone and surrounding areas (e.g. Örgülü and Aktar, 2001, Karabulut et al., 2002, Özalaybey et al., 2002, Ben-Zion et al., 2003). However, yet presented aftershock catalogs still require an improved hypocenter-location accuracy around the eastern part of the rupture, especially in the Akyazı and Karadere-Düzce areas.

Here we analyze recordings obtained by a 36-station network that covered the entire Izmit rupture. The network consists of a nucleus of 15 stations being in operation since 1996 (Sapanca-Bolu network, C. Milkereit et al., [2000]) which was then upgraded by another 21 stations within only four days after the mainshock by the German Task Force for Earthquakes of GFZ Potsdam (Zschau and Grosser, pers. comm.). The combined network allowed to locate ~10000 aftershocks at a threshold of magnitude completeness of 1.1 (see Bohnhoff et al., [2007], for details). Restricting the catalog to events with location errors <5km in lateral and vertical direction, respectively, results in a total of 5163 events that are plotted in map view and as depth section in Figure 1a. The distribution allows identifying two main clusters of activity, named Akyazı and Karadere-Düzce cluster hereafter. At the eastern termination of the rupture a sharp steeply dipping boundary of activity is observed exactly where the subsequent Düzce mainshock initiated 87 days after the Izmit event.

Absolute hypocenter determination was achieved by fitting the arrival time readings to the calculated ones based on a regional 1-D velocity model. Lateral effects of a three-dimensional velocity structure were ignored. However, the use of relative travel times of incoming waves from neighboring events allows to largely eliminate effects of the unknown velocity distribution. Differential travel-time measurements derived from handpicked arrivals and cross-correlation of P- and S-wave windows significantly reduces the hypocenter location error caused by velocity structure and arrival readings (Waldhauser & Ellsworth, [2000]).

The method improves spatial resolution and allows identifying small-scale structures that otherwise remain hidden in clusters. Hand-picked arrival times give a first-order estimate of relative travel times, and accuracy of the hypocenter location is significantly increased by applying waveform cross-correlation. Yet, waveform-based relocation studies for the Marmara Region are rare (Bulut and Aktar, [2007]) despite their potential to refine seismotectonic models of the region. In this study, we analyze the Akyazi and Karadere-Düzce cluster as part of the 1999 İzmit rupture based on an improved relocated aftershock catalog.

## 2. Velocity Model

Absolute hypocenter determination of İzmit aftershocks recorded by the 36-station network was performed using the HYPOCENTER earthquake location program (Lienert et al., [1995]) using 104080 hand-picked P wave arrival times (Bohnhoff et al., [2007]). Location error and RMS residuals of the hypocenters that are located based on a 1-D velocity model (Özalaybey et al., 2002) are indicated in figure 2. The absolute location procedure allows minimizing the RMS value even without a well-known velocity model, but not hypocenter uncertainties. Therefore, we minimized all three parameters (RMS, vertical and horizontal error) simultaneously and derived an improved 1-D velocity model for the Akyazi/Karadere-Düzce region with more than 1000 highest reliable absolute hypocenters. We first performed a trial-and-error procedure on selected hypocenters in order to find a reasonable layering of the velocity model. Here we assume that appropriate layering of the crust can be defined for which the most reliable hypocenters are obtained, in terms of not only average RMS error but also location uncertainty. The RMS includes the systematic errors which can result from an inadequate velocity model; however it might be minimized even if large hypocenter uncertainties exist (e.g. local minimum). We used various initial velocity models proposed earlier for the Marmara Region (Ergin et al., [1997], Gürbüz et al., [2000], Özalaybey et al., [2002], see Figure 1b), and determined the depths of interfaces for which all models converge. In a second step, we used the VELEST inversion code (Kissling et al., [1994]) to obtain a refined P-wave velocity structure. This approach allowed reducing vertical and horizontal errors of the hypocenter locations (Figure 2). The final velocity model is indicated by the bold black line in Figure 1.b.

Absolute location methods usually deal with a system of linear equations called Geiger's Matrix (Geiger, 1910). This matrix consists of the partial derivatives coming from a truncated Taylor approximation of the nonlinear relation between event location and arrival times. During the minimization process, the number of iterations needed to obtain the final model parameters depend on the damping factor for the least-square inversion procedure. The rate of convergence to the true model depends strongly on the accuracy of the starting model (Lay and Wallace, 1995). We therefore decided to repeat the inversion for the entire depths interval from 1 to 25 km in 1 km increments minimizing horizontal and vertical errors. This strategy resulted in 1031 additional well-constrained absolute located hypocenters with accuracy better that 5.0 km and a generally improved location error for the entire catalogue (Figure 2.c).

## 3. Relocation of Hypocenters

The rays originating from different events propagate along a similar path if the events are located close to each other compared to the event-station distance. In such cases, the relative arrival time of each event pair can be compared to the offset between two of the events in three-dimensional space. In a conventional location method, arrival time readings can be used to locate the earthquakes individually. However, the use of relative travel times of event pairs requires taking the difference between linear equation pairs of the Geiger Matrix (Geiger, [1910]). The Double-Difference technique is based on inversion of the linear equation pairs and minimizes double residuals (Double-Difference) of corresponding relative travel times (Waldhauser and Ellsworth, [2000]). This technique allows to significantly improve the relative location accuracy for areas with sufficient seismic activity.

We relocate 4696 aftershocks of the Akyazi/Düzce-Karadere area using the Double-Difference earthquake relocation algorithm (Waldhauser and Ellsworth, [2000]). Relative travel-time data were obtained from both hand-picked arrivals and cross-correlation analysis. The time windows range from -0.1

to 1.4 s framing the handpicked P-wave arrival times. Cosine taper and band-pass filter between 1-20 Hz were applied prior to the cross-correlation based time-delay estimation. We assume that this approach is preferable to estimate the delay times for cross-correlation coefficients >0.55.

More than 500.000 waveforms were correlated that belong to the selected event pairs of separation distances less than 6 km (mean: 2.07 km). Maximum number of neighbors per event is set to 15 to keep the computation time within reasonable limits. 218.482 (39%) of the waveform pairs revealed a sufficient similarity according to the given threshold of 0.55, and thus were considered for the estimation of relative travel times for corresponding event pairs instead of catalog-based data. 87% of the events are strongly paired. The program is then run in a damped least-square mode. Catalog-based data was pre-weighted according to picking quality, whereas cross-correlation data were ranked according to correlation coefficients. The relocated hypocenter catalog contains 4696 events and its high location accuracy is documented by the reduction of average RMS to 29 ms and average relative horizontal and vertical errors of ~300 m and ~400 m, respectively. Therefore, the location accuracy was improves by a factor 6 with regard to initial average absolute location error of 2.4 km along the İzmit rupture.

## 3. Results and Discussion

The relocated catalog of Izmit aftershocks allows identifying a number of structural features. The map view (Figure 3.a) clearly confirms existence of two main clusters of activity in the Akyazi and Karadere-Düzce areas. The majority of events are observed between 6 and 16 km depth and only a small number occurred near the surface. Here, the upper boundary of the seismicity is more pronounced compared to the Akyazı area. This distribution of hypocentral depths is stable even if we use other velocity models formerly proposed for the region (see Figure 1b) confirming upper and lower bounds for hypocentral depth.

The aseismic zone from the surface down to 6 km depth extends along most of the Izmit rupture. Only a local fault patch near the Karadere fault shows ~30 fairly shallow events (see Figure 3.b). A similar aseismic zone down to 5 km depth was observed at the San Andreas Fault near Parkfield (Waldhauser et al., 2004). There, the aseismic zone is restricted only to the locked part of the San Andreas Fault. In our case the absence of shallow seismicity could indicate the first phase of the earthquake cycle at the Izmit-Sapanca segment of the NAFZ after the Izmit mainshock.

The Akyazı hypocenter cluster extends from east of the Sapanca Lake towards the western portion of the Almacık Block (Figure 3.a). Based on the relocated hypocenters we identify two linear features within this cluster. In the SW a prominent N130°E trending plane of hypocenters is observed forming the westward extension of the Mudurnu valley. There, a M>7 earthquake occurred in 1967 (Ambraseys et al., 1969) and its western rupture termination approximately coincides with the eastern end of the observed plane of Izmit aftershocks. The second feature observed within the Akyazi cluster is a NNE-SSW trending plane dipping to the WNW at an angle of ~75° (see arrow in Figure 3.d – profile BB'). This plane correlates with the fault plane of EW-extensional normal faulting aftershocks in this region within the resolved accuracy of ~$10^o$ for the fault strike. We interpret this plane to represent the western termination of the Almacik block (Figure 3.c). Parallel to this fault several aligned hypocenters are observed within the Akyazı Cluster. However, these events do not reflect a plane-like geometry at depth but, on average, represent EW-extensional normal faulting and therefore the pull-apart nature of the Akyazi Plain in general as described by Bohnhoff et al., [2006].

The Karadere-Düzce cluster is located at the northern margin of Almacık Block. Its most prominent planar structure is a N65°E trending fault segment extending for about 25 km along strike. This plane is dipping at ~67° (see arrow in Figure 3.d – profile CC') to the North and is interpreted to represent the depth extension of the Karadere fault that hosted ~1.5m of right-lateral coseismic slip during the Izmit event and that is identified by a very narrow topographical trace at the surface. Focal mechanisms indicate pure strike-slip motion on the fault. Towards the East we observe a more diffuse distribution of aftershocks reflecting an abrupt and steeply dipping termination of activity where the Izmit rupture stopped and where the Mw=7.1 Düzce earthquake initiated 87 days after the İzmit mainshock (Milkereit et al., 2000). The Düzce event mainly propagated towards the east but also re-ruptured parts of the Karadere-Düzce segment west of the mainshock (Umutlu et al., [2004]). Within this activity we find indications for partially parallel oriented smaller structures at 7-15 km depth that are dipping to the North. These planes match with the aftershock-focal mechanisms for events larger than M=4 that all have an almost identical fault plane solutions (Bohnhoff et al., 2006).

The resolution of aftershock hypocenter locations derived here allows us to identify the lateral variations of seismotectonic setting along the İzmit-Düzce segment of the NAFZ. Surface observations (e.g. Barka et al., 2002) and GPS measurements (e.g. Ergintav, 2002) indicate an E-W oriented displacement field as the major characteristic of this area that is caused by the westward movement of Anatolian plate with respect to stable Euroasia (McClusky et al., 2000). In the Akyazi area, the majority of events reflect EW-extensional normal faulting on NS-oriented fault planes that were partly identified by the relocated events. To the NE, the dominant type of faulting turns into right-lateral strike-slip faulting on NW-SE trending fault planes reflecting the Karadere fault. We interpret the lateral changes in characteristic types of faulting along the Izmit rupture to be caused by strong structural variations along this part of the NAFZ, namely the homogeneous Akyazi Block consisting of strong material causing the NAFZ to locally deviate from its regional EW-striking trend.

**Acknowledgments** We thank the German Task Force for Earthquakes hosted at GeoForschungsZentrum in Potsdam and especially C. Milkereit for providing the continuous seismic recordings obtained after the 1999 Izmit earthquake. H. Grosser, M. Baumbach, E. Günther, S. Zünbül, and S. Karakisa performed an excellent maintenance of the network. We thank Dino Bindi, Stefano Parolai and Ethem Görgün for collaborating on data processing and magnitude determination

## References

Ambraseys, N.N., Zatopek, A., (1969). The Mudurnu Valley, West Anatolia, Turkey, earthquake of 22 July 1967 , *Bull. Seismol. Soc. Am.*, 59 (2), 521-589.

Barka, A. H. S. Akyüz, E. Altunel, G. Sunal, Z. Çakir, A. Dikbas, B. Yerli, R. Armijo, B. Meyer, J. B. de Chabalier, T. Rockwell, J. R. Dolan, R. Hartleb, T. Dawson, S. Christofferson, A. Tucker, T. Fumal, R. Langridge, H. Stenner, W. Lettis, J. Bachhuber, and W. Page, (2002), The Surface Rupture and Slip Distribution of the 17 August 1999 Izmit Earthquake (M 7.4), North Anatolian Fault, Bull. seism. Soc. Am., 92(1), 43–60.

Ben-Zion, Y., Peng, Z., Okaya, D., Seeber, L., Armbruster, J.G., Michael, A.J., Baris, S., Aktar, M. (2003) A shallow fault-zone structure illuminated by trapped waves in the Karadere-Duzce branch of the North Anatolian Fault, western Turkey. Geophys. J. Int., 152, 699-717.

Bohnhoff M., Grosser H. and Dresen G., (2006), Strain partitioning and stress rotation at the North Anatolian fault zone from aftershock focal mechanisms of the 1999 Izmit Mw = 7.4 earthquake, Geophys. J. Int., 166, 373–385

Bohnhoff, M., Bulut, F., Görgün, E., Milkereit, C., Dresen, G., (2007), Seismotectonic setting at the North Anatolian Fault Zone after the 1999 Mw=7.4 Izmit earthquake based on high-resolution aftershock locations, subm. to Advances of Geosciences

Bulut F. and Aktar M., (2007), Accurate relocation of Izmit earthquake (Mw=7.4, 1999) aftershocks in Çınarcık Basin using double difference method, Geophysical Research Letters, VOL. 34, L10307, doi:10.1029/2007GL029611.

Ergin, M., M. Aktar, F. Biçmen, A. Yörük, N. Yalçın, and S. Kuleli (1997), Izmit körfezi mikrodeprem çalışması, paper presented at Aktif Tektonik Araştırma Grubu 1. Toplantısı, Aktif Tektonik Araştırma Grubu, Istanbul, 309, Turkey, 8 – 9 Dec

Ergintav, S., Bürgmann, R., McClusky, S., Çakmak, R., Reilinger, R. E., Lenk, O., Barka, A., and Özener, H. (2002), Postseismic Deformation near the İzmit Earthquake (17 August 1999, *M* 7.5) Rupture Zone, Bulletin of the Seismological Society of America, 92: 194 - 207

Geiger, L. (1910). Herdbestimming bei Erdbeben aus den Ankunftszeiten, K. Ges. Wiss. Gott. 4, 331–349.

Gürbüz, C., M. Aktar, H. Eyidoğan, A. Cisternas, H. Haessler, A. Barka, M. Ergin, N. Türkelli, O. Polat, S. B. Uçer, S. Kuleli, S. Barış, B. Kaypak, T. Bekler, E. Zor, F. Biçmen, and A. Yörük (2000). The seismotectonics of the Marmara region (Turkey): results from a microseismic experiment, Tectonophysics 316, 1–17.

Karabulut, H., Bouin, M., Bouchon, M., Dietrich, M., Cornou, C., and Aktar, M. (2002), The Seismicity in the Eastern Marmara Sea after the 17 August 1999 Izmit Earthquake. Bull. Seism. Soc. Am. 92, 1,387–393.

Kissling, E., W. L. Ellsworth, D. Eberhart-Philipps, and U. Kradolfer (1994). Initial reference models in local earthquake tomography, J. Geophys. Res. 99, 19,635–19,646.

Lay, T. and Wallace, T. (1995), Modern Global Seismology, p 221-223, Academic Press.

Lienert, B. R., and J. Havskov , (1995), HYPOCENTER 3.2 - A computer program for locating earthquakes locally, regionally and globally, Seis. Res. Lett., 66, 26-36.

McClusky, S. et al., (2000), Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus, J. Geophys. Res., 105, 5695-5719.

Milkereit, C., S. Zunbul, S. Karakisa, Y. Iravul, J. Zschau, M. Baumbach, H. Grosser, E. Günther, N. Umutlu, T. Kuru, E. Erkul, K. Kling, M. Ibs von Seht, and A. Karahan (2000). Preliminary aftershock analysis of the $M_w$=7.4 Izmit and $M_w$=7.1 Düzce earthquake in western Turkey, in The 1999 Izmit and

Düzce Earthquakes: preliminary results, A. Barka, Ö. Kozacı, S. Aykŭz, and E. Altunel (Editors), Istanbul Technical University, Istanbul, 179–187.

Örgülü, G. and Aktar, M. (2001), Regional moment tensor inversion for strong aftershocks of the August 17, Izmit earthquake (Mw=7.4), Geophysical Research Letters, 28, 371-374.

Özalaybey, S., Ergin, M., Aktar, M., Tapırdamaz, C., Biçmen, F. ve Yörük, A. (2002), The 1999 Izmit earthquake sequence in Turkey: seismological and tectonic aspects, Bulletin of Seismic Society of America, 92, 376-386.

Tibi, R., Bock, G., Xia, Y., Baumbach, M., Grosser, H., Milkereit, C., Karakisa, S., Zünbül, S., Kind, R. and J. Zschau, 2001. Rupture processes of the 1999 August 17 Izmit and November 12 Düzce (Turkey) earthquakes. Geophys. J. Int., 144, F1-F7

Umutlu, N., Koketsu, K., Milkereit, C., (2004), The rupture process during the 1999 Düzce, Turkey, earthquake from joint inversion of teleseismic and strong-motion data, Tectonophysics 391 (2004) 315–324, Tectonophysics 391, 315– 324

Waldhauser, F., and W. L. Ellsworth (2000), A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, Bull. Seism. Soc. Am. 90, 1353– 1368.

Waldhauser, F., Ellsworth, W. L., Schaff, D. P., and Cole, A.,(2004), Streaks, multiplets, and holes: High-resolution spatio-temporal behavior of Parkfield seismicity, Geophysical Research Letters, VOL. 31, L18608, doi:10.1029/2004GL020649

Fatih Bulut, GeoForschungZentrum Section 3.2., Potsdam, Germany. (e-mail: bulut@gfz-potsdam.de)

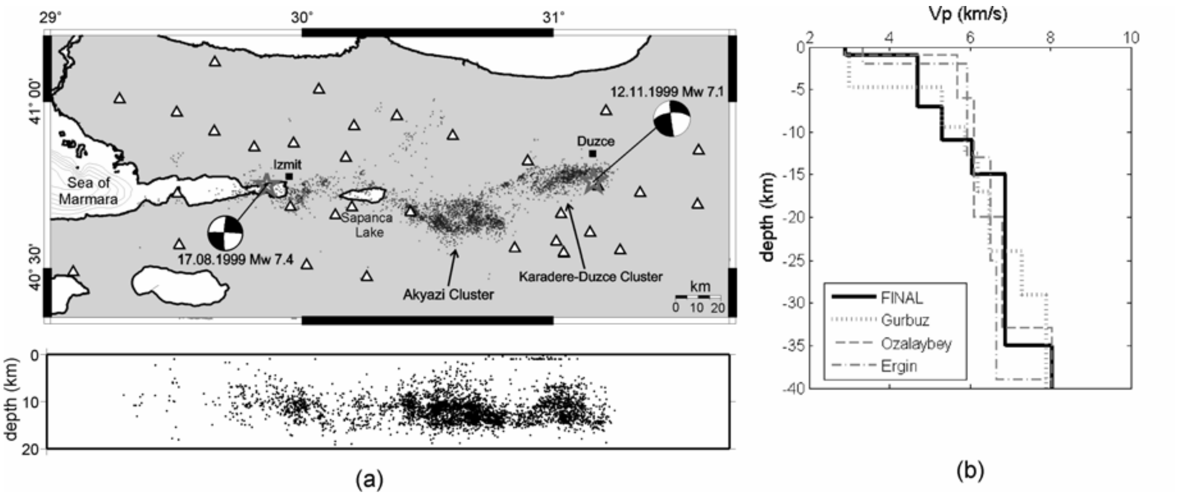

**Figure 1.** (a) Distribution of aftershocks with location accuracy better than 5 km (black dots), and the seismic stations (triangles) used in this study. (b) Initial velocity models (dashed lines) previously proposed for the Marmara Region by Gürbüz et al., [2000], Özalaybey et al., [2002], and Ergin et al., [1997] and the final velocity model (black line: Vp (km/s) = [2.90 4.70 5.30 6.06 6.88 8.06], depths (km) = [0.0 1.0 7.0 11.0 15.0 35.0]). Fault plane solutions from Tibi et al., [2001]

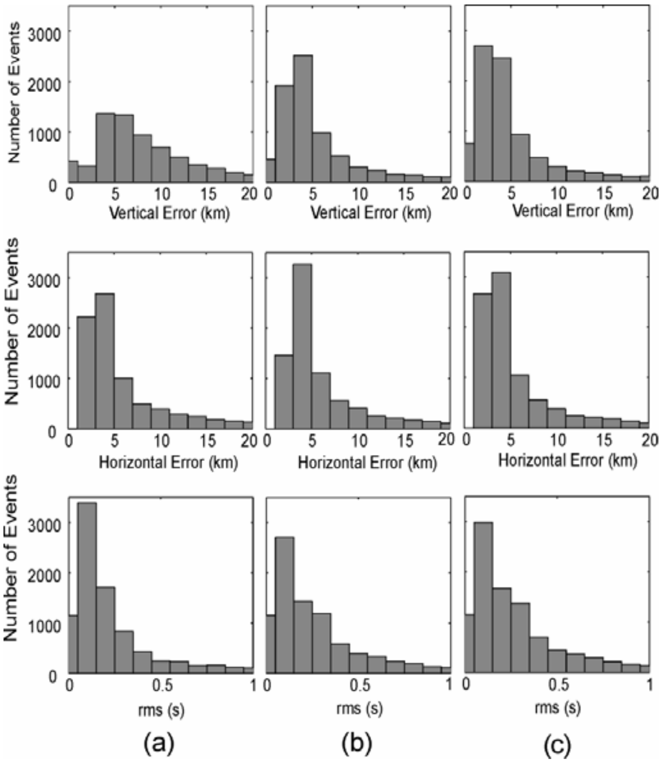

**Figure 2.** Specification of the hypocenters in terms of RMS residual and location error: (a) initial hypocenters, (b) hypocenters located based on the final velocity model (Figure 1.b), (c) obtained by changing the initial depth guess between 1 and 25 km.

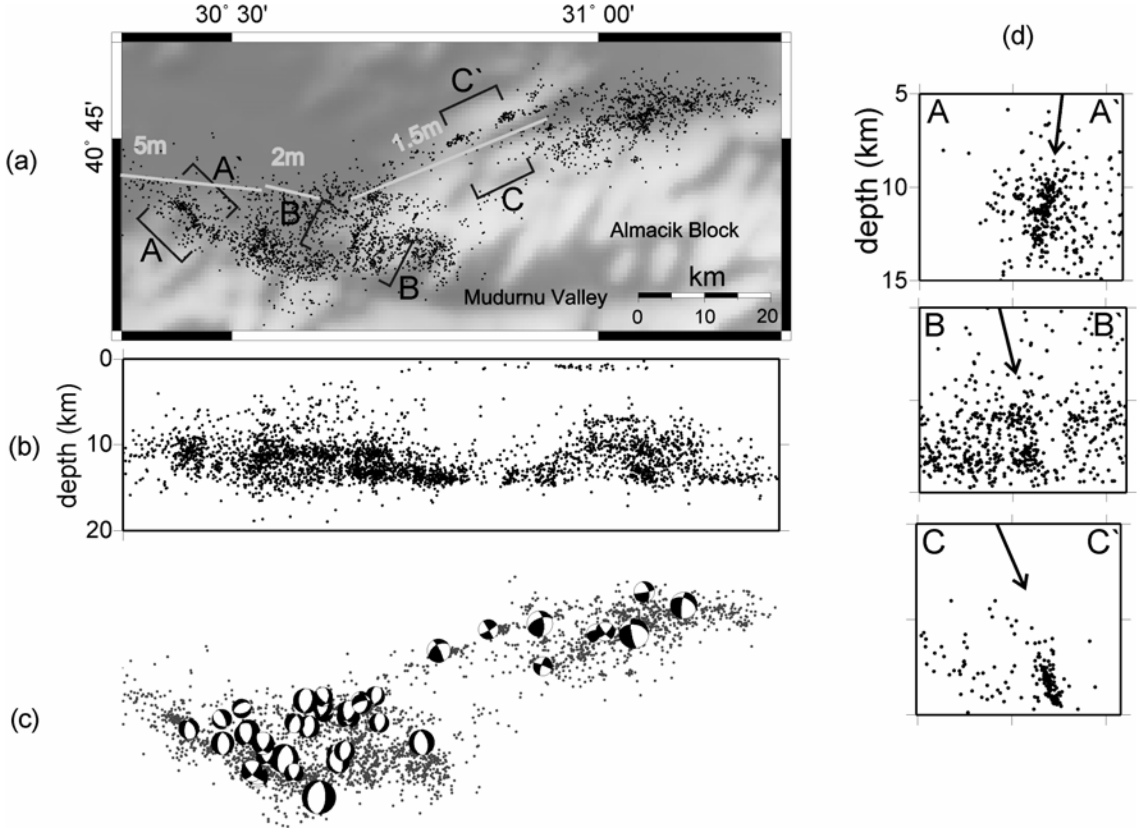

**Figure 3.** (a) Map view of hypocenters to compare with topography, surface trace of the rupture including maximum slip rates (Barka et al., [2002]) and (c) fault plane solution of M>3.0 events (Bohnhoff et al., [2006]). (b) Depth view of entire relocated events and (d) cross sections indicating dip of individual fault segments.