

# The 2005 - 2007 Bala (Ankara, central Turkey) earthquakes: a case study for strike-slip fault terminations

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## | A B S T R A C T |

An intense seismic activity has been observed after the Bala (Ankara, NW central Turkey) earthquakes (30 July 2005: Mw=5.3, 20 December 2007: Mw=5.4, and 26 December 2007: Mw=5.3), continuing up to the present. The epicenters and the focal mechanism solutions of the earthquakes indicate that the right lateral strike-slip Afşar fault, trending N55-60°W, is responsible for the main shocks. The Afşar fault is thought to be the NW continuation of the Tuzgölü fault zone, which is one of the main neotectonic elements in central Anatolia. On the other hand, the aftershock distributions of the 2005 event have a NNE trend, and those of the 2007 event show a NW trending. Some focal mechanism solutions of the 2005 Bala earthquake aftershocks indicate normal and oblique normal faulting that corresponds to the NNE-trending Karakeçili fault. It seems that seismic activation of the NNE-trending Karakeçili fault was triggered by the 2005 main shock (Mw=5.3) that occurred on the NW-trending right lateral strike-slip Afşar fault. The overall neotectonic framework is that the northwestern edge of the Tuzgölü fault zone, represented by the Afşar fault in Bala, terminates in an extensional system represented by the oblique-slip Karakeçili fault.

**KEYWORDS** | Strike-slip faults. Fault terminations. Tuzgölü fault zone. Neotectonics. Bala earthquake. Anatolia.

## INTRODUCTION

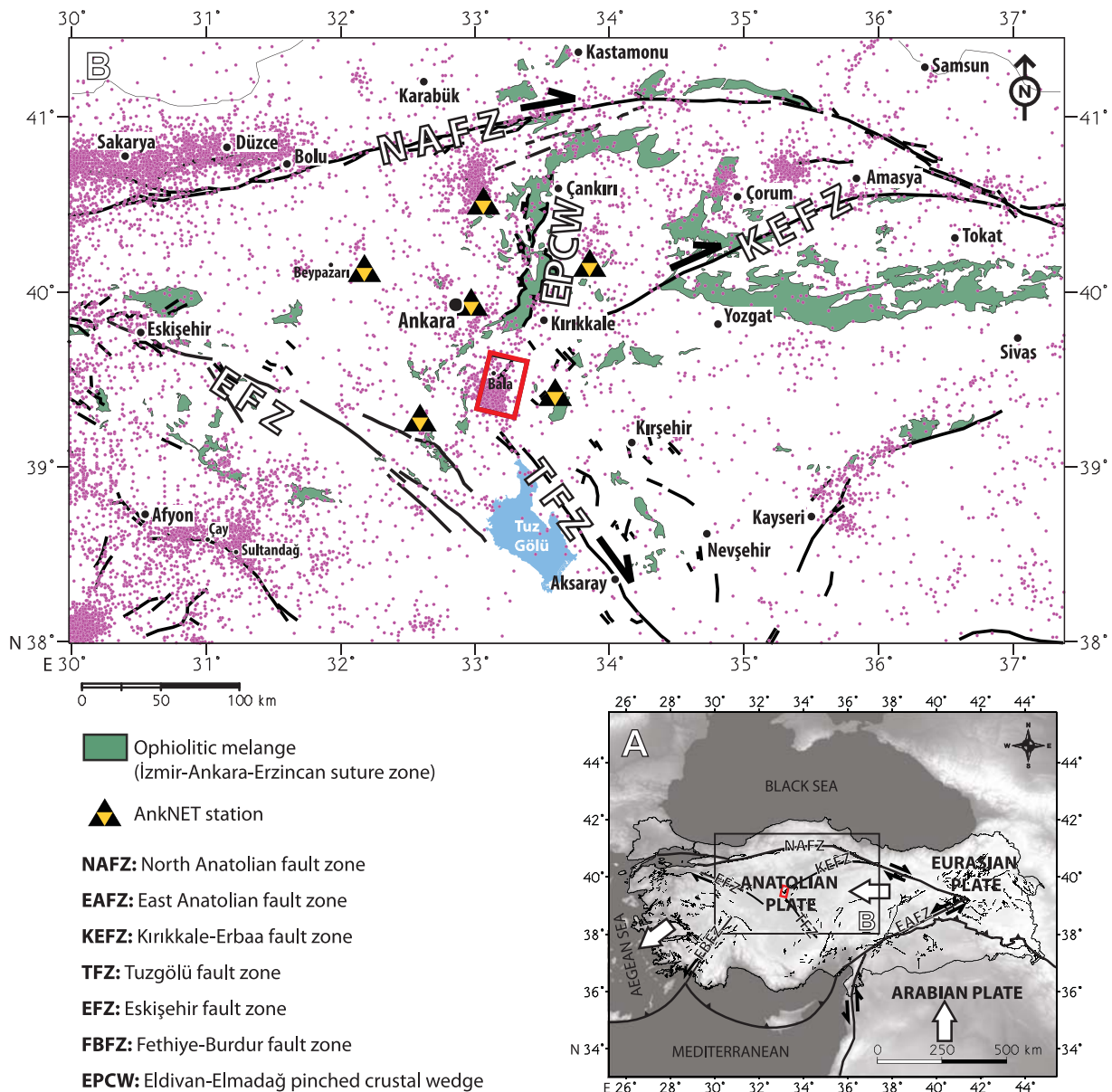
The neotectonics of Turkey was evaluated in the context of plate tectonics (McKenzie, 1972). The neotectonic provinces have been delineated as the East Anatolian contractional province, the Central Anatolian “ova” province, and the West Anatolian extensional province (Şengör, 1979, 1980; Şengör *et al.*, 1985). A cause-effect relationship for the development of the neotectonic provinces has been generally accepted, the triggering event of this relationship was the collision of the Eurasian and the Arabian plates along the Bitlis suture (Dewey *et al.*, 1986). The collision was followed by the development

of the North and East Anatolian fault zones, and by the subsequent westward motion of the Anatolian Plate, which created N-S extensional tectonics in western Turkey (Şengör, 1979, 1980; Şengör *et al.*, 1985). However, Seyitoğlu and Scott (1991, 1996) argued that the initiation of extensional tectonics in western Turkey is older than the collision and therefore the cause-effect relationship is not a proper explanation for the development of the West Anatolian extensional province. The transition from the West Anatolian extensional province to the Central Anatolian “ova” province is roughly shown as a narrow N-S zone by McKenzie (1972) and Şengör *et al.* (1985). On the other hand, Barka and Reilinger (1997) indicate

that the provinces are separated by the Eskişehir and Fethiye-Burdur fault zones (Fig. 1). The normal fault-induced earthquakes of 15 December 2000 Sultandağ (Mw=6.0) and 03 February 2002 Çay (Afyon) (Mw=6.3) (see Fig. 1 for location) (Taymaz and Tan, 2001; Başokur *et al.*, 2002; Emre *et al.*, 2003) changed the perception of the boundary between the western extensional province and that of central Anatolia (Koçyiğit and Özacar, 2003). The contractional structures previously attributed to the intracontinental convergence in NW central Turkey (Koçyiğit, 1991; Koçyiğit *et al.*, 1995) were now shown as neotectonic structures (*i.e.* Eldivan-Elmadağ Pinched

Crustal Wedge) developed through an interaction between the North Anatolian fault zone and the Kırıkkale-Erbaa fault zone (Seyitoğlu *et al.*, 2000, 2009a).

The NE-SW trending right lateral Kırıkkale-Erbaa fault zone and the NW-SE trending Tuzgölü fault zone converge in the Bala region, SE of Ankara (Fig. 1), where three significant earthquakes occurred on 30 July 2005 (Mw=5.3), 20 December 2007 (Mw=5.4), and 26 December 2007 (Mw=5.3). After the 30 July 2005 main shock, intense earthquake activity was observed in the Bala region. This area corresponds to the NW tip of Tuzgölü



**FIGURE 1.** Major neotectonic elements of central Anatolia. The white arrows indicate relative plate motions. The red frame shows the study area. Pink dots represent earthquakes from 1900 to the present. Earthquake data were obtained from the Kandilli Observatory and Earthquake Research Institute of Turkey's catalogue.

fault zone and the main shocks and their aftershocks provide valuable information on the termination of strike-slip systems (Fig. 1).

## ACTIVE FAULTS AROUND BALA

Active faults in the Bala region have been illustrated in unpublished reports (see Şaroğlu *et al.*, 1987) and papers (Koçyiğit, 2003; Özsayın and Dirik, 2007; Rojay and Karaca, 2008; Koçyiğit, 2009; Tan *et al.*, 2010). However, these studies lack detailed field observations and definitions of the actual faults.

The Afşar fault (ARF) and the Karakeçili fault (KKF) are two important active faults of the Bala region (Esat *et al.*, 2009) (Fig. 2). It is easy to envisage the ARF as a continuation of the Tuzgölü fault zone due to its strike, but little is known about the KKF. This fault was previously called the Çatalören fault and interpreted as a left lateral conjugate of the ARF by Koçyiğit, (2003, 2009) and Tan *et al.* (2010). However, in other studies the KKF is described as a NNE-trending oblique-slip normal fault with a variable strike-slip component, bounding the Karakeçili Neogene-Quaternary basin (Türkmen and Özkul, 1999; Saraç, 2003). The KKF is composed of parallel and sub-parallel fault segments that involve basement rocks (mainly flysch and recrystallized limestone of Eocene age) and basin deposits (Neogene clastic sedimentary rocks, limestone, and gypsum). The slightly oblique normal fault surfaces and their slickensides are observed in the contact between the basement rocks and the sedimentary units (Fig. I, Electronic Appendix available at [www.geologica-acta.com](http://www.geologica-acta.com)), and control the topography from the Bala highlands to the lower altitudes in the east (Fig. II). Minor fracturing, breccias and veins, are common brittle features in the basement rocks in the vicinity of the faults. The fracturing is mainly defined by widespread joints. The joints are subvertical, quite linear and several meters long. Their spacing varies from 0.1 to 1m. They occur at either parallel or variable angles to the normal faults. Some of the fractures contain striae, suggesting a shear mode of fracturing. Veins along faults are evidence of fluid presence during deformation. They are up to 1 m wide and traceable for several meters. Their walls are sub-vertical, sharp and plane. The veins are composed of coarse-grained calcite crystals with blocky and elongate shape, and show brecciated textures. The orientation of veins is approximately N-S, similar to that of the successive normal fault scarps seen in the basin deposits.

In the hanging wall of the KKF at the west of Çatalçeşme village, the Quaternary (?) cover has normal fault scarps (Fig. 3A). Maximum displacement ranges from 0.75 to 1m, with slip dissipating towards the fault tip (Fig. 3B, C). The Çatalçeşme seismic reflection study has been performed in

the fault scarps from this area (Fig. 3A, Appendix), and confirms the normal fault nature of the KKF. Most of the displacements seen on the Quaternary (?) cover can be traced in the subsurface (Fig. 4A, B).

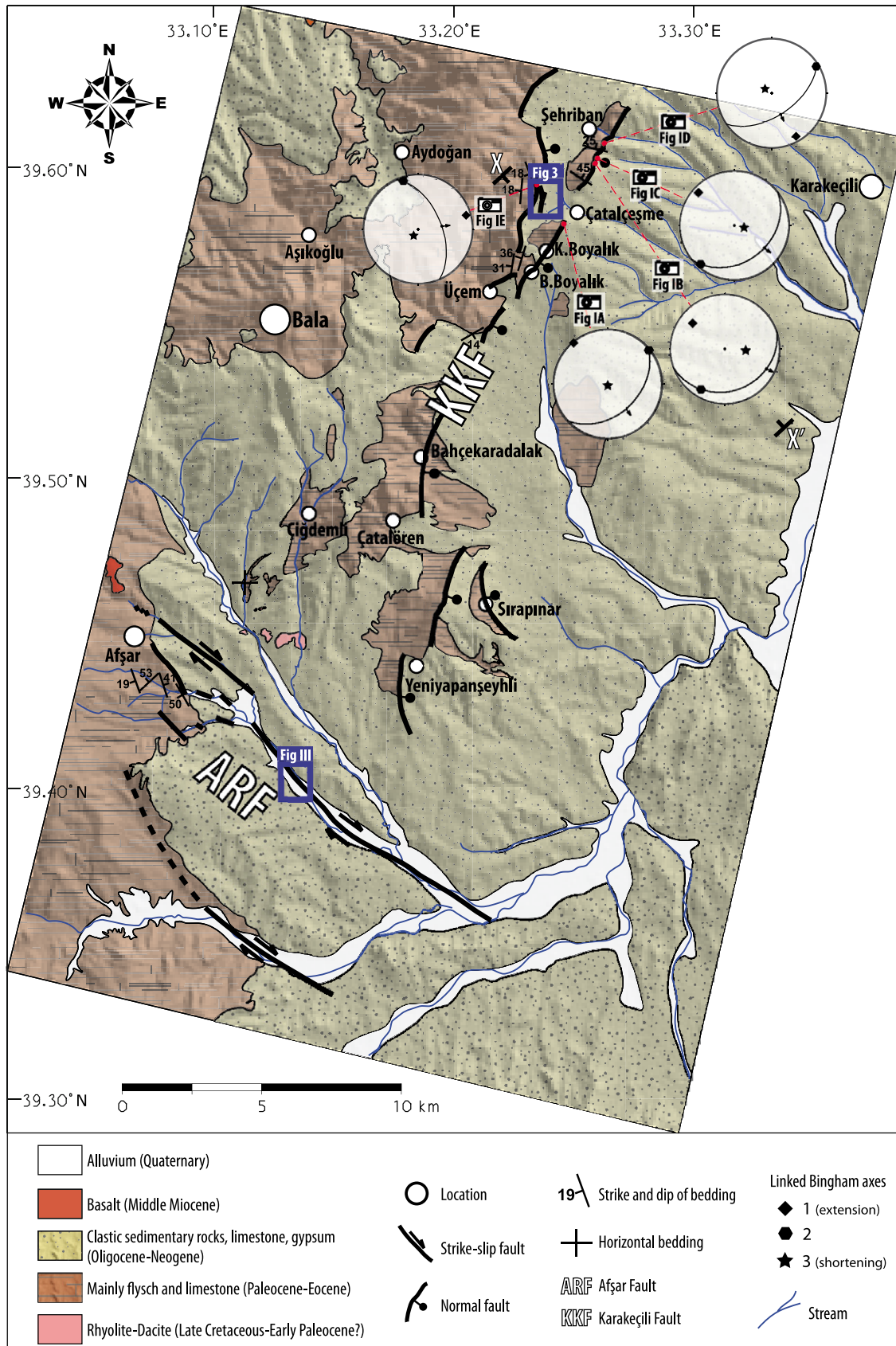
The ARF has a right lateral strike-slip character and it is composed of many segments. The fault traces/surfaces cannot be easily recognized in the field because of intense agricultural overprint. However, the existence of the fault can be determined by careful reconnaissance in the field and by the use of satellite images. Most of the NW-trending segments of the ARF cause a variable right lateral displacement on the stream channels (Fig. 2; Fig. 5A, B). After the 2007 main shock, observations on the graveyard wall of Afşar town provided evidence of subsidiary strike-slip shear fractures. Using these fractures, the trend of the master fault can be estimated as N25°W, which is compatible with the en echelon fault segments determined by the deviations of the stream channels in the north of Afşar (Fig. 5C; Fig. 6). These deviations are coherent with the aftershock distribution towards the SE of Afşar. To test the trend of the master fault estimated from the subsidiary fractures on the graveyard wall, a seismic reflection study has been performed based on the morphological expression of the NW trending stream channels (Fig. III, Appendix). In the Üç Ağıl seismic reflection section (Fig. 7A, B), the trace of the ARF is imaged just under the stream (Fig. III). A typical positive flower structure is observed because the seismic section passes near the end of the segment that shifts toward NE, creating a local restraining stepover (Fig. III).

## SEISMICITY

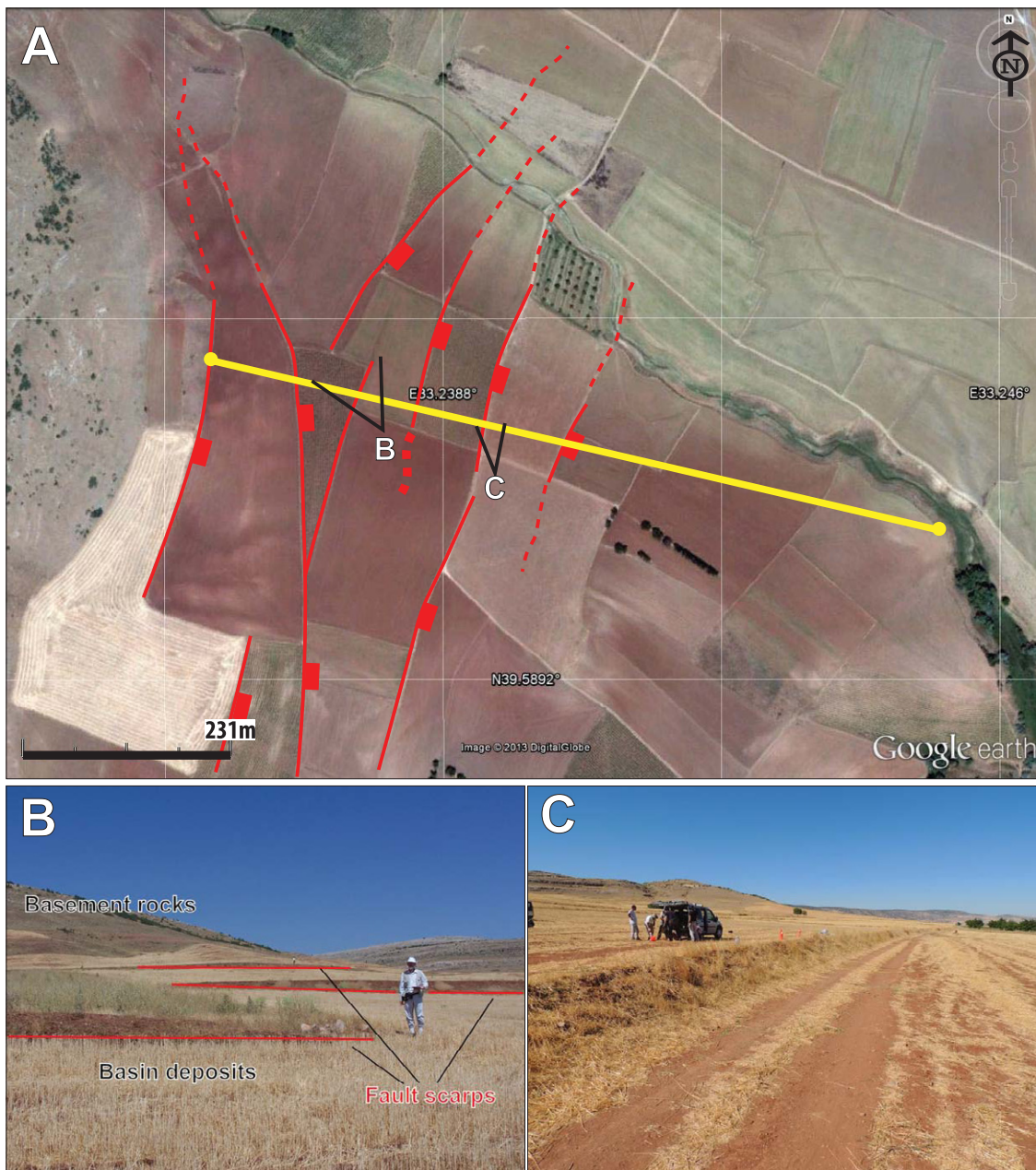
Three significant earthquakes affected Ankara during the historical period (after 1900AD). The first one ( $I_0=IX$ ) occurred in an uncertain location among the cities of Ankara, Çankırı, and Çorum in AD 109 (Soysal *et al.*, 1981). The other two occurred near the city of Ankara on 12 and 15 August 1668. The city center and the Beypazarı town were greatly damaged by these earthquakes (Ambraseys and Finkel, 1995).

In the instrumental period, a considerable number of earthquakes have occurred in central Anatolia affecting Ankara and its vicinity. Some larger than  $M>5.5$  were: the 9 March 1902 Çankırı earthquake ( $M_s=5.6$ ,  $I_0=IX$ ); the 19 April 1938 Kırşehir earthquake ( $M_w=6.4$ ,  $I_0=IX$ ); the 1 February 1944 Gerece (Bolu) earthquake ( $M_w=6.8$ ,  $I_0=X$ ); the 13 August 1951 Kurşunlu (Çankırı) earthquake ( $M_w=6.6$ ,  $I_0=IX$ ); the 7 September 1953 Çerkeş (Çankırı) earthquake ( $M_w=6.0$ ,  $I_0=VII$ ); and the 6 June 2000 Orta (Çankırı) earthquake ( $M_w=6.0$ ).

The Bala region, 50km to the SE of Ankara (Fig. 1), was seismically less active until July 2005, with only small



**FIGURE 2.** Geological map of the Bala area. White circles show the lower hemisphere equal-area stereographic projections of the fault planes. The map is based on our field observations, the ASTER satellite image, and geological maps in Erol (1954) and Akçay *et al.* (2008).



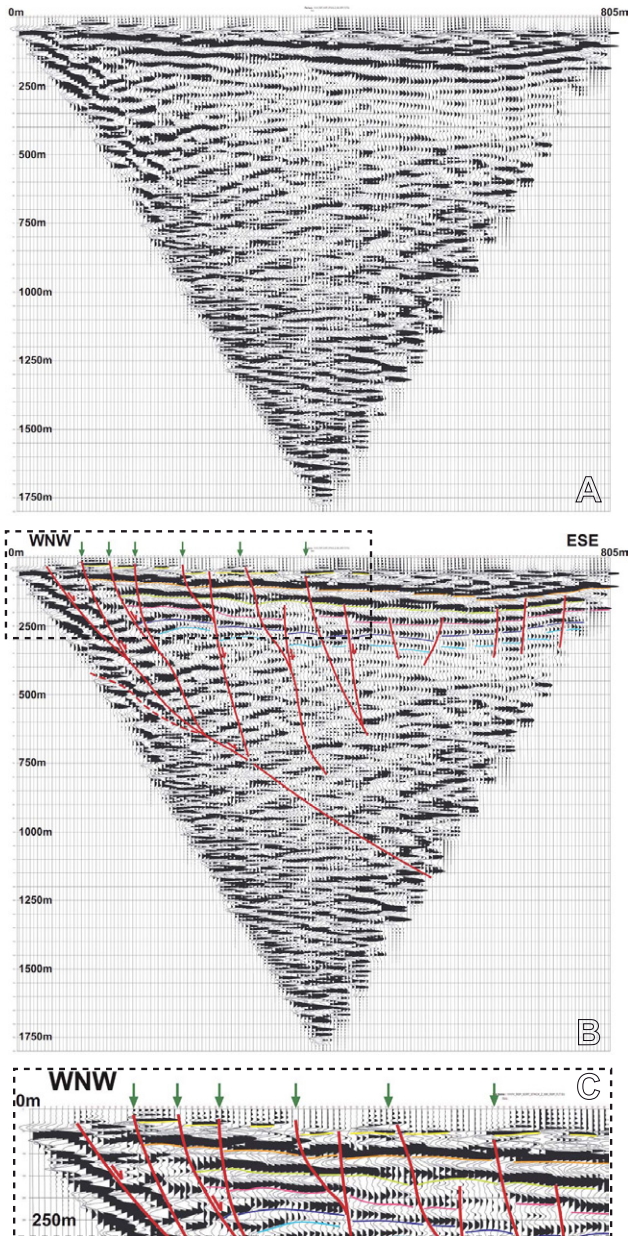
**FIGURE 3.** A) Detailed map of normal fault traces of the Karakeçili fault. Red lines represent the actual fault scarps within the Quaternary (?) units and yellow line shows the location of a seismic reflection study on the KKF. B) Field photo of the normal fault scarps. C) Normal fault scarp and trace of the seismic reflection profile. See Figure 2 for location.

earthquakes of magnitudes  $M < 5$  (Fig. IVA). The largest events were the 4 July 1978 ( $M_b = 4.9$ ) and 21 April 1983 ( $M_w = 4.7$ ) earthquakes. No seismic activity was observed in the region between April 1983 and July 2005.

An earthquake with a magnitude of  $M_w = 5.3$  occurred at a depth of about 6 km near the town of Bala on 30 July 2005 (21:45:0.96 UTC). Following the main shock, a number of aftershocks were observed in the region (Fig. IVB). Fig. VA shows the aftershock distribution within one month after the main shock. The focal parameters of

the main shock and of the largest aftershocks are given in Table 1.

After the 30 July 2005 earthquake a project was launched in January 2007 by the Tectonics Research Group of Ankara University, to investigate the internal deformation of the Anatolian Plate around Ankara. Within the scope of this project, the Earthquake Monitoring Network of Ankara University (AnkNET) was established in September 2007 to record the earthquake activity around Ankara (Fig. 1). It consists



**FIGURE 4.** Çatalçeşme seismic reflection section on the KKF. A) Uninterpreted. B) Interpreted (green arrows represent Quaternary (?) fault scarps' locations); red lines represent the faults. C) Close up view of the area within the frame in B.

of six Güralp 6TD broad-band type seismometers (Seyitoğlu *et al.*, 2009b).

A large event of  $M_w=5.4$  occurred in the Bala region on 20 December 2007 (UTC: 09:48:28.17). Six days later, on 26 December 2007 (UTC: 23:47:09.39), a large aftershock ( $M_w=5.3$ ) shook the region. A time histogram of the events following the 20 December 2007 main shock is shown in Fig. VB. Some large aftershocks that occurred after the 20 December 2007 main shock are given in Table 1.

## Location and re-location process

The waveform data for the 30 July 2005 earthquake and its aftershocks were obtained from the Kandilli Observatory and Earthquake Research Institute of Turkey (KOERI). Nearly 100 events, recorded in high quality by at least 5 stations, were selected from almost 320, and all P and S phases were re-picked before the relocation process. The data of the 20 December 2007 earthquake and its aftershock were collected by the AnKNET. 593 well recorded events were selected for phase picking.

The initial location of all events was performed using the double-difference hypocenter location method developed by Waldhauser and Ellsworth (2000) using the HYPODD algorithm of Waldhauser (2001). In the initial location processes, we used a simple P- and S-wave velocity model (Toksöz *et al.*, 2003) corresponding to the central Anatolian crustal structure. Çıvgın and Kaypak (2012) estimated a new 1D velocity model for the region by using these initial locations and 2955 P- and S-seismic wave phases. This new model (Table 2) was used for relocation of the events.

The main shock location and aftershock distribution for the 30 July 2005 and 20 December 2007 earthquakes are shown in Fig. 8A and Fig. 9A, respectively. The aftershock distribution of the 30 July 2005 earthquake has a NNE-SSW trend on the KKF (Fig. 8A), the epicentral locations of the 20 December 2007 earthquake and its aftershocks have a NW-SE trend on the ARF (Fig. 9A).

## Depth sections

The aftershock hypocenters of the 2005 main shock are distributed in the upper 35km and they are concentrated in the upper 10km (Fig. 8B). However, the earthquakes in the NE of the region are mostly below 10km depth (Fig. 8B, A-A' and D-D' sections). It can be interpreted that the KKF has an E-SE dipping geometry based on the distribution in the D-D' section which is perpendicular to it (Fig. 8B).

On the other hand, almost all aftershocks hypocenters of the 2007 main shock are above 12km depth (Fig. 9B). The depth sections perpendicular to the ARF show that the hypocenters are aligned in a narrow zone of about 4km (Fig. 9B, F-F' and G-G' sections). This aftershock distribution is compatible with the strike-slip nature of ARF.

## Focal mechanism solutions

Focal mechanism solutions for both main shocks and their significant aftershocks were determined by a full waveform moment tensor inversion method which was

**TABLE 1.** Parameters of the focal mechanism solutions related to the Afşar and Karakeçili Faults. Solution of the 04.07.1978 ( $M_b=4.9$ ) earthquake is provided by Kocafe and Ataman (1982). Solutions of the 30.07.2005 ( $M_w=5.3$ ) and the 20.12.2007 ( $M_w=5.4$ ) Bala earthquakes and their large aftershocks are provided by this study

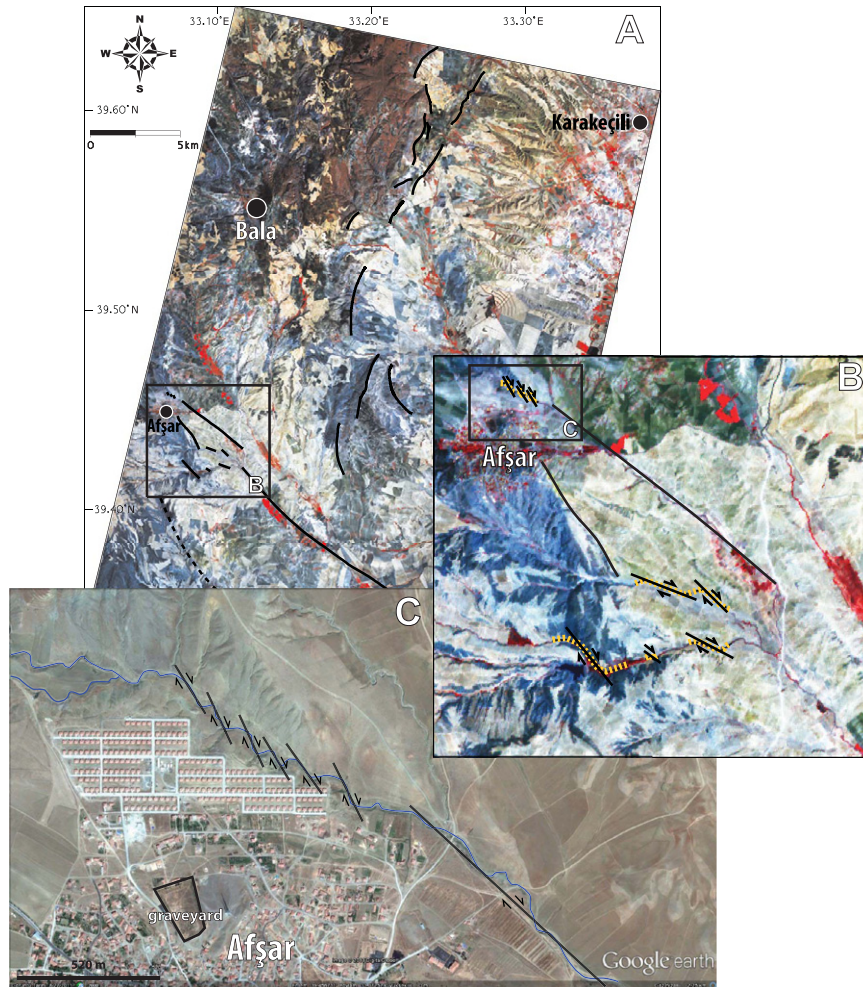
N°	Date (dd/mm/yy)	Time (UTC)	Latitude N (°)	Longitude E (°)	Depth (km)	Magnitude	Nodal Planes			P		T	
							Strike1(°) Strike2(°)	Dip1(°) Dip2(°)	Rake1(°) Rake2(°)	Azimuth (°)	Plunge (°)	Azimuth (°)	Plunge (°)
1	04/07/78	22:39:16	39.450	33.190	23	4.9 (Mb)	303 186	66 44	-129 -36	167	54	59	13
2	30/07/05	21:45:01	39.4061	33.1384	6.391	5.3 (Mw)	301 207	70 80	-169 -21	162	22	255	7
3	31/07/05	00:14:48	39.4213	33.1497	10.869	3.2 (M <sub>D</sub> )	343 180	61 30	-98 -75	223	73	79	16
4	31/07/05	00:45:14	39.4141	33.1392	6.463	3.9 (Mw)	129 278	48 47	-68 -113	112	74	204	0
5	31/07/05	01:09:21	39.4358	33.1515	5.149	3.3 (M <sub>D</sub> )	57 217	56 34	-79 -107	1	75	139	11
6	31/07/05	15:18:19	39.4370	33.0570	17.6	4.5 (Mw)	212 304	79 78	-12 -168	168	16	258	0
7	31/07/05	15:23:25	39.4240	33.0530	12.2	4.1 (Mw)	296 205	87 73	-163 -4	162	14	70	9
8	31/07/05	23:41:35	39.3897	33.1146	8.258	4.6 (Mw)	285 177	66 55	-141 -30	145	44	49	7
9	01/08/05	00:45:07	39.4062	33.0885	12.182	4.4 (Mw)	96 2	85 46	-136 -6	329	33	221	26
10	06/08/05	09:09:27	39.352	33.103	6.8	4.2 (Mw)	282 187	82 64	-154 -9	148	24	52	12
11	20/12/07	07:36:49	39.4123	33.0807	3.799	3.6 (Mw)	138 47	87 67	-157 -4	5	18	270	13
12	20/12/07	09:48:28	39.4107	33.0942	3.963	5.4 (Mw)	113 22	85 79	-169 -5	338	11	247	4
13	21/12/07	21:44:49	39.3997	33.1271	5.42	3.0 (Mw)	177 280	70 59	-33 -156	135	37	230	7
14	26/12/07	23:47:09	39.4135	33.0803	4.516	5.3 (Mw)	154 54	65 70	-158 -27	13	33	105	3
15	27/12/07	07:47:01	39.4550	33.0470	5.073	4.3 (Mw)	157 248	81 88	178 9	22	5	113	8
16	27/12/07	13:47:58	39.4398	33.0640	5.064	4.4 (Mw)	25 174	44 50	-67 -111	21	74	279	3
17	27/12/07	17:56:12	39.4039	33.1035	6.042	3.7 (Mw)	24 143	48 62	-40 -130	2	54	261	8
18	11/01/08	16:07:49	39.4406	33.0454	7.583	3.5 (Mw)	145 46	70 66	-154 -22	6	32	275	3

developed and extended to full waveform data at regional or local distances by Zahradnik *et al.* (2005), based on Kikuchi and Kanamori (1991). For the computation of the earthquake source parameters, we used MATLAB based software called ISOLA-GUI, developed by Sokos and Zahradnik (2008). During the waveform inversion, the same one-dimensional velocity model was used for all focal mechanism solutions.

The focal mechanism solutions of the 2005 and the 2007 earthquakes and of their large aftershocks are shown in Figure 8A and Figure 9A, respectively. Their source parameters are summarized in Table 1. Besides, the focal mechanism solution of the 4 July 1978 ( $M_b=4.9$ ) earthquake obtained from P-wave first motion polarities by Kocafe and Ataman (1982) is given in Figure 8A and Table 1. This event is located on the KKF and indicates oblique-slip normal faulting (Fig. 8A; Table 1).

## FAULT SLIP ANALYSIS

Fault slip data obtained from nodal planes of the focal mechanism solutions and from field observations in the Bala region have been analysed (Table 3). One of the two nodal planes of each focal mechanism solutions has been selected as the actual fault, based on the observation of fault orientations in the field. FaultKin software was used for the analysis (see Marrett and Allmendinger (1990); Rowland *et al.* (2007) for theoretical background of kinematic compatibility). The analysis of the overall data shows that the shortening axis is almost vertical and the extension axis is nearly horizontal. Linked Bingham axes represent these strain axes. According to this strain orientation, the extension axis indicates an extension direction of N81°E in the region (Fig. 10A). Moreover, the uniform direction of the contoured diagrams of the shortening (P) and the extension (T) axes shows that the faults (KKF and ARF) are kinematically compatible (Fig. 10B, C).

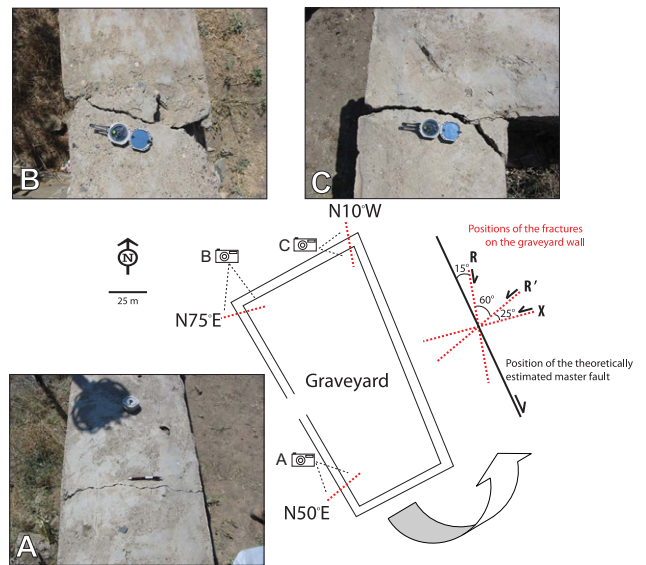


**FIGURE 5.** A) ASTER satellite image of the study area. The black lines represent faults. B) Close up view of the Afşar area; the arrows show displacement directions of the streams. C) Google Earth satellite image; systematic right lateral displacements of the stream are observed north of the graveyard.

**DISCUSSION AND CONCLUSIONS**

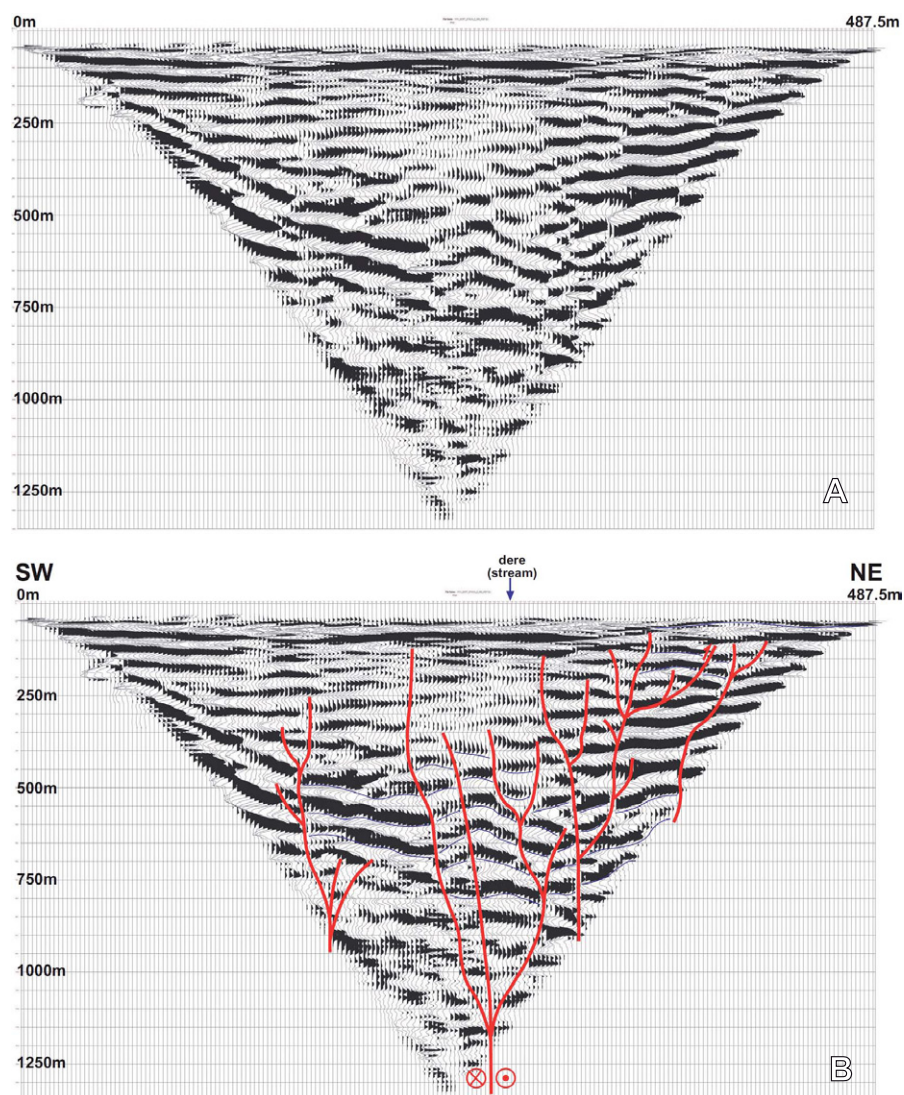
After the main shock on 30 July 2005 through 2009, earthquake clusters with NNE-SSW and NW-SE directions have been recorded. The aftershocks from the 30 July 2005 main shock have a NNE-SSW direction (Fig. IVB; Fig. 8A), and the 20 December 2007 main shock and its aftershocks have a NW-SE trend (Fig. IVC; Fig. 9A). These clusters led some researchers to suggest right and left lateral strike-slip conjugate faults are active in the Bala region (Dirik *et al.*, 2008; Kalafat *et al.*, 2008; Çubuk and Taymaz, 2009; Koçyiğit, 2009; Tan *et al.*, 2010). On the other hand, after the field observations following the 30 July 2005 main shock, Kasapoğlu *et al.* (2005) reported that the earthquake was related to normal faults with a small component of left lateral strike-slip.

The main earthquake and aftershock relocations as well as focal mechanism solutions, together with new



**FIGURE 6.** Earthquake displacements of the graveyard wall in Afşar town. See text for explanation.



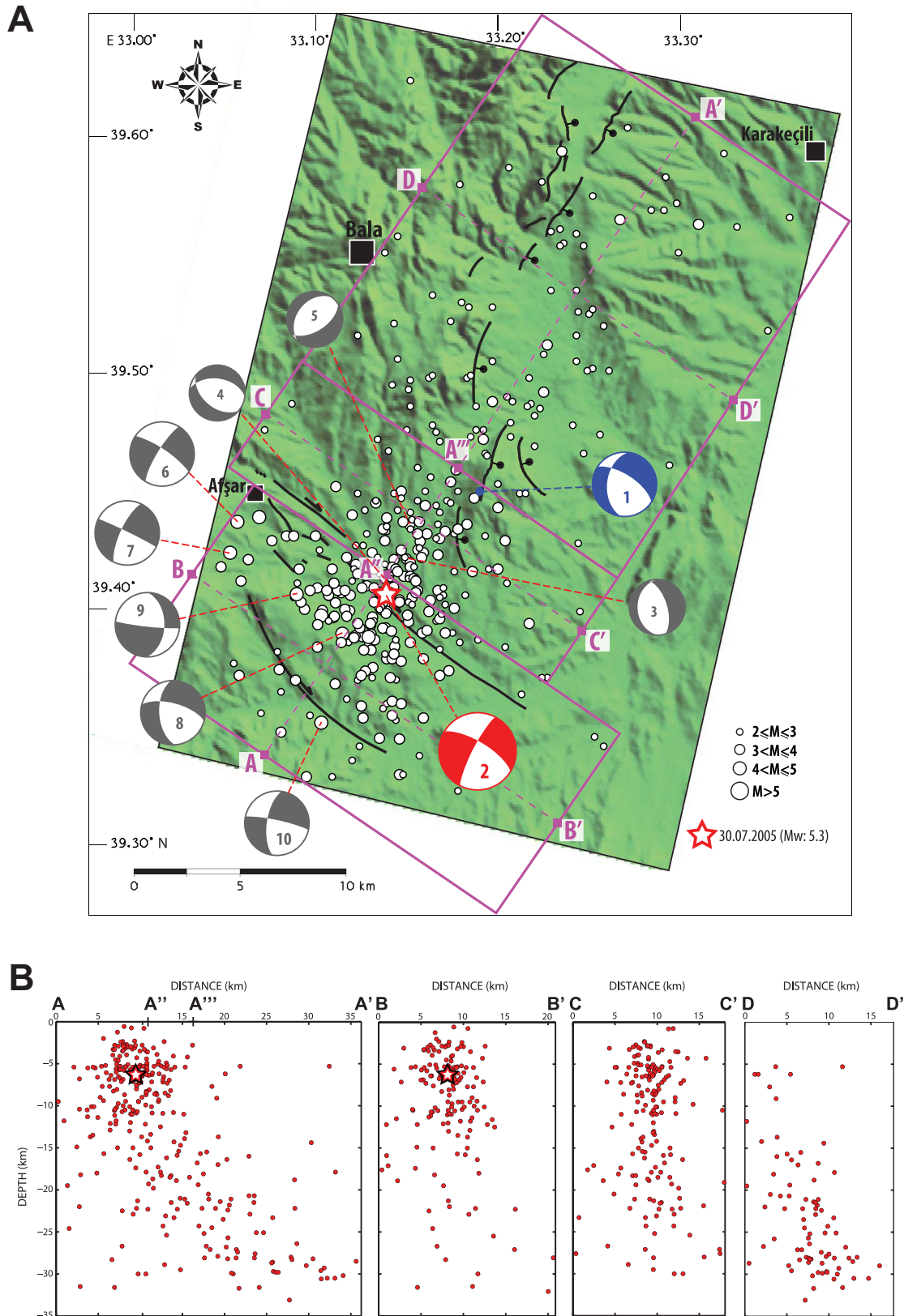


**FIGURE 7.** Üç Ağıl seismic reflection section on the Afşar fault. A) Uninterpreted. B) Interpreted. Red lines represent faults.

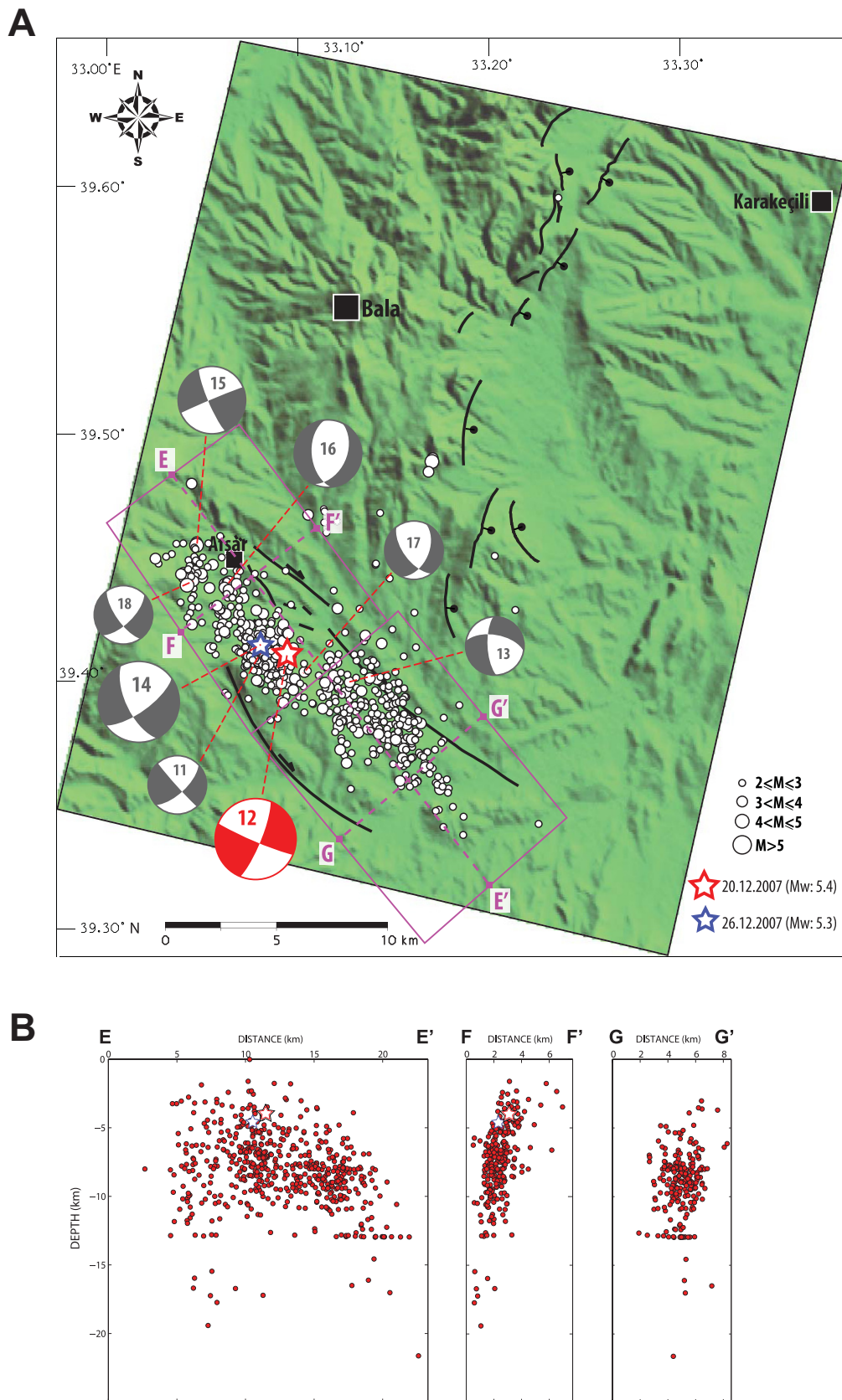
detailed geological observations and seismic reflection studies, lead us to a different interpretation of the Bala earthquakes. We suggest that the main shocks of both the 2005 and the 2007 events occurred on the same right lateral strike-slip fault, the ARF, as shown by the identical fault mechanism solutions having a  $N59^{\circ}W$  trending fault plane. The aftershock distribution of the 2005 main shock and some of the focal mechanism solutions indicate that the normal faulting corresponds with the NNE trending of the Karakeçili fault (KKF). We infer that the 2005 main shock triggered the seismic activity on the KKF. It can be concluded that the northwestern tip of the Tuzgölü fault zone represented by the Afşar fault, is terminated by an extensional system corresponding to the oblique-normal fault segments of the KKF in a similar fashion to the model for strike-slip fault terminations proposed by Kingma (1958) (Fig. 11).

**TABLE 2.** Crustal 1D velocity model used in relocation (Çıvgın and Kaypak, 2012)

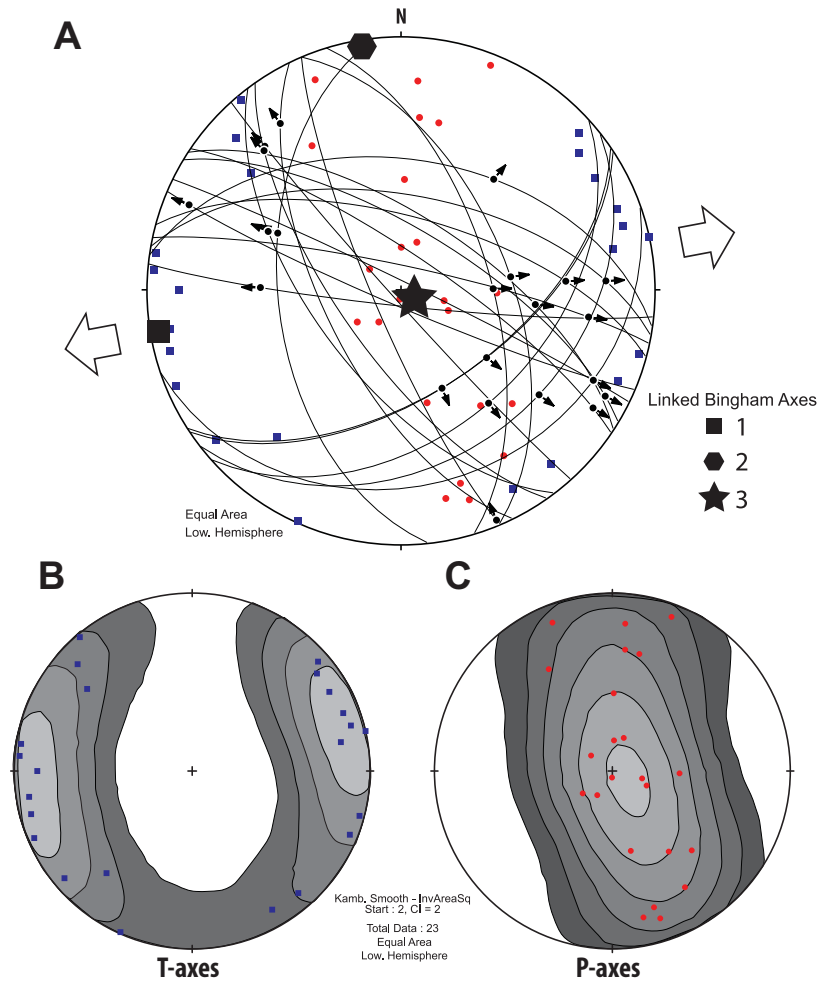
Depth of layer boundaries (km)	$V_p$ (km/s)	$V_s$ (km/s)
00.0 – 08.0	5.25	3.02
08.0 – 13.0	5.82	3.38
13.0 – 19.0	6.06	3.48
19.0 – 30.0	6.15	3.48
30.0 – 31.0	6.47	3.75
31.0 – 32.0	6.53	3.78
32.0 – 33.0	6.55	3.79
33.0 – 34.0	6.69	3.89
34.0 – 35.0	6.73	3.91
35.0 – 36.0	6.85	3.99
36.0 – ...	7.10	4.08



**FIGURE 8.** A) The earthquake activity between 30 July 2005 and 31 August 2005. See Table 1 for the focal mechanism solutions. The epicenter locations were re-calculated using data from the Kandilli Observatory and Earthquake Research Institute of Turkey's catalogue. B) Earthquake depth sections. See A for the section line.



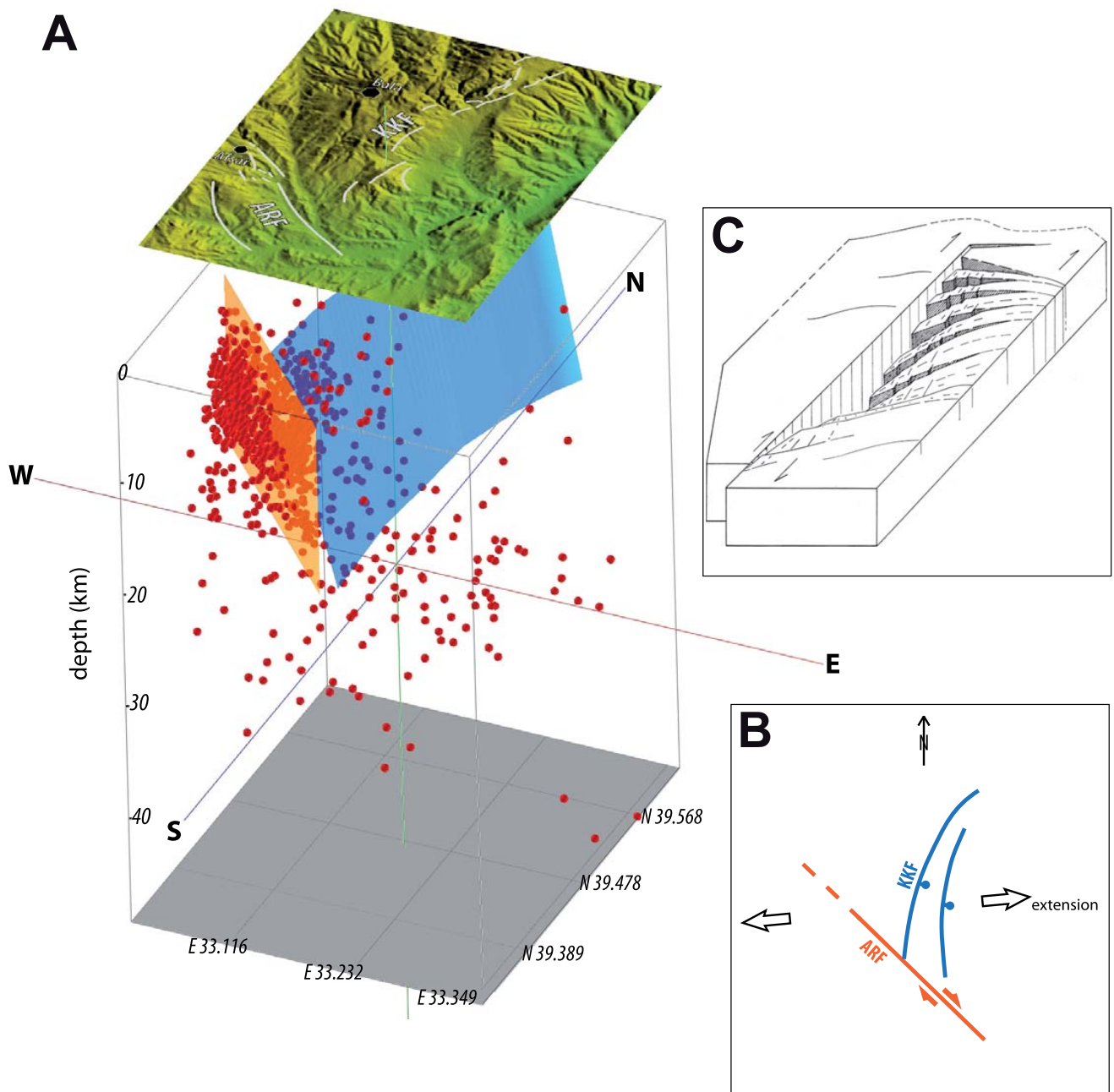
**FIGURE 9.** A) The main shock and its aftershocks recorded by AnketNet from 20 December 2007 to 10 October 2008. See Table 1 for the focal mechanism solutions. B) Earthquake depth sections. See A for the section lines.



**FIGURE 10.** A) Analysis of fault slip data. The linked Bingham axes are 1: 4°/261° (extension axis); 2: 3°/351°; 3: 85°/118° (shortening axis) (plunge/trend). Contoured diagrams of B) the extension axes and C) the shortening axes.

**TABLE 3.** Fault kinematic data obtained from nodal planes of the focal mechanism solutions and from field observations related to the Afşar and Karakeçili Faults in the Bala region (planes are displayed using the right-hand rule)

N°	Fault plane		Striae		Sense of slip	
	Strike(°)	Dip(°)	Trend(°)	Plunge(°)		
1	303	66	96	45	Normal	Focal mechanism solution data (see Fig. 8; Fig. 9; Table 1 for the locations)
2	301	70	117	10	Normal	
3	343	61	89	60	Normal	
4	278	47	40	42	Normal	
5	57	56	128	54	Normal	
6	304	78	122	12	Normal	
7	296	87	115	17	Normal	
8	285	66	87	35	Normal	
9	96	85	271	44	Normal	
10	282	82	98	26	Normal	
11	138	87	317	23	Normal	
12	113	85	292	11	Normal	
13	280	59	87	20	Normal	
14	154	65	324	20	Normal	
15	157	81	157	2	Reverse	
16	174	50	295	46	Normal	
17	143	62	294	43	Normal	
18	145	70	316	24	Normal	
Fig. IA	48	43	142	43	Normal	Field data (see Fig. 2 for the locations)
Fig. IB	71	24	115	17	Normal	
Fig. IC	52	33	127	32	Normal	
Fig. ID	56	56	157	56	Normal	
Fig. IE	337	55	83	54	Normal	



**FIGURE 11.** A) 3D perspective view of the proposed model. Red spheres show the earthquake hypocenters; orange and blue planes represent the approximate position of the ARF and KKF, respectively. B) Simplified map view of the model. KKF: Karakeçili fault, ARF: Afşar fault. C) Model for normal faulting at strike-slip fault-terminations after Kingma (1958).

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# APPENDIX I

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## Seismic Data Acquisition

Seismic Equipment: Geometrics with 4 Geodes (96 channels).  
14Hz vertical geophones.

Seismic Source: P-Gun with 36 fusels.

Source-Receiver Design: Walk-Away (Roll-Along the Cable)  
technique.

Number of Shots: Lines: Çatalçeşme (KKF): 17, Üç Ağıl (ARF):  
21 shots.

Number of Receivers: Lines: Çatalçeşme (KKF): 82, Üç Ağıl  
(ARF): 96 geophones.

Shot Interval: Lines: Çatalçeşme (KKF): 50, Üç Ağıl (ARF): 25  
meters.

Receiver Interval: Lines: Çatalçeşme (KKF): 10, Üç Ağıl (ARF):  
5 meters.

Sampling Interval: Lines: Çatalçeşme (KKF): 1, Üç Ağıl (ARF):  
0.5 milliseconds.

Recording Time: Lines: Çatalçeşme (KKF): 4, Üç Ağıl (ARF):  
2 seconds.

## Seismic Data Processing

Software: W\_Geosoft Visual\_SUNT v6.6.6. The processing  
sequences are:

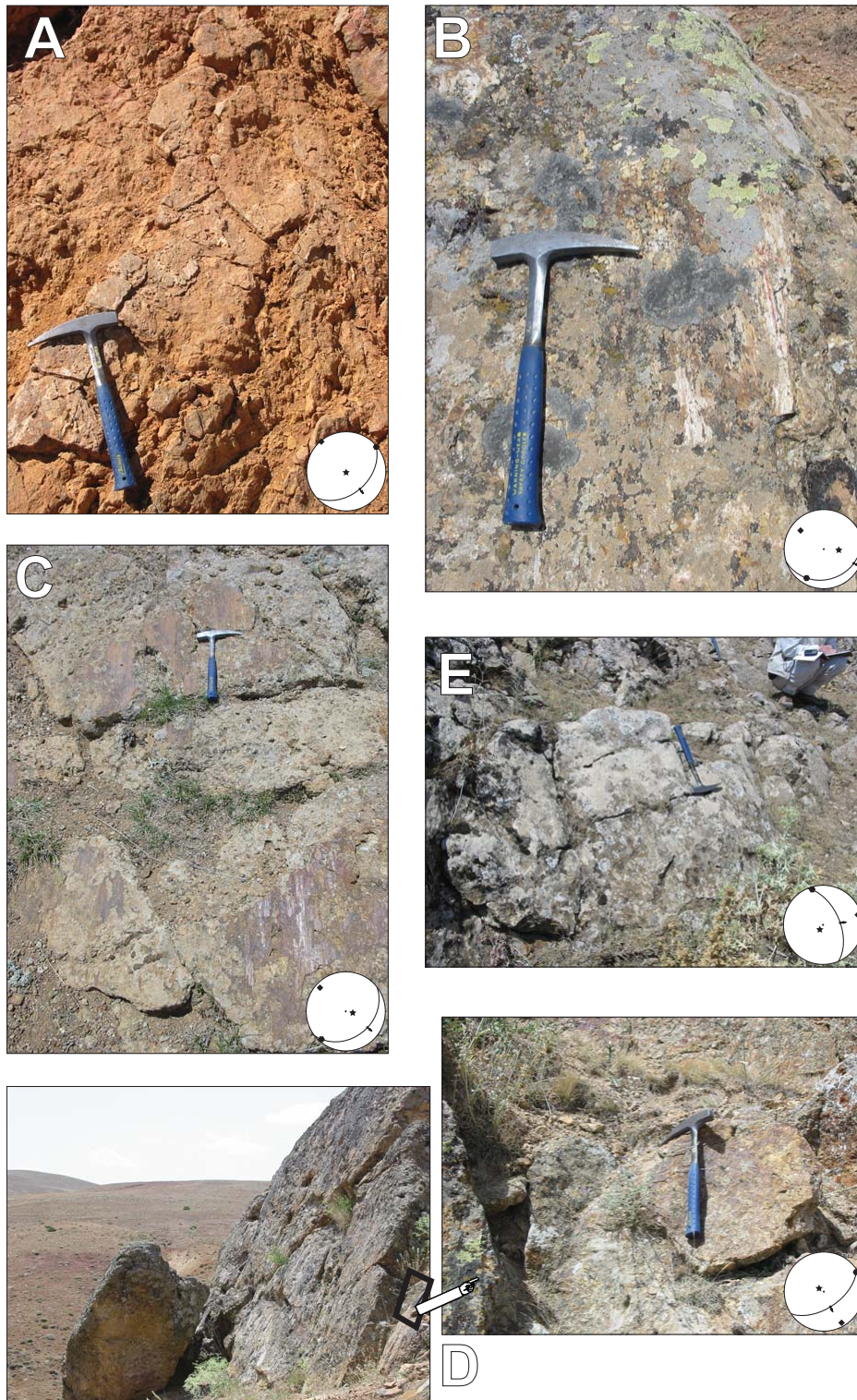
- 1) Geometry Definition
- 2) Static Correction (Elevation)
- 3) Filter (Trapezoidal: 1, 5, 90, 100 Hertz)
- 4) Gain (AGC: Window: 0.5 seconds)
- 5) Trace Edit
- 6) First-Break Mute
- 7) Ground-Roll Mute
- 8) Sort (Major Key: CDP, Minor Key: Signed-Offset)
- 9) Velocity Analysis (at 6 CDP Stations)
- 10) Stack
- 11) Time-to-Depth Conversion
- 12) Lateral Smoothing (Weights: 0.25, 0.5, 1, 0.5, 0.25)



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## ELECTRONIC APPENDIX

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**FIGURE I.** Photographs from the Karakeçili fault surfaces. The lithologies are limestone (A and E) and conglomerate (B, C, and D). White circles show the lower hemisphere equal-area stereographic projections of the fault planes. See Figure 2 for the locations.

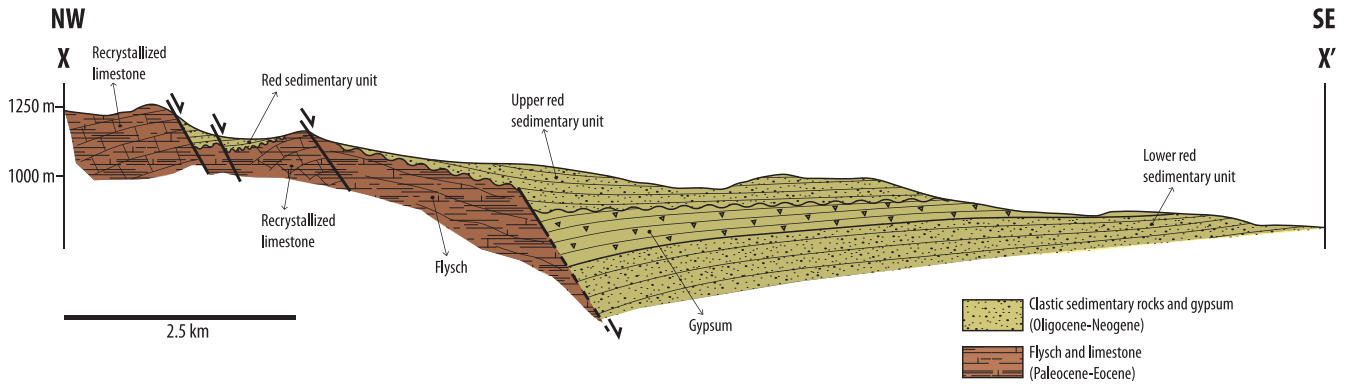


FIGURE II. Geological cross-section showing the inner structure of the Karakeçili Neogene-Quaternary basin. See Figure 2 for the cross-section line.

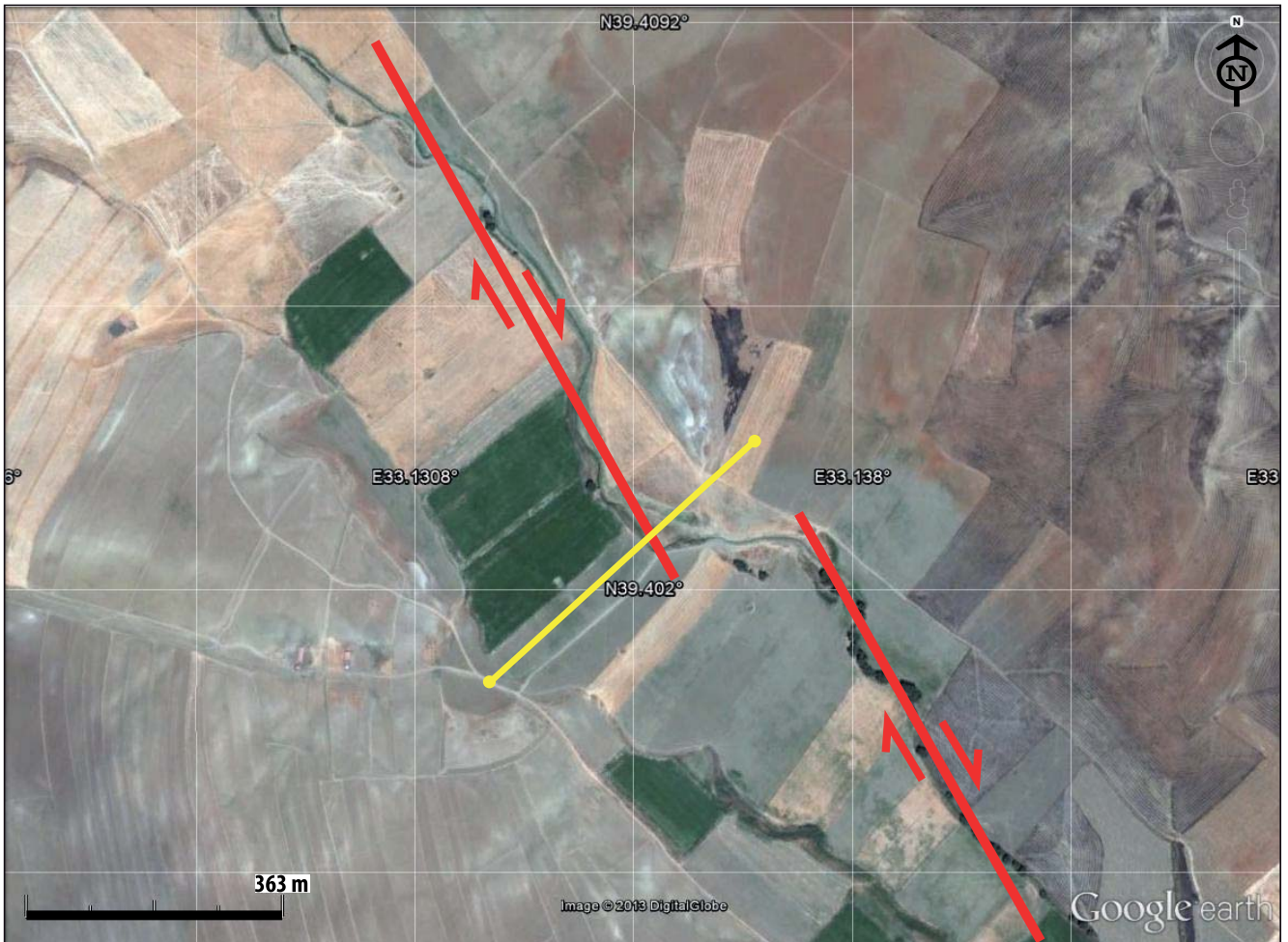


FIGURE III Local restraining stepover of the Afşar fault (red lines) and the Üç Ağıl seismic reflection line (yellow). See Figure 2 for the location.

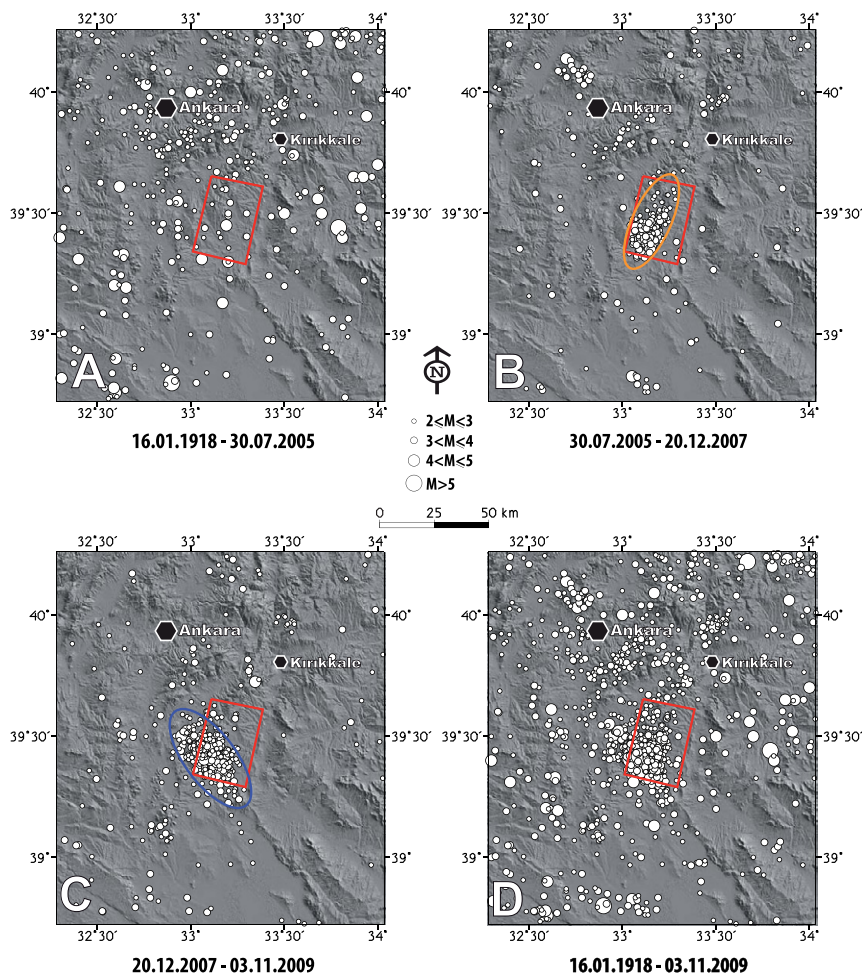


FIGURE IV. The earthquake activity between 16 January 1918 and 03 November 2009. The red frame shows the study area. The ellipses represent the earthquake clustering. Earthquake data were obtained from the Kandilli Observatory and Earthquake Research Institute of Turkey's catalogue.

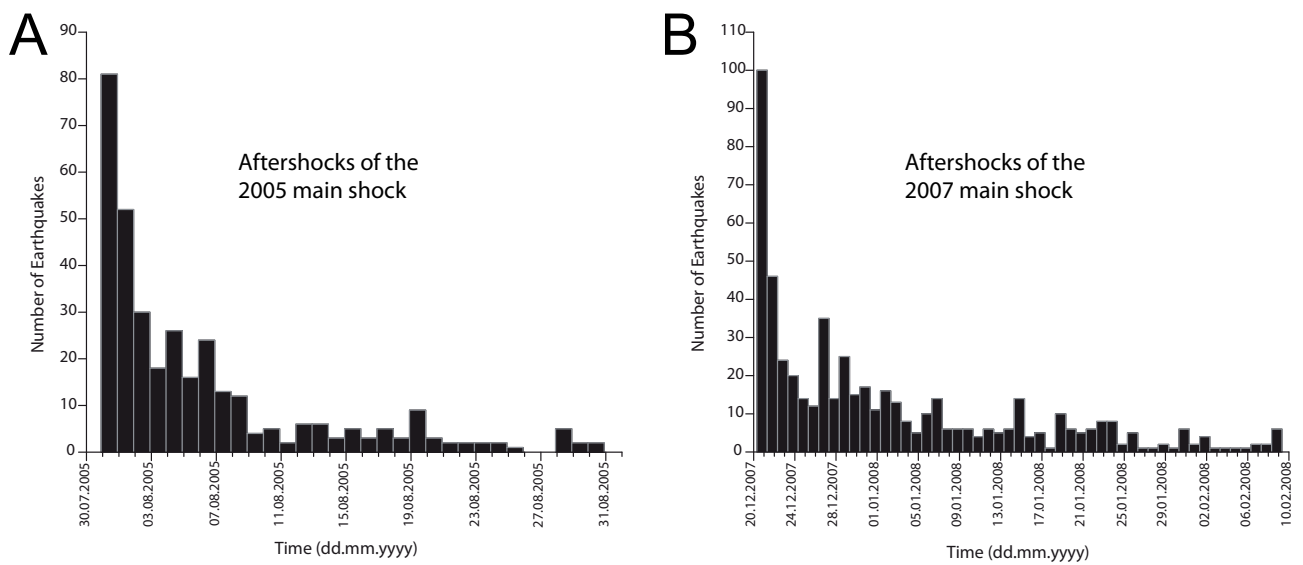


FIGURE V. Histograms showing the number and distribution of aftershocks after the A) 2005 main shock and B) 2007 main shock.