



## A hypothesis for the alternative southern branch of the North Anatolian Fault Zone, Northwest Turkey

*KB Türkiye’de Kuzey Anadolu Fay Zonu’nun alternatif Güney Kol’u için bir hipotez*

**Gürol SEYİTOĞLU<sup>1\*</sup>, Bülent KAYPAK<sup>2</sup>, Bahadır AKTUĞ<sup>2</sup>, Esra GÜRBÜZ<sup>3</sup>, Korhan ESAT<sup>1</sup>, Alper GÜRBÜZ<sup>4</sup>**

<sup>1</sup>Ankara Üniversitesi, Jeoloji Müh. Bl., Tektonik Araştırma Grubu, Tandoğan, Ankara  
(e-mail: seyitoglu@ankara.edu.tr)

<sup>2</sup>Ankara Üniversitesi, Jeofizik Müh. Bl., Gölbaşı, Ankara

<sup>3</sup>Aksaray Üniversitesi, Jeoloji Müh. Bl., Aksaray

<sup>4</sup>Niğde Üniversitesi, Jeoloji Müh. Bl., Niğde

\* Corresponding author: Tel: 90 312 203 3370, Fax: 90 312 215 0487

### ABSTRACT

This paper proposes an alternative route for the southern branch of the North Anatolian Fault Zone (NAFZ) using evidence from morphotectonic features, seismology, GPS and recently published Magnetotelluric and Transient Electromagnetic (MT) data. In this new route, the southern branch connects with the main branch of the NAFZ in Bolu via the Gölpaazarı pull-apart basin and Mudurnu. The slip distribution of the NAFZ as taken from GPS data indicates that the newly hypothesized route is the second most important branch of the NAFZ.

**Keywords:** Earthquake, GPS, Neotectonics, North Anatolian Fault Zone, Turkey

### ÖZ

*Bu makale morfolotektonik özellikleri, sismoloji, GPS ve MT verilerini kullanarak Kuzey Anadolu Fay Zonu'nun (KAFZ) güney kol'u için alternatif bir güzergah önermektedir. Bu yeni güzergahta güney kol, KAFZ'nun ana koluna Gölpaazarı çek-ayır havzası ve Mudurnu üzerinden geçerek Bolu'da bağlanmaktadır. GPS verilerinden hesaplanan KAFZ'nundaki kayma dağılımı, yeni önerilen güzergahın KAFZ'nun Marmara'daki ikinci önemli kolu olduğunu göstermektedir.*

**Anahtar Kelimeler:** Deprem, GPS, neotektonik, Kuzey Anadolu Fay Zonu, Türkiye

## INTRODUCTION

The North Anatolian Fault Zone (NAFZ) is composed of a series of right lateral strike-slip segments (Ketin, 1948) extending from eastern Anatolia to the northern Aegean Sea and it constitutes one of the main neotectonic elements in the eastern Mediterranean (McKenzie, 1972) (Figure 1a). The NAFZ has been active since the Late Miocene time and has an estimated offset of 25-85 km (Seymen, 1975; Şengör, 1979; Barka, 1992). This long term slip rate appears to agree with the current slip rate measured as 17-26 mm/yr by GPS data (Barka and Reilinger, 1997; Reilinger et al., 2006). The middle and easternmost parts of North Anatolian Fault Zone have been studied separately with GPS measurements, middle part (Yavaşoğlu et al., 2011), eastern part (Tatar et al., 2012) and Yedisu segment (Özener et al., 2010; Aktuğ et al., 2013a). Very recently, a complete GPS analysis of both the middle and easternmost parts of North Anatolian Fault Zone, including the continuous GPS stations, was given in (Aktuğ et al., 2015). The latter particularly deserves attention since it incorporates all the available GPS data used in earlier studies and presents a comparative analysis of GPS, inSAR and geological estimates in the literature.

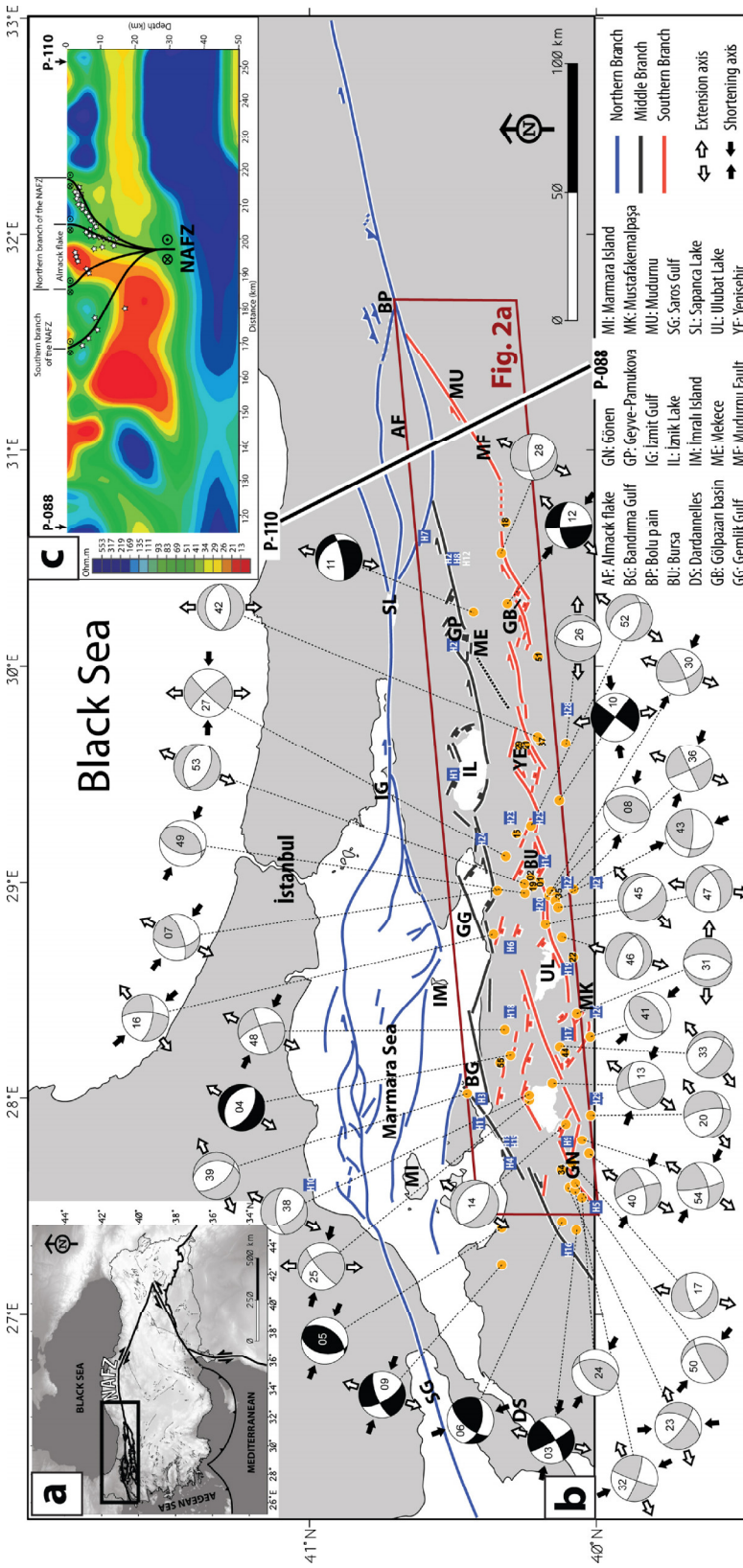
The eastern sector of the NAFZ is limited to a narrow zone, but widens to the west (Şengör et al., 2005) where shear is distributed along three major branches (Figure 1b). The northern branch passes through Lake Sapanca, the İzmit Gulf, the Marmara Sea and the Saros Gulf. The middle

branch is separated from the Almacık flake and passes through Geyve - Pamukova, Lake İzmit, and the Gemlik Gulf before turning southwest in the Bandırma Gulf. The northeast end of the southern branch has previously been thought to diverge from the middle branch via Mekece before continuing southwest through Yenişehir, Bursa, south of Lake Ulubat, Mustafakemalpaşa and eventually turning southwest around Gönen (Figure 1b) (Şengör, 1979; Barka and Kadinsky-Cade, 1988; Koçyiğit, 1988; Barka and Kuşçu, 1996; Emre et al., 1997; Armijo et al., 1999; 2002; Yalıtırak, 2002; Gürer et al., 2003; 2006; Şengör et al., 2005; Kurtuluş and Canbay, 2007; Yılmaz and Koral, 2007; Selim and Tüysüz, 2013; Le Pichon et al., 2014).

A recent active fault map of Turkey, however, considers that the southern branch is connected to the Eskişehir Fault Zone via active normal faulting between Bursa and İnegöl (Emre et al., 2011).

In contrast, the recognition of the Gölpaazarı basin as a pull-apart system (see below), and recently published MT data (Figure 1c) (Kaya, 2010) suggest that the southern branch may extend east through the Gölpaazarı pull-apart basin.

Here, we review the morphotectonic, seismic and MT data and propose a hypothesized new route for the southern branch (Figures 1 and 2a), ultimately representing a nearly 100 km shift of the southern branch of the NAFZ.



**Figure 1.** a) The position of the North Anatolian Fault Zone (NAFZ) in the neotectonic framework of Turkey. b) The NAFZ in northwest Turkey. Blue squares represent the historical seismicity (H). Yellow circles are epicenters of the instrumental period's earthquakes related to the southern branch. Focal mechanism solutions calculated in this paper are marked by grey, and previously published solutions are presented in black. See Table 1 for numbers. Black dotted line indicates the connection of the southern branch to the middle branch of the NAFZ in previous studies (see text). The line between P-088 and P-110 shows the location of MT (Magnetotelluric and Transient Electromagnetic) data from Kaya (2010). Fault lines after (Şengör, 1979; Barka and Kadinsky-Cade, 1988; Barka and Kuşçu, 1996; Emre et al., 1997; Armijo et al., 1999; 2002; Yaltrak, 2002; Şengör et al., 2005; Kurtuluş and Canbay, 2007; Yılmaz and Koral, 2007; Selim and Tüysüz, 2013; Le Pichon et al., 2014). c) Re-evaluated MT section of Kaya (2010) indicating a well developed flower structure of the NAFZ.

**Şekil 1.** a) Türkiye'nin neotektonik çerçevesinde Kuzey Anadolu Fay Zonu'nun (KAFZ) konumu. b) KB Türkiye'de KAFZ. Mavi kareler tarihsel depremleri göstermektedir (H). Sarı daireler Güney kol ile ilgili atelel dönem depremlerin dış merkezlerini göstermektedir. Bu makalede oluşturulan odak mekanizması çözümleri gri ile daha önceki makalelerden alınanlar siyah ile gösterilmiştir. Numaralar için Çizelge 1'e bakınız. Siyah noktalı hat, önceki çalışmalarda KAFZ'nun Orta kolu ile Güney kolu arasındaki bağlantıyı temsil etmektedir (açıklama için metne bakınız). P-088 ile P-110 arasındaki hat, Kaya (2010) tarafından yayınlanan MT verilerinin konumunu göstermektedir. Fay hatları şu çalışmalardan alınmıştır (Şengör, 1979; Barka ve Kadinsky-Cade, 1988; Barka ve Kuşçu, 1996; Emre vd., 1997; Armijo vd., 1999; 2002; Yaltrak, 2002; Şengör vd., 2005; Kurtuluş ve Canbay, 2007; Yılmaz ve Koral, 2007; Selim ve Tüysüz, 2013; Le Pichon vd., 2014). c) Kaya (2010)'a ait MT kesitinin yeniden değerlendirilmesi, KAFZ'nun iyi gelişmiş çiçek yapısını göstermektedir.

## GÖLPAZARI PULL-APART BASIN

The Gölpazarı basin has previously been evaluated as a karstic depression (Ekmekçi and Nazik, 2004) and/or a graben (Çağlar and İşseven, 2004). However, recent publications (Önde and Gürbüz, 2010; Gürbüz and Seyitoğlu, 2014) describe Gölpazarı basin as a 12 km by 4.25 km ideal rhomboidal shaped pull-apart structure. The east northeast - west southwest trending right lateral strike-slip faults create a releasing offset that limits the northwest and southeast margins of the basin, whereas the northeast and southwest margins are bounded by normal faults (Figure 2b). The basin contains only Quaternary deposits  $\geq 300$  m thick, as reported by the State Hydraulic Works (Gürbüz and Seyitoğlu, 2014). The Gölpazarı pull-apart basin is the small-scale equivalent of the adjacent Yenişehir pull-apart system (Yılmaz and Koral, 2007; Gürbüz, 2010), suggesting it is located on the newly hypothesized route of the southern branch of the NAFZ as described in this paper.

## THE ALTERNATIVE ROUTE OF THE SOUTHERN BRANCH

The overall structure of southern Marmara is composed of northeast trending right lateral strike-slip segments and northwest trending normal faults. They are components of large pull-apart structures in which Lakes Manyas and Ulubat, and the plains of Bursa, Yenişehir, and Gölpazarı are located (Figures 1 and 2a). The pull-apart structures decrease in size towards the east, probably due to the diminishing effect of extensional tectonics in western Turkey. Interestingly, this mimics the overall structure of NAFZ recognized by Şengör et al. (2005).

The Manyas-Karacabey Fault limits the eastern border of the Manyas pull-apart, showing

an 8.70 km right lateral displacement of the Koca stream north of Manyas (Figure 2c). Further to the NE, the Çapaz creek is diverted 5.70 km right-laterally, immediately to the south of Karacabey (Figure 2d). The Manyas-Karacabey Fault has not been recognized in previous studies (e.g. Selim and Tüysüz, 2013). The eastern border of the Ulubat pull-apart basin is limited by the Ulubat Fault (Emre et al., 1997), which corresponds a 2.6 km right lateral diversion of the Nilüfer stream at southwest of Bursa (Figure 2e). After the northwest - southeast trending Bursa normal fault (Emre et al., 1997), the southern branch continues northeast with the Yıldırım Fault having 1.22 km right lateral displacement on Kaplıkaya creek between Bursa and Kestel (Figure 2f). The southern branch then continues northeast through the western strike-slip boundary of the Yenişehir pull-apart basin (Yılmaz and Koral, 2007; Gürbüz, 2010) (Figure 2a). The strike-slip faults on the eastern border of this basin have a northeasterly trend. This direction is somewhat compatible with the suggestion of Barka and Kadinsky-Cade (1988) that the southern branch joins the middle branch via Mekece (Figures 1 and 2a, black dotted lines). However, our findings indicate that the strike-slip faults on the eastern border of the Yenişehir pull-apart basin bend from northeast to east northeast and are composed of several en-echelon segments that have right lateral diversions of the Göksu (3.25 km) and Çoklum creeks (0.48 km) (Figure 2g). Another example is the 2.93 km offset of the Sakarya River on Bayırköy Fault (Figure 2h). We are not certain, however, whether the deflections on the rivers/streams have been created by the fault segments or whether the rivers/streams follow the route of existing faults. The southern branch then moves southeast again, creating the western border of the Gölpazarı pull-apart basin (Figure

2a) which is an important structure indicating the location of the main strike-slip branch (see earlier). The southern branch builds a releasing bend towards the east, passes through Mudurnu, and connects to the main branch of the NAFZ just south of the Bolu plain (Figures 1b and 2a). Evidence for the existence of the Mudurnu Fault is clearly seen in the MT section of Kaya (2010, p. 238) and we suggest it connects to the main branch of the NAFZ in a flower structure (Figure 1c).

## **SEISMICITY**

Historical records indicate this new route for the southern branch has an active seismic history except at its most eastern end (Figure 1b). According to data provided by Tan et al. (2008), several remarkable historical earthquakes occurred along the southern branch (see Table 1), some of which were strong and destructive. Among these, the AD 160 earthquake ( $M_s = 7.1$ ) occurred between Yenice and Gönen, and the February 28, 1855 earthquake ( $M_s = 7.1$ ) in Bursa caused extensive damage (Ambraseys, 2002; 2009).

Although historical earthquakes have large location errors, they are in agreement with recent instrumental seismicity (Figures 1b and 2a). Several more recent major earthquakes ( $M \geq 6.0$ ) have also occurred along this branch of the NAFZ. The largest two events are the March 18, 1953 Yenice-Gönen earthquake ( $M_s = 7.1$ ) and the October 6, 1964 Manyas earthquake ( $M_s = 6.8$ ) (Ambraseys, 2002). Several moderate earthquakes ( $5 \leq M < 6$ ) have also been documented in the region (Figure 1b). In order to refine the location of the southern branch, recent earthquakes with a magnitude lower than 5.0 have been relocated and analysed for fault plane solutions (Figure 1b and see Table 1).

We calculated relocation and fault plane solutions for several large earthquakes between 1982 and 2003 using bulletin data obtained from the International Seismological Centre (ISC) and for numerous small-scale earthquakes from 2004 to present using digital waveform data provided by Kandilli Observatory and the Earthquake Research Institute (KOERI).

After relocation, most events are compatible with the new southern branch (Figure 1b). Only a few earthquakes with large location errors are outside of the fault tracks due to lack of observation data or phase reading errors. All earthquakes were relocated with an average number of observations of  $\sim 49$ . The mean station gap in azimuth is  $\sim 73^\circ$  and calculated errors in horizontal and vertical directions are 0.6 and 0.3 km respectively. The average RMS (root mean square) residual is 0.24 s. All minimized location and origin time errors show that the seismicity of the region correlates with the active fault system.

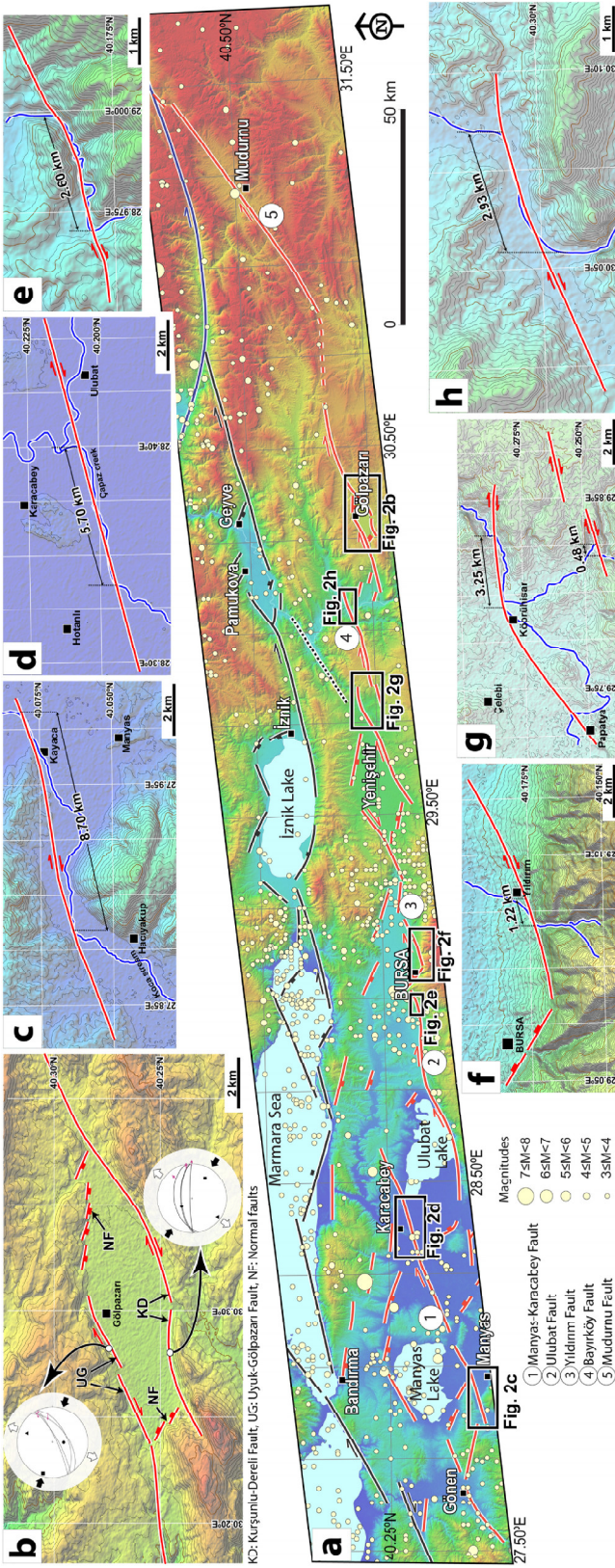
Correlation between seismicity and local tectonics was investigated by looking at the fault plane solutions of selected earthquakes that occurred on the southern branch. We determined the individual focal mechanisms by using P-wave first motion polarities. In the Table, focal mechanisms with a high quality solution are listed, they all tend to have relatively high station distribution values (STDR column) ( $\sim 0.57$  in average). Average misfit for all solutions is 0.06. These results indicate that the focal mechanism solutions are reliable. The focal mechanism solutions on the new route for the southern branch show dominantly northwest - southeast compression and northeast - southwest extension directions. Other than a small minority of solutions, these dominant regional stress directions are compatible with the pull-apart nature of the right lateral strike slip motion for the new southern branch (Figure 1b).





27	31.01.2007	11:02:29.19	40.317	29.119	12.4	2.7 <sup>d</sup>	25	60	0.08	0.1	0.1	0.1	225/316	85/80	170/5	13	35	20	14	0.25	0.83	TS
28	30.04.2007	18:48:54.78	40.332	30.523	3.7	3.5 <sup>d</sup>	32	127	0.08	0.2	0.0	0.0	155/267	45/69	-30/-131	3	3	10	16	0.04	0.26	TS
29	07.05.2007	07:27:51.19	40.269	29.633	5.8	2.9 <sup>d</sup>	30	50	0.08	0.1	0.1	0.1	35/302	70/81	-170/+20	15	20	20	17	0.23	0.76	TS
30	13.06.2007	08:44:50.74	40.158	28.959	20.2	3.2 <sup>d</sup>	37	67	0.29	0.6	0.1	0.1	65/161	80/61	150/12	10	23	40	18	0.00	0.62	TS
31	22.06.2007	17:54:21.62	40.068	28.390	5.9	2.7 <sup>d</sup>	22	164	0.24	0.7	0.2	0.2	175/7	30/61	-100/-84	10	13	15	12	0.25	0.53	TS
32	21.07.2007	04:31:23.91	40.075	27.575	10.4	3.1 <sup>d</sup>	51	62	0.08	0.1	0.0	0.0	109/200	80/85	175/10	8	33	25	25	0.06	0.71	TS
33	22.08.2007	01:11:42.96	40.128	28.239	6.7	3.0 <sup>d</sup>	48	76	0.16	0.2	0.1	0.1	0/127	25/74	-40/-110	0	10	0	23	0.05	0.50	TS
34	10.09.2007	07:58:14.63	40.122	27.669	9.1	2.7 <sup>d</sup>	25	93	0.09	0.2	0.1	0.1	80/272	35/56	-100/-83	63	33	50	8	0.00	0.72	TS
35	03.12.2007	18:13:53.88	40.140	28.936	10.0	3.2 <sup>d</sup>	39	47	0.13	0.2	0.1	0.1	125/217	85/70	-20/-175	8	10	20	20	0.00	0.63	TS
36	28.01.2008	00:50:42.53	40.080	28.968	24.4	3.5 <sup>d</sup>	63	28	0.20	0.3	0.1	0.1	65/155	90/85	175/0	5	15	15	32	0.08	0.57	TS
37	04.02.2008	19:22:21.01	40.196	29.658	5.7	2.8 <sup>d</sup>	36	42	0.05	0.1	0.0	0.0	73/200	54/50	-53/-130	10	25	25	19	0.10	0.65	TS
38	17.03.2008	04:24:46.97	40.234	28.014	11.3	3.5 <sup>d</sup>	55	55	0.08	0.1	0.0	0.0	150/268	50/61	-40/-132	10	13	15	21	0.00	0.66	TS
39	13.06.2008	17:04:11.51	40.450	28.022	11.6	3.0 <sup>d</sup>	46	40	0.21	0.3	0.1	0.1	140/356	60/36	-110/-59	10	5	20	16	0.03	0.57	TS
40	10.07.2008	07:49:53.88	40.026	27.744	10.2	3.7 <sup>d</sup>	58	61	0.10	0.2	0.0	0.0	75/341	65/81	-170/+25	5	5	10	49	0.05	0.57	TS
41	14.10.2008	22:58:50.75	40.021	28.285	5.4	3.2 <sup>d</sup>	55	48	0.21	0.3	0.1	0.1	55/220	50/41	100/78	8	3	0	32	0.02	0.54	TS
42	09.11.2008	16:58:55.61	40.206	29.674	20.8	2.5 <sup>d</sup>	15	158	0.08	0.4	0.1	0.1	90/270	55/35	-90/-90	40	15	20	9	0.00	0.69	TS
43	26.01.2009	12:10:17.61	40.143	28.917	5.5	3.7 <sup>d</sup>	79	27	0.10	0.1	0.0	0.0	200/93	35/79	20/123	18	33	10	40	0.14	0.68	TS
44	18.02.2009	17:22:39.64	40.110	28.213	8.5	3.1 <sup>d</sup>	33	52	0.05	0.1	0.0	0.0	65/218	70/22	-80/-116	18	10	20	19	0.07	0.46	TS
45	08.03.2009	01:16:18.53	40.134	28.886	5.4	3.1 <sup>d</sup>	48	54	0.11	0.2	0.1	0.1	145/302	65/27	-80/-110	18	15	20	27	0.08	0.66	TS
46	25.04.2009	09:59:38.63	40.121	28.745	5.6	2.9 <sup>d</sup>	40	74	0.07	0.1	0.0	0.0	90/294	35/57	-110/-77	8	15	5	25	0.02	0.58	TS
47	20.06.2009	16:00:50.35	40.179	28.805	5.7	3.3 <sup>d</sup>	55	81	0.11	0.1	0.0	0.0	70/306	55/51	-130/-47	13	33	15	27	0.00	0.70	TS
48	01.08.2009	16:42:38.81	40.319	28.317	16.9	3.8 <sup>d</sup>	98	27	0.17	0.2	0.0	0.0	70/340	90/70	-160/0	5	10	15	47	0.05	0.65	TS
49	15.08.2009	02:11:58.86	40.250	28.951	4.6	3.4 <sup>d</sup>	64	26	0.14	0.2	0.0	0.0	40/195	40/53	110/74	10	5	10	31	0.06	0.56	TS
50	18.08.2009	19:06:24.81	40.073	27.606	8.6	3.1 <sup>d</sup>	48	137	0.08	0.1	0.0	0.0	243/350	80/30	118/20	23	23	10	19	0.09	0.62	TS
51	05.09.2009	12:18:44.77	40.204	30.046	7.1	3.2 <sup>d</sup>	19	136	0.07	0.3	0.1	0.1	135/271	30/67	130/70	8	10	10	11	0.00	0.35	TS
52	08.09.2010	20:51:55.64	40.229	29.262	5.9	3.2 <sup>d</sup>	44	80	0.14	0.2	0.1	0.1	105/327	50/48	-120/-59	8	13	10	25	0.05	0.65	TS
53	23.02.2011	05:06:26.92	40.251	28.993	5.7	3.1 <sup>d</sup>	52	61	0.09	0.1	0.0	0.0	120/285	50/41	-80/-102	15	23	15	22	0.04	0.69	TS
54	30.03.2011	17:07:20.12	40.050	27.807	9.8	3.9 <sup>d</sup>	111	22	0.16	0.2	0.0	0.0	75/169	65/81	170/25	3	10	10	62	0.01	0.62	TS
55	10.04.2011	18:51:17.91	40.337	28.164	7.0	3.2 <sup>d</sup>	77	46	0.09	0.1	0.0	0.0	120/249	15/80	-40/-102	8	10	5	36	0.00	0.48	TS





**Figure 2.** a) Details of the alternative route for the southern branch of the NAFZ and the seismic activity of the NAFZ and the seismic activity of southern branch, data from KOERI (1900-2011). The black dotted line indicates the connection of southern branch to the middle branch in previous studies. Numbers in circles indicate faults. b) Gölpaazarı pull-apart basin (after Gürbüz and Seyitoğlu, 2014). Lower hemisphere equal area projections of the fault surfaces with striations are shown in circles. Black square, circle and triangle represents sigma 1, sigma 2 and sigma 3 respectively. c) An 8.70 km diversion of Koca stream on the Manyas – Karacabey Fault, at the north of Manyas. d) A 5.70 km right lateral displacement of Nilüfer stream on the Manyas-Karacabey Fault at the south of Karacabey. e) A 2.6 km right lateral displacement of Yıldırım creek, east of Bursa. f) The bending of the eastern marginal fault of the Yenişehir basin corresponds to the right lateral displacements on the Gökusu and Çoklum creeks. g) A 2.93 km right lateral displacement on the Sakarya river along the Bayırköy Fault.

**Şekil 2.** a) KAFZ Güney kolu'nun alternatif güzergahının ayrıntıları ve Güney kol'un sismik aktivitesi. Sismik veri KRDAE deprem katalogundan alınmıştır (1900-2011). Siyah noktalar hat önceki çalışmalarda Güney kol ile Orta kol arasındaki bağlantıyı göstermektedir. b) Gölpaazarı çekirir havzası (Gürbüz ve Seyitoğlu, 2014). Fay düzlemleri ve kayma çiziklerinin alt yarıküre eşit alan projeksiyonu dairelerde gösterilmiştir. Siyah kare, daire ve üçgen sırası ile sigma 1, sigma 2 ve sigma 3'ü göstermektedir. c) Manyas kuzeyinde, Manyas-Karacabey fayı üzerinde Koca çay'ın 8.70 km'lik sapma göstermesi. d) Karacabey güneyinde Manyas-Karacabey fayı üzerinde Çapaz dere'nin 5.70 km sağ yanal ötelenmesi. e) Ulubat fayı üzerinde Nilüfer Çayı'nın 2.6km sağ yanal yerdeğiřtirmesi. f) Bursa doğusunda, Yıldırım fayı üzerinde Kaplıkaya deresinin 1.22km sağ yanal ötelenmesi. g) Yenişehir havzasının doğu kenar fayının bükülmesi Gökusu ve Çoklum derelerinin sağ yanal yerdeğiřtirmesine karşılık gelmektedir. h) Bayırköy fayı boyunca Sakarya nehrinde 2.93km sağ yanal yerdeğiřtirme.

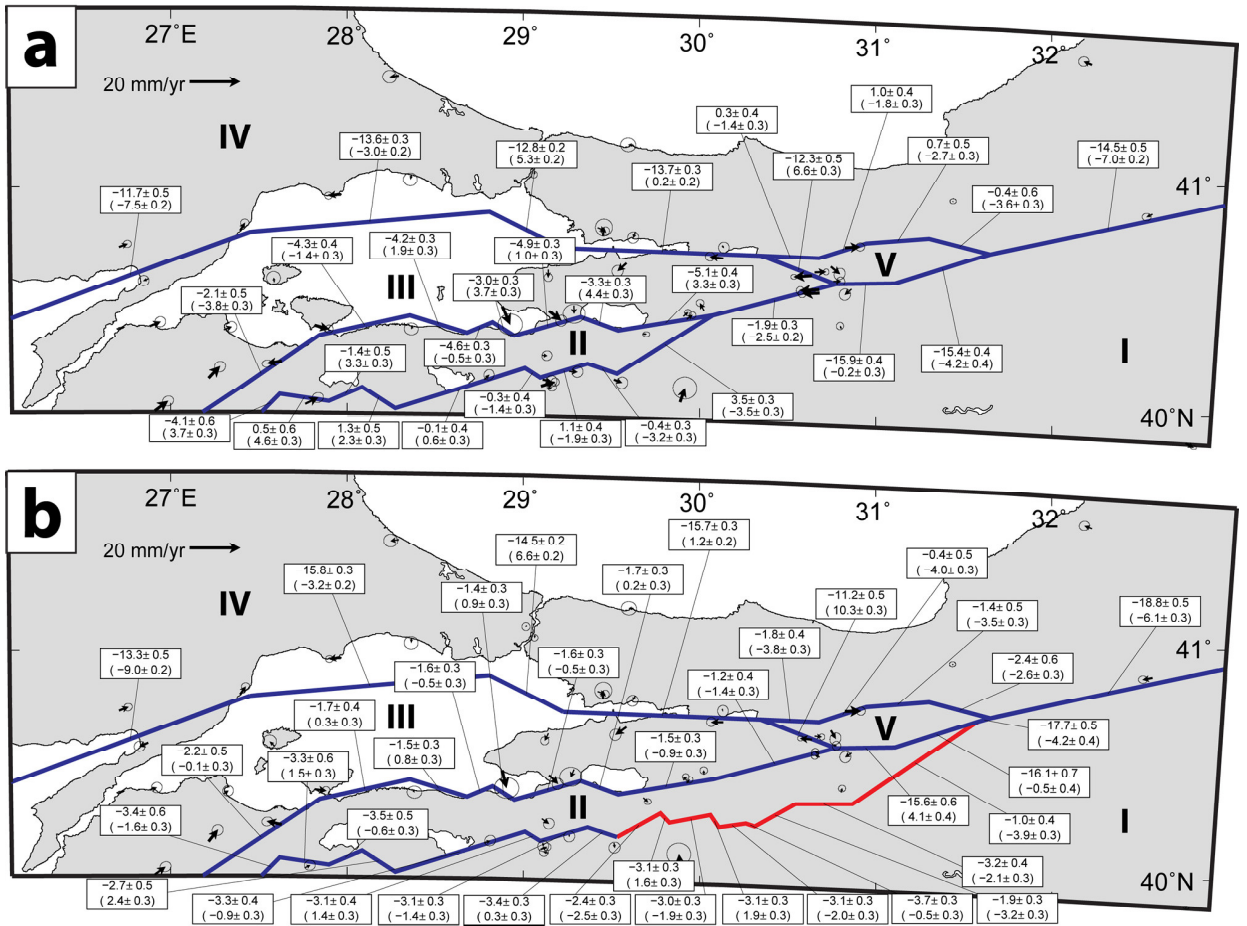
## GPS DATA

Slip partitioning in the Marmara region was previously examined by GPS data such that the computed slips rate range between 23 and 28 mm/yr and between 2.9 to 9.6 mm/yr for the northern and southern branches, respectively (Meade et al., 2002; Nyst and Thatcher, 2004; Reilinger et al., 2006; Aktuğ et al., 2009; Le Pichon and Kreemer, 2010). The majority of these studies consider only two simplified branches of the NAFZ in the Marmara region. Flerit et al. (2004) found slip rates using three branches resulting in slip rates of 17-20, 5 and 2-5 mm/yr for the northern, middle, and southern branches respectively. We employed block modeling to compute the slip rates along boundaries of the fault mapping of this study and earlier works. In this approach, rigid-body motions of each block parameterized by Euler vectors are simultaneously estimated by minimizing the misfit between the modeled and the observed velocities (McCaffrey, 2002; 2005). To account for elastic straining along block boundaries (Okada, 1985), the back slip approach (Matsu'ura et al., 1986) was applied for each fault segment with prescribed fault geometry (Aktuğ et al., 2013b). We assumed vertical faults in Marmara with locking depths of 15 km.

In order to examine slip distribution between the branches of the NAFZ, the Marmara region is divided into 5 blocks using previous fault

definitions (Figure 3a). In this case, the northern branch of the NAFZ has the largest slip values (11.7-13.7 mm/yr) except for the northern part of the Almacık flake. The middle branch has the second largest slip rates, ranging from 2.1 to 5.1 mm/yr. In this configuration, the southern branch is the least important structure with low slip values, (0.1-3.5 mm/yr) and the eastern segment of the southern branch has left-lateral slip rates that are inconsistent with the nature of the Yenişehir pull-apart basin and the entire right lateral nature of the NAFZ.

The newly proposed route of the southern branch in the Marmara region results in a better fit with the GPS velocities (Figure 3b). As shown in Figure 3b, the residuals in the southernmost block are much smaller than those in Figure 3a. The northern branch still has the highest slip rates (11.2-15.8 mm/yr), but the new slip rates indicate that the new southern route has the next highest slip rates, ranging between 1.0 and 3.7 mm/yr. Block modeling with the newly proposed route provides a lower RMS value than using the geometry given in previous studies (2.32 mm/yr versus 2.90 mm/yr). The results of the block modeling were further analyzed statistically to determine whether the improvement in RMS is significant. An F-ratio test of the variances of two different estimations reveals that such a difference in variances is statistically significant at a 95% confidence level.



**Figure 3.** Slip distribution in the Marmara region. **a)** Block boundaries are determined by previous workers cited in Figure 1. **b)** Block boundaries are determined according to the new route of the southern branch of the NAFZ. The slip rates computed using the block model are shown in mm/yr. Top values without parentheses are strike-slip rates, positive being left-lateral. Numbers in parentheses are fault-normal slip rates, positive being closing. Error ellipses are at 95% confidence level.

**Şekil 3.** Marmara bölgesinde kayma dağılımı. **a)** Blok sınırları Şekil 1'de referans gösterilen önceki çalışmalara göre tanımlanmıştır. **b)** Blok sınırları KAFZ'nun Güney Kol'unun yeni güzergahına göre tanımlanmıştır. Kayma değerleri blok modele göre hesaplanmış olup, mm/yıl olarak gösterilmektedir. Parantez içinde olmayan üstteki değerler yanıl kayma değerleridir, pozitif olanlar sol yanaldır. Parantez içindeki değerler faya dik kayma değerleridir, pozitif olanlar yaklaşmayı ifade eder. Hata elipsleri %95 güven düzeyinde gösterilmiştir.

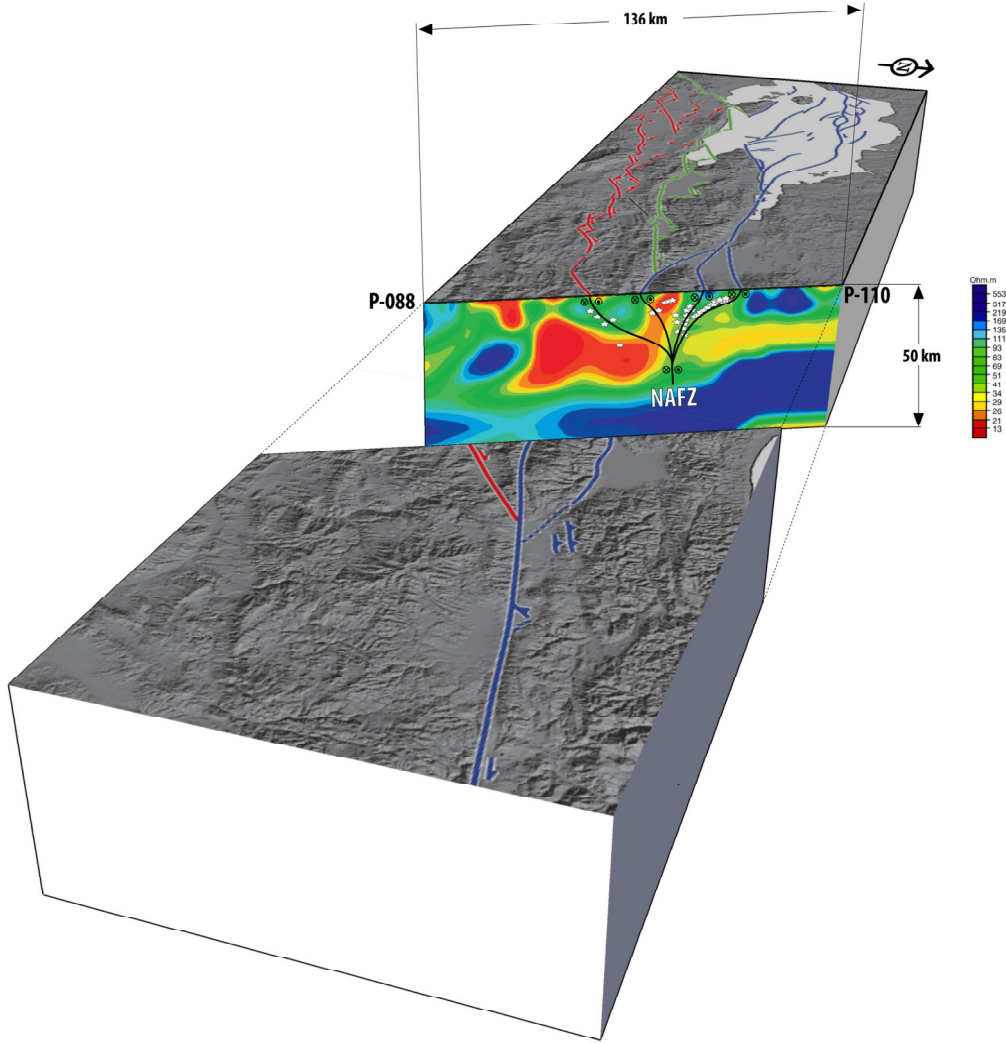
## CONCLUSIONS

The strike of fault segments and the locations of pull-apart basins in northwest Anatolia indicate northwest - southeast compression and northeast - southwest extension due to the right lateral strike-slip system which agrees with the majority of the focal mechanism solutions presented in this paper

(Figure 1b). Seismic activity on the western part of the southern branch is relatively higher than on the eastern part, however, the location of the Gölpazarı pull-apart basin and the re-evaluated MT cross section on the eastern side reveal the location of an alternative route for the southern branch (Figure 4). This new definition better

explains the regional tectonics of the Gölpazarı pull-apart basin and provides a better fit of block modelling to GPS data. Slip distribution among the three branches of the NAFZ in the Marmara region based on GPS data demonstrate that the new route for the southern branch is the second most important branch in the region in terms of slip distribution along the NAFZ.

The suggested hypothesis for a new alternative southern route of the NAFZ, evidenced by morphotectonic features, seismology, GPS and recently published MT data, should be tested in the field by detailed structural analyses and seismic reflection studies.



**Figure 4.** 3D perspective view of the three branched NAFZ in the Marmara region. The hypothesized southern branch is well correlated with the re-evaluated MT data of Kaya (2010).

**Şekil 4.** Marmara bölgesinde üç kollu KAFZ'nun üç boyutlu perspektif görünümü. Güney kol hipotezi, Kaya (2010)'nun yeniden yorumlanmış MT verisi ile uyum içindedir.

## GENİŞLETİLMİŞ ÖZET

Kuzey Anadolu Fay Zonu (KAFZ) doğuda dar bir makaslama zonu içinde yer alırken, batıda Bolu'dan itibaren geniş bir makaslama zonu içerisinde üç ana kola ayrılmaktadır (Şekil 1). Kuzey kol, Sapanca Gölü, İzmit Körfezi, Marmara Denizi ve Saros Körfezi'nden geçer. Orta kol Almacık bloğundan ayrılarak Geyve-Pamukova, İznik Gölü, Gemlik Körfezini izler ve Bandırma Körfezinden GB'ya döner. Güney kol'un KD ucunun Orta kol'dan Mekece üzerinden ayrılarak GB'ya doğru Yenişehir, Bursa, Ulubat Gölü güneyinden Mustafakemalpaşa'yı izleyerek Gönen civarında GB'ya döndüğü bilinmektedir (Şekil 1) (Şengör, 1979; Barka ve Kadinsky-Cade, 1988; Barka ve Kuşçu, 1996; Emre vd., 1997; Armijo vd., 1999; 2002; Yaltırak, 2002; Gürer vd., 2003; 2006; Şengör vd., 2005; Kurtuluş ve Canbay, 2007; Yılmaz ve Koral, 2007; Selim ve Tüysüz, 2013; Le Pichon vd., 2014).

Yakın zamanda yayınlanan Türkiye diri fay haritasında ise Güney kol, Bursa ve İnegöl arasında diri normal faylarla Eskişehir Fay Zonu'na bağlanır (Emre vd. 2011).

Yukarıdaki güzergahlardan farklı olarak, Gölpazarı havzasının bir çek-ayır havza olarak değerlendirilmesinden sonra (Önde ve Gürbüz 2010; Gürbüz ve Seyitoğlu, 2014), MT verilerinin de yayınlanması (Kaya, 2010) ile, KAFZ'nun Güney kolu alternatif güzergahının daha doğuya Gölpazarı çek-ayır havzası ve Mudurnu üzerinden ana KAFZ'na Bolu'da bağlandığı yönündeki bir hipotez bu makalede öne sürülmektedir.

Güney Marmara'nın genel yapısı KD doğrultulu sağ yanal doğrultu atımlı faylar ile KB doğrultulu normal faylardan meydana gelmektedir. Bu yapılar büyük çek-ayır havza sistemlerinin elemanları olup, içlerinde Manyas

ve Ulubat göllerini, Bursa, Yenişehir ve Gölpazarı ovalarını barındırmaktadır (Şekil 1 ve 2). KAFZ Güney kol'una ait alternatif güzergah ve ilişkili morfolojik veriler Şekil 2'de sunulmuştur. Ayrıca Mudurnu fayı güzergahını belirlemek için Kaya (2010) tarafından yayınlanan MT verisi yeniden yorumlanmıştır (Şekil 1 ve 2).

Önerilen Güney kol'un üzerindeki sismik etkinlik batıda doğuya göre daha fazladır. Sismik etkinlik verilerine yeniden konumlandırma işlemi yapılmış, ayrıca yeni odak mekanizma çözümleri elde edilmiştir (Şekil 1; Çizelge 1). Genel bölgesel gerilme dağılımı, sağ yanal doğrultu atımlı sistemin çek-ayır doğası ile uyumlu gözükmektedir.

KAFZ'nun kolları arasındaki kayma dağılımını incelemek için daha önceki fay tanımlamalarına uygun şekilde bir çalışma yapılmış ve burada Güney kol'un en düşük kayma değerlerine sahip olduğu ve doğu segmentinin sol yanal kayma değerlerine sahip olduğu görülmüştür (Şekil 3a). Marmara bölgesinde yeni önerilen Güney kol güzergahına uygun biçimde yapılan çalışmaya göre (Şekil 3b) güney blokta rezidüeller Şekil 3a'ya göre daha düşüktür ve yeni Güney kol ikinci en büyük kayma değerine sahiptir (1.0-3.7 mm/yıl).

KAFZ'nun Biga Yarımadası-GGD Marmara bölgesi anakarası üzerindeki güzergahı hakkındaki bu hipotez arazide daha detaylı yapısal analizler ve sismik yansıma çalışmaları ile test edilmelidir.

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