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# Seismotectonics of the southern branch of North Anatolian Fault Zone along Bolu, Bursa, and İzmir cities and Değirmenlik (Milos) island in the Aegean Sea

## *Bolu, Bursa ve İzmir şehirleri ve Ege Denizi'ndeki Değirmenlik (Milos) adası boyunca Kuzey Anadolu Fay Zonu güney kolunun sismotektoniği*

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**ABSTRACT**

The segment distribution of the northern branch of the North Anatolian Fault Zone (NAFZ) is well determined under the Sea of Marmara by intense seismic reflection studies. However, there is no agreement on the number of branches and their positions in the southern Marmara and western Anatolia, even if the area is not covered by the sea. In this paper, we performed morphotectonic studies with the help of the high-resolution satellite images, seismicity, and focal mechanism solutions of significant earthquakes to determine the segment distribution of the active faults accurately. Thus, the distinction of middle and southern branches of NAFZ in the southern Marmara region is established and the route of southern branch of NAFZ from Bolu to Değirmenlik (Milos) island via Bursa, Balıkesir, and İzmir is documented in detail. Besides, our results demonstrate that the hypotheses of "bend model" and "İzmir-Balıkesir Transfer Zone", which were suggested in previous publications to explain the active fault pattern in southern Marmara and western Anatolia, are not working.

**Keywords:** Aegean Sea, Neotectonics, North Anatolian Fault Zone, Seismicity

***ÖZ***

*Kuzey Anadolu Fay Zonu'nun kuzey koluna ait segment dağılımı Marmara Denizi altında sismik yansıma çalışmaları ile güvenilir olarak tanımlanmıştır. Bununla birlikte, denizle kaplı olmamasına rağmen güney Marmara ve batı Anadolu'da Kuzey Anadolu Fay Zonu'nun kaç kolu olduğu ve bunların konumları hakkında fikir birliği bulunmamaktadır. Bu makalede yüksek çözünürlüklü uydu görüntüleri yardımıyla morfotektonik çalışmalar gerçekleştirilerek, sismik etkinlik ve belirgin depremlerin odak mekanizması çözümleri ile diri fayların segment dağılımlarının doğru şekilde belirlenmesine çalışılmıştır. Böylece güney Marmara bölgesinde Kuzey Anadolu Fay Zonu'nun orta ve güney kollarının ayrımı yapılmış ve güney kolun Bolu'dan başlayan, Bursa, Balıkesir, İzmir üzerinden Ege Denizinde Değirmenlik (Milos) adasına kadar uzanan güzergahı ayrıntıları ile ortaya konmuştur. Bunun yanı sıra sonuçlarımız daha önceki yayınlarda güney Marmara ve batı*

*Anadolu'da diri fay desenini açıklamak için önerilen "büklüm modeli" ve "İzmir-Balıkesir Transfer Zonu" hipotezlerinin geçerli olmadığını göstermektedir.*

***Anahtar Kelimeler:*** *Depremsellik, Ege Denizi, Kuzey Anadolu Fay Zonu, Neotektonik*

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## INTRODUCTION

The North Anatolian Fault Zone (NAFZ) is considered to have three branches between Bolu and the Aegean Sea since mid-70-80's (Crampin and Üçer, 1975; Crampin and Evans, 1986) (Figure 1a). However, some other researchers simultaneously suggest that it has two branches (Dewey and Şengör, 1979; Şengör, 1979; Şengör et al., 1985) (Figure 1b).

Besides the number of branches, there were different arguments about the tectonic style of the northern branch of NAFZ. Şengör et al. (1985) suggest that the northern branch passing from the north and south of Almacık block crosses the Marmara Sea as a single line over Sapanca Lake and reaches the Saros Gulf from Mount Ganos (Figure 1b). On the other hand, Barka and Kadinsky-Cade (1988) and Barka (1992) propose several pull-apart structures under the Sea of Marmara (Figure 1c). Although, this controversy has been solved by the intense seismic reflection and bathymetric data after the 1999 earthquakes (Le Pichon et al., 2001; 2003), the number of branches of the NAFZ and their routes remain problematic in the southern Marmara and western Anatolia.

The middle branch of NAFZ separated from the south of Almacık block can be traced to Geyve, south of İznik Lake, Gemlik Bay and Bandırma to Çan. The "southern branch" was connected to the "middle branch" by the eastern edge of the Yenişehir pull-apart basin (Barka and Kadinsky-Cade, 1988) (Figure 1c).

The suggestion of "middle branch" is generally disregarded by the GPS-based studies which are considering only the north and south branches following Şengör et al. (1985). Their slip rates are 23-28 mm/year for the northern branch, 2.9-9.6 mm/year for the southern branch (Meade et al., 2002; Nyst and Thatcher, 2004; Reilinger et al., 2006; Aktuğ et al., 2009; Le Pichon and Kreemer, 2010; Ergintav et al., 2014). A GPS-based study considering the three branches provides the slip rates of 17-20 mm/year for the northern branch, 5 mm/year for the middle branch, 2-5 mm/year for the southern branch (Flerit et al., 2004).

Contrary to the widely accepted studies considering double branched NAFZ, some papers draw the third, the southern branch of NAFZ between İznik Lake and İzmir in their regional fault maps (Figure 1d and 1e) (Ocakoğlu et al., 2005; Yaltırak et al., 2012) following the Crampin and Üçer (1975) and Crampin and Evans (1986).

Apart from the discussion regarding the number of branches of the NAFZ, there are two completely different views trying to explain the seismic events associated with strike-slip faulting in southern Marmara and western Anatolia. One of them is the left-lateral (Ring et al., 1999) or right-lateral (Uzel and Sözbilir, 2008; Uzel et al., 2013) İzmir-Balıkesir Transfer Zone concept which is believed to separate the regions having different extension values (Figure 1f). The major disadvantage of this concept is the uncertainty in the connection of

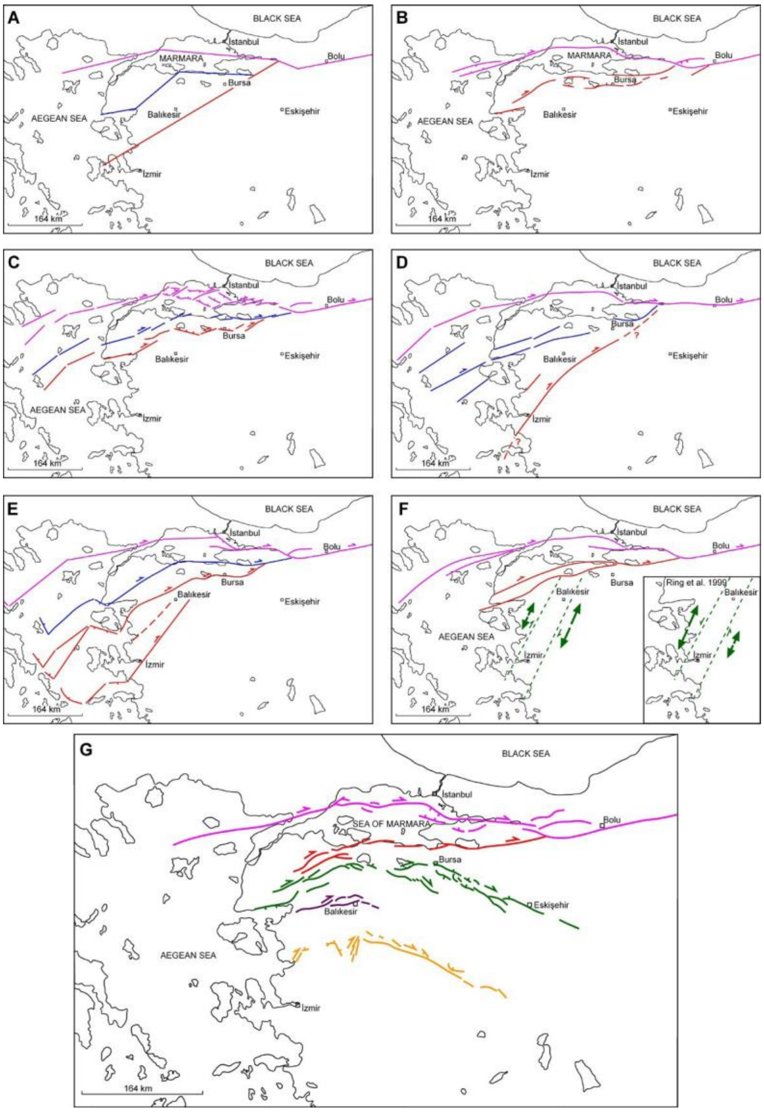


**Figure 1.** The numbers and the locations of the branches belong to the North Anatolian Fault Zone (NAFZ). Fuchsia: Northern branch; Blue: Middle branch; Red: Southern branch; A) Crampin and Üçer, (1975); Crampin and Evans (1986). B) Şengör et al. (1985). C) Barka and Kadinsky-Cade (1988). D) Ocakoğlu et al. (2005). E) Yaltırak et al. (2012). F) Uzel and Sözbilir (2008), Uzel et al. 2013 and Ring et al. (1999) at inset. Green dotted line: İzmir-Balıkesir Transfer Zone. G) Emre et al. (2013, 2018). Green: Manyas-Bursa bend; Purple: Balıkesir bend; Orange: Southern boundary bend.

***Şekil 1.*** *Kuzey Anadolu Fay Zonu'na ait kolların sayısı ve konumları. Fuşya: Kuzey kol; Mavi: Orta Kol; Kırmızı: Güney kol; A) Crampin ve Üçer, (1975); Crampin ve Evans (1986). B) Şengör vd. (1985). C) Barka ve Kadinsky-Cade (1988). D) Ocakoğlu vd. (2005). E) Yaltırak vd. (2012). F) Uzel ve Sözbilir (2008), Uzel vd. 2013 ve ekli küçük resimde Ring vd. (1999). Yeşil noktalı hat: İzmir-Balıkesir Transfer Zonu. G) Emre vd. (2013, 2018). Yeşil: Manyas-Bursa büklümü; Mor: Balıkesir büklümü; Turuncu: Güney sınır büklümü.*

its northeast and southwest ends with the main regional structures.

The other view is the bend model (Emre et al., 2013; 2018) which accepts double branched NAFZ and rejects the idea of the connection between the middle and southern branches of NAFZ (Barka and Kadinsky-Cade, 1988). Moreover, the bend model suggests several arc-shaped right-lateral fault patterns having NE-SW and NW-SE directions, namely the Manyas-Bursa bend, Balıkesir bend, and southern boundary bend (Emre et al., 2018) (Figure 1g). For example, in the Biga peninsula, the NE-SW trending strike-slip faults turn to the E-W direction towards east where the Bursa normal fault is developed, then, this structure connects to the NW-SE trending right-lateral strike-slip Eskişehir Fault Zone (Emreet al., 2018) (Figure 1g). An important implication of this "bend model" is that the right-lateral strike-slip faults in the Biga peninsula and southern Marmara are not related to the NAFZ and they are evaluated as a part of second-order structure, such as the Eskişehir Fault Zone which creates an enormous difference for the earthquake hazard assessment of the major cities like Bursa, Balıkesir, and İzmir.

A contrary hypothesis proposed that the southern branch of NAFZ is separated from the Bolu Plain and forms the Gölpazarı pull-apart basin via Mudurnu and creates Yenişehir, Bursa, Ulubat and Manyas pull-apart basins (Seyitoğlu et al., 2016) (Figure 2). The GPS-based block model in this hypothesis indicates that the southern branch is the second important strand of NAFZ in terms of slip rates (Seyitoğlu et al., 2016).

This paper documents the southwestern continuation of the southern branch of NAFZ based on seismology and morphotectonics (Figure 2) and aims (1) to show the segment distribution of southern branch of NAFZ between Bolu and Değirmenlik (Milos) island, (2) to clarify the distinction between the "middle branch" and "southern branch" of the NAFZ in the southern Marmara region and (3) to demonstrate the structural link between the southern branch of NAFZ and the so-called İzmir-Balıkesir Transfer Zone (Uzel and Sözbilir, 2008; Uzel et al., 2013) via Yenişehir, Bursa and Susurluk valley which refutes the bend model (Emre et al., 2018) in the southern Marmara and western Anatolia.

## MATERIAL AND METHODS

The following base maps and data were used in mapping the faults: (a) the SRTM-DEM and 1:25000 scale topographic maps as elevation/topographic data, (b) high-resolution Google Earth satellite imagery, (c) active fault maps (Emre et al., 2013) and geologic maps of the Mineral Research and Exploration General Directorate (MTA), published papers and reports, (d) the earthquake epicentral distribution and focal mechanism solution data from the institutions and previous studies.

With the help of these base maps and data, the faults were carefully mapped as segments in the GIS environment based on the following morphotectonic features: (a) linear valleys, (b) sharp diversions of stream channels, (c) sag ponds, (d) linear arrangements of springs, (e) elongated ridges, (f) topographical troughs, (g) shutter ridges. We performed field studies in some parts of the study area and collected slickenside and striae data from the faults (Supplementary Data: Appendix A).

The earthquake epicentral distributions and focal mechanism solutions also helped to understand the seismic activity and structural character of the faults. Some of the focal mechanism solutions were produced in this study by using moment tensor inversion. The other focal mechanism solutions are obtained from different sources (Supplementary data: Appendix B). Waveform data and response files of the stations were retrieved from the European Integrated Data Archive (EIDA) and Turkish Earthquake Data Center System (TEDCS) of the Emergency Management Presidency (AFAD). Selected waveforms recorded by

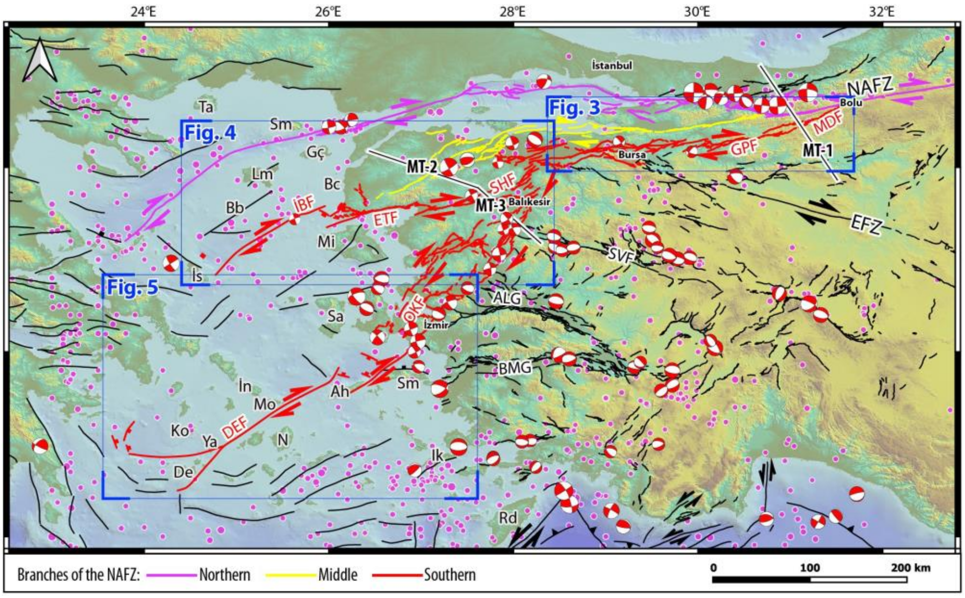


**Figure 2.** The branches of North Anatolian Fault Zone and the locations of MT lines. MT-1 from Kaya (2000); MT-2 and MT-3 from Ulugergerli et al. (2007). NAFZ: North Anatolian Fault Zone; EFZ: Eskişehir Fault Zone; SVF: Simav Fault; İBF: İskiri-Biga Fault; ETF: Edremit Fault; SHF: Susurluk-Havran Fault; OKF: Orhanlı-Karabağ Fault; DEF: Değirmenlik Fault; GPF: Gölpazarı Fault; MDF: Mudurnu Fault; ALG; Alaşehir Graben; BMG: Büyük Menderes Graben; Aegean Islands: Rd: Rodos (Rhodes); De: Değirmenlik (Milos); Ya: Yavuzca (Syros); Mo: Mokene (Mikonos); İn: İstendin (Tinos); Ko: Koyunluca (Serifos); İk: İstanköy (Kos); Ah: Ahikerya (Ikeria); N: Nakşa (Naxos); Sm: Sisam (Samos); Sa: Sakız (Chios); Mi: Midilli (Lesvos); İs: İskiri (Skyros); Bb: Bozbaba (Agios Efstratios); Lm: Limni (Limnos); Bc: Bozcaada; Gç: Gökçeada; Sm: Semadirek (Samothraki); Ta: Taşoz (Thasos). Fault lines from Barka and Kuşcu (1996); Barrier et al. (2004); Emre et al. (2013); Caputo and Pavlides (2013); Seyitoğlu et al. (2016; 2021; 2022); Can (2017). Focal mechanism solutions from Tan et al. (2008), Global CMT Catalogue, Seyitoğlu et al. (2020a, b). Pink circles represent the earthquake epicenters of magnitude ≥5 obtained from the ISC catalogue.

***Şekil 2.*** *Kuzey Anadolu Fay Zonu'nun kolları ve MT hatları. MT-1 Kaya (2000)'den, MT-2 ve MT-3 Ulugergerli vd. (2007)'den alınmıştır. NAFZ: Kuzey Anadolu Fay Zonu; EFZ: Eskişehir Fay Zonu; SVF: Simav Fayı; İBF: İskiri-Biga Fayı; ETF: Edremit Fayı; Susurluk-Havran Fayı; OKF: Orhanlı-Karabağ Fayı; DEF: Değirmenlik Fayı; GPF: Gölpazarı Fayı; MDF: Mudurnu Fayı; ALG: Alaşehir Grabeni; BMG: Büyük Menderes Grabeni. Ege Adaları: Rd: Rodos (Rhodes); De: Değirmenlik (Milos); Ya: Yavuzca (Syros); Mo: Mokene (Mikonos); İn: İstendin (Tinos); Ko: Koyunluca (Serifos); İk: İstanköy (Kos); Ah: Ahikerya (Ikeria); N: Nakşa (Naxos); Sm: Sisam (Samos); Sa: Sakız (Chios); Mi: Midilli (Lesvos); İs: İskiri (Skyros); Bb: Bozbaba (Agios Efstratios); Lm: Limni (Limnos); Bc: Bozcaada; Gç: Gökçeada; Sm: Semadirek (Samothraki); Ta: Taşoz (Thasos). Fay hatları Barka ve Kuşcu (1996); Barrier vd. (2004); Emre vd. (2013); Caputo ve Pavlides (2013); Seyitoğlu vd. (2016; 2021; 2022); Can (2017); Seyitoğlu vd. (2021). Odak mekanizması çözümleri: Tan vd. (2008), Global CMT Catalogue, Seyitoğlu vd. (2020a, b). Pembe daireler büyüklüğü ≥5 olan ve ISC kataloğundan alınan depremlerin dışmerkezlerini temsil etmektedir.*

three-component broadband seismograph stations within 700 km distance from the earthquakes were used to calculate the strike, dip, and rake angles of the nodal planes (possible fault planes) and the azimuth and plunge of the pressure (P) and tension (T) axes. Computer Programs in Seismology of Herrmann (2013) were used for regional moment tensor inversion, which is based on fitting synthetic waveforms of the observed data.

As a result of the study, maps of the active fault segments were produced by using and interpreting/re-interpreting old and new data. Readers must consult the electronic data base which can be visible on the Google Earth software for more details than the presented maps (Supplementary Data: Appendix C).

## THE SOUTHERN BRANCH OF NAFZ BETWEEN BOLU AND YENİŞEHİR

The southern branch of NAFZ separated from the main branch in the south of Bolu Plain and composed of three faults, Mudurnu Fault (MDF), Gölpazarı Fault (GPF) and Bayırköy Fault (BYF) between Bolu and Yenişehir (Figure 3). The segments of MDF generally follow linear valleys between Bolu and Mudurnu. The restraining bend around Feruz controls different flow directions of Mudurnu Suyu to the northeast and Ulu Su to the southwest. In the southwest of Mudurnu, the fault segments of MDF created Göldağı Block which is surrounded by strike-slip faults similar to the Almacık Block (Şengör et al., 1985; Seyitoğlu et al., 2015) (Figure 3). The segments are getting closure to each other in the southwest of Göynük where elongated ridges are typical morphological features (Figure 3; Appendices A and C).

The Gölpazarı Fault (GPF) starts around Köybaşı and its segments create Gölpazarı pull-apart basin (Gürbüz and Seyitoğlu, 2014) (Figure 3). This basin is one of the important morphological evidences unrecognized by the earlier studies that the southern branch of NAFZ is passing from this location. The overall position of Üyük basin also resembles a pull-apart structure and the segments of GPF create a right-lateral shift on the course of Kara Çay and Sakarya River at the north of Bilecik (Figure 3). Moreover, the major right-lateral displacements on both Kara Çay and Sakarya River (i.e., 2.93 km, Seyitoğlu et al., 2016) are created by the Bayırköy Fault (BYF) which provides a connection between Gölpazarı / Üyük and Yenişehir pull-apart structures (Figure 3; Appendices A and C).

## THE SOUTHERN BRANCH OF NAFZ IN THE YENİŞEHİR, BURSA-EAST AND BURSA-WEST PULL-APART BASINS

The linkage of Gölpazarı/Üyük and Yenişehir pull-apart structures via BYF is particularly important to test different tectonic interpretations mentioned in the introduction section. It disproves the suggested connection of the southern branch to the middle branch via Mekece (Barka and Kadinsky-Cade, 1988) (Figure 3). Moreover, the determination of cross-basin fault, the Kayapa-Yenişehir Fault (KYF) (Figure 3) by using morphological and seismic reflection studies supported by the ongoing AFAD-National Earthquake Program (Seyitoğlu et al., 2021), is also important for the evolution of Yenişehir, Bursa-east and Bursa-west pull-apart basins which demonstrates a genetic link of the faults around Bursa to the southern branch of NAFZ contrary to their suggested relationship with the Eskişehir Fault Zone (Emre et al., 2011a; 2018) (Figure 1g).

The seismic events #105_2019.11.16 (Ml=3.0), #106_2019.11.17 (Ml=3.2) and #86_2016.06.07 (ML=4.6) confirm continuation of activity along pull-apart basin bounding faults despite formation of cross-basin fault, the KYF (Figure 3). For a detailed description of basin bounding faults and the cross-basin fault plus seismic activity see Appendices A, B, and C.

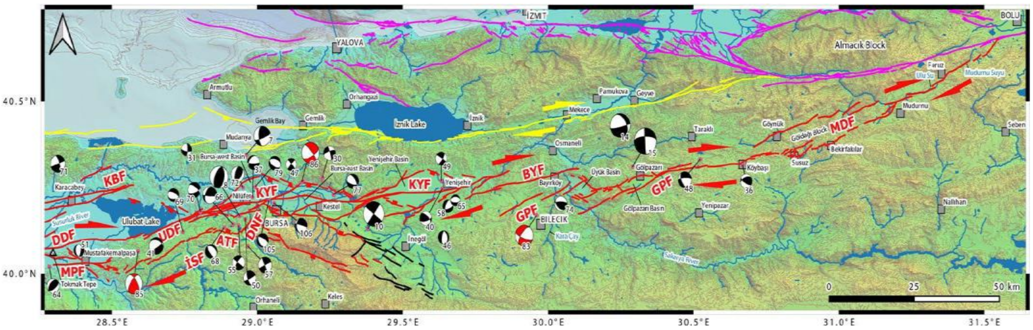


**Figure 3.** The southern branch of NAFZ between Bolu and Ulubat Lake (red fault lines from this paper and Seyitoğlu et al. 2016; 2021). The fuchsia and yellow lines in the north represent northern and middle branch of NAFZ respectively. They are from Emre et al. (2013) and Can (2017). The black lines in the south of İnegöl belong to Eskişehir Fault Zone (after Seyitoğlu et al., 2021). MDF: Mudurnu Fault; GPF: Gölpazarı Fault; BYF: Bayırköy Fault; KYF: Kayapa-Yenişehir Fault; DNF: Doğancı Fault; ATF: Atlas Fault; UDF: Ulubat-Doğanköy Fault; İSF: İnegazi-Sincansarnıç Fault; MPF: Mustafakemalpaşa Fault; DDF: Dorak-Durumtay Fault; KBF: KaracabeyFault.

***Şekil 3.*** *Bolu ve Ulubat Gölü arasında Kuzey Anadolu Fay Zonu'nun güney kolu (kırmızı fay hatları bu makale ve Seyitoğlu vd. 2016; 2021'den alınmıştır). Fuşya ve sarı hatlar sırası ile kuzey ve orta kolu temsil etmektedir. Bunlar Emre vd. (2013) ve Can (2017)'den alınmıştır. İnegöl güneyindeki siyah hatlar Eskişehir Fay Zonu'na aittir (Seyitoğlu vd., 2021). MDF: Mudurnu Fayı; GPF: Gölpazarı Fayı; BYF: Bayırköy Fayı; KYF: Kayapa-Yenişehir Fayı; DNF: Doğancı Fayı; ATF: Atlas Fayı; UDF: Ulubat-Doğanköy Fayı; İSF: İnegazi-Sincansarnıç Fayı; MPF: Mustafakemalpaşa Fayı; DDF: Dorak-Durumtay Fayı; KBF: KaracabeyFayı.*

## THE SOUTHERN BRANCH OF NAFZ BETWEEN ULUBAT LAKE AND EDREMİT GULF VIA SUSURLUK VALLEY

The Ulubat-Doğanköy Fault (UDF) is the common structure between Bursa-west and Ulubat pull-apart basins. Its morphological indicators are quite distinctive at the southeast of Ulubat Lake (i.e., topographical differences, elongated ridges, shifting stream channels). The seismic event #70_2009.06.20 (Md=3.3) can be attributed to UDF (Figure 3). The ENE-WSW trending Dorak-Durumtay Fault (DDF) creates right-lateral displacements on the Mustafakemalpaşa Çayı at the south of Ulubat Lake and in the Susurluk River further west (Figure 3). At the southwest of Bursa, the Doğancı Fault (DNF) follows the Nilüfer Valley and creates a releasing stepover with the İnegazi-Sincansarnıç Fault (İSF) where the Atlas Fault (ATF) having normal faultcharacter is developed. Further to the southwest, Mustafakemalpaşa Fault (MPF) forms a distinctive right-lateral shift on the stream at the town bearing the same name (Figure 3; Appendices A, B, and C).

The northeastern end of Susurluk-Havran Fault (SHF) is located on the Susurluk Valley where the NE-SW trending en echelon segments displaced right-laterally the course of Susurluk River (Simav Çayı) in several locations (Figure 4). Recent seismic activity #120_2020.12.11 (Mw=3.8) Taşköprü earthquake provides a right-lateral strike-slip related focal mechanism solution and confirms the segment distribution of SHF in Susurluk Valley (Figure 4). The segments of SHF in the north of İvrindi are responsible for the seismic event #76_2010.08.12 (ML=4.9) having a right-lateral strike-slip related focal mechanism solution and they reach Havran and Burhaniye (Figure 4; Appendices A, B, and C).

The Edremit Plain is a releasing stepover between the SHF and Edremit Fault (ETF). The short ENE-WSW right-lateral strike-slip segments and WNW-ESE trending normal faults in between constitute the general character of ETF in the north of Edremit Gulf (Figure 4; Appendices A, B, and C).

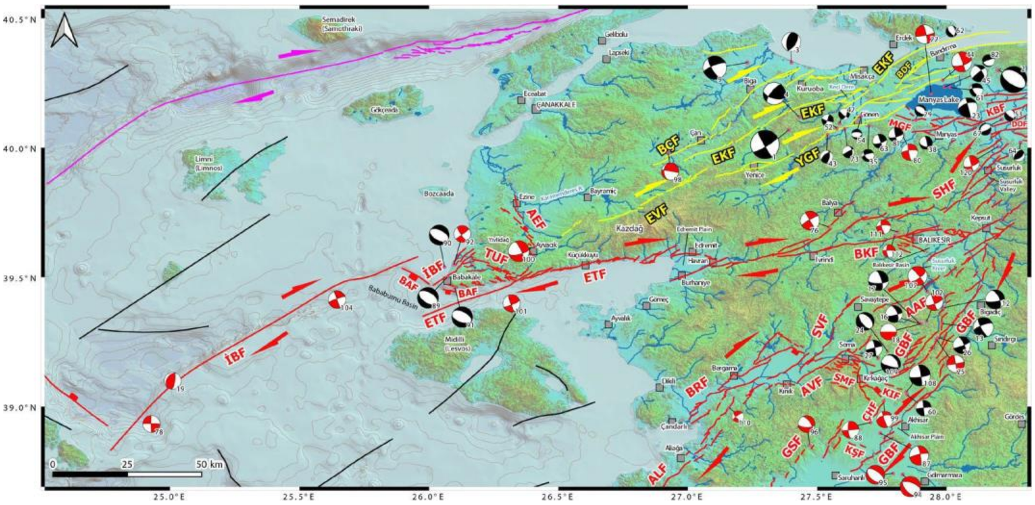


**Figure 4.** The northern (fuchsia), middle (yellow) and southern (red) branches of NAFZ in southern Marmara and northwestern Anatolia. The fault lines from Emre et al. (2013), Caputo and Pavlides (2013), Can (2017) and this paper. DDF: Dorak-Durumtay Fault; MGF: Manyas Gölü Fault; BDF: Bandırma Fault; YGF: Yenice-Gönen Fault; EKF: Edincik Fault; BÇF: Biga-Çan Fault; EVF: Evciler Fault; ETF: Edremit Fault; AEF: Ayvacık-Ezine Fault; TUF: Tuzla Fault; İBF: İskiri-Biga Fault; BAF: Babakale Fault; SHF: Susurluk-Havran Fault; BKF: Balıkesir-Kepsut Fault; AAF: Akçaköy-Ataköy Fault; SVF: Savaştepe Fault; AVF: Avdan Fault; BRF: Bergama Fault; ALF: Aliağa Fault; GBF: Gelenbe Fault; GSF: Gülbahçe-Seyitoba Fault; SMF: Soma Fault; KIF: Kırkağaç Fault; ÇHF: Çobanhasan Fault; KŞF: Kayışlar Fault.

***Şekil 4.*** *Güney Marmara ve Kuzeybatı Anadolu'da Kuzey Anadolu Fay Zonu'nun kuzey (fuşya), orta (sarı) ve güney (kırmızı) kolları. Fay hatları: Emre vd. (2013), Caputo ve Pavlides (2013), Can (2017) ve bu makale. DDF: Dorak-Durumtay Fayı; MGF: Manyas Gölü Fayı; BDF: Bandırma Fayı; YGF: Yenice-Gönen Fayı; EKF: Edincik Fayı; BÇF: Biga-Çan Fayı; EVF: Evciler Fayı; ETF: Edremit Fayı; AEF: Ayvacık-Ezine Fayı; TUF: Tuzla Fayı; İBF: İskiri-Biga Fayı; BAF: Babakale Fayı; SHF: Susurluk-Havran Fayı; BKF: Balıkesir-Kepsut Fayı; AAF: Akçaköy-Ataköy Fayı; SVF: Savaştepe Fayı; AVF: Avdan Fayı; BRF: Bergama Fayı; ALF: Aliağa Fayı; GBF: Gelenbe Fayı; GSF: Gülbahçe-Seyitoba Fayı; SMF: Soma Fayı; KIF: Kırkağaç Fayı; ÇHF: Çobanhasan Fayı; KŞF: Kayışlar Fayı..*

## THE SOUTHERN BRANCH OF NAFZ FROM ULUBAT, MANYAS TO BIGA PENINSULA AND ITS RELATIONSHIP WITH THE MIDDLE BRANCH

The Ulubat Lake is located on a pull-apart basin and its western margin is composed of the strike-slip Karacabey Fault (KBF), similar to the eastern margin that is mentioned above as Ulubat-Doğanköy Fault (UDF) (Figure 3). The segments of KBF right-laterally displace several streams located between Ulubat and Manyas lakes, particularly around Karacabey (Figure 3; Figure 4). The WNW trending semi-parallel normal faults at the south of Manyas Lake constitutes the Manyas Gölü Fault(MGF) (Figure 4). These are releasing offset structures developed both between the segments of Karacabey Fault (KBF), and between the KBF and Yenice-Gönen Fault (YGF). Their normal fault character has been proven by the palaeoseismological study of Kürçer et al. (2017) and the focal mechanism solution of seismic event #29_2005.05.06 (Md=3) (Figure 4).

The NE-SW trending Yenice-Gönen Fault (YGF) can be extended towards the northeast contrary to Emre et al. (2011b). Its en echelon segments can be recognized at the north and northwest of Manyas Lake. The focal mechanism solutions of the seismic events #44_2006.10.20 (ML=5.2) and #45_2006.10.20 (Md=4.4) confirm their right-lateral strike-slip kinematics (Figure 4). The southwest continuation of YGF follows mainly surface ruptures of the #1_1953.03.18 (M=7.4) earthquake (Emre et al., 2011c) (Figure 4).

The active Bandırma Fault (BDF) is drawn to the east-northeast of Bandırma parallel to the southern Marmara coast by Emre et al. (2011b). The seismic reflection studies (Can, 2017) demonstrate that this fault reaches the Gemlik Bay. The onshore continuation of BDF is located on the west of Bandırma and possibly links to the segments of Yenice-Gönen Fault (YGF) (Figure 4).

In the southeast of Erdek, the Edincik Fault (EKF) of Emre et al. (2011b) was drawn on the isthmus between Kapıdağ peninsula and Bandırma (Figure 4). The segments of EKF create right-lateral displacements on the streams at the north of Gönen. The right-lateral shift on the route of Keçi Dere is noteworthy (Figure 4).

We introduce Biga-Çan Fault (BÇF) having segments along Çan and Biga and provides a new interpretation for the segments between Misakça and Kuruoba which is different than the view of Emre et al. (2011b) (Figure 4; Appendices A, B, and C). However, the segment distribution of Evciler Fault (EVF) somewhat corresponds to the Emre et al. (2011c), despite slight differences and newly recognized segments (Figure 4).

It is accepted after the publication of Barka and Kadinsky-Cade (1988) that the middle branch of NAFZ follows south of İznik Lake, Gemlik Gulf, and Biga Peninsula via Bandırma (Figure 1c and 2). When this classification is considered, the middle branch of NAFZ is represented by the Bandırma Fault (BDF), Yenice - Gönen Fault (YGF), Edincik Fault (EKF), Biga-Çan Fault (BÇF), and Evciler Fault (EVF) which ends at the northwest of Kazdağ (Figure 2 and 4). On the other hand, the southern branch of NAFZ represented by the Edremit Fault (ETF) and İskiri-Biga Fault (İBF), and a releasing stepover is created between them at the southwest end of Biga Peninsula (Seyitoğlu et al., 2017). In this releasing stepover, the normal faults of Ayvacık-Ezine (AEF), Tuzla (TUF), and Babakale (BAF) are developed and they control the Yivlidağ range and Bababurnu basin (Yaltırak et al., 2012) (Figure 4; Appendices A, B, and C). The uplift of normal fault controlled Yivlidağ range may create 36 ka BP route change of Karamenderes River (İşler et al., 2008) (Figure 4), but this was attributed to the compressional forces between left stepping Biga-Çan and Edremit faults (Gürer et al. 2021).

## THE SOUTHERN BRANCH OF NAFZ FROM BALIKESİR TO DEĞİRMENLİK (MILOS) ISLAND VIA İZMİR

It is reasonable to accept that major right-lateral shift (22.7 km) on the course of Susurluk River is tectonically controlled in Kepsut (Figure 4). However, it is unrealistic to expect to create such amount of displacement by a fault segment with limited length. It can be said that Susurluk River may follow the existing fault line (Figure 4). The overall structure of Balıkesir-Kepsut Fault (BKF) indicates that the Balıkesir Plain is a releasing stepoverbetween the NE-SW trending right-lateral strike-slip segments and it can be evaluated as a pull-apart basin (Figure 4; Appendices A, B and C). This interpretation provides a meaningful solution to the problem created by the previous studies (Emre et al., 2011c; 2018; Sözbilir et al., 2016b; Sümer et al., 2018) that is the abrupt termination of their Balıkesir and Havran-Balya faults in the middle of western Anatolia without any connection to the major structures (Figure 1g; see also Discussion section).

Further to south, the Akçaköy-Ataköy Fault (AAF) is determined by right-lateral displacements on the several streams including Susurluk River. Its right-lateral strike-slip kinematics is confirmed by the focal mechanism solution of the seismic event #107_2019.12.10 (ML=5.0) (Figure 4; Appendices A, B, and C).

The previously mapped (Şaroğlu et al., 1992; Emre et al., 2011c; 2011d) NNE-SSW trending Gelenbe Fault (GBF) is responsible for the prominent right-lateral shift on the course of Simav Çayı at the west of Bigadiç. The segments of GBF have considerable seismic activities reflecting their right-lateral strike-slip nature (Figure 4; Appendices A, B, and C).

The overall normal fault character of the segments of Soma Fault (SMF) and Kırkağaç Fault (KIF) can be attributed to a releasing stepover between the right-lateral strike-slip faults of Avdan Fault (AVF) and Gelenbe Fault (GBF) (Figure 4). The Neogene Soma basin is fragmented by the youngest structures. A similar tectonic relationship can be mentioned for the west of Soma where right-stepping NE-SW trending strike-slip faults created NW-SE trending normal faults (Figure 4). The examples of this structural framework can be seen among the segments of Avdan Fault (AVF) and Bergama Fault (BRF) having normal and strike-slip characters (Figure 4; Appendices A, B, and C).

The en echelon segments of Bergama Fault (BRF) and Aliağa Fault (ALF) reaches to Çandarlı settlement and Menemen Plain respectively (Figure 4 and 5). The right-lateral strike-slip kinematics of ALF is confirmed by the focal mechanism solution of the recent seismic event #110_2020.08.14 (ML=3.0) and by the kinematic data presented by Sangu et al. (2020) (Figure 4; Appendices A, B, and C).

The western margin of Akhisar Plain is bounded by the segments of Çobanhasan Fault (ÇHF) and Gülbahçe-Seyitoba Fault (GSF). The southwest end of Gelenbe Fault (GBF) reaches to the northeast of Saruhanlı and the NW-SE trending, NE dipping normal fault segments of Kayışlar Fault (KŞF) seem to be developed between GBF and GSF (Figure 4; Appendices A, B, and C).

The dominant structure between Manisa and Kuşadası Gulf is composed of NE-SW trending right-lateral strike-slip faults such as Bornova Fault (BOF), Kubilay Fault (KLF), Foça-Yağcılar Fault (FYF), Seferihisar Fault (SRF), and Orhanlı-Karabağlar Fault (OKF) (Figure 5). The NW-SE trending normal faults (i.e., Menemen Fault (MMF), western part of Manisa Fault (MAF), Karşıyaka Fault (KKF), İzmir Fault (İZF), see Appendix A) are developed in the releasing stepovers between the strike-slip faults. For this reason, the strike-slip faults must be considered as a main seismic source for the metropole İzmir rather than normal faults having short, fragmented segments in the İzmir Bay area (Figure 5; Appendices A, B, and C). The main threat for İzmir is the Orhanlı-Karabağlar Fault (OKF), because its northeast end probably cross-cuts the city center where Kadifekale and Şamlı Tepe are evaluated as pressure ridges (see Appendix A) and its southwest end can be securely located between Sisam (Samos) and Ahikerya (Ikaria) islands indicated by the strike-slip focal mechanism solutions of the seismic events (i.e. #75_2009.12.23 (ML=4.5); #103_2019.08.08 (ML=5.0); #115_2020.10.30 (ML=4.1)) and particularly aftershocks of the recent Sisam (Samos) earthquake #113_2020.10.30 (Mw=6.9) (Figure 5; Appendices A, B, and C).

We evaluated the depression in the northeast of Ahikerya (Ikaria) island as a pull-apart basin which is developed in the releasing stepover between Orhanlı-Karabağlar Fault (OKF) and

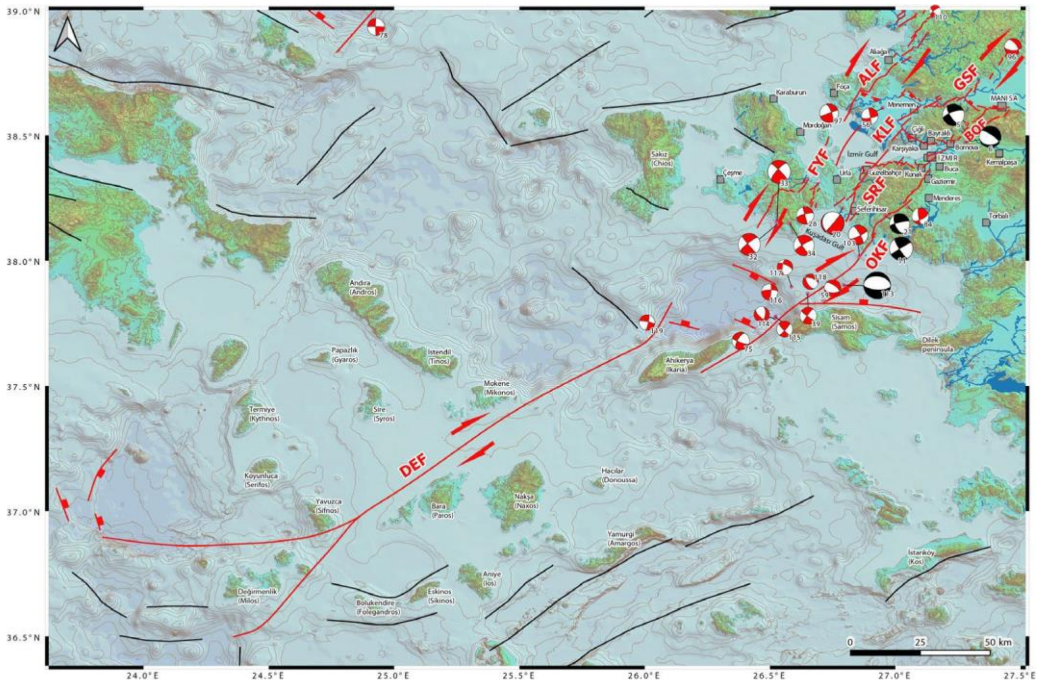


**Figure 5.** The southern branch of NAFZ between Manisa and Değirmenlik (Milos) island. The black fault lines from Caputo and Pavlides (2013). GSF: Gülbahçe-Seyitoba Fault; ALF: Aliağa Fault; KLF: Kubilay Fault; FYF: Foça-Yağcılar Fault; SRF: Seferihisar Fault; OKF: Orhanlı-Karabağlar Fault; DEF: Değirmenlik Fault.

***Şekil 5.*** *Manisa ve Değirmenlik (Milos) adası arasında Kuzey Anadolu Fay Zonu'nun güney kolu. Siyah fay hatları Caputo ve Pavlides (2013)'ten alınmıştır. GSF: Gülbahçe-Seyitoba Fayı; ALF: Aliağa Fayı; KLF: Kubilay Fayı; FYF: Foça-Yağcılar Fayı; SRF: Seferihisar Fayı; OKF: Orhanlı-Karabağlar Fayı; DEF: Değirmenlik Fayı.*

Değirmenlik Fault (DEF) (Figure 5). The position of DEF is drawn with the help of recent focal mechanism solution (i.e., #119_2020.11.06 (ML=4.0)) and the Main Cycladic Lineament of Philippon et al. (2014) that created 50 km right-lateral displacement of the detachment system in the Cyclades (Figure 5; Appendices A, B, and C).

## DISCUSSION

As described above, the southern branch of NAFZ is separated from the main branch at the southwest of Bolu Plain. The NE-SW trending fault segments reach to the north of Mudurnu where the Göldağı block is surrounded by the northern segments via Göynük, and the southern segments following the route of Bekirfakılar and Susuz. After creating Gölpazarı pull-apart basin, the southern branch of NAFZ reaches Bayırköy where the Sakarya River is right-laterally shifted (Figure 3).

The southern branch of NAFZ between Bolu and the Gölpazarı pull-apart basin is relatively less seismic than the other parts. However, re-interpretation of the magnetotelluric and transient electromagnetic (MT) data (Kaya, 2010) demonstrates existing of the southern branch in this area (Seyitoğlu et al., 2016) (Figure 6a). Moreover, the pull-apart nature of Gölpazarı (Gürbüz and Seyitoğlu, 2014) and Üyük basins (Figure 3) indicates that a major strike-slip branch passing through in this location. Kinematic relationship between the Gölpazarı and Bayırköy faults, and their linkage to the faults which bound the eastern margin of Yenişehir pull-apart basin form a different configuration than that of Barka and Kadinsky-Cade (1988) which suggested a linkage

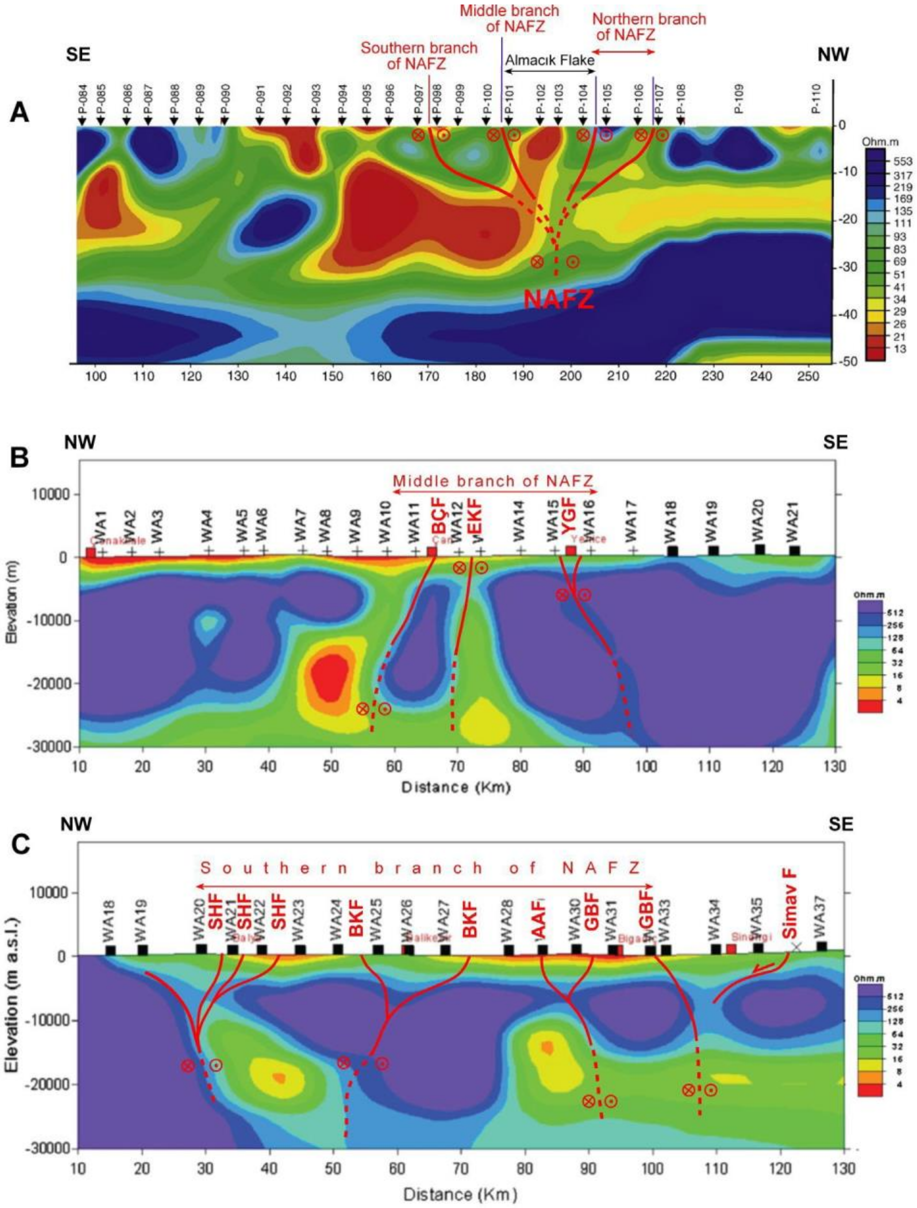


**Figure 6.** The re-interpretation of magnetotelluric and transient electromagnetic (MT) data along the NAFZ. See Figure 2 for locations. A) MT data passing through all branches of NAFZ (after Kaya, 2010 and Seyitoğlu et al., 2016). B) MT data indicates the position of middle branch of NAFZ in Biga Peninsula (re-interpreted after Ulugergerli et al., 2007). C) MT data show details of the southern branch of NAFZ (re-interpreted after Ulugergerli et al., 2007).

***Şekil 6.*** *Kuzey Anadolu Fay Zonu boyunca MT (magnetotelluric and transient electromagnetic) verisinin yeniden yorumlanması. Konumlar için Şekil 2'ye bakınız. A) Kuzey Anadolu Fay Zonu'nun tüm kollarından geçen MT verisi (Kaya 2010 ve Seyitoğlu vd. 2016'dan alınmıştır). B) Biga yarımadasında Kuzey Anadolu Fay Zonu'na ait orta kolun konumunu gösteren MT verisi (Ulugergerli vd., 2007'den yeniden yorumlanmıştır). C) Kuzey Anadolu Fay Zonu'na ait güney kolun detaylarını gösteren MT verisi (Ulugergerli vd., 2007'den yeniden yorumlanmıştır).*

between the middle and southern branches via Mekece (Figure 1c). The Gölpazarı, Üyük, Yenişehir, Bursa-east, and Bursa-west pull-apart basins are developed along the southern branch (Figure 3) and more importantly, the Kayapa-Yenişehir Fault (KYF) is cross-cutting last three pull-apart basins. The KYF creates a nightmare scenario for the seismic evaluation of Bursa city that it is a best candidate for the source of 1855 earthquakes. This relationship also demonstrates that the bend model of Emre et al. (2018), offering a connection between the faults around Bursa and Eskişehir Fault Zone, is not applicable (Figure 1g).

In the southeast of Manyas Lake, the Manyas Gölü Fault (MGF) has a NW-SE trending, NE dipping normal fault which is confirmed by the paleoseismological trench study (Kürçer et al., 2017) and focal mechanism solutions of #2_1964.10.06 (Ms=6.8) and #29_2005.05.06 (Md=3.0) earthquakes (Figure 4; Appendix B). If this information is considered to have a regional significance, the NW-SE trending right-lateral Mustafakemalpaşa Fault of Emre et al. (2013) is contrary to the general situation (Seyitoğlu and Esat, 2022a). Therefore, we evaluated that the northeastern and southwestern slopes of Tokmak Tepe upliftare limited by the NW-SE trending opposite dipping normal faults and it becomes a horst structure between nearly E-W trending right-lateral Dorak-Durumtay Fault (DDF) and Derecik (DKF) / Mustafakemalpaşa (MPF) faults (Figure 3 and 4). The re-interpreted position of MPF is concordant with both the Lalaşahin trench site of Kop et al. (2016) and the 850 m right-lateral shift on Mustafakemalpaşa Çayı, which is previously unexplained by Emre et al. (2011b) (Figure 3) (Appendix A).

There is another important role of the Manyas Gölü Fault (MGF) which provides a connection between southern and middle branches of NAFZ as a releasing stepover structure (Figure 4). The Yenice-Gönen Fault (YGF) and its parallel counterparts, the Ekincik Fault (EKF), Biga-Çan Fault (BÇF), Evciler Fault (EVF), and the Bandırma Fault (BDF) can be classified as the middle branch of NAFZ which is linked to the Gemlik Bay via offshore faults (Can, 2017) in the southern Marmara (Figure 2). The crustal scale discontinuities of the middle branch of NAFZ in the Biga Peninsula can be seen clearly in the re-interpreted MT section (i.e., Biga-Çan Fault, Ekincik Fault, and Yenice-Gönen Fault) (Figure 6b).

The southern branch of NAFZ creates a releasing stepover between Ulubat-Doğanköy Fault (UDF) and Karacabey Fault (KBF) where the Ulubat Lake is located (Figure 3 and 4). The en echelon segments of Susurluk-Havran Fault (SHF) pass through Susurluk Valley and reach Havran that is linked to the Edremit Fault (ETF) at the south of Kazdağı with a releasing stepover in the Edremit Plain (Figure 4). The releasing stepover between Edremit Fault (ETF) and İskiri-Biga Fault (İBF) hosts the Bababurnu pull-apart basin in the Aegean Sea (Figure 4).

The long-lived seismic quiescence along the southern branch in Susurluk Valley has been ended by the recent seismic event #120_2020.12.11 (Mw=3.8) (Seyitoğlu et al., 2020a) and its focal mechanism solution confirms the positions of right-lateral strike-slip segments of Susurluk-Havran Fault (SHF) which is drawn by using morphological and structural evidences such as shift or bend of the semi-parallel multiple stream channels and fault surfaces in the Susurluk Valley (Appendix A; Seyitoğlu and Esat, 2022a) (Figure 4).

There are different arguments on the nature of Edremit Fault (ETF) (Figure 4) in the recent literature. Sözbilir et al. (2016a) mentioned about multi-phased tectonic history for the Edremit Fault (ETF) and conclude that its recent extensional phase produces normal faults. However, Gürer et al. (2016) define the Edremit Fault (ETF) as a right-lateral strike-slip fault. Moreover, the previous field observation of Kurt et al. (2010) indicates that strike-slip faulting cuts the low-angle detachment system of Kazdağ Core Complex. We provide a solution for this controversy with our segment distribution (Figure 4; Appendices A, B, and C). It is suggested that ENE-WSW trending right-lateral strike-slip faults creating releasing stepovers where the WNW-ESE trending normal faults are developed. The trench site of Sözbilir et al. (2016a) nearly corresponds to the strike-slip segments and the sites of necropolis and terrace houses of historical settlement of Antandros are located on the normal fault segments of the Edremit Fault (ETF) (Appendix A). This fault configuration explains both strike-slip and normal faulting observations and there is no need to multi-phased explanations forthe activity of Edremit Fault as suggested by Sözbilir et al. (2016a) (Figure 4).

The active faults between Edremit and Balıkesir have been mapped under the title of Havran-Balya Fault Zone and Balıkesir Fault (Emre et al., 2011c; 2013). These faults are confirmed by paleoseismological studies and their structural data are presented without questioning their regional tectonic meaning (Sözbilir et al., 2016b; Sümer et al., 2018). It is interesting that these faults suddenly end in the middle of western Anatolia with a slight bending towards the southeast (Figure 1g). We re-interpreted these structures and provide segment distributions under the title of Susurluk – Havran Fault (SHF) and Balıkesir-Kepsut Fault (BKF). The segments of BKF create Balıkesir pull-apart basin in the releasing stepover and control the largest right-lateral shift on the Simav Çayı / Susurluk River (Figure 4).

Further south, the NE-SW Akçaköy-Ataköy Fault (AAF) and NNE-SSW Gelenbe Fault (GBF) are located (Figure 4). Especially, Susurluk-Havran Fault (SHF) and Akçaköy-Ataköy Fault (AAF) together with Gelenbe Fault (GBF) are crustal-scale structures of the southern branch of NAFZ as seen in the re-interpreted MT section (Figure 6c).

In the southwest of Balıkesir, one branch reaches to the east of Karaburun Peninsula with the Akçaköy-Ataköy (AAF), Savaştepe (SVF), Avdan (AVF), Bergama (BRF), Aliağa (ALF) and Foça-Yağcılar (FYF) faults. The Bergama and Menemen plains are located on their releasing stepovers (Figure 4 and 5). Sangu et al. (2020) also agree that southern branch of NAFZ reaches the Bergama area.

The other branch reaches to Kuşadası Gulf with the Gelenbe (GBF), Çobanhasan (ÇHF), Gülbahçe-Seyitoba (GSF), Bornova (BOF), Kubilay (KLF), Seferihisar (SRF) and Orhanlı-Karabağlar (OKF) faults. The İzmir Gulf, west of Manisa and Akhisar and Kırkağaç plains are related to the releasing stepovers. The southern branch of NAFZ reaches to the Değirmenlik (Milos) island via a pull-apart basin at the northeast of Ahikerya (Ikaria) island (Figure 5).

The recent seismic activities in the Kırkağaç and Akhisar plain can be explained by the southern branch of NAFZ (Seyitoğlu et al., 2020b). The focal mechanism solutions of 2020.01.22 (Mw=5.5) Musalar-Akhisar earthquake is presented in Figure 7. The focal mechanism solution presented in this paper (Appendix B) and that of KOERI and AUTH are concordant to each other (Figure 7). The aftershock distribution intensifying along the NNW-SSE direction indicates that the fault plane having strike and dip value of N10W, 80NE in the focal mechanism solution is the source of earthquake. This fault plane has a left-lateral strike-slip character. On the other hand, due to the AFAD's focal mechanism solution which is similar to that of USGS, the N23W, 60NW normal fault with a left-lateral component is accepted as earthquake source and linked with the Kırkağaç Fault (AFAD, 2020; Sözbilir et al., 2020) (Figure 7). One of the most outstanding features of seismic activity in the region is the epicentre distribution

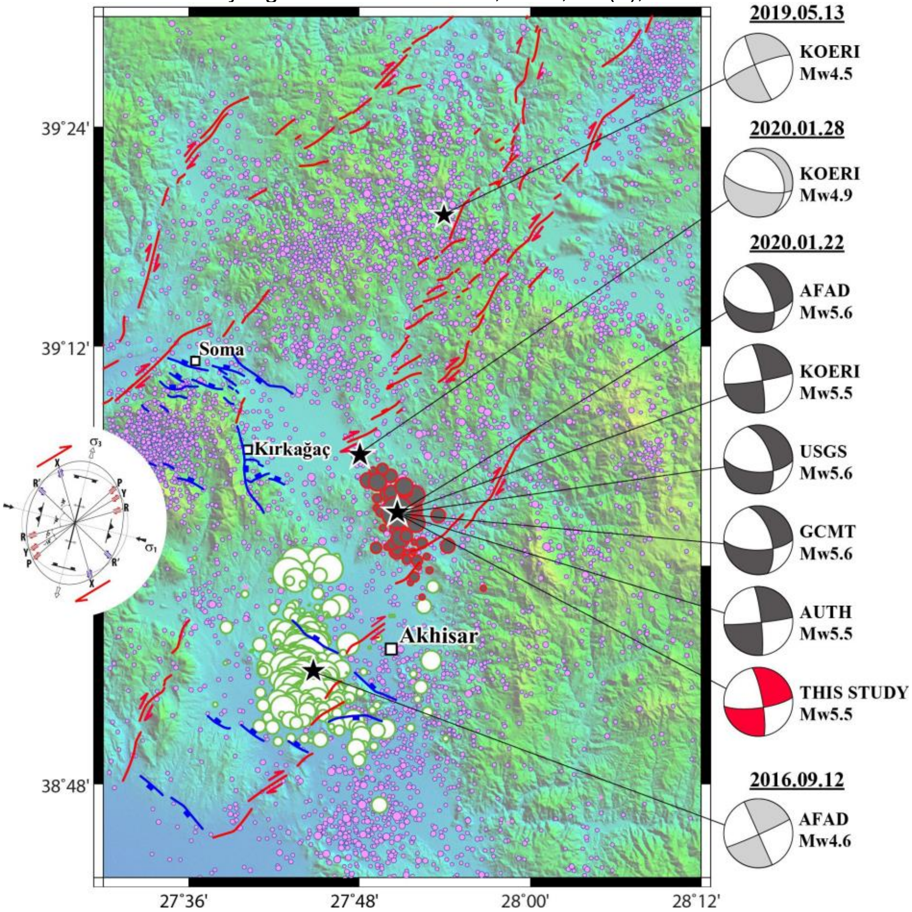


**Figure 7.** Earthquake epicenter distribution and focal mechanism solutions in the Akhisar region (See Appendix B for details). Red and green circles are the aftershocks of the seismic events 2020.01.22 and 2016.09.12, respectively. The distribution of the epicenters reflects the dates of 2000.01.01-2020.01.28 and was obtained from AFAD catalogue. KOERI: Kandilli Observatory and Earthquake Research Institute, Boğaziçi University; AFAD: Disaster and Emergency Management Presidency, Turkish Republic Ministry of Interior; USGS: United States Geological Survey; GCMT: Global Centroid Moment Tensor catalog; AUTH: Aristotle University of Thessaloniki, Seismological Station.

***Şekil 7.*** *Akhisar bölgesinde deprem dışmerkez dağılımı ve odak mekanizması çözümleri (detaylar için Ek B'ye bakınız). Kırmızı ve yeşil daireler sırasıyla 2020.01.22 ve 2016.09.12 sismik olaylarının artçı şoklarıdır. Dışmerkezlerin dağılımı 2000.01.01-2020.01.28 tarihleri arasını yansıtır ve AFAD kataloglarından alınmıştır. KOERI: Kandilli Observatory and Earthquake Research Institute, Boğaziçi University; AFAD: Disaster and Emergency Management Presidency, Turkish Republic Ministry of Interior; USGS: United States Geological Survey; GCMT: Global Centroid Moment Tensor catalog; AUTH: Aristotle University of Thessaloniki, Seismological Station.*

of earthquakes that occurred between 12-30 September 2016 in the south of Akhisar (Figure 7, green circles). The 2016.09.12 (Mw=4.6) earthquake has a similar focal mechanism solution with the 2020.01.22 Musalar-Akhisar earthquake and is interpreted by Kartal et al. (2016) as a left-lateral transfer fault between normal faults. In addition, the 2019.05.13 (Mw=4.5) Kocaiskan-Kırkağaç earthquake locating at the north of 2020.01.22 Musalar

Akhisar earthquake has strike-slip relatedfocal mechanism solution. All these earthquakes, which have an en echelon position to each other, can be related to the left-lateral X-shear in the NE-SW right-lateral shear zone of the southern branch of NAFZ rather than local transfer structures (Figure 7).

The bend model proposed by Emre et al. (2018) has become invalid because the connection of the right-lateral faults to the main NAFZ in Bolu has been shown in this paper. The bend model also does not explain the strike-slip related seismic activity aroundİzmir.

The strike-slip structures around İzmir have been interpreted as transfer zones between main normal faults (Şengör, 1987). The transfer zones by their nature only develop between major normal faults (Gibbs, 1984; Faulds and Varga, 1998). However, as shown in our paper, the strike-slip structures had been developed beyond the major normal faults (i.e., Alaşehir and Simav grabens), therefore this interpretation needs re-consideration.

The weakest point of the İzmir-Balıkesir Transfer Zone model, which is thought to develop due to the different extension rates between the Aegean Sea and western Türkiye (Ring et al., 1999; Uzel and Sözbilir, 2008; Uzel et al., 2013), is lack of definition for the connections to the main structures on its northeast and southwest tips.

For these reasons, the strike-slip related seismic activity in south of Marmara and western Türkiye is best explained by the presence of the southern branch of the NAFZ.

## CONCLUSION

The southern branch of NAFZ separates from the main branch at the southeast of Bolu Plain and creates several pull-apart basins which are enlarged towards west-southwest. The southern branch reaches the Aegean Seaboth in Edremit Gulf and in the south of İzmir. This configuration of the southern branch better explains the recent strike-slip related seismic activity in the western Türkiye rather than the non-integrated solutions such as the previous bend model and the concept of İzmir-Balıkesir Transfer Zone.

The southern branch of NAFZ should be further studied in detail because it implies that the major cities such as İzmir, Manisa, Akhisar, Balıkesir, and Bursa are under the threat of major strike-slip faulting as well as newly built superstructures such as highways and high-speed railways.

## ACKNOWLEDGMENT

Field studies around Bursa have been carried out in the project UDAP-G-18-05 supported by AFAD.

## APPENDIX A

https://dergipark.org.tr/tr/download/issue-file/60473

## APPENDIX B

https://dergipark.org.tr/tr/download/issue-file/60472

## APPENDIX C

https://dosyam.ankara.edu.tr/y93xzyn5

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