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Plio-Quaternary kinematic development and paleostress pattern of the Edremit Basin, western Turkey

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ABSTRACT

The Edremit Basin and Kazdağ High are the most prominent morphological features of the Biga Peninsula in northwest Anatolia. There is still no consensus on the formation of Edremit Basin and debates are on whether the basin evolved through a normal, a right-lateral or a left-lateral strike-slip faulting. In this study, the geometric, structural and kinematic characteristics of the Edremit Basin are investigated to make an analytical approach to this problem. The structural and kinematic features of the faults in the region are described according to field observations. These fault-slip data derived from the fault planes were analyzed to determine the paleostress pattern of faulting in the region. According to the performed analysis, the southern end of the Biga Peninsula is under the influence of the ENE-WSW-trending faults of the region, such as the Yenice-Gönen, the Edremit, the Pazarköy and the Havran-Balıkesir Fault Zones. The right step-over geometry and related extension caused to the development of the Edremit Basin as a transtensional pull-apart basin between the Havran-Balıkesir Fault Zone and the Edremit Fault Zone. Field observations showed that the Plio-Quaternary faults at the Edremit Gulf and adjacent areas are prominently right-lateral strike-slip faults. Our paleostress analyses suggest a dominant NE–SW extension in the study area, as well as NW–SE direction. This pattern indicates the major effects of the North Anatolian Fault System and the component of Aegean Extensional System in the region. However, our kinematic analysis represents the dominant signature of the North Anatolian Fault System in basin bounding faults. The field observations and kinematic findings of this study are also consistent with the regional GPS, paleomagnetic and seismological data. This study concludes that the North Anatolian Fault System is the prominent structure in the current morphotectonic framework of the Edremit Gulf and adjacent areas.

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1. Introduction

The neotectonic evolution of Turkey and its surrounding area is controlled by three primary geodynamic processes: (1) the collision of the Arabian Plate with the Eurasian Plate throughout Bitlis-Zagros Suture Zone, (2) the westward movement of the Anatolian Block throughout the North and East Anatolian Fault Systems starting from the Arabian–Eurasian collision zone (e.g. McKenzie, 1972; Şengör, 1979) and (3) the subduction of the African Plate underneath the Eurasian Plate throughout the Southern Aegean Trench (e.g. McKenzie, 1972; Jackson and McKenzie, 1988; Jolivet et al., 2013). This subduction is also thought to lead the extensional regime in western Turkey.

Our study area is located at northwest Anatolia. The main structural and geological characteristics of the region are the Edremit Gulf, Kazdağ and Madra Mountains, western branches of the North Anatolia Fault System (NAFS) and İzmir Ankara Suture Zone (Fig. 1). The İzmir-Balıkesir Transfer Fault Zone (İBTFZ), is another feature in southeast of the region, which is claimed to form an intersection of the Aegean Extensional System (AES) and the Anatolian Domain (Kaya, 1979; Uzel et al., 2013; Özkaymak et al., 2013; Gessner et al., 2013).

Northwest Anatolia was exposed to the reciprocal interaction of the compression-extension systems during the Late Cenozoic like the entire west Anatolia. The horsts and grabens in western Turkey, which are the most significant morphotectonic features of the region, were also formed during the Late Cenozoic (Fig. 1b). There are primarily two groups of basins according to their geometric positions: the E–W and N–S trending basins. The E–W-trending basins and associated faults are the most distinctive features of western Anatolia (e.g. Şengör, 1979; Yılmaz et al., 2000; Gürer et al., 2001; Bozkurt, 2003; Gürer et al., 2009, 2014; Yılmaz et al., 2010).

Our study area is located at the intersection of the right-lateral strike-slip regime of the ENE-WSW-trending NAFS and the N–S-trending extension by the AES (Fig. 1b). For this reason, it is accepted that the neotectonic deformation of the region has simultaneously been controlled by these two factors (e.g. Taymaz et al., 1991; Yılmaz

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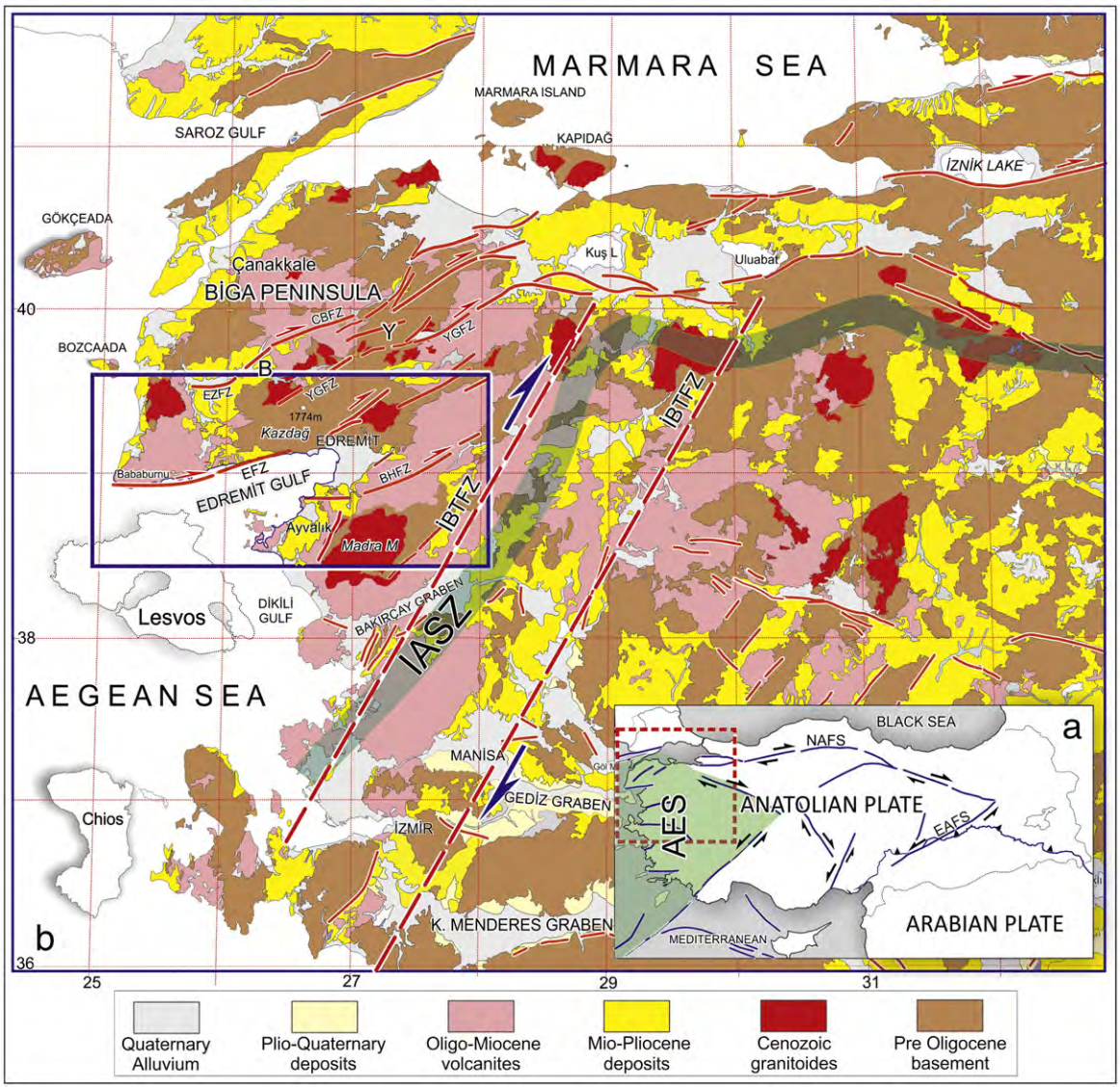


Fig. 1. a. Tectonic map of Turkey showing major tectonic structures (Gürer et al., 2013). b. Simplified geologic map of northwest Anatolia Region (modified from MTA, 2002). IASZ: İzmir-Ankara Suture Zone (Şengör and Yılmaz, 1981), B; Bayramiç, Y; Yenice, EZFZ: Ezine Fault Zone, EFZ: Edremit Fault Zone, HBFZ: Havran-Balıkesir Fault Zone, YGFZ: Yenice Gönen Fault Zone.

et al., 2000; Pfister et al., 2000; Gürer et al., 2003, 2006). We investigated the effects of extensional and strike-slip systems in the region via studying the Edremit Basin which is one of the most significant tectonic structures of northwest Anatolia.

The western part of Edremit Basin is in the Edremit Gulf, while its small eastern part is located on the land. The northern margin of the basin displays a well-developed and basinward-facing step-like morphology due to the considerable amount of normal slip component along the margin-boundary faults. However, owing to the high gradient transverse drainage system shaping the northern margin, this morphotectonic pattern is highly dissected. In particular, the northern margin of Edremit Basin is surrounded by thick and weakly consolidated fan-apron deposits formed by the coalescence of older isolated fans covering areas of 1–3 km^2. The southern edge is indented with less steep hillsides. The highest peak of the region is on the Kazdağ with a height of 1774 m. The length of the gulf is 80 km, while the width increases from 1 to 5 km at the east end to 30 km at the west. The shelf on the northern side of the gulf is particularly steep and narrow. The shelf area on the east and southern edge is less steep and wider. The water depth in the gulf is 100 m on average while the deepest point is 139 m in NE to SW direction. It is bounded by the Müsellim Strait at the narrowest point between the Lesbos Island and the Biga Peninsula to the west, and by the Dikili Strait between Ayvalık and the Lesbos Island to the south. (Fig. 2).

There are several paleomagnetic (İşseven et al., 1995; Schindler, 1997; Kaymakçı et al., 2007) and GPS studies (Straub and Kahle, 1997; Straub et al., 1997; Aktuğ et al., 2009) in the region that explain the opening of Edremit Basin. All of the paleomagnetic studies suggest counterclockwise rotation values between 7–40° around the Edremit Basin. According to paleomagnetic data by İşseven et al. (1995), the northern and the southern blocks around the Edremit Gulf have different rotation directions, which their difference has led to development of the basin.

According to GPS data, the Biga peninsula and its surroundings move to the west and southwest with a velocity of 2–3 cm/year (Fig. 3b) (McClusky et al., 2000; Straub and Kahle, 1997; Aktuğ et al., 2009). The GPS data around the Edremit Gulf show a velocity of 2 cm/year to the SW direction (B. Aktuğ personal communication, 2013). The GPS vectors and the strain directions obtained from them (e.g. Straub and Kahle, 1997 suggest strain extension axes in a NE–SW direction in the northern part of the Edremit Gulf, while a NW-SE strain axis dominant in the southern part (Fig. 3b; Barka and Reilinger, 1997).

Tectonic features of the continental shelf of Bababurnu promontory (Fig. 2) and their relations to those observed onshore and offshore were investigated by multi-channel seismic reflection and seismicity

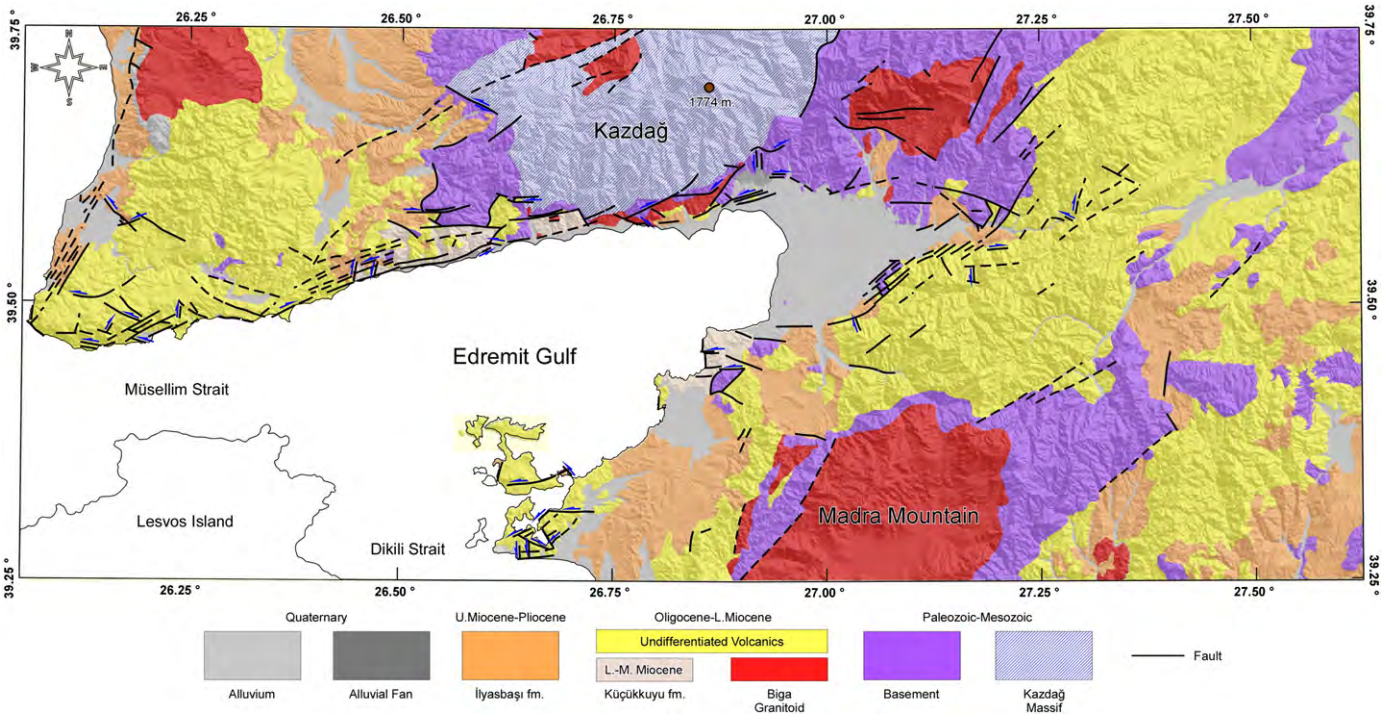


Fig. 2. Simplified geologic map of Edremit Basin and its surrounding area.

in the light of available geological and morphological data (Boztepe-Güney et al., 2001). They concluded that: (1) the Edremit Gulf is a fault bounded basin mainly formed by the E-W trending faults (during Late Pliocene-Pleistocene). (2) N–S extensional regime that produced the westward opening of the Edremit Gulf is still in progress. (3) The major fault zone running parallel to the coastline of the Edremit Gulf has apparently controlled the development of the coastal morphology. Kurtuluş et al. (2009) suggested a structural map and tectonic model for the Edremit Gulf was derived from interpreting 21 deep seismic profiles that trending NE–SW and NW–SE directions within the gulf. According to the authors, there is no evidence of any strike-slip faulting within the study area and the gulf has controlled by only E–W trending parallel normal faults. Yaltırak et al. (2012), interpreted the Bababurnu Basin as a pull-apart structure in the northeastern Aegean Sea based on offshore seismic data. Yılmaz and Karacık (2001) studied the folds and faults around the Edremit Gulf and defined the Kazdağ Mount and the

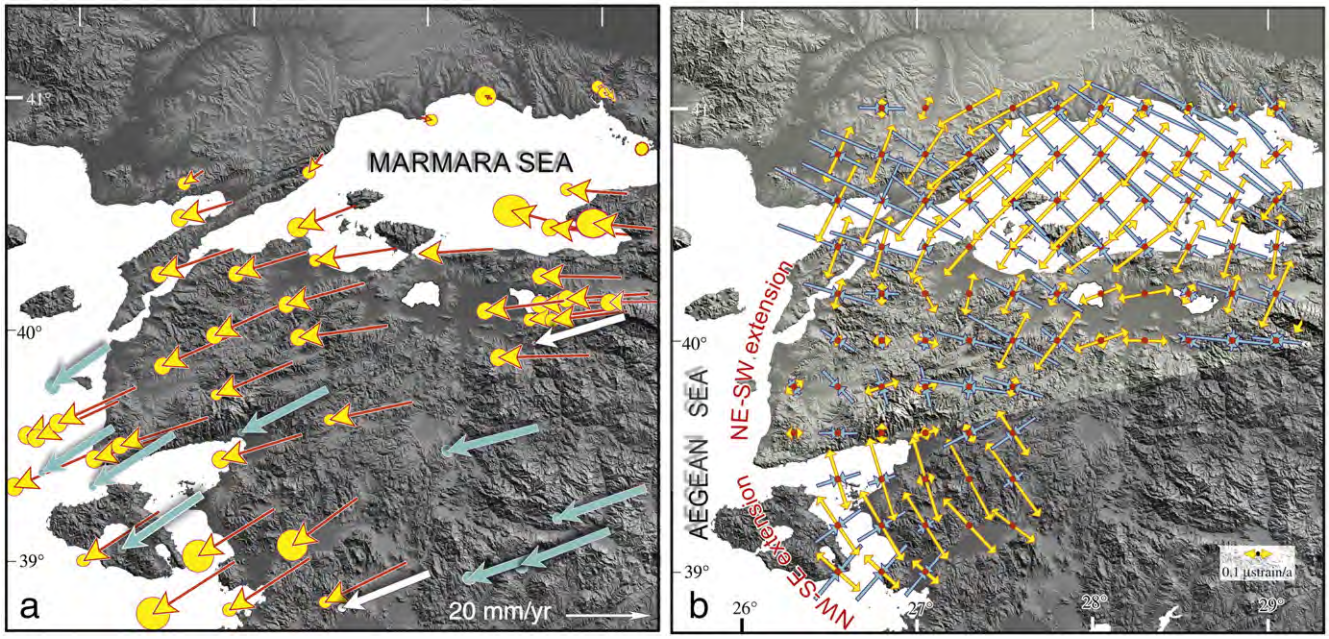


Fig. 3. a. Combined velocity field of western Anatolia with respect to stable Eurasia. Thick blue arrows represent the velocities of survey mode sites determined (Aktuğ et al., 2009). Thick white arrows are velocities at CGPS stations determined (Aktuğ et al., 2009). Thin red-yellow arrows represent velocities taken from Reilinger et al. (2006) and combined with Aktuğ et al. (2009) velocity field. Error ellipses are at 95% confidence level. b. Normal strain rates compiled from GPS data. Yellow arrows show the strain, whereas blue arrows show the compression. Average strain rate is 0.11 μstrain/year (maximum stress 0.31 μstrain/year) Average compression rate is −0.12 μstrain/year (maximum compression −0.47 μstrain/year) (Straub and Kahle, 1997).

Edremit Basin as normal fault bounded horst and graben structures, respectively. Some researchers have argued that the Kazdağ uplift as a metamorphic core complex that expanded during the Oligo–Miocene (Okay and Satır, 2000; Beccaletto and Steiner, 2005; Bonev et al., 2009; Cavazza et al., 2009). Bonev et al. (2009) studied the extensional structures in the south of Kazdağ Massif. They concluded that the massif elevated as a result of the Aegean post-orogenic back-arc extension. The extensional structures to the north and to the south of Kazdağ Massif show opposite dips and kinematics and suggest a latest Oligocene NE–SW-directed bivergent mode for extension of the western side of Kazdağ Massif (Bonev et al., 2009).

Conversely, Erdoğan et al. (2013) suggested that the relationship between the foliation planes and tectonic contacts in the metamorphic rocks of the Kazdağ Massif contradicts the core complex model. The current uplift of the Kazdağ Massif was formed throughout the NAFS during the Plio-Quaternary (e.g. Okay and Satır, 2000; Yılmaz and Karacık, 2001; Beccaletto and Steiner, 2005; Bonev et al., 2009; Cavazza et al., 2009; Erdoğan et al., 2013).

There are various faults in the region formed within various kinematic features during the Neogene-Quaternary. Their structural and kinematic relationships with the lithological units in adjacent areas have not been clearly-studied to date.

There is no agreement on the mechanism by which the Edremit Basin has formed. The geometries and the types of the faults that created and control the basin, the structural relationships among them, and how they are related to the Late Cenozoic sedimentary and magmatic units in the region are the main contested issues. Several researchers have suggested various mechanisms for the origin of basin: (a) strike-slip faults associated with NAFS (e.g. Okay and Satır, 2000), (b) normal faults associated with AES (e.g. Kurtuluş et al., 2009), and (c) coupled effects of both NAFS and AES (e.g. Yılmaz and Karacık, 2001; Boztepe-Güney et al., 2001). None of these studies include any detailed kinematic analyses particularly regarding the Late Miocene-Quaternary faults in the Edremit Basin and adjacent areas. The geometries and types of the faults that created and controlled the Edremit Basin, their interactions with each other, and relationships with Neogene-Quaternary units are still unclear and subject to debate. Our study examines in detail the kinematics of the faults surrounding the basin and their roles in the formation of the basin. The results showed the existence of two dominant minimum horizontal stress (S_{hmin}) trends, NE–SW and NW–SE, in the region. These trends are in consistent with the strike-slip regime of the NAFS and extensional system of the AES.

2. Geological setting

In the Biga Peninsula, while the Paleozoic and Mesozoic metamorphic and ophiolitic rocks and Early Cenozoic plutonic rocks form the basement, the Late Cenozoic sedimentary and volcanic rocks form its cover units (Fig. 2).

The Kazdağ Massif is located on the southern margin of Biga Peninsula as an important ENE-WSW-trending morphological rise between the Edremit Gulf and Yenice-Bayramiç Basin (Figs. 1, 2). The primary lithology of the Kazdağ uplift consists of Paleozoic-Triassic gneiss, amphibolites and marbles (e.g. Bingöl et al., 1975; Duru et al., 2004). This mount is obducted tectonically by the Permo-Triasic Karakaya complex to the east and north, and the Cretaceous Çetmi ophiolithic melange to the west (Duru et al., 2004; Beccaletto and Steiner, 2005; Şengün et al., 2011) where in the Biga Peninsula, the regional N-S compression and intense magmatic activities were prominent during the Early Cenozoic (Yılmaz et al., 2001). Magmatic rocks are particularly common in the Biga Peninsula (Fig. 2). Magmatism is represented by the Middle Eocene and Oligo-Miocene plutonic and volcanic rocks. The intrusions to the north of Biga Peninsula were settled in the periods ranging between the Eocene and Miocene (Karacık et al., 2008). To the south, 31–16 Ma old intermediate and felsic units such as andecites, trachytes, dacites, latites and rhyolites are interbedded with fluvio-lacustrine deposits (e.g. Yılmaz, 1989; Bingöl et al., 1994; Altunkaynak and Yılmaz, 1998; Genç, 1998; Aldanmaz et al., 2000). The last magmatic phase in Western Anatolia is represented by the Late Miocene-Quaternary alkaline products. Olivine basalt, basalt and basanites are the major products of the last volcanism (between 8.4 Ma and 0.13 ± 0.005 Ma; Richardson-Bunbury, 1996; Yılmaz and Karacık, 2001; Alıcı et al., 2002; Aldanmaz et al., 2006).

The sedimentary cover in the region is represented by Neogene-Quaternary units. The largest sedimentary rock formations in the southern part of the Biga Peninsula are the Lower-Middle Miocene Küçükkuyu, the Upper Miocene İlyasbaşı, and the Plio-Quaternary Bayramiç formations (Fig. 2).

3. Method

Paleostress analysis refers to numerous methods used to determine the regional strain tensor consistent with geological structures by combining the direction of fault populations according to fault-slip data. Various techniques have been proposed to estimate the strain tensors (e.g. Angelier and Mechler, 1977; Angelier, 1984; Michael, 1984; Reches, 1987; Fry, 1999; Delvaux and Sperner, 2003). Most of these methods sample the fault that slipped independently within the homogeneous stress area and try to represent the direction of the maximum shear stress on the fault plane by recorded fault-slip data.

Our study analyses the kinematic data measured at different locations around the Edremit Basin. The database compiled as suggested by Sperner and Zweigel (2010) and Hippolyte et al. (2012). In order to determine the fault displacement directions, we took into account the kinematic indicators proposed by Petit (1987) and Doblas (1998). The slickenside striae data were analyzed according to methods proposed by Angelier (1994). For each fault with slickenside striae, we computed: (a) fault plane direction (b) dip direction, (c) dip amount, (d) rake, (e) striae direction and (f) rate referring to the quality of the measured data. The data set was processed using the Direct Inversion Method (INVD) developed by Angelier (1990). The Direct Inversion Method (Angelier, 1990) assumes that the slip is parallel to the calculated maximum shear stress. Thus, it tries to minimize the angle between the calculated maximum shearing stress and the measured direction of slip for each fault plane. As a result, it identifies the most appropriate stress tensor for each group of faults. The identified reduced stress tensor consists of three principal stress axes σ_1, σ_2, σ_3 ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) and the ratio of the principal stress differences $R = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$. The stress axes σ_1, σ_2, and σ_3 correspond to maximum, intermediate, and minimum compressional principal stress axes, respectively (see Angelier (1994) for the details of stress inversion procedure). The principal stress regime is a function of the orientation of the principal stress axes: When σ_1 is vertical, it denotes extension, when σ_2 is vertical, it denotes strike–slip, and when σ_3 is vertical and it denotes compression. Each of these three regimes is associated with a stress ratio R that ranges between 0 and 1 (Angelier, 1994).

The calculated stress by applying the inversion method to heterogeneous data does not characterize the real state of stress. Field observations are important for determining the paleostress based on heterogeneous fault-slip data and to distinguish among the paleostress stages. Heterogeneous sets of fault-slip data was separated into subsets in the field as much as possible. Additionally, the allowable maximum misfit angle (ANG) and the maximum quality estimator (RUP) values (Angelier, 1994) were also taken into account. In the analysis, the ANG (i.e. maximum misfit angle between the observed slip and computed shear stress direction) was taken as 15° and the RUP was taken as 45°. The faults, which exceeded these values, were separated and recomputed as separate tensors.

4. Geometric and kinematic data and paleostress pattern

As mentioned before and summarized in Table 1, there are various suggestions about the role of approximately E-W-trending faults on the uplifting process of the Kazdağ Massif and the formation of the Edremit Basin. Previous researchers generally focused on the uplift of the Kazdağ Massif and only a few of them suggested mechanisms for the development of Edremit Basin. However, none of these works represented any detailed data derived from the fault planes observed in the field. This study discusses the neotectonic features of the region in the light of geometric and kinematic data of the Plio-Quaternary faults based on field observations and discuss them with the current seismological, paleomagnetic and GPS results for the region. The general characteristics of the faults in the Edremit Basin are investigated by the paleostress analysis.

The Biga Peninsula, which is located to the north of Edremit Basin, is shaped under the influences of the NAFS and the AES (e.g., Yılmaz et al., 2000, 2010; Emre et al., 2012). However, the dominant factor that determines the current regional morphology of the peninsula is the NAFS (e.g. Barka and Kadinsky-Cade, 1988). This continental scale structure is observable as a complex fault system due to branching into different strands, particularly in the Marmara region of Turkey, and represents various geometric, geomorphic and kinematic features (e.g. Gürer et al., 2003, 2006; Gürbüz and Gürer, 2009; Kürçer et al., 2008; Demoulin et al., 2013; Selim et al., 2013). As a result of these features, the strike-slip deformation of the NAFS is laterally discontinuous in and around the Biga Peninsula and subdivided into different major en-échelon faults that partially overstepped to form pull-apart and push-up structures. The peninsula is sliced by different fault zones from the north to south. Some of these fault zones are the Edincik, Sinekçi, Manyas, Yenice-Gönen, Sarıköy, Bekten, Evciler, Gündoğan, Kestanbol, Pazarköy, Edremit, Çan-Biga and Havran-Balıkesir Fault Zones (Emre et al., 2012).

Table 1
Mechanisms suggested for opening of the Edremit Basin.and uplifting of the Kazdağ Massif.

Proposed	Edremit Basin	Kazdağ Massif
Siyako et al. (1989)		Late Miocene–Pliocene push-up
İşseven et al. (1995)	Neogene-Quaternary Different velocity of counterclockwise rotation	
Beyhan (1999)	Pliocene Negative flower structure	
Okay and Satır (2000)	Plio-Quaternary NAFS releasing bend	II. Plio-Quaternary NAFS restraining bend
		I. Late Oligocene core complex
Yılmaz and Karacık (2001)	Quaternary Left lateral oblique fault	Late Miocene Oblique faults
Boztepe-Güney et al. (2001)	Late Pliocene-Pleistocene normal fault	
Duru et al. (2004)		Post Miocene core Complex
Beccaletto and Steiner (2005)	Plio-Quaternary NAFS and WAES	II. Plio-Quaternary normal fault
		I. Late Oligocene-early miocene orogenic collapse or back arc basin
Bonev et al. (2009)	Plio-Quaternary high-angle step-like normal faulting	II. Plio-Quaternary high-angle step-like normal faulting
		I. Latest Oligocene aegean post-orogenic back-arc extension
Bonev et al. (2009)		II. Plio-Quaternary high-angle normal fault
		I. Latest Oligocene NE–SW-directed bivergent mode of extension/core complex
Kurtuluş et al. (2009)	Miocene-Quaternary normal fault	
Cavazza et al. (2009)		II. Plio-Quaternary NAFS and WAES
		I.Late Oliogocene-early miocene thermal uplift
Yaltırak et al. (2012)	Quaternary Bababurnu Basin pull apart	
Erdoğan et al. (2013)		Pleistocene E–W trending high angle fault
Demoulin et al. (2013)		Plio-Quaternary back arc and NAFS transpressive

The Plio-Quaternary tectonic of the Edremit Basin is mainly controlled by two of these major right-lateral fault zones that referred as the Edremit and Balıkesir-Havran Fault Zone in accordance with the suggested names of Emre et al. (2012). The Havran-Balıkesir Fault Zone has a right-stepped position in respect to the Edremit Fault Zone. The Edremit Basin has formed due to the right overstepping of these two right-lateral fault zones. The Edremit Basin has a typical lensoidal shape of a pull-apart (e.g. Aydın and Nur, 1982; Mann et al., 1983; Gürbüz, 2010, 2014). Several researchers (e.g., Yılmaz and Karacık, 2001) described the Edremit Basin as a triangular area expanding westward. However, we noticed that the basin is bordered with the Müsellim Rocks, a bathymetric high, located between the Biga Peninsula and Lesbos Island in the west and the Dikili Strait in the south. In this configuration, the Edremit Basin has a lens-shape (Fig. 2).

The Yenice-Gönen Fault Zone extends in an NE–SW direction ends around the north of Kazdağ range. The other ENE-WSW-directed fault zone, the Edremit Fault Zone is partially located on land and partially in the sea between Babakale and Edremit (e.g. Barka and Kadinsky-Cade, 1988; Yılmaz and Karacık, 2001; Gürer et al., 2006; Emre et al., 2012; Yaltırak et al., 2012). These two right-lateral strike-slip fault zones are also in a step-over configuration, but in a left overstepping character. The Kazdağ range extends in an ENE-WSW direction should be uplifted as a result of the compression that developed between these overstepped strike-slip faults (Okay et al., 1991; Okay and Satır, 2000). The Kazdağ range had been extending approximately in an E–W direction until the Pliocene period according to paleomagnetic study results in the region (e.g., İşseven et al., 1995; Kaymakçı et al., 2007). In the Plio-Quaternary period, its direction has rotated by following the entry of NAFS into the region. The Kazdağ range between the Yenice-Gönen and the Edremit Fault Zones rotated in counterclockwise direction and acquired a more E-W direction (Kissel et al., 1989; Zanchi et al., 1990; İşseven et al., 1995). By the rotation of the Kazdağ range, several diagonal faults with right- and left-lateral slips developed in the adjacent areas (Fig. 2).

To analyze the tectonic stress of the region we collected kinematic data along the fault planes in the Neogene-Quaternary units, which are located particularly along the northern and southern margins of the Edremit Basin (Figs. 4, 5). A total of 452 fault-slip data collected from 55 different locations were used to form 66 paleostress configurations. The spatial distributions of measurement stations and the results of the analyses are shown in Table 2.

Direct inversion methods have been applied to analyze the kinematic data. Our results show the existence of two dominant minimum horizontal stress (S_{hmin}) axes: NE–SW and NW–SE (Fig. 6). Additionally, the data from eleven locations have shown extension in both, NE–SW and NW-SE directions. On the other hand, eight stress configurations indicate compression which is consistent with the strike-slip regime in the region. The NE–SW-directed S_{hmin} (σ_3) paleostress field represents 54% of the calculated stress tensors. It has been identified at 36 sites. The estimated mean tensor has principal stress axes oriented: $\sigma_1 = 075^o/84^o$, $\sigma_2 = 313^o/03^o$, $\sigma_3 = 223^o/05$ (Fig. 6). The stress ratio

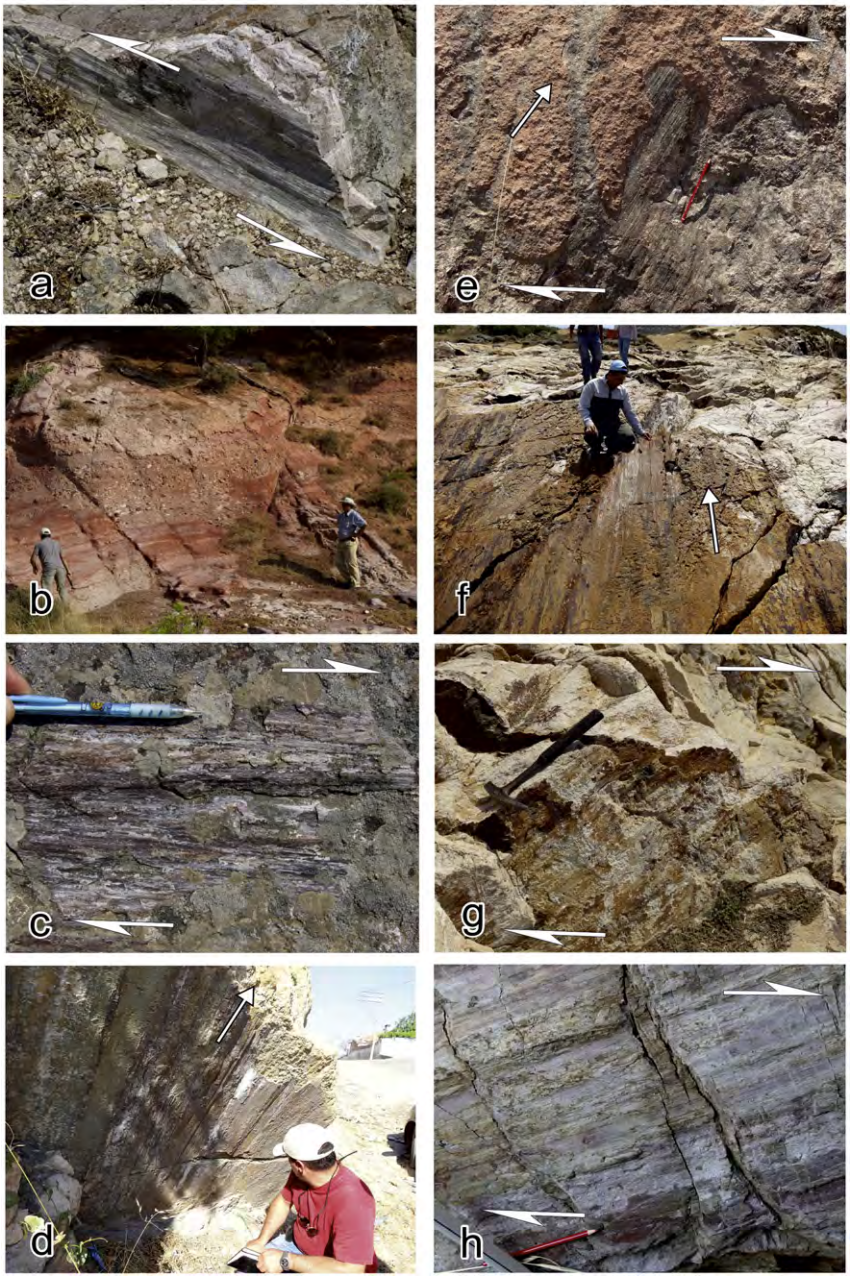


Fig. 4. Field photographs of the Late Cenozoic faults a: E1, b:E4, c:E20, d:43, e:E28, f:E29, g:E29, h: Kartal Yuvası Fault (39.527129 N/ 26.448371 E).

(R) value is 0.74 confirming that this tectonic regime was coexistence of normal faulting and strike–slip stress regimes.

The NW-SE-directed S_{hmin} (σ_3) paleostress field represents 33% of the calculated stress tensors and identified at 22 sites. The estimated mean tensor has principal stress axes oriented: $\sigma_1 = 238^o/65^o$, $\sigma_2 = 045^o/25^o$, $\sigma_3 = 137^o/05$ (Fig. 6). The stress ratio (R) value is 0.77 also confirming that this tectonic regime was coexistence of normal and strike-slip faulting regimes.

Two different main tectonic regimes were identified following a structural and kinematic study of the faults formed during the Late Miocene period and later in the Edremit Basin and adjacent areas. These are related to the diversity of the tectonic regimes associated with the NAFS and the AES.

The average values of σ_3 axes (for NE–SW $\sigma_3 = 223^o/05$ and for NW-SE $\sigma_3 = 137^o/05$) that generated the strike-slip regime and the normal-slip regime resulting from the kinematics of the faults suggest that two different minimum horizontal stress directions (e.g. NE–SW and NW-SE) should be effective in the region. This result is consistent with the GPS vectors in the region (e.g. Straub and Kahle, 1997; McClusky et al., 2000; Aktuğ et al., 2009), the strain axes derived from the GPS data (Straub and Kahle, 1997; Nyst and Thatcher, 2004; Reilinger et al., 2006, 2010; Aktuğ et al., 2009), and the results of the paleomagnetic data obtained from the region (e.g., İşseven et al., 1995; Kaymakçı et al., 2007). Even though the region is under the influence both of the AES and NAFS, the dominant effect on the current structural and morphological features of the Edremit Basin and adjacent areas is the NAFS as evidenced by the geometric and kinematic data.

Moreover, the focal mechanism analyses of the earthquakes that occurred in the Biga Peninsula and adjacent areas suggest normal faulting in different directions and strike-slip faulting associated with the NW-SE compression that generates the NAFS (Fig. 6). In order to determine the current regional strain tensor, the PBT (Pressure-Neutral-Expansion) axes of the focal mechanisms associated with earthquakes of Mw ≥4.0 between 1940 and 2013, were analyzed by the Win-Tensor

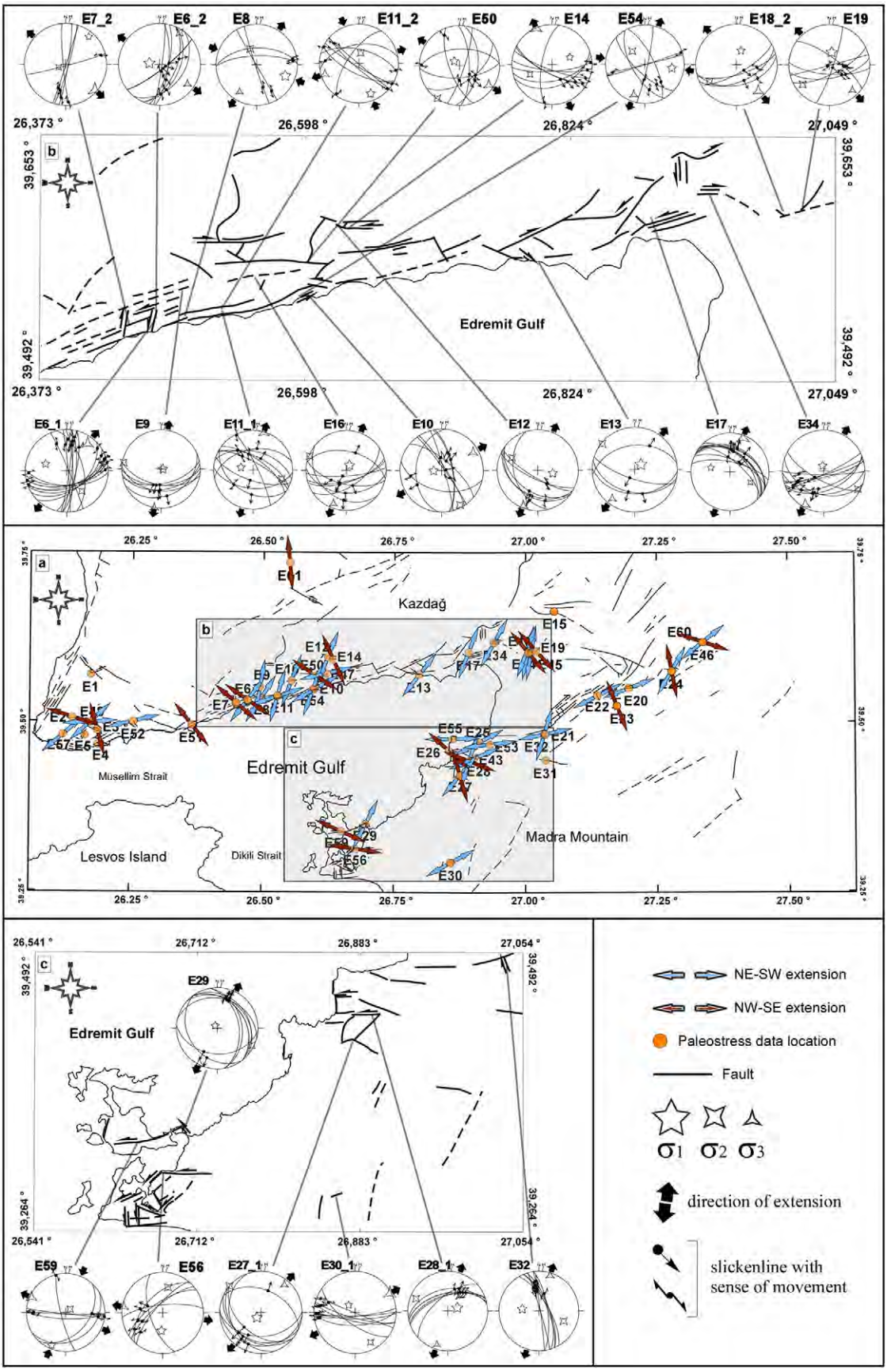


Fig. 5. a) Sampling sites map of Edremit Basin. The arrows show σ3 directions occurring as a result of the kinematic studies conducted on the faults (Gürer et al., 2014). Blue arrows: shows extension in the NE directions, whereas brown arrows show the extension in the NW directions. b–c) Cyclographical traces, stress orientations and striations on the faults (Lower hemisphere Equal area projection) for the (b) North of Edremit basin and (c) South of Edremit basin.

Table 2
Locations and palaeostress orientations for whole data. (σ_1,σ_2, σ_3: magnitude ratios of principle stresses; R: stress ratio; ANG: maximum allowed angular divergence; RUP: maximum allowed quality value.)

Locations		Elevation (m)	Station number	σ1		σ2		σ3		R	Number of faults	RUP	ANG
Latitude	Longitude			Trend	Plunge	Trend	Plunge	Trend	Plunge				
39.5682267551	26.1725737756	46	E1	049	20	308	27	170	55	0.382	8	33	8
39.5045742440	26.1373423432	29	E2	012	40	204	49	108	06	0.716	4	26	11
39.4863213243	26.1850805947	349	E3	073	04	335	63	165	27	0.358	7	21	6
39.4653342909	26.1861043198	81	E4	243	02	334	03	122	86	0.166	7	24	9
39.4785173154	26.1612168795	322	E5	254	56	064	34	157	05	0.691	8	25	6
39.5313901718	26.4706211337	29	E6_1	288	45	143	39	038	18	0.960	17	27	9
39.5313901718	26.4706211337	29	E6_2	276	70	032	09	125	18	0.178	8	37	17
39.5271299161	26.4483714714	160	E7_1	334	09	238	32	078	56	0.179	5	28	7
39.5271299161	26.4483714714	160	E7_2	245	75	040	13	131	06	0.720	5	27	9
39.5338255475	26.4963153608	93	E8	111	26	338	55	213	22	0.096	4	15	6
39.5507737573	26.4936421687	422	E9	094	86	280	04	190	00	0.502	6	11	2
39.5486268233	26.5984422931	70	E10	268	74	152	07	060	14	0.492	8	25	7
39.5374495962	26.5273257348	89	E11_1	282	64	107	25	016	02	0.752	9	34	14
39.5374495962	26.5273257348	89	E11_2	159	19	010	68	252	11	0.569	7	28	10
39.5951517257	26.6238468727	257	E12	101	59	296	30	202	07	0.707	6	32	11
39.5693429865	26.7973293965	7	E13	050	75	308	03	218	15	0.314	4	20	4
39.5910491652	26.6337771619	288	E14	246	40	068	50	336	01	0.934	8	27	12
39.6626155309	27.0536077569	282	E15_1	039	74	286	06	194	15	0.352	10	18	5
39.6626155309	27.0536077569	282	E15_2	033	03	302	10	138	80	0.554	5	27	8
39.5601183684	26.5543411236	367	E16	032	77	291	02	201	12	0.461	8	29	9
39.6019374057	26.8911919491	44	E17	118	41	282	48	021	08	0.915	10	23	6
39.6021700000	27.0048218627	66	E18_1	102	14	349	58	200	28	0.110	4	20	6
39.6021700000	27.0048218627	66	E18_2	238	24	018	60	140	17	0.630	4	24	10
39.6036446193	27.0199229017	68	E19	010	64	234	20	138	17	0.212	6	38	13
39.5495631221	27.1958533523	306	E20	339	12	177	77	069	04	0.645	11	33	11
39.4810352498	27.0365269547	173	E21	168	11	359	79	258	02	0.421	15	33	8
39.5382295765	27.1359077732	316	E22	354	78	152	11	243	05	0.820	5	34	9
39.5234473404	27.1730832979	312	E23_1	301	12	200	42	043	46	0.388	7	23	7
39.5234473404	27.1730832979	312	E23_2	277	55	058	29	158	19	0.685	9	36	8
39.5745688707	27.2775769570	287	E24_1	283	66	123	22	030	07	0.746	7	30	5
39.5745688707	27.2775769570	287	E24_2	075	09	326	65	169	23	0.256	5	27	10
39.4690613621	26.9109784570	33	E25	218	78	331	05	062	11	0.780	9	27	11
39.4566191804	26.8538924398	22	E26	207	68	044	21	312	06	0.663	4	23	9
39.4205220000	26.8755530000	46	E27_1	219	77	310	00	040	13	0.281	7	15	7
39.4205220000	26.8755530000	46	E27_2	096	45	236	38	344	21	0.811	6	35	13
39.4418520021	26.8935297098	92	E28_1	071	69	291	16	198	13	0.274	6	17	5
39.4418520021	26.8935297098	92	E28_2	318	67	204	10	111	21	0.730	4	32	7
39.3484890000	26.6954140000	7	E29	320	84	116	06	207	03	0.727	9	24	5
39.2914805556	26.8570677778	187	E30_1	319	71	153	19	061	04	0.827	8	28	6
39.2914805556	26.8570677778	187	E30_2	045	16	145	31	292	54	0.253	6	36	13
39.4430050000	27.0380735294	143	E31	292	08	196	38	031	51	0.371	4	28	7
39.4811874405	27.0357677976	192	E32	277	55	112	34	017	07	0.566	7	22	7
39.8153538698	27.2312941291	229	E33	252	02	005	86	162	04	0.233	10	28	11
39.6162240000	26.9394200000	54	E34	350	79	118	07	209	08	0.708	9	28	8
39.8650588194	27.2853145189	375	E39	339	75	210	10	118	12	0.148	6	20	8
39.8410972744	27.4125090750	225	E40	092	53	293	35	196	10	0.623	5	26	11
39.7952434533	27.3378672006	249	E41	312	09	220	11	081	76	0.490	10	41	17
39.9209554627	27.2705917399	330	E42	233	67	073	22	340	07	0.654	10	27	6
39.4464197619	26.9021440774	144	E43	303	71	160	15	067	11	0.418	4	21	5
39.6006048344	27.0043433271	39	E44	305	54	092	32	192	16	0.774	10	30	14
39.6013953576	27.0101149808	44	E45	024	71	282	04	190	19	0.542	6	34	15
39.6171312698	27.3368425397	531	E46	144	73	321	17	051	01	0.529	4	27	9
39.5706903622	26.6206969393	275	E47	347	61	167	29	257	00	0.525	5	34	12
39.4977150000	26.1714360000	293	E48_1	107	66	323	20	228	13	0.341	4	34	9
39.4977150000	26.1714360000	293	E48_2	356	27	184	62	087	03	0.413	4	15	4
39.5689686098	26.5987047968	132	E50	309	76	214	1	124	14	0.605	7	30	11
39.4946752188	26.3644454290	32	E51	077	66	228	21	322	10	0.481	9	36	16
39.4992210667	26.2538826667	220	E52	168	56	347	34	077	00	0.751	9	25	11
39.4659854926	26.9319671019	79	E53	162	44	003	44	263	11	0.085	5	27	7
39.5467483333	26.5948866667	18	E54	098	31	316	53	200	19	0.513	6	28	10
39.4740814103	26.8605164103	32	E55	167	52	007	37	269	10	0.144	6	30	7
39.3119297313	26.6758333705	11	E56	184	53	012	36	279	04	0.563	6	27	10
39.4798005701	26.1199060055	370	E57	324	11	078	65	230	22	0.349	4	32	6
39.3379942154	26.6489634671	89	E59	203	10	054	78	294	06	0.731	6	34	7
39.6171312698	27.3368425397	531	E60	185	15	079	47	288	39	0.142	5	28	10
39.7341105641	26.5507188333	402	E61	258	18	129	63	355	20	0.613	5	32	8

software (Delvaux and Sperner, 2003). This analysis also showed the existence of earthquake groups in the region with extensions in two different directions and associated with one compression and one strike-slip movement (Fig. 7).

According to our analyses on the structural and seismological data, the tectonics of the Edremit Basin is characterized by the interaction of a major strike-slip and extensional regimes, which is resulted by a transtensional formation mechanism.

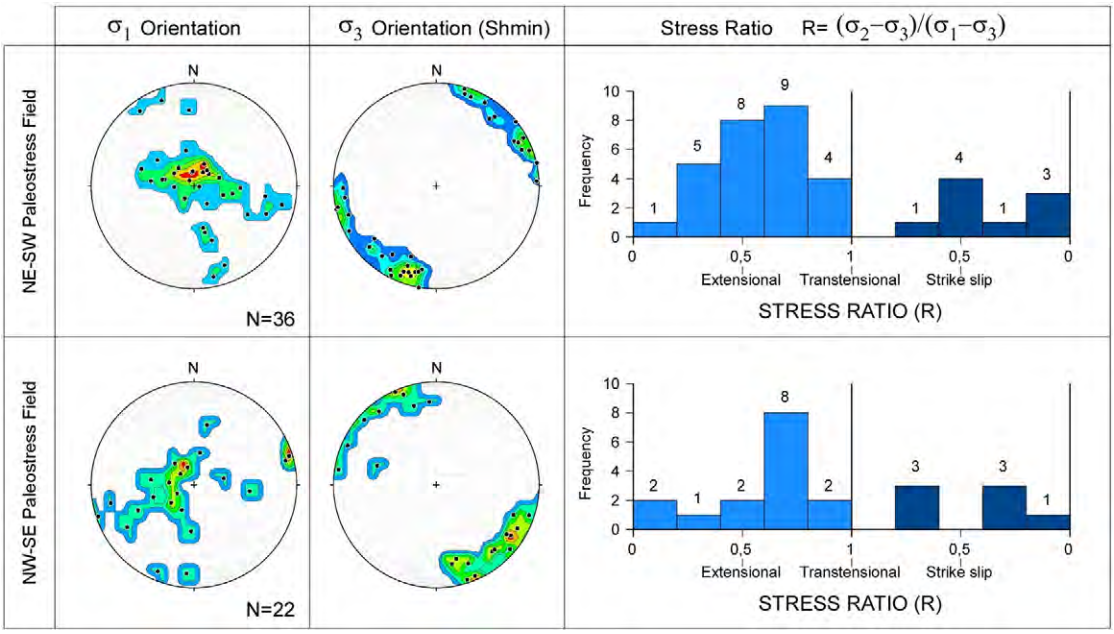


Fig. 6. Density stereoplots for σ_1 and σ_3 orientations and stress ratio (R) histograms for the two paleostress fields obtained. Spherical Gasussian contour stereoplot method. 1% contour intervals represented in lower-hemisphere, equal-area projection.

5. Conclusions

There are several studies related to uplift mechanism of the Kazdağ Massif and relatively less publication on the formation of the Edremit Basin. However, none of these works represents any kinematic data analyze the faulting features to understand the paleostress pattern in the region. This study is approaching to the neotectonic features of the region in the light of fault geometries and their kinematics according to detailed field observations. The findings of this study are briefly listed as below:

1. Although, all of the previous studies in the region showed that the Edremit Basin has a triangular shape in the gulf, we delineate its lensoidal

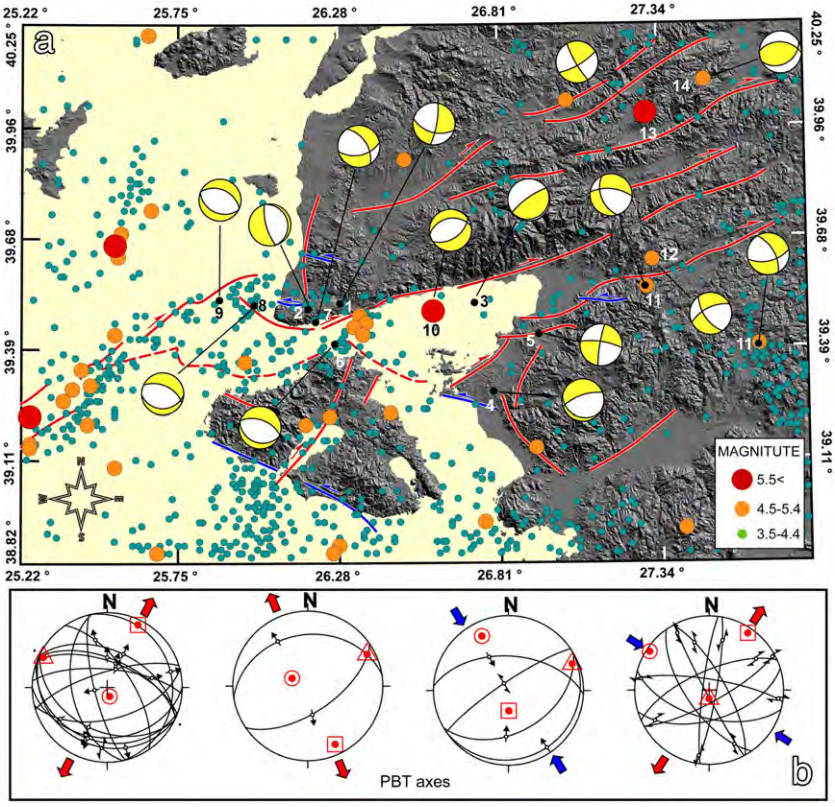


Fig. 7. a. Earthquakes in Biga Peninsula and the surrounding region during the instrumental period (http://www.isc.ac.uk), Fault plane analysis (1–10) Altınok et al., 2012; (11) ISC catalog 2011; (12); Kıyak, 1986; (13) McKenzie, 1972; (14) Taymaz et al., 1991. b. PBT axes that are defined through the focal mechanisms of the earthquakes are prepared with Win-Tensor program (Delvaux and Sperner, 2003) P, B and T axes are shown as circle, triangle and square respectively.

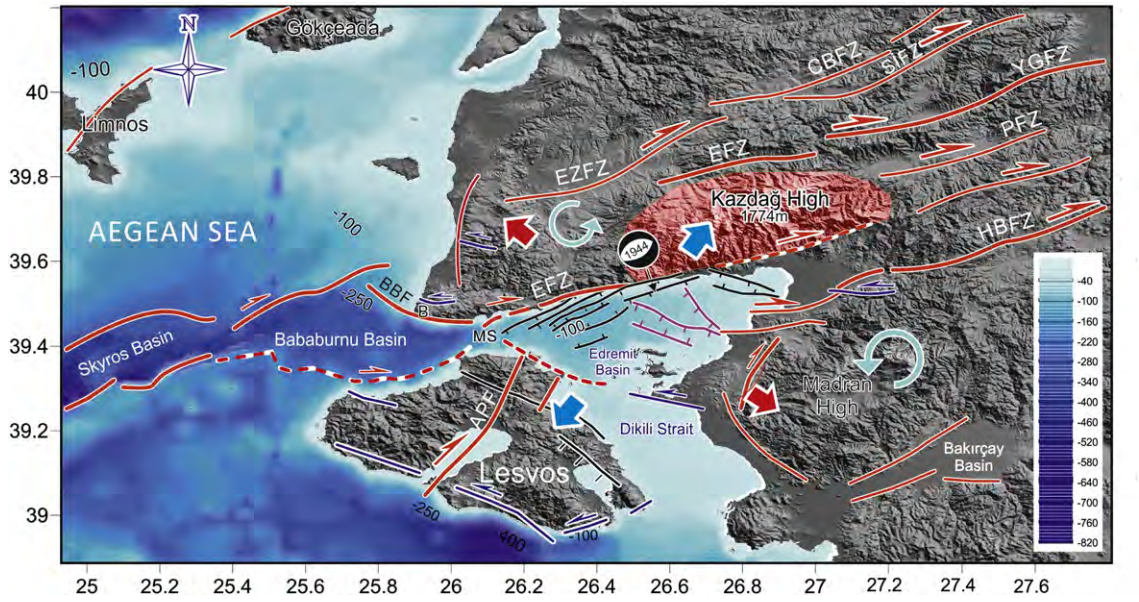


Fig. 8. Distribution of NAFS segments affecting Biga Peninsula. The location of Edremit Basin between the Edremit Fault Zone and the Havran-Balıkesir Fault Zone with a right step over is shown while Kazdağ located between the Yenice-Gönen Fault Zone and the Edremit Fault Zone step over towards the left is uplifting. There are blue lines with blue arrows indicating left-lateral sense. Lesvos Island faults after (black lines, Vacchi et al., 2012; Chatzipetros et al., 2013), Edremit Gulf faults after (purple lines, Beyhan, 1999). APF: Aghia-Paraskevi Fault, BGF: Biga Fault (Yaltırak et al., 2012), EF: Evciler Fault, EZFZ: Ezine Fault Zone, EFZ: Edremit Fault Zone, HBFZ: Havran-Balıkesir Fault Zone, PFZ: Pazarköy Fault Zone, YGFZ: Yenice Gönen Fault Zone, MS: Müsellim Strait. Bababurnu Basin (modified from Yaltırak et al., 2012) and tectonic rotations from (İşseven et al., 1995).

shape by using the bathymetric data together with the topographic data of the region (Fig. 8). The Edremit Basin is a lensoidal-shaped basin which is one of the main geometric types of pull-apart basins.

2. The Edremit Basin is bounded by two right-lateral strike-slip fault zones, the Edremit and Balıkesir-Havran fault zones along its northern and southern sides, respectively.

3. The kinematic analyses of the basin bounding faults represent bi-axial, NE–SW and NW-SE-directed extension directions. This kind of bi-axial extension is also possible in a pull-apart basin formation controlled by a transtensional tectonic regime (e.g., Allen and Allen, 2013). The geometric and kinematic characteristics of the basin bounding faults in the study area indicate a transtensional pull-apart basin mechanism for the Edremit Basin.

4. The NE–SW and NW–SE-directed extensions that determined by our fault kinematic analysis are consistent with the published strain axes derived from the GPS data, which represent a biaxial extension directions for the region (Fig. 3). The earthquake focal mechanism solutions in and around the basin also represent both strike-slip and normal fault features in accordance with similar-directed stress axes.

5. The imprint of NE–SW and NW–SE-directed extensions is verified the mechanic interaction of the NAFS and the AES in this region by fault kinematic data for the first time. This biaxial extension is plausibly worked synchronously during the Plio-Quaternary.

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