Kinematics of the Havran-Balikesir Fault Zone and its implication on geodynamic evolution of the Southern Marmara Region, NW Anatolia

Ökmen Sümer, Bora Uzel, Çağlar Özkaymak and Hasan Sözbilir

Department of Geological Engineering, Dokuz Eylül University, İzmir, Turkey; Department of Geological Engineering, Afyon Kocatepe University, Afyon, Turkey; Earthquake Research and Implementation Center, Afyon Kocatepe University, Afyon, Turkey

ABSTRACT
Cenozoic convergence, collision and subsequent subduction between African and Eurasian plates are accommodating in overriding Eurasian plate both forming the Aegean extension and the North & East Anatolian fault zones. To understand the kinematic evolution of upper crust, here we provide new paleostress data from the Havran-Balikesir Fault Zone located at the interaction area between the North Anatolian Fault Zone (NAFZ) and west Anatolian extensional structures. Paleostress reconstructions of fault-slip data reveal that three distinct deformation phases have been experienced in the region. Phase 1 is represented by left-lateral strike-slip faulting with reverse component in the pre-Pliocene period. The Phase 2 is characterized by approximately N–S trending contraction and associated E–W trending extension in Plio–Quaternary, which is spatiotemporally linked to the initiation of NAFZ through the area. The youngest deformation, Phase 3 is attributed to NE–SW trending extension and NW–SE trending contraction commenced by the Quaternary transpressional tectonics in Southern Marmara Region. These results show that the main contraction axes have been experienced a spectacular anticlockwise rotation (from NW–SE to E–W), which is associated with: (i) the propagation geometry of the NAFZ into the region; (ii) slab roll-back and retreat and tearing process on the Aegean subduction system; and (iii) the existence of inherited structures of the İzmir-Balikesir Transfer Zone.

1. Introduction
The geodynamic structure of Anatolia have been expounded by the tectonic escape-related deformation model of the Anatolian block as a result of the combination with right-lateral strike-slip North Anatolian Fault Zone (NAFZ) and the left-lateral strike-slip East Anatolian Fault Zone (e.g. Bozkurt, 2001; Dewey & Şengör, 1979; Şengör, Göür, & Şaroğlu, 1985). The westward escape of Anatolia consequences with the slab edge processes related to the northward subducting African slab below Eurasia as a result of Africa–Europe converging and collision along the south Aegean (Biryal, Beck, Zandt, & Özacak, 2011; Le Pichon & Angelier, 1979; Meulenkamp, Wortel, van Wamel, Spakman, & Strating, 1988; van Hinsbergen, Kaymakçı, Spakman, & Torsvik, 2010). The surface expression of a tear in the subducting African Slab is associated with the İzmir-Balikesir Transfer Zone (İBTZ) (Gessner, Gallardo, Markwitz, Ring, & Thomson, 2013; Uzel et al., 2015) a deep crustal transform fault zone consisting of NE-trending active crustal strike slip dominated faults (Okay et al., 1996; Okay & Siyako, 1993; Özkaymak, Sözbilir, & Uzel, 2013; Ring, Susanne, & Matthias, 1999; Sözbilir et al., 2008; Sümer, İnci, & Sözbilir, 2013; Uzel & Sözbilir, 2008; Uzel, Sözbilir, Özkaymak, Kaymakçı, & Langereis, 2013). The West Anatolian Extensional Province, which is currently experiencing an approximately N–S continental extension and represented by E-W trending major horst and grabens are bordered by İBTZ to the west (Özkaymak et al., 2013; Ring et al., 1999; Sözbilir, Sarı, Uzel, Sümer, & Akkızar, 2011; Sümer, 2015; Uzel et al., 2013). Therefore, the Southern Marmara Region (SMR) located in a transitional zone between the extensional tectonics (normal fault) dominated western Anatolia and the transpressional (strike-slip) tectonics dominated NAFZ (Figure 1).

Actually, the Marmara province is partly under the influence of the western end of the NAFZ, which splays into a number of branches in around the eastern terminations of the Marmara Sea (e.g. Dewey & Şengör, 1979). Although the previous studies accept that the NAFZ also ramify in this region; however, there is still no consensus on the nature and number of segments in the western part of the fault zone. According to the some researchers, the NAFZ consists essentially of a single fault zone; however, it spays into three strands west of Bolu as northern, middle and southern strands (Barka, 1992; Barka & Kadinsky-Cade, 1988; Güre, Kaymakçı, Çakır, & Özburan, 2003). Even Barka (1992) separated this part of fault zone from the point where the arm branched until the Aegean Sea, which was described as a horsetail structure. Some others researchers specified that the NAFZ divided two main branches namely northern and southern strands (Özalp, Emre, & Doğan, 2013;
Şengör, 1979; Şengör et al., 2005; Sözbilir et al., 2016b). Özalp et al. (2013) is also divided the NAFZ into two branches as the northern and southern in the Marmara region and the southern branch, which separates from each other by rightward step-overs. But in consisted with, fault kinematics studies, structural observations, seismological data, earthquake focal mechanism solutions, GPS (Global Positioning System) studies and shallow seismic reflection data reveal that the northern Aegean region and western termination of the NAFZ is now deformed by under the influence of the both strike-slip and extensional tectonics (Barka & Kadinsky-Cade, 1988; Gürer et al., 2016; Kahle et al., 1998; Papazachos, Papadimitriou, Kiratzi, Papazachos, & Louvari, 1998; Reilinger et al., 1997; Şengör et al., 2005; Taymaz, Jackson, & McKenzie, 1991; Yaltırak, Alpar, & Yüce, 1998; Yaltırak, İşler, Aksu, & Hiscott, 2012).

Since the beginning of the late 50’s, various dominantly ENE-WSW and E-W trending faults and structures had been studied and mapped by numerous studies in the SMR (eg. Barka & Kadinsky-Cade, 1988; Bingöl, 1976; Gürer, Sangu, & Özburan, 2006; Pınar, 1953; Şaroğlu, Emre, & Kuşçu, 1992; Siyako, Bürkan, & Okay, 1989; Yılmaz & Karacık, 2001); however, one of the major active structure in SMR, namely Havran Balikesir Fault Zone (HBFZ), has not been documented until 2011. Fault geometry, segmentation and active tectonic properties of HBFZ is defined and mapped as an active fault by Emre, Doğan, and Özalp (2011) and Emre et al. (2013), for the first time. Because of its critical geological position, definition of this structure was a new development for the region in context of the structural transition of two different geological provinces. After this documentation, Sözbilir et al. (2016a) performed trench-based palaeoseismological investigations in order to dating of past faulting events together with estimates of long-term slip-rates and recurrence intervals. Although, there is still not enough detailed information about the kinematics and tectonic evolution of the HBFZ, which have a great potential to provide significant data for understanding the geodynamics of the SMR. Here, the

Figure 1. (a) Location of the northwestern part of the Anatolia in global scale. (b) Digital Elevation Map (DEM) of the Northwest Anatolia according to deformation style and distribution of tectonic domination of the region. (c) Simplified active fault map of Northwest Anatolia (compiled from Emre & Doğan, 2010; Emre et al., 2013). Hachured area with horizontal lines in (b and c) indicates Izmir Balikesir Transfer Zone (İBTZ) which is represented by transtensional tectonics. Abbreviations: BF, Bursa Fault; UF, Ulubat Fault; MF, Mustafakemalpaşa Fault; OF, Orhangazi Fault; MFZ, Manyas Fault Zone; YGF, Yenice–Gönen Fault; ÇBFZ, Çan-Biga Fault Zone; EF, Evciler Fault; PF, Pazarköy Fault; EFZ, Edremit Fault Zone and the HBFZ, Havran-Balikesir Fault Zone.
main goal of this study is to discuss the deformational pattern and tectonic evolution of the HBFZ in the context of stratigraphic, structural and seismic criteria, marking the tectonic relationship between the İBTZ, WAEP and southern branch of NAFZ.

2. Havran Balıkesir Fault Zone

The main late Cenozoic structures mapped around the Balıkesir area is named here as also Havran–Balıkesir Fault Zone, which is a 10–12 km wide, 120 km long, approximately N70°E-trending fault zone comprising several riedel faults that display a well-developed shear zone pattern with en-échelon elongated hills. Emre et al. (2011) & Emre et al. (2013) and Sözbilir et al. (2016a) suggest that the fault zone consists of two E–W-striking faults, namely Havran-Balya Fault (HBF) to the west, Balıkesir Faults (BF) to the east (Figure 2(a)).

2.1. Havran-Balya Fault (HBF)

The HBF is approximately 90-km-long and exhibits right-stepping en-echelon pattern consisting of 4 main geometric segments (Figure 2). From west to east, these are (i) Havran Segment (HS), (ii) Osmanlar Segment (OS), (iii) Turplu Segment (TS) and (iv) Ovacık (OvS). HBF is nearly linear (WSW-ENE) along the HS, OS and TS to the west, but presents a concave geometry along the OvS to the east as a restraining bend.

HS is an approximately 19 km long dextral strike-slip fault consisting of three right-stepping fault fragment striking an average N50°E with 80° (NW) dip and rakes of slip lines less than 20°. Along the HS, some R' Riedel faults showing the nature of left-lateral strike-slip faulting were also observed. The Havran Segment juxtaposes Holocene alluvial deposits and early-late Miocene volcano sedimentary units between Küçükdere and Havran and controls the southern border of the alluvial Edremit plain (Figure 2). Along the HS, right-laterally deflected streams and elongated ridges parallel to the principle displacement zone of segments indicates the right lateral sense of the segment. HS passes to OS stepping to the right at 5 km east of Eseler village (Figure 2). 30-km-long OS continue further east towards the Topuzlar as a single fault and extends NE-SW orienting with a linear geometry (Figure 3(a)). To the northeast part, OS cut and right laterally displaced the lavas of Hallaçlar volcanic. During the field studies prominent fault planes are also examined that juxtapose the Holocene alluvial deposits and lavas (Figure 3(b)).

Further to east, the Osmanlar Segment passes to Turplu Segment with another right-stepping jump around Kocaavşar village (Figure 2). The Turplu Segment is approximately 16 km long, 1 km wide, NE-trending, S-shaped fault zone lying between Kocaavşar

Figure 2. (a) Morpho-tectonic map on a digital elevation model (DEM) image showing faults (Havran Balya and Balıkesir faults) and fault segments of Havran – Balıkesir Fault Zone (HBFZ). (b) Simplified geological map of study area showing rock units along the HBFZ. Compiled from Duru et al. (2012); Emre et al. (2011) and this study. Focal mechanism solution (FMS) of earthquakes are taken from (1) Eyidoğan (1988); (2) Euro-Med Seismological Centre (EMSC); (3) European and Mediterranean Regional Centroid Moment Tensor (EM-RCMT) and (4) Kalafat et al. (2009), see Table 2 for detailed parameters for these earthquakes.
and Turplu villages. Along the principle displacement zone, it includes some Riedel (R and R') faults localized within the Kocaçay River. The main NE trend is manifested as linear/elongated ridges, linear valleys and escarpments along the segment (Figure 3(c)). Stream channels show some disruption or deflection as they meet a fault. Above all, the SW directed flowing Kocaçay River has a clear right-lateral offset around 8 km N of Turplu village, segment direction turns into N80°E from N50°E, with a spectacular bend.

The 22-km-long OvS is the northernmost part of the HBF and consists of N65°E to N80°W striking and NW dipping transpresional right-lateral strike-slip fault fragments (Figure 2). At several places fault planes were observed with well-developed slickensides. According to mapping studies, this segment starts at west of Ovacık village as nearly in N70°E trend, and bends in N80°W direction in convex curve linear geometry in north of Kirne around Fethiye village, and extends to the east (Figure 3(d)). Along the fault, many stream channel have been displaced by right-lateral slip on the OvS.

2.2. Balıkesir Fault (BF)

Eastern part of the HBFZ is represented by the Balıkesir Fault, which is approximately 70-km-long and reconstructed into two main geometric segments based on the geomorphological expression. From west to east, these are, (i) Gökçeyazı Segment (GS) and (ii) Kepsut Segment (KS) (Figure 2). The 40 km long, 2–5 wide and N70°E-trending GS is highlighted as the most remarkable segment of the HBFZ and extends between İvrindi and Ayşebacı villages (Figure 2).
The segment starts 3 km east of İvrindi, passes through Gökçeyazı village and reaches toward Balıkesir city center. GS exhibits prominent Quaternary fault scarps and significant morphologic variations around the Gökçeyazı village (Figure 4(a)). It can easily trace on morphology with various geomorphological features such as aligned drainage systems, linear/sub-linear valleys, deflected channels, elongated hills and fresh fault scarps. The alignment of the drainages and valleys in NNE–SSW and NNW–SSE directions show the influence of lineaments and faults in the area. West of Balıkesir, stratigraphic contact between the rocks of İzmir–Ankara Zone and the Miocene volcano-sedimentary rocks is right-laterally offset around 4 km along the Gökçeyazı Segment in map view. The fault planes of the GS cut and displaced the rocks of Karakaya Complex and İzmir–Ankara Zone, Oligo–Miocene volcanic rocks and the Quaternary sediments with several subparallel faults having an average dip of 80°E. Well-exposed slickenlines on these planes show strike- to oblique-slip faulting activity with a minor reverse-slip component as indicated by sub-horizontal rakes (17–26°N) (Figure 4(b,c)). Along the fault, the SW-flowing Kocaçay River has a clear right-lateral offset around 10 km in map view to highlight the sense of strike-slip faulting.

The eastern termination of the BF represented by Kepsut Segment (KS) extends about 26 km between Ayşebacı and Eyüpbkü villages marking with the

![Figure 4](image-url). Field photographs of the Balıkesir Fault and its segments. (a) panoramic view of Gökçeyazı Segment, (b) polished fault plane of GS, constituting structural boundary between recrystallized limestones of the İzmir–Ankara Zone and Holocene alluvial deposits, please notice to pushed old rocks over the young ones with reversal movement, (c) well-exposed slickenlines with sub-horizontal rakes, (d – f) Kepsut Segment field photographs, (e) fresh fault scarp of the KS on the Miocene volcanic rocks, (d and f) 2 different slickenlines type of the same fault surface, reactivation is shown by superposed sets of striae. Preliminary strike-slip movement is overprinted by dip-slip lineations with normal movement. Persons for scale in photos are approximately 1.75 m in height, pen is 14 cm long.
discontinuous fault splays. However, generally, the each length of these faults can be traced to a maximum of 10 km. The Kepsut Segment separates the Miocene volcano-sedimentary units and the rocks of İzmir–Ankara Zone, and laterally offset of Miocene rocks is measured as up to 300 m between Kepsut and Eyüpbükü. At the center of the segment, around 250 m deflection along the Kepsut River is also noticeable on topographic maps. Additionally, east of Ayşebacı village the existence of an early strike-slip faulting was documented. Here, the earlier right lateral lines with rakes ranging 11–26° have been overprinted by a series of younger dip-slip striations with an average rake of 75°W to 85°E. The measured fault planes have strikes around N60–80°W with an average dip of 75° to the SW (Figure 4(d–f)).

2.3. Rock units along the HBFZ

Five lithostratigraphic units, range from Permian to recent in age, are defined and mapped along the HBFZ and these are from bottom to top: (i) the latest Permian – middle Triassic metamorphic rocks of Karakaya Complex, (ii) late Cretaceous-Paleocene fysch rocks of the İzmir Ankara Zone, (iii) Oligocene rocks of Hallaçlar volcanics, (iv) Miocene volcano-sedimentary units and, (v) Quaternary alluvium (Figure 2).

The Karakaya Complex is exposed mainly middle part of the HBFZ, lying between western part of the Gökçeyazı Segment and the corridor of Osmanlar and Balikesir segments (Figure 2(b)). Between the Havran and Balikesir regions, Karakaya Complex mainly is mainly made up by recrystallized limestones (Figure 5(a)). It is actually defined in 1970’s around Biga Peninsula as Karakaya formation as a gently metamorphosed unit consisting of dominantly clastic sequences as sandstones, quartzite, siltstone, radiolarite, mudstone and minor metallphylite, spilitic basalt and diabase with Permo-Carboniferous exotic limestone olistostromes (Bingöl, Akyürek, & Korkmazer, 1975; Duru, Pehlivan, Okay, Şentürk, & Kar, 2012). Duru et al. (2012) reported the Karakaya Complex cover Devonian – Carboniferous limestone blocks and paleontological data both matrix and blocks indicating at least latest Permian – middle Triassic age.

Rocks of the İzmir Ankara Zone is exposed mostly between the GS and OvS (Figure 2(b)). These rocks are firstly defined by Brinkmann (1966) as a tectonic belt comprising of; (i) a matrix in fysch facies fine-grained clastic rocks interfingering with pelagic limestone (Figure 5(b)), and (ii) blocks of various size neritic limestone and ophiolites. Duru et al. (2012) is reported the large-scale Permian, Triassic, Jurassic and early Cretaceous blocks in neritic limestone composition, while Okay and Siyako (1993) reported paleontological data from the matrix as late Cretaceous-Paleocene age.

The Hallaçlar volcanics outcrops mainly along the Havran and Osmanlar segments of Havran-Balya Fault (Figure 2(b)). In map view, an approximately 6 km typical right-lateral offset is clearly observed along the unconformity between Hallaçlar volcanics and Karakaya Complex. It is described first by Krushensky (1975) as a Hallaçlar Formation. Here, the volcanic rocks are exposed at the western part of the HBFZ, consisting of lava flows, minor flow-breccia, and tuff. The rocks of andesite and dacite are considerably affected by hydrothermal alteration (Figure 5(c)). The Hallaçlar volcanics have been dated K/Ar age by Krushensky (1975) with 23.6 ± 0.6 Ma. Erkan, Satir, Walter, and Yıldırım (1995) reported the volcanism cover the Hallaçlar volcanics in Biga Peninsula started at least early Oligocene until the end of the Oligocene Epoch.

Volcano-sedimentary units are widespread exposed along almost all of the segments of the HBFZ (Figure 2(b)). These units consist mainly of felsic, intermediate and mafic volcanic rocks and continental clastic sediments and lacustrine carbonate. At the base, near the village of Hallaçlar and İvrindi, these units are represented by grayish-white colored dacitic lavas and pyroclastics (Figure 5(d)). Andesitic and basaltic-andesitic mainly fractured and weathered volcanic rocks are well exposed around Turplu and Ovacık, which are mostly dark gray and brown, locally greenish and light orange color. Interfering clastic-carbonate sequences can be also observed from base to top. These sedimentary rocks consist of predominantly conglomerates, sandstones, and fine-grained sediments accompanying by lacustrine carbonates, which are shown perfect abrupt transitional contacts each other. Especially, on the road-cut of Edremit-Balikesir highway at vicinity of the Küçükdere and Balikesir, these sediments are represented by mainly whitish, light yellow and light brown color (Figure 5(e)). The volcanic rocks within these rock units are dated with K/Ar ages by Krushensky (1975), Benda, Innocenti, Mazzuoli, Raddati, and Steffens (1974) and Erkan et al. (1995) as between 18.2 ± 0.3 and 21.9 ± 0.6 My. Benda et al. (1974) also states that sporomorph assemblage was found in lacustrine sediments supporting this radiometric age data.

Alluvium as a youngest rock unit along the fault zone is mainly exposed along the current drainage network, controlled by HBFZ, itself. Especially in the vicinity of Havran, İvrindi, Gökçeyazı and Karaman, these units are dominantly represented by deposits of alluvial fan, alluvial plain and modern fluvial facies. These deposits overlie the older unit with a clear angular unconformity (Figure 5(f)). Matrix supported part of the alluvial fan deposits contain cobble- to boulder size clasts mainly made up of sandstone, recrystallized limestone and many types of volcanic rocks. The alluvial fan deposits are interbedded with
alluvial plain sediments that made up of fine-grained clastics. They laterally and vertically pass and combine with the planar-stratified, light and dark grayish and yellowish fluvial sediments.

3. Kinematic analysis of the HBFZ

About 130 fault slip data from 11 locations along the HBFZ was collected in order to evaluate the kinematics and stress history of the region. Overprinted slickensides indicating fault reactivation were noted in three of these locations. We provide average two stations from each segment of HBFZ to understand the nature of faulting along the zone (Figure 6, Table 1). Here, we will give the theoretical background for the kinematic analysis of fault-slip data first, then will document our computer-based kinematic results in the light of our field observations along the main displacement zone of HBFZ to
understand the progressive deformation phases across the SMR.

### 3.1. Theoretical background

Paleostress computation from fault slip data allows us not only the orientation of the three principal stress axes, the maximum ($\sigma_1$), intermediate ($\sigma_2$) and minimum ($\sigma_3$) principal stress axes, but also the ratio of the principal stress differences, also known as shape ratio of the stress ellipsoid formulated as $\Phi = (\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$. To do that, a number of graphical (e.g. Alexandrowski, 1986; Arthaud, 1969; Krantz, 1988) and numerical palaeostress methods (e.g. Angelier, 1979, 1984, 1990, 1994; Armijo, Carey, & Cisternas, 1982; Carey & Brunier, 1974; Delvaux & Sperner, 2003; Etchecopar, Visser, & Daignieres, 1981; Fry, 1999; Gephart & Forsyth, 1984; Marret & Almandinger, 1990; Michael, 1984; Will & Powell, 1991; Yamaji, 2000; Yin & Ranalli, 1993; Zalohar & Vrabec, 2007) have been developed for computer-based inversion of structural data. To understand the mode and age of the faulting and the consequent relationships between the extensional and the strike-slip tectonic regimes, paleostress analysis of fault slip data comes into prominence as an important tool because of its efficiency in multi-stage deformed areas (Angelier et al., 1981; Brahim et al., 2002; Hippolyte & Mann, 2011; Kaymakçı, White, & van Dijk, 2000, 2003; Saintot & Angelier, 2002; Sperner et al., 2003; Vandycke & Bergerat, 2001), we used the Direct Inversion Method (INVD) of Angelier (1990) in this study. However, we gave short information below, we refer to Angelier (1994) for a detailed review of the method and to Sperner and Zweigel (2010), and Hippolyte, Bergerat, Gordon, Bellier, and Esput (2012) for data acquisition plus separation techniques. Briefly, the INVD is based on the reduced stress tensor concept and the estimation of the stress ellipsoid by the shape factor ($\Phi$), which varies between 0 and 1. Thus, in areas where the stress ratio approximates 0 or 1, uni-axial stress conditions prevail and faults are not constrained in any direction. Otherwise stress is tri-axial and all of the principal stress magnitudes are significantly different, and the fault orientations tend to develop parallel to $\sigma_2$ directions and they approximate to an Andersonian mechanism (Anderson, 1951). The stress regime is determined by the nature of the vertical ones: extensional when $\sigma_1$ is vertical, strike-slip when $\sigma_2$ is vertical and contractional when $\sigma_3$ is vertical. Delvaux et al. (1997) suggest that the stress regimes also vary in function of the stress ratio: radial extension ($\sigma_1$ vertical, $0 < \Phi < 0.25$), pure extension ($\sigma_1$ vertical, $0.25 < \Phi < 0.75$), transtension ($\sigma_1$ vertical, $0.75 < \Phi < 1$ or $\sigma_2$ vertical, $1 > \Phi > 0.75$), pure strike-slip ($\sigma_2$ vertical, $0.75 > \Phi > 0.25$), transpression ($\sigma_2$ vertical, $0.25 > \Phi > 0$ or $\sigma_3$ vertical, $0 < \Phi < 0.25$), pure contraction ($\sigma_3$ vertical, $0.25 < \Phi < 0.75$) and radial contraction ($\sigma_3$ vertical, $0.75 < \Phi < 1$). During the inversion process, we used the allowable maximum misfit angle (ANG) and the acceptable maximum quality estimator value (RUP) (Angelier, 1994) to separate heterogeneous and incoherent data. The ANG (it’s the maximum misfit angle between observed slip and computed shear stress direction) was taken as 25°. The RUP ranging from 0%
Table 1. Characteristics of stress states used to reconstruct stress regimes as illustrated in Figure 9. Abbreviations: D° and P° – trends and plunges of stress axes in degrees; ϕ – ratio of stress magnitude differences \[\phi = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3}\]; ANG – the average angle between observed slip and computed shear, in degrees (acceptable with ANG < 20°); RUP – criterion of maximum quality value for the ‘INVQ’ method (acceptable results with RUP < 75%).

| Structure Name       | Site Number | \(\sigma_1\) | \(\sigma_2\) | \(\sigma_3\) | \(\phi\) | # | ANG | RUP |
|----------------------|-------------|--------------|--------------|--------------|---------|---|-----|-----|
| Havran – Balkisir Fault Zone |             |              |              |              |         |   |     |     |
| Havran Segment 1 | 1 | 249/07 | 151/47 | 346/42 | 0.134 | 7 | 23 | 44  |
| Havran Segment 2 | 2 | 088/16 | 347/32 | 201/54 | 0.402 | 6 | 24 | 35  |
| Osmanlar Segment 3 | 3 | 286/08 | 021/33 | 183/56 | 0.184 | 14 | 21 | 36  |
| Segment 4 | 4 | 109/01 | 199/20 | 016/70 | 0.224 | 9 | 17 | 47  |
| Ovacik Segment 5 | 5 | 298/09 | 207/09 | 071/78 | 0.325 | 7 | 14 | 41  |
| Segment 6 | 6 | 113/14 | 022/03 | 282/75 | 0.628 | 6 | 12 | 33  |
| Balkisir Fault Gökçeyazı Segment 7A | 7A | 234/01 | 144/15 | 328/74 | 0.295 | 6 | 13 | 30  |
| Segment 7B | 7B | 174/22 | 084/02 | 349/68 | 0.893 | 8 | 14 | 31  |
| Segment 7C | 7C | 128/01 | 218/19 | 034/71 | 0.321 | 12 | 16 | 36  |
| Ovacik Segment 8 | 8 | 309/04 | 041/26 | 210/64 | 0.489 | 7 | 7  | 34  |
| Segment 9 | 9 | 022/49 | 119/07 | 215/40 | 0.685 | 9 | 22 | 50  |
| Kepsut Segment 10A | 10A | 293/40 | 69/40 | 181/24 | 0.673 | 6 | 20 | 36  |
| Segment 10B | 10B | 346/39 | 199/46 | 090/17 | 0.514 | 6 | 6  | 42  |
| Segment 11A | 11A | 303/49 | 137/40 | 041/07 | 0.725 | 7 | 19 | 43  |
| Segment 11B | 11B | 027/81 | 283/02 | 192/09 | 0.405 | 20 | 24 | 49  |

Table 2. Description of the parameters in earthquakes occurred HBFZ and surroundings, which were given focal mechanism solution in the literature. For reference and locations of the earthquakes, see Figure 2a.

| EQ NO | DATE D/M/Y | TIME UTC | LAT. ° | LON. km | DEPTH km | MAG. M | Strike | Dip | Slip | REGION |
|-------|-------------|-----------|--------|---------|----------|--------|--------|-----|------|---------|
| 1     | 23.02.1971 | 19:41     | 39.62  | 27.32   | 10       | 5.5    | 86     | 66  | 160  | Havran/Balkisir |
| 2     | 05.03.1998 | 01:45     | 39.55  | 27.29   | 23       | 4.8    | 273    | 69  | −135 |         |
| 3     | 29.09.2007 | 22:35     | 39.75  | 27.76   | 6        | 4.4    | 109    | 52  | 85   |         |
| 4     | 12.08.2010 | 02:23     | 39.66  | 27.61   | 13.8     | 4.6    | 230    | 40  | 180  |         |

(calculated shear stress parallel to actual striae with the same sense and maximum shear stress) to 200% (calculated shear stress maximum, parallel to actual striae but opposite in sense) was taken here as 50%. If fault slip data exceeding these limits, it were separated from the data set, and then recomputed as a new tensor. Finally, combining qualitative observations and collected fault slip data in homogenous stations led us to obtain a picture of stress state related to regional tectonic events with various styles (extension or contraction), in terms of chronology and orientation.

We also use structural relationships between striations and fault-plane related structures for age relations and sense of motion. In addition to the crosscutting and offset relationships, we also separate the data for the fault slips that can develop under the same tectonic framework. If there were no cross-cutting or overprinting relationships encountered, the age of host lithology, and the similarity of the stress orientations or stress ratios to other sites were considered for which the deformation phase was younger or older (Spemer & Zweigel, 2010; Hippolyte et al., 2012).

3.2. Fault slip data of the HBFZ

At the western most part of the HBFZ on Havran-Balya Fault, we collect 13 fault plane data from 2 localities (site 1 and 2 on Figure 6) to light up the nature of the faulting along the Havran Segment. Movement vectors along the fault planes are generally noted as less than 20° and has kinematic indicators related with right lateral strike-slip deformation. Apart from them, this segment has some R’ Riedel faults showing the nature of left-lateral strike-slip faulting (plot 1, Figure 6). The Osmanlar Segment we collected 21 kinematic data from 2 stations (plots 3 and 4 on Figure 6), fault planes along the principle displacement zone strike around N30°–40°E, and dip on average at 80° to both, SE and NW. Observed movement vectors along the these fault planes are noted between 12° and 36°, whereas the striations of N60°W and N85°E trending, 60–80° dipping subsidiary (R and R’) faults are limited between 20–45°. The northernmost part of the HBFZ characterize with the Ovacik Segment. We collect 12 kinematic data from 2 locations to document the nature of the faulting (plots 5 and 6 on Figure 6). According to field data, observed fault planes are generally dipped approximately 55° to NW. The measured striates manifest that, the main character of this segment is oblique-slip with striations between 40° and 68° including reverse component. Additionally, the right-laterally offsetting is also documented in the S-flowing stream channels due to the effect of this segment. Around Fethiye village, the
fault zone comprises several relatively small-scale faults striking mainly in a NE–SW-direction. Here, after a couple right steps, the HBF can no longer be traceable through the north or east.

Gökçeyazı Segment is highlighted as the most remarkable segment of the BF (Figure 2(a)). We noted more than 40 kinematic measurements from 3 stations data to understand the faulting through this segment (plots 7, 8 and 9 on Figure 6). Around east of Ivrindi village some of the fault planes have locally preserved slickensided surfaces showing strike-slip nature (<20°), on average dipping 80°E. Well-exposed slickenlines are represented here sub-horizontal rakes with minor amount of reverse-slip component (plot 7A in Figure 6). Additionally, we collected 13 overprinted slickenside data supporting the evidence for two more different styles of faulting. The oldest one has average rakes of 20°W associated with left-lateral strike-slip faulting, while the younger set has subvertical striations (> 80°) manifesting the reverse nature of the segment (plots 7B and 7C in Figure 6 respectively). The observed fault planes are generally dipped to old geological unit exposed along the fault zone. The youngest deformation is documented with average rakes of 22°E (plot 7C in Figure 6), and is characterized by right-lateral strike-slip slickenlines. Around Gökçeyazı village, 7 fault plane data related with earlier reverse faulting is also documented along the segment. The measured fault planes have an overall strike of between N65°E and N85°E, and dip of approximately 75° to the SE. Based on 9 fault plane data from Balikesir, well-preserved slickenlines on the planes of Gökçeyazı Segment show right-lateral oblique-slip motion with right-lateral component as indicated by rakes ranging between 20° and 52° (plot 9 in Figure 6).

The easternmost part of the BF at Kepsut Segment, we collected 39 fault plane data from 2 stations (see plots 10 and 11 in Figure 6), westernmost structures of the segment have a dominant dip-slip component with slickensides between 70° and 80°, while the eastern side faults have an oblique-slip fault character having striations ranging between 50° and 65°. Additionally, east of Ayşebaci village the existence of an early strike-slip faulting was documented with 6 kinematic data (plot 10A). Here, the earlier right lateral slickenlines with rakes ranging 11–26° have been overprinted by a series of younger dip-slip striations with an average rake of 75°W to 85°E.

3.3. Paleostress reconstruction of fault-slip data

Based on our paleostress results, three different deformation phases have been separated. First phase is observed along Havran and Gökçeyazı segments as a left-lateral strike-slip faulting with reverse component associated with NE-SW-trending contraction and NW-SE-trending extension. Data of Phase 1 is solely recorded on the rocks of Oligocene Hallaçlar volcanic and older units, and is overprinted by younger kinematic structures. Therefore, the age of this left-lateral strike-slip faulting took most probably place during the Miocene or older palaeotectonic regime. The Phase 2 is recognized on Gökçeyazı and Kepsut segments, as strike-slip and reverse faulting, respectively. Related with approximately NNW–SSE trending contraction and associated ENE–WSW trending extension, Phase 2 took probably place during Plio–Quaternary time interval. This contractual/transpressional stress state was most probably related with initiation of North Anatolian Fault Zone through the area. During Quaternary, Phase 2 is postdated by youngest deformational phase (Phase 3), which is controlled by transpressional tectonics associated with NE–SW striking extension and NW-SE striking contraction. This stress state is characterized by right-lateral strike-slip with a reverse component along the HBFZ.

Phase 1 – Miocene: This first deformational phase including left-lateral strike-slip faulting along the HBFZ is documented in two locations (plots 1 and 7A on Figure 6, for details see Table 1). Horizontal component of principle stress axes are consistent with paleostress direction of NE–SW contraction and related NW–SE extension. Calculated $\sigma_1$ is in subvertical position with approximately 330° trend. The computed kinematic data also define gently plunged maximum principle stress axes ($\sigma_1$) with less than 7° dip whereas dip of $\sigma_2$ varies between 15° and 47°. On the other hand, main trend of both $\sigma_1$ and $\sigma_2$ are logical with about 240° and 150°, respectively. According to shape factors ($\Phi$) ranging between 0.134 and 0.295 suggest that the Phase 1 structures are mostly related with transpressional tectonic setting. Actually, there is no restrict data in the literature on neither left-lateral strike-slip faulting along the southern branch of North Anatolian Fault Zone, nor successive evolution of the HBFZ. Even so, the age of host lithology, and the similarity of the stress orientations/stress ratios to neighbour areas let us to suggest that the first deformation phase is roughly took place during the Miocene time. Therefore, contractual data recorded on the rocks of Oligocene Hallaçlar volcanics and older units are most probably related with the contemporaneous formation of Miocene explosive volcanism and related palaeotectonic regime in the region.

Phase 2 – Plio–Quaternary: Phase 2 is recognized at three locations along the HBFZ (plot 7B, 10A and 11A on Figure 6). During this phase, the orientation of principle stress axes is characterized by oblique to subvertical $\sigma_2$ and $\sigma_3$, while direction of them varies between NW and NE. On the other hand, horizontal component of maximum principle stress axes ($\sigma_1$) have almost similar trend in NNW contraction. The
orientation of the $\sigma_1$ calculated in sites of 7B, 10A and 11A is 174°/22°, 293°/40° and 303°/49°, respectively (Table 1). Based on paleostress computation results, we suggest that the main deformation in the area is NNW–SSE contraction and associated ENE–WSW extension. The shape factors belonging to this deformation phase ranges between 0.673 and 0.893 indicating that the phase 2 structures were formed during the transpressional and pure contractional tectonic regime. Despite of the lack of background data, using the age of youngest units deformed by this phase and the cross-cut relationships at station 7, we can state that the age of phase 2 is most probably Plio–Quaternary. We can also speculate that this contraction dominated deformational phase was most probably related with the first initiation of North Anatolian Fault Zone in to the SMR, which started the neotectonic regime in the region.

Phase 3 – Quaternary: It is the latest phase evidenced by the youngest kinematic data collecting from 10 locations (Figure 6 and Table 1). Due to the fault geometry, this phase has three transitional deformational styles along the HBFZ: (i) transpression on the NE-trending Havran, Osmanlar, Turpul and Gökçeyazı segments; (ii) contraction on the E–W trending Ovacık and Gökçeyazı segments, and (iii) transtension on the NW trending Kepsut Segment. At the western part of the fault zone, where the main direction of fault zone ranges between N50°E and N80°E, the principle stress axes is characterizing by nearly vertical $\sigma_3$ reaching dip angle about 80°, and is indicating right-lateral strike-slip fault planes (plots 2, 3, 4, 7C and 9 on Figure 6, Table 1). Kinematic indicators on the outcrops and the calculated shape factors for the stations ($\Phi < 0.402$) suggest that the deformation style is a predominantly transpression. Here the orientation of maximum stress axes is nearly horizontal dipping less than 16°, while the intermediate one is in oblique position with dip angle of between 9° and 47°. The inverse analysis of the data represents NW–SE trending contraction and associated with NE–SW trending extension. At the central part of the HBFZ, the position of $\sigma_3$ stays vertical, while the $\sigma_1$ oriented on horizontal plane with maximum dip angle of 14°. According to computed $\Phi$ values ranging between 0.325 and 0.685, the tectonic regime here is mostly pure contraction indicating both right-lateral strike-slip and reverse faults (plots 5, 6 and 8 on Figure 6). The results show a consistent NW directed contraction for this area. The stress state at the eastern part of the HBFZ is mainly characterized by the normal or oblique faulting. Hence, the orientations of principle stress axes are generally related with transtensional deformation. Computed shape factors to estimation of the stress state are also support that the Phase 3 structures of the area is shaped in control of transtensional setting. Here the near vertically oriented $\sigma_3$ is characteristic, whereas dip of maximum and intermediate stress axes ($\sigma_1$ and $\sigma_2$) varies between 2° and 81°. The NE–SW trending extension and a perpendicular contraction have been calculated by the INVD technique for the area. The age of Phase 3 is clearly stated as Quaternary with various geomorphological features such as aligned drainage systems, linear/sub-linear valleys, deflected channels, elongated hills and fresh fault scarps. Additionally, fresh fault planes belonging of this phase cut and deform the Quaternary deposits.

In addition, the current deformational pattern is also evidenced with focal mechanism solution of instrumental earthquakes occurred along the HBFZ (Figure 2(a), Table 2). The solutions of 1971 and 2010 earthquakes indicate that slip vectors are 160° and 180°, respectively (plots 1 and 4 on Figure 2(a)). These vectors are showing a right lateral faulting with reverse component and pure strike-slip faulting. According to solution data of the 1998 earthquake, the fault plane that compatible with the main orientation of the fault zone, is also characterized by the right lateral strike-slip faulting. The 2007 earthquake gives most significant data about the contractional nature of the recent faulting along the fault zone (plot 3 on Figure 2(a)). This event is located on the Ovacık Segment of the Havran-Balya Fault, and its focal mechanism solution shows a slip with 85° indicating a reverse faulting. All the earthquake data also support the existence of a contractional deformation with strike-slip transpressional tectonics along the HBFZ. The NW-trending elongated and elevated hills within the HBFZ put emphasis on the contraction along the western and central part of the fault zone, while the Balikesir depression filled with Quaternary deposits display the recent extensional deformation at the eastern part.

4. Discussion

4.1. Evaluation of kinematic data for the marmara region

The present day structural framework and morphology of the Marmara region is mainly characterized by NW–SE, NE–SW and E–W striking en-echelon fault systems and approximately NNE–SSW elongated tectonic domains (Emre et al., 2016; Gürer et al., 2003, 2006; Sözbilir et al., 2016b). In spite of the fact that the kinematic descriptions & tectonic interactions of these faults have significant importance on the understanding of the tectonic evolution of the Marmara province, there is not much paleostress data accumulated through the region yet (Bonev, Beccaletto, Robyr, & Monié, 2009; Dirik, Belindir, Özsayın, & Kutluay, 2008; Gürbüz & Seyitoğlu, 2014; Gürer et al., 2003, 2006,
2016; Kürçer et al., 2012; Özalp, Kürçer, Özdemir, & Duman, 2016; Özden, Över, Kavak, & İnal, 2008; Sözbilir et al., 2016b; Yıldız et al., 2013). Hence, here we will give brief information about literature first, then will discuss the kinematic history of the region by merging prominent outcomes of this study and previous studies.

Along the south coast of the Marmara Sea, Gürer et al. (2003) provided five paleostress stations on neotectonic structures. Their fault slip data indicates that most of the faults in the SE Marmara region have oblique- to dextral slip nature with prominent dip-slip component, related mainly with NE-SW trending extension and NW-SE trending contraction (plots 1 on Figure 7). They also note that the Miocene sequence in the area is intensely folded (locally overturned) and faulted indicating compressional deformation during the Late Miocene. According to structural data from SW of Marmara Sea (Gürer et al., 2006), the NE–SW trending oblique-slip and E–W trending normal faults have been shaped the present-day morphology. Results of their paleostress constructions refer multi directional extension, indicating NE-SW, NW-SE, E-W and N-S trends (plots 2 on Figure 7). They explain this deformation pattern with the idea of transition zone of two different but contemporaneous tectonic regimes during the Late Pliocene–Quaternary: (i) an ongoing N–S extensional regime that prevails over the whole of western Anatolia; (ii) the NE–SW strike-slip deformational regime associated with the NAFZ. On the other hand, their paleostress plots have significant strike-slip component without any compressional stress.

Dirik et al. (2008) collect fault plane data from eight stations along the Yenice-Gönen Fault Zone (YGFZ). Based on their structural data, they document that the nature of faulting is mainly reverse and dextral faulting with reverse component. Paleostress analyses of kinematic data indicate NW-SE contraction (plots 3 on Figure 7). They also find some minor NNE- to NE- trending oblique- to strike-slip faults, relating with the NW-SE extensional regime. They explain this local stress change as the bending mechanism along the fault zone. Özden et al. (2008) reported the inversion of slip vectors measured on fault planes at Bolu Basin indicates that a strike-slip stress regime with consistent NW-trending compression and NE-trending tension is dominant (plots 4 on Figure 7). They also suggested that variations of principal stress magnitudes within the strike-slip stress regime resulting in older transpression to younger transtension as a result of the westward extrusion of the Anatolian block in Quaternary. Bonev et al. (2009) contribute one station from the westernmost part of Kazdağ Core Complex. Based on the field and thin-section data, kinematic

![Figure 7](image-url)

**Figure 7.** Orientation and temporal variation of calculated horizontal component of maximum and minimum stress axes orientation including available paleostress data from the literature. Please note the laterally change in minimum and maximum stress axes direction, from east to west. Green arrows related to Miocene faulting (Phase 1), whereas purple and black arrows characterized Plio–Quaternary (Phase 2) and Holocene (Phase 3), respectively. Hachured area with horizontal lines in indicates İzmir Balikesir Transfer Zone (İBTZ). Big yellow arrows (labeled as 6) are simplified from World Stress Map Project database WSM (www.world-stress-map.org). showing earthquake focal mechanism solution (EFMS). Dashed navy blue lines indicate anticlockwise rotation of the main contraction axes. Data numbers: 1- Gürer et al. (2003); 2- Gürer et al. (2006); 3- Dirik et al. (2008); 4- Özden et al. (2008); 5- Bonev et al. (2009); 6- Heidbach et al. (2010); 7- Kürçer et al. (2012); 8- Yıldız et al. (2013); 9- Gürbüz and Seyitoğlu (2014); 10- Sözbilir et al. (2016b); 11- Gürer et al. (2016); 12- Özalp et al. (2016); 13- This study. Abbreviations: KDF: Kazdağ Detachment Fault, KDM: Kazdağ Massif, YGFZ: Yenice-Gönen Fault Zone, EFZ: Edremit Fault Zone, HBFZ: Havran-Balikesir Fault Zone.
indicators in the Kazdağ Detachment Fault consistently demonstrate a NNE-SSW extension, which refers the Miocene tectonic regime of Biga Peninsula during the exhumation of Kazdağ Massif (plot 5 on Figure 7). Kürçer et al. (2012) are analysed some fault plane data collected from the SW of Çanakkale so called Troy fault. Their paleostress analysis show that the Holocene faulting is mainly related with the NNE-SSW trending contraction and the NNE-SSW oriented tension as a result of transtensional tectonic setting (plot 7 on Figure 7).

On the northern branch of the NAFZ, Yıldız et al. (2013) collect numerous fault slip data along the Ganos Fault. They document that the nature of faulting here is mainly dextral with reverse component, and related stress regime is associated with the NW-SE trending contraction and NE-SW trending extension (plots 8 on Figure 7). They also note that there is some minor NE-SW extension related normal faults and most probably associated with the local transtensional areas along the deformation zone of NAFZ. Gürbüz and Seyitoğlu (2014) is worked one of the Quaternary basins on the southern branch of NAFZ, and collect structural data along the basin margin faults. They present paleostress analysis from two stations, and document that the local paleostress axes are related with the NW-SE trending contraction and NE-SW trending extension (plots 9 on Figure 7).

To clarify the tectonic history of Kazdağ region, Sözbilir et al. (2016b) document some kinematic data collected from the structures along the southern shoulder of the Kazdağ Massif, such as the Edremit Fault Zone (EFZ), and the Kazdağ Detachment Fault (KDF). They present several paleostress plots, and mainly suggest that the region is deformed under (at least) three distinct phases since the Oligocene (plots 10 on Figure 7). Phase 1, the oldest, is related directly to the Miocene detachment faulting along the KDF, and is characterised by N-S directed pure extension. Phase 2 is associated with the strike-slip nature of the Edremit Fault Zone, and related stress axes indicate the NE–SW trending extension and NW–SE trending contraction. According to their statement, this stress state is most probably related with the initiation of the NAFZ through the Edremit area during the Plio–Quaternary. The youngest stress state, Phase 3, is characterised by normal faulting along the EFZ during the Holocene. Paleostress analysis of this deformation includes a NE–SW-striking extension. Gürer et al. (2016) are also came up with numerous fault plane data from the Edremit Bay area. Their paleostress configurations state that the Edremit basin boundary faults represent biaxial, NE–SW and NW–SE directed extension directions (plots 11 on Figure 7). They suggest the whole faults in their observations are plausibly worked synchronously during the Plio–Quaternary, and the mechanic interaction of the NAFZ and the Aegean Extensional System is blamed for this biaxial stress state. Between Edremit Bay and Marmara Sea, Özalp et al. (2016) provides one paleostress analysis collected from a paleoseismic trench walls, along the Bekten Fault. According to their kinematic data the nature of faulting is mainly oblique slip with reverse component. The stress axes orientations indicate NW–SE directed contraction (plot 12 on Figure 7).

Based on structural observations and paleostress configurations of our study and available data in literature, it can be state that the Marmara region has experienced at least three different deformation phases during the late Cenozoic. First phase took place during the Miocene. It is characterized by a N-S trending pure extension in Biga region, while the NE-SW trending contraction and related NW-SE trending extension in Balıkesir region. This deformation period is evidenced with detachment faulting along metamorphic core complexes, and strike-slip faulting with reverse component along the NE and NW directed structures (Figure 7). The Phase 2 took probably place during Plio–Quaternary. It is evidenced along the Edremit, Havran-Balıkesir and North Anatolian Fault Zones with strike-slip, reverse and strike-slip faulting, respectively (Figure 7). Related kinematic data proposed an approximately N–S trending contraction and associated E–W trending extension during the Phase 2. Characterizing by transpressional tectonics in the region, Phase 3 can be state as Holocene. This stress state evidenced by high-angle normal faulting along the E-W trending faulted in the Edremit Bay, while the NE-trending structures, such as HBFZ, YGFZ, and NAFZ have experienced dextral faulting with reverse and normal components depending on fault zone geometry (Figure 7). The Phase 3 is shaped present-day morphology, as well as the seismic activity in the region is controlling by this youngest stress state and related active structures. World stress map data (Heidbach et al., 2010), shows a pattern with anticlockwise rotation on the main compression axes, approximately N-S direction to the east and E-W direction to the west, along the movement from east to west with NAFZ as well as transition zone of the Aegean region (plots 6 on Figure 7). Field kinematics data on especially YGFZ, HBFZ, EFZ as well as northern and southern branch of the NAFZ at Marmara region also close resemblance with this anticlockwise rotation on the same meaning.

4.2. Rotation of recent stress axes: its causes & consequences

The SMR is subjected to differential uplift and subsidence as a result westward escape of the Anatolian block along the NAFZ in the north and to the slab
edge processes related to slab detachment and slab tear at the northern edge of northwards subduction. African slab along the Aegean-Cyprian trench, beneath the Anatolia. Lithospheric deformation of the area is mainly controlled by collision-related tectonic escape and subduction along the Aegean Subduction Zone, including slab roll-back process (Biryol et al., 2011; Faccenna, Bellier, Martinod, Piromallo, & Regard, 2006; Jolivet et al., 2013, 2015; Spakman, Wortel, & Vlaar, 1988). Wortel and Spakman (2000) stated that the slab-tear process begin with an initially small tear in the slab, propagates approximately horizontally and finally develops into a large tear. Additionally they indicated that tearing of oceanic lithosphere increase slab pull down and allows escaping high astenospheric temperatures and melting material into the crust, and even allows for the partly melting of the crust itself. Upper-mantle features such as slab tears and slab edges process, associated hot ascending asthenosphere, and upwelling of hot asthenospheric volumes also contribute to the distribution of the deformatonal pattern throughout the Anatolian block (Biryol et al., 2011). Jolivet et al. (2013) also suggested that the westward direction of mantle flow under the Anatolian block along the NAF (in addition unobserved in Miocene), turn southwest at its western termination and move towards the Aegean slab the present time. However, beside asthenospheric flow, the upper and lower crustal flows have also been commenced after the formation of the NAF in the Marmara Region at around 5 Ma years ago (Jolivet et al., 2013) and accelerate present time toward the Hellenic trench as a result of the progression of the NAF and roll-back process together. Recently, Király, Capitanio, Funiciello, and Faccenna (2017) documented that slab pull force directly affect subduction-induced mantle circulations and increases the induced flow velocities plays an important role in the dynamics of convergent margins. In addition to these, geodetic data such as GPS velocities also shows that the Anatolian–Aegean block relative to stable Eurasia follow the pattern of the NAF east to west to the north and turn to the southwest direction at its western termination and accelerate towards the Hellenic trench (McClusky et al., 2000; Reilinger et al., 1997, 2006), as a result of roll-back process. Papazachos et al. (1998) also indicated that by using focal mechanism solution of the earthquakes, the anticlockwise rotation of the Aegean plate is consisted with GPS measurements. On the other hand, as another component in the geodynamics of the Aegean region, IBTZ is also contributed on the basin formation in the upper crust (Brun et al., 2016; Gessner et al., 2013; Sözbilir, İnci, Erkül, & Sümer, 2003; Sözbilir et al., 2011; Uzel et al., 2015). This strike-slip dominated zone is a pre-existing zone of weakness, realm from the Neo-Tethys Suture (Özkaymak et al., 2013; Sözbilir et al., 2003, 2011; Sümer et al., 2013; Uzel et al., 2013, 2017). It is proposed that this discontinuity is a part of a lithosphere-scale shear zone and controlled bottom-driven crustal deformation, which has been accommodated in the Aegean and the Anatolian continental lithosphere since the Miocene, and may links the North Anatolian Fault Zone to the Hellenic Trench at the present time. Here we can state that with a high degree of probability, Hellenic Trench, NAFZ and IBTZ together with play an important role on the accumulation of the upper lithospheric mantle flow and related deformation pattern on the upper crust.

After the bearings of all these data, such as the initiation/formation of the NAFZ within the Marmara region, the slab roll-back/retreat/tearing processes on the Aegean subduction, corresponding mantle flow circulations, the GPS measurements and the presence of a pre-existence transfer zone of weakness in lithospheric scale (IBTZ), it’s clear that there are many geological elements that played important role together on the deformational pattern for the region. It seems that the NAFZ have formed in a crescent shape where it interacts with the IBTZ and West Anatolian extensional regime. The surface and subsurface interactions of these structures lead to anticlockwise rotation in minimum stress axes across the region. In map view, the NW-SE oriented contractual stress axis at the easternmost part of the HBFZ turn into the E-W oriented contraction at the west. After that, a pure N-S extension at its western termination appears along the Edremit Fault Zone (Figure 7). Consequently, it can be state that as a unique structure, the HBFZ forms a boundary between two different deformational provinces; the Aegean extension to the south and strike-slip dominated Marmara region to the north.

5. Conclusions

To document kinematic evolution of the HBFZ and its consequences in the interaction area of NAFZ and West Anatolian Extensional Province, the structural observations and paleostress configurations have been performed and evaluated with related literature. The main findings of the present study are as follows.

- Havran–Balikesir Fault Zone is a 10–12 km wide, 120 km long, approximately N70°E-trending fault zone which consists of two faults, namely Havran-Balya Fault to west, Balikesir Faults from to east. The Havran-Balya Fault is approximately 90 km long and made up of four main geometric segments; 19 km long Havran, 30 km long Osmanlar, 16 km long Turplu and 22 km long
Ovacık segments. The Balıkesir Fault is approximately 70-km-long and comprise two main segments; 40 km long Gökçeyazı and 26 km long and 1–3 km wide Kepsut segments.

- Paleostress results reveal that three different deformation phases have been observed on HBFZ. Phase 1 is represented by left-lateral strike-slip faulting with reverse component probably place during the Miocene or older and characterized by NE–SW contraction and related NW–SE extension. The Phase 2 is represented by approximately N–S trending contraction and associated E–W trending extension, related with also contraction dominated deformational phase with strike-slip and reverse faulting, which probably placed during Plio–Quaternary time interval with initiation of North Anatolian Fault Zone through the area. Phase 2 is post-dated by youngest deformational phase (Phase 3), which is controlled by transpressional tectonics associated with NE–SW striking extension and NW–SE contraction since Quaternary.

- Formation of the NAFZ at the region, slab roll-back and retreat and tearing process on the Aegean subduction, in addition presence of pre-existence IBTZ have together played important role for currently observed anticlockwise rotation of main contraction axes at the Marmara and the Aegean regions.

- HBFZ is unique structure which is limited two different deformational province Aegean extension to the south and strike-slip dominated Marmara region to the north.

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ORCID

Ökmen Sümer  http://orcid.org/0000-0003-3168-8728
Bora Üzel  http://orcid.org/0000-0003-1703-5026
Çağlar ÖzKaymak  http://orcid.org/0000-0002-0377-1324
Hasan Sözbilir  http://orcid.org/0000-0002-3777-4830

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