Basin Progress – Active Deformation Analysis by Tectonostratigraphic Elements and Geophysical Methods on North Anatolian Fault System (Eastern Marmara Region, Turkey)

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Abstract

The Northern Branch of the North Anatolian Fault System controls and deforms the Izmit Basin and the Sapanca Lake Basin in the study area. Unlike the Sapanca Lake Basin, the oblique normal faults with WNW–ESE trending with maximum length of 5 km in the south of the basin have contributed to the deformation process in the formation of Izmit Basin. The fault sets mainly incline to the north. The N-S width of the dextral strike-slip active deformation was determined as 9 km at Izmit basin and 3.8 km at Sapanca Lake basin. Further, the minimum principal stress axes (σ3) vary in the trending ranges of N11°-74° E, which are caused by the transtensional stresses associated with strike-slip faulting in the Izmit Basin by a different tectonic source than the Sapanca Lake Basin. Besides, the crust depth of main strand of NAFS-NB was determined up to 1112 m by magnetic method. The secondary faults were determined by both magnetic and resistivity methods up to a depth of 110 m. The depression area between Izmit bay and Sapanca Lake on the northern Anatolian fault is an integrated basin with two dextral strike-slip tectonic origins. Thus, the Izmit Basin, along with the main strike-slip faulting, has been developed in the asymmetric negative flower structure, where only the southern boundary has become a fault. The Sapanca Lake Basin is a lazy-Z-shaped pull-apart system formed by the E–W trending fault as a releasing bend. A simple shea deformation ellipsoid with a long axis of approximately 35 km on the Northern Branch of the North Anatolian Fault System is defined for the Izmit – Sapanca integrated basin. Therefore, intra-basin deposits have different depths estimated from the gravity data in the Izmit – Sapanca integrated basin, and the maximum sediment thickness estimated is 2200 m in the middle of the Izmit Basin.

1 Introduction

The North Anatolian Fault System (NAFS) is a right-lateral strike-slip fault with approximate 1200 km length (Fig. 1a), (Barka 1992). It has opened many basins of different lengths and widths and has deformed these basins until the present. Neotectonic history of Anatolia consists of mainly two periods: Oligo-Miocene - Pliocene (Early) and Pliocene - Holocene (Late). In both periods, fault types in different regions of Anatolia developed as segments, faults, and zones (Şengör 1979; Barka 1985; Barka 1992). These faults continue in the sedimentary basins and have left deformation traces recognized in the Plio-Quaternary deposits. In the Late Neotectonic period, the Eastern Anatolian crust plate was compressed. Furthermore, the escape of the Central Anatolian plate to the west occurred along the strike-slip NAFS and East Anatolian Fault System (EAFS) (Şengör et al. 1985; Bozkurt 2001). The NAFS has deformed the entire Marmara region with three main strands; defined as the north (NAFS-NB), south (NAFS-SB) and south-a (NAFS-SB-a) strands (Doğan et al. 2015). These strands extend from Mudurnu (Bolu) in the east to the Gulf of Saros in the west and from the Izmit Gulf in the north to the Biga Peninsula in the southwest (Şengör 1980; Barka 1992; Şengör et al. 2005).

It is necessary to identify the unconsolidated units and the structures in the active faults at different depths. Honkura and İşikara (1991) have showed that weak magnetic zones exist between Izmit – Sapanca over NAFS-NB and between Mekece – Iznik along the NAFS-SB, and they can be related to active faulting (Fig. 1b). Oshiman et al. (1991) have stated that the shapes of magnetic anomalies between Iznik and Geyve on the southern branch of the NAFS are dike-like structures (see Figs. 1a, b). In addition, the structure is also parallel to the direction of faults in the region. Wise et al. (2003) have presented that the fault geometry can be uncovered using gravity, Electrical Resistivity Tomography (ERT), Ground-Penetrating Radar (GPR) and seismic methods in young Quaternary sediments. ERT methods can be used for fault detection (Nyugen et al. 2005). Suzuki et al. (2000) have identified the faults in shallow unconsolidated geological units using the ERT method as well in Shaw Basing area of western the Alberta. The measured resistivity values on faults are relatively low when they are compared to the background formation resistivity values (Bedrosian et al. 2002; Kaya et al. 2013). Ateş et al. (2003) have conducted comparative fault detection using air magnetic, gravity, and seismic data obtained in the Marmara Region. The fault locations can be detected based on the differences between low resistivity and high resistivity values of the geological units and other structural elements in the region ( Çağlar 2001; Ogawa et al. 2001; Ogawa and Honkura 2004). Ateş et al. (2003) have identified the faults in the deep section of the crust along the NAFS-NB based on the high-speed zones and the regions where coincident with gravity and magnetic highs. Bohnhoff et al. (2016b), suggested that a coseismically introduced lateral and vertical slip deficit is systematically compensated postseismically in both the brittle and ductile portions of the crust in east Marmara region.

This study explains the development of an integrated basin-like ISIB consisting of Izmit basin and Sapanca Lake basin with different basin morphology, located on a right-lateral strike-slip fault (NAFS). In this sense, the deformation geometry of the active structural elements, which are associated with lithofacies features, the sedimentary processes of the basin-filling formations, and which are different from each other in each basin, are formed from the surface to a certain depth of the upper crust. The tectonostratigraphic observations made on the surface were correlated with the geophysical data collected by the resistivity, magnetic, gravity, and joint inversion methods, identified the traces of active deformation in the upper depths of the ISIB. Thus, the characteristics and genesis of tectonic sources such as type, length, N-S range and width, creating the deformation zone in the continental crust were studied. The difference of this study from previous studies is that the geometry of the secondary active faults, which play an important role in the setting of the basins in the region, together with the NAFS-NB main fault, was determined by comparing with the geophysical data obtained from both the surface and the deep. Accordingly, the fault
types were detailed in three dimensions and it was determined that IB and SB are integrated basins in two different geometries with different deformation areas, and NAFS-NB was the main tectonic source for these basins to take their present shape.

## 2 Study Area

The study area covers the İzmit basin – Sapanca Lake integrated basin (ISIB) consisting of IB with 21 x 11 km² and SB with 15 x 6 km² (Fig. 1b). The geology of the southern uplift of the ISIB belongs to Armutlu – Ovacık Zone, whereas the geology of the northern uplift of the ISIB belongs to Istanbul – Zonguldak Zone (Yiğitbaş et al. 1999), (Figs. 1a, 2). Both of these uplifts consist of the pre-Plio-Quaternary period rocks and structures. The ISIB developed during the Plio-Quaternary period (Sakınç and Bargu 1989; Bargu and Sakınç 1990; Emre et al. 1998; Bargu 1993; Ünay et al. 2001). The deposits represent the Plio-Quaternary period in the study area, the development of the basins, and the active structural elements controlling the basins in the Pliocene and post-Pliocene (Fig. 2).

### 2.1 Stratigraphic setting

The IB located in the west of the ISIB in the Marmara region and on the NAFS-NB, has 11 km width in N-S and 36 km length in E-W. The Plio-Quaternary basin-filling deposits overlie the basement rocks of the south uplift of the Armutlu – Ovacık zone (see Figs. 1a, 2).

Some studies were conducted on the intra-basin stratigraphic features of ISIB (Altınlı, 1968; Akartuna, 1968; Göncüoğlu et al., 1986; Bargu and Sakınç, 1990; Bargu, 1993; Emre et al., 1998; Doğan, 2001; Alpar and Yalıtrak, 2002; Herece and Akay, 2003). The contact between basin-filling sediments of IB and the basement rocks of the southern mountains seems faulted and has angular unconformity. The Arslanbey formation has developed as a result of alluvial fan deposits and as a result of the deformation of streams in the southern block of depression areas due to active faults until the present (see Fig. 2).

This formation includes all of the upper, middle, and distal typical fan facies. Accordingly, the debris flow levels of the formation are located near the basin boundaries along with the south uplift and consist of a sandy matrix with blocks up to 50–60 cm in diameter (Fig. 3a). The channel and sieved deposits in the middle of the fan section are alternated (Fig. 3b). The fine-grained lithological levels of sieve and flood plain facies (Figs. 3c, d) cover the morphology from the southern boundary of the IB, with a slope angle below 15° to the north. The deposition of Arslanbey formation in the south of IB depends on the energy of the streams within the south watershed. However, the NAFS-NB and related secondary oblique normal faults deformed the morphology consisting of the southern basement rocks in the Plio-Quaternary period.

The Plio-Quaternary Maşukiye formation, mapped in this study for the first time in the south of the IB, has the same lithological characteristics of the unit, which was previously mapped to the northwest of the SB (Bargu, 1993). The Maşukiye formation consists of mainly sandstone, siltstone, and minor claystone fully completed the diagenesis phase, and the fastening of grains is well developed compared to the Arslanbey formation levels. According to the fossils found at the levels of the Maşukiye formation in the northwest of Lake Sapanca, the unit indicates the existence of a freshwater environment with a mean age of 350–400 ka (Bargu 1993). Within the study area, in sandstone and siltstone outcrops of the Maşukiye formation located at the south of İzmit Gulf, the fossils of the Gastropoda type *Planorbarius* (*Planorbarius comeus*) showed abundance zone (Figs. 3e, f). These fossil species have lung respiration and live in stagnant or freshwater environments such as small ponds, lakes. (Büyükmeriç 2018). The age of the unit can be considered as dated back Pliocene – Holocene. The Maşukiye formation overlies the basement rocks in the south of IB, both unconformably and fault-controlled. The Arslanbey formation covers the Maşukiye formation conformantly, or they present a lateral transition in the entire IB (Figs. 3g, h). The marine deposits in the vicinity of İzmit gulf cover these units with unconformity. The Kirazdere formation located around the present streams has river units deposited as a result of climatic changes and deformation in the south block. In the north of IB, the Şirintepe formation is composed of sand and little clay, which represents a marine environment (Altınlı 1968).

The Arslanbey formation, located south of SB, contains only sieve and flood plain deposits. However, the sediments around the shore of Sapanca Lake are associated with the water level change of the lake with clay and little sand. In the southeast of SB, there are some debris flow deposits, which are similar to the appearance of Arslanbey formation in the IB. The sediments with silt, clay, and muddy and sandy clay levels in Lake Sapanca are determined from several cores (< 45 cm) taken from the lake (Gürbüz and Gürer 2008; Schwab et al., 2009; Leroy et al., 2009). The youngest sediments in the basin are levels of Kirazdere formation, which are deposited in the vicinity of the canals of the streams in the south of IB, which are only related to the energy level of the stream flow that depends on the climate. This alluvial unit points to an existing terrestrial environment.

IB includes very thick deposits of lacustrine and alluvial fan facies overlying the basement rocks and the SB contains the basin-filling deposits with less thickness than IB. The faults in the south of the basin in addition to the NAFS-NB main fault have accompanied to the sedimentation of basin-filling deposits in the IB, meanwhile, the NAFS-NB which has only uplifted the southern block has been effective in the
SB. Additionally, changes in the energy level of the water, which are caused by climatic changes in the Plio-Quaternary period, and which constitute the drainage, especially in the southern uplift, and faulting are essential factors in sediment deposition.

2.2 Structures and Kinematics

IB in the west and SB in the east have distinct basin morphologies from each other (Tan and Tüysüz 2011; Tan and Tüysüz 2016). IB is an elliptical shaped, asymmetric basin that narrows into the İzmit gulf and widens toward the east of the İzmit gulf. The SB is an ellipsoid lake basin, and the N–S width of the basin does not differ significantly from west to east. Both the thickness and distribution of intra-basin deposits and the kinds of active faults associated with sedimentation are different in SB and IB. Also, during the Plio-Quaternary period, the Maşukiye formation, which characterizes the lacustrine environment and the Arslanbey formation, and which is the alluvial fan facies unit of the IB, have been deposited under the control of the secondary fault segments along with NAFS-NB. In the SB, only the middle and distal fan (sieve and ood plain) facies of the Arslanbey formation were deposited around the uplifting southern block associated with the main branch of the NAFS-NB. In the vicinity of Sapanca lake, the significant active faults and periodic climatic changes deposited the Sapanca formation (Qs), presenting a lacustrine terrace facies.

The southern uplift of IB consists of four segmentation Sets of 1, 2, 3, 5, and the northern uplift has only Set – 4 (see Fig. 2). Thus, IB has a total of five segmentation zones along with E-W and NE-SW trending. Some segments belonging to the Set-1 zone in the south of IB were ruptured in the August 17, 1999 M 7.4 earthquake and formed an approximately 3 km long normal fault surface rupture (Barka et al. 2002). A transtensional stress regime mainly affects IB (Tan 2007). Tan and Tüysüz (2016) have stated that the NAFS-NB controls the southern uplift topography of the IB and SB. In the southern block of the IB basin, both oblique normal and oblique reverse faults are present in the Set-1 zone. When we approach the hanging-wall blocks of the typical faults, the dipping beds toward the fault plane are observed in all fault zones (Figs. 4a, b, c, d). This situation shows that open and gentle folds in the region are related to oblique normal faulting zone that is followed in the contact of bedrock-Plio-Quaternary and the Plio-Quaternary intra-basin deposits.

All synsedimentary deformation elements in all fault sets (Set-1, 2, 3, 4, 5 zones) have been active, and they constitute the tectonic source for the freshwater lake and alluvial fan sedimentation environments in the southern block. The synthetic and conjugated faults exist along with the prominent tensional fissures in the Set-1 zone (see Fig. 4). These structural elements were active during the deposition of the Maşukiye formation in the lacustrine facies and accompanied the sedimentation of this formation as synsedimentary faults (Figs. 4e, f). This zone also includes secondary active deformation with the NAFS-NB main strand in the uplift of the southern block of IB. The fault segments within the Set-2 zone in southern block of IB were also effective in gaining this N-S width of the basin (Figs. 5a, b, c, d, e). In the whole area under study, syn-sedimentary bedding of the units constituting the basin filling of the IB is seen horizontally in locations away from the tectonic elements. Whereas the areas near the segments in the Set-2 zone gained tilting toward the fault (south) indicate the faults active during sedimentation (Fig. 5f). This change in the bedding is observed in the N–S direction in an area of approximately 2 km from the southernmost fault plane in the zone. The Set-3 fault segments also contain laminated fault rocks, and micro-kink folds synchronous with the deformation near the fault plane (Figs. 6a, b). Both the south and north dipping conjugated faults accompanied by sedimentation of the Arslanbey formation are also indicators of zonal deformation (Figs. 6c, d, e). The deformation within the basement basaltic rocks in the vicinity of these faults is geometrically similar to the faults in the Plio-Quaternary units and is generally in the shape of high-angle planes (Fig. 6f). The tectonic system, which deforms the basement rocks in the southern uplift of IB, also causes the development of small-scale colluvium by the fault segments of the Set-5 zone (Figs. 7a, b, c, d). The fault segments extending approximately 7 km long in E–W direction in the north of IB and İzmit gulf belong to the Set-4 zone (Figs. 7e, f).

The eastern basin (SB) of the ISIB is lake-surrounded, and there is no secondary segmentation, except for the NAFS-NB, which affects the basin formation in the south and north of the SB. Different depth maps of the SB lake (about depth 56 m) basin located on the main branch of NAFS-NB exist. It was stated that this lake basin was opened as a pull-apart with the activity of NAFS-NB related faults (Barka et al. 1997; Barka et al. 2002; Lettis et al. 2002). In addition to the work in the land part of the SB, active faults were identified with 84 km seismic reflection profiles, including 28 profiles in the N-S direction and two profiles in the E-W direction on the continuation of NAFS-NB in Sapanca Lake. According to these measurements, it is stated that Sapanca Lake Basin (SB) is a pull-apart basin developed between the two main right-lateral strike-slip faults with E–W strikes (Gülen et al., 2014, 2015).

The principal stress axes (σ3, σ2, and σ1) on all Plio-Quaternary faults were determined according to the deformational strucutral features data that include conjugate faults, slickensides, strias and fissures in study area. Besides the regional kinematic meaning of the deformational structural features was analyzed by the methods of some authors (Anderson 1951; Carey-Gailhardis and Mercier 1987; Angelier, 1994; Delvaux et al. 1997; Huerta and Rodgers, 1996; Delvaux and Sperner, 2003; Sperner and Zweigel, 2010).

The principal stress directions and stress regime ratio (R) are calculated using the slip vector on the fault plane and synsedimentary conjugate fault slickensides. Also, the stress regime index (R') value is defined by the slickensides. Faults are classified according to R value.
varying between 0 and 1, and $R'$ value (Delvaux et al. 1997; Delvaux and Sperner, 2003). According to this approach, in the pure extensive regime, $R$ is equal to $R'$; in the pure strike-slip regime, the stress regime index is defined in Eq. (1).

$$R' = 2 - R$$

(1)

In addition, in the pure compression regime, the stress regime index is as in Eq. (2).

$$R' = 2 + R.$$  

(2)

The principal stress distributions, including the positions of the slickenside-striae, slickenside-tensional fractures, conjugated faults related to secondary Plio-Quaternary faults in the south of IB were determined in the Wintensor program of Delvaux and Sperner (2003).

The fault sets between the basement rocks in the southern block of IB and the Plio - Quaternary units were numbered 1, 2, 3, 4, and 5, and stress regime created by them were determined, and their effects on the basin development were evaluated. To the south of the SB, there is no secondary segmentation similar to the south of the IB. In the south of IB, the positions of the principal stress axes and stress regimes of the secondary faults within the active deformation area in the south of the main branch of NAFS-NB are determined according to the structural data (Table 1). Based on the data of different structures in the Set-1 zone, active tectonic associated with pure extension and strike-slip is valid, and in this area, the minimum principal stress axis ($\sigma_3$) was found to be dominant in N15° – 45°E (Fig. 8). From the Set-2 fault zone, it was determined that the axes of the ($\sigma_3$) and maximum principal stress axes ($\sigma_1$) are in the N25° – 60°E and N70° – 25° W directions (Fig. 9). The $\sigma_3$-stress axis with N15° – 65°E and the $\sigma_1$-stress axis with N40° – 70°W directions have approximately equal vectorial magnitude and are seen in the Set-3 deformation zone. The Set-4 zone is located in the north of IB, and it is determined that the dominant system in this zone is transtensive in strike-slip activity according to conjugate faults, and these structures cause $\sigma_3$-stress axes in N20° – 35°E directions. The Set-5 fault zone caused the formation of colluvium after deformation of the basement rocks and indicated a transtensive faulting regime with strike-slip in N15° – 60°E. As a result, the distribution of the directions of the principal stress axes of $\sigma_3$ and $\sigma_1$ in the set zones containing all the fault segments around IB have been determined (Fig. 10).
Table 1

Calculation of the principal stress axes ($\sigma_1$, $\sigma_2$, $\sigma_3$) and other paleostress parameters according to the geometric positions of slickenside conjugate faults, striae and fault-fissures located in all fault sets in the south and north of the Izmit basin according to Delvaux and Sperner (2003). ($\alpha$: ratio of stress differences, $\phi$: friction angle, $R$: stress index, $R^\prime$: stress ratio).

| Age and Name of set-data | Type of data and Formation name | Number of data | Latitude | Longitude | Stress regime | $\sigma_1$ (azimuth / plunge) | $\sigma_2$ | $\sigma_3$ | $\phi$ | $\alpha$ | $R$ | $R^\prime$ |
|--------------------------|---------------------------------|----------------|----------|-----------|---------------|-----------------------------|-----------|-----------|-------|--------|-----|---------|
| **Set-1 in Plio-Quaternary units** | slickenside and striae (PlQa) | 4 | 40°41' 11,96'' N | 29°50' 45,52'' E | transtension with strike-slip | 191 / 59 | 296 / 09 | 296 / 09 | 45,7 | 0,6 | 1,00 | 1,00 |
| | conjugated normal faults (PlQa, PlQm) | 16 | 40°41' 11,96'' | 29°50' 45,52'' | pure extensive | 298 / 71 | 118 / 19 | 208 / 00 | 69,59 | 0,5 | 0,75 | 0,75 |
| | slickenside and striae (PlQm) | 6 | 40°41' 57,84'' | 29°48' 03,49'' | transtension with strike-slip | 175 / 63 | 311 / 20 | 47 / 17 | 38,2 | 0,6 | 1,00 | 1,00 |
| | normal faults and fractures (fissure) (PlQa) | 11 | 40°41' 47,89'' | 29°48' 58,94'' | transtension with strike-slip | 288 / 52 | 112 / 38 | 20 / 02 | 67,85 | 0,5 | 0,91 | 0,91 |
| | normal faults and fractures (fissure) (PlQm) | 11 | 40°41' 56,32'' | 29°48' 57,84'' | oblique extensive | 91 / 39 | 317 / 40 | 204 / 25 | 51,51 | 0,7 | 0,71 | 1,29 |
| **Set-2 in Plio-Quaternary units** | conjugated normal faults (PlQa, PlQm) | 28 | 40°40' 55,19'' | 29°56' 45,30'' | pure extensive | 157 / 62 | 325 / 27 | 58 / 05 | 50,81 | 0,6 | 0,70 | 0,70 |
| | normal faults and fractures (PlQm) | 16 | 40°40' 05,80'' | 29°56' 14,29'' | pure extensive | 68 / 16 | 113 / 03 | 204 / 22 | 53,24 | 0,5 | 0,56 | 0,56 |
| | slickenside and striae (PlQa) | 12 | 40°40' 29,06'' | 29°56' 14,29'' | pure strike-slip | 335 / 27 | 140 / 62 | 241 / 01 | 44,20 | 0,6 | 0,50 | 1,50 |
| | slickenside and striae (PlQm) | 5 | 40°40' 28,88'' | 29°56' 57,05'' | pure strike-slip | 336 / 24 | 146 / 66 | 244 / 04 | 44,60 | 0,7 | 0,40 | 1,60 |
| **Set-3 in Plio-Quaternary and basement units** | conjugated normal faults (PlQa) | 12 | 40°40' 46,10'' | 30°00' 03,45'' | pure extensive | 310 / 77 | 126 / 13 | 216 / 01 | 49,53 | 0,5 | 0,67 | 0,67 |
| | slickenside and striae (PlQa) | 4 | 40°40' 35,36'' | 30°00' 45,38'' | transpression with strike-slip | 295 / 33 | 140 / 54 | 33 / 12 | 43,52 | 0,4 | 0,25 | 1,75 |
| | slickenside and striae (in basement) | 7 | 40°40' 40,22'' | 30°00' 14,21'' | transtension with strike-slip | 40 / 22 | 195 / 06 | 306 / 09 | 41,40 | 0,7 | 1,00 | 1,00 |
In the southern part of IB, when all set zones are examined with stress regime index (R’) values according to fault planes including striae and strike-slip transtensive, and conjugate normal faults, the pure extensive regimes seem to be the source (see Table 1). In paleostress analysis in the region, the stress axis with NE trending (α3) is more dominant than the stress axis with NW-trending (α1). The tectonic origin generated from this situation is also related to the existence of segmentation associated with strike-slip in the south of IB, as can be seen from the R’ values obtained from the structural elements analyzed. Principal stress distributions of active faults around IB indicate pure extensive in two locations and strike-slip faulting across the basin and associated dextral oblique extensive tectonic regimes. While the main right-lateral strike-slip fault and secondary oblique segments with a dominant standard component (dip angle ≥ 50°) contribute the basin development in the IB part of the ISIB basin, only the main right-lateral strike-slip fault has effected the present geometric shape of the SB. Hence, the active deformation extending to the south of the basin has shaped the IB since Plio-Quaternary. Therefore, the active stress distribution in the IB extends approximately 11 km, while it is approximately 2 km in the SB, in the N–S direction. It has been determined that the active structures in the south of IB uplift are formed by the oblique normal faults from deep to the surface. This structural geometry shows that IB has the same strike-slip genesis as SB, but that it is a different type of tectonic basin from SB.

### 2.3 Seismicity and GPS

The distribution of historical earthquakes with M > 6.6 along the NAFZ for the last 2300 years had been determined (Bohnhoff et al. 2016a). Najdamadhi et al. (2016), used the above properties to identify and analyze fault zone head waves and direct P arrivals in nearfault seismic data recorded along the Karadere segment of the NAFS. The aseismic zone from the surface down to 6 km depth extends along most of the August-17, 1999 İzmit rupture. Only a local fault patch east of Sapanca lake of NAFS-NB (near the Karadere fault) shows ~ 30 fairly shallow events (Bulut et al. 2007). Especially in the south of IB, focal mechanisms of earthquakes after and before August 17, 1999 earthquake indicate strike-slip faulting with large tensional components. In this zone, it is observed that a greater number of earthquakes occurred in the south of IB than in the south of the SB (Figs. 11a, b). The distribution of earthquakes with an instrumental magnitude of M ≥ 2.0 from 1900 to the present continues for approximately 12 km to the south of the NAFS-NB. The seismogenic zone is about 10 to 15 km deep in the crust. Seismicity catalog of the Kandilli Observatory and Earthquake Research Institute was used for the earthquake data from 1900 to 2018 for the East Marmara Region (KOERI, 2020). According to focal mechanism solutions, the extensional component around IB is more dominant and clear than SB (see Fig. 11b). Substantial lateral stress field heterogeneity following the two main shocks is observed that declines with time towards the post-seismic period that rather reflects the regional right-lateral strike-slip stress field (Ickrath et al. 2015).
The Global Position System (GPS) slip rates and principal stress axes (contraction / extension) distribution data in the study area were determined by fixing the Eurasian block in the north of NAFS-NB (Reilinger et al. 2006). Along the entire NAFS, areas of basins or depressions where different quantities of extension and contraction vectors are formed, and the Anatolian plate forming the southern block of the NAFS move in different directions to the west in the counter clock-wise direction (Reilinger et al. 2006), (Figs. 11c, d). The Marmara region plate (south of Izmit Gulf) taking part in the Late Neotectonic (Pliocene - Holocene) system moves in the E-W direction along the NAFS-NB in the east of the Izmit Gulf in the S65°-80°W direction to the west of the gulf with an average rate of 24 mm/year to the west (Reilinger et al. 2006). The normal fault vertical slip rate is between 0.1 and 5.8 mm/year along the Izmit Basin - Sapanca Lake (Reilinger et al. 2006). It was determined that extensional stress was at N40°–55°E and compressional stress at N30°–40°W directions according to the GPS data obtained in the ISIB and its surrounding. Accordingly, it is seen that the principal extensional stresses are larger and more dominant than contractions around the ISIB (see Fig. 11d). The distribution of aftershock focal mechanisms corresponds to fault segmentation of the NAFZ in the Izmit-Düzce region produced by coseismic slip. Areas with large amounts of coseismic slip show aftershocks that are predominantly strike-slip, but low-slip barriers show mostly normal faulting aftershocks of the Izmit and Düzce 1999 earthquakes (Bohnhoff et al. 2006). Strike-slip faulting (NAFS-NB) deformed the ISIB and its vicinity (Straub and Kahle 1997; Kahle et al. 1998). The easternmost Sea of Marmara, theNAPS splays into different branches producing a complex network comprising the Izmit-Sapanca, Düzce, Iznik, Geyve and Mudurnu faults (Fig. 11e). On the NAFS-NB, Segment 2 (29.3°E–30.4°E) includes the Izmit hypocentre and covers the Izmit–Sapanca area containing 122 Fault mechanism (FM) dominated by a right-lateral strike-slip and minor normal faulting regime (Ickrath et al. 2014), (Fig. 11f).

3 Geophysical Data And Methods

Various geophysical methods can be used to investigate subsurface geology depending on the target properties and the depth of the target itself. In this study, Electric Resistivity Tomography (ERT), magnetic, and gravity methods were chosen to delineate faults in the corresponding territory to investigate the shallow (up to 150 m) and relatively deep (up to 900 m) faults.

This study determined the geometry of faults in the study area and the sediment thickness in the ISIB. For this purpose, the data were acquired with 19-profile resistivity and 21-profile total magnetic field measurements in the field. Mainly, the data were collected perpendicularly to the faulting on the surface. In addition, the Bouguer gravity data were obtained from the Kocaeli Metropolitan Municipality, collected in IB in 2011. The dataset was used in the interpretation of intra-basin deposit thickness in IB. The ERT methods gave underground information around 50–150 m depths based on the vertical geological variation. The depth of the basement was obtained and determined by the magnetic and gravity data. Resistivity and magnetic measurements were acquired only on the secondary faulting in the region.

3.1 Electrical Resistivity

In the ERT studies, a multi-electrode system was used, which consisted of 60 electrodes with 10 m electrode spacing. The data primarily acquired perpendicular to the faults with 145, 290, and 590 m profile lengths (Table 2). As an electrode configuration in the field, the three most commonly used array types, Wenner-Alpha, Wenner-Beta, and Wenner-Schlumberger, were chosen. The measurements were taken with these three electrode arrays to obtain the apparent resistivity distributions of the geological units. By preferring these various types of arrays made it possible to obtain the different data from the geological units and structural elements in the study area. The raw data were processed using the RES2INV program, and afterward, the apparent resistivity cross-section was inverted using the same software (Loke and Barker 1995; Loke 2019). The final inverted resistivity cross-section with respect to the available geological information was interpreted. The data were collected using the three different electrode configurations to apply a joint inversion since the current paths of the various electrode configurations are different. Unfortunately, a joint inversion for electrical data sets in this study was not applied. However, an inversion for each electrode configuration individually was used. The “rms” values of three various inversion results were compared. As a conclusion, the smallest rms (root mean square) value among the inversion results was chosen, since there is an only one geological model at the corresponding territory. The colors of minimum and maximum resistivity values were fixed. Based on these results, the study area consists mainly of two formations in terms of resistivity values. Thus, the color scale between 2 and 110 ohm.m indicates the top of the Arslanbey formation, while the relatively high resistivity values of the region from 111 up to 1300 ohm.m indicate the bottom of Arslanbey formation.
The location of ERT profiles in the study area.

| Profiles | Start coordinates | End coordinates | Profile direction | Profile length (m) |
|----------|-------------------|-----------------|------------------|-------------------|
|          | Latitude Longitude| Latitude Longitude|                  |                   |
| ERT1     | 40.734527 29.963852 | 40.734901 29.956739 | E-W             | 600               |
| ERT2     | 40.73474 29.971991 | 40.734921 29.964913 | E-W             | 600               |
| ERT3     | 40.722258 30.106835 | 40.718192 30.111153 | NW-SE          | 600               |
| ERT4     | 40.715506 30.32723  | 40.712871 30.326456 | N-S             | 300               |
| ERT5     | 40.706407 30.396258 | 40.709007 30.397253 | S-N             | 300               |
| ERT6     | 40.711342 30.398327 | 40.708781 30.397256 | N-S             | 300               |
| ERT7     | 40.702363 29.810829 | 40.70282 29.811737 | SW-NE          | 90                |
| ERT8     | 40.70318 29.812318 | 40.70453 29.812363 | S-N             | 150               |
| ERT9     | 40.694168 29.880369 | 40.696489 29.882084 | SW-NE          | 300               |
| ERT10    | 40.69265 29.881071 | 40.69496 29.882819 | SW-NE          | 300               |
| ERT11    | 40.712151 29.968608 | 40.70945 29.968359 | N-S             | 300               |
| ERT12    | 40.722704 29.967412 | 40.717436 29.968939 | N-S             | 600               |
| ERT13    | 40.67714 29.864307 | 40.674946 29.862185 | NE-SW          | 300               |
| ERT14    | 40.682108 29.86323  | 40.679797 29.864445 | NE-SW          | 300               |
| ERT15    | 40.683272 29.865253 | 40.682612 29.86638 | SE-NW          | 120               |
| ERT16    | 40.696596 30.120834 | 40.695257 30.120817 | N-S             | 150               |
| ERT17    | 40.692948 30.119603 | 40.695624 30.118633 | S-N             | 300               |
| ERT18    | 40.693697 30.115794 | 40.692365 30.115964 | N-S             | 150               |
| ERT19    | 40.691296 30.171013 | 40.693323 30.171512 | E-W             | 240               |

The coordinates, lengths, and directions of 19 profiles of ERT profiles are shown in Table 2. Figure 12 shows the location of 19 profiles in the region. The first 6 profiles (ERT1 - ERT6) were taken on the main fault zone, and the other 13 profiles were taken on the secondary fault zones. The inverted resistivity sections of the ERT profiles are shown in Fig. 13. Resistivity measurements of ERT-1 and ERT-2 profiles were taken approximately 1 km north of the August 17, 1999 earthquake's main surface rupture with a morphologic scarp in the N-S direction (see Fig. 12). In this inverted cross-section in Fig. 12, high resistivity values (110–550 ohm.m) define gravel, and low resistivity values (≤ 110 ohm.m) define silt and clay lithologies. The fault plane observed in the ERT-1 profile at a near-vertical angle is the anti-Riedel fault of NAFS-NB. This fault extends to a depth of approximately 40 m from the surface (Fig. 13a).

The measurements of ERT-2 profile indicate the geological levels belong to the alluvial fan deposits of Arslanbey formation (Fig. 13b). The ERT-3 profile was measured over the main fault (NAFS-NB). The fault plane was determined from the surface to a depth of 90 m, even though the fault extends to the deeper part of the crust. Another antithetic fault, along with the main fault, is south-dipping, indicating a high-angle strike-slip fault zone (Fig. 13c), while the main fault dips northward. The ERT-4 profile was measured over the main fault along the east of Sapanca Lake. The inverted cross-section of ERT-4 indicates that the fault continues to a depth of at least 20 m with an angle of 90° (Fig. 13d). The ERT-5 and 6 profiles are over the main fault (Figs. 13e, f). The ERT-7 and 8 profiles were taken in the Arslanbey formation approximately 300 m north of the surface faults belonging to Set-1 segments (Figs. 13g, h). The ERT-8 profile shows that two normal fault planes, with a horizontal distance of 20–40 m, inclined to approximately 75° to the north, continue at least 30 m deep from the surface. ERT profiles show that a good correlation between the inverted ERT cross-sections and the lithologies of Arslanbey formation, which consists of sand-matrix pebbles, gravel, sand, and clay-silt from bottom to top. In addition, the faults detected in the above ERT measurements are syn-sedimentary and indicate faulting during the deposition process of the Arslanbey formation. The ERT-9 and 10 profiles measured over the fault planes on the surface of the Set-2 segments show that the lithological levels of the Arslanbey formation were deformed to a depth of at least 100 m from the surface by inclined fault planes with 70° – 90° (Figs. 13i, j). The ERT-11 profile was taken on the northern part of the Set-
The profiles of ERT-13, 14, 15 were measured in the Set-5-zone. The results of these ERT profiles show that the faults controlling the upper fan lithologies at the boundary of colluvium or upper fan deposits visible on the surface, continue to deeper parts. (Figs. 13m, n, o). According to these results, faults are mainly inclined to the north and having a dip angle of at least 60°. These results indicate a zone at least 80 m deep in the crust that the segments observed from the surface of the south IB. The profiles ERT-16, 17, 18, and 19 were measured east of the southern segment zones of IB. These ERT measurements were acquired on the north of the morpho-tectonic triangular facets without tracing any stratigraphic fault on the surface. According to these profiles, faulting on the southern edge of IB cannot be traced to the east of Derbent on the surface and deep in the crust (Figs. 13p, r, s, t).

According to the inverted resistivity section in the ISIB, the secondary faulting in the upper ductile zone of the IB crust is primarily dipped over 60° and continues to approximately 100 m depth from the surface. However, faulting is not significant in the border between depression and uplift in the southern part of the SB.

### 3.2 Magnetics

One of the geophysical methods for constraining deep fault geometry in the crust is the magnetic method. A proton magnetometer to measure the total magnetic field was used. The profile lengths were varied between short (150–1500 m) and long (1500–15000 m) distances. The diurnal variation of the magnetic field was obtained from the Kandilli Observatory of Boğaziçi University. Then, the diurnal variation was subtracted/added from the measured total magnetic field. The inclination and declination of the magnetic field of the earth during the study were 5.8° and 5.2°, respectively (Kandilli- Iznik Observatory). A total of 21 profiles total magnetic field measurements were acquired using a proton magnetometer. Measurements can be categorized into two main groups. Seven profiles within the first group measured above the main fault; the remaining 14 profiles were collected above the secondary faults (Fig. 14). The spacing for the total magnetic field measurements was 500 m perpendicular to the main fault, and the spacing for the secondary faults was 10 m. The collected magnetic field measurements acquired in the urban areas were contaminated with some noise. Thus, only four of the measured profiles were modeled. Besides, only ten profiles measured on the secondary faults were modeled. A thin-plate and two-dimensional thick dike of total field equations were used to forward modeling (Raju 2003). For the inversion, the damped least-squares technique was used (Marquardt 1963).

The contact between geological units is defined by both the geological field data and the top of the depths in the magnetic field measurement profiles in Fig. 15. The interpretation of the total magnetic field profiles is given in Table 3. The magnetic anomalies used to determine the surface faults and the continuation of the faults into the basement rocks. Profile M1 was collected in the location of NE of the surface rupture, which was created by the Izmit earthquake on August 17, 1999. A fault plane was determined at a depth to the top of approximately 110 m with a dip of 75° to W (Fig. 15a). The M2 profile was collected over the northern segment of the NAFS-NB, indicating that the main fault continues to at least 83 m depth of subsurface (Fig. 15b). The estimated dip angle of the fault plane is approximately 70° and continues to a depth of the basement rocks where susceptibility differs from the intra-basin deposits. The M3 profile was also being collected over the main fault and along with the contacts of the alluvium and Arslanbey formation. The estimated dip of the fault plane is approximately 65° (Fig. 15c). The M4 profile was acquired over the southern segment of NAFS-NB at the stratigraphic level below the undifferentiated alluvium. The estimated dip angle is approximately 50° (Fig. 15d). The data-set of M6 profile was collected in the Set-1 fault zone. The profile crossed the basement rocks. In addition, faulting observed in the Arslanbey formation in the region is also continuous in the basaltic basement rocks with a dip of 40° and generates a vertical offset of approximately 21 m (Fig. 15e). The M7 and M8 profiles were also taken over the contact of the bedrock - Arslanbey formation and show that the contact continues to depth with a fault. Moreover, it can be seen that the vertical offset is a maximum of 55 m along with the M7 profile, and the minimum vertical offset is around 8 m (Figs. 15f, g).
Table 3

The results of magnetic data collected on the main and the secondary faults (δ: dip angle of the thick dike (varies from 0° to 180°), d: distance of the origin O: from the reference point, h: depth to top of thick dike, b: half-width of thick dike, m: regional slope, c: background level, e: root mean square error (%).

| Profiles | δ (°) | d (m) | h (m) | b (m) | m | c | e   |
|----------|-------|-------|-------|-------|---|---|-----|
| MAG1     | 119.20| 212.06| 110.64| 50.90 | 0.95| 46728.1| 1.53 |
| MAG2     | 148.39| 153.62| 83.05 | 10.41 | 6.66| 46832.7| 3.36 |
| MAG3     | 136.40| 79.68 | 39.64 | 9.33  | 6.42| 47296.3| 3.61 |
| MAG4     | 55.60 | 24.02 | 6.68  | 7.40  | -7.25| 48224.9| 1.07 |
| MAG6     | 58.50 | 105.97| 20.73 | 59.86 | 4.14| 46834.1| 4.07 |
| MAG7     | 51.76 | 182.66| 55.06 | 124.71| 1.03| 46331.9| 2.99 |
| MAG8     | 50.96 | 54.92 | 8.48  | 44.99 | -1.90| 46842.9| 5.90 |
| MAG9     | 48.62 | 72.50 | 18.48 | 27.47 | 7.23 | 46994.3| 4.99 |
| MAG12    | 124.16| 129.04| 20.16 | 36.38 | -1.58| 47124.2| 5.49 |
| MAG13    | 110.63| 413.69| 244.38| -6.04 | 47168.8| 1.20 |
| MAG16    | 53.47 | 5340.01| 775.65| 823.36| -0.08| 47624.9| 2.83 |
| MAG17    | 89.03 | 2901.91| 552.40| 361.36| -0.09| 47766.3| 1.82 |
| MAG20    | 101.01| 2288.50| 1011.37| 296.28| 0.05 | 47278.0| 1.26 |
| MAG21    | 70.11 | 4695.25| 1111.91| 34.75 | -0.15| 48444.7| 18.44 |

These values also indicate that the average thickness of the Arslanbey formation varies based on the magnetic susceptibility differences (from "c" in Table 3). The M9 profile was measured within the Set-1 fault zone. It includes the location where the Kirazdere formation covers the basement rocks. The faulting is started from the surface and continued to a depth of 8 m depth with an inclination of approximately 50° angle. This faulting is observed along with the M8 profile over the morphologic scarp. The thickness of Kirazdere formation in this section is approximately 8 m due to the differences in the magnetic susceptibility values. This value with the fault scarp observed on the surface is equal to the minimum vertical offset of the fault in the basement rocks. The result of the M9 profile indicates that the microzonation in the region continues northward. In this profile, which is in the Set-1 fault zone, the upper-level depth of the faulting is approximately 18 m, and the dip angle is 35° north (Fig. 15). The M12 profile is in the Set-2 fault zone, and the faulting at a depth of approximately 20 m from the surface is inclined to 35° north (Fig. 15). The M13 profile was measured within the Set-2 fault zone, and it was near the north of the morphotectonic triangular facet. The thickness of the Arslanbey formation or the top of the thick dike (fault plane) is at least 244 meters in the region. The dip of the fault is approximately 85° to the north in which the fault stratigraphically cuts the underlying rocks (Fig. 15). The profiles M16, 17, 20, and 21 were measured on the NAFS-NB which includes the surface rupture of the İzmit earthquake of August 17, 1999. The results of these profiles also show that the thickness of the intra-basin deposits toward the middle of the basin varies between 552 and 1112 m. In addition, it can be seen that the estimated dip of the faults based on the magnetic susceptibility variations are between 60° and 90°. Thus, the faults could reach to the basement rocks. The results obtained using the magnetic data indicate that the fault zones extend to the IB intersect of the basement rocks at certain depths of the crust in the south. In addition, the Arslanbey and Maşukiye formations have been developed under the control of NAFS-NB and related faults. The formation thicknesses increase from south to the north (center) of the basin.

3.3 Gravity and Joint Inversion

The residual gravity data-set was provided by the Kocaeli Metropolitan Municipality, which was collected by the Scientific and Technological Research Council of Turkey Marmara Research Center in 2008. The provided gravity data included 7 profiles with N-S trending. Each residual gravity profile was modeled with a prism formula given by Telford (1976). Marquardt (1963) algorithm (the damped least-squares technique) was used to model the gravity anomalies (Fig. 16), (Table 4). The geometry of contacts between basement rocks, and intra-basin sediments was determined by the data obtained from the gravity inversion in the upper crust depth. The geometric shape of the dipping contact between the basement of the crust and intra-basin sediments were determined with the results obtained from the gravity data using the prism model analysis.
Table 4
The results of gravity data collected on the main fault (α: dip angle of the thick dike (varies from 0 - to 180 -), d: distance of the origin O: from the reference point, h: depth to top of thick dike, B: half-width of thick dike, mg: regional slope, cg: background level, e: root mean square error (%)).

| Profiles | α (°) | h (m) | gd (m) | B (m) | mg   | cg   | e     |
|----------|-------|-------|--------|-------|------|------|-------|
| Gra1     | 23.6  | 1440  | 6331.3 | 8168  | -0.0027 | 54.4226 | 0.11875 |
| Gra2     | 27    | 1571  | 5551.4 | 8790.4 | -0.003  | 51.7063 | 0.09013 |
| Gra3     | 25    | 1312  | 5550.4 | 7934.9 | -0.0028 | 47.7013 | 0.14394 |
| Gra4     | 25.4  | 1023  | 4032.9 | 10395.3 | 0.00058 | 19.5567 | 0.19581 |
| Gra5     | 43.3  | 930   | 3117.7 | 9070.7 | -0.0052 | 82.7104 | 0.16607 |
| Gra6     | 54    | 1824  | 3533.3 | 8606.7 | -0.0035 | 61.5291 | 0.10309 |
| Gra7     | 38.7  | 2184  | 4751   | 8922  | -0.0033 | 63.9044 | 0.10648 |

The depth values of intra-basin deposits along the NAFS-NB are variable based on the results of the profiles 1–7 in the IB (see Table 4). According to the surface geological data, the intra-basin deposits in the southern block, which are more common, thick, and generally fault-controlled, are similar in subsurface relative to the northern block.

A better subsurface model can be obtained by combining various geophysical observations (Meju, 1994). More comprehensive information about the structural approach of the combined inversion technique can be obtained from Haber and Oldenburg (1997). In general, it is less reliable to estimate subsurface parameters by only one type of geophysical data set, since nonlinear inversion methods present a uniqueness problem. There are many studies in the literature about joint inversion methods and applications. Zheng and Arkani Hamd (1998), Bosch and McDoughey (2001) have delineated the topography of the basement by gravity and magnetic data based on the combined inversion technique. Gallarda-Delgado et al. (2003) have developed a versatile algorithm using 3D prisms for inversion of gravity and magnetic data. In general, a combination of some geophysical data obtained from various applications increases the correctness of the results (Dobroka et al.1991; Zheng and Arkani Hamd 1998; Bosch ve McDoughey 2001; Delgado et al. 2003).

Each individual inversion result gives an outcome. However, the joint inversion can relatively be used to get much more realistic subsurface result (Meju 1994). For the joint inversion, two profiles (MG-1 and MG-2) with the same coordinates were taken from the gravity and magnetic anomaly maps (Fig. 17a, b). By using these data, the model parameters were estimated with the joint inversion algorithm. The estimated model parameters are given in Table 5. In particular, the result of the joint inversion using gravity and magnetic data not only showed how secondary faulting effects in the IB but has enabled the determination of the geometric shape of the basin floor along the NAFS-NB. The depth of IB increases from west to east along the basin floor as well. According to the data of Gra-1–7 gravity and MAG-16, 17, 20, 21 magnetic profiles, the top boundary of the basement rocks was estimated to have approximately similar undulation with the IB deepened from west to east (Fig. 17d, e). Accordingly, it was determined that the thickness of the intra-basin deposits in IB along the NAFS-NB from west to east could be a maximum of 2200 m. However, different depth values of the upper boundary of the basement rocks obtained from both gravity and magnetic data may be related to the deformation of NAFS-NB along the E – W axis of IB.
### Table 5
The results of joint inversion using the gravity and magnetic data (\(\alpha\): dip angle of the thick dike (varies from 0 - to 180 -), \(h\): depth to top of thick dike, \(g_d\): distance of the origin 0 from the reference point (gravity), \(m_d\): distance of the origin 0 from the reference point (magnetic), \(b\): half-width of thick dike (magnetic), \(B\): half-width of thick dike (gravity), \(m_g\): regional slope (gravity), \(c_g\): background level (gravity), \(m_m\): regional slope (magnetic), \(c_m\): background level (magnetic), \(e\): root mean square error (%)).

|       | MG1  | MG2  |
|-------|------|------|
| \(\alpha\) \(^{(\circ)}\) | 146,5 | 120,6 |
| \(h\) (m)     | 1430,3 | 2021,9 |
| \(g_d\)       | 6555,8 | 3648  |
| \(m_d\)       | 3951,2 | 7452,6 |
| \(b_m\)       | 8648,3 | 8570,3 |
| \(B\)         | 8723,3 | 8489,7 |
| \(m_g\)       | -0,0061 | -0,0027 |
| \(c_g\)       | -2,81  | 64,21  |
| \(m_m\)       | -0,11  | 1,22   |
| \(c_m\)       | 49771,1 | 39551,9 |
| \(e\)         | 1,63   | 1,09   |

In addition, the main rocks of the Sakarya continent forming the southern uplift of the NAFS-NB and the contact of the northern uplift in the basin of the Istanbul-Zonguldak zone (paleo suture zone) may also make this difference (Yılmaz et al. 1995; Yiğitbaş et al. 1999; Elmas and Yiğitbaş 2001). At the western end of Lake Sapanca, Taylor et al. (2019) have determined that the thickness of deposits along the SB varied from 1 to 2,5 km depth from south to north in the basin. To obtain this depth information, Taylor et al. (2019) have used S-wave velocity. Furthermore, the maximum thickness of intra-basin deposits was determined as 1600 m from the south of the NAFS-NB to the north (Özalaybey et al. 2011).

### 4 Discussion
This study is the first study detailed the ISIB from the ground surface to a certain depth (~ 1900 m) of the crust regarding of the stratigraphic and active structural features of the basin-filling deposits based on the sedimentological and paleontological findings and evaluations in IB. Surface geology data and observations determined the types of structural elements of active tectonics that accompanied the sedimentation processes of the Plio-Quaternary deposits in the region.

#### 4.1 Relationship between basins edge (secondary) faults and regional active tectonics
Armutlu Peninsula is located between Istanbul-Zonguldak continent (Rhodope-Pontid fragment) and Sakarya continent and was formed during the paleotectonic stage, which started with the subduction of the northern branch of Neotethys under the continent of Istanbul–Zonguldak in Fig. 1a (Yilmaz et al. 1995). Following the delamination of the oceanic lithosphere, the two continents continued to collide with each other until Late Campanian. In the same period, Paleotectonic structures also developed associated with collision tectonic (Yilmaz et al. 1995; Okay and Tüysüz. 1999). The lithological and structural features of the bedrock units in the southern uplift of the study area have been...
explained in the Armutlu-Ovacık Zone and the northern uplift in the Istanbul - Zonguldak Zone (Yiğitbaş et al. 1999). In the Armutlu Peninsula, following the Middle Eocene volcanism, and after the end of the Eocene Paleotectonic period, the region became morphologically penepane (Yılmaz et al. 1995; Yiğitbaş et al. 1999). After the end of Eocene and subsequent erosion, the Neotectonic period in the region has continued with the strands of the North Anatolian Fault system from the last 5 Ma to the present (Barka 1992; Şengör et al. 2005). Alternatively, Ünay et al. (2001) have determined the activity of NAFS in the region as 3.0–3.5 Ma according to Villanian age obtained from fault-controlled deposits in the southeast of the SB. Some studies on the type and distribution of active faults in the region include the study area on and around the NAFS-NB (Şaroğlu 1988; Barka 1992; Barka 1997; Eisenlohr 1997; Emre et al. 1998; Armijo et al. 1999; Herece and Akay 2003; Şengör et al. 2005; Koral 2007). Alpar and Yaltırak (2002) have mapped some unknown faults in the south of IB and NAFS-NB. Barka et al. (2002) have mapped surface fault ruptures occurred on August 17, 1999 earthquake at least 3 km in length in the south of IB. Characterization of aftershock-fault plane orientations of the 1999 İzmit (Turkey) earthquake using high-resolution aftershock locations (Bulut et al. 2007).

Gürbüz and Güner (2008) have mapped an unidentified fault named "mountain front fault" approximately 20 km along with the contact of basin fill and basement rocks in the south without gathering any field data in the region (on their Fig. 6). Akbayram et al. (2013) have mapped the E-W direction, right-lateral strike-slip fault in the basement rocks, and the basin-filling contact in the south of the NAFS-NB without any data on the surface and deep. Akbayram et al. (2016) have identified a normal fault associated with the NAFS-NB at the uplift-basin topography boundary in the south of IB and the west of İzmit Gulf without any field and structural data (on their Fig. 2). In the map of active faults on the MTA website, three fault groups are identified, named respectively Quaternary, possible Quaternary and Holocene, apart from the surface earthquake ruptures of the August 17, 1999 earthquake on the south of IB (MTA 2019).

Bohnhoff et al. (2016a), found that the largest M7.8–8.0 earthquakes are exclusively observed along the older eastern part of the NAFS that also has longer coherent fault segments while the maximum observed events on the younger western part where the fault branches into two or more strands are smaller. The geometries of NAFS and other active faults in the Marmara region have been defined by different methods along with the mapping of surface ruptures both before and after August 17, 1999 M 7.4 earthquake (Barka 1992; Emre et al. 1998; Barka 1999; Alpar and Yaltırak 2002). Meanwhile, the normal fault surface ruptures have been identified in this study within the Set-1 and Set-2 fault zones of IB (Barka et al. 2002; Lettis et al. 2002), (Fig. 18a).

Tank et al. (2005) have determined that a high resistivity conductive zone indicates the fault plane where the mainshock and aftershocks of 17 August 1999 İzmit earthquake occurred. In the same region, Aşçı et al. (2016) have revealed by conducting resistivity and magnetic studies along the NAFS-SB, that the strike-slip faults deformed the region during the Plio-Quaternary period. Also, the ERT method was applied for both the distribution of faults and determination of Quaternary deposit thickness on the Paganica-San Demitro normal fault system (Pucci et al. 2016). In the above-mentioned basin analysis, the ISIB was evaluated as a single basin and developed as a pull-apart basin under the control of NAFS-NB. However, it can be understood from these studies that the fault type, fault length, distribution of faults around the basin and how the basin developed in the study area, were not fully explained.

This study, on the other hand, defined the geometry of the ISIB for the first time according to the surface and depth data gathered in the crust. The profile directions selected in all methods were perpendicular to the surface faults and ruptures. These structural elements can be seen in Fig. 18. The dextral oblique normal faults determined at different depths of crust are mainly inclined to the north with different dip angles and deform only IB. In particular, geometries of these structural elements show the ellipsoid of dextral simple shear deformation. Accordingly, the N-S width of the dextral simple shear deformation ellipsoid in the study area (in Set 1–4 distance) is approximately 9 km in the IB basin and 3.8 km in the SB basin (Fig. 19). The length of the long axis of the simple shear strain ellipsoid surrounding the two adjacent basins (ISIB) formed by the primary tectonic source of NAFS - NB is approximately 35 km (see Fig. 19). The secondary fault geometries obtained from resistivity, magnetic, and gravity methods pointed the locations of the faults in the deep sections of the only IB crust. Besides, active deformation zones in the region were determined according to the direction and of principal stress axes of the NAFS-NB and other associated secondary segments (mapped of all set zones) controlling the origin of both IB and SB. Based on all results given above, they imply that the IB and SB are on the same right-lateral strike-slip fault. The means that progress of integrated basin (ISIB) has developed the same tectonic origin, but it is a combination of two different basin geometry. This study introduces the term "integrated basin" of IB and SB first time.

4.2 Tectono-geometric model of the basins

Since the ISIB developed in the strike-slip fault setting in this depression, the contraction and extension stresses obtained according to both the fault planes on the surface and GPS data are primarily found together in the right lateral fault planes. Therefore, these terms should be explained in terms of transtensional and transpressional stress regime (see Fig. 11c, Table 1). Active deformation zones were determined based on the distribution of the principal stress axes of the NAFS-NB and the other secondary segments (mapped of all set zones) that control the development of IB and SB (see Fig. 19). IB has been extending with transtensional stresses in the NE direction, while it has been shortening to a minimal extent in the NW direction. The transtensional stresses are significantly more dominant than the transpressional
stresses. Accordingly, the distributions of the principal stresses with the faulting types have controlled and deformed the Sapanca Lake basin. The ENE trending oblique normal faults are located in the stepover section of two main dextral strike-slip faults in the Sapanca Lake (Gülen et al. 2014, 2015). These faults are located on the east and west sides of the lake (see Fig. 19). According to this finding, the NAFS-NB has the primary control of active deformation in both IB and SB. The contact of the intra-basin deposits with the basement rocks at the southern edge of IB consists of active oblique normal faults associated with the NAFS-NB; the same contact is the angular unconformity on the southern edge of the SB. The results obtained using magnetic and gravity data showed that both fault geometries are deep in the crust, and the depths of the bottom boundary of the intra-basin sediments in IB and SB are different. Gravity data near the NAFS-NB and magnetic data in areas with surface faulting in the southern block indicate that the intra-basin sediments are spread from the basin center to the south. In addition, the intra-basin deposits deep on the ductile crust are evenly spread over a wide area. Moreover, especially when the gravity data of this study were compared with the basin geometry model of Taylor et al. (2019) containing intra-basin sediments, the IB is relatively larger, more asymmetric, and broader in the N-S direction than the SB. This geometry is similar to the basin geometry described by Özalaybay et al. (2011). Therefore, the faults of different types and sizes were active in both basins regarding the tectonic setting of the basins. The thickness of the intra-basin sediments was determined around 1400–1700 m, which was associated with the NAFS-NB and oblique normal faults in the IB. Meanwhile, the basin deformation in the SB was associated only with the NAFS-NB. Further, the contact of basement rocks and intra-basin deposits was determined at different depths (930–2184 m) according to the gravity data at IB (see Fig. 16, Table 4). These thickness values are the result of the deformation of the transtensional component of the right-lateral strike-slip fault formed by the NAFS-NB along its main strand (see Figs. 17d, e, Table 5).

The secondary dextral oblique faults associated with the NAFS-NB deformed the southern edge of the basin from the surface to the deep during the expansion of the IB. In the meantime, the SB, which has a stepover geometry, has been opened from north to south on the NAFS-NB, which has approximately 3.8 km length (dextral to the right). Therefore, it can be stated that these two basins have been opened by the same tectonic source, but their geometric shapes and fault types are different (Figs. 20a, b). The main and secondary faults with different structural geometries similar to the shape of the strike-slip faults described by Woodcock and Fischer (1986) and Sylvester (1988) controlled the IB and SB.

In some studies, regarding the formation of ISIB, there are deficiencies between the geometry of the faults around the basins. Accordingly, Barka (1992) has stated that the Izmit-Sapanca basin is a pull-apart basin. Bargu (1993) has interpreted that the normal faults between Yuvacik and Maşuiki (south of IB) in the south of the region between the Izmit basin and Lake Sapanca are active (see Fig. 2). Bargu (1993) stated that the normal faults formed the "Izmit graben" of the Izmit basin - Sapanca Lake basin without presenting any structural data. Without any in-depth geophysical data of the subsurface, 'Izmit-graben' definition is not a correct interpretation. Emre et al. (1998) have stated that the uplift of the basin during the Upper Miocene – Lower Pliocene in the pre-NAFS-NB period caused compression in the region. However, they stated this result without any structural data of the crust. Gürer and Gürbüz (2008) have stated that the Izmit – Sapanca corridor is a Middle Pleistocene aged pull-apart basin without any structural and age data (Rathje et al. 2004).

In the study area, a basin type, which has two different fault geometries, has been developed by the control of strike-slip faults as flower and pull-apart types (Harding 1983; Hempton and Dunne 1984; Hempton and Neher 1986; Sylvester 1988; Nilsen and Sylvester 1999; Bergerat et al. 2003; Swanson 2005; Escalona and Mann 2003; Wu et al. 2009). Thus, it can be concluded that IB is an asymmetric negative-flower structure with a strike-slip tectonic history (see Fig. 20). The fault set with E-W trending in the southern block is approximately 6 km far away from the NAFS-NB. These faults are dextral normal faults (set-zones) developing with the main strike-slip fault. The SB is a lazy-Z- shaped pull-apart basin, including Lake Sapanca, which is adjacent to the IB (see Fig. 20b) and has a 1 km right-hand stepover as well. The SB is associated with the zoning of the right-lateral strike-slip fault with E-W trending (NAFS-NB). The SB has relatively been exposed to a larger scale of active deformation than the SB. Besides, the IB is a deeper basin than the SB. However, both adjacent basins have a different tectonic origin (Fig. 21). To determine the relationship between the fault geometry and the intra-basin deposits in a 3D view, seismic reflection can be useful in both directions. These directions would be parallel and perpendicular to the NAFS-NB trending. The NAFS and related faults have been the primary tectonic source in the opening of some basins as well as in the development of depressions in the Marmara Sea on these strands (Okay et al. 2000; Rolando et al. 2002; Yaltarak 2002; Vardar et al. 2014). Izmit basin and Sapanca Lake basin are the basins developed by the areal deformation of the strike-slip fault system on the NAFS-NB. Similar to these basins are also located inside the Marmara Sea (see Fig. 1a). The beginning of the formation of a localized plate boundary occurred between 4.5 and 3.5 Ma at the location of the present Sea of Marmara by the initiation of a shear zone comparable to the present Grecian Shear Zone in Central Greece. Thus, the first part of the formation of the Sea of Marmara was purely extensional. The present strike-slip system that today cuts across the whole Sea of Marmara and that is called MMF (Main Marmara Fault), began to develop after 2.5 Ma (Le Pichon et al. 2016). Propagation of a strike-slip plate boundary within an extensional environment: the westward propagation of the North Anatolian Fault (Le Pichon et al. 2016).

Accordingly, this study indicates that a three-dimensional approach should be used to reveal the structural history of these basins. Thus, the approximate area of deformation ellipsoids in the Marmara Sea can be determined. The secondary fault sets determined by this study have
active faults. Accordingly, the segments within these sets, and belonging to the eastern Set-2, 3, 5, and segments other than those broken in the August 17, 1999 earthquake, may be ruptured in the future with the break of the main branch of the NAF-NB in the Marmara Sea (see Fig. 20). Accordingly, the faults in set-2, 3, 5 zones can be specified as seismic hazard zones. In future; This study should be supported such as "tomography, receiver functions, MT, seismic reflection" in wider area.

5 Conclusions

This study investigated the basin progress and deformation analysis by tectonostratigraphic elements and geophysical methods on the North Anatolian Fault System along the İzmit Basin – Sapanca Lake corridor. In the section of NAFS-NB, in the Eastern Marmara region, the geometry and sedimentation of the basins indicate that the integrated basin has been deformed by the right-lateral strike-slip fault and secondary components, based on the results of the geological and geophysical studies. Thus, the main and secondary faults have deformed the continental crust and basins. Based on the results of this study in the corresponding region, the following results are concluded:

1. The Maşukuıye formation controlled by an active fault contains freshwater fossils characterized by a low energy lacustrine environment. Besides, the formation consists of fine-grained, well-fastened sedimentary rocks, and has been mapped at the southern block uplift of the NAFS-NB. The age of the fossil-bearing formation is the Plio-Quaternary.
2. The NAŠS-NB with E-W trending is the only main tectonic source in the Plio-Quaternary period and has formed a simple shear deformation ellipsoid in two areas in the region. The IB basin has been developed as an asymmetric negative flower structure basin, which has been deformed primarily by the oblique normal fault sets formed during the main deformation process of the right-lateral strike-slip fault and within the southern block of the fault. IB is located in the NAŠS-NB in the E-W direction.
3. In case the part of the NAŠS-NB in the Marmara Sea ruptures in the future, active faults with a maximum length of 3 km in the southeast of the İzmit basin can also break synchronously. Thus, these areas can be defined seismic hazard zones.
4. SB is a lazy-Z-shaped pull-apart basin that was created by a stepover-releasing bend within the right-lateral strike-slip fault. The basin includes the Sapanca Lake, which is a sag pond. The NE trending transtensional stresses created by the strike-slip fault on the IB basin are both larger in width and greater in vector values than on the SB.
5. The ISIB is a basin (containing dextral simple shear strain with ellipsoid structural elements) that has been opened and developed in different tectonostratigraphic processes. The depths of the basin and the associated intra-basin deposit thickness are highly variable along and perpendicular to the NAŠS-NB. The ISIB has been evolved under the control of only right-lateral strike-slip fault since Plio-Quaternary.

Declarations

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Figures
Figure 1

(a) The basic map of the Neotectonic period and the other structures, geological regions in Anatolia (Okay and Tüysüz 1999), (b) the position of GPS vectors after Reilinger et al. (2006) and the main branches of the NAFS in the Marmara region according to Le-Pichon et al. (2003) and the “horsetail type” splaying formed by the NAFS. NAFS-NB: North Anatolian Fault System Northern Branch, NAFS-SB: North Anatolian Fault System Southern Branch, NAFS-SB(a): North Anatolian Fault System Southern Branch-(a), Ist: Istanbul, S: Sakarya, IZ: İzmit, Du: Düzce, Bo: Bolu, I: Iznik, Ge: Gemlik, Gy: Geyve, A: Akyazı, D: Dokurcun, M: Mekece, AB: Almacık Block, IG: İzmit Gulf, GG: Gemlik Gulf, SG: Saros Gulf, EG: Edremit Gulf, SL: Sapanca Lake, IL: Iznik Lake, UL: Uluabat Lake, ML: Manyas Lake, G: Gönen, B: Biga, C: Çan, Ba: Bayramiç (modified from Barka, 1992; Le Pichon et al., 2001; Armijo et al., 2002; Doğan et al., 2015).
Figure 2

Geological map of the Plio-Quaternary geological units overlaying bedrocks and the active structural elements of the Izmit basin – Sapanca Lake Integrated Basin. The Northern Branch of the North Anatolian Fault System is adopted from Barka et al. (2002) and the faults inside Lake Sapanca are taken from Gülen et al. (2014).
Figure 3

(a) The debris flow of the Arslanbey formation which is one of the filling deposits of the Izmit basin (IB), which was deposited as alluvial fan unit and controlled by the active faults, (b) well-developed laminated channel deposits syn-sedimentary with Arslanbey formation and were accumulated by the streams in the southern block drainage, (c) sieve deposits mainly located in the middle fan section and in the distal-middle fan boundary of the Arslanbey formation (d) The appearance of the lithological contents of the flood plain units deposited in a lower energy environment than the other facies in the distal fan section of the Arslanbey alluvial fan, (e) The appearance of the debris flow deposits of the upper fan facies usually seen at the base of the Maşukiye formation overlying the bedrocks and at the base of the Arslanbey formation overlying the Maşukiye formation (f) A view from the Maşukiye formation, which is mapped to the south of İzmit basin for the first time by this study, which contains the fossils of abundance zone and rarely grifts with small river channel sediments, (g) Hand sample view of fossils of Planorbarius ("Planorbarius comeus"?) kind Gastropoda, which is determined by this study for the first time in the Maşukiye formation, indicating a lacustrine or freshwater environment, and (h) the scale views of the same fossils (personnel communication by Büyükmeriç 2018).
Figure 4

Views of all structural elements related to active fault of the Set-1 fault segments located within the southern block separated by the North Anatolian Fault System Northern Branch (NAFS-NB) and belonging to the Arslanbey formation in the İzmit basin, (a) normal faults in channel deposits, (b) reverse faults, (c) normal faults dipping NE, (d) normal faults dipping SE, (e) The normal fault cutting the sandstones indicating the low energy sedimentation environment within the Maşukiye formation, the appearance of small synthetic and synsedimentary normal faults and fracture sets seen in the upper right photo, (f) conjugate developed normal faults and fissure zoning.
Figure 5

The appearances of all structural elements related to active fault on fault segments in the Set-2 of the southern block separated by the North Anatolian Fault System Northern Branch (NAFS-NB) in the İzmit basin, (a) cutting the flood plain deposits of the Arslanbey formation, (b) conjugate normal faults cutting the channel deposits of the Arslanbey formation, (c) north and south dipping conjugate normal faults that cut the Maşukiye formation with the fracture (fissure) sets, (d) slickenside and striaes of the oblique normal fault cutting the debris flow deposits of the Arslanbey formation along with the dipping lithological level offsetted in the hanging wall block of the normal fault (e) the normal fault which cuts the levels indicating different sedimentary environments of the Arslanbey formation and (f) dipping of the sieve deposits in the Arslanbey formation to the faults (to south) of the Set-2.
Figure 6

Appearances of some active fault-related structural elements in the Set-3 fault segments of the southern block separated by the Northern Branch of the North Anatolian Fault System (NAFS-NB) in the İzmit basin, (a) normal fault cutting sieve deposits of the Arslanbey formation, (b) conjugate normal fault cutting the flood plain deposits, (c) slickenside and striae related to the oblique normal fault plane existed between flood plain and sieve deposits of the Arslanbey formation and the fault rocks containing laminated chalky levels on the fault plane and the dipping of lithological level of the hanging wall block towards the fault plane, (d) normal fault cutting the Arslanbey formation, (e) dipping of the lithological levels in the hanging wall block of the fault with micro-folds in the form of kink band in and around the reverse fault plane due to transpressional stress, and (f) various deformation structures in the bedrocks.
Figure 7

Views from (a) slickensides and striae of the bedrocks in the Set-5 faulting located in the southern block of the Izmit basin, (b) fault controlled colluvium approximately 100 m south of the bedrocks and the conjugate normal faults within the colluvium (c) normal faults within the same colluvium (d) the conjugate normal faults, and (e) conjugate normal faults belonging to the Set-4 numbered fault segments, which cut the Arslanbey formation in the northern block of the Izmit basin and about 300 m apart from each other.
In the Set-1 fault segments; (a) slickensides of the normal fault in Figure 4a and its striae in the foot wall; (b) conjugate normal faults including all Set-1 fault segments, (c) NE dipping oblique normal fault slickensides and its striae in the foot wall in Figure 4e, (d) normal fault dipped to NE in Figure 4e and the fissures that developed into the same dip direction, (e) normal faults dipping SW in Figure 4f and the positions of the principal stress axes of the fissures with the same dip direction.
Figure 9

Within the Set-2 fault segments; (a) conjugate normal faults cutting both Arslanbey and Maşukiye formations, (b) normal faults dipped to SW in Figure 5c and fissures with the same dip-direction. Belonging to Set-4 fault segments of slickenside and striae on SW dipping faults (c) in Figure 5d and (d) in Figure 5c; (e) fault plane slickenside and striae of Figure 7a; and f) principal stress axes of the conjugate normal faults developing within the entire colluvium.
Figure 10

Positions of the principal stress axes in the fault segments of the Set-3; (a) in the conjugate normal faults in Figure 6 a, b, d, (b) in slickenside and striae of the oblique normal fault in Figure 6c, (c) in the slickenside and striae of the fault plane in Figure 6d, (d) in the fault planes in Figure 6d and fissures with the same dip direction, and (e) in the reverse faults in Figure 4b and Figure 6e.
According to KOERI (2020); The distributions of earthquakes (a) in the Marmara Region, (b) in and around the study area since 1900 and focal mechanism solutions of some earthquakes (1, 2, 3, 4 numbered focal mechanisms from Örgülü and Aktar (2001) and 5, 6, 7, 8 from Pınar et al. (2001), (c) The distributions of GPS velocities relative to Eurasia with 95% confidence in the 1988 - 1999 period ellipses in the study area. Top numbers (no parentheses) are strike-slip rates, positive being left lateral, and normal fault slip rates in parenthesis. GG: Gemlik Gulf, IL: İznilk Lake, UL: Uluabat Lake (d) The magnitudes and distributions of T: Extension, C: Contaction stresses are indicated by "strain/au"unit and R: right lateral strike-slip fault, (e) In view of pressure (P) and tension (T) directions obtained from fault mechanism solutions of 17 August 1999 earthquake main and aftershocks (Bohnhoff et al. 2006). (f) In view of pressure (P) and tension (T) directions obtained from fault mechanism solutions of 1999 İzmit and Düzce earthquakes main and aftershocks (Ickrath et al. 2014).
Figure 12
ERT measurement locations on the main fault zone and secondary faults.
Figure 13

The results of ERT measurements collected on the main fault zone and secondary faults.
Figure 14

Magnetic profiles measured on the main fault zone and secondary faults.

Figure 15
Interpretation results of total magnetic field measurements on the main fault zone and location of the secondary faults in the geological formations, the contact between geological units is approximate (Geological sections have been drawn according to field observation. The contact depth between the intra-basin deposits and the basement is possible).

Figure 16
(a) The Residual Bouguer anomaly map of residual gravity profiles on the main fault zone, (b) Evaluation of the profiles.
Figure 17

(a) The map of the results of all gravity profiles, (b) the map of the results of all total magnetic profiles, (c) interpretation of the gravity and magnetic data all together, (d) topography of the basement rocks, based on the interpreted of gravity data, (e) According to the total magnetic field data; possible stratigraphic contact of the basin-rocks and intrabasin border or fastened gravel levels at the base of the intrabasin deposits.
Figure 18

(a) Surface raptures map including the study area shown in the red rectangle in the south of the Izmit Gulf, after the 17 August 1999 earthquake (Barka et al., 2002), views of the vertical offsets of the surface raptures in the Arslanbey formation from the southeast of Örcün village to the northwest; (b) 13 cm offset, (c) 22 cm offset, (d) 25 cm offset and tensional fissures parallel to surface rupture and (e) enechelon geometry of the surface rupture (photos by Doğan and Barka, 2000).
Figure 19

Sizes and locational distributions of principal stress vectors formed by the structural elements of active faults in the IB and SB and structural map of strain ellipsoid boundaries of each basin and ISIB along with the basin boundaries in the study area (faults in Sapanca Lake taken from Gülen et al., 2014).
Figure 20

At the top; Classic pull-apart basin (Dooley and McClay, 1997) with negative flower structure oblique to strike of main dextral fault zone. Structural map and depth section views of (a) asymmetric negative flower structure type Izmit basin (IB) formed by the dextral NAFS-NB and secondary oblique normal fault set-zones in the south of the basin; and (b) releasing bend and lazy-Z shaped pull-apart basin of the Sapanca basin (SB) formed by the right stepover of southern and northern segments of the NAFS-NB (field images taken from Google Earth, 2020).
Figure 21

Cross-section showing that the NAFS-NB controlling the Izmit basin – Sapanca Lake integrated basin (ISIB) and its associated oblique normal faults only control and deform the intra-basin deposits to the south of IB (field view taken from Google Earth, 2020).