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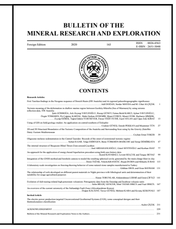

Tectonic meaning of the deformation in shallow marine region between Gaziköy-Mürefte (Sea of Marmara) by using seismic reflection data, NW Anatolia

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Research Article

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ABSTRACT

Within the scope of this paper, seismic reflection and bathymetry studies were carried out in the shallow marine area forming the westernmost part of the Tekirdağ Basin using the R/V Selen Research Vessel within the MTA Marine Research Department. In the study area, ~ 500 km length bathymetry data and ~191 km shallow seismic profiles (41 lines) were collected. By means of the data, tectonic structures and deformation textures of the North Anatolian Fault System (NAFS) in the marine area of Gaziköy were examined. As a result of the processing and interpretation of the seismic sections, compression structures occurring due to the SW rotation of the NAFS in the study area, the morphology of the Ganos depression that formed as a result of faulting and also three different stratigraphic units were distinguished. These units are separated from each other by distinct unconformity surfaces and each unit presents different deformation structures. One of the most significant results obtained from the seismic data is that the unconformity surface that separates the current sediments of the seafloor from the older units is represented by the overlapping structures indicate sea level changes. It has been assessed that this situation occurred as a result of the erosional process developed during sea level fall.

1. Introduction

The North Anatolian Fault System (NAFS) is a right-lateral strike-slip mega shear structure, which is approximately 1500 km length and has primary importance in the tectonic and morphological shaping of Turkey. With these features, the NAFS contains many characteristic structures and undoubtedly the most important one is the Sea of Marmara, which includes 3 huge basins (Çınarcık, Orta and Tekirdağ basins). The Sea of Marmara is the most remarkable inland sea of the world with an area of approximately 11.350 km^2 separated the Black Sea and Aegean Sea by the Istanbul and Çanakkale Straits, respectively (Figure 1). This geographic importance increases the effect of the North Anatolian fault System (NAFS) tectonically. The NAFS, which is a product of the plate motions around Turkey and surroundings, and shapes the region tectonically, enters the Sea of Marmara from the Izmit Bay in the east and crosses the entire marine area in the E-W direction up to the Gaziköy in the west. The effect of the NAFS, which

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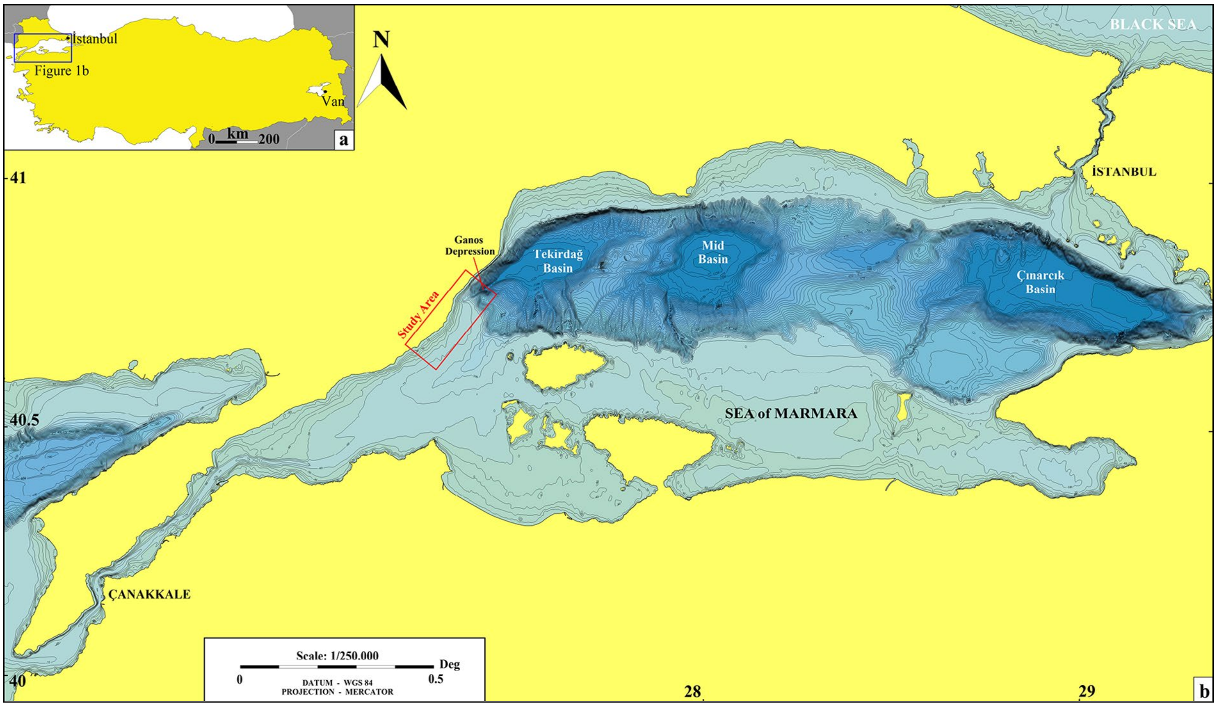

Figure 1- a) Location of the Sea of Marmara in Turkey and b) map showing the study area and bathymetry of the Sea of Marmara. The data was collected by R/V MTA SİSMİK-1 between 1995 - 2003 years under the control of Marine Research Department by using Atlas Deso Echo Sounder and Seisnet Integrated Navigation System (DGPS) with 25 - 50 m resolution of depth and coordinates values. Multibeam data collected from Navigation Hydrography and Oceanography Department (SHODB); MARMARA-2000 (R/V LE SUROIT and R/V ODIN FINDER) with MARMARA-2001 (R/V URANIA) data was used to prepare this map (Yanmaz, 2017).

has a right lateral strike-slip motion, on the formation of the Sea of Marmara has been tried to be explained with different models, and today there is no consensus between them (Pınar, 1943; Ketin, 1969; Kasar et al., 1983; Turgut et al., 1983, 1991; Crampin and Evans, 1986; Barka and Kadinsky-Cade, 1988; Yaltırak, 1995; Wong et al., 1995; Görür et al., 1997; Tüysüz et al., 1998; Armijo et al., 1999, 2005; Sakınç et al., 1999; Okay vd., 2000; Siyako et al., 2000; Aksu et al., 2000; Turgut ve Eseller, 2000; İmren vd., 2001; Gazioğlu et al., 2002; Gökaşan et al., 2003; Yaltırak et al., 2002). These models are not detailed as they are not included in the scope of this study.

The NAFS cuts the Tekirdağ basin, located in the westernmost part of the Sea of Marmara, in the E-W direction and reaches the land area in the near north of Gaziköy (Figure 2). The submarine depression created by the NAFS just before land area is called the Ganos depression. In addition, the fault segment continuing to the terrestrial area is called the Ganos fault (Gutzwiller,1923; Sieberg,1932; Pınar, 1943), and it continues by entering the Aegean Sea from Saros Bay (Yaltırak, 1996). The active faults, which are very dominant in this area, result a quite high earthquake activity (Soysal et al., 1981; Ambraseys and Finkel, 1991, 1995; Guidoboni et al., 1994). In addition to historical earthquakes, the most important earthquake that occurred in the region during the instrumental period was the 9 August 1912 Mürefte-Şarköy earthquake (Mw 7.4). This earthquake affected the Mürefte and Şarköy settlements and was felt very strongly in Tekirdağ, Gelibolu and Çanakkale regions. The damages and loss of life caused by the earthquake are included in an article “Marmara Havzası’nın Hareket-i Arzının Esbabı on 26-27 July 1328 (1912)” written by Doctor Lieutenant M. Sadi on August 28, 1912 (1328). The article also includes the news of Istanbul Newspaper in French, and it is stated that a 400 m long and 5 m deep surface rupture developed in Mürefte village. With the 1912 earthquake, it was determined that tsunamis occurred along the landslides in the Marmara (Altınok vd., 2003). While the earthquakes of 9 August 1912 (Mw 7.4) and 13 September 1912 (Mw 6.8) created some displacements varying between ~ 1.4 and 5.5 m, the amount fault slip (coseismic) and fault segmentation were determined. As a result of evaluating the historical records, the

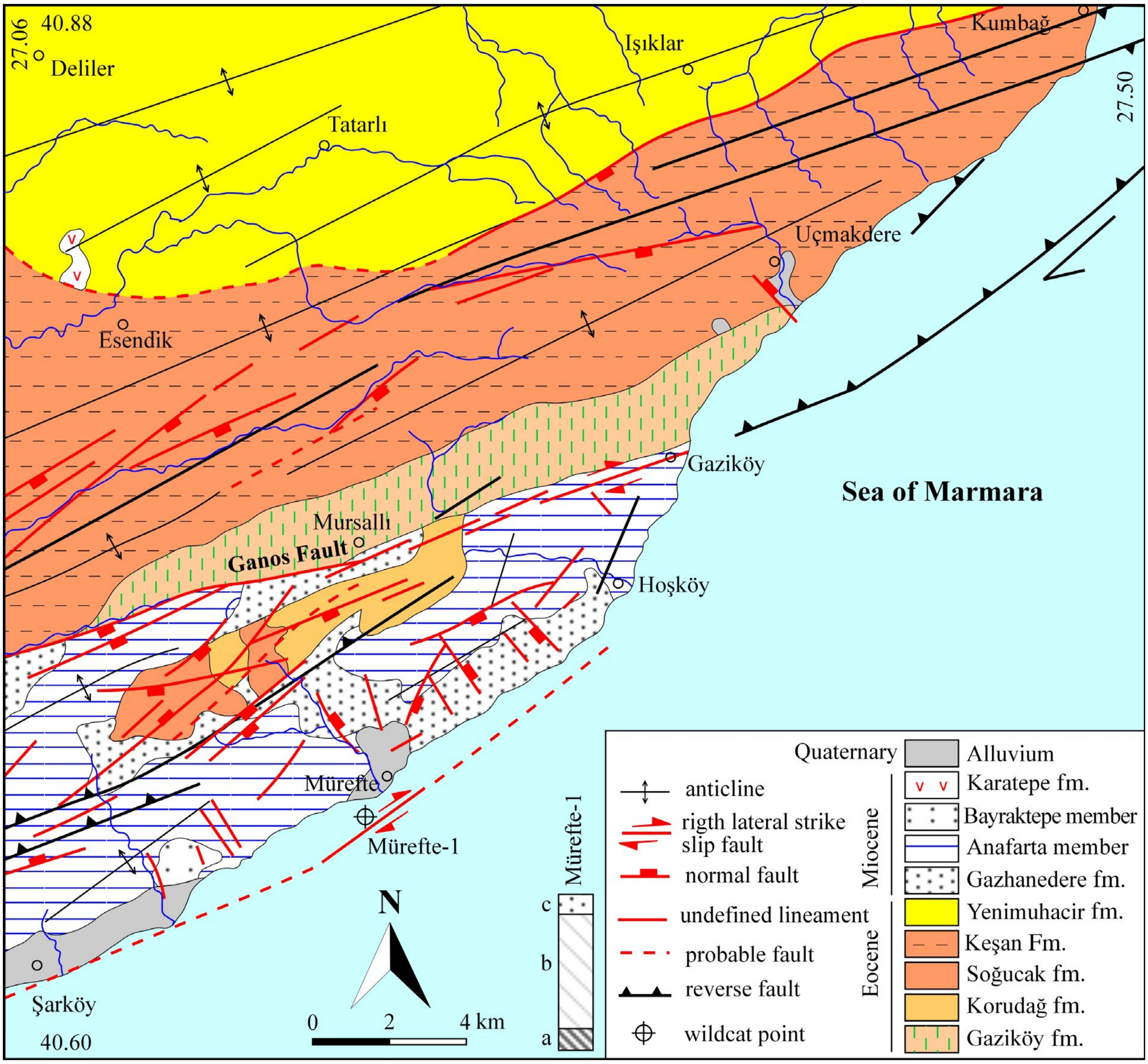

Figure 2- Geological map of the Ganos Fault and its vicinities (Yaltırak, 1996, 2002). the Mürefte-1 offshore wildcat is added in this map (simplified from Yaltırak, 1996). a) Mesozoic units, b) Paleogene units, and c) Gazhanedere formation.

total surface rupture length for two earthquakes was calculated as 150 ± 30 km (Aksoy et al., 2010).

Onshore deformational structures in the previous studies, considering the intensive earthquake activity and the facing of the units from different ages, displays very important evidences of surfacing of NAFS in Thrace region and its deformational imprints for earth sciences. Besides of these onshore studies, there are many researches carried on determining the geological features of the offshore segment of NAFS in the Sea of Marmara. These studies are on geometry and kinematics of NAFS (Tapırdamaz and Yaltırak, 1997; Alpar 1999; Okay et al., 1999, 2000; Halbach et al., 2002; Gürbüz et al., 2000; McClusky et al., 2000; Siyako et al., 2000; Ergin vd., 2000; İmren et al., 2001; Gökaşan et al., 2001, 2002, 2003; Le Pichon et al., 2001, 2003; Rangin et al., 2001, 2004; Armijo et al., 2002, 2005; Alpar and Yaltırak, 2002; Meade et al., 2002; Polonia et al., 2002, 2004; Yaltırak, 2002; Demirbağ et al., 2003), sea level changes and its comparison with Eastern Mediterranean Sea data (Imbrie et al.,1984; Aksoy et al., 1999) etc.

In almost every well cutting section near the study area, three different units have been described (Yaltırak, 1996). From older to younger; number 3 is pre-Miocene base units, number 2 is Miocene deposits and number 1 is late Quaternary to recent sediments. Three units with different ages were determined in the Mürefte-1 offshore wildcat, which was drilled by TPAO. These units are defined as, Mesozoic (a), Paleogene (b) and Miocene (c) units.

Within the context of this study, determination of the deformation of NAFS, whose onshore and offshore stratigraphic and tectonic features are mostly known, between Gaziköy –Mürefte shallow marine area was aimed. Another aim of this study was to identify the erosional and depositional surfaces created by sea level changes, where the present sea level is very shallow.

2. Stratigraphy and Tectonics of the Study Area

2.1. Stratiraphy

Although there are different stratigraphic designations in the studies carried out in Gaziköy and its surroundings, it is seen that the units present similar stratigraphic sequences. The stratigraphic sequence of the region was simplified and presented as shown in figure 2 by Yaltırak (1996). The sequence package overlying the basic units starts with the Gaziköy Formation (Sümengen et al., 1987; Sümengen and Terlemez, 1991; Siyako, 2006), which contains sandstone, siltstone and silicified tuff series formed by the turbiditic sediments of lower-middle Eocene age and deposited in the deep sea environment (Figure 2). Gaziköy Formation (Şentürk et al., 1998), which is gradually transitive with the formations on it, is covered by the Korudağ formation, which is composed of intercalation of sandstone and claystone, with conglomerate of the upper Eocene (Figure 2). Korudağ formation, which consists of submarine fan deposits, is observed in the southern part of the Ganos Fault in the study area (Yaltırak, 1996). This unit is followed by Soğucak Formation (Holmes, 1961) consisting of upper Eocene aged limestones and the Keşan Formation (Gökçen, 1967), which are turbiditic deposits. Yenimuhacir formation (Şentürk et al., 1998), consisting of upper Eocene-lower Miocene aged claystone, siltstone and sandstone spreading in the drainage area of Anadere, which flows into the sea around Kumbağ (Şentürk et al., 1998), has been eroded and covered uncomformably with younger units (Siyako, 2006).

The middle Oligocene Danişment Formation, which is observed in limited areas in the southern part of the Thrace Region but where coal formations are densely observed in the Thrace basin, consists of sandstone layers containing lignites at different levels (Şentürk et al., 1998). This level is then unconformably covered by the middle-upper Miocene Çanakkale Group, in which there are different members (Gazhanedere Fm, Anafarta and Bayraktepe members). This group, which is unconformably covered by the Karatepe formation, consists of basalts observed in the form of lava flow, generally in the form of black, sometimes brown, massive and resistant agglomerates with calcite in places. These basalts, which show column and flow structures, have augite and olivine crystals and have augite, olivine, magnetite paste and have alkaline properties (Şentürk et al., 1998). According to the K/Ar absolute age determinations of the Karatepe formation, the age is upper Miocene (6-9 Ma) (Şentürk et al., 1998).

The top of the stratigraphic sequence is the Quaternary Marmara Formation, which represents various coastal facies and consists of loosely attached sandstones and beach rocks and tufa deposits. These sediments have been detected both in the vicinity of Mürefte, Marmara Ereğlisi and Uçmakdere on land, and in shallow and partially deep areas of more than 100 m in the sea (Siyako, 2006). The formation, which is unconformable with all the older units on land, is harmoniously located in the deep marine parts and unconformably in the shallow parts. According to radiometric age determinations, it was determined that this precipitation was between 240-40 thousand years on terresterial and 400-24 thousand years on sea areas (Siyako, 2006).

2.2. Tectonics

The Tekirdağ basin, located in the westernmost of the three major basins in the Sea of Marmara, is traversed by the NAFS in an approximately E-W direction. The land part of the fault, which comes ashore from the near north of Gaziköy, is called the Ganos fault. Using the earthquake activities recorded by Boğaziçi University Kandilli Observatory Earthquake Research Institute between 2003-2010, it was aimed to reveal the current behavior of the Ganos Fault (Yıldız et al., 2013). The focal mechanism solutions of 12 earthquakes ($M \geq 3.3$) selected from these events were calculated using three component waveform modeling and inverse methods with numerical analysis method. As a result, although the fault has a dominant right-lateral strike-slip motion, it has been shown that there are some normal and thrust components due to some local changes (Yıldız et al., 2013). According to the focal mechanisms of the earthquakes obtained as a result of these analysis: in inverse solutions, the largest principal stress axis (σ1) and the smallest principal stress axis (σ3) are in the horizontal and outer arc; strike-slip stress regime is expressed in which the intermediate stress axis (σ2) is in the center and vertical position. Considering the status of the stress axes, it is clearly stated that the Ganos Fault is a right-lateral strike-slip fault that develops under a compression regime in NW-SE direction and is present in local normal faults with transtensional characteristics (Yıldız et al., 2013). This dominant compression direction is also expected to reveal the deformation structures associated with the tectonic regime in the hardened and unconsolidated sediments in the sea. Within the scope of this study, deformation patterns of units of different ages are interpreted with reference to current stress distributions.

3. Material and Methods

In the geophysical survey completed by the R/V MTA Selen Research Vessel in the study area, 41 (191 km) high resolution multi channel seismic and 500 km bathymetry data were gathered (Figure 3). After the data processing of the seismic profiles were completed, seismic profiles of sufficient quality were selected in order to carry out this study, in addition, all bathymetry data were combined and the sea floor morphology was obtained. In this context, the work plan was implemented in two main methods. The first of these methods is shallow seismic data acqusition phase. The seismic data penetration is minimum of 55 m. This situation have great importance for detecting and distinguishing shallow geological unit deformations under the sea floor. Seismic profiles that best represent both the data quality and structures, that will cross the coastline and the NE-trending Gaziköy fault, are evaluated within the scope of this study.

Seismic profiles were planned by creating a grid with one (1) kilometer intervals in a vertical and parallel position to the geological structures as much as possible. The seismic parameters given in table 1 was used during data collection.

Table 1- Seismic acqusition parameter.

Parameter	
Shot interval (m)	6.25
Group interval (m)	3.125
Number of channel	96
Offset (m)	50
Sample rate (ms)	0,5
Air gun	1x10 inch³

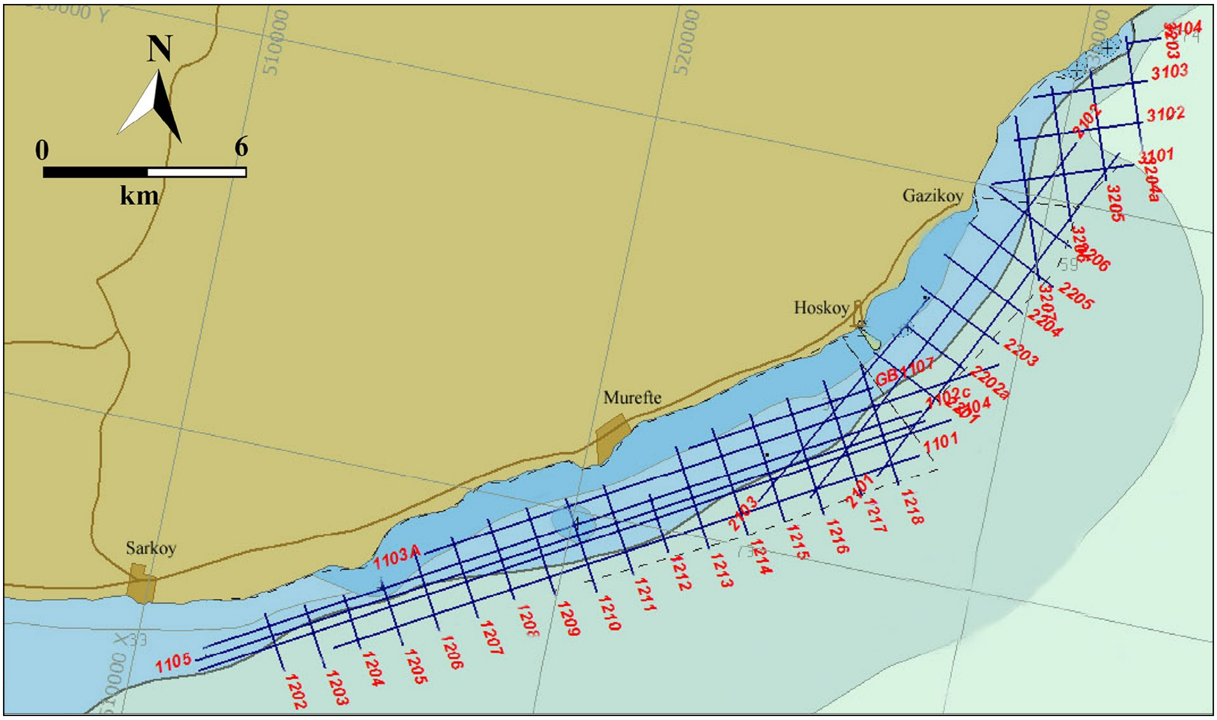

Figure 3- The distribution of interpreted seismic profiles.

Within the scope of this study; The data were processed using Halliburton (Landmark) ProMAX Seismic Processing Software in the MTA Marine Data Processing Laboratory, Department of Marine Research, MTA. A conventional seismic data processing flow was applied. After Kirchhoff time migration step, all seismic sections were converted from time domain (t-x) to depth (x-h) domain by using Dix (1955) interval velocity formula. The second method is to reveal the sea floor morphology within the study area. Bathymetry data of the study area were collected with an ELAC SEABEAM 1050D (30 kHz / 180 kHz) multibeam echosounder and data processing was done with the Hypack Hysweep software. Bathymetry map was prepared in metric system according to WGS84 horizontal datum and UTM Zone 35N (34E-30E) projection system.

As it is apparent in the created bathymetry map, the depth data are mostly compatible with the existing sea maps (navigation maps) (Figure 4). Bathymetric changes in the area (except Gaziköy-Uçmakdere near the shore) range from 10 to 70 m. In a short distance between Gaziköy and Uçmakdere coastal area vertical height difference reach up to 700 m or more. The area with the greatest difference in depth is known as the Ganos pit. The southwestern part of the Ganos depression is also clearly observed on the obtained bathymetry map (Figure 4b). Sharp change in seabed morphology and fault discontinuity are clearly observed in the NW-SSE oriented seismic sections in this area.

4. Seismic Data Interpretation

Within the scope of this study, seismic data were collected along 41 lines in the shallow marine area at the NW of the Sea of Marmara. Active fault traces and seismic stratigraphic data were interpreted from these seismic profiles. 7 seismic sections (Figure 5), which have the potential to provide sufficient data in between Mürefte and southwestern part of Ganos pit, were selected to interpretate soft sediment deformation structures and sediment packets. The geological comments and the information they contain related with these sections are presented in detail.

The stratigraphic equivalence of units a and b, were differentiated in previous studies, is to the unit number 3 in the seismic sections in this study; unit number 2 corresponds to unit c in previous studies (Figure 2). Unit number 1 is defined as current sediments deposited on the continental shelf close the shore.

In this study based on seismic sections, firstly, two longer lines (1101 and 2102) taken parallel to the shore were interpreted and units 1, 2 and 3 were identified in the study carried out. Although the boundary of units 2 and 3 is clearly seen in seismic section 1101 (red border), this boundary has not been determined exactly in seismic section 2102 (Figures 6 and 7). On the other hand, in both sections, the boundary between Miocene-recent units, indicated by green, and sediment overlap structures (red arrows) were observed as a result of the transgression. The common feature seen in both sections is quite a large

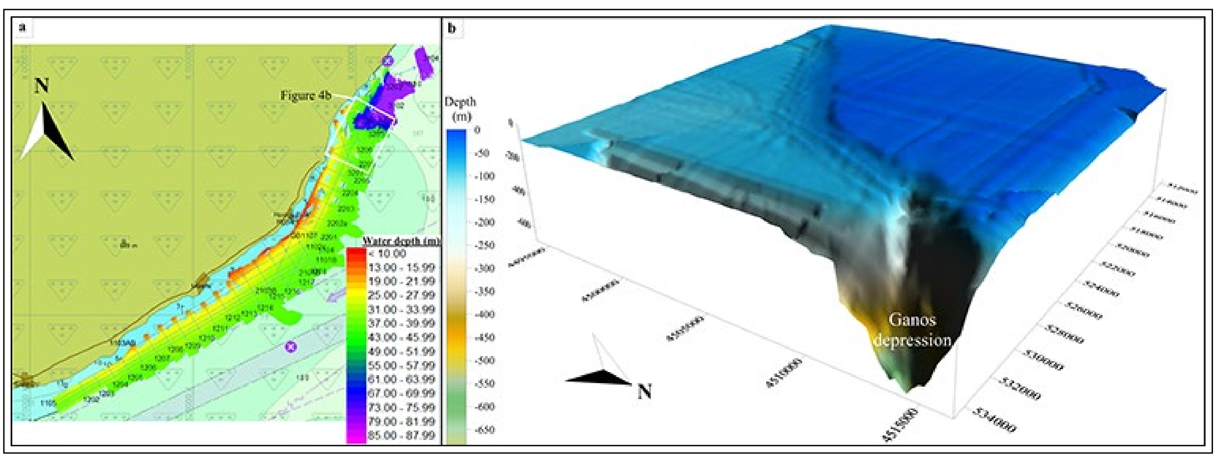

Figure 4- a) Distribution map of bathymetry data collected in the study area and b) 3D view of the area indicated by the white rectangle on figure 4a.

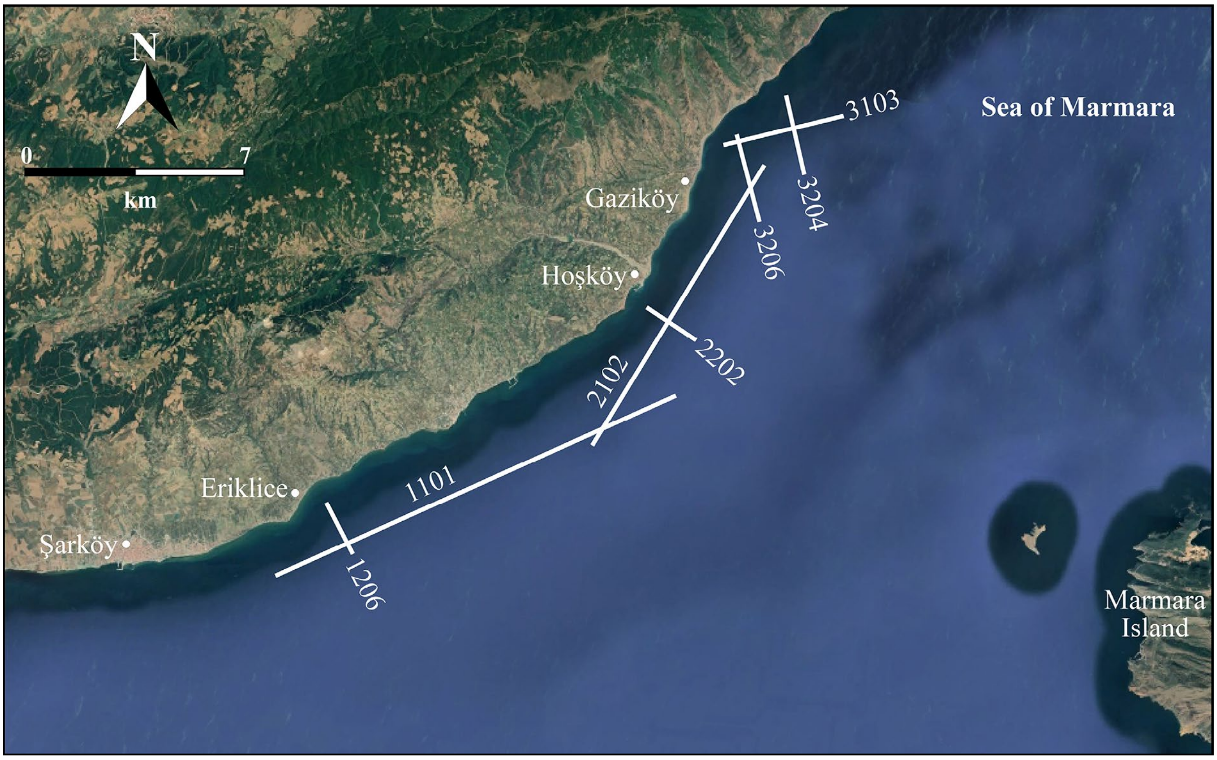

Figure 5- Map showing the locations of interpreted seismic profile.

number of strike-slip faulting structures developed within the older units. These mostly have reverse component and are observed as faulting and folding. The sharp elevation change observed in the NE part of 2101 represents the mostern SW section of the Ganos depression. The Ganos depression forms the SW part of the Tekirdağ basin and clearly shows the deformation texture of the NAFS.

Due to the distortion caused by multiples in section 2101, the boundary between units 2 and 3 could not be clearly distinguished. On the other hand, the boundary between units 1 and 2 and the transcendent structures (red arrows) thought to be connected to sea level could be clearly drawn. In each of the other sections, the boundaries between units 1, 2 and 3 and sediment overflow structures are observed and marked on the

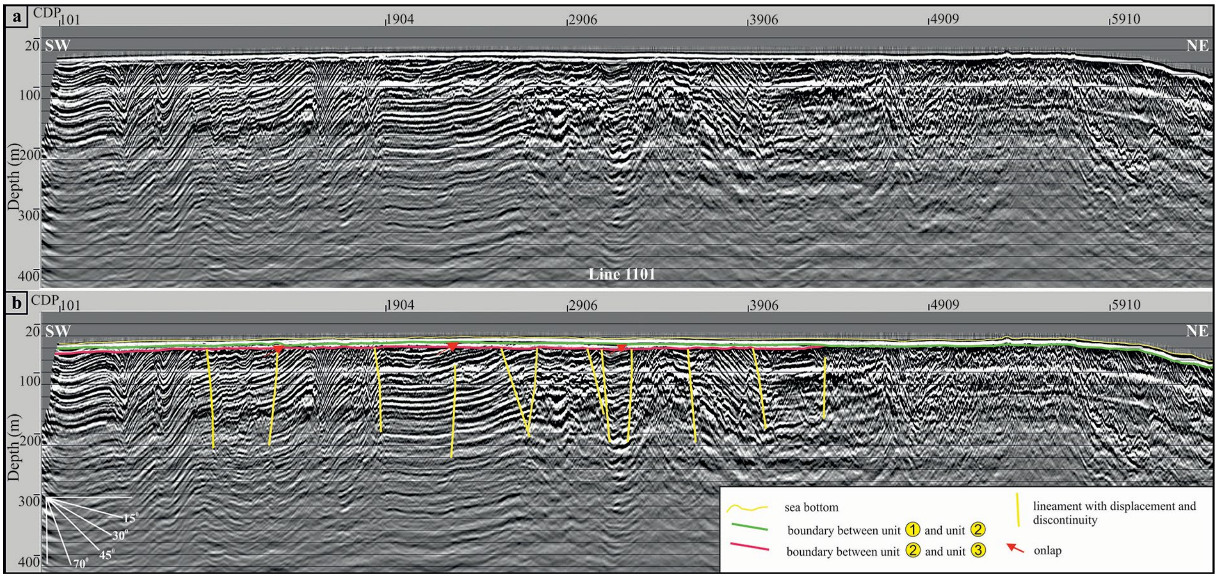

Figure 6- a) Seismic profile 1101 and b) geological interpretation of line 1101.

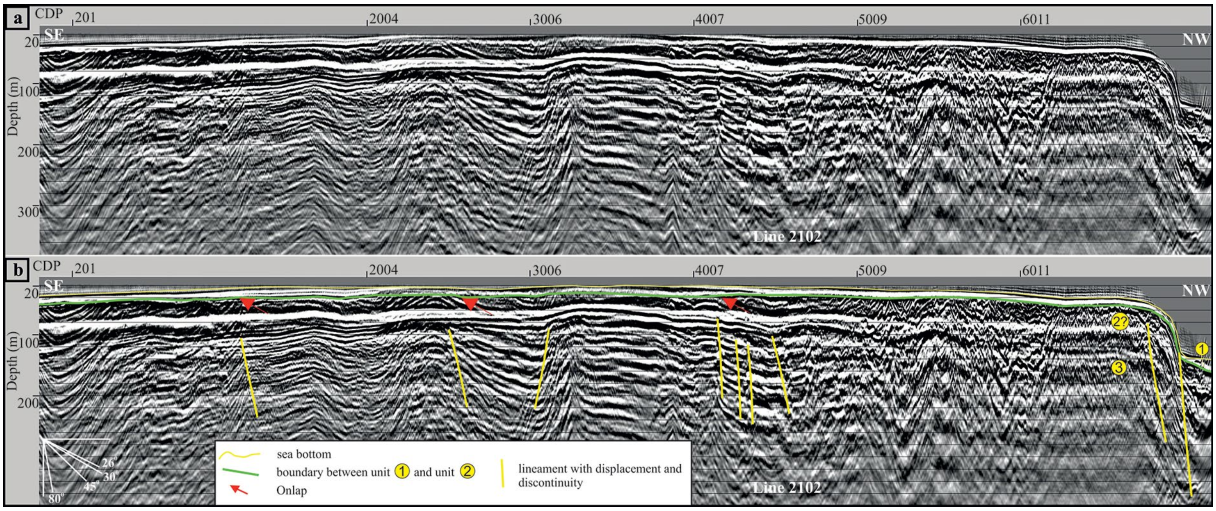

Figure 7- a) Seismic profile 2102 and b) geological interpretation of line 2102.

sections (1206 in figure 8, 2202 in figure 9, 3103 in figure 10, 3204 in figure 11, 3206 in figure12).

In the sections 1101 and 2102, the pre-Miocene units, which are interpreted as 3 units, have undergone extensive deformation. The most important indicator of deformations are faults and folds that observed frequently. The fact that most of these faults are observed only in units number 3 indicates that a tectonic phase quite different from the current tectonic regime was active in this time period. The folds observed in the section 1206 are another finding that supports this conditions (Figure 8). Although the boundary of the units 2 and 3 in the seismic section no. 2202 has not been identified, the slip and folds of the reverse faulting in the 3 unit show the older period

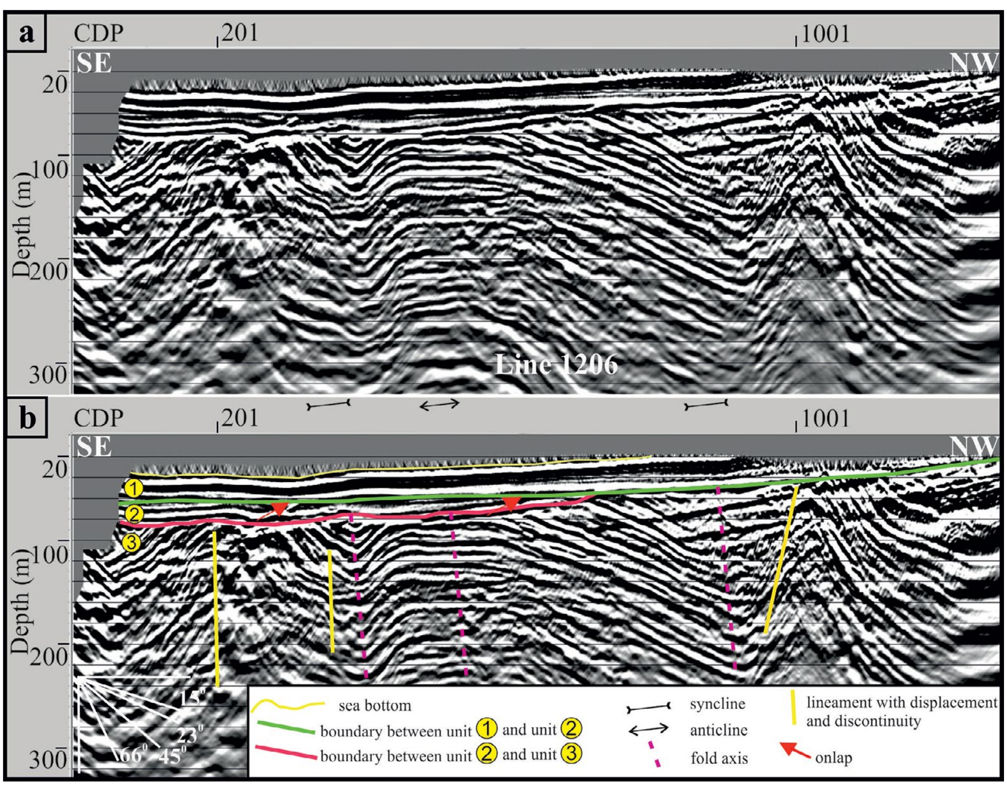

Figure 8- a) Seismic profile 1206 and b) geological interpretation of line 1206.

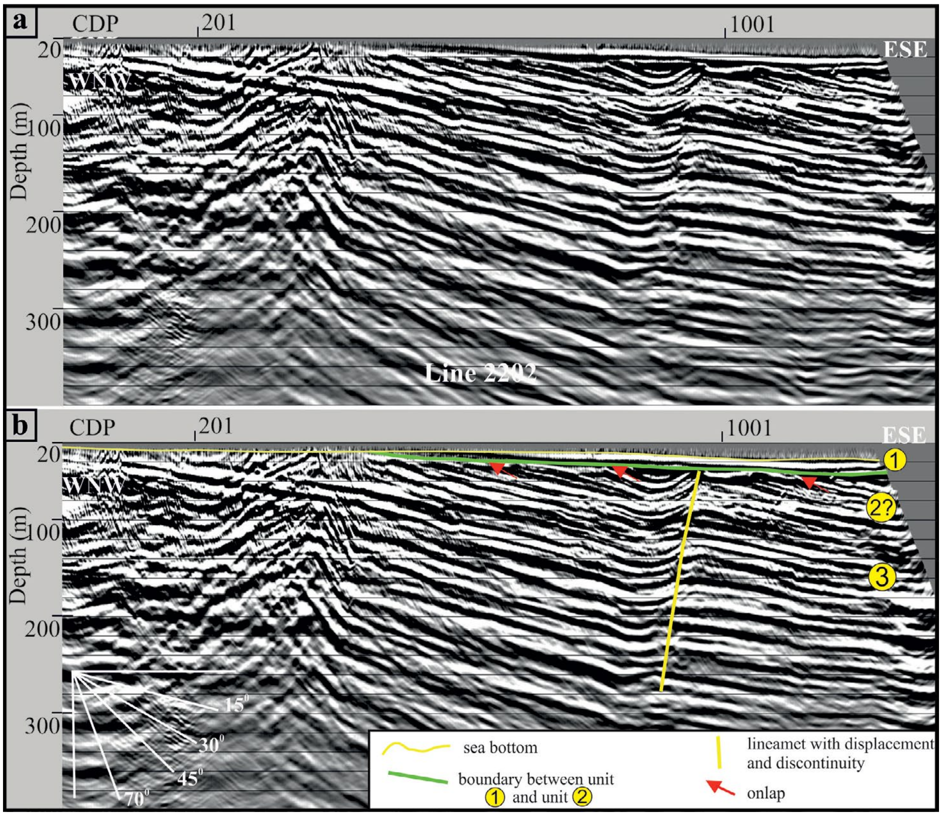

Figure 9- a) Seismic profile 2202 and b) geological interpretation of line 2202.

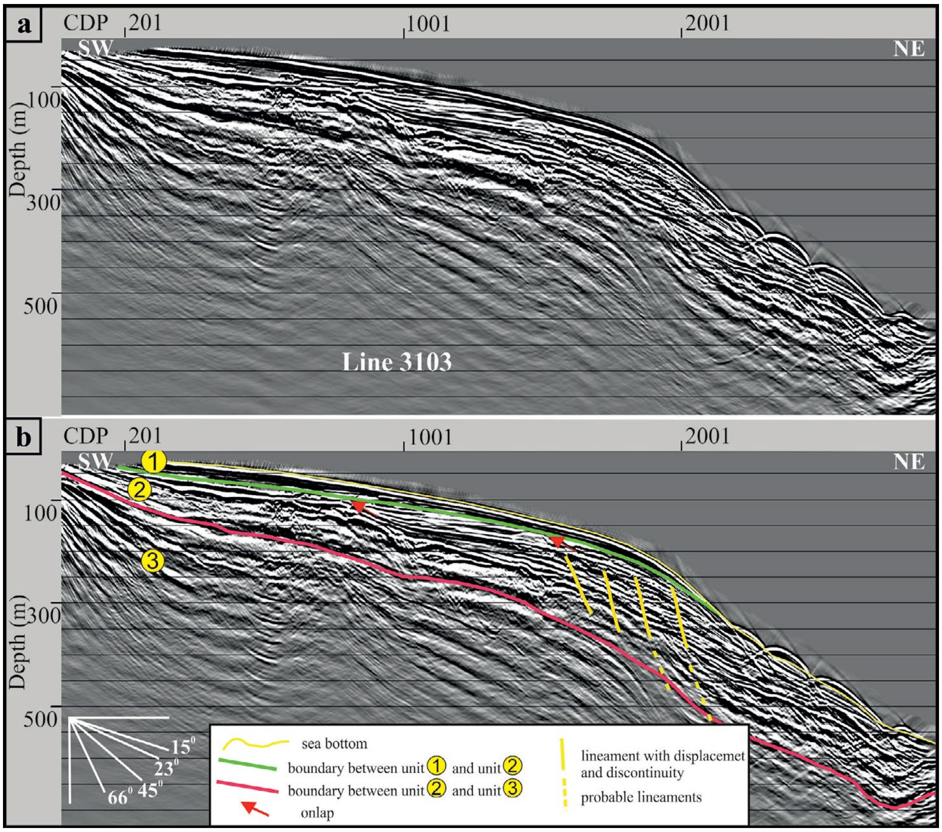

Figure 10- a) Seismic profile 3103 and b) geological interpretation of line 3103.

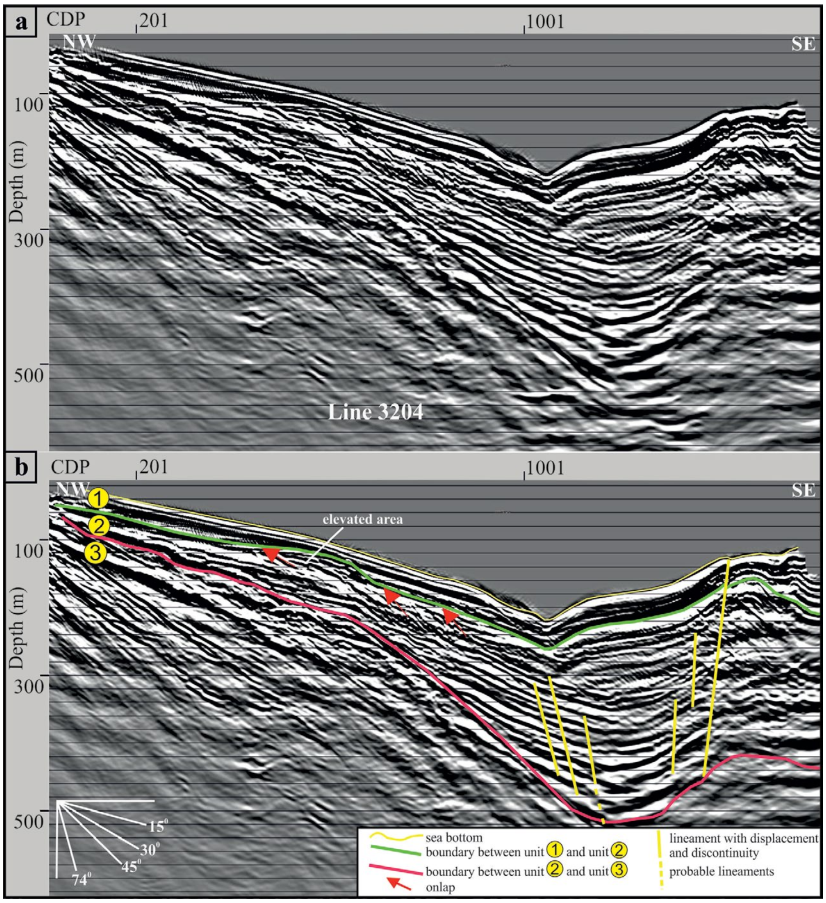

Figure 11- a) Seismic profile 3204 and b) geological interpretation of line 3204.

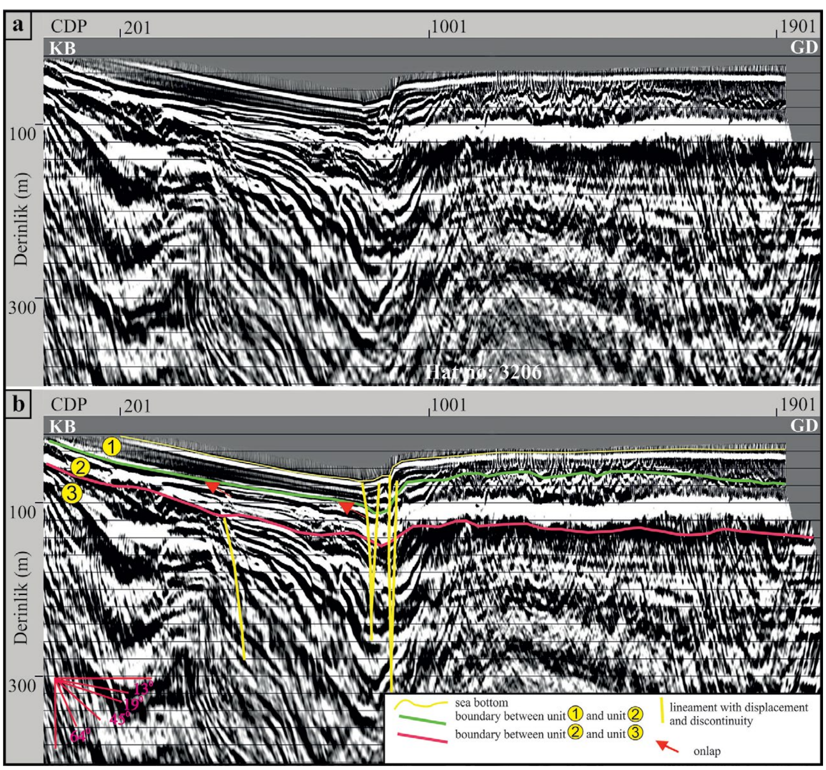

Figure 12- a) Seismic profile 3206 and b) geological interpretation of line 3206.

in this section, when the compressional phase was effective (Figure 9). In addition to these deformation structures that differ from the current tectonic regime, strike-slip faulting traces that still continue today, affecting units no. 2 and 1, are observable in sections. In the sections 2102, 3204 and 3206, a strike-slip faulting structure (with reverse component) indicating the current tectonic regime of the NAFS is observed (Figures 11-12).

In the seismic section number 3206, the faulting geometry with slight vertical offset is clearly observed in the soft sediment in the marine area where the NAFS rises from the Ganos depression to continental shelf and in the areas close to shoreline near Gaziköy that extends to the deep base units. In this section, it is clearly observable that NAFS has deformed by cutting all sediments from the basement units that have undergone dense deformation to the current units.

5. Discussions and Conclusions

Based on geological interpretation of shallow seismic and bathimetry data collected by R/V MTA Selen Reserach Vessel in the northwest of the Sea of Marmara and wildcat in the literature, 3 stratigraphic units were recognized, from older to younger, pre-Miocene basement, Miocene succession and Holocene shelf deposits.

The upper unit (Unit 1), which deposited during late Quaternary transgression, overlies on units (2 and 3) with an angular unconformity (the green lines on seismic sections). The thickness of the unit indicates some variations on different seismic sections with a range between 30-40 m, which is in accordance with the estimated sedimentation rate of 5 – 4 cm/kyr for northeast of the Sea of Marmara, reported by Ediger et al (2018). Having similar sediment source area characteristics, these two region are also easy to compare with each other, despite the considerable distance between them. The Ganos fault, which is a segment of NAFS and reaches to terresterial area in Gaziköy, is distinguisible on seismic sections indicating the recent tectonic activity. It can be proved by cutting through most recent deposits. On seismic section 3206, Ganos fault demonstrates upward branching “negative flower structure”, one of the characteristic features strike slip faults show in cross-sections.

The Unit 2 correspondings Miocene age. The unit is deformed and has an erosional boundary on top of it. There is an angular unconformity between the units and late Quaternary deposits. Near shoreline, the red colored erosional surface on seismic sections can be traced at 40-60 m water depth. According to the literature, 65 m sea level drop (Çağatay et al., 2003; Newman, 2003; Eriş et al., 2007) during Younger Dryas, 11.7 – 12.3 Cal kyr BP (Fairbanks, 1989), resulted in progressive decreasing of water flow from Black Sea to Sea of Marmara, which eventually transform the latter into a lake. The erosional surface interpreted from seismic sections probably indicates the aforementioned sea level drop and coincides with the sea bottom near shore line once exposed to atmospheric conditions.

The unit 3, which is distinguished in seismic sections and corresponding to the pre-Miocene basement units, is clearly different from the unit 2 in terms of structural and deformation pattern. This situation is the most important indicator that two units are subjected to different deformation processes. The discontinuities and folds defining the amount of deformation revealed that the unit 3 was exposed to a compressional tectonic regime more than the unit 2. It is an expected result to observe compression structures especially in transpressional areas in strike-slip regimes. However, the determination of different deformation amount in the unit number 2 and 3 indicates the differences in the dominant tectonic regimes. As a result, the recent strike-slip faulting with reverse component is different from the older tectonic regimes.

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