ORIGINAL RESEARCH PAPER

Northern segment of the North Anatolian Fault in the Gulf of Izmit inferred from marine magnetic anomalies

Sinan Demirel[1] · Bedri Alpar[1] · Cenk Yaltırak[2] · Denizhan Vardar[1] · Hülya Kurt[3]

Abstract

The Gulf of İzmit is a critical basin in assessment of the kinematics of the North Anatolian Fault (NAF) at the eastern margin of the Sea of Marmara. The available seismic reflection data do not provide sufficient and clear evidences to outline the deeper structures because of limited penetration. In agreement with the known main tectonic elements from available seismic data and multi-beam bathymetry, new magnetic data gathered within the scope of this study show E–W trending anomalies and permit us to outline satisfactorily the deeper tectonic setting of the gulf region. The northern strand of the NAF can be evidently correlated with the maxima on the magnetic profiles, implying a significant thinning in the crust along the weakness zone placed between the Istanbul Zone and Karakaya Complex. Such a tectonic structure must have been formed as parallel transform strike-slip pressure, which is different from the characteristic negative-flower structure observed at the East Marmara trough. This pattern occurs in a relatively narrow zone, because it has been superimposed on a paleo-tectonic lineament.

Keywords Marine magnetic · Seismic reflection · Multibeam bathymetry · Tectonic structure · Inversion tectonics

Introduction

The North Anatolian Fault (NAF) is a > 1500 km long right-lateral strike-slip active fault (Şengör et al. 2005). It forms a major continental transform boundary between the Eurasian and Anatolian plates, until terminating at the northern Aegean Sea where the westward escape of the Anatolian block turns into anticlockwise rotational motion. Before the NAF enters the eastern Sea of Marmara through the Gulf of Izmit, it splits into three semi-parallel strands; named on the basis of their geographic latitudes as the northern, middle and southern strands (Fig. 1a). Even though individually they show distinctive seismological, morphotectonic and kinematic properties depending on their locations (Yaltırak et al. 2012), the northern strand of the NAF that is lying between the Istanbul Zone (Palaeozoic) and the Karakaya

Complex (Permian–Triassic), is of particular interest to the earth scientists in the context seismic hazard of the Sea of Marmara region and Istanbul (Barka and Kadinsky-Cade 1988; Görür et al. 1997). Following the latest 1999 earthquakes (August 17 and November 12 with moment magnitudes of 7.6 and 7.2, respectively) that were nucleated on the northern strand of the NAF, many researchers have proposed a number of tectonic and kinematic models for the Gulf of İzmit. Due to the limited penetration of seismic energy and lack of deep seismic data below 1500 ms twt, however, the proposed models depend mostly on the shallow seismic reflection profiles and multibeam bathymetry (e.g. Şengör et al. 1999; Gökaşan et al. 2001; Alpar and Yaltırak 2002; Kuşçu et al. 2002; Polonia et al. 2004; Cormier et al. 2006; Kurt and Yücesoy 2009; Gasperini et al. 2011).

The most common result of the proposed models was that the Gulf of İzmit is a strike-slip basin. This was against the pull-apart system suggested by Barka and Kadinsky-Cade (1988). Şengör et al. (1999), for example, proposed a single right-lateral fault passing along the gulf, as a part of the Main Marmara Fault as they call it. Alpar and Yaltırak (2002) and Kuşçu et al. (2002) suggested that a series of releasing bend structures formed the main fault system along the gulf and the sub-basins were bounded by the secondary faults. Gökaşan et al. (2001) suggested that these secondary

✉ Sinan Demirel
  sinan@istanbul.edu.tr

1 Institute of Marine Sciences and Management, İstanbul University, Vefa, 34134 Istanbul, Turkey

2 Ayazağa, Department of Geological Engineering, Faculty of Mines, İstanbul Technical University, İstanbul, Turkey

3 Ayazağa, Department of Geophysical Engineering, Faculty of Mines, İstanbul Technical University, İstanbul, Turkey
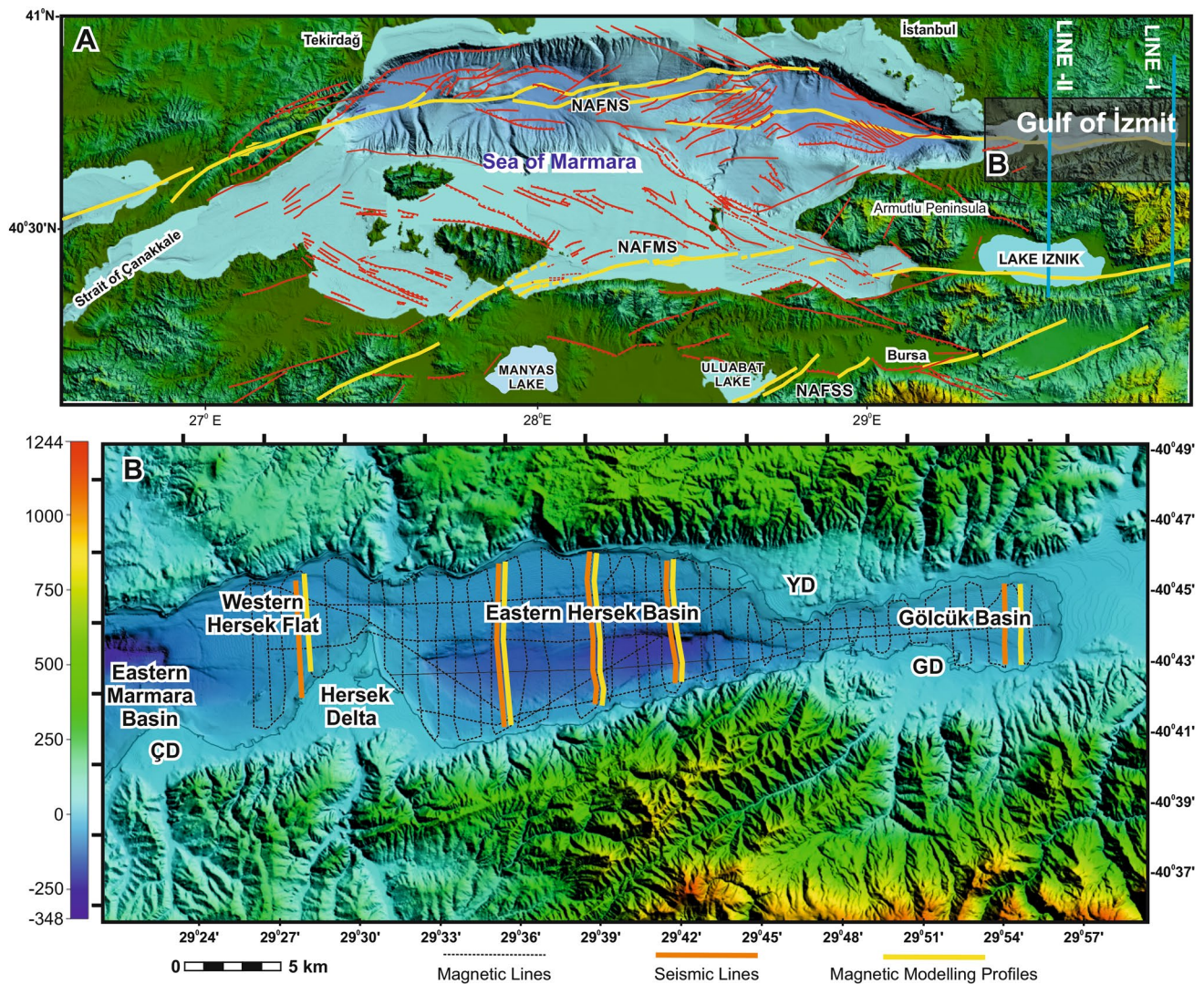
Fig. 1 **a** Active tectonic map of the Sea of Marmara region (compiled from Yaltırak 2002; Vardar et al. 2014). Yellow lines stand for the main fault segments; *NAFNS* the northern strand of the NAF, *NAFMS* the middle strand of the NAF. Red lines represent the secondary faults. Blue lines (Line I and II) show the gravity anomaly profiles given by Ateş et al. (2003). **b** Magnetic survey tract (dotted), seismic reflection lines (orange) and magnetic modelling profiles (yellow) were superimposed on the digital elevation model and multibeam bathymetry. *YD* Yarımca Delta, *GD* Gölcük Delta, *ÇD* Çatal Delta

faults were already existed and later cut by a new rupture of the NAF, corresponding to the uplift of the Armutlu Peninsula to the south. Later, Polonia et al. (2004) outlined three successive depressions along the gulf which were bounded by short, en échelon extensional and strike-slip segments, forming a sequence of pull-apart basins. According to Cormier et al. (2006), the main fault follows the axis of the gulf with a few minor bends and a dip-slip movement is accommodated along the fault. Gasperini et al. (2011) claimed that the deformations of the NAF were almost purely strike slip and concentrated in a relatively narrow zone at the western end of the Gulf of İzmit.

A limited number of airborne gravity and magnetic data confirm that the northern strand of the NAF is located on an old and narrow zone where two separate basins meet (Ateş et al 2003, 2008; Gholamrezaie et al. 2019). The gravity data given by Ateş et al. (2003) reveals that the earth crust becomes thinner along the gulf, eventually along the NAF (see their Fig. 1a). The low-pass filtered aeromagnetic anomalies along the gulf changes between − 200 and 200 nT, lowest at the easternmost subbasin where the northern strand of the NAF enters into the sea (Ateş et al 2008). The aeromagnetic data, however, do not permit to discriminate the magnetic structures below the gulf, and how the northern strand of the NAF is shaped downward and towards the Sea of Marmara. It is particularly important, because Şengör et al. (2005) suggested that the northern strand of the NAF, the one along the Gulf of İzmit, was a shear zone at the

beginning and formed during the last 200 thousand years, while the NAF itself has been active on the İznik—Gemlik line in the southern Marmara since the Upper Miocene. However, gravity and magnetic data do not have sufficient resolution in the gulf. Recently, Gholamrezaie et al. (2019) developed crustal-scale 3-D density models which indicate significant crustal density heterogeneities beneath the Marmara basin, possibly controlling the rheological behaviour along the NAF and segmentation. They defined a density model composed from two main depocenters above a heterogeneous felsic upper crystalline crust. The maximum thickness of the pre-kinematic (lower depocenter) sediments in the Gulf of İzmit is 3000 m, while the thickness of the syn-kinematic (upper depocenter) sediments varies between 1000 and 1500 m. Their thickness distribution displays a subsidence regime during the early phase of basin formation. This is similar to the present-day subsidence regime in the Sea of Marmara. This model evidently supports that the NAF reached the Gulf of İzmit around 3.5 Ma before present as suggested earlier by Alpar and Yaltırak (2002).

The evaluation of marine magnetic data, combined with land geology, available multi-beam bathymetry, marine seismic reflection and gravity anomaly profiles, will strongly help us to understand whether the northern Marmara strand in the Gulf of İzmit lies in a narrow zone or it occupies a larger zone. These possibilities may have a direct impact on the stress variability along the gulf, which should be considered in building geomechanical models. Therefore the main aim of this study is to differentiate the basement from sedimentary cover, identify overlying mantle structures and magnetic response of the northern segment of the NAF along the Gulf of İzmit using marine magnetic data collected by SeaSPY proton magnetometer.

Sea floor morphology and geology

The Gulf of İzmit comprises three basins; the western Hersek flat, eastern Hersek basin and Gölcük basin (Fig. 1b). The eastern Hersek (central) basin is the largest one, with a maximum depth of − 208 m (Alpar and Yaltırak 2002). It is 20 km long and 3–10 km wide. The average slope of southern margin is 7°, steeper than the northern one. The Gölcük basin is 16 km long, 2–5 km wide with a maximum depth of − 40 m. The western Hersek flat (outer basin) is a passage zone to the deep basins of the Sea of Marmara. Two relatively shallow sills, offshore the Hersek Peninsula (54 m) and the Yarımca Delta (33 m), separate these three basins. The faults onshore are oblique to the main segment and can be classified in two groups (Alpar and Yaltırak, 2002); ENE–WSW trending right-lateral oblique faults developed under the dextral shear regime, like the Karamürsel Fault,

and NW–SE trending extensional faults, e.g. the Kavaklı Fault (Fig. 2).

The geological setting of the northern and southern blocks of the Gulf of İzmit are different. The sedimentary packages at the basement of the northern block, the Istanbul Zone, stand for shallow and deep-sea environments (Okay and Tüysüz, 1999). The basement is unconformably overlain by terrestrial and shallow-marine Triassic formations (Altınlı 1968), the shallow marine Cretaceous formations (Akveren) and by the Paleocene—Early Eocene shallow marine formations (Korucu) (Seymen 1995). The basement of the southern block, on the other hand, consists of Palaeozoic—Triassic subduction-accretion units packages, metamorphosed during Triassic (Okay and Tüysüz 1999). It is called the Karakaya Complex which is unconformably overlain by the Cretaceous formations (Akveren), Lower-Middle Eocene shallow marine clastic sedimentary rocks (Kaytazdere fm) and Middle-Upper Eocene volcanic rocks (Kızılbent fm) (Genç and Yılmaz 1997). Neogene and post-Neogene units, which are directly related with NAF, overlain these sequences. The Miocene to Pleistocene stratigraphic units are the formations of Yalova, Samanlıdağ and Marmara (Emre et al. 1998; Alpar and Yaltırak 2002; Fig. 2). The upper Miocene-lower Pliocene Yalova Formation is distributed throughout the Armutlu Peninsula, together with the members of Kılınç and Yalakdere siliciclastic succession, which rests unconformably over the basement rocks. The Samanlıdağ formation consists of 20–50 m-thick coarse sandstone and conglomerate lenses of upper Pliocene-lower Pleistocene age and represents braided river and alluvial fan deposition. There are three large alluvial fans covering the coastal areas; the deltas of Yarımca, Çatal, Hersek and Gölcük (Fig. 1b).

Materials and methods

Magnetic data may help determine basement, sub-seafloor structures and internal composition (Golynsky et al. 2013; Guevara et al. 2013; Doo et al. 2015). In this study, ship-track marine magnetic data were acquired in 2014 by using SeaSPY proton magnetometer manufactured by the "Marine Magnetics Corporation" of Canada (Fig. 1b). The sensor of the magnetometer was towed 3–5 m below sea level and 30 m far from the boat. The sampling frequency was 2 Hz Magellan Proflex 500 GNSS system was used for navigation; with a precision of ~ 1 m. Maptech® Marine Software was used for navigation tracking the planned routes on digital charts. The vessel velocity was held at 6 knots. The layback corrections were applied to the data simultaneously during the survey. All data, longer than 1000 km, were converted to CSV format by BOB program. Spikes along the profiles that may be associated with human activities, such as
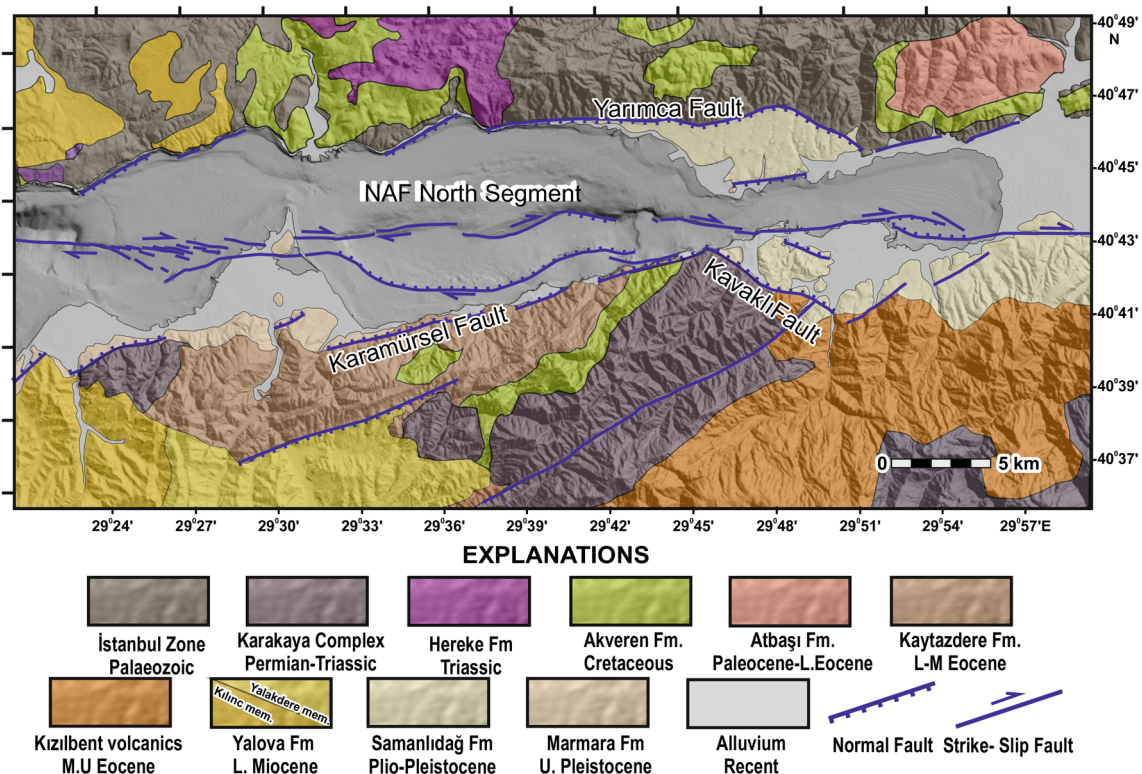
Fig. 2 Generalized geological map of the Gulf of İzmit, Eastern part of the Sea of Marmara, Turkey (revised from Yaltırak and Alpar 2002; Türkecan and Yurtsever 2002)

submarine cables, metal containing excavation material etc., were initially eliminated virtually. Unprocessed magnetic anomaly map shows that magnetic data is much affected by some disturbing effects (Fig. 3a). Diurnal corrections were applied to remove time-dependent variations in the ambient magnetic field. The correction data were obtained from the official web site of INTERMAGNET—the global network of observatories, monitoring the Earth's magnetic field. The correction values and the measured data were synchronized by using FORTRAN codes. The removal of the IGRF (International Geomagnetic Reference Field) performed employing the IGRF 2012 (Thébault et al. 2015). The second step is filtering the data to a gridded dataset in order to remove or reduce non-geological effects caused by long-wavelength noise along the survey lines. The decorrugation filter (Butterworth and Directional Cosine) was applied to the data to acquire error grid, using the trading program GEOSOFT-OASIS. Levelling error channel calculated from error grid for separating high-frequency geological signal from the longer-wavelength levelling errors. In order to smooth noise and levelling errors filtering was applied using a cut off filter After the levelling process, the final data were gridded using the "random gridding" (Fig. 3b) with minimum curvature system (Briggs 1974). The gridded dataset (grid cell size 500×500 m) was then

reduced to the pole (RTP) to migrate the observed field from the magnetic inclination and declination (Fig. 3c), to what the field would look like at the magnetic pole. The inclination and declination values for RTP were 58 and 5 (Ateş et al. 2008), respectively (Fig. 3c). This helps interpretation since any asymmetry in the reduced to pole field can then be attributed to source geometry and/or magnetic properties. According to Li et al. (2009), major tectonic structures such as faults and basement uplifts can be more readily identified from a magnetic map after the reduction to the pole than from the original magnetic anomaly map. Upward continuation tends to remove shorter wavelengths produced by near-surface sources (Fig. 4). The magnetic models were then calculated by the Talwani method (Fig. 5). The fitting errors to observed curves are given in Fig. 5. From the general onshore geology, four main units can be differentiated from north to south (Fig. 2) with different magnetic properties. In our magnetic models, approximate magnetic susceptibilities for the basement rocks are utilized from the measurements given for the Paleozoic (Pre-Eocene) stratigraphic sequence exposed on the Istanbul Zone; that is 2.10×10^{-3} cgs (Öksüm et al. 2015 for the stations 16 and 17). The magnetic susceptibility for the overlaying sediments has been set to zero, considering $3–5 \times 10^{-5}$ cgs units for the top soils along the nearest coastal area (Canbay et al. 2010).

Fig. 3 a Raw magnetic anomaly field grid. **b** Processed field. **c** RTP grid. Values in nT
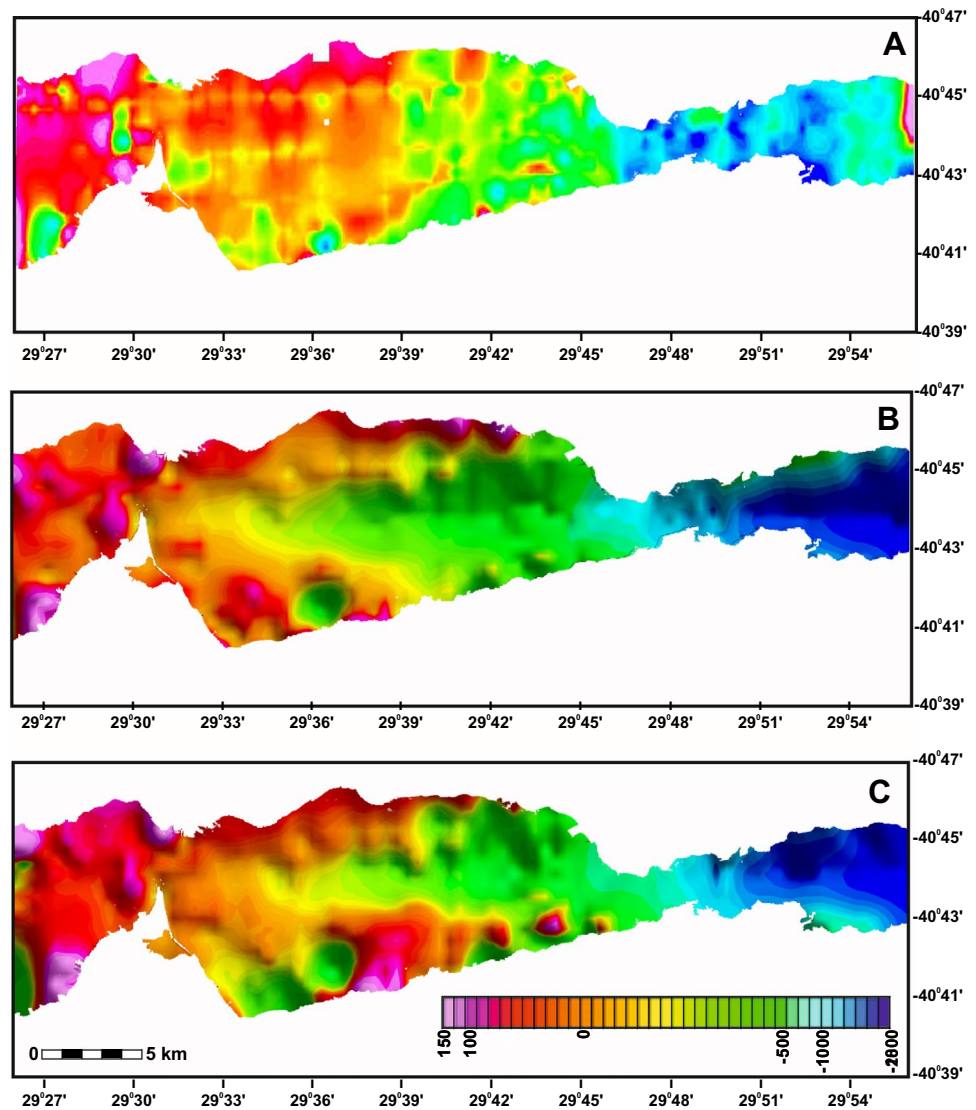
The multichannel seismic reflection data gathered by the Directorate of Mineral Research and Exploration of Turkey in 1999 using a couple of 45 cu in air guns and processed at the data processing centre of the Istanbul Technical University have been reinterpreted. The number of channels was 18. The shot offset and distance between the hydrophone groups were 12.5 m. The distance between two successive shots were either 6.25 or 12.5 m, depending on the seismic section. With these field parameters, the fold coverage was 9- or 18, recorded at a 1-ms sample rate.

The bathymetry map is from the single-beam data collected by the Department of Navigation, Hydrography and Oceanography of the Turkish Navy in 1999, and the multibeam data collected by R/V Odin Finder and R/V Urania in 2000 and 2001 for the western and central basins (Polonia et al. 2004; Cormier et al. 2006; Kurt and Yücesoy 2009). Three multibeam systems used were Simrad EM300 (30 kHz), EM3000 (300 kHz) and portable SeaBeam 1180 (180 kHz), providing a vertical resolution of about 10 cm. The gridded depths and Aster v2 topography data were merged by using the GIS software Global Mapper© (Fig. 1b).

Results

Interpretation of marine magnetic data

The levelled magnetic field data grids indicate a relatively continuous ascending trend on magnetic values along the Gölcük and eastern Hersek basins (Fig. 3b, c). The lowest magnetic values in the studied area were observed at the central part of the Gölcük basin, possibly related with widely distributed alluvium units (Fig. 2), with a W–E trending wedge shaped geometry diving towards the eastern Hersek basin. The highest magnetic levels can be seen

Fig. 4 **a** 300 m upward continuation grid of RTP, **b** interpreted seismic sections and CHIRP data zoomed for the top 30 ms of Line 5s (Kuşçu et al. 2002), **c** the gravity profiles I and II deducted from the gravity anomaly maps by Ateş et al. (2003), which are crossing the basins of Eastern Hersek (west) and Gölcük (east), respectively
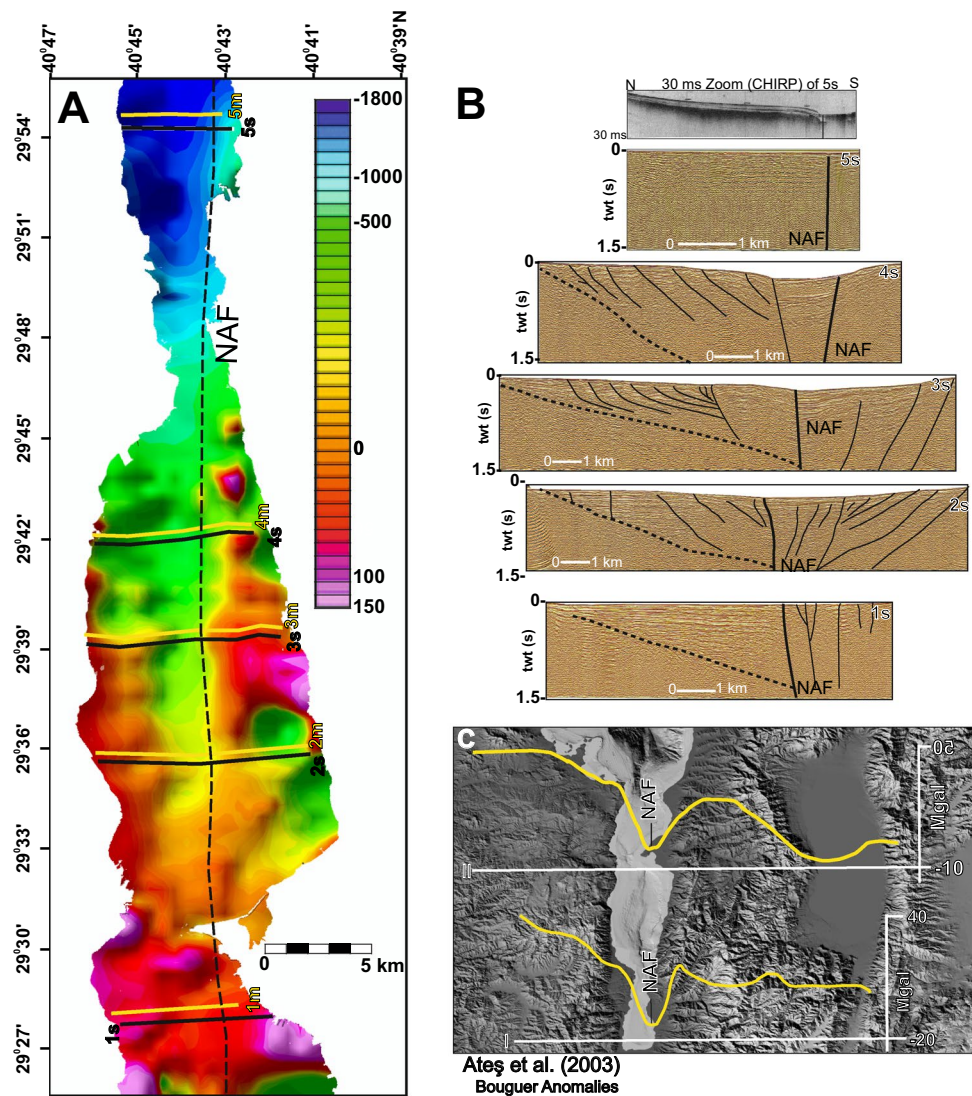
at the southern and northern part of the western Hersek flat (Fig. 3b). The wedge-shaped negative magnetic anomaly dominant at the northern half of the eastern basin has been interrupted by some high magnetic anomalies just to the east of the Hersek delta and along the northern coast (Figs. 3c, 4a). The low level of magnetic values along the basin indicate an important contrast with the positive magnetic values gathered at the northern and southern sides. The high magnetic anomalies has longer wavelength at the western side of the Hersek Delta where the highest magnetic levels have been distributed (Figs. 3c, 4a). The southern part of the central basin has lower magnetic values against the higher values along the northern coasts. The shear mechanism borders the high- and low-magnetic anomalies observed at the eastern Hersek and Gölcük basins; while it causes higher magnetic values at the western Hersek flat.

In order to determine deep basement structures and to outline the main tectonic elements extending along the Gulf

of İzmit, 2-D modelling of the magnetic anomaly field were performed along five selected N–S profiles (Fig. 5). Two main blocks can be seen to the north (Istanbul Zone) and south (Karakaya Complex), separated by a main fault zone where the crust is relatively thin (see also the line locations in Figs. 1a , 5c, and Ateş et al. 2003).

The magnetic anomaly values along the Profile 5 in the Gölcük basin changes between − 2000 and − 1000 nT (Fig. 4a). A simple narrow graben extends in the Gölcük basin with its relatively steep slopes (Fig. 6), which was almost hidden on the seismic reflection profiles (e.g. Figure 8 given by Kurt and Yücesoy 2009) due to limited acoustical penetration. However, the active faults, affecting the sea floor, interpreted from the high-resolution Sparker reflection profiles (Fig. 2, given by Alpar 1999) support such a narrow graben structure. The thickest part of the Plio-Quaternary sediments is located at the easternmost part of the Gulf where no acoustic basement could be identified (Fig. 4).

Fig. 5 2-D magnetic models and profiles along the lines given in Figs. 1 and 4. The errors represent the fitting differences between the observed and calculated curves
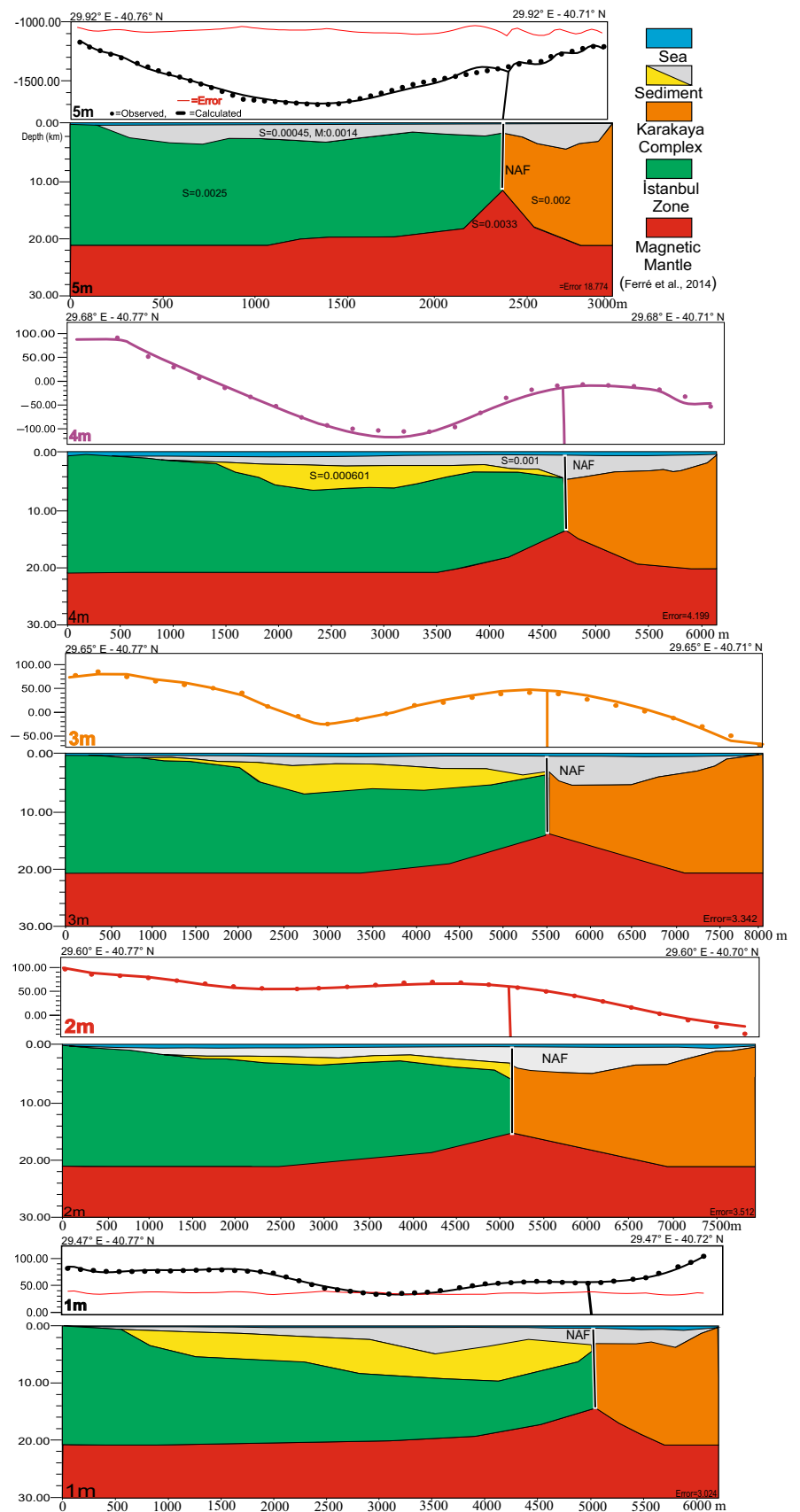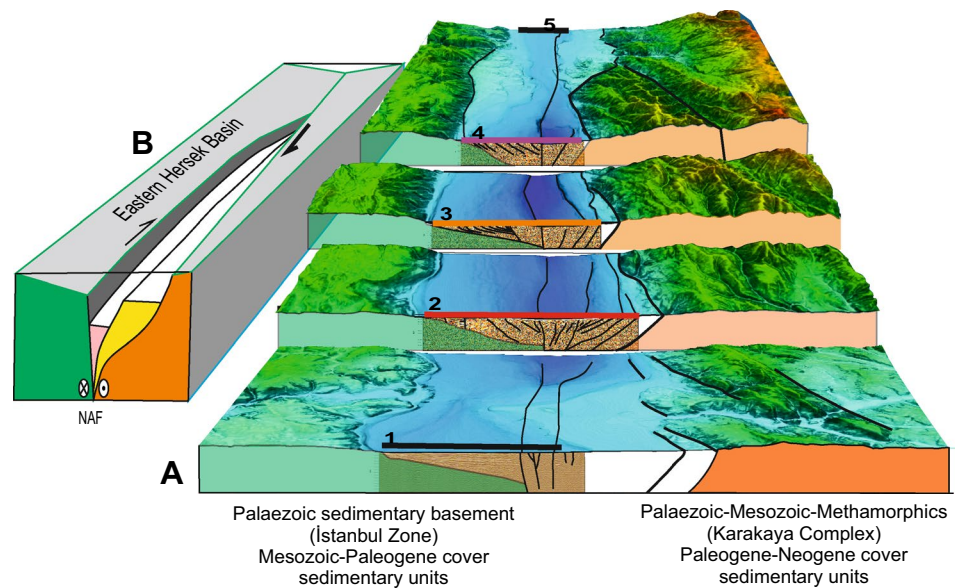
Palaezoic sedimentary basement (İstanbul Zone)
Mesozoic-Paleogene cover sedimentary units

Palaezoic-Mesozoic-Methamorphics (Karakaya Complex)
Paleogene-Neogene cover sedimentary units

Integration of marine magnetic response and seismic data

The acoustical basement, that is the interface between the bedrock and the post-Neogene sediments, consists of a low-slope discontinuity at the northern side of the Gulf, while it is characterized by oblique-normal faults with right-lateral component at the southern side (Fig. 4b). Such a system must have been developed together with the formation of the NAFNS (the dashed line in Fig. 4a). The magnetic Profile 3 representing the eastern side of the eastern Hersek basin, for example, shows a sub-basin structure at the southern part, and bounded by the secondary faults. Further east, the magnetic curve along the Profile 2 has low amplitude, implying gradual changes between the northern and southern margins of the basin. On the magnetic Profile 1 along the western Hersek flat, the southern basements seems to be higher, possibly due to vertical tectonic uplift. Such an uplift has been proposed depending on the Pleistocene formations elevated on the Hersek Delta (Alpar and Yaltırak 2002). In general, the main fault system observed on the seismic sections A–E (Fig. 4b) corresponds to the elevation point of the values in the magnetic profiles. The low magnetic anomalies cannot be easily correlated with the shallow post-Neogene sediments (1 s twt).

Discussion and conclusion

The geophysical studies carried out in the Gulf of İzmit are mainly based on shallow reflection and partly multibeam bathymetry. In spite of an agreement between the researchers that the northern strand of the NAF is the main fault zone in

the Gulf of İzmit, crossing the basins along the gulf as the dominant tectonic element and controlling the evaluation of the gulf and the secondary faults, a number of different ideas are put forward for its nature and timing of propagation (Fig. 1a).

This study provides a new perspective to assess the tectonic setting of the region and verify the suggested structural models and geologic evolution of the Gulf of İzmit. The spatial distribution of the magnetic lineaments are sub-parallel to the general geological trends and to main tectonic elements (Figs. 3b, c, 4a). The general orientation of the northern strand of the NAF can be clearly traced on both the magnetic grids and 2D magnetic models (Figs. 4 , 5). The most important correlation between the magnetic data and re-interpreted seismic sections is the correspondence of the main fault (NAFNS) as a single piece extending downwards, characterized with magnetic rises on the NS-trending profiles, where the magnetic values start to increase. Such a correlation indicates a significant thinning of the crust along the main fault (Fig. 5). The Istanbul Zone (Ordovician–Carboniferous) consists of un-metamorphosed and mostly continuous Palaeozoic sedimentary series, while the Karakaya Complex is characterised by highly deformed and partly metamorphosed clastic and volcanic series of Permian and Triassic age. The Intra-Pontide Ocean closed between these zones during the Paleocene as a weakness zone (Yaltırak 2002). In Plio-Quaternary, this zone (Late Triassic–Early Jurassic) must have been reactivated, and causing the crust getting thinner. Moreover, this argument can be supported by the magnetic values in the RTP grids, which are rising towards the Hersek Point.

Over time, a series of tectonic events occurred after the formation of the Intra-Pontide suture zone. In Eocene, a

post-collisional basin was opened on the Armutlu Peninsula over the basement of Karakaya Complex to the south of this basic tectonic line, and postcollisional magmatism developed (Genç and Yılmaz 1997). The axis of the gulf was formed by superimposed tectonic constructions up to the beginning of Miocene and the main tectonic elements have existed since that time. Therefore, the NAF is a fault system that follows an old main tectonic line between the Armutlu (Karakaya Complex) and Kocaeli Peninsulas (İstanbul Zone). Under these circumstances, the attitude and relationship between the main fault and border faults must have been continued for a long period of geological time.

The findings in this study indicate that the strand of the NAF along the Gulf of İzmit also overlaps with the narrow boundary zone between the northern and southern blocks at the deeper part (Figs. 3, 4 , 6). The negative flower structure, which can be outlined at the shallow parts of the seismic sections, also overlaps with the zone where the earth crust getting thinner. The relatively narrow negative gravity anomalies overlapping with our magnetic anomalies are more evident than the ones across the southern strand of the NAF along the Lake İznik (Figs. 3c , 4c).

The characteristic basin morphology and splaying tectonic setting with short fault segments (see Polonia et al. 2004) seem to be dominated on the magnetic grids of the western Hersek flat. The compressing bending geometry of the Armutlu Peninsula may be the reason of the westward rise of the magnetic basement. The magnetic basement, deeper in the east, is divided into two zones by a ridge in the west. Considering that the marine terraces on the Hersek Delta are oriented at the ridge direction, the uplift is still ongoing. Polonia et al. (2004) and Cormier et al. (2006) claimed that the northern strand of the NAF is rather young, depending on the Pleistocene raised coastal deposits characterized by locally abundant shells and associated nearshore deposits. Yaltırak et al. (2014), however, determined that the marine terraces observed on land have uplifted steadily for the last 230 ka. The marine terraces that are still rising on the Hersek Delta (Marmara Formation) are the evidence for the presence of a compressional regime in the western part of the Gulf (Alpar and Yaltırak 2002). The authors reported that the strike-slip system extending westward in the eastern Marmara Trough turned into a negative flower structure at the western Hersek flat, and they explained its relation with the Gulf of İzmit; the faults bounding the Armutlu Peninsula had a thrust component. The NAFNS splays westward, starting from the Hersek Delta, and the southern block is compressed (Yaltırak 2002). Figure 5 shows the relationship between the magnetic data and the general trends of the faults in a block model as revealed from the magnetic profiles and interpretation of the multi-channel seismic data. An evaluation of the bathymetric elements in the Gulf and the fault map together with the model will permit the tectonic

setting of the region to be understood much better. The NAF enters the sea at the easternmost end of the Gulf, cuts the Gölcük basin with a slight northward twist, and follows the centre of the Eastern Hersek basin and southern edge of the main trough before dissecting the apex of the Hersek Delta (Fig. 2). From this point on, the NAF continues to the Sea of Marmara from the centre of the WNW trending high-magnetic values (Fig. 4). Such a description seem to be related with the older geological structure of the zones on which the strike-slip faults occurred later.

In conclusion, the right-lateral main fault has releasing bend character and the basin develops with secondary faults oblique to the main fault. Some ridges and sub-basins have been formed where the main fault bends. The crustal thinning along the NAF must have been resulted under the tectonic setting of the northern strand of the NAF. In fact, the total slip of the NAF in the Eastern Marmara is about 58–59 km (Yaltırak, 2002). Based on the movement given by the GPS slip vectors, the development of such a total slip must have been completed in 3.5 million years. The transforming process of the shear zones to the strike slip, as proposed by Tchalenko (1970) for strike-slip fault zones, should have been taken a short time here because it depends on the inversion of an old fault system along the main axis of the Gulf. The model that describes the Gulf of İzmit best is the work handled by Ben-Avraham and Zoback (1992) on the Dead Sea Rift and El Pillar Fault. Ben-Avraham (1992) evaluated the tectonic troughs developed with normal faults parallel to the main fault under the transform parallel strike-slip basins (Fig. 6). The RTP grid seems to be the most suitable grid representing the tectonic setting of the Gulf of İzmit.

References

Alpar B (1999) Underwater signatures of the Kocaeli earthquake (August 17th 1999). Turk J Mar Sci 5(3):111–130

Alpar B, Yaltırak C (2002) Characteristic features of the North Anatolian Fault in the eastern Marmara region and its tectonic evolution. Mar Geol 190(1–2):329–350

Altınlı İE (1968) İzmit-Hereke-Kurucadağ alanının jeoloji incelemesi MTA Dergisi 71:10–16 (**in Turkish**)

Ateş A, Kayıran T, Sincer I (2003) Structural interpretation of the Marmara region, NW Turkey, from aeromagnetic, seismic and gravity data. Tectonophysics 367:41–99

Ateş A, Bilim F, Büyüksaraç A (2008) Bektas Ö (2008) A tectonic interpretation of the Marmara Sea, NW Turkey from geophysical data. Earth Planet Space 60:169–177

Barka AA, Kadinsky-Cade K (1988) Strike-slip fault geometry in Turkey and its influence on earthquake activity. Tectonics 7:663–684

Ben-Avraham Z (1992) Development of asymmetric basins along continental transform faults. Tectonophysics 215:209–220

Ben-Avraham Z, Zoback MD (1992) Transform-normal extension and asymmetric basins: an alternative to the pull-apart models. Geology 20:423–426

Briggs JC (1974) Machine contouring using minimum curvature. Geophysics 39:39–48

Canbay M, Aydın A, Kurtuluş C (2010) Magnetic susceptibility and heavy-metal contamination in topsoils along the Izmit Gulf coastal area and IZAYTAS (Turkey). J Appl Geophys 70:46–57

Cormier MH, Seeber L, McHugh CMG, Polonia A, Çağatay N, Emre Ö, Gasperini L, Görür N, Bortoluzzi G, Bonatti E, Ryan WBF, Newman KR (2006) North Anatolian Fault in the Gulf of Izmit (Turkey): rapid vertical motion in response to minor bends of a nonvertical continental transform. J Geophys Res—Solid Earth. https://doi.org/10.1029/2005JB003633

Doo WB, Hsu SK, Armada L (2015) New magnetic anomaly map of the East Asia with some preliminary tectonic interpretations. Terr Atmos Oceanic Sci 26:73–81

Emre Ö, Erkal T, Tchepalyga A, Kazancı N, Keçer M, Ünay E (1998) Neogene-quaternary evolution of the Eastern Marmara region, Northwest Turkey. Bull Min Res Explor Inst Turk 120:119–145

Ferré EC, Friedman SA, Martín-Hernández F, Feinberg JM, Till JL, Ionov DA, Conder JA (2014) Eight good reasons why the uppermost mantle could be magnetic. Tectonophysics 624:3–14

Gasperini L, Polonia A, Bortoluzzi G, Henry P, Le Pichon X, Tryon M, Çağatay N, Géli L (2011) How far did the surface rupture of the 1999 Izmit earthquake reach in Sea of Marmara? Tectonics 30:1–20. https://doi.org/10.1029/2010TC002726

Genç ŞC, Yılmaz Y (1997) An example of postcollisional magmatism in Northwestern Anatolia: the Kızderbent volcanic (Armutlu peninsula, Turkey). Turk J Earth Sci 6:33–42

Gholamrezaie E, Scheck-Wenderoth M, Bott J, Heidbach O, Strecker MR (2019) 3-D crustal density model of the Sea of Marmara. Solid Earth 10:785–807

Gökaşan E, Alpar B, Gazioğlu C, Yücel ZY, Tok B, Doğan E, Güneysu C (2001) Active tectonics of the Izmit Gulf (NE Marmara Sea): from high-resolution seismic and multi-beam bathymetry data. Mar Geol 175:273–296

Golynsky AV, Ivanov SV, Kazankov AJ, Jokat W, Masolov VN, von Frese RRB and the ADMAP Working Group (2013) New continental margin magnetic anomalies of East Antarctica. Tectonophysics 585:172184

Görür N, Çağatay N, Sakınç M, Sümengen M, Şentürk K, Yaltırak C, Tchaplyga A (1997) Origin of the Sea of Marmara as deduced from Neogene to quaternary paleogeographic evolution of its frame. Int Geol Rev 39:342–352

Guevara NO, Garcia A, Arnaiz M (2013) Magnetic anomalies in the Eastern Caribbean. Int J Earth Sci 102:591–604

Kurt H, Yücesoy E (2009) Submarine structures in the Gulf of İzmit, based on multichannel seismic reflection and multibeam bathymetry. Mar Geophys Res 30:73–84

Kuşçu İ, Okamura M, Matsuoka H, Awata Y (2002) Active faults in the Gulf of Izmit on the North Anatolian Fault, NW Turkey: a high resolution shallow seismic study. Mar Geol 190(1–2):421–443

Li CF, Cheng B, Zhou ZY (2009) Deep crustal structures of eastern China and adjacent seas revealed by magnetic data. Sci China, Ser D Earth Sci 52(7):984–993

Okay AI, Tüysüz O (1999) Tethyan sutures of northern Turkey. In: Durand B, Jolivet L, Horváth F, ve Séranne M(eds) The Mediterranean Basins: tertiary extension within the Alpine orogen. Geological Society, London, (Special Publication) Vol 156, pp 475– 515.

Öksüm E, Hisarlı ZM, Cengiz Çinku M, Ustaömer T, Orbay N (2015) New paleomagnetic results from ordovician sedimentary rocks from NW Anatolia: tectonic implications for the paleolatitudinal position of the Istanbul terrane. Tectonophysics 664:14–30

Polonia A, Gasperini L, Amorosi A, Bonattia E, Bortoluzzi G, Çağatay N, Capotondia L, Cormier M-H, Görür N, McHugh C, Seeberc L (2004) Holocene slip rate of the North Anatolian Fault beneath the Sea of Marmara. Earth Planet Sci Lett 227:411–426

Şengör AMC, Demirbağ E, Tüysüz O, Kurt H, Görür N, Kuşçu I (1999) A preliminary note on the structure of the Gulf of Izmit: implications for the westerly prolongation of the North Anatolian Fault. In: M Karaca, DN Ural (eds.) Proceedings of ITU-IAHS international conference on the Kocaeli Earthquake, 17 August 1999, Istanbul Technical University Press House, pp 25–37

Şengör AMC, Tüysüz O, İmren C, Sakınç M, Eyidoğan H, Görür G, Le Pichon X, Rangin C (2005) The North Anatolian Fault: a new look. Annu Rev Earth Planet Sci 33:37–112

Seymen İ (1995) İzmit Körfezi ve Çevresinin Jeolojisi, İzmit Körfezi Kuvaterner İstifi (Ed. E. Meriç) 1–22 (in Turkish).

Tchalenko JS (1970) Similarities between shear zones of different magnitudes. Bull Geol Soc Am 81:1625–1639

Thébault E, Finlay CC, Alken P, Beggan CD, Canet E, Chulliat A, Langlais B, Lesur V, Lowes FJ, Manoj C, Rother M, Schachtschneider R (2015) Evaluation of candidate geomagnetic field models for IGRF-12. Earth Planets Space 201567:79. https://doi.org/10.1186/s40623-015-0228-9

Türkecan A, Yurtsever A (2002) Geological map of istanbul sheet (1/500000). The General Directorate of Mineral Research and Exploration, Ankara, Turkey

Vardar D, Öztürk K, Yaltırak C, Alpar B, Tur H (2014) Late Pleistocene-Holocene evolution of the southern Marmara shelf and sub-basins: middle strand of the North Anatolian fault, southern Marmara Sea, Turkey. Mar Geophys Res 35:69–85

Yaltırak C (2002) Tectonic evolution of the Marmara Sea and its surroundings. Mar Geol 190(1–2):493–529

Yaltırak C, Alpar B (2002) Evolution of the middle strand of North Anatolian Fault and shallow seismic investigation of the southeastern Marmara Sea (Gemlik Bay). Mar Geol 190(1–2):307–327

Yaltırak C, İşler EB, Aksu AE, Hiscott RN (2012) Evolution of the Bababurnu Basin and shelf of the Biga Peninsula: Western extension of the middle strand of the North Anatolian Fault Zone, Northeast Aegean Sea, Turkey. J Asian Earth Sci 57:103–119

Yaltırak C, Aksu AE, Hiscott RN (2014) Late Pleistocene uplift history along the Eastern Marmara Sea (Northern Armutlu Peninsula) determined from raised coastal deposits and global sea-level variations, Implications of Late Quaternary Sea Level Changes on the Eastern Mediterranean and Black Sea Coasts, International Workshop in the framework of Turkish-German Science Year 2013–2014, Işık University, Şile, Istanbul, Turkey 31 August–6 September 2014