The active Main Marmara Fault

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Received 31 May 2001; accepted 16 July 2001

Abstract

This paper presents selections from and a synthesis of a high resolution bathymetric, sparker and deep-towed seismic reflection data set recently acquired by the French Ifremer R.V. Le Suroît in an E-W deep trough that forms the northern half of the Sea of Marmara in NW Turkey. It includes the first high resolution complete bathymetric map of this area. A single, throughgoing dextral strike-slip fault system, which is the western continuation of the northern branch of the North Anatolian Fault, cuts this trough lengthwise and joins the 1999.8.17 Kocaeli earthquake fault with the 1912.8.09 Şarköy–Mürefte earthquake fault, both of which display strike-slip offset. In its eastern one fourth, the structure follows closely the northern margin of the deep trough, whereas in the west it hugs its southern margin. The eastern one fourth of the structure has a minor component of its displacement distributed across the deep trough owing to a possible original bend in the course of the dextral structure. The present course of the North Anatolian Fault in the Sea of Marmara originated some 2×10^5 a ago, by cutting across the older basin fabric generated by a dominant NNE–SSW extension before it began taking up major motion in the Pliocene. © 2001 Published by Elsevier Science B.V.

Keywords: Sea of Marmara Region; active faults; seismic profiles; reflection; bathymetry

1. Introduction

Landforms related to strike-slip faults tend to be much less conspicuous, commonly discontinuous along the strike of the fault and usually shorter-lived than those forming along convergent or divergent plate boundaries. An evolving strike-slip shear zone generally creates a band of deformation, which narrows with time [1–3]. Genera-
tions of structures succeed and superimpose one another, being the expressions of contrasting local and transient strain regimes [3,4]. Segments of pure strike-slip often appear as straight faults of modest topographic expression. Associated secondary fracture and fault families are hard to recognise in the field and even harder to date. These are the main reasons why large strike-slip faults have been recognised much later than the products of convergent or divergent plate boundaries, despite the common occurrence of destructive earthquakes that characterise their seismic behaviour [3].

The North Anatolian Fault (NAF) in the Sea of Marmara is a relatively young (on the order of a few Ma) active strike-slip fault zone in the floor of a sea of moderate depth. Its tectonics were poorly known in spite of its high potential for producing large earthquakes. Historical records indicate the occurrence of major destructive earthquakes in the Sea of Marmara, affecting Turkey’s most populous and richest region with 80% of her industry and her largest city (population > 10 000 000) Istanbul [5–8].

Following the disastrous Mw 7.4 1999.8.17 Kocaeli earthquake [9], a major effort was coordinated by the Turkish Scientific and Technological Research Council (TÜBİTAK) to obtain a better estimation of the seismic potential of the Marmara fault system. This paper presents for the first time observations made during a cruise of French Ifremer R.V. Le Suroît, in September 2000, that obtained in particular the first high resolution (equivalent to a 1/50 000 scale topographic map on land) complete bathymetric map of this area (Fig. 1). This cruise was part of a French–Turkish bilateral cooperation programme coordinated by INSU and TÜBİTAK. It was cofinanced by the ECHO division of the European Community.

2. The Marmara problem

The northern strand of the NAF enters the Sea of Marmara at the head of the Gulf of İzmit [10,11] and exits it just south of Ganosdag near Mürrefte [10,12] (Fig. 1). The geometry and even the nature of the fault under the sea is still a matter of debate owing to paucity of observations.

The NAF began forming in the late medial Miocene ( ~11 Ma) [10,13], but it is unlikely that a major throughgoing principal strike-slip displacement zone could have been established prior to the Pliocene ( ~5 Ma) [14,15]. Its seismicity creates one or more major (M > 6.5) earthquakes per decade since 1939 [16]. The epicentres of these shocks display a regular westerly migration from the eastern end of the fault towards the Sea of Marmara [10,16,17]. These deformations are a response to the westerly escape of an Anatolian block [10,13,18–20] with a velocity of about 20 mm/a [21–24] with respect to Eurasia.

When Ketin [18] identified the NAF as a major dextral strike-slip fault zone, he did not continue it into the Sea of Marmara. Pinar [25] had earlier drawn a single fault, of unspecified nature, bisecting the Gulf of İzmit and the three Marmara deeps that had been mapped by the H.I.M.S. Selânik expedition in 1894 [26], after the destructive 1894 ‘Istanbul earthquake’ [6,8]. She called this fault the Main Marmara Fault and pointed out that the three deeps are located in a larger, E–W orientated trough delineated by the 200 m isobath: “The axis of this trough appears as an arc of great radius, going from Ganos to the entry of the Gulf of İzmit” [25].

Most later authors interpreted the trough [25] mentioned (hereinafter Marmara Trough) as a rift [18–20,27], whose bounding faults were thought to coincide with its morphological margins.

Fig. 1. Bathymetric map of the Marmara Trough with the main active structures. Main active faults are shown by thick black lines. The width of the lines refer to the relative importance of the faults. Please refer to the legend in the figure for other features. Also shown in an inset are the GPS motion arrows with their ellipses of error (from the data in [24]) with respect to an internally undeformed ‘Central Marmara Block’ to the south of the Marmara Trough. Note how the 20 mm/yr vectors to the north are parallel to the trace of the PDZ as discovered by our survey.
Fig. 2. Bottom reflectivity map of the eastern Ganos Basin. The double tracks are ship tracks. The numbered fault-plane solutions of strong (4-4.4) aftershocks of the Kocaeli earthquake (see Fig. 1) are shown in a magnification. Solution BK is from a magnitude 4, 24 March 2001 earthquake after S. Özalaybey (personal communication, 2001). Fault-plane solutions are shown as lower-hemisphere stereographic projections; compressional quadrants are black, dilatational quadrants white. Insets show details of image.
Most subsequent interpreters of the existing coarse bathymetric data and the single-channel seismic reflection profiles followed this view and depicted the Marmara Trough as a rift basin with oblique extension [12,28–30]. By contrast, Şengör and Dewey, and Şengör assumed generally E–W orientated strike–slip along the Sea of Marmara and ascribed the NE earthquake slip vector trends to secondary extension along an E–W shear zone [10,13,31].

The 1999.8.17 Kocaeli earthquake was the last in the series of westerly migrating major shocks along the NAF [9] leaving the segment in the Marmara Sea as the only portion of the western NAF that has not been broken during the 20th century. Interpreting the historical record as indicating at least two events with magnitudes significantly larger than 7 (1509.9.10 and 1766.5.16: see [7]), Le Pichon et al. [32] argued that a fault longer than 100 km was necessary to generate them. Taking the GPS observations as indicating strike–slip displacement along such a fault, they drew a single, throughgoing, strike–slip fault along an arc nearly coincident with the fault drawn by Pinar [25]. Le Pichon et al. [32] argued that this fault was probably a very young structure, cutting across the older structures that formed the present morphology of the Sea of Marmara in an attempt by the NAF to ‘clean’ its course, similar to the evolution observed in its more easterly segments [13,14].

This paper presents the results of investigations made in an attempt to locate the structures that might localise the next major earthquake in the Sea of Marmara. These were obtained during the R.V. Le Suroît Marmara cruise, a comprehensive high resolution bathymetric, sparker and deep-towed seismic reflection survey of the Marmara Trough. The first complete multibeam (EM300) map of the Marmara Trough with a 25 m gridding is shown in Fig. 1. Reflectivity maps were simultaneously realised (Fig. 2). Approximately 1850 km of sparker profiles (Fig. 3) and 700 km of higher resolution deep-towed seismic reflection (PASISAR data, Fig. 4) were recorded, together with side-lateral sonar images. In addition, we were able to use the R.V. Sismik-1 multichannel data obtained earlier by TÜBİTAK and the Mineral Research and Exploration Directorate of Turkey (MTA) that have a greater penetration but a lower resolution [33]. The analysis of this complex data set has led to the active faults map in Fig. 1. For more details, the reader is referred to the atlas that will be published shortly by Ifremer and that will include the complete cartographic set as well as extracts of geophysical data [34].

3. Active structures of the Marmara Trough

This paper deals only with the active structures within the Marmara Trough, the target of the R.V. Le Suroît survey and the site of the largest amount of active slip in the Sea of Marmara ([32] and inset of Fig. 1). We present our observations from east to west, beginning with the Çınarcık Basin.

3.1. The Çınarcık Basin

The principal displacement zone (PDZ) of the NAF enters the Sea of Marmara as a single main dextral fault strand [11]. It seems to continue along the northern escarpment of the Çınarcık Basin, but the precise manner of the junction is conjectural owing to a major landslide burying the fault trace (Fig. 2). Farther west than the landslide, a series of short, en échelon fault segments forming small escarpments are generally connected with one another by longer, less conspicuous, straight fault segments (Fig. 2, inset B).

Örgülü and Aktar [35] and Özaylabey et al. [36] obtained reliable right-lateral fault–plane solutions on well-localised strong aftershocks of the Kocaeli earthquake (see Fig. 2, solutions 2, 5 and 28 after [35]). These corroborate the inference from the map pattern that the young scarps seen at the foot of the northern escarpment of the Çınarcık Basin (Fig. 2, inset B) are surface expressions of active right-lateral faults. These faults hug the foot of the northern escarpment continuously and turn into an E–W orientation at the NW corner of the Çınarcık Basin, where the structural picture becomes complicated (Fig. 1).

A peculiar feature of the active northern
boundary fault of the Çınarçık Basin east of 29°E is the presence of a narrow sedimentary furrow formed from a V-shaped sagging of the sedimentary layers that appear to consist of turbidites (Fig. 3). The sagging is very recent as it only affects the upper 40 m. The fault generally occupies the bottom of the V and gives the impression of a negative flower structure nested atop the active fault strand. Still more peculiar is the near coincidence of this feature in E–W extent with the field of normal faults to be described in the next paragraph. East of 29°00′E we no longer see it.

The southern margin of the Çınarçık Basin is more irregular and less steep. An about 10 km wide field of closely spaced, NW striking and very gently NE-concave faults with a significant normal component characterises this margin between 29°09′E and 28°57′E (hereinafter Çınarçık extensional field, Fig. 2, inset A). Fig. 4 is a deep towed PASISAR profile that illustrates the nature of the extension, tilted blocks on the margin (extract A) and normal faults in the basin (extract B). The longitudinal extent of this extensional field coincides with the longitudinal extension of the normal faulting earthquake cluster to the west of Yalova (solutions 14, 15, 16 and 22 in Fig. 2; see also [35]). Thus the earthquake cluster appears to be the direct southern prolongation of the Çınarçık extensional field (see Özálaybey et al. [36] for exact location of this cluster). This extensional field is located at the western extremity of an E–W dextral fault segment, coming out of the İzmit Gulf, that was activated during the after-shock sequence of the Kocaeli earthquake (see Özálaybey et al. [36]). One dominantly dextral fault–plane solution with minor extension (no 24 in Fig. 2) obtained by [35] marks the transition from pure strike-slip to extension.

West of this extensional field, the fault strikes turn S-concave and they gradually pass into a field of thrust faults and intervening folds (Fig. 1; hereinafter the Yeşilköy field of shortening). Thrust faults and folds in fact occupy nearly the whole of the west margin of the Çınarçık Basin.

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**Fig. 3.** Single-channel sparker section of a N–S profile across the Çınarçık Basin. Note the deep sedimentary furrow along its northern margin and the area of normal faulting to the south (the Çınarçık extensional field). The vertical exaggeration is about 20. The vertical scale in two-way travel time. 100 ms is about 80 m by considering an average velocity of the water column and uppermost sediments.
Fig. 4. Deep-towed PASISAR section along line s11-s12 within the Cinarcik extensional field. The streamer is towed 75 m above the sea-floor and the surface sound source is a sparker. The geometrical correction has been made to restore the proper geometry. The vertical exaggeration is about 20 for the section and 10 for the insets. The vertical scale is in m. Extract A shows tilted blocks on the margin, extract B normal faults in the basin.
and form its boundary against the Central High (Fig. 1; also see below). That they are thrusts are illustrated in Fig. 5. This NE-SW PASISAR profile shows a broad 80°E fold to the south, then a series of parallel thrusts in the central portion (extract A in Fig. 5). Their strikes and trends fan northward into near N-S orientations as seen in Fig. 1. In fact, three prominent N-S trending spurs in the bathymetry of the NW corner of the Çınarcık Basin are interpreted as complex box-folds bounded in part by steep thrust faults (see the broad fold in the northern portion of Fig. 5). These peculiar features were totally unknown and unsuspected before. They give, together with the narrow furrow in the north and the field of NE-concave normal faults in the south, precious clues for the interpretation of the complicated tectonics of the eastern part of the Sea of Marmara as we shall see below.

3.2. Central High

The Çınarcık Basin is delimited in the west by a broad high with complex bathymetry and structure. Although this portion of the Main Marmara Fault is the one least expressed in the seismic reflection data, the PDZ seems to continue as a single strand to an ENE trending elongate basin, called the Kumburgaz Basin by [37], which designation we adopt. The NE half of this basin is delimited by sinuous thrust faults that converge eastwards to the PDZ. South of the thrust front along the southern margin of the basin is a family of NW striking, gently SW-concave normal fault traces. We have assumed that these faults extend eastward to shorter ones observed on a sparker line just north of the meandering deep canyon emptying into the Çınarcık Basin (Fig. 1). Between the Kumburgaz Basin and the Central Basin, the PDZ appears essentially as a single strand with ENE striking short splays (Fig. 1).

3.3. Central Basin

A band of steeply dipping thrust and oblique-throw compressional faults connect the PDZ of the western part of the Central High with a fat spindle-shaped fault zone in the middle part of the Central Basin (Figs. 1 and 6). The bathymetry combined with the reflectivity and seismic reflection data outline a pattern of NW striking left-lateral to oblique-extensional fault set delimited to the N and S by short, *en échelon* segments of oblique-extensional faults outlining the spindle-shape. Fig. 7 shows a deep towed PASISAR profile that follows the northern scarp and crosses the NW-SE trending faults. It suggests that these structures are not created by pure extension (notice in particular the broad gentle folding) and that a significant component of strike-slip is present. This spindle-shaped structure joins the PDZ at both ends, which shows neither a right nor a left step (in the sense of Rodgers [38]) as it crosses the structure (Fig. 6, inset) and thus the structure must have neither net extension nor net compression across it now. In fact, this spindle-shaped structure greatly resembles the rotational fault sets seen along other strike-slip faults of diverse scales. A similar structure (but on a left-lateral fault) that formed just to the SW of the town of Dasht-e Bayaz along an 80 km long fault zone in Iran was described by [39].

The PDZ at the western end of the spindle-shaped structure changes again into a single strand fault zone along which the western margin of the Central Basin appears dextrally offset for 4 ± 1 km. The margins of the Central Basin are morphologically sharp, the northern margin more so than the southern. The *en échelon* scarps in the central part of the northern margin and the fairly straight NW striking scarp in front of the SW margin may be active. However, they are not independent throughgoing strands of the PDZ and that is why we do not think that they now accommodate significant displacement. This appears to be confirmed by the fact that we see no clear evidence for active faults there on the PASISAR data. The thrusts placed along the NW margin by [33] look on our bathymetric map (Fig. 5) rather too dissected by gullies, whose lowermost courses seem invaded by the basin-floor sediments, to be now active.

3.4. Western High

The Western High is much narrower than the
Fig. 5. Top: single-channel marker profile across the Ysylkoy field of shortening with same characteristics as in Fig. 3. Bottom, PASISAR profile along part a of the same profile with same characteristics as in Fig. 4. The PASISAR demonstrates the presence of active thrusts.
Eastern High, has a similar general NE trend and is deeply dissected by one E–W trending straight furrow that now houses the PDZ. North of the PDZ, the bathymetric fabric is defined by generally E–W trending highs and intervening depressions that may be expressions of formerly active fault strands in the eastern part of the High, whereas a generally NE trending fabric dominates the western part. In fact, here İmren et al. [33] identified five major NE striking thrust faults of inconsistent vergence. No fresh scarps are associated with any of those and we think they are now inactive.

3.5. Tekirdağ Basin

The spindle-shaped Tekirdağ Basin [33,37,40] is the westernmost of the three major deeps of the Sea of Marmara. It immediately adjoins the 945 m high Mt. Ganos (İşkûr Dağları) to the west, the most prominent and isolated topographic high of eastern Thrace south of the Strandja Mountains (Yıldız Dağları).

The PDZ defines the southern margin of the Tekirdağ Basin in the form of a near-continuous string of low and fresh scarp segments as seen on Fig. 8 (including its insets A and B). At the SW extremity of the Basin, the PDZ takes a W–SW bend (see Fig. 8, inset A) and joins the Ganos Fault on land [40]. The major escarpment, rising abruptly from the floor of the Ganos Deep to delimit Mt. Ganos to its SE, seems only in part controlled by an active fault, which veers into an ENE strike towards the interior of the Basin just SE of Kumbağ. North of where the scarp bounding fault leaves the scarp, the bathymetric expression of the latter continues but changes character. Significantly, the abrupt topography of Mt. Ganos stops exactly where the active fault segment veers into the Basin just SE of Kumbağ. North of where the scarps oblique to the PDZ interrupt or accompany the main strand.

4. The character of the Main Marmara Fault today

In this section, we discuss the characteristics of the Main Marmara Fault in two unequal parts in the framework of a synthesis and interpretation of the data presented above plus other relevant information from the literature. We first deal with the relatively simpler western three-fourth (‘the single strand dominant sector’) and then discuss the more complex tectonics of the Çınarcık Basin.

4.1. The single strand dominant sector

Between 28°48′E and 27°24′E the PDZ of the Main Marmara Fault exhibits all the typical characteristics of a major, active, throughgoing strike-slip fault (cf. [1–4]). Its main trace is straight and strikes N83°E. Only within and to the south of the Kumburgaz Basin and in the Central Basin crowded families of structural elements oblique to the PDZ interrupt or accompany the main strand.

In the eastern half of the Kumburgaz Basin, the bounding ENE elements probably formed as P-shears [1]. They now create relief and most likely accommodate oblique shortening as judged from their strikes parallelling trends of nearby fold axial traces (Fig. 1). These partly compressional features are connected with the PDZ to their NW by a family of closely spaced faults, whose strikes are compatible with their being normal faults in a tension-gash orientation (cf. [4,41]).

Between the Kumburgaz Basin and the Central Basin, the PDZ is joined from the south by N60°E faults that we interpret as P-shears. Be-
Fig. 6. Colour-coded bathymetric map of the Central Basin with an interpretation of the fault pattern. Note in the inset that there is no offset between the main fault portions on both sides of the basin as shown by the dashed line that joins them.
between the last P-shear and the dominant ENE striking faults of the eastern margin of the Central Basin, the PDZ swings into a Riedel (R-shear: [1]) orientation (N80°W). This Riedel segment then joins the ENE striking structures east of the Central Basin. Both their gently sinuous traces and their orientation close to that of a P-shear suggest that they accommodate oblique shortening. Two such major faults define a 22 km long strip.

The 20 km long and 10 km wide spindle-shaped structure in the middle of the Central Basin houses a family of closely spaced, NW striking, straight faults that turn in the S and in the N into ESE striking en échelon faults with significant vertical separation on some of them. From this relationship we infer that the NW striking faults are anti-Riedels (R'-shears: [1]) with left-lateral offset. Because no right or left step of the PDZ is observed across the spindle-shaped structure, we infer that it represents a gently negative flower structure rotating in a clockwise direction that formed on the PDZ and does not interrupt its continuity at depth. It probably will not stop an earthquake rupture, as its suggested homologue in the Dasht-e Bayaz earthquake [39] did not either (The Almacik Flake to the E of the Sea of Mar-

Fig. 7. PASISAR profile along the northern innermost scarp of the Central Basin. Same characteristics as in Figs. 4 and 5 bottom. The en échelon NW–SE faults that cut the sedimentary column are accompanied by some short wavelength and intermediate wavelength folding.
mara, another homologue, did, but it is nearly three times as large as the Central Basin structure [13]). The spindle-shaped flower structure of the Central Basin is connected with the Tekirdağ Basin by a throughgoing main strike-slip strand. The fault defining the southern margin of the Tekirdağ Basin looks as if it consists of a series of linked P- and R-shears.

The PDZ between 28°48’E and 27°24’E has all the hallmarks of a developing throughgoing strike-slip fault zone at what Tchalenko [1] termed the ‘post-peak structure’ stage, at which P-shears form and interconnect pairs of R-shears. As illustrated by Wilson ([41], Fig. 3) the R-shears commonly also connect with extensional structures forming an interconnected, almost ‘braided’ structure. This ‘post-peak structure’ is best developed within the Basins (including the Kumburgaz Basin) along the PDZ of the Main Marmara Fault west of 28°48’E, whereas the Highs are cut by much simpler single or at most double strand throughgoing faults resembling what Tchalenko called ‘pre-residual structure’ [1]. In any case, these structural patterns imply that the PDZ has not yet reached its stable ‘residual structure’ stage yet.

The dominance of the ‘post-peak’ and ‘pre-residual structural’ patterns is in part related to the syn-sedimentary nature of these structures. How-

Fig. 8. Bottom reflectivity map of the Tekirdağ Basin. Insets show details of structures. Compare this with Fig. 1 and note that the Mt. Ganos prominence disappears as soon as the fault bounding its eastern scarp leaves the scarp west of Kumbağ and turns into the basin. This is a strong argument for the present inactivity of the scarp farther north.
ever, they suggest that the formation of this structure is very recent and a very young age is further corroborated by the $4 \pm 1$ km dextral offset along the PDZ of the western margin of the central Deep (Figs. 1 and 5). If the PDZ is now accommodating $\sim 20$ mm displacement per annum, the 4 km offset gives a maximum age of about $2 \times 10^5$ a for the present PDZ. The Kumburgaz Basin, a part of the PDZ of the Main Marmara Fault, was receiving the turbidites disgorged from the Büyükçekmece canyon (Fig. 1), whose age is no older than the Pleistocene (cf. [42], especially figure 10). It is important to note that Çağatay et al. [43] have shown that an important change in tectonic style occurred in the Gulf of Saros 200 000 a ago. This change might be related to the emplacement of the throughgoing Marmara fault in the whole Marmara area.

4.2. The Çınarçık Basin sector

This is the structurally most complex part of the Main Marmara Fault. Our observations corroborated only the existence of an active fault along the northern scarp from among the previous interpretations (e.g. [28,29,37]). All other structures we encountered and mapped were previously unknown and mostly unsuspected. Only Wong et al. [29] mapped a set of N-dipping normal faults near the middle of the Basin south of Istanbul, and Okay et al. (see figure 3 in [37]) showed that the Central High is occupied on its eastern flank by a large fold that is probably inactive today [33].

The observation we find critical is that the eastern half of the basin is characterised by transtension and the western margin of the basin by strong transpression. The Yeşilköy field of shortening is the axis of this triangular zone produced by the two sharp bends of the PDZ, first to the right as it comes out of the Gulf of İzmit then to the left as it turns back to 265°E (Fig. 1). One should expect a large component of extension along the N–W trending portion of the PDZ. Yet the four well-constrained fault–plane solutions along or near it (Fig. 2, no 2, 5, 28 and BK) are nearly pure strike-slip. It seems that this complex area allows the PDZ to be nearly pure dextral strike-slip along its whole length in spite of the two steep bends. This implies the existence of partitioning of motion within the eastern part of the Çınarçık Basin as proposed independently on seismological ground by [36].

This partitioning implies a northward component of motion of the eastern Çınarçık Basin with respect to the Marmara block to the south that results in the formation of the Çınarçık extensional field and its southern prolongation on the Armutlu peninsula west of Yalova. The northward component of motion is absorbed to the west in the Yeşilköy field of shortening that acts as a left-lateral shear band. With such a scheme, simple kinematic considerations show that the strike-slip motion on the northern Çınarçık slope is close to the full North Anatolian 20 mm/yr velocity. The extension absorbed in the Çınarçık field should be about 8 mm/yr to the NW and the left-lateral strike-slip in the Yeşilköy compressional shear band about 5 mm/yr.

5. The relationship of the Main Marmara Fault to other structures in the Sea of Marmara

It is clear that neither the Marmara Trough nor the basins it houses can be results of the activity of the present Main Marmara Fault. The present motion of the latter is nowhere suitable to create the structures it cuts across (Fig. 1). Its extreme youth ($\sim 2 \times 10^5$ a) stands in stark contrast to the much greater antiquity of the Marmara basins [13,42,44] and indicates that a significantly different mechanism must have formed the latter, before they were cut by the Main Marmara Fault about $2 \times 10^5$ a ago.

There are also other active faults in the Sea of Marmara, mostly of normal type especially in the southern shelf area [45,46], whose relations to the Main Marmara Fault needs clarification.

5.1. Relationship to older structures

It is unclear how the older, now largely inactive structures of the Sea of Marmara originated. Gökür et al. [44] have shown that a lacustrine basin, with continental shoreline facies all around, occu-
The present Marmara Trough. In the later medial Miocene and earlier late Miocene (late Asta-
aranacian to Vallesian), a marine tongue trans-
gressed over the fluvio-lacustrine substratum
along the northern coastal areas of the present
Sea of Marmara. This marine tongue extended
from the Aegean Sea via the Saros rift trough
[13,42,44]. During this time the rest of the Sea
of Marmara, including its present wide shelf re-
gion in the south (Fig. 1), was mostly land.

In the later late Miocene, the connection with
the Mediterranean was broken and the brackish
waters of the Paratethys invaded the present Mar-
mara Trough area with a broad littoral zone of
continental sedimentation to the south. Much of
the wide southern shelf still remained land. The
late Pliocene witnessed the mixing of the Mediter-
anean and Paratethyan waters in the future Sea
of Marmara. This mixed water invaded the nor-
eastern fringe of the southern shelf, which, until then,
had remained dry [44]. In the medial and late
Pleistocene, the shorelines of the Sea of Marmara
acquired nearly their present outline [42,44].

What is important in the history summarised
above is the *progressive enlargement* of the Mar-
mara Basin as a whole since the medial Miocene.
Late medial Miocene was also the time when the
initial motion along the broad shear zone that
was to become the NAF and the onset of the
Aegean rift system in western Turkey took place
[13,47,48]. It thus seems that the Marmara
Trough originated at the same time and most
likely in response to the same events. What makes
it problematic is that it is a part both of the strain
regime of the NAF *and* the western Anatolia N–S
extensional regime. Since the NAF did not begin
to accommodate major dextral strike-slip until
the beginning of the Pliocene, it is likely that the
western Anatolia N–S extension was the domi-
nant influence on the future Sea of Marmara
area during the late Miocene. If, however, even
a minor component of right-lateral shear is im-
posed on the N–S extension, then a NNE–SSW
extension direction would be obtained.

Two main observations make an extensional
origin of the Marmara Trough, indeed the whole
of the Sea of Marmara likely. (1) Its floor became
progressively deeper while its basinal area became
progressively larger throughout its history. (2)
The three Marmara Basins have sediment thick-
nesses of at least 1000–1500 m [33]. The strati-
ographic history of the Marmara area shows that
the extension probably started in the medial Mio-
cene. We propose that this extension created the
Marmara Trough and its Basins as cross-basins in
a NNE–SSW extensional system.

A thin tongue of marine ingestion from the
Gulf of Saros into the Sea of Marmara in the
late Pliocene (see Fig. 8, [44]) followed the course
of the present Ganos Fault. We take this as in-
dicating the establishment of the NAF in the Sea
of Marmara. It is likely that this initial fault zone
was broader than the present throughgoing PDZ
and it may have employed the border faults of the
original Marmara Trough. In this case any origi-
nal NNE–SSW trending cross-features would be
thrown into compression and rotate further into
NE–SW direction. The NNE to NE striking thrust and fold structures mapped by [33] and
[37] corroborate this inference. The present PDZ
probably formed to avoid these compressional
features and to generate a cleaner course as do
most strike-slip faults in the world [1–4].

The difference between the Çınarcık Basin and
the rest of the present PDZ is probably a refection
of an original bend in the course of the
throughgoing fracture that may have been deter-
mined by the underlying complex, suture-domi-
nated basement structure.

5.2. Relationship to active structures

The main Marmara Fault is not the only active
structure now moving within the Sea of Marmara
although it takes up by far the largest part of the
active displacement. Other, mainly extensional
structures with dominant E–W and WNW strikes
populate the southern shelf and create such promin-
ent rotated fault blocks as the Kapidag Penin-
sula and the islands of Marmara and Imrali
[45,46]. This is a form of strain partitioning where
the Main Marmara Fault accommodates the main
dextral strike-slip component, while the south
Marmara structures take up the modest N–S to
NE–SW extension.
6. Conclusions

A single throughgoing strike-slip fault system nearly bisects the Marmara Trough and connects the 1999.8.17 Kocaeli earthquake fault with the 1912.8.9 Şarköy–Mürefte earthquake fault. In the eastern one fourth of the Marmara Trough, the PDZ follows closely the northern margin of the basin, whereas in the Tekirdağ basin it hugs its southern margin. The eastern one fourth of the PDZ has a minor component of its displacement distributed across the Çınarcık Basin and the adjacent Central High that are related to the two successive sharp bends of the dextral PDZ. The PDZ of the Main Marmara Fault originated some $2 \times 10^5$ a ago, by cutting across the older basin fabric generated by a dominant NNE–SSW extension before the NAF began taking up major motion in the Pliocene. The present N–S to NNE–SSW active extensional structures probably indicate strain partitioning in the Sea of Marmara area. The evolution of the Main Marmara Fault closely resembles other strike-slip fault zones studied on land, but offers more detailed insight into its architecture and history owing to its ongoing activity and the facilities of seismic reflection profiling.

Acknowledgements

We thank Philippe Le Pape, the Captain and Hervé Tallec, the Chief engineer of the R.V. Le Suroît for their attention and effort during the cruise. André Le Bot was of great help for the onboard bathymetric data processing. Hervé Nouzé helped with the PASISAR data processing. We also thank Genavir on board technical staff, particularly Pascal Pelleau. We thank Nicolas Chamot-Rooke for GPS data processing and David Tsang Hin Sun for his computer support. We thank Namik Kemal Pak, the president of TÜBİTAK and Gürsün Sağlamner, the Rector of the ITÜ for their support of this study. General Ergin Celasin, the Commander of the Turkish Air Force, is thanked for securing permission to operate in restricted waters in the Sea of Marmara. We thank Captain Nazım Çubukçu, the Commander, and the officials of the Department of Navigation, Hydrography and Oceanography of the Turkish Navy for their collaboration. We also thank the Mineral Research and Exploration Directorate of Turkey (MTA) for their support.

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