Tectonics
February 2011, Volume 30, 11 Pages
http://dx.doi.org/10.1029/2010TC002726

How far did the surface rupture of the 1999 İzmit earthquake reach in Sea of Marmara?

Luca Gasperini[a, *], Alina Polonia[a], Giovanni Bortoluzzi[a], Pierre Henry[b], Xavier Le Pichon[b], Michael Tryon[c], Namik Çağatay[d], Louis Géli[e]

[a]ISMAR, CNR, Bologna, Italy
[b]CEREGE, Aix-en-Provence, France
[c]Scripps Institution of Oceanography, La Jolla, California, USA
[d]EMCOL, Faculty of Mining, ITU, Istanbul, Turkey
[e]Ifremer, Plouzané, France

*: Corresponding author : Luca Gasperini, email address : luca.gasperini@ismar.cnr.it

Abstract:

An open problem concerning the Mw 7.4, 1999 İzmit earthquake along the North Anatolian Fault (NAF) system is the apparent conflict between estimates of strike-slip deformation based on field and remote sensing data. This is due to the fact that the main strand of the NAF west of the epicenter lies below the Sea of Marmara. Seismological evidence and models based on synthetic aperture radar interferometry suggest that coseismic and early postseismic displacement accumulated after the earthquake could have reached the western end of the İzmit Gulf and possibly the southern edge of the Çınarcık Basin, tapering off along the northern coast of the Armutlu Peninsula, more than 60 km from the epicenter. This scenario is not confirmed by onshore field observations that point toward a termination of the surface rupture around 30 km to the east. These discrepancies convey high uncertainties in the estimate of the tectonic load produced by the İzmit earthquake on the adjacent fault segment toward Istanbul. We analyzed data from different sources, including high-resolution marine geophysical surveys and two Nautile dives along the fault-controlled canyon that connects İzmit Çınarcık basins. Our observations suggest that the surface rupture of the 1999 İzmit earthquake propagated through the shallow Gulf but did not reach the deep Marmara basins. In fact, along the slope between Çınarcık and the western end of the İzmit Gulf, we do not observe fault-related ruptures affecting the seafloor but rather a series of active gas seeps and “black patches” that mark the presence of known active faults. Our findings have implications for seismic risk assessment in the highly populated region of Istanbul, both for the estimate of tectonic load transferred to the next fault segments and the location of the next earthquake.

1. Introduction

The first benchmark for the new discipline of submarine earthquake geology, which aims to reconstruct the earthquake records in the submarine environment, is testing its ability to unequivocally document the effects of the most recent events at the seafloor. These effects vary significantly depending on earthquake magnitude and distance from the inferred epicenter, and can be classified into two broad categories: 1) direct, such as ruptures and fractures along given fault strands, which can form scarps or other morphological features at the seafloor; or 2) indirect, such as mass wasting and associated turbidites induced by the earthquake shaking whose effects could be eventually preserved in the sedimentary sequence. The 1999 Mw 7.4 İzmit earthquake, on the North-Anatolian Fault (NAF), which hit northwestern Turkey causing over 20,000 casualties and heavy damage, has been, in that sense, an important case history (Figure 1). While the maximum right-lateral slip was measured close to the epicenter, fault-related ruptures also propagated westward, in the Gulf of İzmit, a shallow embayment of the Sea of Marmara consisting of three interconnected basins, from W to E, the Darıca, Karamürsel, and Gölcük (Figure 2).

Soon after the earthquake, an international team mapped coseismic deformation close to the epicenter (Barka et al. 2002; Hartleb et al. 2002; Langridge et al. 2002; Rockwell et al. 2002), but the total length of the rupture remained undetermined because its western extension was under the water in the İzmit Gulf. Several studies using various data sets (near-field strong motion records, far-field body waves, GPS measurements, and SAR interferometry) have also attempted to characterize the coseismic slip distribution, with differing results (Bouchon et al. 2000; Reilinger et al. 2000; Yagi and Kikuchi 2000; Tibi et al. 2001; Wright et al. 2001; Bürgmann et al. 2002; Delouis et al. 2002; Feigl et al. 2002). These data, and the analyses of the aftershock distribution during several weeks after the event, were used to suggest that strike-slip deformations related to the main shock extended over the entire İzmit Gulf and entered well into the Sea of Marmara, up to 29.1° E longitude (Gülen et al., 2002). In a recent work based on the relocation of the aftershock activity, (Bulut and Aktar, 2007), it has been suggested that a distinct Tuzla/Çınarcık cluster might have been triggered by the 1999 İzmit main shock. This could imply that the effect of the 1999 earthquake affected the entire İzmit Gulf reaching more than 50 km west of the epicenter; however, it does not mean that the earthquake also ruptured part of the Princess Island/Çınarcık Basin segment (Figure 1).

Due to the nature of these data and to the fact that the fault trace lays below the İzmit Gulf waters, it was not possible at that stage to decide whether coseismic and early post-seismic strain could have been accommodated by surface ruptures or diffuse deformation. Field-geology observation carried out on land suggested that surface rupture due to the 1999 event ended east of the Hersek Peninsula, in the middle of the İzmit Gulf (Figure 2). In fact, no evident surface break was observed across the Hersek Peninsula, but only some minor cracks near its tip, where the long-term morphology indicates the passage of a large strike-slip fault (Çakır et al., 2002).

GPS-based models of coseismic and post-seismic deformation supported this second scenario, suggesting an abrupt drop in coseismic slip close to the Hersek Peninsula (Reilinger et al, 2000). However, this model is based on two arbitrary assumptions: 1) a fault segmentation based on the morphology of the İzmit Gulf shorelines; and 2) the presence of an extensional right-step of the NAF in correspondence to the Hersek Peninsula.

Although surface rupture and total deformation after a large earthquake could be different along a given fault strand due to several factors including diffuse deformation and subsurface displacements, determining the extent of surface rupture is important to infer tectonic load and possibly predict future behavior of seismogenic faults. For this reason, we attempted to estimate the extent of the surface rupture of the 1999 İzmit earthquake using geophysical data collected during several marine-geological expeditions in the Sea of Marmara, as well as direct observations carried out during two Nautile submersible dives in 2007.

2. Methods

Data used in this work come from different sources. The shelves and adjacent slopes of the northeastern Sea of Marmara, including the Gulf of İzmit, were mapped using high-resolution multibeam echosounders during three cruises with the R/V Odin Finder in October 2000 (MARMARA2000) and R/V Urania in 2001, 2005, and 2009 (MARMARA2001, 2005 and 2009). During those cruises we also collected close-spaced grids of high-resolution seismic reflection profiles, side-scan sonar mosaics, and images collected using ROV (Remote Operating Vehicle)-mounted video cameras, along the submerged trace of the NAF (material and methods are described elsewhere, see Polonia et al., 2002; 2004; Gasperini et al., 2009).

Two dives were also carried out using the submersible Nautile for direct observation of the seafloor during the MARNAUT cruise (Henry et al., 2007). A direct observation carried out using a video camera on board a deep-towed vehicle (the Medusa system) was performed during the MARMARA2009 cruise (Gasperini et al., 2009).

3. The North Anatolian Fault in the İzmit Gulf

The E-W aligned strike-slip deformation pattern that characterizes the NAF system can be followed on land for about 1200 km from the Karliova triple junction in east Turkey to the Marmara Sea by analyzing aerial and satellite images, as well as by using digital terrain models, that highlight the presence of a relatively narrow principal displacement zone (Sengor et al., 1985). However, the northern branch of the NAF, that accommodates over 80% of the Anatolia-Eurasia relative motion (Armijo et al., 2002; Meade et al., 2002), disappears below the Sea of Marmara just west of the 1999 İzmit epicenter, and cannot be traced using field and remote sensing observations. Prior to the 1999 earthquakes of Düzce and İzmit, marine geological data in the Sea of Marmara and in the Gulf of İzmit were scarce. Geophysical data, including high-resolution bathymetric maps and seismic reflection profiles, have since been extensively collected in the İzmit Gulf and in the deep Marmara basins as a consequence of the international effort that followed the disasters. The morphobathymetric map of the İzmit Gulf compiled with high-resolution mutibeam echosounder data (Polonia et al., 2004; Cormier et al., 2006) is among those results. It shows a complex pattern of releasing and restraining bends along the submerged trace of the NAF that causes the subsidence of three main basins separated by sills (Figure 2). While the easternmost Gölcük Basin is a shallow embayment with maximum depths < 30 m, the Darıca and Karamürsel depressions accommodate significant extension. These two basins, however, show different morphologies. Karamürsel is a rhomb-shaped depression reaching a maximum depth of about 200 m at its center. The reason why transtensional fault scarps bounding the basin shelves are exposed is that its depocenters subside at a rate faster than the sediment supply (about 1 mm per year during the Holocene, c.f. Polonia et al., 2004), and this causes formation of a rough topography characterized by two central depressions separated by a ridge. The transtensional fault scarps show apparent vertical displacements of several tens of meters, too large to result from a single event. As a consequence, high resolution multibeam images do not allow us to constrain the surface rupture of the 1999 event. However, Cormier et al. (2006), based on differences in seafloor reflectivity pattern, suggest a possible termination of the 1999 rupture within the Karamürsel Basin.

The Darıca Basin (Figure 3) is shallower than Karamürsel, and does not show a well-defined depocenter. The principal displacement zone of the NAF system emerges from a generally flat topography forming steps and ridges oriented E-W (strike-slip), NW-SE (transtensive), and SW-NE (transpressive), particularly in the center of the basin and close to the Hersek Peninsula, where the deformation zone appears wider. It converges again into a narrow E-W aligned furrow at the entrance of the İzmit Gulf.

A common pattern observed in the three basins is that deformation zones widen at the basin centers and become narrow, and comparatively more focused, at their edges.

4. Following the 1999 rupture

After the 1999 İzmit and Düzce events, this area was extensively surveyed during several cruises by different research groups. Extensional NW-SE oriented depressions and tension gashes, alternated by E-W oriented strike-slip fault scarps displacing the seafloor, were also mapped at a wider scale using multibeam and side-scan sonar imagery, as well as high-resolution seismic profiles that allow for vertical resolution in the acoustic sub-seafloor imaging on the order of a few cm (Polonia et al., 2004; Cormier et al., 2006). Close to the epicenter, in the shallowest end of the İzmit Gulf (Gölcük Basin, Figure 1) the surface rupture of the 1999 earthquake was clearly visible soon after the earthquake, both by geophysical imagery (high-resolution seismic reflection profiles, multibeam and side-scan sonar) and direct observations carried out using ROV-mounted video cameras (Polonia et al., 2002). ROV-mounted video cameras allowed direct observations of the seafloor where fresh rupture scarps affecting the muddy sea floor are visible (Figure 4). Further to the west, towards Karamürsel, the deformation pattern associated with the İzmit earthquake was less easily identified for several reasons. First, fault slip decreases westward from the epicenter, where a maximum strike-slip surface displacement of 5.5 m was observed (Çakır et al, 2003). Second, moving towards the basin depocenters we observe strain partitioning between dominantly strike-slip and dip-slip fault segments. The latter are characterized by prominent vertical scarps resulting from the cumulative displacement of several earthquakes. This made evaluating the effects of the last event difficult. Third, where deformation affects a flat bottom and strain patterns resulting from a single event may potentially be recorded, the muddy seafloor might not have been competent enough to form or preserve scarps. This is possibly the case in the Darıca Basin.

West of the Hersek Peninsula, however, relevant observations have been carried out. From the western coast of Hersek to a transpressive high formed at a left-lateral step of the NAF (Figure 3), we carried out high resolution multibeam and side-scan sonar surveys. Here, an E-W oriented rectilinear segment of the NAF accommodates almost purely strike-slip deformation along a narrow deformation zone (< 5 m). The fault trace appears as a 0.5 m-high scarp on multibeam bathymetry, and a low backscatter alignment on side-scan sonar images; it is also visible on high-resolution seismic reflection profiles, that penetrate the fine-layered Holocene marine sediments (Figure 5). Remarkably, a furrow (probably an anchor drag) crosses the fault scarp just west of Hersek. This furrow is apparently offset by the fault, as shown by side-scan images and bathymetric data (Figure 5). The relatively low resolution of the images (footprint about 25 cm) does not allow us to accurately estimate the right-lateral offset observed, which would probably fall between 0.5 and 1 m. The apparent displacement of this feature suggests that the 1999 surface rupture could have reached this sector and, in this case, should have also affected the Hersek promontory onshore.

However, clear surface ruptures were not observed onshore Hersek (Kozacı, 2002; Lettis et al., 2002). A possible explanation is that the Hersek promontory is a pressure ridge formed at a left-lateral stepover of the NAF. In this context, fault slip at depth may result in diffuse strain at the surface without obvious strain markers.

Toward the west, the western end of Darıca Basin is marked by a canyon that bends sharply across the NAF trace at the center of the İzmit Gulf, connecting it with the deep Çınarcık (Figure 3). The canyon is intersected by the NAF and appears to be right-laterally displaced by about 100 m. Several lines of evidence indicate that this displacement has been accumulated during the last 10,000 years, corresponding to a slip-rate of 10 mm/y (Polonia et al., 2004). Analysis of near-bottom microtopography collected during the MARMARASCARPS cruise using the ROV Victor (Armijo et al., 2005) suggested that the bottom of the canyon could be affected by a recent rupture that, due to the relative hardness of the canyon bottom, could have a good potential of forming a scarp. This line of reasoning induced us to plan a dive along the canyon during the MARNAUT cruise using the submersible Nautile to gather visual evidence of recent ruptures from the canyon bottom.

4.1 The Nautile dives

Multibeam bathymetry and micro-bathymetry data collected using ROV VICTOR during the MARMARASCARP cruise (Armijo et al., 2005) were used to precisely locate the main trace of the E-W trending strike-slip fault. A part of the fault is buried below a large landslide that, originating from the southern shelf, modifies the trend of canyon incision (Figure 6). The fault could only be visible E and W of the landslide front. Accordingly, we started our submersible survey (dive-1657) from the Çınarcık Basin floor at 900 m water depth, aiming to follow westward the inferred strike-slip fault track (Figure 6). Several morphological scarps were observed along our route, particularly close to the N wall of the canyon, where they may also be due to erosion and gravity failures of the steep slope or by erosion of the canyon floor by turbidity currents. Indeed, none of these morphological scarps were clearly associated with the track of the NAF, as inferred by morphobathymetric data, except for one 25 cm scarp at the bottom of the canyon at 660 m of water depth (Figure 7). This feature was at first interpreted as a good candidate for the surface expression of a strike-slip fault, with a minor dip-slip component, possibly related to the 1999 event. This hypothesis arose from several lines of reasoning, including observation that deposition rates in the area could span between 3.6-5 mm/y (Çağatay et al., 2003; Polonia et al., 2004). Because recurrence time of large earthquakes (large enough to cause surface rupture) is about 250 years along a given strand of the NAF (Ambraseys, 2002), and that possible dates of the penultimate event in this segment could be 1766 or 1894 (Ambraseys and Jackson, 2000), a vertical scarp on the order of 25 cm could be potentially buried in less than 200 years. However, the strike of the observed feature was parallel to other scarps attributed to gravity failure along the canyon wall; moreover, the analysis of morphobathymetric data did not confirm the presence of a continuous fault scarp corresponding with our observation.

After dive 1657 we decided to follow the rupture further to the east along the NAF track. The most favorable place to do this observation is the sharp bend of a canyon at the İzmit Gulf entrance (Figure 3). The subsequent dive (1670) presented some logistical difficulties such as heavy maritime traffic, shallow depths (170-100 m), and high turbidity with a visibility range not exceeding 2.5-3 m. However, most of the dive was carried out very close to the bottom (2 m) and we could observe clearly any feature on the bottom. Fortunately, the detailed morphobathymetric maps allowed a precise navigation along the NAF track. The dive began where the canyon bends from E-W to N-S at a depth of about 200 m. The bottom of the canyon was ubiquitously draped by bioturbated soft mud. No evidence of fresh scarps or erosion were observed, neither scours, nor ripple marks that could eventually indicate tractive processes at the seafloor. At one point in the canyon we tested the consistence of the seafloor using the arm of Nautile, that penetrated without effort the uppermost 40 cm (test site of Figure 8). Within the canyon, the presence of the fault could only be noticed by an abrupt increase in the slope below 190 m depth. We then followed the E-W offset of the scarp on the east wall of the canyon (Figure 8) but could not see any evidence of fresh faulting. Interestingly, three small black patches (Figure 9) were found in the area were the east wall of the canyon is offset by the fault. Apparently, toward north, the gully related to the fault has been filled by sediments. We noted a change in the nature of sediment cover that appeared to be somewhat coarser immediately north of the scarp. As for the gully of the fault east of the canyon, it has a regular E-W 10-12° north slope with an offset of about 9 m, but no outcrop or scarp of any kind was observed, and we did not see any other indication of venting activity. No fresh ruptures were observed during the dive, although the probable fault trace was crossed at least 5 times between the canyon and the dive termination 1 km further east.

4.2. The Medusa survey

During the MARMARA2009 cruise we surveyed the western end of the Darıca basin using "Medusa", a deep towed multisensor system, able to carry out oceanographic measurements (CTD, oxygen, etc.) as well as to collect high-definition images of the seafloor, as part of the as part of the Marmara Demonstration Mission (Marmara-DM) project of the European Seafloor Observatory Network of Excellence (ESONET NoE). During the survey, Medusa was equipped with two methane sensors to detect possible methane anomalies related to the presence of fluid flow along faults (Gasperini et al., 2009). We focused our attention in the area between the Nautile 1657 dive to the east, and the last evidence of 1999 rupture observed west of Hersek. The video camera on board Medusa enabled us to observe possible evidence of surface rupture along the NAF track, just west of the displaced canyon (Figure 10). Considering that the fault trace east and west of this point was surveyed using the Nautile, evidence for seafloor rupture west of the Darıca basin is, at best, patchy.

5. The "black patches"

During the MARNAUT Nautile dives, numerous so called "black patches" were observed marking the fault zones in the Sea of Marmara floor (Zitter et al., 2008; Géli et al., 2008; Tryon et al., 2010) and visual observations and coring during the MARNAUT cruise confirmed the presence of abundant carbonate concretions within them. Such features are typical indicators of relatively continuous emission of methane at the seafloor. The anaerobic oxidation of methane (AOM) triggers a suite of biogeochemical reactions that ultimately result in production of black Fe and Mn sulfide mineral assemblages. The overall AOM reaction can be expressed as:

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O \tag{1}$$

This process is mediated by a consortium of methane oxidizing archaea and sulphate-reducing bacteria (Boetius et al., 2000; Orphan et al., 2001). Methane originates from below from microbial degradation of organic matter or from deeper thermogenic hydrocarbon generation and passes upwards as a dissolved component in pore fluid advection or as a buoyant gas phase. The sulfate source is the overlying water column, with sulfate diffusing across the sediment-water boundary. Secondary reactions include precipitation of authigenic carbonates, and precipitation of a variety of Mn and Fe sulfides (Çağatay et al., 2008). The latter dominate the sulfidic sediment of methane seeps and give it the black color. Fe oxyhydroxides often make up a significant percentage of ocean margin seafloor sediment and these are prone to biogeochemical reduction, often by a microbial intermediary.

These black sediment patches are indicators of active methane emissions, either as free gas or, more commonly, dissolved in pore water. The emissions must be rapid enough to keep the bottom boundary layer anoxic. Flow measurements made in such environments have indicated typical outflow rates of millimeters to meters per day (LaBonte, 2007, Tryon et al. 2002). Sulfide oxidation is rapid (Millero et al. 1987; Wang and Chapman 1999) and in the absence of outflow, oxygenated bottom water will interact with the sediment and it will quickly (days) lose its black color. One control on how long the site has been active is the presence or absence of carbonates. The AOM reaction produces bicarbonate and leads to the production of authigenic calcium carbonate and, at methane seeps, this occurs at and just below the seafloor. While there are many factors affecting the accumulation rate, as a general rule significant carbonate cements, concretions, or structures relates to a relatively long lifetime of venting activity on the order of some tens of years or more. Thus long-term flow along faults causes the near-surface sediment to be more indurated and thus more capable of being fractured during deformation rather than deforming plastically. These fractures will also tend to be better preserved.

Given the above, we conclude that the black patches marking the fault track at the seafloor within the canyon indicate a persistent tectonic-driven fluid flow from the subsurface and that, should surface ruptures occur, any vertical offset should be preserved more readily than elsewhere. Observation of free gas in the water column not visible during previous surveys, indicate that in most places in the İzmit Gulf this flow was enhanced after the 1999 İzmit earthquake (Kuşcu et al., 2005; Alpar et al., 1999) and possibly immediately before this event as a consequence of a strain change in the subseafloor. However, according to these studies, gas releases along the seafloor expression of the fault were mostly observed east of the Hersek Peninsula, while to the west they appeared more diffuse. This is consistent with the sparse evidence for methane emission from Nautile and Medusa surveys and further suggests that seafloor ruptures were sporadic in this area.

6. Discussion

The surface rupture related to the 1999 İzmit earthquake below the Marmara Sea probably ended in the Darıca basin, west of the Hersek Peninsula (Figure 2). Although possible clues of this surface rupture were observed in the Çınarcık eastern slope, along a fault-controlled canyon, they were not confirmed by observations carried out in the shallower and most favorable location at the entrance of the İzmit Gulf. However, in the light of rupture heterogeneity, widespread ground fishing and surface erosion, it is conceivable that submarine surface expressions further to the west in the deep Çınarcık basin could easily be erased, hidden or overlooked. As far as our observations are concerned, the morphology of the seafloor is critical for unequivocally locating the presence of a recent fault-related rupture. In fact, in the case of complex topography and fault scarps produced by multiple events it would be very difficult to recognize the effect of the last earthquake. Another important factor is the competence of the seafloor: a "soupy" mud-dominated seafloor appears to be unsuitable for forming and preserving fresh scarps. As was observed during both the MARNAUT and MARMARASCARPS cruises, fault ruptures are often associated with fluid emissions from the subseafloor. As discussed above, these emissions help in the creation and preservation of these fault scarps. This also suggests that observations of evidence of long-term fluid flow without the presence of fractures/scarps indicate that no recent ruptures occurred in that location. Our observations are in agreement with recent estimates of coseismic slip based on combined tectonic observations and SAR data (Çakır et al., 2003). Yet, it is puzzling that no surface rupture is found at locations where the seafloor fault trace is well defined, suggesting that earthquake ruptures only occasionally reach the seafloor or that the seafloor does not necessarily show traces of seismogenic rupture. Slip near the western end of the 1999 İzmit earthquake rupture, in W Darıca and Çinarcik may have occurred only at depth. These observations could indicate that stress release is incomplete along this part of the North Anatolian Fault, and that the next earthquake would possibly nucleate in this area and propagate westward. This conclusion, however, also depends on the slip distribution of the 1894 rupture. This earthquake occurred in the region of Çinarcik Basin and the western part of the İzmit Gulf but its exact location is not certain (Ambraseys, 2009). Furthermore, post-seismic extension occurred in the Çınarcık Basin (Ergintav et al., 2009). This should result in a decrease of Coulomb stresses on fault branches in Eastern Çınarcık and in some amount of westward stress transfer not accounted for by co-seismic models. In alternative scenarios for future earthquakes, nucleation may occur on the western side of the Sea of Marmara seismic gap, or near Istanbul at the fault bend on the western side of Çınarcık Basin (Oglesby et al., 2008).

Since the westernmost evidence for seafloor rupture was observed close to the canyon displaced by the NAF at the İzmit Gulf entrance, this location appears an ideal observation point for monitoring the seismic activity along the NAF trace for the following reasons:

1) it is the westernmost location of the NAF that did not show surface ruptures associated with the 1999 İzmit earthquake; thus, it is an area where the next earthquake along the northern branch of the NAF could nucleate;

2) it has black sulfidic sediment patches caused by gas and fluid emissions along the track of the NAF; this occurrence could be used to study correlations between seismicity and fluid emission.

3) it is an area characterized by a “focusing” of the NAF principal deformation zone, which is constituted here by a single strike-slip segment;

4) it is a relatively accessible area, due to the moderate water depth and its proximity to the coastline.

Due to these considerations, this area was selected for a 1-year monitoring experiment that started last September in the frame of the ESONET NoE Marmara-DM project. A SN-4 class seafloor observatory, equipped with several sensors including a wide-band seismometer and a methane sensor, was deployed close to the canyon, at 150 m of water depth during MARMARA2009 cruise

(Gasperini et al., 2009). Results from this experiment will help in analyzing possible relationships between seismicity and gas emissions from the seafloor.

7. Conclusion

A number of independent observations, including high-resolution seismic reflection profiles and acoustic imagery of the İzmit Gulf and Çınarcık basin seafloor, combined with direct underwater observation carried out using ROVs and the Nautile submersible, all suggest that the surface rupture associated with the Mw 7.4, 1999 İzmit earthquake tapered-out in the Darıca Basin, before the eastern termination of the İzmit Gulf. Part of the tectonic load associated with stress release at the ruptured İzmit segment has been transferred in this area, increasing the probably for a future event to nucleate there. We found that at this location, deformation associated with the NAF is almost purely strike-slip and concentrated in a relatively narrow zone. Moreover, a few black patches of reduced sediment close to the seafloor trace of the fault indicate fault-controlled fluid and gas emission. Since the hydrogeologic system is directly coupled to the tectonic system through the interaction of strain, stress state, and fluid pressure and its resultant flow, this location may be ideal for monitoring post seismic, precursory, and/or systematic hydrologic variations through the seismic cycle.

Aknowledgements

We thank captain and crew of cruises MARMARA-2001, -2005 and –2009 (R/V Urania), as well as MARMARASCARPS and MARNAUT (R/V L'Atalante). The Marmara2009 cruise was partly funded by ESONET NoE Marmara-DM project. Thanks are also due to the "Medusa" team, and in particular to G. Etiope, G. Marinaro and F. Furlan, for providing the image shown in Figure 10. L.G. would like to thank Rolando Armijo for invitation on board of L'Atalante during MARMARASCARPS cruise, and for stimulating discussions on the subject. Finally, we thank Georg Dresen and an anonymous referee for improving the quality of the manuscript.

References

Alpar, B. (1999). Underwater signatures of the Kocaeli Earthquake (August 17th 1999), Turkish Journal of Marine Sciences, 5(3), 111-130.

Ambraseys, N.N., (2002). The seismic activity of the Marmara Sea region over the last 2000 years. Bulletin of the Seismological Society of America. 92,1, 1-18.

Ambraseys, N.N, Jackson, J.A., (2000). Seismicity of the Sea of Marmara (Turkey) since 1500. Geophysical Journal International. 141, 3, F1-F6.

Armijo, R., Meyer, B., Navarro, S., King, G., Barka, A.A., (2002). Asymmetric slip partitioning in the Sea of Marmara pull-apart: a clue to propagation processes of the North Anatolian Fault?. Terra Nova, 14, 80-86.

Armijo et al, (2005). Submarine fault scarps in the Sea of Marmara pull-apart (North Anatolian Fault): Implications for seismic hazard in Istanbul. Geochemistry Geophysics Geosystems, 6, Q06009

Barka, A. et al., (2002). The surface rupture and slip distribution of the 17 August 1999 İzmit earthquake M 7.4, North Anatolian fault, Bull. seism. Soc. Am., 92, 43–60.

Boetius, A., Ravenschlag, K., Schubert, C.J., Rickert, D., Widdel, F., Gieseke, A., Amann, R., Jørgensen, B.B., Witte, U., Pfannkuche, O., (2000). A marine microbial consortium apparently mediating anaerobic oxidation of methane. Nature 407, 623–626.

Bouchon, M., Toksoz,N., Karabulut,H., Bouin M.P., Dietrich, M., Aktar, M., Edie, M., (2000). Seismic imaging of the İzmit rupture inferred from the near-fault recordings. Geophys. Res. Lett. 27, 3013–3016.

Bulut, F., Aktar, M., (2007). Accurate relocation of İzmit earthquake (Mw=7.4, 1999) aftershocks in Çınarcık Basin using double difference method. Geophysical Research Letters, 34, L10307.

Bürgmann, R., Ergintav, S., Segall, P., Hearn, E.H., McClusky, S., Reilinger, R.E., Woith, H., Zschau, J., (2002). Time-dependent distributed after slip on and deep below the İzmit earthquake rupture. Bull. seism. Soc. Am. 92, 126–137.

Çağatay, M.N. Görür, N. Polonia, A., Demirbağ, E., Sakınç, M., Cormier, M.-H., Capotondi, L., McHugh, C., Emre, Ö., Eriş, K., (2003). Sea level changes and depositional environments in the İzmit Gulf, eastern Marmara Sea, during the late glacial-Holocene period. Marine Geology, 202, 159-173.

Çağatay, M.N., Belucci, L. Polonia, A. Sancar, U. Dikçe, D. Eriş, K. Damcı, E., Gasperini, L. Görür, N. Henry, P. Zitter, T.A.C. Geli, L. Tryon, M., 2008. Sedimentary earthquake records in the Sea of Marmara, EGU 2008 meeting, Vienna, 2008.

Çakır, Z., de Chabalier, J.B., Armijo, R., Meyer, B., Barka, A.A., Peltzer, G., (2003). Coseismic and early post-seismic slip associated with the 1999 İzmit earthquake (Turkey), from SAR interferometry and tectonic field observations. Geophys. J. Int. 155, 93–110.

Cormier, M.-H., Seeber, L., McHugh, C.G., Polonia, A., Çağatay, N., Emre, Ö., Gasperini, L., Görür, N., Bortoluzzi, G., Bonatti, E., Ryan, W.B.F., Newman, R., (2006). North Anatolian Fault in the Gulf of İzmit (Turkey): Rapid vertical motion in response to minor bends of a nonvertical continental transform. Journal of Geophysical Research, 111, doi:10.1029/2005JB003633.

Delouis,B., Giardini, D., Lundgren, P., Salichon J., (2002). Joint inversion of InSAR, teleseismic and strong motion data for the spatial and temporal distribution of earthquake slip: application to 1999 İzmit mainshock. Bull. seism. Soc. Am., 92, 278–299.

Ergintav, S., McClusky, S., Hearn, E., Reilinger, Cakmak, Herring, T., Ozener, H., Lenk, O., 4, Tari, E., (2009). Seven years of postseismic deformation following the 1999, M=7.4 and M=7.2, İzmit -Duzce, Turkey earthquake sequenze. Journal of Geophysical Research, 114, B07403.

Feigl, K.L. et al., (2002). Estimating slip distribution for the İzmit main shock from coseismic GPS, ERS 1, RADARSAT, and SPOT measurements, Bull. seism. Soc. Am., 92, 138–160.

Gasperini, L., et al., (2009). MARM2009: marine geological study of the North-Anatolian Fault beneath the Sea of Marmara. Cruise Report. ISMAR-CNR technical report, Bologna, November 2009. http://projects.bo.ismar.cnr.it/CRUISE_REPORTS/2009/MARM09_REP

Géli, L., et al., (2008). Gas emissions and active tectonics within the submerged section of the North Anatolian Fault zone in the Sea of Marmara. Earth Plan. Sci. Lett. 274, 34–39.
Gülen, L, Pinar, A, Kalafat, D, Ozel, N, Horasan, G, Yilmazer, M, Isikara, A.M., (2002). Surface fault breaks, aftershock distribution, and rupture process of the 17 August 1999 İzmit , Turkey, earthquake. Bull. seism. Soc. Am. 92, 230-244.
Hartleb, R.D., et al., (2002). Surface rupture and slip distribution along the Karadere segment of the 17 August 1999 İzmit and the western section of the 12 November 1999 Duzce, Turkey, earthquakes. Bull.seism.Soc. Am., 92, 67–78.
Henry, P., et al., 2007. Marnaut Cruise Investigating cold seeps along the northern branch of the North Anatolian Fault in the Sea of Marmara. Cruise Report. http://www.cdf.u-3mrs.fr/~henry/marmara/
Kozacı, Ö., (2002). Paleoseismological studies on the Yalova segment of the North Anatolian Fault in the Hersek Delta. MSc. Thesis. Eurasian Institute of Earth Sciences. İstanbul Technical University, 116p.
Kuşcu, I, Okamura, M, Matsuoka, H, et al. (2005). Seafloor gas seeps and sediment failures triggered by the August 17, 1999 earthquake in the Eastern part of the Gulf of İzmit, Sea of Marmara, NW Turkey. Marine Geology, 215, 193-214.
LaBonte, A.L., Brown, K.M., Tryon, M.D., (2007). Monitoring periodic and episodic flow events at Monterey Bay seeps using a new optical flow meter, Journal of Geophysical Research, 112, B02105, doi:10.1029/2006JB004410.
Langridge, R.M., Stenner,H.D, Fumal,T.E., Christoffereson, S.A., Rockwell, T.K., Hartleb, R.D., Bachhuber, J. & Barka, A.A., (2002). Geometry, slip distribution, and kinematics of surface rupture on the Sakarya fault segment during the 17 August 1999 İzmit , Turkey, earthquake. Bull. seism. Soc. Am., 92, 107–125.
Lettis, W., Bachluber, J., Witter, R., Brankman, C., Randolph, C.E., Barka, A.A., Page, W.D., Kaya, A., (2002). Influence of releasing step-overs on surface fault rupture and fault segmentation: Examples from the 17August 1999 İzmit earthquake on the North Anatolian Fault, Turkey. Bull. seism. Soc. Am. 92 (1), 19–42.
Meade, B.J., Hager, B.H, McClusky, S.C., Reilinger, R.E; Ergintav S., Lenk O., Barka, A.A, Ozener, H., (2002). Estimates of seismic potential in the Marmara region from block models of secular deformation constrained by GPS measurements. Bull. seism. Soc. Am. 92, 208-215.
Millero, F. J., Hubinger S., Fernandez, M., Garnett, S., (1987). Oxidation of H2S in seawater as a function of temperature, pH, and ionic strength. Environmental Science and Technology, 27: 439–448.
Oglesby, D.D., Mai, P.M., Atakan, K., Pucci, S., (2008). Dynamic models of earthquakes on the North Anatolian fault zone under the Sea of Marmara: Effect of hypocenter location. Geophyical Research Letters,. 35, L18302, doi:10.1029/2008GL035037.
Orphan, V.J., House, C.H., Hinrichs, K.-U., McKeegan, K.D., de Long, E.F., (2001). Methaneconsuming Archaea revealed by directly coupled isotopic and phylogenetic analysis. Science 293, 494-487.
Polonia, A., Cormier, M-.H., Çağatay, N., Bortoluzzi, G., Bonatti, E., Gasperini, L., Seeber, L., Gorur, N., Capotondi, L., McHugh, C., Ryan, W.B.F., Emre, O., Okay, N., Ligi, M., Tok, B., Blasi, A., Busetti, M., Eris, K., Fabretti, P., Fielding, E.J., Imren, C., Kurt, H., Magagnoli, A., Marozzi, G., Ozer, N., Penitenti, D., Serpi, G., Sarikavak, K., (2002). Exploring submarine earthquake geology in the Marmara Sea. EOS Transactions AGU, 83, 229, 235-236.
Polonia, A, Gasperini, L., Amorosi, A., Bonatti, E., Çağatay, N., Capotondi, L., Cormier M.-H., Gorur, N., McHugh, C., Seeber, L., (2004). Holocene Slip rate of the North Anatolian Fault beneath the Sea of Marmara. Earth and Planetary Science Letters, 427, 411-426.

Reilinger, R.E., Ergintav, S., Burgmann, R., McClusky, S., Lenk, O., Barka, A.A., Gurkan, O., Hearn, L., Feigl, K.L., Cakmak, R., Aktug, B., Ozener, H., Toksoz, M.N., 2000. Coseismic and Postseismic Fault Slip for the 17 August 1999, M 5 7.5, İzmit , Turkey Earthquake. Science, 289, 5484,1519-1520.

Rockwell, T.K., Lindval, S., Dawson, T., Langridge, R., Lettis, W., Klinger, Y., (2002). Lateral offsets on surveyed cultural features resulting from the 1999 İzmit and Duzce earthquakes, Turkey. Bull. seism. Soc. Am., 92, 79–94.

Sengor, A.M.C., Görür, N, Saroglu, F., (1985). Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study. In: Biddle KT, Christie-Blick N (eds) Strike-slip faulting and basin formation, vol.37. Society of Economic Paleontology Mineralogists, Tulsa, OK, USA, pp 227–264 (special publication).

Tibi, R., Bock, G., Xia, Y., Baumbach, M., Grosser, H., Milkereit, C., Karakisa, S., Zunbul, S., Kind, R., Zschau, J., (2001). Rupture processes of the1999 August 17 İzmit and November 12 Duzce (Turkey) earthquakes. Geopys. J. Int., 144, F1–F7.

Tryon, M.D., K.M. Brown, M.E. Torres, (2002). Fluid and chemical fluxes in and out of sediments hosting hydrate deposits on Hydrate Ridge, OR, II: Hydrological processes, Earth and Planetary Science Letters, 201 (3-4), 541-557.

Tryon, M. D., P. Henry, M. N. Çağatay, T. A. C. Zitter, L. Géli, L. Gasperini, P. Burnard, S. Bourlange, and C. Grall (2010), Pore fluid chemistry of the North Anatolian Fault Zone in the Sea of Marmara: A diversity of sources and processes, Geochem. Geophys. Geosyst., 11, Q0AD03, doi:10.1029/2010GC003177.

Wang, F. and Chapman P.D., (1999). Biological implications of sulfide in sediment—A review focusing on sediment toxicity. Environmental Toxicology and Chemistry, 18, 2526–2532.

Wright, T., Fielding, E., Parsons, B., (2001). Triggered slip: observations of the 17August 1999 İzmit (Turkey) earthquake using radar interferometry. Geophys. Res. Lett., 28, 1079–1082.

Yagi, Y. and Kikuchi, M., (2000). Source rupture process of the Kocaeli, Turkey earthquake of August 17,1999 obtained by joint inversion of near-field data and teleseismic data. Geophys. Res. Lett. 27, 1969–1972.

Zitter, T.A.C., et al., (2008). Cold seeps along the main Marmara fault in the Sea of Marmara (Turkey), Deep Sea Research, Part I, **55**, 552-570.

Figures

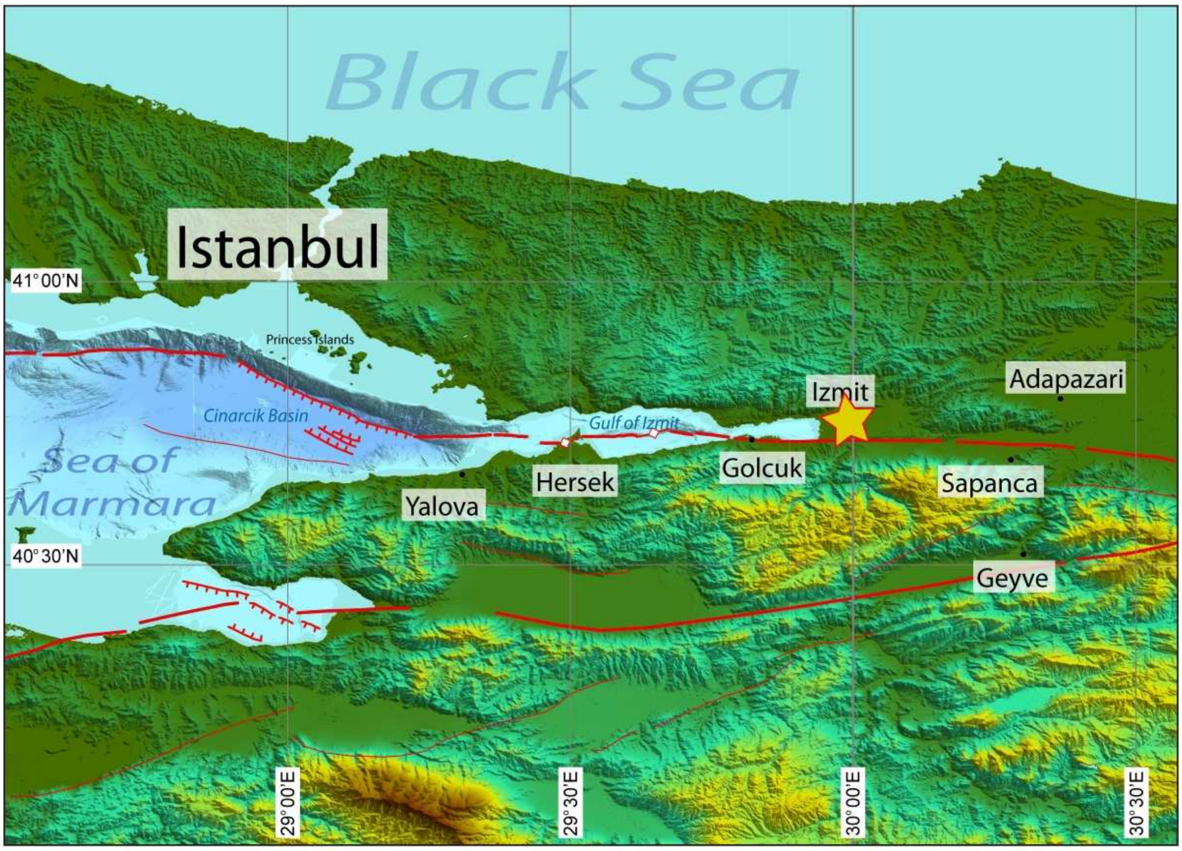

Figure 1. Tectonic map of the NAF system in the E Marmara region. Epicenter of 1999 İzmit earthquake (yellow star) is indicated. Topographic data are from SRTM database; Bathymetric data are from different sources, including: Le Pichon et al., (2001); Polonia et al. (2004); Gasperini et al.(2009). Red lines indicate NAF track, both in the N and S strands. Position of faults is from different works, including: Sengor et al. (1985); Le Pichon et al., (2001); Armijo et al. (2002).

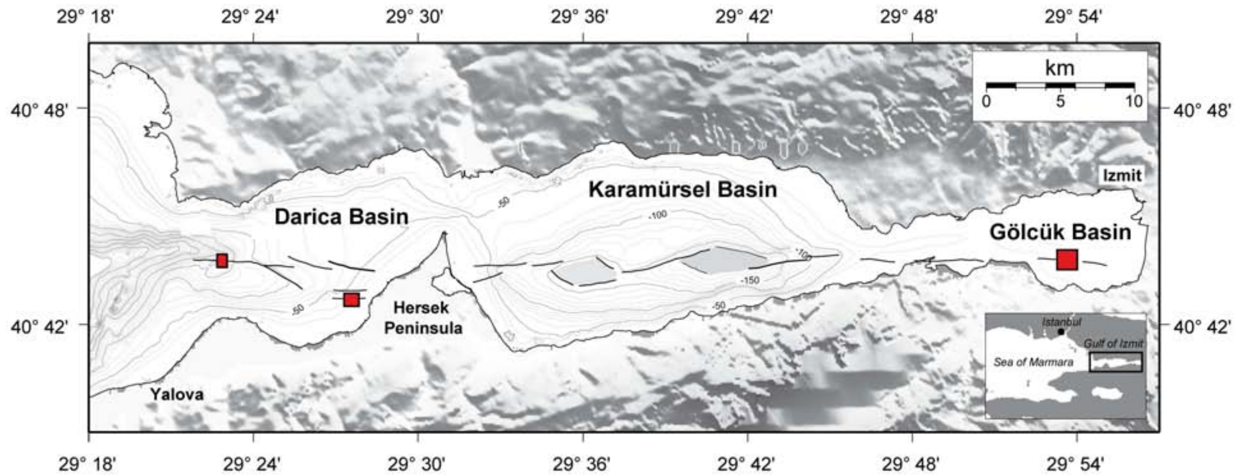

Figure 2. Tectonic map of the İzmit Gulf, along the North Anatolian Fault (NAF) system (from Polonia et al.,2004; modified). Three sedimentary basins are indicated, Darıca, Karamürsel and Golcük, from W to E, as well as main tectonic features along the NAF track. Red boxes indicate locations where surface rupture associated to 1999 İzmit earthquake were observed.

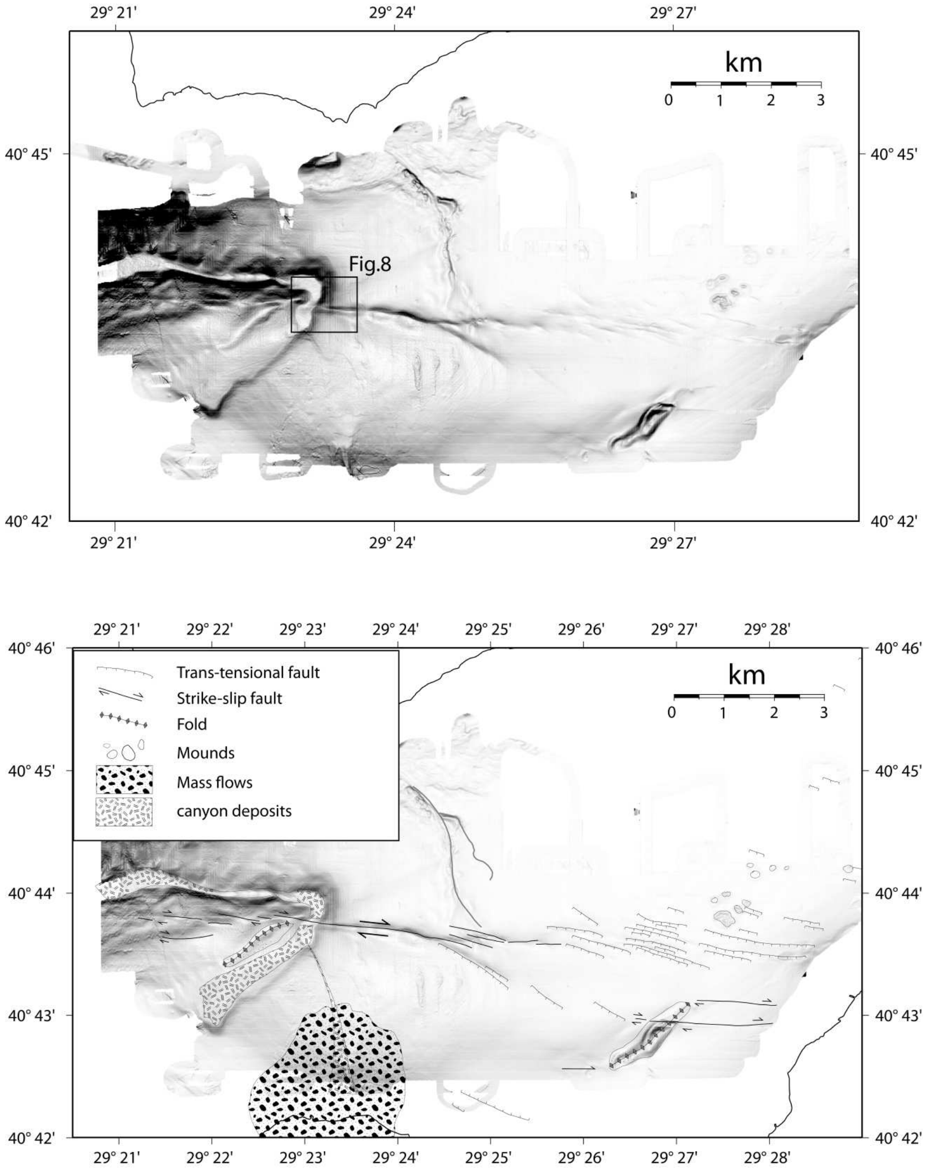

Figure 3. Morphostructural map of the Darıca Basin, showing different tectonic domains. Pure strike slip-deformation is observed only in the W end of the basin, where the diffuse pattern of en-echelon transtensional faults merge to a single, localized E-W oriented fault track. Box indicates location of the map shown in Figure 8.

Figure 4. Earthquake-related surface rupture observed close to the epicenter of the 1999 İzmit earthquake using an ROV video camera during MARMARA2001 cruise.

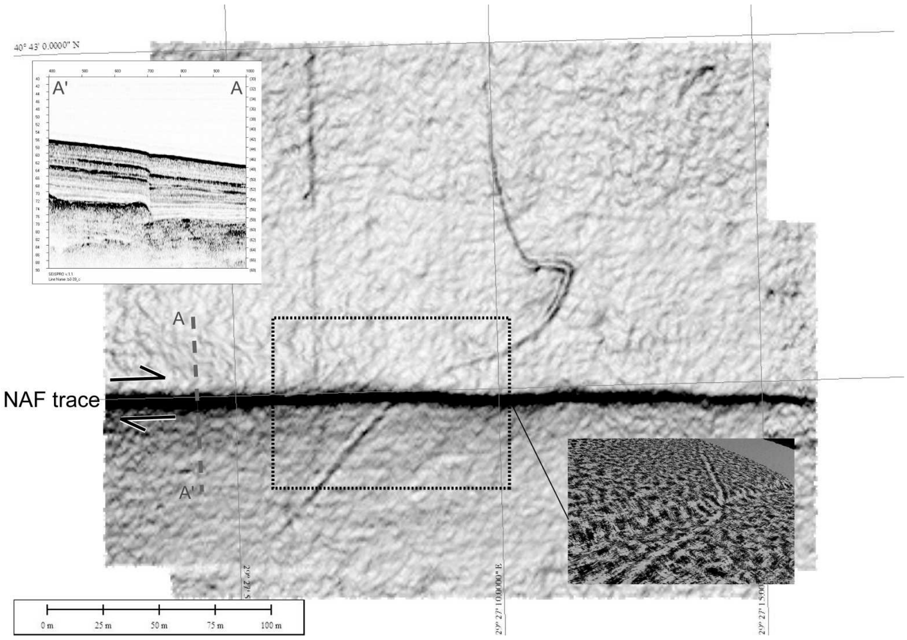

Figure 5. Multibeam-based slope map of the MAF fault trace W of the Hersek Peninsula. Insets show a chirp-sonar seismic section (A-A') across the fault track, and a 3D-image that was obtained combining multibeam and side-scan sonar data. The 3D-image shows a track at the seafloor (probably an anchor drag) intersecting at high angle the strike-slip fault, and showing a displacement in a range between 1 and 0.5 m.

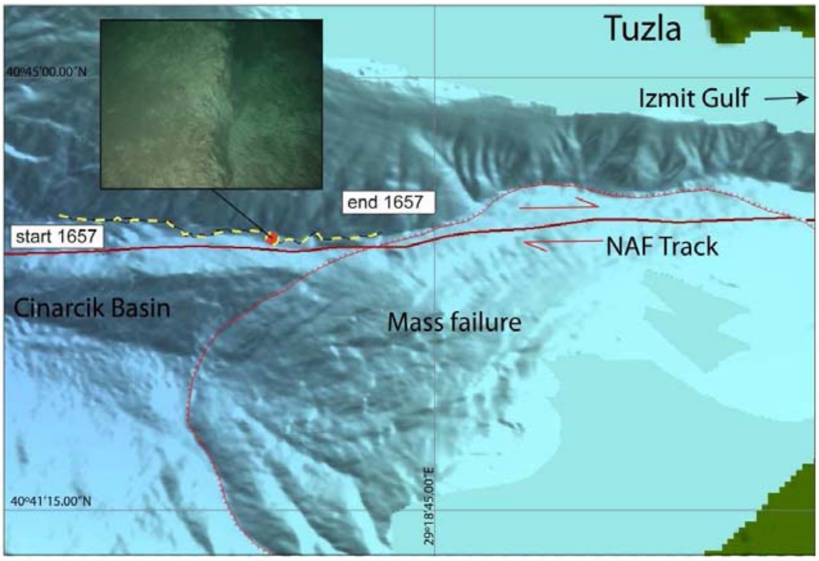

Figure 6. Morphobatimetric map of the Çınarcık basin and the W end of the İzmit Gulf. The track of the 1657 Nautile dive is indicated (yellow dash line), as well as the position of a fresh scarp described in the text as a possible candidate for the 1999 surface rupture (inset and Figure 7) .

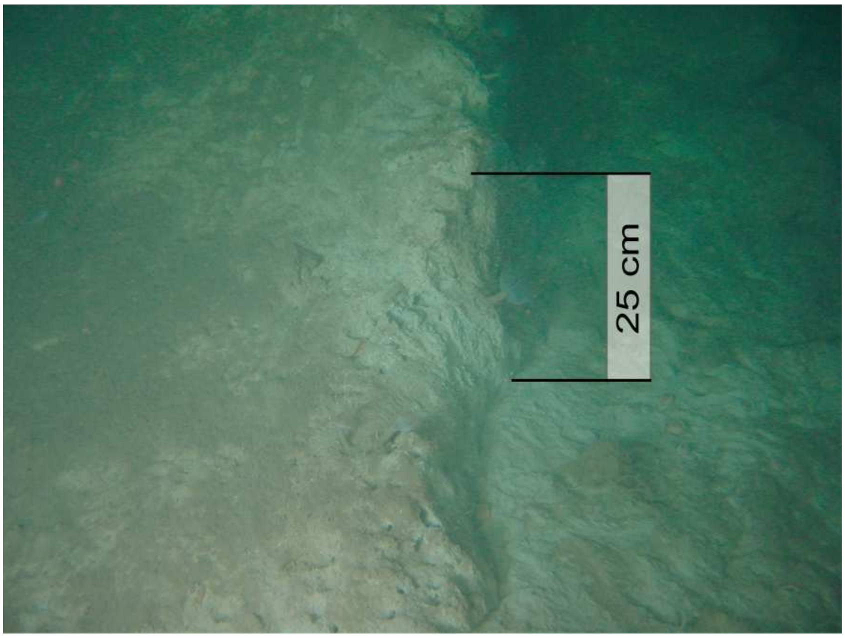

Figure 7. Seafloor picture collected during Nautile dive 1657 in the canyon connecting Çınarcık to the İzmit Gulf. The scarp observed at the seafloor in not the result of tectonic rupture, but more likely differential erosion at the canyon flanks (see text).

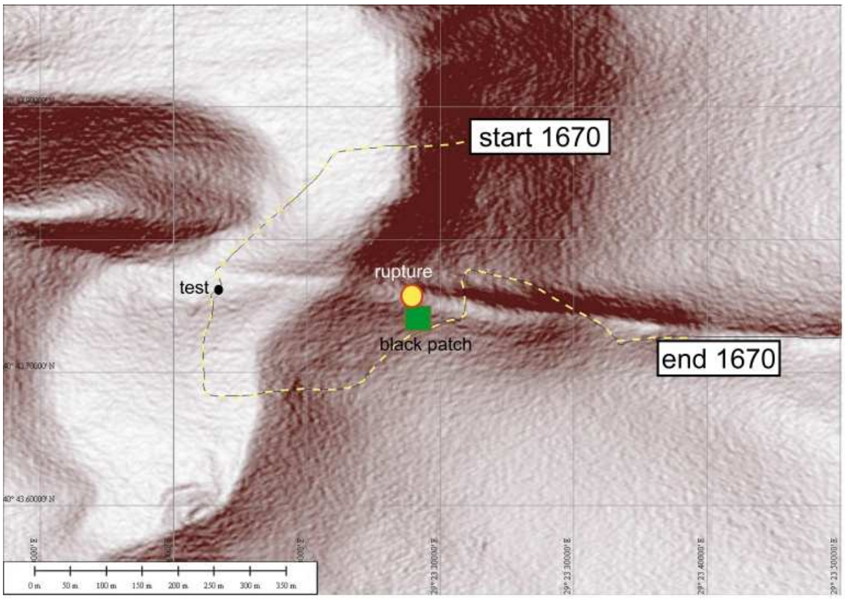

Figure 8. Track of Nautile Dive 1670 during MarNaut cruise. Black dot indicates the test site during dive (push core); green square indicates location were black patches were observed (see Figure 9); yellow circle indicates site were the westernmost surface rupture, possibly related to the 1999 İzmit earthquake was observed using the Medusa camera (see Figure 9).

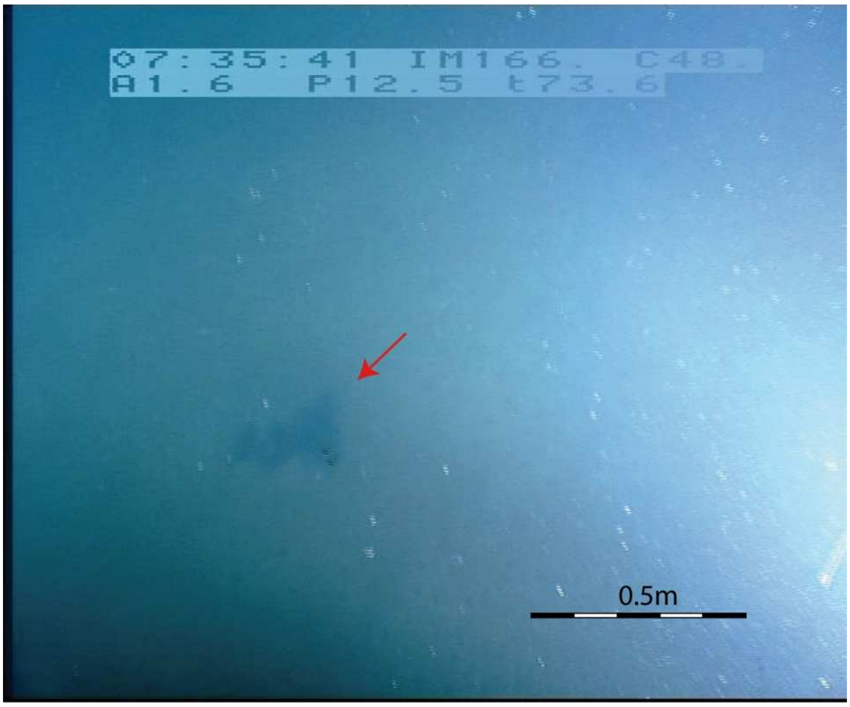

Figure 9. Seafloor image collected during Nautile dive 1670 showing one of the black patches observed close to the western termination of 1999 rupture (see Figure 8 for location).

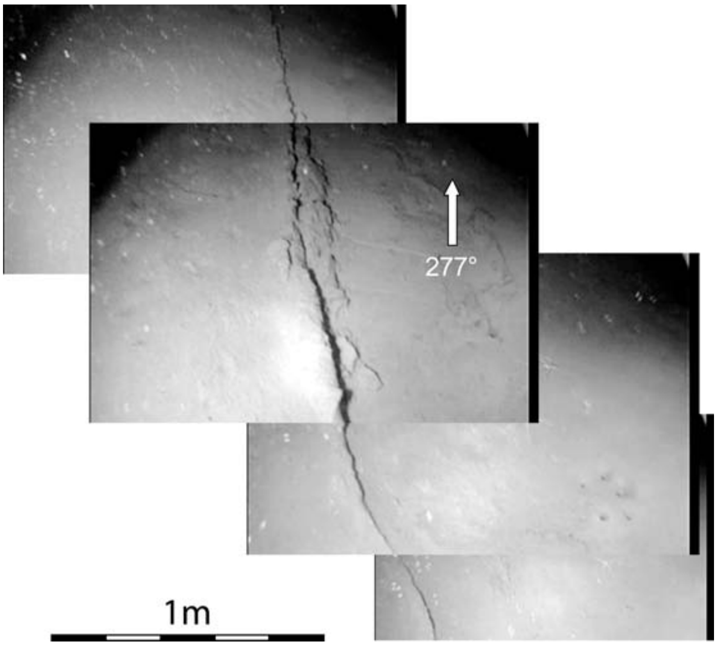

Figure 10. Image of a scarp at the seafloor possibly related to the 1999 earthquake collected using Medusa (Figure 8 for location).