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Western Termination of the Mw 7.4, 1999 İzmit Earthquake Rupture: Implications for the Expected Large Earthquake in the Sea of Marmara

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Abstract: The Mw 7.4, August 17, 1999 İzmit earthquake ruptured a ~100-km-long onshore section of the North Anatolian Fault (NAF) in the eastern Marmara region, causing the loss of more than 20,000 people and extensive destruction. The western termination and total length of the earthquake rupture is still a matter of debate because the surface rupture goes offshore in the Gulf of İzmit after displaying a coseismic displacement of ~5 m. Such a considerable slip implies that the fault rupture must definitely continue some distance westward on the sea floor, but where exactly it terminated is difficult to determine. This issue is critical for determining the size of the Marmara seismic gap, south of İstanbul. Therefore, to explore the fault scarps associated with the 1999 rupture on the sea floor, we have studied ultra-high resolution bathymetry (0.5 m resolution) acquired with a remotely operated submersible during the MARMARASCARPS cruise, an innovative approach which proved to be useful in seeking earthquake surface deformation on the sea floor. The analysis of microbathymetry suggests that the 1999 İzmit earthquake rupture extended westward at least to 29.38°E longitude about 10 km west of the Hersek Delta in the Gulf of İzmit. It is clearly expressed as a sharp fault break with a 50 cm apparent throw across the bottom of a submarine canyon. Further west, a pronounced and linear fault rupture zone was observed, along with fresh en-échelon cumulative fault scarps. We infer that the seismic break continues westwards, reaching a total length of ~145 km at around 29.24°E longitude, consistent with the 1999 rupture deduced from SAR interferometry. It appears to stop at the entrance of the Çınarcık Basin where a normal faulting component prevails. We suggest that fault complexity at the junction between dominant strike-slip faulting along the İzmit fault and significant normal faulting in the Çınarcık Basin may act as a barrier to rupture propagation of large earthquakes.

Key Words: North Anatolian Fault, Sea of Marmara, 1999 İzmit earthquake, submarine fault scarps, stress interaction

1999 İzmit Deprem (Mw 7.4) Kırığının Batı Ucu: Marmara Denizi'nde Beklenen Büyük Deprem İçin Önemi

Özet: Doğu Marmara'da Kuzey Anadolu Fayı'nın (KAF) kara üzerindeki 100 km'lik bir parçasını kıran Mw 7.4, 17 Ağustos 1999 İzmit depremi, 20000 den fazla can kaybına ve büyük yıkıma neden olmuştur. 1999 İzmit depremi yüzey kırığının Gölcük'te ~5 m'lik bir yanal atım ürettikten sonra İzmit Körfezi'nde denize girmesi sebebiyle kırığın batıda nerede sonlandığı hala tartışma konusudur. Bu büyüklükteki bir atım, fay kırığının önemli miktarda batıya doğru denizaltında devam ettiğini göstermektedir. Ancak tam olarak nerede sonlandığı belirlenememiştir. Bu konu, Marmara sismik boşluğununun özelliklerinin belirlenebilmesi ve bununla baglantılı olarak Marmara bölgesi ve özellikle 20 milyondan fazla kişinin yaşadığı İstanbul metropolitanını tehdit eden deprem tehlikesinin ortaya konulabilmesi açısından son derece önemlidir. Bu çalışmada İzmit depremi yüzey kırığının deniz tabanında meydana getirdiği fay sarplıklarını araştırmak amacıyla, MARMARASCARPS seferi esnasında uzaktan kumandalı bir denizaltı ile toplanan yüksek çözünürlüklü (0.5 m) batimetri verileri incelenmiştir. Bu yöntem ile deniz tabanında depremlerin yüzey defomasyonu başarılı bir şekilde tespit edilebilmekte ve fay geometrisi ayrıntılı olarak ortaya konulabilmektedir. Mikrobatimetri verisinin analizi sonucunda İzmit depremi yüzey kırığının, Hersek yarımadasının en az 10 km batısında, 29.38° Doğu boylamına kadar ulaşmış olduğu görülmektedir. Bir denizaltı kanyonunun düz tabanı boyunca izlenen taze fay kırıklarına ait güncel sarplığın düşey atımı 0.5 m'dir. Bu noktadan batıya devam edildiğinde, çizgisel dar bir fay zonu boyunca kademeli (*en-échelon*) kümülatif sarplıklar tespit edilmiştir. Bu zon boyunca doğrultu-atımlı faylanmanın karakteristik yapıları olan küçük çek-ayır havzalar ve basınç sırtları gözlenmektedir. Morfolojik analizler sonucunda 1999 yüzey kırığının 29.26°E boylamına kadar uzandığı ve toplam uzunluğunun ~145 km'ye bularak normal faylanmanın görülmeye başlandığı Çınarcık Havzası girişinde sonlanmış olabileceği tespit edilmiştir. Elde edilen sonuçlar, saf yanal-atımlı İzmit fayı ile normal faylanmanın kontrol ettiği Çınarcık Havzası kesişiminin 1999 kırığının ilerlemesini durduracak bir bariyer oluşturmuş olabileceğini göstermektedir.

Anahtar Sözcükler: Kuzey Anadolu Fayı, Marmara Denizi, 1999 İzmit depremi, denizaltı fay sarplıkları, gerilme etkileşimi

Introduction

The Mw 7.4, 17 August 1999 İzmit earthquake (M_o 1.7–2.0 x 10^{20} Nm) was not a surprise because westward migrating earthquakes had already taken place along the North Anatolian Fault (NAF) all the way from Erzincan to the İzmit region, breaking a ~1000-km-long section of the NAF since 1939 (Toksöz *et al.* 1979; Barka 1996; Stein *et al.* 1997). Like falling dominos, these triggered earthquakes reached the İzmit region, following the southern boundary of the Almacık Block (Figure 1a) (Barka 1996). Together with the 12 November 1999 Düzce event (Mw 7.1), these two earthquakes ruptured almost the entire northern boundary of the Almacık Block (Figure 1a) and the İzmit fault segment (Figure 1b).

The 1999 İzmit earthquake nucleated on the NAF south of İzmit with bilateral rupture propagation to the west and east breaking four fault segments, (i.e. the Karadere, Sakarya, Sapanca and Gölcük segments) with a total length of 100 km on land (Figure 2a, b). They are separated by up to 4-km-wide stepovers with both releasing and restraining bends (Barka *et al.* 2002). The maximum horizontal offset produced along the surface break was 5.5 m on the Sakarya segment, immediately east of Sapanca Lake (Figure 2c) (Barka *et al.* 2002).

Active faults in the vicinity of the İzmit rupture, particularly around the rupture tips, are now loaded with high static stress whose peak value is equivalent to tens of years of stress accumulation at a normal tectonic rate (Hubert-Ferrari *et al.* 2000; Çakır *et al.* 2003a). An accurate estimate of static stress changes caused by an earthquake on the neighbouring active faults depends heavily on the source parameters of the earthquake itself. Therefore, the rupture parameters of the 1999 İzmit earthquake need to be well constrained to assess the seismic hazard in the İstanbul metropolitan area that hosts nearly 20 million of people.

Although the surface rupture of the 1999 earthquake was very well documented onshore, the offshore continuation in the Gulf of İzmit still remains ambiguous because the coseismic surface faulting of the İzmit earthquake disappears offshore west of Gölcük, immediately after displaying a right-lateral offset of about 5 m (Figures 1b & 2c) (Barka *et al.* 2002). Further west, field observations did not reveal any evidence for a surface rupture in the Hersek Delta except some ground cracks and open fissures, suggesting that the rupture propagation must have stopped somewhere between Gölcük and Hersek within the Karamürsel Basin (Pınar *et al.* 2001; Kozacı 2002; Lettis *et al.* 2002; Cormier *et al.* 2006). However, GPS and InSAR modelling (Reilinger *et al.* 2000; Wright *et al.* 2001; Delouis *et al.* 2002; Çakır *et al.* 2003b) together with the analysis of aftershock distribution (Karabulut *et al.* 2002; Özalaybey *et al.* 2002), suggest that the rupture most probably continued westward beyond the Hersek Peninsula along the Hersek-Çınarcık segment.

While the study of fault scarps on land has been a successful tool to determine constraints on fault rupture kinematics and earthquake cycles, it is at the pioneering stage for submarine environments. Recent advances in high-resolution submarine imaging allow us to apply a similar approach on the sea floor. After the 1999 İzmit earthquake, many scientific cruises have been carried out in the Sea of Marmara in order to highlight the geometry of active faults and earthquake ruptures on the seafloor. Some of these cruises mainly focused on collecting high resolution geophysical data, i.e. R/V Odin Finder (2000) and R/V Urania (2001), in the Gulf of İzmit in order to image the fault geometry and the offshore extension of the 1999 İzmit rupture

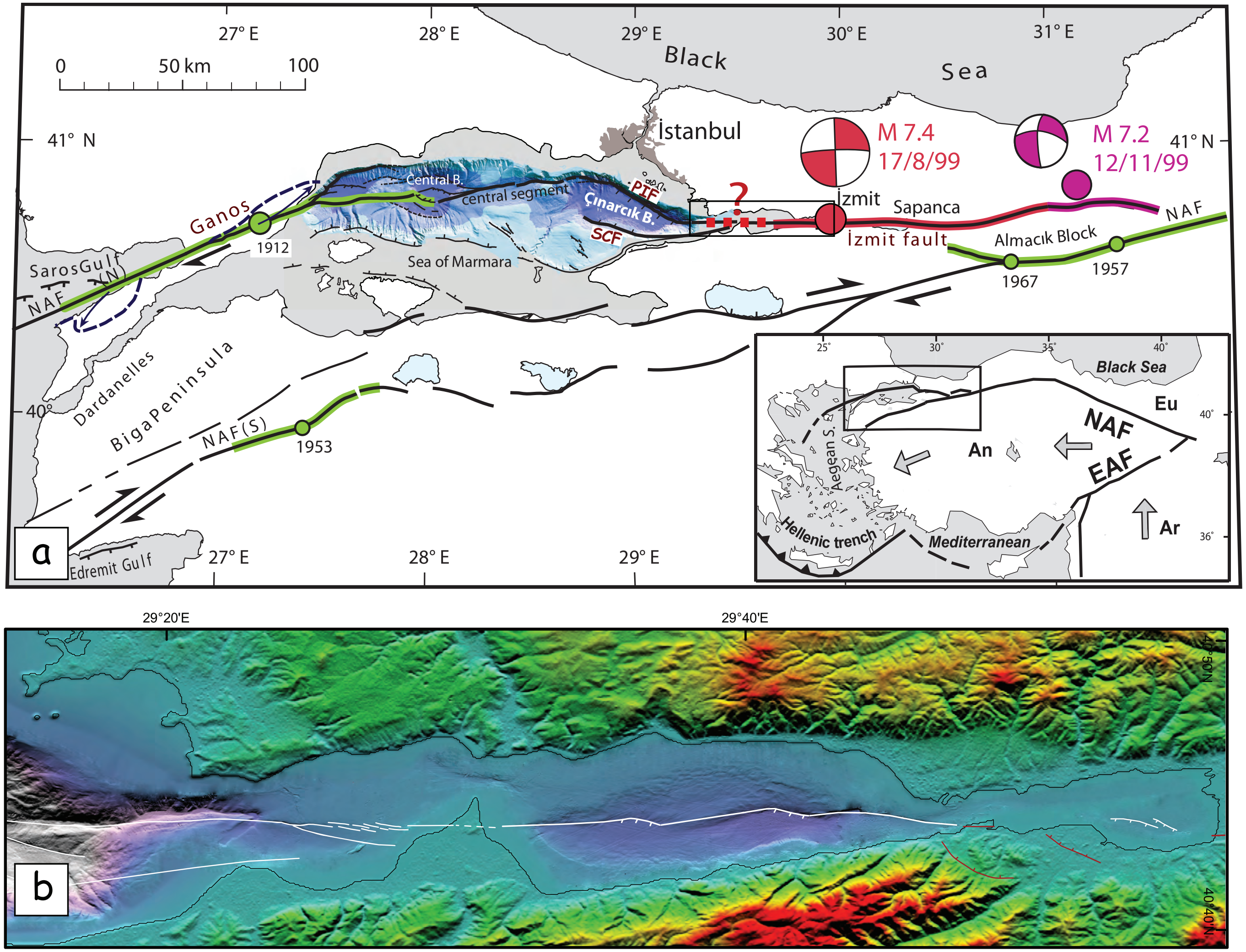

Figure 1. **(a)** Tectonic map of the Marmara region including the EM300 bathymetry of the Sea of Marmara, showing the active faults (Armijo *et al.* 2002) and surface ruptures of the 1999 İzmit (red) and Düzce (purple) earthquakes (Barka *et al.* 2002) with focal mechanism solutions from Harvard CMT. Green lines with dates show the 20th century surface ruptures before the 1999 events. Red question mark with the dashed lines indicates the uncertainty of offshore extension of the 1999 İzmit earthquake rupture. Inset map depicts the tectonics of the eastern Mediterranean with arrows showing the movement of Arabia (Ar) and Anatolia (An) relative to Eurasia (Eu). (PIF– Princes Islands Fault, SCF– Southern Çınarcık fault). **(b)** Shaded (from North) relief image of the Gulf of İzmit mosaicked using SRTM (90 m) for land and multi beam bathymetry from Le Suroit (25 m), Odin Finder (10 m) and SHOD (~10 m). White and red lines show the submarine active faults and the 1999 İzmit rupture, respectively.

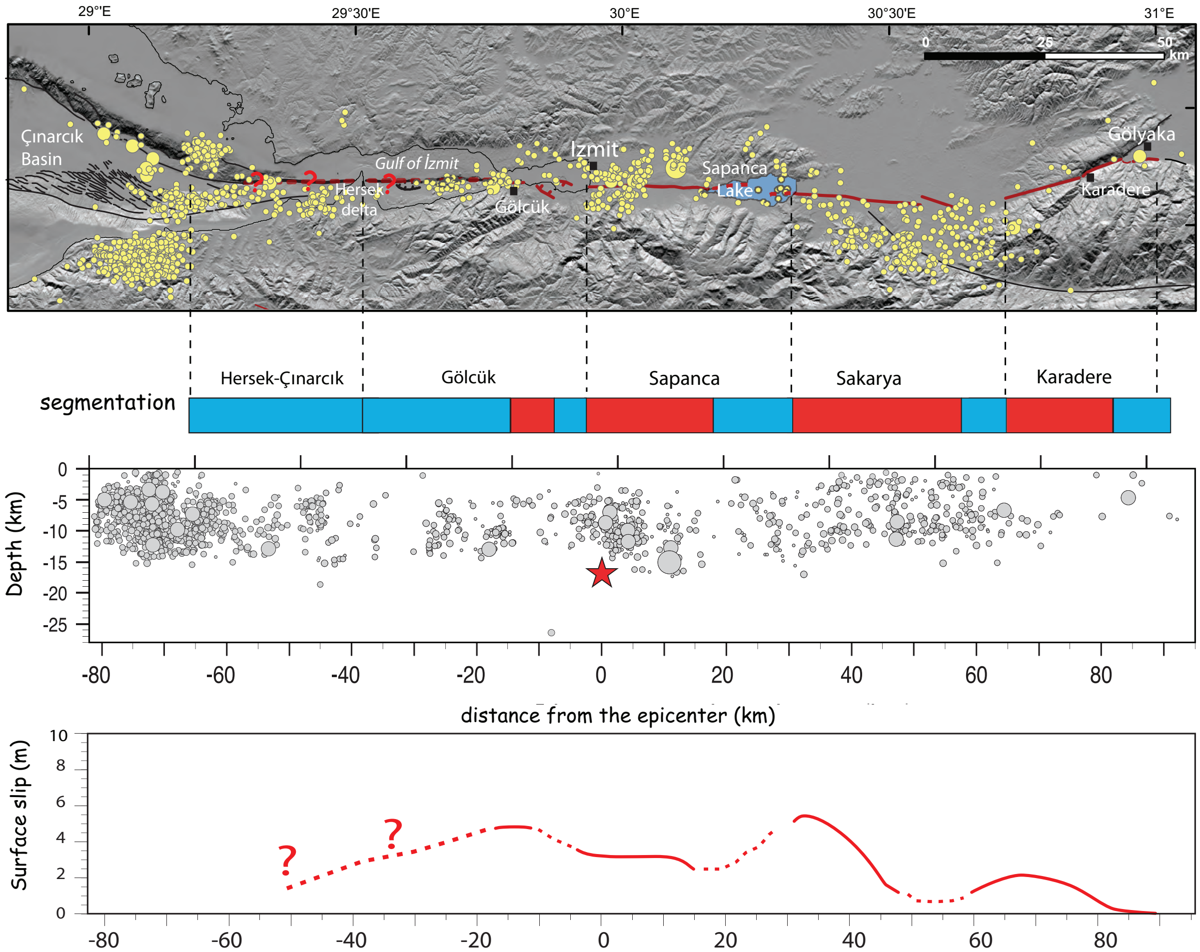

Figure 2. **(a)** Shaded relief map of the Mw 7.4 1999 İzmit earthquake rupture area in the east of Marmara Sea, showing fault segments in black lines (Armijo *et al.* 2002) and 1999 İzmit surface rupture in red lines (Barka *et al.* 2002). Red question marks denote the uncertainty concerning the submarine portion of the İzmit rupture. Yellow circles are $M_L > 2$ aftershocks recorded between August 20 and October 20 1999 by the TUBİTAK permanent network (Özalaybey *et al.* 2002). Red star locates the epicentre of the 1999 İzmit earthquake. The blue-red bar below the map distinguishes individual fault segments that ruptured during the İzmit earthquake; red and blue bars indicate whether or not offsets are observed and measured along the fault rupture. **(b)** Depth cross section of the aftershocks taken parallel to the E–W strike. Red star represent the mainshock hypocentre. The aftershocks extend in an uninterrupted continuation further west from the Hersek delta along the axis of the İzmit Gulf up to the Çınarcık Basin. **(c)** Slip distribution diagram of the 17 August 1999 İzmit surface rupture (after Barka *et al.* 2002). Slip values are extrapolated in dashed lines where there is no direct observation of slip achieved from offshore segments.

(Polonia *et al.* 2002, 2004; Cormier *et al.* 2006). While the combined study of multi-beam and side-scan sonar maps together with the chirp profiles illustrated the fault geometry clearly along the Gulf of İzmit, deformation associated with the 1999 İzmit surface rupture offshore was not identified directly other than some fresh looking cracks found in the Gölcük Basin (Polonia *et al.* 2002). Consequently, the MARMARASCARPS cruise performed in 2002 collected the first ultra-high-resolution bathymetry (microbathymetry) along the active faults in the Sea of Marmara to characterize in detail the submarine fault scarps (Armijo *et al.* 2005). In this study, we present a detailed map of the 1999 İzmit rupture offshore in the western Gulf of İzmit accompanied by our analysis of microbathmetry extracts (0.5 m resolution) from the MARMARASCARPS campaign and inferences concerning the western termination of the offshore fault rupture. We explore the rupture geometry, segmentation, kinematics and morphology of this section of the NAF combining high resolution bathymetric data acquired during other cruises (Polonia *et al.* 2004; Cormier *et al.* 2006), and discuss the controversial extent of fault rupture within the Sea of Marmara. We also perform Coulomb stress modelling with two possible rupture tips to calculate static stress changes caused by the İzmit earthquake on the neighbouring active faults.

Tectonic Framework

The right-lateral North Anatolian transform fault between the Eurasian and Anatolian plates is one of the most prominent and seismically active structures of the Eastern Mediterranean (inset diagram in Figure 1a) (Barka 1996; Armijo *et al.* 1999; Şengör *et al.* 2004). The NAF has an extremely well-developed narrow and simple trace from Karlıova in the east to the Mudurnu valley in the west. However, west of Mudurnu, the NAF splays into two major fault strands known as northern and southern NAF. The northern branch runs through Sapanca Lake and enters the Sea of Marmara through the İzmit Gulf, while the southern branch runs south of the Biga and Armutlu peninsulas through İznik Lake, Bursa and Gemlik Bay. According to GPS observations, most of the lateral motion appears to be transferred obliquely northward, from the main fault to the northern branch, across the Sea of Marmara basin (McClusky *et al.* 2000; Armijo *et al.* 2002; Reilinger *et al.* 2006). The Sea of Marmara is characterized by the 70-km-wide stepover between two well-known strike-slip faults, İzmit and Ganos, which ruptured during the 1999 İzmit and 1912 Ganos earthquakes and appears to be among the clearest examples of pull-apart basins in the world (Armijo *et al.* 2002). The Neogene and Quaternary tectonics puts the northern Marmara under an extensional regime that has caused significant overall subsidence (Armijo *et al.* 2002; Hirn *et al.* 2003; Müller & Aydın 2005). The northern Marmara stepover is formed by smaller steps bounding three deep basins (Tekirdağ, Central and Çınarcık basins) with more active subsidence than in the rest of Marmara (Barka & Kadinsky-Cade 1988; Wong *et al.* 1995; Armijo *et al.* 2002).

The northern branch of the NAF enters the Sea of Marmara through Gulf of İzmit and its purely strike-slip regime already becomes slightly transtensional forming two interconnected basins (i.e., Karamürsel and Gölcük) (Figure 1b). These are depressions, bounded by short, en-échelon, extensional and strike-slip segments (Polonia *et al.* 2004). The bathymetric mapping indicates that the NAF branches into two segments west of the Hersek Delta (Figure 3a); the E–W-trending Hersek-Çınarcık and the ENE–WSW-trending Hersek-Yalova segments. The latter segment runs parallel to the coast and branches into numerous smaller normal faults that partially bound the south of Çınarcık Basin. The 25-km-long Hersek-Çınarcık segment connects to the Princes Islands fault (PIF) that bounds the Çınarcık Basin to the north (Figure 3a). Here, it makes a ~14-km-step to the north and continues westward along the Central segment in the Sea of Marmara (Figure 1a). Analyses of the high-resolution bathymetric data and seismic profiles show that the largest stepover along the northern branch is located offshore in the Çınarcık Basin (Armijo *et al.* 2002). The strike-slip motion between Hersek-Çınarcık and Central segments is transferred via the NW–SE-trending Princes Islands fault. Oblique opening along this fault results in the formation of the deep Çınarcık extensional basin filled with sediments of up to 5 km thick (Carton *et al.* 2007) and represents a major structural complexity along the NAF where the transcurrent tectonics transfers into an oblique extension resulting in significant thinning in the brittle crust.

High Resolution Bathymetric Data Acquisition

After the 1999 İzmit earthquake numerous scientific cruises have been carried out to investigate the active faults in the Sea of Marmara. The Turkish-French cruise of Ifremer R.V. Le Suroit obtained the first complete high resolution bathymetric map of the deep basins of the Sea of Marmara in 2000 (Le Pichon *et al.* 2001; Armijo *et al.* 2002). The high-resolution bathymetry (~25 m), seismic reflection and side scan sonar imaging mapped in fine detail

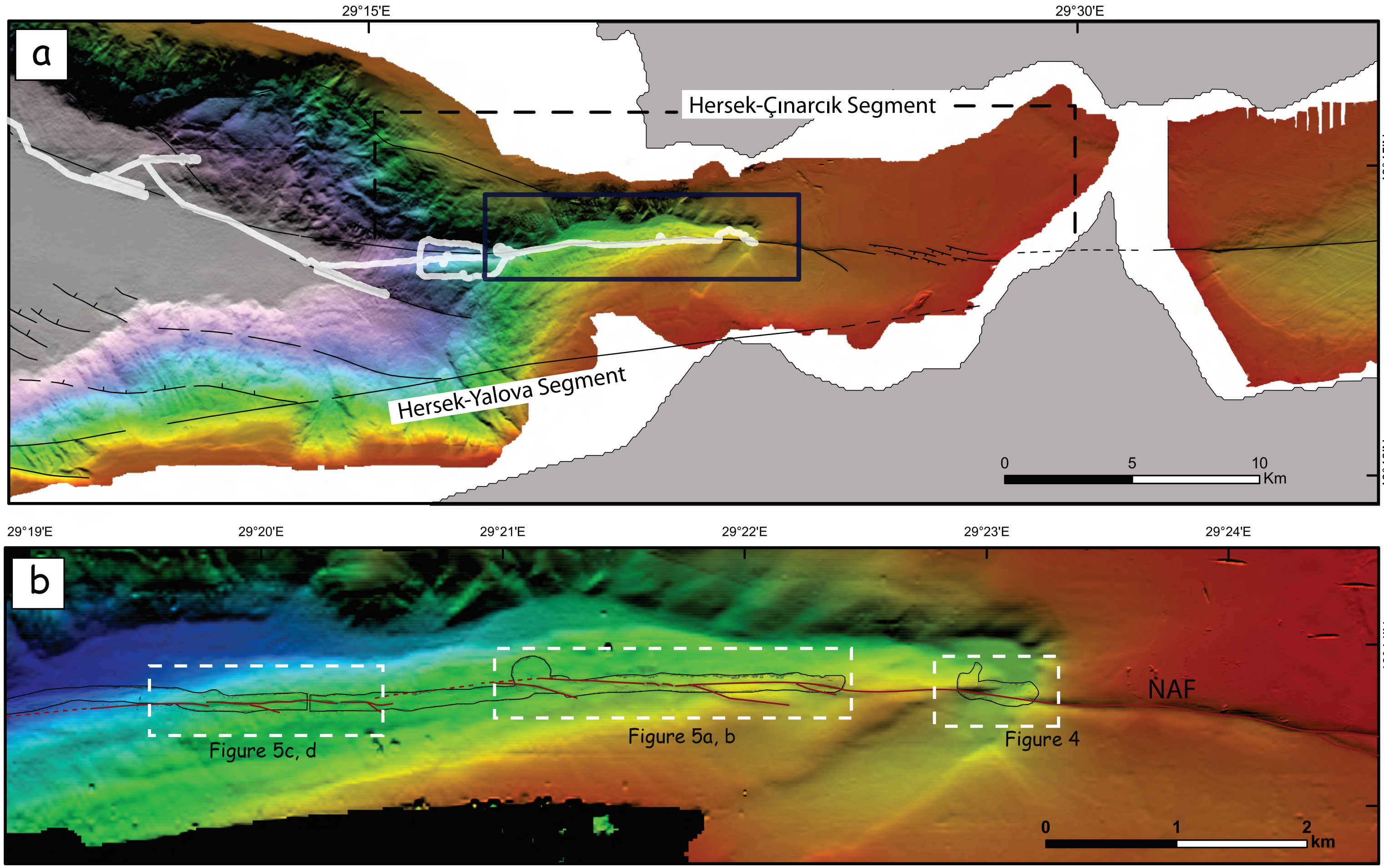

Figure 3. **(a)** Bathymetry map of the western Gulf of İzmit. Map combines EM300 bathymetry (25 m resolution) west of Hersek with multibeam bathymetry (10 m resolution) obtained by R/V Urania in the east. The active fault segments (e.g., Hersek-Çınarcık, Hersek-Yalova segments) are indicated by black lines. The white line shows the track of ROV microbathymetry coverage in this area along the active fault strands. The Quaternary submarine canyon (framed in the black box enlarged in Figure 3b) meets the 1273-m-deep Çınarcık Basin in its western extremity. **(b)** Morphology of the submarine canyon. Map combines multibeam bathymetry (10 m resolution with 0.1 m vertical accuracy) obtained by R/V Odin Finder (Polonia *et al.* 2004; Cormier *et al.* 2006) with the microbathymetry (black outline) collected with Seabat 8101 mounted on ROV Victor 6000 (0.5 m resolution, 0.1 m vertical accuracy). Faults (red lines) are identified from the microbathymetry.

the submarine active faults in the Marmara Sea. In particular, the side scan sonar towed 200 m above the seafloor documented the detailed morphology of fault scarps. In 2002, another Turkish-French cruise, Marmarascarps, collected ultra-high resolution, high-precision bathymetry data (microbathymetry) focusing on the main submarine faults in the northern Sea of Marmara. During the Marmarascarps cruise, video-photo imaging and ultra-high-resolution bathymetric mapping of the sea floor were carried out with the unmanned submersible (ROV Victor 6000), since other methods such as seismic reflection, side scan sonar or multi beam bathymetry could not resolve surface fault ruptures of individual earthquakes. The new dataset revealed the presence of well-preserved fault scarps associated with recent and historical large earthquakes in the Sea of Marmara (i.e. 1999 İzmit, 1912 Ganos, 1894 Çınarcık earthquakes). These observations allowed the identification of the fault scarps associated with the 1912 Ganos earthquake on the western side of the Marmara Sea (Armijo *et al.* 2005).

The ROV was operated with a Seabat 8101 multibeam sounder to survey faults over a total length of about 300 km with an average horizontal resolution of 0.5 m and a vertical accuracy of 10 cm, using a high-precision submarine navigation system (less than 10 m of uncertainty) based on a DGPS positioning of the vessel. Exploration at low altitude over the sea bottom (2 m) was made in specific sites to make direct visual observations of the fault breaks. The point wise micro-bathymetric data were gridded and plotted using Generic Mapping Tools (Wessel & Smith 1995). In this study, we also combined multibeam bathymetry data collected in the Western and Karamürsel basins of the Gulf of İzmit by R/V Odin Finder (2000) and R/V Urania (2001) (Polonia *et al.* 2004; Cormier *et al.* 2006) (Figure 1b).

Offshore Extension of the 1999 İzmit Earthquake Rupture: Submarine Fault Scarps West of Hersek

The westernmost section of the 1999 İzmit earthquake surface rupture was observed onshore west of Gölcük where the fault rupture crosses the Navy base with a 4.7 m right-lateral offset (Barka *et al.* 2002) and enters the Gulf of İzmit. From this point westward, the fault entirely runs offshore and thus it becomes difficult to identify the rest of the surface rupture (Figure 1b). However, Polonia *et al.* (2002) presented towed camera images of fresh-looking polygonal cracks offshore from Gölcük filled by black and yellowish mud possibly related to fluid or gas escape during 1999 earthquake. Such evidence of gas seepage was also introduced by Kuşçu *et al.* (2005) from chirp profiles acquired during a post-earthquake cruise off Gölcük. Further west, faulting becomes transtensional in the Karamürsel Basin by composite strike-slip and normal faulting (Figure 1b). Cormier *et al.* (2006) described here a series of lineaments that strike subparallel to the main fault branch east of the Karamürsel Basin and interpreted them as open cracks or moletracks. No other significant inferences were made for the 1999 fault break in the Karamürsel Basin except for a small slump which was probably triggered by the 1999 İzmit earthquake (Cormier *et al.* 2006). No ground rupture was observed in the Hersek Delta although the Hersek lagoon reportedly subsided by about 20–30 cm (Lettis *et al.* 2002). The absence of surface rupture across the Hersek Delta can be explained by the attenuation of faulting within the deltaic sediments (Gülen *et al.* 2002). The most likely scenario, however, is that the amount of right-lateral slip across the Hersek Delta is rather small and distributed or absent since it is located at the western end of the Gölcük segment. This was also observed in the Akyazı bend where there is a gap in surface rupture between the Sakarya and Karadere segments.

Sets of E–W-striking, en-échelon, open cracks with throws of up to 25 cm were mapped in the Taşköprü Delta west of Hersek (Figures 1b & 3a) (Barka *et al.* 2002; Gülen *et al.* 2002; Emre *et al.* 2003). These fractures are probably due to lateral spreading of unconsolidated deltaic sediments. North of the Taşköprü delta, the multibeam bathymetry exposes a prominent Quaternary submarine canyon which is offset right-laterally by the Hersek-Çınarcık segment (Figure 3a, b). Polonia *et al.* (2004) inferred a ~100 m right-lateral offset from the sea-floor reflectivity based on CHIRP sonar data. The submarine canyon runs north, but as it deepens it makes a sharp westward turn towards the Çınarcık Basin (Figure 3a, b). It has a relatively flat bottom (at 180 m depth), suggesting that it is now inactive and filled with Holocene sediments. The canyon was active during the Last Glacial sea-level lowstand until about 11 kyr

BP when it was submerged by the Holocene sea-level rise (Çağatay *et al.* 2003; Polonia *et al.* 2004).

The flat floor of the canyon represents the ideal place to search for the sea floor rupture of the 1999 İzmit earthquake, since its levelled surface could preserve only the last earthquake rupture. The ultra high resolution bathymetry data from the Marmarascarps campaign systematically covered the extent of the Hersek-Çınarcık segment aiming to detect the continuation of the surface rupture (Figure 3a, b). Indeed, the microbathymetry shows a remarkable linear rupture across the canyon floor with a sharp south facing scarp (Figure 4a–c). The scarp illustrates an apparent throw of 50 cm (Figure 4d) and moletrack morphology. The Mw 7.4 İzmit earthquake produced a line of moletracks with alternating topography, generally not exceeding 50 cm, while producing consistent right-lateral offsets of ~5 m (Barka *et al.* 2002; Ferry *et al.* 2004). Slope-degrading processes, such as gravity collapse, sliding, talus creep, are expected to be more effective along the canyon compared to in other places on the sea bottom. Therefore, sediment transport must be high enough to bury any individual event and thus the scarp at the bottom of the canyon is most likely to be associated with the 1999 İzmit earthquake. The InSAR modelling indicates a minimum of 2 m horizontal displacement in this area (Çakır *et al.* 2003b), suggesting ~14° rake giving the 0.5 m throw on the canyon floor. Similar vertical and horizontal offsets are common, especially along the Sakarya segment of the 1999 İzmit rupture (see *table 1* in Lettis *et al.* 2002). We also re-measured the offset of the submarine canyon using the eastern edge of the canyon floor and the topographic high in its western edge. Its eastern edge is offset 120±10 m right-laterally. The offset of the topographic high seems rather sharper than the edge of the canyon which gives a right-lateral offset of 130±10 m. Although we are able to measure the cumulative offset from the edges of the canyon, the individual horizontal offset related to the 1999 rupture is hard to assess due the lack of required markers on the seafloor (comparable to man-made features on land).

Further west, the ROV microbathymetry reveals a set of significant fault breaks mostly in a left-stepping en-échelon arrangement, running parallel to the E–W section and southern slope of the canyon (Figures 3 & 5). The fine-scale morphology of these submarine scarps is well preserved and can be continuously traced in the microbathymetry for ~5 km. Morphological features typical of strike-slip faulting such as oblique secondary fault branches, sag ponds (Figure 5a, b) and push-ups (Figure 5c, d), accompany the main fault trace here. Push-up ridges and sag ponds alternate at segment ends or at slight fault bends (Figure 5b, d). The dimensions of these features (50–80 m long; 20–30 m wide) suggest that they resulted from cumulative movements of past events. Topographic profiles constructed from the microbathymetry at this site resolve the fine-scale morphology of these scarps (Figure 6a). As in the canyon floor, nearly all the scarps face upslope to the south and their heights range between 0.5 and 6 metres. The maximum vertical throw is measured as ~6.2 m along this section (Figure 6b). Vertical offsets of up to 2.5 m were observed along the surface rupture on land but, large vertical displacements are located only on extensional jogs mainly in Gölcük and Sapanca (Figure 2). Vertical throws along the main rupture zone are however much lower as expected. Therefore, vertical displacements of up to 6.2 m along the Hersek-Çınarcık segment represent at least three or more earthquakes. The fresh fault scarp morphology in the canyon slope suggests that they were most probably re-activated by a recent event which can be attributed to the western extension of the 1999 rupture. These cumulative scarps can be associated with some of the historical earthquakes that are thought to have taken place on this segment, e.g., 1509, 1719, 1754 and 1894 (Ambraseys & Finkel 1991, 1995; Ambraseys 2002). Detailed investigation of the canyon sedimentary units across the fault may reveal which offshore segments were broken during these earthquakes.

Coulomb Stress Modelling of the 1999 İzmit Earthquake: Implications for the Expected Large Earthquake in the Sea of Marmara

We have conducted Coulomb stress modelling in order to understand how the active faults in the eastern Sea of Marmara were affected by the static stress transfer due to the 1999 İzmit earthquake. We calculate Coulomb stress change on faults considering

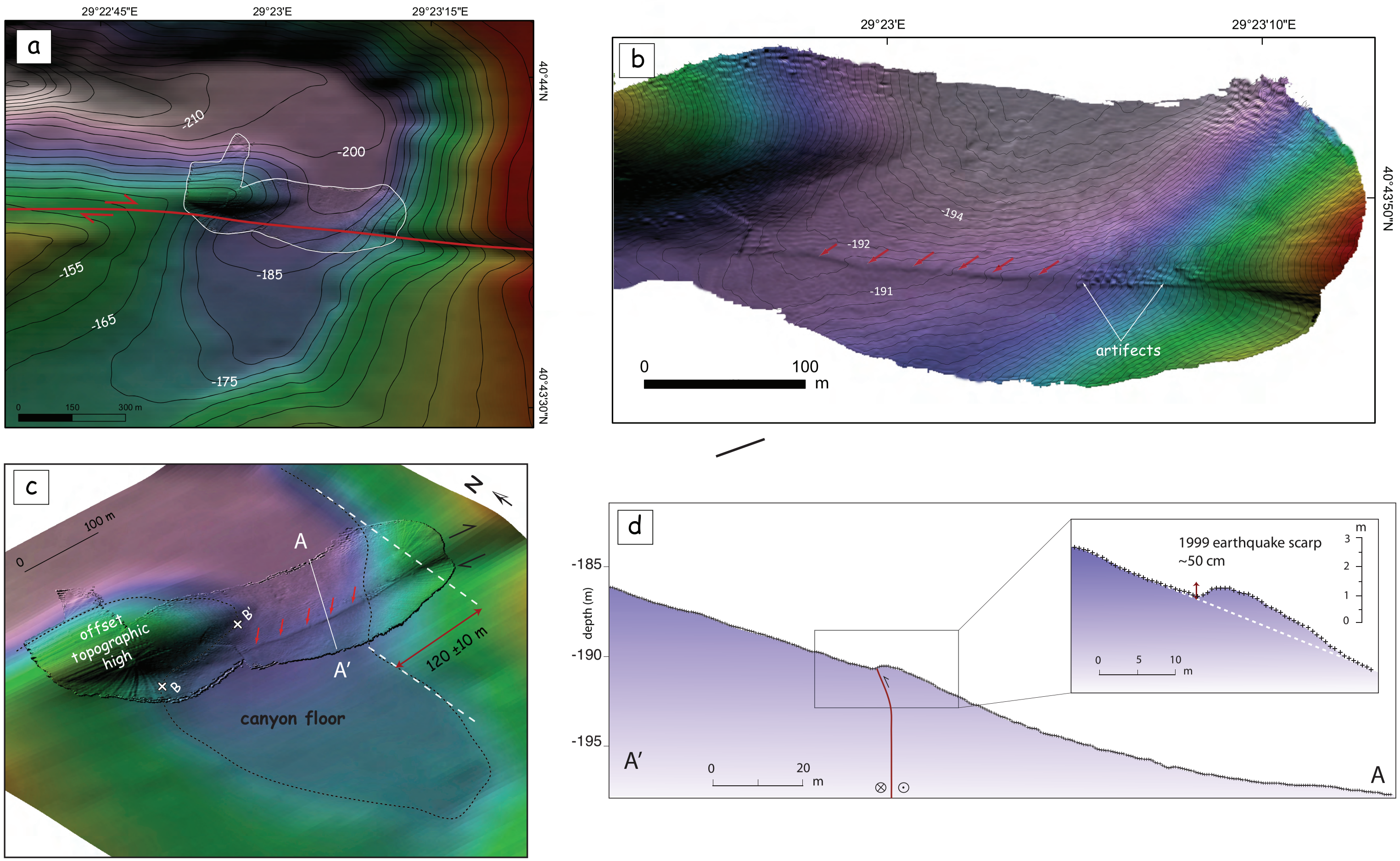

Figure 4. **(a)** Microbathymetry combined with multibeam bathymetry resolves the morphology of the canyon floor. Contours at every 10 m are plotted from the multibeam bathymetry and every 0.5 m from the microbathymetry **(b)** Enlargement of the microbathymetry extract of the canyon floor. A sharp, nearly linear fault break cuts across the bottom of the canyon. Note the offset of contour lines while crossing the fault trace. **(c)** Oblique 3-D microbathymetry view of the canyon floor. The fault trace is sharp and continuous. Shading from north exposes the south-facing scarp clearly. Red arrows highlight the rupture trace. White line displays the location of the topographic profile. White dashed lines indicate the eastern edge of the canyon offset right laterally by the fault (120±10 m). B-B' represents the offset of the eastern edge of the topographic high (130±10 m) **(d)** Enlarged profile across the scarp on the canyon floor. Profile resolves the fine-scale morphology of the south-facing scarp with an apparent throw of 50 cm (less than one contour line in the microbathymetry).

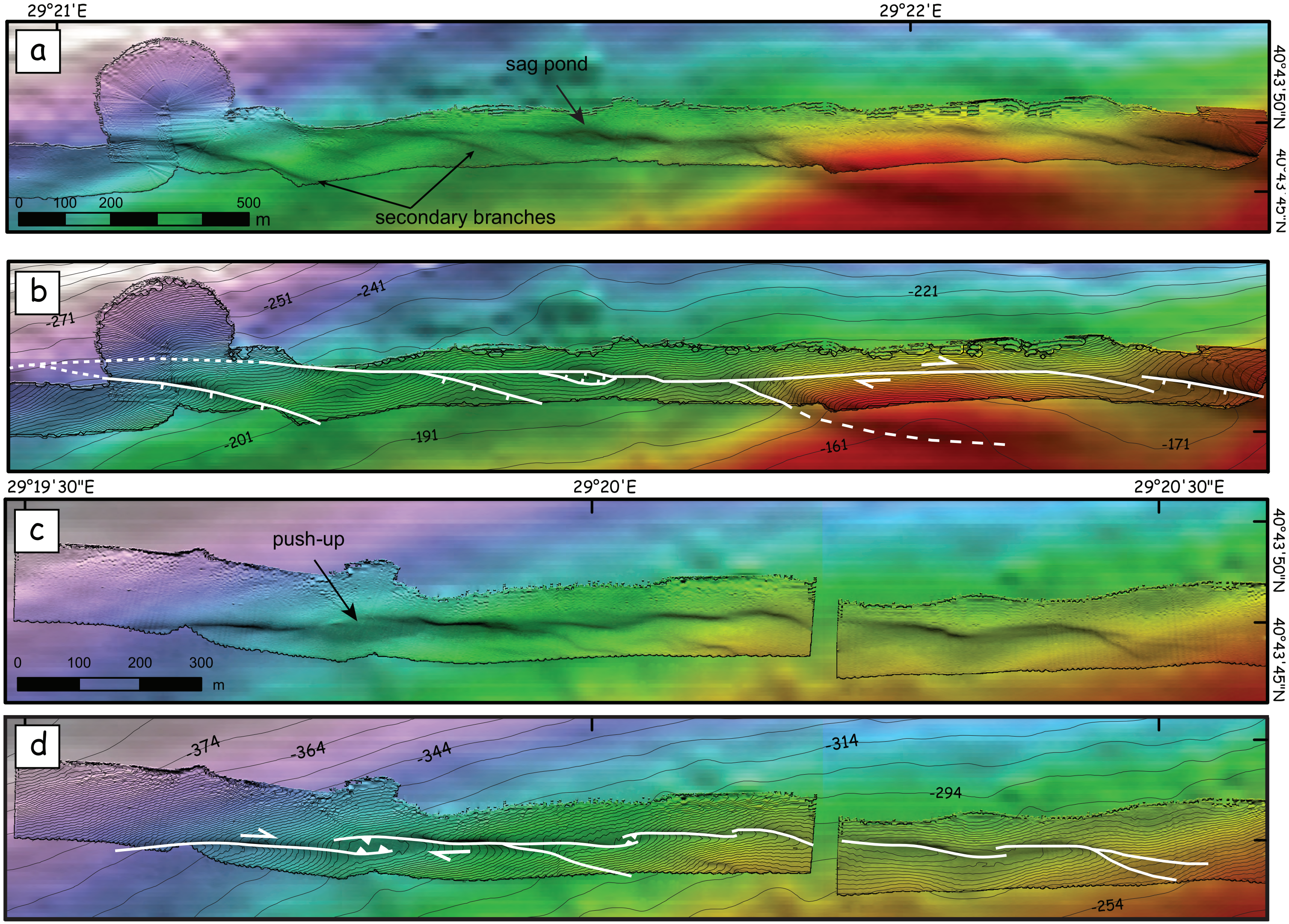

Figure 5. Morphology along the southern slope of the submarine canyon from the combined bathymetry as in Figure 4. **(a)** Central part of the submarine canyon. A continuous fault break can be traced with left-stepping en-échelon steps, secondary branches and a sag pond. **(b)** Fault map deduced from the microbathymetry with contours at an interval of 1 m. **(c)** Westernmost section of the submarine canyon. The fault scarps are in a clear left-stepping en-échelon array producing push-up structure at the segment ends. **(d)** Fault map interpreted from the microbathymetry with contours at an interval of 1 m.

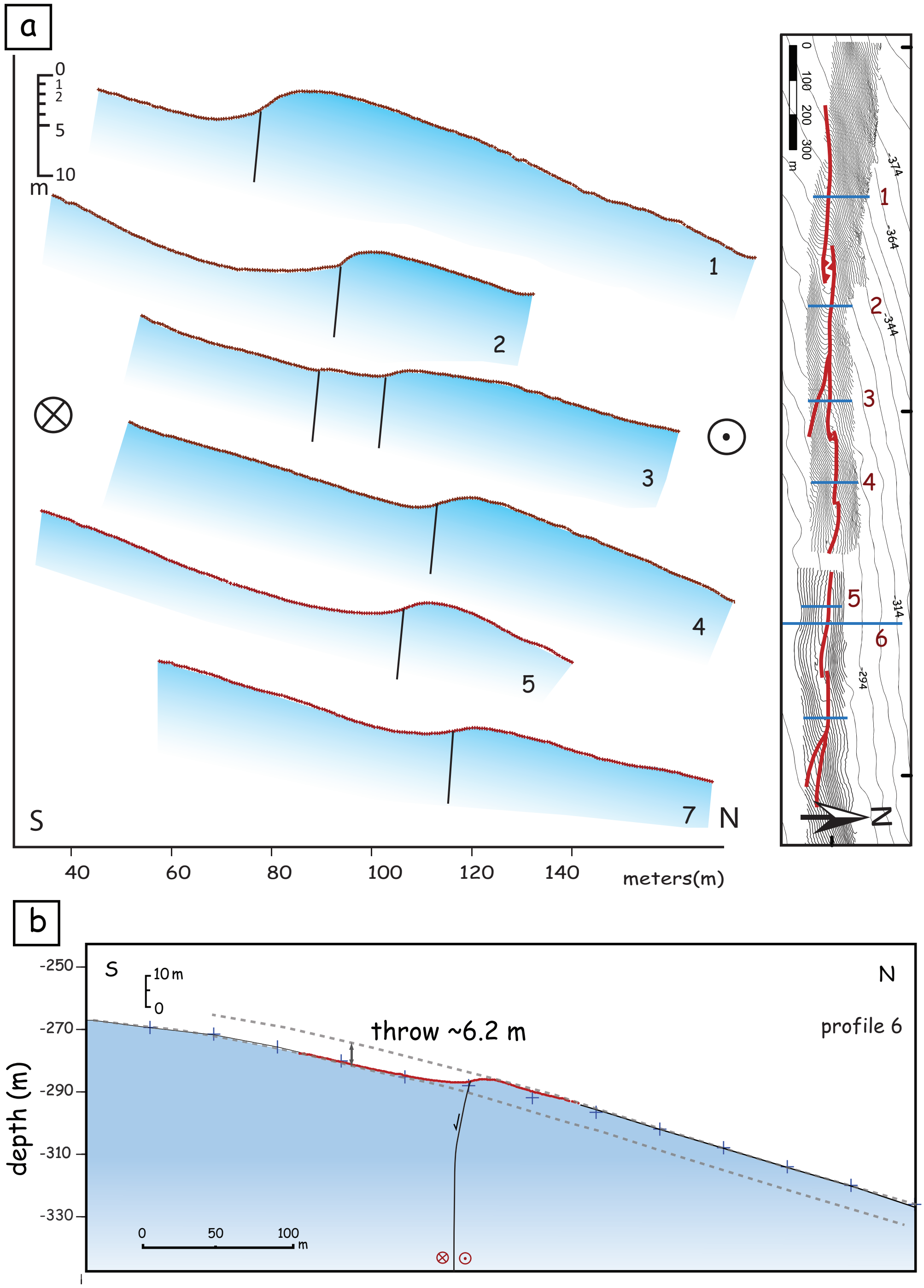

Figure 6. **(a)** Profiles constructed from the ROV microbathymetry with locations shown on the side map (same as Figure 5d). Note that all the scarps face upslope southward. Vertical exaggeration is 2. **(b)** Profile constructed with combined bathymetry. The microbathymetry data (red line) resolves details of the scarp morphology that are not determined with the bathymetry background (blue crosses). Blue dashed line represents the initial slope morphology before faulting. Fault offsets the slope with a clear normal component. Apparent throw measured here is 6.2 m.

two scenarios; rupture terminating (1) near Hersek on the eastern side of the delta or (2) near Yalova about 30 km west of Hersek. We calculate the static stress resolved on the active faults of Armijo *et al.* (2002) using Coulomb 3.1 software developed in the USGS (Toda *et al.* 2005). In the first model, the rupture tip is placed at the western end of the Gölcük segment located east of the Hersek Peninsula around the tip of the Karamürsel Basin. We use a model fault of ~120 km long with distributed (tapered) slip (equivalent of Mw= 7.4) and a coefficient of friction of 0.4. As illustrated in Figure 7a, this model predicts that the İzmit earthquake gives rise to the highest static stress changes in the Hersek-Çınarcık and Hersek-Yalova segments. However, if the İzmit rupture extended 30 km further west rupturing the Hersek-Çınarcık segment, the stress on the Hersek-Yalova segment would not increase, but would decrease significantly, becoming negative. On the other hand, the Princes Islands fault receives 3–4 bars more static stress (Figure 7b). Therefore, in this scenario, while the earthquake potential on the Hersek-Yalova segment is reduced by the termination of İzmit rupture at the entrance to the Çınarcık Basin, the high static stress increase moves further west, bringing the southern and northern boundary faults of the Çınarcık Basin closer to failure.

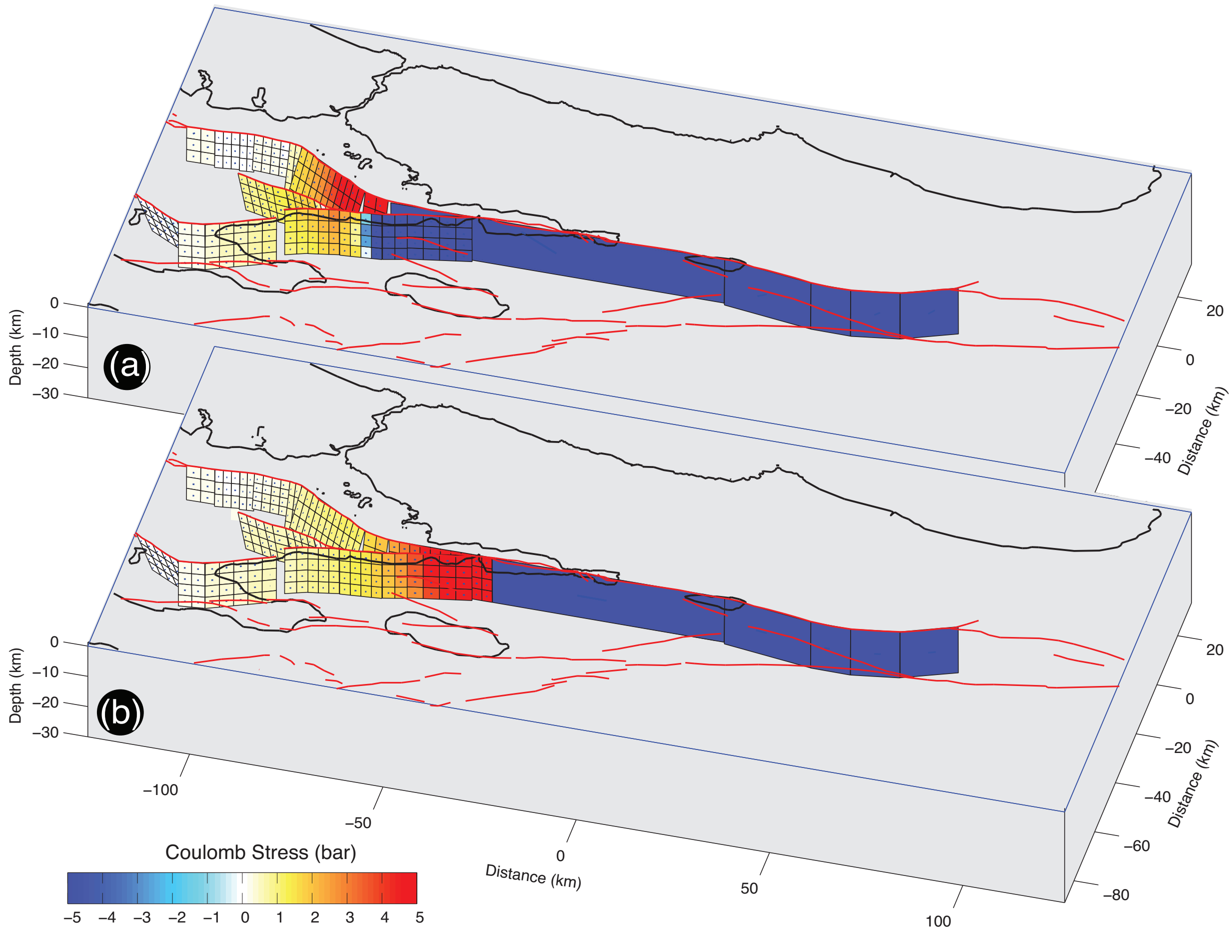

Figure 7. Coulomb stress changes on active faults due to the 1999 İzmit earthquake calculated using Coulomb 3.1 software (Toda *et al.* 2005) with a tapered slip distribution and a coefficient of friction of 0.4. Two possible rupture terminations for the İzmit earthquake were tested. In the first model **(a)** the rupture reaches the entrance of the Çınarcık Basin as we interpret in this study, whereas in the second model **(b)** it terminates just east of the Hersek Delta. Note that in the first model the Hersek-Yalova segment, unlike the Princes Island fault, is not loaded by the İzmit earthquake.

Recent studies incorporating the coseismic slip distribution on land (Altunel *et al.* 2004) and sea floor (Armijo *et al.* 2005) together with the analysis of historical seismograms (Aksoy *et al.* 2009) from the 1912 Ganos earthquake, suggest that the 1912 rupture probably extends from Saros Bay in the west all the way to the Central Basin in the east (Figure 1a). Consequently, if the İzmit fault rupture did not extend west of the Hersek Peninsula, the unbroken section of the NAF under the Sea of Marmara consists of three segments, i.e., the Central Marmara, the Princes Island and the Hersek-Çınarcık segments. These three fault segments may rupture alone or together, and this appears to depend on where the earthquake initiates (Oglesby *et al.* 2008). If the earthquake initiates on the Princes Islands fault, the simulations suggest that rupture, probably, will not propagate in to the neighbouring faults. However, if the earthquake nucleates around the western tip of the Central Marmara segment and propagates eastwards, it seems very likely that the Princes Islands and Hersek-Çınarcık segments will fail as well. The same will also be true if the rupture starts around the eastern tip of the Hersek-Çınarcık segment and propagates westwards. Therefore, if this segment did not rupture during the İzmit earthquake, the probability of a multi-segment rupture is much higher.

Conclusions

The analysis of the ultra-high resolution bathymetry data gathered during the MARMARASCARPS cruise presents evidence that the 1999 İzmit earthquake rupture extends in Gulf of İzmit further west than the Hersek Delta and continues with the Hersek-Çınarcık segment. The supporting evidence is the presence of a fresh fault scarp with a relatively small vertical offset (i.e., 50 cm) across the floor of a Quaternary submarine canyon located ~10 km west of Hersek at 29.38° E longitude (Figure 4). Westward, distinctive fault breaks with higher throws (up to 6.2 m) are traceable for 5 km up to 29.326° E by using microbathymetry (Figures 3 & 5). Although the 1999 break could not be pointed out individually as clearly as in the canyon floor, the fine scale morphology of these fault scarps implies that the rupture continues up to the entrance of the Çınarcık Basin, reaching a total length of ~145 km at around 29.24°E. Instead of stopping in the middle of the straight Hersek-Çınarcık fault segment, the rupture must have propagated all the way to the entrance of the Çınarcık pull-apart basin, where the strike-slip tectonic regime of the NAF significantly changes into oblique extension (Figure 8) (Armijo *et al.* 2002). Our microbathymetry results at the eastern section of the Çınarcık Basin along the Princes Islands fault segment (Figure 3a) do not present any evidence for a recent surface rupture, suggesting that 1999 İzmit earthquake rupture did not proceed further west along the PIF.

Dynamic rupture studies of earthquakes as well as historic observations show that large stepovers (> 4 km wide) play a crucial role in earthquake rupture termination (Barka & Kadinsky-Cade 1988; Harris & Day 1993, 1999; Oglesby 2005; Wesnousky 2006; Elliott *et al.* 2009). In a recent study, Elliot *et al.* (2009) suggested that the gradual increase in complexity toward a stepover will incrementally reduce the rupture energy, causing a gradual decrease of the coseismic slip and prevent the rupture propagation through the stepover. Therefore, we consider that the Çınarcık pull-apart basin between the large stepover (~14 km wide) of the strike-slip İzmit and Central segments in the Sea of Marmara most probably acted as a barrier to rupture propagation and induced the termination of the 1999 İzmit earthquake (Figure 8).

We conclude that the 25-km-long Hersek-Çınarcık segment was broken as the fifth segment during the 1999 İzmit earthquake together with the other four rupture segments (Karadere ~30 km, Sakarya ~25 km, Sapanca ~30 km, Gölcük ~35 km) mapped in the field (Barka *et al.* 2002). Consequently, the static stress transferred by the İzmit earthquake on to the faults bounding the Çınarcık Basin is now significantly (3–4 bars) higher than could have been caused by the rupture termination east of Hersek (Figure 7b). However, failure of the Hersek-Yalova segment is not promoted by the İzmit earthquake as it is located mostly in the stress shadow. Since the Hersek-Çınarcık segment was broken during the İzmit earthquake, it is unlikely that a future earthquake can nucleate around Hersek and propagate westward, breaking both the Princes Islands and Central segments.

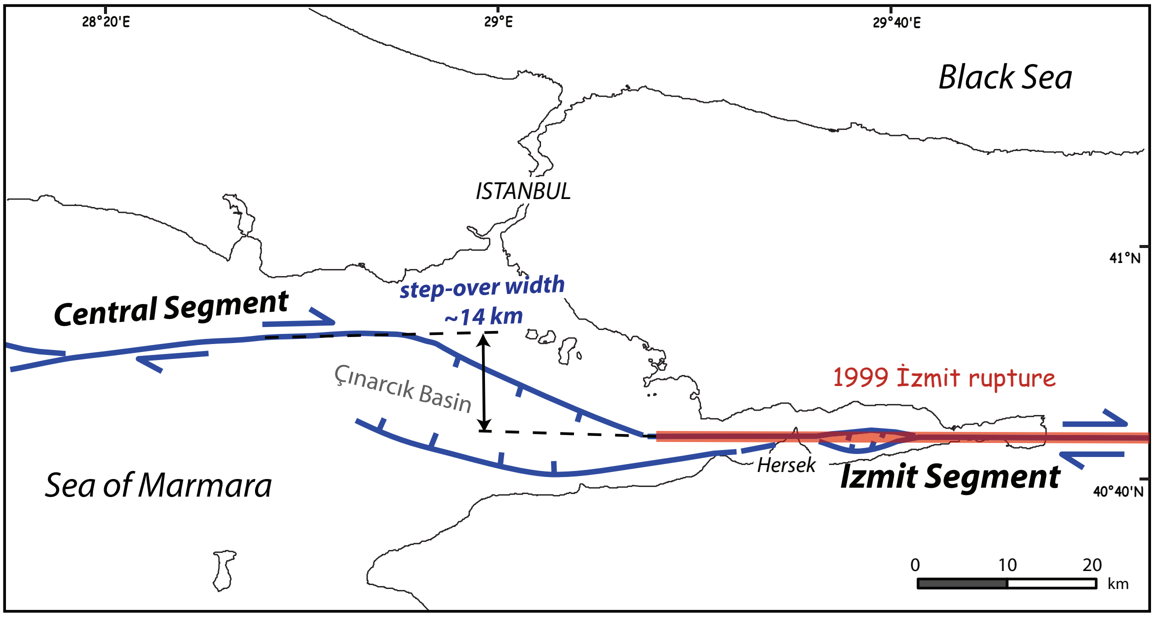

Figure 8. Schematic active fault map of the eastern Sea of Marmara showing the 10-km-wide stepover between the İzmit and Central fault segments. Red line marks the western extension of the 1999 İzmit earthquake stopping at the entrance of the Çınarcık pull-apart basin.

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