

Asymmetric slip partitioning in the Sea of Marmara pull-apart: a clue to propagation processes of the North Anatolian Fault?

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ABSTRACT

Between 1939 and 1999 the North Anatolian fault (NAF) experienced a westward progression of eight large earthquakes over 800 km of its morphological trace. The 2000-km-long North Anatolian transform fault has also grown by westward propagation through continental lithosphere over a much longer timescale (~10 Myr). The Sea of Marmara is a large pull-apart that appears to have been a geometrical/mechanical obstacle encountered by the NAF during its propagation. The present paper focuses on new high-resolution data on the submarine fault system that forms a smaller pull-apart beneath the Northern Sea of Marmara, between two well-known strike-slip faults on land (Izmit and Ganos faults). The outstandingly clear submarine morphology reveals a segmented fault system including pull-apart features at a range of scales, which indicate a dominant transtensional tectonic regime. There is no evidence

for a single, continuous, purely strike-slip fault. This result is critical to understanding of the seismic behaviour of this region of the NAF, close to Istanbul. Additionally, morphological and geological evidence is found for a stable kinematics consistent both with the long-term displacement field determined for the past 5 Myr and with present-day Anatolia/Eurasia motion determined with GPS. However, within the Sea of Marmara region the fault kinematics involves asymmetric slip partitioning that appears to have extended throughout the evolution of the pull-apart. The loading associated with the westward propagation process of the NAF may have provided a favourable initial geometry for such a slip separation.

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Introduction

Unlike oceans with magnetic anomalies, active deformation of the continents is determined from the evolution of the morphology. Relief and other morphological features, such as offset river valleys, result from accumulation of displacement increments during repeated earthquakes (e.g. King *et al.*, 1988; Stein *et al.*, 1988; Yeats *et al.*, 1997). A complete picture of an active region integrates morphological evidence with the geological evolution. In recent years this perspective has been applied to the study of the main faults of Turkey and Greece and, more specifically, to the North Anatolian fault (NAF). Both the morphological and the geological evidence require localized deformation and indicate a westward, plate-scale propagation of the NAF over the past 10 Myr (Armijo *et al.*, 1996,1999; Hubert-Ferrari *et al.*, 2002a). Such propagation appears mechanically similar to the process of rift propagation associated with continental break-up (Hubert-Ferrari *et al.*, 2002b) and seems to involve long-term strength

of the upper mantle. The Sea of Marmara pull-apart (Fig. 1) is an important structure on the NAF, but detailed study of this feature has only been possible previously from data on both sides of the pull-apart where the structure is well constrained. Offset geological markers across the main faults provide estimates of the total lateral displacement (85 km) and of slip rates over the past 5 Myr since the NAF propagated across the area (Armijo *et al.*, 1999). The occurrence of large earthquake ruptures [1912 Ganos earthquake (M 7.4) 1999 Izmit and Düzce earthquakes (M_w 7.4; 7.2), [Fig. 1] has provided examples of right-lateral slip increments corroborating the strike-slip morphology of the active faults on land. However, large earthquake ruptures are likely to occur within the next decades along the submarine faults beneath the Sea of Marmara (e.g. Hubert-Ferrari *et al.*, 2000; Parsons *et al.*, 2000). The new data comprise high-resolution bathymetry, seismic and sonar soundings, which enable the geometry of the main active faults of the Marmara Basin to be determined and the late Quaternary fault morphology and kinematics described. These kinematics are compared both with the larger scale displacement field obtained for the past 5 Myr and with the

present-day motion determined using GPS. This approach allows the degree of slip partitioning across the fault system to be determined and the possible mechanical evolution of the pull-apart to be discerned. It is of particular interest to assess whether the structure of the Sea of Marmara results chiefly from diffuse extensional deformation of the Aegean domain, or from localized lithospheric shear associated with the NAF.

The Sea of Marmara pull-apart system

In the Sea of Marmara region, the right-lateral NAF splays into two major fault branches that are about 100 km apart, before entering the Aegean westwards (Fig. 1, insert). According to available geological and geodetic data (Armijo *et al.*, 1999; McClusky *et al.*, 2000), most of the lateral motion appears to be transferred obliquely northward, from the main to the northern branch, across the large rhomb-shaped basin that the two branches embrace. Therefore, the Sea of Marmara is basically an extensional step-over, or pull-apart structure (Fig. 1). Such a configuration requires substantial subsidence and localized crustal stretching.

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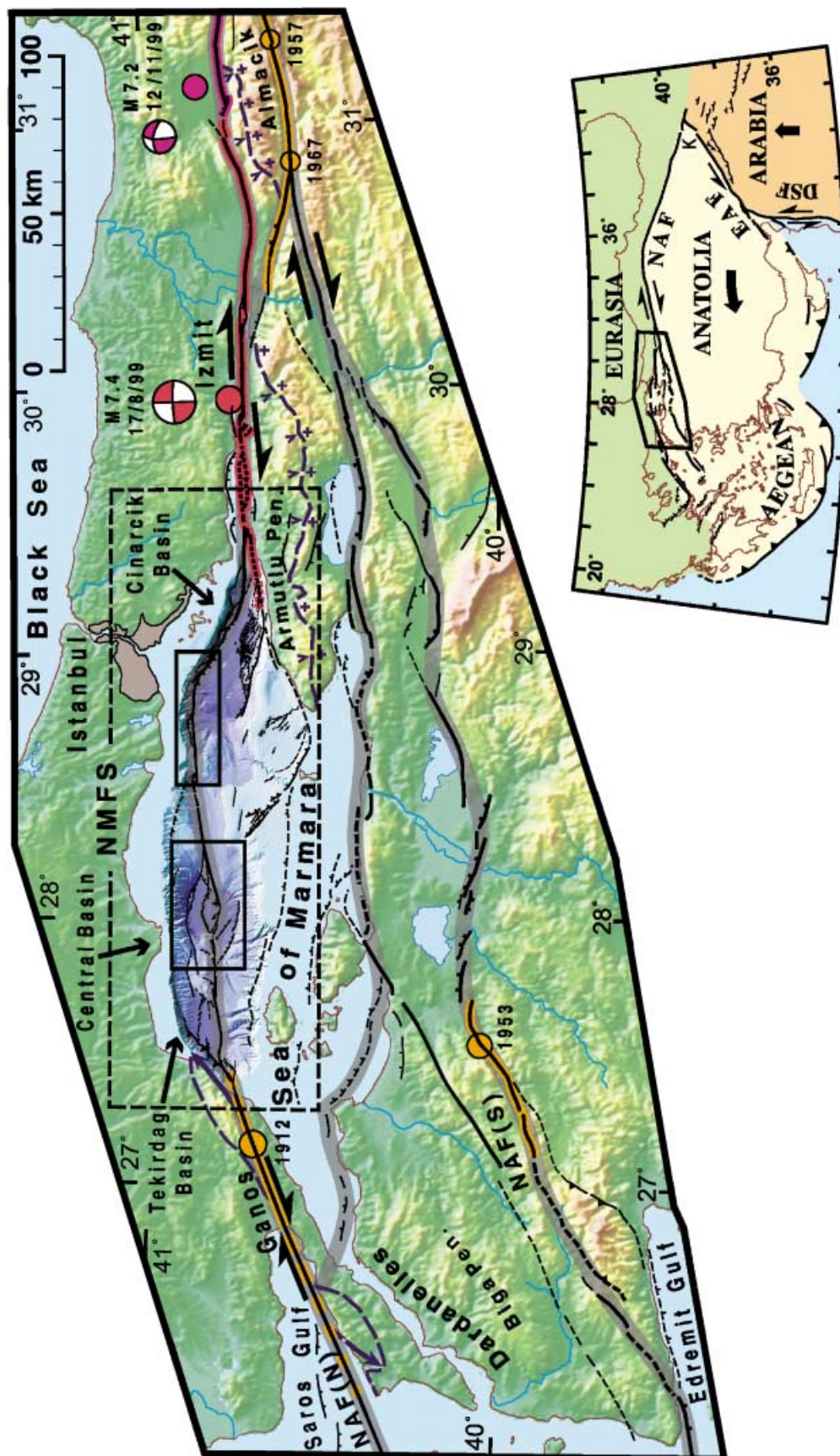


Fig. 1 Active tectonics in Sea of Marmara pull-apart (redrawn from Armijo *et al.*, 1999) including the new EM300 bathymetry and the newly mapped submarine faults. The North Anatolian fault (NAF) splits westward into two main branches 100 km apart forming the larger pull-apart. Most of the lateral motion is transferred across Marmara to the northern branch (N). The sinuous southern branch (S) bypasses the pull-apart but accommodates much less motion. A smaller pull-apart called the North Marmara Fault System (NMFS) interconnects the deep northern basins (Tekirdag, Central and Cinarcik basins) with two large strike-slip faults on land (Izmit and Ganos faults). Recent earthquake breaks and fault plane solutions are outlined. Cuts (faults overlaid with grey) and geological markers (dashed blue) used for restoring slip in Fig. 5(b) are the same as discussed in Armijo *et al.* (1999). Details of the cuts within the NMFS follow the new data. Boxes indicate details enlarged in Figs 3, 4. Inset shows the tectonic setting of continental extrusion in eastern Mediterranean. The Anatolia–Aegean block escapes westward from the Arabia–Eurasia collision zone, towards the Hellenic subduction zone. EAF, East Anatolian fault; DSF, Dead Sea fault.

Accordingly, the Marmara basin contains significant amounts of recent sediment (average thickness 1–2 km), which is very thick in the deeper northern basins (> 6 km) and is cut by large normal faults, as observed in seismic profiles (e.g. Parke *et al.*, 1999). Within the larger Marmara pull-apart, a smaller pull-apart is formed by an oblique submarine fault zone which links the two strike-slip branches that ruptured in 1912 and 1999 (Ganos and Izmit faults). This oblique submarine zone is here termed the North Marmara Fault System (NMFS). Within the NMFS two shallower ridges at about 700-m depth separate an arrangement of three deep basins (with depths over 1000 m; from east to west, Cinarcik, Central and Tekirdag basins). Several recent studies using seismic reflection profiles have proposed detailed maps of the submarine structure (e.g. Okay *et al.*, 1999; 2000; Parke *et al.*, 1999; Imren *et al.*, 2001). Although the dataset is similar, each interpretation is different and it is difficult to explain the discrepancies. The present contribution uses high-resolution data on the NMFS collected during the French–Turkish cruise carried out aboard RV *Suroit* in September–October 2000. They include a EM-300 multibeam bathymetry map with 25 m gridding (Fig. 2), back-scatter and side-scan sonar imagery, and seismic reflection profiles using surface and deep-towed streamers. Le Pichon *et al.* (2001) recently presented these data, a fault map and a tectonic interpretation. The present contribution offers a discussion of the outstanding morphological features clearly exposed in two selected areas (Figs 3 and 4) and provides a tectonic interpretation consistent with our knowledge of the NAF elsewhere.

The morphology of the active faults is well preserved on the seafloor. Fault scarps probably resulting from many seismic events can be followed over tens of kilometres and described in detail. Individual breaks that may correspond to earthquakes in the recent past are also distinguishable. Most scarps show clear normal and strike-slip fault morphology, forming bends and pull-apart features at a range of scales. As anticipated (e.g. Barka and Kadinsky-Cade, 1988), active faulting along the NMFS is

segmented and appears to interconnect the largest pull-apart basins (Cinarcik, Central and Tekirdag Basins) with the Izmit and Ganos faults on land (Fig. 1).

In the middle of the Central Basin (Fig. 3), distinct *en echelon* fault scarps enclose a pull-apart with a characteristic rhomb shape. The individual scarps strike NW–SE and display clear normal fault morphology across the most recent sediment. They are, on average, 1–2 km long and the flat floor of the pull-apart is 20–60 m deeper than the surrounding seafloor. Clear young fault scarps with similar strike also run at the base of the much larger – probably longer term – escarpments located at the edges of the Central Basin. Both the inner and outer faults of the basin thus have normal components of slip and appear to splay, in map view, from linear right-lateral fault segments striking ENE–WSW, which are located east and west of the pull-apart structure. Between these two segments, the extensional step-over is about 4 km. The nested graben structure that characterizes the geometry of the subsiding Central Basin in cross section is well portrayed in the seismic profiles (Fig. 3, lower panel). Indeed, nested pull-apart features are indicative of a long-lived geological structure in the Central Basin, controlled by a stable mechanism.

The underlying kinematics governing active faulting in the NMFS appear to be well determined at the sharp bend connecting two major fault segments with different strike, south of Istanbul (Figs 1 and 4). The fault seen west of the bend is a linear strike-slip fault striking N80°E that crosses the shallower area separating the Central and Cinarcik basins. A ridge intersecting the fault is offset 3.5 km right-laterally. This feature provides us with an estimate of displacement on the NMFS over the past few 10^5 years (see caption of Fig. 4). In contrast, the fault east of the bend is at the base of the large NW–SE-striking escarpment forming the northern edge of the Cinarcik Basin. An arrangement of *en echelon* normal fault scarps with throws of 60–100 m is seen along this fault. This suggests that composite normal and strike-slip during repeated earthquakes is responsible for the creation of the

Fig. 2 Bathymetric map of the North Marmara Fault System (NMFS) (contours in metres).

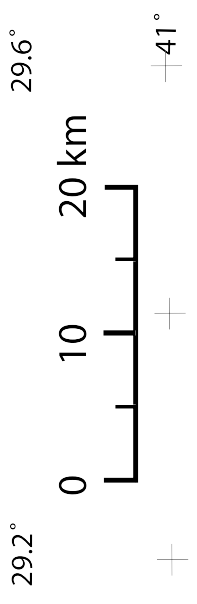
1000-m-high, 40-km-long, North Cinarcik escarpment. Interestingly, two parallel fault traces 1–2 km apart are observed over 10 km in the bend area, suggesting slip partitioning: almost purely right-lateral slip across the southern linear fault; significant normal slip across the fault at the base of the large escarpment. Similar features have been described elsewhere in basins under oblique extension (Armijo *et al.*, 1986; Yeats *et al.*, 1997).

Finally, some compressional structures can be deduced from the seafloor morphology and seismic profiles at the appropriate contractional bends and stepovers of the NMFS. These are minor features. Examples are found in the western half of the Sea of Marmara, over the two sides of the central pull-apart basin (Fig. 3). Thrusting seems particularly prominent at the Ganos bend, at the western end of the NMFS (Fig. 1), where active folding has been described on land (Armijo *et al.*, 1999).

Kinematic reconstruction, slip partitioning within the pull-apart

The foregoing observations of the fault morphology and kinematics can be used to make a simple reconstruction of the NMFS such as that presented in Fig. 5(a). The motion is assumed to be localized on the larger submarine faults and the strike-slip segments identified on land. This stage of reconstruction incorporates neither deformation on smaller faults, nor slip on faults whose trace does not definitely link with the larger faults. Restoring the 3.5-km right-lateral slip observed in the morphology (Fig. 5a) indicates where and how extensional (yellow) and compressional (pink) deformation should be accommodated and defines the motion across the NMFS over the past few 10^5 years. These kinematics can be compared with independently determined, longer-term geological information and larger-scale kinematics.

The reconstruction of the overall Marmara pull-apart at ≈ 5 Ma (Fig. 5b) is from Armijo *et al.* (1999)



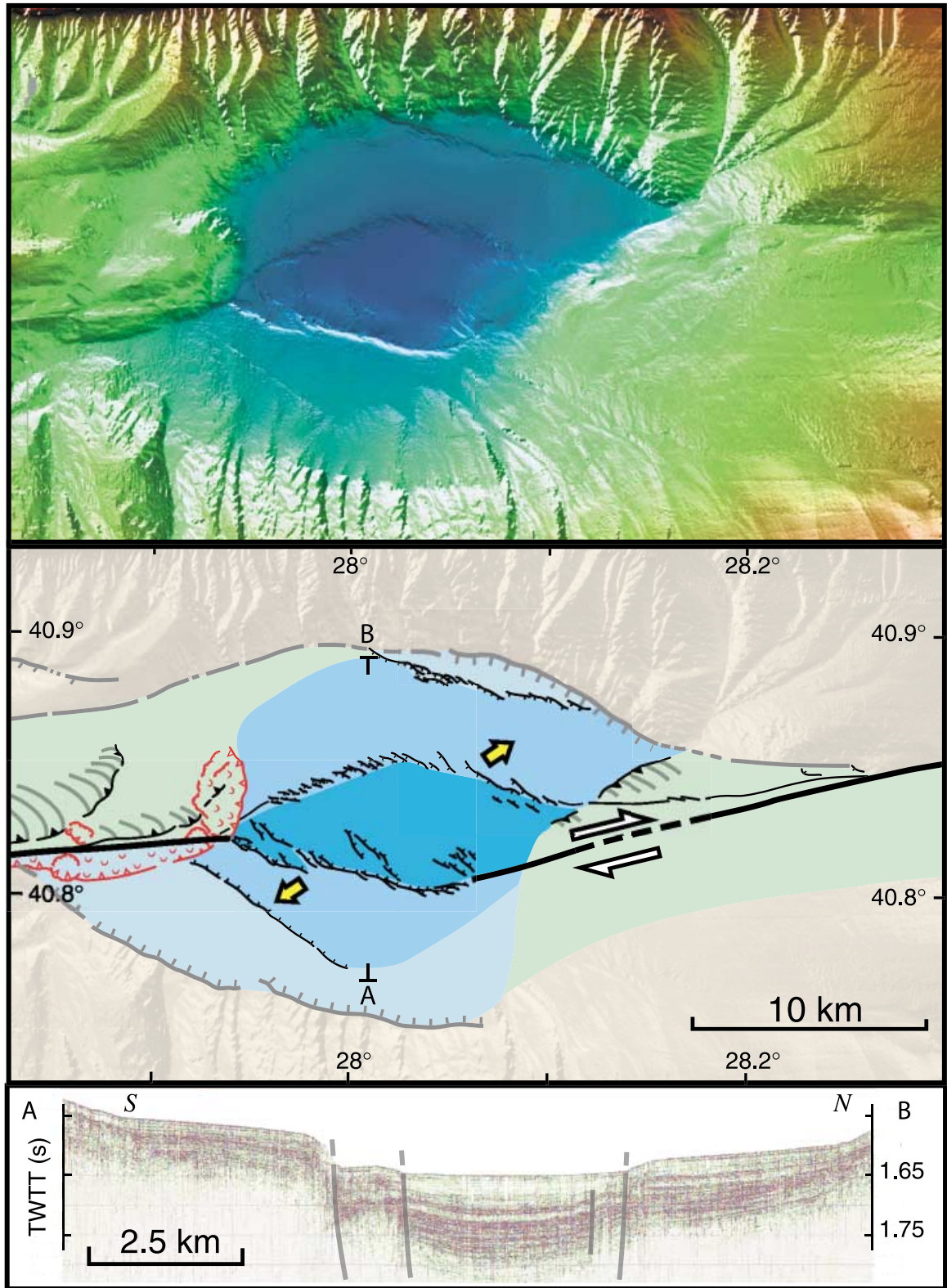


Fig. 3 Details of the Central Basin. An internal pull-apart has formed within the larger pull-apart structure. Outline (middle) shows *en echelon* normal faults and corresponding extension direction (yellow arrows). Subsidiary zones of compression (hatched) may exist on eastern and western sides of the pull-apart. Main strike-slip faults in bold. Slumped areas shown in red. Nested rift-in-rift structure and young sediment fill are seen in the cross section (A–B; below, single-channel sparker profile).

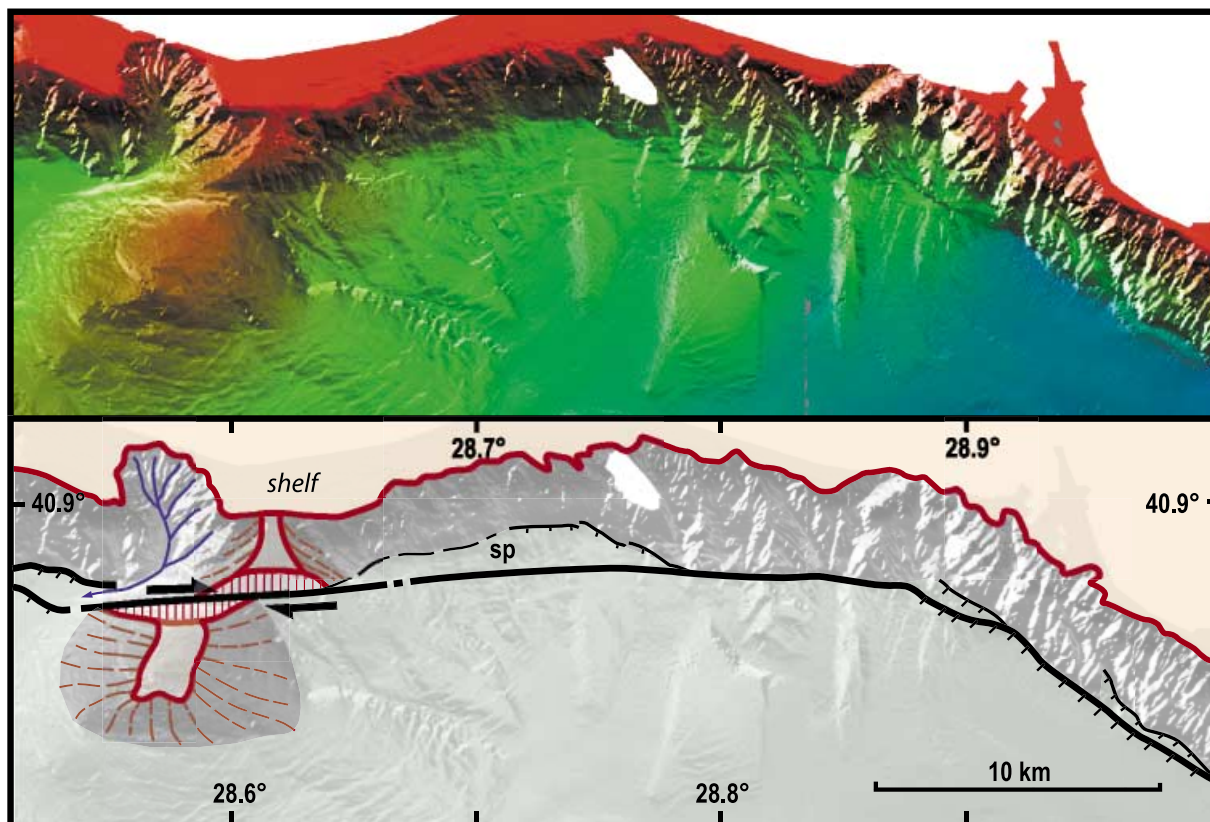


Fig. 4 Connection between normal and strike-slip faulting at the fault bend north-west of Cınarcık basin (south of Istanbul). Scarps 50–100 m high, striking NW at the base of the steep rough slopes of the 1000-m-high basin margin (to the NE) turn into a right-lateral WSW-striking fault (to the SW). Note the ridge that is laterally offset 3.5 km and the apparent slip partitioning at ‘sp’. The morphological offset here is the clearest found in the bathymetry of the Sea of Marmara. Taking a possible slip-rate range of 1–2.5 cm yr⁻¹ (consistent with 50–100% of the rates derived from the geological observations and from the GPS measurements) gives possible offset ages of 1.4–3.5 × 10⁵ yr.

(slightly modified). The Anatolia–Eurasia direction of motion is the same as that determined with GPS (McClusky *et al.*, 2000; purple arcs in Fig. 5a and b). The model restores the initial geometry of structural markers just prior to the NAF propagation through the Dardanelles region and involves 85 km total right-lateral displacement of Anatolia relative to Eurasia, most of it (70–90%) accommodated across the Northern Branch. The displacement field obtained involves slip partitioning in the Sea of Marmara. Specifically, a larger proportion of strike-slip motion, relative to extension, appears to be accommodated NE of the pull-apart, across the NMFS. Conversely, a more extensional regime is expected across the shelf SW of the pull-apart, consistent with the dominant normal faulting observed in the seismic profiles (Parke

et al., 2000). No difference can be resolved for the direction of motion determined across the NMFS in the two reconstructions shown in Fig. 5, despite the different timescales (see caption of Fig. 5b).

Mechanical implications

The North Marmara Fault System involves oblique extension and is segmented. This is inconsistent with the hypothesis of a single, through-going, purely strike-slip fault (Le Pichon *et al.*, 2001). The NMFS includes significant fault step-overs that could arrest propagation of large seismic ruptures. Thus, the relatively complex geometry and kinematics of active faults along the NMFS appear consistent with the inference that destructive historical earthquakes have been generally smaller in the

Sea of Marmara than elsewhere along the NAF (Ambraseys and Jackson, 2000).

Motions over 10⁵ yr and 5 × 10⁶ yr in the Sea of Marmara region are consistent with the broader kinematics of the extrusion of Anatolia derived from space geodesy (McClusky *et al.*, 2000). Any overall opening attributable to Aegean extension (e.g. Sengör *et al.*, 1985; Parke *et al.*, 1999) is small and the extension that has created the Marmara basin results from the overall step-over formed with the northern branch of the NAF. The southern branch of the NAF takes up some right-lateral motion, but this is no more than 20% of the total. Within the Marmara pull-apart, block motion describes the kinematics with one block boundary (the NMFS) carrying a greater ratio of strike-slip to normal motion than others. The same asym-

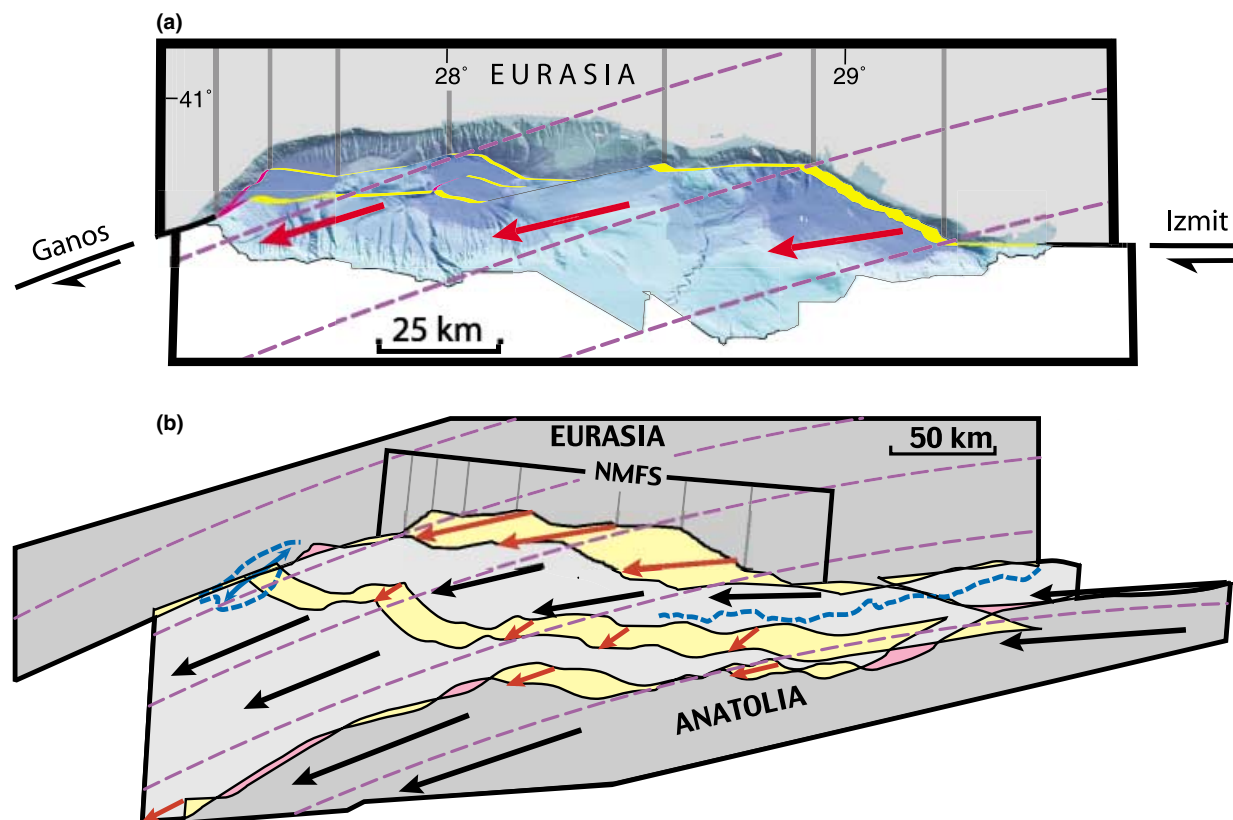


Fig. 5 Kinematic model of the Sea of Marmara pull-apart. (a) Reconstruction of the submarine NMFS in the late Quaternary (last few 10^5 yr). The 3.5-km-offset ridge of Fig. 4 is restored. Overlaps and gaps in the reconstruction (in yellow and pink, respectively) are regions where extension and compression have occurred leading to the present geometry. They emphasize the stepped pull-apart geometry. Large normal faulting along the north Cinarcik escarpment (2 km extension) and significant thrusting at the Ganos bend (0.5 km contraction) are expected. Red arrows show the direction of motion of the southern block relative to Eurasia. The direction of Anatolia/Eurasia motion deduced from GPS measurements is also shown (purple arcs constructed with Euler pole from McClusky *et al.*, 2000). Vertical grey lines indicate the simplified boundary used in (b). (b) Reconstruction at ≈ 5 Ma with geological markers (in dashed blue) restored and the corresponding displacement field (slightly modified from Armijo *et al.*, 1999). The Anatolia–Eurasia direction of motion obtained in the previous reconstruction by Armijo *et al.* (1999) was, within errors, the same as that deduced from GPS (McClusky *et al.*, 2000). To simplify, the Anatolia/Eurasia motion is taken strictly parallel to the GPS model [purple arcs as in (a)]; however, the average Anatolia/Eurasia velocity deduced across Marmara for the past 5 Myr is 17 mm yr^{-1} , somewhat less than the $22 \pm 3 \text{ mm yr}^{-1}$ determined using GPS (Kahle *et al.*, 2000). Black vectors are relative to the northern block (Eurasia); red vectors are relative to the adjacent block. Vectors inside the pull-apart deviate from Anatolia/Eurasia circles because reconstruction requires slip partitioning. The Submarine NMFS is indicated by grey lines and the northern frame of A is rotated to its initial position. The reconstruction shows that significant, long-term, oblique extension has occurred over the NMFS. The direction of motion across it (large red arrows, locally referred to Eurasia) is indistinguishable from that of the shorter-term motion determined in (a). This is because the two reconstructions (a) and (b) require primarily right-lateral slip along the Izmit and Ganos faults.

metric slip separation seems to have persisted since the inception of the NAF in the region.

Two overall explanations for slip separation are possible:

1 Slip partitioning is an effect of gravity. Faulting commences with oblique slip on one feature. However, with time the topography created by the dip-slip component creates stresses that resist further opening. The normal component of motion conse-

quently migrates to new structures while strike-slip motion persists on the original feature.

2 Slip separation is attributed to asymmetric loading during propagation of the NAF. During a first stage the NAF at depth deviates to the north, instead of propagating further southwestwards along the arc determined by the rotation of Anatolia. This causes oblique extensional features to form, consistent with the NE-dipping normal

faults in the southern Sea of Marmara, which may have provided the initial asymmetry to the pull-apart. As the motion propagates to the surface, strike-slip becomes more concentrated on the northern fault system, which has more adapted geometry, rather than on the early normal faults. This system once established then persists as the northern NAF propagates farther southwestward, across the Dardanelles into the Aegean (Armijo *et al.*, 1999).

The two mechanisms are not mutually exclusive, but for the first, structures should evolve with time. In the absence of clear evidence for such evolution, it is proposed that the asymmetric slip partitioning within the pull-apart is an effect of propagation. A more detailed knowledge of the structure and stratigraphy of the Sea of Marmara, together with information from land studies should allow this scenario to be refined and modelled.

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