

# Westward propagation of the North Anatolian fault into the northern Aegean: Timing and kinematics

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## ABSTRACT

We present new evidence for the propagation processes of the North Anatolian fault. Folding in the Dardanelles Straits region allows us to document the timing of the deformation preceding, and the finite displacement after, the passage of the propagating tip of the fault. The accuracy of the observations is due to interplay between deformation and the sea-level changes in the Mediterranean (the well-known Messinian regression followed by the Pliocene transgression). The long-term kinematics around the Sea of Marmara pull-apart (total displacement of about 85 km over the past 5 m.y.) is similar to the present-day kinematics deduced from space geodesy. At a larger scale, westward propagation of the North Anatolian fault over nearly 2000 km in the past 10 m.y. appears to be associated with strain recovery, suggesting that the continental lithosphere retains long-term elasticity.

## INTRODUCTION

Since the advent of plate tectonics, a challenging problem has been the transient mechanical behavior of the lithosphere at evolving plate boundaries. Yet, propagation of plate-scale faults through the continental crust and lithosphere has received little attention, mainly because pertinent observations are scarce. The active right-lateral North Anatolian fault, a feature long considered a continental transform (Ketin, 1948; McKenzie, 1972) is an excellent example to study. The fault now forms the boundary between Eurasia and Anatolia, which were previously welded together (Fig. 1). Wrenching along the fault apparently started after closure of the Bitlis suture along the Arabia-Eurasia collision zone in Miocene time (e.g., Sengör et al., 1985). Closer to the Hellenic subduction zone, a zone of diffuse, transtensional deformation in the northern Aegean and central Greece (Fig. 1) can be viewed as a large process zone related to the westward propagation of the North Anatolian fault, which implies current, wholesale extrusion of the Anatolia-Aegean block (Armijo et al., 1996; Reilinger et al., 1997). However, to establish its present, nearly 2000-km-long trace between the Karlova triple junction (Eurasia-Anatolia-Arabia) and the tip of the Corinth Rift in Greece, the North Anatolian fault must have grown and propagated, possibly accumulating variable displacement along strike. Our aim here is to present and discuss new tectonic observations concerning this evolution in a key area around the Sea of Marmara and the Dardanelles, where the fault enters the Aegean (Figs. 1, 2).

## SHEARED FOLDS IN THE DARDANELLES

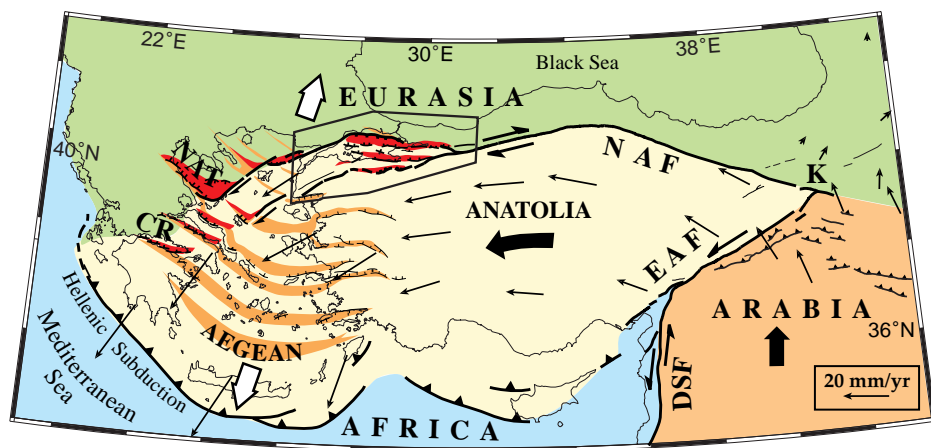
The Sea of Marmara forms a conspicuous, active pull-apart basin (Fig. 2). It has a characteristic rhomb shape, flanked by large north- and south-dipping normal faults, well-imaged in seismic profiles (Wong et al., 1995), and by two major strike-slip branches of the North Anatolian fault that are about 100 km apart. The region has strong background seismicity and many of the mapped faults have produced large earthquakes (e.g., Barka and Kadinsky-Cade, 1988). For example, two strike-slip earthquakes of M 7.4 (Ganos in 1912; Yenice-Gonen in 1953) ruptured 60-km-long segments along the northern and southern branches of the North Anatolian fault. Another large (M 7.1) earthquake ruptured a similar fault length at the eastern junction between the two branches (Mudurnu in 1967). However, the efficiency of the transfer of the North Anatolian fault lateral motion across the extensional Marmara basin is not clear over the long term. Moreover, the total lateral displacement of the fault and the amount of crustal extension in the Marmara Sea remain undetermined. Also unknown is the proportion of the slip taken up by the southern and northern branches of the fault, west of the Marmara pull-apart, where both enter the Aegean.

The northern branch of the North Anatolian fault strikes N70°E, forming a sharp angle with the average strike (N110°E) of the major normal-dextral faults in the Sea of Marmara (Figs. 2, 3). North of the Dardanelles, the fault has a linear trace across the mountainous Ganos Dagh-Gelibolu Peninsula region. The Dardanelles is

also a region where, unexpectedly, recent folding and crustal shortening can be documented. Mapping the fold structure in some detail (Fig. 3A) allows us to constrain its geometry and age, as well as to explain the shortening within the extensional environment and its relation to the kinematics of the North Anatolian fault.

The folds are restricted to a distance within 30 km of the trace of the fault. Their average strike is N45°E, consistent with the dextral slip on the fault. The axes are more than 20 km long, with uniform anticline-syncline spacing of about 10 km. More closely spaced folds are seen, however, south of Ganos Dagh, between the towns of Gazikoy and Gelibolu (Fig. 3A). The folds north of the North Anatolian fault involve mostly the Eocene-Oligocene sediments of the southern Thrace basin. By contrast, the folds south of the fault involve Miocene deposits as well, with identical styles and without any noticeable unconformity. Dips in both the Paleogene and Neogene rocks reach 90° in some places, and tight secondary folds are common. Involving mostly Eocene sedimentary rocks, the Ganos anticline forms the highest dome in the region (924 m) and is truncated obliquely, on its southern limb, by the North Anatolian fault.

Four main anticlines are seen south of the fault. The three smaller ones between Gazikoy and Gelibolu have similar structure, a narrow core of pre-Cenozoic rocks, including dislocated blocks of marble and serpentinite (attributable to the Intra-Pontide suture; Yilmaz et al., 1997), and an envelope of Eocene rocks and less resistant Miocene strata. The three folds have, however, significantly



**Figure 1.** Tectonic setting of continental extrusion in eastern Mediterranean. Anatolia-Aegean block escapes westward from Arabia-Eurasia collision zone, toward Hellenic subduction zone. Current motion relative to Eurasia (GPS [Global Positioning System] and SLR [Satellite Laser Ranging] velocity vectors, in mm/yr, from Reilinger et al., 1997). In Aegean, two deformation regimes are superimposed (Armijo et al., 1996): widespread, slow extension starting earlier (orange stripes, white diverging arrows), and more localized, fast transtension associated with later, westward propagation of North Anatolian fault (NAF). EAF—East Anatolian fault, K—Karlıova triple junction, DSF—Dead Sea fault, NAT—North Aegean Trough, CR—Corinth Rift. Box outlines Marmara pull-apart region, where North Anatolian fault enters Aegean (Fig. 2).

different morphologies. The highest anticline to the northeast, near Gazikoy (669 m) is very well preserved; it has a nearly intact domal shape in the soft Miocene rocks. The middle anticline is less elevated (444 m) and clearly more eroded. The third anticline to the southwest, where the envelope of Miocene strata is the most eroded and almost entirely blanketed by younger alluvium and colluvium, is the lowest (280 m). This suggests that the less eroded anticline immediately south of the Ganos anticline is the youngest and currently the most active. This also supports the view that, south of the North Anatolian fault, folding activity decays southwestward along the trace of the fault, as the age of the folds increases.

Farther southwest in the Gelibolu Peninsula there is another prominent anticline in Eocene rocks, similar to that in Ganos, but more eroded (Fig. 3, A and B). It is flanked to the south by a syncline with similar size and internal structure in middle to upper Miocene rocks (continental Ghazanedere Formation followed by the fluvio-lacustrine-marine Kirazli Formation). The syncline has been deeply eroded and unconformably overlain by clastic deposits of the Conkbayiri Formation near the southeast-plunging front of the Gelibolu anticline and, some kilometers south of this front, by the flat-lying marine layers of the Alçitepe Formation. The latter covers both sides of the Dardanelles, filling a 200-m-deep canyon in-

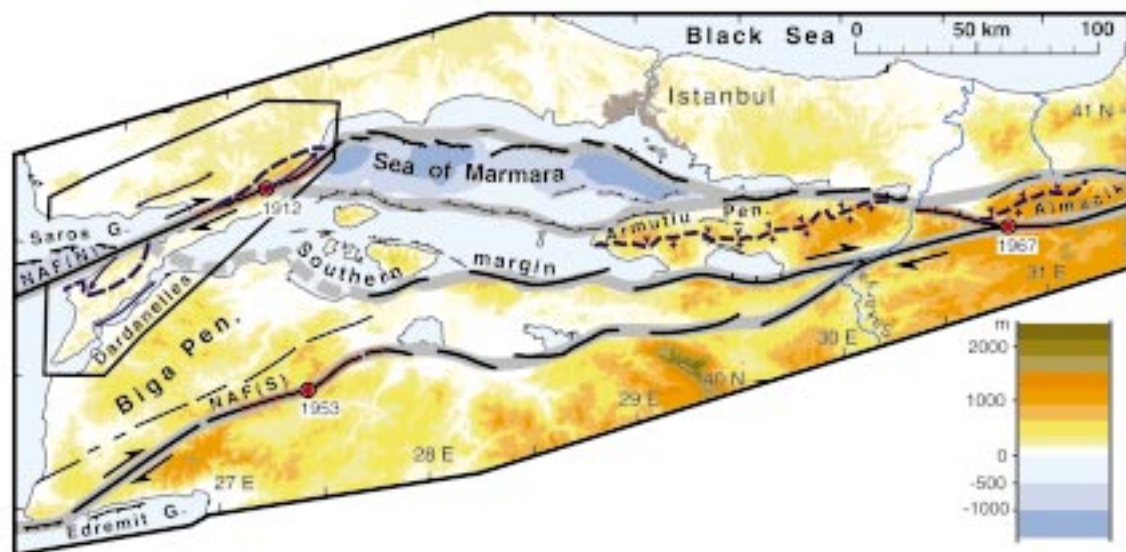
cised in the tightly folded upper Miocene rocks, nearly parallel to the present straits. The Alçitepe Formation contains abundant fauna of “maetra”-type association (Sümengen and Terlemez, 1991), which is indicative of a substantial transgression connecting the Black Sea through the Sea of Marmara with the Aegean Sea and the Mediterranean. Presumably, the canyon filled by the Alçitepe Formation represents the widespread early Pliocene marine transgression that followed the well-known Messinian crisis of the Mediterranean Sea, characterized by prevalent regression and erosion (Ryan and Cita, 1978). If this inference is correct, the age of the folding in the Dardanelles is constrained within narrow bounds from ca. 7 to 5 Ma. Finally, the Gelibolu anticline is truncated on its northern limb by the North Anatolian fault, which separates the fold from the bottom of the transtensional Saros Gulf by a steep, ~1-km-high escarpment.

The features in the Dardanelles region are explained simply by right-lateral offset of about 70 km along the trace of the North Anatolian fault, as illustrated in Figure 3C. The proposed match of the two truncated anticlines (Ganos and Gelibolu) depicts the probable geometry of the fold structure before it was cut and laterally offset by the fault. Our interpretation implies, in keeping with the morphological observations, that continuing right slip on the fault has produced younger and younger folds south of it, in front of the Ganos anticline, where a prominent fault bend seemingly has acted as a long-lived, compressional buttress.

## MARMARA PULL-APART KINEMATICS AND IMPLICATIONS

Using the foregoing description, it is possible to reconstruct the entire Sea of Marmara region at ca. 5 Ma, just prior to propagation of the North Anatolian fault across the Ganos-Gelibolu anticline (Fig. 4A). We propose two simple hy-

**Figure 2.** Geometry of active tectonics in Sea of Marmara region. North Anatolian fault (NAF) splays westward into two main branches 100 km apart. Northern branch (N), cutting Dardanelles structure (box, corresponding to Fig. 3) connects Sea of Marmara with Saros Gulf. Within Marmara pull-apart, the most important faults with normal-slip component bound deep northern basins. Diffuse faulting is also seen in southern shelf and margin. Sinuous southern branch (S) bypasses pull-apart. Red lines indicate three earthquake breaks. Gray lines are cuts used for restoring slip (Fig. 4). Contact between Sakarya metamorphic rocks (+) and Eocene volcanic rocks (v), nearly coincident with Intra-Pontide suture, is represented in Armutlu Peninsula and in Almacik block (from Yilmaz et al., 1997).



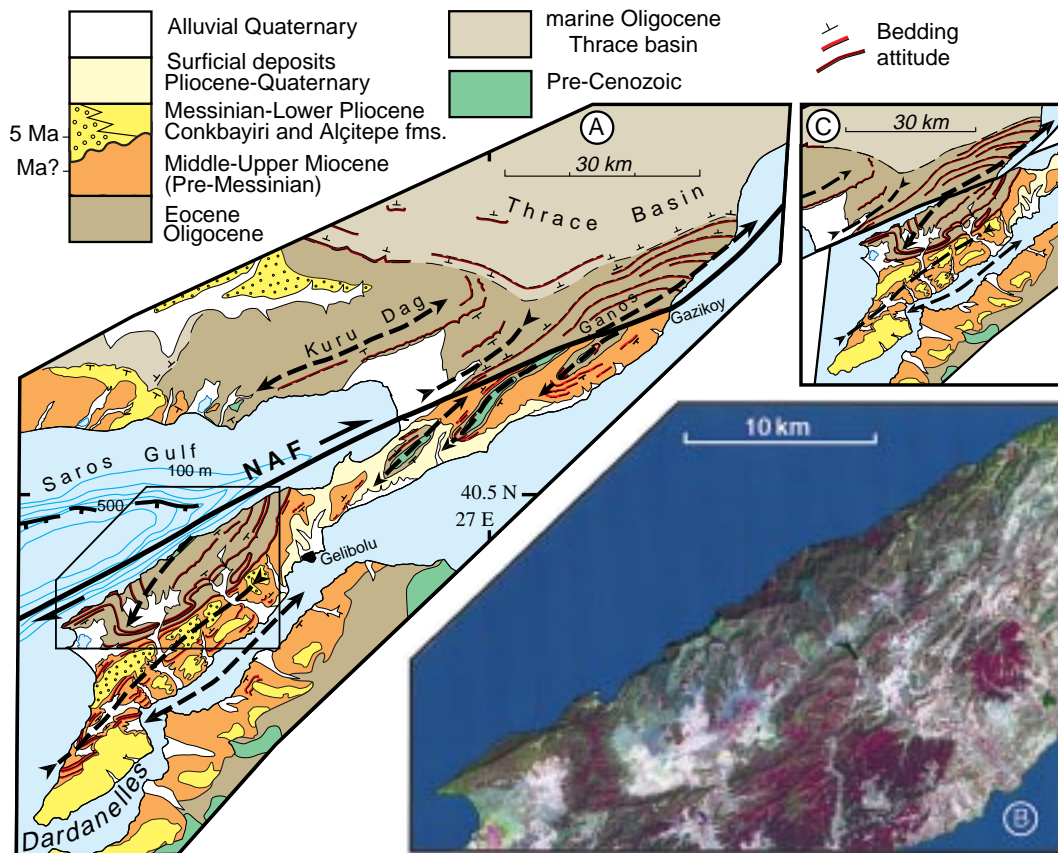


Figure 3. Offset structure in Dardanelles (Ganos Dag–Gelibolu Peninsula). A: Simplified geologic map (modified from Sümengen and Terlemez, 1991). Folding involves sedimentary rocks as young as late Miocene. Near Dardanelles Straits, folded structure is deeply eroded and unconformably overlain by clastic deposits and transgressive marine sediments of Messinian–early Pliocene age (ca. 5 Ma). B: Detail of Landsat thematic mapper showing anticline truncated by North Anatolian fault south of Saros Gulf (box in A). C: Restoring initial fold geometry requires  $70 \pm 5$  km slip on northern branch of North Anatolian fault.

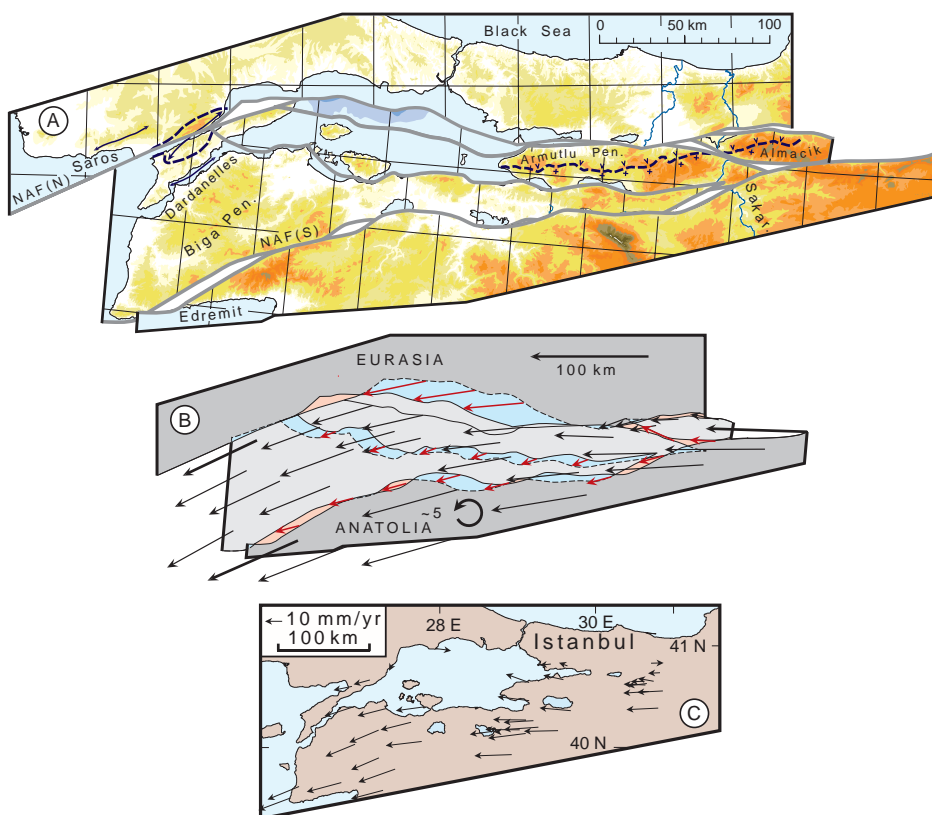


Figure 4. Kinematic model for Sea of Marmara region. A: Reconstruction at ca. 5 Ma with Dardanelles main anticline restored as in Figure 3C ( $70$  km slip on northern branch of North Anatolian fault [NAF]) by using main fault cuts, geologic markers, and grid as in Figure 2. Minimizing overlaps (extension) and gaps (compression) between blocks requires  $5^\circ$  counterclockwise rotation of southern block (Anatolia) relative to Eurasia. Almacik block rotates more ( $10^\circ$ ). Apparent structural offset in Armutlu Peninsula and Almacik block (contact between Eocene volcanic rocks and Sakarya metamorphic rocks) is reasonably restored, as is course of Sakarya River. B: Corresponding displacement field. Black arrows indicate movement relative to northern block (Eurasia); red arrows, relative to adjacent block. Blue indicates overlaps; pink indicates gaps. Total right-lateral slip on North Anatolian fault at eastern side of model is about  $85$  km, with  $15$ – $20$  km shortening across fault zone. Dextral slip on southern branch is  $15$ – $25$  km, consistent with geometry of compressional and extensional jogs. Average stretching is  $300\%$  in northern basins of Sea of Marmara and  $30\%$  in the southern shelf margin. C: Current velocity field as deduced from GPS (from Straub et al., 1997).



potheses: (1) that deformation is localized over the long term within the known fault zones and thus can be described as displacement and rotation of rigid blocks, and (2) that displacement parallels the North Anatolian fault, so that extension and compression components across the main faults are minimized, except where observed. For this preliminary reconstruction, we used maps with a fixed conical projection; these are handled more easily than spherical shells. The corresponding displacement errors across the 400-km-wide region are less than  $0.5^\circ$  in direction and 2% in magnitude.

The model in Figure 4A is not unique, but it is intended to provide first-order estimates of displacement and rotation and will be refined by further investigation. However, consistent observations on both sides of the Marmara pull-apart indicate that the model is robust. West of Marmara, the model restores in detail the geometry of the Ganos-Gelibolu anticline by the time the Pliocene transgression filled the Dardanelles canyon with sediment. The early Pliocene coastline of the Saros Gulf was simpler, similar to that of the Edremit Gulf. East of Marmara, the model restores a reliable structural marker, having the appropriate geometry and size; the northern edge of the Sakarya metamorphic rocks (Yilmaz et al., 1997) forms a steep, continuous, 150-km-long contact with Eocene volcanic rocks. Finally, the model restores a geomorphological marker, a possible earlier course of the Sakarya River (Westaway, 1994).

The reconstruction at 5 Ma implies that overall right-lateral displacement of Anatolia relative to Eurasia is 85 km (Fig. 4B). The uncertainty is about 10 km, mainly because slip on the southern branch of the North Anatolian fault is poorly constrained (15–25 km?). However, it is one-third to one-sixth as much as that along the northern branch. The model implies  $5^\circ$  counterclockwise Anatolia-Eurasia rotation. Differential rotations between smaller blocks are not resolved, however. An exception is the Almacik block, which requires twice the rotation of Anatolia. The model includes extension due to dextral displacement of the fault but is independent of extension related to the Aegean. Extension in the Marmara pull-apart is widespread but uneven; 25% of it appears to be distributed within the southern shelf margin, and 75% concentrated in the northern deep basins, where stretching is intense ( $\sim 300\%$ ). Compression, by contrast, is very local. An example is the Ganos bend, consistent with the young folding observed there. Other examples are found along the southern branch of the North Anatolian fault, where compressional and extensional jogs seemingly alternate.

Comparison of the 5 m.y. displacement field with the velocity field deduced from 6 yr of GPS measurements in the same region shows that both kinematic patterns are similar (Fig. 4, B and C). The small differences are within the uncertainties or may be explained, for instance, by transient

behavior during the seismic cycle. Motion in Gelibolu (70 km) and across the Marmara region (85 km) in the past 5 m.y. implies a 14 mm/yr average slip rate on the northern branch of the North Anatolian fault and a 17 mm/yr velocity between Anatolia and Eurasia. This is somewhat less than the  $22 \pm 3$  mm/yr observed around Marmara with GPS (Straub et al., 1997). Moreover, the 5 m.y. displacement field in Marmara is strikingly consistent with the Anatolia extrusion kinematics derived at a larger scale from space geodesy (Fig. 1), although with similar discrepancies concerning velocity. Finally, both the long-term and the GPS models imply substantial shortening across the fault immediately east of the Marmara extensional region.

A direct consequence of the above is that models with rigid blocks moving coherently seem appropriate to describe, over 5 m.y., the kinematics of the Marmara region. Thus, steady deformation localized on large faults appears to be the dominant mechanical process. However, inception of movement in far distant parts of the North Anatolian fault is not coeval. The fault originated possibly at ca. 10 Ma in eastern Anatolia (Sengör et al., 1985; Barka, 1992), crossed the Dardanelles anticline to enter the Aegean at 5 Ma, and reached the Corinth Rift in central Greece at 1 Ma (Armijo et al., 1996). This implies westward, plate-scale propagation of the fault over the past 10 m.y. However, the total displacement across the fault documented in Marmara appears comparable to that less well constrained in eastern Anatolia ( $\sim 80$ – $90$  km; e.g., Sengör et al., 1985). Accordingly, the long-term average slip rate in the Marmara region would be twice as fast as that in eastern Anatolia, suggesting that the central part of the North Anatolian fault has nearly caught up, in the past 5 m.y., with the displacement in eastern Anatolia. This would reflect long-wavelength, long-term strain recovery in the region surrounding the fault. Fault propagation and transient strain at this range of scales (1000 km, 10 m.y.) suggest elastic behavior, similarly scaled, in the continental lithosphere. Finally, at smaller scale, compressional strain associated with a restraining bend at the tip of the westward-propagating North Anatolian fault explains well the formation of the Dardanelles anticline between 7 and 5 Ma.

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