Anatomy of the North Anatolian Fault Zone in the Marmara Sea, Western Turkey: Extensional Basins Above a Continental Transform

Ali E. Aksu, Tom J. Calon, Richard N. Hiscott, *Department of Earth Sciences, Centre for Earth Resources Research, Memorial University of Newfoundland, St. John's, Newfoundland A1B 3X5, Canada, aaksu@sparky2.esd.mun.ca*
Doğan Yaşar, *Institute of Marine Sciences and Technology, Dokuz Eylül University, Haydar Aliyev Caddesi No. 10, Inciraltı, Izmir 35340, Turkey*

ABSTRACT

Although it straddles an area of extreme earthquake risk, the origin of the Marmara Sea transtensional basin has been enigmatic. Recently acquired high-resolution seismic profiles and earthquake hypocenter locations show the crustal architecture to be characterized by a negative flower structure, bounded by two west-trending sidewall faults that are linked to a single vertical to steeply south-dipping master fault that extends to depths of >30 km. The negative flower structure has a complicated architecture consisting of relatively intact detached basinal blocks, separated by southwest-trending ridges which serve as strike-slip transfer zones between the basins. The basins and ridges are rotating counterclockwise, accommodated by the southward retreat of the southern sidewall of the flower structure as crustal material is passed from its eastern to western end along the transtensional strike-slip zone. This new interpretation provides a better context for understanding seismicity in the region and for understanding complexities of fault segmentation in large transtensional basins along continental transforms in zones of tectonic escape.

INTRODUCTION

In the January issue of *GSA Today*, Reilinger et al. (2000) explained the inevitability of destructive earthquakes along the North Anatolian transform fault of northern Turkey as a consequence of the westward tectonic escape of the Aegean-Anatolian Plate from a collision zone between the converging African and Eurasian plates (Fig. 1, inset). They pointed to the lack of a detailed map of faults crossing the locally deep (>1200 m) floor of the Marmara Sea (Fig. 2A) as an impediment to establishing the precise mechanics of faulting and earthquake generation. This region is of critical concern because devastating earthquakes over the past 100 years have progressed westward along the plate boundary toward the Marmara Sea region (Reilinger et al., 2000). Because of poor constraints on fault geometry, conflicting tectonic interpretations have been proposed for the deep basins of the Marmara Sea and associated seismicity (Fig. 2C and 2D). Comparisons of existing models show that separate groups of authors have advocated different locations for fundamental

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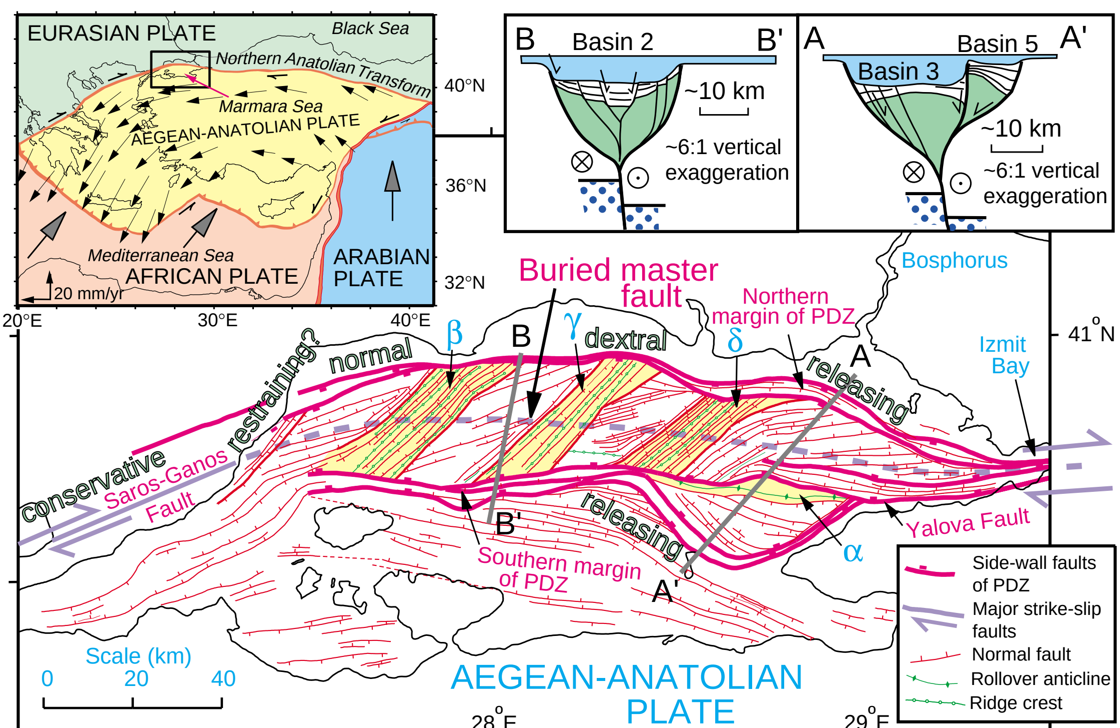

Figure 1. Structural map showing margins of principal deformation zone (PDZ), major strike-slip faults (half arrows), and normal faults with ticks on hanging wall. Areas α, β, γ, and δ are major ridges. Structural features are taken directly from interpreted seismic profiles along closely spaced survey tracks (Fig. 2E), so this figure is just like the field map of a land geologist. The only interpreted features are buried, dashed trace of dextral North Anatolian transform fault (NATF) and inferred zones of compression (restraining bends) and extension (releasing bends). Upper left inset is simplified tectonic map of eastern Mediterranean region, showing sense of plate motion (large gray-headed arrows) and global positioning system (GPS) horizontal velocities of Aegean-Anatolian plate (from Reilinger et al., 2000) relative to a fixed Eurasian plate (thin black arrows scaled in length to GPS velocities in mm/yr). Half arrows indicate transform or strike-slip faults. Cross sections A–A' and B–B' show our perception of architecture of elongate negative flower structure where it has central anticlinal swell and step-out basin perched on edge of principal deformation zone (A–A'; compare Fig. 4A), and where it encloses symmetrical graben (B–B'; compare Fig. 4B). Green substratum in cross sections represents older deposits beneath Pliocene to Quaternary basin fill.

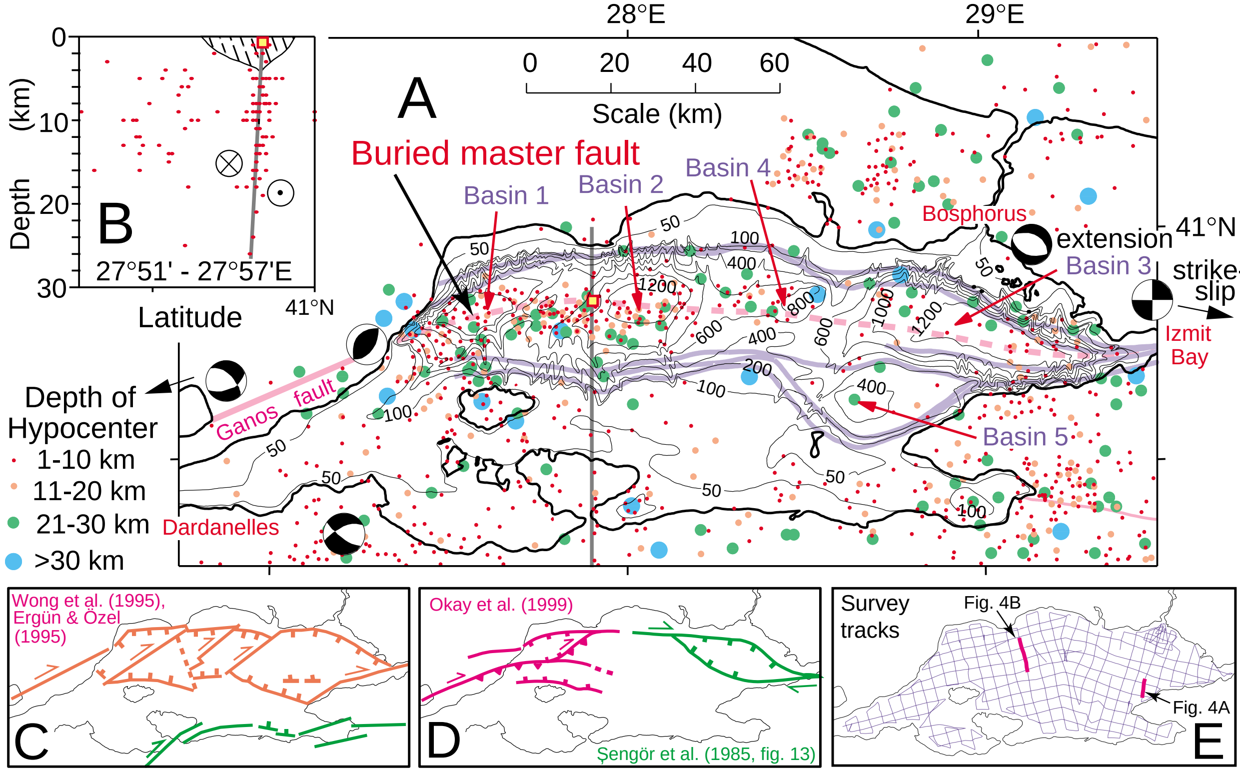

Figure 2. A: Bathymetry simplified from Aksu et al. (1999), depths of hypocenters of selected 1970–1998 earthquakes (Boğaziçi University, Kandilli Geological Observatory; see koeri.boun.edu.tr), margins of principal deformation zone (PDZ, thick purple lines), and position of steeply dipping dextral master fault (thick pink lines) to west of Marmara Sea (= Saros-Ganos fault) and as dashed line where buried beneath elongate negative flower structure along axis of principal deformation zone. Of five principal basins, four straddle principal deformation zone and lie directly above buried North Anatolian transform fault. Soccer-ball–shaped symbols are lower-hemisphere projections of fault-plane solutions for selected large earthquakes (compiled by Kiratze and Papazachos, 1995; Wong et al., 1995; Yalıtırak et al., 1998); quadrants with compressional first motion are black. B: Cross section along north-south line at ~27.6°E in A, showing distribution of earthquake hypocenters in band of latitudinal width 0.06', projected into cross section. Other cross sections are essentially identical and reveal location and dip of buried master fault (= North Anatolian transform fault) beneath principal deformation zone. Patterned region from 0 to 5 km depth is outline of principal deformation zone from seismic displays of Okay et al. (1999). Note lack of correlation between earthquake hypocenters and sidewall faults of principal deformation zone. C and D: Contradictory fault patterns proposed for Marmara Sea by various authors. E: Survey tracks of seismic grid used to construct Figure 1 and locations of seismic profiles of Figure 4.

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strike-slip faults, contrasting asymmetries for adjacent strike-slip basins, and different linkages with faults on land. This high level of uncertainty as to the first-order geometry of structures makes it impossible to confidently evaluate the seismicity of the Marmara Sea area.

The Marmara Sea region is also an important place for understanding the nature of transform plate boundaries. The North Anatolian transform fault forms the northern boundary of the Aegean-Anatolian plate and accommodates its westward escape by dextral strike-slip movement (Fig. 1, inset). The Marmara Sea is located on the transform fault, at a place where a notable southwestward swing occurs in the velocity field of the Aegean-Anatolian plate and where a broad zone of faults swings gradually to the southwest to connect the North Anatolian transform fault to the Saros-Ganos fault (Figs. 1 and 2). Global positioning system measurements constrain the horizontal velocity field of the Aegean-Anatolian plate relative to a fixed Eurasia (Reilinger et al., 2000), demonstrating a counterclockwise rotation of the Aegean-Anatolian plate and a progressive southwestward increase in plate velocity in the Aegean region (Fig. 1, inset).

Published tectonic models have failed to properly explain the origin of the Marmara Sea because of poor seismic coverage and insufficient use of available earthquake data. For example, cross-sectional plots of the locations of earthquake hypocenters beneath the deeper areas of the Marmara Sea (Fig. 2B) show that the steep marginal fault scarps enclosing the deep basins are not fundamental crustal-scale faults (i.e., none of these are main strands of the North Anatolian transform fault). Instead, the plate boundary fault lies directly beneath the axis of the Marmara Sea, where it is buried by a structurally complex zone of rhombohedral to elongate basins and ridges. This observation, combined with new maps of bathymetry (Fig. 2A) and fault traces (Fig. 1) that we have prepared from closely spaced seismic profiles (Fig. 2E), allows us to rule out origination of the Marmara Sea as either a pull-apart basin (Fig. 3A) or a transform-parallel strike-slip basin (Fig. 3B), and shows that it is instead a rather unconventional negative flower structure with complex internal geometry (Fig. 3C). Mann (1997) formulated a general model for the formation of large transtensional basins in zones of tectonic escape emphasizing the hybrid nature of such basins in terms of both pull-apart and transform-normal extensional styles. We believe that this notion is directly applicable to the Marmara Sea.

BATHYMETRY

Bathymetry provides a first-order data set for inferring the positions of surface faults, the geometry of uplift and subsidence, and the interaction of faulting and sedimentation. The Marmara Sea is a 30–35-km-wide and 150-km-long, west-trending depression that consists of steep-flanked basins and ridges (10°–30° slopes) nestled between a 3–5-km-wide shelf dominated by eroded Tertiary bedrock in the north and an ~30-km-wide shelf in the south (Fig. 2A). There are five deep depressions within the central zone of basins and ridges. Westernmost basins 1 and 2

(Tekirdağ and Central Marmara Basins of Wong et al., 1995) are elongate, southwest–trending rhombohedral depressions deeper than 1100–1200 m. Easternmost basin 3 (Çınarcık Basin of Wong et al., 1995), at >1200 m depth, is a west-northwest–trending elongate depression. Basins 4 and 5 are significantly shallower features. Basin 4 (~800 m deep) is perched on the broad southwest-trending ridge separating basins 2 and 3, whereas basin 5 is a shallow (~370 m deep), crescent-shaped depression perched high on the southern slope of basin 3 (Fig. 4A). The three ridges that separate basins 1–4 (β, γ, and δ in Fig. 1) have water depths shallower than 600 m. The flanks of the ridges are generally segmented by steps, creating a rugged and terraced appearance. The west-trending ridge α (Figs. 1 and 4A) separates basins 3 and 5; here, the seafloor rises ~100 m above the floor of basin 5, then quickly descends to basin 3.

UPPER CRUSTAL FAULT ARCHITECTURE

Faults were imaged seismically on 40 in.^{3} airgun profiles and precisely transferred to a base map (Fig. 1). The upper crustal architecture in the Marmara Sea is characterized by an intricately linked fault system with two long west-trending boundary faults called sidewall faults. The zone between is referred to as the *principal deformation zone.* The sidewall faults are actually zones of narrowly spaced faults that dip steeply toward the axis of the principal deformation zone. They show close correlation with bathymetry.

The principal deformation zone swings gradually to a west-southwest trend in the western Marmara Sea, the northern sidewall fault linking to the Saros-Ganos fault via a set of faults along the western margin of basin 1 (Fig. 1). The southern sidewall fault appears to link to the west into a relay of southwest-trending faults with normal throw extending to the eastern Dardanelles. To the east, the two sidewall faults converge in western Izmit Bay, linking with the main northern strand of the North Anatolian transform fault. The architecture of the principal deformation zone thus displays an overall elongate tapered shape (Fig. 1). Basin 5 (Figs. 2A and 4A) is considered to be an out-step zone of the southern margin of the principal deformation zone, bounded by an arcuate fault zone that merges with the southern sidewall fault both to the east and west, and likely at depth (Fig. 1, section A–A').

The principal deformation zone consists of a shingled array of four basins and three ridges oblique to the trend of the sidewall faults (Figs. 1 and 2A). Basins 1, 2, and 4 and their bounding ridges β, γ, and δ are arranged in an en echelon pattern, controlled by the southwest trend of the ridges. The western margin of basin 1 is defined by steep southwest-trending faults with considerable normal throw. This fault zone occupies a position similar to that of the marginal faults of the ridges. To the northeast, the fault zone links with the northern sidewall fault; to the southwest, it follows the northern shoreline of the Dardanelles and does not merge with the southern sidewall fault. Furthermore, the zone is not cut by the Ganos fault as was suggested by Okay et al. (1999) (Fig. 2D). The 10–15-km-wide ridges are cut by narrowly spaced, southwest-trending, high-angle faults, many of which extend to the seafloor, creating a rugged topography. The boundaries between the ridges and adjacent basins are prominent fault scarps. The Pliocene to Quaternary basinal strata converge dramatically onto the flanks of the ridges (Fig. 4B). Normal-sense drag on the faults suggests upward propagation of fault tips to the surface (Fig. 4B). The convex-upward internal stratal architecture of ridges β, γ, and δ is attributed to pervasive faulting concentrated in narrow zones, normal throw increasing toward the edges of the basins. The linkage of the faults in the ridges with the sidewall faults is poorly resolved because of the spacing of the seismic grid. However, the ridge-margin faults clearly bend in a clockwise sense toward the sidewall faults, compatible with dextral displacement (Fig. 1).

Crustal blocks containing basins 1, 2, and 4 have well-defined rhombohedral shapes with aspect ratios of ~2.3:1. The internal structure of these blocks is defined by a central graben with south-southwest–trending normal faults that dip both northward and southward (Figs. 3C and 4B). Each basinal depocenter lies oblique (20°–25°) to both the sidewall faults and the ridge-margin faults. The depocenters are truncated by the ridge-margin faults, and their tapered ends are strongly dissected by faults. The setting of basin 3 is fundamentally different in that the depocenter is almost completely enveloped by the sidewall faults of the principal deformation zone. Only at its western edge is this block bounded by the southwest-trending faults of the eastern flank of ridge δ (Fig. 1). Basin 5 is an asymmetric half graben developed above a north-dipping listric normal fault with its associated rollover anticline (Figs. 1, section A–A' and 4A). This fault is interpreted as a footwall splay of the southern sidewall fault.

PULL-APART, TRANSFORM-NORMAL EXTENSION, OR SOMETHING DIFFERENT?

All previous tectonic models correctly note the fragmentation of the Marmara Sea into small crustal blocks, but adhere to classical models of pull-apart basin formation along releasing bends or stepovers within an east-trending dextral strike-slip system (Fig. 2C and 2D)(Ergün and Özel, 1995; Wong et al., 1995; Okay et al., 1999). Okay et al. (1999) considered basin 1 to be a flat-bottomed, negative flower

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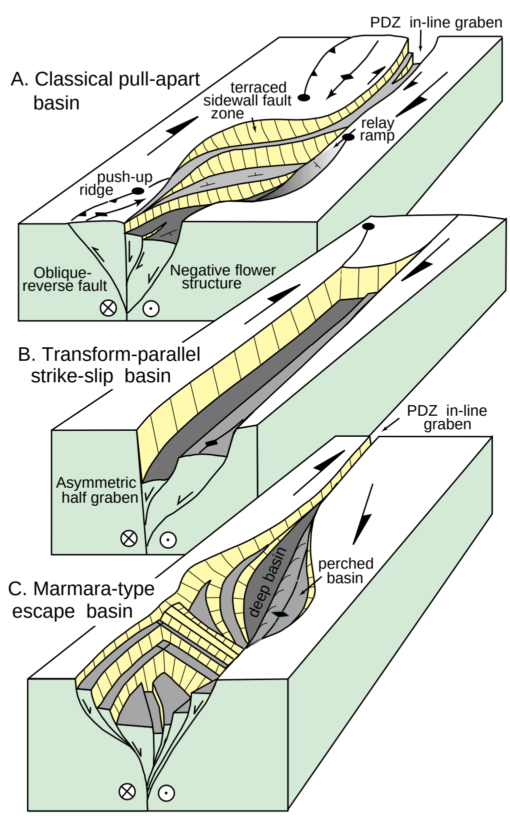

Figure 3. Contrasting geometries of strike-slip basins in dextral system. In all views, yellow surfaces are slopes facing reader. A: Classic pull-apart basin (Dooley and McClay, 1997) with negative flower structure oblique to strike of master fault. B: Transform-parallel strike-slip basin with asymmetrical, elongate half-graben structure (modified from Ben-Avraham and Zoback, 1992). C: Marmara-type escape basin with in-line symmetrical flower structure above single buried master fault.

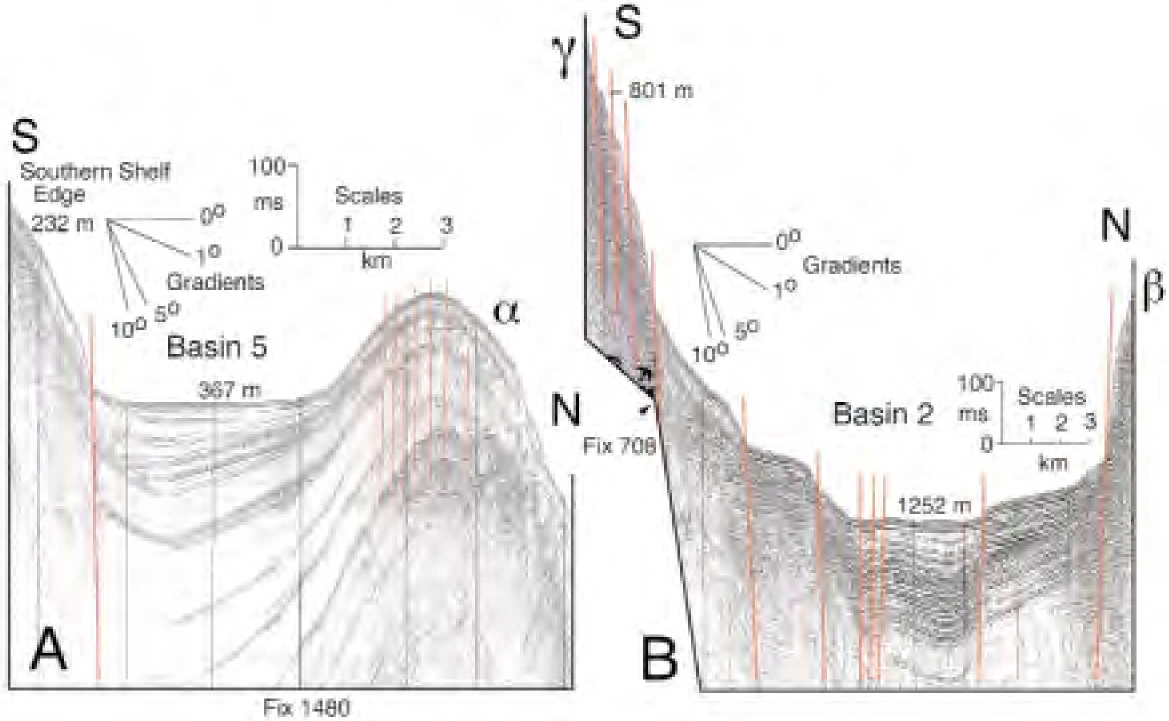

Figure 4. Single-channel seismic reflection profiles across basins 5 (A) and 2 (B) showing syntectonic architecture of basin fill and its relationship to basin boundaries and faults (red lines). See Figure 2E for location.

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structure that is detached at the base of the Pliocene to Quaternary sediments and is oriented transverse to the main stem of the North Anatolian transform fault. This requires that the North Anatolian transform fault cross the Marmara Sea, merging with the northern sidewall fault (Fig. 2D) to form a releasing bend as it curves toward the Saros-Ganos fault. Eastward in their model, the North Anatolian transform fault swings along a restraining segment coinciding with the western margin of ridge β, an inferred push-up swell. Wong et al. (1995) and Ergün and Özel (1995) recognized five blocks, consisting of three rhomb-shaped basins and two intervening transpressional push-up structures aligned with a southwest trend oblique to the main dextral North Anatolian transform fault (Fig. 2C). In other models, the northern and southern sidewall faults are considered to be normal fault segments, allowing subsidence of the basins, whereas the ridges form arrays of linking oblique-normal faults accommodating rotation between the blocks (e.g., Şengör et al., 1985, their Fig. 12).

The detailed geometry of the fault network in the principal deformation zone and the location of earthquake hypocenters beneath its axis reveal a negative flower or tulip structure. The tulip structure is the suprastructure of the principal deformation zone, extending only to depths of ~4–5 km (Fig. 1 cross sections and Fig. 2B). It links below ~5 km into a single vertical to steeply south-dipping stem, extending to depths of at least ~30 km (Fig. 2B). The tulip structure delimits an area of major Pliocene to Quaternary subsidence, with an aspect ratio of 5.5:1, that is in line with the buried master fault. The root of the tulip structure is thus a prominent, doubly plunging depression of the tipline of the buried master fault, situated across the central part of the Marmara Sea at a depth of ~4–5 km. Contrary to the earlier models of Okay et al. (1999) and Wong et al. (1995), all faults show considerable normal throw and upward fault-tip propagation, suggesting that the entire negative flower structure is in a state of wholesale crustal extension. We propose that this extension is partitioned between the basins and ridges. The basins represent relatively intact detached blocks, whereas ridges serve as strike-slip transfer zones between the basins linking the prominent sidewall faults.

The occurrence of a highly elongate, in-line negative flower structure above a centrally positioned buried master fault precludes an origin as a classic pull-apart basin. This conclusion is supported by the internal architecture of the flower structure where various fault elements are oriented exactly opposite to the geometry expected for a right-handed, releasing strike-slip system (Fig. 3A and 3C). Whereas the dimensional aspect ratios of ~3:1 for the individual basins are compatible with the ratios observed for classic pull-apart basins (Mann et al., 1983), the overall ratio of ~6:1 for the in-line flower structure as a whole is anomalous. The geometry of an in-line negative flower structure conforms better with models of basin development related to transform-normal extension (Fig. 3B; Ben-Avraham and Zoback, 1992). However, the presence of faults oblique to the sidewall faults is not a feature of such models.

This segment of the North Anatolian transform fault has been in transtension since at least 5 Ma (Armijo et al., 1999), acting as a relatively “soft” transform margin, where deformation is distributed across a linked network of strike-slip and extensional faults. We propose that the east-trending normal faults delineating basin 3 record this extension in the region where the strike-slip system feeds crustal material into the flower structure. Conversely, basins 1, 2, and 4 record the progressive feed-through and counterclockwise rotation of the crustal material that has progressively slipped into the zone of transtension since the Pliocene. The rotation of the crustal blocks is allowed by the southward retreat of the southern sidewall of the flower structure, as exemplified by basin 5, and is accommodated by strike-slip along the faults in the ridges. The ridges and basins act like rotating domino blocks within the envelope of the flower structure above the centrally located master fault. It is noteworthy that microseismicity in the Marmara Sea region is concentrated in swarms, situated along the western and eastern edges of the principal deformation zone (Crampin and Evans, 1986) where the greatest displacement incompatibilities should occur.

It is clear that the highly anomalous, intricate architecture of the Marmara Sea flower structure creates a challenging kinematic problem, particularly as to how transtension is geometrically accommodated along the buried master fault and how seismicity is partitioned between the master fault (seismic slip) and the principal deformation zone (predominantly aseismic slip). Further, the fault patterns that we describe here point to an alternative deformation style and architecture for transtensional basins that is not represented in existing literature (Fig. 3C), and that may be an important element of shallow-level continental transform systems and microplate sutures.

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