



# Uplift and subsidence from oblique slip: the Ganos–Marmara bend of the North Anatolian Transform, Western Turkey

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## Abstract

Bends that locally violate plate-motion-parallel geometry are common structural elements of continental transform faults. We relate the vertical component of crustal motion in the western Marmara Sea region to the NNW-pointing  $\sim 18^\circ$  bend on the northern branch of the North Anatolian Fault (NAF-N) between the Ganos segment, which ruptured in 1912, and the central Marmara segment, a seismic gap. Crustal shortening and uplift on the transpressive west side of the bend results in the Ganos Mountain; crustal extension and subsidence on the transtensional east side produce the Tekirdağ Basin. We propose that this vertical component of deformation is controlled by oblique slip on the non-vertical north-dipping Ganos and Tekirdağ segments of the North Anatolian Fault. We compare Holocene with Quaternary structure across the bend using new and recently published data and conclude the following. First, bend-related vertical motion is occurring primarily north of the NAF-N. This suggests that this bend is fixed to the Anatolian side of the fault. Second, current deformation is consistent with an antisymmetric pattern centered at the bend, up on the west and down on the east. Accumulated deformation is shifted to the east along the right-lateral NAF-N, however, leading to locally opposite vertical components of long- and short-term motion. Uplift has started as far west as the landward extension of the Saros trough. Current subsidence is most intense close to the bend and to the Ganos Mountain, while the basin deepens gradually from the bend eastward for 28 km along the fault. The pattern of deformation is time-transgressive if referenced to the material, but is stable if referenced to the bend. The lag between motion and structure implies a 1.1–1.4 Ma age for the basin at current dextral slip rate (2.0–2.5 cm/year). Third, the Tekirdağ is an asymmetric basin progressively tilted down toward the NAF-N, which serves as the border fault. Progressive tilt suggests that the steep northward dip of the fault decreases with depth in a listric geometry at the scale of the upper crust and is consistent

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with reactivation of Paleogene suture-related thrust faults. Fourth, similar thrust-fault geometry west of the bend can account for the Ganos Mountain anticline/monocline as hanging-wall-block folding and back tilting. Oblique slip on a non-vertical master fault may accommodate transtension and transpression associated with other bends along the NAF and other continental transforms.

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## 1. Introduction

Continents are replete with pre-existing structures that persist as weaknesses and tend to be reactivated in successive orogenic events. This behavior is exemplified by the multi-phased evolution of Anatolia during and after the closure of Tethys (Dewey and Şengör, 1979; Şengör and Yılmaz, 1981; Yılmaz et al., 1997). During the last few million years, this persistent tectonic boundary has been dominated by the North Anatolian Fault (NAF), a 1500-km-long

dextral fault system associated with the westward flight of Anatolia (Ketin, 1968; McKenzie, 1972; Şengör, 1979; Barka and Kadinsky-Cade, 1988). This E–W transcurrent boundary is spatially correlated with the Early Eocene suture of Neo-Tethys (Fig. 1). Like other continental transform boundaries, the western NAF is wide and involves a number of distinct fault-strands that exhibit branching, offsets and bends, basins, and uplifts. Pre-existing weak faults may contribute to complexity by guiding kinematics in directions oblique to plate vectors

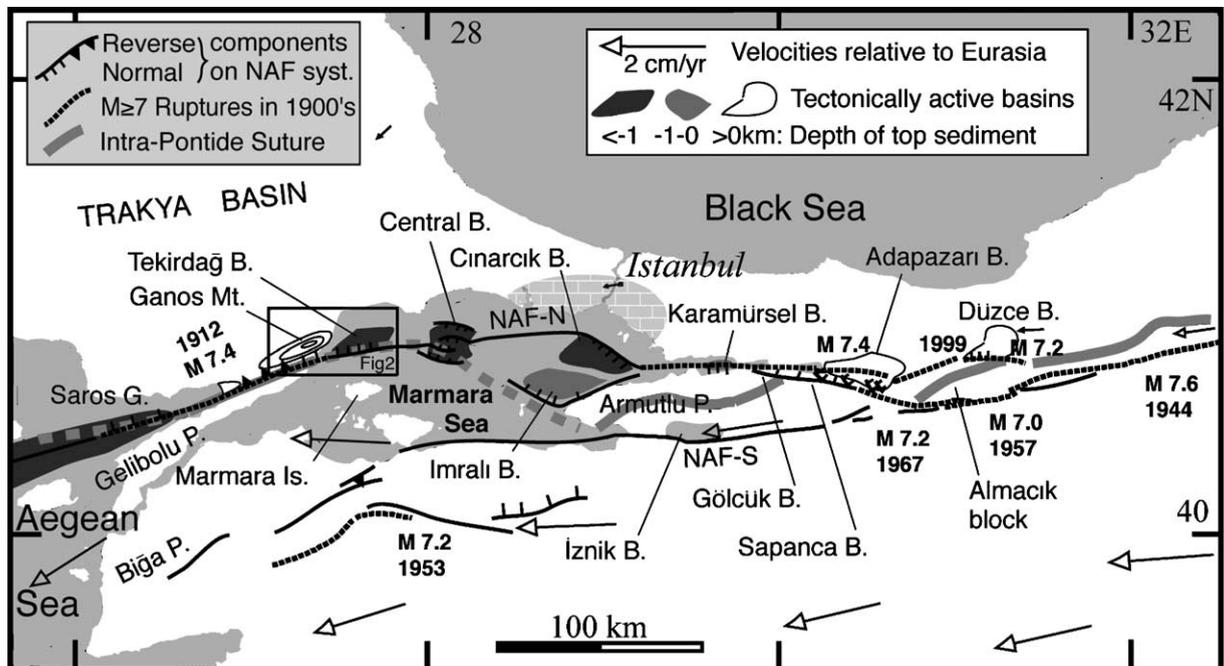


Fig. 1. Tectonic sketch map of the North Anatolian transform (NAF) in the Marmara Sea region. Geodetic velocity vectors (selected to avoid clutter) are relative to Eurasia (McClusky et al., 2000). West of 32°E, the transform splits into a northern branch and a southern branch. They absorb 4/5 and 1/5 of the motion, respectively (Meade et al., 2002). Note the close spatial correlation between the northern branch and the suture that terminated northward subduction beneath the Western Pontides in the early Eocene (Yılmaz et al., 1997). The study area (boxed) is centered on a prominent north-pointing bend along the northern branch. P.=Peninsula; G.=Gulf; B.=Basin; NAF-N, NAF-S northern and southern branches of the NAF, respectively.

(e.g., Okay et al., 2000). Other structures within the boundary zone must then absorb the discordant strain component, thus, strain is partitioned (Barka et al., 2000; Armijo et al., 2002). As the boundary evolves, oblique faults in the shear zone may be expected to passively rotate toward plate vectors. This strain-weakening process tends to narrow and simplify the deformation (Scholz, 2002, p. 124). Alternatively, “intraplate” deformation external to the transform may increase the complexity and the width of a continental transform by forcing changes in transform geometry. Aegean extension is penetrating into Anatolia south of the Marmara region, and into the Balkan region north of the Aegean segment of the NAF, thus compromising the assumption of rigid plate motion and warping the plate boundary (Şengör et al., 1985; Taymaz et al., 1991; Hubert-Ferrari et al., 2000; McClusky et al., 2000). A possible consequence is the Ganos bend of the NAF at the western end of the Marmara Sea. This bend is associated with transpression and is probably responsible for the topographic barrier separating this sea from the Mediterranean (Şengör et al., 1985; Armijo et al., 1999; Yaltrak et al., 2002). This paper argues that the Tekirdağ Basin is transtensional and is also associated with that bend. Vertical tectonics related to the Ganos bend may be representative of many other bend-related basins and uplifts along the NAF and possibly other continental transforms.

## 2. Regional setting

The North Anatolian Transform (NAF) is broadly arcuate over an angle of  $\sim 90^\circ$  and is consistent with the notion that the Anatolian block is rotating rigidly counterclockwise relative to the Asian plate (e.g., Reilinger et al., 1997). Generally, this transform is a zone of deformation with a prominent master strand, which absorbs much, but not all, of the strain. At the scale of large earthquake ruptures, the main fault tends to deviate from plate-motion geometry so that strain is partitioned between it and other branches of the system. Structural complexity and diffuse seismicity increase as the NAF branches westward of  $32^\circ\text{E}$  into multiple strands characterizing the Marmara Sea area and western Anatolia (Fig. 1). These strands display bends, lateral jogs, and numerous prominent syntec-

tonic basins (e.g., Barka and Kadinsky-Cade, 1988; Aksu et al., 2000). The wide extensional double bend in the Marmara region (e.g., Armijo et al., 1999; Okay et al., 2000) may stem from pre-existing structure controlling the shape of the NAF. Possible candidates include lithospheric weakness associated with the southern passive margin of the Black Sea oceanic basin (Steckler and ten Brink, 1986), the Terzili fault system associated with Eocene–Oligocene Trakya (Thrace) Basin (e.g., Okay et al., 2000; Yaltrak, 2002) and the early Eocene suture of Neo-Tethys (Fig. 1). Even a pre-existing structure oblique to plate motion can be reactivated, as long as part of the motion is taken up by other structures. Thus, the westward broadening of the deformation may reflect divergence between Anatolian kinematics and the initial geometry of the NAF. Additionally, increasing southward pull from Aegean subduction and roll-back may change Anatolian kinematics and increase the extension component in the Marmara region (Şengör, 1979; Taymaz et al., 1991).

Many discrete basins separated by prominent ridges punctuate the western NAF. Some of these basins are intramontane and are filled by sediment, but several basins in the Marmara Sea are sediment starved, despite high sedimentation rates (Namik Cagatay, unpublished work, 2002). The northernmost strand of the transform in the Marmara region (the NAF-N; Fig. 1) can be designated ‘master fault’. It absorbs nearly 4/5 of the plate motion (Meade et al., 2002) and flanks the most active basins along the deeper northern part of the Marmara Sea (Şengör et al., 1985; Barka and Kadinsky-Cade, 1988; Taymaz et al., 1991; Görür et al., 1997; Smith et al., 1995). After the disastrous 1999 earthquakes and the raised expectation of another major earthquake in the Marmara gap (Toksöz et al., 1979; Parsons et al., 2000; Hubert-Ferrari et al., 2000), the geometry and kinematics of the NAF in northwestern Turkey is being intensely studied by surveys of bathymetry and subsurface structure in the Marmara Sea (Le Pichon et al., 2001; Rangin et al., 2001; Armijo et al., 2002; İmren et al., 2001; Demirbağ et al., 2003; Polonia et al., 2002; Yaltrak, 2002; Hirn et al., 2003), by geodetic monitoring of the strain field (McClusky et al., 2000) and by high-resolution seismological, geological, and paleoseismic studies of the main ruptures and aftershocks (e.g., Karabulut et al., 2002;

Özalaybey et al., 2002). The new high-resolution data are stimulating hypotheses on the evolution of the NAF and, in particular, can begin to test 3-D models that account for the vertical component of deformation.

Following the structural analysis of the NAF by Barka and Kadinsky-Cade (1988), this boundary has been widely considered as the type-transform for “pull-apart” structures. These structures were described as extensional jogs or double-bends on strike-slip faults. With few notable exceptions, vertical dextral master fault strands were mapped or postulated to track plate kinematics and thus to account for the transform motion, but not for the extension derived from the pull-apart geometry. This task was generally ascribed to dip-slip faults at high angle to

the transform in a system where the strain is fully partitioned (e.g.; Barka et al., 2000). Furthermore, quantitative three-dimensional deformation models at extensional jogs on strike-slip faults (Westaway, 1995) do not generally consider oblique slip on non-vertical master faults. Extensional right jogs were mapped in the Central Marmara Basin (Armijo et al., 2002), in the Sapanca Basin (Awata et al., 2002), in the Gölcuk Basin (Letts et al., 2002), but not in the Karamürsel Basin (Cormier et al., 2003; Fig. 1). Especially the large basins tend to be flanked or bisected by continuous fault segments. East of the Marmara Sea, the 1967 and 1999 ruptures illuminated two strands of the fault system on either side of the Almacik block. The Düzce and Adapazarı intra-montane basins north and west of this block,

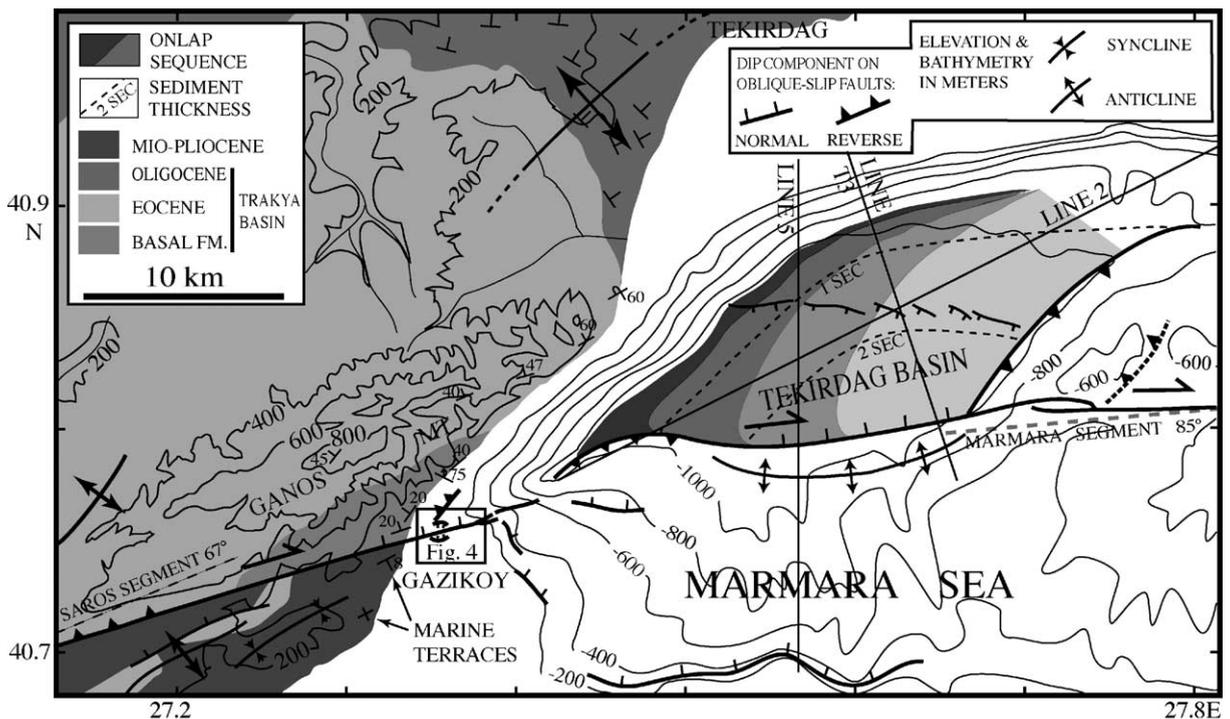


Fig. 2. Topography, bathymetry, and geology of the Ganos bend. The Ganos Mountain uplift and the Tekirdağ Basin are situated on the transpressive and transtensive sides, respectively, of the north-pointing Ganos bend on the northern branch of the right-lateral North Anatolian Fault (NAF-N). The bend appears as a broad  $\sim 18^\circ$  curve at the scale of this map, but is sharp on a regional scale (Fig. 1). Fault trace is locally distorted by shallow gravitational collapse structures. Both uplift and basin are asymmetric, with the highest structural relief close to the fault. The basin is tilted obliquely toward the border fault, the NAF-N. The  $10\text{--}15^\circ$  dip of the exposed northern flank of the basin continues under the sediment (Fig. 3). The depth of the basin increases eastward along the NAF, but the depocenter has progressively shifted westward (the onlap is tone-coded as in Fig. 3). Formation dips on land are generally small, except on Ganos Mountain, which is a large NNW-dipping monocline sub-parallel to the Ganos segment (Okay et al., 2003). Our structural interpretation incorporates elements from Okay et al. (1999), Armijo et al. (2002), and İmren et al. (2001). Bathymetry is from Rangin et al. (2001) and geology is from Sentürk et al. (1998).

respectively, do not display extensional-jog geometry and are separated instead by the restraining Karadere double bend (Fig. 1; Hartleb et al., 2002; Seeber et al., 2000). A releasing double bend characterizes NAF-N geometry through the eastern Marmara basins (Cınarcık), but the nature of this basin remains controversial (e.g., Okay et al., 2000; Le Pichon et al., 2001; Armijo et al., 2002; Demirbağ et al., 2003). The main structural feature associated with the western Marmara (Tekirdağ) basin is a regional strike change of the NAF, the “Ganos bend”. The main hypotheses in this paper are that the vertical component of crustal deformation in the western Marmara area is controlled by the Ganos bend, that the Tekirdağ Basin and the Ganos uplift are the result of oblique slip on a non-vertical north-dipping segment of the NAF, and that this regime has been stable through the development of that basin.

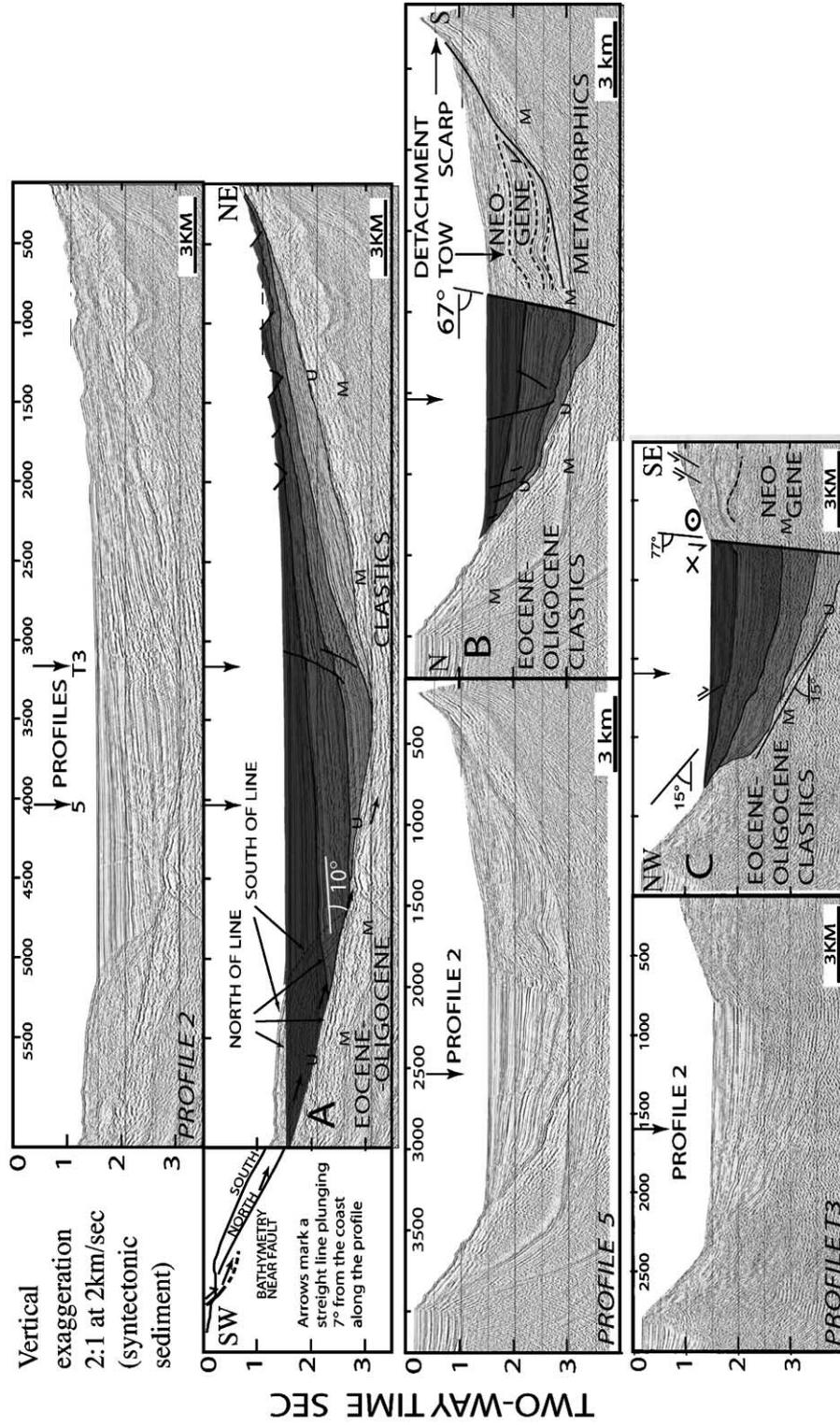
The segment of the northern strand of the NAF (NAF-N) through the western Marmara Sea continues uninterrupted westward into the Ganos segment across the Gelibolu Peninsula and into the Saros Gulf of the northern Aegean Sea (Fig. 1). The main structure separating the Ganos and the Marmara segments is a NNW-pointing bend of about  $18^\circ$  on the NAF-N. The bend is sharp at the regional scale of Fig. 1, but is gradual and characterized by second-order sinuosity at the scale of a few tens of kilometers shown in Fig. 2. We argue below that at least some of the complexities in the trace of the NAF-N along the Tekirdağ Basin reflect shallow-rooted gravity-collapse structures, which do not affect the fault at seismogenic depths. Kinematically, the bend marks a segment boundary. Accordingly, the 1912 rupture of the Ganos segment is thought to terminate near the Marmara coast (Ambraseys and Finkel, 1987; Altunel et al., 2000; Ambraseys, 2002; Fig. 1). Regionally, the bend marks a transition in the regime on the north side of the NAF-N. East of the bend, the region north of the Marmara Sea is now tectonically stable (Emre et al., 1998) and this portion of the NAF-N marks a relatively sharp northern boundary of the deformation. In contrast, a broad zone of N–S extension is active in the north Aegean, north of the NAF-N, and west of the bend. This extension may displace the NAF-N southward relative to Asia and thus increase the bend (Şengör et al., 1985; Okay et al., 1999).

### 3. The Tekirdağ Basin: progressive tilting

#### 3.1. Fault-normal tilting: fault dip decreases with depth

The Tekirdağ is a rhomboidal basin with a ~40-km-long axis sub-parallel to the transform and a width of ~15 km. The NAF-N bounds the basin to the south (Figs. 1 and 2). In most interpretations of recent multichannel and bathymetric data, the Tekirdağ is an extensional basin (Wong et al., 1995; Ergün and Özel, 1995; Parke et al., 2000; Okay et al., 1999; İmren et al., 2001; Armijo et al., 2002; Yaltrak and Alpar, 2002). A number of structures are generally thought to contribute to the subsidence, including compressional structures. As in many other basins, active turbiditic surfaces in the Marmara are nearly horizontal ( $<0.3^\circ$ ) and are sharply bounded from the much steeper basin flanks, which typically receive only hemipelagic sediment. Turbidites are often bright reflectors and thus convenient markers of differential vertical deformation. Seismic-reflection profiles display deeper basin sediments, presumably also turbidites, dipping progressively steeper into the NAF-N where they are sharply cut off (Fig. 3A,B). The  $15\text{--}20^\circ$  steep escarpment flanking this basin to the north continues as an unconformity below the syn-tectonic sediments with no significant change in dip. This surface was originally horizontal because the basal sediment, presumably turbidites, rests conformably on it (Fig. 3A,B). The tilting hinges ~5–20 km north of the fault and the tilt-radius seems to increase upward through the section and eastward across the basin. In our interpretation, this tilting accounts for the basin and is directly related to a dip-slip component on the segment of the master fault bordering the basin. Such wide tilted panels offer strong constraints on fault geometry and kinematics in the upper crust, to depths well below the depth range covered by the seismic data required to image the tilting.

Progressive tilting of syn-tectonic sediments implicates the NAF-N as the primary structure responsible for the Tekirdağ Basin. The main auxiliary structure is a tear fault, which branches off at the eastern end of the border segment on the NAF-N and bounds the basin to the east (Fig. 2). This is a steep north-side-down fault with a throw decreasing toward the northeast (Okay et al., 1999). A subtle and broad NE-striking anticline



marks the north end of the tilting (Fig. 2; Şentürk et al., 1998). We interpret this anticline as a roll-over structure directly related to the tilting. Quaternary uplift associated with it may be responsible for drainage changes (Okay and Okay, 2002). In our interpretation, other basin-related active structures (Smith et al., 1995, Parke et al., 2000; Le Pichon et al., 2001; Yaltrak and Alpar, 2002; İmren et al., 2001; Demirbağ et al., 2003; Okay et al., 1999; Armijo et al., 2002; Yaltrak, 2002) are shallow-rooted and display both extension and compression features that are typically associated with gravitational collapse in response to tectonically enhanced slopes (see below). In particular, a detachment coinciding with the basal unconformity (Okay et al., 1999) may fit into the gravitational collapse family of structures and cannot be ruled out, but it is not required to account for the main features of the basin.

The overall geometry of the Tekirdağ Basin is highly asymmetric, but also remarkably consistent through the sedimentary sequence, suggesting a uniform pattern of growth. As the border fault of an extensional basin, the NAF-N is expected to dip north, toward the basin. The profiles suggest a steep dip in the upper reach of the fault (Fig. 3B,C; Okay et al., 1999; Yaltrak and Alpar, 2002). Regional tilting is common in extensional basins and may provide constraints on the geometry and kinematics of the fault below the reach of seismic reflections. Progressive tilting can be accomplished by a planar normal fault if the footwall block and thus the fault are also rotating about a horizontal axis (e.g., Wernicke, 1981; Şengör, 1987). Regional southward tilting south of the border fault, however, is inconsistent with the northward dip of the bathymetry and of top crystalline basement and with northward thickening of Neogene sediments (Figs. 2 and 3, profile 5). If the slip is oblique, hanging-wall tilting can also be accomplished by an irrotational fault

that changes dip along strike. The dip of the border fault would need to decrease eastward to account for progressive tilting in the Tekirdağ Basin. Evidence from the profiles, however, suggests an opposite trend, leading to an almost vertical NAF-N at the eastern end of the basin (Fig. 3C). The only acceptable alternative, therefore, is that the fault is upwardly concave, with a dip that decreases with depth (i.e., ‘listric’). The large rotation radius (5–20 km) implied by the progressive tilting suggests a fault concavity extending into the mid-to-lower crust. Such geometries may be common for a young continental transform developed along a pre-existing suture. Conceivably, south-verging crustal-scale thrust faults inherited from the northward subduction of Neo-Tethys and the ensuing Early Eocene suture (Fig. 1; Yılmaz et al., 1997) could be reactivated in the current right-transpressive NAF regime, just like Miocene extension structures were reactivated in the current transpressive regime of the Transverse Ranges in California (Seeber and Sorlien, 2000). Earthquake data show that the Karadere and the Düzce segments of the 1999 ruptures have steep to intermediate dips to the north and intersect shallow-dipping faults in the mid crust (Seeber et al., 2000). With such geometries, the NAF can account for transtension or transpression by oblique slip without partitioning the strain to other faults.

### 3.2. A diachronic basin: stable but shifting pattern of subsidence

As might be expected in a transtensional regime, the tilt in the Tekirdağ Basin is oblique to the border fault. Unlike the profiles normal to the border fault, the profile along the long axis of the Tekirdağ Basin (Fig. 3A) displays a nearly symmetric bowl-shaped basement surface, but, similarly to fault-normal profiles, the pattern of sedimentation and basin growth are

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Fig. 3. Structure of the Tekirdağ Basin inferred from seismic-reflection profiles collected by the General Directorate of Mineral Research and Exploration (MTA) in 1997 and located in Fig. 2. The lithological interpretation and profile T3 are from Okay et al. (1999). Profiles 2 and 5 are from Parke et al. (2003). The basin is asymmetric. The fastest subsidence is along the border fault, which is the northern branch of the NAF (see Fig. 2). The current turbiditic floor of the basin is nearly horizontal. Older strata, probably also turbiditic, are progressively tilted toward the southwest, obliquely to the border fault. The contact with the basement is conformable in the east and north sides of the basin and becomes gradually more discordant, up to 15°, on the western side of the basin (A). We interpret this contact to be depositional, except locally as a result of gravity collapse-related faults. The Southern Boundary fault on the south side of the fault (B; Okay et al., 1999) detaches the Neogene sequence from the metamorphic basement. We interpret it as a gravity collapse structure with extensional scarp at the top, and compressional fold at the toe. This major slump intersects the NAF at a depth of about 2.5 km and may steepen the upper 1 km of the fault. West from the profile in B, the slump is apparently more active and has overturned the fault (Fig. 8).

remarkably asymmetric. Sediment layers dip and thicken to the west, along the NAF-N. In the northeastern part of the basin, basal sediments are conformable to the basement interface, but they abut sharply the southeast-dipping basement surface north of the fault in the western side of the basin. This geometry is displayed on the west side of Fig. 3A and is qualitatively similar to the fault-sediment geometry on the south side of Fig. 3B,C. This similarity may suggest that faults control both the north- and south-facing flanks of the basin in an inverse flower structure (Okay et al., 1999), but does not require it. While the

nearly normal sediment-basement angle along the south flank of the basin does require a fault, an onlap relation is a plausible alternative to account for the 10–15° angle on the western flank (Figs. 2 and 3A). This is our preferred hypothesis because rapid subsidence is occurring, not only on the basin side, but also on the basement side of that interface (see below). Conformable sedimentation, as displayed in the older and now less active eastern part of the basin, is expected at the onset of subsidence, when the basement surface is still shallow and sub-horizontal. In contrast, turbidites are now onlapping the western

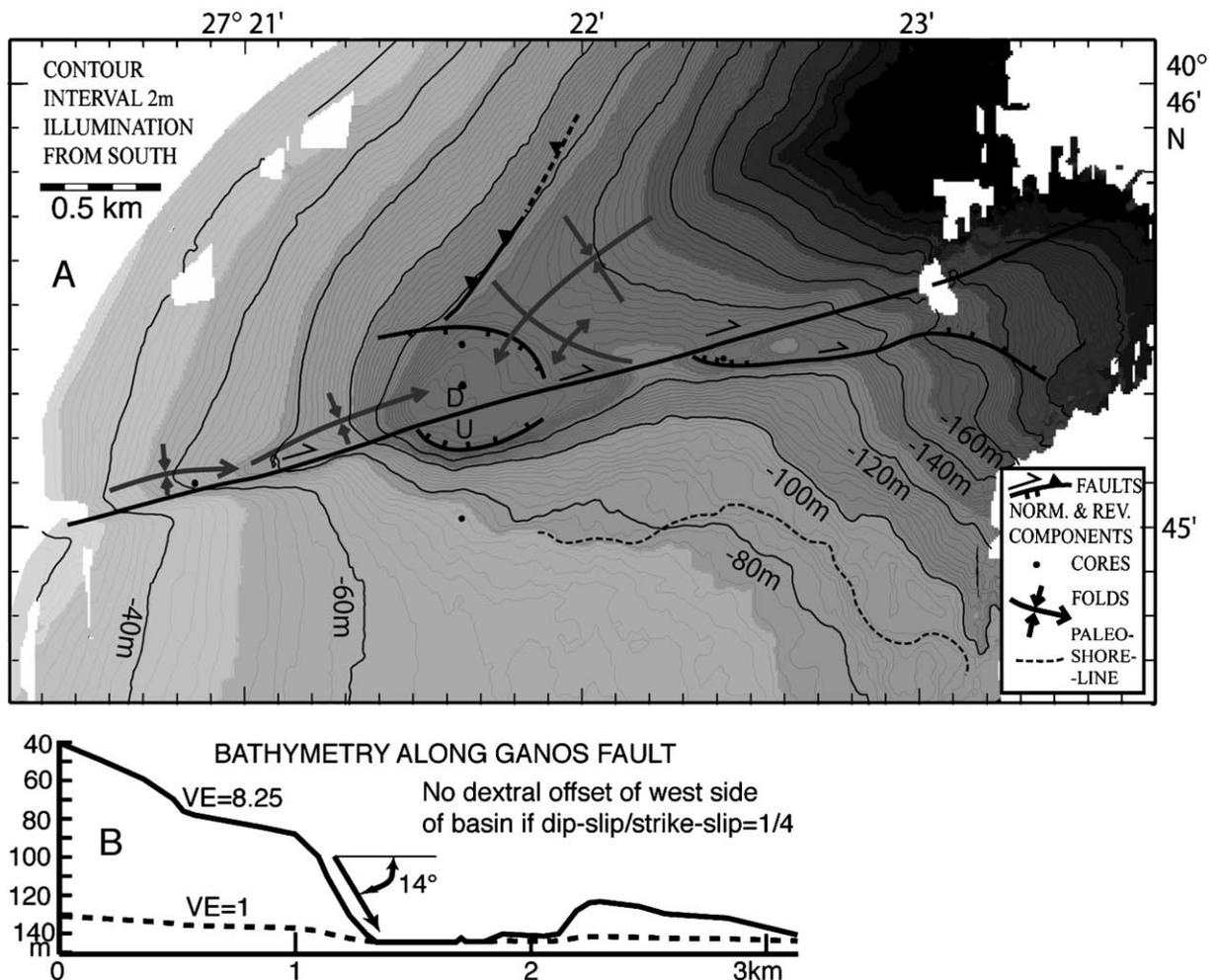


Fig. 4. (A) Bathymetry of a small area (2.5 × 5 km) where the Ganos fault crosses the shelf of the western Marmara Sea (located in Fig. 2). Multibeam sonar data from the R/V Urania 2001 cruise (Polonia et al., 2002). The structural interpretation is based on a grid of shallow-penetration (chirp) profiles (Fig. 5). (B) Bathymetric profile along the Ganos fault. The small basin is cut by the fault (Fig. 5C), but it is not offset, suggesting that the local slip vector is parallel to the west flank of the basin, which dips at 14° along the fault.

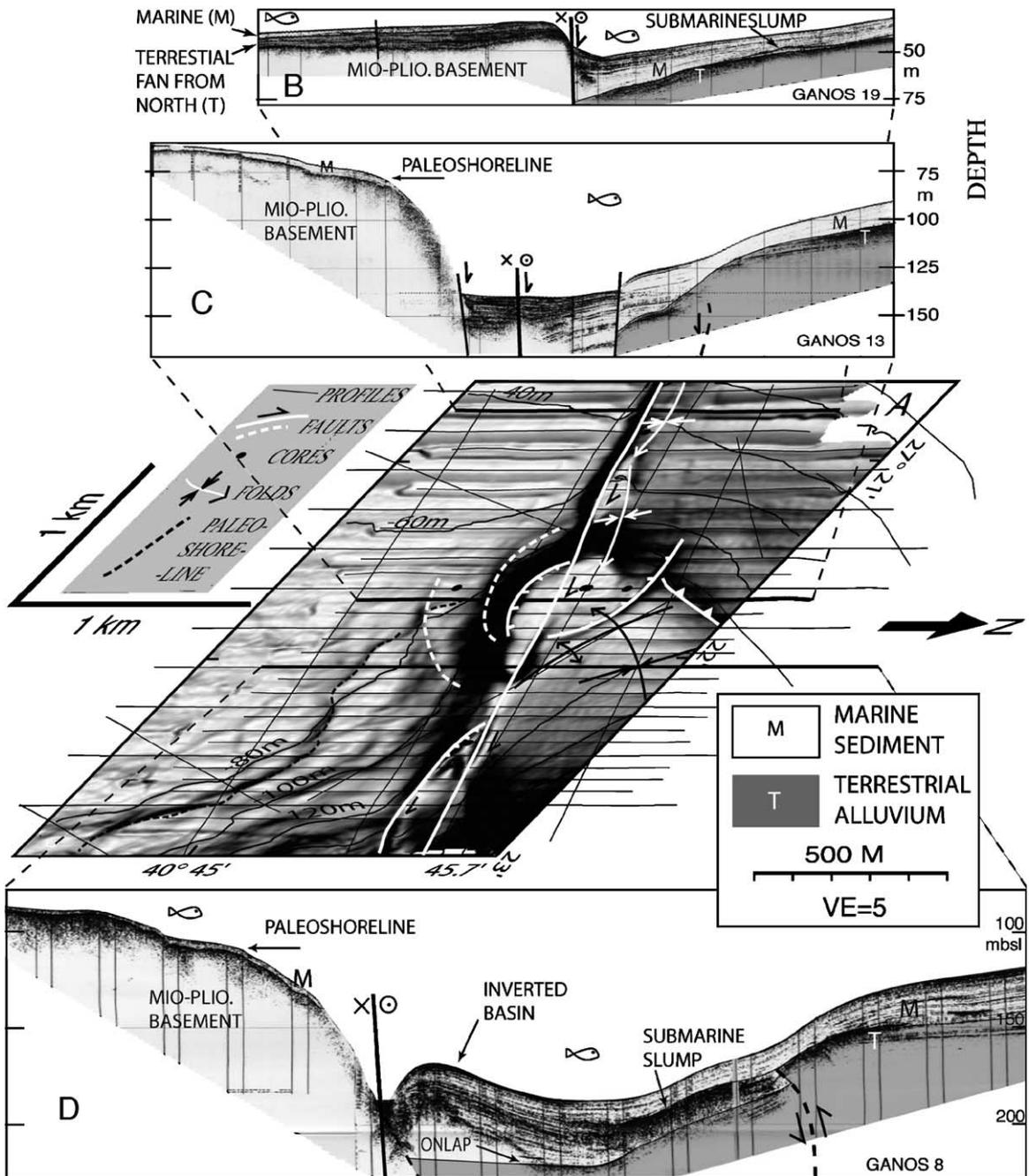


Fig. 5. Secondary structure associated with the Ganos Fault on the shelf offshore of Gaziköy (located in Fig. 2). (A) Relief map from the bathymetric data in Fig. 4. (B, C, D) Selected chirp profiles from a dense grid (A). Data from the 2001 R/V Urania Cruise (Polonia et al., 2002). The terrestrial-to-marine transition is marked by a change from anastomosing reflective strata to more parallel and less reflective strata. It is most clearly displayed on the north side of B, and is tentatively identified in the other sections. On the south side of B, the top marine bed thickens southward, while lower strata, presumably terrestrial fans from Ganos Mountain (Fig. 6), thin to the south. The anticline north of the fault in D strikes NW and is interpreted as a roll-over structure associated with the border fault of the parasitic basin (A). The reverse geometry of the secondary fault in D may reflect down-slope motion of shallow layers (compare with Figs. 3B and 8).

flank of the basin at a significant angle. In this basin, subsidence is migrating westward thus the tilting and subsiding western flanks reaches the 1.2 km depth of turbidites with a 10° tilt (Fig. 3A).

The structure of the Tekirdağ Basin suggests a relatively simple and persistent pattern of deformation, but this deformation is progressively shifting relative to the material (e.g., Crowell, 1987) and is, therefore, time-transgressive or diachronous. Subsidence rate and basin depth are highly discordant (Fig. 2). Tilting and subsidence are progressively younger and faster toward the west, but the basin is progressively deeper toward the east. The deepest portion of the basin is next to the eastern end of the border fault (Okay et al., 1999). Our data, discussed below, show very rapid subsidence at shallow depth near the coast west of the basin, where the basin is only incipient. Time-transgressive subsidence may typify transform basins.

### 3.3. Compression overprinted by extension structures in a stable regime

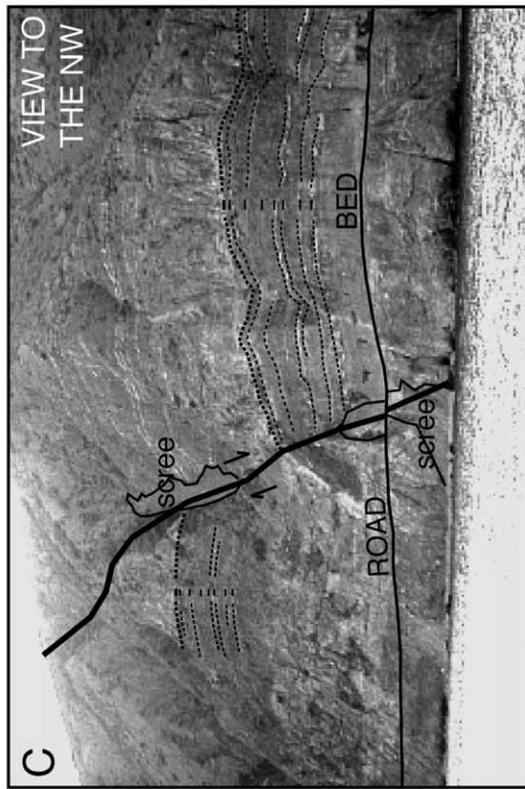
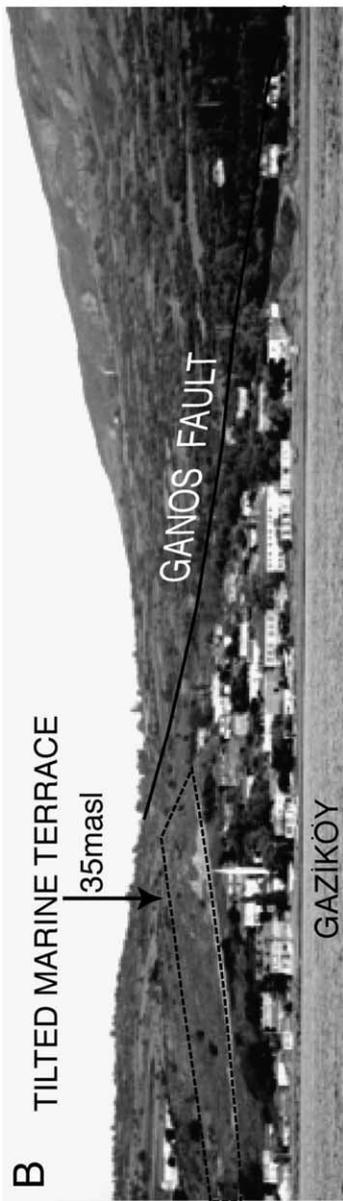
The 2001 R/V *Urania* Cruise mapped micro-bathymetry (with a hull-mounted multibeam) and shallow sub-bottom stratigraphy (with a chirp profiler) where the Ganos fault enters the Marmara Sea (Figs. 4 and 5; Polonia et al., 2002). In this survey area, the depth ranges from ~50 to ~200 m and the fault has a prominent geomorphic expression. South of the fault, depth contours strike N–S and are widely spaced across a clearly defined shelf. At the fault, the seafloor steps down in a 20–100 m north-facing scarp. For over 10 km northeast of the fault, the shelf is prominently absent and depth contours are tightly spaced, marking the submarine extension of the steep and gravitationally unstable southeast flank of Ganos Mountain (Fig. 2). Rapid change in elevation is required for the shoreline not to develop a significant erosional indentation.

The elevation, geomorphic, and structural contrast across the fault on and offshore near the coast is

ascribed to a downward component of motion and southward tilting on the north side of the fault (e.g., Figs. 5B,C,D and 6A). The block on the south side of the fault seems relatively stable. The well-developed shelf (Fig. 4) suggests little long-term change in elevation. Marine terraces are preserved along the Dardanelles Strait, including one tilted 8° to the SE and up to 35 masl, a few hundred meters south of the NAF-N at Gaziköy (Fig. 6B), which was dated 120–135 kyears BP (Yaltrak et al., 2002). A comprehensive analysis of these terraces yields a regional late Quaternary uplift rate of 0.4 mm/year south of the Ganos fault (Yaltrak et al., 2002). A submerged wave-cut surface is recognized on the shelf south of the fault in Figs. 4 and 5. This paleoshoreline is tilted to the southeast, in the same direction as the shoreline deposit exposed near Gaziköy (Fig. 6B), but only by 1°, or about 1/10 as much. The submerged shoreline is about 80 m deep, near the depth of a prominent and widely recognized shoreline controlled by the Dardanelles sill depth and probably formed during the Marmara lacustrine stage of the last glaciation (Newman et al., 2003).

In contrast, vertical motion on the north side of the NAF-N is rapid. This motion maintains a north-facing scarp even though large active fans pour sediment over it from the steep south flank of Ganos Mountain (Figs. 5B,C,D and 6A). An unconformity along the near-shore profile in Fig. 5B can be traced on both sides of the fault. It separates a regularly bedded southward thickening sequence at the top from an underlying more reflective sequence with laterally inhomogeneous bedding generally thickening to the south. We interpret this interface as the transition from terrestrial to marine sediment. On the stable south side of the fault, this interface is now about 43 m deep. This depth implies an early Holocene age (10–7 ka; e.g., Yaltrak et al., 2002) assuming it stems only from eustatic sea-level rise. The fan below the unconformity came from the highland to the north and thus was continuous across the fault at the time of the transgression. The unconformity is now offset verti-

Fig. 6. View of the Ganos coast from offshore. (A) Alluvial fans from Ganos Mountain are dammed by the Ganos fault because the motion of the north side of the fault has a downward component, as shown by profiles offshore (Fig. 6). A steep north dip on the Ganos fault is observed along the Tekirdağ Basin (Fig. 3), but is hypothetical here. The tilted marine terrace in B (strike 65, dip 8° to the southeast) is dated to 120–135 ka (Yaltrak et al., 2002). No terraces are known and the shelf is missing along the Ganos coast north of the fault. The normal/left-lateral fault in C (located in Fig. 2) is one of the most prominent faults exposed along the south flank of Ganos Mountain.



cally 40 m. The subsidence rate would then be about 4–6 mm/year and the NAF-N would have a rake of 9–17° (using a left-handed co-ordinate system) if the dextral velocity is 20–25 mm/year (McClusky et al., 2000; Meade et al., 2002). The vertical offset across the fault near the coast at Gaziköy is increasing rapidly, but is small. At the same locality but at a larger scale, the Ganos topographic high (Fig. 2) stems from long-term Quaternary uplift north of the fault. At the coast, Eocene basement outcrops 0.5 km north of the fault and is projected to be only a few tens of meters deep at the fault (Fig. 6). We conclude that near the Ganos coast, the north side of the NAF-N is subsiding fast, but has started subsiding only recently.

Holocene structure near the coast on land and on the shelf west of the Tekirdağ Basin resembles the much larger and mature structure of the basin (compare Figs. 3B,C and 5B,C). Along the fault-subparallel profile (Fig. 3A), the basement surface north of the fault drops eastward with a continuous uniform slope from the coast, down the flank of the basin, and then below the turbidites to the center of the basin. The continuity of this surface suggests continuity in the kinematics from the coast to the tilted turbidites and is inconsistent with the north-dipping fault at the base of the Ganos escarpment proposed by Armijo et al. (2002). The reverse fault in Figs. 4 and 5D has only a subtle and local topographic expression and may be associated with gravity collapse of the type discussed below for the south flank of the basin. Subsidence is progressively younger westward through the basin (Figs. 2 and 3A) and is very young at the coast. The westward decrease in basin depth is thus interpreted as progressively younger onset of subsidence and as westward growth of the basin relative to the north side of the fault.

The basin stems from oblique slip on the NAF-N east from the Ganos bend and this kinematics is propagating westward on the north side of the fault. This suggests that the cause of this kinematics is fixed to the south side of the fault. If so, the onset point of the basin would be stationary relative to the south side of the fault and the rake on the NAF-N east of the bend would be the same as the intersection of this fault and the basement surface north of the fault, which plunges eastward at about 8° (Fig. 7). This plunge is at the low end of the range of rakes calculated from the shallow structure near the coast.

This result lends support to the concept that the basin is controlled by the Ganos bend on the transform and that this bend is fixed to the southern side of the fault. In this model, the western side of the basin is stationary relative to the south side of the fault, but the eastern side of the basin moves eastward at the dextral velocity of the fault (Fig. 7). The deepest and possibly the oldest point in the basin near the eastern end of the Tekirdağ segment of the NAF-N is about 28 km east of the youngest structure related to the basin near the coast (Fig. 2A). At the current dextral rate (20–25 mm/year; Meade et al., 2002), the basin would be formed in 1.1–1.4 million years.

The growth of the Ganos High north of the NAF-N and west of the Ganos bend has been ascribed to the transpressive geometry of this segment (e.g., Armijo et al., 1999; Okay et al., 1999). Vertical motion north of the fault is down on the transtensive side and up on the transpressive side of the bend. North of the fault, topography increases gradually from the Gulf of Saros to the bend, similarly to the gradual increase in basement depth east of the bend. In our model, both are ascribed to oblique slip on the NAF-N. Such kinematics would accommodate transpression and transtension, respectively, provided the NAF-N dips to the north, not only east of the bend, but also west of it. The juxtaposition of the Ganos bend with the highest topography and the westernmost and youngest subsidence north of the fault (Fig. 2) is predicted in a regime, which is stable relative to the footwall block of the fault and to the bend, and is thus diachronic or time-transpressive in a frame of reference tied to the hanging wall block. This model can also account for another apparent discrepancy between vertical motion in the Holocene and in the Quaternary along the NAF-N. The sediment-filled landward extension of the Saros graben at the west end of the transpressive segment near the Saros Gulf implies Quaternary subsidence north of the NAF-N. In five trenches, however, the north side of the fault is consistently displaced upward by Holocene fault ruptures (Fig. 1; Rockwell et al., 2001). This motion could stem from local anomalies along the strike-slip fault, but could also manifest onset of uplift leading to the Ganos Mountain. If substantiated, such opposite signals from Holocene and Quaternary records would again suggest a lag between motion and structure in a stable but diachronic regime where the rock migrates eastward

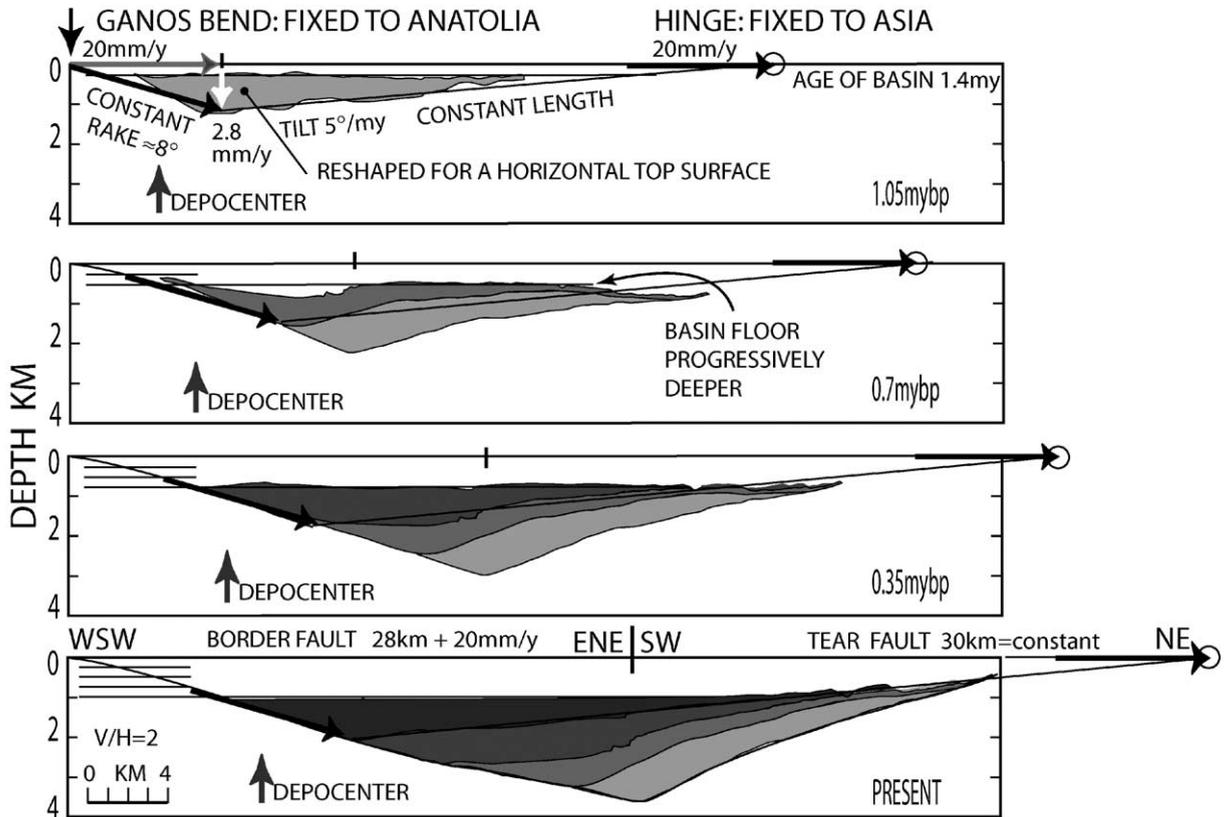


Fig. 7. Evolution of the Tekirdağ Basin inferred by back-stripping the progressively tilted sediments (compaction, isostatic response, and secondary faults and folds are neglected). This evolution is represented by depth sections of the deep side of the asymmetric basin, along the border and tear faults flanking the basin to the south and to the east, respectively (Fig. 2). The section "PRESENT" is constructed by modifying Fig. 3A according to Fig. 3B,C and by assuming a seismic velocity of 2.0 km/s in the sediment. Back-stripping leads to the earlier sections. The western end of the basin is fixed to the Ganos bend and to the south side of the northern branch (NAF-N) of the NAF. Layers are gray-coded as in Fig. 3 and their ages assume a steady 20 mm/year dextral slip rate. While the western flank of the basin along the NAF-N maintains a dip of  $\sim 8^\circ$  and lengthens at  $\sim 20$  mm/year, the NE side along the tear-fault remains  $\sim 30$  km long, but steepens at  $\sim 5^\circ/\text{Myr}$ . The western end of the basin deepens by 2.8 mm/year.

through a deformation field fixed to the bend, like water in a standing wave.

#### 4. Gravitational collapse structures

The portion of the NAF-N across the western Marmara shoreline and onto the shelf is marked by a prominent valley, which is controlled by an asymmetrical syncline (Fig. 4 and 5). This syncline is interpreted as a drag fold over the oblique-slip fault with the steeper southern limb merging into the fault. The north limb of the valley climbs directly up to the southern slope of Mount Ganos (Okay et al., 1999).

Unprotected by a shelf, the submarine valley receives much sediment directly from the mountain, yet, it survives as a depression, partly because the sediment is channeled to the basin and partly because the syncline, as an expression of the vertical component on the fault, is very active. The syncline is narrow close to shore where marine sediment is relatively thin and widens toward the east (Fig. 5). An eastward increase in the thickness of marine sediment is expected because the east-dipping and subsiding north side of the fault was submerged progressively earlier to the east. Thicker sediment may account for the eastward broadening of the drag syncline.

#### 4.1. Circular parasitic basin

A prominent 0.5-km-wide circular “parasitic” basin is superimposed on the drape syncline and straddles the fault (Figs. 4 and 5). Sedimentation in this basin is high and probably punctuated in association with large earthquakes (McHugh et al., 2003). Nevertheless, the basin is starved (i.e., it persists as a depression), suggesting rapid subsidence. In our interpretation, this basin is controlled by a shallow-rooted listric border fault. This fault is positioned where the drag syncline widens abruptly, suggesting an abrupt down-slope increase in sediment thickness. We interpret this and many other secondary faults and folds, both extensional and compressional, as shallow-rooted gravity collapse structures on the over-steepened flanks of the basin (e.g., Stewart, 1999). This fault is unusual in being closely coupled with the NAF-N. The normal fault rims the up-slope side of the parasitic basin on the south side of the NAF-N and the related roll-over anticline dams the basin down-slope, on the north side of the NAF-N. The distance between fault and roll-over structure is only 1/2 km, suggesting that the border fault is concave along dip as well as along strike and reaches only shallow depth. The NAF-N cuts across the basin and offsets bedding vertically (Fig. 5C), but does not offset the basin horizontally (Fig. 4). Lack of horizontal offset is possible if the border fault of the parasitic basin and the Ganos fault share the same slip-vector orientation. This vector is thus along the intersection between the NAF-N and the west rim of the basin, which dips  $14^\circ$  eastward along the NAF-N (Fig. 4B). The rake of the Ganos fault at the parasitic basin is thus within the range deduced from the vertical offset of the transgression unconformity in Fig. 5B and is less than twice the regional  $8^\circ$  dip of the basement surface along the Tekirdağ segment of the NAF-N (Figs. 2 and 7).

#### 4.2. Basinward warp on the border fault from gravity collapse

The regional geometry of the NAF-N is locally warped in a relatively small northward lobe on the western side of the Tekirdağ Basin. This lobe is about 8 by 2 km along and across strike, respectively (Fig. 2). The NAF-N is traced along the basin edge at the base of this lobe and is manifested by a set of right-

stepping en echelon folds that suggest right-reverse motion around the lobe (Demirbağ et al., 2003; Armijo et al., 2003). These folds are limited to the fault zone and they manifest some shortening, but probably not enough to account for the 2 km width of the lobe. We favor the hypothesis of a gravity collapse of the south flank of the basin (Gazioğlu et al., 2002). The lobe is interpreted as a detached slab moving down the south flank of the basin and impinging on the NAF-N (Fig. 8). This detachment is identified with the north-dipping South Boundary fault of Okay et al. (1999). They place this shallow-dipping fault (average dip  $13^\circ$ ; Fig. 3B) between metamorphic basement and Neogene strata. The Neogene continental and shallow marine clastic sequence in the Marmara region is characterized by weak lithologies and is prone to gravity collapse (Emre et al., 1998). Okay et al. (1999) also identify an extensional head scarp near Marmara Island and a compressional fold at the toe of this structure abutting the NAF-N at a depth of about 2.5 km (Figs. 2 and 3B). This detachment impinges on the shallow portion of the NAF-N buttressed only by relatively compliant syntectonic sediment.

The detachment sketched in Fig. 8 is in line with the South Boundary detachment imaged in Fig. 3B.

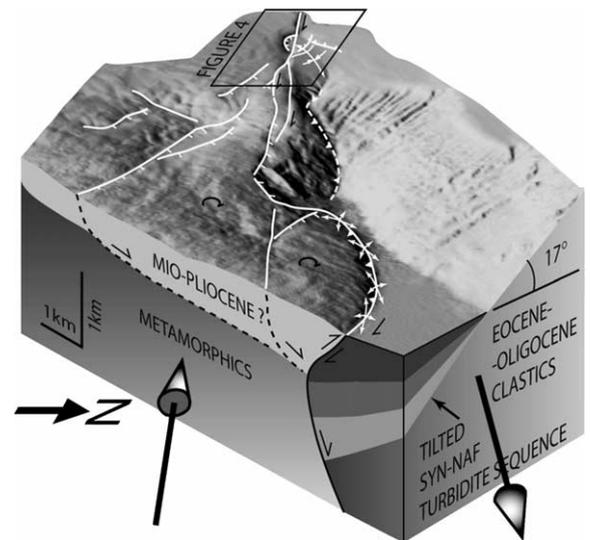


Fig. 8. Perspective view looking southwest of the western end of the Tekirdağ Basin (bathymetry from Rangin et al., 2001). Interpretation is based on profiles in Fig. 3, particularly 3B, and on the map in Fig. 4.

The detached slab needs to be sufficiently deep to avoid being cut by the NAF-N and shallow enough to leave the deeper part of the basin unaffected, as shown by the longitudinal profile in Fig. 2C. It also needs to move down slope sufficiently to account for the lobe. The required up-dip extension may be distributed. Detachment scarps with typical roll-over geometries are suggested by the chiseled surface on the southern flank of the basin upslope of the lobe (Fig. 8; Rangin et al., 2001). This morphology is common on the steep flanks of Karamürsel Basins (e.g., Cormier et al., 2003). It is often associated with folds draped over listric faults, which are rooted in weak sediment layers dipping toward the basin (Stewart, 1999).

The shallow part of the NAF-N warps northward in response to pressure by the detachment, flips to a south dip, and operates as a right-reverse fault near the surface (Fig. 8). Shortening of the turbidites can be much less than the amount of northward warping of the fault if sedimentation keeps up with the gravity collapse. As the fault is gradually warped northward, turbidite flows are dammed by the advancing lobe and the basin becomes narrower without significant shortening. Clockwise rotation of the detached interval may account in part for the dextral motion. Clockwise rotation may also account for the 1 km jog to the left at the west end of the loop. Right-stepping en echelon anticlines are imaged around the entire lobe, including the transtensive east side (Armijo et al., 2003). This is consistent with rapid northward advance and clockwise rotation of the lobe. Yet, the overall effect of this fault-normal convergence is subdued and thus shallow-rooted and tectonically insignificant. Gravity collapse may affect the entire southern flank of the Tekirdağ Basin and thus over-steepen the shallow portion of the NAF-N flanking syntectonic sediment (e.g., Fig. 3B,C).

### 5. A transform bend-indenter model

The Ganos bend and related structure (Fig. 2) inspired the conceptual model of an upper crustal bend-indenter at a transform boundary (Fig. 9). In the lower crust, the boundary may conform to the Euler circle of plate kinematics. In the upper crust, a fault bend violates this kinematics and is connected to the lower crust by a shallow-dipping portion of

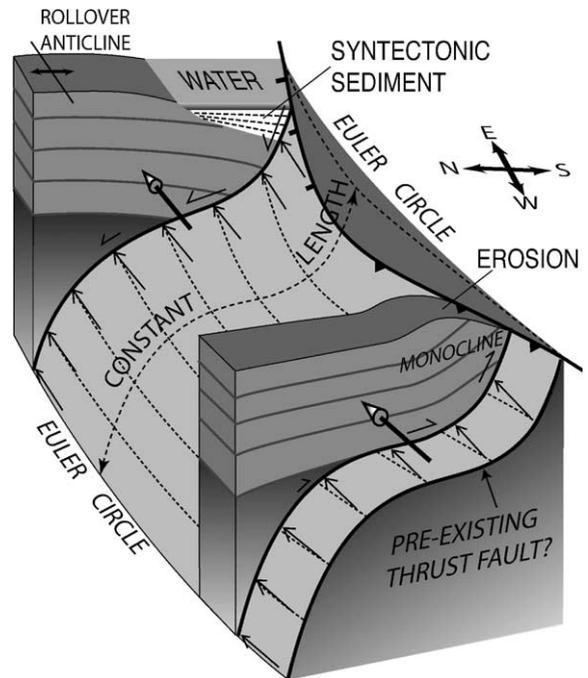


Fig. 9. A conceptual model of an upper crustal bend-indenter at a transform boundary. The boundary conforms to the Euler circle of plate kinematics in the lower crust, but deviates into a bend in the upper crust. The connection between shallow and deep portions of the fault is shallow dipping. The listric shape down to mid-crustal depths is relevant to progressive tilting of syntectonic sediments toward the fault in the Tekirdağ Basin and is plausible for a reactivated preexisting structure inherited from the Eocene suture (Fig. 1). Transform-normal shortening and extension on the transpressive and transtensive sides of the bend are accommodated by dip-slip components on the fault, only in the upper crust. Hanging-wall folding absorbs some of the shortening and reverse slip while roll-over does not diminish the normal component.

the fault. The resulting transpression and trans-tension on opposite sides of the bend can then be accounted for by oblique slip exclusively in the upper crustal portion of the fault. Decreasing dip down to mid-crustal depths is relevant to progressive tilting of sediments toward the NAF-N and to the associated roll-over structure 10–20 km north of the fault (Fig. 2). The Ganos segment of the NAF-N is rather linear across the Gelibolu peninsula and is thus steep at the surface. A north dip decreasing with depth similar to the one on the transtensional side of the bend is possible, however, and would allow oblique slip and uplift on the north side of the fault to accomplish the required horizontal shortening (Fig. 9).

A concave-upward geometry is observed in many dip-slip faults. Such geometry could characterize thrust faults inherited from the Eocene suture spatially correlated with the NAF and possibly reactivated in the current regime (Fig. 1). Much of the uplifted hanging-wall (northern) block on the transpressive side is eroded, transported eastward, and deposited in the trough on the transtensive side. This unloading and loading contributes to vertical motion on both sides of the bend. The kinematics are not necessarily antisymmetric, however, since it may include a net component of extension or compression. Furthermore, hanging-wall folding is likely to absorb some of the shortening and reverse slip on the transpressive side, while roll-over folding on the transtensive side may absorb extension (Kurt et al., 1999), thus permitting uniform slip on the fault (Fig. 9).

The conceptual model in Fig. 9 requires that the hanging-wall side of the fault move dextrally relative to the bend. This model can account for the Ganos Mountain and the Tekirdağ Basin, provided the bend is a persistent feature. The model does not require that the footwall (southern) side be fixed to the bend. Internal deformation on both sides, however, would tend to eliminate the bend. Instead, strain softening may lock the bend to the stronger side of the fault and concentrate bend-related off-fault deformation on the other side. This hypothesis predicts that the fault at a geometric asperity will separate two off-fault regimes, one distinctly more active than the other. Most of the current vertical motion from the Saros Gulf to the western Marmara Sea is on the north side of the NAF-N, suggesting that the Ganos bend is moving west relative to Asia. Other bends along the NAF, such as the SSW-pointing bend at the eastern end of the Çınarcık basin and the NNW-pointing bend at the western end of the Düzce basin, exhibit similar deformation patterns which are largely limited to one side of the fault. Fault geometry, primarily fault dip, may have a major role in determining which side yields. Generally, bend-related deformation in the Marmara region is consistently on the hanging-wall side of the fault.

The hypothesis that transform bends as rigid indenters are moving with the side of the transform opposite the one that is absorbing bend-related deformation has interesting implications for the tectonic evolution of the Marmara region. According

to this hypothesis, both bends associated with the Çınarcık basin are moving with the Asian plate, while the Ganos bend is moving with the Anatolian block. The zone of subsidence between these bends marked by the Marmara Sea is thus expanding along the fault. This hypothesis is consistent with the reconstruction proposed by Armijo et al. (2002) and contributes a rationale for the geometry of the fault system.

## 6. Discussion: transitional versus steady state tectonics

Current fault geometry and kinematics in the Marmara region as displayed by earthquake ruptures and by active-fault maps has been interpreted by some to show less extension than would be expected from the long-term structure of the basins. In this view, the extension responsible for the basins took place earlier in the evolution of the NAF and the current regime in the Marmara region is primarily transcurrent (e.g., Le Pichon et al., 2001; İmren et al., 2001). This hypothetical transition, however, needs to be very recent or ongoing because border faults and other basin-related structures do affect shallow sediment and are still active. In another view, the western NAF is in a stable transtensional regime and basin formation in the Marmara may be ongoing (e.g., Okay et al., 2000; Armijo et al., 2002). This debate has implication for hazard. The Marmara seismic gap is more likely to rupture in a single large earthquake in the case of a through going strike-slip fault parallel to plate motion (Le Pichon et al., 2001). In contrast, a master fault segmented by a series of basins coupled with the dextral motion is more likely to rupture in more frequent but smaller earthquakes. An evolutionary model is more complicated, and it is particularly astonishing if it requires a major tectonic transition to coincide with the present. It is justified only if steady-state tectonics is ruled out.

This paper contributes to the debate between steady state and transitional tectonics by comparing Holocene and Quaternary structure along the Tekirdağ border fault. Our high-resolution data image Holocene sediment and thus display current deformation at the juncture between the Ganos and the Marmara segments where the NAF-N cuts the western Marmara

Sea shelf. We compare this deformation with published data both on land to the west and in the Tekirdağ Basin to the east. A common feature along this portion of the NAF-N is that current and accumulated Quaternary vertical motions as recorded in a material-anchored reference frame are opposite. This change in kinematics, however, does not require a change in tectonic regime. The vertical component of deformation is active north of the NAF-N, but the pattern of this deformation is likely to be stationary relative to the Ganos bend and to the southern side of the NAF-N. This leads to a characteristic systematic lag between accumulated structure and deformation, which we propose to characterize as “diachronic”. We thus interpret contrasting Holocene and Quaternary structures in terms of a steady-state regime where the Asian side of the NAF-N moves around the bend from the compressional side to the extensional side of the NAF-N (Fig. 10). Likewise, the asymmetric late Quaternary subsidence characterizing the Tekirdağ

Basin is the result of a steady deformation pattern fixed to the south side of the NAF-N and affecting the north side of the NAF-N in a westward progression. At any time during this process, the highest topography is expected to coincide with the bend and to the onset of subsidence.

We have shown that basin growth in the eastern Marmara Sea is ongoing and that it is related to the same fault kinematics over both short (e.g., Holocene) and long terms (e.g., late Quaternary). This regime appears to have operated in a remarkably steady mode through the formation of the Tekirdağ Basin through the late Quaternary. The model of diachronic vertical deformation can be tested at other bends along the NAF and other transforms. Particularly promising candidates are the Cınarcık basin and the İzmit–Cınarcık bend in the eastern Marmara Sea, and the Düzce basin and the Karadere–Düzce bend along the branch of the NAF that ruptured in 1999 (Barka et al., 2001).

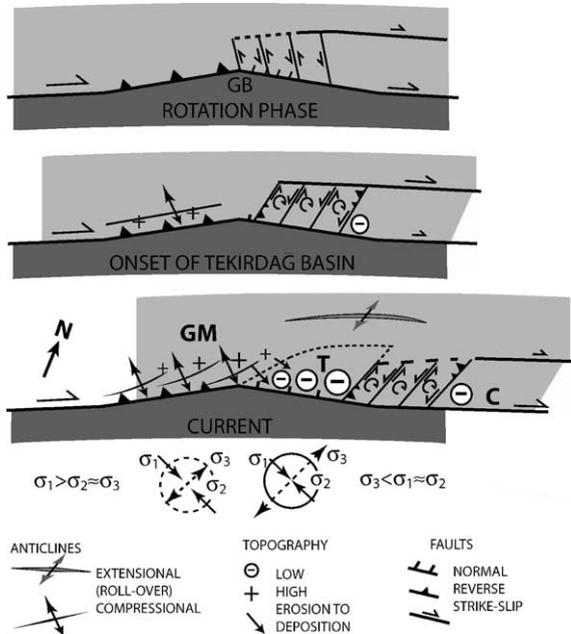


Fig. 10. Uplift and basin evolution at the Ganos bend on the North Anatolian Fault. Stress axes may be similarly oriented on the transpressive and transtensive sides of the bend, but the relative magnitudes are expected to differ. The early clockwise-rotation phase is speculative and it is not necessary to account for the vertical tectonics around the bend. GM=Ganos Mountain; T=Tekirdağ Basin; C=Central Basin; GB=Ganos Bend.

## 7. Conclusions and speculations

- (1) Bends on regional high-rate transcurrent faults are common features. Off-fault vertical strain near the bend is a likely consequence. Transpressive uplift and transtensive subsidence are prominently associated with the Ganos–Marmara bend of the Northern Branch (NAF-N) of the NAF. This deformation, however, is primarily on the north side of the fault, suggesting that the bend is anchored to the Anatolian side. Such asymmetry in the motion relative to a transform bend may be common. Bend-related vertical deformation may occur preferentially on the hanging-wall side of non-vertical transcurrent faults.
- (2) The Tekirdağ Basin is positioned on the transtensive east side of NNW-pointing Ganos bend of the NAF-N. It is an asymmetric basin with the NAF-N as an oblique slip north-dipping border fault. With a rake of about  $8^\circ$ , the NAF-N can account for the basin geometry and size with about 28 km of dextral displacement. The oblique slip tilts the basin obliquely relative to the fault and subsidence is fastest near the fault and near the bend. The panel of progressively

tilted syntectonic strata has a radius of 10–20 km and provides unique constraints on fault geometry much deeper than the reach of the data. It suggests that the dip of the fault decreases with depth into the mid-crust. With a similar geometry on the compressive west side of the bend, the NAF-N can account for uplift and the Ganos anticline/monocline on the north side by a reverse component and by hanging-wall-block folding. This way, the bend may affect only the upper crust where fault normal strain is accommodated by oblique slip with no partitioning. Several other basins along the NAF show asymmetric growth and progressive tilting and are associated with fault bends. The rupture in the M 7.2 Düzce earthquake in 1999 had a geometry similar to the one proposed for the Ganos Fault and occurred on the transtensive side of a bend similar to the one in Ganos.

- (3) The Tekirdağ Basin is growing in the current tectonic regime. Sediment thickness distribution and tilting have been progressively changing through the evolution of the basin as expected in a steady-state diachronic regime where the pattern of vertical motion is steady, but moves laterally. The current deformation near the bend is both qualitatively and quantitatively consistent with the structure of the basins and a recent change in tectonic regime is not required. Assuming a constant dextral slip rate, the age of the Tekirdağ Basin is only 1.1–1.4 Ma, according to our reconstruction. This basin may thus be substantially younger than the NAF and be symptomatic of a mid-Quaternary change in tectonic regime.

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