Rapid subsidence and sedimentation from oblique slip near a bend on the North Anatolian transform fault in the Marmara Sea, Turkey

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ABSTRACT

Several basins are developing near bends on strands of the North Anatolian transform fault in northwest Turkey. Oblique slip on these faults, rather than strain partitioning, accounts for transtension and subsidence. These basins are asymmetric, and tilt and subside most rapidly at their narrow ends near the bends. The turbidite surface marking the floor of the Cinarcik Basin (eastern Marmara Sea) was mostly abandoned at a sudden drop in sedimentation, which was likely coincident with the 14 ka lake-sea transition, and is now a warped reference surface from which we can measure strain and sedimentation. Subsidence and tilt are rapid, but do not require late Quaternary changes in regime. They are linked to transcurrent motion by slip parallel to an oblique bend on the North Anatolian fault and suggest tsunamogenic vertical motion in large Marmara Sea earthquakes.

Keywords: continental transform, fault bend, basin subsidence, North Anatolian fault.

INTRODUCTION

Basins are common along continental transforms and are often linked to fault bends or jogs that require deformation within a finite zone, including vertical kinematics. This deformation is recorded in the sediment and constrains the evolution of the transform, provided horizontal and vertical motions are clearly linked by the geometry and kinematics of the fault system. While many models have been proposed (e.g., Crowell, 1987), correlations between horizontal and vertical motions in specific basins remain largely qualitative, and available data often cannot differentiate between competing models (e.g., study area). We use high-resolution images of the bathymetry and shallow subbottom to reconstruct vertical deformation in a submarine basin as marked by a warped horizon. Our approach is generally applicable to basins receiving a sea-level modulated sediment flux from the continental shelf. The pattern of deformation is clearly related to a bend in the main strand of the transform and points to a specific fault geometry that accounts for the bend with minimal off-fault deformation. This model may apply to a wider class of bend-related transforms basins.

The 1700-km-long North Anatolian dextral fault accommodates the westward motion of Anatolia relative to Asia. This continental transform is notorious for destructive earthquakes (Ambraseys, 2002). A propagating sequence of ruptures during the twentieth century has reached westward to the Marmara segment, which is expected to rupture next in a particularly destructive earthquake (e.g., Toksöz et al., 1979). Branching and transtensional tectonics increase westward as the North Anatolian fault enters the Aegean Sea–western Turkey region of backarc extension (Fig. 1; McKenzie, 1972; Şengör et al., 1985). The North Anatolian fault is the type transform for basin formation (Barka and Kadinsky-Cade, 1988). The 150-km-long Marmara Sea is traversed by the northern strand of the transform (LePichon et al., 2001), which carries much of the plate motion (20–25 mm/yr; Meade et al., 2002). This sea covers three major starved basins, which have water depths of ∼−1.2 km (Fig. 1). The rectangular central basin has been interpreted as a classic ''pull-apart'' structure (Armijo et al., 2002). The western (Tekirdag) and eastern (Cinarcik) basins, instead, are triangular half grabens bordered to the south and north, respectively, by the northern strand of the North Anatolian transform fault (Fig. 1). These basins are similarly positioned on the extensional side of prominent fault bends, with depocenters at their narrow ends near the bends (Okay et al., 2000). Triangular transform-bend–related basins occur also further east (Fig. 1). These bends involve nonvertical segments of the North Anatolian transform fault that have oblique slip and are fixed to the footwall sides, which are relatively stable (Seeber et al., 2004). Thus, fault geometry, which may be inherited from pre-existing sutures (Fig. 1), controls kinematics and is critical for modeling the seismogenic behavior of the fault system.

The Cinarcik segment of the North Anatolian fault next to the Cinarcik Basin is particularly oblique to plate motion (Fig. 2). It is a key element for Marmara Sea tectonics and for hazard in Istanbul, but interpretations remain divergent despite recent intense investigations. We use multibeam bathymetry (Rangin et al., 2001) and chirp seismics (Polonia et al., 2004) to investigate the uppermost sediments in the basin. In the tectonically active environment, fresh turbidites are quasi-horizontal (Fig. 3), probably because they are reworked by strong earthquakes into homogenites (McHugh et al., 2006), and are thus markers for vertical deformation. Turbiditic supply to the basin fluctuates, and the area covered by the most recent sediment grows and wanes while the basin floor tilts. The flux of turbidites from the shelf to the basin is high at glacial maxima and low sea levels, but can drop dramatically when sea level rises and makes room for sediment on the

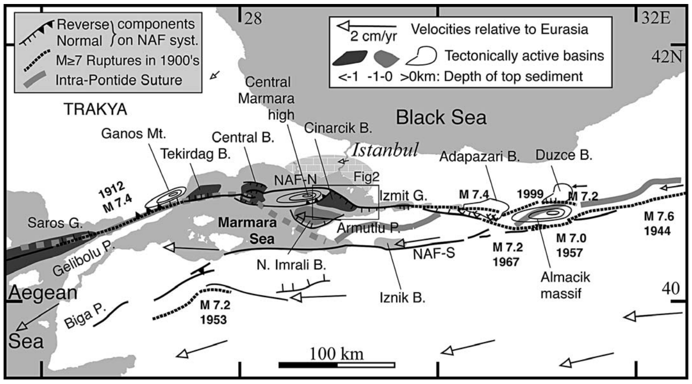

Figure 1. Tectonic sketch map of Marmara Sea region. West of 32°E, North Anatolian transform splits into northern and southern branches (NAF-N and NAF-S). They absorb 4/5 and 1/5 of motion, respectively (geodetic velocity vectors are relative to Eurasia; McClusky et al., 2000). NAF-N follows early Eocene suture (Yılmaz et al., 1997). Cinarcik Basin (boxed) is on extensional side of prominent south-pointing bend along NAF-N. P—Peninsula; G—Gulf; B—Basin.

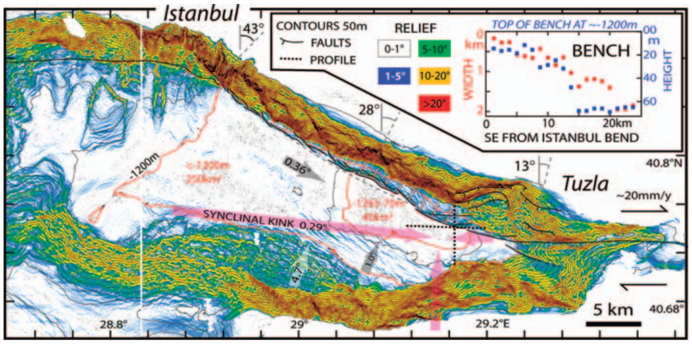

Figure 2. Relief and bathymetry of Cinarcik Basin (Rangin et al., 2001). This triangular half graben is bordered on north by arcuate transtensional segment of northern North Anatolian transform fault between Tuzla and Istanbul bends. This fault forms south-facing monocline on horizontal "bench" at base of footwall escarpment. Bench height and width (inset plot) decrease linearly westward and vanish near Istanbul bend. Bench narrows abruptly toward east across toe of large slump. Basin tilts toward depocenter at narrow eastern corner. Deepest part is maintained horizontal (−1265 to −1270 m) by turbidite sedimentation. It is surrounded by abandoned turbidite surface, which was deformed into three tilted panels separated by synclinal kinks (black and red arrows, respectively) and into bench on footwall side of fault. Bench and tilted panels reach ~−1200 m, above which flanks of basin become steeper. Sharp truncation of channels at slope change (e.g., southern flank) is strong evidence for depositional contact. Contour-subparallel corrugations are probably from shallow-rooted low-displacement normal faults accommodating downslope motion of tilted turbidites (Stewart, 1999). Steep walls around basin are rocky outcrops subject to erosion (Armijo et al., 2005).

shelf (e.g., Nardin, 1983). An increase in drowned shelf area is expected to reduce fresh turbidite cover on a tilting basin floor. We thus interpret panels of sediments around the area of current deposition as older turbidites deposited just prior to a reduction in turbidite area. They are covered only by relatively thin pelagic sediment and are tilted by tectonics. In contrast to expected large changes in sediment flux, patterns and rates of deformation are likely to remain stable at the time scale of glacial cycles, so that tilt can be a proxy for age.

THE CINARCIK BASIN

In plan view, the Cinarcik is a narrow triangular basin bordered on the northeast side by the 30-km-long transtensional Cinarcik segment of the northern North Anatolian fault, between the southwest-pointing bend near Tuzla and the northeast-pointing bend near Istanbul (Fig. 2). The Cinarcik segment is extensionally oblique to local approximately east-west plate motion (Fig. 1; Meade et al., 2002) and separates the 1200–1270-m-deep floor of the basin from a steep (20°–25°) escarpment, which is the eroded footwall of the southwest-dipping fault (Figs. 2 and 3; Okay et al., 2000; LePichon et al., 2001; Imren et al., 2001; Armijo et al., 2002; Demirbag et al., 2003). In contrast to several kilometers of basin subsidence south of the south-dipping fault (Carton, 2003), the footwall block north of the fault is relatively stable. The northern shelf is wide (Fig. 1), it is marked by a paleoshoreline at the Dardanelles sill depth (Cormier et al., 2006), and the Pliocene-Pleistocene Istanbul Plateau has modest elevation and little tilting or warping (Emre et al., 1998). The vertical velocity field is not only one-sided across the Cinarcik segment, but also along it. The depocenter is at the narrow eastern end of the basin, near the Tuzla bend (Fig. 2). It is characterized by a remarkably horizontal but relatively small area of active turbidite deposition surrounded by a wider basin "floor" with distinct panels of tilted sediment.

The "bench" is a strip of elevated seafloor sediment at the base of the northern escarpment on the footwall side of the northern Cinarcik segment (Fig. 2). Neglecting small fans fed by the escarpment, the top of the bench is nearly horizontal at ~−1200 m and is elevated above the basin floor by a monocline controlled by the dip component of the fault (Figs. 2 and 3). En-echelon "scarps" characterize this monocline and mark the trace of the fault (Armijo et al., 2005). Bench width and height are proportional. They taper to the west, reflecting gradual shallowing of the basin floor, and vanish where the floor rises to −1200 m at the Istanbul bend of the fault. A slump disrupts the bench at the southeastern end of the basin, but the frontal monocline of the bench continues around the Tuzla bend and into Izmit Gulf as the trace of the northern branch of the North Anatolian transform fault. On the hanging-wall side of the basin, the horizontal area of active sedimentation merges into three subplanar "panels," which are gently tilted toward the depocenter and are separated by synclinal kinks, like the tilted floor of an auditorium (Fig. 2). Upslope, these panels merge onto steeper and probably older sediment panels, which in turn merge into rocky escarpments. The top of the bench and the boundary between first- and second-order panels form an ~1200-m-deep "bathtub ring" around the basin, which marks a sharp change not only in seafloor dip, but also in drainage morphology. Prominent erosional channels are truncated at that boundary and are absent below it (Fig. 2), strongly supporting an onlap and not a fault contact interpretation of this ring.

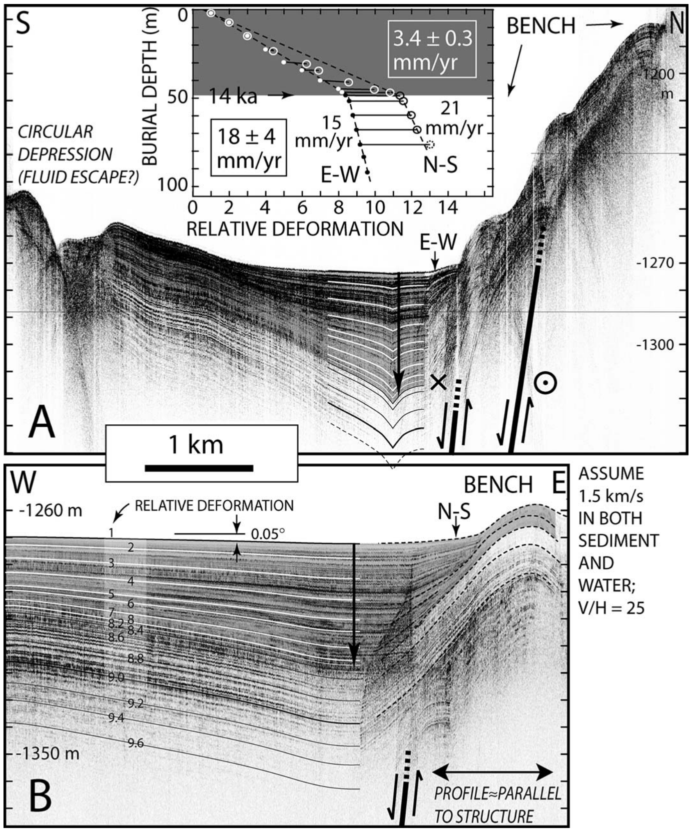

Figure 3. N-S (A) and E-W (B) Chirp profiles across depocenter of basin (Fig. 2). Syndepositional normal displacement on blind border fault raises bench above basin floor and progressively deforms sediments. Same beds are traced in each profile and are connected in plot. Tracings match beds by scaling vertical amplitude (numbers in B). Shape and horizontal position are identical in each profile, indicating steady pattern of deformation. If its rate is also steady, ~50-m-deep bend in deformation-depth plots implies sharp drop in sedimentation rate, which is assumed to coincide with lacustrine-to-marine transition and onset of water-level rise in Marmara Sea at 14 ± 0.5 ka. Note that drop in sedimentation occurs at same horizon that pinches out, marking emergence of bench. Compaction is unaccounted for, but it reduces both thickness and tilt. A slump and secondary faults distort bench at these profiles (Fig. 2).

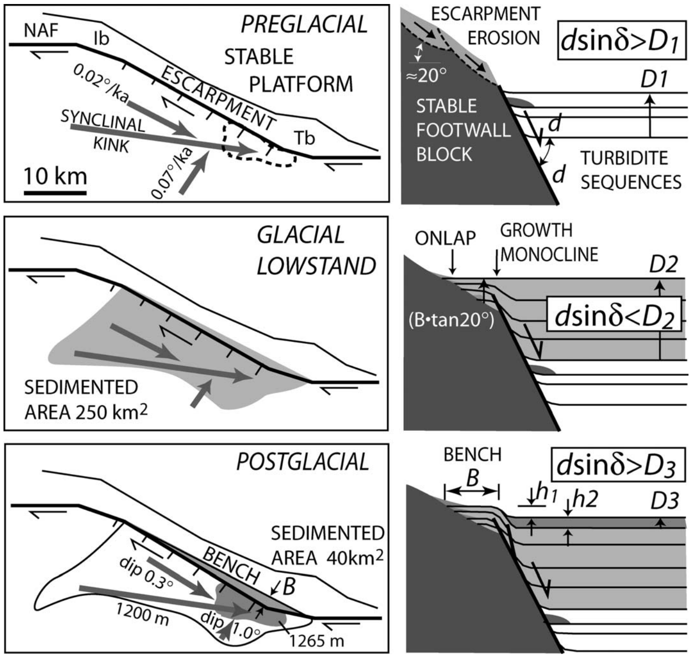

Figure 4. Interaction between fault-controlled subsidence and sedimentation in Cinarcik Basin, assuming stable footwall and steady tectonics through last glacial cycle. Basin tilts but sedimentation maintains horizontal area, size and depth of which is controlled by variable turbidite rates. Sedimentation during high preglacial sea level may resemble current pattern: turbidite accumulation D is slower than subsidence dsinδ and is confined to hanging-wall side of fault at eastern end of basin. Basin floor deepens. Escarpment erosion maintains a slope of ~20° above fault. During glacial lowstand, sedimentation is much higher and overtakes subsidence (Figure 3). Turbidite floor shallows and covers fault and footwall block over a width B = 2 km at the Tuzla bend (Tb). Low sedimentation returns at the lake-sea transition (LST) 14 ± 0.5 kybp with rising post-glacial sea level. Turbidite floor subsides and retreats below footwall. The broad pre-LST turbidite surface is warped into a bench monocline. The total elevation offset at the depocenter since LST, h1+h2 = 50+57 ± 10 m yields a subsidence rate dsinδ = 7.7 ± 1.3 mm/yr. If bench was accumulated from 75 ka to 15 ka when sea level was ≤−85m, inferred thickness of bench suggests average sedimentation D2 = dsinδ +(Btan20°)/60 k.y. ≈ 20 mm/yr. Similar rate is measured in Figure 3 for uppermost pre–lake-sea transition section.

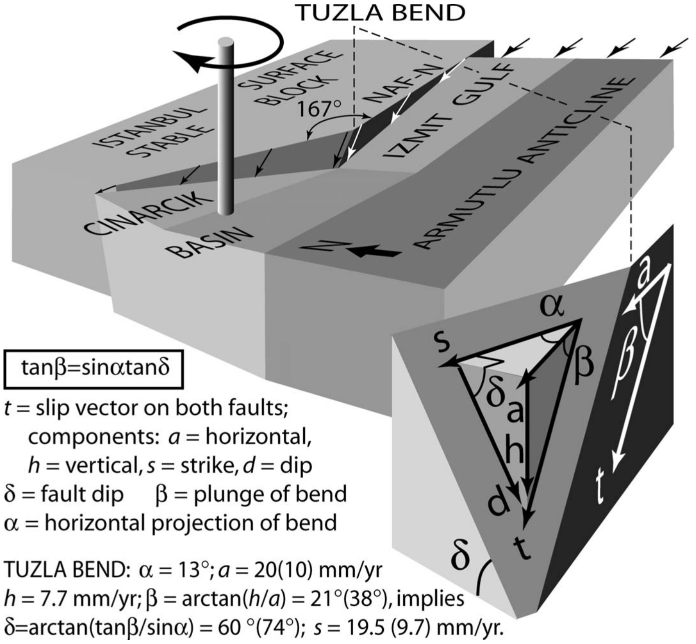

Figure 5. Subsidence in eastern Marmara Sea is accounted for by motion parallel to oblique bend on northern North Anatolian transform fault (NAF-N) near Tuzla. If western Izmit segment is vertical and moves 10–20 mm/yr, eastern Cinarcik segment needs to dip 74–60° south to subside at 7.7 mm/yr (Fig. 4). Westward decrease in dip slip implies clockwise rotation of basin.

The shape of the Cinarcik Basin floor is accounted for by tectonic warping of the paleohorizontal turbidite surface abandoned since a reduction of the area of deposition. In this hypothesis, the bench and tilted panels below the ''bathtub ring'' are vestiges of the latest major turbidite sequence covering the trace of the Cinarcik segment, the base of the steep escarpment to the north and much of the basin on the footwall block to the south (Fig. 2). This area is much wider than the area of current turbidites (Fig. 2) and implies an earlier period of faster sedimentation. The chirp profiles at the depocenter (Fig. 3) display progressive deformation. While the pattern of deformation is uniform, the ratio between deformation and sediment thickness changes abruptly ~50 m below the depocenter. This horizon is also the uppermost turbidite covering the bench (Fig. 3B). Two independent observations thus point to the same abrupt drop in sedimentation.

We assume that the drop in turbidite flux correlates with the lake-sea transition in the Marmara Sea and the onset of sea-level rise at 14 ± 0.5 ka (Çagatay et al., 2003; McHugh et al., 2006). We then derive sedimentation rates from thicknesses and progressive deformation of horizons through the sections imaged at the depocenter (Fig. 3). Post–lake-sea transition sedimentation is relatively steady, averaging 3.4 ± 0.3 mm/yr, and is in good agreement with core measurements (Çagatay et al., 2003; Mercier de Lepinay et al., 2003). Sedimentation in the late pre–lake-sea transition was much higher, 18 ± 4 mm/yr. The height of the bench (excluding post–lake-sea transition pelagic sediment; Figs. 3 and 4) yields a 7.7 ± 1.3 mm/yr subsidence rate, which is intermediate between pre– and post–lake-sea transition sedimentation rates. The subsidence includes both tectonic subsidence and compaction and can be considered absolute because vertical motions of the footwall block are within the uncertainty (Cormier et al., 2006). The top of both bench and tilted panels, the ''bathtub ring'' at −1200 m, and the pre–lake-sea transition depocenter, now at −1320 m (Fig. 2), define an inverted 9 km^3 pyramid of increased post–lake-sea transition basin volume (an average rate of 73m^3/hr!). Late pre–lake-sea transition sedimentation is more than twice the rate of subsidence at the depocenter, implying a sediment flux exceeding the volume rate. In contrast, post–lake-sea transition turbidite is only 0.7 km^3, an order of magnitude less than the volume increase.

Subsidence from Slip Parallel to an Oblique Fault Bend

The Cinarcik Basin is primarily the result of subsidence caused by a dip component on the Cinarcik segment. This down-to-the-south fault motion starts on the subvertical Izmit segment and increases westward, from 2 to 4 mm/yr 15 km east of the Tuzla bend (Cormier et al., 2006) to 7.7 mm/yr at the bend, and then it decreases along the south-dipping Cinarcik segment, vanishing 30 km west of the bend (Figs. 2–4). These segments intersect along an oblique ''bend'' plunging west, where they differ in strike by 13° (Fig. 2). This bend can be fixed to both sides of the northern North Anatolian transform fault, provided the slip vector is parallel to the bend (Fig. 5). The bend is thus like a rail guiding oblique fault motion with relatively little off-fault deformation (Figs. 2 and 3). A 20 mm/yr (or 10 mm/yr; Polonia et al., 2004) rate on the Izmit segment will produce 7.7 mm/yr subsidence (neglecting compaction) if the Cinarcik segment dips 60° (or 74°) south. This model also predicts that the Cinarcik Basin is rotating clockwise at 0.018°/k.y. The rotation accounts for ~1/4 of the dextral motion on the northern branch and thus absorbs significant slip from the fault near Istanbul (Fig. 1). This rotation is consistent with the northward component exhibited by geodetic-motion vectors in the Armutlu Peninsula (Fig. 1).

CONCLUSIONS

1. Subsidence at the Cinarcik Basin depocenter near the Tuzla bend of the northern strand of the North Anatolian fault is 7.7 ± 1.3 mm/yr. During the last Marmara lacustrine phase, depocenter sedimentation of 18 ± 4 mm/yr overtook subsidence, thus covering the border fault and much of the floor of the basin. This implies a sediment flux $\geq 6 \times 10^5$ m^3/yr, the rate of basin-volume increase below −1200 m. At the marine incursion, sedimentation dropped abruptly to 3.4 ± 0.3 mm/yr, and the basin has been deepening since.

2. The North Anatolian transform fault tends to account for transtension and vertical thinning by oblique slip. Slip is dextral and down-to-the-south over a 50 km portion of this fault centered at the Tuzla bend. Two synclinal hinges plunging toward the bend account for the pattern of vertical motion south of the Cinarcik segment. Lack of other Holocene structure suggests that slip is parallel to the bend. The observed subsidence and dextral motions can be produced with a 21° (38°) west-plunging bend between a vertical Izmit segment and a Cinarcik segment dipping 60° (74°) southwest. The Cinarcik Basin rotates clockwise at 0.018°/k.y., thus absorbing ~1/4 of the dextral motion south of Istanbul.

3. Turbidites, probably reworked as homogenites, in starved basins along active transforms are precise horizontal markers. Deposition surfaces abandoned by abrupt decrease in turbidite flux related to sea-level rise can be sharp age markers. High-resolution bathymetry and shallow-penetration seismics can detect these marker horizons and thus constrain regional tilts, subsidence, and fault offsets over the last glacial cycle.

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REFERENCES CITED

Ambraseys, N.N., 2002, The seismic activity of the Marmara Sea region over the last 2000 years: Bulletin of the Seismological Society of America, v. 92, p. 1–18, doi: 10.1785/0120000843.

Armijo, R., Meyer, B., Navarro, S., King, G.C.P., and Barka, A.A., 2002, Asymmetric slip partitioning in the Sea of Marmara pull-apart: A clue to propagation processes of the North Anatolian fault?: Terra Nova, v. 14, p. 80–86, doi: 10.1046/j.1365-3121.2002.00397.x.

Armijo, R., and 22 co-authors, 2005, Submarine fault scarps in the Sea of Marmara pull-apart (North Anatolian fault): Implications for seismic hazard in Istanbul: Geochemistry, Geophysics, Geosystems, v. 6, Q06009, doi: 10.1029/2004GC000896.

Barka, A.A., and Kadinsky-Cade, K., 1988, Strike-slip fault geometry in Turkey and its influence on earthquake activity: Tectonics, v. 7, no. 3, p. 663–684.

Çagatay, M.N., Görür, N., Polonia, A., Sakinç, M., Cormier, M.-H., Capotondi, L., McHugh, C.M.G., Emre, Ö., and Eris, K., 2003, Sea-level changes and depositional environments in the Izmit Gulf, eastern Marmara Sea, during the late glacial–Holocene period: Marine Geology, v. 202, p. 159–173, doi: 10.1016/S0025-3227(03)00259-7.

Carton, H., 2003, Structure of the Cinarcik Basin (eastern Marmara Sea) from densely spaced multi-channel reflection profiles: Lithos Science Report, v. 5, p. 69–76.

Cormier, M.-H., Seeber, L., McHugh, C.M.G., Polonia, A., Çagatay, M.N., Emre, Ö., Gasperini, L., Görür, N., Bertoluzzi, G., Bonatti, E., Ryan, W.B.F., and Newman, K.R., 2006, The North Anatolian fault in the Gulf of Izmit (Turkey): Rapid vertical motion in response to minor bends of a non-vertical continental transform: Journal of Geophysical Research, v. 111, B04102, doi: 10.1029/2005JB003633.

Crowell, J.C., 1987, Late Cenozoic basins of onshore Southern California: Complexity in the hallmark of their tectonic history, *in* Ingersol, R.V., and Ernst, W.G., eds., Cenozoic basin development of coastal California, Rubey Volume VI: Englewood Cliffs, New Jersey, Prentice-Hall, p. 207–241.

Demirbag, E., Rangin, C., LePichon, X., and Şengör, A.M.C., 2003, Investigation of the tectonics of the Main Marmara fault by means of deep-towed seismic data: Tectonophysics, v. 361, p. 1–19, doi: 10.1016/S0040-1951(02)00535-8.

Emre, O., Erkal, T., Tchapalyga, A., Kazancı, N., Kecer, M., and Ünay, E., 1998, Neogene-Quaternary evolution of the eastern Marmara region, northwest Turkey: Bulletin of the Mineral and Research and Exploration, v. 120, p. 119–145.

Imren, C., LePichon, X., Rangin, C., Demirbag, E., Ecevitoglu, B., and Görür, N., 2001, The North Anatolian fault within the Sea of Marmara: A new interpretation based on multi-channel seismic and multi-beam bathymetry data: Earth and Planetary Science Letters, v. 186, p. 143–158, doi: 10.1016/S0012-821X(01)00241-2.

LePichon, X., Şengör, A.M.C., Demirbag, E., Rangin, C., Imren, C., Armijo, R., Görür, N., Çagatay, M.N., Mercier de Lepinay, B., Meyer, B., Saatcılar, R., and Tok, B., 2001, The active main Marmara fault: Earth and Planetary Science Letters, v. 192, p. 595–616, doi: 10.1016/S0012-821X(01)00449-6.

McClusky, S.C., Bassalanian, S., Barka, A.A., Demir, C., Ergintav, S., Georgiev, I., Gurkan, O., Hamburger, M., Hurst, K., Kahle, H.-G., Kastens, K., Kekelidze, G., King, R.W., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadariya, M., Ouzounis, A., Paradissis, D., Peter, Y., Prilepin, M., Reilinger, R.E., Sanli, I., Seeger, H., Tealeb, A., Toksoz, M.N., and Veis, G., 2000, Global positioning system constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus: Journal of Geophysical Research, v. 105, p. 5695–5719, doi: 10.1029/1999JB900351.

McHugh, C.M.G., Seeber, L., Cormier, M.-H., Dutton, J., Çagatay, N., Polonia, A., Ryan, W., and Görür, N., 2006, Submarine earthquake geology along the North Anatolian fault in the Marmara Sea, Turkey: A model for transform basin sedimentation: Earth Planetary Science Letters (in press) p. F1632.

McKenzie, D.P., 1972, Active tectonics of the Mediterranean region: Geophysical Journal International, v. 30, p. 109–185.

Meade, B.J., Hager, B.H., and Reilinger, R.E., 2002, Estimates of seismic potential in the Marmara region from block models of secular deformation constrained by GPS measurements: Bulletin of the Seismological Society of America, v. 92, p. 208–215, doi: 10.1785/0120000837.

Mercier de Lepinay, B., Laberyrie, L., Çagatay, N., and the MARMARACORE science team, 2003, Interplay between recent sedimentation and active tectonics in the Marmara Sea: abstractEAE03A12694.

Nardin, T.R., 1983, Late Quaternary depositional systems and sea level change; Santa Monica and San Pedro Basins, California continental borderland: American Association of Petroleum Geologists (AAPG) Bulletin, v. 67, p. 1104–1124.

Okay, A.I., Kaslilar-Ozcan, A., Imren, C., Boztepe-Güney, A., and Kusçu, I., 2000, Active faults and evolving strike-slip basins in the Marmara Sea, northwest Turkey: A multichannel seismic reflection study: Tectonophysics, v. 321, p. 189–218.

Polonia, A., Gasperini, L., Amorosi, A., Bonatti, E., Bertoluzzi, G., Cagatai, N., Capotondi, L., Cormier, M.-H., Gorur, N., McHugh, C., and Seeber, L., 2004, Holocene slip rate of the north Anatolian fault beneath the Sea of Marmara: Earth and Planetary Science Letters, v. 227, p. 411–426, doi: 10.1016/j.epsl.2004.07.042.

Rangin, C., Imren, C., Crusson, A., Normand, A., Le Drezen, E., and Le Bot, A., 2001, Marine atlas of the Sea of Marmara (Turkey): Brest, Institut Français de Recherche pour l'Exploitation de la Mer, Special publication, 11 plates and 1 booklet.

Seeber, L.O., Emre, M., Cormier, C., Sorlien, C., McHugh, C.M.G., Polonia, A., and the team of the 2000 *Urania* cruise in the Marmara Sea, 2004, Uplift and subsidence from oblique slip: The Ganos-Marmara bend on the North Anatolian transform, western Turkey: Tectonophysics, v. 391, p. 239–258.

Şengör, A.M.C., Görür, N., and Saroglu, F., 1985, Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study, *in* Biddle, K.T., and Christie-Blick, N., eds., Strike-slip deformation, basin formation, and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 37, p. 227–264.

Stewart, S.A., 1999, Geometry of thin-skinned tectonic systems in relation to detachment-layer thickness in sedimentary basins: Tectonics, v. 18, p. 719–732, doi: 10.1029/1999TC900018.

Toksöz, M.N., Shakal, A.F., and Michael, A.J., 1979, Space-time migration of earthquakes along the North Anatolian fault zone and seismicity gaps: Pure and Applied Geophysics, v. 117, p. 1258–1270, doi: 10.1007/BF00876218.

Yılmaz, Y., Tuysuz, O., Yigitbas, E., Genç, S.C., and Şengör, A.M.C., 1997, Geology and tectonic evolution of Pontides, *in* Robinson, A.G., ed., Regional and petroleum geology of Black Sea and surrounding region: Tulsa, American Association of Petroleum Geologists, p. 183–226.

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