CONTINENTAL TRANSFROM BOUNDARIES: TECTONICS, EARTHQUAKES, SEDIMENTATION, FLUIDS AND PALEOCLIMATE

by

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ABSTRACT

Continental transform boundaries cross heavily populated regions and are associated with destructive earthquakes. Even though these settings have been extensively studied, the origin and tectonic evolution of the submerged segments of continental transforms remains controversial.

Drilling into these transform basins can recover a long-term, high-resolution record of their growth, of the temporal pattern of large earthquakes that punctuated this growth, and of both the local and global paleoceanographic conditions that existed during their evolution. Instrumenting the boreholes could provide information constraints on fluid pressure and deformation considered essential processes for geohazard studies.

The Marmara Sea, Turkey is a natural laboratory for such studies due to: 1) extensive geophysical data that has provided a unique and growing coverage, but still lack essential constraints from direct sampling of the stratigraphy. 2) The progressive tilting in some of the basins allow sampling of the entire syntectonic sequence with relatively shallow cores. 3) New information from stratigraphy and structural growth would improve earthquake hazard assessment in an area facing major risk. 4) The Marmara Sea has been selected to become a focus site to monitor geohazards and to study the relations between fluids and seismicity, within the European Seafloor Observatory Network (ESONET) and there are two initiatives: the Kandilli Marmara Sea Bottom Observatory (MSBO) project and the ESONET Marmara Demonstration Mission project.

The new outcomes will provide key information of the age, spatial, and temporal evolution of continental transform boundaries, it will greatly improve assessment of seismic hazards, further develop methodology for the emerging field of submarine earthquake geology, address major issues, such as the partitioning between fluid from deep sources possibly relevant to earthquakes and fluid from the compaction and dewatering of shallow sediments, and extract a long term record of paleoceanography and paleoclimatology for regional and global correlations.

Continental Transform Boundaries

Continental transforms represent a small fraction of the world plate boundaries but they shape many densely populated areas and are thus disproportionately associated with destructive earthquakes. Transform faults are steep and release seismic energy close to the surface so that smaller and more frequent earthquakes can be damaging. These faults tend to develop parallel to continental margins, often in the wake of subduction systems and relic suture zones, and can remobilize accretionary prisms and zones of thinned continental lithosphere at the edge of overriding plates. Perhaps as a consequence, continental transforms are often wide zones of deformation with multiple fault strands. Continental transform boundaries can be associated with "borderland" physiography, relic suture zones, or characterized by submerged areas of thinned continental crust with a complex morphology of basins and ridges. Examples include the southern California Borderland associated with the San Andreas fault system, the Marmara Sea and north Aegean Sea associated with the North Anatolian fault system, and the Venezuelan borderland and Cariaco Basin associated with the El Pilar fault system. Continental transforms are often associated with submerged closed basins that are 30-100 km-long and 1-5 km-deep. Transform basins have been studied worldwide for their hydrocarbon potential and for unique information on the evolution of the transform as recorded in syntectonic sediment. Nevertheless, the origin and tectonic evolution of these basins remains controversial.

Drilling in Marmara Sea by a future Ocean Drilling Program can recover a long-term, high-resolution record of the growth of the transform basins, of the temporal pattern of large earthquakes that punctuated this growth, and of both the local and global paleoceanographic conditions that existed during their evolution. Instrumenting the boreholes could provide information constraints on fluid pressure and deformation considered essential processes for geohazard studies. At present, the Marmara basins have only been sampled to depths of ~60 m. Therefore, all models proposed for the age and temporal evolution of these basins are inferred. Such records in combination with existing geophysical data would provide a new basis for:

1. Understanding the origin and temporal and spatial evolution of continental transforms by exploiting the unique sedimentary record of submarine syn-tectonic basins. A chronology of the basin growth will constrain dextral and vertical motions, including the tilting and subsidence that is observed on the Marmara basins. It will also test whether basin growth is steady state or time-transgressive.
2. Linking earthquake rates and sequencing (e.g., earthquake-earthquake triggering), and the partitioning of strain among different strands of the transform with structural growth, sea level, sedimentation rates and paleoclimate. Better understanding of how seismogenesis relates to other geologic observables would improve earthquake forecasting and hazard assessment along the North Anatolian fault and other continental transforms.
3. Dramatic changes in sedimentation, flora and fauna occur as these basins shift from marine to lacustrine environments. Sea level and tectonics open and close pathways between the basins and the world ocean. These unique paleoceanographic markers can be used to unravel climate, water exchange and the tectonic evolution of the transform basins.
4. As a seismic gap along a continental transform, the Sea of Marmara is a unique place to monitor fluid escape at a plate boundary through an earthquake cycle in a submarine setting. Instrumented boreholes would address major issues, such as the partitioning between fluid from deep sources possibly relevant to earthquakes and fluid from the compaction and dewatering of shallow sediments.

Why the Marmara Sea?

Four main points favor this drilling project: 1) There is extensive geophysical coverage. The transform basins in the Marmara Sea have a unique and growing geophysical database, but still lack essential constraints from direct sampling of the stratigraphy. 2) The progressive tilting in some of the basins allow sampling of the entire syntectonic sequence with relatively shallow cores. 3) New information from stratigraphy and structural growth would improve earthquake hazard assessment in an area facing major risk. 4) The Sea of Marmara has been selected as a focus site to monitor geohazards and to study the relations between fluids and seismicity, within the European Seafloor Observatory Network (ESONET), funded by the European Commission (e.g., *Cagatay et al.*, *2009*). There are currently two separate but complementary initiatives to implement seafloor observatories in the Marmara Sea: the Kandilli Marmara Sea Bottom Observatory (MSBO) project and the ESONET Marmara Demonstration Mission project.

Background

The North Anatolian fault (NAF) extends east-west for over 1600 km across Turkey and is one of the world's major continental transforms (Fig. 1a). In NW Turkey, the NAF splays into northern and southern branches that are separated by about 100 km [Fig 1; *Armijo et al.*, *1999; 2002*]. The northern branch crosses the northern part of Marmara Sea, and it presently accommodates most of the relative plate motion between Eurasia and the Anatolia microplate [*Reilinger et al.*, *2000*]. The Marmara Sea is comprised of three main extensional basins, each 1200 m deep, and separated by ridges. The basins (Fig. 1b) are named from west to east: Tekirdag, Central, and Cinarcik. Izmit Gulf extends east of Cinarcik Basin (Fig. 2).

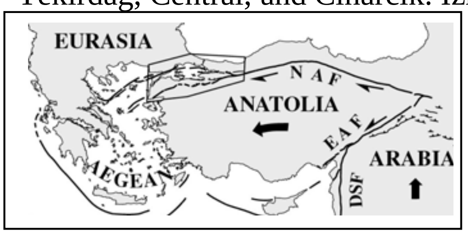

Fig. 1a. The North Anatolia Fault (NAF) accommodates right lateral motion between the Anatolia microplate and Eurasia at a relative rate of ~24 mm/y [McClusky et al., 2000; Reilinger et al., 1997]

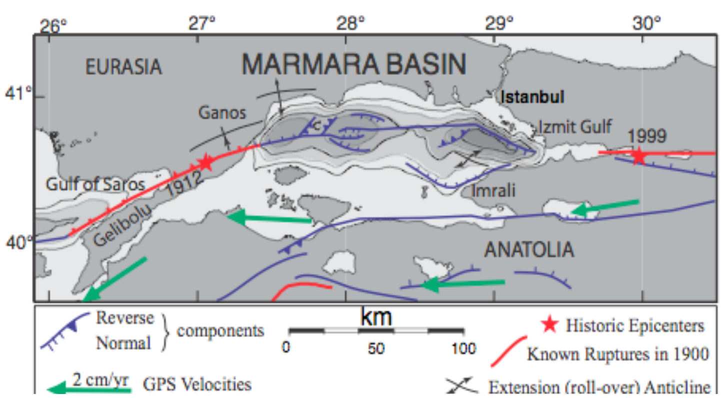

Fig. 1b. Tectonic sketch of the Marmara Sea showing the documented ruptures from the 20th century (red) [Ambraseys 1995; 2002; Polonia et al., 2004; Seeber et al., 2004; 2006; Cormier et al., 2006]. GPS velocities relative to Eurasia.

In 1912, an M>7 earthquake ruptured the Ganos segment of the transform from the western shore of the Marmara Sea to the Gulf of Saros in the Aegean (Fig. 1b). Since 1939, a sequence of seven M>7 earthquakes ruptured progressively westward along the entire NAF east of the Marmara Sea [*Töksöz, 1979; Barka and Kadinsky, 1988; Barka*, *1996*]. The most recent and westernmost events in this sequence, the Mw7.4 Izmit and the Mw7.2 Duzce main shocks of 1999, were particularly destructive (~17,000 deaths). Together they ruptured about 160 km of the fault system, including a segment in the Gulf of Izmit, in the eastern Marmara Sea [*Barka*, *1999*; *Reilinger et al.*, *2000*; *Toksöz et al.*, *1999*]. The only portion of the NAF that did not rupture in the 20th century is the segment beneath the Marmara Sea. The length and segmentation of this portion of the NAF will control the size and possibly the number of future earthquakes expected to close the gap. The last major earthquakes in that area occurred in 1766 [*Ambraseys and Finkel*, 1995] and 1894 [*Ambraseys, 1995; 2002*]. The Marmara Sea is, therefore, identified as a seismic gap that has accumulated as much elastic strain as what was released by slip in the 1999 sequence [*Hubert-Ferrari et al.*, *2000*; *Parsons et al.*, *2000*; *2004; Reilinger et al.*, *2000*].

As a result of the two disastrous 1999 earthquakes, investigations of the Marmara Sea by Turkish and international teams have been extensive, yielding new paradigms for the evolution of continental transforms and paleoclimate *[Okay et al., 1999; 2000; İmren et al., 2001; Rangin et al., 2001; Çağatay et al., 2003; Le Pichon et al., 2001;2003; Leroy et al., 2002; Awata et al., 2002;Polonia et al., 2002; Parker et al., 2003; Sato et al., 2004; McNeil et al., 2004; Halbach et al., 2004; Armijo et al., 2002; 2005; Cormier et al., 2006; Seeber et al., 2004; 2006; McHugh et al., 2006; Bindi 2007; Carton et al., 2007*; *Steckler et al., 2008; Sorlien et al., 2008; TAMAM Scientific Party, 2008; Geli et al., 2008; Wang et al., 2009*].

The context of the Sea of Marmara is well suited for earthquake fault monitoring and, owing to the importance of earthquake risk for the Istanbul area, large efforts are being made to build an observatory network covering the onshore and offshore realms. Data acquired from land stations since the 1999 earthquake have shown that the Cinarcik Basin area is being affected by long term postseismic extension [*Ergintav et al. 2009*] associated with microseismic activity localized offshore [*Karabulut et al., 2002*]. Gas emissions are also being monitored. While gas emitted from the Çinarcik basin is predominantly of relatively shallow origin, the hydrocarbon gases expelled from faults cutting the highs are of deep thermal origin, and several other sites showed evidence of a mantle source [Geli et al., 2008; Zitter et al., 2008; Burnard et al., 2008; Bourry et al., 2009]. Land seismologic network and permanent GPS stations sets a framework, from which offshore monitoring closer to the main fault is being planned. Five cabled seismological observatories will be deployed in 2009 by KOERI (Kandili Observatory and Earthquake Research Institute). In parallel, monitoring at the seafloor of fluid parameters (flux, composition and pore pressure) and microseismicity is taking place as a demonstration mission of ESONET (European Seafloor observatory Network of Excellence). The objective of ESONET and EMSO (European Multidisciplinary Seafloor Observation) is the implementation of permanent deep-sea observatories around Europe, and the Marmara Sea is one of the most advanced sites. In this context, borehole monitoring in the Sea of Marmara would strongly complement these efforts by significantly improving the quality of pore pressure and fluid composition records and would open the road for in situ strain measurement.

Existing Data

Geophysical surveys collected high-resolution multibeam bathymetry, side-scan sonar, subbottom profiles (CHIRP), multichannel seismics and wide angle data, and a large collection of gravity and piston cores (Fig. 2a) *[Aksu et al., 2000; Rangin et al., 2001; Le Pichon et al., 2001; 2003; Çağatay et al., 2003; Polonia et al., 2002; 2004; Armijo et al., 2002; 2005; Cormier et al., 2006; Seeber et al., 2004; 2006; McHugh et al., 2006; Carton et al., 2007; Becel et al., Steckler et al., 2008; Sorlien et al., 2008; TAMAM Scientific Party, 2008; Geli et al., 2008*]. These data have provided information on the surface morphology of the basins and fault, the texture of the shallow sediments, and the sedimentary and structural architecture of the shallow and deep subsurface.

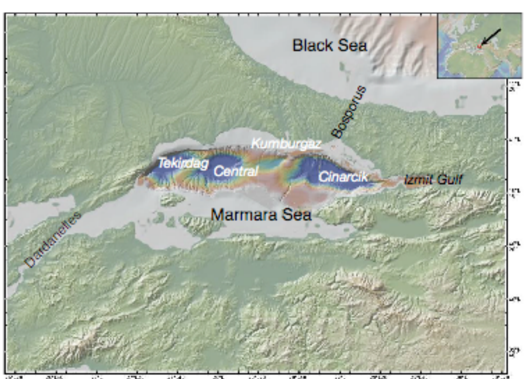

Fig.2a. Multibeam bathymetry of the Marmara Sea showing Tekirdag, Central, Kumburgaz, Çinarcik Basins, and Izmit Gulf. Water exchange between the Aegean Sea and Black Sea occurs through the Dardanelles and Bosporus Straits, respectively. Multibeam bathymetry from Le Pichon et al. [2000], Rangin et al. [2001].

The majority of these data sets are available for planning drilling sites and monitoring boreholes. In

2008 the Turkish American MArmara Multichannel project (TAMAM) collected >2700 km of high-resolution multichannel seismic (MCS) reflection plus shallow-penetration chirp profiles (Fig. 2b). The data is providing new details on stratigraphy and structure, and obtained stratigraphic ties between subbasins in the Marmara Sea necessary to reconstruct the recent history of the Marmara.

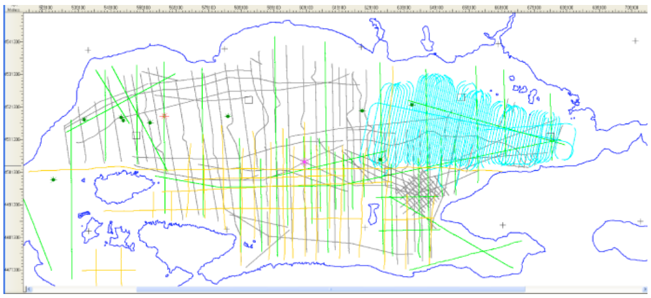

Fig. 2b. Partial navigation track of seismic lines in the Marmara Sea: cyan SeisMarmara Leg 2; yellow Marathon Petroleum; green MTA97; brown TAMAM. R/V Marion Dufresene cores, green circles. Marathon well, pink circle.

Details regarding the fault system beneath the Marmara Sea provided by the suite of extensive data sets are challenging traditional models for transform tectonics. Some authors account for structural complexities as relics from the initial stage of the plate boundary and propose that through-going transcurrent faults and inactive basins characterize the current regime [*Le Pichon et al.*, 2001; 2003]. Alternatively, basins may grow in a steady-state regime. Crustal thinning and subsidence may stem from pull-apart fault geometries and strain partitioning [*Armijo et al.*, 1999; 2002; 2005], transtension along a transform fault with elements of compression *[Okay et al., 1999; 2000; Steckler et al., 2008]*, or from oblique slip on non-vertical through going master faults [*Okay et al., 1999; Seeber et al.*, 2004; 2006].

Given the wealth of geophysical information and shallow sediment sampling, it is critical that the deeper subsurface is sampled through drilling. The deepest piston cores recovered by the *R/V Marion Dufresne* did not penetrate more than 60 m, thus barely sampling the Quaternary. A borehole drilled by Marathon Petroleum provided sediment ages that group the top 40 m as Quaternary and the rest as Miocene-Pliocene until they reach the Cretaceous. The problem with this study is that the fossils used to identify the Pleistocene and Pliocene are similar and may have led to setting the boundary between the Quaternary and Pliocene shallower than it should be. Deep subsurface drilling and more detailed biostratigraphic studies are required to verify the tectonic evolution, stratigraphy and paleoceanography of the Marmara Sea.

Earthquakes and Sedimentation

Some investigations in the Marmara Sea have also focused on the newly evolving field of submarine earthquake geology. Plate boundary faults typically re-rupture every few centuries to several millennia. Therefore, data on multiple ruptures require historic as well as prehistoric information. Paleoseismology is a primary tool for seismic hazard evaluation that is well established on land [e.g., *Sieh 1981; Dolan et al., 1995; McCalpin 1996; Yeats et al., 1997; Emre et al., 2003; Rockwell et al., 2001;* 2002; *Klinger et al., 2003; Atwater et al., 2004; Altunel et al., 2004; Marco et al., 2005*] and is a rapidly evolving tool for the underwater environment. Recent underwater studies have attempted to unravel the effects of fault segmentation, fault slip, and/or permanent deformation associated with seismo-turbidites *[McNeilan et al., 1996; Zachariasen et al., 1999; Goldfinger et al., 2003; Polonia et al., 2004; Seeber et al., 2006; Cormier et al., 2006; Sarı and Çağatay, 2006; McHugh et al., 2006; Beck et al., 2007*; *Seeber et al., 2007]*. Despite much progress, submarine earthquake geology is still in its infancy. Results from the Marmara Sea are encouraging so far and reveal that the North Anatolian Fault may rupture stepwise across each transform basin. Typically, such basins are asymmetric, steep-sided, and flat-bottomed (Fig. 3). Seismic profiles indicate thick turbiditic sequences tilted toward the bounding transform fault. Rapid subsidence and distal sedimentation preserve this record at the depocenters and open the prospect of retrieving records of seismicity over geologic time scales (>100,000 yr).

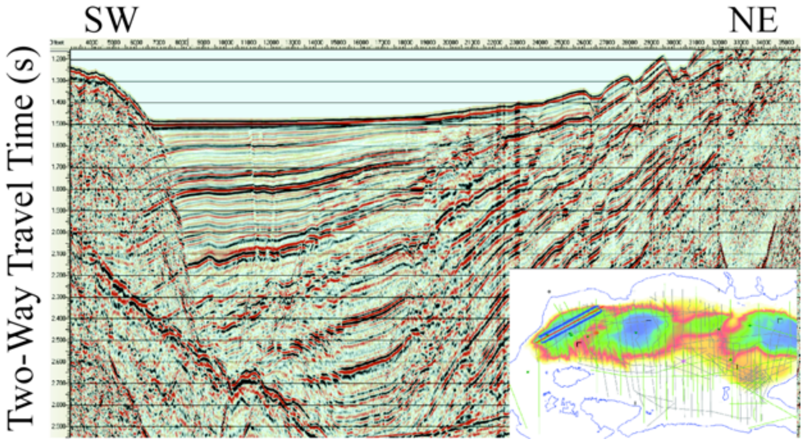

Fig. 3. MTA97-02 seismic profile across Tekirdag basin showing subsidence towards the fault and thick sedimentary deposits at "depocenters" [Parke et al., 2003]. Drilling the tilted syntectonic sequences to the SW and the "depocenters" will provide both the tectonic evolution of the basin and its record of seismicity.

The sediments of the "depocenters" are dominated by characteristic deposits termed "homogenites" [*McHugh et al., 2006; Beck et al., 2003].* "Homogenites", a term first introduced by *Kastens and Cita [1981*] and later on by *Cita et al. [1984; 1996],* have been correlated with tsunamis, caldera collapse and large earthquakes around the world [*Siegenthaller et al., 1987; Sturm et al., 1995; Syvitsky & Schafer, 1996*; *Chapron et al., 1999, Arnaud et al., 2002; Hakimian et al., 2009] and with large earthquakes in the Marmara Sea* [*McHugh et al., 2006; Sari & Çağatay, 2006; Beck et al., 2007; Çagatay et al., 2008*]. From the base up, the signature of these events begins with a sharp basal contact followed by numerous mm- to cm- scale sand and silt laminations. All laminae are normally graded and are contained within a 50-cm-thick fining upward and otherwise homogeneous deposit. Grain size analyses confirmed two levels of normal grading: 1) within individual laminae and 2) of the whole sequence (Fig. 4).

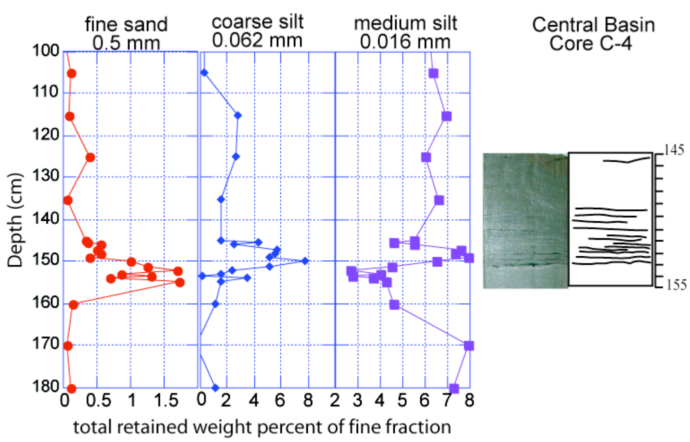

Fig. 4 Grain size analyses showing normally graded laminae and overall fining-upwards trend of one homogenite deposit in Central Basin. The horizontal axis is the total weight percent of the fine fraction for 80 cm of core length, for fine sand, coarse silt, and medium silt. The vertical axis shows the thickness of the deposit (50 cm). Photo of core shows the sharp basal contact and multiple, fining-upwards laminae.

Linkages Between Paleoceanography and Tectonics

Because of their closed-contour shapes and shallow sills that connect them with the world's oceans, transform basins provide some of the best paleoclimatic and paleoceanographic records (e.g., Cariaco Basin, northern Venezuela). The Marmara Sea is especially significant because it controls the water exchange between the Aegean and Black Seas. During the Last Glacial (Oxygen Isotope Stage 2) Marmara Sea was a fresh-brackish water lake isolated from the global ocean (Fig. 2). As a result of these transformations, there have been dramatic shifts in depositional environments from marine to lacustrine with the complete replacement of the sediments fauna and flora. These transitions can be used as markers to unravel Marmara's tectonic history. Drilling would verify the timing of deposition and rate of tectonic subsidence of at least four stacked lowstand delta complexes, which are preserved by subsidence on the downthrown side of the Imrali fault (Figs. 5, 1b). If these delta sequences mark ~100ky intervals between low stands, 400 m of subsidence suggest rates of 1 mm/y *[Steckler et al., 2008; Sorlien et al., 2008; TAMAM Scientific Party, 2008].*

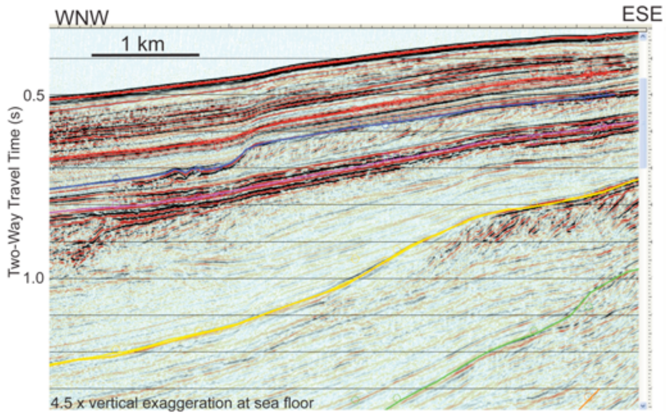

Fig. 5. Vertically-stacked shelf-edge deltas beneath blue, magneta, yellow and green horizons. They formed at sea-level or lake level during the late Quaternary glacial periods and are possibly spaced every ~100,000 years. They are now 400 to 900 m deep. Drilling into these deltas will permit to verify the estimated subsidence of 400 m in 400,000 years at 1mm/yr and also provide information on paleoclimate and paleoceanography.

The timing and mechanism of the reconnection of the Black Sea and Marmara Sea to the world ocean for the late Pleistocene and Holocene have been highly controversial *[Stanley and Blanpied, 1980; Ryan et al., 1997; 2003; Görür et al., 1997; Çağatay et al., 1999; 2000; Aksu et al., 1999; 2002; Çağatay et al., 1999; 2000].* Questions remain regarding the level of Marmara Lake at the time of marine incursion and whether the Black Sea outflow to Marmara was vigorous and continuous at the time of the reconnection *[Ross and Degens, 1974; Stanley and Blanpied, 1980; Lane-Serff et al., 1997; Aksu et al., 1999; 2002; Kaminsky et al., 2002; Mudie et al., 2002]* or discontinuous *[Ryan et al., 1997; 2003; Major et al., 2002; 2006; Myers et al., 2003; Sperling et al., 2003; Giosan et al., 2005].* Drilling into the Marmara Sea will provide information about paleoclimate and pale-oceanography of the region as well as the global ocean since the Plio-Pleistocene to the present.

Expected New Outcomes

This deep drilling project addresses key issues regarding the age, growth and seismogenic behavior of major continental transform faults. The results will be highly relevant to the investigation of other transform boundaries and submarine seismogenic zones worldwide. Drilling will permit us to obtain:

- The age of the basin and its temporal evolution, an important test for existing models. Existing data from the Marmara Sea and other transform basins suggest astonishingly rapid tilting and subsidence, which may affect erosion and sedimentation processes and imply young ages for the basins. The proposed drilling and dating of the sediments will test these hypotheses and provide constraints on models relating to transform motion and basin development.
- Long-term earthquake chronology can be established from dating earthquake-related sediment in precisely located cores. Such chronology will highlight systematics in earthquake recurrence and greatly improve assessments of seismic hazards.
- Further develop methodologies for submarine earthquake geology, an emerging field that can be applied worldwide. Continuous long-term coverage from multiple settings in the same basin is essential for understanding the timing, spatial distribution, and processes of earthquake-triggered sedimentation. When coupled with high-resolution seismic images the core data can form the basis for reconstructing 3D fault kinematics, rather than 2D geometry, thus providing fault parameters more pertinent to modeling rupture propagation.

- The sediments that will be obtained coupled to seafloor morphological features derived from the existing geophysical data will provide information on the vertical component of motion contributing to the understanding of the evolution of continental transform basins.
- Borehole instrumentation and monitoring at one or more holes would be important for studying relations between inter- and co-seismic strain in the vicinity of the NAF.
- The Marmara Sea basins contain a record of paleoclimate and paleoceanography that needs to be extracted and can provide high-resolution records for regional and global correlations. Semi-isolated basins can preserve enhanced paleoclimatic records (e.g., Santa Barbara Basin).

Path to Achieving Goals

The first step would be to schedule an international meeting or workshop to develop a tectonic and paleoceanographic drilling strategy for the Marmara Sea. We will make use of existing data, which is substantial *[Okay et al., 1999; 2000; İmren et al., 2001; Rangin et al., 2001; Çağatay et al., 2003; Le Pichon et al., 2001;2003; Leroy et al., 2002; Awata et al., 2002; Polonia et al., 2002; 2004; Parker et al., 2003; Sato et al., 2004; McNeil et al., 2004; Halbach et al., 2004; Armijo et al., 2002; 2005; Cormier et al., 2006; Seeber et al., 2004; 2006; McHugh et al., 2006; Mart et al., 2006; Bindi 2007; Carton et al., 2007*; *Steckler et al., 2008; Sorlien et al., 2008; TAMAM Scientific Party, 2008; Geli et al., 2008; Wang et al., 2009*].

The IODP drilling targets should include tilted syntectonic sequences that allow samples of early strata within relatively shallow sections; the basin's depocenters for submarine earthquake geology; the ridges that separate the basins and stacked delta complexes for paleoclimate and tectonics, and sites near the main fault for tectonics. The drilling sites should be selected collaboratively between the participants and based on an integrated approach that combines the existing data and complements the ESONET and EMSO projects. This strategy would take into account the precise geometry of the fault system, the pathways for sediment transport, and the likely sources of fluid venting.

References

Aksu, A.E., Calon, T.J., Hiscott, R.N., Yasar, D., 2000. Anatomy of the North Anatolian fault zone in the Marmara Sea, Western Turkey: Extensional basins above a continental transform. GSA Today, June 2000, 3-7.

Aksu, A.E., Hiscott, R.N. and Yasar, D. 1999. Oscillating Quaternary water levels of the Marmara Sea and vigorous outflow into the Aegean Sea from the Marmara Sea-Black Sea drainage corridor. *Marine Geology* 153, 275-302.

Aksu, A.E., Hiscott, R.N., Kaminski, M.A., Mudie, P.J., Gillespie, H., Abrajano, T., Yasar, D. 2002. Last glacial-Holocene paleoceanography of the Black Sea and Marmara Sea: stable isotopic, foraminiferal and coccolith evidence. *Marine Geology* 3, 160, 1-31.

Altunel, E. M. Meghraoui, M., Akyüz, H. S. , Dikbas, A. Characteristics of the 1912 co-seismic rupture along the North Anatolian Fault Zone (Turkey): implications for the expected Marmara earthquake, *Terra Nova* 16 (2004) 198-204.

Ambraseys, N. N., C. F. Finkel, The Seismicity of Turkey and Adjacent Areas - A Historical Review, 1500-1800, *EREN, Istanbul*, 1995, 240 pp.

Ambraseys, N.N., and Jackson, J.A. Seismicity of the Sea of Marmara (Turkey) since 1500, *Geophysical Journal International*, *141*, F1-F6, 2000.

Ambraseys, N. N. The seismic activity in the Marmara Sea region over the last 2000 years, *Bulletin of the Seismological Society of America*, 92 (2002) 1-18.

Armijo R., Meyer B., Hubert A., Barka A. A., Westward propagation of the north Anatolian fault into the northern Aegean: Timing and kinematics, *Geology* 27 (1999) 267-270.

Armijo R., Meyer B., Navarro S., King G. C. P., Barka A. A., Asymmetric slip partitioning in the Sea of Marmara pull-apart: a clue to propagation processes of the North Anatolian Fault? *Terra Nova*, 14 (2002) 80-86.

Armijo, R., N. Pondard, B. Meyer, G. Uçarkus, B. Mercier de Lepinay, J. Malavieille, S. Dominguez, M.-A. Gustcher, S. Schmidt, C. Beck, M. N. Çağatay, Z. Çakir, C. Imren, K. Eris, B. Natalin, S. Özalaybey, L. G. Tolun, I. Lefèvre, L. Seeber, L. Gasperini, C. Rangin, Ö. Emre, and K. Sarikavak, Submarine fault scarps in the Sea of Marmara pull-apart (North Anatolian Fault): Implications for seismic hazard in Istanbul, *Geochemistry, Geophysics, Geosystems*, 6, Q06009, 2005.

Arnaud F., Lignier V., Revel M., Desmet M., Beck C., Purchet M., Charlet F., Trentesaux A., Tribovillard N., Flood and earthquake disturbance of ^{210}Pb geochronology (Lake Anterne, NW Alps), *Terra Nova* 14 (2002) 225-232.

Atwater, B. F., Tuttle, M. P., Schweig, E. S., Rubin, C. M., Yamaguchi, D. K., and Hemphill-Haley, E., Earthquake recurrence inferred from paleoseismology, in Gillespie, A. R., Porter, S. C., and Atwater, B. F., eds., "The Quaternary period in the United States: Developments in Quaternary Science 1", Elsevier, p. 331-350, 2004.

Awata, Y., T. Yoshioka, et al. (2000). Segment structures of the surface ruptures associated with the August 17, 1999 Izmit earthquake, Turkey. XXVII General Assembly of the European Seismological Commission (ESC), Lisbon University, Lisbon, Portugal.

Barka, A.A., and K. Kadinsky-Cade, Strike-slip fault geometry in Turkey and its influence on earthquake activity, *Tectonics*, *7* (3), 663-684, 1988.

Barka, A.A., Slip distribution along the North Anatolian fault associated with the large earthquakes of the period 1939 to 1967, *Bulletin of the Seismological Society of America*, *86* (5), 1238-1254, 1996.

Barka A. A., The 17 August 1999 Izmit earthquake, *Science* 285 (1999) 1858-1859.

Beck, C., J.-L. Schneider, B. Mercier de Lepinay, N. Çağatay, L. Labeyrie, J.-L. Turon, E.

Wendenbaum, S. Boutareau, G. Menot-Combes, I. Hadjas, MARMARCORE Scientific Party, Geophysical Research Abstracts, 5 (2003) 12778.
Beck, C., de Lepinay M., Schneider, J.-L., Cremer, M., Çağatay, N., Wendenbaum, E., Boutareaud, S., Mynot, G., Schmidt, S., Weber, O. 2007. Late Quaternary co-seismic sedimentation in the Sea of Marmara's deep basins. *Sedimentary Geology* 199, 65-89.
Bécel, A., M. Laigle, B. de Voogd, A. Hirn, T. Taymaz, A. Galvé, H. Shimamura, Y. Murai, J.-C. Lépine, M. Sapin, S. Özalaybey et al., Moho, crustal architecture and deep deformation under the North Marmara Trough, from the SEISMARMARA Leg 1 offshore–onshore reflection–refraction survey, Tectonophysics (2008), doi:10.1016/j.tecto.2008.10.022
Bindi, D., S. Parolai, et al. (2007). "ML Scale in Northwestern Turkey from 1999 Izmit Aftershocks: Updates." Bulletin of the Seismological Society of America 97(1B): 331-338.
Bourry, C., et al, (2009). Free gas and gas hydrates from the Sea of Marmara, Turkey: Chemical and structural characterization. Chemical Geology, doi:10.1016/j.chemgeo.2009.03.007.
Burnard, P, S Bourlange, P Henry, L Geli, B Marty, B Natalin, C Sengor, Fluid Sources on the North Anatolian Fault in the Sea of Marmara From He Isotope Measurements, AGU Fall meeting, San Francisco 15-19 Décembre 2008.
Çağatay, M.N., O. Algan, M. Sakinç, C.J. Eastoe, L. Egesel, N. Balkis, D. Ongan, and H. Caner, A mid-late Holocene sapropelic sediment unit from the southern Marmara sea shelf and its paleoceanographic significance, *Quaternary Science Reviews, 18*, 531-540, 1999.
Çağatay. M.N., Görür, N., Algan, A., Eastoe, C.J., Tchapalyga, A., Ongan, D., Kuhn, T., Kuscu, I. 2000. Late Glacial-Holocene palaeoceanography of the Sea of Marmara timing of connections with the Mediterranean and the black Sea. *Marine Geology* 167, 191-206.
Çağatay, M.N., N. Görür, A. Polonia, E. Demirbag, M. Sakinç, M.-H. Cormier, L. Capotondi, C.M.G. McHugh, Ö. Emre, and K. Eris, Sea-level changes and depositional environments in the Izmit Gulf, eastern Marmara Sea, during the late glacial–Holocene period, *Marine Geology, 202*,159-173, 2003.
Çağatay, N., et al, (2009), The Marmara-DM Project, Esonews, vol.3, Issue 1, Spring 2009, http://www.esonet-noe.org/news_and_events/esonews_letters/2009_06_09_esonews
Carton, H., S. C. Singh, A. Hirn, S. Bazin, B. de Voogd, A. Vigner, A. Ricolleau, S. Cetin, N. Ocakoglu, F. Karakoc and V. Sevilgen (2007). "Seismic imaging of the three-dimensional architecture of the Cinarcik Basin along the North Anatolian Fault" Journal of Geophysical Research 112(doi:10.1029/2006JB004548): B06101.
Chapron E., Beck C., Pouchet M., Deconninck J. F., 1822 earthquake-triggered homogenite in Lake Le Bouget (NW Alps), *Terra Nova* 11 (1999) 86-92.
Cita, M. B., Beghi, C., Camerlenghi, A., Kastens, K.A., McCoy, F.W., Nosetto, A., Parisi, E., Scolari, F., Tomadin, L. 1984. Turbidites and megaturbidites from the Herodotus abyssal plain (eastern Mediterranean) unrelated to seismic events. *Marine Geology* 55, 79-101.
Cita, M. B., Camerlenghi, A., Rimoldi, B. Deep-sea tsunami deposits in the eastern Mediterranean: new evidence and depositional models, *Sed. Geology* 104 (1996) 155-173.
Cormier, M.-H., L. Seeber, C.M.G. McHugh, A. Polonia, M.N. Çağatay, O. Emre, L. Gasperini, N. Gorur, G. Bortolouzzi, E. Bonatti, W.B.F. Ryan, K. Newman, The North Anatolian fault in the Gulf of Izmit (Turkey): Rapid vertical motion in response to minor bends of a non-vertical continental transform, *JGR* 111, doi:1029/2005JB003633, B04102, 2006.
Dolan, J. F. , Sieh, K.E. , Rockwell, T. K. , Yeats, R. S., Shaw, J. H. , Suppe, J. , Huftile, G. , Gath, E. Prospects for larger or more frequent earthquakes in greater metropolitan Los Angeles, California, *Science* 267 (1995) 199-205.

Emre, Ö., Y. Awata, and T. Y. Duman, Surface Rupture Associated with the 17 August 1999 Izmit Earthquake, 280 pp., *General Directorate or Mineral Research and Exploration, Ankara Turkey*, 2003.

Ergintav, S., S. McClusky, E. Hearn, R. Reilinger, R. Cakmak, T. Herring, H. Ozener, O. Lenk, and E. Tari, 2009. Seven Years of Postseismic Deformation following the 1999, M = 7.4, and M = 7.2, Izmit-Duzce, Turkey Earthquake Sequence, J. Geophys. Res., doi:10.1029/2008JB006021, 2009.

Géli, L., Henry, P., Andre, C., Zitter, T., Çağatay, N., Mercier de Lepinay, X. LePichon, AMD Sengor, N. Gorur, B. Natalin, G. Ucarkus, S. Ozeren, D. Volker, L. Gasperini, S., Bourlanger and the Marnaut Scientific Party 2008. Gas emissions and active tectonics within the submerged section of the North Anatolia Fault zone in the Sea of Marmara. *Earth Planet. Sci. Lett.*, 274(1-2): 34-39.

Giosan, L. Mart, Y., McHugh, C.M., Vachtman, D., Çağatay, N.M., Kadir, E.K., Ryan, W.B. 2005. Megafloods in Marginal Basins: New Data from the Black Sea. *EOS Trans. AGU* 86 (52): PP32A-03.

Gökasan, E., E. Demirbag, F.Y. Oktay, B. Ecevitoglu, M. Simsek, and H. Yüce. 1997. On the origin of the Bosphorus. *Marine Geology* 140, 183-199.

Gökasan E., Algan, O., Tur, H., Meriç, E., Türker, A., Simsek, M. 2005. Delta formation at the southern entrance of Istanbul Strait (Marmara sea, Turkey): a new interpretation based on high-resolution seismic stratigraphy. *Geo-Marine Letters* 25, 370-377.

Gökasan E., Ergin, M. Ozyalvac, M., Ibrahim Sur, H., Tur, H., Görum, T., Ustaömer, T. Gul Batuk, F., Alp. H., Birkan, H., Turker, A., Gezgin, E., Ozturan, M. 2008. Factors controlling the morphological evolution of the Canakkale Strait (Dardanelles, Turkey). *Geo-Mar Letters* 28, 107-129.

Görür, N., M.N. Çağatay, M. Sakinç, M. Sümengen, K. Sentürk, C. Yaltirak, and A. Tchapalyga. 1997. Origin of the Sea of Marmara as deduced from Neogene to Quaternary Paleogeographic evolution of its frame. *International Geology Review* 39, 342-352.

Goldfinger C., Nelson C. H., Johnson J. E., The shipboard Scientific Party, Holocene earthquake records from the Cascadia subduction zone and northern San Andreas fault based on precise dating of offshore turbidites, *Annual Review of E&PS* 31 (2003) 555-577.

Hakimian, A., McHugh, C., Seeber, L. 2009. Sedimentation and Earthquakes in the Eastern Mediterranean Sea: Characteristics and Depositional Processes. *62nd Geological Congress, Ankara, Turkey.*

Halbach, P., E. Holzbecher, et al. (2004). "Migration of the sulphate-methane reaction zone in marine sediments of the Sea of Marmara - can this mechanism be tectonically induced?" Chemical Geology 205(1-2): 73-82.

Hubert-Ferrari A., Barka A. A., Jacques E., Nalbant S. S., Meyer B., Armijo R., Tapponier P., King G. C. P., Seismic hazard in the Marmara Sea region following the 17 August 1999 Izmit earthquake, *Nature* 404 (2000) 269-273.

Imren, C., X. Le Pichon, et al. (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 186: 143-158.

Kaminski, M.A., Aksu, A., Box, M., Hiscott, R.N., Filipescu, S., Al-Salameen, M. 2002. Late Glacial to Holocene benthic foraminifer in the Marmara Sea: implications for Black Sea-Mediterranean Sea connections following the last deglaciation. *Marine Geology* 19, 165-202.

Karabulut, H., Bouin, M.-P., Bouchon, M., Dietrich, M., Cornou, C., Aktar, M., (2002), The seismicity in the Eastern Marmara Sea after the 17 August 1999 Izmit earthquake, Bull. Seismol. Soc. Am., 92: 387-393

Kastens, K. A., Cita, M. B. Tsunami-induced sediment transport in the abyssal Mediterranean Sea, *Geological Society of America Bulletin* 92 (1981) 845-857.

Klinger, Y., K. E. Sieh, E. Altunel, A. Akoglu, A. A. Barka, T. E. Dawson, T. Gonzalez, A. Meltzner, and T. K. Rockwell, Paleoseismic Evidence of Characteristic Slip on the Western Segment of the North Anatolian Fault, Turkey, *Bul. of the Seismol. Soc. of Amer.* 93, 2003.

Lane-Serff, G.E., Rohling, E.J., Bryden, H., Charnock, H. 1997. Postglacial connection of the Black Sea to the Mediterranean and its relation to the timing of sapropel formation. *Palaeoceanography* 12, 169-174.

Le Pichon, X., *et al*., (2000). Marine atlas of the Sea of Marmara (Turkey), Ifremer Publications

Le Pichon X., Sengör A. M. C., Demirbag E., Rangin C., Imren C., Armijo R., Görür N., Çağatay M. N., Mercier de Lepinay B., Meyer B., Saatçilar R., Tok B., The active main Marmara fault, *Earth and Planetary Science Letters* 192 (2001) 595-616.

Marco S., Rockwell T. K., Heimann A., Frieslander U., A. Agnon, Late Holocene activity of the Dead Sea Transform revealed in 3D paleoseismic trenches on the Jordan Gorge segment, *Earth and Planetary Science Letters* 234 (2005) 189-205.

Major, C.O., Ryan, W., Lercolais, G., Hajdas, I. 2002. Constraints on Black Sea outflow to the Sea of Marmara during the last glacial-interglacial transition. *Marine Geology* 190, 19-34.

Major, C.O., Goldstein, S.L., Ryan, W.B.F., Lercolais, G., Piotrowski, A.M., Hajdas, I. 2006. *Quaternary Science Reviews* 25, 2031-2047.

McCalpin, J. P. . Paleoseismology, Academic Press (1996) 588 pp.

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., Toksöz M. N., Veis G., Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus, *Journal of Geophysical Research* 105 (2000) 5695-5719.

McHugh, C. M. G., L. Seeber, M.-H. Cormier, J. Dutton, M. N. Çağatay, A. Polonia, W. B. F. Ryan, and N. Görür, Submarine earthquake geology along the North Anatolian Fault in the Marmara Sea, Turkey: A model for transform basin sedimentation, *Earth and Planetary Science Letter*s, 2006 248, 661-684. doi:10.1016/j.epsl.2006.05.038

McNeill, L. C., A. Mille, et al. (2004). "Extension of the North Anatolian Fault into the North Aegean Trough: Evidence for transtension, strain partitioning, and analogues for Sea of Marmara basin models." Tectonics 233, doi:10.1029/2002TC001490.

Mudie, P.J., Rochon, A., Aksu, A.E., 2002. Pollen stratigraphy of Late Quaternary cores from Marmara Sea: land-sea correlation and paleoclimatic history. *Marine Geology* 190, 233-260.

Myers, P.G., Wielki, C., Goldstein, S.B., Rohling, E.J., 2003. Hydraulic calculations of postglacial connections between the Mediterranean and the Black Sea. *Marine Geology 201, 253-267*.

Okay, A.I., Demirbag, E., Kurt, H., Okay, N., Kusçu, I. 1999. An active, deep marine strike-slip basin along the North Anatolian fault in Turkey. *Tectonics* 18, 129-147.

Parke, J. R., R. S. White, et al. (2003). "The Sea of Marmara: A two-dimensional seismic reflection profile data archive." Geochemistry, Geophysics, Geosystems 4(doi:10.1029/2002GC000493). Parsons, T., S. Toda, R.S. Stein, A.A. Barka, J.H.

Dieterich, Heightened odds of large earthquakes near Istanbul: An interaction-based probability calculation, *Science, 288*, 661-665, 2000.

Parsons, T., S. Toda, R.S. Stein, A.A. Barka, J.H. Dieterich, Heightened odds of large earthquakes near Istanbul: An interaction-based probability calculation, *Science, 288*, 661-665, 2000.

Parsons T. (2004). Recalculated probability of M>7 earthquakes beneath the Sea of Marmara. *Journal of Geophysical Research*, 109, doi:10.1029/2003JB002667.

Polonia A., Cormier M.H., Çağatay M.N., Bortoluzzi G., Bonatti E., Gasperini L., Seeber L., Gorur N., Capotondi L., McHugh C.M.G., Ryan W.B.F., Emre O., Okay N., Ligi M., Tok B., Blasi A., Busetti M., Eris K., Fabretti P., Fielding E.J., Imren C., Kurt H., Magagnoli A., Marozzi G., Ozer N., Penitenti D., Serpi G., Sarikavak K., 2002, Exploring submarine earthquake geology in the Marmara Sea, *EOS Transactions AGU* 83 229, 235-236.

Polonia, A., L. Gasperini, A. Amorosi, E. Bonatti, G. Bortoluzzi, M. N. Çağatay, L. Capotondi, M.-H. Cormier, N. Görür, C. M. G. McHugh, L. Seeber, Holocene slip rate of the North Anatolian Fault beneath the Sea of Marmara, *E&PSL* 227, 411-426, 2004.

Rangin, C., E. Demirbag, C. Imren, A. Crusson, A. Normand, E. Le Drezen, and A. Le Bot, *Marine Atlas of the Sea of Marmara (Turkey)*, Ifremer, 2001.

Reilinger, R. E., M. N. Toksöz, S. C. McClusky, A. A. Barka, 1999 Izmit, Turkey earthquake was no surprise, *GSA Today* 10 (2000) 1-6.

Reilinger R. E., McClusky S. C., Oral M. B., King R. W., Toksöz M. N., Barka A. A., Kinik I., Lenk O., Sanli I., Global Positioning System measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone, *Journal of Geophysical Research* 102 (1997) 9983-9999.

Rockwell, T. K., A. A. Barka, A. G. Dawson, H. S. Akyüz, K. Thorup, Paleoseismology of the Gazikoy-Saros segment of the North Anatolian fault, northwest Turkey: Comparison of the historical and paleoseismic records, implications of regional seismic hazard, and models of earthquake recurrence, *Journal of Seismology* 5, 2001.

Rockwell, T. K., S. Lindvall, T. E. Dawson, R. M. Langridge, W. R. Lettis, and Y. Klinger, Lateral Offsets on Surveyed Cultural Features Resulting from the 1999 Izmit and Düzce Earthquakes, Turkey, *Bulletin of the Seismological Society of America*, 92, 79-94, 2002.

Ross, D. A., Degens, E. T. 1974. Recent sediments of the Black Sea, (Eds.) E. T. Degens, D. A. Ross, The Black Sea Geology, Chemistry and Biology, Tulsa: *Am. Assoc. Petrol. Geol. Mem*. 20, 183-199.

Ryan, W.B.F., Pitman, W.C., Major, C.O., Shimkus, K., Moskalenko, V., Jones, G.A., Dimitrov, P., Görür, N., Sakinç, M., Yüce, H. 1997. An abrupt drowning of the Black Sea shelf. *Marine Geology* 138, 119-126.

Ryan, W.B.F., Major, C.O., Lericolais, G., and Goldstein, S. L. 2003. Catastrophic flooding of the Black Sea. *Annual Review Earth Planetary Science* 31, 525–254.

Sari, E., and Çağatay, M. N., 2006. Turbidites and their association with past earthquakes in the deep Cinarcik Basin of the Marmara Sea. *Geo-Marine Letters* 26, 69-76.

Sato, T., J. Kasahara, et al. (2004). "A study of microearthquake seismicity and focal mechanisms within the Sea of Marmara (NW Turkey) using ocean bottom seismometers (OBSs)." Tectonophysics 391: 303-314.

Seeber, L., Ö. Emre, M.-H. Cormier, C.C. Sorlien, C.M.G. McHugh, A. Polonia, Scientific Team of Marmara2001, Uplift and Subsidence from Oblique Slip: The Ganos-Marmara

Bend of the North Anatolian Transform, Western Turkey, *Tectonophysics*, 391, 239-258, 2004.
Seeber, L., M.H. Cormier, C.M.G. McHugh, O. Emre, A. Polonia, and C.C. Sorlien, Subsidence and sedimentation at a transform bend: The Çinarcik Basin and the North Anatolian Fault in the Marmara Sea, Turkey, 2006. *Geology* 34(11), p. 933-936.
Siegenthaler, C., Finger, W., Kelts, K. Wang, S. 1987. Earthquake and seiche deposits in Lake Lucerne, Switzerland. *Eclog. Geol. Helv*. 80 241-260.
Sieh, K. E. . A review of geological evidence for recurrence times for large earthquakes, in: Earthquake Prediction, An International Review, (Eds.) D. W. Simpson and P. G. Richards, Maurice Ewing Series, 4 (1981) 181-207, American Geophysical Union, Washington, DC.
Sorlien, C. C., L. Seeber, J. Diebold, D. Shillington, M. S. Steckler, S. Gurcay, H. M. Kucuk, S. D. Akhun, D. Timur, D. Dondurur, H. Kurt, E. Perincek, P. Ozer, C. Imren, S. Cuskun, E. Buyukasik, M. Devatoglu, G. Cifci, and E. Demirbag, 2008. The seismic stratigraphic record of Quaternary deformation across the North Anatolian fault system in southern Marmara Sea, Turkey. *Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract T21A-1915.*
Stanley, D.J., Blanpied, C. 1980. Late Quaternary water exchange between the eastern Mediterranean and the Black Sea. *Nature* 266, 537-541.
Steckler, M.S., Cifci, G., Demirbag, E., Akhun, S.D., Buyukasik, E., Cevatoglu, M., Coskun, S., Dieborld, J., Dondurur, D., Gurcay, S., Imren, C., Kucuk, H.M., Kurt, H., Ozer, P.G., Perincek, E., Seeber, L., Shillington, D., Sorlien, C., Timur, D. 2008. High Resolution Multichannel Imaging of Basin Growth Along a Continental Transform: The Marmara Sea Along the North Anatolian Fault in NW Turkey. *Eos Trans. AGU 89 (53), T21A-1921.*
Sturm, M., Siegenthaler, C., Pickrill, R.A., 1995. Turbidites and "homogenites". A conceptual model of flood and slide deposits. Publ. IAS-16th *Regional Sedimentology*, Paris 22, 140.
Syvitski, J.P.M. and Schafer, C.T., 1996. Evidences for an earthquake-triggered basin collapse in Saguenay Fjord, Canada. *Sedimentary Geology* 104, 127-153.
TAMAM Scientific Party, 2008, International Collaboration images the North Anatolian fault system in Marmara Sea, Turkey: subsided lowstand deltas, onlapping basin fill, thrust-fold transverse ridges, transtension, and distributed active faulting. *Annual Meeting Southern California Earthquake Center, Proceedings and Abstracts v. XVIII, poster 1-121, p. 133.*
Toksöz, M.N., A.F. Shakal, and A.J. Michael, Space-time migration of earthquakes along the North Anatolian fault zone and seismicity gaps, *Pure and Applied Geophysics*, *117*, 1258-1270, 1979.
Toksöz, M.N., R.E. Reilinger, C.G. Doll, A.A. Barka, and N. Yalcin, Izmit (Turkey) earthquake of 17 August 1999: first report, *Seismological Research Letters*, *70* (669-679), 1999.
Wang, L., R. Wang., et al. (2009). Afterslip and viscoelastic relaxation following the 1999 M7.4 Izmit earthquake from GPS measurements. Geophysical Journal International 178(3):1220-1237.
Yeats, R. S. Allen, C. R., Sieh, K. E. . Earthquake Geology (1997) 568 pp, *Oxford University Press, New York.*
Zachariasen, J., Sieh, K., Taylor, F.W., Lawrence, E.R., Hantoro, W.S. . Submergence and uplift associated with the giant 1833 Sumatran subduction earthquake: Evidence from coral microatolls. *JGR*, 104, 895-9191, 1999.
Zitter, T.A.C., *et al.* (2008). Cold seeps along the main Marmara fault in the Sea of Marmara (Turkey), *Deep Sea Research*, Part I, **55**, 552-570.