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Exploring Submarine Earthquake Geology in the Marmara Sea

The disastrous 1999 earthquakes in Turkey have spurred the international community to study the geometry and behavior of the North Anatolian Fault (NAF) beneath the Marmara Sea. While the area is considered mature for a large earthquake, the detailed fault geometry below the Marmara Sea is uncertain, and this prevents a realistic assessment of seismic hazards in the highly-populated region close to Istanbul.

Two geological/geophysical surveys were recently conducted in the Marmara Sea: the first in November 2000 with the R/V *Odin Finder*, and the second in June 2001 with the R/V *CNR-Urania*. Both were sponsored and organized by the Institute of Marine Geology of the Italian National Research Council (CNR), in cooperation with the Turkish Council for Scientific and Technical Research (TÜBITAK) and the Lamont-Doherty Earth Observatory of Columbia University. Multi-beam bathymetry, multi-channel seismic reflection profiling, magnetometry, high-resolution CHIRP sub-bottom profiling, and bottom imaging were carried out with a remotely operated vehicle (ROV). Over 60 gravity and piston cores were collected.

The main objectives were to identify and date fault ruptures on the sea floor, define the spatial-temporal distribution and the style of deformation and tectonic movements in this portion of a major continental strike-slip boundary, and acquire elements useful for assessing seismic hazards. Both sedimentary and topographic features that define piercing lines were studied to estimate the slip along the fault and to reconstruct the post-glacial paleo-oceanographic history of the Marmara Sea—including the effects of glacio-eustatic paleoclimatic fluctuations on the exchange between the Marmara and the Black Sea on one side, and the Mediterranean on the other. The two studies are related because detailed stratigraphy and dated morphological features such as erosional channels, submarine canyons, and paleo-shorelines can provide key markers for paleoseismology.

The major finding of this research is that the geological study of earthquakes—paleoseismology—is feasible under water. Accurate sea-bottom topography and shallow sub-bottom profiles were obtained over key portions of the eastern Marmara Sea. Faults were successfully located with an accuracy of 1–2 m. Sediment cores collected over these faults allow us to correlate disturbances in the sediment column with submarine fault activity. These data and ^{14}C datings will allow estimates of Holocene slip rates and identification of individual earthquakes on fault segments of the North Anatolian plate boundary.

The North Anatolian Fault System

The North Anatolian Fault system (NAF), one of the world's major continental transform systems, separates the Anatolian and the Eurasian plates for more than 1,600 km in northern Turkey. The motion is primarily right-lateral, with a slip rate, estimated from Global Positioning System (GPS) geodetic measurements, at approximately 24 mm/y [*McClusky et al.*, 2000]. The Marmara Sea is located near the transition between the right lateral strike-slip regime of the NAF to the east, and the extensional regime affecting most of the Aegean Sea to the west. The Marmara Sea includes three basins deeper than 1000 m that accommodate the splaying of the NAF system into several strands.

The intense seismicity of the NAF system is documented by a remarkably good record of historical earthquakes in the region [*Ambraseys and Finkel*, 1995]. A sequence of eight M>7 earthquakes has progressively ruptured this boundary from east to west during the last century. The most recent and western-most events in this sequence, the M 7.4 Kocaeli and M 7.1 Duzce main shocks of 1999, were particularly destructive. They ruptured about 160 km of this fault system, including a submarine portion in the Gulf of Izmit, eastern Marmara Sea [*Barka*, 1999; *Reilinger et al.*, 2000; *Wright et al.*, 2001]. However, little strain has been released since the mid-1700s by earthquakes along 150 km of the transform through the Marmara Sea. The segment of the NAF connecting the Gulf of Saros and the western Marmara Sea (Ganos Fault, Figure 1) ruptured in 1912; this is the only large rupture in the Marmara basin during the last century. Therefore, this submarine portion of the NAF system constitutes a seismic gap where the accumulated elastic strain is about as large as that released by slip in the 1999 sequence [*Reilinger*

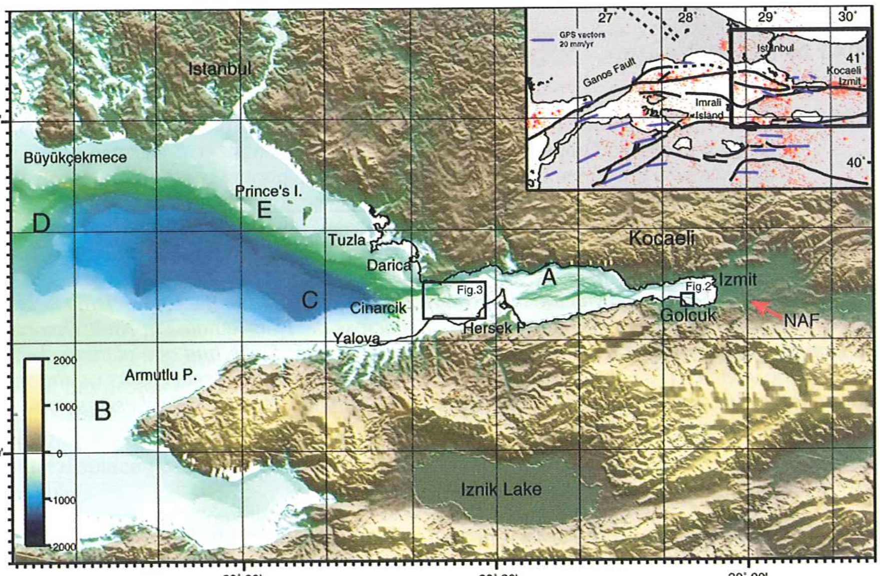

Fig. 1. This shaded relief map of the Marmara region combines (a) the Odin Finder and Urania 20-m resolution Digital Terrain Model, (b) data acquired by the Hydrographic Institute of the Turkish Navy (SHOD), and (c) the International Bathymetric Chart of the Mediterranean data (IBCM), with (d) onland European Research Satellite SAR interferometric Digital Elevation Model. The map clearly shows the North Anatolian Fault entering the Gulf of Izmit from western Turkey (red arrow). The epicenter of the M 7.4 17 August 1999 Kocaeli earthquake is represented by the largest red circle in the inset map. The tectonic model used in the inset map is taken from Okay et al. [2000]. Capital letters represent the key areas investigated during the two surveys (A: Gulf of Izmit; B: east of Imrali Island; C: Çinarcik Basin; D: the near-shore area southwest of Istanbul (Büyük Çekmece); E: Prince's Islands).

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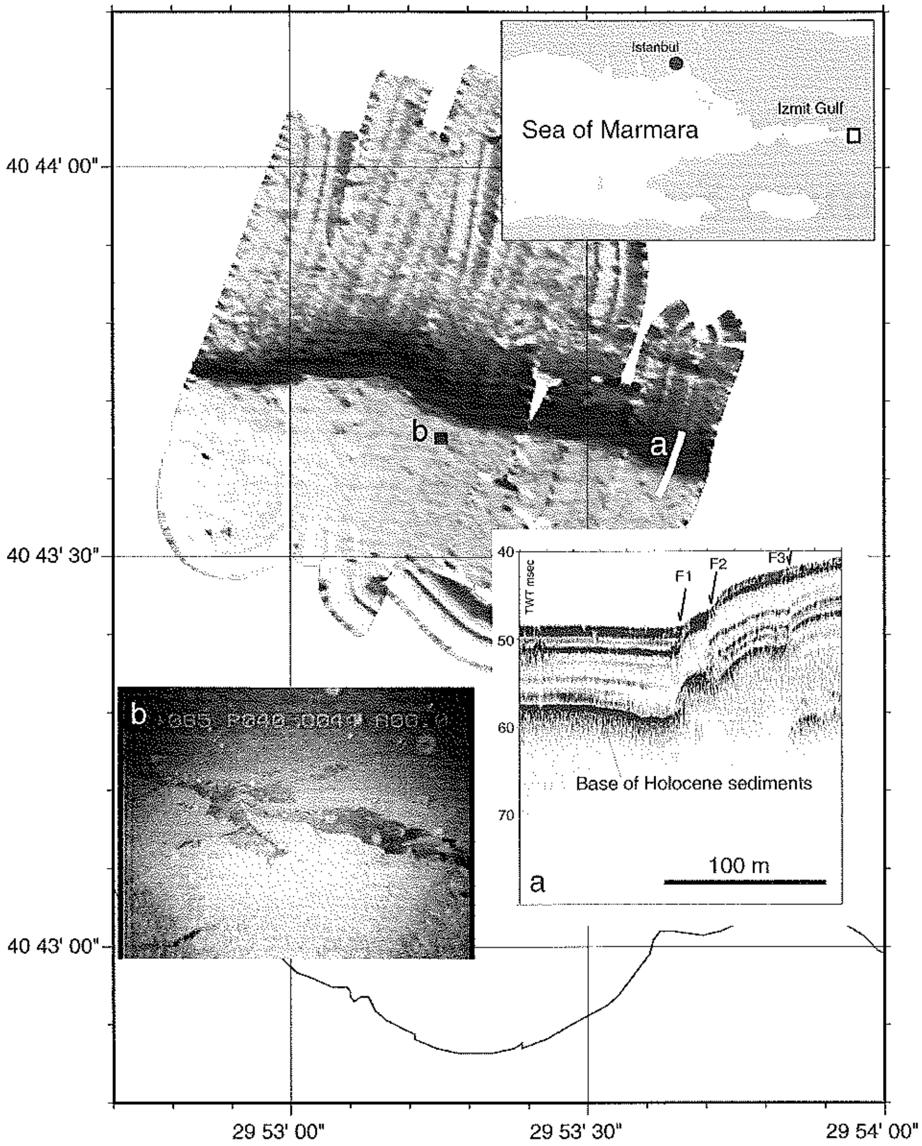

Fig. 2. This shaded-relief bathymetric map shows the eastern basin of the Gulf of Izmit near the towns of Izmit and Golcuk. (a) Sub-bottom profile across the North Anatolian Fault; Holocene sediments displacement is related to a system of at least three faults, and one of them clearly reaches the seafloor (F2). (b) This ROV image shows the system of recent cracks on the sea floor, filled by black and yellowish mineralizations presumably related to fluid escape enhanced by fault movement during and after the 1999 rupture.

et al., 2000; *Hubert-Ferrari et al.*, 2000]. Different earthquake scenarios can be described, in terms of how the strain gap in the Marmara Sea between the 1912 and 1999 ruptures will be filled, with different implications for the hazard facing the circum-Marmara region; a good understanding of the seismogenic behavior of the submarine strands of the NAF system is critical.

Research Equipment and Methods

Estimates of seismic hazards around the Marmara Sea require the identification of the active faults, the association of these faults with specific historic earthquakes, and dating their most recent ruptures at the same scale as typical paleoseismic studies on land. While paleoseismology has become a primary tool for seismic hazard evaluation on land, submarine paleoseismology has seldom been attempted, mainly because of the limited resolution of available marine geophysical techniques. Rapid developments in imaging and sampling techniques now make this approach possible.

High-resolution multi-beam and side-scan sonar maps and CHIRP sub-bottom profiles have been combined with carefully positioned core samples. Integrated navigation systems with Differential Global Positioning System (DGPS) and gyrocompass (GYRO) sensors were used. To improve accuracy, some cores and the side-scan sonar tow fish, were positioned with Hydroacoustic Positioning and Ranging (HPR) transponders. The data were thereby referred to the ship's center of gravity.

This approach, called submarine earthquake geology, is used to resolve the shallow geometry and kinematics of the fault system in the Marmara Sea, and to study the geological effects of individual earthquakes; that is, the effects of the fault motion along the rupture plan and secondary structures derived from the shaking, such as landslides near the fault.

Work was concentrated in the Gulf of Izmit, an east-west elongated feature located along the NAF system near its 1999 rupture, and at the offshore extension of the Ganos Fault in the Marmara Sea—the segment of the NAF that ruptured in 1912. We also surveyed the near-shore area southwest of Istanbul (Büyük Çekmece), the Çinarcik basin, the region close to the Prince's Islands, and an area east of Imrali Island (inset, Figure 1) to investigate other possible branches of the NAF system [e.g., *Okay et al.*, 2000].

Preliminary Results

The NAF enters the Gulf of Izmit from the east, where it ruptured during the 1999 earthquakes; it bisects the entire Gulf, passing through the Hersek promontory (Figure 1). Several strands of the NAF were traced as troughs or steps in sea-floor topography, and as growth structures in the shallow subsurface. In places, a single major fault trace was found, and its position could be mapped with a resolution of less than a few meters; in other areas, several strands were found in a zone up to 1 km wide (Figures 2 and 3). Along-strike topography identified local complexities depending on whether secondary tectonic deformation or sedimentary or erosional processes dominate.

The Eastern Gulf of Izmit and the 1999 Rupture

The fault trace offshore of Izmit is represented by a 5–6-m-high scarp with a base that is 36–40 m below sea level (Figure 1 and 2). A CHIRP profile orthogonal to the main strand of the NAF (Figure 2a) shows that Holocene sediments are as thick as 7–8 m. Their displacement is related to a system of at least three faults, and one of them clearly reaches the sea floor.

Video observations made with an ROV deployed along the fault trace did not detect any fresh rupture close to the fault scarp, suggesting that the last rupture may have occurred on the facing scarp that defines the southern shore. Alternatively, the scarps may be covered by deposition of re-suspended sediments during earthquakes. Mapping of fresh ruptures and the tilting of the shore face alongshore support the first interpretation [*R. Armijo*, pers. commun., 2001]. Nonetheless, a system of fresh-looking polygonal cracks are present at the sea bottom, filled by black and yellowish mud, related perhaps to fluid escape during and after the 1999 rupture (Figure 2b); chemical

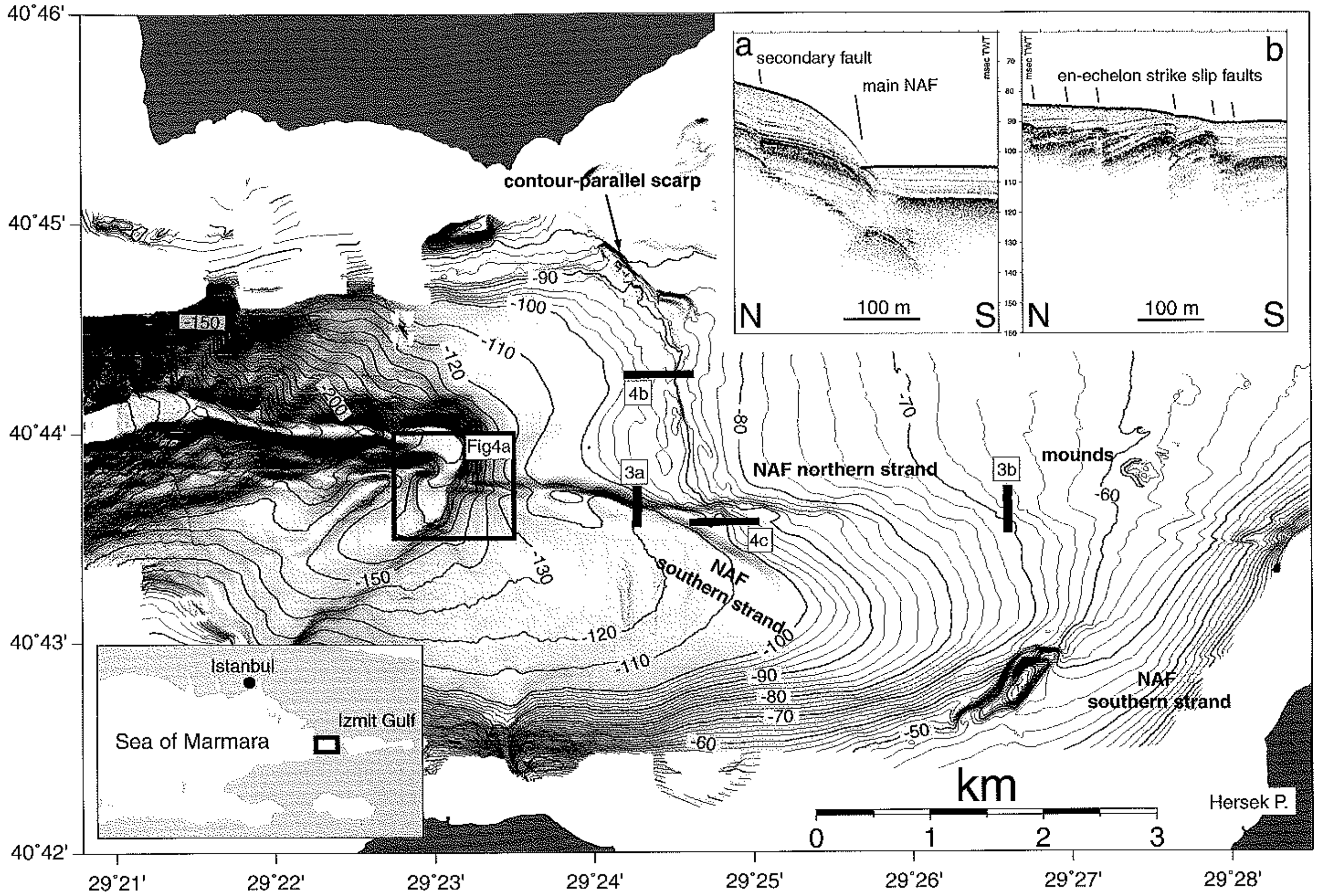

Fig. 3. This shaded relief bathymetric map shows the western Gulf of Izmit. A major right-lateral branch of the North Anatolian Fault system bisects the gulf west of the Hersek peninsula. This branch splays between two strands about 1 km across. Each strand consists of a series of en-enchelon, left-stepping fault segments. Deformation in the east is distributed among different structures represented by the en-enchelon left-stepping faults imaged in part c, while in the west deformation is confined to a narrower region (b). To the east, north of the North Anatolian Fault, a series of ridges bordered by peripheral depressions is controlled by fault activity. These ridges are interpreted as related to fluid flow or degassing processes. South of the North Anatolian Fault, an uplifted structural high, possibly related to a local transpressive regime, is offset by the southern strand of the North Anatolian Fault.

analysis of the pore fluids from these deposits are necessary to confirm this interpretation. Several mounds located on or close to active strands of the NAF were mapped farther west in the Gulf of Izmit; they could be related to fluid expulsion and degassing processes driven by fault activity (Figure 3). Gas plumes are commonly detected in the water column of the Gulf of Izmit by high-resolution seismic profiles.

Western Gulf of Izmit

The main branch of the NAF system bisects the western portion of the Gulf of Izmit. West of the Hersek Peninsula, the fault splays eastward into two east-west strands about 1 km apart located at 40°43.5'N and 40°42.83'N (Figure 3). The fault strands merge in a single fault zone at about 29°24.33'E under a water depth of 110 m. Each fault strand consists of west-northwest en-echelon, left-stepping fault segments; each segment, approximately 1 km long, has produced subtle topographic anomalies less than 1 m high. CHIRP profiles confirm that these anomalies are due to faults that displace Holocene sediments (Figure 3b).

Westward, toward the Çinarcik Basin, the NAF follows the south wall of a deeply eroded canyon as a series of en-echelon, left-stepping fault segments. It displaces the canyon head right laterally by about 100 m near 29°23'E.

Synthetic Aperture Radar (SAR) interferometry modeling [*Wright et al.*, 2001] indicates that the 1999 earthquake affected the entire Izmit Bay from the epicenter at the eastern end, to the western end close to the Çinarcik basin. However, our data suggest that the 1999 event did not rupture the sea floor of the Izmit Gulf west of the Hersek peninsula, where SAR data indicate 1.5 m of slip. Multibeam and CHIRP data and ROV images do not show fresh scarps or other indicators of recent seismic activity. Pinar et al. [2001] also suggest that the western termination of the 1999 rupture is located east of the Hersek promontory.

We cannot exclude the possibility of a lack of mechanical coupling between the seismogenic basement and the sediments above; this would inhibit brittle deformation on the sea floor. Another possibility is that the upper few meters of the sediments have very little cohesion and "flow" across the basement fault scarp, or that fresh fault scarps may be buried by deposition of re-suspended sediments after each earthquake. Mud with very little cohesion sampled in that area supports this hypothesis.

We found a northwest-southeast-trending structure in front of the Hersek promontory (Figure 1) close to the northern coast that appears to continue on land close to Darica and Tuzla. This structure probably plays a secondary role in the plate motion, but it may affect the behavior of the major faults. It may be related to the fault system known as the

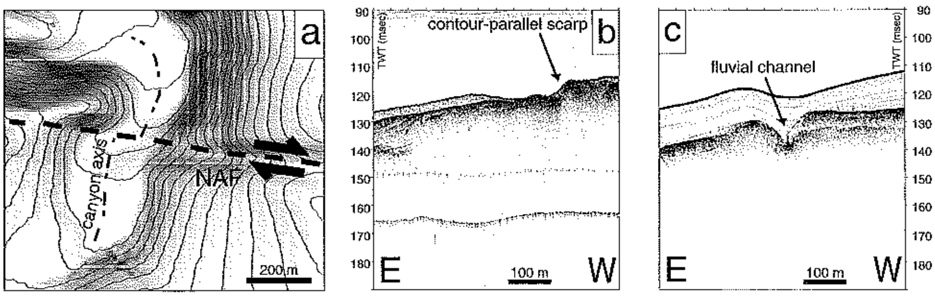

Fig. 4. (a) This multibeam map shows the region where the canyon is offset right-laterally by about 100 m along the east-west main branch of the North Anatolian Fault (see figure 3 for its location). Figures 4b and 4c are two CHIRP profiles collected across the presumed paleo-shoreline and the fluvial channel (see figure 3 for their location).

Prince's Island segment, which is recognized by Pinar et al. [2001] as one of the potential sites for future earthquakes.

Displacement Rate Along the NAF

Topographic-sedimentary structures such as canyons, channels, and scarps have important implications for earthquake geology. Contour-parallel scarps may represent paleo-shore faces and could thus represent horizontal paleo-reference levels—that is, piercing lines—whose offset along the fault strands in the different regions of the Marmara basin may be used to estimate the NAF Holocene horizontal and vertical slip rates.

The present slip rate of the NAF has been estimated at 24 mm/yr from geodetic measurements [*McClusky et al.*, 2000]. We will investigate the fault movement for the Holocene and how the displacement is distributed among the different strands of the NAF system in the Gulf of Izmit. Tight grids of multibeam and CHIRP profiles and core transects were collected in three key areas where piercing points—submerged canyon, paleo-shorelines, and fluvial channel—were recognized.

Submarine Canyon

In the western Gulf of Izmit, a submarine canyon connects the Gulf's continental shelf to the Çinarcik 1200-m-deep basin. The east-west-trending canyon shows a sharp 90° bend to the south, west of 29°23′ (Figure 3). There, the canyon axis trends north-south, and the east-west-trending NAF offsets right-laterally by about 100 m the canyon axis (Figures 3 and 4a). A tight grid of multibeam and CHIRP profiles have been acquired in this region, along with some cores. Future three-dimensional reconstruction of channel geometry and ^{14}C datings will contribute to reconstructing the fault movement.

Contour-parallel Scarp

High-resolution bathymetric maps and CHIRP sub-bottom profiles reveal a prominent contour-parallel scarp, which we identify as evidence of a possible submerged shoreline at a depth of approximately 85 m in the Gulf of Izmit (Figures 3 and 4). The scarp is also observed offshore of the Büyük Çekmece areas and east of Imrali Island, and it delineates a "rough-smooth" transition across the 85-m isobath and sub-horizontal sedimentary sequences onlapping near the isobath.

The presumed paleo-shoreline trends north-south in the Gulf of Izmit near 29°24′E and intersects the fault trace at approximately 29°25′E (Figure 3). CHIRP sub-bottom profiles indicate that sub-surface strata outcrop at the scarp (Figure 4b). Its morphology is possibly related to beach erosion and low stand deposits. Gravity cores from this feature bottomed in coarse-grained sediments with pebbles and gravel.

The 85-m-deep scarp, if it is a paleo-shoreline, has important implications both for earthquake geology and for paleo-oceanography. Its formation would be related to the mechanisms and timing of water exchange between the Mediterranean, Marmara, and Black Seas. The sill depth in the Dardanelles strait during the Last Glacial Maximum has been estimated at 85 m below present sea level [*Ryan et al.*, 1997], and it may have controlled the formation of the 85-m paleo-shoreline of the fresh water Marmara Lake [*Çagatay et al.*, 2000]. Stratigraphic analysis of cores collected across this shoreline close to the NAF and ^{14}C dating could provide a precise age for the ensuing transgression through the Dardanelles Strait. The datings will also be used to estimate both the horizontal and vertical slip rate of the NAF where the scarp is displaced along the fault trace.

Fluvial Channel

CHIRP records and multi-beam images across an erosional channel show that the channel is displaced right-laterally along the fault zone. This channel is now inactive, having being partially buried by recent Holocene mud deposits (Figure 4c). Five cores were recovered along a north-south transect across the channel. Two of them bottomed in a deposit containing pebbles of meta-igneous and sedimentary rocks with a biogenic fraction, including euryhaline assemblage of benthic forams, pelecypods, and gastropods. Preliminary interpretations suggest a surface offset of about 100 m for the channel axis. Carbon-14 age determinations and a three-dimensional reconstruction of the channel geometry—both in progress—will put this estimate on firmer ground and will allow measurement of the slip rate since the channel became inactive.

Implications

Our preliminary results indicate that paleoseismology can be applied successfully to the sea floor if it is combined with high-resolution geophysical/geological techniques. Very accurate positioning surface and sub-surface systems are needed to precisely locate all of the geophysical measurements, as well as the sediment sampling stations. Furthermore, to obtain long-term reconstructions of the activity of the major faults, this approach has to be combined with regional and interdisciplinary studies such as basin-wide paleo-oceanography, stratigraphy, and large-scale tectonics.

The ongoing analysis of this data set should help answer the following questions:

- Is the plate motion through the Marmara Sea partitioned between distinct structures accommodating the transcurrent and extensional components of motion?
- Do faults with complementary roles in these partitioned systems rupture in repeatable sequences?
- Is the Marmara Sea seismic gap going to be filled by a single large rupture or by a sequence of smaller ruptures?
- What is the paleo-oceanographic history of the Marmara Sea since the Last Glacial Maximum?
- What is the history of its communication with the Black Sea on one side and the Mediterranean on the other?

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