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Seafloor fault ruptures along the North Anatolia Fault in the Marmara Sea, Turkey: Link with the adjacent basin turbidite record

Cecilia M.G. McHugh [a,b,*], Nicole Braudy [a,1], M. Namik Çağatay [c], Christopher Sorlien [d], Marie-Helene Cormier [e,2], Leonardo Seeber [b], Pierre Henry [f]

[a] School of Earth and Environmental Sciences, Queens College, City University of New York, Flushing, NY 11367, USA
[b] Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA
[c] ITU EMCOL, Faculty of Mining, Ayazaga, 34469 Istanbul, Turkey
[d] Earth Research Institute, University of California, Santa Barbara, CA 93106, USA
[e] Department of Geological Sciences, University of Missouri, Columbia, MO 65211, USA
[f] CNRS, College de France, CEREGE UMR 7330, 13545 Aix en Provence Cedex 04, France

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ABSTRACT

The relation between seafloor fault ruptures and the generation of turbidity currents was investigated to better understand the structural growth of tectonic basins with direct implications for earthquake hazard assessment. This study focuses on the Holocene earthquake record of transtensional basins in the Marmara Sea, Turkey, that are associated with the North Anatolian Fault system. The physical and chemical composition of three 10 m-long cores recovered from the Central Basin was studied at high-resolution and turbidite–homogenite units were identified. Turbidite–homogenite units (T–H units) are complex deposits that consist of a sharp basal contact and multiple fining upward beds of sand to coarse silt, above. All are capped by a 25 cm to 75 cm thick layer of medium to fine silt. A chronology developed from radiocarbon and short-lived radioisotopes allowed the correlation of these T–H units to the historical record of earthquakes that in Turkey goes back 2000 years. We found that the best location to recover the most complete sedimentation record is in the deepest part of a basin or "depocenter" where T–H units constitute ~80% of the sediments. A very good correlation was established between T–H units in Central Basin and proximal inferred historic epicentres along the central Marmara segment of the North Anatolia Fault that occurred in 1343, 860, 740, and 557 AD, and two more distal earthquakes that occurred in 268 and 1963 (or possibly1964). These sedimentation events can then be referred to as "seismo-turbidites".

The results when compared to findings from other transform basins in Marmara Sea reveal a very good correlation between T–H units and historic ruptures. Most importantly, there is a strong correlation between the inferred locations of historical earthquakes and the preservation of turbidite–homogenite units in the basin adjacent to the inferred rupture. The 740 AD earthquake correlates with T–H units in Izmit Gulf and Central Basin and could represent a multi-segment rupture of the NAF. Generally, T–H units appear to be clustered through the Holocene sections, suggesting temporal earthquake clustering in the Marmara Sea region. Such clustering may account for the lack of T–H units and hence large ruptures through the Central Basin since 1343.

1. Introduction

The link between earthquakes and the generation of mass-wasting and turbidity currents resulting in the deposition of "seismo-turbidites" has been studied in diverse submarine tectonic settings in recent years to better understand the risk of earthquakes, and tsunamis to coastal populations. Most studies focus on convergent plate boundaries, such as Cascadia offshore western North America (Goldfinger et al., 2003, 2007; Goldfinger, 2011), Galicia, offshore Galicia and Portugal (Gracia et al., 2010; Masson et al., 2011; Bartolome et al., 2012), Kuril trough offshore Japan (Nakajima and Kanai, 2000; Noda et al., 2008), Chile trench offshore Chile (St-Onge et al., 2012), and Hikurangi trench offshore New Zealand (Pouderoux et al., 2012). In contrast to these convergent margin settings, nearshore continental transform boundaries are associated with comparatively smaller but more frequent shallower earthquakes. Because they cross heavily populated regions, earthquakes can be

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[*] Corresponding author at: School of Earth and Environmental Sciences, Queens College, City University of New York, Flushing, NY 11367, USA. Tel.: +1 718 997 3322; fax: +1 718 997 3299.
E-mail address: cmchugh@qc.cuny.edu (C.M.G. McHugh).

[1] Present address: Department of Geoscience, The University of Wisconsin, Madison, WI 53706, USA.

[2] Present address: University of Rhode Island, Graduate School of Oceanography, Narragansett, RI 02811, USA.

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disproportionally damaging, primarily not only due to shaking (e.g., liquefaction, land-slides), but also due to ground deformation. Even small-localized tsunamis have been associated to strike-slip earthquakes due to dip-slip motions along faults that generated failures and mass wasting (Hornbach et al., 2010; Altinok et al., 2011). Sediments in transform basins preserve unique information about earthquake-triggered sedimentation. These sediments have been studied in the Enriquillo–Plantain Garden sinistral transform fault offshore Haiti (McHugh et al., 2011a), the North Anatolia Fault beneath Marmara Sea (McHugh et al., 2006; Sari and Çağatay, 2006; Beck et al., 2007; Çağatay et al., 2012; Drab et al., 2012; Eris et al., 2012), the El Pilar fault in Cariaco Basin, Venezuela (Thunell et al., 1999; Lorenzoni et al., 2012), and the Alpine strike slip fault in New Zealand (e.g., Barnes, 2009). Land paleoseismic studies of the Dead Sea transform have contributed much to the understanding of these transform fault systems by characterizing large and fine scale structures and producing a record of paleoearthquakes (e.g., Marco and Agnon, 1995; Ken-Tor et al., 2001; Migowski et al., 2004). Within the past ten years, much progress has been made in the field of submarine paleoseismology, understanding processes linking submarine earthquakes with sedimentation events and developing techniques for addressing earthquake recurrence intervals and segmentation of fault systems.

What earthquake effects cause sedimentation events? Ground shaking and/or permanent sea-floor deformation such as steepening of slopes? How strong do these effects need to be? These fundamental questions have important practical corollaries: Could a seismo-turbidite in a transform basin be triggered by a distal earthquake several segments away from that basin, or alternatively, is it indicative of a proximal seafloor rupture across that same basin? If the latter is generally the case, earthquake-triggered deposits have the potential of identifying the segment of the transform boundary that ruptured and whether the rupture reached the sea floor. Previous investigations of the Cascadia convergent plate boundary have identified fault segments based on the provenance of the turbidites (Goldfinger et al., 2003, 2007; Goldfinger, 2011). In the Hikurangi subduction margin offshore New Zealand, synchronous turbidites were linked to a specific source based on an onland paleoearthquake record, and used to determine earthquake recurrence intervals (Pouderoux et al., 2012). Prior investigations of the North Anatolia Fault dextral transform boundary beneath the Marmara Sea showed that turbidites in three of the main sub-basins were generally deposited adjacent to the fault segment that ruptured (McHugh et al., 2006). A more complex relation between earthquakes and turbidites was found in the well-documented 2010 Mw 7 Haiti earthquake that was associated to the sinistral Enriquillo–Plantain-Garden transform boundary (McHugh et al., 2011a, 2011b). Factors such as low sediment supply in the Haiti carbonate margin and a complex earthquake rupture with strike-slip and thrust components may have played a role in the generation of mass-wasting and turbidity currents in this margin where a one-to-one correlation between sedimentation and earthquakes was not found (McHugh et al., 2011b; Taylor et al., 2011). Here we further explore the relation between sea floor fault ruptures and the generation of turbidity currents to better characterize fault segmentation and seismic hazards. Submarine paleoseismology techniques are applied to study three ~10 m-long cores recovered from Central Basin and using multibeam bathymetry and chirp high-resolution sub-bottom profiles. Central Basin is one of the main basins in Marmara Sea associated with the North Anatolian Fault system. The results from Central Basin are then compared to findings from other basins in Marmara Sea and from transform basins in other tectonic settings.

The main objectives are to: 1) Investigate if all segment-rupturing earthquakes generate submarine sediment failures and sedimentation events, and if there is a one-to-one correlation between earthquakes and turbidites. 2) Link each event in the sedimentation record to specific earthquake ruptures, determining earthquake recurrence intervals. 3) Extend the record of earthquake-generated sedimentation to the early Holocene. The threshold for historical earthquakes considered in this study is magnitude Ms ≥6.8, as assigned by Ambraseys (2002a). Most studies to date have concentrated on the late Holocene within the span of historic earthquakes. A longer earthquake record will contribute to a better understanding of earthquake ruptures along continental transform boundaries in general. But in particular, these results could be critical for geohazards assessment of heavily populated coastal regions such as the Marmara Sea that include the city of Istanbul.

2. Background

The North Anatolian Fault (NAF) extends east west for 1600 km across Turkey and is one of the world's major continental transforms (Fig. 1). The NAF accommodates right-lateral motion between Eurasia and the Anatolia plate. GPS measurements show a relative motion of 23–25 mm/yr (Straub et al., 1997; McClusky et al., 2000; Reilinger et al., 2010). The Marmara Sea is a transtensional trough spatially and genetically associated with the northern branch of the NAF (NAF-N; Fig. 1). The Marmara Sea is subdivided into subsiding Plio-Pleistocene basins that are as deep as 1200 m and separated by ridges 550 m deep (Rangin et al., 2001). From west to east the main basins are Tekirdag, Central, Kumburgaz, Cinarcik, and Izmit Gulf (Fig. 1).

The 1912 Mw 7.4 Ganos earthquake ruptured the NAF-N on land (Rockwell et al., 2001, 2009; Ambraseys, 2002a; Altunel et al., 2004; Aksoy et al, 2010; Meghraoui et al., 2012). Armijo et al. (2005) proposed that the 1912 rupture extended for ~140 km from the Gulf of Saros, ending in the Central Basin step-over in Marmara Sea (Fig. 1). East of Marmara Sea, the NAF ruptured in a sequence of seven Ms > 7 earthquakes progressively from east to west, starting in 1939 (Toksöz et al., 1979; Barka and Kadinsky-Cade, 1988; Barka, 1999; Toksöz et al., 1999). The latest and westernmost events, the 1999 Mw 7.4 Izmit and the Mw 7.2 Duzce earthquakes, were destructive (~17,000 deaths). The Marmara segment of the NAF is the only remaining unruptured seismic gap (Ambraseys, 2002a) and has accumulated as much elastic strain as released in the 1999 sequence (Hubert-Ferrari et al., 2000; Parsons et al., 2000; Reilinger et al., 2000). To the east of Marmara Sea, it has also been proposed that the 1999 seafloor rupture extended for ~80 km into Marmara Sea (Aksoy et al., 2010; Gasperini et al, 2011; Uçarkus et al., 2011). Other studies are more conservative in their estimates of the length of the 1999 seafloor ruptures into Izmit Gulf. Cormier et al. (2006) proposed that while the aftershock distribution and geodetic data indicate that the subsurface rupture extended 50 km into Marmara Sea, direct evidence is lacking for any seafloor rupture extending beyond 25 km west of Izmit. The extent of both the 1912 and 1999 seafloor ruptures has implications for understanding and modelling seismic risk for the segment of the NAF that presumably remains locked under Marmara Sea. It is therefore critical to provide as much geological information on historic and pre-historic ruptures as possible.

3. Submarine paleoseismology prior results

The Marmara Sea basins are excellent for submarine paleoseismology studies because they are closed basins that have preserved turbidites in their deepest part (Fig. 1). Structurally, the progressive tilting in some of the basin floors towards the fault has preserved thick turbidite deposits in the basins deepest part or “depocenters” (Fig. 2; Cormier et al., 2006; Seeber et al., 2006; Kurt et al., 2013). Coring in these depocenters has allowed the recovery of a record of turbidites that have been dated effectively (McHugh et al., 2006; Çağatay et al., 2012). Most importantly, these T–Hs were linked to a historic record of earthquakes that goes back 2000 years (Ambraseys and Finkel, 1995; Ambraseys and Jackson, 2000; Ambraseys, 2002a). Additionally, a very thick homogenite (~2 m) was dated at 14.6 cal ka BP in Central Basin (Beck et al., 2007), and based on geochemical elemental composition correlations were made of earthquake-triggered turbidites across basins (Drab et al., 2012). Other