Tectonophysics 608 (2013) 980–995

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Seismotectonics of the Armutlu peninsula (Marmara Sea, NW Turkey) from geological field observation and regional moment tensor inversion

J. Kinscher [a,b,*,1,2], F. Krüger [a], H. Woith [b], B.G. Lühr [b], E. Hintersberger [c], T.S. Irmak [d], S. Baris [d]

[a] Institut für Erd- und Umweltwissenschaften, Universität Potsdam, Potsdam, Germany
[b] Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum — GFZ, Potsdam, Germany
[c] Department for Geodynamics and Sedimentology, University of Vienna, Vienna, Austria
[d] Department of Geophysics, Kocaeli University, Kocaeli, Turkey

ARTICLE INFO

Article history:
Received 26 February 2012
Received in revised form 5 June 2013
Accepted 17 July 2013
Available online 27 July 2013

Keywords:
Seismotectonics
Moment tensor inversion
Brittle fault analysis
Morphotectonics
North Anatolian Fault Zone (NAFZ)
Marmara Sea

ABSTRACT

The Armutlu peninsula, located in the eastern Marmara Sea, coincides with the western end of the rupture of the 17 August 1999, İzmit M_W 7.6 earthquake which is the penultimate event of an apparently westward migrating series of strong and disastrous earthquakes along the NAFZ during the past century. We present new seismotectonic data of this key region in order to evaluate previous seismotectonic models and their implications for seismic hazard assessment in the eastern Marmara Sea. Long term kinematics were investigated by performing paleo strain reconstruction from geological field investigations by morphotectonic and kinematic analysis of exposed brittle faults. Short term kinematics were investigated by inverting for the moment tensor of 13 small to moderate recent earthquakes using surface wave amplitude spectra. Our results confirm previous models interpreting the eastern Marmara Sea Region as an active transtensional pull-apart environment associated with significant NNE–SSW extension and vertical displacement. At the northern peninsula, long term deformation pattern did not change significantly since Pliocene times contradicting regional tectonic models which postulate a newly formed single dextral strike slip fault in the Marmara Sea Region. This area is interpreted as a horsetail splay fault structure associated with a major normal fault segment that we call the Waterfall Fault. Apart from the Waterfall Fault, the stress strain relation appears complex associated with a complicated internal fault geometry, strain partitioning, and reactivation of pre-existing plane structures. At the southern peninsula, recent deformation indicates active pull-apart tectonics constituted by NE–SW trending dextral strike slip faults. Earthquakes generated by stress release along large rupture zones seem to be less probable at the northern, but more probable at the southern peninsula. Additionally, regional seismicity appears predominantly driven by plate boundary stresses as transtensional faulting is consistent with the southwest directed far field deformation of the Anatolian plate.

1. Introduction

During the last century, an apparently westward migrating series of disastrous earthquakes occurred along the North Anatolian Fault Zone (NAFZ) starting in Erzincan northeast Anatolia (Barka, 1996). The 17 August 1999, İzmit M_W 7.6 (referred to as "İzmit'99" throughout the text) and the 12 November 1999, Düzce M_W 7.2 earthquakes constitute the last events of this series located at the eastern edge of the Marmara Sea in NW Turkey (Fig. 1). The İzmit'99 rupture marks the easternmost limit of an around 150 km long off shore seismic gap across the Marmara Sea (Armijo et al., 2002) where the NAFZ converts from a continuous right lateral moving transform master fault into a complex interaction of three major fault strands (e.g. Barka, 1997; Barka and Kadinsky-Cade, 1988). GPS velocity measurements demonstrated that surface motions in the Marmara Sea region differ from the far field motion of the Anatolian plate indicating slip partitioning of dextral strike slip and perpendicular extension (e.g. Flerit et al., 2003; Hergert and Heidbach, 2010). However, most seismotectonic models presented so far are not able to unambiguously explain both, observed deformation pattern and historical seismicity (e.g. Armijo et al., 2002; LePichon et al., 2001). Depending on model predictions, the Marmara seismic gap could rupture by a single large earthquake with a magnitude M ~ 7 (Hubert-Ferrari et al., 2000; Parsons, 2004) or by several smaller earthquakes (Hergert and Heidbach, 2010). Hence, implications derived from each seismotectonic model related to the seismic hazard for the megacity of Istanbul located at the northern border of the eastern Marmara Sea region may differ significantly, depending on the model.

* Corresponding author at: Universität Potsdam, Institut für Erd- und Umweltwissenschaften, Karl-Liebknecht-Str. 24-25, 14476 Potsdam Golm, Germany. Tel.: +49 331 977 2116.
E-mail address: j.l.kinscher@gmail.com (J. Kinscher).
[1] Now at L'Institut National de l'EnviRonnement Industriel et des RisqueS INERIS Nancy, France.
[2] Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum GFZ, Stiftung des Öffentlichen Rechts des Landes Brandenburg, Telegrafenberg, 14473 Potsdam. Tel.: +49 331 288 0.

0040-1951/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2013.07.016

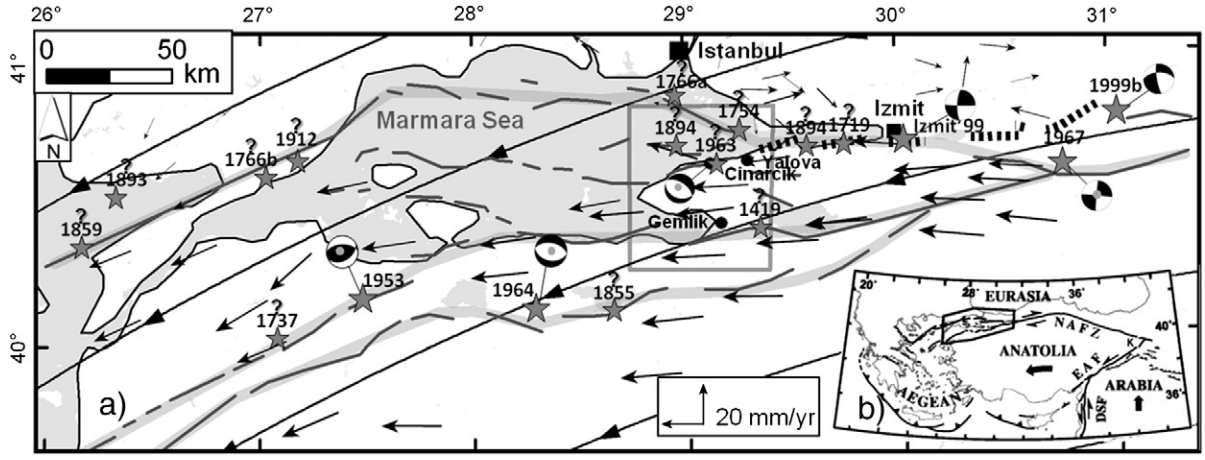

Fig. 1. Marmara Sea (a) study area of the Armutlu peninsula (gray square, Fig. 2), fault segments (black lines) of the northern, middle and southern strands (thick light gray lines) of the splitting NAFZ at the Marmara Sea region, and the surface rupture (dashed black lines) of the İzmit'99 earthquake (compiled from Armijo et al. (2002), Barka (1997), and Barka et al. (2002)). GPS velocity vectors (small black arrows, taken from Ergintav et al. (2007)) partially deviate from the relative southwest directed far field motion of the Anatolian plate (continuous black lines with arrows indicating plate motion approximated by Euler circles taken from McClusky et al. (2000)). Gray stars indicate larger historical earthquakes ($M_S \geq 6.8$) since the 18th century and the 1419 event in the Maramara Sea region (event location and date are referred by Ambraseys (2002) except for location of the 1894 event and the 1963 M_W 6.3 event which are taken from Armijo et al. (2005) and Bulut and Aktar (2007), respectively). Focal mechanisms are taken from Taymaz et al. (1991) (lower hemisphere plot with gray dot center) and Harvard Global Centroid Moment Tensor catalog (GCMT) (Dziewonski et al., 1981; Ekström et al., 2012) (lower hemisphere plot). (b) Tectonic setting of the Anatolian plate and location of the Marmara Sea region (black bordered area) (modified from Armijo et al. (2002)).

In this study, new seismotectonic data from the Armutlu peninsula is presented (Fig. 1). The peninsula is located at the eastern edge of the Marmara Sea Basin, southeast of the megacity of Istanbul and directly bounded by the northern strand of the NAFZ that ruptured during the İzmit'99 earthquake. In order to predict the probability for a propagation of large earthquakes into the Marmara Sea, a better understanding of the regional seismotectonic setting is inevitable.

We investigated and compared the long term and short term deformation patterns at the Armutlu peninsula to evaluate and improve the regional seismotectonic model. Long term deformation patterns are approached from morphotectonic characteristics and brittle fault analysis at the northern peninsula based on geological field work and remote sensing data. Recent deformation patterns are obtained from regional moment tensor inversion (RMTI). As a prerequisite for moment tensor inversion, the regional shear wave velocity structure of the upper crustal layer investigated to obtain accurate Greens functions for mid-period surface waves. The results are summarized and presented by seismoctectonic maps and simplified models for the northern and southern Armutlu peninsula indicating the active faults segments and their kinematics. In addition, the results are discussed in light of previous regional seismotectonic models, the state of stress, and earthquake hazard in the eastern Marmara Sea region.

2. Investigation area

The Armutlu peninsula is located in the eastern Marmara Sea southeast of the megacity of Istanbul. Recent internal deformation at the Armutlu peninsula seems to be dominated by NE–SW extension (Eisenlohr, 1995; Straub et al., 1997). Abundant microseismic sources with $M_L > 0.4$ were recently detected by the local Armutlu seismic network (ARNET) (Tunç et al., 2011) and by the regional seismic network of the Kandilli Observatory and Earthquake Research Institute (KOERI). Microseismicity was enhanced after the İzmit'99 event (Karabulut et al., 2002; Özalaybey et al., 2002), but was already present before the İzmit'99 event (Bariş et al., 2002). After the İzmit'99 event, seismic activity increased significantly more at the northern realm of the peninsula compared to the southern part (Karabulut et al., 2002; Özalaybey et al., 2002) (Fig. 2). Two larger historical earthquakes have been reported for the northern region in 1894 (M ~7) (Armijo et al., 2005) and in 1963 (M_W 6.3) (Bulut and Aktar, 2007). At the southern peninsula faulting is determined by the middle strand of the NAFZ. In this region, large earthquakes occur less frequently compared to the northern strand with the last large event in 1419 ($M_S \geq 6.8$) (Fig. 1, Ambraseys, 2002; Barka and Kadinsky-Cade, 1988). On the 24 October

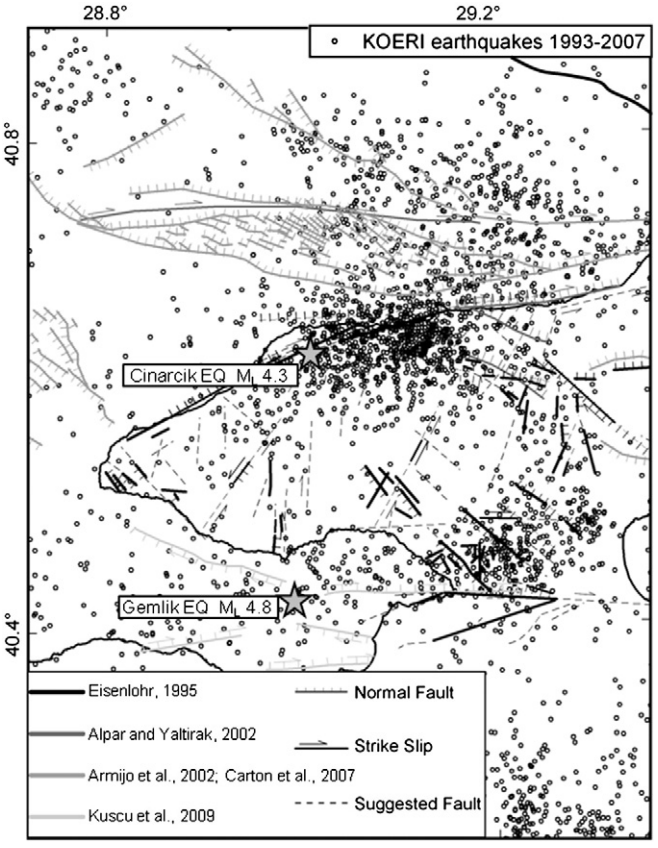

Fig. 2. Armutlu peninsula fault segments taken from previous tectonic studies (Alpar and Yaltırak, 2002; Armijo et al., 2002; Carton et al., 2007; Eisenlohr, 1995; Kuşçu et al., 2009), low to moderate seismicity ($M_L \leq 5$; taken from a confidential KOERI catalog), and the Çınarcık earthquake as well as the Gemlik earthquake (gray stars, see text). Note: The earthquake cluster east of the Gemlik event consists of quarry blasts mainly!