Tectonophysics 674 (2016) 147–165

Contents lists available at ScienceDirect

Tectonophysics

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

Review Article

Maximum earthquake magnitudes along different sections of the North Anatolian fault zone

Marco Bohnhoff [a,b,*], Patricia Martínez-Garzón [a], Fatih Bulut [a], Eva Stierle [a], Yehuda Ben-Zion [c]

[a] Helmholtz-Centre Potsdam GFZ German Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[b] Department of Earth Sciences, Free University Berlin, Malteser Strasse 74-100, 12249 Berlin, Germany
[c] Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, USA

ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form 14 February 2016
Accepted 15 February 2016
Available online 3 March 2016

Keywords:
Seismology
Historical seismicity
Continental transform faults
Fault-zone characteristics
North Anatolian fault zone
Maximum earthquake magnitude

ABSTRACT

Constraining the maximum likely magnitude of future earthquakes on continental transform faults has fundamental consequences for the expected seismic hazard. Since the recurrence time for those earthquakes is typically longer than a century, such estimates rely primarily on well-documented historical earthquake catalogs, when available. Here we discuss the maximum observed earthquake magnitudes along different sections of the North Anatolian Fault Zone (NAFZ) in relation to the age of the fault activity, cumulative offset, slip rate and maximum length of coherent fault segments. The findings are based on a newly compiled catalog of historical earthquakes in the region, using the extensive literary sources that exist owing to the long civilization record. We find that the largest M7.8–8.0 earthquakes are exclusively observed along the older eastern part of the NAFZ that also has longer coherent fault segments. In contrast, the maximum observed events on the younger western part where the fault branches into two or more strands are smaller. No first-order relations between maximum magnitudes and fault offset or slip rates are found. The results suggest that the maximum expected earthquake magnitude in the densely populated Marmara–Istanbul region would probably not exceed M7.5. The findings are consistent with available knowledge for the San Andreas Fault and Dead Sea Transform, and can help in estimating hazard potential associated with different sections of large transform faults.

Contents

* Corresponding author at: Helmholtz-Centre Potsdam GFZ German Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany.
E-mail address: bohnhoff@gfz-potsdam.de (M. Bohnhoff).

http://dx.doi.org/10.1016/j.tecto.2016.02.028

1. Introduction

Estimates of seismic hazard depend on the maximum expected (and/or maximum possible) earthquake size in the region of interest (e.g., Field et al., 2009). However, instrumental earthquake catalogs cover only approximately 100 years, substantially less than typical recurrence times of major earthquakes (e.g., Parsons, 2004; Ben-Zion, 2008). Consequently, there is currently no reliable method for determining the hazard potential of large earthquakes along major fault systems.

Subduction zones host the largest earthquakes on Earth due to the large overall available brittle rupture surfaces (e.g., Ruff, 1996). Continental transform faults such as the San Andreas Fault in California, the Dead Sea Transform fault in the Middle East, or the North Anatolian Fault Zone in Turkey (referred to as NAFZ hereafter) tend to produce earthquakes with magnitudes M typically not exceeding ~8, releasing ~30 times less seismic energy compared to the recent mega-thrust events in Indonesia (2004 Sumatra), Chile (2010 Maule), and Japan (2011 Tohoku-Oki). Despite this fact, M8 type earthquakes along continental strike-slip faults pose a substantial seismic hazard since they can occur nearby or directly through densely populated regions such as the Los Angeles Basin, the San Francisco Bay area, or the Istanbul metropolitan region. Constraining the expected maximum earthquake size in such regions can have significant societal benefits and improve the understanding of long-term physical processes acting along major faults.

The size of large earthquakes is commonly quantified by the scalar seismic moment (Aki, 1966) $M_0 = \mu \cdot \Delta\mu \cdot A$, where $\Delta\mu$ is slip, A is the rupture area and μ is effective rigidity (typically assumed $\sim 3 \cdot 10^{10}$ Pa for crustal earthquakes). For strike-slip faults, the rupture area can be simplified as the product of rupture length and vertical depth extension. While a fraction of fault slip in the seismogenic depth range can be aseismic (e.g., Ben-Zion and Lyakhovsky, 2006; Avouac, 2015), we assume for simplicity (given the available information) that the entire 15–20 km thick seismogenic part of the crust is activated during M > 6.5 earthquakes. Consequently, the seismic moment and therefore the magnitude are directly related to the rupture length and the average slip. Observations indicate that plate-bounding transform faults are typically segmented, and that earthquake slip can be limited to a single fault segment, or may activate several fault segments in multi-segment failures (Sieh et al., 1993; Barka et al., 2002; Eberhart-Philips et al., 2003; Kondo et al., 2010). The rupture patterns at given locations may change and evolve on long term when individual segments combine to form a larger, more uniform, and simplified potential slip zone (Wesnousky, 1988; Ben-Zion and Sammis, 2003; Papageorgiou, 2003). In consequence, this can lead to increasing maximum magnitudes with fault-zone development.

The geometrical and structural parameters of fault zones may change with time reflecting the fault evolution from a young, short, and segmented state toward a more continuous and larger fault zone (e.g. Tchalenko, 1970; Sengör et al., 2005; Wechsler et al., 2010). The development of a strike-slip fault is reflected in several parameters such as the geological age, cumulative offset across the fault, slip rates, and length of the individual coherent segments. As a consequence of the structural development, the resulting maximum likely magnitude may also increase. The cumulative offset across the fault combines information on the fault age and the average deformation rate. The length of individual fault segments tends to increase with total offset, and hence with age, as initially small and separated segments coalesce to form larger joint segments (e.g. Wesnousky, 1988; Stirling et al., 1996).

In this study, we present and analyze a catalog of historical seismicity for the entire NAFZ in Turkey based on numerous historical and paleoseismic records. The results are discussed in relation to available information on fault age, cumulative offset, slip rates, and geometrical parameters associated with different parts of the NAFZ. The presented earthquake catalog covers the last 2300 years and appears to be complete down to M_s7.3, i.e. it is unlikely that earthquakes larger than 7.3 for the time period considered are missing in the catalog. The data compilation provides field evidence that the maximum observed earthquake magnitude along the fault increases with fault age along the eastern and central part of the fault. The cumulative offset along the fault is approximately constant, which may be partially related to slip rate changes along the fault. The larger maximum observed earthquake magnitude (M up to ~8) along the eastern NAFZ compared to the western part (M up to ~7.4) may be related to different levels of structural development. These results are in agreement with available historical and instrumental seismicity data for two other major strike-slip faults, the San Andreas Fault and the Dead Sea Transform.

2. The North Anatolian Fault Zone

The NAFZ is one of the largest currently active continental strike-slip faults in the world extending along more than 1200 km from the Karliova triple junction in the east to the northern Aegean in the west (Fig 1A). The NAFZ was described in the late 1940s (Ketin, 1948) and it is now one of the best-studied strike-slip fault zones on Earth. The fault developed in relation to the northward migrating Arabian Plate in the east and the southward rollback of the Hellenic subduction zone in the west (Armijo et al., 1999; Flerit et al., 2004; LePichon et al., 2015). The NAFZ marks a narrow fault zone along its eastern and central parts, while branching into two or three sub-parallel strands is evident west of 31°E (Fig. 1B). The current slip rates are about 20 mm/yr in the east and 25 mm/yr in the west (Barka, 1992; McClusky et al., 2000; Reilinger et al., 2006). The NAFZ sustains predominantly right-lateral strike-slip faulting mechanisms, but in the western part, normal faulting earthquakes are also observed due to the transtensional setting produced by the slab pull of the Hellenic subduction zone (Flerit et al., 2004; Bohnhoff et al., 2005). Earthquake source mechanisms indicating transpression are not observed along the entire fault zone (Fig. 1C) (Sengör et al., 2005; Ekström et al., 2012). The NAFZ provides an important natural laboratory for understanding earthquake mechanics and fault behavior over multiple earthquake cycles due to its long and extensive historical record of large earthquakes (Ambraseys and Finkel, 1987, 1991, 1995; Ambraseys, 2002). Despite the long historical record of the region, a catalog of historical earthquakes for the entire North Anatolian Fault Zone is not yet available.

Over the past centuries, the NAFZ sustained several cycle-like sequences of large-magnitude (M > 7) earthquakes (Stein et al., 1997). Of these, the most prominent and best studied is the sequence of the 20th century that ruptured all but the Sea of Marmara segments in a series of westward propagating events, with the most recent being the Izmit (M_w 7.4) and Düzce (M_w 7.1) earthquakes of 1999 (e.g. Parsons et al., 2000; Reilinger et al., 2000; Barka et al., 2002) (Fig. 2). In the following, we summarize information on large seismic events and on fault segments for the western, central, and eastern portion of the NAFZ. Throughout the text, we consistently refer to surface wave earthquake magnitudes (M_s) converting moment magnitudes for instrumental earthquakes to M_s following the relation proposed by Scordilis (2006) as discussed later in the text. Individual NAFZ fault sections described in the text are indicated in Fig. 1A and shown in more detail in Figs. 2–4.

2.1. Western NAFZ (26°–32°E)

The northern NAFZ branch in the west hosts most of the current deformation as determined from GPS measurements (Straub et al., 1997; Ergintav et al., 2014). Its trace is narrow and well-defined along the Marmara segment and the Ganos Fault, while the branching most likely further increases beyond the northern Aegean to the west (Fig. 2). There, no M > 7 earthquakes are reported in historical records. The most recent 2014 M6.9 Aegean earthquake (Bulut, 2015) fits well