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Tsunamigenic potential of outer-rise normal faults at the Middle America trench in Central America

José A. Álvarez-Gómez [a,b,*], Omar Q. Gutiérrez Gutiérrez [a], Íñigo Aniel-Quiroga [a], M. González [a]

[a] Environmental Hydraulics Institute "IH Cantabria", Universidad de Cantabria, C/ Isabel Torres n° 15, Parque Científico y Tecnológico de Cantabria, 39011 Santander, Spain
[b] Department of Geodynamics, Faculty of Geology, Universidad Complutense de Madrid, C/ José Antonio Novais, s/n, 28040 Madrid, Spain

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ABSTRACT

The Middle America trench is formed by the subduction of the Cocos and Rivera plates under the Caribbean and North American plates. The subduction interface presents low coupling in Central America showing its seismicity a high frequency of outer-rise normal fault earthquakes. These outer-rise earthquakes are generated on the inherited structures of the seafloor-spreading fabric during the subducting plate bending. We analyze focal mechanism data in combination with the available structural data of the outer-rise normal faults in order to constrain the rupture characteristics of the outer-rise normal earthquakes. A new empirical scaling relationship is developed to define earthquake magnitudes from normal fault dimensions in the outer-rise context. We numerically model the tsunami wave propagation due to the worst outer-rise tsunamigenic source in the area to estimate its damaging potential. Wave elevations higher than 2 m are common at the coast in front of the fault extent, with maximum wave elevations of 8 m. The capability of these faults to generate ocean-wide tsunamis is low, however, they can produce significant tsunamis locally.

1. Introduction

Although less frequent than the subduction thrust earthquakes, the outer-rise normal earthquakes have generated destructive tsunamis in the past (e.g. Fujii and Satake, 2008; Gusman et al., 2009; Satake et al., 1992). As was pointed out by Satake et al. (1992): "This has important implications to future hazard assessment, particularly from tsunamis, since most hypothetical tsunamis have been assumed to be generated from underthrusting events associated with subduction"; specially in those subduction zones where the tsunamigenic underthrusting events are not usual.

The Middle America trench is formed by the subduction of the Cocos and Rivera plates under the Caribbean and North American plates (Fig. 1). This trench can be divided into two main segments: the Mexican and the Central American; where the upper plate is respectively the North American and the Caribbean. The tectonics on both segments is markedly different due to the motion of the respective upper plates (Fig. 1). While the North American plate is moving towards the trench, the Caribbean plate is moving in the opposite direction, away from the trench (Burbach et al., 1984). This fact makes the coupling on both segments of the subduction different and hence the seismic behavior too. The Mexican segment is coupled while the Central American is uncoupled (Álvarez-Gómez et al., 2008; Guzmán-Speziale and Gómez-González, 2006; Lyon-Caen et al., 2006; Pacheco et al., 1993). One of the characteristics of the low coupled subductions is the high frequency of normal intraslab earthquakes in the upper part of the slab, particularly the outer-rise earthquakes (Christensen and Ruff, 1988); due to the efficient transmission of the slab pull forces towards the upper part of the subducting plate (Conrad et al., 2004). These intraslab earthquakes are probably the largest events in uncoupled subduction zones, rather than the underthrusting events (Satake et al., 1992).

The bathymetry of the Middle America Trench offshore of Central America shows a very clear pattern of outer-rise normal faulting (Ranero et al., 2003, 2005) and the frequency of outer-rise normal earthquakes is high compared to other subduction zones worldwide, comparable to the activity of other low-coupled subductions like Marianas or Sunda.

Considering the history of tsunamis in Central America, the local sources are those that present the greatest threat. Fig. 2 shows the epicenters of the sources of tsunamis in Central America according to the work of Fernández (2002). To these we added the recent events of Chile in 2010 and Japan in 2011, that also were recorded in Central America. From the distant sources only the event of 1957 in the Aleutian Islands generated notable damage. This event caused victims in El Salvador causing major damage to the port of Acajutla. Of the tsunamis that have hit the Pacific coast of Central America only 4 have been generated by distant sources (including the two recent tsunamis of Chile and Japan) versus 30 local events (considering also local the event that occurred in 1906 off the coast of Colombia) 7 of which were damaging (Fig. 2). Local tsunamis associated with the subduction zone have

* Corresponding author at: Department of Geodynamics, Faculty of Geology, Universidad Complutense de Madrid, C/ José Antonio Novais, s/n, 28040 Madrid, Spain. Tel.: +34 913944721.
E-mail addresses: joseantonio.alvarezgomez@unican.es, jaalvare@geo.ucm.es (J.A. Álvarez-Gómez).

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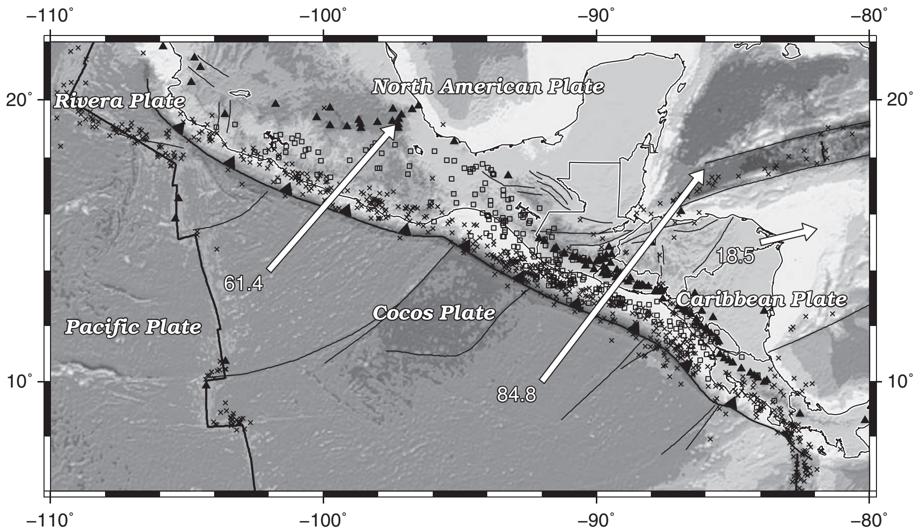

Fig. 1. Tectonic setting of the Middle America Trench. The arrows show the direction and magnitude of the plate motions taking the North American Plate fixed from the model GSRM 1.2 (Kreemer et al., 2003); the label is the motion magnitude in mm/year. The triangles show the position of the Holocene volcanoes (Siebert and Simkin, 2002). Cross symbols represent the shallow seismicity (<50 km) and squares the rest of the seismic Global CMT catalog (Ekström et al., 2012).

been classically attributed to earthquakes due to subduction of the Cocos plate under the Caribbean plate (Fernández et al., 2000) although no details of the focal mechanism exist. The outer-rise normal earthquakes are common in Central America and may play an important role as local sources of destructive tsunamis.

In this work we analyze available structural and seismic data in order to characterize the potential outer-rise normal seismic tsunamigenic sources. In addition we numerically model the tsunami wave propagation due to the worst case outer-rise tsunamigenic source in the area.

2. Analysis of the seismicity

In order to constrain the orientation parameters of the potential outer-rise tsunamigenic sources we have used the Global CMT seismic catalog (Ekström et al., 2012) to analyze the focal mechanism characteristics of the outer-rise seismicity. This catalog has been filtered in order to select the outer-rise normal earthquakes. The geographical extension of the seismic data is shown in Fig. 3 and comprises earthquakes since 1976 with magnitudes M_W between 4.5 and 8.0.

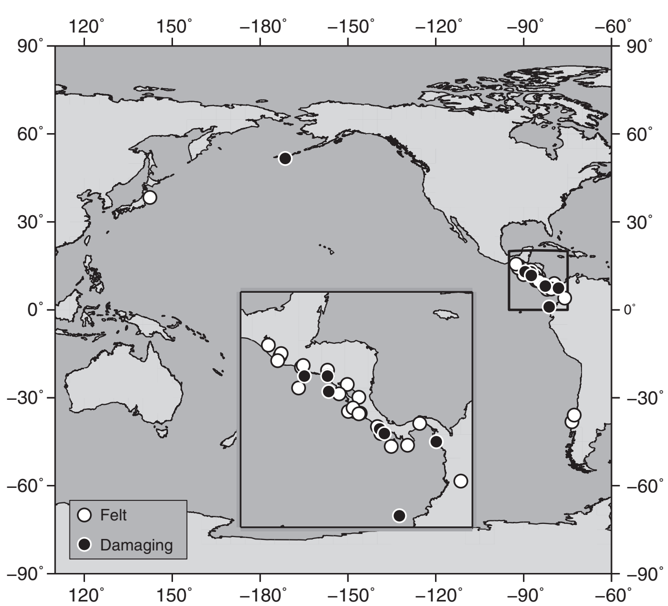

Fig. 2. Tsunami catalog of the pacific coast of Central America. The map shows the epicenters of the events. White circles: nondestructive tsunamis. Black circles: damaging tsunamis. The data is from Fernández (2002) except for the recent events of Chile 2010 and Japan 2011.

The catalog is composed of 1871 events that have been classified by the rupture type using the classification diagram shown in Fig. 3 (Álvarez Gómez, 2009). 440 events of the catalog are normal or normal-directional, 695 are strike-slip or strike-slip with dip-slip component and 736 are reverse or reverse-directional.

The outer-rise events have been selected applying a distance filter from the trench and a depth threshold: a band of 100 km from the trench and a maximum depth of 50 km (Fig. 4). The maximum depth of 50 km is an initial assumption, but below it will be shown that a maximum depth of 30 km for the occurrence of these outer-rise normal earthquakes is a good estimation, in accordance with previous works (Chapple and Forsyth, 1979; Lefeldt and Grevemeyer, 2008; Spence, 1986). From the 440 normal events of the catalog 31 are located near the trench and shallower than 30 km deep.

We used the program ZMAP (Wiemer, 2001) in order to obtain the b-value of the Gutenberg–Richter law for these events (Fig. 5). The value obtained is 1.02, close to the value of 1, proposed as universal for the law, specially on small earthquakes (Andrews, 1980; Hanks, 1979; Olsson, 1999). The range of magnitudes for the calculation of the law and the number of events is limited, although the range of variation of the b-value is not large.

From the b-value obtained we can estimate return periods for this kind of outer-rise earthquakes. The annual rate for an earthquake with magnitude Mi or greater is defined by the equation:

$$\lambda_{Mi} = \exp \alpha - \beta Mi, \tag{1}$$

where $\alpha = a \times \ln(10)$ and $\beta = b \times \ln(10)$; a and b are the parameters of the Gutenberg–Richter law. The return period is defined as the inverse of the annual rate of exceedance: $T = 1/\lambda_{Mi}$. In Table 1 the return periods for the exceedance of several magnitudes are shown. The values of the return period range between 2 years for a magnitude 5.5 earthquake and 560 years for a magnitude 7.9 earthquake (the maximum magnitude estimated from the geology in this work as shown below).

Table 1
Return periods for outer-rise normal earthquakes in the Middle America Trench. See explanation in the text.

Magnitude (M_W)	5.5	6.0	6.5	7.0	7.5	7.9
Return period (years)	2.00	6.46	20.89	67.61	218.77	559.76