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Original paper

The 4 December 1948 earthquake (Mw 6.4): Evidence of reverse faulting Beneath the Tres Marías escarpment and its implications for the Rivera-North American relative plate motion

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Resumen

El temblor del 4 de diciembre de 1948 es el sismo más grande que ha sido registrado en el segmento norte del límite de placas Rivera-Norteamérica. Este evento ocasionó muertes y daños importantes en el penal de las Islas Marías. En este trabajo se recopilaron sismogramas de estaciones regionales y telesísmicas con el fin de determinar su mecanismo focal. El mecanismo resultante muestra una falla inversa de alto ángulo con los ejes P orientados NE-SW. El mecanismo obtenido coincide con las soluciones de dos temblores más pequeños localizados a lo largo del Escarpe de las Tres Marías. La magnitud estimada para el evento de 1948 es de M_w6.4. Este valor está basado en la amplitud de las ondas superficiales registradas en la estación De Bilt (Holanda). La dirección de deslizamiento del mecanismo resultante puede interpretarse como el reflejo del movimiento relativo entre las placas de Rivera y Norteamérica. De esta manera la placa de Rivera parece estar cabalgando por debajo del Escarpe de Tres Marías en dirección NE-SW. El mecanismo obtenido contribuye a la estimación del movimiento relativo entre ambas placas en una región donde existen pocos datos al respecto.

Palabras clave: Placa Rivera, movimiento relativo Rivera-Norteamérica, Escarpe de las Tres Marías, temblor del 4 de diciembre de 1948.

Abstract

The largest historical earthquake along the northern segment of the Rivera–North American plate boundary occurred on 4 December 1948. This event caused casualties and important damage in the penal colony on the Tres Marías Islands. Seismograms were collected from regional and teleseismic stations in order to determine the focal mechanism solution. The resulting mechanism shows high-angle reverse faulting with P axes oriented NE-SW. The mechanism obtained agrees with the solutions of two smaller-magnitude earthquakes located also on the Tres Marías Escarpment. The estimated magnitude for the 1948 event is M_w6.4, based on the amplitude of the surface waves recorded at the De Bilt (Netherlands) seismic station. The slip direction of the resulting mechanism is interpreted as reflecting the relative motion between the Rivera and the North American plates. Thus the Rivera plate appears to be underthrusting beneath the Tres Marías Escarpment in a NE-SW direction. The source mechanism obtained here helps to constrain the relative motion between these two plates where data is sparse.

Key words: Rivera plate, Rivera-North American plate motion, Tres Marías Escarpment, 4 December 1948 earthquake.

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Introduction

The Tres Marías Islands earthquake of 4 December 1948 (M_w6.4) is the largest instrumentally recorded earthquake that has occurred along the Tres Marías Escarpment (Figure 1), on the northwestern end of the Rivera-North America subduction zone. This event appears to reflect the relative motion between the Rivera and the North American plates (RIV-NAM). The direction and rate of relative motion of the RIV-NAM plate boundary in this region has been a source of controversy due to the low rate of seismic activity, added to the poor local seismic coverage (DeMets and Stein, 1990; Pardo and Suárez, 1993).

Current estimates of the rate and direction of relative motion along this boundary have been obtained by combining the angular velocity vectors of relative motion between the Rivera–Pacific and Pacific-North American plates. The errors and uncertainties associated with the angular velocity vectors of each of these plate pairs add up to large uncertainties in the resulting poles of relative motion (e.g. DeMets and Stein, 1990; DeMets *et al*., 1994; Bandy and Pardo, 1994; Lonsdale, 1995; Bandy *et al*., 1997; DeMets and Wilson, 1997). Assuming that the seismic slip of this event reflects the motion on the RIV-NAM plate boundary, investigating the slip direction would provide an important constraint on the direction of motion between these two tectonic plates.

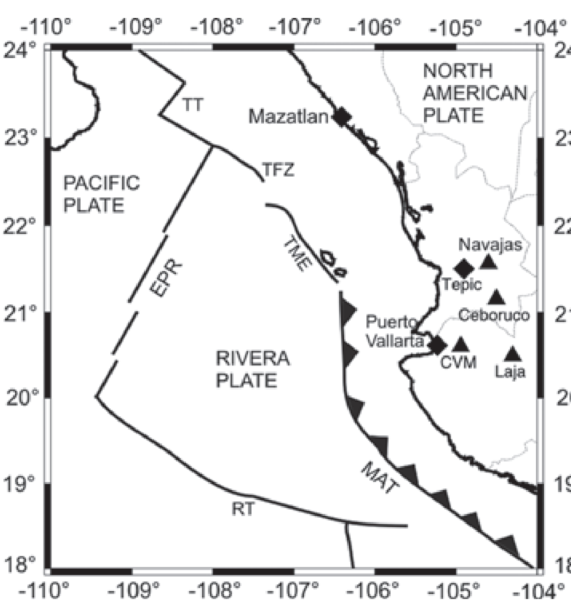

Figure 1. Tectonic boundaries of the Rivera Plate. The abbreviations are: Tres Marías Escarpment (TME), Tamayo Fracture Zone (TFZ), Middle American Trench (MAT), East Pacific Rise (EPR), Tamayo Transform (TT) and Rivera Transform (RT). The triangles represent volcanoes and the diamonds are cities.

The southeastern segment of this plate boundary was the site of three of the largest subduction earthquakes observed in Mexico during the last 100 years: the 3 June 1932 (M_s8.2) and 18 June 1932 (M_s7.8) earthquakes (Singh *et al*., 1985), and the 9 October 1995 event (M_w8.0) (Courboulex *et al*., 1997; Melboune *et al*., 1997; Pacheco *et al*., 1997; Escobedo *et al*., 1998). The rupture zones based on the aftershock distributions are shown on Figure 2. To the northwest of the rupture zone of the 1932 events, however, there are no other known large subduction events, either from the historical or the instrumental records and the seismicity decreases in both magnitude and frequency from what is observed to the southeast (Figure 2).

Nevertheless, low-level seismicity has been observed along the Tres Marías Escarpment and on the eastern segment of the Tamayo Fracture Zone (Figures 1 and 2). DeMets and Stein (1990) suggested that the seismicity in this region reflects the RIV-NAM relative motion. The solution proposed here agrees with the focal mechanism solutions of two events near the Tres Marías Escarpment: the solution of Goff *et al*. (1987) for the earthquake of 9 February, 1976 and the Global CMT solution for the earthquake of 11 February, 2007 (Figure 3).

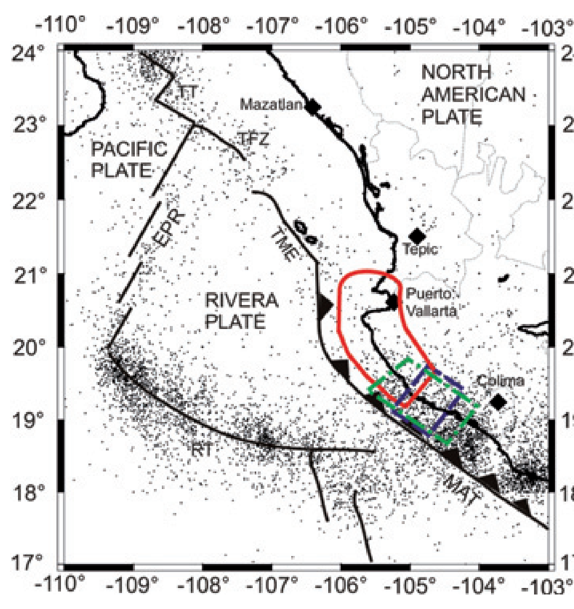

Figure 2. Map showing the seismicity of the area of study. Notice that to the northwest of the 1932 rupture, the number and magnitude of the earthquakes on the RIV-NAM boundary decrease sharply. Red and blue contours indicate rupture zones for event June 3 and 18, 1932 respectively. The green contour indicates aftershock area for event October 9, 1995. Other abbreviations as in Figure 1.

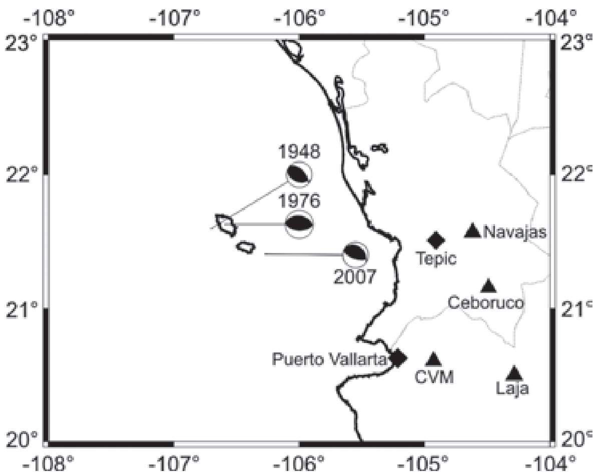

Figure 3. Focal mechanisms of the 1948 event at 21.6ºN, 106.7ºW and of the 1976 and 2007 earthquakes. The epicentral location of the 1948 event is the one reported by the ISS. The triangles indicate volcanoes and diamonds represent cities.

Figure 4. Focal mechanism solution for the 1948 earthquake. Open circles indicate dilatational first motions and closed indicate compressional first motions. The abbreviations are as follows: Guad, Guadalajara; Pue, Puebla; and Tac, Tacubaya.

Data and methodology

Polarity data from thirteen regional and teleseismic records were obtained (Table 1). From Table 1 it can be seen that only three stations are located at distance of more than 30º. Unfortunately, the body waves on these teleseismic records were not of sufficient quality to attempt modeling or inverting the data for a focal mechanism solution and hypocentral depth. For this reason, only first motion data were available to estimate the focal mechanism solution.

The teleseismic record of the De Bilt station showed a clear train of surface waves. This seismogram was used to estimate M_s (Gutenberg, 1945). The surface wave magnitude obtained was converted to *Mw* using the scaling relations proposed by Geller (1976) and relations of seismic moment with the surface wave magnitude proposed by Hanks and Kanamori (1979). The resulting magnitude of the 1948 event yields M_w6.4. In comparison, the magnitudes M_w of the 1976 and 2007 events were 5.4 and 5.0, respectively.

Analysis of the data

The resulting focal mechanism from first motion data is show on figure 4, using the epicentral location reported by the International Seismological Summary (ISS): 21.6ºN 106.7ºW. The focal mechanism shows high-angle, reverse faulting with P axes oriented NE-SW. The focal parameters are listed on Table 2.

The resulting focal mechanism is poorly constrained for two reasons: Firstly, there is a dearth of stations in the range of 180º to 270º of azimuth. Secondly, there are only a small number of seismic records from stations located at epicentral distances greater than 30º (Table 1). Take-off angles for regional records are more sensitive to the local velocity structure and the location of first motion data on the stereographic hemisphere are more uncertain.

Table 1. Stations Used in this Study

Station	Distance °	Azimuth °	Polarity* °
Mazatlán	1.6	10	D
Guadalajara	3.3	106	N
Manzanillo	3.4	139	C
Tacubaya	7.4	106	C
Puebla	8.4	106	N
Veracruz	10.2	102	D
Tucson	11.2	342	C
Mérida	15.9	89	D
Pasadena	16.1	323	C
Mount Hamilton	21.7	316.5	C
Huancayo	45.5	134	C
La Paz	53.5	131	C
De Bilt	85.7	35	C

*C indicates a compressional first motion
*D indicates a dilational first motion
*N indicates a nodal arrival

Table 2. Nodal Plane Parameters.

Focal transmition solution			
Plane 1	316°	54°	126°
Plane2	108°	40°	46°

First motions observed in Guadalajara and Puebla show nodal arrivals. Tucson, on the other hand, shows an impulsive compressional first motion. We use these observations, together with the change in polarity observed between the dilational arrivals in Mazatlan and Merida, and the compressional first motion observed in Tucson, to constrain the nodal plane dipping to the NW. Unfortunately, the other plane is not constrained by the data available. The auxiliary plane dipping to the SE and shown on Figure 4, was selected to be similar to the Global CMT solution of the 2007 event. Thus the solutions proposed by Goff *et al*. (1987) and the Global CMT are similar to the solution proposed in this work, all indicating reverse faulting with axes of maximum compression oriented NW-SE.

Summary and conclusions

The focal mechanism obtained for the 4 December 1948 earthquake shows that the Rivera plate is underthrusting the North American plate in a SW to NE direction beneath the Tres Marias Escarpment. The motion along the plate boundary appears to take place at a high angle and not in the typical low-angle faulting expected in subduction zones. This suggests that subduction of the Rivera plate ends southwest of the Tres Marias Escarpment and that this high-angle, reverse faults are elevating the escarpment topographically. The mechanism obtained for the 1948 event is similar to that obtained for two smaller magnitude events reported elsewhere. The relative motion between RIV and NAM, beneath the Tres Marias Escarpment, probably takes place at a slow rate based on the paucity of seismicity and the relatively low magnitude of the instrumental earthquakes recorded.

The 1948 event is the largest instrumental earthquake recorded to date in this region and no information on previous historical events in the area exists. Assuming that the slip vectors of the earthquakes in this region reflect the relative motion between RIV-NAM, the Rivera plate converges with the continental margin a a SW to NE direction. The mechanisms determined here, together with those of other events, are used to constrain the direction of relative motion between these two plates using the slip direction of the earthquakes that have occurred along this plate boundary (Jaramillo, 2010; Suárez *et al.*, 2010).

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