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Large earthquake rupture process variations on the Middle America megathrust

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ABSTRACT

The megathrust fault between the underthrusting Cocos plate and overriding Caribbean plate recently experienced three large ruptures: the August 27, 2012 (M_w 7.3) El Salvador; September 5, 2012 (M_w 7.6) Costa Rica; and November 7, 2012 (M_w 7.4) Guatemala earthquakes. All three events involve shallow-dipping thrust faulting on the plate boundary, but they had variable rupture processes. The El Salvador earthquake ruptured from about 4 to 20 km depth, with a relatively large centroid time of ~19 s, low seismic moment-scaled energy release, and a depleted teleseismic short-period source spectrum similar to that of the September 2, 1992 (M_w 7.6) Nicaragua tsunami earthquake that ruptured the adjacent shallow portion of the plate boundary. The Costa Rica and Guatemala earthquakes had large slip in the depth range 15 to 30 km, and more typical teleseismic source spectra. Regional seismic recordings have higher short-period energy levels for the Costa Rica event relative to the El Salvador event, consistent with the teleseismic observations. A broadband regional waveform template correlation analysis is applied to categorize the focal mechanisms for larger aftershocks of the three events. Modeling of regional wave spectral ratios for clustered events with similar mechanisms indicates that interplate thrust events have corner frequencies, normalized by a reference model, that increase down-dip from anomalously low values near the Middle America trench. Relatively high corner frequencies are found for thrust events near Costa Rica; thus, variations along strike of the trench may also be important. Geodetic observations indicate trench-parallel motion of a forearc sliver extending from Costa Rica to Guatemala, and low seismic coupling on the megathrust has been inferred from a lack of boundary-perpendicular strain accumulation. The slip distributions and seismic radiation from the large regional thrust events indicate relatively strong seismic coupling near Nicoya, Costa Rica, patchy zones of strong seismic coupling in the shallowest megathrust region along Nicaragua and El Salvador, and small deeper patchy zones of strong seismic coupling near Guatemala, which can be reconciled with the geodetic observations as long as the strong coupling is limited to a small fraction of the megathrust area.

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1. Introduction

The Middle America subduction zone (Fig. 1) is distinctive in having pronounced forearc translation parallel to the trench despite the lack of strong obliquity of the plate convergence direction along much of the plate boundary. The extensive GPS data collected over the past two decades (Alvarado et al., 2011; Alvarez-Gomez et al., 2008; Correa-Mora et al., 2009; DeMets, 2001; Franco et al., 2012; Guzman-Speziale and Gomez-Gonzales, 2006; LaFemina et al., 2009; Lyon-Caen et al., 2006; Rodriguez et al., 2009; Turner III et al., 2007) indicate forearc trench-parallel motions along Nicaragua and El Salvador relative to a fixed Caribbean plate have a velocity of 14–15 ± 2 mm/yr toward the diffuse triple junction between the Cocos (CO), Caribbean (CA) and North America (NA) plates. The geodetic observations also indicate very little trench-perpendicular ground velocity that would be expected if the offshore megathrust boundary is locked and significant upper plate convergent strain accumulating.

These geodetic observations have led to the notion of a relatively rigid forearc sliver, or Middle America microplate, extending all the way from Costa Rica to Guatemala. During at least the last several decades of GPS measurements there appears to be very weak interplate coupling between the CO plate and the CA plate forearc sliver along El Salvador and Nicaragua with, at most, limited regions of strong megathrust coupling located offshore of Guatemala and southern Nicaragua. To account for the block-like motion of the forearc sliver in the presence of weak interplate coupling and lack of oblique convergence offshore of El Salvador and southeastern Guatemala, the driving force for the sliver has been attributed to the Cocos Ridge collision with the

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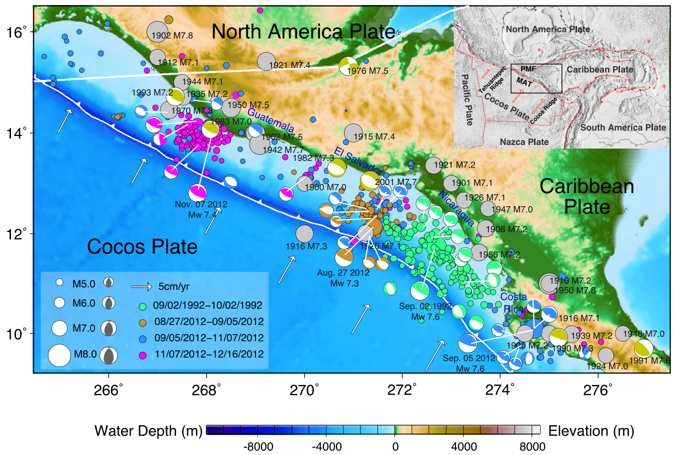

Fig. 1. Large earthquakes around the Middle American subduction zone from Costa Rica to Guatemala. Gray circles indicate epicenters of $M \geqslant 7.0$ events from 1900 to 1975 from PAGER-CAT (Allen et al., 2009). Focal mechanisms are global Centroid Moment Tensor (gCMT) solutions for $M \geqslant 7.0$ events from 1976 to 2012 (olive) plotted at the USGS/NEIC epicenters. Color-coded circles are epicenters for aftershock sequences of the September 2, 1992 Nicaragua (M_W 7.6) tsunami earthquake (green), the August 27, 2012 El Salvador (M_W 7.3) earthquake (brown), the September 5, 2012 Costa Rica (M_W 7.6) earthquake (blue), and the November 7, 2012 Guatemala (M_W 7.4) earthquake (magenta). Correspondingly colored gCMT mechanisms for these four sequences are shown. White curves indicate the Middle America Trench (MAT) boundary (barbed) between the Cocos Plate and Caribbean Plate, and the approximate North America and Caribbean plate boundary. Arrows indicate plate motion direction and rate relative to a fixed Caribbean plate computed using model NUVEL-1 (Argus and Gordon, 1991). The Cocos Plate subducts northeastward beneath the Caribbean Plate at 75 to 85 mm/yr with ∼20–25% obliquity along Nicaragua, and at 65 to 75 mm/yr offshore of El Salvador and Guatemala with negligible obliquity. The inset map shows the regional plate tectonic setting. The red vectors indicate the plate motions relative to a fixed Caribbean Plate for model NUVEL-1. The relative motion between North America and Caribbean plates is left-lateral with rate of ∼20 mm/yr across the Polochic–Motagua Fault zone (PMF).

CA plate along southern Costa Rica and/or pinning of the westernmost triangular region of the CA plate between the converging CO and NA plates near the triple junction (Franco et al., 2012; LaFemina et al., 2009). In contrast to the Mexican subduction zone to the northwest, where generally strong seismic coupling between the converging NA and CO plates is found, the upper CA plate is moving away from the MAT such that lower tectonic and seismic coupling may be expected. However, the inference of little megathrust coupling is complicated by the GPS sites being located far from the MAT, as well as by uncertainty in the locations and rupture characteristics of historical seismic events in the region.

Large subduction zone earthquakes do occur along the MAT (Fig. 1), including sources that produce destructive tsunami, like the 1902 Guatemala and 1992 Nicaragua tsunami earthquakes (Fernandez et al., 2000; Kanamori and Kikuchi, 1993), and there are an unusual number of outer-rise and down-dip normal faulting events along the arc (Supplemental Fig. S1). Casual inspection of the seismicity in Figs. 1 and S1 does not immediately suggest very weak seismic coupling, especially allowing for possible landward mislocation of some of the historical large events in the regions. As a result, there is substantial uncertainty regarding the potential for much larger underthrusting events in the region than have been documented in the seismological record.

Earthquake focal mechanism and seismic strain rate analyses (DeMets, 2001; Guzman-Speziale and Gomez-Gonzales, 2006; Harlow and White, 1985; McNally and Minster, 1981; White and Harlow, 1993; Pacheco et al., 1993) indicate that only ∼10% to 20% of the CO–CA plate motion is seismically manifested in trench-perpendicular underthrusting events, so the cumulative seismic activity in Figs. 1 and S1 actually does fall far short of the plate motion convergence rate even allowing for uncertainty in older event locations and mechanisms. Despite this, numerous strike-slip events occur along the Middle America volcanic arc, as is typically observed for strain partitioning that accompanies oblique subduction in strongly-coupled regions (DeMets, 2001; Fitch, 1972; McCaffrey, 1992). It has been estimated that the strike-slip earthquake strain budget may match the geodetic rates, suggesting 80–100% seismic coupling of that boundary of the sliver (Correa-Mora et al., 2009).

In 2012, the megathrust between the CO and CA plate sliver experienced three large ruptures: the August 27, 2012 M_W 7.3 El Salvador, September 5, 2012 M_W 7.6 Costa Rica, and November 7, 2012 M_W 7.4 Guatemala earthquakes (Table S1). Together with the September 2, 1992 M_W 7.7 Nicaragua event (Table S1), these large thrust earthquakes shed light on the nature of the Middle America megathrust rupture processes in the context of the geodetic inferences of very weak plate boundary seismic coupling extending from Guatemala to northern Costa Rica. We analyze the rupture characteristics of the four large events and aftershock sequences for the three 2012 events (Fig. 1) to explore the nature of megathrust failure properties along the MAT.

2. Rupture process characteristics of large earthquakes

We first quantify the overall faulting parameters for the four large thrust events along the MAT. These are the largest events on the megathrust for which we have high quality observations, and they define the minimum degree of seismic coupling of the plate boundary.

2.1. W-phase inversion

Three-component W-phase signals in the 1.67–5.0 mHz passband were inverted for point-source moment tensors for the 1992 and 2012 events. Fig. S2 shows that the preferred solutions for: (a) the 1992 Nicaragua event with seismic moment of 4.1×10^{20} Nm (M_W 7.7), centroid time shift of 47.8 s, depth 15.5 km, and a best double-couple solution with strike 289.0°, dip 14.7°, and rake 65.3°; (b) the 2012 El Salvador event with seismic moment of 9.6×10^{19} Nm (M_W 7.3), centroid time shift of 23.0 s, depth 15.5 km, and a best double-couple solution with strike 284.4°, dip 17.2°, and rake 78.9°; (c) the 2012 Costa Rica event with seismic moment 3.3×10^{20} Nm (M_W 7.6), centroid time shift of 19.5 s, depth 30.5 km, and a best double-couple solution with strike 303.4°, dip 15.7°, and rake 94.2°; and (d) the 2012 Guatemala event with seismic moment of 1.2×10^{20} Nm (M_W 7.3), centroid time shift of 10.6 s, depth 23.5 km, and a best double-couple solution with strike 293.1°, dip 28.5°, and rake 77.8°. Examples of waveform fits for each case are shown in Supplemental Fig. S3. The estimates of depth and centroid time shift are similar to the centroid depths of 15 km, 12.0 km, 29.7 km, and 21.3 km, and centroid time shifts of 44.5 s, 20.1 s, 15.4 s and 9.6 s from the global Centroid Moment Tensor (gCMT) project (http://www.globalcmt.org/CMTsearch.html) for the 1992 Nicaragua and 2012 El Salvador, Costa Rica, and Guatemala events, respectively. Although their magnitudes are similar, the W-phase centroid time shift of the El Salvador event is ∼3 times larger than for the Guatemala event, and about half that for the 1992 Nicaragua tsunami earthquake, whose overall source time function duration is ∼100 s (Kanamori and Kikuchi, 1993). This indicates a relatively slow rupture process of the 2012 El Salvador earthquake.

2.2. Finite-fault rupture inversions

Finite-fault rupture models were developed using teleseismic P waves for all four large events. Fig. 2 summarizes the slip distribution models found from the P wave ground motions in the frequency band 0.005–0.9 Hz using the linear inversion procedure

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