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Seismicity rate increases associated with slow slip episodes prior to the 2012 M_w 7.4 Ometepec earthquake

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ABSTRACT

The March 20, 2012 M_w 7.4 Ometepec earthquake in the Oaxaca region of Southern Mexico provides a unique opportunity to examine whether subtle changes in seismicity, tectonic tremor, or slow slip can be observed prior to a large earthquake that may illuminate changes in stress or background slip rate. Continuous Global Positioning System (cGPS) data reveal a 5-month-long slow slip event (SSE) between ∼20 and 35 km depth that migrated toward and reached the vicinity of the mainshock a few weeks prior to the earthquake. Seismicity in Oaxaca is examined using single station tectonic tremor detection and multi-station waveform template matching of earthquake families. An increase in seismic activity, detected with template matching using aftershock waveforms, is only observed in the weeks prior to the mainshock in the region between the SSE and mainshock. In contrast, a SSE ∼15 months earlier occurred at ∼25–40 km depth and was primarily associated with an increase in tectonic tremor. Together, these observations indicate that in the Oaxaca region of Mexico shallower slow slip promotes elevated seismicity rates, and deeper slow slip promotes tectonic tremor. Results from this study add to a growing number of published accounts that indicate slow slip may be a common pre-earthquake signature.

1. Introduction

The megathrust fault in subduction zones, which is host to the world's largest earthquakes, exhibits several types of seismic and slip behavior. Earthquakes, or stick-slip behavior, typically occur at shallow depth (<∼25 km), while aseismic continuous creep, or stable sliding, typically occurs deeper along the plate interface (>∼25 km). Recent studies have revealed episodic tremor and slip (ETS) can form a transition zone between stick-slip and stable sliding along the plate interface at depths of ∼25 km to as much as 80 km depth (Rogers and Dragert, 2003; Schwartz and Rokosky, 2007). Geodetic evidence of transient deformation reveals slow slip events (SSEs) are often accompanied by a tremor signal, commonly referred to as tectonic tremor. Matched-filter template scanning reveals tectonic tremor is an outcome of intense swarms of low-frequency earthquakes (e.g., Shelly et al., 2007) more easily triggered than traditional seismicity (Rubinstein et al., 2007; Thomas et al., 2009). Other studies show swarms of traditional earthquakes occur during SSEs (Crescentini et al., 1999; Delahaye et al., 2009; Linde et al., 1996; Lohman and McGuire, 2007; Montgomery-Brown et al., 2009; Ozawa et al., 2007; Vidale et al., 2011; Vallée et al., 2013). Both observations are consistent with models that suggest SSEs along a megathrust transfer stress to adjacent stick-slip sections of the plate interface, which increases the probability of seismicity, whether it be increased seismicity rates or a large-to-great earthquake (Dragert et al., 2004; Mazzotti and Adams, 2004; Colella et al., 2011; Segall and Bradley, 2012). Modeling efforts also complement laboratory experiments (Scholz et al., 1972) and numerical simulations (Tse and Rice, 1986; Kato and Hirasawa, 1999) that suggest large earthquakes can be preceded by small amounts of stable slip. A central focus since

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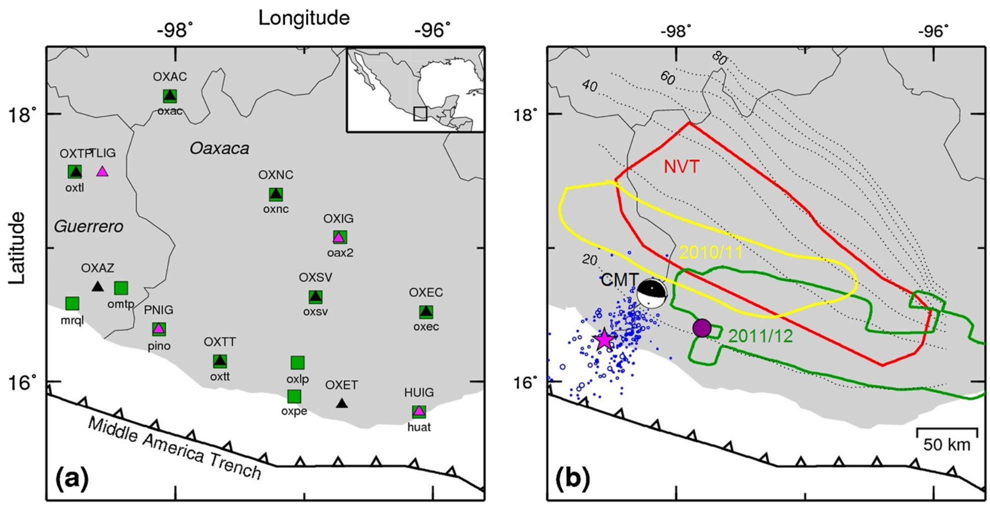

Fig. 1. A map of the study area: Oaxaca region, southern Mexico. State borders are plotted as solid lines. (a) The location of cGPS (green squares, lowercase names) and seismic stations (black triangles represent temporary stations and pink triangles represent permanent stations, upper case names). (b) The various forms of seismic and slip behavior, and the slab depth contours (dotted lines) (Fasola et al., 2016). The 2010–2011 SSE (yellow curve, Graham et al., 2015) was correlated with tectonic tremor (red curve, Fasola et al., 2016; see also Fig. S3). The 2011–2012 SSE (green curve; Graham et al., 2014), which was active immediately prior to the M_w 7.4 Ometepec earthquake. The USGS epicenter and CMT focal mechanism are plotted at the original USGS epicenter. The epicenter determined by the local network is updip of the USGS location (pink star); repeating earthquakes (blue circles, Fasola et al., 2016) detected with the template matching method on Ometepec aftershocks; and a seismic swarm first detected in 2006 near the downdip edge of the seismogenic zone (purple circle, Skoumal et al., 2016). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the discovery of SSEs has been to detect and identify connections between SSEs and large megathrust earthquakes.

The March 20, 2012 M_w 7.4 Ometepec earthquake off the coast of southern Mexico occurred at a depth of ∼15 km along the subduction megathrust with a pure thrust focal mechanism and aftershocks distributed along the subduction interface (Figs. 1 and S1, Supplementary Material) (UNAM Seismology Group, 2013). The Ometepec earthquake provides a unique opportunity to investigate the patterns of slow slip, tremor, and changes in seismicity rates prior to a large earthquake. This study describes the history of SSEs in the Oaxaca region of Mexico, which includes a SSE immediately preceding the Ometepec earthquake and examines the evidence for tremor or changes in seismicity rates prior to the earthquake. The study also investigates spatial and temporal patterns of seismicity in advance of the Ometepec earthquake. Finally, the observations are considered in the context of other studies that show potential relationships between slow slip, tremor, increased seismicity rates, and large earthquakes.

2. Previous geodetic and seismic observations

A network of continuous Global Positioning Stations (cGPS) and seismic stations have been operating in the Oaxaca region since 1993. 14 cGPS were installed between 1993 and 2011, and 7 three-component broadband seismometers were installed in 2006 (Fig. 1a). 2 additional stations were deployed in 2008 to the west of Oaxaca in eastern Guerrero, and 5 additional stations were permanently added in and around the Oaxaca state to from the Servicio Sismológico Nacional (SSN) array achieve a station spacing of ∼70 km (Fig. 1a).

cGPS solutions indicate a northward long-term, interseismic strain accumulation and a southward strain release during SSEs (Brudzinski et al., 2007; Correa-Mora et al., 2009). Since 1993, SSEs in the Oaxaca region were documented to occur every 1–2 years with durations of ∼2–4 months (Brudzinski et al., 2007). Geodetic inversions for the SSEs in 2004, 2005/6, 2007, 2008/9, and 2011/12 indicate that SSEs occurred in the transition zone downdip of the seismogenic zone defined by historic earthquakes (Fig. 1b) (Correa-Mora et al., 2009; Graham et al., 2014, 2015). Conversely, the 2010/11 SSE occurred further inland and downdip of the typical SSEs observed in Oaxaca (Fig. 1b; Graham et al., 2015).

The first study to exploit seismic data from this network identified tectonic tremor episodes throughout 2006–2007 that lasted a few days, occurred as often as every 2–3 months (Brudzinski et al., 2010). Tremor locations defined a trench-parallel band immediately downdip of SSE locations previously determined by cGPS inversions (Fig. 1b and Fig. S3). The observed tectonic tremor did not correlate temporally with observed SSEs. This observation resembles those from Nankai in Japan where only weak amounts of tectonic tremor are observed during large, long SSEs at ∼20–30 km depth detected with cGPS and an abundance of tectonic tremor is observed during small, short SSEs at ∼30–40 km depth detected with tiltmeters (Obara et al., 2004; Hirose and Obara, 2005). Since such high precision geodetic instruments are not available in Oaxaca, the typical short duration tectonic tremor may be coincident with the small, short, deep slow slip that occurs below the current resolution of the cGPS (Brudzinski et al., 2010).

More recently, Fasola et al. (2016) analyzed seismic data from the local network from 2006 to 2012, which includes the Ometepec earthquake and its aftershock sequence, to construct a catalog of earthquakes for the region and update tremor locations to determine the geometry of the plate interface. The distribution of well-located earthquakes delineated the geometry of the subducting plate and revealed a sharp bend in a shallow to steeply dipping slab from western to eastern Oaxaca (Fig. 1b, dotted lines). The updated catalog of tremor distributions (Fasola et al., 2016) together with cGPS measurements (Graham et al., 2015) showed SSEs propagate across the sharp bend in the subducting plate, which indicated the plate is not torn in this location.

3. Observations prior to the Ometepec earthquake

The March 20, 2012 M_w 7.4 Ometepec earthquake occurred off the coast of the Oaxaca region of Mexico along the subduction megathrust. The USGS location of the event was at the downdip edge of the seismogenic zone (Fig. 1b), close to the western limit of the preceding SSE (described below). However, the first motions from the local seismic network indicate the earthquake initiated ∼30 km updip (Fig. S1, Supplementary Material), significantly shal-