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Testing Earthquake Links in Mexico From 1978 to the 2017 M = 8.1 Chiapas and M = 7.1 Puebla Shocks

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Key Points:
- The 19 September M = 7.1 Puebla shock was not triggered by the M = 8.1 Chiapas off-shore event
- The extensive postseismic deformation of the 2012 M = 7.5 Oaxaca earthquake promoted the occurrence of the recent M = 7.1 Puebla earthquake
- Recurring pattern of stress interactions between thrust and normal-type earthquakes is identified

Supporting Information:
- Supporting Information S1

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Abstract The M = 8.1 Chiapas and the M = 7.1 Puebla earthquakes occurred in the bending part of the subducting Cocos plate 11 days and ~600 km apart, a range that puts them well outside the typical aftershock zone. We find this to be a relatively common occurrence in Mexico, with 14% of $M > 7.0$ earthquakes since 1900 striking more than 300 km apart and within a 2 week interval, not different from a randomized catalog. We calculate the triggering potential caused by crustal stress redistribution from large subduction earthquakes over the last 40 years. There is no evidence that static stress transfer or dynamic triggering from the 8 September Chiapas earthquake promoted the 19 September earthquake. Both recent earthquakes were promoted by past thrust events instead, including delayed afterslip from the 2012 M = 7.5 Oaxaca earthquake. A repeated pattern of shallow thrust events promoting deep intraslab earthquakes is observed over the past 40 years.

1. Introduction

Western Mexico is a collision zone, where the Rivera and Cocos plates are subducting under North America at rates from 69 mm/yr to 75 mm/yr near the recent M = 8.1 Chiapas earthquake (DeMets et al., 2010). During the last 40 years, dozens of significant events have occurred along the plate boundary, with the most destructive being the 19 September 1985 M = 8.0 Michoacan earthquake that caused ~10,000 fatalities and left ~700,000 people homeless (Figure 1). On 19 September 2017, a M = 7.1 earthquake struck near Mexico City only 2 h after the earthquake drills in commemoration of the 1985 Michoacan earthquake took place. This event was preceded by the offshore 8 September M = 8.1 Chiapas earthquake. Although the distance between these earthquakes exceeds 600 km, their timing raised questions about a potential link.

Triggered earthquakes caused by the passage of seismic waves (dynamic triggering) and/or coseismic fault displacements that lead to elastic stress redistribution (static triggering) can persist from days to years following a large mainshock (Omori, 1894; Parsons, 2002; Parsons et al., 2014; Stein, 1999; Utsu, 1961). Recent cases of earthquake-mediated fault interactions at high magnitudes are well documented around the world including in New Zealand, China, and Turkey (Stramondo et al., 2011; Parsons & Segou, 2014 among others). Here we study the empirical frequency of large magnitude earthquake occurrence in Mexico and investigate dynamic and static mechanisms of earthquake triggering to assess possible links between the September 2017 events.

2. Seismicity and Coseismic Stress Changes

We estimate the cumulative frequency (empirical probability) of earthquake occurrence at regional distances in Mexico to determine the significance of observing two large earthquakes within a 2 week interval since 1900 (Figure 1). Globally, the static stress change reach of $M \geq 7$ earthquakes in triggering others is less than 300 km (Parsons, 2002). Here we consider $M \geq 6$ and $M \geq 7$ earthquakes that happened more than 300 km apart in Mexico since 1900 to assess the frequency of large earthquake pairings outside local aftershock zones. We determine that 14% of the total number for both magnitude thresholds occur within 2 weeks, which is indistinguishable from the same analysis using a catalog with randomized interevent times (drawn from a uniform interevent time distribution with actual locations retained) (Figure 1b). This demonstrates that the September 2017 pairing of M = 8.1 and M = 7.1 earthquakes could be random chance but does not rule out a physical link.

We thus investigate whether the 19 September M = 7.1 Puebla earthquake was triggered by the 8 September M = 8.1 Chiapas earthquake. Physical models of local earthquake interaction can be described by Coulomb

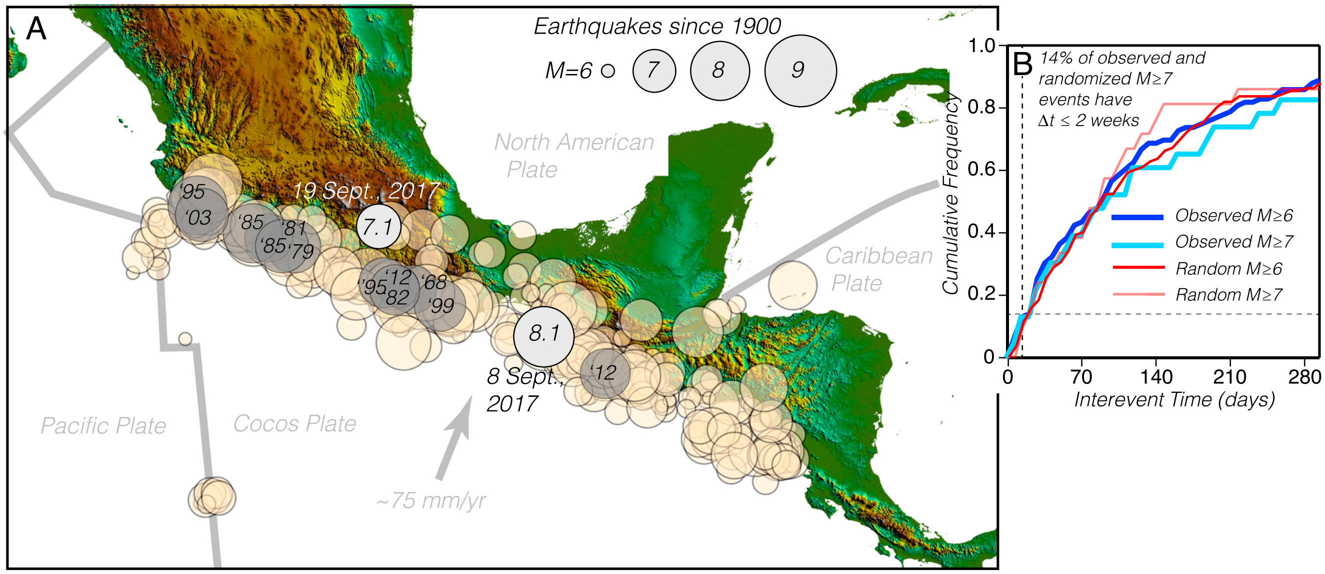

Figure 1. Post 1900 $M \geq 6$ seismicity in central Mexico. (a) Locations of $M \geq 6$ earthquakes, and the dates of the most significant events during the past 50 years are noted. Plate boundaries are shown as gray lines, and the convergence of the Cocos plate relative to North America is shown. (b) To gauge the frequency that pairs of large earthquakes in Mexico occur close in time, but not in space, we express the post-1900 earthquake catalog as a function of interevent times and show that 14% of all $M \geq 7.0$ events that happened more than 300 km apart occurred within 2 weeks of each other. We find no significant difference using randomized interevent times (Poisson process), which implies that the timing between the 8 and 19 September earthquakes could be random chance.

failure stress (ΔCF), where stress calculated changes depend on an accurate representation of the seismic source and the knowledge of the target fault geometry. We estimate (ΔCF) using the equation,

$$\Delta \text{CF} = \Delta|\overline{\tau_f}| + \mu'(\Delta\sigma_n), \mu' = \mu(1 - B_k) \tag{1}$$

where $\Delta|\overline{\tau_f}|$ is the change in shear stress (fault parallel) on the receiver fault, μ' is the apparent coefficient of friction, here taken as 0.4 (Mikumo et al., 2002), $\Delta\sigma_n$ is the change in normal stress, and B_k is Skempton's coefficient, which accounts for pore fluid pressure. Stress values are estimated by slipping an elastic dislocation representation for each mainshock slip model using Okada's (1992) equations.

We calculate the expected stress redistribution from the M = 8.1 Chiapas earthquake at a regional scale to assess the static stress transfer hypothesis (Figure 2). The September 2017 earthquake sources are represented by the finite fault models (National Earthquake Information Center (NEIC), 2017a, 2017b), available from the National Earthquake Information Center event page (8 September Chiapas event: strike 315° and dip 73°; 19 September Puebla event: strike 111° and dip 42°). Static stress changes decay as a function of distance cubed, as demonstrated by a miniscule (0.0001 MPa) calculated stress change at the hypocenter of the 19 September Puebla earthquake (Figure 2). We interpret this as a rejection of static triggering as the physical mechanism linking those events, because the lower threshold for triggering is thought to be 0.01 MPa (e.g., Hardebeck et al., 1998).

We examine regional earthquake rates before and after the 8 September 2017 M = 8.1 Chiapas earthquake outside ($r > 300$ km) the local aftershock zone to assess the potential for delayed dynamic triggering (Figure 2, insets) using the seismicity catalog available from the Web page of the Servizio Sismologico National of the Universidad Nacional Autónoma de Mexico (source: http://www.ssn.unam.mx) A strong indication that dynamic triggering occurred after the Chiapas earthquake would include a statistically significant earthquake rate increase that correlates with the onset of seismic waves from that event. However, we find no evidence of a rate increase in the regional catalog outside the local aftershock zone but instead a rate decrease (Figure 2).

Unlike static stress changes, dynamic triggering can happen at any distance away from a mainshock (e.g., Velasco et al., 2008). We thus analyze the regional seismicity catalog from 1979 to 2017 to determine the potential for dynamic triggering in central Mexico from remote ($r > 1000$ km) and local (300–1,000 km)

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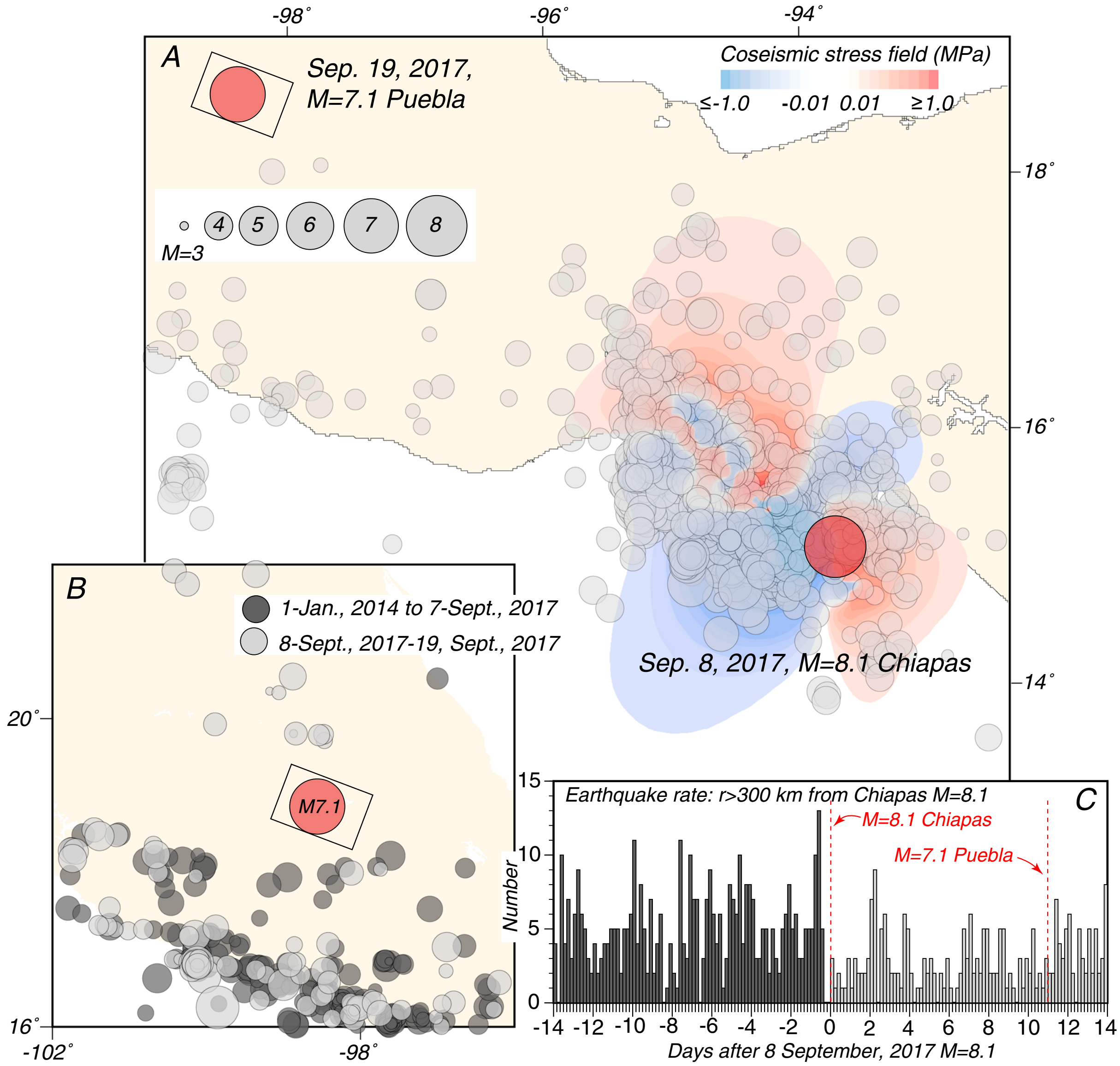

Figure 2. Static and dynamic triggering potential from the 8 September 2017 $M = 8.1$ Chiapas earthquake. (a) The pattern of stress change caused by the 8 September $M = 8.1$ Chiapas earthquake is mapped, showing that it does not reach the location of the 19 September $M = 7.1$ Puebla rupture plane (strike 111°, dip 42°, rake −98°, and target depth 50 km). Earthquakes following the 8 September event are plotted, with most clustering around that mainshock. (b) There is little indication of increased seismicity in the vicinity of the 19 September shock, and (c) there was actually a general reduction in the local earthquake rate at distances greater than 300 km away from the 8 September shock, lending little support for a dynamic triggering response.

sources in different time windows following the method of Parsons et al. (2014). We find no evidence of possible dynamic triggering of local earthquakes at range greater than 300 km in Mexico at high significance (Figure 2 and see supporting information).

Large earthquakes ($M > 7$) in Mexico fall broadly into two categories: thrust events on the plate interface at shallow depth along the coast and normal faulting events within the deeper, bending portion of the subducted plate (Figure S2). Modeling studies show that normal fault events occur as a mechanical consequence after slip on the shallow thrust (Cocco et al., 1997; Gardi et al., 2000; Mikumo et al., 1999); thus, both the 8 September $M = 8.1$ Chiapas, and the 19 September $M = 7.1$ Puebla earthquakes were likely influenced by prior shallow thrust slip. Here a compilation of stress changes from past thrust earthquakes illustrates possible interactions with normal faults along the central Mexico margin (Figure 3). Our estimates confirm the conclusions of Mikumo et al. (2002) supporting a link between the $M = 7.8$ 1978-$M = 7.5$ 1999 Oaxaca and the $M = 8.1$ 1985-$M = 7.1$ 1997 Michoahan earthquakes. We also calculate stress increases at the hypocenters of other

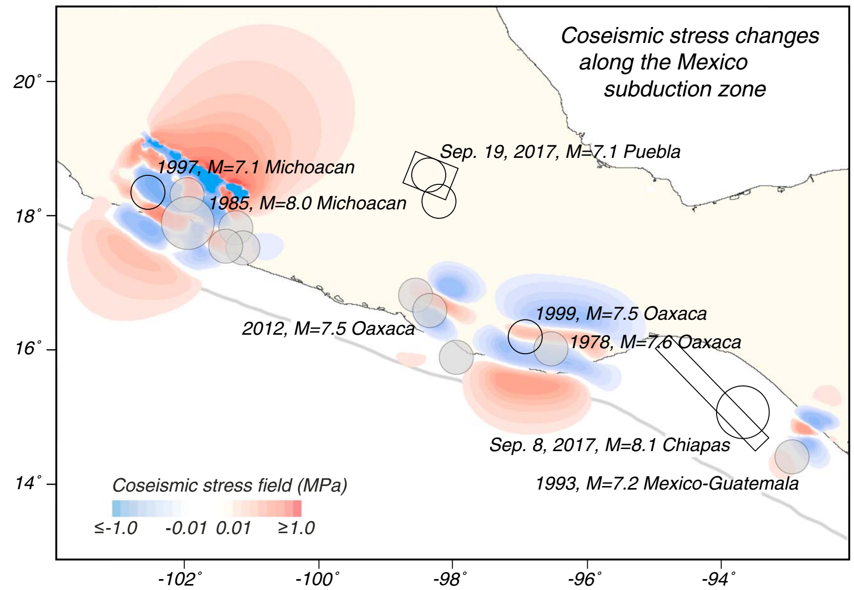

Figure 3. Static stress triggering interactions along the Mexican margin. The pattern of coseismic stress changes caused by past large thrust events (solid circles) is mapped, illustrating interaction with normal-type events (open circles). There is no evidence to link static stress changes from the 2012 $M = 7.5$ Oaxaca coseismic effects, or any other known $M \geq 7$ event with the occurrence of the 18 September $M = 7.1$ Puebla earthquake. The 1993 $M = 7.2$ Mexico-Guatemala increased stress on the 8 September $M = 8.1$ Chiapas rupture plane that is adjacent to the 1993 rupture. Additional examples are plotted including the 1978–1999 Oaxaca and 1985–1997 Michoacan earthquakes (Mikumo et al., 2002). The receiver geometry for the stress interactions between event pairs was refined (1978–1999 Oaxaca: strike 300°, dip 49°, rake −78°, and target depth 50 km; 1985 Michoahan-1997: strike 292°, dip 82°, rake −106°, and target depth 40 km; 1993 Mexico-2017 Chiapas: strike 315°, dip 73°, rake −96°, and target depth 50 km; 2012 Oaxaca-2017 Puebla: strike 111°, dip 42°, rake −98°, and target depth 50 km). Gray line shows the approximate location of the plate boundary.

normal faulting earthquakes events, such as the 1997 $M = 7.1$ Michoacan (ranging from −0.4 MPa to 0.057 MPa, for target depths $z = 40 \pm 10$ km) and 1999 $M = 7.5$ Oaxaca earthquake (0.035 MPa stress increase) (Figure 3). While coseismic static stress changes have explained the largest normal fault earthquakes over the past 40 years, none of these interactions during the past decades can explain the 19 September 2017 $M = 7.1$ Puebla earthquake. The coseismic effects of the $M = 7.5$ 2012 Oaxaca earthquake do not exert any influence at distances greater than 150 km (Figure 3). However, our results suggest that the Chiapas event may have been influenced by a 1993 $M = 7.2$ shock (Figure 3) with stress increase calculated from −0.003 to 0.002 MPa (variable slip, $z = 50 \pm 10$ km) to 0.06 MPa (uniform slip) at the eastern part of the recent rupture.

For source representations, we use previously published slip distributions for the 1993 $M = 7.2$ Mexico-Guatemala, the 1985 $M = 8.0$ Michoacan, and 2012 $M = 7.5$ Oaxaca earthquakes (Mendoza, 1993; NEIC, 2012; Ye et al., 2016). For the 1978 $M = 7.6$ Oaxaca earthquake, we use uniform slip distributions with rupture dimensions taken from the empirical relationships of Wells and Coppersmith (1994) with kinematic and geometrical characteristics taken from the Global Centroid Moment Tensor (Ekström et al., 2012) catalog (1978 Oaxaca: strike 274°, dip 7°, and rake 57°). For evaluating the links between pairs, the receiver geometry follows the kinematic characteristics and seismic parameters of the target event, as noted in each figure.

3. Postseismic Deformation

Postseismic deformation following large thrust events is documented to last for decades (Mikumo et al., 2002) and has been documented after large thrust events in Mexico (Melbourne et al., 2002) together with other aseismic phenomena such as nonvolcanic tremor (Brudzinski et al., 2014) and slow-slip events (Graham et al., 2014a). The 20 March 2012 $M = 7.5$ Oaxaca earthquake was the first in Mexico to be observed by multiple continuous GPS stations, which enabled estimation of its postseismic slip distribution (Graham et al., 2014b). During the first 6 months after the 2012 March $M = 7.5$ Oaxaca earthquake, postseismic afterslip generated a cumulative geodetic moment ~40% larger than the initial mainshock and covered a fault area 10

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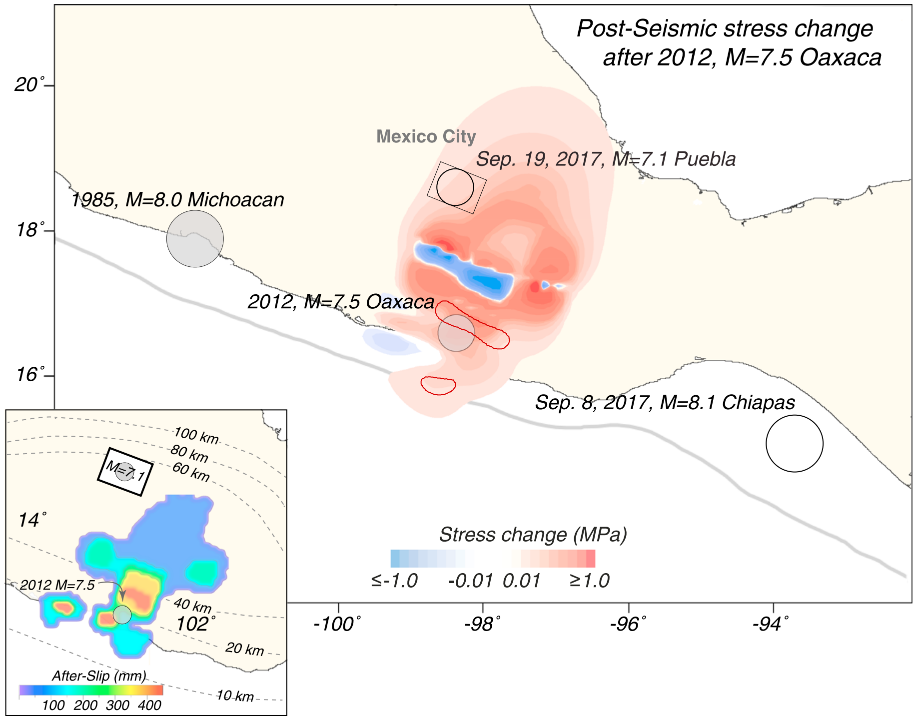

Figure 4. Postseismic stress changes following the M = 7.5 Oaxaca 2012 earthquake. Stress is increased on the 18 September M = 7.1 Puebla rupture by 0.01–0.1 MPa. The detected delayed afterslip (inset) roots at the Puebla rupture, acting here as receiver (strike 111°, dip 42°, rake −98°, and target depth 50 km), promoting the occurrence of normal fault events farther inland. The inset maps the postseismic slip distribution following the 2012 Oaxaca earthquake and shows isodepth contours of the subducting Cocos plate from Graham et al. (2014b). Gray line shows the approximate location of the plate boundary.

times larger than the coseismic rupture zone, extending up to 220 km inland (Graham et al., 2014b). The M = 7.1 Puebla rupture area was rooted at the western extension of the afterslip surface. We calculate the stress changes due to the postseismic afterslip of the 2012 Oaxaca earthquake and find a stress increase between 0.01 and 0.1 MPa on the 19 September 2017 M = 7.1 Puebla rupture plane (Figure 4). Thus, the most important link with 2017 Puebla earthquake comes from the 2012 M = 7.5 Oaxaca earthquake, and not the 2017 M = 8.1 Chiapas shock.

4. Conclusions

We find that the September 2017 deep intraslab earthquakes in Mexico were triggered by preceding shallower subduction interface events. While these two earthquakes occurred just 11 days apart, we must go back to 2012, and as far as 1993 to find the most likely triggering events. These patterns have repeated over the past 40 years with pairings being separated by years to decades. We demonstrate the importance of stress changes from postseismic deformation extending along the flat ramp of the Mexico subduction zone following the most recent large thrust event, the 2012 M = 7.5 Oaxaca earthquake in its role of triggering the 19 September M = 7.1 Puebla earthquake. It is very likely that postseismic afterslip has magnified stresses on the deeper part of the subducting Cocos plate in the past and will do so in the future. Geodetic monitoring after future thrust earthquakes in the Mexican subduction zone will help to locate the most likely locations for accompanying intraslab normal fault shocks beneath central Mexico.

Large earthquake triggering involving megathrust and intraslab events has been discussed widely for coupled subduction zones (Dmowska et al., 1986). Lay et al. (2017) provide coseismic and delayed paradigms of such interactions for the 2006–2009 Central Kyril, 2009 Samoa/Tonga, 2011–2012 Japan trench, and the 2016 Solomon islands earthquakes. According to Scholtz (2012), earthquake interaction and heterogeneity of coupling control the temporal clustering of great earthquakes, featuring as an example the Oaxaca segment of the Mexico subduction zone. Recent results suggest that the Chiapas earthquake occurred in a region "between the trench and the fault intersection with the megathrust that appears to be frictionally coupled" (Ye et al., 2017). In our case, we document an interaction between the highly coupled shallow plate interface, where similar earthquakes are repeated almost periodically (Scholtz, 2012), with the conditionally stable region below Central Mexico, where widespread afterslip is observed (Graham et al., 2014b).

Looking forward from the September 2017 events, the shallower parts of the subduction interface farther seaward are positively loaded (0.01–0.06 MPa) following the M = 8.0 Chiapas earthquake, while the M = 7.1 Puebla rupture has locally loaded the subhorizontal subduction ramp by 0.01–0.5 MPa (Figure S3).

Acknowledgments
The Authors have equally contributed the analysis and preparation of the manuscript. The earthquake catalog used in this analysis is available through the UNAM seismic network and the Global Centroid Moment Tensor webpage.

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