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Key Points:

- 2014 South Napa earthquake triggered tremor at Parkfield
- A major tremor sequence occurred 10 h later and lasted more than 3 weeks
- The major tremor sequence was delay triggered and likely driven by a slow-slip event

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5

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Delayed dynamic triggering of deep tremor along the Parkfield-Cholame section of the San Andreas Fault following the 2014 *M*6.0 South Napa earthquake

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Abstract Large, distant earthquakes are known to trigger deep tectonic tremor along the San Andreas Fault and in subduction zones. However, there are relatively few observations of triggering from regional distance earthquakes. Here we show that a small tremor episode about 12–18 km NW of Parkfield was triggered during and immediately following the passage of surface waves from the 2014 M_w 6.0 South Napa main shock. More notably, a major tremor episode followed, beginning about 12 h later, and centered SE of Parkfield near Cholame. This major episode is one of the largest seen over the past several years, containing intense activity for ~3 days and taking more than 3 weeks to return to background levels. This episode showed systematic along-strike migration at ~5 km/d, suggesting that it was driven by a slow-slip event. Our results suggest that moderate-size earthquakes are capable of triggering major tremor and deep slow slip at regional distances.

1. Introduction

Tectonic tremor is a subtle and semicontinuous vibration radiating from deep within major plate boundary faults around the world [*Peng and Gomberg*, 2010; *Beroza and Ide*, 2011, and reference therein]. Tremor is extremely sensitive to external stress perturbations and can be instantaneously triggered by a few kilopascals (kPa) of oscillating stresses from surface waves of large distant earthquakes [*Hill and Prejean*, 2015] or solid Earth tides [e.g., *Thomas et al.,* 2012].

One of the most well-studied tremor regions is the Parkfield-Cholame section of the San Andreas Fault (SAF). Several recent studies examined interactions of SAF tremor and earthquakes in the immediate vicinity and long-range distances. For example, *Nadeau and Guilhem* [2009] and *Shelly and Johnson* [2011] reported a clear increase of tremor activity in this region following the 2004 M_w6.0 Parkfield earthquake. In addition, *Shelly and Johnson* [2011] found that the 2003 M_w6.5 San Simeon earthquake (about 60 km to the west of Parkfield) appeared to cast a 'stress shadow' in the creeping section of the SAF northwest of Parkfield and temporarily slowed down tremor activities there for 3–6 weeks.

Guilhem et al. [2010] systematically examined instantaneously triggered tremor (i.e., modulated by the surface waves) along the Parkfield-Cholame section for main shocks between the distance range of 100 and 1200 km and identified four cases with dynamic stresses larger than 10 kPa and distances beyond 600 km. *Shelly et al.* [2011] found that the 2007 M_w5.4 Alum Rock and 2008 M_w5.4 Chino Hills earthquakes triggered tremor along the Parkfield-Cholame section of the SAF. Their epicentral distances to Parkfield are 208 and 326 km, respectively, and in both cases, the first detected tremor occurred a few minutes after the passage of surface waves. *Aiken et al.* [2015] found that the 2012 M_w7.7 Haida Gwaii and 2013 M_w7.5 Craig earthquakes triggered tremor around the Eastern Denali Fault at the distance range of 600–900 km. However, the prevalence of tremor triggering by moderate-size events at intermediate distances (~100–500 km) and the relationships among distant main shocks triggered tremor, and background tremor activities remain unclear.

In this study, we conduct a detailed investigation of tremor activity around the Parkfield-Cholame section of the SAF following the 2014 M_w6.0 South Napa earthquake that is about 310 km away (Figure 1 and Figure S1

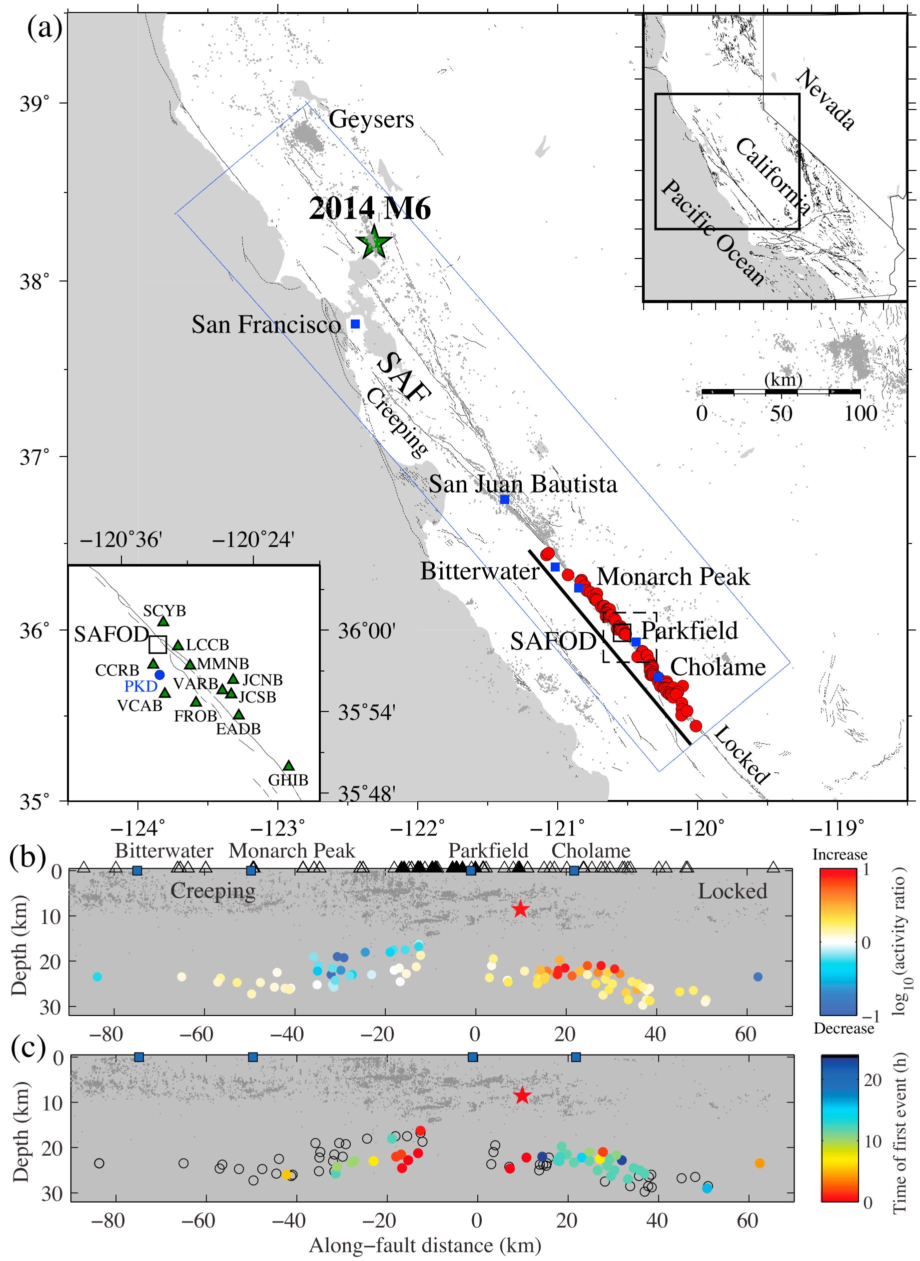

Figure 1. (a) Map view of the study region in central California. Red circles mark the 88 tremor template locations. The gray dots are regular earthquakes occurred in 2014. The gray lines mark active faults in the study region. Green star marks the 2014 *M*6 South Napa earthquake. The seismicity in the blue rectangles is plotted in Figure S1. The solid line marks the cross section shown in Figure 1b. The inset on the top right marks the study region in a larger map of California. The inset on the bottom left shows a zoom-in plot of stations around Parkfield. (b) Along-strike view of the San Andreas Fault showing 88 tremor families (circles), color coded by the $\log_{10}$ of activity rate 30 days after the South Napa main shock divided by average rate during the previous 4 years. Gray dots are regular earthquakes. Red star marks 2004 *M*6 Parkfield earthquake hypocenter. Locations of places named on the map in Figure 1a are marked by blue squares on cross section. (c) Same plot as Figure 1b, except that the tremor locations are color coded by the time of the first tremor event after the South Napa event.

in the supporting information). This is the largest earthquake to strike the San Francisco Bay Area since the 1989 M_w6.9 Loma Prieta earthquake [*Brocher et al.,* 2015]. It produced a dynamic stress of ~32 kPa (peak ground velocity ~0.32 cm/s) at Parkfield, well above the inferred triggering threshold of a few kilopascals from previous studies in this region [*Peng et al.,* 2009; *Guilhem et al.,* 2010].

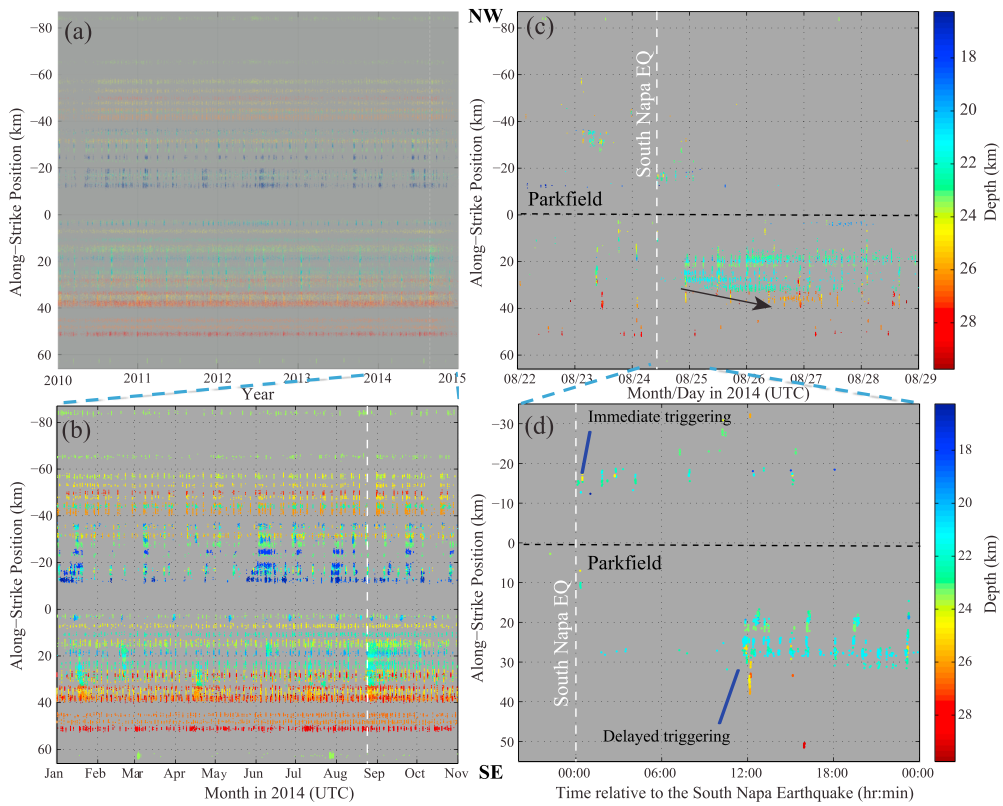

Figure 2. (a) Along-strike positions versus occurrence time of all tremor (LFEs) detected between years 2010 and 2014. The LFEs are color coded by their hypocentral depths. The vertical dashed line marks the occurrence of the 2014 M_w6.0 South Napa earthquake. (b) A zoomed view showing the tremor activity from January to November in 2014. (c) A further zoomed view showing the tremor activity within 1 week of the 2014 South Napa earthquake. The black arrow marks an apparent migration speed of 5 km/d. Because detected events are assigned to the most similar template location, an artificial but realistic scatter in the along-strike positions (normal distribution and standard deviation of 0.5) is introduced for plotting clarity. (d) A further zoomed view showing the tremor activity within 1 day of the South Napa earthquake. The two blue bars mark the immediate activating of tremor activity NW of Parkfield and an apparent delayed triggering of major tremor activity near Cholame.

2. Analysis Procedure

The analysis procedure generally follows those of previous studies [*Guilhem et al.*, 2010; *Shelly et al.*, 2011] and is briefly described here. We use tremor catalog [*Shelly and Hardebeck*, 2010] obtained from scanning 14 year (starting in mid-2001) of continuous data with waveforms of 88 low-frequency earthquakes (LFEs) as templates. The template and continuous waveforms are filtered in 2–8 Hz. The location of the best matching template is assigned to each detected event, which range in the depth of ~16–30 km (lower crust and uppermost mantle) and span ~150 km along the SAF strike (Figure 1b). A total of more than 900,000 individual events were detected as of early 2015. We then identify potential changes of tremor rates in the LFE-detected catalog around the occurrence time of the 2014 South Napa event. To establish the background activity level, we examine along-strike distributions of all detected tremor events starting from 2010 (Figure 2). For comparison, we also examine spatiotemporal evolutions of microearthquakes listed in the Northern California Seismic Network (NCSN) catalog (magnitude range −0.6 to 6.0) during the same time period (Figure S1).

In addition to examining tremor and earthquake catalogs, we also visually identify changes in high-frequency radiations around the South Napa main shock by analyzing continuous waveform data recorded at the High Resolution Seismic Network (HRSN, 250 samples/s), the broadband station BK.PKD (100 samples/s), and the San Andreas Fault Observatory at Depth (SAFOD) main hole SF.MH026 (1000 samples/s). Following recent studies [*Guilhem et al.*, 2010; *Aiken et al.*, 2015], we apply a band-pass filter of 10–40 Hz to all seismic data to suppress potential coda waves from the distant main shock source region, take the envelope, smooth the results, and compare with velocity seismograms at broadband station BK.PKD (Figure 3). We also

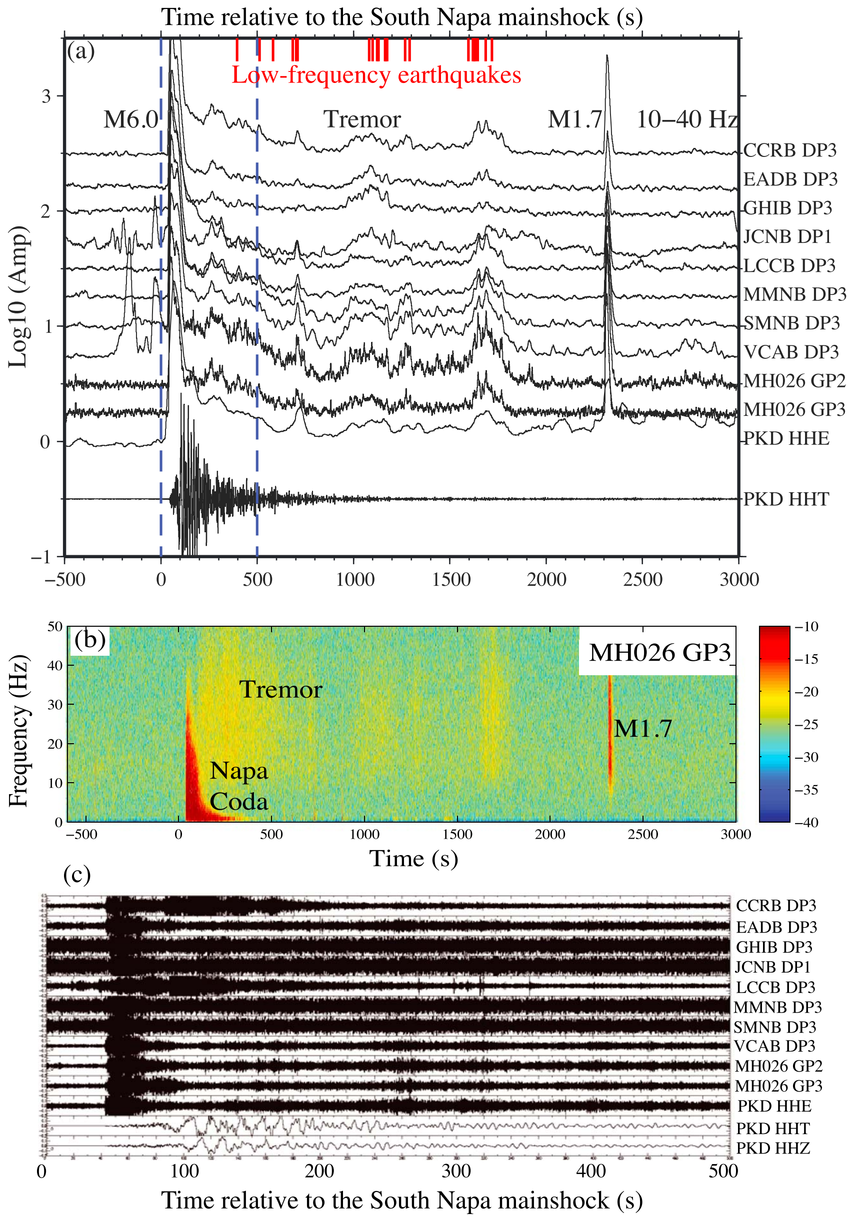

Figure 3. (a) The 10–40 Hz filtered envelopes showing tremor around Parkfield. Short red bars on the top mark the detected tremor events listed in the low-frequency earthquake (LFE) catalog [*Shelly and Hardebeck*, 2010]. The bottom trace is the unfiltered transverse component seismogram at station BK.PKD. (b) The spectrogram at station SF.MH025 showing the *P* and coda waves of the South Napa main shock, tremor activity immediately following the main shock, and a magnitude *M* 1.7 earthquake. (c) A zoom-in of 10–40 Hz filtered traces showing weak tremor signals during surface waves of the South Napa main shock. The bottom two traces are unfiltered transverse and vertical component seismograms at station BK.PKD.

compute the spectrogram at the SF.MH026 and selected HRSN stations to identify potential changes in high-frequency radiations immediately before and after the main shock (Figures S2 and S3).

3. Results

As shown in Figure 2d, we find a major tremor episode near Cholame began about 12 h following the South Napa main shock. This is the largest tremor episode as listed in the tremor catalog over the past several years (Figures 2, S4, and S5), containing intense activity for ~3 days and lasting more than 3 weeks before returning to the background levels. This zone shows up clearly in Figure 1b, which compares the rate of detected events in each family during the 30 days following the South Napa main shock versus the average rate for the family during the previous 4 years. The major episode started at ~30 km southeast of Parkfield and expanded mostly southeastward to a full extent of about ~20 km in total length within the next ~2 days, with an apparent migration speed of ~5 km/d (Figure 2d). We also identify a minor activity beneath Cholame starting less than 2 h after the South Napa event (Figures 1c and 2d) in a family with significant episodes only every few months. Minor tremor activity also occurred at ~15 km northwest of Parkfield during the passage of the surface waves (Figures 1–3).

Our waveform examination also reveals clear high-frequency signals during and after the surface waves on the seismometer at 2.4 km depth in the SAFOD main hole SF.MH026 (Figures 3b and S2). While signals above 40 Hz could be contaminated by instrumental and electronic noise, signals between 10 and 40 Hz were coherent with nearby stations northwest of Parkfield and started about 80 s at the beginning of the surface waves (Figure 3a). This is consistent with the immediate activation of a minor tremor activity northwest of Parkfield as observed from the tremor catalog alone (Figure 2d). However, we do not observe clear modulation of high-frequency signals with surface waves, as was found in other recent studies [*Peng et al.,* 2009; *Guilhem et al.,* 2010]. It is worth noting that the LFEs were detected in the frequency range of 2–8 Hz, while the envelopes were prefiltered in the range of 10–40 Hz. The fact that tremor events mostly occurred at times (between 100 and 1800 s) when the envelope amplitudes are high (Figure 3a) suggests that they reflect the same source processes.

We also examined microearthquake activities in Northern California following the South Napa main shock (Figure S1). While clear increases were found in its aftershock zone and Geysers [*Meng et al.,* 2014], we did not observe any clear changes along the Parkfield-Cholame section or along the creeping section of the SAF to the northwest (Figure S1).

4. Discussions

The major tremor sequence southeast near Cholame started about 12 h after the main shock, suggesting that the sequence might have been delay triggered [e.g., *Shelly et al.,* 2011]. Because of the delay, one may argue that the coincidence of the South Napa event and the major tremor sequence could be due to random chance (i.e., not triggered). We suggest that this is unlikely for the following reasons. First, large episodes are relatively rare and have, in the past, occurred once every few months (Figures 2a and S4). In particular, the tremor rate right after the South Napa main shock is the highest since 2010 (Figure S5). The close timing (~12 h) and relative infrequent occurrence of these large episodes makes a strong case of triggering. In addition, some weak tremor in an episodic (usually quiescent) family was detected near Cholame starting ~2 h after the main shock and seemed to build up to the major sequence over the next several hours (Figure 2b), again suggesting a possible causal relationship.

Nadeau [2015] reported a similar observation of triggered major tremor episodes at the Parkfield-Cholame section following the South Napa main shock. He also found an apparent ~12 h delay before major tremor activities occurred at Cholame. In addition, *Nadeau* [2015] reported a moderate increase of tremor activity in the creeping section ~1 month following the main shock and inferred a slow migration speed of 2.2 km/d north. Our results do not corroborate such a conclusion, given that the LFE detections along the creeping section at this time are consistent with background activity (Figure 2b). This discrepancy could reflect different sensitivities in the tremor versus LFE-detected catalogs [*Nadeau and Guilhem*, 2009; *Shelly and Hardebeck*, 2010] in this region. In particular, *Nadeau* [2015] used an envelope technique [*Nadeau and Guilhem*, 2009] to identify and locate tremor, while in this study we used the 88 LFE template families to detect LFEs within the tremor episodes [*Shelly and Hardebeck*, 2010]. Although the LFE template approach only detects tremor occurring near template locations, it can detect single, low-amplitude LFEs, as opposed to requiring a high-amplitude, extended duration (>3 min) episode for envelope detection [*Nadeau and Guilhem*, 2009]. The LFE detection technique is also less affected by concurrent earthquake activity, giving an additional advantage shortly after the distant South Napa earthquake during the most active part of the aftershock sequence.

Our observations are generally consistent with a few recent studies that have documented possible triggered major tremor sequences around active plate boundary regions. For example, *Rubinstein et al.* [2009] suggested that the 2007 M_w8.1 Kuril Island earthquake likely preceded the start of the 2007 Episodic Tremor and Slip (ETS) event in Cascadia. *Zigone et al.* [2012] also found that the second phase of the 2009–2010 ETS event in Guerrero, Mexico, was delay triggered by the 2010 M_w8.8 Maule, Chile, earthquake. In the Mexico case, clear tremor is modulated and triggered by the surface wave of the Maule main shock, followed by sustained tremor activities that peaked at 3 days after the distant main shock. In the meantime, clear GPS signals also revealed activation of the second phase of a major slow-slip event (SSE). Finally, *Shelly et al.* [2011] also found that the 2002 M_w7.9 Denali Fault and 2008 M_w7.9 Wenchuan earthquakes triggered tremor episodes along the Parkfield-Cholame section of the SAF that extended several days.

Compared to the strongly modulated tremor in Mexico following the Maule earthquake, and many clear cases of triggered tremor at Parkfield following the Denali Fault, Wenchuan, and other large distant earthquakes [*Peng et al.,* 2009], we did not observe clear modulated tremor during the surface wave of the South Napa event (Figure 3b). This is likely because the South Napa event is much smaller and closer to the triggered region and hence produces surface waves with shorter periods than those for the Maule main shock. While shorter-period surface waves can still perturb the fault system, they may be too fast to turn tremor activity on and off, especially if tremor (or SSE) has certain nucleation time [e.g., *Guilhem et al.,* 2010]. In addition, it may also be difficult to observe high-frequency modulation if multiple source zones are activated due to differing travel times to the stations. Furthermore, due to the close distance, *P* coda waves of the main shock partially overlap with the tremor frequency band. In other words, even if high-frequency modulation occurs, it might not be as clearly observed as it is for more distant main shocks.

Another difference with the Mexico case is that we did not observe any geodetic signals associated with this major tremor sequence at Cholame, even with sensitive borehole and laser strainmeters (D. Agnew, personal communication, 2014). This is consistent with the lack of geodetic signals related to Parkfield tremor episodes in general, likely because of their relatively small size of cumulative moment (no more than moment magnitude M_w of 5 [*Shelly*, 2010]), and lack of sensitivity to detect SSEs (with M_w around 5) at depths below 15 km [*Smith and Gomberg*, 2009]. Nevertheless, a clear expanding tremor front as shown in Figure 2, along with other observations of tremor migration in this region [*Shelly,* 2010, 2015], suggests that tremor in this region could be also driven by localized SSEs as well.

In summary, our results demonstrate that moderate-size earthquakes are capable of triggering tremor (and SSEs) at regional distances. It is still not clear whether similar triggered events may sometimes lead to additional moderate to large earthquakes. Better quantifying such delayed triggering may help us to better understand potential interactions of large earthquakes at regional and long-range distances [*Michael*, 2011; *Johnson et al.,* 2015].

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