Widespread Triggering of Nonvolcanic Tremor in California

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Tremor away from volcanoes (*1*), termed nonvolcanic tremor, reflects a fault slip regime different than that of earthquakes. Relative to radiation from earthquakes, tremor signals have longer durations, have fewer or no abrupt wave onsets, and are depleted in high frequencies. Tremor has almost exclusively been found in subduction zones: Cascadia, southwestern Japan, Mexico, Costa Rica, and Alaska; there is only one study documenting tremor outside a subduction-dominated region, on the strike-slip San Andreas Fault in Parkfield, California (*2*). In Japan and Cascadia, nonvolcanic tremor has been shown to occur concurrently with slippage across the interface between subducting and overlying plates, both lasting for days to months (*3*). The pace and amount of slip are much smaller than those during earthquakes that rupture comparably sized fault areas, and thus these slow events radiate less seismic energy. The physical relation between the slow slip and tremor generation remains speculative. Recent studies in subduction zones have identified short bursts of tremor with the same measurable characteristics as those associated with slow slip, but triggered by the strong shaking of distant earthquakes (*4*). Because nonvolcanic tremor is preferentially observed in subduction zones, nearly all causative mechanisms proposed appeal to conditions expected in them. We show that the conditions required for its generation must exist in a wider variety of tectonic environments by presenting observations of nonvolcanic tremor at seven sites along the transform plate boundary in California triggered by the 2002 7.8 moment magnitude Denali Fault, Alaska, earthquake.

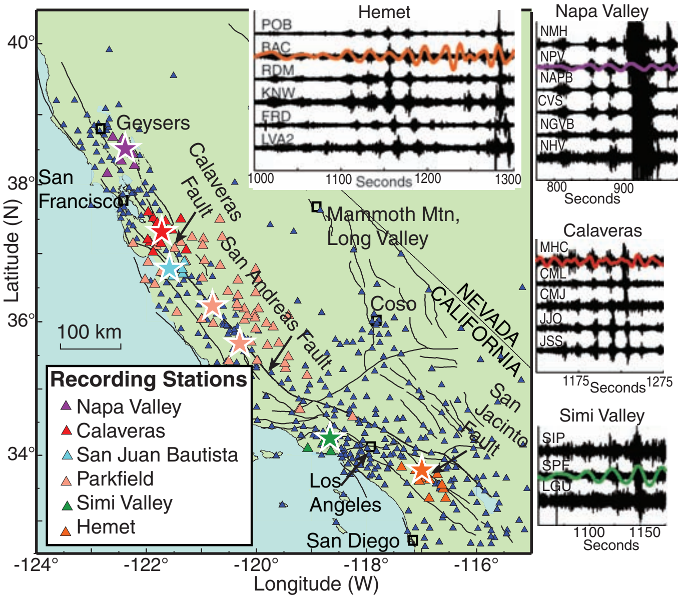

Fig. 1. Map of the locations of tremor sources [stars (*5*)], stations that recorded signals from each tremor source (triangles color coded to the respective sources, see legend), stations that showed no tremor (dark blue triangles), and major faults (black lines). **(Insets)** Examples of the tremor signals associated with four regions where single tremor sources are identified. The Denali surface waves have been filtered out to highlight the tremor (black seismograms), and colored traces show the transverse component of the surface waves from Denali at one unfiltered broadband station in each region, noting that the amplitudes on the radial and vertical components do not differ significantly. Depending on the tremor site, we observed tremor triggering by both Love and Rayleigh waves. The last large bursts in the Hemet and Napa Valley signals are characteristic of nearby earthquakes. Each seismogram has been scaled to make the tremor easily identifiable, times are referenced to the Denali earthquake origin time, and recording stations are labeled.

We examined all available recordings of the Denali earthquake waves from seismic stations in California. We identified triggered nonvolcanic tremor as high frequency (about 3 to 15 Hz), nonimpulsive seismic energy that pulses with the period of the passing surface waves. This energy is not associated with nearby earthquakes or with the Denali earthquake itself. We identified tremor from seven sources that we located by using tremor envelopes as input to a grid-search algorithm (*5*). These locations range from the desert southeast of Los Angeles to Napa Valley in the north (Fig. 1).

Although the observed tremor bursts span a large transect of California, five sources locate close to or on dominant strike-slip faults: the San Andreas, the San Jacinto, and the Calaveras faults. The Simi Valley and Napa Valley sources are likely on more minor faults. Some models of tremor associated with slow aseismic slip in subduction zones invoke frictional behaviors expected in regions transitional between where the fault is locked and earthquakes occur and where it is slipping freely below (*6*). Such transition zones also must exist at shallow depths both below the top few km of fault segments known to creep continuously and laterally between locked segments and those that creep for most or all of their depth. The distribution of these various behaviors is known for most faults in California. However, we find no clear correlation between where the faults are creeping, locked, or transitional and where tremor occurs.

Many studies have speculated that aseismic slip and tremor are related to the release of fluids from dehydration of the subducting plate (*1*). Given this expected correlation between fluids and nonvolcanic tremor, we examined the data from stations close to the Coso and Geysers geothermal fields. We identified signals of many triggered earthquakes, but no tremor was apparent. These findings agree with previous work on triggered earthquakes at these sites and at the hydrothermal regions in Long Valley Caldera and Mammoth Mountain (*7*). The lack of triggered tremor in these geothermal regions implies that high fluid pressure and/or temperatures, although they may be necessary, are not alone sufficient to produce tremor.

In interpreting our results, it is important to note where we found triggered tremor as well as where we did not. The paucity of triggered tremor in hydrothermal regions and its lack of correlation with local, ambient slip behavior suggest that very specific conditions (e.g., temperature, pressure, fluid content, and frictional properties) control where tremor and earthquakes occur. The wide geographic extent of the triggered tremor indicates that it is more common than previously recognized and that the necessary conditions exist in a wide range of tectonic environments.

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Supporting Online Material

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This PDF file includes:

Materials and Methods

Materials and Methods: Tremor Identification and Location

We identify tremors from a single source based on a coherent arrival pattern at a cluster of stations and a fading of the signals with increasing distance. We examined all available broadband and short period seismic recordings archived at the Northern and the Southern California Earthquake Data Centers. For each region we compute an average location for all of the bursts of tremor, by computing the envelope of all the tremor bursts at each station. We then shift the tremor envelopes in time according to a predicted travel time from the trial source locations distributed over a volumetric grid to each station. Finally, we compute the cross-correlations of all station pairs for each trial location. The most probable location is that which maximizes the correlations (stars in Figure 1). Contours of equal correlation values provide qualitative measures of the location uncertainties; in the best cases coordinates can be confidently resolved within about 5 km to tens of km in the worst cases. Depths are generally more poorly constrained; for the Hemet, Simi Valley, southern Parkfield, northern Parkfield, San Juan Bautista, Calaveras, and Napa Valley sources we estimated depths of 12 km, 40 km, 20 km, 50 km, 5 km, 18 km, and 30 km, respectively.

In the Parkfield region two distinct sources can be distinguished for successive tremor bursts (thus two stars); the southern source locates in the vicinity of those identified by Nadeau and Dolenc (2). These sources are also visible at the stations that recorded the San Juan Bautista source. The Simi Valley source location has large uncertainty, which is expected given observations at only 3 stations.

In all cases, the distribution of stations where tremor is both observed and absent qualitatively constrains the tremor source to be near those that record it. An asymmetry of stations surrounding a source and lack of signal at stations amid others where tremor is clear plausibly can be attributed to higher noise levels (e.g. stations north of the Hemet source are in more populated areas and/or atop valley sediments, both noise-amplifying characteristics), noting that many of the tremor signals are just above the noise level. Additionally, particularly in the north, waves arriving from a vigorous earthquake swarm at the Geysers and from multiple tremor sources sometimes make correlations difficult.

Inference of a triggering relationship using the timing of the tremor bursts and the triggering waves requires information not available; *i.e.*, correcting the timing of both to that at the tremor source location, estimation of stress tensor components from the recorded waves, and projection of them to the probable faults or fractures hosting the tremor.