nature geoscience

LETTERS

PUBLISHED ONLINE: 8 MAY 2011 | DOI: 10.1038/NGEO1141

Triggered creep as a possible mechanism for delayed dynamic triggering of tremor and earthquakes

David R. Shelly[1]*, Zhigang Peng[2], David P. Hill[1] and Chastity Aiken[2]

The passage of radiating seismic waves generates transient stresses in the Earth's crust that can trigger slip on faults far away from the original earthquake source. The triggered fault slip is detectable in the form of earthquakes[1-3] and seismic tremor[4-7]. However, the significance of these triggered events remains controversial[8,9], in part because they often occur with some delay, long after the triggering stress has passed. Here we scrutinize the location and timing of tremor on the San Andreas fault between 2001 and 2010 in relation to distant earthquakes. We observe tremor on the San Andreas fault that is initiated by passing seismic waves, yet migrates along the fault at a much slower velocity than the radiating seismic waves. We suggest that the migrating tremor records triggered slow slip of the San Andreas fault as a propagating creep event. We find that the triggered tremor and fault creep can be initiated by distant earthquakes as small as magnitude 5.4 and can persist for several days after the seismic waves have passed. Our observations of prolonged tremor activity provide a clear example of the delayed dynamic triggering of seismic events. Fault creep has been shown to trigger earthquakes[10-12], and we therefore suggest that the dynamic triggering of prolonged fault creep could provide a mechanism for the delayed triggering of earthquakes.

Since its discovery[4], tectonic tremor has been observed on the deep extension of several major faults in a variety of tectonic settings[10,13]. Tremor activity is exceedingly sensitive to small stresses imparted by tides[14] and earthquake seismic waves[5–7]. Growing evidence indicates that tremor is composed of many overlapping events, individually called low-frequency earthquakes[15] (LFEs), each generated by shear slip on the deep fault[16]. These LFEs seem to be similar in many respects to shallower repeating earthquakes and may be generated at small asperities on the deep fault. Large episodes of tremor, spanning tens to hundreds of kilometres and lasting several days to a few weeks, have been observed in some subduction zones, where accompanying deformation consistent with deep fault slip can be observed geodetically[13]. Beneath the central San Andreas fault (SAF), shorter, smaller bursts of tremor activity located on the lower-crustal extension of the fault suggest a similar phenomenon[17], although such events are ageodetic—too small to be detected by present global positioning system or strain instruments[18]. Although slow slip can occur in some locations without generating detectable tremor[11], in places where it is observed, tremor provides a method of inferring slip that is too small to be detectable geodetically[17].

Recent studies have demonstrated tremor triggering during large-amplitude surface waves of regional and teleseismic events in both subduction zones and the strike-slip SAF[7,10,13,19,20]. Although triggered and ambient tremor are observed in similar locations, the exact relationship between them has remained poorly constrained[21].

Further to relatively minor tremor episodes triggered during the passage of seismic waves, it has been suggested that large episodic tremor and slip (ETS) events, which persist for more than a week, are sometimes dynamically triggered in the Cascadia subduction zone[13]. Similar extended tremor episodes may be triggered in southwest Japan[4]. Even more common, perhaps because they are easier to observe, are reports of shallow triggered slip events. One study[22] examined previously published observations of (mostly shallow) triggered aseismic slip following ten California earthquakes. Although it found that most of the triggered slow-slip events were consistent with triggering by static-stress transfer, three events were incompatible with this model, suggesting a role for dynamic triggering.

Regular earthquakes can also be triggered by dynamic stresses[1–3,23]. In addition to instantaneous triggering at some locations, other sites experience a delayed onset and some see elevated activity sustained for days to weeks. Whereas the mechanism of instantaneous dynamic triggering can be understood in terms of known failure mechanisms[24], the mechanism of delayed dynamic triggering is less evident, because dynamic stresses last only as long as the passing waves. It has been proposed[25] that an Omori decay of dynamically triggered events could be explained if seismic waves alter frictional contacts, and thus the mean critical slip distance. Other investigators have proposed that delays may result from pore-fluid redistribution induced by the seismic waves[26], or may simply reflect regular aftershocks of instantaneously triggered events[27].

Here we examine the proposition that dynamically triggered extended-duration tremor reflects small, triggered creep events on the lower-crustal SAF. We further argue that this offers a possible mechanism for delayed dynamic triggering of earthquakes—specifically that earthquakes may be triggered by creep events that are themselves triggered.

We identify 17 regional and teleseismic earthquakes between mid-2001 and early 2010 that trigger tremor in the Parkfield area (Supplementary Table S1). Of these 17, 13 have been reported previously[5,7]. Given the distribution of incident angles for these events, we expect triggering from Love surface waves to dominate (Supplementary Fig. S1), but we make no attempt here to provide a systematic analysis of potential triggering events.

Further to previously reported triggering earthquakes, we see triggered tremor associated with four additional regional and teleseismic events (see Supplementary Information). This includes triggering from the relatively small moment magnitude (M_w) 5.4 2007 Alum Rock and 2008 Chino Hills California earthquakes. In particular, these examples suggest that strong long-period (>15 s)

[1]US Geological Survey, Menlo Park, California 94025, USA, [2]Georgia Institute of Technology, Atlanta, Georgia 30332, USA. *e-mail: dshelly@usgs.gov.

NATURE GEOSCIENCE DOI: 10.1038/NGEO1141

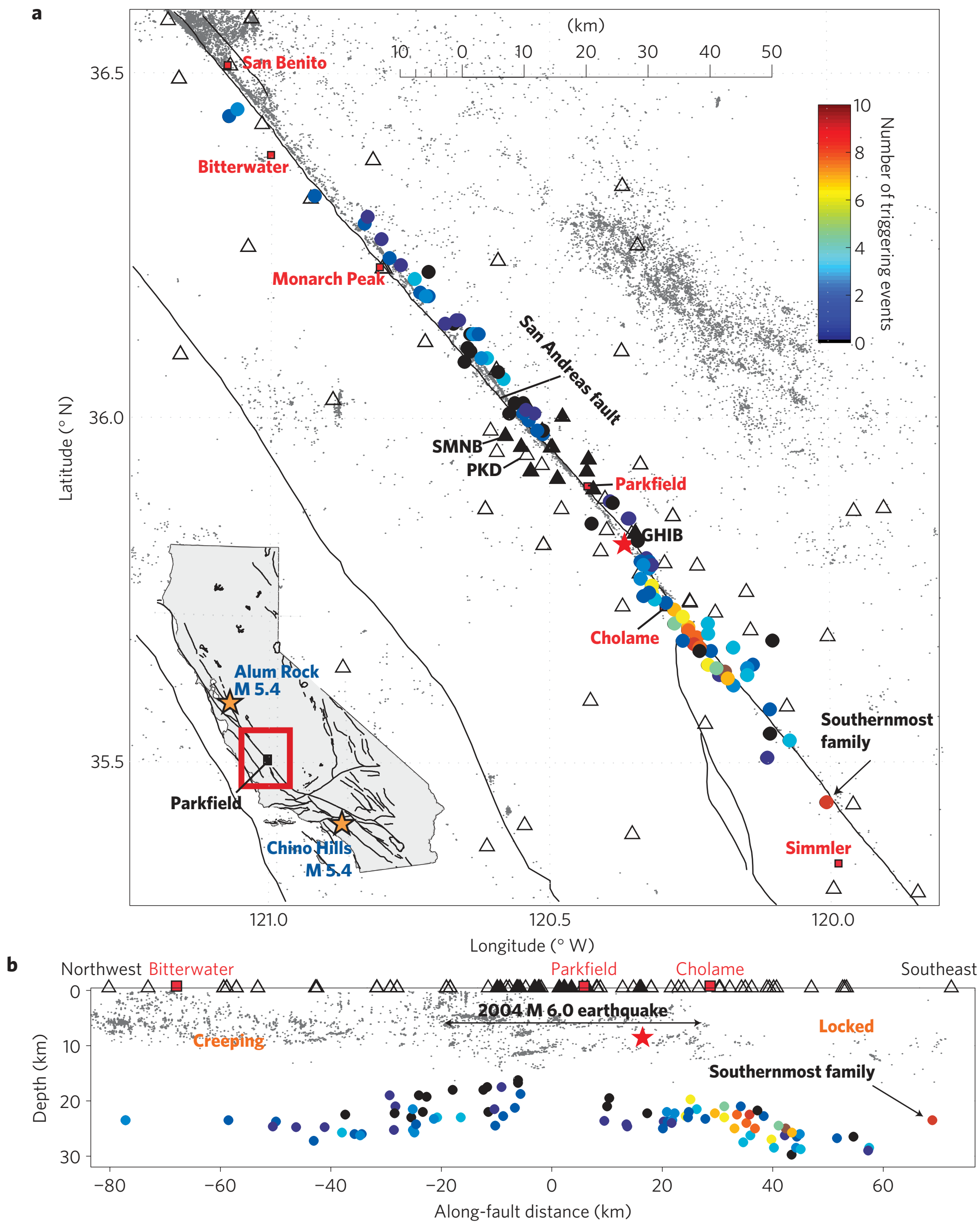

Figure 1 | Tremor-family locations and triggering prevalence. a, Map view. Inset: area of map view (red square) and locations of Alum Rock and Chino Hills earthquakes (orange stars). **b**, An along-fault cross-section. Colours indicate the number of earthquakes that have triggered activity for each of 88 identified tremor families[28]. This determination includes delayed events (see Methods). Triangles indicate seismic stations; filled triangles are borehole stations used for event detection. SMNB, PKD and GHIB are seismic stations referenced in other figures. Micro-earthquakes are shown as small grey dots. The red star and black arrowed line in **b** show the hypocentre and approximate extent, respectively, of the 2004 M_w 6.0 Parkfield earthquake. Figure modified from ref. 28.

energy, sometimes thought essential for dynamic triggering, is not required. Triggering from the 2009 M_w 7.3 Honduras and M_w 8.1 Samoa earthquakes is also reported here.

Our analysis is based on waveform matching through cross-correlation with 88 waveform templates developed for the central SAF (Fig. 1; ref. 28). As it relies on the shape and timing of seismic waveforms across multiple stations, this technique allows us to detect and precisely locate individual LFEs and track migration of tremor, even in the presence of competing signals. Furthermore, it permits us to examine triggering of each event family (the group of events matching a given template) separately, which in some cases allows us to confidently classify even delayed events as triggered.

We find triggered tremor from the same families as those showing activity at other times. Despite probable triggering of multiple sources simultaneously, which would tend to inhibit event detection, the triggered tremor is well matched by our template families (Fig. 2 and Supplementary Figs S3 and S4). In fact, we sometimes observe activity initiated in multiple sites: for example, the 2004 M_w 9.1 Sumatra event initiated activity in at least five different patches of the fault (Supplementary Fig. S4 and Movie S1). The 'triggerability' of different families seems to vary, however (Fig. 1). In particular, for the 17 triggering events identified here, the shallowest (<20 km depth) tremor families are infrequently triggered. Although this may be partially a function of their generally lower amplitudes[28] (Supplementary Fig. S2), which might cause these sources to be masked by stronger concurrent sources, there is no simple relationship between family amplitude and the observed triggering frequency (Supplementary Fig. S2).

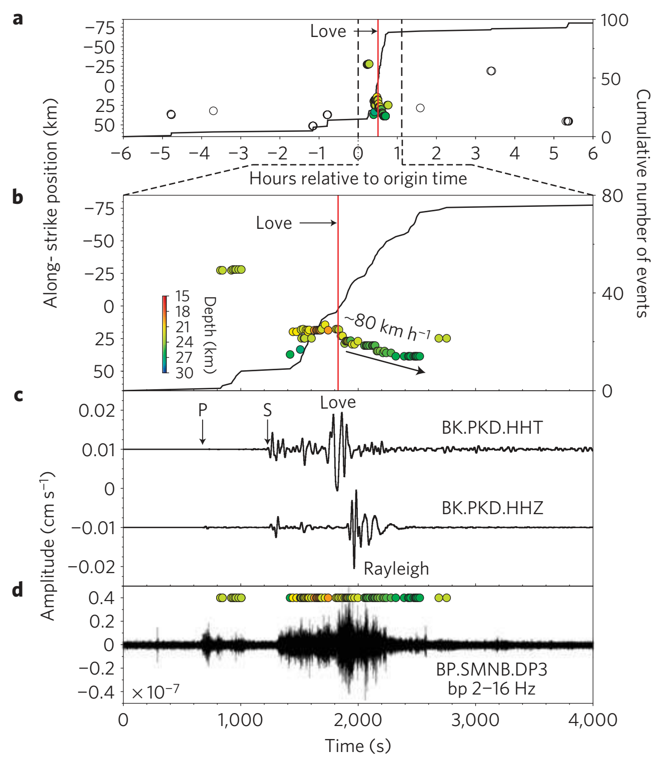

Figure 2 | Tremor triggered by the 2009 M_w 8.1 Samoa earthquake. **a**, Detected tremor during a 12-h period centred on the earthquake origin time. Coloured events are those that are triggered, occurring after the P-wave arrival. Colour indicates estimated depth[28]. **b**, Tremor migration, which occurs during and after the surface-wave arrivals, progressing towards the southeast at ~80 km h^{-1}. **c**, Transverse- and vertical-component waveforms from broadband seismic station PKD (see Fig. 1), low-pass filtered at 10 s, recording the arriving teleseismic waves. **d**, High-frequency (2–16 Hz) waveform from borehole station SMNB. See also Supplementary Movie S2.

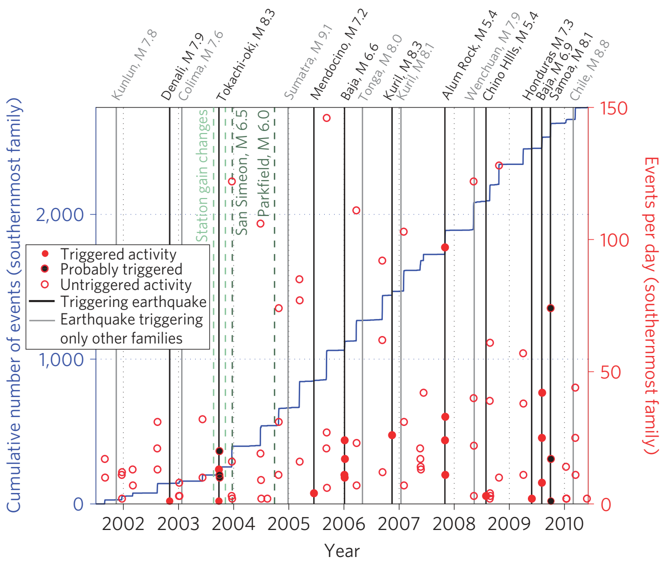

Figure 3 | Tremor activity in the southernmost family, mid-2001 to mid-2010. Blue line shows cumulative events. Red circles show the number of events per day—only days with two or more detected events are shown. Filled circles are those that are considered to be triggered (red) or 'probably triggered' (black), including multi-day sequences (see Methods). Black vertical lines show earthquakes that triggered activity in this family; grey lines show events that triggered tremor only in other families. Events are labelled along the top, along with the moment magnitude (M_w). Note triggering by earthquakes as small as M_w 5.4. Activity bursts in December 2003 and May 2008 occurred before the San Simeon and Wenchuan earthquakes, respectively, and thus were not triggered.

Precise locations of triggered tremor reveal that the tremor source often systematically migrates distances of 10–20 km over 10–30 min. Figure 2 and Supplementary Movie S2 show the example of the 2009 Samoa earthquake, which exhibits clear migration in the triggered tremor sequence towards the southeast at ~80 km h^{-1}. In fact, triggered events commonly show coherent migration of the tremor source over a period of minutes to around an hour during and shortly after the passage of the main seismic waves of a triggering event, for example the 2010 M_w 8.8 Chile earthquake[20] (Supplementary Fig. S3 and Movie S3) and the 2004 M_w 9.1 Sumatra earthquake (Supplementary Fig. S4 and Movie S1). The migration occurs at speeds of ~40–100 km h^{-1} (~11–28 m s^{-1}), much slower than the propagation of triggering waves of ~4,000 m s^{-1}. This behaviour implies that although activity is initiated by passing waves, it grows and migrates of its own accord, reflecting a triggered transient slip event.

In some locations, owing to the infrequent activity of particular sources, even localized and delayed activity can be confidently considered as triggered. A prime example is the southernmost identified family, where large bursts of activity lasting a few days are typically followed by 2–6 months of quiescence. In this family, nearly 18% of total activity seems to be triggered by teleseismic or regional earthquakes (Fig. 3). Whether triggered or untriggered, activity in this family is highly clustered in time. This particular family may be especially susceptible to triggering by regional earthquakes, as it is triggered by all five regional events that have been observed to trigger tremor anywhere in the region (Supplementary Table S1).

Occasionally, multi-day bursts affecting many families may be triggered. The 2002 Denali fault earthquake seems to show this type of behaviour. In this case, the activity rate increases with the arrival of seismic waves from the earthquake, continues to accelerate for ~1 day and returns to background levels ~3 days following the event (Fig. 4). Similar behaviour is seen at other times for untriggered bursts in this zone[17]. The extended acceleration of activity following the trigger is inconsistent with a simple 'aftershock' effect[27], again suggesting that triggered fault creep may regulate the swarm-like occurrence of tremor.

Whereas some instances of aseismic fault slip (creep events) induce tremor activity, others trigger earthquakes. The resulting seismic expression probably depends on the fault-zone properties[10]. Earthquakes triggered by creep events have been observed at a variety of depths in several locations including New Zealand[11], Obsidian Buttes near the Salton Sea[12], Hawaii, Boso Peninsula (Japan), Mexico and San Juan Bautista on the SAF (ref. 10). These triggered earthquakes probably result from shear stress increases induced by slip on neighbouring patches of the fault, although fluid pressure changes could also play a role.

If a creep event is dynamically triggered, earthquakes may be triggered secondarily, probably with some time delay, as creep evolves. A similar mechanism was proposed to explain an earthquake sequence in Iceland, where postseismic slip of a triggered earthquake probably triggered a subsequent event[29]. Whether triggered or not, aseismic slip may be the driving force of many earthquake swarms[30].

Evidence presented here and elsewhere indicates that dynamic stresses from seismic waves of distant earthquakes can trigger dominantly aseismic fault slip, which may in turn trigger tremor or earthquakes, depending on the fault environment. In these cases, the temporal evolution of seismicity may reflect the evolution of the aseismic process. Therefore, triggered tremor on the SAF in many cases can be considered as secondarily triggered, that is, driven by

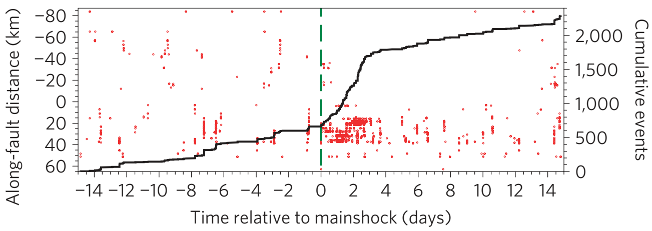

Figure 4 | Multi-day tremor episode triggered by the 2002 M_w 7.9 Denali fault earthquake. The along-strike distance (left axis—see Fig. 1) versus the occurrence time of detected tremor events within 15 days of the teleseismic earthquake. The green dashed line marks the occurrence time of the earthquake. The solid line shows the cumulative number of detected tremor events over this time period (right axis). Note the acceleration in activity rate during the first 1–2 days following the earthquake, indicating that activity may be governed by a growing creep event.

a triggered creep event. The situation may be analogous for tidal triggering of slow slip and tremor, given that the slip rate seems to be tidally modulated, at least in Cascadia[31].

Once initiated, triggered tremor episodes on the SAF are indistinguishable from non-triggered tremor, suggesting that the dynamic stresses from the triggering earthquake simply act as a catalyst for ongoing tectonic stress release in the form of small-scale ETS events. The fact that both the ambient and triggered tremor match the same sets of templates suggests that they share common sources and a common mechanism of shear slip on the deep extension of the fault[14,16]. Whether or not a given earthquake triggers activity may depend equally on the readiness for failure of each fault patch and the amplitude of the triggering waves.

Even multi-day triggered deep slip events inferred here are too small to be observed on near-surface geodetic instruments. This lack of geodetic detectability is not surprising, considering the relatively small area of tremor activation and the small slip suggested by the relatively short recurrence period of events[17]. In fact, sub-seismogenic zone slip (>15 km depth) up to M_w 5 is likely to remain hidden[18]. Given this, and the fact that slow-slip events can occur without generating detectable tremor, it is unknown how widespread smaller creep events might be. On parts of the deep SAF and elsewhere, tremor provides a means to illuminate episodic creep that is not detectable by surface geodetic instruments. Extrapolating the results presented here, small, triggered creep events may be much more common than recognized at present and could underlie many extended-duration triggered earthquake sequences. This mode of secondary triggering could help explain observations of delayed dynamic earthquake triggering and might represent an important mechanism for earthquake triggering in general.

Methods

Event detection and location. Our analysis is based on waveform matching through cross-correlation with 88 waveform templates developed for the central SAF (Fig. 1; ref. 28). Tremor events are detected on the basis of summed correlations across 25 channels of seismic data, selected from among borehole seismic stations composing the High Resolution Seismic Network (HRSN). Data are filtered between 2 and 8 Hz. Locations are based on P- and S-wave arrival-time estimates picked from stacked seismograms at dozens of surface and borehole stations. See ref. 28 for detailed methods. Events are assigned to the location of the best-matching waveform template. The group of events matching each template forms an 'event family'.

Triggered-event definitions. For Fig. 1, triggered activity is that continuing, with a gap of 30 min or less, following initiation (in one or more families) during the passing waves from the remote earthquake. For this figure, once 30 min has passed with no tremor in any family, subsequent events are not considered triggered.

For Fig. 3, owing to the infrequent episodes of activity in this southernmost family, we are able to expand our criteria. With the exception of the Samoa earthquake (for which activity in this family began ~12 h after the surface-wave passage, and is thus considered only 'probably triggered'), activity in this family initiates during or shortly after the passage of the teleseismic or regional surface waves, during the main triggered sequence (that considered as triggered for Fig. 1). For this family we also consider activity following with a gap of less than 24 h as triggered. The Tokachi-oki sequence contains a gap of ~33 h in detected activity. Therefore, activity after this gap is considered 'probably triggered'.

Received 8 October 2010; accepted 28 March 2011; published online 8 May 2011

References

1. Hill, D. P. *et al.* Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake. *Science* **260,** 1617–1623 (1993).
2. Velasco, A. A., Hernandez, S., Parsons, T. & Pankow, K. Global ubiquity of dynamic earthquake triggering. *Nature Geosci.* **1,** 375–379 (2008).
3. Freed, A. M. Earthquake triggering by static, dynamic and postseismic stress transfer. *Annu. Rev. Earth Planet. Sci.* **33,** 335–367 (2005).
4. Obara, K. Nonvolcanic deep tremor associated with subduction in southwest Japan. *Science* **296,** 1679–1681 (2002).
5. Peng, Z., Vidale, J. E., Wech, A., Nadeau, R. M. & Creager, K. M. Remote triggering of tremor around the Parkfield section of the San Andreas fault. *J. Geophys. Res.* **114,** B00A06 (2009).
6. Rubinstein, J. L. *et al.* Seismic wave triggering of non-volcanic tremor, ETS, and earthquakes on Vancouver Island. *J. Geophys. Res.* **114,** B00A01 (2009).
7. Guilhem, A., Peng, Z. & Nadeau, R. M. High-frequency identification of non-volcanic tremor triggered by regional earthquakes. *Geophys. Res. Lett.* **37,** L16309 (2010).
8. Felzer, K. R. & Brodsky, E. E. Decay of aftershock density with distance indicates triggering by dynamic stress. *Nature* **441,** 735–738 (2006).
9. Richards-Dinger, K., Stein, R. S. & Toda, S. Decay of aftershock density with distance does not indicate triggering by dynamic stress. *Nature* **467,** 583–586 (2010).
10. Peng, Z. & Gomberg, J. An integrated perspective of the continuum between earthquakes and slow-slip phenomena. *Nature Geosci.* **3,** 599–607 (2010).
11. Delahaye, E. J., Townend, J., Reyners, M. E. & Rogers, G. Microseismicity but no tremor accompanying slow slip in the Hikurangi subduction zone, New Zealand. *Earth Planet. Sci. Lett.* **277,** 21–28 (2009).
12. Lohman, R. B. & McGuire, J. J. Earthquake swarms driven by aseismic creep in the Salton Trough, California. *J. Geophys. Res.* **112,** B04405 (2007).
13. Rubinstein, J. L., Shelly, D. R. & Ellsworth, W. L. in *New Frontiers in Integrated Solid Earth Sciences* (eds Cloetingh, S. & Negendank, J.) 287–314 (Springer, 2010).
14. Thomas, A., Nadeau, R. & Bürgmann, R. Tremor-tide correlations and near-lithostatic pore pressure on the deep San Andreas fault. *Nature* **462,** 1048–1051 (2009).
15. Shelly, D. R., Beroza, G. C. & Ide, S. Non-volcanic tremor and low frequency earthquake swarms. *Nature* **446,** 305–307 (2007).
16. Ide, S., Shelly, D. R. & Beroza, G. C. Mechanism of deep low frequency earthquakes: Further evidence that deep non-volcanic tremor is generated by shear slip on the plate interface. *Geophys. Res. Lett.* **34,** L03308 (2007).
17. Shelly, D. R. Migrating tremors illuminate deformation beneath the seismogenic San Andreas fault. *Nature* **463,** 648–652 (2010).
18. Smith, E. F. & Gomberg, J. A search in strainmeter data for slow slip associated with triggered and ambient tremor near Parkfield, California. *J. Geophys. Res.* **114,** B00A14 (2009).
19. Obara, K. Time sequence of deep low-frequency tremors in the southwest Japan subduction zone: Triggering phenomena and periodic activity. [in Japanese with English abstract and legend]. *J. Geogr.* **112,** 837–849. (2003).
20. Peng, Z., Hill, D. P., Shelly, D. R. & Aiken, C. Remotely triggered microearthquakes and tremor in Central California following the 2010 M_w 8.8 Chile earthquake. *Geophys. Res. Lett.* **37,** L24312 (2010).
21. Beroza, G. C. & Ide, S. Deep tremors and slow quakes. *Science* **324,** 1025–1026 (2009).
22. Du, W-x., Sykes, L. R., Shaw, B. E. & Scholz, C. H. Triggered aseismic fault slip from nearby earthquakes, static or dynamic effect. *J. Geophys. Res.* **108(B2),** 2131 (2003).
23. Hill, D. P. & Prejean, S. G. in *Treatise on Geophysics* Vol. 4 (ed. Schubert, G.) 257–292 (Earthquake Seismology (ed. Kanamori, H.), Elsevier, 2007).
24. Hill, D. P. Dynamic stresses, Coulomb failure, and remote triggering. *Bull. Seismol. Soc. Am.* **98,** 66–92 (2008).
25. Parsons, T. A Hypothesis for delayed dynamic earthquake triggering. *Geophys. Res. Lett.* **32,** L04302 (2005).
26. Brodsky, E. E. & Prejean, S. G. New constraints on mechanisms of remotely triggered seismicity at Long Valley Caldera. *J. Geophys. Res.* **110,** B04302 (2005).

27. Brodsky, E. E. Long-range triggered earthquakes that continue after the wave train passes. *Geophys. Res. Lett.* **33,** L15313 (2006).
28. Shelly, D. R. & Hardebeck, J. L. Precise tremor source locations and amplitude variations along the lower-crustal central San Andreas Fault. *Geophys. Res. Lett.* **37,** L14301 (2010).
29. Árnadóttir, T., Geirsson, H. & Einarsson, P. Coseismic stress changes and crustal deformation on the Reykjanes Peninsula due to triggered earthquakes on 17 June 2000. *J. Geophys. Res.* **109,** B09307 (2004).
30. Roland, E. & McGuire, J. J. Earthquake swarms on transform faults. *Geophys. J. Int.* **178,** 1677–1690 (2009).
31. Hawthorne, J. C. & Rubin, A. M. Tidal modulation of slow slip in Cascadia. *J. Geophys. Res.* **115,** B09406 (2010).

Acknowledgements

We are grateful to T. Parsons and B. Chouet for reviewing this manuscript. Data were obtained from the Northern California Earthquake Data Center (NCEDC). Station PKD and HRSN stations are operated by the University of California, Berkeley. Z.P. and C.A. are supported by the National Science Foundation (EAR-0809834 and EAR-0956051).

Author contributions

D.R.S. designed and carried out the tremor detection. Z.P. analysed the broadband data of triggering earthquakes. D.R.S., Z.P. and D.P.H. analysed and interpreted the results. D.R.S. wrote the manuscript, with contributions from all authors. Figures were constructed by D.R.S. (Figs 1, 3 and Supplementary Fig. S2 and Movies), Z.P. (Fig. 4), D.P.H. (Supplementary Fig. S1) and C.A. (Fig. 2 and Supplementary Figs S3–S5).

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to D.R.S.