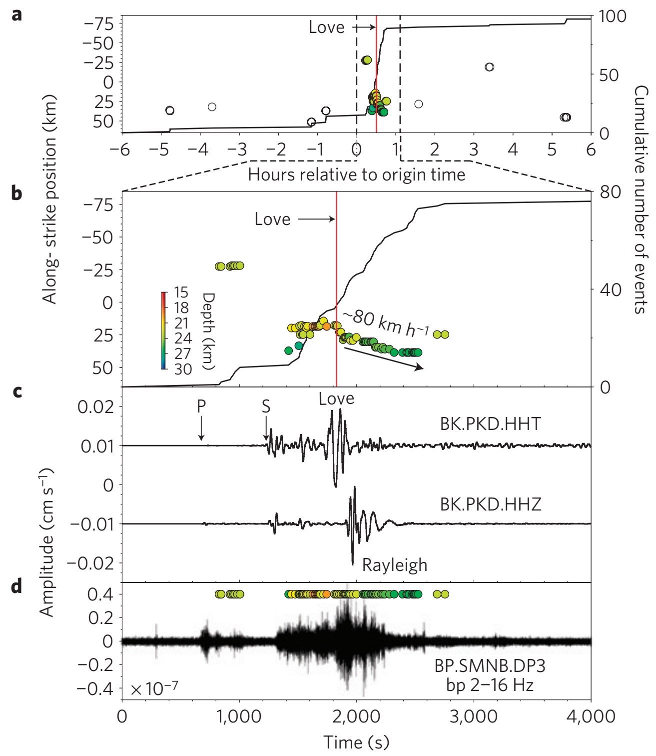

Figure 2 | Tremor triggered by the 2009 M_w 8.1 Samoa earthquake. **a**, Detected tremor during a 12-h period centred on the earthquake origin time. Coloured events are those that are triggered, occurring after the P-wave arrival. Colour indicates estimated depth[28]. **b**, Tremor migration, which occurs 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.

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).

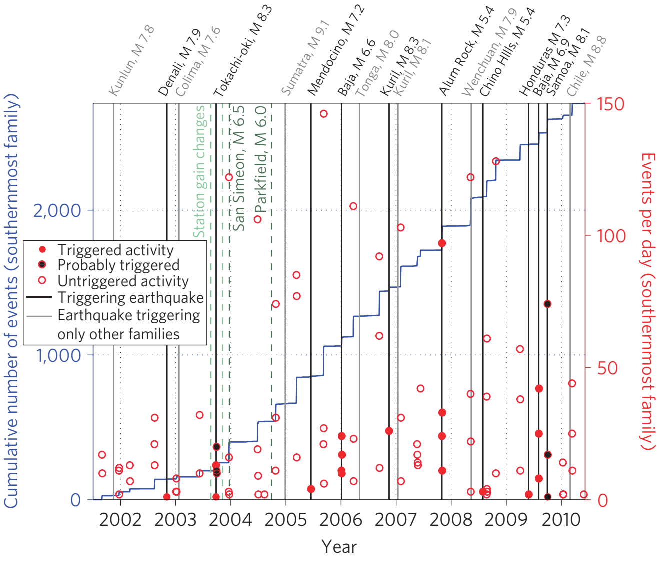

Figure 3 | Tremor activity in the southernmost family, mid-2001 to mid-2010. Blue line shows cumulative events. Red circles show the number of events per day—only days with two or more detected events are shown. Filled circles are those that are considered to be triggered (red) or 'probably triggered' (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.

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'.

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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

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