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Rapid tremor reversals in Cascadia generated by a weakened plate interface

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Slow slip along the plate interface at subduction zones can generate weak seismic tremor in a quasi-periodic process called episodic tremor and slip. This process differs in character from regular earthquake rupture and can release stresses that build up on the deep plate interface. Here we analyse the spatial and temporal evolution of the five largest episodic tremor and slip events between 2004 and 2009 in northern Washington on the Cascadia subduction zone. We find that the events are similar, but not identical because they initiate in different locations and propagate along the plate interface at different average speeds of 7 to 12 km per day. Our analysis reveals that tremor can migrate rapidly back, away from the region where tremor and slip are advancing, through parts of the plate interface that have just ruptured in the past three days. These rapid tremor reversals propagate backwards for tens of kilometres at speeds that are 20 to 40 times faster than the relatively slow, steady advance of episodic tremor and slip. Our observations suggest that once the plate interface is weakened by the initial advance of episodic tremor and slip, it allows stresses to induce slip more easily or fluid pressure waves to migrate back more rapidly, generating rapid tremor reversals.

Episodes of weak seismic radiation (termed tremor) and slow slip occur together in a coupled process that has been detected recently in several subduction zones[1–5]. The episodes are called Episodic Tremor and Slip (ETS) in Cascadia and Slow Slip Events (SSE) in Japan. Reference 6 provides a recent review of Cascadia-wide ETS. In contrast with regular earthquakes, tremor signals exhibit low amplitudes, long durations, and emergent character. In northern Washington, ETS manifests in SSE that last 2–4 weeks, extend over 150 km along strike of the Cascadia subduction zone, and involve a moment release equivalent to a M6.4 to 6.8 earthquake. Recurring every 12–15 months, they are tantalizingly near-periodic in occurrence, compared with the aperiodicity of regular earthquakes.

The nature and location of ETS has important implications for the mechanics and seismic hazards of subduction zones. The source character and scaling of tremor seem distinct from regular earthquakes[7]. Furthermore, the process propagates at speeds much slower than regular earthquakes. These aspects of ETS pose a major challenge to understanding its physics. The total moment release in the northern Cascadia ETS is a large fraction of that accumulated over an inter-ETS period[8,9]. Thus, stress accumulation in the ETS portion of subduction zones is probably much less than that in the locked zone, which lies updip. In Cascadia, the locked zone is known to be capable of M9 earthquakes[10]. Therefore, the location of the ETS region may help to delineate the lower bound of the zone likely to slip seismically in great megathrust earthquakes[9]. Furthermore, episodic stress transfer by ETS adjacent to the locked zone points to a potential role in triggering large megathrust earthquakes, and motivates tremor-monitoring efforts.

Here, we compare the behaviour of five large ETS in northern Washington and report a new phenomenon, in which tremor travels rapidly back across a region through which the ETS has very recently ruptured. We then discuss three distinct ETS propagation processes with different velocities, all of which are anomalously slow compared with seismic velocities.

Tremor catalogues

We analyse tremor location catalogues for the July 2004, September 2005, January 2007, and May 2008 ETS in northern Washington[8], as well as the more recent May 2009 event[11]. These are derived using a waveform envelope cross-correlation and clustering algorithm[12]. Together, the five catalogues represent ~110 days of relatively strong tremor and ~16,000 locations.

The location procedure yields epicentral locations with estimated errors of about ±8 km, but depth determinations are highly uncertain[12]. Therefore, we focus mainly on epicentral locations. However, we also consider the implications if all the tremor is located on the plate interface, and for that purpose assume that the interface is described by a 3D model of the subducting plate[13]. Several recent results support the concept that the majority of tremor concentrates on the plate interface between the over-riding and down-going plates[14–17], although evidence also suggests some tremor occurs throughout a large volume above the interface[18]. As discussed below, the former concept seems more consistent with the occurrence of Rapid Tremor Reversals (RTR).

Comparison of ETS space–time evolution

To assess and compare along-strike ETS propagation velocities, we projected the tremor epicentres from the five episodes onto a straight line, obtained by fitting the epicentres of the 2007 ETS (Fig. 1), which is the most spatially extensive of the five ETS. Epicentres from all five episodes are projected onto this common along-strike line, so that the along-strike propagation behaviour can be readily examined.

The left panels of Fig. 1 show maps of the tremor locations during the five ETS, whereas distance along the projection line (black line in the maps) versus time is shown on the right. Epicentres are colour-coded by depth to the plate interface model[13] below, with red to purple to blue denoting increasing depth.

Although the space–time evolution is similar for the five ETS, they are not exact replicas. All five episodes share the

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