In situ conditions and the mechanics of slow earthquakes along subduction megathrusts: Insights from laboratory experiments

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Over the last several years, seismic and geodetic observations have led to the discovery that fault slip occurs across a continuous spectrum of slip rates and durations, ranging from normal earthquakes that last seconds to minutes, to low frequency and very low frequency earthquakes (LFE and VLFE), to slow slip events that unfold over weeks to months. In many, though not all cases, slow earthquake phenomena occur near the updip and downdip edges of the seismigenic portion of faults that rupture coseismically. Although observations of these events are widespread, their mechanics and the in situ conditions in their source regions are not well known. Here, we report on two sets of laboratory investigations aimed at better understanding the processes that underlie slow earthquakes, with a focus on subduction megathrusts.

First, we integrate laboratory measurements of acoustic velocity and consolidation behavior for sediments from the Nankai Trough with a well-constrained regional seismic velocity architecture, to estimate in situ pore pressure and stress in the outer forearc where swarms of VLFE nucleate. We show that the VLFE occur exclusively in the region of highest predicted fluid overpressures, where normalized pore pressures are 74–87% of lithostatic. In this region, estimated horizontal stresses are also anomalously low, ~30% of the value expected for fully drained conditions. This result is consistent with similar observations suggesting elevated pore pressures in the source area of slow slip events at other margins, including Hikurangi and Costa Rica.

Second, we describe laboratory friction experiments that illustrate mechanisms that may explain the emergence of slow earthquakes. In a suite of carefully controlled experiments on fine-grained quartz gouges, we show that repeated laboratory slow stick-slip events occur near the transition between stable and unstable slip, controlled by the interplay of fault frictional properties, effective normal stress, and elastic stiffness of the surrounding rock. Notably, stick-slip event velocity and duration vary systematically as the stability threshold is approached; regular stick-slip events occur in the unstable regime and slow slip and chaotic modes occur near the stability phase boundary. We also show that natural sediment and fault zone samples from subduction zones exhibit rate-weakening behavior at low slip velocity, transitioning to rate-strengthening at higher slip velocity. These characteristics could allow slow unstable sliding in these materials, but would suppress rapid unstable slip.