SEISMOLOGY

Diary of a wimpy fault

Subduction zone faults can slip slowly, generating tremor. The varying correlation between tidal stresses and tremor occurring deep in the Cascadia subduction zone suggests that the fault is inherently weak, and gets weaker as it slips.

Roland Bürgmann

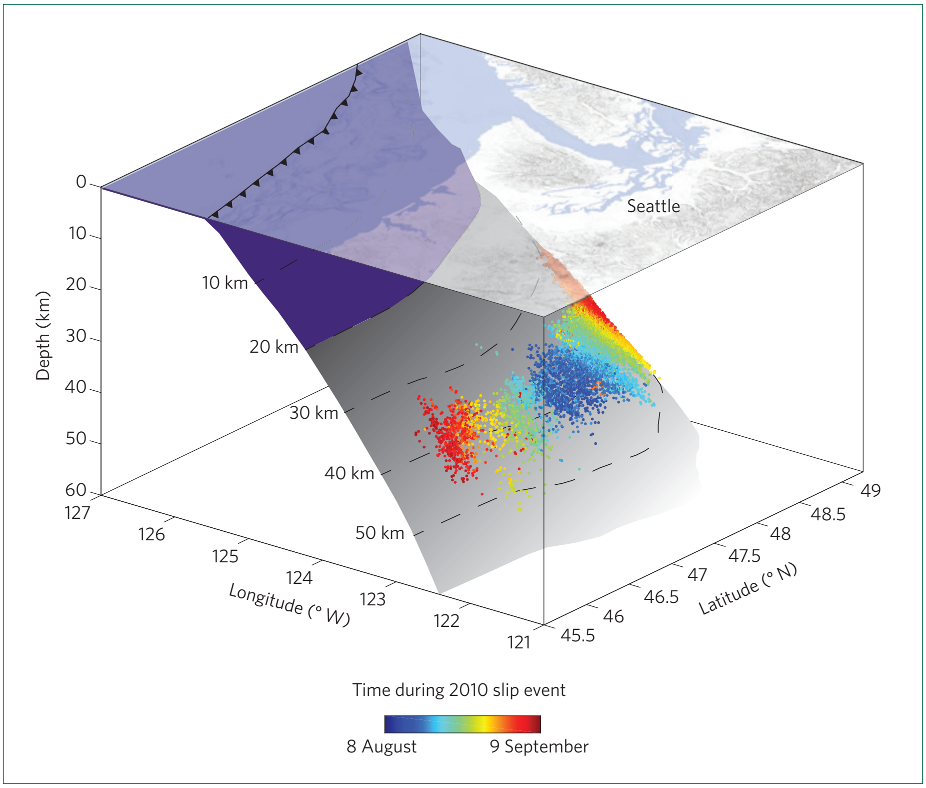

Figure 1 | Recurring slip events deep on the Cascadia subduction zone are illuminated by tremors. The tremor locations (circles) are coloured by date of occurrence during a month-long tremor-and-slip episode in 2010. Houston[1] finds that the correlation between tremor and tidal stress at a point on the fault strengthens during a slip event, implying that the fault weakens as slip evolves. At depths of less than about 20 km (purple shaded region), the megathrust appears to be locked and therefore builds up stress towards the next great subduction earthquake. Figure courtesy of Aaron Wech, US Geological Survey.

The discovery of tectonic tremor in the deep roots of plate-boundary subduction zones in Japan and North America was a great surprise. These unusual and low-amplitude seismic signals emanate from a depth in the Earth where rocks should be too hot and too viscous to produce seismic events. The tremors were found to be caused by episodic slow-slip events on the deep sections of plate-boundary faults, well below the parts of the fault that produce great earthquakes. Tremors can be triggered and modulated by the small stresses associated with body and ocean tides, implying that the faults that generate them must be very weak. Writing in *Nature Geoscience*, Houston[1] analyses tremor events in the Cascadia subduction zone between 2007 and 2012. She shows that not only are the deep parts of the fault very weak, but that the fault becomes weaker during individual slip events.

Tremors are the weak cousins of regular earthquakes. While it took decades of painstaking work to document the modest effect of tides on regular earthquakes, tremors were found to be easily triggered by these transient stresses[2]. This extreme sensitivity to very small stress changes indicates that the tremor-producing fault is frictionally weak, in large part due to fluids in the fault zone being at near-lithostatic pressure. That is, the overburden of rock is counteracted by fluid pressures of comparable magnitude in the fault. The high fluid pressure leads to a very low effective frictional strength of the fault, and slip and tremor can readily respond even to tiny tidal shear stresses of less than 100 Pa (ref. 3).

Houston[1] explores in detail the occurrence of tens of thousands of tremors created by six slow-slip events in the Cascadia subduction zone between 2007 and 2012 (Fig. 1). Each slow-slip event took several weeks to complete, with the slip front propagating at rates of several kilometres per day along a nearly 200-km-long stretch of the fault. At any given point on the fault, tremors and slip continue for several days but accumulate only two to three centimetres of total offset during each slip event[4]. Houston finds that not only is tremor (and thus fault slip) modulated by tides, but the strength of the correlation between the tides and tremors increases as slow slip progresses. This implies that the fault becomes increasingly sensitive to tides and progressively weakens as slip reaches a total of a few centimetres. So, not only are tremor-producing faults easily pushed around by external forces, they continue to weaken as they go.

Tremors have a story to tell about how deep faults work. The complex distribution of tremors in space and time and their response to external stresses illuminate the mechanical properties of the deep fault[5,6]. Some frictional models of slow-slip events feature slip-weakening distances that are large compared with those found in laboratory experiments (10^{-5} to 10^{-6} m); however, there are a number of alternative ways in which models can be parameterized to produce such events[6,7]. The observation of a slowly increasing correlation of tides and tremors during the Cascadia slow-slip events indicates that the fault may indeed need to slip a relatively large distance, on the scale of a centimetre, before it weakens to its frictional sliding strength.

Houston suggests that the observed drop in fault strength over the course of a slow-slip event could involve the breakage of mineral precipitates in the fault zone. The minerals rapidly regrow in the approximately 14-month-long recurrence interval between slow-slip events, during which time the fault strength recovers and stress accumulates[8]. Interestingly, a transition from tremor modulated by the rate of peak tidal shear stress to tremor modulated by the amplitude of peak tidal shear stress during a large slow slip event has recently been documented in Cascadia[9]. This observation adds another twist to the relationship of tides and tremors and should further illuminate the underlying physics of the slow-slip process.

Tremor-producing faults are weak, but it was not known if the weakness stems only from very high fluid pressures or if the fault-zone rocks also have a very low friction coefficient. Taking advantage of differences in the temporal variations of tidal fault-perpendicular stress and mean stress (pressure), Houston is able to estimate the intrinsic, fluid-pressure-independent friction coefficient for the fault *in situ*. She finds values for the average friction coefficient well below 0.2 — much lower than most known rock types, with friction values between 0.6 and 0.8. Such low values require unusually weak fault zone materials, such as talc, graphite and saponite, to effectively lubricate the fault zone. Saponite breaks down at temperatures well below those found in the tremor zone, but talc and graphite can be stable to very high temperatures and pressures[10], so could exist in the deep fault zone beneath the Cascades.

Above the weak tremor zone in Cascadia, the seismogenic part of the fault is strongly coupled and capable of producing great megathrust ruptures. The last such event in 1700 was a not-so-wimpy magnitude 9 earthquake. Given that the Cascades are home to large cities such as Seattle, Portland and Vancouver, we must continue to investigate potential links between slip on the deep subduction zone and megathrust earthquakes on locked parts of the fault. In the process, we are bound to learn more about the physics of deep plate-boundary faulting with improved and targeted seismologic, geodetic, gravity, and electro-magnetic observations, including those from space-borne systems, borehole sensors, and seafloor instrumentation. As large earthquakes often initiate close to the tremor zone, insights gained from these observations may enable improved characterization of time-dependent earthquake hazard and of precursory processes that appear to precede some large earthquake ruptures. ❐

Roland Bürgmann is in the Department of Earth and Planetary Science, University of California, Berkeley, California 94720–4767, USA.
e-mail: burgmann@seismo.berkeley.edu

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GLACIER CHANGE

Dynamic projections

Mountain glaciers around the world are in decay. According to a modelling study that — unusually — includes full ice flow physics, those in Western Canada will largely be restricted to the coastal region by the year 2100.

Andreas Vieli

Glaciers are abundant in the world's high mountain regions, and they are sensitive to changing climatic conditions. They can influence river discharge and water resources, particularly in arid regions such the Tien Shan in Central Asia[1]. In past decades, many mountain glaciers have been observed to progressively shrink in mass and extent in response to atmospheric warming[2]. Mass loss of mountain glaciers currently contributes about 0.7 mm of sea-level rise per year[2], similar to the combined addition from the ice sheets of Greenland and Antarctica. However, predictions on regional to global scales are uncertain: they rely heavily on upscaling from a small, well-studied subsample of the world's 170,000 glaciers[3]. Writing in *Nature Geoscience*, Clarke *et al.*[4] present a comprehensive modelling framework that simulates the large-scale evolution of glaciers in Western Canada at high resolution, and fully account for glacier flow.

Changes in glacier extent and volume result from variations in the surface mass balance, that is, the balance between accumulation of snow in the colder high-elevation areas of a glacier and ice melt in low-elevation ablation areas. Surface mass balance is therefore directly steered by local meteorological factors such as air temperature and snow fall. Ice flow, caused by gravity, then transfers ice from the accumulation to the ablation area. Glaciers respond to changing climatic conditions by adjusting their shape, a process that involves ice flow. However, these dynamic adjustments take time and result in a delayed and smoothed response of glacier geometry to the climatic signal.

Regional to global scale projections of glacier change that are relevant for sea-level estimates and hydrology face the challenge of dealing with very large numbers of glaciers, each with a different geometry. Observations from glaciers are limited, therefore projections largely rely on models of surface mass balance derived from a few tens of glaciers that have been measured in detail. These are then scaled-up to whole glacier populations based on simple attributes