SEISMOLOGY

Taking it slow

The 2011 Tohoku-oki earthquake ruptured part of a fault that typically slips in slow, transient events. Laboratory experiments show that when fault rocks are sheared at slow, plate tectonic speeds, the fault can slip either quickly or slowly.

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The discovery of prevalent slow-slip events upended our previous idea that faults usually fail either in earthquakes or creep at tectonic rates. We now understand that portions of faults fail during slower, transient events — much like an earthquake, except slip occurs over days, weeks or months, and therefore produces very little shaking. The relationship between slow slip and earthquakes is not yet clear. Writing in *Nature Geoscience*, Ikari *et al.*[1] have now demonstrated that faults that host shallow slow-slip events might also experience pronounced shallow earthquake rupture, as observed during the 2011 Tohoku-oki earthquake.

Insight into fault slip speeds can be gleaned from laboratory friction experiments. Rate-and-state friction laws[2,3] suggest that a fault rock can be either velocity-strengthening or velocity-weakening; when pushed at faster speeds the rock becomes stronger or weaker, respectively. Earthquakes can only nucleate in velocity-weakening material, so the seismogenic zone, which is often located at intermediate depths in a fault, is assumed to be mostly composed of velocity-weakening material. In contrast, both the shallower and deeper extents of faults are thought to be composed of velocity-strengthening material. Earthquakes can propagate through velocity-strengthening patches, which we can observe when earthquakes rupture to the Earth's surface, but earthquakes cannot nucleate in these regions. It is the transition between sections of a fault that typically hosts slow-slip events. All seismogenic faults should therefore have regions in which the fault rocks exhibit a transition in frictional behaviour, between velocity-strengthening and velocity-weakening[4]. In addition to transitions up and down fault dip, slow slip can occur along fault strike and around velocity-strengthening patches within the seismogenic zone[5].

The 2011 Tohoku-oki earthquake offshore from Japan ruptured the plate boundary fault all the way to the Earth's surface. Part of what made this earthquake unusual was that the shallow extent of the fault slipped the most[6,7], with movement of approximately 50 to 80 m. Intriguingly, a nearby portion of the fail had previously experienced shallow, slow-slip events[8,9], which suggests the fault was at or near the frictional transition. Yet friction experiments on fault rocks retrieved by drilling into the Tohoku-oki fault zone as part of the Japan Trench Fast Drilling Project (Fig. 1) suggest that these rocks are mostly velocity-strengthening when slipping at sub-seismic rates[10]. However, as is standard when testing the velocity dependence of a material, the experiments were run at speeds much greater than typical tectonic plate movement.

Figure 1 | Fault rocks from the Japan Trench plate boundary. Samples of the fault rocks that ruptured during the 2011 Tohoku-oki earthquake were retrieved by drilling into the plate boundary as part of the Japan Trench Fast Drilling Project. By very slowly shearing the fault rocks in the laboratory, Ikari and colleagues[1] showed that slow and fast fault slip occur spontaneously in samples when *in situ* composition and fabric are retained. Scale bar in cm. Figure adapted from ref. 1, NPG.

In contrast, Ikari and colleagues[1] sheared rock samples from the Tohoku-oki fault zone very, very slowly — at speeds of just a few nanometres per second, equivalent to plate tectonic rates. Under these conditions, the fault rocks displayed velocity-weakening behaviour. Furthermore, a range of slip styles, including both slow-slip events and stick-slip events akin to earthquakes, arose spontaneously. The laboratory-generated slow-slip events exhibited slip velocities of around double the rate at which the sample was sheared, which is very similar to the measured rates of slow slip observed in subduction zones around the Pacific Ocean. Because the fault rocks exhibit both unstable and quasi-unstable behaviour, shallow fault patches that host slow slip might be places where large, shallow slip will occur during an earthquake, with the possibility of devastating tsunamis to follow.

Ikari *et al.* go on to show that two important qualities of the fault rock — mineralogy and fabric, or orientation of the minerals — may be responsible for the unusual ability of the Japan Trench to host both slow slip and earthquakes. Fault rocks from the Japan Trench contain smectite, a hydrous clay. Yet when illite, a less-hydrous clay, was subjected to the same sliding tests at slow velocities, it exhibited no transition in frictional behaviour. In addition, some fault samples were sheared with their original fabric, created in the fault zone, intact. Other samples were crushed into a powder first and then reshaped for the experiment. Only the samples with pre-existing fabric generated spontaneous slow-slip events.

Despite these advances, we are still only beginning to understand the conditions necessary and mechanism responsible for slow-slip events. Slow slip is relatively common along subduction zones, including south-west Japan, Cascadia, Alaska, Costa Rica and Hikurangi, but it is not ubiquitous. If slow-slip events occur at friction transitions, we should observe slow-slip events on all seismogenic faults. This absence could be due to observational constraints in some regions, but in others slow slip is most likely lacking or extremely subdued. For instance, slow slip has been documented on very few continental faults, and those that do usually experience triggered rather than spontaneous slow-slip events. Temperature, effective stress, rheology and loading velocity all influence where transitional friction behaviour occurs along faults. Given these many unknowns, it remains unclear whether slow slip plays a role in promoting the next big earthquake on a given fault.

Although many uncertainties remain, Ikari and colleagues[1] have shown that the frictional properties of fault rocks can explain how both fast and slow fault slip could occur on the same part of a fault. Thus, in subduction zones worldwide, it is possible that any shallow fault patch that typically generates slow-slip events could also host large, shallow slip during earthquakes and tsunamis. ❐

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