

Earthquakes: Caught in the act

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Faults break under the stress of plate tectonic forces, but the processes immediately preceding rupture are enigmatic. Monitoring of a remote oceanic fault that breaks regularly indicates that rupture is controlled by physical properties of the fault zone.

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The outer layer of Earth is broken into about a dozen main and many minor tectonic plates¹. Their long-term motions relative to each other are quite well known and typically vary from close to zero to more than 100 mm per year. These motions, however, are usually not continuous. Instead, plate movements are jerky, resisted by the frictional strength of fault rocks. Sudden plate movements manifest as earthquakes when the stresses loading the faults exceed a critical level². A better understanding of the short-term processes that lead to and immediately precede earthquake rupture could potentially provide an early warning tool, and is thus of great societal significance. However, these processes are currently not well understood. Writing in *Nature Geoscience*, McGuire *et al.*³ capture a complete earthquake sequence on an oceanic transform fault at the East Pacific Rise and identify parts of the fault that rupture in large earthquakes, as well as regions that act as rupture barriers and earthquake-initiation zones.

Without a fundamental understanding of the physics of earthquakes, significant progress in earthquake forecasting is unlikely. To this end, rather than studying complicated fault zones on land, it may be advantageous to study fast-moving faults in the oceans; here oceanic crust and upper mantle rock composition is simpler and more homogeneous, resulting in fairly well-known rheological and thermal properties of the faults. The faults also experience only moderately sized maximum earthquakes (magnitudes 5.5-6.5) and thus have short earthquake cycles. Repeating earthquakes with recurrence times of between 4 and 24 years have been observed on several ridge transform faults that link segments of mid-ocean ridges and accommodate horizontal movements between plates in the Pacific Ocean⁴⁻⁶.

Studying faults on the ocean floor has its drawbacks; in particular they are difficult to access. However, the latest generation of ocean-bottom seismometers allows continuous ground motion monitoring for a whole year at a time. Ocean-bottom seismometers were deployed along the Gofar transform fault on the East Pacific Rise in December 2007 because part of the fault was forecast to rupture in a magnitude 6 earthquake during 2008⁴. In spectacular fashion, the earthquake did occur in September 2008 and the entire sequence, including fore- and aftershocks, was recorded.

McGuire *et al.*³ analysed the seismic data recorded on the Gofar transform fault before and after the 2008 earthquake. They found that the earthquake was preceded by a week-long intense swarm of foreshocks. The foreshocks were confined to a region of about 10 km in length, separating the part of the fault in the west that ruptured in 2008 from a part farther east that ruptured in a similar-sized earthquake in 2007. These two distinct fault patches that are capable of generating magnitude 6 earthquakes seem to have ruptured repeatedly, about every five years in at least two complete cycles, without breaking the intervening 2008 foreshock zone. Thus, the foreshock zone seems to act as a long-lived rupture barrier that prevents simultaneous rupture on fault patches to the west and east of it (Fig. 1).

The foreshocks seemed to extend to greater depths than the aftershocks, and seismic shear waves moving through the foreshock region were slowed by about 3%. The reduction in seismic velocity implies that larger stress changes occurred in the foreshock zone than expected from the relatively small foreshocks. The stress changes could have been caused by the fault slipping aseismically. Creep of this part of the fault might have built up stresses on neighbouring fault sections and eventually triggered the magnitude 6 earthquake. However, seafloor geodetic data to corroborate a creep event do not exist.

These observations also imply that the foreshock zone becomes stronger when slipping. This velocity-strengthening frictional behaviour promotes stable sliding in the foreshock zone and effectively limits earthquake size by stopping ruptures that propagate into it. The physical properties in the foreshock zone thus differ from the remainder of the fault where friction is reduced when slip occurs, allowing large ruptures to develop. McGuire *et al.*³ suggest the differences are due to a combination of rock alteration, high porosity and high pore fluid pressure in the foreshock zone, which would point to a potentially significant influence of fluids in controlling earthquake ruptures on oceanic faults.

This fault structure – a creeping foreshock zone flanked by sections capable of large ruptures – implies that some faults could have specific rupture-preparation zones that are capable of triggering large earthquakes. If these zones persist through time and if we could identify them along transform faults on land, such as the San Andreas or North Anatolian faults, monitoring efforts could focus specifically on these zones to detect changes in slip behaviour that would point to an increased likelihood of an impending larger earthquake. Similarly, it has been suggested that bends in faults should be monitored because these, too, seem to be associated with rupture initiation⁷.

Rupture-preparation zones, though, are characterized by unusual material properties, and so are probably more difficult to identify than changes in fault geometry. And the observations from the Gofar fault could be unique. Similar studies at other ridge transform faults covering different rates of fault motion and fault lengths are needed to map rupture behaviour more generally. Further instrumentation (for example, seafloor geodesy) would be extremely useful to identify and measure aseismic creep events. Ideally, target sites to catch repeating earthquakes would be instrumented over at least one complete seismic cycle to test longevity and persistence of rupture-preparation zones. A candidate fault is the eastern Blanco transform fault, offshore Oregon, USA, where earthquakes account fully for the predicted plate motions⁸ and two fault patches show repeating earthquakes recurring about every 15 years⁵. The Regional Cabled Network of the Ocean Observatories Initiative, a network of scientific instruments, will span the Juan de Fuca plate in the Pacific Ocean and could be relatively easily extended to the Blanco fault. With an expected 25-30 year lifespan, this cabled network would cover more than a complete seismic cycle for each fault patch.

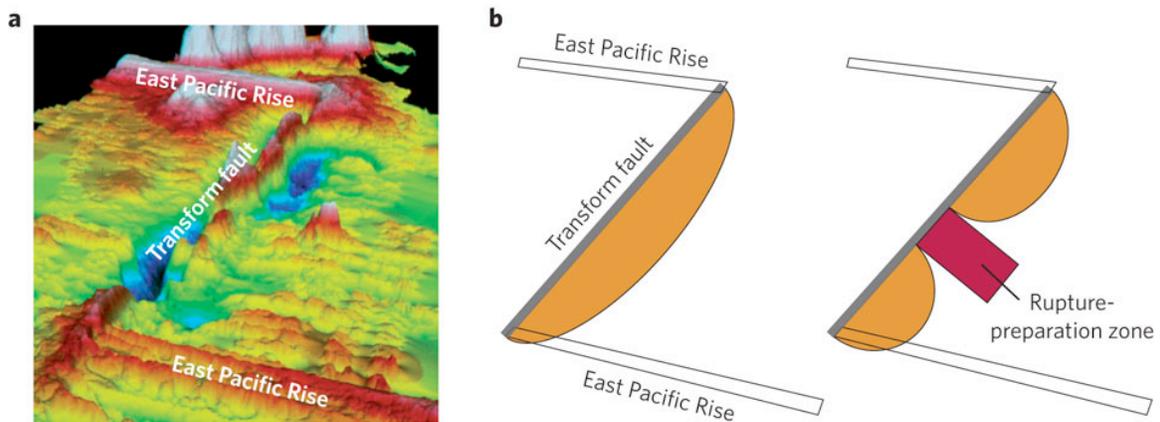
McGuire *et al.*³ provide a detailed look at seismic behaviour on an oceanic ridge transform fault, using the latest generation of ocean-bottom seismometers. Enhanced fluid circulation could cause parts of the fault to act as a barrier to fault rupture and could facilitate slow, aseismic slip that may ultimately trigger a main rupture on an adjacent fault section. Identification of similar rupture-preparation zones in faults on land could provide an early warning tool for large earthquakes.

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Figure 1 Transform fault on the Pacific Ocean floor.



a, A transform fault cutting across the East Pacific Rise links sections of the mid-ocean ridge and accommodates horizontal movements between plates in the Pacific Ocean. **b**, A simple transform fault (left) can rupture in a single, large earthquake. In contrast, more complex transform faults (right) are composed of segments separated by a rupture-preparation zone. The rupture-preparation zone could help confine earthquake rupture to individual segments of the fault, but could also potentially trigger earthquakes on neighbouring segments. McGuire *et al.*³ show that different parts of the Gofar transform fault, East Pacific Rise, behave differently during an earthquake sequence, probably as a result of variations in the material properties of the fault along its length. They identify potential rupture-preparation zones that, if also identified in faults on land, could provide an early warning tool for large earthquakes.