Seismology

Stressed to quaking point

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The Earth's crust can deform catastrophically in earthquakes, but it's difficult to predict exactly what causes such failure. Analysing thousands of small shocks might help us better understand how earthquakes occur.

In the study of earthquake mechanics, one of the biggest problems is pinning down the initial conditions. The slip history and the initial stress field around a fault are rarely known with certainty, making it tricky at best to work out what conditions trigger an earthquake. Uncertainty over fault conditions limit hypothesis-testing and hamper both fundamental studies of earthquake physics and empirical attempts to predict earthquakes. Toda and colleagues[1] (page 58 of this issue) now report a new way to circumvent this problem. Rather than relying on estimates of the absolute stress state, they use the rate of stressing to study earthquake nucleation and seismic deformation. They find that regions stressed at higher rates experience more earthquakes in a given period, in agreement with fault-friction theory[2].

Toda *et al.* used a dense network of seismometers in the Izu Islands volcanic chain, south of Tokyo (Fig. 1), and a seismic catalogue extending back to 1980 to measure changes in the rate of earthquake occurrence around one of the most seismically energetic magma intrusions ever known[3] — in 2000 the region was hit by a 'swarm' of more than 7,000 shocks. The authors infer that a vertical fracture, 8 km below the surface and 5 km × 15 km in area, was forcibly expanded to a width of 20 m by magma intrusion at an average rate of 300 $m^3 s^{-1}$ during a two-month period. In some areas the local stressing rate increased by a factor of up to 1,500 relative to the background rate. By comparing seismic activity before and after the intrusion, the authors find that earthquake rates jumped by a factor of nearly 1,000 in the areas of highest stressing rate, some locations suffering daily the equivalent of 1,000 earthquakes of magnitude 3 or more. They also show that the rate of seismic activity decreases in areas where the stressing rate decreases, in agreement with previous work[4].

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Figure 1 **Miyakejima, Izu Islands, August 2000. Mount Oyama erupts as the islands suffer thousands of earthquakes.**

Significant in the work of Toda *et al.*[1] is their use of earthquake observations to test seismicity–rate theory[2] and the laboratory-derived friction laws[5] on which it is based. The friction laws indicate that fault strength is not well described by a simple stress threshold but rather is a function of strain rate and recent slip history — that is, the 'frictional state'. History- or state-dependence of friction accounts for time-dependent strengthening of frictional contacts and for the fact that a finite displacement is necessary for the frictional resistance to make a transition from one set of conditions to another — for example, from stationary to sliding contact, or from steady sliding at one velocity or normal stress to another. Friction rate and state effects are well documented in laboratory experiments; however, testing how well they apply to earthquake faults has proved difficult and controversial.

At issue is whether the same processes that occur under laboratory conditions also govern seismic failure in the field, because the latter may involve slip rates of up to several metres per second and significant shear heating. Although the laboratory laws can reproduce much observed fault behaviour (including slow earthquakes, aseismic strain transients, dynamic rupture and interseismic fault healing[5,6]), the stumbling block is that numerical simulations of these phenomena in the field must generally use parameter values that differ from those measured in the laboratory. Seismic and geodetic observations can rarely specify friction values with sufficient precision to resolve the discrepancy. But Toda *et al.* have devised a different type of test, combining field-based estimates of the friction parameters with laboratory-based predictions of seismic behaviour.

Dieterich's seismicity–rate theory[2] predicts that a stress perturbation vanishes sooner if the background stressing rate is higher. As aftershocks are a product of the stress perturbation generated by the main shock, their duration — the time for the seismicity to return to the pre-mainshock level — should scale inversely with stressing rate. The Izu Islands swarm includes five magnitude-6 earthquakes, and Toda *et al.* record a strong inverse correlation between aftershock duration and stressing rate: aftershocks of magnitude-6 earthquakes, which would normally go on for several years, lasted only a day in the areas of highest stressing rate.

This agreement between theory and observation is a significant step forward for earthquake mechanics. The seismicity–rate theory also predicts a relationship between aftershock duration, stressing rate, and a friction parameter that describes the instantaneous friction response to a step change in slip velocity. Modelling studies show that larger values of the friction parameter prolong the time needed to reach instability[7]; hence, aftershock duration increases with the friction parameter. Laboratory experiments[8] show that the parameter (which is always positive) is between 10^{-3} and 10^{-2}, in good agreement with the value obtained by Toda *et al.*[1] from measured aftershock durations and stressing rates.

Seismicity–rate theory also predicts that a change in stress level will have a markedly different effect from a change in stressing rate, and Toda *et al.* show how this could improve understanding of postseismic behaviour. The main shock of an earthquake increases the stress around a rupture, but this increase decays rapidly because the brittle crust behaves as a stiff elastic material. In contrast, the effective stiffness is expected to be significantly lower in some cases, including large earthquakes that rupture into the frictionally viscous region below the seismogenic zone. Toda *et al.* note that the combined effects of a jump in stress level and stressing rate could help explain transient behaviour observed after large earthquakes.

Given the issues discussed above, it is clearly difficult to predict details of a particular earthquake, including when and where it may nucleate. But the method of Toda *et al.* presents an opportunity to test earthquake theories that could lead the way to fundamental breakthroughs. The correlation between stressing rate and seismicity may help in forecasting swarm or aftershock damage; however, there is still the problem of rupture size and understanding how earthquakes stop. Because large earthquakes appear to be seismically identical to small shocks, forecasts and damage predictions will remain limited, at least for the moment, to minimum estimates. ■

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1. Toda, S., Stein, R. S. & Sagiya, T. *Nature* **419,** 58–61 (2002).
2. Dieterich, J. H. *J. Geophys. Res.* **99,** 2601–2618 (1994).
3. http://sicarius.wr.usgs.gov
4. Dieterich, J. H., Cayol, V. & Okubo, P. *Nature* **408,** 457–460 (2000).
5. Marone, C. *Annu. Rev. Earth Planet. Sci.* **26,** 643–696 (1998).
6. Scholz, C. H. *Nature* **391,** 37–42 (1998).
7. Roy, M. & Marone, C. *J. Geophys. Res.* **101,** 13919–13932 (1996).
8. Blanpied, M. L., Marone, C., Lockner, D. A., Byerlee, J. D. & King, D. P. *J. Geophys. Res.* **103,** 9691–9712 (1998).