Earthquake science

Faults greased at high speed

Chris Marone

The dynamics of the tectonic faults that produce earthquakes remain puzzling. An inference from laboratory experiments could help: at high rates of slip, friction at the interface may fall dramatically.

For several decades now, geophysicists have been trying to understand why the energy budget for tectonic faulting does not seem to add up. The problem is that faults appear to be more slippery — less constrained by friction — than has been predicted by laboratory and theoretical work. The measurements of rock friction, described on page 436 of this issue by Di Toro and colleagues[1], may put things on firmer ground. They show that friction of quartz-rich rock is indeed high at low slip rates, consistent with previous studies, but that under certain conditions it drops dramatically as slip velocity approaches a few millimetres per second.

Conventional wisdom is that missing expenses are the cause of the imbalance in the faulting budget. On the income side of this budget are the driving forces of plate tectonics and the elastic energy stored in Earth's crust. Laboratory measurements of fault-zone friction indicate that the frictional stress during faulting near Earth's surface should be of the order of 50–100 megapascals. This implies that substantial frictional heat is produced during faulting, because the other main energy expenses — radiation of seismic waves, and the creation of surface area from the production and comminution of 'wear material' — are thought to account for only a small fraction of energy dissipation. The problem is that the expected frictional heat is missing[2,3].

To study the strength of frictional contact between rock surfaces, Di Toro and colleagues used an apparatus that applies rotary shear to the samples. The apparatus allows only comparatively small unidirectional movement, so the authors sheared samples back and forth to achieve the large net displacements that occur at earthquake faults. As in previous experiments in geophysical rock mechanics, they sheared samples under the high stresses expected to apply at tectonic faults.

Consistent with existing data, Di Toro *et al.* found that the coefficient of friction was 0.6–0.7 at low sliding velocities (up to 1 mm s^{-1}). However, their experiments show that the coefficient for novaculite — a rock composed of silicon dioxide (quartz) — decreases dramatically to values as low as 0.2 when the shearing velocity exceeds 1–10 mm s^{-1}. This effect is transient. On returning to lower sliding velocity, the coefficient of friction returns to high values. Identical experiments on samples of granite did not show the same reduced friction (or 'weakening') at high speed. So the authors infer that the weakening mechanism is related to the formation of a thin layer of silica gel, which acts as grease between the surfaces.

It seems likely that, in addition to the presence of quartz, a key factor in these experiments is the low rate of heat production. Previous laboratory studies of high-speed rock friction did not find appreciable weakening[4] and reported significant shear melting, possibly because they involved greater acceleration and faster shear rates than those studied by Di Toro and colleagues. Further work is needed to understand the weakening mechanism discovered by Di Toro *et al.*, but their findings may provide a helpful clue in balancing the faulting budget. As applied to tectonic faults, the results indicate that frictional stress and shear heating may be much lower than expected — implying that faulty assessments of income, rather than of expenses, are at the root of the energy budget imbalance.

There are several reasons for caution in attempting to extrapolate the new results to tectonic faults. Foremost among these are the roughness of faults and the thick accumulations of 'fault gouge' — granular wear material — within fault zones. Samples used in laboratory friction experiments are very smooth compared with natural faults, and it is not clear if a thin layer of silica gel could effectively lubricate a rough, gouge-filled fault. Laboratory experiments[5] on quartz gouge do not exhibit the extreme frictional weakening seen by Di Toro *et al.* Furthermore, fault rocks and gouge tend to be composed of several minerals, which would argue against a weakening mechanism that operated only on quartz-rich rocks.

Nonetheless, several lines of evidence seem to point to a high-speed, dynamic weakening of fault zones[6]. The threshold weakening velocity reported by Di Toro *et al.* would help in relating this dynamic weakening to seismic data. Previous analyses of frictional weakening[7,8] have been predicated on the expectation that considerable weakening would occur only for large earthquakes of magnitude 5 or greater. However, seismic-stress reduction — that is, the drop in frictional stress caused by earthquakes — is remarkably consistent over at least six orders of magnitude in fault dimension, and earthquake frequency–magnitude distributions obey a self-similar power-law relation over this same range. These observations are good evidence that the physics of earthquake rupture is the same for small and large earthquakes.

The work of Di Toro *et al.* implies that dynamic weakening does not have a threshold determined by earthquake magnitude: in their experiments the onset of weakening occurs at only a few millimetres per second, which would be reached even for very small earthquakes. In the context of this model, all earthquakes would experience considerable dynamic weakening and there would be no break in earthquake scaling relations. Furthermore, because shear heating would be negligible, dissipation of seismic energy would be dominated by radiation of seismic waves and creation of surface area.

The new results are a step forward in understanding rock friction and how it may change as faults accelerate from slip rates associated with creep and plate tectonic motion (millimetres per year) to seismic slip rates of metres per second. It will be necessary to find out if the weakening mechanism described applies to rough surfaces and can be extended to tectonic faults. If it can, we would have at least a partial solution to the problematic energy budget for faulting. But faults that experience substantial aseismic creep and do not generate earthquakes would still be expected to have high frictional strength and significant shear heating. ■

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