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

NATURE

100 YEARS AGO

An interesting paper on a familiar subject, the relation of temperature to the keeping property of milk, has reached us from Storrs, Connecticut. The view of the writer, Mr. H. W. Conn, the well-known dairy bacteriologist, is that the keeping of milk is more a matter of temperature than of cleanliness. He points out that at 50° F. milk may not curdle for two weeks, whereas at 70° F. it may keep but forty-eight hours, and at 95° F. but eighteen hours. This curdling is due to the action of bacteria, and the effect of temperature on their multiplication is surprising. Thus at 50° the ordinary milk organisms increase about 5-fold in twenty-four hours, but at 70° they may multiply 750-fold in the same time.

From *Nature* 28 January 1904.

50 YEARS AGO

At a conference called by the Federation of British Industries in London, on January 14, to discuss the shortage of science teachers in schools, the president, Sir Harry Pilkington, said that the national interest demands that enough science teachers of quality, for all types of educational institution, shall teach and train students in the next few years, so that our scientific and industrial leadership of the world over the next generation may resist challenges… Of the good academic men with fine personal qualities — of whom industry, research and the universities and schools must all have some — there are not enough to go round… The answer to the shortage of graduate teachers in science is that "we must make sure we are using well all the scientists we have in research and in industry and that we must somehow again make schoolmastering attractive to the young man of spirit, imagination and ambition". How is this to be done? More and more people are coming to think that the benefits of salary and other differentials must go to good men who actually do the teaching as opposed to good organizers and administrators in the schools… There is considerable evidence, culminating in the latest report of the Advisory Council on Scientific Policy, to show that Great Britain is already behind some of its important industrial competitors in the application of science. To meet this situation we need not only a restoration of our former standards of science teaching but also a considerable advance on these standards.

From *Nature* 30 January 1954.

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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Materials science

A natural solution to corrosion?

Stuart Lyon

Corrosion damage can be reduced if inhibitor molecules are introduced into a metal's environment. As inhibitors may themselves be noxious, the inhibitory properties of natural amino acids are now under scrutiny.

It is one of those peculiar aspects of human nature that certain topics are not to be discussed in polite company. If such discussion becomes unavoidable, we disguise the true nature of the activity by euphemism. So, a rat catcher becomes a 'rodent control operative' and a toilet cleaner might be styled 'sanitary inspector'. Of course, being human, we scientists and engineers also aim to improve the image of our fields of endeavour. Hence, studies in pollution become 'environmental protection' and hot-dip galvanized steel is now 'surface engineered'. Sadly, some topics appear forever irredeemable.

Corrosion is both one of those topics that no one really wants to talk about, and one that seems to have no acceptable alternative description. It is also a subject that touches all our lives. In industrialized economies, material degradation through corrosion costs at least 2–3% of gross national product per annum. However, up to a third of these costs might be saved through the implementation of advanced techniques for controlling corrosion. One such technique, using natural amino acids, is now pursued by Ashassi-Sorkhabi and colleagues[1], in work published in *Applied Surface Science*.

In practice, corrosion may be reduced by contriving to modify the chemistry of the material surface, or of its environment, to slow the rate of any reaction between them. For example, environmental modification may involve the addition of small quantities of chemical inhibitors, which profoundly affect the kinetics of the individual electrochemical reactions that together comprise the corrosion process. Corrosion inhibitors are widely used, for example in the water treatment of boilers, and in commercial and domestic heating and cooling systems, where conventional formulations often include species (such as nitrite or benzoate) that have significant toxicity. As a result, proper disposal is awkward and comes at a substantial cost.

Another complication arises in the form of the mineral acids that are typically used in industrial processes for cleaning and descaling metals, and also to acidify oil wells — here, a strong acid, such as hydrochloric acid, is injected at intervals into a well to aid the break-up of rock strata and ease the extraction of oil. The presence of acid will obviously speed up the corrosion of the carbon-steel well-casings and pipes of the drilling rigs (Fig. 1), although inhibitors can be added to control it. But, once again, large quantities of used, contaminated, inhibitor-treated acid cannot be simply neutralized and dumped: inhibitors such as phosphonates, alkynes and quaternary ammonium salts are significant biohazards and pollutants in their own right.

It was therefore with some interest that I read Ashassi-Sorkhabi and colleagues' paper[1], in which they consider the use of the simple amino acids alanine, glycine and leucine as corrosion inhibitors for carbon steel in hydrochloric acid. In acid inhibition, effective inhibitors generally form a monolayer (or perhaps multilayers) on a metallic surface, which is oxidized to some degree, depending on the pH of the environment; electron-donating groups such as N, O, S and P on an inhibitor molecule can often enhance strong adsorption. Because the inhibitor layer interferes with electron transfer and excludes the active acid from the metal surface, the rate of corrosion is reduced — although this simplistic mechanism is by no means the whole story.

In studying the effect of their chosen amino acids, Ashassi-Sorkhabi and colleagues have used a standard electrochemical method, called potentiodynamic polarization, to work out the surface coverage of each species on the metal. The electrochemical potential of the metal in the environment is brought to some negative value, then swept to a more positive value and the current is measured simultaneously. Changes in the current flow as the environment changes (that is, as the concentration of amino acid in the hydrochloric acid is varied) provide information about the reaction kinetics at the acid–metal interface, and hence about the overall rate of corrosion.

The three amino acids prove to be quite functional — although not outstanding — corrosion inhibitors. At concentrations of 0.1 and 0.01 moles in 0.1-molar acid, their presence reduces the corrosion rate by between 50% and 90%, which implies at least a doubling of component lifetime. And, of course, the disposal of a naturally occurring amino acid is considerably less of a problem than for more conventional inhibitors.

GETTY IMAGES

Figure 1 **Acid attack: drill pipes on oil rigs suffer corrosion.**