A section of California's San Andreas fault on the Carrizo Plain, seen from the air.

Photo credit: Ian Kluft, published under the

Earthquakes in the lab: a new device for measuring high-speed friction

An earthquake in your lab might sound like an undesirable thing, but that is exactly what **Professor Terry E. Tullis** at Brown University intends to achieve with his new machine. Designed to measure the high-speed friction that occurs at high pressure between rocks in an earthquake, this one-of-a-kind device can provide new insights into the underlying mechanics of earthquakes and a better understanding of the deformation of rocks under such extreme physical conditions.

Earthquakes kill thousands of people every year. In their wake, they also leave billions of pounds of infrastructure damage, survivors displaced from their homes, and aftershocks, meaning many more earthquakes for months to come. Despite this, predicting the exact moment an earthquake will occur is still an impossibility.

Earthquakes occur mainly due to the natural movement of the Earth's plates. The faults that form the boundaries between tectonic plates are prevented from moving most of the time by friction. While the plate boundaries are thus locked together, the bulk of the plates are still moving relative to each other, building the stress and strain energy near the faults. When the stress somewhere on the fault becomes sufficiently large to overcome static friction, the rocks on that part of the fault start to slip and slide at a lower friction value, called dynamic friction. The size of the patch on the fault that is slipping at this lower friction level grows, expanding rapidly to allow a significant part of the fault to slip rapidly. This releases the built-up energy and allows the rocks across the plate-boundary faults to move past each other, catching up with the bulk of the plates.

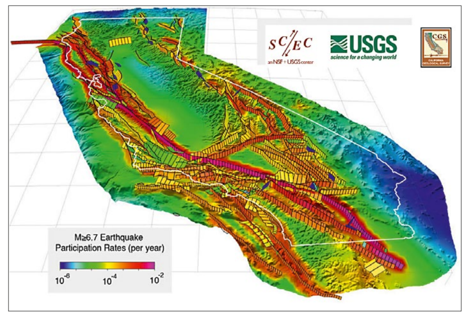
This rapid release of all the stress and strain energy that has built up as a result of the inexorable motion of the plates is the phenomena known as an earthquake. The strain energy is very rapidly converted to seismic energy and frictional heat. The details of the rapid change from static to dynamic friction on a fault is what determines both how rapidly the ground will shake and the ultimate destructive power of the quake. The Richter magnitude scale, or the number given to an earthquake to describe its severity, increases with the size of these seismic waves.

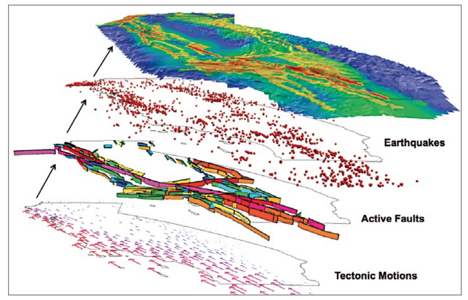
Friction is a subject of great fascination to Professor Terry E. Tullis at Brown University. His research is all about trying to understand the fundamental mechanisms of earthquakes. With this understanding, in the future it might be possible to determine whether faults give off some indication that they are about to slip rapidly or how big a growing earthquake might become. If this were possible, it could perhaps lead to developing systems capable of predicting seismic events.

Finding a way to run laboratory experiments to understand frictional behaviour at elevated pressure and high speed is crucial for understanding the behaviour at the earthquake source

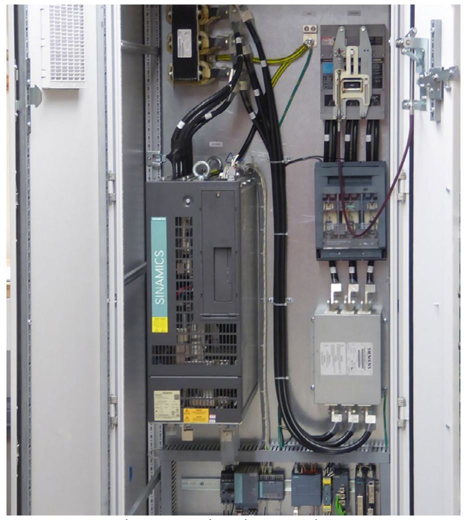
THE DREAM MACHINE

Professor Tullis uses laboratory-based experiments that attempt to recreate and monitor the physical conditions found at the sites of earthquakes, combined with computational modelling. To attempt to recreate earthquake conditions experimentally, a variety of machines are used to subject rock samples to the pressures, stresses, temperatures, slip speeds, and slip amounts that occur during earthquakes. Because the factors and conditions at which earthquakes occur are so extreme, it is hard to reproduce all of them in the laboratory. Consequently, none of the various machines in use are able to reproduce all of these conditions.



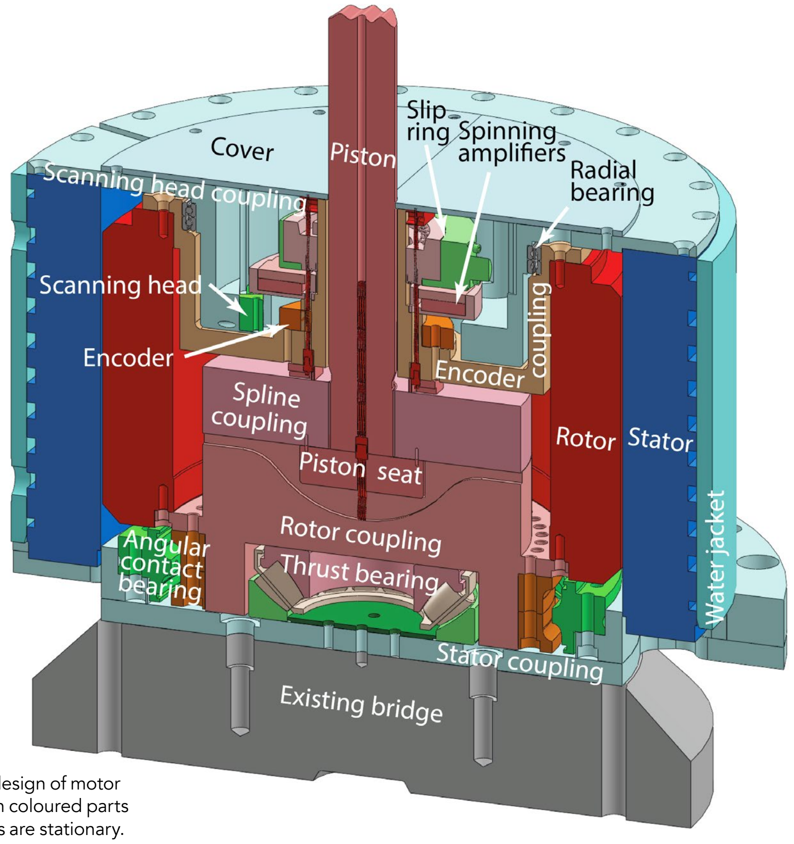


Top: Uniform California Earthquake Rupture Forecast. Bottom: Several data sets from California. Both images from Southern California Earthquake Center, USC.


Components that control and power the 100 kW servo motor.

At Brown University in 1980 Professor Tullis designed and built what is still a unique high-pressure, rotary-shear machine that is capable of reproducing many of the relevant earthquake conditions, including the pressures, stresses, and slip amounts. Ring-shaped samples inside a high-pressure vessel are forced to slide over one another due to the action of a 7.5 kilowatt (ten horsepower) motor, and the static and dynamic friction of the rocks can be measured. This machine has performed many experiments which have greatly expanded our understanding of earthquake instabilities. Now Professor Tullis and his group are investigating how to make it even better.

The so-called 'Dream Machine' is a concept that was developed by experts in the field of rock friction experiments. This would be a machine capable of exactly mimicking all of the real conditions found in earthquakes. This would include being able to create the very high slip speeds found in seismic events while the rocks are at high pressure, such as exists in the depths of the Earth where earthquakes occur. While the study of high-speed friction effects has been underway for a few years, all the experiments have been done at atmospheric pressure using relatively low stresses. Finding a way to run laboratory experiments to understand frictional behaviour at elevated pressure and high speed is crucial for understanding the behaviour at the earthquake source.



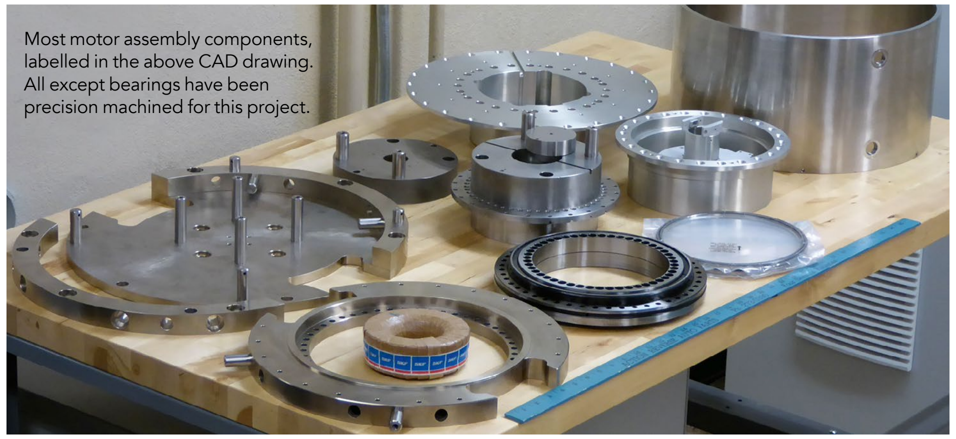
Prof Tullis's CAD design of motor assembly. Reddish coloured parts rotate while others are stationary.

Professor Tullis' machine is unique in approaching natural conditions for studying friction events

SEISMIC LABORATORY EVENTS UNDER PRESSURE

However, the technical challenges of producing the Dream Machine are numerous. Much as rubbing your hands together is one way to convert friction into heat energy, the rubbing together of plates during a quake can generate temperature increases of hundreds of degrees. Immense pressures are involved because the weight of the overlying rocks means that the plates push hard against each other as they rub together. This means that any lab-based equipment needs to be capable of operating under such extreme conditions and generating sufficiently high power to rub the samples rapidly enough against each other whilst applying huge pressures.

While the development of the Dream Machine is still in the pipeline, Professor Tullis is making the next big leap to such equipment. He is in the process of upgrading the current machine at Brown University by adding a 100 kilowatt (135 horsepower) servo motor to the drive system. This will allow the rotational slip speed of the sample to increase from the present ten millimetres per second to four metres per second, a speed equal to those on a fault during earthquakes. Furthermore, the motor assembly designed by Professor Tullis includes a device that allows slip on the sample to be measured and thus controlled to the amazing precision of one billionth of a meter, or 100,000 times smaller than the diameter of a human hair.


Most motor assembly components, labelled in the above CAD drawing. All except bearings have been precision machined for this project.

Q&A

What type of samples will you be looking at in your new apparatus?

We will look at a range of rock types, trying to use ones that are typically found in natural faults. We sometimes study rocks that have only one mineral in them, such as quartz or mica, so we can understand the behaviour of the components that make up more complex rocks, such as granite, but we also study the more complex rocks themselves.

What was the greatest technical challenge you faced in its development?

There have been three challenging stages so far. The first was finding components that would fit in the available space in my machine, namely a motor with sufficient speed and power, an encoder with sufficient precision to measure its rotation accurately, and a motor controller that could power the motor and listen to the encoder as well as another existing measurement device (a resolver). The second challenge was designing all the details of the motor assembly so that the frameless motor and the encoder would all fit together with the necessary bearings and fixtures into a small existing space. The third was getting all of the pieces, some quite large, machined with sufficient precision that the motor will run smoothly at 1800 revolutions per second without vibration, all within a constrained budget.

What do you think are the key unanswered questions in the mechanics of earthquakes?

There are many, but certainly one of the most important is discovering how large the stresses are on faults before, during and after earthquakes. Seismic observations suggest that the net stress reductions typical for an earthquake are relatively small, certainly compared to what might be expected, given the large changes between static and dynamic friction measured in lab experiments. So we need to understand how friction on real faults changes during what we call the seismic cycle, namely how it increases with time between earthquakes, how it evolves during the initiation phase of frictional failure across the locked fault, and how it depends on the speed and amount of slip during and right after an earthquake. Laboratory studies of how friction changes during the seismic cycle are important to this understanding. However, it is also critical to learn what frictional processes actually are important on faults in the Earth, and thus what is the real-world relevance of the frictional behaviour studied in the lab.

How do you think dynamic friction effects could be used in earthquake forecasting systems?

Understanding how friction changes during the initiation phase of an earthquake is probably the most relevant aspect for learning whether the Earth may emit signals that could be used to anticipate earthquake occurrence. Dynamic friction is only relevant once the earthquake is underway. However, it is important for how large the earthquake will be and hence how much damage it can produce. It likely is also important for how long it may be before the stress can build up again enough for the next earthquake to occur.

What timescale do you think the Dream Machine will be achievable on?

This depends on many factors, including our developing understanding of dynamic friction that we hope will come out of the machine we are now building, and hence what the community sees as continuing to be important. Clearly adequate financial and skilled personnel resources are key. My guess is that it will be perhaps ten years before it can be built.

Detail

RESEARCH OBJECTIVES

Professor Tullis has designed a one-of-a-kind machine to measure the frictional properties of rock at high pressure during earthquakes. The data obtained from this machine will greatly enhance our understanding of how and why earthquakes occur.

FUNDING

National Science Foundation (NSF)

BIO


Professor Tullis received his BA from Carleton College in 1964, attended Columbia University for one year, then UCLA, where he got both his MS (1967) and PhD (1971). He started at Brown University in 1970 and was promoted to full Professor in the Department of Geological Sciences in 1989. Though officially retired as of 2005, Professor Tullis is still actively doing research within the department.

CONTACT

Prof Terry E. Tullis
Professor (Research) and Professor Emeritus
Department of Earth, Environmental, and Planetary Sciences
Brown University
Providence, RI 02912-1846
USA

E: terry_tullis@brown.edu
T: +1 401 787 2210
W: https://vivo.brown.edu/display/ttullis

Back in 1980, motor and measurement technology did not even come close to allowing this motor assembly to be built. The modified high-pressure rotary shear machine will allow the study of high-speed friction-weakening mechanisms in conditions similar to those in the crustal earthquakes that are abundant on all plate boundaries. While the pressures and temperatures attainable by Professor Tullis' modified machine will still not be as high as the experimental community's ultimate aim, this machine is unique in approaching natural conditions for studying friction events.

All of this is crucial for enhancing our knowledge of the fundamental physics of earthquakes. One hope is that this understanding might enable us to read signals from the Earth that could anticipate the location, size, and timing of damaging earthquakes.