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Drilling Into Faults Quickly After Earthquakes

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What will it take to advance from current empirical models of earthquake initiation and fault slip to a full physics-based understanding of rupture processes? The most important requirements include knowledge of absolute stress levels on the fault during an earthquake, how stresses recover afterward to prepare for the next event, how one earthquake promotes or inhibits another, and how material properties of a particular fault affect its propensity to fail catastrophically rather than creep.

Immediately after a large earthquake, an opportunity exists to fill these knowledge gaps. For a few years after a major earthquake, the fault is observably changing and a deep borehole can capture measurable signals to address the key questions.

The Need for Boreholes Through Active Faults

Earthquakes occur when rising local stress overcomes the fault's frictional strength. A large earthquake occurs, rather than a small one, when strength is pervasively low or stress accumulation is high over a large region of the fault. However, the strengths of faults and their time and slip dependences are generally unknown, especially for large displacements and high slip velocity. Current laboratory evidence suggests that friction could drop dramatically during an earthquake, but actual fault friction levels of a large earthquake have never been measured. Rapid temperature and direct stress measurements in a borehole can measure this friction.

After a fault slips, local strain is released and the final fault strength may be low due to dynamic frictional processes. In the long intervals between earthquakes, fault strength recovers slowly. However, recent work has shown that observable proxies for fault strength, such as seismic velocity, ground deformation, permeability, and aftershock rate, all change quickly after an earthquake [*Brenguier et al.,* 2008; *Kitagawa et al.,* 2002]. Scientists can use boreholes to capture these transients and thus better identify the physical processes controlling strength on a fault.

Additionally, recent studies show that fluids, mineralogy, and deformational structures all play important roles in fault behavior. Specific combinations of these material properties lead faults to episodic slip (earthquakes) as opposed to gradual creep [*Dixon and Moore,* 2007]. Clarifying the controlling physical and chemical conditions of faults can only be done by sampling and instrumenting faults that have ruptured in large earthquakes. During healing following an earthquake, new surface area generated by fracturing is attacked by rapid chemical reactions that can destroy the record of slip, so making observations soon after an earthquake is important.

Current data suggest that up to 80% of all earthquakes are triggered by another earthquake, and therefore earthquake triggering provides a general window into earthquake initiation [*Marsan and Lengliné,* 2008]. A quickly drilled borehole can record the stresses and interactions of aftershocks. Illuminating triggering mechanisms is an important step toward earthquake prediction.

Key Borehole Measurements: Temperature, Stress, and Strain

Temperature profiles across the fault are the most direct way to quantify coseismic friction [e.g., *Tanaka et al.,* 2006; *Kano et al.,* 2006]. Because most frictional resistance is dissipated as heat, any temperature increase on the fault at the time of the earthquake is potentially interpretable as a cumulative measure of frictional heat generated during slip [*Lachenbruch and Sass,* 1980]. To obtain the largest and most unambiguous signal possible, these measurements must be recorded soon after earthquake slip, and at depths where shear stress is sufficiently large to generate an observable temperature anomaly (0.2°C; see Figures 1a and 1b).

Advection of frictionally generated heat by fluid flow following an earthquake must also be considered when interpreting downhole temperature data [*Kano et al.,* 2006]. *Fulton et al.* [2010] illustrated that temperatures across a fault zone should not be markedly affected by fluid flow driven away from the fault by locally elevated pore pressure (e.g., due to thermal pressurization or shear compaction). Repeated measurements are also important to monitor the evolution of thermal anomalies with time and to separate drilling-induced anomalies from frictional heating signals.

Another way to quantify fault strength is to measure absolute stress directly. Determining the stress profile during rapid response fault zone drilling, including the orientations and magnitudes of three-dimensional stresses, may reveal how stress changes are induced by fault rupture. Borehole studies can provide information about vertical stress by downhole density logging, about minimum horizontal stress by extended leak-off test and hydraulic fracturing, about maximum horizontal stress by breakout width analyses [*Zoback et al.,* 2003], and about three-dimensional stress by anelastic strain recovery (ASR) tests on core samples [*Lin et al.,* 2006].

Some of the clearest evidence for frictional dissipation at faults is seen in analyses of fine-scale structures of core samples. For instance, the presence of any melt rock (pseudotachylyte) is an immediate indicator of high frictional heating early in the slip process. Depending on the melt composition and permeability of the host rock, low friction during slip may be inferred later in the earthquake once melt has lubricated the surface. Geometric structures can also be used to assess the dynamic fluidization of the gouge and thus its likely rheology. If pseudotachylyte or fluidization structures are found, follow-up laboratory experiments can help determine the rheology of the melt or granular flow. Grain-size distribution and fracture density also contain key information about dissipation. The energy absorbed in fracturing and surface creation is energy not dissipated by any other means, like friction. Thus, observing structures in the core and borehole wall provides insight into frictional behavior and localization processes that ultimately control the effective stress. Fault zone mineralogy changes rapidly during the healing process, so one must make core observations as quickly as possible.

Seismometers and strainmeters for recording aftershocks and afterslip are important components of the program needed to characterize the postseismic activity. The low noise conditions of boreholes enable much better resolution for recording small seismic and strain signals.

By E. E. Brodsky, J. Mori, and P. M. Fulton

Prior Drilling Projects

Drilling projects following the 1995 M_w 6.9 earthquake in Kobe, Japan, and the 1999 M_w 7.6 earthquake in Chi-Chi, Taiwan, pioneered rapid drilling as an approach to earthquake physics that provides some important and tantalizing results.

The Nojima Fault Zone Probe following the Kobe earthquake demonstrated that the friction on the fault was lower than had been previously expected [*Ikeda et al.*, 2001; *Tsukahara et al.*, 2001; *Yamamoto and Yabe*, 2001].

The Taiwan Chelungpu Fault Drilling Project following the Chi-Chi earthquake built on the technical and scientific experience of Nojima in an effort to constrain the friction on the fault in different ways. A shallow borehole captured the first temperature measurement at 300-meter depth 15 months after the earthquake and inferred a coefficient of friction of at most 0.1 [*Tanaka et al.*, 2006]. Later, measurements in a deep hole were made at 1.1 kilometers, and once again, a low coefficient of friction was inferred [*Kano et al.*, 2006].

Although measurements taken in the San Andreas Fault Observatory at Depth (SAFOD) borehole that crosses the San Andreas Fault are not designed to constrain the amount of heat generated from a particular large earthquake, the lack of a heat flow anomaly in the borehole and surrounding area is also consistent with low frictional resistance during slip averaged over long periods of time [*Williams et al.*, 2006].

All of these projects were able to place only upper bounds on the coefficient of friction because of depth and time limitations (Figure 1c). By contrast, a faster, deeper hole could directly measure the absolute value of friction.

The Nojima project also captured the recovery of the fault. Repeat injection experiments indicate at least a 50% permeability decrease in the fault zone over the 3 years following the earthquake [*Kitagawa et al.*, 2002]. These data suggest that chemical and mechanical processes were rapidly changing the fracture networks in the fault, and therefore these poorly understood processes were likely changing the strength.

The Taiwan project also provided constraints on fluid properties of fault zones. Microstructures in the core include grain injections that imply that the fault gouge flowed during an earthquake [*Otsuki et al.*, 2005]. Using a pair of boreholes to perform cross-hole experiments, hydrogeological tests constrained the damage zone permeability even closer to the fault than was possible in the Nojima case and thus provided a constraint on fluid flow during earthquakes [*Doan et al.*, 2006].

Planning for the Next Earthquake

These past projects highlight what needs to happen next. Deeper and faster measurements are necessary to obtain the desired temperature data and to observe the healing process of the fault. Following the devastating 2008 Wenchuan, China, earthquake, the Wenchuan Fault Scientific Drilling Program is coming closest to the targeted specification, with the start of drilling within 6 months after the earthquake. However, no project has yet reached the scientifically required target of drilling deep enough to measure a low coefficient of friction directly (Figure 1).

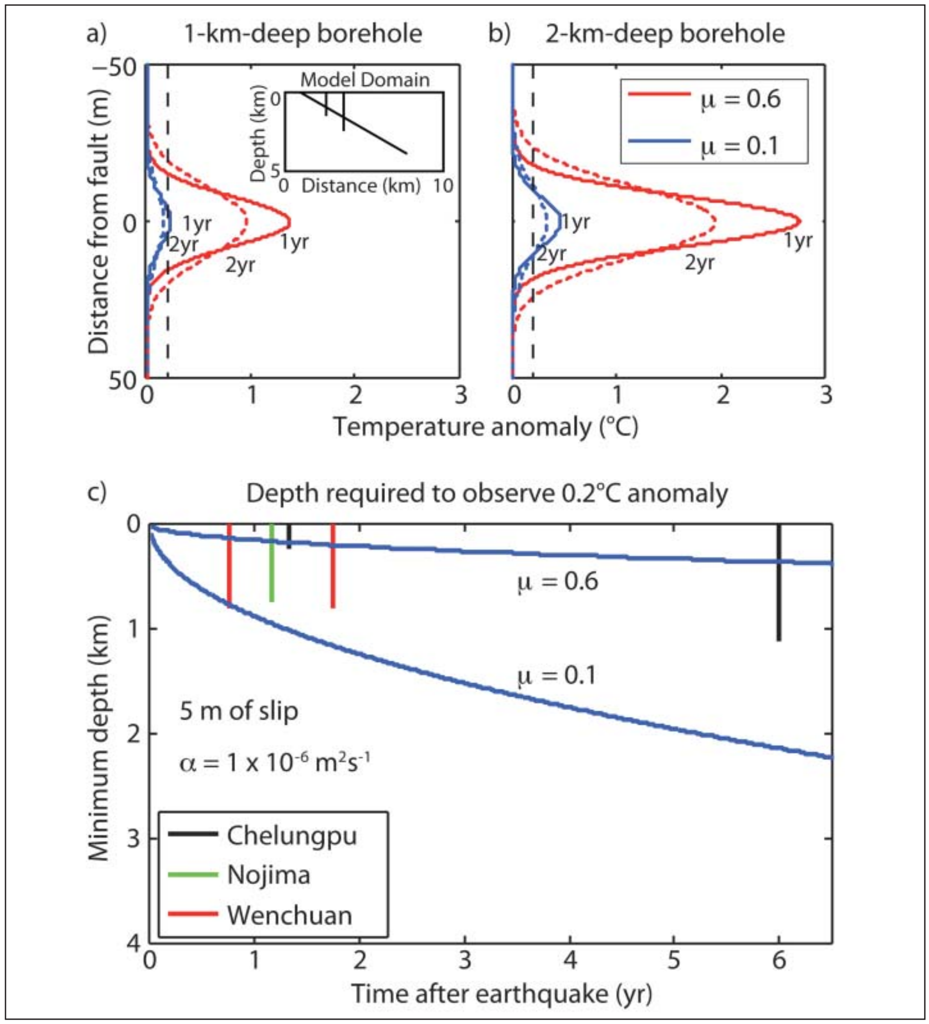

Fig. 1. Modeled frictional temperature anomalies resulting from a thrust earthquake with 5 meters of slip assuming a thermal diffusivity (α) of 10^{-6} square meters per second. (a) Temperature anomaly for a borehole intersecting the fault at a depth of 1 kilometer. Red and blue curves show frictional heating for effective friction coefficients (μ) of 0.6 and 0.1, representing a strong and weak fault, respectively. Solid and dashed curves show the frictional heating anomaly 1 and 2 years, respectively, after the earthquake. Dashed black line shows the assumed detection threshold of 0.2°C; temperatures lower than this value cannot firmly be attributed to fault processes. (b) Temperature anomaly for a borehole intersecting the fault at 2-kilometer depth. Note how the deeper boreholes allow scientists to see a clearer temperature signal in both types of faults. (c) Blue curves show the minimum depth of borehole intersection with a fault to observe a temperature anomaly of 0.2°C as a function of time. The depth and timing of borehole completion of fault zone drilling experiments are shown as vertical lines at the top of the plot. Calculations and plots are from Fulton et al. *[2010].*

On land, earthquakes with at least 1 meter of surface slip typically happen every 2–3 years in accessible areas with sufficient infrastructure (Figure 2). In the United States the 1992 M_w 7.3 Landers (California), 1999 M_w 7.1 Hector Mine (California), and 2002 M_w 7.9 Denali (Alaska) earthquakes would all have been reasonable targets, along with the 1999 M_w 7.3 Izmit, Turkey, earthquake.

Rapid response drilling is obviously technically and logistically challenging. The more planning that is done now, the more likely it will be successful when a large earthquake provides the window of opportunity. A 2008 workshop jointly sponsored by the International Continental Scientific Drilling Program (ICDP) and the Southern California Earthquake Center (SCEC) prepared a science and technical plan for the drilling community, acknowledging the wide range of sites that may be encountered and the scientific issues to be addressed [*Brodsky et al.*, 2009] (see http://www.pmc.ucsc.edu/~rapid/). The group also recommended that international agencies embark on several specific preparatory activities and scientists compile necessary information on regional faults and extant boreholes, so that a drilling project can be quickly initiated to observe the valuable ephemeral properties of a large earthquake.

Fig. 2. Earthquakes on land with documented surface slips of greater than 1 meter during the past 20 years. Similar earthquakes in the future should be evaluated as candidates for rapid response drilling.

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MEETING

Interactive Workshop Discusses Nonlinear Waves and Chaos

Eighth International Nonlinear Wave Workshop; La Jolla, California, 1–5 March 2010

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Nonlinear waves and chaos were the focus of a weeklong series of informal and interactive discussions at the Eighth International Nonlinear Wave Workshop (NWW8), held in California. The workshop gathered nonlinear plasma and water wave experts from the United States, France, Czech Republic, Germany, Greece, Holland, India, and Japan. Attendees were from the fields of space, laboratory, and fusion plasma physics, astrophysics, and applied mathematics.

Special focus was placed on nonlinear waves and turbulence in the terrestrial environment as well as in the interstellar medium from observational, laboratory, and theoretical perspectives. Discussions covered temperature anisotropies and related instabilities, the properties and origin of the so-called dissipation range, and various coherent structures of electromagnetic as well as electrostatic nature. Reconnection and shocks were also topics of discussion, as were properties of magnetospheric whistler and chorus waves. Examples and analysis techniques for superdiffusion and subdiffusion were identified. On this last topic, a good exchange of ideas and results occurred between a water wave expert and a plasma expert, with the rest of the audience listening intently.

The workshop was sponsored by the International Union of Radio Science, the American Physical Society Division of Plasma Physics, and University of California, San Diego. The results will be published in the joint AGU/European Geosciences Union journal *Nonlinear Processes in Geophysics*.

The format of NWW workshops is different from most scientific meetings and workshops. All speakers get an equal amount of time for their talks (graduate students may opt for half time), and thus there are no "principal speakers." Audience members may interrupt the speaker with questions of clarification or physics at any time during the talks (session chairs must cut off overly lengthy questions if they occur). All attendees must give a talk. The number of attendees is kept small (fewer than 35) to allow for adequate discussion and interaction. Attendance is by invitation only. Currently active and leading experts on topics are chosen so that the level of discussion will remain high. Finally, the workshops are kept flexible enough that authors can change the topic of their talks during the meeting to present results more along the mainstream of the workshop; this was done