MEETINGS

Radiated Energy and the Physics of Earthquake Faulting

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On the third day of a recent AGU Chapman Conference, held in Portland, Maine, near the Two Lights fault zones and the Fort Foster brittle zone, conference participants spent the gray June day scrambling over rocky ledges above the crashing surf along the coast of the Atlantic Ocean.

With field trip leader Mark Swanson, who with his students has studied the area in detail over the past 20 years, participants examined evidence of ancient earthquakes from about 300 million years ago when these rocks were 8 to 10 kilometers deep. This evidence included pseudotachylytes—glass generated by heating during fault slip at midcrustal depths.

In the preceding technical sessions of this conference, there had been discussion of pseudotachylytes. Now, for seismologists, this view of an ancient earthquake rupture, occasionally veined with pseudotachylytes, frozen in time, was humbling. For embedded in those rocks was more fault-zone complexity than could possibly be accommodated in the models used to simulate earthquakes.

In many ways, this fieldtrip encapsulated the themes of this conference, which focused on the energy changes that take place during earthquakes. In particular, exhumed faults such as those observed during the field trip provide some of the most direct evidence available concerning the physical mechanisms that may influence the earthquake energy budget, including melting (pseudotachylytes) due to frictional heat generation.

The conference was held to discuss the many controversial aspects of earthquake energy budgets. Radiated seismic energy, a fundamental measure of an earthquake, has a history of study extending back about 90 years (in 1915, Galitzin published an energy estimate of the 1911 Pamir earthquake in central Asia), and yet there is remarkably little agreement over its estimation, scaling, and interpretation.

The other terms in the budget are even more problematic. Estimations of fracture energy, associated with rupture-surface expansion, are highly uncertain because they can be inferred only from dynamic rupture models. Similarly, estimates of the frictional energy have been inconclusive despite ambitious programs to measure and analyze heat flow and other relevant data.

Although the energy budget can be summarized quite simply (released elastic strain energy = radiated seismic energy + fracture energy + energy to overcome fault friction), arguments concerning its components typically range over an order of magnitude.

Accordingly, nearly 130 Earth scientists from 14 countries visited Portland to debate the energy budgets of earthquakes. Their expertise included observational and theoretical seismology, fault-zone geology, laboratory rock mechanics, fracture mechanics, and geochemistry.

Each technical session included two short keynote talks, intended partly to provide background, but mostly to provoke discussion and argument, which accounted for the vast majority of the time. Further discussion took place around 70 posters, an important part of the conference.

Measurement of Radiated Energy

The first session concerned the best understood component of the energy budget, the radiated energy. Although this is the only component that can be measured directly, different techniques for its estimation often yield a wide range of results for a given earthquake. During this session, however, it became clear that technologies for radiated energy estimates have recently improved to the extent that these discrepancies can be reduced substantially.

This was illustrated during a special evening session devoted to the seismic energy of the 26 December 2004 Sumatra earthquake. Despite the challenges of estimating the energy radiated by this enormous earthquake, three independent methods, reviewed by workshop co-convener Hiroo Kanamori, gave results that were within a factor of three of one another and are low for an earthquake of this magnitude. That is, this was a "slow" earthquake, as evidenced by the devastating tsunami and the relatively small damage from ground shaking.

The agreement between independent techniques for measuring the seismic energy of this great earthquake is an encouraging indication of progress in the ability to measure this source parameter. About 10 years ago, in contrast, independent seismic energy estimates for the 1992 Landers, California earthquake showed a range covering an order of magnitude.

Scaling of Radiated Energy

The discussion of how to measure radiated energy gave way to debate concerning its scaling and how this parameter is affected by factors such as tectonic setting and fault maturity. Is the ratio of radiated energy to seismic moment constant, or does it increase in some systematic way with increasing earthquake size? Although much evidence was presented regarding this question, nothing resembling a consensus seemed to emerge.

This ongoing disagreement within the Earth science community may be attributed partly to other factors that affect the ratio of energy to moment. That is, tectonic setting, fault maturity, and bandwidth limitations all seem to influence this ratio and thus may obscure the nature of energy scaling.

The question of seismic energy scaling is part of the more general issue of whether small and large earthquakes differ in terms of their physics of faulting. As proposed by Brace and Byerlee in the 1960's, abrupt frictional slip (stick-slip) in laboratory experiments could involve the same rupture processes as crustal earthquakes, small and large.

More recently, however, many mechanisms have been invoked to argue that large earthquakes differ in essential ways from small ones. Many of the proposed mechanisms involve frictional heating that may cause melting (and form pseudotachylytes), fluid pressurization, flash melting, several types of lubrication, and other weakening effects. These mechanisms are usually thought to be activated at some threshold slip, often in the range of 0.1 to 1 meter, and result in substantial dynamic weakening of the fault zone, yielding enhanced slip rates and energy radiation.

Much of the discussion concerned the extent to which seismological, geological, and laboratory observations motivate the hypothesis that large and small earthquakes are fundamentally different.

Insights From Laboratory Experiments and Numerical Modeling

Two sessions were devoted to insights contributed by numerical modeling of earthquakes and the simulation of earthquake rupture processes in laboratory experiments. Dynamic rupture models that replicate earthquakes are crucial to the understanding of the parts of the earthquake energy budget that are, at least to some extent, unobservable. Fracture energy, as mentioned earlier, is perhaps best constrained by means of rupture models, although laboratory experiments have contributed considerably to the understanding of this enigmatic term in the energy budget. Whereas the dynamic rupture models constrain the size of the fracture energy, the physical nature of this energy change is best defined by geologic and laboratory data.

During the conference, a consensus, based partly on studies of exhumed faults, seemed to emerge that fracture energy is not simply the energy associated with the creation of new surface area but instead includes a substantial component of frictional energy loss during fault slip.

Concerning the issue of whether large and small earthquakes involve different rupture physics, the laboratory results remain equivocal. Rupture processes that could dynamically weaken faults at large slips and slip rates have been produced in laboratory experiments, but it remains to be seen whether these effects are likely to occur in natural earthquakes.

Exhumed Evidence

The third day of the conference, including the field trip, featured observations and discussions of exhumed faults. Seismogenic faults at depth can be directly observed following tectonic uplift and erosion (e.g., the coastal outcrops near Portland). Mining and drilling can also expose ruptures in situ; the discussion included examples of both.

Drilling for the San Andreas Fault Observatory at Depth intersects seismic source zones near the recent Parkfield earthquake, and in Taiwan the Chelungpu-fault drilling project reveals evidence of large-slip behavior during the 1999 Chi-Chi earthquake. Similarly, deep-level gold mining operations in South Africa occasionally expose rupture zones of mining-induced earthquakes. Debate on the apparent scarcity of fault-generated pseudotachylytes focused on whether they were rarely generated or only rarely preserved in recognizable form.

Fault localization was another issue that featured prominently in the discussion during this long, intense day. The fault systems that had been observed in the field earlier that day involved total slips of several meters, distributed over zones at least a few meters wide. These examples of immature faults, their 300-million-year age notwithstanding, were shown to have slipped during one or a few earthquakes. By contrast, the Punchbowl fault in southern California shows 44 kilometers of slip localized to a zone less than a meter wide, an example of a mature fault.

Fault Strength

This question of whether energy budgets on mature and immature faults differ was pursued further during the final afternoon of the conference, when the strength of mature, active faults was debated. Although in situ stress measurements suggest that crustal strength is generally consistent with expectations based on laboratory friction measurements (Byerlee's law), many types of data and analyses suggest that major active faults, including plate boundaries, are considerably weaker.

The San Andreas fault is the best studied example of this, and for nearly 40 years the arguments concerning its strength have persisted. Determining the strength of the San Andreas fault, as well as other major active faults is critical to understanding earthquake energy changes. If the San Andreas is as strong as expected from laboratory results, then frictional energy losses are much larger than the other components in the energy budget. If the San Andreas fault is as weak as suggested by analysis of heat flow data, for example, then this component is much less prominent in the budget, at least for earthquakes that rupture mature, active faults.

The discussion involved observations and analyses of heat flow, in situ stresses measured at depth, stress direction indicators, hydrologic data, and exhumed-fault evidence of fault strength. Although this longstanding question was not resolved to everyone's satisfaction, the discussion sharpened the understanding of the remaining uncertainties.

One of the primary goals of this conference was to encourage Earth scientists in different disciplines to share their various perspectives concerning the physics of earthquake faulting. This goal was certainly achieved as indicated, for example, by the many comments from field geologists during the technical session on dynamic rupture models of earthquakes and, perhaps even more so, by the theoretical seismologists who were among the most enthusiastic participants crawling over the coastal outcrops to scrutinize the 300-million-year-old earthquakes.

An AGU monograph, to be published in December 2006, will describe the discussions, arguments, and main results of this conference in more detail.

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References

Brace, W. F. and J. D. Byerlee, Stick slip as a mechanism for earthquakes, *Science*, 153, 990-992.

—A. McGarr, U.S. Geological Survey, Menlo Park, Calif.; R. E. Abercrombie, Department of Earth Sciences, Boston University, Boston, Mass.; H. Kanamori, Seismological Laboratory, California Institute of Technology, Pasadena; E-mail: mcgarr@usgs.gov

Young Scientist Network Holds Inaugural Workshop

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The vulnerability and sustainability of the global human-environment system is poised on a threshold of uncertainty in the near- and long-term future. The future of the planet may at least be partly in the hands of young scientists.

Because Earth system science has become increasingly integrative and the need for international communication is increasingly important, an international young scientist network was established in June 2005 as a key activity of the Analysis, Integration, and Modeling of the Earth System (AIMES) project of the International Geosphere-Biosphere Programme.

The goal of this network is to facilitate communication between young scientists who work on a wide range of biophysical and chemical climate models, those who work on models that include human decision making such as land use models or economic models, and scientists who analyze the observations that test these models.

The network will promote collaboration between the natural and social sciences and the discussion of the human-environment system as an integral component of Earth system models. An important element of the network is to encourage participants from developing countries to contribute their expertise in quickly changing and highly vulnerable environments and to enhance the human resources in important regions of the globe that will be needed for future science projects.

As a step toward fuller integration of Earth system science, the AIMES Young Scientist Network was inaugurated at a workshop in Breckenridge, Colo., in June 2005. (The former name of the network, the International Post-doctoral Network for Earth System Science, was changed following the workshop.)

Participating in the three-day meeting were 52 young scientists from 18 countries (Argentina, Australia, Bangladesh, Brazil, Canada, France, Germany, Ghana, India, Italy, Nigeria, Poland, Portugal, Russia, Switzerland, United Kingdom, United States, and Zimbabwe). Conference participants reflected the broad geographic composition of the network members.

While most participants are involved with the biological, chemical, and physical sciences, about one-fourth work on problems involving human decision making.

During the workshop, all participants presented a talk or poster on their research. In addition, two invited senior scientists gave introductory presentations on the two workshop topics. The first topic, on "*The end of nature? Human-Earth systems interactions*," was introduced by John Reilly of the Massachusetts Institute of Technology (MIT), Cambridge. The second topic, on "*Is there a scenario in the class? Different views of the future (multi-scaled approaches to Earth system modeling)*," was introduced by Ron Prinn of MIT.

The two workshop themes were well-reflected in participant presentations. One hot topic in the first session was how integrated assessment models were used by decision makers to understand scenarios that would achieve climate stabilization. Urbanization and urban development in the context of the global carbon cycle and climate change also were discussed.

The discussions highlighted difficulties in quantifying uncertainties, particularly in the context of the human/natural environment system and the consequences to the policy and assessment communities. Participants noted that greater involvement of scientists with a background in the social sciences is needed to help deal with these important issues.

The second session was devoted to using a hierarchy of models to examine the complexities of the coupled biogeochemical-climate system. Presentations ranged from studies of processes at local sites, to regional modeling studies and meta-analyses of global climate change experiments. One focus of the session presented was the aspect of physical coupling between land, ocean, and atmosphere and the biogeochemical interactions. Discussions underlined the importance, when linking biophysical and climate system science, of applying a wide range of modeling tools, such as simple conceptual models, models of intermediate complexity, and full three-dimensional general circulation models.