SCEC-Sponsored Workshop

Stress Triggering Conference Opens Window to Master Model

By Ross Stein, USGS Menlo Park

SCEC sponsored the conference "Earthquake Stress Triggering, Fault Interaction, and Frictional Failure" on June 8-10 in Carmel. Convened by Ross Stein, with financial support from the USGS, the conference hosted 57 participants.

In addition to the usual suspects, six came from Europe, and seven graduate students attended. This was the second stress triggering conference convened by SCEC. Thanks to Ruth Harris and Joan Gomberg, the collection of 13 papers growing out of the first conference will appear in *JGR* this fall.

Since its inception, SCEC has catalyzed research on how one earthquake sets up the next by the transfer of stress. If demonstrated, such a phenomenon could provide part of the foundation for the mythical Master Model. More than any other events, the 1992 Landers and 1994 Northridge earthquakes and their aftershocks have fueled studies of stress triggering.

SCEC's role has been important not only because it coordinated these earthquake investigations, but because SCEC encouraged people from different disciplines and viewpoints to attack these problems and to present their ideas and hash out their differences in intensive workshops and SCEC's annual meetings.

At the Carmel conference there was palpable excitement because, as more evidence pours in, some tenets of stress triggering are proving durable. Earthquakes in sequences tend to promote each other successively. Aftershocks tend to occur where the Coulomb stress is calculated to have risen and tend to be absent where it has dropped.

Uncertainty in these calculations, such as the friction coefficient, is beginning to diminish; the major faults exhibit very low values of friction, and minor faults show very high values. At the meeting, there was also frustration that other elements of stress transfer continue to baffle or elude us. Foreshocks, for example, just don't seem to stress the site of mainshocks. There are huge gaps in our understanding of dynamic stress triggering and transient stressing, including why friction can vary so strongly between two faults.

Earthquake Sequences

In closely spaced sequences, one shock generally stresses the site of the next (as shown in talks given by Massimo Cocco and Concetta Nostro; Deng and Lynn Sykes; Ruth Harris and Bob Simpson; Jian Lin), and these effects are visible for years and perhaps decades.

For continental thrust, normal faults, and young strike-slip faults, there is a strong sensitivity to unclamping; on major strike-slip faults, there is a strong sensitivity to shear stress change (Tom Parsons, Ross Stein, Bob Simpson, Paul Reasenberg). This suggests that faults may become frictionally weaker with age, cumulative slip, or length. Could this be the result of a slip-rate or healing-rate dependence (Chris Marone), material properties in evolved faults (Mike Blanpied, and Dave Lockner), large faults behaving more brittlely (Tom Heaton), rate and state constitutive behavior (Jim Dieterich), or poroelastic effects (Steve Miller, Jim Rice, and Paul Segall)?

Aftershocks show a strong sensitivity to Coulomb stress changes. Even more convincing, the seismicity rate jumps by an order of magnitude where Coulomb stress is calculated to rise by 1 bar after an earthquake and the seismicity rate drops where stress decreases (Shinji Toda, R. Stein, and J. Dieterich). This stress-change dependence of seismicity is seen both on the major faults and throughout the crustal volume surrounding a major earthquake (Greg Anderson, Jeanne Hardebeck) and is mirrored in the creep response of major faults (Roland Bürgmann). Although aftershocks are small, they are abundant and thus furnish good statistical tests of stress transfer, although perhaps not good enough to satisfy Yan Kagan.

Although large earthquakes tend to be preceded by an increasing rate of smaller shocks over a wide area encompassing the future earthquake (Charlie Sammis), foreshocks do not appear to promote failure at the future hypocenter (Ellsworth, Doug Dodge, and Greg Beroza). A break in the clouds is hinted by the result that the Lake Elsman "foreshocks" appear to have unclamped the Loma Prieta fault where it subsequently slipped the most (Hugo Perfettini, R. Stein, R. Simpson, M. Cocco).

Photos: Tom Henyey

Patio talk. Left: Ross Stein, Roland Bürgmann, Fred Pollitz, Bill Foxall, Oona Scotti. Middle: Monica Stein, Sharon Lack Stein, Nano Seeber, Mark Petersen, Dave Schwartz, Tom Rockwell. Right: Jim Rice, Yan Kagan, Charlie Sammis, Chris Marone , John Rundle.

Network and historical catalogs permit long-term statistical tests of stress transfer, subject to the nodal-plane ambiguity of the focal mechanisms and uncertainty in models of the secular stress conferred by fault slip at depth. Catalog analyses (SCSN and Harvard CMT) do exhibit stress triggering, but such tests are very sensitive to the rules and treatment of the catalog (Dave Jackson and Yan Kagan; Ruth Harris and Bob Simpson). New tools for dealing with nodal-plane ambiguity (Jeanne Hardebeck and Egill Hauksson), however, should permit better tests in the near future.

Although very large prehistoric earthquakes are tantalizing targets for investigation, it is going to be very tough to study stress transfer from the paleoseismic record because of imprecise fault slip distributions and earthquake dates (Dave Schwartz, Tom Rockwell). But knowledge of the timing and extent of the most recent prehistoric event is rapidly improving (for example, along the Landers, northern San Andreas and southern Hayward faults). This will enable estimates of the total stress state at the start of the historical catalogs and will be valuable for synthetic large-scale interaction models (John Rundle, Steve Ward).

Some stress triggering workshop participants took the optional sunset sail on the 65-ft sloop Zeus.
Above, left to right: Oona Scotti, Tom Rockwell, Roland Bürgmann
Below, left to right: Hugo Perfettini, Guy Ouillon, Mike Shulters, Dave Jackson

Photos: Ross Stein

Transient and Dynamic Coulomb Stress Change

Results incorporating viscoelastic deformation into stress calculations are promising (Shelly Kenner, Jian Lin, and Andy Freed) but have just begun to explore 3D effects (Fred Pollitz and Roland Burgmann; Jishu Deng). The stress transferred during the passage of the seismic waves is much larger than the static changes, particularly at large distances. Nevertheless, calculation of such transient stress changes is much more difficult (Debi Kilb and Paul Bodin), particularly when more realistic constitutive behavior is considered during the earthquake rupture process (Joan Gomberg).

Stress changes can be translated into earthquake probability changes with the help of the state/rate constitutive relations (S. Toda, R. Stein, Jim Dieterich, R. Harris, and B. Simpson). This has the potential to produce numbers that can be used by planners, emergency management people, and practitioners of seismic hazard analysis. Unlike the probabilities used today, such stress-based probabilities have the virtue that they are consistent with the occurrence aftershocks. What sets them apart is that they are highly time-dependent—even when the Poisson assumption is used.

What's Next?

More studies of earthquake sequences are needed to look closely at earthquake interaction; these are the building blocks for ideas about the role stress change plays in seismicity. The ideal is to probe large shocks falling within dense seismic, strong motion, and geodetic networks. This allows variable slip models to be developed, which in turn make stress calculations more accurate.

The prospects for such cases are best in California, Japan, New Zealand, and Hawaii. More effort is needed wringing results from earthquake catalogs (SCSN, Harvard CMT, JMA), using a set of testing rules on which everyone can agree, and SCEC is spearheading such an effort. Catalogs could also be used to validate probabilities based on stress change. But better secular stress models are essential to look at catalogs that span more than several decades, because the secular stress changes become as large as the earthquake stress changes. Such secular models are notoriously difficult to validate because different stressing models produce nearly identical surface displacements. Investigations of dynamic triggering are bound to reveal new insights about earthquake occurrence, as are 3D viscoelastic models and elastic models with spatially variable stiffness. Studies of the effect of super-low friction minerals, such as Brucite, and super-high pore-pressure fault zones could also prove enormously important.

Somewhere off in the future is an understanding of earthquakes that—while falling far short of prediction—would nevertheless supply a probabilistic forecast of where the next earthquakes, both large and small, are more likely to strike At Carmel we could imagine such a future, although we only grappled with tools we hope will lead us there.