Abstracts of oral presentations
<table>
<thead>
<tr>
<th>Oral Presentations</th>
</tr>
</thead>
</table>
| **Multiscale modeling and characterization of granular matter: From grain scale kinematics to continuum mechanics**  
José E. Andrade and Carlos F. Avila, California Institute of Technology |
| S1 |
| **Probabilistic theory of static and cyclic fatigue lifetime of quasibrittle and brittle structures based on nano-mechanics**  
Zdeněk P. Bažant¹ and Jia-Liang Le², ¹Northwestern University, ²University of Minnesota |
| S2 |
| **Numerical modeling of fault branch activation in subduction zones and strike-slip settings**  
Nora DeDonnyn, James R. Rice, and Renata Dmowska, Harvard University |
| S3 |
| **Flow of compressible fluids through cracks in elastic bodies and excitation of volcanic tremor**  
Eric M. Dunham, Darcy E. Ogden, Stanford University |
| S4 |
| **Dependence of the rate of diffusive escape from an energy well on the dimensionality of the well**  
L. Ben Freund, University of Illinois and Brown University |
| S5 |
| **Atomistic simulations and modeling of plastic deformation mechanisms in hierarchical nanotwinned metals**  
Huajian Gao, Brown University |
| S6 |
| **Energy states and wrinkle patterns of buckled films on compliant substrates**  
John W. Hutchinson, Harvard University |
| S7 |
| **Rupture characteristics of large intermediate-depth earthquakes and their generation mechanism**  
Miaki Ishii¹, Eric Kiser¹, Charles H. Langmuir¹, Peter M. Shearer², and Hitoshi Hirose³  
¹Harvard University, ²University of California San Diego, ³NIED |
| S8 |
| **On the effective properties of heterogeneous materials and cross-property connections**  
Mark Kachanov, Tufts University |
| S9 |
| **Reproducing source characteristics of the 1999 Chi-Chi earthquake in a model with laboratory-based fault properties**  
Nadia Lapusta and Hiroyuki Noda, California Institute of Technology |
| S10 |
| **Frictional ageing due to adhesion changes at the nanoscale, relevant to the origin of the evolution effect in rate and state friction**  
Qunyang Li¹, Terry E. Tullis², David L. Goldsby², and Robert W. Carpick¹  
¹University of Pennsylvania, ²Brown University |
| S11 |
| **Frictional behavior of oceanic transform faults and influence on earthquake characteristics**  
Yajing Liu, Mark D. Behn, and Jeffrey M. McGuire, Woods Hole Oceanographic Institution |
<p>| S12 |</p>
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Models for lithium-ion battery performance and damage</td>
<td>S13</td>
</tr>
<tr>
<td>Robert M. McMeeking$^{1,2,3}$, Rajlakshmi Purkayastha$^1$, Esther Bohn$^4$, Thomas Eckl$^4$, and Jake Christensen$^5$</td>
<td></td>
</tr>
<tr>
<td>University of California Santa Barbara, $^2$University of Aberdeen, $^3$INM, $^4$Robert Bosch GmbH, Corporate Research and Advance Engineering, $^5$Robert Bosch LLC</td>
<td></td>
</tr>
<tr>
<td>Prediction of ductile fracture surface roughness</td>
<td>S14</td>
</tr>
<tr>
<td>Alan Needleman$^1$, Viggo Tvergaard$^2$, and Elisabeth Bouchaud$^3$</td>
<td></td>
</tr>
<tr>
<td>University of North Texas, $^2$The Technical University of Denmark, $^3$SPEC/GIT</td>
<td></td>
</tr>
<tr>
<td>Identifying the unique ground motion signatures of super-shear vs. sub-Rayleigh earthquakes: Theory, experiments and seismic risk</td>
<td>S15</td>
</tr>
<tr>
<td>Ares J. Rosakis$^1$, Michael Mello$^1$, Harsha S. Bhat$^{1,2}$, Swaminathan Krishnan$^1$, and Hiroo Kanamori$^1$</td>
<td></td>
</tr>
<tr>
<td>California Institute of Technology, University of Southern California</td>
<td></td>
</tr>
<tr>
<td>Slow slip and dynamic rupture in subduction zones with application to Cascadia</td>
<td>S16</td>
</tr>
<tr>
<td>Paul Segall and Andrew M. Bradley, Stanford University</td>
<td></td>
</tr>
<tr>
<td>Subduction-zone seismicity and emerging new problems in fault mechanics</td>
<td>S17</td>
</tr>
<tr>
<td>Toshihiko Shimamoto, Institute of Geology China Earthquake Administration</td>
<td></td>
</tr>
<tr>
<td>Poroelasticity of gels — when mechanics meets chemistry</td>
<td>S18</td>
</tr>
<tr>
<td>Zhigang Suo, Harvard University</td>
<td></td>
</tr>
<tr>
<td>A model for turbulent hydraulic fracture and applications to crack propagation at glacier beds</td>
<td>S19</td>
</tr>
<tr>
<td>Victor C. Tsai, U. S. Geological Survey</td>
<td></td>
</tr>
<tr>
<td>Wave-modulated orbits in rate-and-state friction</td>
<td>S20</td>
</tr>
<tr>
<td>John R. Willis, University of Cambridge</td>
<td></td>
</tr>
</tbody>
</table>
Multiscale modeling and characterization of granular matter: From grain scale kinematics to continuum mechanics

José E. Andrade and Carlos F. Avila

Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, USA

Granular sands are characterized and modeled here by explicitly exploiting the discrete-continuum duality of granular matter. Grain-scale kinematics, obtained by shearing a sample under triaxial compression, are coupled with a recently proposed multiscale computational framework to model the behavior of the material without resorting to phenomenological evolution (hardening) laws. By doing this, complex material behavior is captured by extracting the evolution of key properties directly from the grain-scale mechanics and injecting it into a continuum description (e.g., elasto-plasticity). The effectiveness of the method is showcased by two examples: one linking discrete element computations with finite elements and another example linking a triaxial compression experiment using computed tomography and digital image correlation with finite element computation. In both cases, dilatancy and friction are used as the fundamental plastic variables and are obtained directly from the grain kinematics. In the case of the result linked to the experiment, the onset and evolution of a persistent shear band is modeled, showing for the first time 3D multiscale results in the post-bifurcation regime with real materials and good quantitative agreement with experiments.

Reference:

Probabilistic theory of static and cyclic fatigue lifetime of quasibrittle and brittle structures based on nano-mechanics

Zdeněk P. Bažant¹ and Jia-Liang Le²

¹Civil Engineering and Materials Science, Northwestern University, Evanston and ²Civil and Env. Engrg., University of Minnesota

The design of various engineering structures, such as bridges, infrastructure, aircraft, ships, dams, nuclear structures, as well as microelectronic components and medical implants, must ensure an extremely low probability of failure, typically < 10⁻⁶ per lifetime. Such a low probability is beyond the means of histogram testing. Therefore, one must rely on some physically based probabilistic model for the statistics of structural lifetime. This study focuses on the structures consisting of quasibrittle materials, which are brittle materials with inhomogeneities that are not negligible compared to structure size (exemplified by concrete, fiber composites, tough ceramics, rocks, sea ice, bone, wood, and many more at micro- or nano-scale). Brittle structures are the large size limit. This paper begins by reviewing a recently developed theory of the lifetime distribution of quasibrittle structures under constant loads (static fatigue), and then focuses on a new theory of the lifetime distribution of quasibrittle structures under cyclic fatigue. The formulation of this theory begins with the derivation of the probability distribution of critical stress amplitude by assuming that the number of cycles and the stress ratio are prescribed. The Paris law for fatigue crack growth is physically explained and derived under certain plausible assumptions about the damage accumulation and build-up of residual stress in the cyclic fracture process zone at the tip of subcritical crack. This law is then used to relate the probability distribution of critical stress amplitude to the probability distribution of fatigue lifetime. The nano-macro transitions are deduced from the statistics of series and parallel couplings and from the equality of nano- and macro-based energy dissipation rates. The Basquin law and the S-N curves are also fit in this unified theory. The main consequence is that quasibrittle materials must exhibit a marked size (and shape) effect on the mean structural lifetime under both the static and cyclic fatigue. The theory matches the experimental size-shape effect data and the systematic deviations of lifetime histograms of various quasibrittle structures from the Weibull distribution.

References

Numerical modeling of fault branch activation in subduction zones and strike-slip settings

Nora DeDontney¹, James R. Rice¹,², and Renata Dmowska²

¹Dept. Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA
²School Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA

Problems of dynamic rupture path selection through branched fault systems are of utmost importance in the determination of seismic hazard assessments. Branched fault geometries occur frequently in both strike-slip and dip-slip settings. In subduction zones, the accretionary prism deforms internally as material from the downgoing oceanic plate is incorporated and this is achieved by slip on the faults internal to the prism that branch from the subduction zone interface. Splay faults have been observed or inferred in multiple locations, but there is not yet a consensus on their role in subduction zone earthquakes. The Wenchuan earthquake illustrates a branched geometry [Hubbard and Shaw, 2009] in a fold and thrust belt where the rupture encountered multiple intersections between faults at depth. The surface rupture of the 1992 Landers earthquake is a strike-slip event that shows a complex path of rupture propagation in which the multiple fault branches ruptured and linked two major faults.

As we look at the issue of what will a rupture do when it reaches a fork in the road, we realize that there are a considerable number of parameters and considerations that will affect which faults rupture during a given event. The factors that influence coseismic branch activation have been extensively studied [Poliakov et al.; Kame et al.; Oglesby et al., 2003, 2004; Bhat et al., 2004, 2007] and show that the rupture velocity, pre-stress orientation and fault geometry influence rupture path selection. We show further that the ratio of sigma_1/sigma_3 (equivalently, the seismic S ratio) also plays a significant role in determining which faults are activated. We also show that the relative strengths of the faults will determine the rupture path, and that if the main fault is statically weaker than the branch fault, the rupture is unlikely to propagate onto the branch. This is a particularly important factor in the subduction zone setting, as much theory suggests that the basal fault is weaker than the overlying material.

Additionally, inelastic off-fault deformation may be extensive in the area of the fault junction, and therefore important in determining fault activation. By incorporating the effects of plasticity, through the use of the Drucker-Prager pressure dependent yield criterion, we account for the energy expended in off fault deformation and are able to determine the effect, if any, of plasticity on the branching behavior. We also find that the incorporation of plasticity inhibits opening at the branching junction for those models with a low orientation of principal stress, validating assumptions about the behavior and interaction of the faults at the branching junction. The introduction of plasticity prevents opening from occurring as the non-cohesive material is unable to support in which the fault normal stress is reduced to zero, indicating that plasticity is an important consideration, especially at the low principal stress orientations that are found in natural settings like subduction zones.
Flow of Compressible Fluids Through Cracks in Elastic Bodies and Excitation of Volcanic Tremor

Eric M. Dunham¹, Darcy E. Ogden¹

¹Department of Geophysics, Stanford University, Stanford, CA, USA

We investigate the eruption of fluids through conduits in elastic bodies, with particular focus on the excitation of seismic waves by conduit wall oscillations induced by fluid flow. The models are presently two-dimensional with plane strain elastic response, such that the conduits most closely represent magma-filled dikes. The fluid response is idealized using quasi-one-dimensional mass and momentum balance equations for isothermal compressible flows, including both gravity and frictional drag. The mixture of exsolved gas and liquid melt is treated as a single phase fluid with an equation of state that captures the extreme changes in compressibility that occur as gas exsolves. Both the elastic wave equation and the fluid equations are solved with high order finite differences. The fluid and solid response is fully coupled: elastic deformation changes the cross-sectional area of the conduit through which fluid flows, and changes in fluid pressure push the conduit walls in and out. Because elastic wave speeds are nearly an order of magnitude faster than the fluid sound speed, elastic equilibrium is approached very rapidly over the time scale of fluid flow.

We have conducted a preliminary study of a dike filled with overpressurized magma breaking Earth's surface. Contact with the much lower atmospheric pressure at the surface drives a rarefaction down into fluid at the fluid sound speed; in the rarefaction, fluid pressure drops and gas exsolves. This induces a suction on the conduit walls that pulls them together. The reduction in conduit width occurs not only within the rarefaction, but also ahead of it due to the nearly instantaneous elastic response. This compresses the fluid ahead of the rarefaction, increasing its pressure. The resulting pressure gradient decelerates the rarefaction.

We also see that as the rarefaction continues to propagate, the system becomes unstable and the conduit walls begin to vibrate, such that the fluid is alternately being compressed and expanded, with characteristic periods of ~0.1-1 s. Synthetic seismograms at the surface feature pronounced Rayleigh waves excited by the initial suction of the conduit walls when the dike first breaks the surface, followed by emergent oscillatory signals arising the conduit wall vibrations. The latter are reminiscent of volcanic tremor.

The origin of conduit wall oscillations is investigated further by performing a stability analysis of steady flows. In the short wavelength limit the response of the fluid and solid is fully decoupled, and the perturbations take the form of neutrally stable propagating waves: sound waves in the fluid and Rayleigh waves in the solid propagating along the conduit walls. As the wavelength increases, the response becomes increasingly coupled. In certain parts of parameter space (generally for sufficiently rapid unperturbed fluid velocities), these coupled waves become unstable. The connection between this instability and the conduit wall oscillations is presently being explored.
Dependence of the rate of diffusive escape from an energy well on the dimensionality of the well

L. Ben Freund¹

¹Materials Science and Engineering, University of Illinois at Urbana-Champaign and School of Engineering, Brown University

A commonly used idealization when describing separation of a chemical bond between molecules is that of an energy well prescribing the dependence of energy of interaction between the molecules in terms of a “reaction coordinate”. The energy difference between the peak to be overcome and the root of the well is the so-called activation energy, and the overall shape of the well dictates the kinetics of separation through a constitutive assumption concerning transport. An assumption tacit in this description is that the state of the bond involves with only a single degree of freedom as the system explores its energy environment under random thermal excitation. In this discussion, we will consider several bonds described by one and the same energy profile. The cases differ by the fact that the energy profile varies along a line extending from the root of the well in the first case, along any radial line in a plane extending from the root of the well in a second case, and along any radial line in space extending from the root of the well in a third case. To focus the discussion, we determine the statistical rate of escape of states from the well in each case, requiring that the profile of the well is the same in all three cases. It is found that the rates of escape vary with depth of the well differently in the three cases considered and, thus, is sensitive to the dimensionality of the well.
Atomistic simulations and modeling of plastic deformation mechanisms in hierarchical nanotwinned metals

Huajian Gao

1School of Engineering, Brown University, Providence, Rhode Island 02912, USA

The rapid development of synthesis and characterization of nanostructured materials as well as unprecedented computational power have brought forth a new era of materials research in which experiments, simulation and modeling are performed side by side to probe the mechanical properties of nanostructured materials. This talk will present some recent studies on plastic deformation mechanisms in hierarchical nanotwinned metals (e.g., [1]).

In conventional metals, there is plenty of space for dislocations to multiply so that the strength of material is often controlled by dislocations interaction with grain boundaries (Hall-Petch strengthening) and other obstacles. For nanostructured materials, in contrast, multiplication and motion of dislocations are severely confined by the nano-scale geometries so that continued plasticity can be expected to be source-controlled. Here we show a dislocation source controlled mechanism in nanotwinned metals in which there are plenty of dislocation nucleation sites while dislocation motion is not confined. We found that dislocation nucleation plays the governing role in the strength of such materials, resulting in their softening below a critical twin thickness. Atomistic simulations and a kinetic theory of dislocation nucleation in nano-twinned metals show that there exists a transition in deformation mechanism, which occurs at a critical twin boundary spacing where the strength is maximized, from the classical Hall-Petch type of strengthening due to dislocation pile-up and cutting through twin planes to a dislocation nucleation governed softening mechanism with nucleation and motion of partial dislocations parallel to the twin planes. Our studies indicate that the critical twin boundary spacing for the onset of softening in nano-twinned Cu and the maximum strength depend on the grain size: the smaller the grain size, the smaller the critical twin spacing, and the higher the maximal strength of the material.

Selected Reference:

Energy states and wrinkle patterns of buckled films on compliant substrates

John W. Hutchinson¹

¹School of Engineering and Applied Sciences, Harvard University, Cambridge, MA

Thin stiff films on compliant elastic substrates subject to equi-biaxial compressive stress states are observed to buckle into various periodic mode patterns including checkerboard, hexagonal and herringbone, all of which will be documented. These modes are characterized and ranked by the extent to which they reduce the elastic energy of the film-substrate system relative to that of the unbuckled state over a wide range of overstress. A new mode is identified and analyzed having nodal lines coincident with an equilateral triangular pattern. Two methods are employed to ascertain the energy in the buckled state: an analytical method which supplies an upper-bound and a full numerical analysis. The upper-bound is shown to be surprisingly accurate to large levels of overstress. Except at small states of overstress, the herringbone mode has the lowest energy, followed by the checkerboard, with the hexagonal, triangular and one-dimensional patterns lowering the energy the least. Transitions between modes are discussed. An intriguing finding is that the hexagonal and triangular modes have the same energy in the buckled state and, moreover, linear combinations of these two modes exist having the same energy providing a continuous equi-energy path between them. Experimental observations of various periodic modes are discussed with reference to the energy landscape and with respect to the role that an initial curvature of the film may play in selecting specific patterns.
Rupture characteristics of large intermediate-depth earthquakes and their generation mechanism

Miaki Ishii¹, Eric Kiser¹, Charles H. Langmuir¹, Peter M. Shearer², and Hitoshi Hirose³

¹Department of Earth & Planetary Sciences, Harvard University, Cambridge, MA, USA
²Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA
³National Research Institute for Earth Science and Disaster Prevention, Tsukuba, Ibaraki, Japan

Intermediate-depth earthquakes (earthquakes occurring between 100- and 400-km depth) cannot be generated by brittle failure of material thought to be the cause of shallow-focus earthquakes. Many mechanisms have been proposed, but observations have been scarce to test these hypotheses. We have investigated the rupture characteristics of large, intermediate-depth earthquakes between 2000 and 2008 using data from a dense network of stations in Japan, and propose a new mechanism for their occurrence.

The foremost observation is that most of the earthquakes show slip that is confined in depth, i.e., sub-horizontal rupture. Furthermore, a significant fraction of the events consists of subevents that are well-separated in depth. For example, an Mw 7.4 event in Hindu Kush region has 2 sub-horizontal rupture planes that are separated by about 70 km in depth and by about 10 seconds in time. These events suggest that dynamic triggering is common for large earthquakes between 100- and 400-km depth.

Based upon these results, we propose a new mechanism for earthquake generation at intermediate depths that involves pre-existing faults and water. The complementary set of outer-rise faults generated before plate subduction becomes nearly horizontal and vertical below 100-km depth. The sub-horizontal faults preferentially develop into weak zones by serpentinization from water that is released by general slab dehydration. The reduction in the strength within the horizontal faults relative to the surrounding material helps initiate shear instability, and once slip begins on the fault, temperature increase from frictional heating enhances further slip through dehydration embrittlement. The runaway nature of slip and availability of many sub-horizontal weak zones, together with the presence of water, make the condition nearly ideal for dynamic triggering. This model suggests that the occurrence, depth extent, and complexity of intermediate-depth earthquakes may be related directly to availability of water from plate subduction.
On the effective properties of heterogeneous materials and cross-property connections

Mark Kachanov

1Department of Mechanical Engineering, Tufts University, Medford, MA, USA

Quantitative characterization of microstructures is discussed. The usual microstructural parameters, such as volume fraction or crack density, are not always adequate for mixtures of inhomogeneities of diverse and “irregular” shapes that are typical in materials science applications. Hence, prior to discussing an effective property as a function of a microstructural parameter, the argument of this function should be identified.

Two main difficulties in this context are (1) describing mixtures of diverse shapes, where the main challenge is to find a contribution of an individual inhomogeneity to the considered property, and (2) non-ellipsoidal shapes and various shape “irregularities”. These factors are of primary importance; for example, the effect of shapes is at least as important as the one of interactions.

Proper microstructural parameters are generally different for different physical properties. In cases when they are sufficiently similar for two properties, cross-property connections between the two can be established; elasticity and conductivity are examples. If they are substantially different for two properties, the latter cannot generally be interrelated; elasticity and fracture are examples (fracture processes cannot generally be monitored by a loss of elastic stiffness).

These issues are illustrated on several materials science applications.

References
Reproducing source characteristics of the 1999 Chi-Chi earthquake in a model with laboratory-based fault properties

Nadia Lapusta\textsuperscript{1,2} and Hiroyuki Noda\textsuperscript{3}

\textsuperscript{1}Division of Geological and Planetary Sciences and \textsuperscript{2}Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, USA

We study the mechanics and physics of earthquakes through a unique simulation approach that reproduces both earthquakes and slow slip, with full inclusion of inertial effects during simulated earthquakes, in the context of a 3D model. The approach incorporates laboratory-derived rate and state friction laws, involves slow, tectonic-like loading, resolves all stages of seismic and aseismic slip, and results in realistic rupture speeds, slip velocities, and stress drops. Our simulations show that a number of observed earthquake phenomena can be explained by interaction of earthquakes and slow slip, including complex spatio-temporal patterns of earthquake sequences (Kaneko Avouac, and Lapusta, Nature Geoscience, 2010), peculiar properties of small repeating earthquakes (Chen and Lapusta, JGR, 2009), and rupture transition to intersonic speeds.

In this work, we create a scenario similar to the 1999 Chi-Chi earthquake in a fault model governed by Dieterich-Ruina rate-and-state friction, supplemented with temperature and pore pressure evolution due to shear heating (Noda and Lapusta, JGR, 2010). During dynamic rupture, shear heating may lead to spontaneous pore pressurization which would lower the effective compressive stress and weaken the fault. Our model fault has two regions: one with velocity-weakening steady-state friction and higher permeability (the Southern region) and the other one with velocity-strengthening steady-state friction and lower permeability (the Northern region). The fault properties used in the model are motivated by laboratory measurements on rock samples taken from boreholes on the Chelungpu fault that hosted the earthquake (Tanikawa and Shimamoto, JGR, 2009).

Our model with laboratory-based fault properties reproduces several interesting observations about the Chi-Chi earthquake, which is one of the best-studied events. In the model, earthquakes always nucleate in the Southern region, as occurred in the Chi-Chi earthquake. When earthquakes enter the Northern region, lower permeability there activates dynamic weakening due to pore pressurization, and the Northern region ends up having larger slip in such model-spanning events. At the same time, velocity-strengthening friction in the Northern region reduces the high-frequency content of the rupture tip. Hence the Northern region has higher slip but lower high-frequency radiation, as indicated by observations.

Our ultimate goal is to use the developed simulation methodology, in conjunction with seismic and geodetic observations, to find fault properties consistent with all aspects of fault behavior, both seismic and long-term.
Frictional ageing due to adhesion changes at the nanoscale, relevant to the origin of the evolution effect in rate and state friction

Qunyang Li\textsuperscript{1}, Terry E. Tullis\textsuperscript{2}, David L. Goldsby\textsuperscript{2}, and Robert W. Carpick\textsuperscript{1}

\textsuperscript{1}Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104, USA and \textsuperscript{2}Department of Geological Sciences, Brown University, Providence, RI 02912 USA

Rate and state friction represents our best understanding of the frictional behavior of rocks along faults in the Earth's crust. It involves two separate effects: the direct effect and the evolution effect. The direct effect describes the immediate change in frictional resistance upon a change in slip velocity and is always positive, \textit{i.e.}, an increase or decrease in slip velocity results in an increase or decrease in frictional resistance, respectively. The evolution effect describes a change in frictional resistance that results from changes in the time of contact across the frictional interface. The latter is manifested in frictional resistance that increases with the log of the stationary contact time, \textit{i.e.}, an evolution of strength with time. A related manifestation is an evolution of friction with slip distance upon a change in sliding velocity, such that an increase or decrease in sliding velocity results in a decrease or increase in friction, respectively. The net change in friction is the sum of the direct and evolution effects, and can be either negative (velocity weakening) or positive (velocity strengthening), depending on the relative magnitudes of the two effects. Understanding this behavior is important for earthquake mechanics, since velocity strengthening always produces stable sliding, whereas velocity weakening can produce either unstable (\textit{i.e.}, earthquakes) or stable sliding, depending on the elastic loading stiffness. Although extremely successful at modeling earthquake phenomena, rate and state friction remains empirical in nature. Determining the physics underlying the evolution effect is important, as it would enable extrapolation of experimental data from the laboratory to earthquakes. Two explanations for the evolution effect exist: either the sizes of contacts grow or the strengths of the interfacial bonds grow with increases in log time. It has proven very difficult to ascertain whether one dominates. Our recent experiments suggest that increases in interfacial bond strengths may dominate.

We have conducted nanoscale single-asperity friction experiments in an atomic force microscope (AFM), using silica as the AFM tip and silica, diamond, or graphite as the substrate. Our experiments are similar to macroscopic slide-hold-slide experiments via which Dieterich first discovered the evolution effect. We find that the increase in static frictional strength as a function of log time – the evolution effect at the nanoscale – is much larger than that found in macroscopic experiments. A model involving micro-asperities within a macroscopic contact can explain how the macroscopic asperity can show a much smaller evolution effect due to progressive failure of micro-asperities as shear displacement occurs. This strong evolution effect only occurs in silica-on-silica experiments, not in silica on diamond or on graphite. Holding an AFM tip out of contact from the silica surface at 40% relative humidity, followed by sliding in contact, shows a lower static friction than if the tip stays in contact with the substrate. These latter two observations can be explained by time and environmental effects on bond strength, but not by increases in asperity area. These results indicate that time-dependent changes in bond strength can explain the macroscopic evolution effect and calls into question a dominant role for the explanation based on time-dependent increases in contact area.
Frictional behavior of oceanic transform faults and influence on earthquake characteristics

Yajing Liu¹, Mark D. Behn¹, and Jeffrey M. McGuire¹

¹Department of Geology and Geophysics, Woods Hole Oceanographic Institution, MA, USA

The relatively simple thermal and kinematic structures of mid-ocean ridge transform faults (RTFs) make them the ideal sites to study earthquake behavior in the strike-slip tectonic setting. Based on a global compilation of 65 RTFs with a combined length of 16,410 km, Boettcher and Jordan [2004] and Boettcher and McGuire [2009] summarized the following earthquake scaling relations. (1) By contrast to continental strike-slip faults, a small percentage, ~15%, of total moment on RTFs is released in seismic events. The effective seismic area scales linearly with the total potential seismogenic area AT above a reference isotherm, typically, 600°C. (2) The largest earthquake does not rupture the entire AT. Rather, its rupture area scales with \( \sqrt{AT} \). (3) Seismicity (1964-2009 GCMT and ISC catalogs) follows a tapered frequency-moment distribution, which can be predicted for future time periods using plate-motion rates, fault-lengths, and constants from fitting relations (1) and (2) to past periods.

In this study, we apply the lab-derived rate and state friction law to simulate RTF earthquake cycles, in order to understand the above characteristics. We use gabbro friction data under hydrothermal conditions [He et al., 2007] constrained by the thermal structure from a half-space cooling model. Earthquakes of various magnitudes, as well as aseismic events, spontaneously occur on the fault over many cycles. In two end-member scenarios: (1) short and fast spreading RTF (fault length L=100 km, spreading rate V=140 mm/yr), and (2) long and slow spreading RTF (L=625 km, V=30 mm/yr), we found that ~60% of total moment is released in a slow slip mode, that is, slip is above plate-motion rate but not related to earthquakes. For the short/fast case, every 2-4 years magnitude 4 or less earthquakes repeatedly rupture a small (< 0.1L) region around the along-strike center where the width of the frictionally unstable zone W is the largest, resulting in an extremely low (<0.01) coupling coefficient. For the long/slow case, greater earthquakes of magnitude 6 to 7 repeat every 80-120 years due to a much larger AT. The largest earthquake continues to nucleate where W is the largest, while smaller earthquakes also emerge at locations closer to the ridges. The seismic coupling coefficient is close to 0.15, the average estimate by Boettcher and Jordan [2004]. A more sophisticated thermal model that incorporates realistic oceanic lithosphere rheology and effects of shear heating and hydrothermal circulation [Roland et al., 2010] will be used to constrain the friction parameter distribution. Specifically, we will focus on the Quebrada, Discovery and Gofar fault system on the East Pacific Rise, where abundant OBS data are available to constrain our model, to study the conditions that control the transition between aseismic and seismic slip, and the presence of frictional barriers and its effects on earthquake rupture.
Models for lithium-ion battery performance and damage

Robert M. McMeeking\textsuperscript{1,2,3,4}, Rajlakshmi Purkayastha\textsuperscript{2}, Esther Bohn\textsuperscript{5}, Thomas Eckl\textsuperscript{5} and Jake Christensen\textsuperscript{6}

\textsuperscript{1}Mechanical Engineering Department, University of California, Santa Barbara, California, USA
\textsuperscript{2}Materials Department, University of California, Santa Barbara, California, USA
\textsuperscript{3}School of Engineering, University of Aberdeen, Aberdeen, Scotland
\textsuperscript{4}INM – Leibniz Institute for New Materials, Campus D2 2, Saarbrücken, Germany
\textsuperscript{5}Robert Bosch GmbH, Corporate Research and Advance Engineering, Stuttgart, Germany
\textsuperscript{6}Robert Bosch LLC, Palo Alto, California, USA

Models are developed for the transport of Li ions in the electrolyte of lithium ion batteries, their diffusion through storage electrode particles, and their kinetics through the surface of the particles between the electrolyte and the particles. As a consequence of the Li ion intercalating in the storage particles, their lattice swells, leading to elastic stress when the concentration of Li ions in the particles is not uniform. The models of transport are based on standard concepts for multi-component diffusion in liquids and solids, but are not restricted to dilute solutions, or to small changes in the concentration of the diffusing species. In addition, phase changes are permitted during mass transport as the concentration of lithium varies from the almost depleted state of the storage particle to one where the material is saturated with its ions. The elastic swelling and shrinkage may involve very large dilatations, which are allowed for in the formulation of the model. Thus, the models are suitable for storage particle, where the amount of Li can vary by large amounts depending on the state of charge, for staging as observed in the storage process in graphite, for the enormous swelling that takes place when silicon is used for storage, and for electrolytes in which the concentration of Li ions is high. The model is used to compute the processes of charging and discharging the battery to assess the parameters that influence the development of stress in the storage particles, and to deduce the likelihood of fracture of the storage particle material. The objective is to assess designs of porous electrode microstructures that permit rapid charging and discharging, but obviate the likelihood of fracture and other mechanical damage that limit the performance and reliability of the battery.
Prediction of ductile fracture surface roughness

Alan Needleman\textsuperscript{1}, Viggo Tvergaard\textsuperscript{2} and Elisabeth Bouchaud\textsuperscript{3}

\textsuperscript{1}Department of Materials Science and Engineering, University of North Texas, Denton, TX, USA, \textsuperscript{2}Department of Mechanical Engineering, The Technical University of Denmark, Lyngby, Denmark, and \textsuperscript{3}CEA-Saclay Orme des Mesiers, SPEC/GIT, Bâtiment 772, Gif-sur-Yvette, France

Experimental observations have shown that the roughness of fracture surfaces exhibit certain characteristic scaling properties. Here, ductile crack growth under mode I, plane strain, small scale yielding conditions is analyzed. Although overall plane strain loading conditions are prescribed, full 3D analyses are carried out to permit modeling of the three dimensional material microstructure and of the resulting three dimensional stress and deformation states that develop in the fracture process region. An elastic-viscoplastic constitutive relation for a progressively cavitating plastic solid is used to model the material. Two populations of second phase particles are represented, large inclusions with low strength, which result in large voids near the crack tip at an early stage, and small second phase particles, which require large strains before cavities nucleate. The larger inclusions are represented discretely and various three dimensional distributions of the larger particles are considered. The scaling properties of the predicted fracture surfaces are calculated and the results are compared with experimental observations.
Identifying the unique ground motion signatures of super-shear vs. sub-rayleigh earthquakes: theory, experiments and seismic risk

A.J. Rosakis¹, M. Mello¹, H.S. Bhat¹,³, S. Krishnan¹,², H. Kanamori ²

¹Division of Engineering and Applied Science, ²Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA,
³Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA

Directly studying earthquakes presents a host of insurmountable difficulties, the least of which is our inability to trigger earthquakes of various magnitudes at will and the lack of means of scrutinizing the behavior at depth while the quake propagates. We have developed techniques to produce miniature laboratory earthquakes and follow their progress with high-speed imaging tools. Our quakes mimic actual quakes, and have demonstrated the existence of "super-shear" or "intersonic" rupture speeds. The propagating fronts of such intersonic ruptures feature a Mach-cone of shear shock waves similar to that of supersonic aircraft. This unusual feature produces potentially catastrophic ground shaking signatures (equivalent to sonic booms) with unexpected implications to building safety and seismic hazard analysis.
Slow slip and dynamic rupture in subduction zones with application to Cascadia

Paul Segall¹, Andrew M. Bradley¹

¹Geophysics Department, Stanford University, Stanford, CA, USA

Seismic and geodetic observations are consistent with slow-slip events (SSE) occurring down-dip of the locked megathrust in regions of anomalously high pore pressure \( p \). We hypothesize that at low effective normal stress \( \sigma - p \), dilatancy stabilizes velocity weakening faults, whereas at higher \( \sigma - p \), thermal pressurization overwhelms dilatancy, leading to dynamic rupture. We present two-dimensional half-space simulations that include rate-state friction, dilatancy (following Segall and Rice [1995; JGR]), and heat and pore-fluid flow normal to the fault --- all processes which Jim Rice not only studied, but produced seminal analyses. The coupled system of equations is an index-1 differential algebraic equation (DAE) in slip \( \delta \), state \( \theta \), fault zone porosity \( \phi \), \( p \), and temperature \( T \). We integrate \( \theta \), \( \phi \), and \( \delta \) explicitly; solve the stress-balance equation on the fault; and integrate \( p \) and \( T \) implicitly.

We take depth-variable frictional properties (based on lab experiments on gabbro, similar to that Liu and Rice [2009; JGR]) that yield a transition from velocity strengthening to weakening friction at ~33 km depth. We assume low effective stress, presumed to be driven by dehydration reactions, in the ~25 to ~40 km depth range. Simulations reveal generic behavior: dynamic events (DE) repeat every few hundred years, and between each DE starts with a quiescent period followed by a long sequence of SSE. During this period, the SSE moment rates generally (but not monotonically) increase with time. Eventually slip speeds become high enough to induce thermal pressurization, which nucleates a DE. The predicted behavior, in terms of SSE slip, stress drop, and repeat time bear many similarities to SSE in Cascadia. In related numerical experiments we explore the role of heterogeneous permeability in generating low-frequency earthquakes and tremor. In all cases examined, slow slip fails to accommodate plate motion, and DE propagate through the SSE zone, which if accurate represents a significant increase in hazard to large cities in the Pacific Northwest.

To test model predictions against GPS data, we develop a pseudo-3D method that accounts for the markedly non-planar geometry of the plate interface. The approach employs 3D elastic Green's functions but assumes that slip rate is a function of depth only, as computed in the physics based model. We discuss whether or not steady creep is required above the SSE region to satisfy the inter-ETS GPS velocities, and the distribution of physical parameters that might permit this to occur.
Subduction-zone seismicity and emerging new problems in fault mechanics

Toshihiko Shimamoto

1State Key Laboratory of Earthquake Dynamics, Institute of Geology
China Earthquake Administration, P. O. Box 9803, Beijing 100029, China

A traditional view of velocity weakening as a required property for seismogenic fault motion was challenged for the 1999 Chi-Chi earthquake based on laboratory data indicating velocity strengthening for the northern part of Chelungpu fault which displaced even more than the northern part (Tanikawa and Shimamoto, 2008, JGR). They proposed that rate-and-state friction at slow slip rates controls the earthquake nucleation, whereas intermediate to high-velocity friction dictates the growth processes into a large earthquake. Noda & Lapusta (2009, JpGU) demonstrated by dynamic modeling that such a scenario is indeed possible. These results and recent modeling of slow slip in subduction zones (e.g., Lie & Rice, 2007, JGR; Shibazaki & Shimamoto, 2007, GIJ) lead me to reevaluate seismogenic-zone drilling projects in Nankai Trough (Shimamoto, 2009, AGU; 2010, JpGU). The seven major tasks below in fault mechanics have thus emerged for better understanding of subduction-zone seismicity.

**Task 1**: High-velocity (HV) friction of faults to evaluate the response of shallow accretionary prism to earthquake rupture coming from depths. **Task 2**: Friction and fracture experiments to determine velocity dependence of faults and post-failure curve for understanding low-frequency earthquakes in shallow subduction zones. **Task 3**: Reexamination of exhumed accretionary prism such as Shimanto belt with a renewed view that background deformation of accretionary prism itself is overprinted by impulse-like deformation due to rupture propagation from depths. **Task 4**: High-temperature and ultralow effective-pressure ($P_e$) friction experiments to understand slow slip and nonvolcanic low-frequency tremors in the transitional regime. Recent modeling of slow slip by several groups strongly suggests that $P_e$ is on the order of several MPa or lower in the slow-slip regime. Some fault rocks may retain brittle frictional properties even at high temperatures, but other rocks may not. Shimamoto and Noda (2101, AGU) propose an empirical law linking the rate-and-state fault constitutive law and rate-and-state flow law (Noda and Shimamoto, 2010, GRL). This will be useful for modeling slow slip and low-frequency tremors and will give insight on designing experiments to cover the brittle to fully plastic fault motion using realistic rocks. **Task 5**: Deformation mechanisms along megathrust faults, particularly evaluation of the significance of pressure solution. **Task 6**: Studies on hydrofractures, permeability and fracture seal in metamorphic environments which are needed to analyze pore-pressure ($P_p$) evolution in subduction zones. How unusually high $P_p$ can be maintained in slow slip regime is a difficult but an exciting problem. $P_p$ may be the most important factor in delineating the megathrust and slow-slip regimes. **Task 7**: Dynamic analysis of slow slip and megathrust earthquake cycles using realistic fault properties are needed to understand how a megathrust earthquake initiates. Recent modeling of Matsuzawa et al. (2009, AGU; 2010, JpGU) brought about changes in frequency of slow slip prior to a megathrust earthquake. Earthquake forecast might become possible by exploring interactions between megathrust and slow slip regimes.
Poroelasticity of gels —when mechanics meets chemistry

Zhigang Suo

School of Engineering and Applied Sciences, Kavli Institute for Bionano Science and Technology, Harvard University, Cambridge, MA 02138, USA

Professor James R. Rice has made seminal contributions to our understanding of the flow of a liquid in a porous and deformable medium. While his attention has been focused on geological phenomena, his teaching has greatly influenced my students and me as we study the flow in an elastomeric gel—an aggregate of a solvent and a polymeric network. Gels have many uses, including personal care, drug delivery, tissue engineering, microfluidic regulation, and oilfield management. Mixtures of macromolecular elastomers and mobile molecules also constitute most tissues of plants and animals.

An elastomeric gel couples mechanics and chemistry. When an elastomer imbibes a solvent and swells, the amount of swelling can be large and reversible, regulated by environmental stimuli, such as force, electric field, pH, salinity, and light. The deformation is usually anisotropic and inhomogeneous. This talk describes a theory of elastomeric gels, developed within nonlinear continuum mechanics and chemical thermodynamics, and motivated by molecular pictures and empirical observations. The theory is illustrated with examples of swelling-induced large deformation, contact, and bifurcation. The theory is further illustrated with recent experiments.
A model for turbulent hydraulic fracture and applications to crack propagation at glacier beds

Victor C. Tsai

1Geologic Hazards Science Center, United States Geological Survey, Golden, CO, USA

Meltwater generated at the surface and base of glaciers and ice sheets is known to have a large impact on how ice masses behave dynamically, but much is still unknown about the physical processes responsible for how this meltwater drains out of the glacier. For example, little attention has been paid to short-timescale processes like turbulent hydraulic fracture, which is likely an important mechanism by which drainage channels initially form when water pressures are high. In recent work (Tsai and Rice, JGR, 2010), we have constructed a model of this turbulent hydraulic fracture process in which overpressurized water is assumed to flow turbulently through a crack, leading to crack growth. One important limitation of this work is that it only strictly applies in the limit of short crack length, 2L, compared to glacier height, H, whereas relevant observations of supraglacial lake drainage, jokulhlaups and sub-glacial lake-to-lake transport episodes do not fall in this regime. In subsequent work (Tsai and Rice, EGU, 2010), we improve somewhat upon this model by explicitly accounting for a nearby free surface. We accomplish this by applying the approach of Erdogan et al. [Meth. Anal. Sol. Crack Prob., 1973] to numerically calculate elastic displacements consistent with crack pressure distribution for a crack near a free surface, and use these results as before to simultaneously satisfy the governing fluid, elastic and fracture equations. Our results are analogous to the zero fracture toughness results of Zhang et al. [Int. J. Numer. Anal. Meth. Geomech., 2005], but applied to the case of turbulent flow rather than laminar flow of a Newtonian viscous fluid. These newer results clarify the importance of the free surface and potentially explain discrepancies between our previous modeling results and observations of supraglacial lake drainage by Das et al. [Science, 2008]. However, the numerical challenges increase as 2L becomes comparable to or much larger than H. We hope to ultimately develop simpler analyses for that range which make use of (visco)elastic plate theory at positions along the uplifted ice sheet that are remote from the fracturing front. This approach may also be of interest for tidal interactions with the ice-shelf grounding line location.
Wave-modulated orbits in rate-and-state friction

J. R. Willis

1University of Cambridge, UK

A spring-block system has been widely used as a model to display some of the features of two slabs in sliding contact. Putelat, Dawes and Willis (2008) demonstrated that equations governing the sliding of two slabs could be approximated by spring-block equations, and studied relaxation oscillations for two slabs driven by uniform relative motion at their outer surfaces, employing this approximation. The present work revisits this system. The problem is first formulated exactly, with full allowance for wave reflections. Since the sliding is restricted to be independent of position on the interface, this leads to a set of differential-difference equations in the time domain. Formal but systematic asymptotic expansions reduce the equations to differential equations. Truncation of the differential system at the lowest non-trivial order reproduces a classical spring-block system, but with a slightly different “equivalent mass” than was obtained in the earlier work. Retention of the next term gives a new system, of higher order, that contains also some explicit effects of wave reflections. The smooth periodic orbits that result from the spring-block system in the regime of instability of steady sliding is “decorated” by an oscillation whose period is related to the travel time of the waves across the slabs. The approximating differential system reproduces this effect with reasonable accuracy, when the mean sliding velocity is not too far from the critical velocity at which the steady state becomes unstable. The differential system also displays a period-doubling bifurcation as the driving velocity is increased. The investigation is not complete at the time of writing but it is tempting to speculate that this possible route to chaotic motion may offer some insight into earthquake intermittency. This is joint work with Thibaut Putelat.

Reference
Abstracts of poster presentations
## Poster Presentations

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Institution(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab stress and strain rate as constraints on global mantle flow</td>
<td>Laura Alisic, Michael Gurnis, Georg Stadler, Carsten Burstedde, Lucas Wilcox, Omar Ghattas</td>
<td>1California Institute of Technology, 2University of Texas at Austin, 3HyPerComp</td>
</tr>
<tr>
<td>Relations between slow slip and tremor in models of fault asperity interactions mediated by transient creep</td>
<td>Jean-Paul Ampuero</td>
<td>California Institute of Technology</td>
</tr>
<tr>
<td>A rate-dependent plasticity model for dilative granular media</td>
<td>José E. Andrade, Phong B.H. Le, Quisi Chen, Carlos F. Avila</td>
<td>California Institute of Technology</td>
</tr>
<tr>
<td>Inferring fault friction laws from geodetic observations of co-post- and interseismic deformation</td>
<td>Jean-Philippe Avouac, Hugo Perfettini, Andrew Kosistsky, Sylvain Barbot, Shu-Hao Chang</td>
<td>1California Institute of Technology, 2Institut de Recherche pour le Développement</td>
</tr>
<tr>
<td>Seismic streaks and holes: geometric control of the Parkfield Mw6.0 earthquakes</td>
<td>Sylvain Barbot, Nadia Lapusta, Jean-Philippe Avouac</td>
<td>California Institute of Technology</td>
</tr>
<tr>
<td>The dynamics of the onset of frictional slip</td>
<td>Oded Ben-David, Gil Cohen, Jay Fineberg</td>
<td>Hebrew University of Jerusalem</td>
</tr>
<tr>
<td>Slip-stick: the evolution of frictional strength</td>
<td>Oded Ben-David, Shmuel M. Rubinstein, Jay Fineberg</td>
<td>1Hebrew University of Jerusalem, 2Harvard University</td>
</tr>
<tr>
<td>An experimental and theoretical study of asymmetric earthquake rupture propagation caused by off-fault fracture damage</td>
<td>Harsha S. Bhat, Ares J. Rosakis, Charles G. Sammis</td>
<td>1University of Southern California, 2California Institute of Technology</td>
</tr>
<tr>
<td>Effect of dehydration reactions on the stability of creeping faults</td>
<td>Nicolas Brantut, Jean Sulem, Alexandre Schubnel</td>
<td>1Ecole Normale supérieure, 2Ecole des Ponts Paris Tech</td>
</tr>
<tr>
<td>Damage and rupture dynamics at the brittle/ductile transition: the case of gypsum</td>
<td>Nicolas Brantut, Alexandre Schubnel, Yves Guéguen</td>
<td>Ecole Normale Supérieure</td>
</tr>
<tr>
<td>Nematic elastomers: instabilities and relaxation</td>
<td>Pierluigi Cesana</td>
<td>California Institute of Technology</td>
</tr>
<tr>
<td>AES for multiscale localization modeling in granular media</td>
<td>Qiushi Chen, José E. Andrade, Esteban Samaniego</td>
<td>1California Institute of Technology, 2Universidad de Cuenca</td>
</tr>
<tr>
<td>Interaction of small repeating earthquakes in a rate and state fault model</td>
<td>Ting Chen and Nadia Lapusta</td>
<td>California Institute of Technology</td>
</tr>
<tr>
<td>Title</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>The geochemical signature of carbonate-hosted seismogenic faults</td>
<td>P14</td>
<td></td>
</tr>
<tr>
<td>N. De Paola(^1), G. Chiodini(^2), T. Hirose(^3), C. Cardellini(^4), S. Caliro(^2), and T. Shimamoto(^5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^1)University of Durham, (^2)Instituto Nazionale di Geofisica e Vulcanologia, (^3)Japan Agency for Marine-Earth Science and Technology (JAMSTEC), (^4)Universita’ di Perugia, and (^5)Institute of Geology, China Earthquake Administration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formulation of pulse-like ruptures on velocity-weakening interfaces and its relation to stability properties of steady-state sliding</td>
<td>P15</td>
<td></td>
</tr>
<tr>
<td>Ahmed Elbanna, Nadia Lapusta, and Thomas H. Heaton, California Institute of Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gutenberg-Richter breakdown and the smallest earthquakes at the San Andreas Fault Observatory at Depth</td>
<td>P16</td>
<td></td>
</tr>
<tr>
<td>William L. Ellsworth, U. S. Geological Survey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Origin of strong velocity weakening in high-speed rotary shear experiments on gabbro: Partial melting of the gouge layer</td>
<td>P17</td>
<td></td>
</tr>
<tr>
<td>Yuri Fialko and Kevin Brown, University of California San Diego</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental study of ground motion attenuation of thrust faults</td>
<td>P18</td>
<td></td>
</tr>
<tr>
<td>Vahe Gabuchian(^1), Ares J. Rosakis(^1), Nadia Lapusta(^1), and David D. Oglesby(^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^1)California Institute of Technology, (^2)University of California</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flash heating of crustal rocks at near-seismic slip rates</td>
<td>P19</td>
<td></td>
</tr>
<tr>
<td>David L. Goldsby, and Terry E. Tullis, Brown University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shearing resistance of aluminum at high strain rates and at temperatures approaching melt</td>
<td>P20</td>
<td></td>
</tr>
<tr>
<td>Stephen E. Grunschel(^1), Rodney J. Clifton(^2), and Tong Jiao(^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^1)ASML, Wilton, (^2)Brown University</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The SCEC-USGS dynamic earthquake rupture code verification exercise: regular and extreme ground motion</td>
<td>P21</td>
<td></td>
</tr>
<tr>
<td>Ruth A. Harris(^1), Michael Barall(^2), Ralph Archuleta(^3), Brad Aagaard(^4), Jean-Paul Ampuero(^4), Joe Andrews(^4), Victor Cruz-Atienza(^5), Luis Dalguer(^6), Steven Day(^7), Benchun Duan(^8), Eric Dunham(^9), Geoff Ely(^10), Alice Gabriel(^6), Yoshihiro Kaneko(^11), Yuko Kase(^12), Nadia Lapusta(^4), Shuo Ma(^7), Hiroyuki Noda(^4), David Oglesby(^13), Kim Olsen(^7), Daniel Roten(^7), Surendra Somala(^4), and Seok Goo Song(^6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^1)U.S. Geological Survey, (^2)Invisible Software, (^3)University of California Santa Barbara, (^4)California Institute of Technology, (^5)Universidad Autonoma de Mexico, (^6)Swiss Federal Institute of Technology, (^7)San Diego State University, (^8)Texas A&amp;M University, (^9)Stanford University, (^10)University of Southern California, (^11)University of California San Diego, (^12)Geological Survey of Japan, (^13)University of California Riverside</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linking postseismic and interseismic deformation along the North Anatolian Fault Zone: The role of transient rheology and low-viscosity shear zones</td>
<td>P22</td>
<td></td>
</tr>
<tr>
<td>Elizabeth H. Hearn, University of British Columbia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size effects in the failure conditions of systems with strong velocity-weakening frictional interfaces and pulselike ruptures</td>
<td>P23</td>
<td></td>
</tr>
<tr>
<td>Thomas H. Heaton and Ahmed Elbanna, California Institute of Technology</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Properties of dynamic slip pulses in a 2D slab</td>
<td>P24</td>
</tr>
<tr>
<td>Yihe Huang¹, Jean-Paul Ampuero¹, and Luis A. Dalguer²</td>
<td></td>
</tr>
<tr>
<td>¹California Institute of Technology, ²SED, ETH Zürich</td>
<td></td>
</tr>
<tr>
<td>BIEM simulation of non-planar earthquake rupture, and its extension to inhomogeneous medium</td>
<td>P25</td>
</tr>
<tr>
<td>Nobuki Kame, University of Tokyo</td>
<td></td>
</tr>
<tr>
<td>Persistence of coseismic rupture asperities as inferred from interseismic geodetic observations</td>
<td>P26</td>
</tr>
<tr>
<td>from Northeastern Japan</td>
<td></td>
</tr>
<tr>
<td>Ravi V. S. Kanda¹,², Eric A. Hetland³, and Mark Simons¹</td>
<td></td>
</tr>
<tr>
<td>¹California Institute of Technology, ²National Taiwan University, ³University of Michigan</td>
<td></td>
</tr>
<tr>
<td>Modeling shallow slip deficit in large strike-slip earthquakes using simulations of spontaneous</td>
<td>P27</td>
</tr>
<tr>
<td>rupture in elasto-plastic media</td>
<td></td>
</tr>
<tr>
<td>Yoshihiro Kaneko and Yuri Fialko, University of California San Diego</td>
<td></td>
</tr>
<tr>
<td>Frequency dependent rupture characteristics of the 2010 Mw 8.8 Chile earthquake as imaged by</td>
<td>P28</td>
</tr>
<tr>
<td>back-projection</td>
<td></td>
</tr>
<tr>
<td>Eric Kiser and Miaki Ishii, Harvard University</td>
<td></td>
</tr>
<tr>
<td>Cohesive zone law extraction from an experimental peel test for soft adhesive materials</td>
<td>P29</td>
</tr>
<tr>
<td>Christopher Kovalchick, Shuman Xia, and Guruswami Ravichandran</td>
<td></td>
</tr>
<tr>
<td>California Institute of Technology</td>
<td></td>
</tr>
<tr>
<td>Quantized crystal plasticity in nanocrystalline metals</td>
<td>P30</td>
</tr>
<tr>
<td>Lin Li¹, Peter M. Anderson¹, Steven Van Petegem², and Helena Van S wygenhoven²</td>
<td></td>
</tr>
<tr>
<td>¹Ohio State University, ²Paul Scherrer Institute</td>
<td></td>
</tr>
<tr>
<td>Physical modeling of a slope failure during 2005 typhoon Nabi in Japan</td>
<td>P31</td>
</tr>
<tr>
<td>Henry Ling¹, and Hoe I. Ling²</td>
<td></td>
</tr>
<tr>
<td>¹Academy for the Advancement of Science and Technology, ²Columbia University</td>
<td></td>
</tr>
<tr>
<td>Micromechanics of dilatancy, critical state and shear bands in granular materials</td>
<td>P32</td>
</tr>
<tr>
<td>Sinisa Dj. Mesarovic¹, Jagan M. Padbidri², and Balasingam Muhunthan¹</td>
<td></td>
</tr>
<tr>
<td>¹Washington State University, ²Georgia Institute of Technology</td>
<td></td>
</tr>
<tr>
<td>A Bayesian approach to kinematic models of all phases of the seismic cycle</td>
<td>P33</td>
</tr>
<tr>
<td>Sarah Minson, Francisco Ortega, Junle Jiang, Anthony Sladen, Nina Lin, and Mark Simons</td>
<td></td>
</tr>
<tr>
<td>California Institute of Technology</td>
<td></td>
</tr>
<tr>
<td>Simultaneous measurement of real contact area and fault normal stiffness during frictional</td>
<td>P34</td>
</tr>
<tr>
<td>sliding</td>
<td></td>
</tr>
<tr>
<td>Kohei Nagata², Brian Kilgore², Masao Nakatani³, and Nick Beeler⁴</td>
<td></td>
</tr>
<tr>
<td>¹JMA, ²U. S. Geological Survey, ³ERI</td>
<td></td>
</tr>
<tr>
<td>Coating delamination on cylindrical substrates</td>
<td>P35</td>
</tr>
<tr>
<td>Ruzica R. Nikolic¹ and Jelena M. Djokovic²</td>
<td></td>
</tr>
<tr>
<td>¹University of Kragujevac, ²University of Belgrade</td>
<td></td>
</tr>
</tbody>
</table>
Definitions of average stress drops for heterogeneous slip distribution: Implications for dynamic rupture process from earthquake energetics

Hiroyuki Noda, Nadia Lapusta, and Hiroo Kanamori, California Institute of Technology

Earthquake dynamics and potential tsunamis in the Greater Antilles Subduction Zone

David D. Oglesby¹, Eric L. Geist², and Uri S. ten Brink²
¹University of California, Riverside, ²U. S. Geological Survey

Strain localization within a fluid-saturated fault gouge layer during seismic shear

John D. Platt¹, James R. Rice¹,², and John W. Rudnicki³
¹Harvard University, ³Northwestern University

Heating, melting, weakening and strengthening in a finite shear zone during earthquake slip

Alan Rempel, University of Oregon

Strain localization within a fluid-saturated fault gouge layer during seismic shear

John D. Platt¹, James R. Rice¹,², and John W. Rudnicki³
¹Harvard University, ³Northwestern University

Earthquake-induced structural failures and mechanical characteristics of relevant seismic waves

Koji Uenishi, Kobe University

Poromechanical processes below the seafloor: steady sedimentation and landslide initiation

Robert C. Viesca and James R. Rice, Harvard University

A fixed-point iteration method with quadratic convergence

Kevin P. Walker¹ and Sam Sham²
¹Engineering Science Software, Inc., ²Oak Ridge National Laboratory
Slab stress and strain rate as constraints on global mantle flow

Laura Alisic¹, Michael Gurnis¹, Georg Stadler², Carsten Burstedde², Lucas Wilcox²,³, and Omar Ghattas²,⁴,⁵

¹Seismological Laboratory, California Institute of Technology
²Institute for Computational Engineering and Sciences, The University of Texas at Austin
³HyPerComp
⁴Jackson School of Geosciences, The University of Texas at Austin
⁵Department of Mechanical Engineering, The University of Texas at Austin

Dynamically consistent global models of mantle convection with plates are developed that are consistent with detailed constraints on the state of stress and strain rate from deep focus earthquakes. These are computed using the adaptive finite element code Rhea. Around plate boundaries, the local resolution is ~1 km. Models that best fit plateness criteria and plate motion data have strong slabs that have high stresses. The regions containing the Mw 8.3 Bolivia and Mw 7.6 Tonga 1994 events are considered in detail. Modeled stress orientations match stress patterns from earthquake focal mechanisms. A yield stress of at least 100 MPa is required to fit plate motions and matches the minimum stress requirement obtained from the stress drop for the Bolivia 1994 deep focus event. The minimum strain rate determined from seismic moment release in the Tonga slab provides an upper limit of ~200 MPa on the strength in the slab.
Relations between slow slip and tremor in models of fault asperity interactions mediated by transient creep

Jean-Paul Ampuero¹

¹Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA

The coupled phenomena of episodic slow slip and tectonic tremor offer an exceptional opportunity to investigate the rheology and heterogeneity of active faults at depth. Tremor activity might provide a natural creepmeter to monitor aseismic slip with high resolution, including possible precursory slip associated with the nucleation of large earthquakes. Recently, a hierarchy of tremor migration patterns has been observed in Cascadia. On the longest time scales, tremor migrates along strike at a speed of order 10 km/day, coincident with the propagating front of slow slip events. At shorter time scales, tremor swarms coined “rapid tremor reversals” propagate backwards along-strike at speeds of order 100 km/day. At even shorter time scales, tremor streaks propagate along-dip at speeds of order 1000 km/day. Interestingly, some of the natural tremor migration patterns are also observed in laboratory experiments of slow sliding in gels and of slow rupture along weak interfaces in plexiglass. Whereas the largest scale migration pattern is naturally explained by triggering of tremor by a propagating slow slip pulse, the origin of the two other patterns remains unknown. I propose a unifying framework to understand these three patterns and their relation to the spatial distribution of slip rate within the underlying slow slip pulse. Numerical models of tremor generated by brittle asperities present in the deep, mainly ductile portions of a fault reveal that migrating tremor swarms arise from a cascade of triggering between asperities mediated by propagating creep perturbations analogous to afterslip. The speed of these creep waves controls the tremor migration speed. Theoretical arguments and numerical simulations show that the propagation speed of creep transients correlates strongly with the background slip rate, implying that larger slip rates at the leading front of a large scale slow slip pulse produce faster tremor migration, slower slip within the pulse implies slower tremor migration. The model also predicts that the source areas of tremor swarms have large aspect ratios. This source shape implies pulse-like ruptures that are consistent with the proportionality between moment and duration observed for slow earthquakes. The universality of that scaling law is linked to the relations between the characteristic length scales of the slow slip pulse. The model also yields further predictions that could be tested by observations affordable in the near future.
A rate-dependent plasticity model for dilative granular media

José E. Andrade¹, Phong B.H. Le¹, Qiushi Chen¹ and Carlos F. Avila¹

¹ Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, USA.

A rate-dependent plasticity model for dilative granular media is proposed in this work. The main goal of the model is to bridge the hitherto seemingly disparate solid- and fluid-like behavioral regimes of granular materials.

In the granular mechanics framework, solid-like behavior is typically tackled with rate-independent plasticity models emanating from Mohr-Coulomb plasticity theory. It can be seen that rate effects are not important under quasi-static deformation but apparently become dominant during faster rates. On the other hand, fluid-like behavior of granular media is treated using constitutive theories amenable to viscous flow, e.g., Bingham fluid. One main difference is the role of dilatancy, which plays the key role during solid-like behavior but vanishes in the fluid-like regime.

In the present work, we present a model that can seamlessly transit between solid- and fluid-like regimes. In this model, the material strength $\mu$ is defined in the sense of Coulomb [1] such that $\mu = -q / p$ is the mobilized frictional resistance (strength) defined as the ratio of shear stress, $q$, and pressure, $p$. Furthermore, $\mu$ is proportional to the dilatancy $\beta$ (defined as the slope of the volumetric deformation vs. shear strain, i.e., $\partial \varepsilon_v = \beta \partial \varepsilon_s$) and to the residual strength $\mu_0$, which is rate dependent. At large deformations, the dilatancy is completely spent ($\beta = 0$), and the material reaches an incompressible state where the material behaves much like fluid and its strength is given by the residual strength, i.e., $\mu = \mu_0$.

The main appeal of the model is its simplicity and its ability to reconcile the classical plasticity and rheology camps. The predictiveness of the model is demonstrated by comparing direct numerical simulations using discrete particle mechanics and the proposed continuum model. In addition, the proposed model is also used to study the rate-dependent effects in triaxial compression, penetration and shear band problems.

REFERENCES

Inferring fault friction laws from geodetic observations of co-post- and interseismic deformation

Jean-Philippe Avouac¹, Hugo Perfettini², Andrew Kosistky¹, Sylvain Barbot¹, Shu-Hao Chang¹

¹ Geology and Planetary Sciences Division, California Institute of Technology
² Institut de Recherche pour le Développement, Grenoble, France

Thanks to the development of global positioning systems and of remote sensing geodetic techniques we can now monitor surface strain associated with the different phases of the seismic cycle with unprecedented spatial and temporal resolution. These data, eventually combined with other type of observations, make it possible to investigate faults dynamics and eventually derive fault-constitutive laws. This presentation will provide an overview summary of recent case studies [Bruhat et al., submitted; Konca et al., 2008; Perfettini and Avouac, 2007; Perfettini et al., 2010]. The main conclusions coming out of these studies are the following. 1-The rate-and-state formalism initially developed from laboratory friction experiments can successfully be used to model afterslip and interseismic slip observed on natural faults. In particular the dependency of friction on the logarithm of the sliding velocity (in the rate-strengthening regime) is needed to explain the typical 1/t decay of afterslip velocity. 2-Faults frictional properties vary in space with interfingering of rate-weakening and rate-strengthening patches. The consistency between laboratory results and observations on natural faults do not necessarily imply that the exact same physics applies however. This point would need to be investigated. Also, while it has long been shown that the rate-and-state formalism is appropriate to develop realistic models of the seismic cycle when fault properties are homogeneous, observations of natural faults call for efforts to assess the influence of frictional heterogeneities.

Clusters of seismicity along various segments of the San Andreas faults and other tectonic settings have been observed to be highly organized in both space and time. High-resolution relocation of these seismic events reveal distinctive features including repeating earthquakes with hypocenters localizing along sub-horizontal streaks and large areas of the plate interface being seemingly devoid of seismicity. The time and spatial patterns of seismicity are suggestive of rheological transitions within the fault zone. We test the assumption that long-lived patterns of seismicity can be used to map three-dimensional variations of frictional properties: without other constraints, seismic holes can be indicative of either locked or creeping regions and surrounding seismicity marks the transition from velocity-weakening to velocity-strengthening friction properties. One challenge to using this assumption is that the current models of the 2004 Parkfield Mw6.0 earthquake, derived from both GPS and synthetic-aperture radar (InSAR), do not show a clear correlation between slip distribution and seismicity. We use the interseismic velocity on the Parkfield segment of the San Andreas fault to build new models of the 2004 coseismic event: areas that don't creep steadily may be expected to contribute to coseismic slip. We show that, due to a rather poor resolution of geodetic data for fault slip at depth, one may find a final slip distribution that reconciles seismological and geodetic observations and show great correlation with patterns of seismicity on the San Andreas Fault. Using the seismicity holes and streaks as markers for transitions in friction properties, we build a physically-based dynamic model of the long-term seismic cycle that mimics the Mw6 20-30 year repeaters at Parkfield. We find a distribution of friction properties that generates repeating Mw6.0+/-0.1 events with a 20 year recurrence interval, where each individual event can explain the observed surface displacement in the co- and postseismic intervals during and following the 2004 Parkfield earthquake. Our results indicate that one may use background seismicity to constrain kinematic inversion of geodetic data for slip distribution where data resolution is not sufficient to place robust constraints on slip location. The interpretation of fault behavior in terms of spatial variations of frictional properties may greatly help design physically-based models of earthquake cycles in order to understand and mitigate seismic risk.
The dynamics of the onset of frictional slip

Oded Ben-David\textsuperscript{1}, Gil Cohen\textsuperscript{1} and Jay Fineberg\textsuperscript{1}

\textsuperscript{1}The Racah Institute of Physics, The Hebrew University of Jerusalem, Givat Ram, Jerusalem Israel

How frictional motion initiates is a fundamental question in fields ranging from material science to geophysics. Frictional slip is triggered by different modes of crack-like rupture fronts that propagate along the thin interface that separates two sheared bodies. We present detailed and real-time measurements of the spatial and temporal evolution of the real area of contact along a spatially extended rough frictional interface. These are supplemented by measurements of both the shear, $\tau(x)$, and normal, $\sigma(x)$, stresses, where $x$ is the spatial location along the interface in the sliding direction. We first show that, even under “ideal” types of loading, values of the shear, $\tau(x)$, and normal, $\sigma(x)$, stresses along the interface can vary significantly. In particular, we show that $\tau(x)/\sigma(x)$ can, locally, far exceed the coefficient of static friction, $\mu_S$, without precipitating slip. We then show that the initiation of slip is mediated by a number of possible (slow, sub-Rayleigh, or supershear) rupture modes. The selection of these modes is coupled to the local value of the stress ratio, $\tau(x)/\sigma(x)$, prior to slip initiation. We conclude by demonstrating that $\mu_S$ is not a constant, but varies systematically by nearly a factor of 2, as stress distributions along the interface are varied. Thus, how loads are applied to a system governs both the threshold for the onset of slip and the resulting rupture dynamics. These results point to the key role of nonuniformity along frictional interfaces and have important implications to the prediction, selection and arrest of different modes of rapid frictional failure. These results also apply to earthquakes, which are ruptures within natural faults.

Reference:
**Slip-stick: the evolution of frictional strength**

Oded Ben-David\(^1\), Shmuel M. Rubinstein\(^2\) and Jay Fineberg\(^1\)

\(^1\)The Racah Institute of Physics, The Hebrew University of Jerusalem, Givat Ram, Jerusalem Israel and \(^2\)Present address: School of Engineering and Applied Sciences, Harvard University, Cambridge, MA

Frictional strength is governed by the resistance to shear of the large ensemble of discrete contacts that forms the interface that separates two sliding bodies. An interface's overall strength is determined by both the real contact area and the contacts' shear strength. While the average motion of large, slowly sliding bodies is well-described by empirical friction laws, interface strength is a dynamic entity which is inherently related to both fast processes such as detachment/re-attachment and the slow process of contact area rejuvenation. We show how frictional strength evolves from extremely short to long time scales, by continuous measurements of the concurrent local evolution of the real contact area and the corresponding interface motion (slip) from the first microseconds when contact detachment occurs to large (100sec) timescales. We identify four distinct and inter-related phases of evolution. First, all of the local contact area reduction occurs within a few microseconds, upon the passage of a crack-like front. This is followed by the onset of rapid slip over a characteristic time, whose value suggests a fracture-induced reduction of contact strength before any slip occurs. This rapid slip phase culminates with a sharp transition to slip at velocities an order of magnitude slower. Immediately upon slip arrest, “aging” commences as contact area increases with a characteristic time scale provided by the system's local memory of its effective contact time prior to slip arrest. We show how the singular logarithmic behavior generally associated with aging is regularized at short times. These results provide a comprehensive picture of how frictional strength evolves from the short times and rapid slip velocities at the onset of motion to aging at the long times following slip arrest.

References:


An experimental and theoretical study of asymmetric earthquake rupture propagation caused by off-fault fracture damage

Harsha S. Bhat\textsuperscript{1,2}, Ares J. Rosakis\textsuperscript{2}, and Charles G. Sammis\textsuperscript{\dagger}

\textsuperscript{1}Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA and \textsuperscript{2}Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, USA

The interaction between a dynamic mode II fracture on a fault plane and off-fault damage has been studied experimentally using high-speed photography and theoretically using finite element numerical simulations. In the experimental studies, fracture damage was created in photoelastic Homalite plates by thermal shock in liquid nitrogen and rupture velocities were measured by imaging fringes at the tips. Two cases were studied: an interface between damaged and undamaged Homalite plates, and an interface between damaged Homalite and undamaged polycarbonate plates. Propagation on the interface between damaged and undamaged Homalite is asymmetric. A ruptures propagating in the direction for which the compressional lobe of its crack-tip stress field is in the damage (which we term the ‘C’ direction) is unaffected by the damage. In the opposite ‘T’ direction, the rupture velocity is significantly slower than the velocity in undamaged plates at the same load. Specifically, transitions to supershear observed using undamaged plates are not observed in the ‘T’ direction. Propagation on the interface between damaged Homalite and undamaged polycarbonate exhibits the same asymmetry, even though the elastically “favored” ‘+’ direction coincides with the ‘T’ direction in this case indicating that the effect of damage is stronger than the effect of elastic asymmetry. This asymmetric propagation was also simulated numerically by incorporating the micromechanical damage mechanics formulated by Ashby and Sammis (PAGEOPH, 1990) into the ABAQUS dynamic finite element code. The quasi-static Ashby/Sammis formulation has been improved to include modern concepts of dynamic fracture mechanics, which become important at the high loading rates in the process zone of a propagating rupture.
The stability of creeping faults is studied under the effect of shear heating, pore fluid pressurization and dehydration reactions. Recent data on fault rocks mineralogy (e.g. Sulem et al., 2004); have revealed the presence of a significant amount of clays and hydrous phyllosilicates along major subsurface fault zones. These minerals are thermally unstable and can release adsorbed and/or structural water while turning into a denser reaction product. Such reactions enhance the pore fluid pressurization because they release fluid, but they limit the temperature rise caused by shear heating because they are endothermic. The effect of mineral decomposition has been shown to influence faults mechanical behavior during seismic slip (Brantut et al. 2008, 2010, Sulem and Famin, 2009). In this work we investigate their effect on the stability of stationary fault motion.

The governing equations are derived and the stability of the system is studied at the vicinity of the equilibrium temperature of the reaction. It is shown that the dehydrating layer remains very thin, while the temperature in the slip zone is kept very close to the equilibrium temperature. By performing a linear stability analysis, we show that chemical reactions can change a stable behavior into an unstable one when the pore pressure effect is larger than the endothermic effect. Numerical simulations show that dehydration reactions can trigger an arrest of the fault slip, and/or transient slip events induced by chemical pressurization.

In subduction zones, dehydration reactions can change the motion of creeping faults embedded in serpentinites. The onset of the reaction can be marked by a transient acceleration of the fault motion up to a few meters per year, which corresponds to the order of magnitude for slow and silent slip events detected in several subduction zones. The magnitude of such events seems to be proportional to their duration. We conclude that such metamorphic reactions have first order effects on pore pressure and temperature in faults, and can strongly modify the nucleation of unstable slip.

References

Triaxial tests on gypsum polycrystals samples are performed at confining pressures $P_c$ ranging from 2 to 95 MPa and temperatures up to 70°C. During the tests, stress, strain, elastic wave velocities and acoustic emissions are recorded. At $P_c<=$10 MPa the macroscopic behaviour is brittle, and above 20 MPa the macroscopic behaviour becomes ductile. Ductile deformation is cataclastic, as shown by the continuous decrease of elastic wave velocities interpreted in terms of microcracks accumulation. Surprisingly, ductile deformation and strain hardening is also accompanied by small stress drops from 0.5 to 6 MPa in amplitude. Microstructural observations of the deformed samples suggest that each stress drop corresponds to the generation of a single shear band, formed by microcracks and kinked grains. At room temperature, the stress drops are not correlated to acoustic emissions (AEs). At 70°C, the stress drops are larger and systematically associated with a low frequency AE (LFAE). Rupture velocities can be inferred from the LFAE high frequency content and range from 50 to 200 m/s. The LFAEs amplitude also increases with increasing rupture speed, and is not correlated with the amplitude of the macroscopic stress drops. LFAEs are thus attributed to dynamic propagation of shear bands. In Volterra gypsum, the result of the competition between microcracking and plasticity is counterintuitive: dynamic instabilities at 70°C may arise from the thermal activation of mineral kinking.
**Nematic elastomers: instabilities and relaxation**

Pierluigi Cesana¹

¹Division of Civil and Mechanical Engineering, California Institute of Technology, Pasadena, CA, USA

Nematic liquid crystal elastomers are a class of materials which associate a liquid crystalline microstructure composed of rigid rod-like molecules with an elastic continuum matrix made of cross-linked polymeric chains.

The relaxation of a free-energy functional which describes the order-strain interaction in nematic elastomers is obtained explicitly. We work in the regime of small strains (linearized kinematics). Adopting the uniaxial order tensor theory (Frank model) to describe the liquid crystal order, we prove that the minima of the relaxed functional exhibit an effective biaxial nematic texture, as in the de Gennes order tensor model. In particular, this implies that, at a sufficiently macroscopic scale, the response of the material is soft even if the order of the system is assumed to be fixed at the microscopic scale. The relaxed energy density satisfies a solenoidal quasiconvexification formula.
AES for multiscale localization modeling in granular media

Qiushi Chen¹, José E. Andrade¹, and Esteban Samaniego²

¹Civil & Mechanical Engineering, California Institute of Technology, Pasadena, CA 91125, USA and ²Civil Engineering School, Universidad de Cuenca, Cuenca, Ecuador

This work presents a multiscale strong discontinuity approach to tackle key challenges in modeling localization behavior in granular media: accommodation of discontinuities in the kinematic fields, and direct linkage to the underlying grain-scale information. Assumed enhanced strain (AES) concepts are borrowed to enhance elements for post-localization analysis, but are reformulated within a recently-proposed hierarchical multiscale computational framework. Unlike classical AES methods, where material properties are usually constants or assumed to evolve with some arbitrary phenomenological laws, this framework provides a bridge to extract evolutions of key material parameters, such as friction and dilatancy, based on grain scale computational or experimental data. More importantly, the phenomenological softening modulus typically used in AES methods is no longer required. Numerical examples of plane strain compression tests are presented to illustrate the applicability of this method and to analyze its numerical performance.
Interaction of small repeating earthquakes in a rate and state fault model

Ting Chen¹ and Nadia Lapusta¹,²

¹Division of Geological and Planetary Sciences and ²Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, USA

Small repeating earthquake sequences can be located very close, for example, the San Andreas Fault Observatory at Depth (SAFOD) target cluster repeaters "San Francisco" and "Los Angeles" are separated by only about 60 - 70 m. These two repeating sequences also show closeness in occurrence time, indicating substantial interaction. Modeling of the interaction of repeating sequences and comparing the modeling results with observations would help us understand the physics of fault slip.

Here we conduct numerical simulations of two asperities in a rate and state fault model (Chen and Lapusta, JGR, 2009), with asperities being rate weakening and the rest of the fault being rate-strengthening. One of our goals is to create a model for the observed interaction between "San Francisco" and "Los Angeles" clusters. The study of Chen and Lapusta (JGR, 2009) and Chen et al (EPSL, 2010) showed that this approach can reproduce behavior of isolated repeating earthquake sequences, in particular, the scaling of their moment versus recurrence time and the response to accelerated postseismic creep.

In this work, we investigate the effect of distance between asperities and asperity size on the interaction, in terms of occurrence time, seismic moment and rupture pattern. The fault is governed by the aging version of rate-and-state friction. To account for relatively high stress drops inferred seismically for Parkfield SAFOD target earthquakes (Dreger et al, 2007), we also conduct simulations that include enhanced dynamic weakening during seismic events. As expected based on prior studies (e.g., Kato, JGR, 2004; Kaneko et al., Nature Geoscience, 2010), the two asperities act like one asperity if they are close enough, and they behave like isolated asperities when they are sufficiently separated. Motivated by the SAFOD target repeaters that rupture separately but show evidence of interaction, we concentrate on the intermediate distance between asperities. In that regime, the interaction can be quite complex and varying with time. One of the interesting behaviors is the overlapping rupture areas of events that nucleate on separate asperities. Another interesting behavior is alternating between events that rupture a single asperity and events that rupture both asperities at the same time. These and other features lead to variability of moment and recurrence time for individual repeaters consistent with Parkfield target repeaters.
The geochemical signature of carbonate-hosted seismogenic faults

N. De Paola1, G. Chiodini2, T. Hirose3, C. Cardellini4, S. Caliro2, and T. Shimamoto5

1Rock Mechanics Laboratory, Earth Sciences Department, University of Durham, UK.
2 Osservatorio Vesuviano, Istituto Nazionale di Geofisica e Vulcanologia, Naples, Italy.
3 Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan.
4 Dipartimento di Scienze della Terra, Universita’ di Perugia, Perugia, Italy.
5 Institute of Geology, China Earthquake Administration, Beijing, China.

Laboratory experiments have been performed at sub- (≈ 0.01 m/s) to seismic slip rates (>1 m/s) on dolomite gouges of the Triassic Evaporites in Northern Apennines (Italy), which hosted the 1997 Colfiorito Mw ≤ 6 earthquakes.

Experimental faults are lubricated as marked falls in the steady state sliding friction coefficients, \( f \approx 0.1 \), is observed at seismic slip rates, as opposed to values of \( f \geq 0.6 \) attained for sub-seismic slip rates. Fault lubrication was associated with decarbonation reactions and CO\(_2\) emissions triggered by frictional heating in the experimental slip zone which produced: 1) new and exotic mineral phases (e.g. Mg-calcite, periclase/brucite, lime/portlandite); 2) isotopic fractionation between the newly generated and the original mineral phases.

When extrapolated to natural seismic fault conditions, experimental results show that coseismic release of CO\(_2\) can represent a shallow and localised source of very high fluid fluxes in the brittle crust, comparable to measured fluxes from deeper sources (e.g. mantle degassing). Modelling results show that when large amounts of coseismically released CO\(_2\) interact with deep saline aquifers, the geochemical signature produced may be very weak and difficult to detect in groundwater. Conversely, it should be possible to measure and monitor the geochemical signature of large amounts of coseismically released CO\(_2\) which are directly dissolved in shallow, less saline aquifers.

We conclude that the integration of microstructural/mineralogical observations and geochemical data from experimental faults allow the definition of a distinct and measurable geochemical signature associated with high temperature physical-chemical processes. During earthquake propagation in natural carbonate fault zones, the operation of the same processes observed in the laboratory can: a) release significant amounts of CO\(_2\), which are comparable to those released by deeper sources (e.g. mantle degassing); b) represent a relatively shallow and localised source of very high fluid fluxes of CO\(_2\) in the brittle crust; c) produce groundwater post-seismic geochemical signatures which can potentially be measured and monitored, depending on the geochemical nature of the aquifers present at different depths.

The integration of results from laboratory experiments, performed at seismic condition in carbonate rocks, and geochemical analyses can: a) aid in the development and calibration of monitoring strategies of geochemical properties of water in seismically active areas; b) provide insights into seismic fault zone processes (e.g. constraints on the coseismic temperatures).
Formation of pulse-like ruptures on velocity-weakening interfaces and its relation to stability properties of steady-state sliding

Ahmed Elbanna\textsuperscript{1}, Nadia Lapusta\textsuperscript{1,2}, and Thomas H. Heaton\textsuperscript{1,2}

\textsuperscript{1}Division of Engineering and Applied Science and \textsuperscript{2}Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA

Prior studies have shown that velocity-weakening interfaces can produce both crack-like ruptures, for higher prestress levels, and pulse-like ruptures, for lower prestress levels and sufficient amounts of weakening. More complex rupture patterns, such as multiple pulses of slip, may result for intermediate levels of prestress. Such multiple pulses occur due to destabilization of steady sliding behind the front of the crack-like rupture that forms after the nucleation stage. The spacing of the multiple pulses can be predicted from linearized stability analysis of the steady sliding; it corresponds to the wavelength of the perturbation with the maximum growth rate. Whether the transition from the crack-like rupture to multiple pulses occurs within the rupture duration depends on the growth rates, which are higher for more pronounced velocity weakening.

Here we explore the possibility that transition from the initial crack-like rupture to a self-healing pulse can also be understood based on such stability analysis. We conduct simulations of dynamic ruptures in a 2D anti-plane fault model with rate and state friction that involves enhanced weakening at seismic slip velocities motivated by flash heating. The fault has uniform prestress, except in a small overstressed region with Gaussian prestress distribution used for rupture nucleation. For a range of model parameters that favors slip pulses, we find that the decrease of sliding velocity behind the front of the initial crack causes significant increase in the maximum growth rate of unstable modes and increase in the contrast between their phase velocities. The combined effect of dispersion and mode growth lead to further decrease in the slip rate behind the rupture front. When this slip rate ultimately drops below a certain value, which is dependent on the friction law and the initial prestress, we observe that several modes grow simultaneously with a growth rate comparable to the mode with maximum growth rate and that many of those modes acquire a zero phase velocity. We hypothesize that this simultaneous growth of the stationary modes leads finally to the local arrest of rupture and formation of slip pulses. Phase velocities of the growing wavelengths influence the speed of the healing front of the resulting slip pulses and hence influence how the width of the pulse changes with its propagation.

We will report on our current efforts to turn these observations into a predictive theory of rupture mode selection on uniformly pre-stressed velocity-weakening interfaces. The effect of the nucleation procedure, which is clearly present in the formation of self-healing pulses, may be possible to incorporate through the different characteristics of the initial crack-like rupture.
Gutenberg-Richter breakdown and the smallest earthquakes at the San Andreas Fault Observatory at Depth

William L. Ellsworth¹

¹U. S. Geological Survey, Menlo Park, CA, USA

The pioneering work on frictional instability by Jim Rice and his many students, beginning with Andy Ruina in 1980, introduced the concept of a minimum earthquake size through the recognition that steady-state slip in a nucleation zone with radius

\[ h^* = \frac{G d_c}{(B-A) \sigma} \]

or larger is required for an earthquake instability to occur. In the expression for \( h^* \), \( G \) is the shear modulus, \( d_c \) is the sliding distance over which friction evolves, \( B-A \) is the velocity weakening parameter and \( \sigma \) is the effective normal stress. Laboratory derived values for \( d_c \) and \( B-A \) suggest that the minimum earthquake should have a magnitude well below \( M_w = 0 \), assuming that the range of stress drops observed at larger magnitude continues to apply. Indeed, earthquakes with \( M_w < -3 \) have been observed in the SAFOD borehole and events with \( M_w < -4 \) have been observed in deep mines in South Africa. It remains an open question, however, how to connect the minimum source dimension for nucleation, \( h^* \), to either the magnitude of the minimum earthquake or earthquake population statistics for the smallest earthquakes.

To explore this problem, the frequency-magnitude distribution of earthquakes occurring within a 1 km radius of the SAFOD borehole was studied. Between May 2009 and August 2010 a total of 120 earthquakes with \( M_w \geq -2.0 \) were detected by a high-gain 15 Hz seismometer installed in the SAFOD main hole at a depth of 2550 m below the land surface. These earthquakes exhibit a linear Gutenberg-Richter frequency-magnitude relation with \( b = 0.7 \) for \( M_w \geq -0.5 \). Below \( M_w -0.5 \), however, the G-R relation breaks down and \( b = 0.3 \) or smaller. The breakdown is not believed to be an artifact of incomplete detection of events, but rather reflects a change in earthquake population statistics.

At SAFOD, both the effective normal stress, \( \sigma \), and shear modulus, \( G \), are known from in-situ measurement, leaving only the rate-and-state parameters \( d_c \) and \( B-A \) as unknowns in the expression for \( h^* \). Under the assumption that \( d_c \) has a distribution peaked between 10\( \mu \)m and 100 \( \mu \)m, and that \( B-A \) lies in the range between 0.001 and 0.01, a simple statistical model is developed for the distribution of minimum earthquakes growing out of the nucleation zone. Using this model, the observed frequency-magnitude distribution for events within 1 km of SAFOD are adequately explained by laboratory-derived values for the rate-and-state friction parameters \( d_c \) and \( B-A \).

Needless to say, the resulting match is neither unique nor required by the model. Instead, it points out the value of future work connecting the initiation of rupture to the physical processes that control its termination.
Origin of strong velocity weakening in high-speed rotary shear experiments on gabbro: Partial melting of the gouge layer

Yuri Fialko and Kevin Brown

1Institute of Geophysics and Planetary Physics and 2Geosciences Research Division, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA

Over the last decade a number of experimental studies of rock friction at slip rates approaching the seismic range reported dramatic variations in the coefficient of friction, with an onset of strong weakening at slip rates in excess of several centimeters per second, followed by strengthening due to wholesale melting, and secondary weakening due to viscous dissipation in a continuous melt layer. The strengthening phase has been attributed to high viscous stresses in the developing melt layer (Fialko and Khazan, 2005) or re-freezing of incipient melt patches (Hirose and Shimamoto, 2003), and predicted to depend on normal stress, due to a transition from stress-sensitive friction to stress-insensitive viscous flow (Fialko and Khazan, 2005). The origin of strong velocity weakening has been a matter of debate. The proposed mechanisms include flash melting of micro-asperities (Rice, 2006), silica gel lubrication (Goldsbay and Tullis, 2002), powder lubrication (Reches and Lockner, 2009), and thermal decomposition and degassing (Han et al., 2007). Here we report on results of high-speed rotary shear experiments performed on ring samples of fine-grained gabbro at slip rates of 1-50 cm/s and normal stresses of 0.5-5 MPa. Experimental data indicate a dependence of the critical weakening velocity on normal stress, supporting the hypothesis of the thermal origin of weakening. According to the flash melting mechanism, such dependence may arise through dependence of the background temperature (mean temperature of the slip zone) on normal stress and slip history. Our modeling of the interface temperature (constrained by direct measurements of temperature at few millimeters away from the contact area) however indicates that the critical weakening velocity does systematically depend on the instantaneous temperature. The observed drop in the apparent coefficient of friction is rather abrupt in time. Inspection of the slip interface at the time of friction drop revealed glassy rings formed in the middle of the contact due to partial melting of the gouge layer. This observation contradicts earlier reports (e.g., Shimamoto et al.) of incipient melting associated with the strengthening phase of apparent friction. We interpret strong weakening observed in gabbro experiments in terms of formation and smearing of pockets of melt that concentrate stress because they are initially strong, but occupy a relatively small fraction of the nominal contact area. Such partial melting occurs when the average temperature of the slip interface is well below the solidus (by a factor of 2 or more). We speculate that the overall weakening is achieved due to a volume increase upon melting, which decreases normal stress on the rest of the interface. This interpretation is supported by a dilation of the slip zone (and concomitant increase in the applied normal stress) at the onset of weakening. As a fraction of melt covering the contact increases (e.g., at higher slip rate and/or normal stress), shear resistance increases, leading to enhanced heat generation and rapid wholesale melting, as observed in the experiments.
Experimental study of ground motion attenuation of thrust faults

Vahe Gabuchian\textsuperscript{1,3}, Ares J. Rosakis\textsuperscript{1,3}, Nadia Lapusta\textsuperscript{2,3}, and David D. Oglesby\textsuperscript{4}

\textsuperscript{1}Graduate Aerospace Laboratories, California Institute of Technology, \\textsuperscript{2}Division of Geological and Planetary Sciences, California Institute of Technology, \\textsuperscript{3}Division of Engineering and Applied Science, California Institute of Technology, and \\textsuperscript{4}Earth Sciences, University of California, Riverside

The waves sent through the earth’s bulk during earthquakes induce complex ground motion on the surface of the earth. This study experimentally investigates the near-fault ground motion on the earth’s free surface caused by thrust faults, specifically, the differences between a Supershear event versus a sub-Rayleigh event. Photoelastic images along with laser vibrometer velocity traces are used in unison to determine the relation of ground motion signatures to the various incoming portions of the wave field, including P waves, S waves, rupture front, and in the case of an event that has transitioned to Supershear, the additional features of the Mach cones and the trailing Rayleigh rupture. Focus is placed on the spatial attenuation of ground motion with distance away from the fault trace, namely the strong attenuation of the trailing-Rayleigh signature and the much weaker attenuation of the Mach cone signatures. The experimental signatures are compared to numerically generated traces. The implication of the complex space-time ground motion of thrust faults is considered for the safety of buildings, to complement the work of Mello, Bhat, Krishnan, Rosakis, and Kanamori on strike-slip faults.
Flash heating of crustal rocks at near-seismic slip rates

David L. Goldsby and Terry E. Tullis

Department of Geological Sciences, Brown University, Providence, RI 02912 USA

The friction coefficient of rocks measured at slow, quasi-static slip rates in the laboratory obtains ‘Byerlee’s-law’ values of 0.6 to 0.85. At seismic slip rates, an extraordinary reduction in the friction coefficient of crustal silicate rocks likely results from intense, transient, so-called 'flash' heating of microscopic asperity contacts and the resulting thermal degradation of their shear strength. To investigate flash-heating phenomena in rocks, friction experiments were conducted on a variety of crustal rocks at near-seismic slip velocities \( V \) up to 0.4 m/s and displacements <45 mm, conditions conducive for activation of flash-heating effects but not melting of the entire slip surface. Samples were tested in rotary shear at a normal stress of 5 MPa. Each experiment was begun by sliding at \( V=10 \) \( \mu \)m/s for several mm of slip, then at a continuously varying velocity up to 0.4 m/s for ~45 mm of slip. Up to a characteristic weakening velocity \( V_w \) of ~0.1 to 0.25 m/s (depending on rock type), values of the friction coefficient \( f \) are in the range 0.6 to 0.8 and are nominally independent of \( V \). Above \( V_w \), \( f \) falls off precipitously as \( 1/V \) and is nearly a pure function of \( V \). At the highest velocity of ~0.4 m/s, values of \( f \) of 0.2 to 0.4 are obtained. Experimental results are compared with Rice’s model of flash heating (Rice, 1999; 2006). In the Rice model, \( V_w=(\pi \alpha/D)[\rho c (T_w-T_f)/\tau_c]^2 \), where \( \alpha \) is thermal diffusivity, \( D \) contact size, \( \rho c \) specific heat, \( T_w \) a weakening temperature above which the contact shear strength \( \tau_c \) is negligible, and \( T_f \) the average temperature of the sliding surface. Taking appropriate values of these parameters yields values of \( V_w \) that are in very good agreement with the experimentally derived values of \( V_w \), though the uncertainty in parameter values, particularly \( D \) and \( \tau_c \), is significant. The Rice model also contains an expression for the effect of flash heating on macroscopic friction above \( V_w \): \( f=(f_0-f_w)V_w/V + f_w \), where \( f_0 \) is the low-speed friction coefficient and \( f_w \) is the friction coefficient of the contacts in the weakened state, assumed to be negligibly small. The experimentally derived trend of \( f \) with \( V \) above \( V_w \) is in good agreement with Rice’s expression for \( f=f(V) \) when it is modified slightly such that weakened contacts have finite \( f_w \) (Beeler et al., 2008). While questions remain, for example, about whether distributed shearing and sub-\( \mu \)m contact dimensions result in values of \( V_w \) on natural faults that are larger than seismic slip rates, it is likely that dynamic fault weakening due to flash heating is active during nucleation and propagation of at least some earthquake ruptures. Extrapolated values of \( f \) due to flash heating at seismic slip rates are sufficient to explain the lack of an observed heat flow anomaly along some active faults like the San Andreas Fault. The velocity-weakening frictional behavior due to flash heating may explain how some earthquake ruptures propagate as self-healing slip pulses rather than as conventional cracks.
Shearing resistance of aluminum at high strain rates and at temperatures approaching melt

Stephen E. Grunschel\textsuperscript{1}, Rodney J. Clifton\textsuperscript{2} and Tong Jiao\textsuperscript{2}

\textsuperscript{1} ASML, Wilton, CT and \textsuperscript{2} Brown University, Providence, RI

High-temperature, pressure-shear plate impact experiments have been conducted to investigate rate-controlling mechanisms for plastic deformation of high-purity aluminum at high strain rates ($10^6\text{s}^{-1}$) and at temperatures approaching melt. The objective of these experiments was to look for a possible change in rate-controlling mechanism of dislocation motion from thermally activated motion of dislocations past obstacles to phonon drag as the temperatures became high enough that thermal activation became relatively unimportant. The results show an upturn in shearing resistance with increasing temperature at high temperatures, suggestive of a change in rate-controlling mechanism. However, the upturn is too steep to be described by a usual phonon drag model with a drag coefficient that is proportional to temperature. Various explanations are being investigated.
The SCEC-USGS dynamic earthquake rupture code verification exercise: regular and extreme ground motion

Ruth A. Harris¹, Michael Barall², Ralph Archuleta³, Brad Aagaard¹, Jean-Paul Ampuero⁴, Joe Andrews⁴, Victor Cruz-Atienza⁵, Luis Dalguer⁶, Steven Day⁷, Benchun Duan⁸, Eric Dunham⁹, Geoff Ely¹⁰, Alice Gabriel⁶, Yoshihiro Kaneko¹¹, Yuko Kase¹², Nadia Lapusta⁴, Shuo Ma⁷, Hiroyuki Noda⁴, David Oglesby¹³, Kim Olsen⁷, Daniel Roten⁷, Surendra Somala⁴, Seok Goo Song⁶

¹U.S. Geological Survey, ²Invisible Software, ³University of California Santa Barbara, ⁴California Institute of Technology, ⁵Universidad Nacional Autonoma de Mexico, ⁶Swiss Federal Institute of Technology, ⁷San Diego State University, ⁸Texas A&M University, ⁹Stanford University, ¹⁰University of Southern California, ¹¹University of California San Diego, ¹²Geological Survey of Japan, ¹³University of California Riverside

We summarize progress by the SCEC-USGS Dynamic Rupture Code Verification Group, that examines if SCEC and USGS researchers’ spontaneous-rupture computer codes agree when computing benchmark scenarios for dynamic earthquake rupture. We have examined ‘regular’ dynamic ruptures on vertical strike-slip faults and on normal faults, at a range of resolutions, and, ‘extreme’ dynamic ruptures on a normal fault. The ‘extreme’ dynamic ruptures were designed as complete stress-drop, supershear ruptures that would be most likely to produce maximum possible ground motions. These simulated ruptures could be thought of as very unlikely, but still possible. Among the ‘extreme’ dynamic rupture benchmarks were those targeted to test two simplified versions of the Andrews et al. [BSSA, 2007] numerical simulations for hypothesized maximum-possible ground motion at a site near Yucca Mountain. To test the Andrews et al. methodology, we constructed a benchmark for a planar dipping normal-fault set in a medium where the off-fault response was designated to be elastic (TPV12), and another benchmark where the off-fault response was designated to be plastic (TPV13). Although most of our group’s previous benchmarks have concentrated on 3D solutions, both the TPV12 and TPV13 benchmarks were offered with both 2D and 3D options, partly because the Andrews et al. study was conducted in 2D, and partly because it is important to understand the differences and similarities among 2D and 3D rupture propagation and ground motion predictions. Seven researchers’ codes participated in the TPV12 2D benchmark test, seven participated in the TPV12 3D test, six participated in the TPV13 2D benchmark test, and four participated in the TPV13 3D test. Our findings were similar to those hypothesized in the Andrews et al. publication. At a formerly proposed site for a nuclear waste repository, that was modeled to be 1-km from the fault, at 300 m depth, our 2D elastic benchmark simulations produced the largest vertical and largest horizontal velocities, and the next largest values were those produced by the 2D plastic simulations. Our next ‘regular’ benchmark exercises involve thermal pressurization on a planar strike-slip fault, and slip-weakening on branching vertical strike-slip faults. For more information about our group and our benchmark exercises, please see our website, scecdata.usc.edu/cvws, and read our paper, Harris et al., Seismological Res. Lett., 2009.
Linking postseismic and interseismic deformation along the North Anatolian Fault Zone: The role of transient rheology and low-viscosity shear zones

Elizabeth H. Hearn

Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, British Columbia, Canada

Postseismic deformation following the Izmit-Duzce earthquake sequence has been explained as resulting from rapid, frictional afterslip in the middle to upper crust and viscoelastic relaxation of lower crust and upper mantle layers. A Burgers rheology for the lower crust and upper mantle, with two characteristic viscosities ($2 \times 10^{19}$ Pa s and at least $5 \times 10^{20}$ Pa s), and a characteristic evolution time of about ten years, is consistent with both the later postseismic and the highly localized and stationary interseismic deformation. However, for reasonable postseismic strain rates in the lower crust and upper mantle, these parameter values are not consistent with laboratory experiments.

I have developed a suite of earthquake cycle models to assess whether the addition of a lithosphere-scale viscous shear zone could also explain the dramatic postseismic and essentially stationary interseismic deformation. These models incorporate 10 to 60 km-wide channels of relatively low-viscosity, Maxwell viscoelastic material embedded in the lower crust and upper mantle, which are modeled with depth-dependent power-law or Maxwell viscoelastic rheologies.

Models with narrower viscous shear zones yield deformation which is somewhat more stationary throughout the earthquake cycle than that produced by halfspace viscoelastic models incorporating the shear zone viscosity. These models also produce differential stresses high enough to allow dislocation creep in the mantle and lower crust outside the shear zone, for reasonable mineral grain dimensions. However, to explain the near-field deformation, a time-varying effective viscosity is still required in the channel material. For the required, rapid evolution of the effective viscosity in the channel material to be consistent with available laboratory data, extremely high strain rates ($10^{11}$/s) are required. This suggests rapid postseismic relaxation of a network of narrow ultramylonite strands within the channel. The temporary reduction in the effective viscosity of the shear zone material should cause it to deform postseismically in response to total stress, rather than just the coseismic stress change, potentially leading to a postseismic increase in the rate of fault-normal extension or compression.
Size effects in the failure conditions of systems with strong velocity-weakening frictional interfaces and pulselike ruptures

Thomas H. Heaton¹,² and Ahmed Elbanna²

¹Division of Geological and Planetary Sciences and ²Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, USA

We use a spring block model to characterize some basic features of the dynamic rupture of systems with strong velocity-weakening frictional interfaces failing in the self-healing slip pulse mode. We show that as a consequence of using this class of friction laws, size effects are introduced into the systems failure conditions. The long time simulation of the model reveals that these size effects are manifested in: i) the evolution of a scale dependent prestress with the average prestress required to propagate a rupture of a given length decreasing with the increase of that length, and ii) the tuning of the model into a state of size-dependent dissipation, in which the energy per unit length required to displace the model for a given value of total displacement generally decreases as the overall system length increases (Fig. 1). We show that these results are consistent with the velocity weakening nature of the friction law and the pulse dynamics and should be independent of the model specific details. Longer ruptures accumulate, on average, larger slips that are propagated by larger slip pulses. Due to the velocity-weakening friction, the faster the slip rate the smaller the friction will be. Accordingly, larger slip pulses will experience smaller friction and will be able to propagate further in lower average prestress while dissipating less friction. Finally, we discuss the implications of these observations on our understanding of the dynamics of real faults in the Earth’s crust.

Fig.1: Scaling of dissipated energy per unit length per unit slip with the corresponding rupture (system) length in the spring block model. Longer ruptures dissipate less energy per unit slip compared to smaller ones and will generally have smaller average prestress
Properties of dynamic slip pulses in a 2D slab

Yihe Huang\textsuperscript{1}, Jean-Paul Ampuero\textsuperscript{1}, and Luis A. Dalguer\textsuperscript{2}

\textsuperscript{1}Seismological Laboratory, California Institute of Technology, Pasadena, CA, USA
\textsuperscript{2}SED, ETH Zürich, Zürich, Switzerland

Earthquake ruptures are believed to propagate predominantly as self-healing pulses yet the dynamics of these pulses is not completely understood: what controls their rise time and rupture speed? Large earthquake ruptures (M larger than 7) necessarily behave as pulses due to healing by the waves reflected at the top and bottom of the seismogenic zone. To obtain insight on the dynamics of self-healing pulses on very long faults we studied dynamic ruptures running across the middle longitudinal plane of a 2D elastic slab of finite thickness $H$. Reflected waves from boundaries are also present in this 2D problem and pulse-like ruptures are naturally produced. We studied this model numerically, applying the spectral element method implemented in the SEM2DPACK code, assuming uniform slip-weakening. We monitored the relation between rupture properties such as final slip, peak slip rate, stress drop, rise time and rupture speed. We found a transition between sustained and dying pulses as a function of slab thickness $H$, well predicted by a critical ratio of fracture energy to potential energy. The limiting speed of sustained rupture is independent on $H$ and is consistent with analytical results based on a non-classical crack tip equation of motion appropriate for this geometry. In super-shear ruptures rise time approaches the travel time of the reflected phases, but in sub-shear ruptures it decreases continuously to much shorter values due to reflected waves faster than rupture fronts. The rupture arrest transition controlled by $H$ and the supershear transition controlled by background stresses are observed also in 3D ruptures on very long faults. We will also report on the mechanism of reflected waves for the generation of dynamic slip pulses.
BIEM simulation of non-planar earthquake rupture, and its extension to inhomogeneous medium

Nobuki Kame

\(^1\)Earthquake Research Institute, the University of Tokyo, Tokyo, Japan

Various numerical approaches have been developed to simulate earthquake dynamic rupture propagation. Among them boundary integral equation method (BIEM) is a very powerful tool in modeling of non-planar rupture geometry when the medium is considered homogeneous. We here present our previous BIEM studies on non-planar earthquake rupture simulation and introduce our ongoing challenge for the extension of BIEM to inhomogeneous medium (XBIEM).

Kame and Yamashita (GRL, 1999; GJI, 1999, 2003) applied BIEM to a problem that how a path of fresh rupture might be chosen in the first faulting event in an otherwise virgin domain. They focused on the effect of only shear stress at the crack tip on radial planes from it in determining the momentary direction of rupture. Their simulation showed that the crack tip bifurcates into two branches at the high-speed propagation stage due to the stress wave localization near the crack tip. The growth of each branch was arrested after increasing the bending angle. They clearly showed a significant effect of non-planar geometry on arresting of rupture propagation.

Kame, Rice and Dmowska (JGR, 2003) studied another type of problem in rupture path selection, that how a rupture chooses its path along pre-existing fault strands with a complex, branched morphology. They showed definitive results on the basic analysis of path selection at a branch junction: whether a branch from a main fault was chosen or not by rupture depended on (a) branch geometry, (b) rupture front speed as the junction is approached, and (c) direction of principal compression in the regional pre-stress field. This has been remarkably successful in explaining observed rupture path selections at branch junctions. The research was also tested by the 2002 Denali earthquake. Bhat, Dmowska, Rice and Kame (BSSA, 2004) successfully reproduced dynamic rupture transfer from the Denali to Totschunda fault.

XBIEM is a challenge for the extension of BIEM applicable to inhomogeneous medium (Kame, EOS, 2010). In the formulation of XBIEM an inhomogeneous body is assumed to be split into complementary homogeneous subregions and their interfaces are considered extended boundaries. Boundary integral equations are first derived on both crack(s) and extended boundaries and then coupled by imposing boundary conditions. Ideally XBIEM is free to handle (i) non-planar interfaces, (ii) non-planar crack, (iii) arbitrary incidence angle of crack to interface, and (iv) rupture along interface. Preliminary results of numerical implementation will be shown.
Persistence of coseismic rupture asperities as inferred from interseismic geodetic observations from Northeastern Japan

Ravi V. S. Kanda¹,², Eric A. Hetland³, and Mark Simons¹

¹Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA, ²Global Change Research Center, National Taiwan University, Taipei, Taiwan, and ³Department of Geological Sciences, University of Michigan, Ann Arbor, MI, USA

Inversions of interseismic geodetic data near subduction zones image the megathrust locked over spatially smooth and extensive regions, in contrast to the smaller discrete asperities estimated by earthquake source studies. Such smooth, broad regions may be a consequence of a lack of model resolution and the resulting need for regularization inherent to the use of onshore geodetic data. It is also possible that the inferred interseismically coupled regions are larger than the collective asperity sizes for known earthquakes due to an incomplete earthquake catalog. Hence, the different levels of apparent coupling implied by interseismic and seismic-source inversions have very different implications for regional seismic hazard.

Here, we focus on the Japan-Kurile megathrust off northeastern Japan. We test the hypothesis that mechanical coupling on a configuration of asperities inferred only from the locations of past earthquakes is sufficient to explain geodetic observations. The alternative is that these data require additional regions of the megathrust to be coupled. Underlying our hypothesis is the assumption that known asperities persist across multiple earthquake cycles.

We use a 3-D mechanical model of stress-dependent interseismic creep along the megathrust, considering frictional rheologies and known spatio-temporal distribution of large earthquakes (Hetland et al. 2010). Here, we apply their method to curved fault surfaces in a geo-referenced coordinate system, containing multiple asperities experiencing an arbitrary sequence of seismic ruptures. These mechanical models predict that late in the seismic cycle, there are relatively smooth, long wavelength regions of very low slip-rates on the megathrust interface surrounding these asperities, owing to the "stress-shadow" effect of seismic ruptures. Such "physical smoothing" around asperities provides a more realistic alternative to the artificial smoothing introduced by model regularization in inversions of interseismic geodetic data.

We find that most of the present horizontal components of geodetic data in northeastern Japan can indeed be explained by the stress-shadow effect following seismic ruptures on known asperities, over surrounding rate-strengthening regions of the megathrust. However, we cannot fit the vertical components of geodetic data well, because we consider ruptures only on the megathrust interface in the context of an elastic half-space. Such an approach ignores potentially important processes such as anelastic crustal deformation, surface processes, and subduction erosion, over the seismic cycle time scale.
Modeling shallow slip deficit in large strike-slip earthquakes using simulations of spontaneous rupture in elasto-plastic media

Yoshihiro Kaneko and Yuri Fialko

Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California – San Diego, La Jolla, CA, USA

Slip inversions of several large strike-slip earthquakes point to coseismic slip deficit at shallow depths (< 3-5 km), i.e., the amount of coseismic slip sharply decreases towards the Earth surface (e.g., Fialko et al., 2005; Bilham, 2010). Examples include the 1992 M7.3 Landers earthquake, the 1999 M7.1 Hector Mine earthquake, the 2005 M6.5 Bam earthquake, the 2010 M7.0 Haiti earthquake, and the M7.2 Sierra El Mayor (Mexico) earthquake. Determining the origin of shallow slip deficit is important both for understanding physics of earthquakes and for estimating seismic hazard, as suppression of shallow rupture could greatly influence strong ground motion in the vicinity of active faults. Several mechanisms may be invoked to explain the deficit. A widely accepted interpretation is the presence of velocity-strengthening fault friction at shallow depths where the coseismic slip deficit is compensated by afterslip and interseismic creep. However, geodetic observations indicate that the occurrence of interseismic creep and afterslip at shallow depths is rather uncommon, except for certain locations near major creeping segments of mature faults and/or in areas with thick sedimentary covers with overpressurized pore fluids (e.g., Wei et al., 2009). Fialko et al. (2005) proposed that extensive inelastic failure of the shallow crust in the interseismic period or during earthquakes may result in coseismic slip deficit at shallow depths. In this work, we investigate whether inelastic failure of the shallow crust can lead to shallow coseismic slip deficit using simulations of spontaneous earthquake sequences on vertical planar strike-slip faults. To account for inelastic deformation, we incorporate off-fault plasticity into 2-D models of earthquake sequences on faults governed by laboratory-derived rate and state friction (Kaneko et al., 2010). Our preliminary results suggest that coseismic slip deficit could occur in a wide range of parameters that characterize inelastic material properties. We will report on our current efforts on identifying key parameters of fault friction and bulk rheology that link to the degree of coseismic slip deficit over multiple earthquake cycles.
Frequency dependent rupture characteristics of the 2010 Mw 8.8 Chile earthquake as imaged by back-projection

Eric Kiser\textsuperscript{1} and Miaki Ishii\textsuperscript{1}

\textsuperscript{1}Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA

Back-projection results of the February 27, 2010, Mw 8.8 Chile earthquake reveal that this earthquake consists of two distinct events with different slip characteristics. The event that slips mostly south of the epicenter releases its energy at low frequency, implying slow slip. This event triggers the second event to the north, which is characterized by high-frequency energy and a fast propagation speed. The spectral complexity demonstrates that the rupture mechanism is specific to large earthquakes, hence they cannot be related easily to properties of small earthquakes. These distinct slip behaviors help resolve the discrepancy between seismic and geodetic observations, and point out the need to consider data from a wide range of frequencies to fully assess the hazards of giant earthquakes.
Cohesive zone law extraction from an experimental peel test for soft adhesive materials

Christopher Kovalchick\textsuperscript{1}, Shuman Xia\textsuperscript{1}, and Guruswami Ravichandran\textsuperscript{1}

\textsuperscript{1}Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, USA

The measurement of interface mechanical properties between an adhesive layer and a substrate is significant for optimization of a high-quality interface and is of significance in numerous applications including biological systems and electronic packaging. A common method for measuring these properties is the peel test. Although analytical models exist for the peeling of elastic adhesives from smooth surfaces, there is a need for rigorous experiments in this area. Tests are conducted using a newly-developed peel arrangement capable of peel angles from 0 to 180 degrees. Experimental validation is achieved through a series of displacement-controlled tests using elastic adhesive tapes. The steady-state peel force is measured at each angle and compared to the predicted value based upon the governing relations of Kendall and Rivlin.

Using a basic imaging technique, the fibrillation zone of a simple adhesive material at the contact point between the adhesive and a rigid surface is imaged in great detail. By measuring key parameters in this process zone, an inverse technique is used to derive an angle-dependent cohesive zone law in order to describe the material behavior of the adhesive using the principles of finite deformation beam theory and fracture mechanics. The law is input into a finite element simulation and compared to the experimental adhesion energy, showing excellent correlation.

Process zone of an elastic adhesive peeled from a glass substrate
Quantized crystal plasticity in nanocrystalline metals

Lin Li¹, Peter M. Anderson¹, Steven Van Petegem², and Helena Van Swygenhoven²

¹Materials Science and Engineering, The Ohio State University, Columbus, OH, USA and ²Paul Scherrer Institute, Villigen-PSI, CH 5232, Switzerland

This work reports on new insight to the underlying deformation phenomena in nanocrystalline (NC) metals with grain size ~10 to 30 nm. This is achieved by interpreting recent measurements of residual lattice strain in NC metals in terms of quantized crystal plasticity simulations of NC material. These recent measurements show that residual lattice strains change rather modestly after imposing uniaxial plastic strains up to ~2%. Also, residual peak widths from x-ray diffraction measurements decrease over this plastic strain regime. This is in sharp contrast to conventional grain size metals, for which residual strains and peak widths increase with imposed plastic strain. This has motivated hypotheses related to grain boundary sliding or deformation of a distinct grain boundary phase, separate from the grain interior.

This paper presents an alternate hypothesis—namely, that these effects are due to a process termed quantized crystal plasticity [1]. In particular, single slip events across nm scale grains impart large (~1%) increments in grain-average plastic strain. Thus, plasticity does not proceed in a smooth, continuous fashion but rather via large jumps, imparting violent grain-to-grain redistributions in stress. Finite element simulations employing this approach predict the experimental trends in residual strain and peak width mentioned, but only under certain conditions. First, the distribution of critical stresses for slip activation is very different from that for conventional grain material—namely, no events occur below a rather large threshold stress ~1/grain size. Second, a very asymmetric distribution predominates above this threshold, signifying that a relatively large number of easier-to-slip grains is balanced by a minority of harder-to-slip grains.

The quantized crystal plasticity approach, coupled with the asymmetric distribution of critical strength for slip, captures other unique features of NC metals, including unprecedented magnitudes of recoverable plastic strain, hysteresis during stress cycling, and required strain to achieve fully plastic flow [2]. An outcome is the ability to bridge the disparity in length and time scales between MD simulations and physical experiments.

Hurricanes and associated landslides may intensify in an environment affected by global warming. This study provided answers as to why landslides are more likely during heavy rainfall. A series of centrifuge simulations were performed on a rainfall-induced landslide that occurred in Japan in 2005 due to Typhoon Nabi. The simulations were conducted on a gentle slope made of a sand-clay mixture under 100 times earth’s gravity to replicate the conditions of a 27-m high slope. Different amounts of precipitation were applied in increments to the slope surface and the excess pore pressure was monitored. The study showed that incremental rainfall of less than 200 mm caused local failures and rainfall approaching 400 mm resulted in global failures that coincided with field observations. The shear strength tests showed that under increasing amount of moisture, the apparent cohesion of soil was reduced, and eventually diminished as the soil became saturated. An infinite slope stability analysis indicated that a loss of soil’s apparent cohesion and an increase in the water table due to infiltration were responsible for the landslide.
Micromechanics of dilatancy, critical state and shear bands in granular materials

Sinisa Dj. Mesarovic¹, Jagan M. Padbidri³, and Balasingam Muhunthan²

¹School of Mechanical and Materials Engineering, ²Department of Civil and Environmental Engineering, Washington State University, Pullman WA, USA
³George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA

We use numerical simulations to uncover the (1) micromechanism of dilatancy and critical state, (2) the intrinsic length scale that characterizes shear bands in granular materials.

Dense granular materials exhibit a peculiar behaviour – dilatancy – volume increase when sheared under constant pressure. More precisely, when sheared under constant pressure, their either dilate or decreases, depending on the combination of pressure and porosity. The critical state is the boundary between dilating and compacting states when material shears at constant volume. The set of critical state points in the pressure-porosity space forms the critical state line. The phenomenological Critical state theory, based on such observations, and its modifications, are at the core of modern geomechanics. Yet, current understanding of dilatancy and critical state is purely empirical. The fundamental question: what are the micromechanisms that produce dilatancy and compaction? – has not been answered, except in a vague manner. The classic simplistic answer that nearly rigid particles must climb over each other to accommodate the imposed shear, only brings about other questions: Why other materials don’t dilate as the rigid sphere model of atoms would predict? Why the critical state depends on pressure?

We show that the key to this distinct granular behaviour is the presence of intrinsic stress, the existence of which has been postulated earlier, but its physical nature has remained conjectural. We use the graph theory representation of particles assemblies, first to provide the micromechanical definition of the intrinsic stress, then to quantify its effect on the change of volume under shear.

Persistent shear bands in granular materials occur at later stages of deformation. Typically, widths of shear bands are about 10-20 particle diameters. What determines this length? Strain localization in the form of shear bands is accompanied by accompanied by massive rolling of particle. On a single contact level, rolling is favored over frictional sliding, as a mechanism for rearrangement of particles. Yet, on a level of an assembly, rolling is constrained by neighbors. The result is a characteristic rolling correlation length. Our numerical simulations, specifically designed for this problem, indicate that the transmission of rotations depends on direction. Specifically, it depends on the strength of the force chain branch in that direction. The maximum propagation distance is comparable to observed widths of shear bands.
A Bayesian approach to kinematic models of all phases of the seismic cycle

Sarah Minson¹, Francisco Ortega¹, Junle Jiang¹, Anthony Sladen¹, Nina Lin¹, and Mark Simons¹

¹Division of Geological and Planetary Sciences, Institute of Technology, Pasadena, CA, USA

Determining a spatially variable slip model (be it for co-seismic, inter-seismic, or post-seismic deformation) is an inherently under-determined problem: there is no unique solution to the inverse problem of determining the slip history at depth as a function of space (and possibly time) when our data are only limited observations at the Earth's surface. Traditional inverse techniques rely on model constraints and regularization to generate one model from the possibly broad space of all possible solutions. However, Bayesian methods allow us to determine the ensemble of all possible source models which are consistent with the data and our a priori assumptions about the physics of the deformation process. We will present a variety of Bayesian deformation models for all phases of the seismic cycle in the Chile subduction zone, including an inter-seismic coupling model for the megathrust interface, a co-seismic finite fault kinematic model of the 2007 Mw 7.7 Tocopilla, Chile earthquake, and both co-seismic and post-seismic slip models of the 2010 Mw 8.8 Maule, Chile earthquake. Because we have employed a Bayesian methodology, which allows straightforward error analysis that is often not possible with traditional optimization methods, we will explore the uncertainties and resolution of each of these models.
Simultaneous measurement of real contact area and fault normal stiffness during frictional sliding

Kohei Nagata¹, Brian Kilgore², Masao Nakatani³, and Nick Beeler⁴

¹JMA, Tokyo, Japan, ²USGS Earthquake Science Center, Menlo Park, California, ³ERI, Tokyo, Japan, ⁴USGS Cascades Observatory, Vancouver, Washington

The tectonic stresses that lead to earthquake slip are concentrated in small regions of solid contact between asperities or gouge particles within a fault zone. Fault strength is thought proportional to the contact area within the shearing portion of the fault zone. Accordingly, many fault properties of interest to earthquake hazard research, e.g., occurrence time, recurrence interval, precursory slip, shear induced dilatancy, triggered earthquake slip, are believed to be controlled by processes acting at the highly stressed contact regions. Unfortunately the contact-scale physical processes cannot be easily observed or measured directly for natural faults and they are also difficult to observe even in controlled laboratory experiments. In this pilot study we simultaneously directly measure contact area using transmitted light intensity (LI) [Dieterich and Kilgore, 1994; 1996] and continuously monitor the normal stiffness of the fault using acoustic wave transmission (AT) [Nagata et al., 2008]. Our objective is to use known contact area from LI to determine conditions where AT may be used to infer area of contact, such that AT can be used monitor contact area in experiments using non-transparent materials.

Interface stiffness is monitored using compressive acoustic waves transmitted across the fault. Because the fault is more compliant in compression than the surrounding rock, the fault has elastic wave transmission and reflection coefficients that depend on the elastic contrast, specifically on the fault stiffness. Contact area is measured by LI: regions in contact transmit light efficiently while light is scattered elsewhere; therefore transmitted light intensity is proportional to contact area. LI and AT are expected to be correlated; elastic contact models suggests that interface stiffness goes as the square root of contact area. We observe LI and AT for sliding at slip speeds between 0.01 and 10 microns/s and normal stresses between 1 and 2.5 MPa while conducting velocity-step, normal stress-step and slide-hold-slide tests. AT and LI correlate during all tests, at all conditions, and in fact show a linear dependence in all cases.

However, the intercept and the slope of the linear relationship depends on the conditions (slip speed, proximity to steady state and, in some cases, on displacement). We explore some aspects of the relationship between LI and AT near steady-state with a simple contact model. In general our empirical observations suggest that changes in AT are proportional to changes in contact area, allowing the acoustic transmissivity to be used to infer changes in contact area for non-transparent materials such as natural fault rocks.
Coating delamination on cylindrical substrates

Ruzica R. Nikolic¹, and Jelena M. Djokovic²

¹Faculty of Mechanical Engineering, University of Kragujevac, Serbia and ²Technical Faculty of Bor, University of Belgrade, Bor, Serbia

In this paper is considered delamination of coating subjected to compressive stress on a cylindrical substrate. This problem is particularly interesting in oxide coating on wire elements exposed to extreme temperatures and in ceramic coatings on turbine engine blades or other components that operate at high temperatures. Using the results of J.W. Hutchinson the mentioned problem is discussed from the aspect of application of the linear elastic fracture mechanics concept for interfacial crack. The energy release rate and the mode mixity for the case of delamination in the axial and radial directions are determined. It is shown that results also depend on whether the substrate is convex or concave. Delamination in the radial direction in the case of the concave substrate is harder but it is more likely when the substrate is convex. Delamination in the axial direction is equally likely in both cases.

Results are confirmed by a simple experiment of a label, soaked in water, placed on a glass bottle, as a convex surface and on the interior of a glass jar, as a concave surface. In the former case the blisters appear on the label’s vertical edge and propagate in the radial direction, while in the latter case the blisters appear on the label’s horizontal edge and propagate in the axial direction.

The wet label on the convex surface (mineral water bottle).

The wet label on the concave surface (the interior side of a glass jar).
Definitions of average stress drops for heterogeneous slip distribution: Implications for dynamic rupture process from earthquake energetics

Hiroyuki Noda\(^1\), Nadia Lapusta\(^1,2\), and Hiroo Kanamori\(^1\)

\(^1\)Division of Geological and Planetary Sciences and \(^2\)Division of Engineering and Applied Science, California Institute of Technology, Pasadena, CA, USA

An averaged stress drop is a measure of static stress redistribution and one of the fundamentally important seismological parameters. In spite of the fact that it is widely referred to in many discussions on earthquake source processes, its physically precise meaning is often obscure so that it has been difficult to develop a rigorous discussion connecting the source process and seismic observation. In the present study, we introduce several different definitions of averaged stress drops, and discuss differences between them for ruptures with heterogeneous stress drop distribution. Especially, the focus is put on the energy partitioning in earthquakes. The seismologically observed stress drop, \(\overline{\Delta\sigma_M}\), is an average of stress drop distribution with the slip distribution due to uniform stress drop as a weighting function which is different from the true averaged stress drop over a ruptured area, \(\overline{\Delta\sigma_A}\). We show that the proper stress drop, \(\overline{\Delta\sigma_E}\), to be used in the estimation of available energy is the averaged stress drop with the actual slip distribution as a weighting function. Investigation of randomized uniform stress drop models have revealed that introduction of heterogeneity and increase in the roughness of the slip distribution result in increase in \(\overline{\Delta\sigma_E}/\overline{\Delta\sigma_M}\), indicating that the use of \(\overline{\Delta\sigma_M}\) in the estimation of available energy causes its underestimation and thus overestimation of radiation efficiency, \(\eta_R\). Note that \(\overline{\Delta\sigma_M}\), as well as \(\overline{\Delta\sigma_A}\), depends on the ruptured area the estimation of which has uncertainty. We propose an empirical method to approximate \(\overline{\Delta\sigma_E}\) by \(\overline{\Delta\sigma_M}\) by reducing the ruptured area using a threshold although it depends on the roughness of the slip distribution and overall characteristic shape of the slip distribution which probably reflects the feature of dynamic rupture propagation, such as pulse-like versus crack-like ruptures. \(\overline{\Delta\sigma_E}/\overline{\Delta\sigma_M}>1\) indicates that the previously estimated \(\eta_R\) (typically from 0.25 to 1) is the upper limit if there is unresolved small scale heterogeneity. We also define the shear stress as a function of slip which represents the dynamic rupture process and comparable to \(\overline{\Delta\sigma_E}\). Based on this definition, we can conclude using a physically clear logic that the scenario of the strong fault (i.e., interseismic shear stress on the fault is comparable to the static strength) with small averaged stress drop in energetic sense is not realistic.
Earthquake dynamics and potential tsunamis in the Greater Antilles Subduction Zone

David D. Oglesby¹, Eric L. Geist², and Uri S. ten Brink³

¹Department of Earth Sciences, University of California, Riverside, CA, USA and ²US Geological Survey, Menlo Park, CA, USA, ³US Geological Survey, Woods Hole, MA, USA

Using the 3D finite element method, we model the dynamics of potential earthquakes in the Greater Antilles Subduction Zone. This zone has a branched fault geometry undergoing oblique convergence, with slip partitioned between the plate boundary and the smaller strike-slip Septentrional and Bunce faults; these strike-slip faults cut the hanging wall down to the plate boundary thrust. Our interest is to determine the circumstances under which rupture may propagate across more than one fault in the system. Under reasonable assumptions about earthquake nucleation and possible extent of rupture, we find that earthquakes may spontaneously propagate from the Septentrional fault to the plate boundary thrust and vice versa. Thus, there may be more routes to a tsunamigenic earthquake than have been previously assumed in this region, and the strong ground shaking may be brought closer to populated areas. However, equally reasonable assumptions produce ruptures that are constrained only to single faults. We will discuss the results in relation to historical earthquakes in the region as well as their potential to produce damaging tsunamis.
Strain localization within a fluid-saturated fault gouge layer during seismic shear

John D. Platt$^1$, James R. Rice$^{1,2}$, and John W. Rudnicki$^3$

$^1$School of Engineering and Applied Science, Harvard University
$^2$Department of Earth and Planetary Sciences, Harvard University
$^3$Department of Civil and Environmental Engineering and Mechanical Engineering, Northwestern University

Observations indicate that seismic shear on a fault is extremely localized, with most strain occurring in a narrow zone less than a few mm wide within a broader ultracataclastic zone (Chester and Chester, Tectonophys.1998; Chester and Goldsby, SCEC 2003; Chester et al., EOS 2003; Heermance et al., BSSA 2003; Wibberley and Shimamoto, JSG 2003; Chester et al., Columbia Un. 2004). Heermance et al. noted that the zone of most intense shear is only 50 to 300 microns wide for the Chelungpu Fault of the 1999 Chi-Chi Taiwan earthquake, as intersected at 350 m depth in a borehole. Also, study (Rice, JGR 2006) of the Chester and Goldsby thin-section micrograph for the surface-exposed Punchbowl fault suggest most shear occurs only over 100 to 300 microns width within a nominal 1 mm wide shear zone.

To investigate factors which might set the scale of this localization process, we model a homogeneous, fluid-saturated gouge layer of width $h$ that is being sheared between two saturated poroelastic half-spaces. If the gouge is non-dilatant and has a friction coefficient which is constant, or rate-weakening, then only two forms of deformation are possible (Rice, 2006): homogeneous shear, or slip on a mathematical plane. By assuming a rate-strengthening friction (appropriate for a fault gouge which has achieved high temperatures by ongoing frictional heating), with logarithmic dependence of friction on strain rate, and otherwise following the thermal pressurization formulation by Lachenbruch (JGR 1980) and Mase and Smith (JGR 1987), we find localization of strain to a finite width band to occur within the gouge layer, provided $h$ is large enough.

We infer the width of this band based on the physical properties of the gouge. For a given shear velocity $V$ accommodated across the gouge layer, the width is shown to be only weakly dependent on $h$ and, within the uncertainty of parameter choices, is predicted to be on the scale of 50 to 100 microns when $V = 1$ m/s. We also studied the weakening of the gouge layer as a function of time, comparing localized and homogeneous shear, the latter with a constant friction coefficient. We find that the localization process leads to additional weakening of the gouge layer, and examine how this additional weakening is controlled by the properties of the gouge. Future studies of this type should include gouge dilatancy as an additional stabilizing feature which contributes to determining the width of the shear zone.
Heating, melting, weakening and strengthening in a finite shear zone during earthquake slip

Alan Rempel

1Department of Geological Sciences, 1272 University of Oregon, Eugene, OR 97403

The temperature increases on faults during earthquakes are believed to play a central role in controlling fault strength. With realistic parameter values, models of thermal pressurization within a finite shear zone predict a strength evolution that is consistent both with seismological constraints and with idealized treatments in which slip is localized to a mathematical plane. However, the temperature evolution is sensitive to the shear-zone thickness. This implies that the shear width exerts a further indirect control on strength evolution because of the sensitivity of flash heating to the background fault temperature. A simple treatment of melt-layer growth at asperity contacts suggests that an initial weakening phase at slip rates greater than the weakening velocity is followed by strengthening once the contact lifetime becomes so short that the average melt-thickness decreases at faster slip-rates. A linear stability analysis suggests that the consequent velocity-strengthening behavior should cause the shear-zone width to increase. Since the critical contact lifetime for flash heating to produce strengthening becomes shorter at higher fault temperatures, broadening of the shear-zone width is expected to occur only once the solidus temperature of the fault constituents is approached. The reduction in the rate of temperature increase with broader shear widths may be responsible for limiting the occurrence of macroscopic melting and the generation of pseudotachylites.
Shaping via active deformation of synthetic and natural elastic sheets

Eran Sharon^1

^1The Racah Institute of Physics, The Hebrew University of Jerusalem

Many natural structures are made of soft tissue that undergoes complicated continuous shape transformations as a result of the distribution of local active deformation of its "elements". Currently, the ability to mimic this shaping mode in manmade structures is poor.

I will present some results of our study of actively deforming thin sheets.

Theoretically, we have formulated an elastic theory for such bodies and derived from it an approximate 2D plate theory for plates with intrinsic non-Euclidean metric.

Experimentally, we use environmentally responsive gel sheets that adopt prescribed metrics upon induction by environmental conditions. With this system we study the shaping mechanism and energy scaling in different cases of imposed metrics.

Finally, we measure growth of wild types and mutants leaves, attempting to link between their local growth tensors and the different evolution of their global shape.
Slip on the surface and slip at depth: Insights from 3D elastodynamic earthquake models

Bruce E. Shaw

Lamont Doherty Earth Observatory, Columbia University, Palisades, NY, 10964, USA

Slip at the surface of the Earth plays a fundamental role in earthquake science, being a direct observation of the earthquake source unmediated by uncertain underdetermined inversions. At the same time, because of the unique location of the surface, at the free surface in a velocity weakening regime above the seismogenic zone, questions remain as to how slip at the surface relates to slip at depth. How representative is what we see at the surface of what happens at depth? How are they similar and in what ways do they differ? We focus on large earthquakes, since those are the events that break the surface. Studying long sequences of complex events on a 3D elastodynamic model which has a velocity weakening seismogenic layer surrounded by logarithmically velocity strengthening layers above and below, we examine a variety of behaviors in seeking to answer these questions. A number of interesting behaviors are found, including penetration of free surface effects deep into the seismogenic layer, and penetration of rapid slip from the seismogenic layer deep into the velocity strengthening layer below. An application of this work to a new pathway for seismic hazard analysis, based on slip-length scaling at the surface is discussed.
Mechanics of layer-by-layer coated electrospun nanofiber mats

M.N. Silberstein¹, J.N. Ashcraft², D. Liu², P.T. Hammond², G.C. Rutledge², and M.C. Boyce¹

¹Department of Mechanical Engineering and ²Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA

Electrostatic fiber formation or “electrospinning” is a robust method for creating non-woven mats of fibers from a wide variety of polymers. These fibers are continuous with nanoscale diameters, resulting in low weight mats with high surface area and porosity[1]. Hence, nanofibrous mats provide an ideal mechanical scaffold for numerous applications either alone or as part of a composite membrane where a matrix can be used to impart other chemical functionality. Specifically, they hold potential as direct methanol fuel cell (DMFC) polymer electrolyte membranes when coated with a highly ionically conductive and methanol impermeable but mechanically deficient polyelectrolyte.

In this study the mechanical behavior of the specific composite membrane of electrospun amorphous Nylon conformally coated via layer-by-layer deposition with PDAC/sPPO is experimentally investigated and modeled. Uniaxial tensile tests are conducted on composite membranes as well as on bare electrospun mats and stand-alone PDAC/sPPO films. The stand-alone film is found to be stiff (~1GPa) but tear at low strain(~1%) under ambient conditions and to lose its shape without application of any force under hydrated conditions (DMFC membranes operate hydrated). The uncoated mat is found to be elastic-plastic with moderate stiffness (~50MPa) and yield stress (~2MPa), a sufficiently large break strain (>100%) and only moderately hydration dependent. The uncoated mat is found to have a distinct transverse contraction behavior: at small strains (<0.2%) there is a slight expansion but as the axial strain is increased the mat contracts in the transverse direction at a ratio greater than 1:1. The coated mat is found to have an intermediate stiffness under ambient conditions (~300MPa) and tears at strains similar to the stand-alone film (~1%). Under hydrated conditions, the coated mat is found to behave similarly to the uncoated mat with elastic-plastic behavior, a slight increase in the modulus and yield stress, and sufficiently large break strain. The transverse strain history is similar to the uncoated mat, but the contraction is shifted to a larger strain, suggesting that the coating provides resistance to collapse of the porous electrospun mat structure.

A microstructurally-informed elastic-viscoplastic constitutive model of the composite is developed which takes into account the fiber properties, the networked structure of the nonwoven mat, and the hygro-mechanical behavior of the polyelectrolyte. The PDAC/sPPO film is modeled as an elastic material with a shear modulus that depends strongly on hydration. The electrospun mat model itself is based off the mat microstructure as explained in detail in Silberstein et. al.[2]. This model is seen to well capture both the stress-strain behavior and the transverse strain behavior under both ambient and hydrated conditions.

Wrinkles of a stiff layer on a pre-stretched soft substrate

Jeong-Yun Sun¹, Shuman Xia³, Myoung-Woon Moon², Kyu Hwan Oh¹, and Kyung-Suk Kim³

¹Department of Materials Science and Engineering, Seoul National University, Seoul 151-742, Republic of Korea, ²Future Interdisciplinary Fusion Technology Division, Korea Institute of Science and Technology, Seoul 136-791, Republic of Korea and ³School of Engineering, Brown University, Providence, RI 02912, USA

Wrinkles of a thin stiff layer attached on a soft substrate have been observed widely in nature, ranging from bio cellular to geological crust wrinkles. Formation process of such wrinkles have been recognized recently as an attractive means of making two-dimensional self-organized patterns at multiple length scales for various applications such as designing and fabricating flexible electronics, pitch-controllable gratings and adhesion-controlling surface patterns. Deformation-induced wrinkles are well known to be formed by compressive buckling of the surface layer. However, due to its broad-scale nonlinear deformation characteristics involved in its formation process, mechanics of large amplitude wrinkles have not been well understood. In particular, extensive material property combinations of the bi-material system as well as underlying nonlinear deformation mechanisms produce very rich patterns of clustering and folding of wrinkles for which responsible formation processes have not yet been uncovered.

In this presentation we first provide analytical solutions for the early stage wrinkling development based on the first-order perturbation analysis of thin stiff layer buckling on a pre-stretched soft substrate. This rigorous derivation of the solution provides closed-form critical strain and corresponding wavelength of the layer buckling on an incompressible neo-Hookean substrate pre-stretched with large finite deformation. The analytical results are then used to investigate the experimental results on mechanical behavior of large-amplitude wrinkles. Subsequent finite element analysis shows that the experimentally observed multi-mode folding patterns and associated mechanics of large-amplitude wrinkles are found to be caused by large nonlinear deformation of the substrate and/or asymmetric bending of the surface layer.
Exploring the role of viscoelastic ice rheology for glacial flow modeling

Jefferey Thompson¹, and Mark Simons¹

¹Seismological Laboratory, California Institute of Technology, Pasadena, CA, USA

Modelers traditionally treat glaciers as either viscous or elastic bodies, with the choice of rheological model dictated by the timescale of the problem of interest. With the advent of high-rate GPS monitoring of glaciers, researchers have now observed short timescale processes of glaciers in great detail, in particular, the response of ice streams to oscillatory forcing by ocean tides (e.g., Bindschadler et al., 2003, Gudmundsson, 2006). Examples of models describing the behavior of ice streams under tidal forcing include: an elastic body over a viscous till layer (Anandakrishnan, 1997), a viscous sliding law relating surface motion to basal shear stress (Gudmundsson, 2007), and a bending linear viscoelastic beam (Reeh, 2003). Here, we explore the sensitivity of the tidal response of a theoretical tidewater glacier using a nonlinear viscoelastic material model based on the Glen ice model (Glen, 1952). We are particularly interested in the response of the ice’s surface velocity, the phase lag between the tidal and glacial motion, and the distance up-glacier that the tide influences the ice’s flow.

We use the finite element modeling (FEM) software package PyLith (Aagaard et al., 2008) to model an ice stream flowing under the influence of gravity and a semidiurnal (twelve hour) tide. We find that the material model and its associated parameters control the phase delay between the peak tidal stresses and the flow velocity of the ice. However, the basal boundary condition, not the rheology, is the primary control on the distance from the grounding line that we observe a response of the ice to the tidal forcing. The distance this tidal perturbation is seen up glacier in our fixed-base (“frozen bed”) models falls far short of the distances observed on some real ice streams. We find that a viscoelastic material model is capable of explaining some surface observations, but that the basal boundary condition is just as important to realistic modeling of ice streams.
Early results from the SCEC earthquake simulator comparison project

Terry E. Tullis1, Michael Barall2, Keith Richards-Dinger3, Steven N. Ward4, Eric Heien5, Olaf Zielke6, Fred Pollitz7, James H. Dieterich3, John Rundle5, Burak Yikilmaz6, Donald Turcotte5, Louise Kellogg5, Edward H. Field7

1Brown University, 2Invisible Software, 3UCR, 4UCSC, 5UCD, 6ASU, 7USGS

Earthquake simulators are computer programs that simulate long sequences of earthquakes; Jim Rice has been a pioneer in this field as in many others. If such simulators could be shown to produce synthetic earthquake histories that are good approximations to actual earthquake histories they could be of great value in helping to anticipate the probabilities of future earthquakes and so could play an important role in helping to make public policy decisions. Consequently it is important to discover how realistic are the earthquake histories that result from these simulators. One way to do this is to compare their behavior with limited knowledge we have from the instrumental, historic, and paleoseismic records of past earthquakes. Another, but slow process for large events, is to use them to make predictions about future earthquake occurrence and to evaluate how well the predictions match what occurs. A final approach is to compare the results of many varied earthquake simulators to determine the extent to which the results depend on the details of the approaches and assumptions made by each simulator.

Five independently developed simulators, capable of running simulations on complicated geometries containing multiple faults, are in use by some of the authors of this abstract. Although similar in their overall purpose and design, these simulators differ from one another widely in many important ways. They all require as input for each fault element a value for the average slip rate as well as a value for friction parameters or strength drop due to slip. They share the use of the boundary element method to compute stress transfer between elements. None use dynamic stress transfer by seismic waves. Two notable differences are in how or whether they approximate such dynamic stress transfer and in their assumptions about the constitutive properties of the faults.

The earthquake simulator comparison project of the Southern California Earthquake Center is designed to allow comparisons among the simulators and between the simulators and past earthquake history. The project uses sets of increasingly detailed realistic fault geometries and slip rates taken from California, excluding the Cascadia subduction zone. In order to make as close comparisons between the simulators as possible we have developed shared data formats for both input and output and a growing set of tools that can be used to make statistical comparisons between the simulator outputs. To date all five simulators have run some versions of a Northern California fault model and are in various stages of running an All California fault model. The plan in the near future is to run them on the Uniform California Earthquake Rupture Forecast (version 3) fault model that is being developed by the Working Group on California Earthquake Probabilities. Initial comparisons show significant differences among the simulators and some differences from observed earthquake statistics. However, it is too early in the process to infer too much from these preliminary results. For example, all simulators in the first comparison use identical, but poorly constrained, strength drop values. These may need to be separately "tuned" for each simulator to match the observed earthquake recurrence intervals; such "tuning" is underway.
Earthquake-induced structural failures and mechanical characteristics of relevant seismic waves

Koji Uenishi

1Research Center for Urban Safety and Security, Kobe University, Kobe, Japan

We study the mechanical behavior of structures (more specifically, tunnels, slopes, and a group of surface buildings) subjected to dynamic disturbances, and from the structural failure patterns observed on the occasion of several earthquakes we “inversely” evaluate the physical properties of associated seismic waves. The results suggest “unexpected” mechanical behavior of structures that has not been recognized by the conventional approach usually employed in engineering seismology: Structures are expected to serve as sensors that respond only to waves of particular type, frequency and propagation direction and may be able to “detect” dominant frequency components of seismic waves.

Example 1: Failures of underground structures, at depth and near the surface, caused by the 1995 Hyogo-ken Nanbu (Kobe), Japan, earthquake. The epicenter of the quake is located very close (some 20 km) to the developed urban area and even underground structures, which were considered to be earthquake-resistant, suffered severe damage. Two-dimensional elastodynamic model analyses show that the observed failures were induced most likely by vertical oscillations of relatively high frequencies (over 10 Hz).

Example 2: Dynamic failure of fill slopes in the residential areas of Sendai City, Japan. The 1978 Miyagi-ken-oki earthquake generated crack openings at the top of the slopes but no cracks were found on the slopes themselves. A two-dimensional semi-analytic evaluation of the reflection and transmission of Rayleigh surface waves at the corner of a simple, wedge-shaped linear elastic slope indicates that the superimposition of the reflected and incident waves may induce strong stress amplification and generate open cracks at the top of the slope at a specific position. The dynamic wave amplification largely depends on the slope inclination, and from the field observation we can again “inversely” estimate the dominant frequency components of the incident surface waves, which are in a relatively higher range (some 10 Hz).

Example 3: Structural damage to multiple buildings caused by the 1976 Friuli, Italy, earthquake where a surprisingly “regular” (periodic) damage distribution was found in the epicentral area: Each adjacent building experienced completely different mechanical performance, i.e., one building totally collapsed while the next one was almost undamaged, and this alternate “collapsed-undamaged” pattern was repeated further. Similar (but more irregular) structural damage distribution was reported in Wajima City after the 2007 Noto Peninsula, Japan, earthquake. By considering the dynamic interaction between a group of surface buildings through the anti-plane waves in the ground, we can show that the dynamic interaction can induce totally different behavior of the buildings (like observed in Italy in 1976) and the eigenfrequencies of the collective multiple-building system (“town” or “city”) become lower than the resonant frequency of a single building. The phenomenon may be called the “town effect” or “city effect.”
Poromechanical processes below the seafloor: steady sedimentation and landslide initiation

Robert C. Viesca¹ and James R. Rice¹,²

¹School of Engineering and Applied Science and ²Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA

Continental slopes extend offshore from the continental shelf edge to the start of deep ocean abyssal plains, over which water depths increase from several hundred meters to several kilometers. These shallow slopes are of just a few degrees but, remarkably, host landslides kilometers in scale. Additionally, point-like features on the seafloor, known as pockmarks, are evidence for focused fluid escape from the thick, compacting deposits of sediment underlying the seafloor.

With such a dynamic environment in mind, we aim to represent several near-seafloor processes through geomechanical models. One focus is a simple model of the sedimentation and compaction process that has led to the environment of accumulated sediment we see today. Reducing the problem to its simplest elements and constraining the model with available data, we may predict the sediment pore fluid pressure distribution with depth. We find good agreement with observations if we account for observed reductions in fluid permeability with compaction. Beyond this, we look to natural phenomena (such as those leading towards the creation of pockmarks) as a source of further elevated fluid pressures in the sediment pore spaces. These pressures are likely to initiate submarine slope failure through the reduction of the frictional strength between sediment particles. Furthermore, experimental observations indicate that strength may be lost once failure initiates as long-lived particle contacts are disrupted, and such behavior may lead to localized deformation of the sediment under shear.

Taking slope movement to be the result of the shearing of a thin layer (or effectively, slip on a surface), we combine scenarios for locally elevated pore pressures with slip-weakening fracture mechanics representations of a shear rupture to study its growth to a point of catastrophic failure. Through doing so, we may hypothesize that some scenarios may or may not be likely mechanisms behind landslides on very shallow slopes. One such mechanism explored here incorporates the reasonable expectation that these sediments compact under shear. This local compaction reduces permeability and may interfere with an otherwise uniform flow field driven by larger scale sediment compaction discussed above. This obstruction elevates pore pressures and may promote further failure, which may enlarge the obstruction and be a source of positive feedback. Solving the problem whereby fluid flow within a porous media is coupled to fracture-like deformation, we do find that solutions for crack length may be unstable (i.e., failure may be quasitatically self-propagating once initiated) and that conditions exist under which dynamic rupture may be initiated.
A fixed-point iteration method with quadratic convergence

Kevin P. Walker¹ and Sam Sham²

¹Engineering Science Software, Inc., Smithfield, RI, USA and ²Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

In this work we show that the linearly convergent fixed-point iteration scheme

$$x_\alpha = f_\alpha(x)$$

for \(\alpha = 1, 2, 3, \ldots, N\) comprising a system of \(N\) nonlinear equations can be transformed into the quadratically convergent algorithms

$$x_\alpha = f_\alpha(x)\prod_{\nu=1}^{N} \left(\frac{x_\nu}{f_\nu(x)}\right)^{\beta_\nu^\alpha}, \text{ with } \beta_\nu^\alpha = \sum_{p=1}^{N} \left( \frac{1}{f_p} \frac{\partial f_p}{\partial x_\nu} - \frac{\delta_{\nu p}}{x_\nu} \right)^{-1} \frac{1}{f_\alpha} \frac{\partial f_\alpha}{\partial x_p}$$

$$x_\alpha = f_\alpha(x)\prod_{\nu=1}^{N} \exp\left(\beta_\nu^\alpha \left[ f_\nu(x) - x_\nu \right]\right), \text{ with } \beta_\nu^\alpha = \sum_{p=1}^{N} \left( \delta_{\nu p} - \frac{\partial f_p}{\partial x_\nu} \right)^{-1} \frac{1}{f_\alpha} \frac{\partial f_\alpha}{\partial x_p}$$

for \(\nu, \alpha = 1, 2, 3, \ldots, N\). Here \(\delta_{\nu p}\) is the Kronecker delta, and the Einstein summation convention is suspended. These quadratically convergent algorithms for obtaining the roots are derived with the use of power law and exponential unit root functions, and appear to be new to the literature, though the method of obtaining the algorithms by equating functional derivatives to zero is well known. Methods for obtaining higher order rates of convergence and larger radii of convergence are discussed.