Seismic radiation from regions sustaining brittle damage

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Dynamic changes of elastic moduli in source volumes are predicted to produce "damage-related-radiation" associated with products of the changes of elastic moduli and total elastic strain components in the source volume [Ben-Zion and Ampuero, 2009]. Decreasing elastic moduli (as produced by brittle deformation of low-porosity rocks and explosions) increase the radiation to the bulk, while increasing moduli (which may be produced during the formation of compaction bands in porous rocks) decrease the radiation. Order of magnitude estimates show that in cases with high initial shear stress the damage-related contribution to the seismic motion (neglected in standard calculations) can have appreciable amplitude. A decomposition analysis indicates that the damage-related-radiation is expected to have an appreciable isotropic component. A number of recent studies found evidence for isotropic source terms of earthquakes in geometrically-complex structures and other cases likely involving fresh faulting. Ross and Ben-Zion [2013] observed systematic rotations of double-couple-constrained aftershock mechanisms near the edges of the 1992 Landers earthquake. Synthetic calculations show that the observed rotations can result from neglecting small isotropic components in the derivation of the double-couple mechanisms. Castro and Ben-Zion [2013] observed amplification of P radiation of about 5-10 in the frequency range 1-10 Hz from aftershocks of the 7.2 El Mayor-Cucapah 2010 earthquake, consistent with isotropic source terms produced by rock damage. Kwiatek and Ben-Zion [2013] found anomalously low ratios of S-to-P radiated energy of well-recorded earthquakes in the Mponeng deep gold mine, South Africa, consistent with enhanced-P damage-related radiation. Ross et al. [2014] found statistically-significant explosive isotropic components for several $M_w > 4.2$ events in the complex trifurcation area of the San Jacinto fault zone, corresponding to ~0.4-8% of the total potency/moment of the sources. The results can have important implications for multiple aspects of earthquake physics, discrimination of small explosions from earthquakes and other topics.

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Reproducing the supershear portion of the 2002 Denali earthquake rupture in laboratory

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A notable feature of the 2002 Mw 7.9 Denali, Alaska, earthquake was that a unique set of near-field seismic ground motion records, at Pump Station 10 (PS10), captured the passage of a supershear rupture followed by what was surmised to be a secondary slip pulse, 'Trailing Rayleigh Pulse' (Dunham and Archuleta, 2004; Mello et al., 2010). Motivated by the unique features contained in these near-field ground motion records, which were obtained only 3 km away from the fault, a series of scaled laboratory earthquake experiments was conducted in an attempt to replicate the dominant features of the PS10 ground motion signatures. Particle velocity records bearing a striking similarity to the Denali ground motion records are presented and discussed. The success of the comparison opens up the possibility of routinely generating near source ground motion records in a scaled and controlled laboratory setting that could be of great societal interest towards assessing seismic hazard from large and potentially devastating earthquakes.

Wave Propagation through Interconnected Networks of Conduits and Cracks: Application to Volcanoes and Hydraulic Fracturing

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In both volcanoes and industry hydraulic fracturing operations, fluids are present within interconnected networks of pipe-like conduits and cracks within an elastic solid. The geometry of this plumbing system, and in some cases the composition of the fluid, are often poorly known yet of considerable interest. Waves propagating through this system provide one means of inferring the geometry and fluid properties. This talk spans two projects in this general topic. The first project examines very long period (VLP, ~30 s) seismic signals observed at Kilauea Volcano, Hawaii. These oscillatory motions, with impulsive onset and gradual decay over more than ten minutes, are triggered by rockfalls into an open lava lake. We interpret the VLP signals in terms of the eigenmodes of a vertical column of magma. Magma is idealized as a mixture of liquid melt and exsolved gas, and our study accounts for compressibility, nonequilibrium mass exchange between the gas and liquid phases, stratification, gravity, and buoyancy. Preliminary results suggest that VLP periods, decay rates, and seismic source centroid locations can be used to constrain total volatile content of the magma. The second project is motivated by hydraulic fracturing operations in the oil and gas industry, in which multiple fluid-filled fractures branch off of a fluid-filled wellbore. We study how tube waves within the wellbore, which can be generated as water hammers by rapid shut-in at the wellhead, generate crack waves in the hydraulic fractures. Resonant frequencies of the fractures, which are controlled by fracture length and aperture, are expressed in tube wave reflections. Thus measurements at the wellhead of reflected tube waves might be used to monitor fracture growth.

Experimental and theoretical investigation of the temperature dependence of rock friction

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It is generally agreed that the thickness of the seismogenic layer is controlled by temperature. Inparticular, the termination of seismicity at depth of 12-15 km in the continental crust is associated with the onset of plasticity in quartz at temperature of about 300 deg. C, and a transition from the velocity-weakening to velocity-strengthening behavior of typical crustal rocks such as granite. However, this view is based on relatively small set of experiments. Mitchell et al., (2013) reported velocity-weakening behavior of Westerly granite at temperatures up to 450 deg. C from laboratory tests using a heated direct shear apparatus and solid samples. Here we present results from recent experiments done on thick gouge at both dry and wet conditions at temperature up to 600 deg. C. We find that the rate dependence parameter (a-b) progressively decreases with temperature over the entire temperature range, leading to more unstable slip at higher temperature. This tendency is enhanced at hydrothermal conditions. Similar results are also obtained for gabbro (a representative rock for the oceanic crust). Taken at face value, these results warrant re-evaluation of the mechanisms responsible for the termination of seismicity in the middle continental crust and of the nature of the brittle-ductile transition.

At high slip rates, frictional heating may substantially increase temperature of the slip interface compared to the background temperature. Laboratory studies of frictional properties of rocks at slip velocities approaching the seismic range (0.1–1 m /s) have revealed a complex evolution of the dynamic shear strength, with at least two phases of weakening separated by strengthening at the onset of wholesale melting. The second post-melting weakening phase is governed by viscous properties of the melt layer and is reasonably well understood. The initial phase of extreme weakening, however, remains a subject of much debate. Brown and Fialko (2012) argued that the initial weakening of gabbro is associated with the formation of hotspots and macroscopic streaks of melt ('melt welts'), which partially unload the rest of the slip interface. Melt welts begin to form when the average rate of frictional heating exceeds 0.1–0.4 MW per square meter, while the average temperature of the shear zone is well below the solidus (250–450 °C). Similar heterogeneities in stress and temperature are likely to occur on natural fault surfaces during rapid slip, and to be important for earthquake rupture dynamics.

Experimental Constraints on Dynamic Fault Weakening Due to Flash Heating and Thermal Pressurization of Pore Fluids

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Geophysical observations and laboratory friction experiments on rocks at high slip rates suggest that faults are dynamically weak during earthquakes. Here I present experimental evidence for two dynamic fault-weakening mechanisms, so-called flash heating of asperity contacts, and thermal pressurization of pore fluids. Weakening due to flash heating arises from severe thermal degradation of contact strength at a critical asperity temperature generated by sufficiently rapid slip. *Rice* (2006) estimated a critical weakening velocity V_w for flash heating of silicate rocks of ~0.1 m/s. To test the flash-heating model, experiments were conducted at ambient pressure in rotary shear on unsaturated rocks at sliding velocities V up to ~0.4 m/s and at a constant normal stress of 5 MPa. The experiments reveal a $1/V$ dependence of friction on velocity above a value of V_w of ~0.1 m/s for the silicate rocks tested (*Goldsby and Tullis*, 2011), in excellent accord with theoretical treatments of flash-heating behavior (e.g., *Rice*, 2006).

While thermal pore-fluid pressurization has been studied theoretically for many decades, and invoked in earthquake simulations, its activation in laboratory experiments has remained elusive. To fill this gap, we conducted thermal-pressurization experiments in a high-pressure rotary-shear gas apparatus, on confined, low permeability, fully saturated samples of Frederick Diabase and SAFOD gouge (*Goldsby et al.*, EOS, 2014). Samples were pressurized and subjected to an externally applied fluid pressure to saturate them, then subjected to a constant applied fluid pressure during sliding. Rapid sliding of the diabase bare-surface samples and the SAFOD gouge samples at a slip rate of 4.8 mm/s reveal a dramatic decrease in shear stress. Over the first 28 mm of rapid slip, the test on the diabase yielded a characteristic decay in shear strength in excellent agreement with the Mase-Smith-Rice solution for shear stress on a plane due to thermal pore-fluid pressurization; the data also display a characteristic weakening distance of ~0.5 m, in quantitative agreement with the value of L^* in Rice's treatment calculated using appropriate values of rock and fluid properties. Deviations of the data from the theoretical solution at sliding displacements larger than 28 mm (i.e., the emergence of a plateau in the shear stress vs. displacement curve) arise because the rock sample is not a semi-infinite half space as assumed in the model of *Rice* (2006), and heat is lost via conduction into steel components of the sample assembly.

While these results appear to confirm the theoretical predictions, critical questions remain about the efficacy of flash heating and thermal pore-fluid pressurization on natural faults. All natural faults generate gouge; distributed shearing over a sufficient thickness of gouge during an earthquake may yield contact-scale slip rates smaller than the laboratory-determined value of V_w, ~ 0.1 m/s. The pore-fluid pressurization experiments were conducted in a manner that minimized dilation of the samples during rapid slip; dilation of coseismically shearing fault zones may prevent significant pressurization of pore fluids on natural faults.

A Universal (?) Nanometric Flow Mechanism for Earthquake Sliding

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Earthquake instability requires fault weakening during slip. The mechanism of this weakening is central to understanding earthquake sliding. Here we show experimentally that in both high speed sliding at low pressure and faulting at high pressure, phase transformation plays a major role, yielding a profoundly weak nanocrystalline sliding zone or, rarely, melt. Microstructures preserved in the Punchbowl Fault, a deeply-eroded ancestral branch of the San Andreas Fault of California, and rare pseudotachylytes, are consistent with these observations. We propose that the physical mechanism of low-resistance sliding of most crustal and mantle earthquakes is flow by grain-boundary sliding of nanometric gouge that is formed either as the *cause* of sliding (high pressure) or as an early *consequence* of sliding (low pressure, high-speed). This mechanism intrinsically resolves two major conflicts between laboratory results and natural faulting -- lack of a thermal aureole around major faults (San Andreas Fault heat flow paradox) and the rarity of pseudotachylytes.

Continuumnization of regularly arranged rigid bodies to estimate overall properties

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An assembly of rigid bodies have been used to estimate overall properties of soil and rock. Homogenization, which computes volume average of strain and stress by integrating displacement and force of particles, is used as a mathematical tool. This paper presents a new tool, called continuumnization. This tool derives a field equation of displacement functions by replacing difference of particle motion and force with spatial differentiation of the function. Elastic properties that relate local motion (translation and rotation) to local force and torque are rigorously computed. It is shown that, at dynamic state, the computed elastic properties allow the presence of modes that exponentially decays as well as ordinary oscillating modes. Also, it will be discussed that the coupling terms of translation and rotation might be a source of damping for waves which have long wave length and travel in long distance.

Response of rate-and-state faults to quasi-static stress perturbations

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Faults respond to stress perturbations with changes in seismicity. One classic example of such response is aftershock sequences that follow large earthquakes and have decay with time well described by empirical Omori's law. Another example is non-trivial period-dependent response to periodic stress perturbations in Nepal, where seismicity shows significant variations due to annual monsoon-induced stress variations but not to semidiurnal tidal stresses of the same magnitude.

Dieterich (Tectonophysics, 1994) derived equations for seismicity rate changes on rate-and-state faults in response to quasi-static stress perturbation using simplifying assumptions about earthquake nucleation, including a one-degree-of-freedom spring-slider system to represent elastic interactions. This spring-slider rate-and-state model (SRM) can reproduce the Omori's law in response to a static stress step, and it has been actively used to interpret observations of aftershock sequences in terms of $a\sigma$, where a is a rate-and-state parameter and σ is the effective normal stress. The inferences of $a\sigma$ are one to two orders of magnitude smaller than what is expected based on lab-derived values of a of about 0.01 and effective normal stresses given by overburden minus hydrostatic pore fluid pressure. The SRM model cannot reproduce the observed response of seismicity to periodic stress perturbations in Nepal.

We show that the seismicity response of continuum rate-and-state models (CRM), in which a finite rate-and-state fault is embedded in an elastic medium, can be qualitatively and quantitatively different from the SRM predictions. The two models, SRM and CRM, exhibit qualitatively similar seismicity behaviors in some simple cases, e.g. when nucleation sites in CRM are located in the middle of rate-weakening regions and have nearly uniform properties. However, the response is qualitatively different for nucleation sites with significantly heterogeneous properties or those located close to the boundary between the locked and creeping regions; this is because, in such cases, time evolution of the nucleation process is significantly different from the one approximated by the SRM. We find that the continuum rate-and-state models can reproduce the period-dependent seismicity response in Nepal for plausible sets of rate-and-state parameters. Our studies also indicate that $a\sigma$ can be substantially underestimated based on the SRM. This work has been done with Yoshihiro Kaneko (Kaneko et al., JGR, 2008), Thomas Ader, Jean-Philippe Avouac, and Jean-Paul Ampuero (Ader et al., GJI, 2014).

Earthquakes on Oceanic Transform Faults: Scaling Relations and Rupture Patterns

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Ocean bottom seismometer deployments along the Gofar, Quebrada and Discovery transform faults, East Pacific Rise (EPR), have revealed strong along-strike variation in M6 earthquake rupture extent and earthquake swarm activity. Along the ~ 100 km western segment of Gofar, an active-source refraction survey found ~ 10-20% P wave velocity reduction that extended all the way to the Moho in a ~ 10 km long zone that acted as a "barrier" to previous cycles of M6 ruptures [McGuire et al., 2012; Roland et al., 2012]. The low velocity zone is interpreted to result primarily from enhanced fault zone porosity. That this region appears to behave as a rupture barrier is interesting from a frictional point of view because it nucleates intense microseismicity and hence is at least in large part velocity-weakening (unstable slip). In this study, we use a 3D strike-slip fault model with rate-state friction to investigate how the presence of a high-porosity, strong dilatancy effect zone on a generally velocity-weakening transform fault could lead to a persistent M6 earthquake rupture barrier. Rate-state frictional parameters are based on experimental results on gabbro gouge under hydrothermal conditions, and constrained by the tomoDD relocation of seismicity on Gofar [Froment et al., 2014]. Our modeling results can reproduce the ~ 5 year recurrence interval of M6 earthquakes on two ~ 20 km segments separated by a ~ 10 km zone with effective dilatancy strengthening. A stronger dilatancy effect leads to a lower seismic coupling coefficient in the barrier zone. There, the release of energy is manifested in various forms of aseismic deformation, including postseismic slip and interseismic slow slip events. The modeled slow slip migration speed and equivalent stress drop are comparable to those estimated from earthquake swarms on transform faults [Roland and McGuire, 2009], and suggest that such swarm activity is primarily driven by aseismic transient slip events.

The elastodynamics of defects: moving dislocations and expanding inclusions with transformation strain and evolution of damage by dynamic asymptotic homogenization

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The fields radiated from moving dislocations (screw, edge, loops) in isotropic and anisotropic media in general nonuniform transient motion will be presented: far fields, near fields, transition from subsonic to supershear motion and equation of motion of a dislocation. "Driving forces" on moving defects are defined as configurational forces on the basis of Noether's theorem, and result in analogous equations of motion for dislocations and phase boundaries with transformation strain. The energetics of evolution of the defects (in translation, rotation and scaling) are governed by the dynamic J, L, M, integrals, and in the framework of dynamic asymptotic homogenization this evolution is related analytically to macroscopic dissipation. Finally, the Dynamic Eshelby Tensor will be presented for a self-similarly expanding ellipsoidal Eshelby inclusion (that preserves the interior constant stress Eshelby property) which allows for the analytical solution of self-similarly expanding ellipsoidal inhomogeneities with transformation strain.

Compression Cracking and Exfoliation

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Tensile failure of solids has been extensively studied. Compression failure, on the other hand, has received less attention. Historically, Bridgman's experiments on compression failure of brittle materials such as rocks led to "paradoxes" that have since been named after him. Features common to these paradoxes include formation of tension cracks in specimens subjected to pure compression. Post-experiment electron microscopy of compressively failed samples has resulted in further confusion, since microscopic tensile cracks are seen to have emanated from a variety of defects in various directions, though predominantly in the direction of maximum compression.

Over the past three decades, several developments have helped to bring the issue of *brittle failure in compression* to a level of basic understanding. All Bridgman paradoxes have been fully resolved. Models which quantitatively explain axial splitting, faulting, and transition from brittle to ductile modes of failure have been developed, and, most importantly, the mechanisms of fracturing in *loading* and *unloading* have been captured experimentally and by laboratory models. Examination of quasi-static and dynamic experimental results, suggests that pre-existing flaws of progressively smaller dimensions are activated at progressively higher pressures, leading to tensile cracking and plastic deformation in the neighborhood of these flaws. In compression, even ceramics such as silicon nitride or silicon carbide, show dislocation activities, and may potentially fail in *ductile mode* under extreme pressures. In my presentation, I will examine the application of these findings to rock burst, exfoliation, and large-scale crustal failure in compression.

The role of thermal decomposition during an earthquake

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Geophysical and laboratory observations suggest that mature faults weaken significantly at seismic slip rates. Thermal pressurization and thermal decomposition are two mechanisms commonly used to explain this dynamic weakening. Both mechanisms rely on pore fluid pressurization with thermal pressurization achieving this through thermal expansion of native solids and pore fluid and thermal decomposition by releasing additional pore fluid during a reaction. Several recent papers have looked at the role thermal pressurization plays during a propagating earthquake but no models have studied the role of thermal decomposition during dynamic rupture.

We present the first solutions to account for thermal decomposition during dynamic rupture, solving for self-healing slip pulses propagating at a constant rupture velocity. First, we show that thermal decomposition has a distinctive signature with longer slip durations, larger total slips, and increased slip rates near the trailing edge of the slip pulse. Next, we show that accounting for more than one weakening mechanism allows for multiple slip pulses to exist at a given background stress, with some solutions corresponding to different balances between thermal pressurization and thermal decomposition, and others corresponding to activating a single reaction multiple times. Finally, we study how the rupture properties – such as slip duration, rupture velocity and total slip – depend on the fault properties, and show that the impact of thermal decomposition is largely controlled by the ratio of the hydraulic and thermal diffusivities and the ratio of pore pressure generated to energy absorbed by the reaction.

Earthquake physics in light of high-velocity laboratory experiments followed by high-resolution of fault gouge

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Faults undergo profound weakening during the unstable slip of earthquakes. High-velocity experiments provide an effective tool to test theoretical models of this weakening, and more importantly to reveal direct, physical evidence for the mechanisms of dynamic weakening relevant to earthquakes. In an extensive series of experiments at the University of Oklahoma, we tested more than ten types of rocks and powders at slip velocities up to 1 m/s and at normal stress up to 15 MPa. The experimental faults were analyzed down to the 10 nm scale, and the analysis revealed evidence for three weakening mechanisms. First, powder-lubrication by ultrafine gouge grains (20-50 nm) that form afresh during slip. Second, the formation of tiny (~ 1 micron diameter) powder rolls that spontaneously converted the experimental faults into 'roller-bearings'. Both these mechanisms were observed in several lithologies. The third mechanism is fault smoothing (roughness drops below Ra ~ 0.1 micron), which dominate the weakening of carbonate rocks. Finally, we tested the experimental faults by impact loading with a finite amount of energy, which is the expected loading mode on a fault patch during an earthquake. These experiments showed constitutive friction relations that fundamentally differ from those of steady-state experiments on the same samples, suggesting that loading style may not be ignored.

Shear localization due to thermal pressurization of pore fluids in rapidly sheared granular media

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Field observations of mature, well-slipped, earthquake fault zones show that the majority of shear is often localized to principal slipping zones of order 10-100 micrometers width within a broader gouge layer of order 10-100 mm wide (with all that being a feature locating within a much broader, 1-10s m wide, damage zone bordering the fault). Such fault gouges are often rate-strengthening, especially at higher temperatures, and are then resistant to shear localization under slow deformation.

We show that extreme localization is, instead, a predicted consequence of rapid straining, with related shear heating, of fluid-infiltrated gouge on time scales that are too short for significant pore-fluid drainage or heat conduction. The localization is due to development of highly elevated pore pressure, hence of lowered Terzaghi effective stress, from thermal expansion of the fluid (i.e., thermal pressurization of the pore fluid, when expansion is constrained by a low-permeability host).

Results are presented for two versions of the process: In the classical one, the pore fluid pre-exists in the gouge as groundwater. In another, the study of which was pioneered by J. Sulem and co-workers, thermal decomposition reactions in hydrated silicates (clays, serpentines) or carbonates within gouge are triggered as temperature rises, releasing as volatile a fluid phase (H_2O or CO_2) at high pressure.

The studies reported have been carried out in collaboration with, and with major contributions from, John D. Platt (Carnegie Institution, Washington, DC), John W. Rudnicki (Northwestern University), and Nicolas Brantut (University College, London). Some of the work is published in JGR in 2014 (doi: 10.1002/2013JB010710 and 010711) and some is in review there as of late 2014.

Marine Ice Sheet Dynamics Over Short and Long Timescales

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The dynamics of marine-based ice sheets, like the West Antarctic Ice Sheet, are of interest due to the possibility of catastrophic loss of ice as the ice sheet edge retreats in a warming climate. The migration of this "grounding line", the location where the ice sheet goes from overlying ground to overlying ocean water, is crucial to understand in order for accurate predictions of ice sheet stability to be made. In this work, we therefore consider two very different components of grounding line migration, one at tidal timescales and one pertaining to longer term stability.

In the first part of this talk, we address the problem of how grounding lines migrate due to tidal forcing. We find that using a crack model for the grounding line motion predicts the grounding line is not generally at hydrostatic equilibrium and furthermore that migration is inherently asymmetric and non-linear, with migration distances that are not proportional to the tidal load. In the second part of this talk, we address the problem of how ice sheet profiles and stability are modified with more realistic basal boundary conditions. Specifically, we introduce Coulomb friction as a modification to the standard power-law rheology and find that the basal rheology necessarily transitions to the Coulomb regime near the grounding line. With this new modification, we predict a "tapering off" of the ice sheet profile in a boundary layer near the grounding line which results in very different basal stresses. This, in turn, changes the long-term stability of the ice sheet, with the ice sheet becoming more sensitive to climate perturbations. In both parts of this talk, we therefore find new areas of ice sheet mechanics that must be accounted for in order to accurately predict the future of marine-based ice sheets.