NG12C-1038 1330h POSTER

Ultrasonic Velocities in Lightly-Loaded Natural and Synthetic Granular Media*

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The seismic properties of near surface soils are of interest for a variety of problems, including pore fluid identification and tracking, wave propagation modeling, geotechnical site characterization, static corrections for reflection seismology, and locating underground objects. Ultrasonic velocities increase rapidly when a granular material is loaded as contact stress and area and coordination number of grain contacts increase. Porosity, grain size and distribution, grain shape, and mineralogy all play a role in determining this nonlinear response. We adapted the ultrasonic pulse transmission method to measure compressional (P) and shear (S) wave velocities at ultrasonic frequencies (100-500 kHz) for lightly loaded artificial soils (to 0.1 MPa maximum). Samples were fabricated from Ottawa sand (some with montmorillonite added), Santa Cruz beach aggregate, artificial glass beads, and alumina spheres. All materials were characterized with the SEM before the experiments. We focused on packing, mineralogy, and hysteretic effects in our study and found that compressional velocities vary from 200 to 700 m/s over the narrow loading range investigated as a result of these effects. In light cyclic loading of pure Ottawa sand we observed hysteretic effects in the shear mode velocity, implicating sticking of the grains. Our measurements demonstrate a cubic relationship between stress and compressional wave velocity for pure quartz sand, as predicted by Hertzian contact theory when grain roughness is incorporated. The sand/clay mixtures were found to have very different properties from pure sand. The clay bridged sand grains creating more area at the contacts and higher sound speeds over the narrow loading range, but suppressed the strong nonlinear behavior predicted by Hertzian contact theory.

*This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract number W-7405-ENG-48 and was supported specifically by the Environmental Management Science Program of the Office of Environmental Management and the Office of Energy Research.

NG12C-1039 1330h POSTER

Instabilities of stressed crystal surfaces in contact with a fluid

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The rheology of the Earth's crust is closely related to the deformation under stress of the mineral grains. In sedimentary rocks and many metamorphic systems matter transport in the fluid phase makes dissolution-precipitation processes the most effective pathway for mineral deformation.

Earlier studies on the dissolution of stressed crystals in undersaturated solutions have shown that stress corrosion can lead to roughening of interfaces. The corrosion pattern develops due to gradients in elastic energy along a free crystal surface with an initial random noise-like roughness. This so called Assaro-Tiller-Grinfeld instability has a positive feedback because dissolution will cause further increase in elastic energy, which in turn will speed up dissolution.

We have performed experiments on soluble brittle salts in saturated solutions as an analogue of minerals in the Earth's crust. We have studied the onset of the Assaro-Tiller-Grinfeld instability and the nonlinear evolution of corrosion-precipitation patterns beyond the initial surface roughening. In the experiments we stress small crystals of NaClO3 in a saturated solution and monitor the evolving surface patterns in situ with a video camera.

Our experiments show that stress corrosion-recipitation can lead to a non-stable roughness (Assaro-Tiller-Grinfeld instability) that develops deep grooves on the crystal surface. The system then breaks its symmetry and undergoes a secondary instability, an imperfect period doubling that produces a coarsening of the surface roughness. During the coarsening grooves travel upwards on the crystal surface which suggests that there are concentration gradients in the fluid next to the crystal. While the pattern coarsens and the wavelength between neighbouring grooves grows the pattern changes from a one dimensional structure of parallel horizontal grooves to a two dimensional structure with horizontal and vertical grooves. Finally, one large groove travels across the crystal surface leaving behind a perfectly flat crystal.

Our experiments suggest that stress corrosion-precipitation is a transient mechanism that can lead to a new equilibrium of the solid-fluid system under stress.

NG12C-1040 1330h POSTER

Universal scaling in transient creep

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When aggregates of small grains are pressed together in the presence of small amounts of solvent the aggregate compacts and the grains tend to stick together. This happens to salt and sugar in humid air, and to sediments when buried in the Earths crust. Stress concentration at the grain contacts cause local dissolution, diffusion of the dissolved material out of the interface and deposition on the less stressed faces of the grains. This process, in geology known as pressure solution creep, plays a central role during compaction of sedimentary basins during tectonic deformation of the Earth's crust in strengthening of active fault gouges following earthquakes and in ceramics. Experimental data on pressure solution creep has so far not been sufficiently accurate to understand the transient processes at the grain scale. Here we present experimental evidence that pressure solution creep does not establish a steady state interface microstructure as previously thought. Conversely, pressure solution creep strain and the characteristic size of interface microstructures grow as the cubic root of time. Transient creep with the same scaling is known in metallurgy (Andrade creep). The apparent universal scaling of pressure solution transient creep is explained here using an analogy with spinodal dewetting.

NG12C-1041 1330h POSTER

Scaling invariance of stylolites roughness

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Stylolites are thin irregular rock-rock interface zones that are formes via the stress induced dissolution and precipitation of sedimentary (usually monomineralic) rocks such as sandstones, limestones or evaporites. Twenty two limestone stylolites surfaces have been opened and sampled using several profiling techniques at laboratory scale: mechanical profiler, laser profiler and stereophotography. Three families of stylolites are described in terms of self-affinity. We used two independent analysis techniques of the topography measurement: Fourier and Wavelet spectra. Both are consistent and show two regimes of self-affinity. At low scales, the roughness exponent is ζ_1=1.1 and significanltly different from that of large scales: ζ_2=0.5. The cross-over length is show to be different for each family of stylolites and controls the eyes aspect of the stylolites. No significant anisotropy of the roughness is observed. When considering the cross-over length, a collapse of the different roughness spectra can be obtained and leads to a unified description of stylolites roughness.

NG12C-1042 1330h POSTER

Re-Thinking the Contradictions of Soil Moisture Spatial Variability

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In 1998, Famiglietti and his coauthors noted two contractions in the literature related to spatial variability of soil moisture fields. The first relates to the increase or decrease in soil moisture variance with the mean soil moisture, and the second relates to the ability of topographic indices or other measures of topography to explain the spatial pattern of soil moisture. Through analyzing remotely-sensed soil moisture data collected during three field campaigns (i.e., Moonson'90, Washita'92, and SGP'97), it was found that: (1) the relationship of mean soil moisture and variance depends on mean soil moisture state, i.e., soil moisture variance increases during dry-down process if mean soil moisture is between porosity and field capacity, otherwise variance decreases with dry-down if mean soil moisture is less than field capacity; (2) Without considering the correlation between rainfall and topography, topographic effects on soil moisture could be misinterpreted; and (3) soil moisture fields show three distinct scaling regimes during dry-down periods, i.e., atmospheric-dominated; transitional; and land surface characteristic-dominated.

NG21A MCC: Hall C Tuesday 0830h

Nonlinearity and Nonlocality in Hydrology and Geophysical Transport Processes Posters *(joint with H)*

Presiding: **D Benson,** Desert Research Institute**; M Meerschaert,** University of Nevada

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NG21A-0924 0830h POSTER

Controlled-source Electromagnetic Responses of Spatially Hierarchial Geological Media

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The controlled-source electromagnetic (CSEM) induction technique is gaining importance as a valuable near-surface geophysical tool for hydrogeophysical site assessment. However, CSEM responses are oftentimes difficult to interpret owing to the complexity of the host geological environmemnt. Bedding planes, joints, fracture zones, and other geological features conspire to generate a medium in which electrical conductivity is variable over a hierarchy of spatial scales. Rocks at each length scale offer different patterns of heterogeneity that reflect the complex interplay of their formative geological processes. The result is a rough, spatially hierarchial geological structure that leaves a similar imprint on the electrical conductivity structure. Even though CSEM induction obeys diffusive physics and is therefore inherently a smoothing operation, observed CSEM responses from a variety of geological settings have in common very rough spatial variability. In fact, CSEM profiles invariably are examples of fractional Brownian motion (fBm) signals. Existing algorithms for forward modeling of CSEM responses solve however the governing Maxwell equations in piecewise constant gridblocks of electrical conductivity. This pragmatic view of the subsurface electrical structure is outdated and inaccurate. The purpose of my presentation is to introduce hydrogeophysicists to the fractal nature of observed CSEM responses and to develop new concepts in forward modeling taking into account rough, spatially hierachial electrical conductivity structures. The CSEM response of man-made, non-fractal objects embedded in a fractal geological medium is also discussed in the context of target detection and discrimination algorithms. Practical applications to problems in applied hydrogeophysical investigations are emphasized.

NG21A-0925 0830h POSTER

Transition Probability / Markov Chain Approach for Groundwater Flow Modeling: A Fractal Perspective

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The usefulness of transition probability / Markov chain approach for groundwater flow modeling has increasingly been realized, as the approach possesses certain important advantages over the traditional Gaussian approach. However, such advantages are usually assessed in terms of only the basic statistical properties of groundwater flow parameters, such as mean, variance, and correlation. In the wake of recent reports on the presence of fractal behavior in groundwater flow phenomenon, the present study investigates the fractal properties of the groundwater flow fields generated by the transition probability / Markov chain model. The flow fields are analyzed using a variety of fractal techniques, ranging from common statistical tools (autocorrelation function, power spectrum, probability distribution function) to mono-fractal (box dimension) to multi-fractal (statistical moment scaling function) techniques. Preliminary results indicate the presence of multi-fractal behavior in the pore velocity distribution.

NG21A-0926 0830h INVITED POSTER

Nonlocal and Localized Analyses of Conditional Mean Transient Flow in Bounded, Randomly Nonuniform Domains

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We consider the effect of measuring randomly varying hydraulic conductivities on numerical predictions, without resorting to either Monte Carlo simulation or upscaling, of transient flow in bounded domains driven by random source, initial and boundary terms. Our aim is to allow optimum unbiased prediction of hydraulic head and flux by means of their respective ensemble moments conditioned on measurements of hydraulic conductivity. These predictors have been shown by Tartakovsky and Neuman (1998) to satisfy exactly a space-time nonlocal (integrodifferential) conditional mean flow equations in which the mean flux is non-Darcian. Exact nonlocal equations have been obtained for second conditional moments of head and flux that serve as measures of predictive uncertainty. The authors developed recursive closure approximations for the conditional moment equations through expansion in powers of a small parameter sigmaY representing the standard estimation error of lnK. The authors explored the possibility of localizing the exact moment equations in real, Laplace- and/or infinite Fourier-transformed domains. In this paper we show how to solve recursive closure approximations of nonlocal conditional moment equations numerically, to first order in sigmaY, in a bounded two-dimensional domain. Our solution is based on Laplace transformation of the moment equations, parallel finite element solution in the complex Laplace domain, and numerical inversion of the solution from the Laplace to the real time domain. We present a detailed comparison between numerical solutions of nonlocal and localized moment equations, and Monte Carlo simulations, under superimposed mean-uniform and convergent flow regimes in two dimensions. The results are shown to compare very well for variances of conductivity as large as 4. The degree to which parallelization enhances computational efficiency is explored.

NG21A-0927 0830h INVITED POSTER

Origins and consequences of heavy-tailed residence time distributions resulting from solute exchange

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Tracer tests in both groundwater and streams frequently yield breakthrough curves with power-law behavior at late-time, going as $c \sim t^{-k}$ after a pulse injection. In our experiments, we have found values of k in laboratory porous media between 2 and 3, and values of k in streams between 1 and 2. We review these experimental data, examine the physical significance and source(s) of the power-law behavior, and discuss the consequences for scaling in porous media and streams. The most interesting case involves $k < 3$, which appears to be common and which has the following consequences. (1) Modeling of the experiment by conventional mass transfer or effective medium approaches always cause key parameters to change with scale. (2) Estimation of the characteristic residence time (if it exists) in the immobile or storage zone is impossible. Such difficulties are most severe when the experimental and prediction timescales are very different. In such cases, a modeling method that preserves the nonlocal-in-time behavior should always be used (e.g., fractional derivatives, CTRW, or ADE with a power-law memory function).

NG21A-0928 0830h INVITED POSTER

A Brief History of Fractional-time Solute Transport Models in Hydrogeology

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In recent years there has been rapid exploration of the various mathematical ways in which tailing behavior of subsurface solutes undergoing transport and maybe reactions can be represented. In this overview we describe physical and mineralogical causes for such phenomena, original conventional models based on conceptualizations of hierarchical pore geometry or reactive site availability, and nonlocal fractional-time models based on macroscopic tailing behavior. Linkages are drawn among multidomain, multirate, fractional-time, and exposure-time based modeling approaches.

NG21A-0929 0830h POSTER

Immobile particles, fractal time, and the case of the missing mass.

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First-order transfer of mobile solute into an immobile phase results in a time-nonlocal governing equation of motion. In a Lagrangian sense, this is also a definition of a continuous time random walk. Under certain circumstances, the two approaches are equivalent. If the random time spent in an immobile state has finite mean, then the transport eventually converges to a local equation (with linear retardation) in the long-time limit. In this case, the amount of mass in the mobile phase also converges to a constant value. If the mean is infinite (or effectively so) then the mobile mass always declines and the governing equation may contain a fractional time derivative. Since monitoring wells preferentially sample the mobile phase, mass recovery always declines. The moments of the plume grow "nonlinearly" compared to a Fickian equation, but the fractional equations are linear and easily solved.

The order of the fractional time derivative is directly related to both the rate of mobile mass decline and the slope of the late-time breakthrough curve when plotted on a log-log scale. An analysis of the MADE site tests shows evidence of this behavior, but random rests of particles alone do not explain the shape of the plume. While particles are in motion, they make motions of highly disparate sizes that tend to follow a power-law distribution. The leading edge of the plume reflects the space-nonlocality of the process that is well modeled by a fractional space operator.

URL: http://www.hydro.unr.edu/homepages/schumerr/pubs/MIM.pdf

NG21A-0930 0830h POSTER

Fractional Derivatives and Coupled Space-Time Diffusion

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Continuous time random walks are useful models for diffusion processes. In the CTRW scheme, a random waiting time is followed by a random particle jump. In a coupled CTRW, the waiting time and the jump are statistically dependent, so for example a very long waiting time might be followed by an unusually large particle jump. Governing equations for long time limits of CTRWs are fractional diffusion equations, an extension of the classical diffusion equation incorporating fractional derivatives in space and time. This paper describes a new kind of fractional diffusion equation associated with long time limits of coupled CTRWs. Because of the space-time coupling, these equations involve fractional derivatives that blend both space and time. These equations may be useful to model flow in porous media and other physical systems characterized by a link or coupling between the subdiffusive tendencies caused by particle sticking or trapping, and the superdiffusive influence of very large particle jumps.

NG21A-0931 0830h INVITED POSTER

Advection and dispersion in time and space

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Previous work showed how moving particles that rest along their trajectory lead to time-nonlocal advection-dispersion equations. If the waiting times have infinite mean, the model equation contains a fractional time derivative of order between 0 and 1. In this talk, we propose a new advection-dispersion equation utilizing a fractional time derivative of order between 1 and 2. Solutions to this equation are obtained by a kind of subordination. The form of the time derivative seems to be related to the probability distribution of particle waiting times. In principle, the distribution of random time that particles spend in an immobile state is easily measured, and then the order of the fractional time derivative can be inferred.

NG21A-0932 0830h POSTER

Novel Dynamics with the Addition of Diffusion to a SOC System

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Numerous models based on the idea of self-organized-criticality (SOC) have been proposed in the last decade. These models have often successfully reproduced much of the underlying dynamics of the very different physical systems they have been applied to: from traffic jams and earthquakes to accretion disks, solar flare dynamics and turbulent transport of plasmas. However, a number of these systems have secondary relaxation mechanisms, in addition to the intermittent avalanches characteristic of SOC. Diffusion

and avalanche transport are examples of two transport mechanisms that frequently coexist. Understanding the dynamical interaction between these varied mechanisms is important if we are to understand both the proposed robustness of the SOC paradigm and the real behavior of the physical systems being modeled.

Diffusion, or diffusion like processes, are common in many physical systems. For example, in addition to the dominant "discrete" earthquakes, other mechanisms are available to relax tectonic stress such as plastic deformation and creep. While in solar flare or accretion disk dynamics, diffusion and/or convection of energy or mass can provide alternative transport mechanisms whose role is often ignored.

We show that neglecting the diffusion processes, or other similar transport mechanisms, can lead to a reduction of the range of dynamics found in the SOC like models and therefore a narrowing of the relevance of these models for physical systems. We show how diffusion can strongly modify the SOC dynamics while remaining a very subdominant transport mechanism. A dynamical transition takes place in the system as the relative importance of diffusive transport increases beyond a critical threshold. The role of the avalanche-like transport events characteristic of the self-similar SOC state is then abruptly taken over by quasi-periodic constant-size edge-triggered events. As a result, the system loses its "Self Organized Critical" properties. We show that the required diffusion for this to happen is remarkably small. These results while suggesting a reduction of the robustness of the SOC paradigm broaden the dynamics available though such simple models. The possible implications for relevant systems such as earthquake dynamics will be discussed.

NG21A-0933 0830h POSTER

Modeling flow and sedimention of slurries

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Many natural processes involve flows of sediments at high particle concentrations. The equations describing such two-phase flows are highly nonlinear. We will give an overview of the performance of a continuum constitutive model of suspensions of particles in liquid for low Reynolds number flows. The diffusive flux model (Leighton and Acrivos, J. Fluid Mech., 1987, and Phillips et al., Phys. Fluids A, 1992) is implemented in a general purpose finite element computational program. This constitutive description couples a Newtonian stress/shear-rate relationship (where the local viscosity of the suspension is dependent on the local volume fraction of solids) with a shear-induced migration model of the suspended particles. The momentum transport, continuity, and diffusive flux equations are solved simultaneously. The formulation is fully three-dimensional and can be run on a parallel computer platform. Recent work introducing a flow-aligned tensor correction to this model has had success in representing the anisotropic force that is seen in curvilinear flows. Gravity effects are added in an approach similar to that of Zhang and Acrivos (Int. J. Multiphase Flow, 1994). The model results are compared with laboratory data obtained with Nuclear Magnetic Resonance (NMR) of evolving particle concentration profiles in complex flows, as well as in batch sedimentation. Interesting secondary flows appear both in the experiment and model. Overall, good agreement is found between the experiments and the simulations.

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy. The authors would like to acknowledge support for this work by the U.S. Department of Energy, Division of Engineering and Geosciences, Office of Basic Energy Sciences.

NG21A-0934 0830h POSTER

Direct Simulation of 2D Fluid-Particle Sedimentation : Velocity Fluctuations and Diffusion.

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Motivated by the study of environmental fluids with massive particle sedimentation, we have used direct numerical simulations to study massive particles falling in a viscous fluid with periodic boundaries in a two-dimensional geometry. We computed different cases involving different particle concentration ranging from 0.02 to 0.4, and three different regimes characterized by the particulate Reynolds number and the Stokes number.

The mean settling velocity verify the Zaki-Richardson law, and is similar to published experimental results. The probability distribution function for the particulate horizontal fluctuating velocity is found to be almost gaussian while it is rather an exponential in the vertical direction showing an intermitent behavior.

The velocity variance exhibits a maximum for an intermediate concentration which increases with Reynolds number. The variances scale like the product of concentration with the mean settling velocity.

The anisotropy based on the ratio of the vertical over horizontal particle velocity fluctuations decreases with the particulate Reynolds number. However, this is not observed at concentrations higher than 0.4 where the interactions between particles predominates over gravity.

A statistical particle diffusivity can be defined as the product of the mean free path by the mean fluctuation velocity. However, it is also proportional to the anisotropy in the vertical direction and it is the reverse in the horizontal. Furteher ongoing extensions will be discussed, especially an analysis of the fluid structures induce by the non-local hydrodynamic interactions between the settling particules.

NG21B MCC: Hall C Tuesday 0830h

Damage Rheology and Physics of Earthquakes Posters *(joint with S, T, MR)*

Presiding: **Y Ben-Zion,** University of Southern California**; D L Turcotte,** Cornell University

NG21B-0935 0830h POSTER

Off-Plane Secondary Faulting and Damage Induced by a Dynamic Slip-Pulse

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The analysis of the stress field near the tip of a semi-infinite dynamic mode II rupture (Poliakov et al., *JGR*, in press, 2002; http://esag.harvard.edu/dmowska/PDR.pdf), with slip-weakening failure, is extended to the case of a dynamic slip pulse of finite length. Slip-weakening occurs over distance R at the tip, and slip itself takes place over a region of total length L before locking occurs at the trailing edge. The slipping configuration moves in steady state at constant velocity v_r. The important parameters are the scaled stress drop $(\sigma^o_{yx} - \tau_r)/(\tau_p - \tau_r)$ and rupture velocity v_r/c_s, the pre-stress ratio $\sigma^o_{xx}/\sigma^o_{yy}$, residual to peak strength ratio τ_r/τ_p, and peak friction coefficient on the fault plane $f_p = \tau_p/(-\sigma^o_{yy})$ where σ^o_{ij} is the initial stress state, τ_p and τ_r are the peak strength to initiate slip and residual strength at large slip, and v_r and c_s are the rupture and shear velocity. $R^*_o = (3\pi/4)\mu G/(\tau_p - \tau_r)^2$ is the slip weakening zone size in the low rupture velocity, low stress drop limit, where G is the fracture energy and μ the rigidity. The scaled actual zone size R/R^*_o depends on v_r/c_s and, weakly, on $(\sigma^o_{yx} - \tau_r)/(\tau_p - \tau_r)$. The Poliakov et al. (2002) solution is the asymptotic limit of the current model when $L/R^*_o \to \infty$ and $\sigma^o_{yx} \to \tau^+_r$. The major difference between the slip pulse analyzed here and their solution is that the size of the region which supports Coulomb failure reaches a maximum value for the slip-pulse on the order of R^*_o when $v_r > 0.9c_s$. For $G \approx 0.5$ to 5 MJ/m^2, secondary faulting should extend to distances on the order of $R^*_o \approx$ 4-40 m from the principal slip surface if $\tau_p - \tau_r = 100$ MPa, but 25 times larger if if $\tau_p - \tau_r = 20$ MPa. The damage model formulated by Ashby and Sammis (*Pure Appl. Geophys.*, 1990) is used to estimate the lateral extent of gouge formation in the slip-pulse stress field. By modeling the nucleation, growth and interaction of individual microfractures, this damage mechanics allows us to estimate the contribution of gouge formation to the fracture energy and the seismic radiation field. Seismic radiation is calculated by integrating the moment tensors of individual growing cracks over space and time in the evolving damage zone following the methodology in Johnson and Sammis (*Pure Appl. Geophys.*, 2001).

NG21B-0936 0830h POSTER

Effects of Pre-Stress State and Rupture Velocity on Dynamic Fault Branching

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We consider a mode II rupture which propagates along a planar main fault and encounters an intersection with a branching fault that makes an angle with the main fault. Within a formulation that allows the failure path to be dynamically self-chosen, we study the following questions: Does the rupture start along the branch? Does it continue? Which side is most favored for branching, the extensional or compressional? Does rupture continue on the main fault too? What path is finally self-chosen? Failure in the modeling is described by a slip-weakening law for which the peak and residual strength, and strength at any particular amount of slip, is proportional to normal stress. We use the elastodynamic boundary integral equation method to allow simulations of rupture along the branched fault system.

Our results show that dynamic stresses around the rupturing fault tip, which increase with rupture velocity at locations off the main fault plane, relative to those on it, could initiate rupture on a branching fault. As suggested by prior work [Poliakov, Dmowska and Rice, 2002, http://esag.harvard.edu/dmowska/PDR.pdf], whether a branching rupture, once begun, can be continued to a larger scale depends on principal stress directions in the pre-stress state and on rupture velocity. The most favored side for rupture transferring on a branching fault switches from the extensional side to the compressive side as we consider progressively shallower angles of the direction of maximum pre-compression with the main fault. Simultaneous rupturing on both faults is usually difficult for a narrow branching angle due to strong stress interaction between faults, which discourages rupture continuation on the other side. However, it can be activated by enhanced dynamic stressing when the rupture velocity is very near the limiting velocity (Rayleigh wave velocity for mode II). It can also be activated when the branching angle is wide because of decreasing stress interaction between faults. Natural examples seem consistent with the simulations we present.

NG21B-0937 0830h POSTER

Aftershocks and Damage Mechanics

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All earthquakes are followed by an aftershock sequence. A universal feature of aftershock sequences is

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