we augment the model with damage-related viscosity to account for inelastic deformation that precedes brittle failure.

Analytical and numerical results based on the model formulation reproduce key features of rock behavior under large strain, including damage self-organization and localization into a narrow zones, crack extension path under mixed mode loading and more. The damage model includes post-failure behavior (healing) that allows a stick-slip motion along a narrow zone with localized damage. Averaging such stick-slip motion in space and time fits the experimentally observed relations of rate- and state-dependent friction between slip velocity, normal, and shear stress components. Three dimensional numerical simulations reproduce the main features of a quasi-static fault nucleation observed in a triaxial laboratory test. Additional model features compatible with seismicity patterns are discussed in a companion presentation by Ben-Zion and Lyakhovsky.

### NG22A-04 1415h

### The void Limit of Two-phase Damage; Applications to Shear Localization and Shear-Enhanced Compaction

Yanick Ricard[1] (yanick.ricard@ens-lyon.fr)

David Bercovici[2] (david.bercovici@yale.edu)

[1] ENS Lyon / CNRS, 46 allee d'Italie, Lyon 69364, France

[2] Yale University, P.O. BOX 208109, New Haven, CT 056520, United States

Using a classical averaging approach, we derive the limit of a two-phase viscous theory, when both the viscosity and the density of the less viscous phase become zero. The resulting model describes the behavior of a porous matrix containing voids. The presence of surface tension at the surface of the matrix grains is taken into account. In addition to the equations of matrix mass and momentum conservations, non-equilibrium thermodynamic considerations allow us to propose an energy balance where both mechanical heat dissipation and storage of surface energy are taken into account. This model gives therefore a simple description of an isotropic damage theory that we use to interpret the failure envelopes of rock samples. For a sample under triaxial compression, the theory predicts in a mean stress/differential stress plane, the positions of the dilations or compressions and the rates of porosity changes. Comparisons with various sandstone experiments show that the experimental failure envelopes corresponds exactly to a critical rate of porosity change according to our equations, either negative (shear enhanced compression) or positive (fracture). One of the parameters of our equations that characterizes the percentage of work that is not dissipated but is stored as surface energy appears surprisingly constant for all sandstone experiments of the data base that we compiled. The dependencies of the failure envelope as a function of porosity (cohesion strength, onset of grain crushing, onset of dilation, and maximum sustainable differential stress) are very satisfactorily predicted by our approach.

### NG22A-05 1430h

### Correlations in the damage zone and fracture roughness

Jean Schmittbuhl[1] (+33 1 44 32 22 18; Jean.Schmittbuhl@ens.fr)

Alex Hansen[2] (Alex.Hansen@phys.ntnu.no)

[1] Laboratoire de Geologie - UMR 8538, Ecole Normale Superieure, 24 rue Lhomond, Paris 75231, France

[2] Department of Physics, NTNU, Trondheim 7491, Norway

We suggest that the observed large-scale universal roughness of brittle fracture surfaces is due to the fracture process being a correlated percolation process in a self-generated damage gradient. We show that the roughness exponent $\zeta$ of an in-plane crack front slowly propagating along a heterogeneous interface embeded in a elastic body, is in full agreement with a correlated percolation problem in a linear gradient. We obtain $\zeta = \nu/(1+\nu)$ where $\nu$ is the correlation length critical exponent. We develop an elastic brittle model based on both the 3D Green function in an elastic half-space and a discrete interface of brittle fibers and find numerically that $\nu = 1.5$, which therefore yields $\zeta = 0.6$. We also obtain by direct numerical simulations $\zeta = 0.6$ in excellent agreement with our prediction. This modelling is for the first time in close agreement with experimental observations. Moreover, for three-dimensional brittle fractures, the gradient is quadratic and the roughness exponent is shown to be: $\zeta = 2\nu/(1+2\nu)$. A mean-field theory gives $\nu = 2$, leading to $\zeta = 4/5$ in full accordance with the universally observed value $\zeta = 0.80$.

### NG22A-06 1445h

### Physical Interpretation of Laboratory Friction Laws in the Context of Damage Physics

John B Rundle[1] (530-752-1500; rundle@physics.ucdavis.edu)

Kristy F Tiampo[2] (303-492-4779; kristy@cires.colorado.edu)

Jorge SS Martins[2] (303-492-4779; jorge@cires.colorado.edu)

William Klein[3] (617-353-2118; klein@buphy.bu.edu)

[1] Department of Physics University of California, Davis, One Shields Ave., Davis, CA 95616, United States

[2] CIRES, University of Colorado, 216 UCB, Boulder, CO 80309, United States

[3] Department of Physics, Boston University, 575 Commonwealth Ave., Boston, MA 02215, United States

Frictional on sliding surfaces is ultimately related to processes of surface damage, and can be understood in the context of the physics of dynamical threshold systems. Threshold systems are known to be some of the most important nonlinear, self-organizing systems in nature, including networks of earthquake faults, neural networks, superconductors and semiconductors, and the World Wide Web, as well as political, social, and ecological systems. All of these systems have dynamics that are strongly correlated in space and time, and all typically display a multiplicity of spatial and temporal scales. Here we discuss the physics of self-organization and damage in earthquake threshold systems at the microscopic laboratory scale, in which consideration of results from simulations leads to dynamical equations that can be used to derive results obtained from sliding friction experiments, specifically, the empirical rate-and-state friction equations of Ruina. Paradoxically, in all of these dissipative systems, long-range interactions induce the existence of locally ergodic dynamics, even though the dissipation of energy is involved. The existence of dissipative effects leads to the appearance of a leaky threshold dynamics, equivalent to a new scaling field that controls the size of nucleation events relative to the size of the background fluctuations. The corresponding appearance of a mean field spinodal leads to a general coarse-grained equation, which expresses the balance between rate of stress supplied, and rate of stress dissipated in the processes leading to surface damage. We can use ideas from thermodynamics and kinetics of phase transitions to develop the exact form of the rate-and-state equations, giving clear physical meaning to all terms and variables. Ultimately, the self-organizing dynamics arise from the appearance of an energy landscape in these systems, which in turn arises from the strong correlations and mean field nature of the physics.

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## NG22B MCC: 130 Tuesday 1515h

## Recent Advances in Nonlinear Geophysics IV: Hydrology/Nonlinear Waves *(joint with H, S, T)*

*Presiding:* **C Lomnitz,** National University of Mexico /UNAM**; D Benson,** Desert Research Institute**; M Meerschaert,** University of Nevada

### NG22B-01 1515h INVITED

### Wave-Wave Coupling: A Nonlinear Phenomenon of Classical Physics

Eryk Infeld (011-4822-621-6085; einfeld@fuw.edu.pl)

Soltan Institute for Nuclear Studies, Hoza 69, Warsaw 00-681, Poland

Linear physics does not admit the possibility of wave coupling. With the advent of nonlinear research, wave-wave coupling has been observed and described theoretically in many media. For example, in hydrodynamics the Euler equations can lead to the Nonlinear Schroedinger Equation (NLS), which in turn admits three-wave coupling. Simple theory yields surprisingly good results [1, 2]. In plasma physics, the wave coupling phenomenon can be derived directly from the Vlasov equation [3]. Recent interest has been renewed when four-wave coupling was observed in experiments on Bose-Einstein condensates. Here, a successful theory has recently been developed based on the Gross-Pitayevski equation, a NLS for this condensate. Although now four waves may couple instead of three, the ideas and even the formalisms are almost identical [4]. Other fields in which the phenomenon is observed include optics and even population studies. When looking for this effect in new fields, one should ask whether similar coupling mechanisms are in place.

References [1] E Infeld, Phys Rev Letters 47 717, 1981 [2] E Infeld and G Rowlands, Nonlinear Waves, Solitons and Chaos, CUP, 1990, second edition, Chapter 5. [3] R C Davidson , Methods in Nonlinear Plasma Theory, Academic, NY, 1972, chapter 6. [4] M. Trippenbach et al., Phys. Rev. A 62, 023608, 2000.

### NG22B-02 1545h

### T Waves at the Seafloor: Coupled Seismoacoustic Modes and Spiciness

Rhett Butler (202-682-2220; rhett@iris.edu)

The IRIS Consortium, 1200 New York Avenue, Washington, DC 20005, United States

T waves are routinely observed at the Hawaii-2 Observatory (H2O) on the seafloor between Hawaii and California, even though the seafloor (4979 m) is substantially below the conjugate depth of the SOFAR channel. These interface T waves, termed Ti, show specific polarization characteristics in the sediments at H2O and underlying basement (at the OSN-1 borehole site). The sedimentary observations are polarized dominantly on the radial-horizontal direction, whereas the borehole measurements are dominantly vertical. The frequency spectra displays a modal structured of seismoacoustic coupling on the seismometer and hyrdrophone observations. The polarization of individual modes exhibits elliptical particle motion characteristic of Rayleigh waves. Ti is observed at H2O with frequencies up to 80 Hz at 2200 km from the Blanco Fracture Zone, 2.5-15 Hz at 5500 km from earthquakes near Kamchatka, and 5-15 Hz at a distance of 9400 km from the Pacific-Antarctic Ridge. Energy analyses of Ti indicate that below around 5 Hz, Ti dominantly propagates as seismoacoustic coupled Rayleigh modes in the sediments, whereas above 5 Hz the dominant energy is observed on the hydrophone. Seismoacoustic modal coupling in Ti above 5 Hz may be locally generated in part from energy scattered from the SOFAR channel. It is hypothesized that the higher frequency (>5 Hz) components of Ti include scattering of T waves from the SOFAR channel to the seafloor attributable to "spiciness", the variability of temperature and salinity along a surface of constant density due to air-sea fluxes, turbulent mixing and advection. While dynamically neutral in the ocean by virtue of the density compensation, sound speed correlates positively with both temperature and salinity, so that spicy structures create velocity heterogeneity which scatter T waves. The 5-80 Hz frequency range and corresponding wavelengths observed at H2O suggests spicy length scales of 300 to 20 m in the region of the H2O site.

### NG22B-03 1600h INVITED

### Anomalous Dispersion, Finite-Size Lyapunov Exponents, the Full Intermediate Scattering Function and 3D-PTV

john h cushman[1] (jcushman@purdue.edu)

monica moroni[2] (monica.moroni@uniroma1.it)

[1] purdue university, mathematics department math sciences building, west lafayette, in 47907, United States

[2] university of rome "la sapienza", DITS via eudossiana 18, rome 00184, Italy

Velocity fluctuations over evolving scales of motion, on the scale of observation, often lead to anomalous dispersion of conservative tracers in fluid mechanics studies of turbulence and heterogeneous porous media. Recent theories of anomalous dispersion lead to space-time non-local constitutive models for the flux of concentration, which can adequately model this problem. We review one such model, which has its foundations in non-equilibrium statistical mechanics. The basic premise is that knowledge of the evolution of the self-part of the intermediate scattering function is all that is required to model the phenomena of interest. We derive the basic integro-partial-differential equation this function satisfies and solve the inverse problem to obtain the kernels and use these to describe the wave-vector and frequency dependent dispersion tensor. Subsequently we use this information to study the transition from anomalous to Fickian dispersion. We also make use of the finite size Lyapunov exponent in the description of the dispersive process. Three-camera, three-dimensional, particle -tracking velocimetry experiments are undertaken to study dispersion within a matched-index heterogeneous porous medium. Particle trajectories, mean square displacements, velocity covariance's, intermediate scattering functions, classical dispersion tensors, wave-vector and frequency dependent generalized dispersion tensors and the finite-size Lyapunov exponents are obtained. Comparisons are made in the small frequency and small wave vector limits to obtain the transition from preasymptotic to asymptotic dispersion.

**NG22B-04 1615h INVITED**

### A Unified Framework for Anomalous Transport in Geological Formations

Harvey Scher[1] (89342545; harvey.scher@weizmann.ac.il)

Andrea Cortis[1] (89344230; andrea.cortis@weizmann.ac.il)

Brian Berkowitz[1] (89342098; brian.berkowitz@weizmann.ac.il)

[1]Department of Environmental Sciences, Weizmann Institute of Science, P. O. Box 26, Rehovot 76100, Israel

We developed a unified framework to model the anomalous transport of tracers in highly heterogeneous media. While the framework is general, our working media in this study are geological formations. The basis of our approach takes into account the different levels of uncertainty, often associated with spatial scale, in characterizing these formations. The effects on the transport of unresolved, smaller spatial scale heterogeneities (residues) are treated probabilistically with a continuous time random walk (CTRW) formalism, while the larger scale variations (trends) are included deterministically. The CTRW formulation derives from the ensemble average (EA) of a disordered system, in which the transport in each realization is described by a Master Equation. We numerically solve the transport equations for given field-size heterogeneous domains (specifying the trends), wherein each cell or *pixel* contains an EA of systems comprised of the unresolved small-scale heterogeneities. The EA of these systems is constrained by the density of residues and the average velocity (determined from the steady-state flow field of the entire domain) for each cell. Accurate numerical inverse Laplace Transforms allow solutions with a general (cell-dependent) $\psi(\mathbf{s}, t)$, the joint probability density for a displacement $\mathbf{s}$ with an event-time $t$. The method applied to one EA domain obtains the boundary-value solution to a (spatial) differential equation with an arbitrary, physically based, Laplace Transform of $\psi(\mathbf{s}, t)$. This approach, thus, obviates the need to restrict the $\psi(\mathbf{s}, t)$ to specialized forms, e.g., a power-law tail; the restriction can limit the time range of physical applicabilty. We apply the unified framework to non-stationary domains generated by fracture systems and porous rock characterized by permeability maps. We demonstrate results of transport calculations in one- and two-dimensional domains, for a variety of (large-scale) heterogeneity structures, (small-scale) material properties and boundary conditions.

**NG22B-05 1630h INVITED**

### Aging Continuous Time Random Walks

Eli Barkai (574 631 5235; jbarkai@nd.edu)

Notre Dame University, Department of Chemistry and Biochemistry, Notre Dame, IN 46556-5670, United States

Diffusion and relaxation in many disordered systems exhibits anomalous behaviors, for example a mean square displacement of a tracer particle may follow $\langle r^2 \rangle \sim t^{\alpha}$. The continuous time random walk (CTRW), introduced by Montroll and Weiss (1965), is a stochastic framework applied extensively to model such anomalous behaviors. In recent years it has become clear that anomalous diffusion processes may exhibit aging behavior. We investigate aging CTRW, previously introduced by Monthus and Bouchaud (1996) in the context of diffusion in glasses. Now the Green function $P(\mathbf{r}, t_a, t)$ depends on the age of the diffusion process, instead of the usual Montroll–Weiss Green function $P(\mathbf{r}, t)$. An exact equation for the Fourier double Laplace transform of the aging CTRW Green function $P(\mathbf{r}, t_a, t)$ is derived, thus generalizing the Montroll–Weiss equation to the aging regime. Asymptotic long time $t$ and long time $t_a$ behaviors of aging CTRW are derived. Aging CTRW might be applied to any random walk process, described by standard CTRW, provided that aging initial conditions are satisfied. For example, recently, the approach was successfully applied to chaotic diffusion generated by a deterministic non-linear low dimensional system.

URL: http://www.nd.edu/~jbarkai

**NG22B-06 1645h INVITED**

### Does Neglecting Facies Structure Obscure the Underlying Fractal Descriptions of Natural Heterogeneity: Levy Versus Gaussian Behavior of Increment Ln(K).

Fred J Molz (864-656-1003; fredi@clemson.edu)

Environmental Engineering and Science Dept., Clemson University, 342 Computer Court,, Anderson, SC 29625, United States

When applying non-stationary stochastic processes with stationary increments (stochastic fractal models) to heterogeneous property distributions, it is often convenient to deal with the increments of natural log of the property, such as hydraulic conductivity (i.e., delta[Ln(K)]). According to theory, such increment distributions should have a mean of zero independent of measurement separation (lag), and a variance, or analogous property, that displays a power function dependence on lag. Ln(K) will then be a non-stationary stochastic fractal, and the exponentiated K distribution itself will display some of the properties of a multifractal. Most delta[Ln(K)] data sets developed during the past decade have displayed Levy-like probability density functions (PDFs). In these cases, the underlying non-stationary fractal is fractional Levy motion, which when exponentiated results in a K distribution having infinite statistical moments. This led past researchers to truncate the Levy PDFs used in applications, or to describe the distribution as being Levy-like rather that having true Levy tails. Recently, evidence has been developed that Levy-like behavior can result from the (possibly) unintended superposition of several Gaussian distributions. From a geological perspective, a given body of rock is often composed of several different facies, with facies type resulting from some mixture of different depositional environments, different materials, different climates, and other considerations. It probably does not make physical/mathematical sense to mix data from a set of facies when attempting to derive the statistics relating to a property distribution such as Ln(K). It can also be shown that adding together and re-normalizing a set of Gaussian distributions, with means of zero and different variances, produces a PDF having a Levy-like interior, but ultimately, of course, displaying Gaussian tail behavior. This motivates the working hypothesis that individual facies will display Gaussian behavior in the relevant delta[Ln(K)] PDFs, and that the Levy-like model has resulted, at least in part, due to mixing data from different facies. Three sets of data that support this viewpoint are presented and discussed, one from an alluvial fan, a second from an eolian sandstone, and the third from a bioturbated, near-shore sandstone. Possible limitations of the working hypothesis are discussed also.

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