seed iSERVO project is underway to illustrate the approach. It involves development of web based services and portals to enable different numerical simulation models contributed by Australia, Japan and USA to be run using several "standard" crustal fault system models (strike-slip, intraplate, and subduction). The iSERVO Grid is being constructed from Web services enhanced to be consistent with Grid Forum standards. The system uses distributed computing including high performance computers and distributed heterogeneous databases using OGSA interfaces. These are accessed with portals exploiting the new portlet standards. The iSERVO project aims to lead to an international virtual laboratory for solid earth systems simulation that builds on complementary efforts worldwide, and hence, to provide a basis to foster breakthrough advances in grand challenge science questions such as that of earthquake forecastability.

URL: http://www.quakes.uq.edu.au/ACES

NG12B-05 1500h INVITED

Computing and Visualizing the Complex Dynamics of Earthquake Fault Systems: Towards Ensemble Earthquake Forecasting

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We consider the problem of the complex dynamics of earthquake fault systems, and whether numerical simulations can be used to define an ensemble forecasting technology similar to that used in weather and climate research. To effectively carry out such a program, we need 1) a topological realistic model to simulate the fault system; 2) data sets to constrain the model parameters through a systematic program of data assimilation; 3) a computational technology making use of modern paradigms of high performance and parallel computing systems; and 4) software to visualize and analyze the results. In particular, we focus attention of a new version of our code Virtual California (version 2001) in which we model all of the major strike slip faults extending throughout California, from the Mexico-California border to the Mendocino Triple Junction. We use the historic data set of earthquakes larger than magnitude M > 6 to define the frictional properties of all 654 fault segments (degrees of freedom) in the model. Previous versions of Virtual California had used only 215 fault segments to model the strike slip faults in southern California. To compute the dynamics and the associated surface deformation, we use message passing as implemented in the MPICH standard distribution on a small Beowulf cluster consisting of 10 cpus. We are also planning to run the code on significantly larger machines so that we can begin to examine much finer spatial scales of resolution, and to assess scaling properties of the code. We present results of simulations both as static images and as mpeg movies, so that the dynamical aspects of the computation can be assessed by the viewer. We also compute a variety of statistics from the simulations, including magnitude-frequency relations, and compare these with data from real fault systems.

URL: http://cse.ucdavis.edu/~rundle/

NG12B-06 1520h

Wavelet and Statistical Thresholding of convection plumes in High-Rayleigh number flows

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We present some novel approaches to the problem of analyzing the characteristic properties of temperature plumes in high Rayleigh number (Ra) convection flows. The datasets are computed at $Ra = 10^6$ to 10^9. As Ra increases, the characteristic width of the upwelling and downwelling patterns decreases as $Ra^{-1/2}$ and occupy a increasing small fraction of the volume. In the presence of ever increasing data set sizes, it is necessary to develop compression algorithms that are consistent with the physics of the flow (which is localized within these plumes).

We describe two approaches for plume identification. The first technique uses second generation wavelets combined with thresholding to only retain 1-5 percent of the dominant wavelet coefficients. The particular wavelets used permit a one to one identification between each wavelet and a point in physical space. By displaying those points corresponding to wavelets whose coefficients are above a user-specified threshold, the structure of the plumes becomes clear.

There is also a need to study the morphology of the plumes, including their surface, volume and other characteristics. We explore a computational approach that constructs probability density distributions (pdf/histogram) of variables integrated over the isosurface of temperature as a function of temperature. The novel approach lies in performing this computation using one pass through the data. By choosing appropriately the values integrated, one derives information on the distribution of functional values, gradients, and curvature. Maxima and inflection points become characteristic properties of the flow. We study their variation as a function of Ra. This technique is also applied to automatic color map selection; we illustrate the results on our datasets.

NG12C MCC: 2010 Monday 1600h

From Microscale to Macroscale: Models for Material Damage Mechanics and Earth System Dynamics and Their Relation to Seismicity and Earthquakes I *(joint with S, T, AE, GC, MR)*

Presiding: **J B Rundle,** University of California, Davis**; R Shcherbakov,** University of California, Davis**; D L Turcotte,** University of California, Davis

NG12C-01 1600h

A Damage Mechanics Model for the Continuum Rheology of the Upper Continental Crust

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Deformation of the lithosphere is clearly complex. Ideally, the lithospheric plates are rigid and displacements are restricted to plate-boundary faults. But it is clear that broad zones of deformation occur within the lithosphere, particularly the continental lithosphere. Although this deformation may be primarily restricted to faults in the upper continental crust, it may still be appropriate to treat this deformation using a continuum approach. A standard engineering approach to brittle deformation of a solid is to use damage mechanics. There is also a close association between damage mechanics and the behavior of fiber bundles. We derive a continuum model for deformation assuming that broken fibers in a fiber bundle are instantaneously replaced by new, unstressed fibers. The result of our analysis is a non-Newtonian viscous rheology. We show that the same result can be obtained using damage mechanics directly. Using Omori's law for the decay of aftershocks, we conclude that the power-law exponent in the non-Newtonian rheology is in the range 5 to 15. With this strong nonlinear viscous rheology, the behavior of the deforming upper crust approaches that of a perfectly plastic material.

NG12C-02 1615h INVITED

A generalized law for aftershock rates in a damage rheology model

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Aftershocks are the response of a damaged rock surrounding large earthquake ruptures to the stress perturbations produced by the large events. Lyakhovsky et al. [JGR, 1997] developed a damage rheology model that provides a quantitative treatment for macroscopic effects of evolving distributed cracking with local density represented by a state variable a. The equation for damage evolution, based on the balance equations of energy and entropy and generalization of linear elasticity, accounts for both degradation and healing as a function of the existing strain tensor and material properties that may be constrained by lab data (rate coefficients and ratio of strain invariants separating states of degradation and healing). Analyses of stress-strain and acoustic emission laboratory data during deformation leading to brittle failure indicate further [Liu et al., AGU, F01; Hamiel et al., this meeting] that the fit between model predictions and observations improves if we also incorporate gradual accumulation of a non-reversible deformation with a rate proportional to the rate of damage increase. For analysis of aftershocks, we consider the relaxation process of a material following the application of a strain step associated with the occurrence of a mainshock. The coupled differential equations governing the damage evolution and stress relaxation can be written in non-dimensional form by scaling the elastic stress to its initial value and the time to characteristic time of damage evolution td. With this, the system behavior is controlled by a single non-dimensional ratio R = td/tM representing the ratio between the damage time scale to the Maxwell relaxation time tM. For very small R there is no relaxation and the response consists of constant rate of damage increase until failure. For very large R there is rapid relaxation without significant change to the level of damage. For intermediate cases the equations are strongly coupled and nonlinear. The analytical solution for the damage evolution contains error functions and is richer than a simple power law relation. However, the results associated with the analytical expression can be fitted well for various values of R with a power law similar to the modified Omori law for aftershocks. This also holds for 3D numerical simulations of aftershock sequences with our damage rheology model. Initial results based on 3D simulations indicate that high values of R corresponding to low viscosity material produce diffuse (swarm-like) aftershock sequences, while low values of R corresponding to more brittle material produce clear (Omori-like) aftershock sequences.

NG12C-03 1630h

Damage Mechanics: Connecting the Microscale and Macroscale in Material Deformation

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Material damage occurs when microscopic processes of dislocation dynamics and microcrack formation are produced in association with strain and fracture mechanisms operating on the macroscopic scale. Here we discuss the physics of self-organization and damage at the "microscopic" scale. We begin by writing a free energy functional that connects the microscale with the macroscale processes. Since damage represents a modification of a brittle elastic system, we expect to find that the interactions produce the mean field dynamics characteristic of elastic systems. Sudden transitions in the state of these systems can be understood in the context of first order phase transitions, where the influence of the classical limit of stability, or spinodal, is felt. The 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 form of standard equations for material damage, 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. We demonstrate that these ideas lead to

dynamical equations, and we derive the scaling properties of the solutions. We also compare with laboratory data and show reasonable agreement in certain cases.

NG12C-04 1645h INVITED

Simulation of evolution effects in microscale and macroscale models of fault systems

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Numerical simulation models provide a means to probe the physics and dynamics of fault systems. Results from three different simulation models are presented: the particle based or micro-scale Lattice Solid Model (Mora and Place, 2002), cellular automaton models (e.g. Weatherley et al, 2002), and parallel fault continuum models (Mora and Weatherley, 2003). Each model has a different degree of realism in terms of its ability to capture the physics of crustal fault systems. The particle model captures evolution effects in the micro-scale structure of the model such as fracture or damage evolution and grain rearrangements. The CA models simplify dynamics of stress transfer and elasticity within a system and assume a "frozen" structure representing frictional strength on a fault or fault distribution. The continuum parallel fault model assumes a frozen structure but makes no simplification of the elasto-dynamics. Calculations of the "inverse metric" demonstrate periods of ergodicity and non-ergodicity as well as evolution effects such as growth in correlation lengths prior to major events consistent with the view that crustal fault systems can be theoretically analysed using statistical physics concepts, and that large earthquakes may sometimes exhibit precursors similar to critical phenomena. Calculations of the time-correlation function demonstrate that memory effects play an important role and imply that the memory kernel needs to be included in mean-field theoretical analyses such as Klein et al, 2000.

NG12C-05 1700h

Differing Comminution Characteristics of Quartz and Feldspar in Westerly Granite Simulated Gouge

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BSE images of the gouge (35% K−feldspar, 32% plagioclase, 28% quartz, 5% mica; particle size $\leq 88\mu$m) deformed in rotary frictional sliding at room temperature and 25MPa normal stress were studied at 250x, 500x, and 1000x magnification. We quantified changes in size and shape of the gouge particles as a whole and quartz and feldspar particles separately in samples with 3, 10, 65, and 409mm displacement. Following binarization, semi-thresholding technique was used to resolve K-feldspar particles from total image. We developed a particle pixel-averaging algorithm to resolve quartz from plagioclase feldspar, and new shape descriptor Particle Outline Linearity (POL) for relatively precise quantification of shapes of particles $\geq$500 pixels (1-4μm). Results correlate sequence of texture images, particle size distribution (PSD), fractal dimension (D), and POL data with shear displacement. As represented by changes in D, particle size reduction rate with respect to shear displacement (rate of comminution) is higher for quartz than feldspar. For the applied range of shear displacement quartz and feldspar appear to have different but converging PSD in the same gouge. Log-linear fit to the data suggests that D=2.6 distribution is achieved in 3-5mm of shear first in the whole gouge followed by feldspars while quartz PSD does not attain the value until $\sim$25mm of shear displacement. POL data indicates that Quartz and feldspar particle shapes begin to diverge within the initial 10mm of displacement. Feldspars becoming more angular while quartz particles tend to become rounder. In view of the POL data we interpret the comminution rate difference as follows. Cleavage fracture is effective in reducing the size of largest feldspar particles resulting in a wider size range and lower D values than quartz. Largest quartz particles, however, tend to become round by indentation fracture and abrasion, shedding small fragments in the process. Quartz PSD thus tends to become almost bimodal with a fraction of smaller particles that progressively result in higher D values. Size modality differences between quartz and feldspar are evident on most of the texture images. This preliminary study provides some microstructural basis for explaining differences in laboratory frictional behavior and development of localization structures between quartz and granitic gouges.

URL: http://www.louisville.edu/∼j0hadi01/

NG12C-06 1715h

Scaling Particle Size in Fault Gouge: Variable Fractal Dimension or Non-Fractal Distribution?

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The particulate nature of fault-gouges is believed to be the product as well as the control of earthquake rupture and fault slip. It is expected that the particle-size distribution (PSD) will display a fractal dimension that develops by grain comminution and progressive fault slip. We examine this expectation by measuring the PSD with laser particle size analysis (with 0.04 to 2,000.00 microns range), and observations with scanning and transmission electron microscopy. The gouges of two faults were studied: (1) The exhumed fault-zone of the San Andreas at Tejon Pass, California, with > 80 samples collected along a 70 m fault-normal traverse and a few sub-meter exposures within the pulverized Cretaceous Tejon Lookout granite (Wilson et al, 2003, Fall meeting, AGU); and (2) A "new-born" fault formed during the M=3.7 1997 earthquake in Hartebeestfontein gold mine, Klerksdorp, South Africa. The quartzitic gouge of this fault was collected at the focal zone, which was mined more than one year after the earthquake. We ran the laser particle size analysis for continuous periods up to three days while conducting multiple PSD measurements of a single sample. The main results are: (1) The PSD of the gouge powders from both faults systematically vary with measurement time due to progressive grain disaggregation; e.g., the mean grain size (by volume) drops from an initial value of 5.9+/-22.8 micron to 0.5+/-0.2 microns after 72 hours. The sub-micron nature of the gouges is verified by SEM and TEM. (2) PSD data for a wide, relevant range (0.04-2,000 microns) revealed that fractal dimensions of a single sample could range from 1.7 to 3.6 during the initial measurement. (3) The grain disaggregation (with running time in the laser analyzer) led to bi-modal fractal distributions with anomalous values as well as non-fractal distributions. We conclude that the frequently observed fractal nature of a gouge reflects the particulate agglomeration of finely fragmented grains, and does not represent the true gouge dimensionality or the gouge comminution associated with earthquake rupture. Finally, the intense pulverization with generation of large surface area in the studied gouges could contribute significantly to the earthquake energy balance.

NG12C-07 1730h

Multiscale Trend Analysis of Temporal (Un)Correlations Between Coda Q and Seismicity in California

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We introduce a statistical technique, based on the recently developed Multiscale Trend Analysis (MTA), for quantifying correlations between non-stationary processes observed at irregular non-coincident time grids. This technique is applied to studying the temporal correlation between the dynamics of the ductile and brittle layers in the Earth lithosphere. Our results confirm the previously reported strong positive correlation between the coda Q inverse and seismicity and its drop before major earthquakes observed in California. The proposed technique has significant advantages over the conventional correlation analysis: (1) MTA allows one to work directly with non-coincident time series without preliminary resampling the data; (2) The correlation is defined via the stable objects — trends — rather than noisy individual observations, hence it is highly robust; (3) The correlations are quantified at different time scales. The suggested technique seems promising for the wide range of applied problems dealing with coupled time series.

NG12C-08 1745h

Nonlinear Effects of Dynamic Stress on Particle Behavior in Fluids and Porous Media

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Stress (seismic) waves have long been known to induce observable changes in porous flow behavior in the Earth's crust. Different types and degrees of flow changes will occur with different combinations of stress wave parameters, such as frequency, amplitude, wave mode and duration, and with the medium properties, such as permeability, elastic moduli, geometry, mineralogy, saturation and ionic strength. Numerous international research projects are investigating physical mechanisms to understand the stress-induced flow phenomenon over a size range of nano- to macro-scale. One of the mechanisms being studied in detail is nonlinear coupling of dynamic stress energy to sub-pore size particle behavior. This is an important mechanism because the distribution of particles in a porous medium will directly affect the permeability. Initial results will be presented from a new laboratory experimental project aimed at characterizing stress/particle interactions at two scales: microscopic (sub-micron) and bench-top (cm to m). Individual particle behavior in an ultrasonic field is being characterized with a microscopic, video image-processing system, focused on a glass flow-visualization cell that contains known particle/fluid suspensions. Using 3- and 1-micron diameter polystyrene spheres suspended in non-flowing water, three types of behavior are observed when the glass cell is excited with acoustic energy at 0.1-10 MHz: 1) Particle conglomeration and alignment at specific locations in the cell, 2) Induced fluid convection and particle entrainment, and 3) Changes in particle attachment to and detachment from the glass cell walls. Experimental examples of all three types of behavior will be shown, as well as initial results of characterizing the combinations of physical forces involved and simulating the behaviors numerically. Effects of stress/particle interactions on meso-scale porous flow are being investigated in the seismic range of frequencies (1-1000 Hz), using a core holder apparatus that mechanically strains 1-inch diameter porous rock samples during constant-rate fluid flow. Experiments have shown that axial stress oscillations at 10-100 Hz can cause both enhancement and reduction of bulk fluid flow through sandstone core samples. At 50 Hz and approximately 10e-04 strain amplitude, in-situ clay particles fouling the pore throats of a Berea sandstone sample were re-mobilized and expelled, causing a 20% increase in permeability. New experiments are being performed where known particle supensions are injected into a clean porous core sample and the effects on permeability are measured with and without stress stimulation and under different initial flow conditions. Particle flux and retention data will be compared with similar data from the microscopic visualization experiments above. This work is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Geosciences Division.