soil moisture at four sites, and rainfall at five sites. Streamflow is measured at the outlet. Based on digital elevation data, DHSVM explicitly accounts for the spatial distribution of the stream and road networks, soil depth, soil and vegetation types. The model run period, including warm up, calibration and validation, is from August 1997 to January 2001. Field measurements provide forcing data, calibration data, and guidance in parameter selection. Model calibration and validation were done by aggregating simulated hourly soil moisture and stream flow into daily values and comparing them with aggregated daily measurements. For the calibration period, RMSEs of soil moisture and streamflow were lower than the observed variability as represented by the standard deviation, median absolute deviation, and (for stream flow) interquartile range. Model performance drops in validation period, but RMSEs remain near or lower than observed variability. We ran DHSVM with and without roads to examine their effects. Significant effects of roads were found despite the very low proportion of the watershed covered by roads and road banks. Streamflow for road and non-road cases was significantly different ($p < 0.0001$) based on the Wilcoxon signed rank test. In general, roads increase peak volume for short, intense storms, but reduced whole-period discharge by about 5.5%. Soil moisture was affected in cells where roads occur. In cells where water exited the road onto the hillslope, soil moisture was higher than it was without the road. In cells with roads, but without water flowing onto the hillslope, soil moisture was higher in some cases and lower in others.

URL: http://webdata.soc.hawaii.edu/climate/Roads1/Roads.html

H51A-08 0945h

Observation And Simulation Of Monsoon Rainfall Over A Tropical Mountainous Region In Southeast Asia

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From 1998, as a part of GAME-Tropics (the Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment (GAME)) research activities in Thailand in Southeast Asia, high-temporal-resolution ground-based rainfall observations have been conducted in a mountainous area. It is clear that the quantity of rainfall varies with elevation in this watershed throughout the rainy season. The orographic characteristics of rainfall are attributed to higher duration and frequency rather than to intensity. A two-dimentional, nonhydrostatic compressible dynamic-equations model was used. In this numerical experiment, two mechanisms were observed: 1) Convective clouds over mountains are activated in the evening, and 2) stratus formed by radiative cooling or heating at the tops of clouds and low-level orographically triggered convective clouds cause a seeder-feeder mechanism. The results of the simulation are quite consistent with the fact that a larger quantity of rainfall recorded at a higher altitude can be attributed to a greater duration and higher frequency rather than to a greater intensity of rainfall.

H51B MCC: 3024 Friday 0800h

Interactions Between Fluids and Fractures II *(joint with T, V, NG, MR)*

Presiding: **L C Murdoch,** Clemson University**; L Germanovich,** Georgia Institute of Technology

H51B-01 0800h

Experimental Analysis of the Role of Fluid Transport Properties in Fluid-Induced Fracture Initiation and Propagation

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It is well known that pore fluid pressure fundamentally influences a rock's mechanical response to stress. However, most measures of the mechanical behavior of rock (e.g. shear strength, Young's modulus) do not incorporate, either explicitly or implicitly, pore fluid pressure or transport properties of rock. Current empirical and theoretical criteria that define the amount of stress a given body of rock can support before fracturing also lack a direct connection between fluid transport and mechanical properties. Our research goal is to use laboratory experimental results to elucidate correlations between rock transport properties and fracture behavior under idealized loading conditions. In strongly coupled fluid-solid systems the evolution of the solid framework is influenced by the fluid and vice versa. These couplings often result in changes of the bulk material properties (i.e. permeability and failure strength) with respect to the fluid's ability to move through the solid and the solids ability to transmit momentum. Feedbacks between fluid and solid framework ultimately play key roles in understanding the spatial and temporal evolution of the coupled fluid-solid system. Discretely coupled models of fluid and solid mechanics were developed a priori to design an experimental approach for testing the role of fluid transport parameters in rock fracture. The experimental approach consists of first loading a fluid saturated cylindrical rock specimen under hydrostatic conditions and then applying a differential stress such that the maximum stress is perpendicular to the cylinder long axis. At the beginning of the test the minimum stress and the fluid pressure are dropped at the same time such that the resulting difference in the initial fluid pressure and the final fluid pressure is greater than the final minimum stress. These loading conditions should produce a fluid driven tensile fracture that is perpendicular to the cylinder long axis. Initial analyses using numerical simulations with similar boundary conditions suggest that resulting fracture propagation rates and fracture spacing are controlled by the rocks hydraulic diffusivity. Modeled rocks with higher permeability had fractures with larger apertures, more localized deformation, and greater fracture spacing. Intuitively, these results are consistent with permeability controlling the time required for pressure to come to equilibrium with the new boundary conditions. Finally, more general goals of this research include using these core-scale experimental data and discrete simulation results to calibrate larger-scale, more traditional continuum models of geologic deformation.

URL: http://www.nmt.edu/~dboutt/AGUFALL03/

H51B-02 0815h INVITED

Fluid Flow in Rock Fractures

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Understanding the hydraulic properties of rock fractures is an issue of great importance in fields such as petroleum engineering, groundwater hydrology, and underground waste isolation. Traditionally, models of fluid flow through rock fractures have been based on the cubic law, which asserts that the local value of the fracture transmissivity is equal to $h^3/12$, where h is the fracture aperture. The local cubic law is mathematically equivalent to assuming that flow in the fracture is governed by the Reynolds lubrication equation. However, this equation is only applicable if the aperture does not change too abruptly, and flowrates are suitably low. These two limitations have led, over the previous decade or so, to a series of computational and experimental investigations aiming to better understand the applicability of the lubrication approximation. These investigations (Mourzenko et al., J. Phys., 1995; Brown et al., GRL, 1995; Yeo et al., Int. J. Rock Mech., 1998; Nicholl et al., WRR, 1999) have showed that the Reynolds equation may over-predict the transmissivity of a fracture by as much as 100%. Other analyses, both theoretical and computational, have concluded that the linear relationship between pressure drop and flowrate will break down if the Reynolds numbers reach some critical value, variously estimated to be between 1-100 (Oron and Berkowitz, WRR, 1998; Brush and Thomson, WRR, 2003). The implication of these results has been that the full three-dimensional, nonlinear Navier-Stokes equations are needed to accurately simulate fluid flow in a rock fracture. In a recently completed project at Imperial College, a surface profilometer was used to measure fracture profiles every 10 microns over the surface of a replica of a fracture in a red Permian sandstone, to within an accuracy of a few microns. These surface data were used as input to two finite element codes that solve the Navier-Stokes equations and the Reynolds equation, respectively. Numerical simulations of flow through these measured aperture fields were carried out at different values of the mean aperture, corresponding to different values of the relative roughness. Flow experiments were also conducted in molds of two regions of the fracture. At low Reynolds numbers, the Navier-Stokes simulations yielded transmissivities for the two fracture regions that were within 6% and 11% of the measured values, whereas the value predicted by the Reynolds simulations were too high by 21% and 43%. We interpret these results as verifying, for apparently the first time in a real rock fracture, that (a) that the Reynolds equation over-predicts the transmissivities, and (b) the Navier-Stokes equation, with the no-slip boundary condition on the fracture walls, is indeed the correct model for fluid flow in a fracture. The initial deviations from linearity, for Reynolds number around 1, are consistent with the "weak inertia" model developed by Mei and Auriault (J. Fluid Mech., 1991) for porous media, and with the results obtained computationally by Skjetne et al. (J. Fluid Mech., 1999) on a two-dimensional self-affine fracture. In the regime $15<Re<100$, both the computed and measured transmissivities could be fit very well to a Forchheimer-type equation, in which the additional pressure drop varies quadratically with the Reynolds number. The computed and "measured" Forchheimer coefficients differed by about 30%, however. Examination of computed velocity profiles indicates that, in some regions of the fracture, there are strong deviations from a parabolic velocity profile. This should have implications for processes such as solute transport, and dissolution/precipitation of minerals.

H51B-03 0830h

Hydraulic Fracturing in Cohesionless Particulate Materials

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This work examines the mechanisms of hydraulic fracturing in cohesionless particulate materials. The fracturing liquid is injected into dry particulate materials, which are practically cohesionless. The liquid flow is localized in thin self-propagating crack-like conduits (Figure 1). By analogy we call them 'cracks' or 'hydraulic fractures.' When a fracture propagates in a solid, new surfaces are created by breaking material bonds. Consequently, the material is in tension at the fracture tip. Because the particulate material is already 'fractured,' no new surface is created and no fracturing process per se is involved. Moreover, all material parts are in compression since the material cannot bear any tension. Therefore, the conventional fracture mechanics principles cannot be directly applied. Based on the laboratory observations, performed on three dry particulate materials (Georgia Red Clay, silica flour, and fine sand), this study offers a physical concept to explain the observed phenomenon. The goal of this study is to determine the controlling parameters of fracture behavior and to quantify their effects. The presented model is based on fracture propagation due to unloading caused by the opening of the propagating fracture. The sufficiently unloaded particulate material yields in the fracture process zone, creating

inclined slip planes (shear bands) that are kinematically associated with mode I fracture opening near the process zone. This creates space for continued liquid flow.

URL: http://www.ce.gatech.edu/~leonid/rockmechgroup/research.html

H51B-04 0845h

Seismic Monitoring of Mineral Precipitation in a Single Fracture

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Natural fractures and faults may be subjected to chemical dissolution and/or chemical precipitation of minerals that alter the fracture properties by changing the size and strength of the contact area and/or filling-in the void space. In this study, we used seismic measurements to monitor mineral deposition and its effect on hydraulic properties of single fractures. Hydraulic and seismic measurements were made prior to and after the deposition of $CaCO_3$ in initially water-saturated fractures in granitic samples (110 mm x 104 mm x 70 mm). The transmitted compressional waves were recorded in 1 mm increments within a 64 mm by 64 mm region of the sample to determine the spatial variation in fracture properties. Plane wave 1 MHz transducers were used to send and receive the signals. Four pairs of ports were distributed around the perimeter of the fracture to measure the variation in flow as a function of position. During mineral deposition, the flow rate at each port was monitored and the acoustic response was monitored at the center of the sample. Over a period of a month after mineral deposition, acoustic measurements were recorded over the two-dimensional region. Fluid flow measurements were repeated one month after chemical invasion. We observed that largest increases in seismic amplitudes after mineral precipitation occurred for fractures that were initially more compliant. The initial aperture of the fracture controls the amount and time-rate of mixing of the chemicals used to induce precipitation because mixing of the two chemical species is slower for smaller aperture fractures. The flow rate through the sample decreased by an order of magnitude and certain ports no longer supported flow, i.e., the flow paths to certain ports were blocked by mineral deposition. The most reliable seismic indicator that the fracture has been altered is the shift in the most probable frequency in the received signal. The most probable frequency shifted to higher frequency after chemical invasion indicating a stiffening of the contact regions of the fracture and possibly a reduction in fracture aperture through mineral deposition. The frequency shift may provide a seismic diagnostic method for remote assessment of alteration of a fracture by mineral deposition. Acknowledgments: The Authors acknowledge support of this research by the Geosciences Research Program, Office of Basic Energy Sciences, US Department of Energy. LJPN wishes to acknowledge Purdue University Faculty Scholar.

H51B-05 0900h

Dissolution of Limestone Fractures from Cooling Thermal Waters

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Most previous studies of dissolution growth in karst fractures have focused on meteoric systems. Calcite has a retrograde solubility with respect to temperature, therefore different behavior would be expected in hydrothermal systems. As deep geothermal waters rise through karst formations, they cool and maintain their dissolutional aggressiveness. We have developed several models to investigate the growth of calcite fractures in an effort to understand hypogene cave development. Our models include three-way coupling between flow, heat and mass transfer. We will present results of this work in one and two dimensional variable-aperture fractures and contrast meteoric and geothermal cases. Growth of meteoric systems is commonly measured in terms of the breakthrough time. As the overall fracture aperture and flow rate increase, calcite-unsaturated water occupies the entire fracture. The time when this first occurs is considered the breakthrough time. In meteoric systems breakthrough typically appears at the onset of turbulent flow. Results from our one dimensional simulations indicate breakthrough occurs earlier in hypogene systems than in meteoric systems. In hypogene systems a thermal gradient along the fracture length combined with retrograde solubility allows growth along the entire fracture. When the aperture increases over the length of the fracture, a rapid increase in flow rate occurs. As the flow rate increases there is a switch from conduction dominated heat transfer to convection dominated heat transfer which reduces calcite solubility in the fracture and slows growth.

H51B-06 0915h INVITED

Active Faulting and Regional Flow in the Corinth Rift

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The Corinth Rift, in western Greece, opens at the yearly rate of 1.5 cm/year with an uplift of its southern shore reaching locally 1 mm/year and elevations reaching 2500 m. The fault system on this southern shore involves a set of parallel fault segments with lengths reaching up to 40 to 50 km and offsets of the order of 1000 m. In the context of the European Corinth Rift Laboratory development, a 1000 m deep borehole has been drilled on the seashore, through the smaller Aegion fault, re-activated during a magnitude 6.2 earthquake, in 1995. The upper 490 m of the well intersects a series of quaternary conglomerates interbedded locally with horizons of calcilutite (calcite mud) which become predominant in the lower 250 m of this section. From 490 m to 690 m a strongly tectonized radiolarite series is encountered till the well penetrates a cretaceous series of fractured limestone, locally karstified. The 15 m thick fault zone, encountered between 750 m and 790 m, within the limestone, has been cored through its whole length and shows crystalline calcite grown in multidecimetric open cavities, within the fault breccia. A one-meter thick siliceous fault gouge made up from the radiolarite is intersected at 760 m. Laboratory permeability measurements yield 9 to 15 10^{-18} m^2 for the calcilutite and 0.9 to 2.0 10^{-18} m^2 , for the fault gouge. Production tests conducted during the drilling operation yield a hydraulic conductivity of 10^{-5} to 10^{-4} m/s for the upper conglomerates (200m depth) with no artesian flow. The limestone encountered just above the fault, below the radiolarite, is artesian with a 0.5 MPa overpressure and a flow rate equal to 0.7 m^3/h. Its hydraulic conductivity has been measured to be about 10^{-7} m/s. Below the fault, an artesian flow is produced through local karsts observed down to 960 m, with a total flow rate of about 50 m^3/h and a 1MPa overpressure, in no flow conditions. The downhole temperature is only 32° C, for an upper-hole temperature of 17°C. The fault is intersected some 250 m below the local sea-floor in the rift. Hence this active normal faults system acts as a strong hydraulic barrier, east-west oriented, while the mountainous terrain of the southern shore produces a natural hydrostatic load that induces downward flow down to depths, which remains to be ascertained. Geological observations, in the nearby Cyclades islands, some 300 km to the east, suggest meteoritic flow may reach the brittle-ductile transition.

URL: http://www.corinth-rift-lab.org

H51B-07 0930h

A Quantitative Assessment of the Influence of Structural Setting on Fault Hydraulic Property Distributions

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It is generally agreed that faults are an important control on groundwater flow, but relatively little work has been done to link structural setting with fault hydraulic properties at a level of detail appropriate for field-scale numerical modeling. The present study examines the influence of the structural setting on fault permeability by comparing spring temperature distributions from two geothermal areas in the Alvord Basin of southwest Oregon. Geothermal springs near the Borax Lake site occur along the trace of a normal fault, and appear to have developed a quasi-steady state spatial distribution. Geothermal vents in the Mickey Hot Springs area occur in a restricted zone between two fault splays; mean spring temperature at Mickey Hot Springs is significantly higher than at Borax Lake, and the center of spring activity shows evidence of migration with time. A geostatistical analysis of spring temperatures is used to quantify the differences in permeability distributions between the two sites, and illustrates the importance of including structural data in the development of realistic hydraulic property sets for numerical models of groundwater flow at fault-controlled sites.

URL: http://www.uidaho.edu/biogeochemistry

H51B-08 0945h

One Year of Massive Fluid Production Test in KTB Pilot Hole, Germany

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Germany's deep drilling program KTB in the years of the pre-surveys (1984 - 86), the active drilling phase (1987 - 94), and during operation of the deep crustal laboratory (1995 - 2000) has revealed a wealth of new geoscientific data. The full potential of the two KTB boreholes – the 4.0 km deep pilot hole (KTB-VB) and the 9.1 km deep main hole (KTB-HB), both in crystalline environment – has, however, not yet been exploited. A new series of in-situ experiments on the kilometer scale, addressing relevant open questions on hydrogeological, geochemical, rock mechanical, and other issues has started in 2002 under the new program 'ENERGY AND FLUID TRANSPORT IN CONTINENTAL FAULT SYSTEMS'. The activities are focused on large scale fluid production and injection tests in two major fault systems, at 4 km and 7.2 km depths. They are part of Germany's contribution to the International Continental Drilling Programme (ICDP). A massive fluid withdrawal test in the fault system at 4 km depth took place from June 2002 till June 2003. The average yield during the test was 50 l/min brine, with similar amount of gas, mainly N2; draw down was more than 600 m. In-situ permeability and fluid availability were found to be significantly larger than anticipated. We did not observe any significant changes in the concentrations of dissolved fluid constituents. Isotope ratios were constant throughout the production period. Rare earth element concentrations of the produced fluids were extremely low. A down-hole seismometer in the KTB-HB has detected a number of small seismic events near the active KTB-VB, presumably triggered by the hydraulic forcing. The second phase of this new series of KTB experiments is planned to start in April 2004 and will include a massive fluid injection test in the KTB-VB, lasting for again 12 months. Monitoring and analysis of induced microseismicity and the detectability of other geophysical observables will be key issues. International partners who are interested in the coming or future experiments are most welcome to participate.

URL: http://www.icdp-online.org/sites/ktb/index/index.html

H51C MCC: Level 2 Friday 0830h

Water Quality of Hydrologic Systems Posters *(joint with B)*

Presiding: **M Gooseff,** Utah State University**; E W Boyer,** State University of New York

H51C-1044 0830h POSTER

When Good Tracers Go Bad: Tracer-dilution Sausage Recipes Revealed

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