tial distribution was then integrated with the socio economic data to formulate an action plan, which includes suggestion of alternative Landuse/Landcover practices. Such a plan is useful for natural resources management and for improving the socio-economic status of rural population on a sustainable basis. Keywords: Natural Resources, Remote Sensing, Morphometry sustainable development.

H42E-1129 1330h POSTER

Pecos River Water Management Project

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Sandia National Laboratories is providing technical assistance to farmer members of the Carlsbad Irrigation District (CID) to better plan the storage, delivery, and application of water to the Carlsbad Project. The surface waters along the Pecos River are allocated by the State of New Mexico to three major entities: 1) The State of Texas - each year a percentage of water from the natural river flow must be delivered to Texas as governed by the Interstate Streams Commission; 2) CID farmer members - a fixed portion of water must be delivered to the farming members of the CID; and 3) wildlife - an amount of water must be allocated to support the wildlife habitat in the Pecos River, most notably, the endangered Pecos Bluntnose Shiner Minnow. The Pecos Bluntnose Shiner Minnow habitat preference is under investigation by other state and national agencies and preliminary work has established that water depth, water velocity, and sediment activity (dunes, ripples, etc.) are the key parameters influencing minnow habitat preference. The amount of water (river flow rate) necessary to maintain a preferable habitat to support this species has yet to be determined. With a limited amount of water in the Pecos River and its reservoirs, it is critical to allocate water efficiently such that habitat is maintained, the farmers of the CID are supported, and New Mexico meets its commitments to the State of Texas. This study investigates the relationship between flow rate in the river and water depth, water velocity, and sediment activity. The goal is to establish a predictive tool that supports informed decisions about water management practices along the Pecos River that will maximize water available for agriculture and the State of Texas while maintaining the aquatic habitat.

H42F MCC: Level 2 Thursday 1330h

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

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

H42F-1130 1330h POSTER

Effect Of Interaction On Apertures Of Multisegmented Natural Veins

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Echelons of multisegmented fluid-driven natural fractures (such as dikes, veins, and sometimes joints) with consecutive overlapping are one of the most common types of structures in the Earth's crust. The mechanical behavior of these fractures is quite different from that of single fractures, because of the interaction between the segments. In this work we compute the apertures of a highly segmented calcite vein, with 71 segments, in siltstone (Culpeper Quarry, Virginia) described by Vermilye and Scholz [1995]. The effect of elastic interaction between the segments is considered at three different special scales and accurately evaluated by solving the corresponding system of singular integral equations. For comparison, the case of ignored interaction is also considered. Our results unambiguously suggest that the effect of interaction highly affects the vein apertures. By using two net pressures in the vein as fitting parameters, it is possible to obtain an excellent match of the computed and measured apertures (based on 3,000 data points). This indicates two episodes in the history of vein evolution. Based on the performed simulation, a concept of effective fracture (vein) has been suggested. This is a single fracture of the same overall size (length) as the real vein. It is also pressurized by two net pressures that are determined by fitting the field data. As a result, practically the same net pressures are obtained as by accounting for the full interaction between the vein segments. The concept of effective fracture allows the sufficiently accurate computation of the vein (fracture) apertures, but without considering the interaction between the multiple segments.

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

H42F-1131 1330h POSTER

Experiments on Hydraulic Fracturing in Weakly Cemented Sediments

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Hydraulic fracturing in weakly cemented sediments was studied in the laboratory. Viscous liquids were injected into dry sediments at a constant flow rate while the injection pressure was monitored. The injected liquid solidified after the experiment, and was extracted from the particulate sample. The liquid flow appears to be localized in thin conduits. Often, these channels resemble cracks; by analogy we call them hydraulic fractures. Also, non-fracture phenomena (e.g. cavity expansion, leak off) occur under certain conditions. Different transition stages (i.e., from bulb to thin fracture) can exist. The appearance of the fractures depends on (i) the density, (ii) the particle size distribution and (iii) the stress state (both stress ratio and magnitude) of the particulate materials, and (iv) the viscosity and (v) the flow rate of the injection fluid. The properties of the particulate media (i to iii) and the injection liquid (iv to v) affect the shape and thickness of the fractures. In contrast, the initial stress ratio in the sediment (iii) controls the orientation of the fractures. The injection pressure is affected by all five parameters. Since all the tested materials exhibit strain-softening behaviour, the obtained results suggest that the mechanism of fracture propagation may be due to localized shear bands originating from the fracture tip. The slip of the shear band sides is inclined with respect to the main fracture plane. This results in the normal (mode I) fracture opening, which creates space for continued fluid flow at the fracture tip during its propagation.

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

H42F-1132 1330h POSTER

Forms and Analysis of Hydraulic Fractures at Shallow Depth

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The form of a hydraulic fracture plays a key role in the performance of the fracture during environmental remediation projects. Fractures that are relatively thick and flat lying are suited to improve the performance of remediation wells, whereas fractures that are steeply dipping may be suited to the creation of reactive barriers. To sharpen the resolution of the details of fracture form at shallow depth in Piedmont soil, the vicinity of four hydraulic fractures initiated at 1.5 m depth was excavated and mapped on trench exposures. The data from these maps were used to characterize fracture form, including geometry, sand thickness, distribution of sand within the fracture, and ground surface deformation during fracturing. The fractures were roughly elliptical in plain view, and the centers of the fractures were offset from the injection casing. In general, they were shaped like gentle bowls whose sides dip from 12 to 16 degrees. A peculiar aspect of the fracture form occurred in the vicinity of the injection casings, where three of the fractures curved downward and then back up to produce gentle trough-like structures around the casings. The finite element code FRANC2D was modified to simulate fluid flow in a propagating fracture. The modified code predicts curved fracture traces that are gentle bowl-like forms, where the enveloping medium is uniform and characterized by material properties similar to field conditions, and ambient stresses result from body forces. Another model was created using two layers, where the elastic modulus of the upper layer was greater than that of the lower layer. Fractures simulated using this model curve downward toward the softer layer, and then curve upward as they become longer to produce a trough-like form similar to the field. The fractures were created in a layer of relatively stiff clayey silt that was underlain by softer saprolite, and this layering may be able to explain the downward propagation observed in the field. Additional simulations have been conducted to evaluate the effects of fracture toughness and in situ state of stress on fracture form, and preliminary results suggest that these parameters can explain field observations from a variety of sites.

H42F-1133 1330h POSTER

Discriminating Between Different Fracture Network Geometries Using Well Test Analysis

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Realistic 3D geometrical models of different styles of fracture networks have been investigated based on well-exposed examples of fault and joint networks from exposures in southwest England. From these, generic models of various types of strike-slip and normal faults have been built. These form the basis of a series of well test simulations designed to analyse and quantify the influence of different fracture elements on hydraulic behaviour. In this methodology, each fault and fracture segment is discretised individually as a plane using a triangular mesh; realistic transmissivity and storativity values are then assigned to the different parts of the mesh. A commercial finite element code is used to solve the pressure diffusion equation for a transient case in these meshes. The simulations have been tested against other numerical codes. Experiments were conducted with constant and varying fault transmissivities and varying well positions relative to the fault network. Monitoring pressure drawdown in observation wells around the fault network simulated interference tests. The results demonstrate that a single geometrical structure may display significantly different pressure responses at a single well; as a function of distance to the well and of the transmissivity distribution within the fracture network and matrix. Where the fracture network is well connected, it is the ratio of the fracture to matrix transmissivity that dominates the behaviour of the pressure diffusion. Preliminary conclusions are that fracture properties have a higher order effect on pressure diffusion than fracture density.

H42F-1134 1330h POSTER

Evolution of Fracture Permeability

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Pore fluid flow and fluid composition within fractured rocks is a subject of primary importance to fields including hazardous waste isolation and remediation, oil and gas production, geothermal energy extraction, and formation of vein fillings and ore deposits. For these reasons, considerable effort has been placed on characterization and modeling of flow in fractures and fracture systems. We are investigating the complex active chemical interaction between pore fluid and fractures that causes the fluid composition and topography of these systems to change over time. Our experimental model consists of $CaSO_4$ samples pressed with a constant force against an inert textured fracture surface. Pore fluids ranging from unsaturated to supersaturated which are at a variety of flow rates are introduced to one end of the sample in order to actively alter the

topography of the CaSO4 surface. Using a laser profiler, we are able to quantitatively monitor the changing surface topography over time as it relates to the measured sample permeability and calcium saturation of the pore fluid. These methods allow us to create and analyze many features seen in natural fractures, including high-flow dissolution channels, plateaus, and caverns formed from precipitate. In addition, the laser profile of the sample surface can be used to produce a map of aperture across the sample. Using this information, we have applied numerical modeling via finite difference and lattice Boltzmann methods to calculate pore fluid flow direction and magnitude over the entire sample surface. This research is part of an integrated program using quantitative observations of fractures and veins in drill core as well as quantitative and visual observations of flow and chemical dissolution and precipitation within replicas of rough-walled fractures in order to refine our models and work toward a predictive capability.

H42F-1135 1330h POSTER

Discrete-Fracture Implicit-Pressure Implicit-Saturation Control-Volume Finite-Element Simulation of Multiphase Flow in Complexly Fractured Rock

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Meter- to kilometer-scale multiphase fluid flow in complexly fractured rock is difficult to investigate in experiments, but is of wide scientific and economic interest. Numerical simulation is an attractive alternative to experiments but physical realism requires an adequate discretization of the flow equations in space and in time (1), the exact representation of material interfaces and a separate interior of the fractures (2), and a treatment of the non-linearities in the equations arising from the dependence of phase mobility on saturation and history-dependent capillary pressure - saturation relationships (3). The simultaneous spatial discretization of the rock matrix and fractures with large aspect ratios can be achieved with unstructured grids. However, even if large-aspect ratio hybride prism-tetrahedron-pyramid-hexahedron FE meshes (LARHM) are used, the smallest cells will occur inside fractures or at their intersections where the fastest flow will take place. This disqualifies transport schemes that are constrained by the grid Courant number, because a prohibitively large number of very small time steps would be necessary to model the fluid displacement of interest. Here we present our first CVFE-LARHM-based computations of the Buckley-Leverett equation in porous media with discrete three-dimensional fracture representations. Our original implicit pressure - implicit saturation scheme is second-order accurate in space and in time. This is demonstrated for the linear and the Brooks-Corey relative-permeability and capillary-pressure relationships in the fractures and the matrix, respectively, evaluating the schemes accuracy and performance through a comparison with an established CFL-dependent IMPES FEM-CV higher-order accurate schemes. We show that our new scheme largely overcomes the CFL limitation. It still weakly relates to CFL as it becomes increasingly diffusive when CFLmax=1 is exceeded. In unstructured fracture-matrix models, flow velocity in the fractures is typically 2-3 orders of magnitude higher than in the matrix where suitable elements can be up to 1,000 times larger. Thus, for a reasonable global choice of CFL_{max} (100-10,000), the scheme is sub-CFL and second-order accurate in the coarse matrix. Its more diffusive super-CFL behavior in fast-flowing fracture segments is offset by their orders-of-magnitude higher refinement. A limit on time step size is imposed by the progressive invalidation of the velocity field by the changing saturation. Ways to relax this limit by predicting saturation changes using the shock velocity are shown.

H42F-1136 1330h POSTER

Factors influencing the occurrence of fluoride-rich groundwaters in in a faulted area of Korea

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Factors regulating the fluoride concentration in groundwaters were investigated using natural isotope tracers and geochemical data in the southeastern part of Korea where not a few public water-supply wells show fluoride levels exceeding the drinking water limit (1.5 mg/L). In the study area, the F-rich public wells are distributed along the major faults, especially in the terrain of the F-rich granitic rocks. Their isotopic and geochemical characteristics are consistent with those of the deep-circulating paleogroundwaters, of which F concentrations are enriched by prolonged water-rock reactions. This observation reflects that rock chemistry, groundwater age, well depths, and pathways for the F-enriched deep groundwaters are the important factors for the occurrence of high F groundwaters. However, high F groundwaters are rarely observed in the faults where the associated fractures are widely developed. Isotopic signature provides an evidence for deep penetration of recently recharged groundwater into the fault zone, indicating that the artesian pressure, which moves the F-rich groundwater in the deep aquifer upward along the fault plane, is easily dispersed when the fault zone is wide. This shows that the hydrogeologic condition of the fault is also an important factor for the occurrence of high F groundwaters.

H42F-1137 1330h POSTER

Geometric Analysis of Vein Fracture Networks From the Awibengkok Core, Indonesia

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Fracture network systems within rocks are important features for the transportation and remediation of hazardous waste, oil and gas production, geothermal energy extraction and the formation of vein fillings and ore deposits. A variety of methods, including computational and laboratory modeling have been employed to further understand the dynamic nature of fractures and fracture systems (e.g. Ebel and Brown, this session). To substantiate these studies, it is also necessary to analyze the characteristics and morphology of naturally occurring vein systems. The Awibengkok core from a geothermal system in West Java, Indonesia provided an excellent opportunity to study geometric and petrologic characteristics of vein systems in volcanic rock. Vein minerals included chlorite, calcite, quartz, zeolites and sulphides. To obtain geometric data on the veins, we employed a neural net image processing technique to analyze high-resolution digital photography of the veins. We trained a neural net processor to map the extent of the vein using RGB pixel training classes. The resulting classification image was then converted to a binary image file and processed through a MatLab program that we designed to calculate vein geometric statistics, including aperture and roughness. We also performed detailed petrographic and microscopic geometric analysis on the veins to determine the history of mineralization and fracturing. We found that multiphase mineralization due to chemical dissolution and re-precipitation as well as mechanical fracturing was a common feature in many of the veins and that it had a significant role for interpreting vein tortuosity and history of permeability. We used our micro- and macroscale observations to construct four hypothetical permeability models that compliment the numerical and laboratory modeled data reported by Ebel and Brown. In each model, permeability changes, and in most cases fluctuates, differently over time as the tortuosity and aperture of veins are affected by the precipitation, dissolution, and re-precipitation of minerals, and also by mechanical fracturing. In all of our cases we interpret a first-phase mineral dissolution stage where permeability gradually declines as the vein is blocked by inward growing minerals. Hereafter, permeability may briefly increase with the onset of internal fracturing within the vein or by a phase of mineral dissolution opening up new pathways for fluid flow. Eventually we infer that permeability will decline again as second stage minerals are deposited in the fluid flow pathways.

H42F-1138 1330h POSTER

Fundamental Experiments Of Fluid-Rock Reaction Due To A Mechanochemical Process: Implication For Seismic Fault Zones

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Fracture zones within active fault zones are known to be passages of fluids. The fluid penetration in the fracture zone leads into fluid-rock interaction that changes the physical and chemical properties of the fault zone materials, possibly affecting the dynamic behavior of the fault itself. The evidences of the interactions between fluids and destructed rocks are obtained as anomalous concentrations of gases and chemical elements along active faults (e.g., Wakita et al., 1980; Tanaka et al., 2001). One of the characteristic products is hydrogen gas that has been detected relative to fault activities since Wakita et al. (1980) found hydrogen anomalies along an active fault. The generation of hydrogen gas is due to the radical reaction between water molecule and active Si radicals on the new surface of crushed quartz grains (Kita et al., 1982; Kameda et al., in press). Another characteristic product in the fault zone is submicron size of low strength materials such as amorphous and clays which seem to be formed by fluid-mineral reactions like dissolution-precipitation and alteration reactions (e.g., Tanaka et al., 2001). In order to understand the fluid-rock reactions during the pulverization of rocks, we performed batch-style crushing experiments of single crystals of quartz, alkali feldspar and biotite and granites with pure water (pH7) under argon-filled conditions using a glove box at the ambient temperature and pressure. We measured pH of the solutions and hydrogen gas concentrations using a glass electrode and gas chromatograph, respectively. BET (Brunauer, Emmett and Teller) method was adopted for precise measurements of net surface areas of the samples, in order to estimate the destructed atomic bonds. Furthermore, cations and anions in the water are also measured by PerkinElmer atomic absorption spectrometry and Toso ion chromatograph. pH values decrease for the experiments of quartz single crystal with increasing crushing times, while the other single crystal and granite experiments show the pH increases. Hydrogen gas and BET surface area linearly increase with increasing the experimental duration time for all the crushing experiments. In the case of quartz, both amounts of hydrogen gas and hydrogen ions increase proportionally with increasing the newly formed surface area. The amounts of the hydrogen gas are consistent with the amounts of Si radicals estimated from electron spin resonance measurements by Hochestrasser and Antonini (1972). This indicates that the hydrogen gas was generated by consuming the most of Si radicals on the newly formed surface. The hydrogen ions, whose amounts are 5 times larger than those of the hydrogen gas, can be explained by the dissociation of silanols that are produced on the new quartz surface by hydrolysis (Saruwatari et al., submitted). For the other minerals and granite, the hydrogen gas is also generated by the Si radicals as same as quartz, whereas the amounts of hydrogen ions decrease with increases of Na+ and K+. The amounts of the alkali metal ions are more than those expected from the static dissolution and the increase of surface area. The discrepancy may be originated from the pulverization process. At the presentation, we will discuss the effect of the newly formed surface on the fluid-mineral reactions. Hochstrasser and Antonini, 1972, Surface Sci 32, 644-664. Kita et al., 1982, JGR 87, 10789-10795. Kameda et al., In Press, Bull. Chem. Saruwatari et al., submitted, Phys. Chem. Min. Tanaka et al., 2001, JGR 106, 8789-8810. Wakita et al., 1980, Science 210, 188-190.

H42F-1139 1330h POSTER

Fault Permeability Estimated From Rate of Sea Water Recharge Into an Underpressured Hydrocarbon Reservoir

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Methane has leaked from the offshore South Ellwood fault at least since discovery of the South Ellwood field at Platform Holly. The fault bounds the north side of the field and has 600 meters of normal offset. The reservoir, which is fractured Monterey shale

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at one kilometer depth, was initially 5% over hydrostatic pressure, but is currently at 25% below hydrostatic pressure. Production fluid in well tubing that connects the platform and reservoir is isolated from the ocean. New data indicate that the ocean is in direct hydraulic communication with the reservoir in the vicinity of the fault. Quartz pressure sensors were installed at about one km depth in five wells during a 15 day production shut down. A well that intersects the fault at reservoir depth (about one km subsea), shows a pressure variation that matches the frequency of the ocean tide. Within +/- 1 minute, there is no lag between the predicted tide signal and the pressure variation in the well. The pressure change is less than predicted from sea heights, which we attribute to compressibility of the gas in the fault zone. The other wells (160m-1 km from the fault) do not show the tidal signal, indicating that pressure change is not a general effect of the tide on the earth's crust. During testing, fluid pressures increased at a rate of 55 Pa/hr (0.008 psi/hr) in the well adjacent to the fault. We conclude that the pressure recovery from sub-hydrostatic conditions is due to sea water flowing down the fault into the under pressured reservoir. From this data we calculate the permeability of the South Ellwood Fault to be about 20 md, a value similar to the overall field permeability in the fractured Monterey reservoir.

H42F-1140 1330h POSTER

Flow in fractured and permeable media: impedance spectroscopy as a probe for flow characterisation and saline breakthrough mechanisms

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Recent experiments have been undertaken using AC impedance spectroscopy as a probe for changes in rock properties and saline breakthrough curves. In impedance spectroscopy a fixed frequency sinusoidal drive voltage is applied across a sample and the amplitude and phase-lag of the resultant sinusoidal current is measured. Using measurements made across a range of frequencies enables the electrical characterisation of a sample in terms of a simple RCL network model. Thus if a sample is flooded with a solution of known ionic strength, the connectivity and apparent fluid cross-sectional area can be derived from the equivalent DC resistance value, R. We have conducted steady-state flow experiments with simultaneous impedance measurements on 50-90mm long cylindrical samples (38mm diameter) of chalk and microfractured granite. In these flow experiments we have introduced of a step concentration change in saline strength at the inflow end of the sample and examined the impedance response during the expected evolution of this initial step function into a classical advection-dispersion profile during flow down the sample. We present a simple mathematical model for the deconvolution of the impedance evolution with time in terms of the fundamental parameters of aperture, flow rate, and advection-dispersion .We apply this model to data for flow through porous chalk and microfractured granite media. Results for the fractured medium, when compared to existing studies of flow in porous sandstones, reveal that at low Peclet numbers even a very fine-scale isotropic microfracture network is significantly less dispersive than the equivalent porous medium.

H42F-1141 1330h POSTER

Effects of Sand-Filled Hydraulic Fractures during Air Sparging

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The effectiveness of air sparging is limited in fine-grained formations, such as clay-rich saprolite, where low permeability restricts flow rates. The purpose of this work is to investigate the effectiveness of using hydraulic fractures to increase the performance of air sparging in relatively low permeability materials. The approach has been to conduct step-rate, air-injection tests into conventional wells and wells intersecting fractures, and then to evaluate the results of these tests using analytical and numerical models. Fieldwork is being conducted in an area underlain by saprolite weathered from granitoid gneiss. Permeability of the saprolite ranges from 1x10-12 to 5x10 -12 m2 according to slug test data. Five wells have been used for testing: three non-fractured and two fractured wells. Well tests involved injecting air at constant pressure and monitoring transient flow rates until the flow approximately equilibrated over 10 to 60 minutes, then incrementally increasing pressure and repeating the flow monitoring. Field results were expressed in terms of the initial specific sparge capacity (Q/(P-H-E)) where Q is mass flow rate, P is injection pressure, H is hydrostatic pressure, and E is air entry pressure. The specific sparge capacity of conventional wells ranges from 0.3 to 0.6 m3/(Mpa min), whereas it is several times greater for fractured wells (0.8 to 3.5 m3/(Mpa min)) at the field site. Field data have been analyzed using analytical and numerical models. We use the step-rate data and invert an analytical solution adapted from Philip (J. Contam. Hydro., 1998) to estimate the in situ relative permeability function during sparging. This approach indicates that permeability ranges from 0.4x10-12 to 2x10-12 m2, which is remarkably similar to the slug test data. It also indicates that the in situ air entry pressure is approximately 31 kPa, and the exponent constant in the Gardner relative permeability function ranges from 0.12 to 0.25 m-1. Numerical analyses have been conducted using TOUGH2 to estimate gas distribution from the transient data, and to evaluate the effects of fracture length and thickness on sparging performance.

H42F-1142 1330h POSTER

Multi-scale characterization of rock fracture surfaces using roughness analysis and geostatistics

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Surface roughness is a major factor in the determination of strength, deformability and fluid flow properties of rock joints. The surface roughness coupled with stresses that act on the fracture plane determine the geometry of the contacts and void distribution. Therefore, in the evaluation of the hydro-mechanical behavior of a rock fracture it is necessary to consider the contribution of the roughness. Experimental flow tests show that with increasing shear displacement, the fracture becomes heterogeneous, anisotropic, and more permeable in the direction perpendicular to the displacement. On the other hand, dry shear tests show that the surface fails in areas facing the shear direction. The empirical description of the surface proposed by Grasselli can be extended to all possible directions, resulting in a polar diagram that represents the directional distribution of the roughness over the surface (the roughness rose). The ability of this method has been shown to not only illustrate the differences in roughness, but, coupled to the shear tests results, also to quantify its contribution to the shear strength. In this paper, the method proposed by Grasselli for quantifying the roughness is compared to a geostatistical approach that has been developed to analyze and process spatially distributed observations. The semivariogram allows for the analysis of the spatial variability of surface roughness in a given orientation, providing a model that describes the statistical features of the surface. Two different surfaces, one with a strong anisotropic roughness, and the other almost isotropic, have been analyzed with the two methods. Both methods are able to capture the major geometric feature of the surfaces, with a good agreement of the findings. The results constitute the base-case for trying to couple the two discussed methodologies, in order to create a multi-scale methodology for the quantification of the roughness. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

H42F-1143 1330h POSTER

The role of fracture intersections in DNAPL migration below the water table

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Dense non-aqueous phase liquids (DNAPL's) are a common source of groundwater contamination. Because DNAPL's are denser than water, they may rapidly migrate through surficial sediments and enter fractures within the underlying bedrock. In order to locate, assess, and remediate DNAPL's within fractured bedrock, we must first understand the distribution, or structure, of the fluid phases (water and DNAPL) within the fracture network. Phase structure will be ultimately dependent on the mechanisms through which a DNAPL invades the water-saturated fracture network. Previous numerical simulations and experimental observations in two-dimensional fracture networks have shown that aperture variability, network geometry, and horizontal groundwater flow all affect the balance between capillary, viscous, and gravitational forces that controls DNAPL invasion. However, two-dimensional fracture networks restrict the influence of intersections between fractures, which may form their own network of barriers or conduits. Here, we conduct simple experiments to consider the influence of a single three-dimensional fracture intersection on DNAPL invasion. Artificial intersections are fabricated from glass plate to allow visualization of the invasion process. We then conducted experiments over a range of intersection geometries and boundary conditions. Observations are compared to simulations based on a Modified Invasion Percolation (MIP) model. Results show that intersection geometry influences DNAPL migration, and thus the three-dimensional phase structure of DNAPL in fractured rocks.

H42F-1144 1330h POSTER

Part I - In Situ Characterization Of Hydromechanical Coupling Between Stress And Permeability Of Single Fractures From Bore Hole Coupled Pressure-Deformation tests : Experiments In The Coaraze Fractured Rock Reservoir (France).

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In order to characterize the effect of hydromechanical coupling on the permeability of single fractures inside a fractured rock mass, we carried out pressure-deformation jacking tests into boreholes in the natural Coaraze laboratory. This site is a 19000 m^3 fractured calcareous reservoir where repetitive hydraulic loadings are produced by the closure of a floodgate located on a spring, at the downstream of the site. Simultaneous normal deformation and pressure measurements in several fractures and in the rock matrix show that the rock mass behaves elasticaly and that micrometric deformations mainly concentrate along fractures. Calculated normal stresses on the fractures range between 60 and 130 kPa. Jacking tests were done on 6 fractures, and repeated for 30 and 50 kPa hydraulic loadings in order to quantify fracture permeability variations. Single fracture planes were isolated by two packers between which a device allowed the measurement of pressure and deformation normal to the fracture plane. Before the experiment, initial pressure in the fracture between the packers was constant. The tests consisted in water injection with a small overpressure that did not exceed 25% of the initial pressure in order that it did not influence the fracture surrounding rock volume. Permeabilities were deduced with a 25% uncertainty. For the 50 kPa loading experiment, permeabilities cluster in two groups, high permeable fractures (group 1) ranging between 300 10^{-5} and 130 10^{-5} $m^2.s^{-1}$ and, low permeable fractures (group 2) ranging between 4 and 60 10^{-5} $m^2.s^{-1}$. When the hydrostatic loading is decreased to 30 kPa, there is a 50 to 60% variation of the two groups permeabilities characterized by an increase of group 2 permeabilities and a decrease of group 1 permeabilities. Opposite behaviors of groups 1 and 2 highlight two very different hydromechanical effects. When the floodgate is closed, group 1 fractures are quickly filled with water because they are very permeable, and

their deformation instantaneously follows pressure variations, a normal opening with a pressure increases and a normal closure with a pressure fall. Group 2 fractures are filled with water with a delay of several minutes to several hours because they are low permeable. During this delay, their deformation is mainly influenced by group 1 deformation. This experiment shows that the permeability of fractured rock masses is very sensitive to stress changes at shallow depth (or low in-situ stress) and that hydromechanical behavior of a few fractures have substantial effects on all the rock mass permeability.

H42F-1145 1330h POSTER

Part II - Evaluation Of Coupled Hydromechanical Analysis Of A Fractured Rock Mass By The Multi-scale Comparison Between Experimental And Numerical Modeling Datas From The Coaraze Natural Site.

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A comparison between 2D UDEC numerical modeling and in-situ hydromechanical (HM) measurements is performed to better understand the coupling processes in a fractured media. Measurements come from the Coaraze site that is a natural 19000 m^3 site where geometrical, hydraulical and mechanical parameters are known. Pressure and normal displacements on 10 single fractures inside the site and surface tilting are permanently measured. Repetitive hydraulic loadings are produced by the closure of a floodgate located on a spring of the site. A 100 kPa water pressure increase cause instantaneous elastic deformation of fractures and rock matrix. Those datas were used to evaluate a coupled hydromechanical numerical analysis at the single fracture and at the whole rock mass scales. At the single fracture scale, the high non-linear relationship between measured normal displacements and pressures is well explained with a variable normal joint stiffness model modified from Bandis law in order to take into account the joint environment. The more general deformation of the rock mass results from the complex heterogeneous stress-permeability behavior of the fracture network. High permeable fractures apertures change of a factor 2 in response to changing fluid pressure whereas there is a low change of low permeable fractures apertures. A 2D UDEC model of the entire rock mass that takes into account the heterogeneity of constant normal joints stiffnesses deduced from single fracture analysis and permeabilities measured in the field best fit experimental datas. Nevertheless, model results remain far from measurements (10 to 20% differences) mainly because fractures network geometry and permeabilities high heterogeneity need to be simplified to run the model. This analysis shows that it is possible to deduce hydromechanical non-linear laws from in-situ hydromechanical tests on single fractures with a good accuracy. Nevertheless, even with these laws taken as input parameters, it remains insufficient to restore a satisfying general behavior of a rock mass.

H42F-1146 1330h POSTER

Numerical simulations of the dissolution of calcite fractures

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The dissolution of fractured calcite in aqueous solutions of carbon dioxide is investigated numerically. The chemical kinetics is described by Plummer-Wigley-Parkhurst (PWP) model, in which the dissolution of calcite is a result of simultaneous reactions with hydrogen ions, carbonic acid and water. The velocity field in the fracture is calculated using a lattice-Boltzmann technique, while the transport of dissolved species is modeled by a random walk algorithm. The numerically modeled morphological changes in the fracture are compared with laboratory experiments on dissolution of Carrara marble.

H42F-1147 1330h POSTER

Free Flows at the Interface of Grooved Geometries

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A solution to the problem of shallow laminar water flow above a permeable surface composed of deep grooves is presented. Previous studies proposed theoretical, experimental, and numerical insight with no single general solution to the problem. Many studies have used the Brinkman equation, while others showed that it does not represent the actual interface flow conditions. Here we show that the interface macroscopic velocity can be accurately modeled by introducing a modification to the Brinkman equation. A moving average approach was proved to be successful when choosing the correct representative elementary volume and comparing the macroscopic solution with the average microscopic flow. As the size of the representative elementary volume was found to be equal to the product of the square root of the permeability and an exponential function of the porosity, a general solution is now available for any brush configuration. Given the properties of the porous media (porosity and permeability), the flow height and its driving force, a complete macroscopic solution of the interface flow is obtained. The presentation will begin with a theoretical background and the mathematical formulation of the modified Brinkman equation (MBE). Then, a comparison between the macroscopic velocity profile obtained by the MBE and the result of the microscopic numerical solutions will be presented. The comparison was obtained for laminar flows through a variety of 37 groove geometries. Measurement results of the micro-scale velocity field using Particle Image Velocimeter (PIV) inside and above a fractal Cantor-Taylor brush configuration will be shown. The results obtained for the Cantor-Taylor brush configuration and for the other 36 groove geometries show that the modified Brinkman equation (MBE) accurately describes the macroscopic velocity profile given that the flow regime is laminar.

H42F-1148 1330h POSTER

Salt Precipitation and Dissolution in an Unsaturated Porous Media Under Non-Isothermal Conditions

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Salt precipitation and dissolution in unsaturated porous media is an important process to understand, both for agricultural soils (fertilizer movement) and for its effects in controlling water flux and potential contaminant transport in arid regions (migration of fluids and solutes to fractures and the land surface). Since evaporation is a key process to consider in both scenarios, it is necessary to consider heat and energy flow. A brief discussion/history of the salt precipitation/dissolution problem is given, then using the principles of continuum mechanics and mixture theory, a set of governing equations for salt precipitation and dissolution is developed. The equations are general in the sense that the following are considered: 1) non-isothermal conditions; 2) porosity is a function of solid phase salt concentration; 3) all parameters are functions of the appropriate thermodynamic variables. The equations are limited in that only near-ground surface conditions are considered. This is generally not a serious limitation since this location is likely the most seriously affected by rapid temporal changes in temperature and other boundary conditions. Further simplification of the problem is achieved by considering only "simple" salts (defined here as non-pH buffered salts that dissolve/precipitate only as a function of liquid phase ionic concentration) and flow regimes that do not result in finger flow of liquids. Initial and boundary conditions are developed for the following physically relevant conditions: 1) fertilizer salts introduced to an initially wet (but unsaturated) soil; 2) salt formation on free surfaces in arid climates; 3) water imbibition of fresh water into saline porous media. Work to date on solution of the initial boundary value problems is presented.

H42F-1149 1330h POSTER

Simulating Multiphase Flow in Complex Fracture With Smoothed Particle Hydrodynamics

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The smoothed particle hydrodynamics (SPH) method was used to simulate multiphase flow in fractures with complex geometries. Originally developed for astrophysical problems more than 20 years ago, SPH is now finding applications in hydrogeology. The fully Lagrangian nature of SPH allows the front separating the fluids to be modelled without employing complex front trucking schemes. SPH does not require the construction of a grid that would introduce numerical dispersion. The surface tension and fluids wettability are simulated by attractive and repulsive fluid-fluid and fluid-boundary interparticle interactions. The fracture geometry was generated from self-affine fractal surfaces. The fractal model is based on the observation that the fracture of brittle materials, including rocks, generates surfaces that have a self-affine fractal geometry, which can be characterized by a Hurst exponent with a material independent (universal) value of about 0.75. Our model qualitatively predicts such complex multiphase flow phenomenon as phase separation and fluid fragmentation. Such behaviors are very difficult to model with grid-base methods. A detailed comparison between numerical results and laboratory experiments is needed to quantitatively validate the model.

H42F-1150 1330h POSTER

The Implication of Structural Discontinuities in Rock Slope Stability Analysis: Example of Katsuura-Ubara, SE-Japan.

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Discontinuities in rocks such as faults, joints and bedding occur at different orientations with respect to the principal stress; knowing the type and characteristics of fractures will benefit our understanding of the bulk physical properties of rock masses. The present paper attempts to bridge a strong relationship between structural discontinuities and slope instabilities in the vicinity of Boso Peninsula SE Japan, marked by steep sedimentary rock forming slopes. The rocks are essentially constituted of sandstone, mudstone or their alternation of Miocene age. The bed generally strikes EW or NESW and dips toward N or NW. Aerial photo-interpretation backed up by intensive field mapping of geological and geomorphological features revealed four main stages of deformation with different mechanisms which can be inferred from microstructures at the scale of SEM (Scanning Electron Microscope) and thin section. The representation of discontinuities and the evaluation of their angular relationships with regard to the drainage map indicate that the fracture intersection and fracture network geometry greatly influence the fluid flow properties. It was verified that seepage is mainly noticeable in most recent origin discontinuities suggesting that the fracture age and origin are very important in order to access the water transmissivity. On the other hand a quantitative description of the discontinuities in term of orientation, spacing and density suggests that the fracture system in this area controls the orientation and the morphology of the slopes. These examples illustrate how a precise knowledge of

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the fracture network is essential for the analysis and design of slopes. The method used in this paper is relatively simple with acceptable degree of accuracy, and it shows a significative participation of the fracture analysis as an important tool for solving problems concerning the various stages of the slope stability analysis. Keywords: Structural discontinuities; Slope Stability; Drainage map

H42F-1151 1330h POSTER

Fluid-rock interaction at Las Cañadas aquifer, Tenerife, Canary Islands

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Las Cañadas caldera, located at the central part of Tenerife, Canary Islands, is a large volcanic depression (16 × 9 km). The caldera is opened to the sea at the north side and filled by continuous layers of lava flows and fall deposits. These volcanic deposits form a good hydrogeological trap which is the largest ground water reserve of the island. In comparison, the basement of the caldera has low permeability. Numerous galleries (horizontal drains) intercept the Las Cañadas aquifer. During the last century, this aquifer has been overexploited depleting the water table as well as the water quality. The Teide-Pico Viejo volcanic complex is located at the margin of the caldera. The ascent of deep magmatic gases (e.g. CO_2) confers aggressiveness to the waters causing rock dissolution and alteration. The aim of this work is to study water-rock interactions in Las Cañadas aquifer. Chemical diagrams showing the relative composition of Mg, Ca, Na and K as described by Giggenbach (1988) indicate that the waters discharged by the galleries correspond to the process of rock dissolution and evolution towards full rock-fluid equilibrium. The lower contents in Ca and Mg are found in the galleries which reach more deeply the north flank of the Teide Volcano, suggesting mineral precipitation and heating in this zone. Geochemical modeling of fluid-rock interactions using Chiller (Reed and Spycher, 1984) show that the gases discharged at Teide summit cannot generate the water compositions observed at Las Cañadas. These gases represent the separated phase of a condensation process within the volcanic edifice. Modeling of the gas-enriched Las Cañadas waters from the recharge zone with phonolitic rocks from the caldera show that the galleries waters correspond to the dissolution of 1 to 7 g of rock÷liter of water and a relatively shallow circulation. The simulations suggest that waters have not encountered the $\sim 250^{\circ}$C temperature region suggested by the gas geothermometers. This behavior suggests that the heat source in this system is deep as suggested by geophysical studies.

URL: http://iter.es

H42F-1152 1330h POSTER

Geologic Controls on Groundwater Flow and Contaminant Transport in Fractured Bedrock

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This project involves strategic hydrogeologic investigation and remediation of chlorinated solvents in fractured bedrock and overlying alluvium in Northern California. Primary contaminants include 1,1,1-TCA, 1,1-DCE and 1,1- DCA. The source area includes recoverable DNAPL, with a maximum accumulated thickness of 29 feet in a well, and dissolved concentrations in excess of 500 mg/L. The dissolved plume extends away from the source through an extensive fracture network to a depth of 450 feet. The investigation involved drilling monitoring wells to depths up to 700 feet, borehole geophysics, a seismic reflection survey, and aquifer testing. Optical and acoustic televiewer logging were used to map the fracture network, which is dominated by west, southwest, south, and east dipping features. The seismic reflection survey identified en-echelon, southeast dipping normal faults and antithetic, southwest dipping reverse faults that are generally consistent with the orientation of structures in the nearby San Andreas fault zone. The primary fault strikes are generally parallel to those of the dominant fracture sets. Notable lithologic discontinuities in the Franciscan bedrock were documented across major faults, possibly related to significant vertical and strike-slip offset. The seismic reflection survey provided a useful guide for drilling by predicting areas of higher fracture density. Slug tests and acoustic waveform, conductivity, temperature, and static/dynamic heat pulse flow meter logging were used to establish that flow is primarily through the fractures and conductive portions of the alluvium. These data were used to install an effective multilevel well network, establish a ground water flow pattern that reflects geologic controls and regional gradient, and support remediation evaluations. Remediation evaluations include dissolved phase remediation bench tests, DNAPL recovery, and monitored natural attenuation (MNA). The dissolved phase bench tests are in progress. DNAPL has been periodically recovered from fractured bedrock for two years. DNAPL recovery rates declined over time except immediately following a 5.3 Richter magnitude earthquake, which apparently caused a temporary increase. A pilot test demonstrated that dewatering and applying a vacuum to the well increased the DNAPL recovery rate by approximately 2500 percent over rates prior to pilot testing. The MNA results indicate that abiotic and biotic degradation are active, consistent with the apparent steady state condition of the dissolved plume over two years of monitoring. Based on the results, the remedial strategy for the site includes periodic DNAPL recovery with monitored natural attenuation. This study demonstrates the effective use of combined geologic, geophysical, and hydrologic investigation methods to support remedial planning.

H42G MCC: Level 2 Thursday 1330h

Hillslope Hydrologic Processes: New Directions in Monitoring and Modeling II Posters *(joint with NG)*

Presiding: **J P McNamara,** Boise State University**; N E Peters,** U.S. Geological Survey**; P A Troch,** Hydrology and Quantitative Water Management, Wageningen University

H42G-1153 1330h POSTER

Hydrometric Analysis of the Panola Mountain Research Watershed, Georgia, USA: Linkage Among Rainfall, Watershed Wetness, and Stormflow

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Relations between stormflow characteristics and soil-moisture content, water-table elevation, and precipitation were evaluated for the 41-ha Panola Mountain Research Watershed (PMRW) for water years 1986 through 2001 to refine the conceptualization of stormflow generation. During the 16-year period, precipitation (<1% snowfall) averaged 1,220 mm and annual water yield averaged 30%, ranging from 16% to 50%. Rainfall was relatively uniform throughout the year. For 759 rainstorms, median stormflow (median duration of 33 h) water yield for all rainstorms was small (2.3%), ranging from 1.8% to 7.6%, with the highest median percentage occurring during the dormant wet winter season, when rainfall replenishes the soil-moisture deficit and recharges ground water. Runoff and stormflow were highly correlated with rainfall; the relation indicates that runoff is generally higher for comparable rainfall during the winter compared to the other seasons, which is consistent with higher moisture deficits and higher evapotranspiration in the other seasons. Stormflow water yield correlates best with storm-period maximum soil-moisture content and with storm-period maximum water-table elevation. Furthermore, the relations are linear above thresholds for the entire period and vary by season. For moderate to large rainstorms, relations among wetness parameters and stormflow water yield are better (less scatter) and more consistent when the watershed is seasonally wet than when it is dry. Soil-moisture content (minimum or maximum) is highly correlated among soil depths and with water-table elevations. Stormflow water yield is linearly related to soil-moisture content at 70 cm above 37% volumetric moisture content, occurring 20% of the time. Maximum water-table elevation is linearly related to maximum soil-moisture content above a threshold, and the soil-moisture threshold increases with upslope position; the soil-moisture threshold for flow to occur at a trench hillslope site is 41%, occurring <0.5% of the time. General relations among streamflow, soil moisture, and water-table response are attributed to variable source areas.

H42G-1154 1330h POSTER

Parameterization and Assessment of a Distributed Hydrologic Model

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Verification of distributed hydrologic models is rare due to the lack of spatially detailed field measurements and a common mismatch between the scale at which soil hydraulic properties are measured and the scale of a single modeling unit. In this study two of the most commonly calibrated parameters, soil depth and the vertical distribution of lateral saturated hydraulic conductivity (Ks), were eliminated by a spatially detailed soil characterization and results of a hillslope-scale field experiment. The soil moisture routing (SMR) model, a simple distributed hydrologic model, was modified to represent the dominant hydrologic processes for the Palouse region of northern Idaho. The model was applied to a 2 ha catchment without calibration to measured data. Distributed responses were compared to perched water depth measurements made every 12 hours over a three year period on a 10 x 15 m grid. The modified SMR model simulated the perched water table fluctuations across the catchment during the hydrologically active season remarkably well especially given that one mm of error in the water balance would result in an error of 20 mm in water table depth. Simulations also captured water table fluctuations during a year with high spatial variability of snow accumulation and snowmelt rates at up-slope, mid-slope, and toe-slope positions with Nash-Sutcliffe efficiencies as high as 0.79, 0.70, and 0.52, respectively. In one location in the catchment, consistent over-prediction of perched water table heights indicated a localized recharge zone which was not identified by the soil morphological survey. Our detailed data set with its spatial variability in soil properties and dynamic hydrologic measurements is ideal for verification of distributed hydrologic models. Modeling results in this paper show that the simple GIS-based SMR model is physically sound.

H42G-1155 1330h POSTER

Spatial Dynamics of Soil Moisture at Hillslope and Small Catchment Scales

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We present observations of soil moisture patterns in relation to topography in a small, Mid-Atlantic Piedmont basin over a full annual cycle, including a period of severe drought. We document spatial variation in near surface (upper 6 cm) soil moisture, which has an important influence on soil biogeochemical cycling, at a local (25 m2) scale and examine topographic patterns of plot level soil moisture means and variances at the catchment scale. These field observations were