to a downstream fining sand bedded meandering channel bordered by floodplains up to 14 km in width. Tailings of sand and silt constituted about one-third of the mine related load, with the rest of the sediment being a rocky waste and landslide materials. Three distinct depositional zones developed: a prograding debris fan which gave way to a downstream tapering wedge of braided gravel , which in turn abruptly shifted to a sand bedded reach, forming a separate downstream tapering wedge of aggradation. The debris flow reach caused massive channel incision and hillslope erosion upslope of the fan; aggradation in the gravel reach caused bed surface fining, considerable channel widening and elimination of vegetated island bars; and the aggradation in the sand bedded reach induced chronic flooding (which led to forest dieoff), accelerated channel migration (due to bar growth), levee growth, plugging of tie channels and massive infusion of sediment onto the floodplain. The largest aggradational response in the system was just below the mine and just downstream of the gravel-sand transition. For the 15 year period, 30% of the sediment was stored in the fan and gravel bedded reaches, 18% in the bed of the sand bedded channel, 17% on the adjacent floodplains, 2% was dredged from the channel and only 28% of the total load was transported to the lower end of the middle Fly. Modeling which generally predicts well the field observations, demonstrates that: 1) about 70% of the gravel input broke down to silt and clay, 2) channel widening (which is not modeled) strongly reduces aggradation thickness, 3) sand aggradation is damped by steepening slopes and increased transport, 4) rates of overbank deposition markedly increases with channel bed aggradataion, and 5) post-mining (and end of sediment input) , the aggraded gravel will eroded and disperse downstream (though trapped within the gravel reach), whereas the sand slug will move as an aggradation wave downstream for many decades. These findings demonstrate that upstream sediment pulses are strongly damped by particle attrition, channel widening and transient storage effects. Prediction of downstream fining of the sand bedded reach and channel width change in response to large fluctuations in sediment load remain significant theoretical challenges.

H51F-11 1130h

Sediment Transfer-Storage Relations for Degrading Alluvial Reservoirs

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The routing of sediment through a drainage system is mediated by transfer-storage relations that are particular to each alluvial reservoir, which contains a channel and floodplain. We propose that sediment transfer rate for a given annual distribution of streamflow is a positive function of sediment storage and examine these relations for degrading reservoirs in which sediment is evacuated by incision and corrasion.

Previous laboratory experiments of sediment-starved channels that model gravel-bed rivers show rapid, linear degradation in initially unarmored beds during non-selective transport, followed by decreasing rates of incision with the onset of selective transport, armoring, and bed structuring. Together, these phases of incision produce nonlinear decreases in sediment output with decreasing bed elevation. A comparison of experimental results and numerical simulations of armoring indicates that the depth of incision achieved at a final low reference transport rate depends on initial transport stage and particle sorting. Typical values of Shields stress for gravel-bed rivers force deep incision in well-sorted material (sigmaG<1) and shallow incision (a few surface layers or less) in poorly sorted material (sigmaG>1.5). This contrast suggests that changes in storage in response to variations in sediment supply are small in river reaches with poor sorting and large in those with superior sorting.

Nakamura and Kikuchi [1996] find that, in the absence of large floods, the annual rate of erosion of floodplain surfaces decreases exponentially with age. We use their model for corrasion in the Saru River, Japan, and arbitrary functions for rates of incision suggested by our previous analysis to simulate degradation over a 40-year period, starting with an initially filled alluvial reservoir. Storage volume decreases more rapidly than exponential regardless of whether or not incision is modeled as exponential with time. This suggests that a general form of sediment transfer-storage relations for degrading alluvial reservoirs is positive and nonlinear.

H51F-12 1145h

Self-Organized Criticality as a General Principle of Riverbank Failure

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Cellular "sandpile" models of river bank failure can display "self-organized criticality" (SOC), demonstrating that short-term local geomorphic instability may generate broader-scale, basin-scale stability (i.e., consistent system-wide patterns of failure). The cells in the models have simple local rules so that sediment leaves the cell (i.e., bank failure occurs) when a certain threshold is reached. Failures occur at all scales, ranging from one cell to many contiguous cells failing at the same time. Magnitude/frequency plots of the spatial and temporal failure patterns display precise power-law relationships. Mapping of riverbank failures along 180 kilometers of northern Yellowstone Park streams confirms that the spatial distribution of failures in different basins display power-law relationships similar to those predicted in the automata simulations. The slope of the power law line in these plots, known as the tau-exponent, varies primarily with channel slope and near-channel bank materials.

Based on the model and field data results, we hypothesize that the power law magnitude/frequency distribution is a general rule in most or all river systems. If in fact riverbank systems are at a critical state rather than an equilibrium state, then long-term local stability is an unlikely or even impossible engineering or restoration goal. The probable existence of criticality in natural stream settings suggests that local human alterations designed to increase channel stability, while lowering the local frequency of small failures, will only encourage an increase in the magnitude of system-wide, low-frequency large failures. One of the larger problems in interpreting the riverbank failure power laws is the distinct possibility of other existing organizing theories besides SOC. Several theories of landscape development predict globally convergent behavior with power law spatial and temporal patterns, and this theoretical equifinality is an obstacle that must be explored if the hypothesized SOC riverbank principles are to be validated or falsified. Improved cellular models of riverbank failure that include more physically realistic rules in coupled-map lattice simulations are required for testing the effect of riverbank stabilization and restoration projects.

H51G MC: 125 Friday 1030h

Chemical Heterogeneities and Contaminant Transport in the Vadose Zone I *(joint with NG, B)*

Presiding: **E D Mattson,** Idaho National Engineering Environmental Laboratory**; P V Brady,** Sandia National Laboratories

H51G-01 1030h INVITED

Analysis of Radionuclide Migration through a 200-m Vadose Zone Following a 16-year Infiltration Event

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The CAMBRIC nuclear test was conducted beneath Frenchman Flat at the Nevada Test Site on May 14, 1965. The device was positioned in heterogeneous alluvium, approximately 70 m beneath the ambient water table, which is itself 220 m beneath the ground surface. Approximately 10 years later, groundwater adjacent to the test was pumped steadily for 16 years to elicit information on radionuclide migration in the saturated zone. The pumping well effluent – containing mostly "mobile" radionuclides such as tritium, 14C, 36Cl, 85Kr, 129I, and 106Ru – was monitored, discharged to an unlined ditch, and allowed to infiltrate into the ground or flow towards Frenchman Lake, just over a kilometer away. This created an unexpected and remarkable second experiment in which the migration of the effluent through the 220 meters of unsaturated media, back to the water table, could be studied. In this paper, the pumping and effluent data are being utilized in conjunction with a series of geologic data, new radionuclide measurements, isotopic age-dating estimates, and vadose zone flow and transport models to better understand the movement of radionuclides between the ditch and the water table. Measurements at the water table, in a monitoring well 100m away from the ditch, have indicated rising levels of tritium since 1993, roughly 16 years after its initial discharge into the ditch. Modeling and tritium age dating have suggested 2 to 5 years of this 16-year transit time occurred solely in the vadose zone. They also suggest considerable recirculation of the pumping well discharge back into the original pumping well. Surprisingly, no 14C was observed at the water table, suggesting its preferential retention, possibly due to precipitation or other chemical reaction, in the vadose zone. Overall, the long term nature of the experiment, the variety of chemical measurements and isotopic interpretations, and their incorporation into a unified modeling analysis, have contributed to a unique perspective for interpreting radionuclide migration in this system.

This work was conducted under the auspices of the U.S. Department of Energy by the University of California and Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

H51G-02 1045h INVITED

Relationships Between Physical and Chemical Heterogeneity in Geologic Media: The Role of Surface Area

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The availability and effective use of clean groundwater are becoming ever increasing concerns throughout the world because of increased population growth and the accompanying increases in agricultural production, mineral and fossil fuel exploitation, urbanization, and industrialization. Anthropogenic activities have resulted in localized contamination of the vadose zone and large amounts of under lying groundwater. In many instances the technology and underlying science needed for long-term management of contaminated lands are lacking. One particularly important issue limiting effective environmental management is the influences of physical and chemical heterogeneity on the transport and biogeochemical processes controlling the subsurface distribution of contamination. Physical heterogeneity has been the focus of extensive research over the last twenty years; chemical heterogeneity has received less attention. However, understanding subsurface heterogeneity requires a recognition that geological processes (e.g, sedimentary deposition) that produce primary heterogeneity as well as secondary processes (e.g., diagenesis) that modify the heterogeneity can result in correlations between physical and chemical subsurface properties. The characteristics and abundance of surface area and its effects on subsurface processes provides the linkage between physical and chemical heterogeneity in subsurface media.

H51G-03 1100h INVITED

Defining the Speciation and Chemical Dynamics of Contaminants Within the Vadose Zone

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Chemical properties in addition to biological and physical factors will in part dictate the attenuation of trace elements; ultimately, elemental speciation will be a determinant. Thus, defining the speciation of trace elements within natural environments is necessary to determine their cycling and hazard. A multitude of techniques are currently available to accomplish this task. Here a number of spectroscopic and microscopic techniques are described that have the ability to provide chemical and structural information on metal ions

within complex media common to vadose zone environmentsa truly challenging task. X-ray absorption spectroscopy (XAS) in particular has gained attention for its ability to speciate elements within soil solids. However, rarely is a single technique capable of adequately addressing the intricate nature of soils and, thus, a multitude of complementary techniques are required. In proper combination, spectroscopic/microscopic techniques, possibly with extraction or physical methods, can provide a detailed description of metals within soils and help to define soil quality. The evolution of iron phases upon a transition from an aerobic to anaerobic environment and the subsequent impact on contaminant retention are used to illustrate the complexity of vadose environments. Moreover, this example serves to demonstrate the need for multiple spectroscopic techniques in determining the speciation of trace elements.

H51G-04 1115h

Direct and High-Resolution Measurements of Retardation and Transport in Whole Rock Samples under Unsaturated Conditions

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Evaluation of chemical sorption and transport is very important in the investigations of contaminant remediation, risk assessment, and waste disposal (e.g., the potential high-level nuclear waste repository at Yucca Mountain, Nevada). Characterization of transport parameters for whole rock samples has typically been performed in batch systems with arbitrary grain sizes and a high water/rock ratio. Measurement of these parameters under conditions more representative of fractured rocks in situ provides a better understanding of the processes occurring there.

The effective Kd approach has been commonly employed to quantify the extent of contaminant-medium-fluid interactions. Unrepresentative Kd values will lead to unrealistic assessments of contaminant transport. Experimentally determined Kd values are predominantly obtained from batch experiments under saturated and well-mixed conditions. Batch-sorption experiments can be problematic because: (1) saturated conditions with large waterrock ratios are not representative of the in situ vadose condition, and (2) crushed rock samples are used, with the sample size (in the range of microns to sub-millimeters) chosen more or less arbitrarily and mainly for experimental convenience, and (3) for weakly sorbing contaminants, a batch-sorption approach can yield variable and even negative Kd values, because of the inherent methodology of calculating the Kd values by subtracting two large numbers (i.e., initial and final aqueous concentration).

In this work, we use an unsaturated transport-sorption approach to quantify the sorption behavior of contaminants and evaluate the applicability of the conventional batch-sorption approach in unsaturated rock. Transient experiments are designed to investigate water imbibition and chemical transport into the rock sample (with size in the centimeter range) by contacting one end of a sample with water containing chemical tracers. Capillary-driven imbibition transports chemicals farther away from the source. Sorbing chemicals will be subjected to retardation that leads to delayed transport (compared to nonsorbing chemicals). This approach enables us to investigate the contaminant-medium-fluid system with weak (yet nonzero) sorption. Two profiling techniques, rock drilling (with a sampling interval of 1 mm) and laser ablation-inductively coupled plasma-mass spectrometry (with a spatial resolution of ∼20 microns), have been developed to measure chemical concentration as a function of distance in the sample. The results shows that Kd values for sorbing chemicals (e.g., lithium, and cesium) are consistently much lower (3-7 times) than the data from the batch-sorption approaches reported in the literature. This new approach generates more realistic sorption data (under unsaturated transport conditions) for flow and transport modeling.

H51G-05 1130h INVITED

Hydrologic and Chemical Controls on Vadose Zone Microbiology

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Fluxes of water, comtaminants, and other nutrients; contaminant type; availability of sediment-associated nutrients; and redox conditions control microbial population density, distribution, and structure. This presentation will provide an overview of the microbiology of the vadose zone below the soil horizons, and the hydrologic and chemical controls on vadose zone microbiology. Important considerations for improving the performance of bioremediation in the vadose zone will also be presented.

H51G-06 1145h

Intra-aggregate Biogeochemical Dynamics of Chromium Contamination and In-situ Remediation

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Transport of redox-sensitive contaminants through the vadose zone is typically complex because of the broad range of transport times and reaction rates encountered over short distances. Multi-region flow and transport models are often used to describe fast advective transport through fractures and macropores, and slower diffusion-dominated transport within sediment blocks and soil aggregates. However, transport and reactions occurring within the diffusion-controlled domains that often make up most of the subsurface are commonly only inferred or assumed. Direct measurements within soil aggregates and sediment blocks are needed to understand biogeochemical processes. This is demonstrated through laboratory studies of chromium contamination of soil aggregates, and subsequent in-situ remediation (reduction of Cr(VI) to Cr(III)) by organic carbon infusion. Spatially resolved determination of Cr concentrations and oxidation states using micro-XANES, and spatially-resolved microbial community analyses were done on synthetic and natural soil aggregates. During the diffusion-limited contamination process, more Cr(VI) was transported, but to shorter distances, in more microbially active aggregates. Sharply terminated diffusion fronts, within 2 to 10 mm of the aggregate surface, result from increasing Cr(VI) reduction rates with depth. Infusion of organic carbon into previous Cr(VI)-contaminated aggregates resulted in more rapid reduction to Cr(III) with higher organic carbon concentrations, and lower reduction rates in more highly contaminated sediments. These results show that intra-aggregate Cr dynamics are strongly diffusion-limited in more microbially active systems, and that bulk soil chemical and microbial characterization can obscure relevant biogeochemical processes.

H52A MC: Hall D Friday 1330h

Environmental Vadose Zone Hydrology *(joint with B)*

Presiding: **T Harter,** University of California, Davis**; M Young,** Desert Research Institute

H52A-0364 1330h POSTER

Assessment of Surrogate Fractured Rock Networks for Evidence of Complex Behavior

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A complex system or complex process is -"one whose properties are not fully explained by an understanding of its component parts". Results from field experiments conducted at the Hell's Half-Acre field site (Arco, Idaho) suggest that the flow of water in an unsaturated, fractured medium exhibits characteristics of a complex process. A series of laboratory studies is underway with sufficient rigor to determine if complex behavior observed in the field is in fact a fundamental characteristic of water flow in unsaturated, fractured media. As an initial step, a series of four duplicate experiments has been performed using an array of bricks to simulate fractured, unsaturated media. The array consisted of 12 limestone blocks cut to uniform size (5cm x 7 cm x 30 cm) stacked on end 4 blocks wide and 3 blocks high with the interfaces between adjacent blocks representing 3 vertical fractures intersecting 2 horizontal fractures. Water was introduced at three point sources on the upper boundary of the model at the top of the vertical fractures. Water was applied under constant flux at a rate below the infiltration capacity of the system, thus maintaining unsaturated flow conditions. Water was collected from the lower boundary via fiberglass wicks at the bottom of each fracture. An automated system acquired and processed water inflow and outflow data and time-lapse photographic data during each of the 72-hour tests.

From these experiments, we see that a few general statements can be made on the overall advance of the wetting front in the surrogate fracture networks. For instance, flow generally converged with depth to the center fracture in the bottom row of bricks. Another observation is that fracture intersections integrate the steady flow in overlying vertical fractures and allow or cause short duration high discharge pulses or "avalanches" of flow to quickly traverse the fracture network below. Smaller scale tests of single fracture and fracture intersections are underway to evaluate a wide array of unit processes that are believed to contribute to complex behavior. Examples of these smaller scale experiments include the role of fracture intersections in integrating a steady inflow to generate giant fluctuations in network discharge; the influence of microbe growth on flow; and the role of geochemistry in alterations of flow paths. Experiments are planned at the meso and field scale to document and understand the controls on self-organized behavior. Modeling is being conducted in parallel with the experiments to understand how simulations can be improved to capture the complexity of fluid flow in fractured rock vadose zones and to make better predictions of contaminant transport.

H52A-0365 1330h POSTER

Unsaturated Flow Through Fractured and Nonwelded Tuff

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