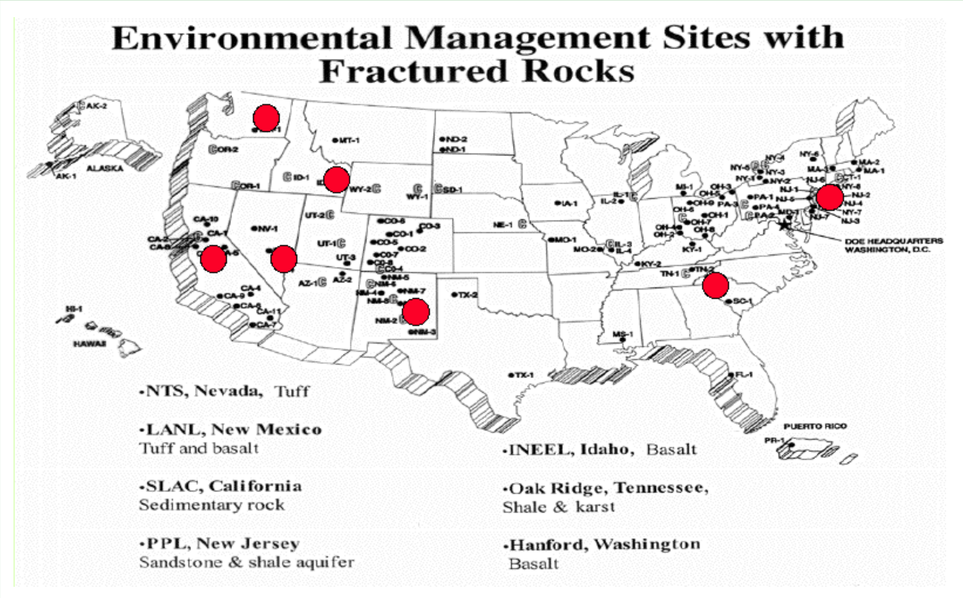
Statement of the Problem



INEEL Fractured Rock Research Needs

To protect human health and the environment, numerous INEEL sites require remediation and long-term monitoring

Contaminants in fractured rock include VOCs and radio nuclides (Cs, Sr, U, Tc)

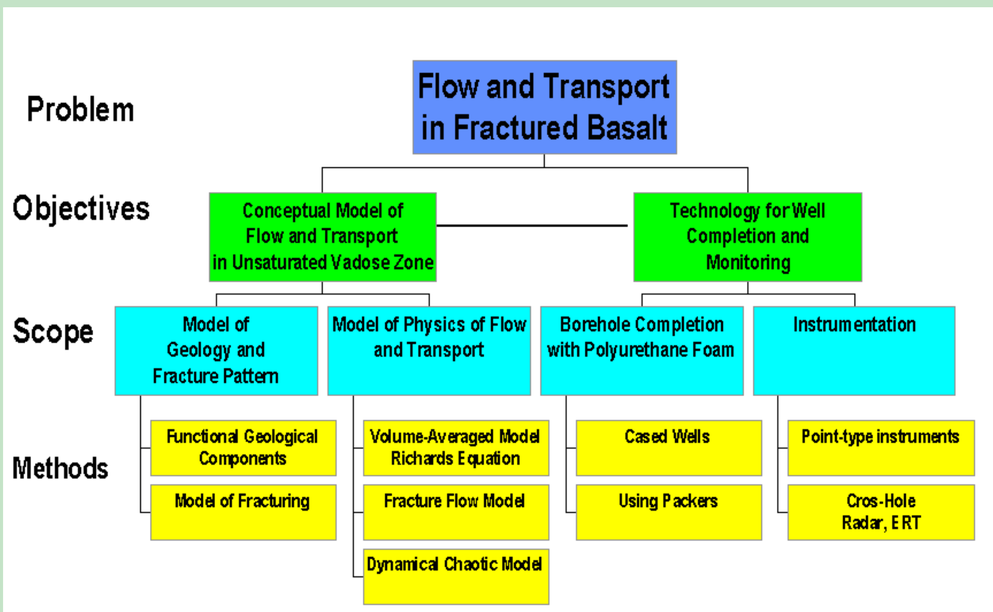
Available characterization and monitoring technologies for fractured rocks are often expensive or inadequate

Baseline Approaches

Porous medium methods, which are designed for homogeneous systems but poorly suited to strongly heterogenous and fractured systems (especially basalt)

Dual-porosity and dual-permeability methods, which are designed for fractured rocks, but their application requires many assumptions if one does not have site-specific characterization

Objectives



Determine if and when dynamical chaos theory can be used to investigate infiltration of fluid and contaminant transport in heterogeneous soils and fractured rocks

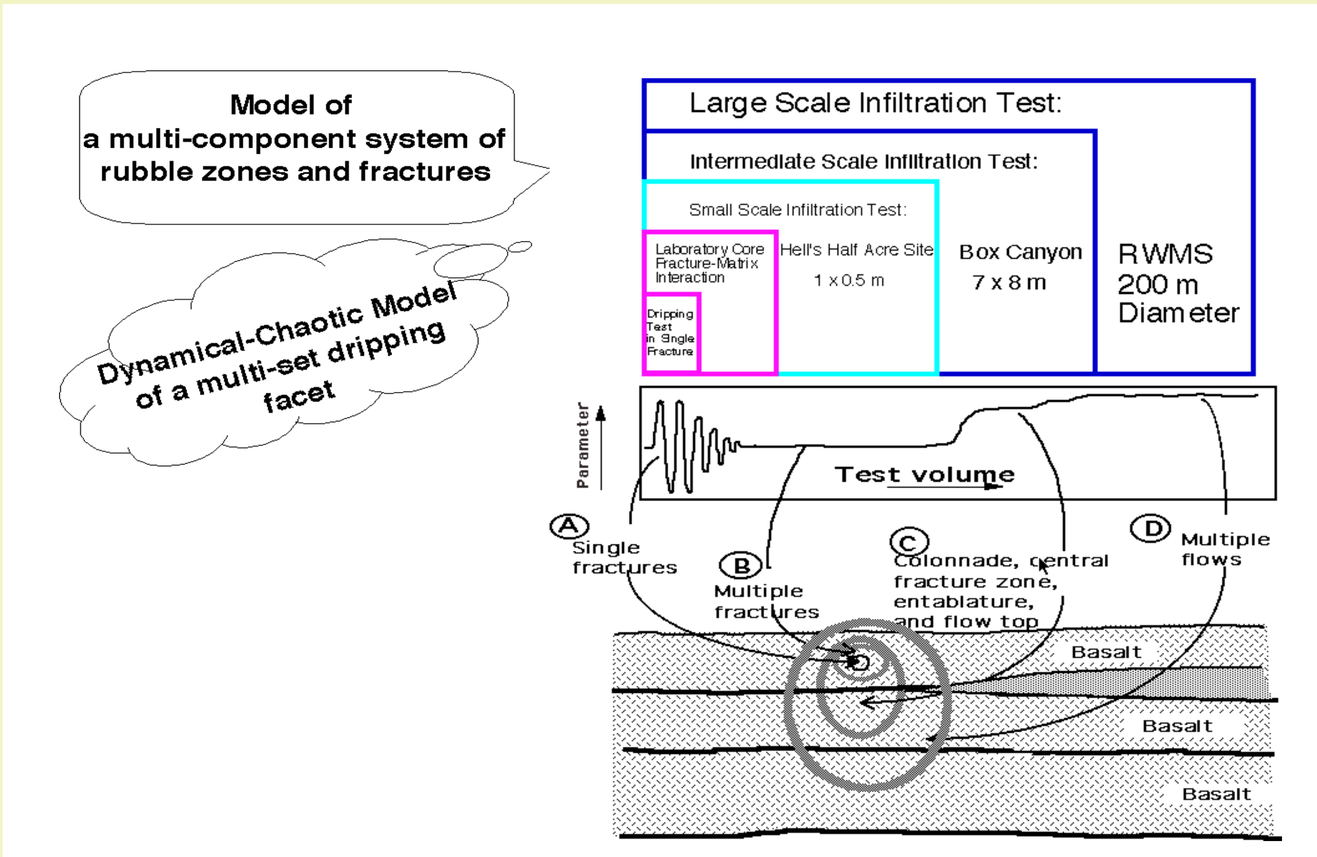
Evaluate chaotic behavior of flow in laboratory and field experiments using methods from nonlinear dynamics

Evaluate the impact these dynamics may have on contaminant transport through heterogeneous fractured rocks and soils, and how it can be used to guide remediation efforts

Develop a conceptual model and mathematical and numerical algorithms for flow and transport, which incorporate both (a) the spatial variability of heterogeneous porous and fractured media, and (b) the description of the temporal dynamics of flow and transport, which may be chaotic

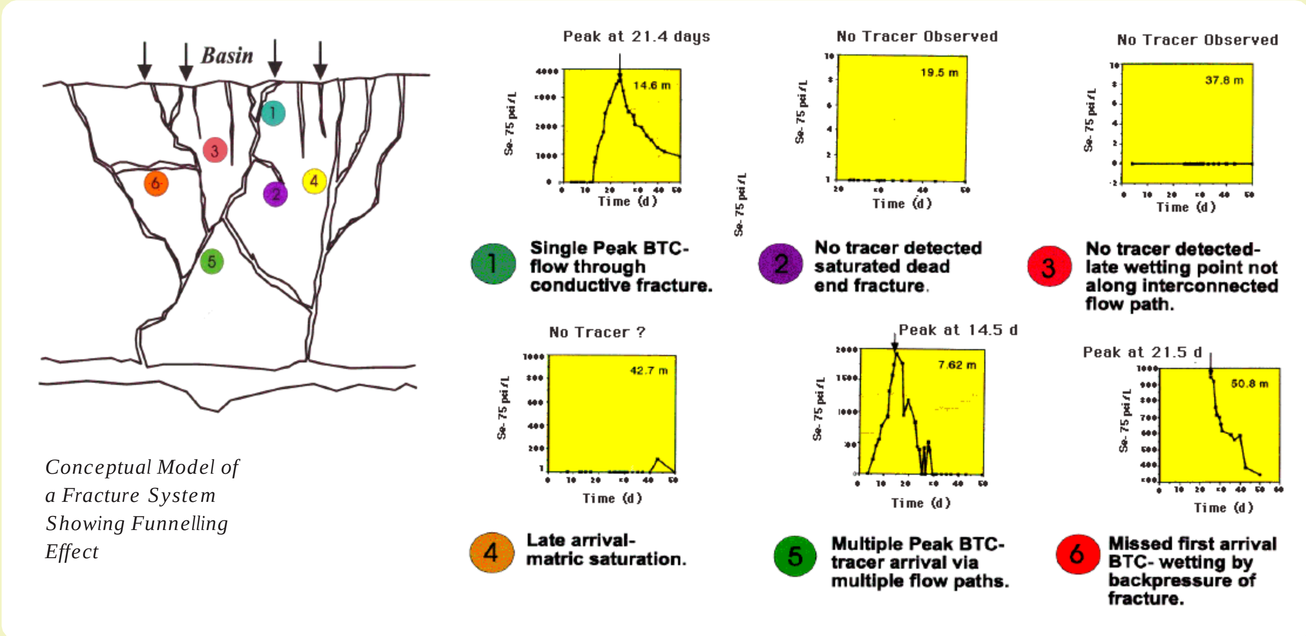
Develop appropriate experimental field and laboratory techniques to detect diagnostic parameters for chaotic behavior of flow

Methods and Results

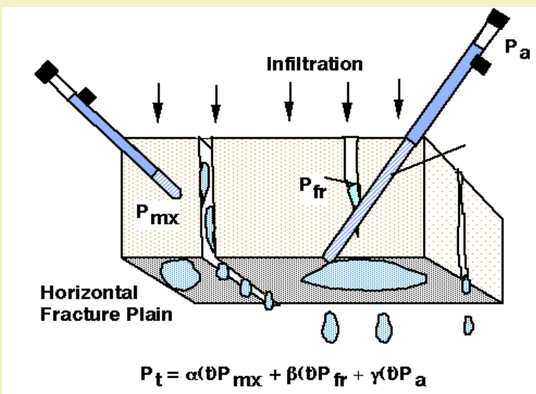


Large-Scale Infiltration Test

Typical Multimodal Breakthrough Curves for Se-75 Observed During the Test



Conceptual Model of a Fracture System Showing Funnelling Effect

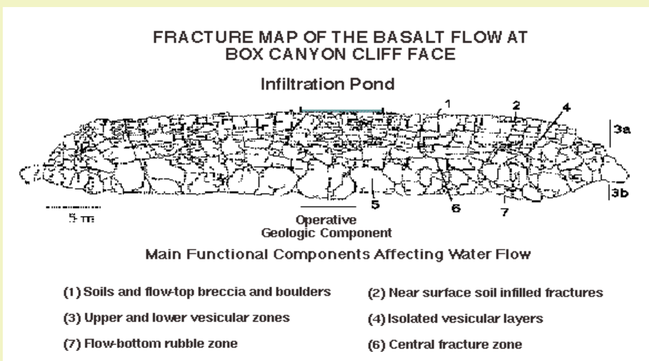


The Tensiometer Gauge Pressure:

Is primarily affected by the water-conducting component that transmits water into or out of the ceramic cup of the tensiometer:

During drying -- by matrix pressure, and
During wetting -- by fracture pressure

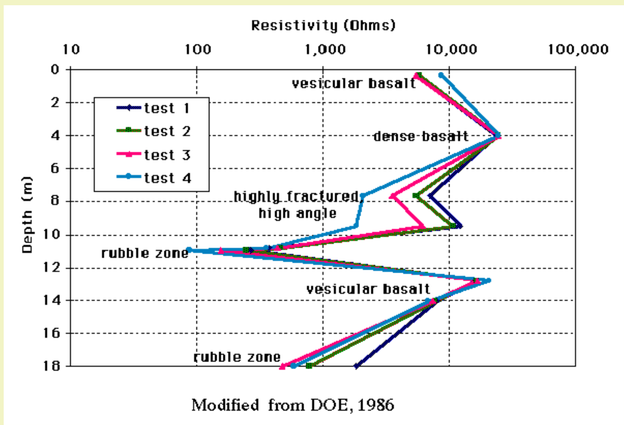
Intermediate-Scale Ponded Infiltration Tests in Fractured Basalt at Box Canyon Site



Fractured Basalt:

Is highly heterogeneous with localized fast flow paths

Has nonconductive fractures and matrix where contaminants are accumulated

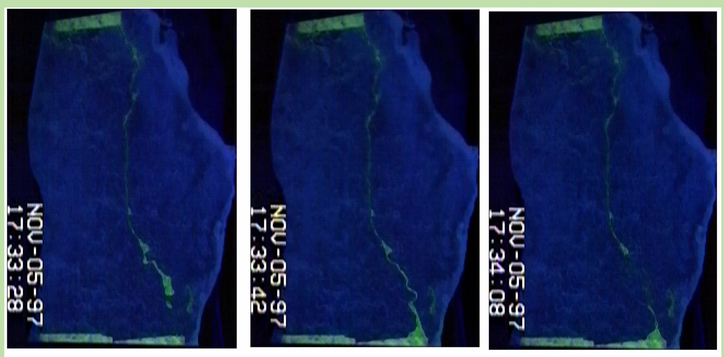


Depth profiles of time averaged resistivity in well II-5 during pulsed infiltration tests showing that the tracer appeared mostly within the fractured zones

Laboratory Investigations of Water Dripping Phenomenon

Water Seepage in a Fractured Basalt Replica

We investigate dripping water between parallel plates as a model of water seepage through fractured rock and look for the existence of a chaotic component of such flow. This can be viewed as an extension of the classic chaos experiments with the "dripping faucet" (Shaw, 1984) to drips in the presence of capillary forces as they are affected by the surface properties and the small aperture of the parallel plates.

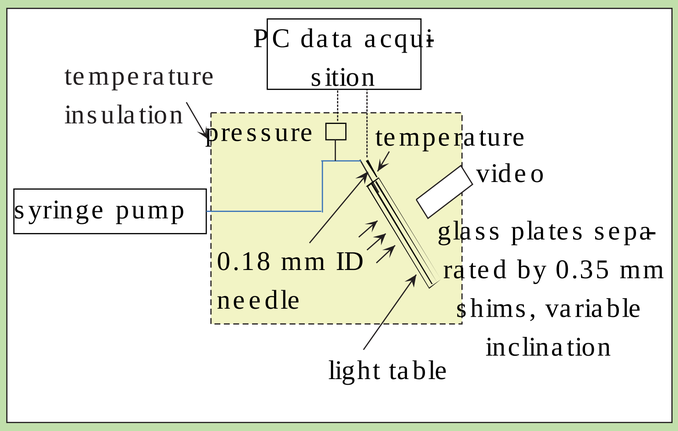


Water seepage through a dense basalt fracture is visualized by mating the fracture with a transparent replica of the other fracture half, dyeing the water with a fluorescent dye and illuminating with near-UV light.

Time-varying water seepage in fractures undergoes channeling during a cycle of filling and draining.

While deterministic numerical models with stochastically distributed soil properties can describe the general spatial features of liquid distribution, they do not describe intermittent flow, which can significantly affect predictions of solute travel-time and solute-solid interaction.

Design of Water Dripping Experiments



A constant flow rate of water to a needle emplaced between parallel glass plates of sub-millimeter separation.

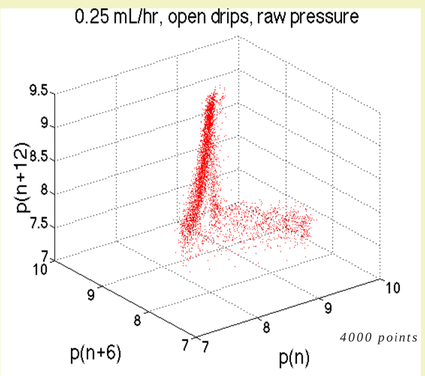
Pressure responds to the formation and release of drips from the needle, verified by video photography.

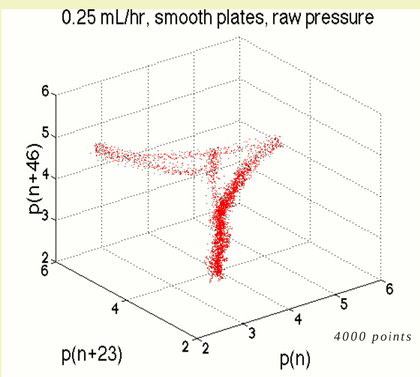
The time-trend of the pressure is measured for a range of flow rates and surface texture of the glass plates.

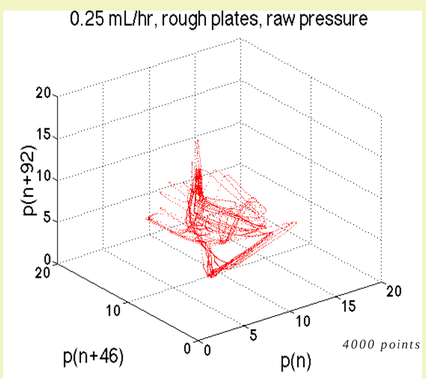
Effect of Capillarity on Attractor

The presence of chaos in the dripping data is characterized with phase-space plots for the raw pressure measurements, and the times between drips.

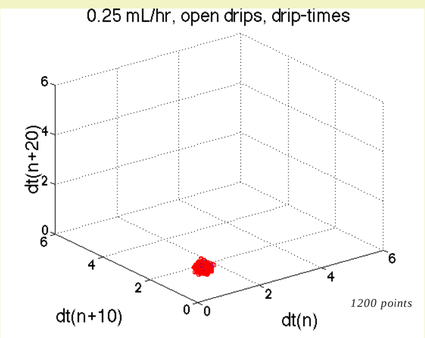
Pressure data. Attractors using the pressure data for the open drip , smooth plates, and rough plate conditions for 0.25 mL/hr show an increased deterministic-chaotic component as the flow regime becomes more complex.

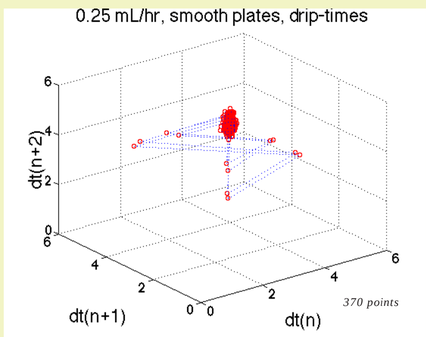


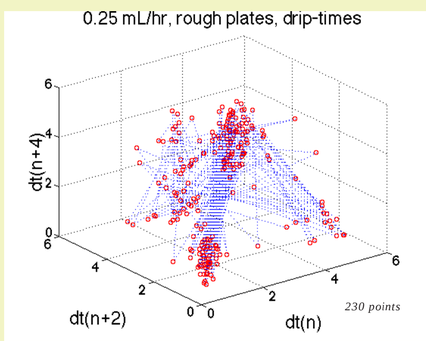




Drip-time data. The attractors using the times between drips reveal a similar trend.

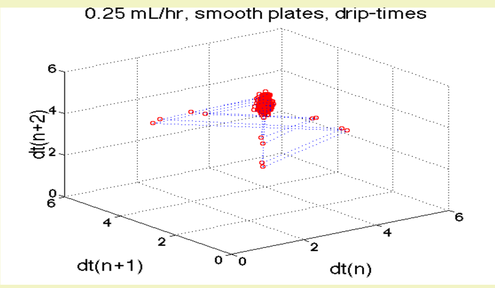


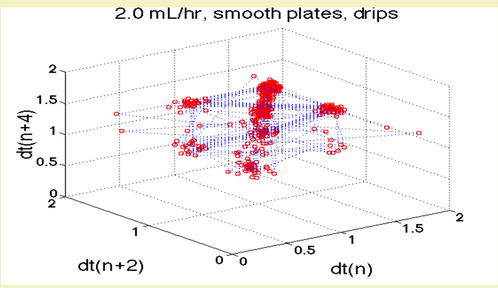


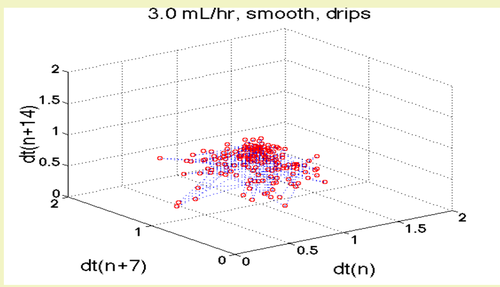


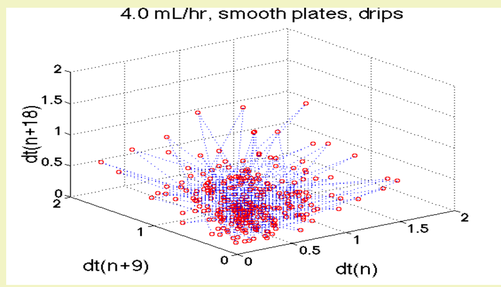
Effect of Flow Rate in Smooth Plates on Attractor of Pressure Data

Drip-time data. At higher flow rates in the smooth plates, the drip-time attractors suggest a trend towards random behavior



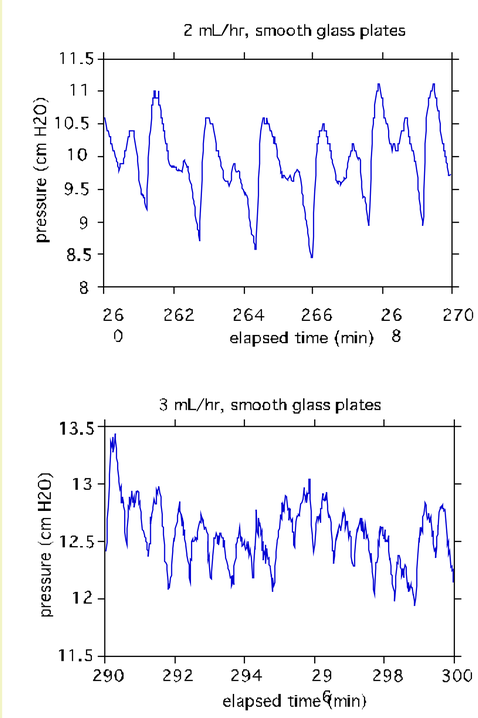






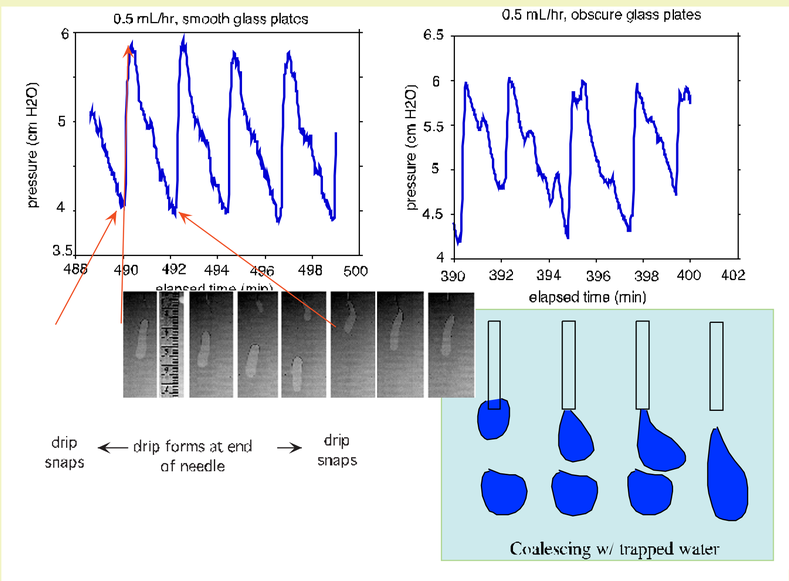
Results of Experimental Observations

Water Seepage in Parallel Plates as a Function of Flow Rate



As flow rates increase, the frequency of dripping increases, and the pressure signal has more peaks per drip.

Effect of Glass Plate Texture on Water Drips



The water thread snaps in the smooth plates when the weight of the water drop overcomes the capillary forces due to the presence of the small aperture.

In the rough plates, the drop merges with residual water in the region of the needle, generating a longer drop that overcomes the capillary forces and flows down the plates, as shown in the cartoon.

Summary

The observed relationship between the measured pressure and flow behavior allows us to identify how various features (capillarity, surface roughness, and flow rate) of the fracture models contribute to chaotic or random behavior.

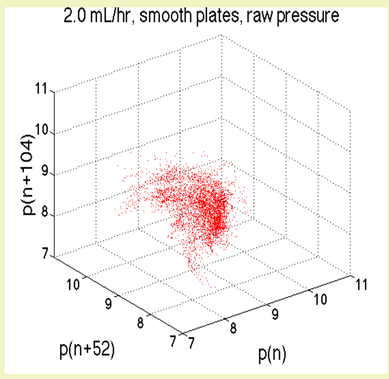
The dripping needle into open space is a physical analog to observed water drips from fractures into larger openings. Capillarity combined with gravity introduce a deterministic chaotic component that becomes more stochastic as the flow rate increases and surface roughness appears.

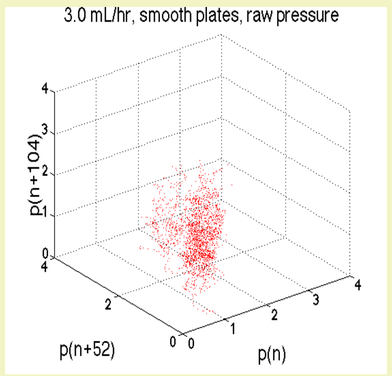
The pressure fluctuations are mostly controlled by the dripping phenomenon. At higher flowrates, the random component is introduced as the lower frequency oscillations increases.

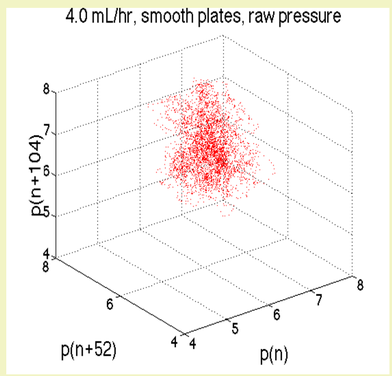
The detailed investigation of pressure and dripping phenomena reveals the contributions of the different physical processes affecting flow behavior that may ultimately be used to understand flow behavior in small-field experiments.

Pressure data. The difference in the attractors for the raw and filtered data shows the contribution of the low frequency oscillations (not due to dripping). Filtering the data "condenses" the attractor and leaves only the effect of dripping. The loss of structure with increasing flow rate indicates an increase in the stochastic component of flow.

Raw Data



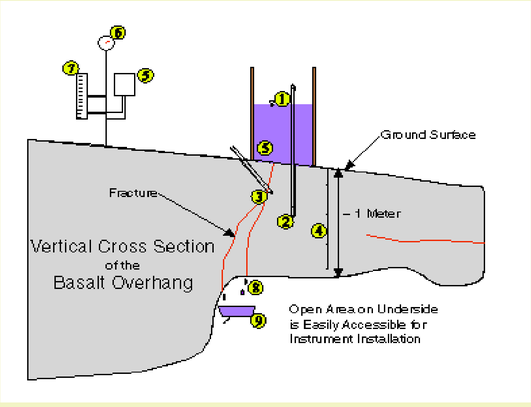




Methods and Results

Small-Scale Infiltration Test at Hell's Half Acre Site

Test Design and How It is Useful



1. HEAD AND INFILTRATION RATE AND/OR INFLOW RATES-- Mass balance of the system, Boundary conditions for modeling efforts, determining temporary variations in flow/infiltration.

2. BASALT MATRIX WATER PRESSURE -- Examine wetting front propagation and volume of water imbibed into matrix, aid in determination of mass balance, examine drain-out of matrix following testing.

3. FRACTURE WATER PRESSUR -- Define head field around matrix blocks, examine pressure propagation through system, aid in mass balance calculations, compare with laboratory experiments.

4. BASALT TEMPERATURE -- Determine flue viscosities, examine thermal gradients in basalt matrix, examine any thermal effects of flowpaths.

5. AIR AND WATER TEMPERATURES-- Determine fluid viscosities, use as background for instrument corrections, examine thermal effects on flow.

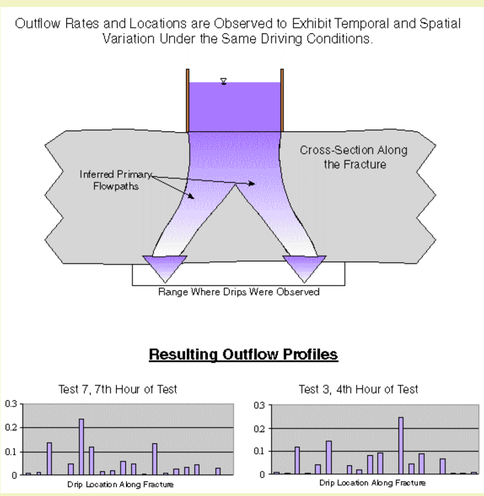
6. BAROMETRIC PRESSUR -- Determine boundary conditions, examine pressure relationships between the air phase and liquid phase, calculate instrument efficiency.

7. PRECIPITATION -- Provide background values for mass balance calculations, determine larger scale head/moisture fields at the research site.

8. OUTFLOW DRIP INTERVAS -- Examine with high resolution the temporal and spatial variability of fracture outflow, provide detailed time series data for chaotic analysis, compare with laboratory experiments.

9. OUTFLOW RATES ALONG FRACTURE-- Examine temporal and spatial variation of outflow, determine mass balance of the system.

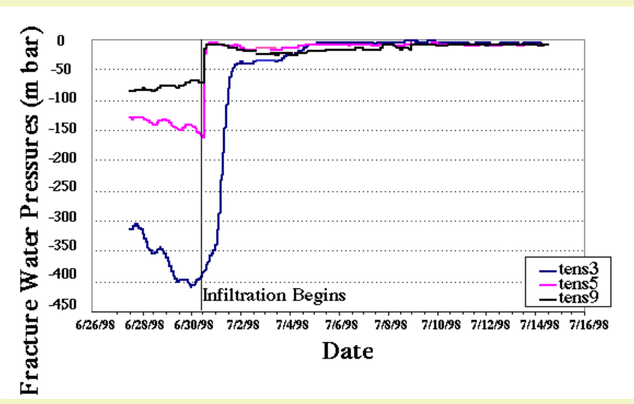
Flow Path Observations



One-hour time slices of fracture outflow as measured by drip sensors positioned along the express of the fracture. The bars are normalized to the relative fraction of the total outflow that was observed at a particu lar location along approximately 1.5 m of the fracture. Under the same driving head in the infiltration gallery and similar fracture and waster pressures, the fraction of the outflow is observed to vary temporally and spatially. The investigation of this phenomenon is ongoing.

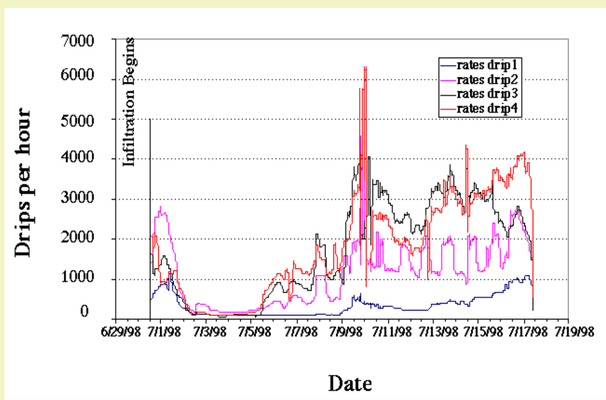
Outcrop Research Results

Fracture Water Pressures



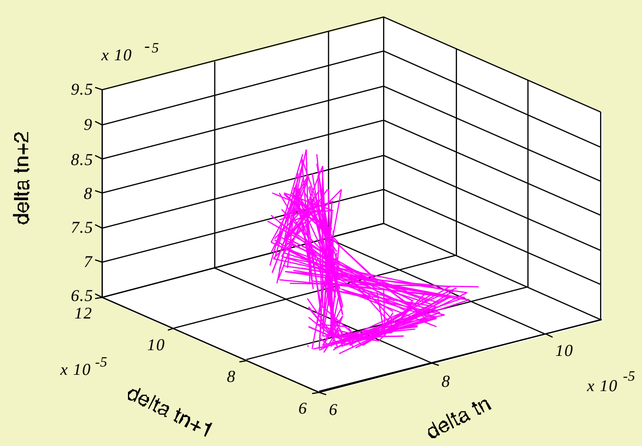
Fracture water pressure was affected rapidly by filtering water and remained practially constant thereafter

Drip Outflow



Drip outflow rate exhibits a three-stage temporal behavior, as was previously observed in soils with entrapped air (Faybishenko, 1995).

3D Attractor of Water Dripping From a Fracture



t is time between drips

Conclusions

Ponded infiltration tests were conducted at two fractured rock field sites: the Hell's Half Acre (the scale of 1 x 0.5 m) and the Box Canyon (scale of 7 c 8 m) sites. A new discovery coming from the field experiments is the temporary and spatial instability of water flow affecting in rock permeability.

Several new technologies have been developed including piezoelectric probes, a leak detection system, a laser surveying system, and a 3D Electrical Resistivity Tomography system.

TOUGH2 numerical modeling with a hierarchical pattern of column-bounding and column-normal fractures confirmed the presence of complex, irregular flow paths for liquid-phase tracer, as well as air trapping and escaping in the vadose zone.

Laboratory experiments showed the presence of chaotic behavior in water seepage through fracture models, and the pervasiveness of highly localized and extremely nonuniform flow paths in the plane of the fracture.

The magnitude of deterministic-chaotic and stochastic components in the data was analyzed using a set of nonlinear dynamical parameters such as Hurst exponent, Lyapunov exponent, capacity dimension, correlation dimension, information dimension, correlation time, and constructed and three-dimensional attractors in phase-space.

Ongoing theoretical studies have shown that as a fluid film flows vertically on a fracture surface, it is inherently unstable and may exhibit chaotic behavior, even for low Reynold's numbers. Film waviness may enhance transfer of contaminants from rock to fluid by as much as five times, carrying contaminated fluid down a fracture much faster than expected by classical flat film theory.

Planned Activities for 1998-99

Additional field and laboratory experiments will be performed to examine the fracture/matrix interactions. Instrument a new HHA site.

Data will be analyzed from DOE sites (INEEL, Hanford, LBNL, LLNL, and others).

Reports will be written and made available to the environmental community at large. Papers will be submitted to Water Resources Research and Groundwater journals.

The methodology developed will be recommended to DOE sites where monitoring and remediation of contaminants using vacuum extraction, air stripping, steam injection, barriers, etc., are problems .

The Scientific Significance of the Vadose Zone Research for DOE

The development of a unique nonlinear-dynamics method for data sets such as fracture and matrix flow rates, pressure, and tracer concentrations.

The results of this project are expected to change the current approach used by industry to predict flow and transport in environmental systems.

Because the nonlinearity of environmental systems limits their predictability, we aim to determine how far into the future it is realistic to predict the state of the environmental system, and determine the bounds for contaminant transport. This information will be used to design remediation efforts.

The significance of the research for the DOE will be in the form of technology developed for vadose zone monitoring and in improved vadose zone site characterization and predictability.

Applications for Site Engineering Remediation and Characterization

Fate and transport modeling.

Risk assessment under CERCLA, and performance assessment per NRC regulations.

Enhanced decontamination of soils using vacuum extraction and groundwater treatment using a modified pump-and-treat approach.

Ongoing and potential applications at INEEL, LBNL, Yucca Mountain, Hanford, and Apache Leap Site .

Publications

Faybishenko, B. et al., A Chaotic-Dynamical Conceptual Model to Describe Fluid Flow and Contaminant transport in a Fractured Vadose Zone, in Environmental Management Science Program Awards Fiscal Year 1997 Annual Report Progress, Lawrence Berkeley National Laboratory Report, LBNL-41192. 1997

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Finsterle, S., and B. Faybishenko, What does a tensiometer measure in fractured rocks?, LBNL Report-41454, 1998; to be published in Proceedings of the International Conference "Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media" held in Riverside, CA, October, 1997.

Podgorney, R. K. et al., Basalt Outcrop Infiltration Tests to Evaluate Chaotic Behavior of Unsaturated Flow in Fractured Rock, Data Summary Report--1997 Field Season, Idaho National Engineering and Environmental Laboratory, 1998.

Pruess, K., B.Faybishneko, and G.S.Bodvarsson, Alternative concepts and approaches for modeling flow and transport in thick unsaturated zones of fractured rocks, J. Contaminant Hydrol, submitted 1998.

Acknowledgments:

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Data Set Access:

FTP//Zenith.lbl.gov/pub/chaos