U.S. Department of Energy
Office of Civilian Radioactive Waste Management

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Unsaturated Zone Flow and Transport: Conceptual Models and Independent Lines of Evidence

Presented to:
U.S. Nuclear Waste Technical Review Board Panel on the Natural System

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Outline

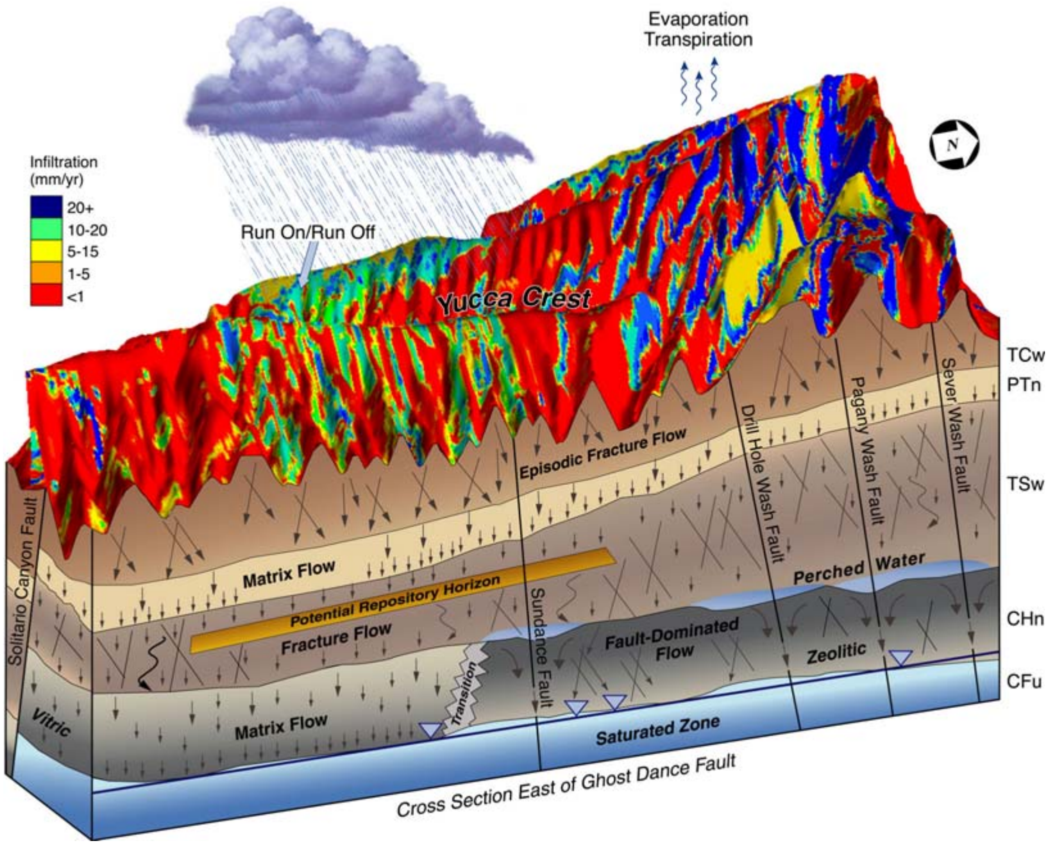
- Future climate projections
- Percolation and runoff for net infiltration
- Representation of geology for unsaturated zone (UZ) modeling
- Representing flow and transport in a fractured rock
- Flow in unsaturated fractures
- Episodic transient flow; fast flow paths
- Large-scale lateral flow

Outline
(Continued)

- Matrix-dominated flow in the CHnv
- Matrix diffusion
- Radionuclide source term; drift shadow concept
- Transport time of a passive tracer
- Conclusions

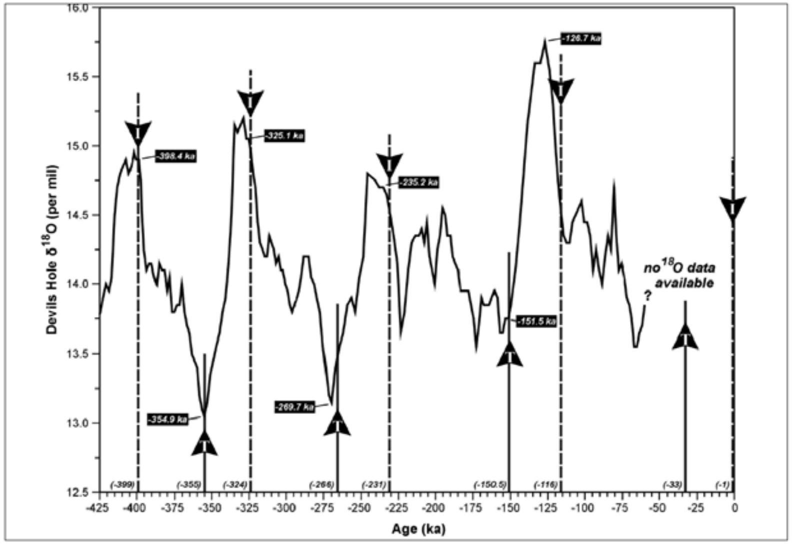
Processes for Unsaturated Zone Flow

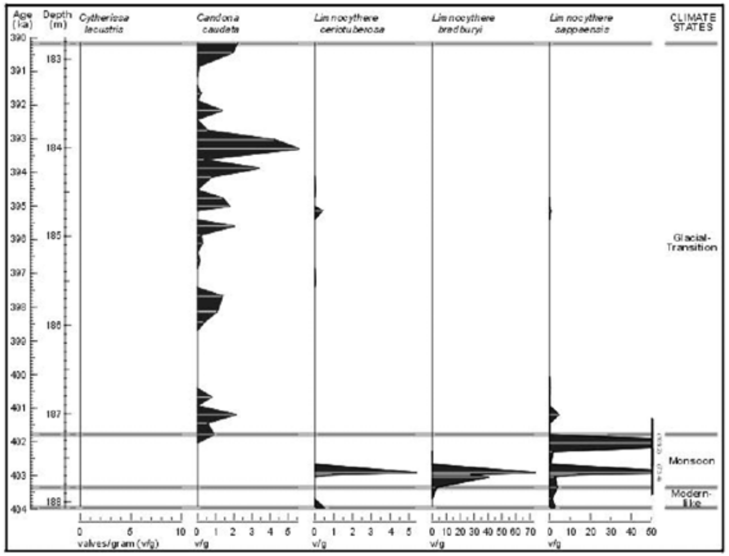
- Climate
- Infiltration
- Flow in fractured rock
- Lateral flow
- Perched water
- Fault flow



Future Climate Projections

- Climate projections are based on the concept of climate cycles
  - Climate cycles recorded at Devils Hole have been correlated to earth orbital patterns
  - Specifications for the climate periods anticipated over the next 10,000 years are derived from ostracod species stratigraphic distribution from Owens Lake and other fossil records





Future Climate Projections

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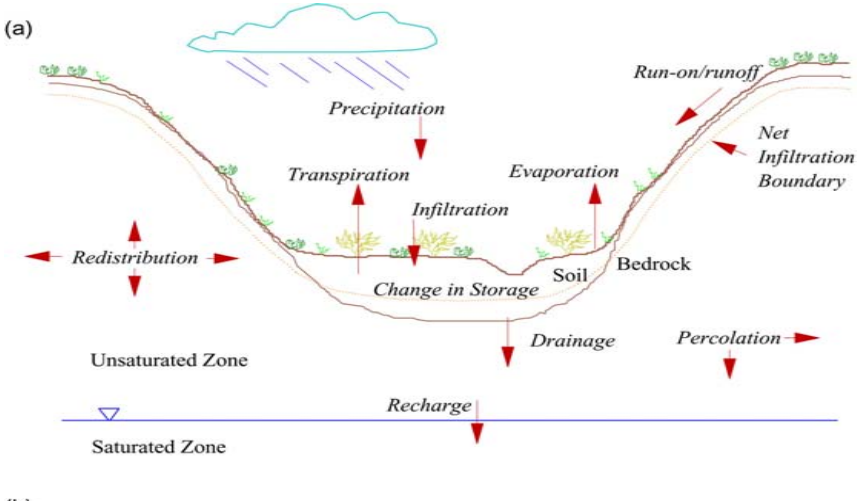
Figure 15. Meteorological Stations Selected (Table 2) to Represent Future Climate States at Yucca Mountain, Nevada

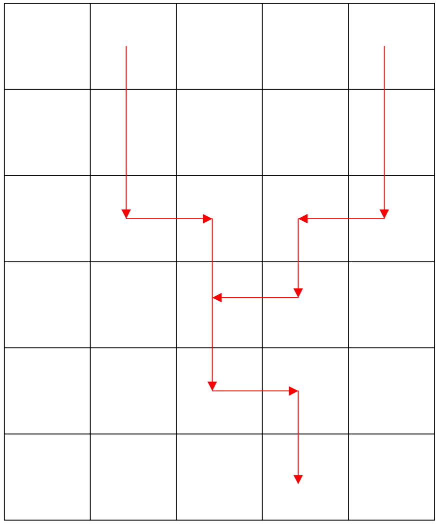
Temperature and precipitation ranges associated with the Owens Lake data are used to select analog climate sites to represent future climates.

The lower and upper bound climate analogs define climate uncertainty propagated into infiltration, UZ flow, and UZ transport.

Percolation and Runoff for Net Infiltration

- Net infiltration is treated using a water balance model
- Percolation treated as a vertical, piston flow process
- Runoff patterns treated as a geometric process; active channels saturated for fixed durations based on runoff observations

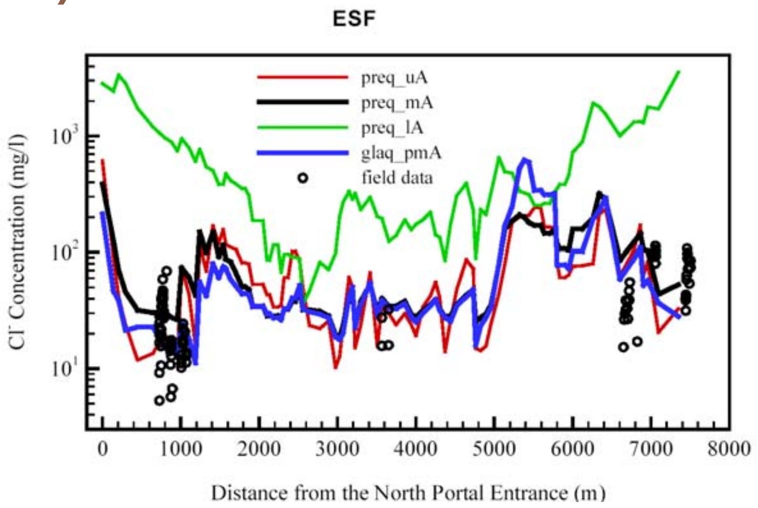


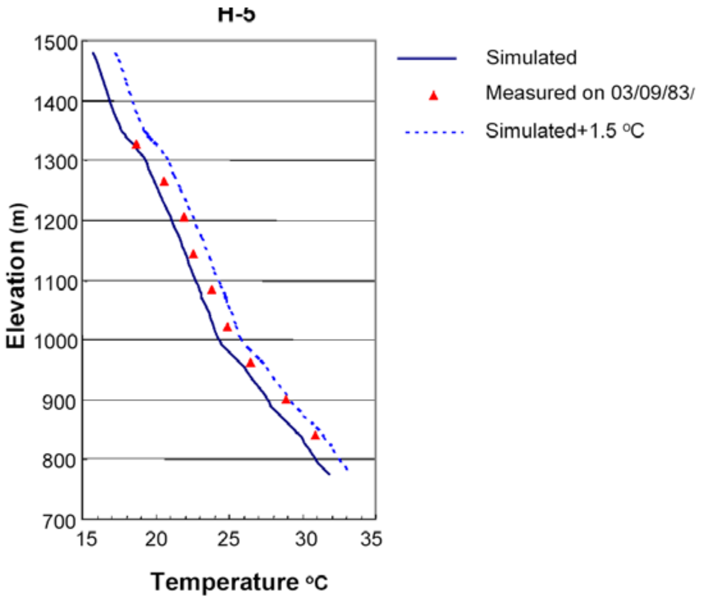


Percolation and Runoff for Net Infiltration

(Continued)

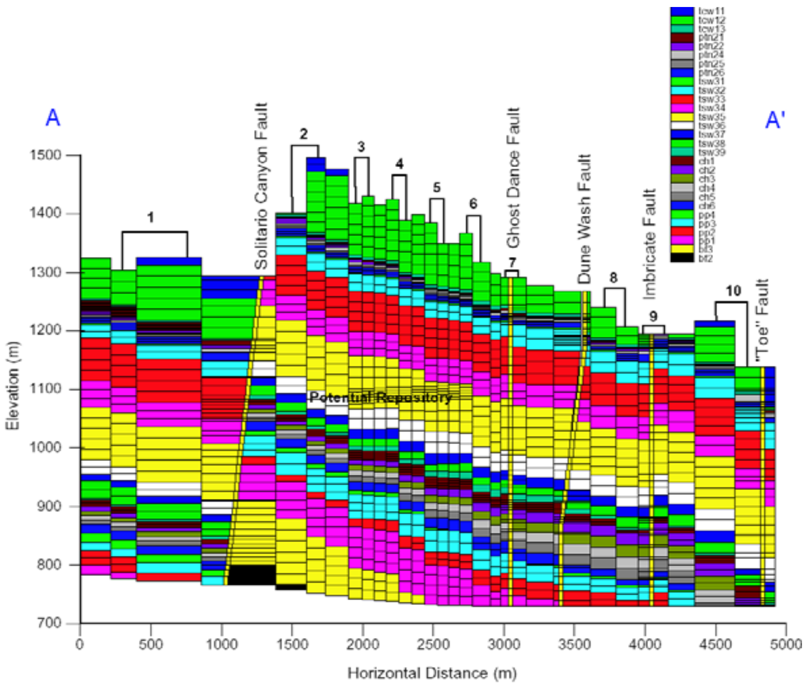
- **Average present-day net infiltration ranges from approximately 1 to 11 mm/yr, with an expected value of about 4 mm/yr**
  - **Comparisons with chloride concentrations in the Exploratory Studies Facility (ESF) and temperatures profiles predicted by the UZ flow model support the infiltration models results**
  - **Additional evidence from isotopic data, secondary calcite deposition, and saturated zone chloride data support the range of predicted infiltration**

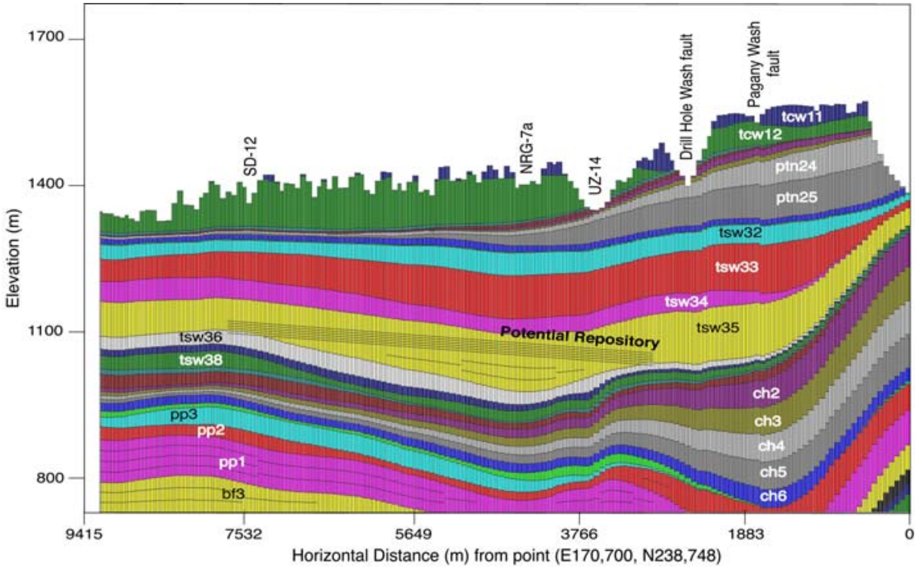




Hydrogeologic Variability and Structure

- **Geology defined by:**
  - **Extensive surface mapping and trench studies**
  - **Stratigraphy of tuff layers from over 60 deep boreholes and more than 10 km of tunnels**





This information, combined with detailed hydrologic measurements, has resulted in 32 hydrogeologic units; properties within units are homogeneous, except for zeolitic alteration.

Hydrogeologic Variability and Structure

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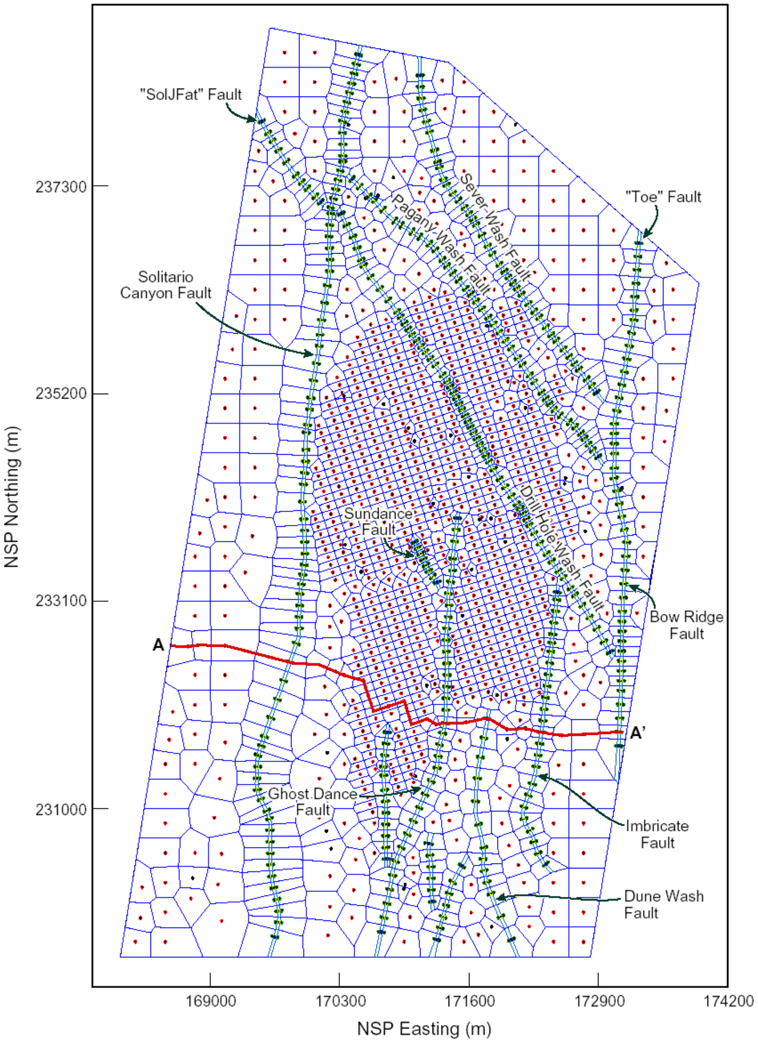
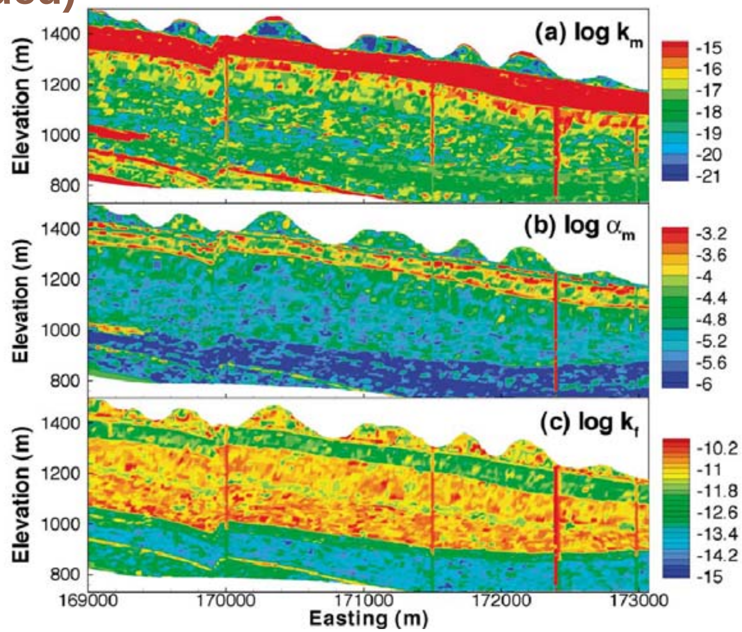


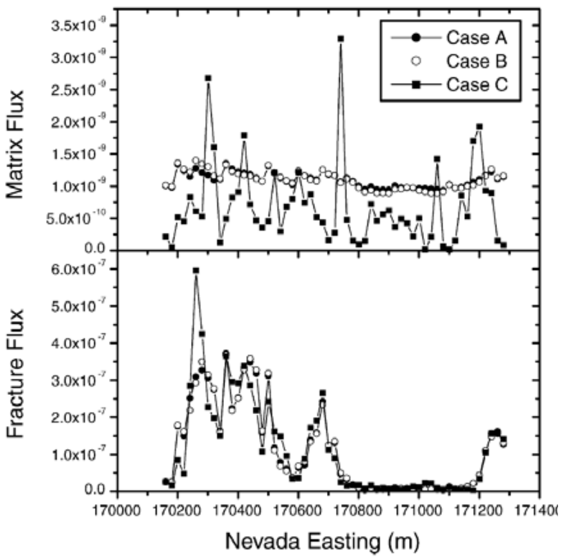
- Major faults are included as vertical or inclined discrete features
- Vertical grid dimension ranges from 1 to 20 m; 5 m in the repository
- Horizontal grid dimensions in the repository are on the order of 100 m
- Grid sensitivity studies varying grid dimensions by a factor of 4 resulted in variations in transport times of 10 to 20 percent

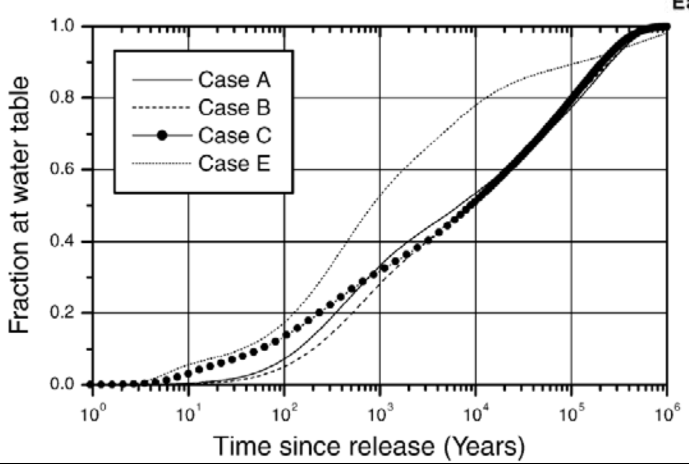
Hydrogeologic Variability and Structure

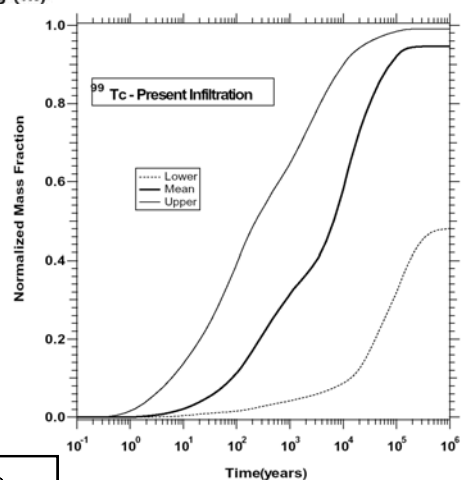
(Continued)

- **Finer-scale 2-D cross-sectional model**
- **Heterogeneity in k_f, k_m, and α_m within hydrogeologic units investigated**





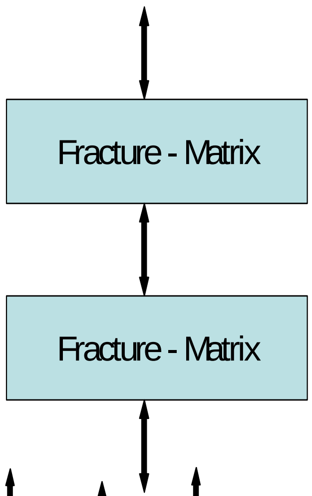




The data shown in these figures are based on a model that is appropriately conservative for TSPA analyses and not intended to represent expected breakthrough of radionuclides or groundwater travel time for unsaturated zone portion of the Yucca Mountain flow system.

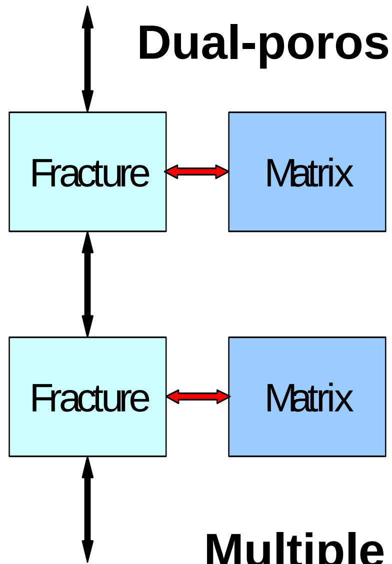
Representing Flow and Transport in Fractured Rock

Equivalent continuum



Capillary disequilibrium expected due to low permeability and unsaturated conditions of matrix. Perched and pore waters appear to be in chemical disequilibrium.

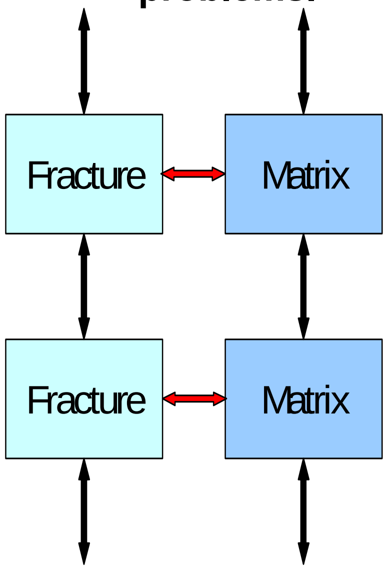
Dual-porosity



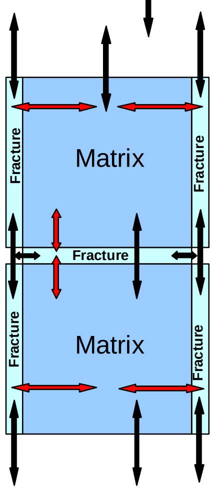
Matrix permeability indicates that global flow will occur, and in some units dominate

Dual-permeability

Captures main features of problem. Underestimates f-m interaction for transient problems.

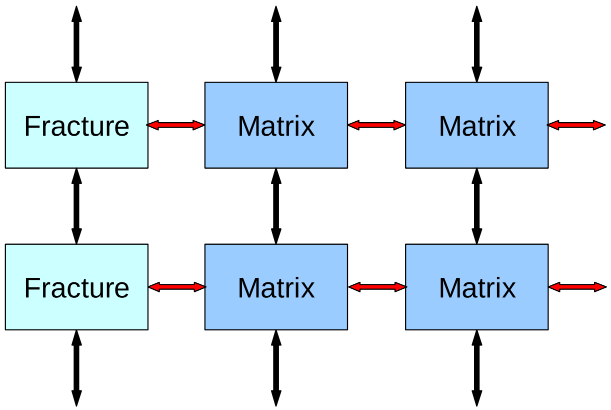


Discrete fracture



Density of fracturing relative to the scale of the problem suggests that a continuum approach is appropriate.

Multiple interacting continua

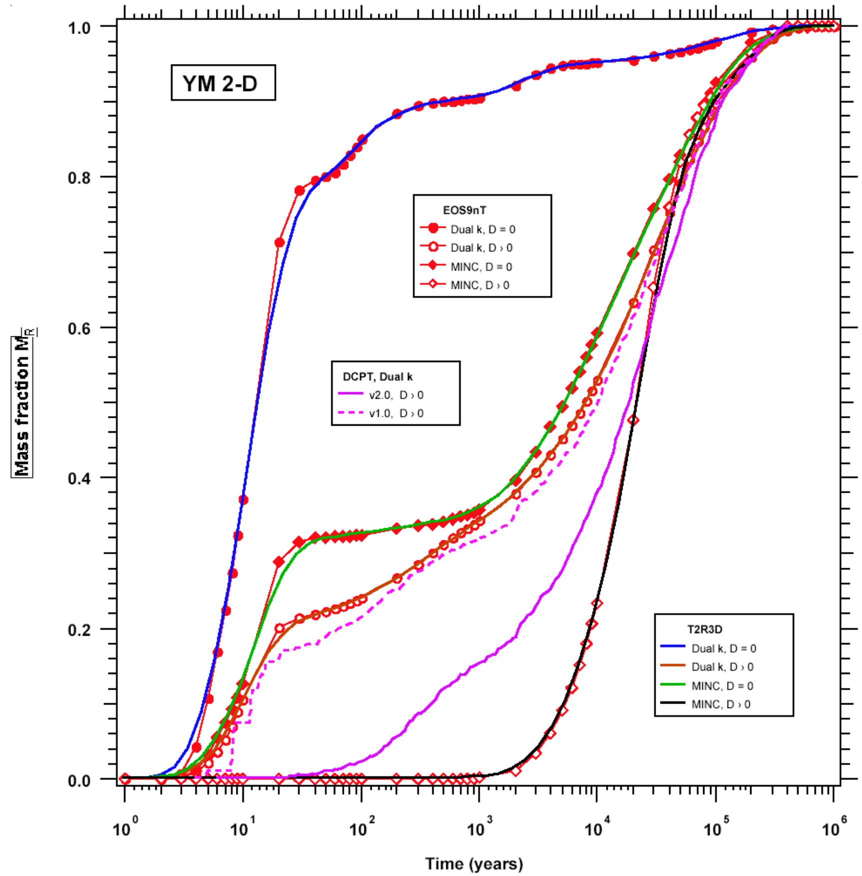


Multiple interacting continua (MINC) not expected to be significant for steady-flow, but may be important for transport.

Representing Flow and Transport in Fractured Rock

(Continued)

- **MINC method shown to result in slower transport as compared with dual-permeability. The true differences may not be as pronounced because:**
  - **MINC model not calibrated**
  - **Differences tend to be exaggerated in 2-D as compared with 3-D**



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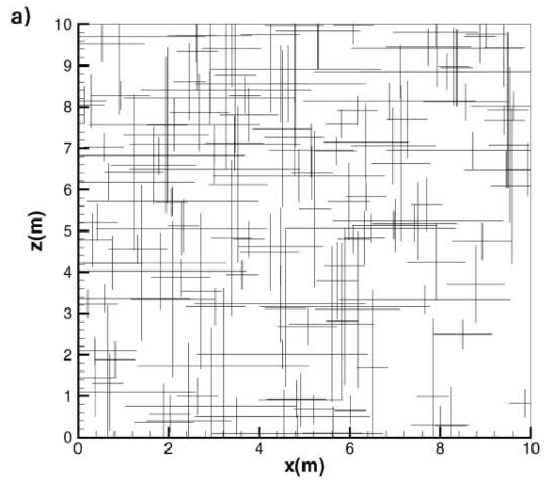
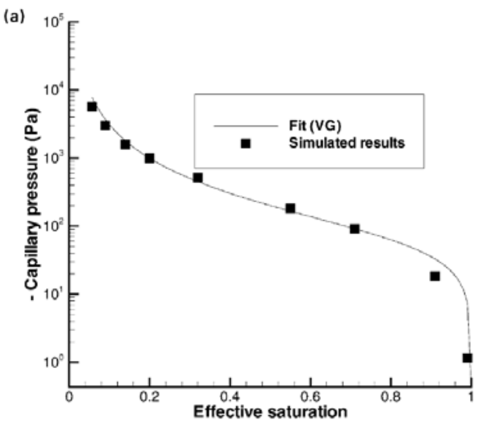
Flow in Unsaturated Fractures

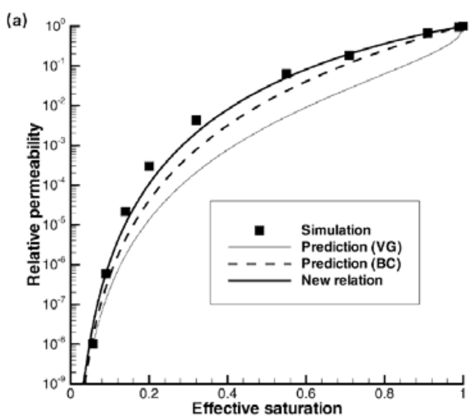
Small-scale discrete fracture network models have been used to investigate Darcy flow models for fractures.



Capillary pressure in the fractures match the van Genuchten model.

Relative permeability predictions found to be lower in general, but match well at low saturations.





Flow in Unsaturated Fractures
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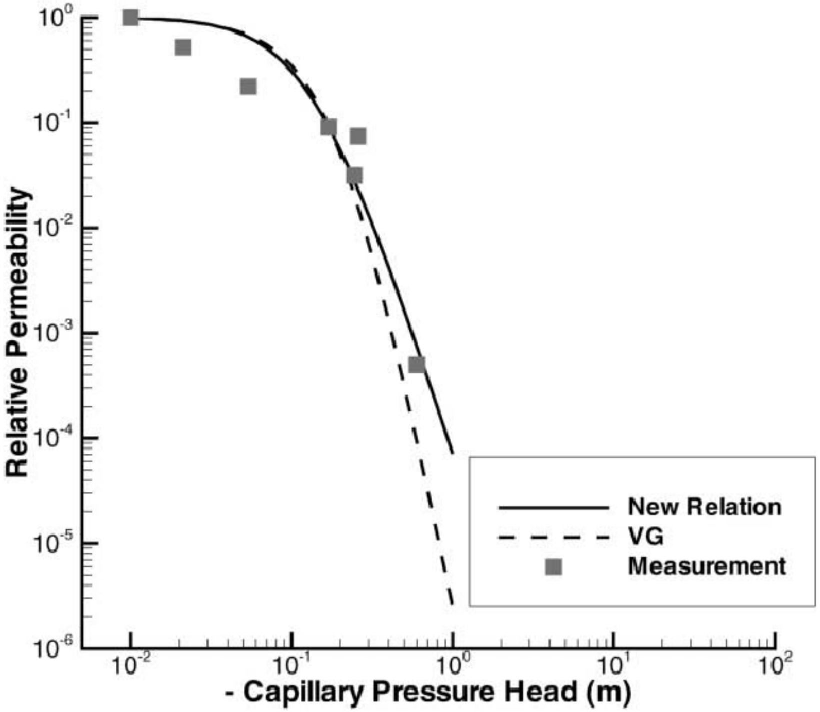


Small-scale field tests were conducted with a disk infiltrometer to investigate fracture capillary pressure-relative permeability characteristics.

Note that the test data is limited to higher saturations.

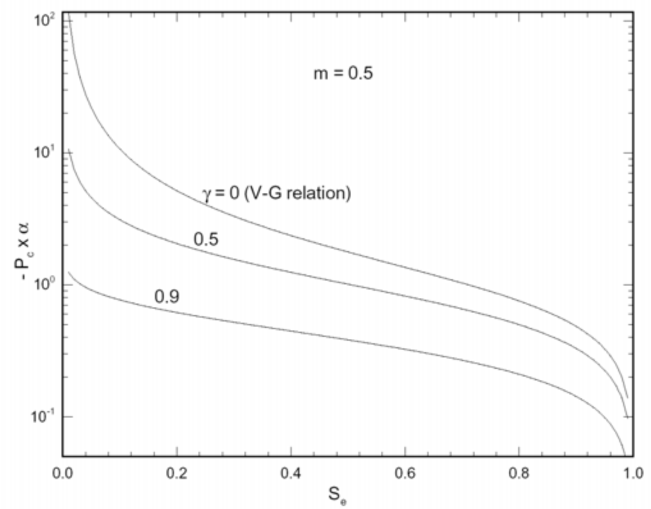
Effects of Flow Focusing in a Fracture Network

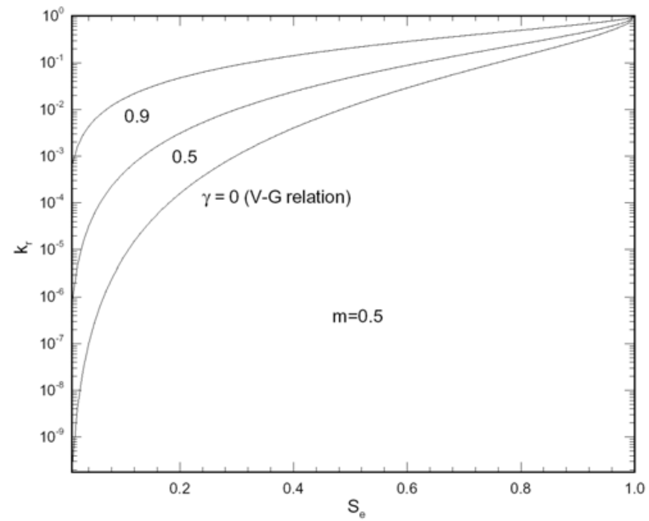
Preferential flow in single fractures and fracture networks has been observed in laboratory tests and field tests.

To account for this phenomenon, the van Genuchten model for fractures was modified using the active fracture model.

Active fracture hypothesis

$$f_a = S_e^{\gamma}$$





Effects of Flow Focusing in a Fracture Network

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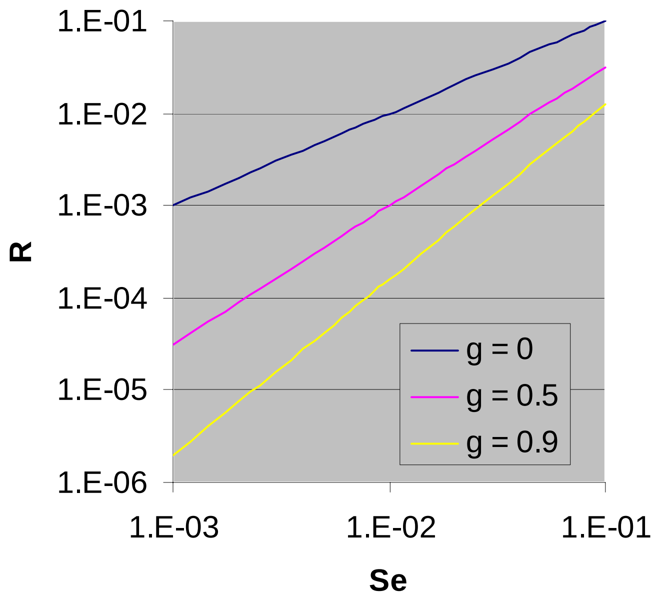
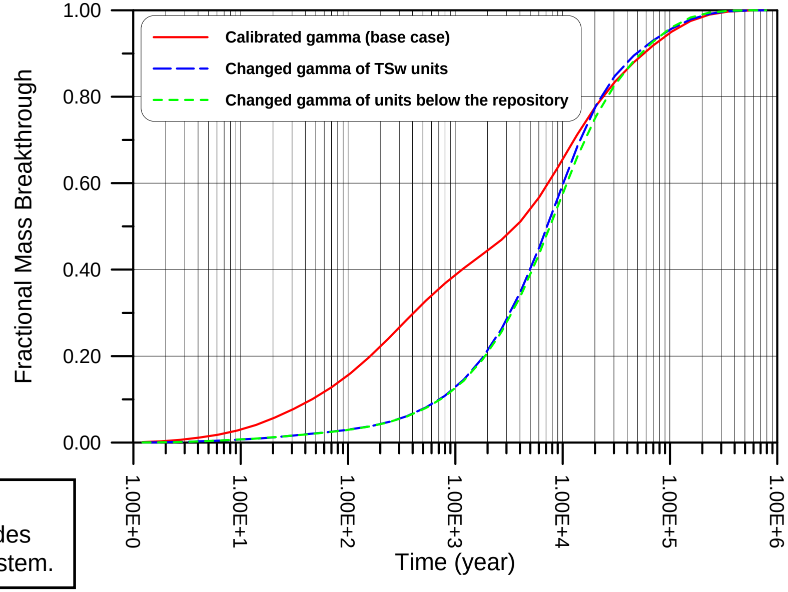


- The active fracture model introduces a fracture-matrix interaction factor, R, that accounts for:
  - Wetted fracture-matrix interface area
  - Flowing fracture spacing
- Radionuclide transport sensitivity analyses show significant effects of the active-fracture parameter



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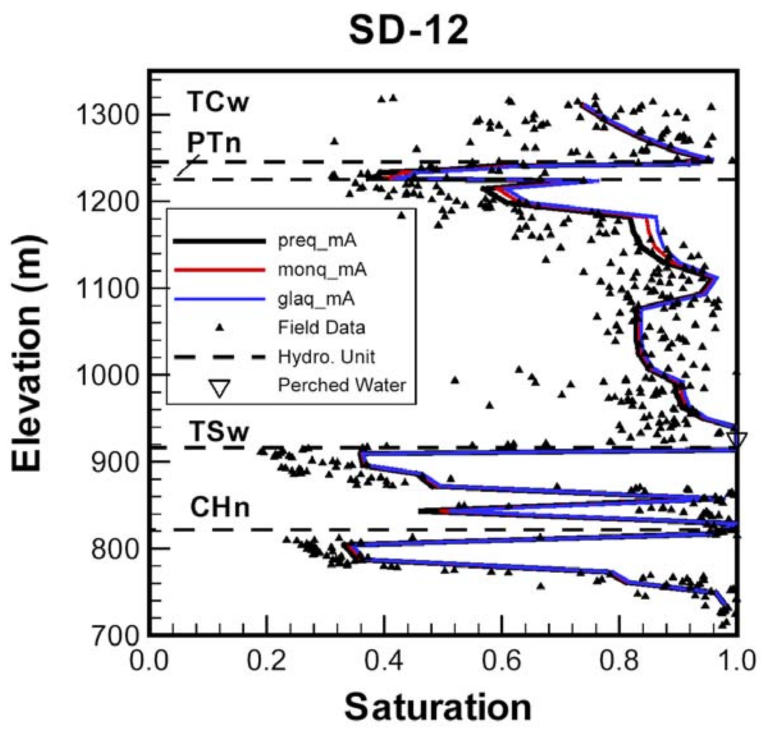
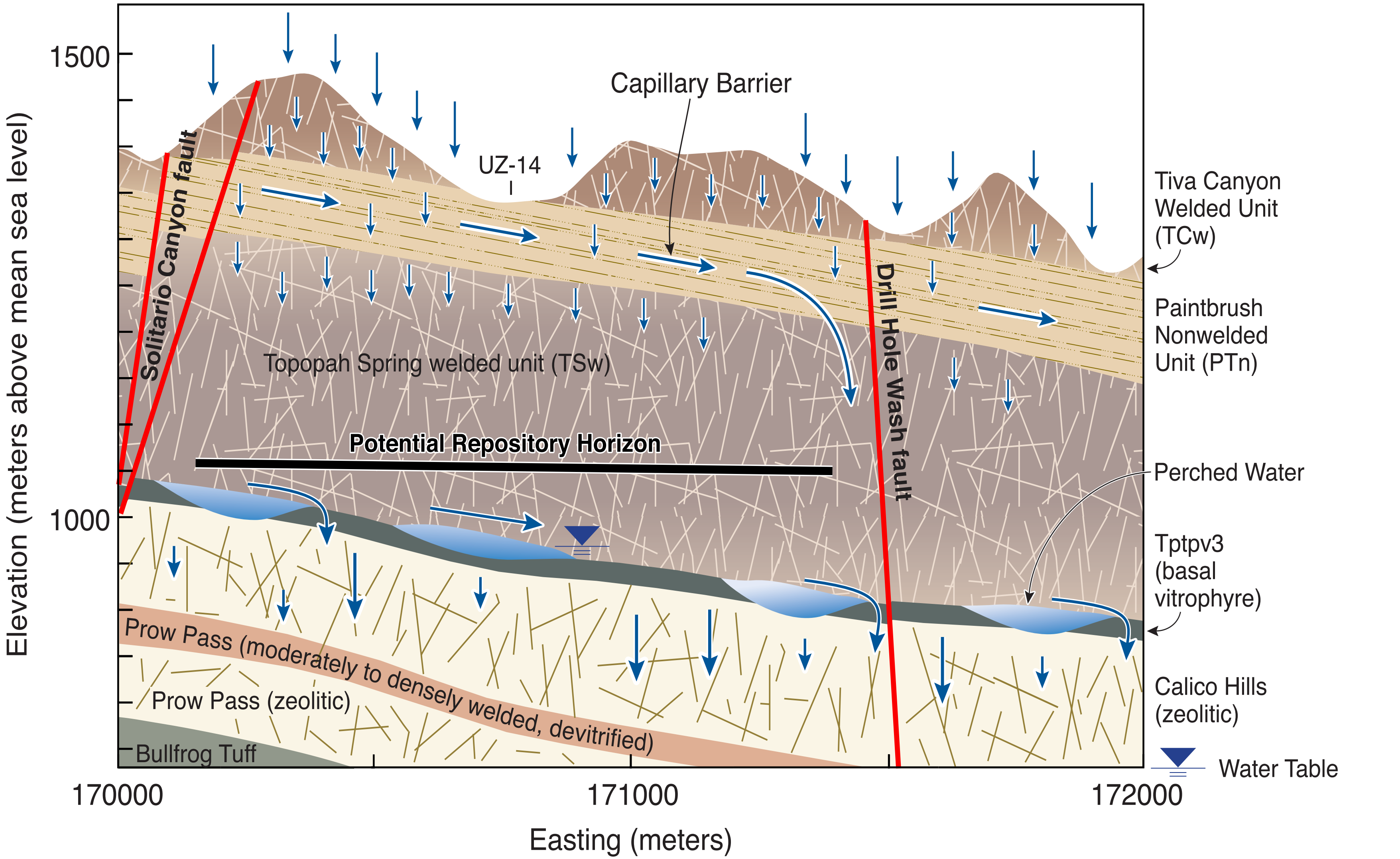
Effects of Flow Focusing in a Fracture Network

(Continued)



- The active fracture model is used to match water saturation and potential data. A reduced fracture-matrix interaction is essential to fit the existing data
- Independent evidence for the active fracture concept comes from the frequency of secondary calcite coatings on fractures in the TSw

Mountain Scale Flow Patterns



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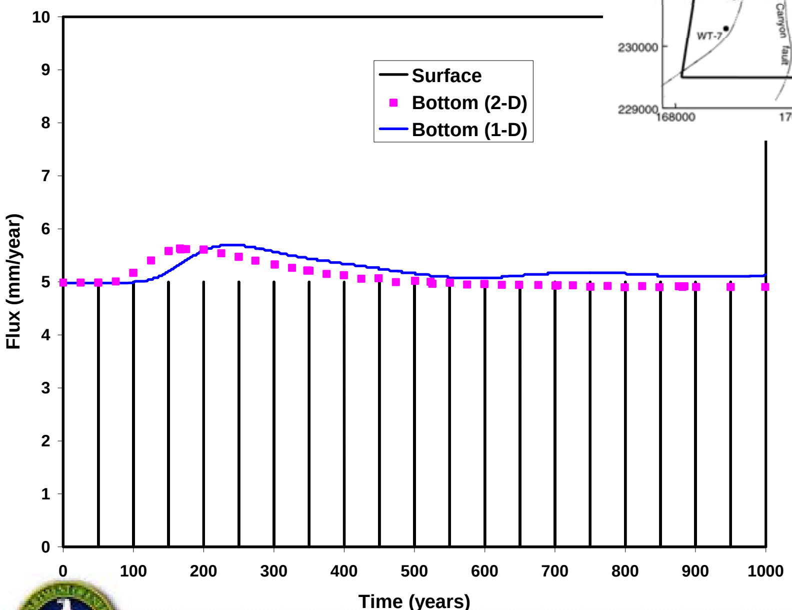
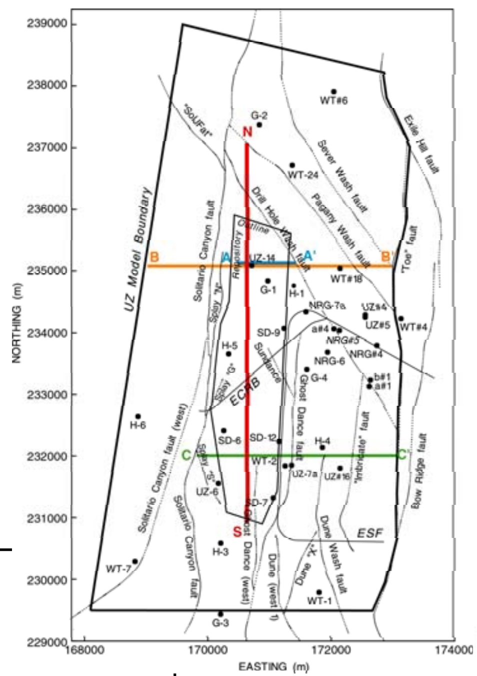
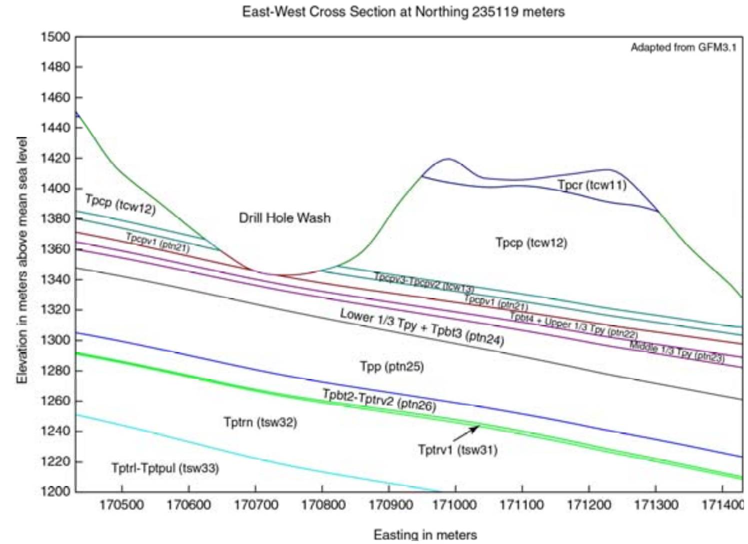
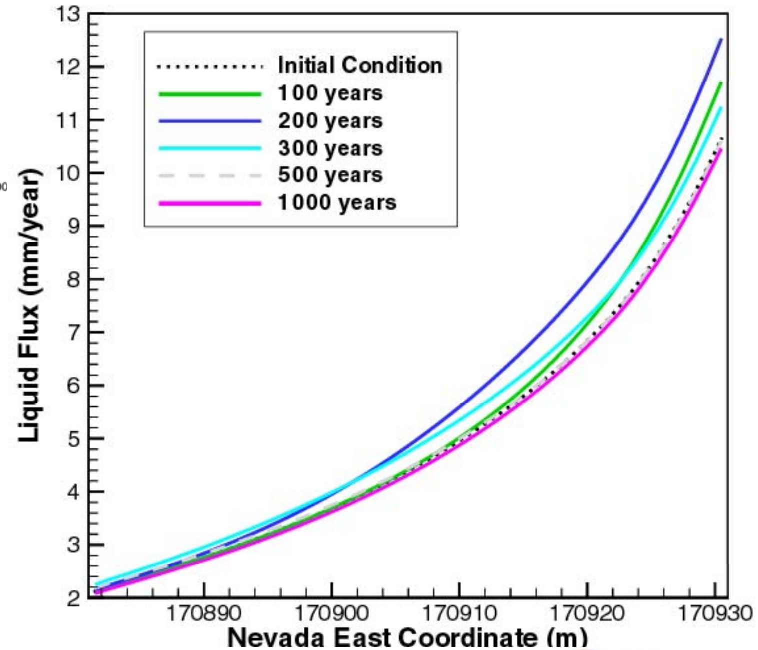
Episodic Transient Flow

Episodic transient flow is expected to be damped out by the high matrix permeability and capillary properties of the PTn.



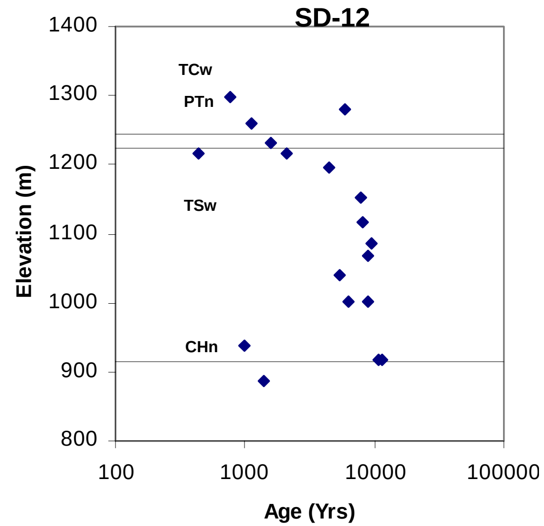


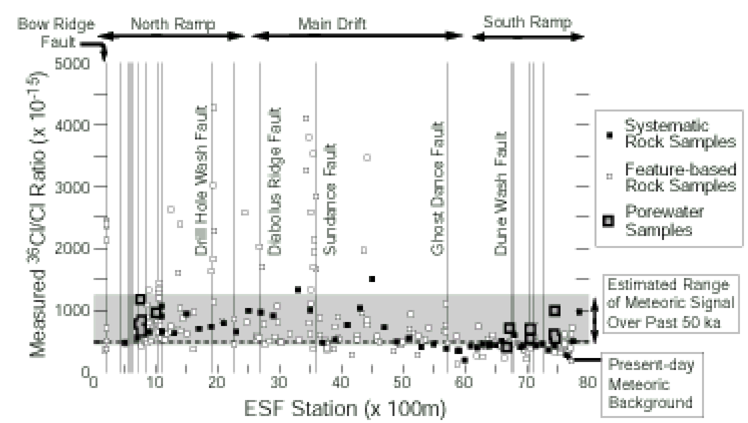


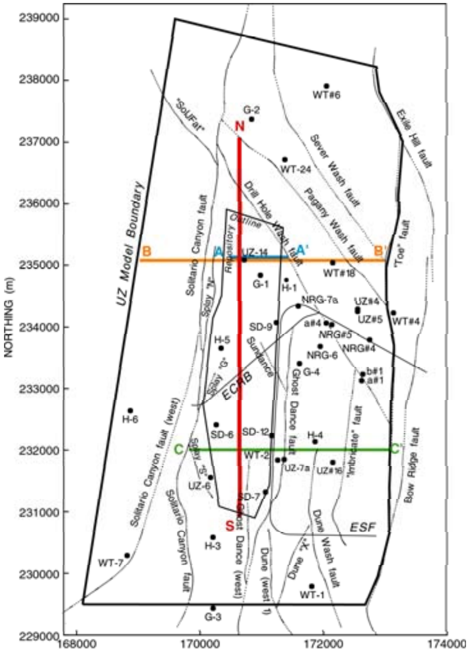


Episodic Transient Flow and Fast Flow Paths

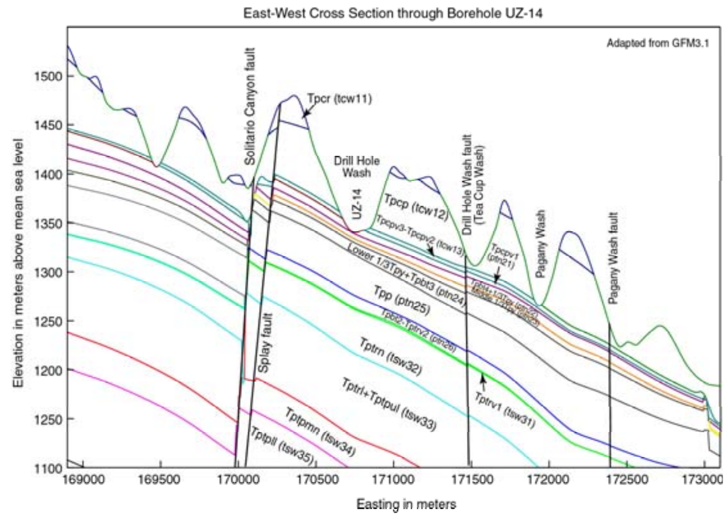
- **Current data does not support fast flow paths for significant amounts of flow:**
  - **Carbon-14 data indicates ages of pore water that generally range from 1,000 to 10,000 years**
  - **Chlorine-36 data remain controversial, but suggest fast flow paths are associated with faults through the PTn or low-angle features in the TSw**
  - **The lack of bomb-pulse chlorine-36 in perched water suggests that the quantity of fast flow is small**



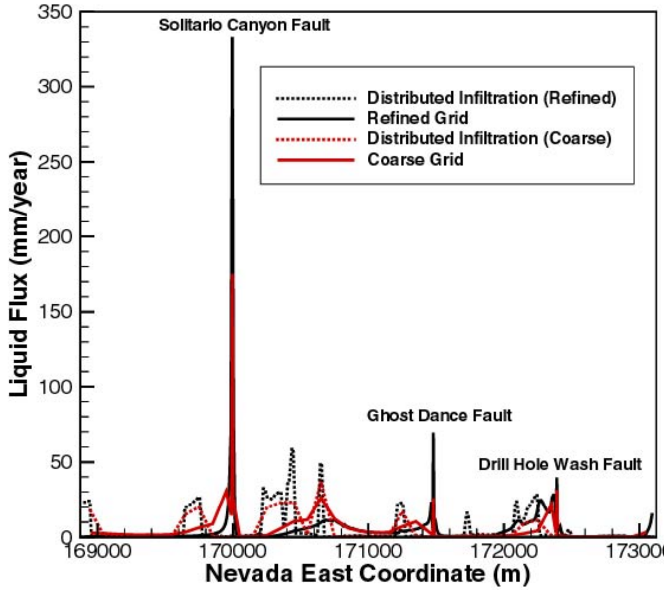


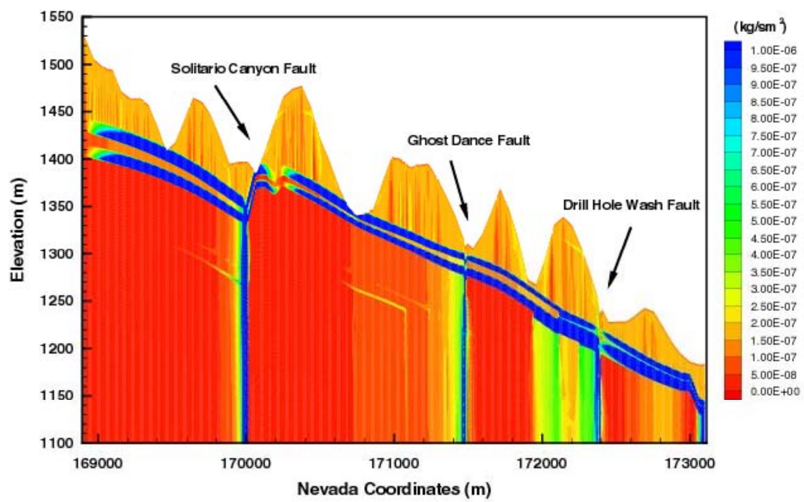


Large-Scale Lateral Flow



Lateral flow due to capillary barriers in the PTn is found in the UZ flow model.

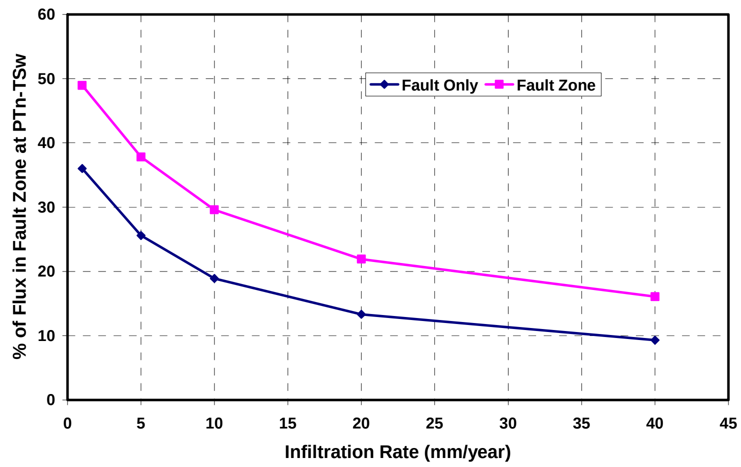


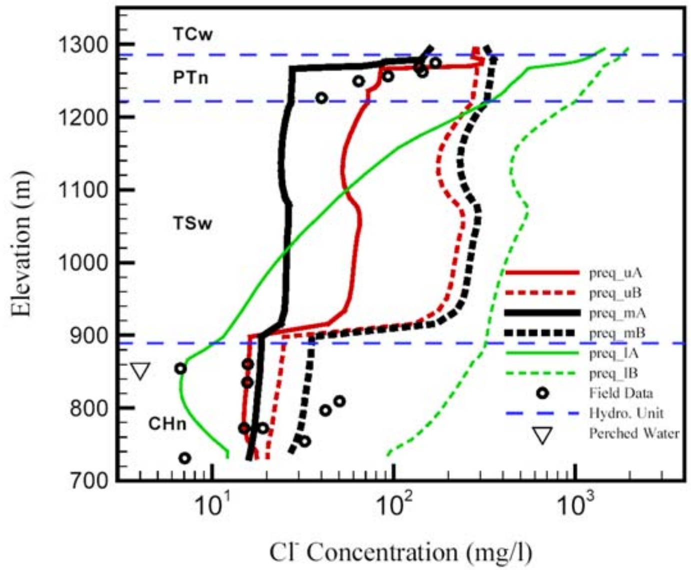


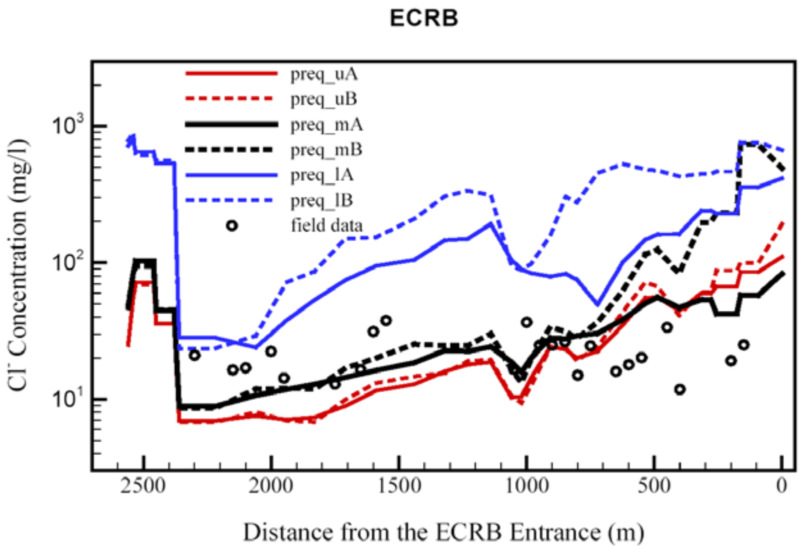
Large-Scale Lateral Flow
(Continued)

Lateral diversion results in partial diversion and decreases with increasing infiltration.

Chloride data provides evidence for lateral diversion in the PTn.

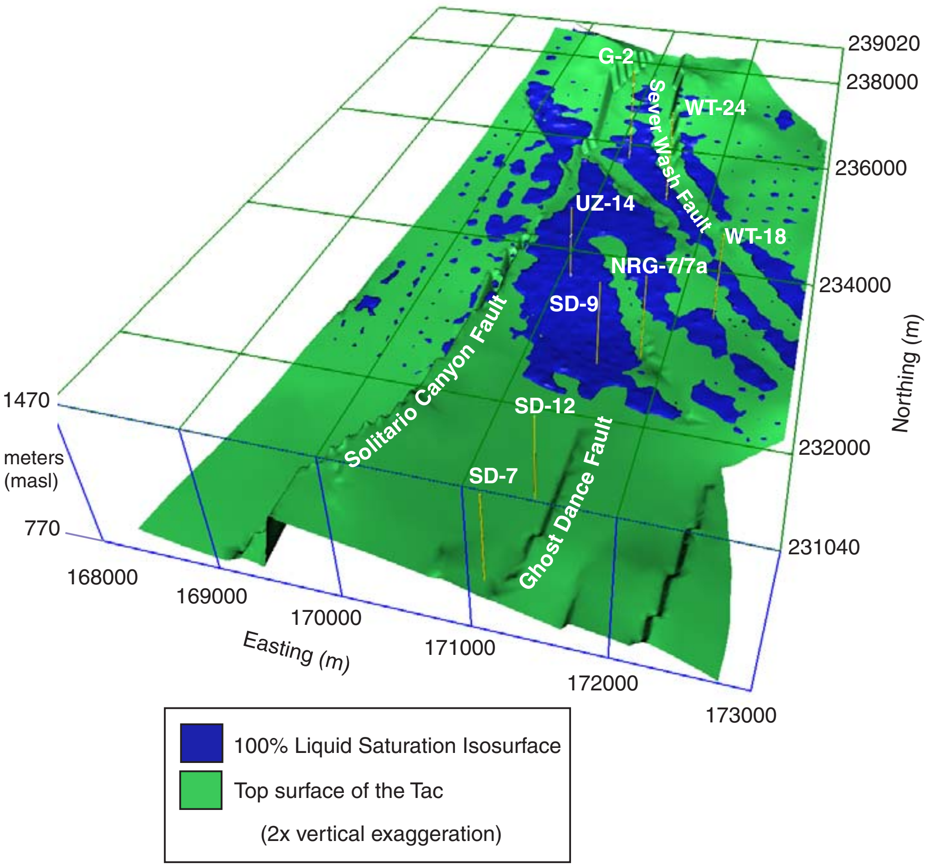






Large-Scale Lateral Flow
(Continued)

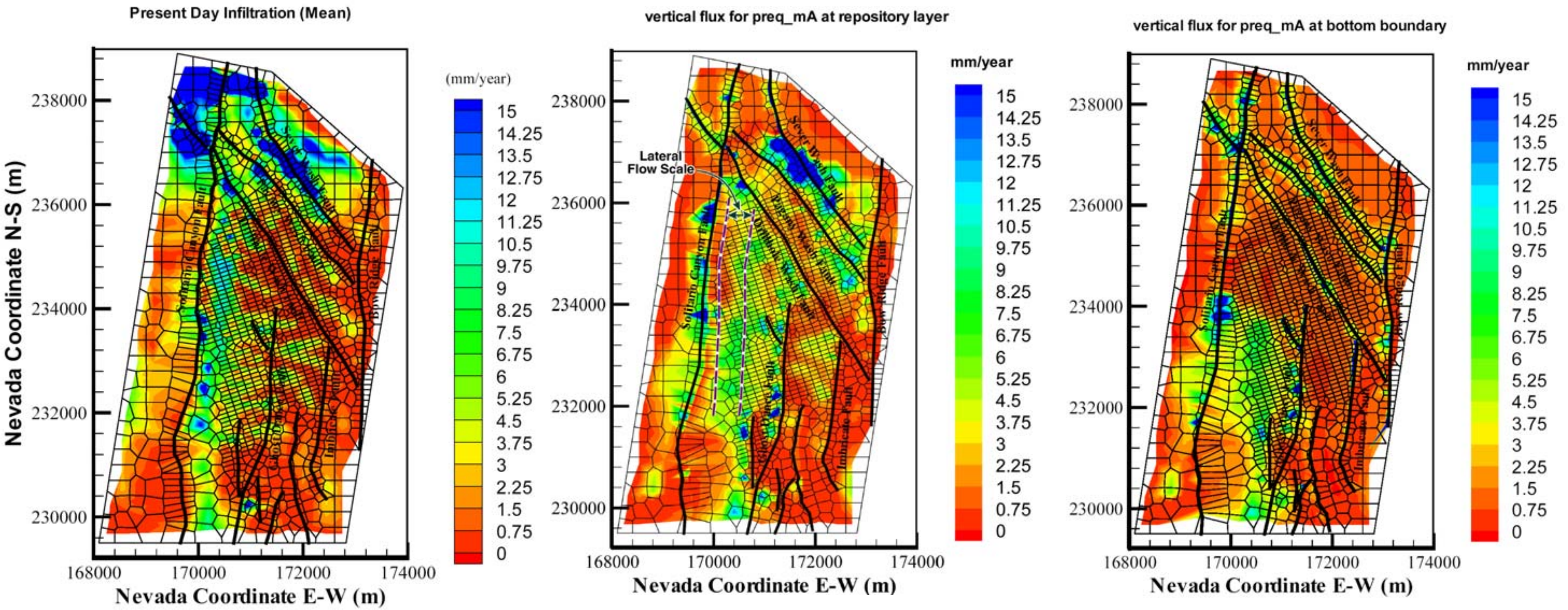
- **Existence of perched water bodies infers that fracture permeability below perched water is low**
- **Lateral flow due to permeability barriers is expected below the repository at perched water bodies and low-permeability zeolitic interfaces**
- **Partial diversion minimizes contact with zeolitic tuff**



Large-Scale Lateral Flow

(Continued)

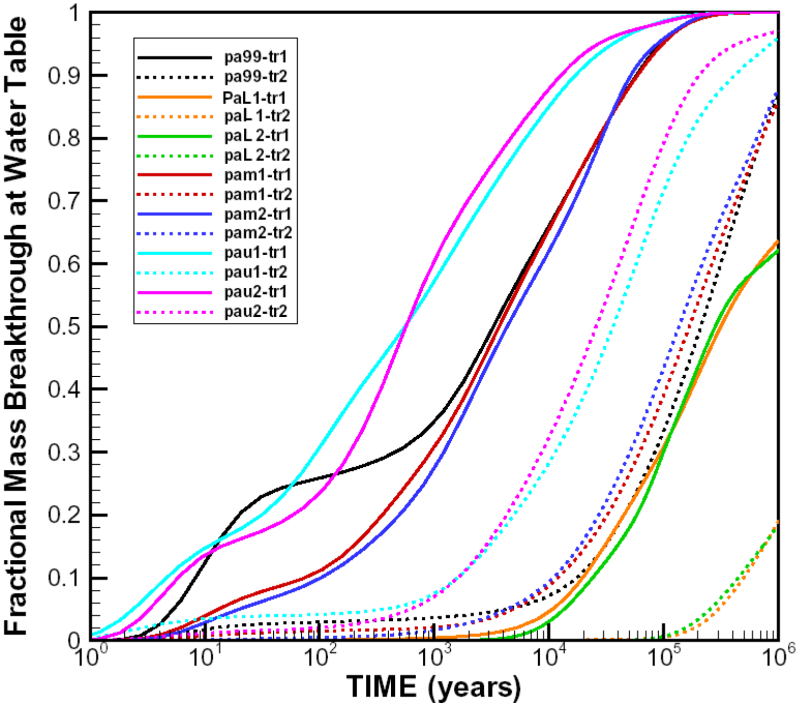
Model results suggest flow focusing into faults

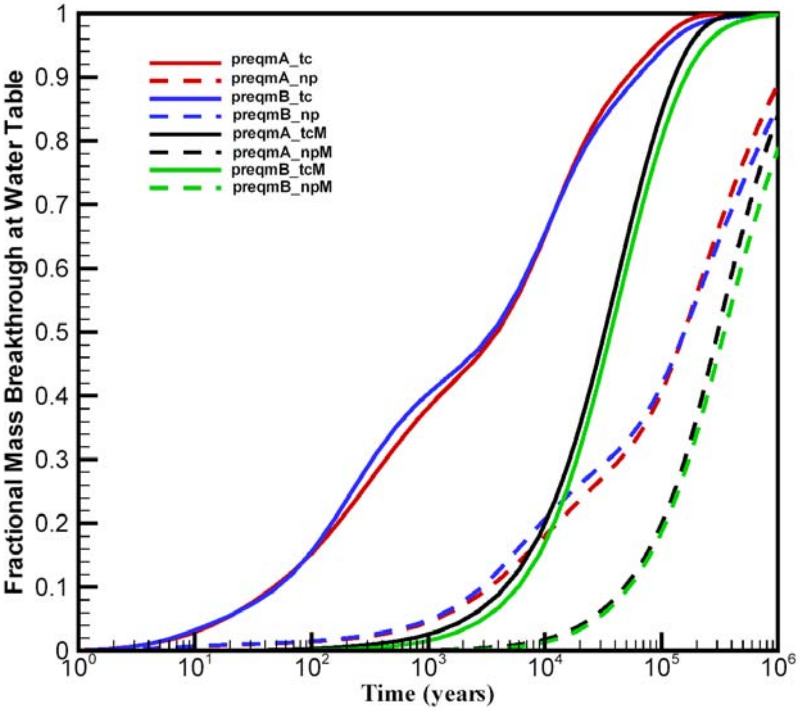


Large-Scale Lateral Flow

(Continued)

Effects of lateral flow in the PTn on radionuclide transport predictions are small.



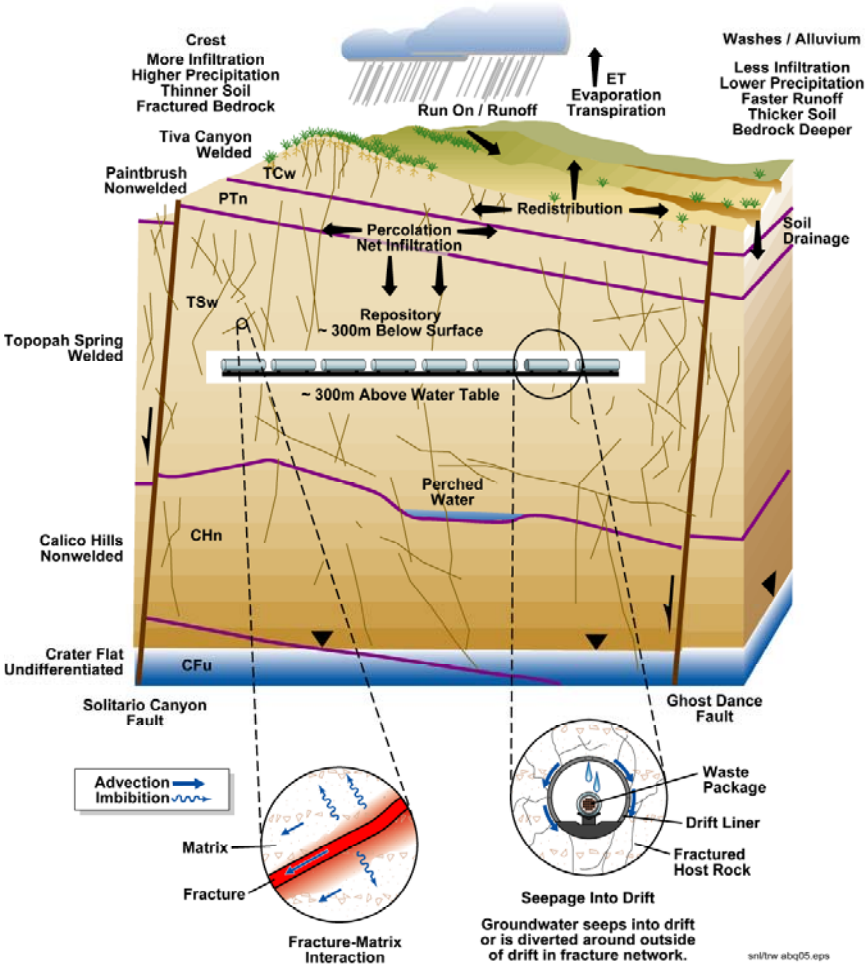


Lateral diversion below the repository has an impact on transport, but variations between realistic models are small.

The data shown in these figures are based on a model that is appropriately conservative for TSPA analyses and not intended to represent expected breakthrough of radionuclides or groundwater travel time for unsaturated zone portion of the Yucca Mountain flow system.

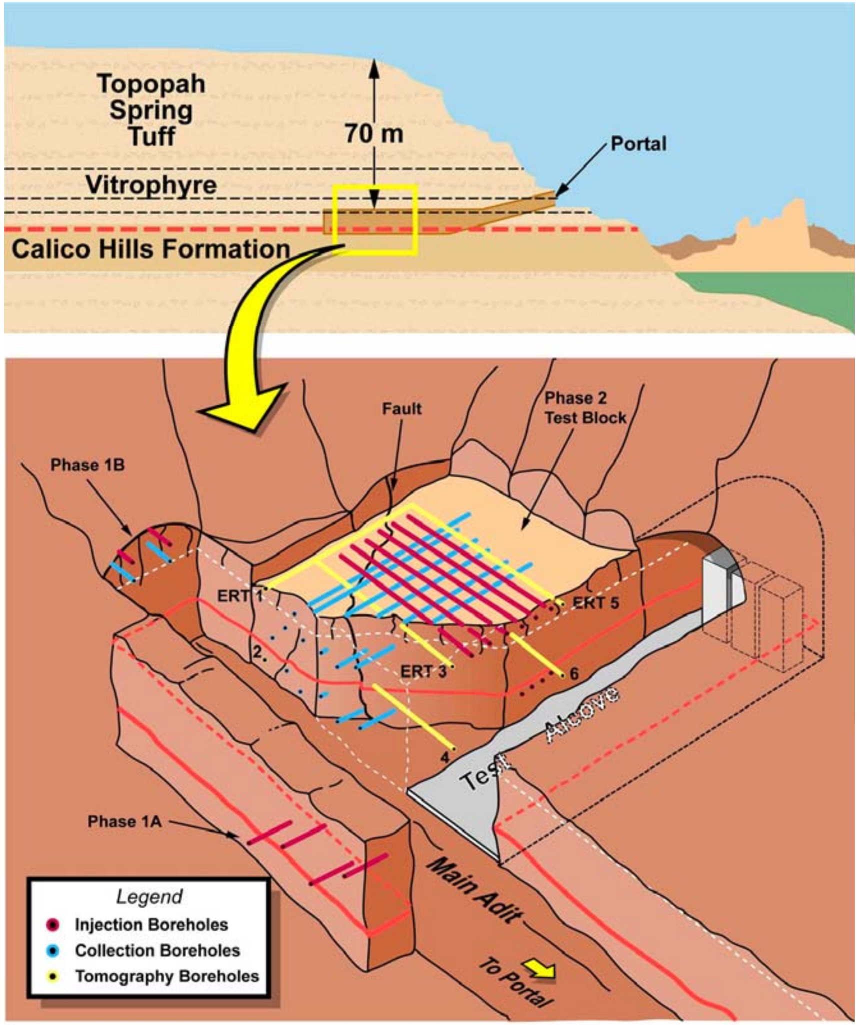
Process for Unsaturated Zone Transport

- All processes pertaining to flow are important to transport
- Flow behavior in the CHnv
- Matrix diffusion
- Radionuclide source term; drift shadow
- Sorption
- Colloids



Busted Butte Transport Test

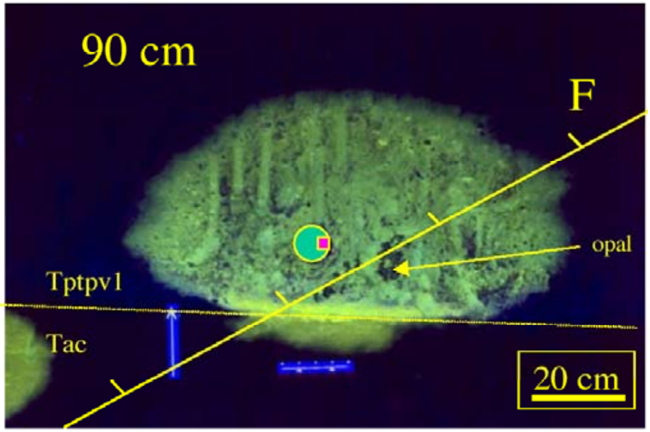
- **Studies:**
  - **Inject multi-tracer solutions into borehole arrays in and above Calico Hills vitric tuff**
  - **Track plume migrations with periodic ground penetrating radar imaging between borehole pairs**



Busted Butte Transport Test
(Continued)

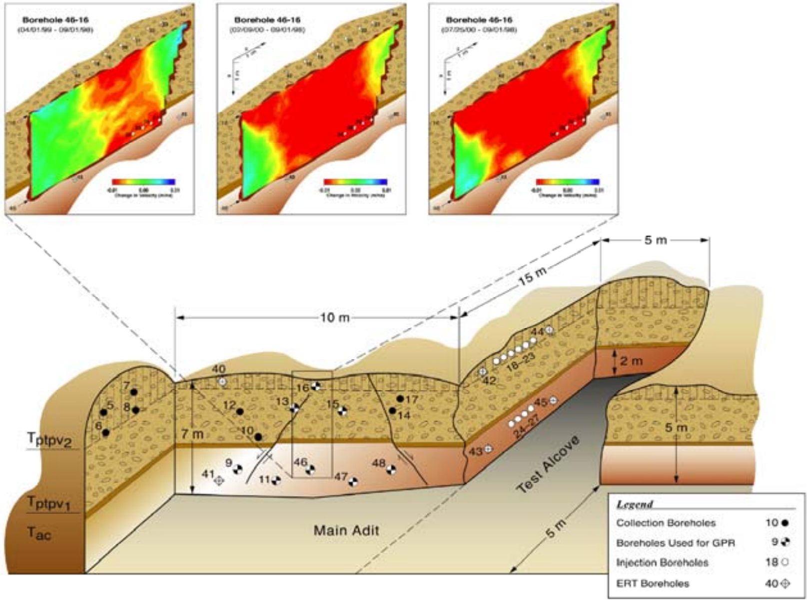
Phase 1A tests showing fluoroscene plume.

Calico Hills vitric tuff has simple porous medium characteristics with well-defined plume pattern.



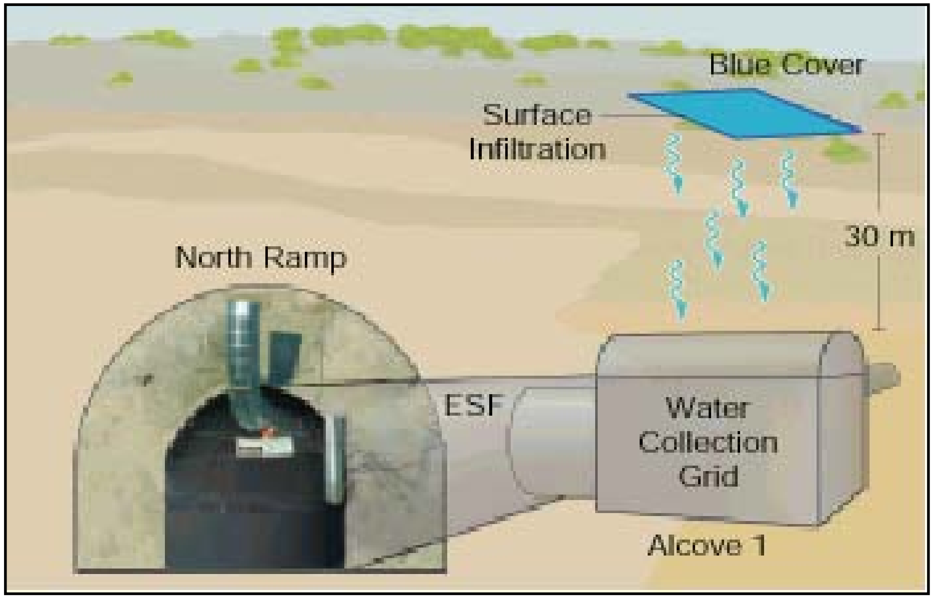
Phase 2 injection tests monitored using ground-penetrating radar.

The spread of the flow pattern is indicative of a porous media flow process.



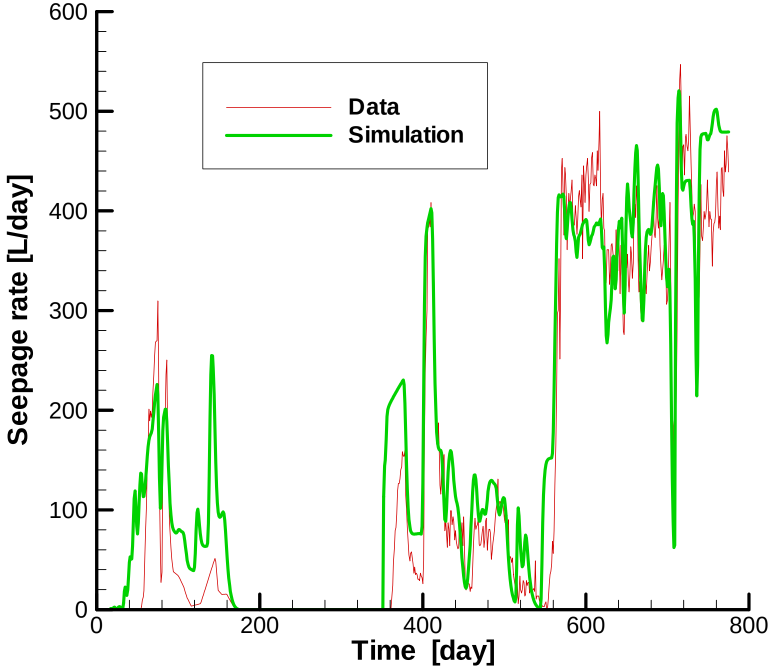
Transport Tests at Alcove 1

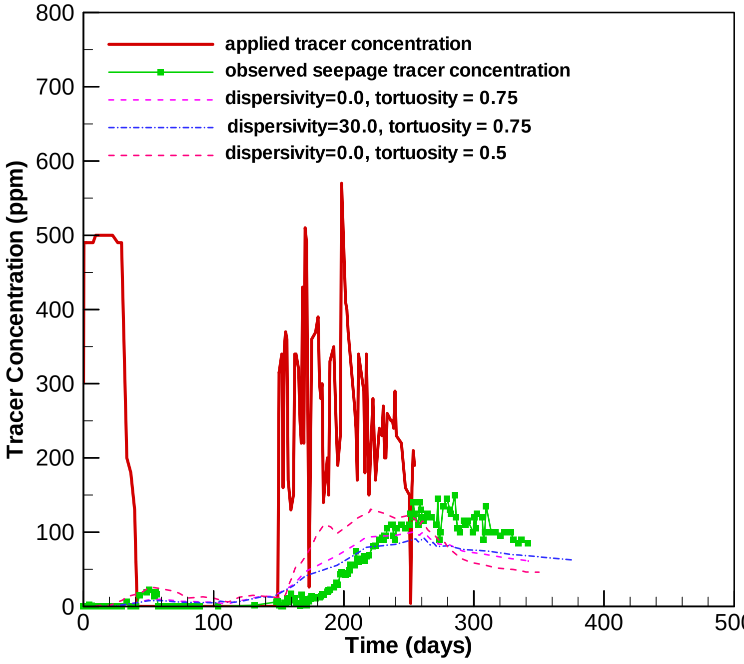
- **Transport tests were conducted between the ground surface and Alcove 1 in the TCw unit. Lithium bromide was used as the tracer**
- **In addition to transport, flow and seepage test results were obtained**
- **Water uptake rates were on the order of 30 mm/day; indicates that surface bedrock permeability is substantially lower than values in the rock interior**



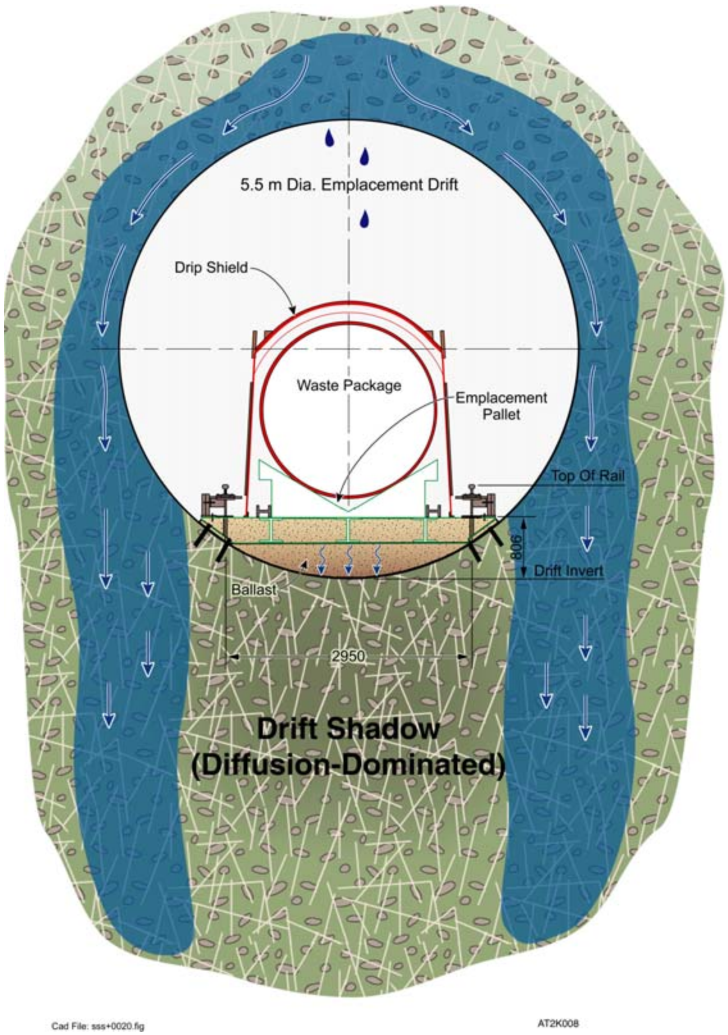
Transport Tests at Alcove 1
(Continued)

- MINC model used for transient flow and transport experiment. Hydrologic properties calibrated to seepage data
- Results indicate matrix diffusion plays a significant role in transport through densely welded tuffs. Fracture-matrix interaction appears to be larger than initial estimates





Radionuclide Source Term and Drift Shadow

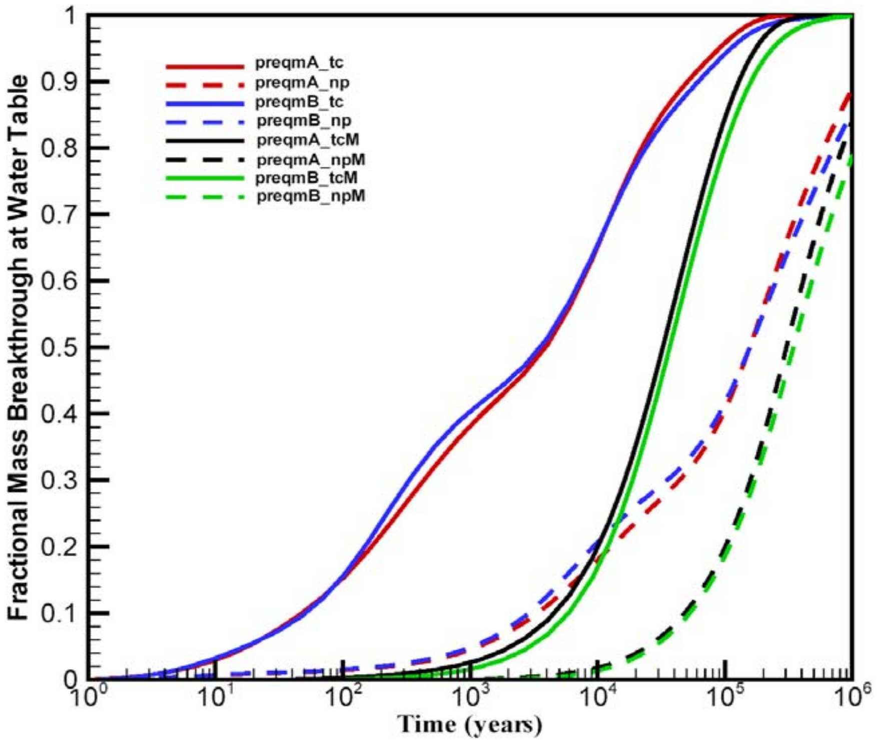


- **Modeling studies have shown that a drift shadow will form when drift seepage is diverted**
- **Transport initiated in drift shadow is much slower due to two effects:**
  - **Radionuclides leaving the drift predominantly enter the rock matrix**
  - **Radionuclides enter a zone in which fracture flow is negligible**

Radionuclide Source Term and Drift Shadow

(Continued)

Results indicate that greatly reduced transport rates are expected for transport initiated in rock matrix regardless of the specific flow dynamics.

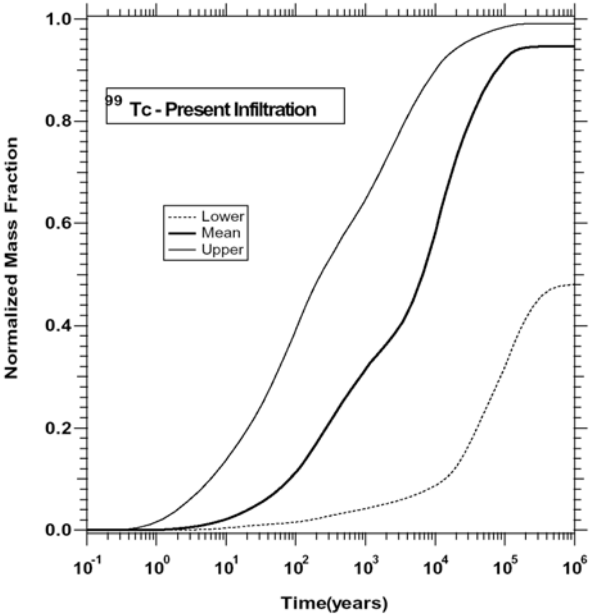


The data shown in this figure are based on a model that is appropriately conservative for TSPA analyses and not intended to represent expected breakthrough of radionuclides or groundwater travel time for unsaturated zone portion of the Yucca Mountain flow system.

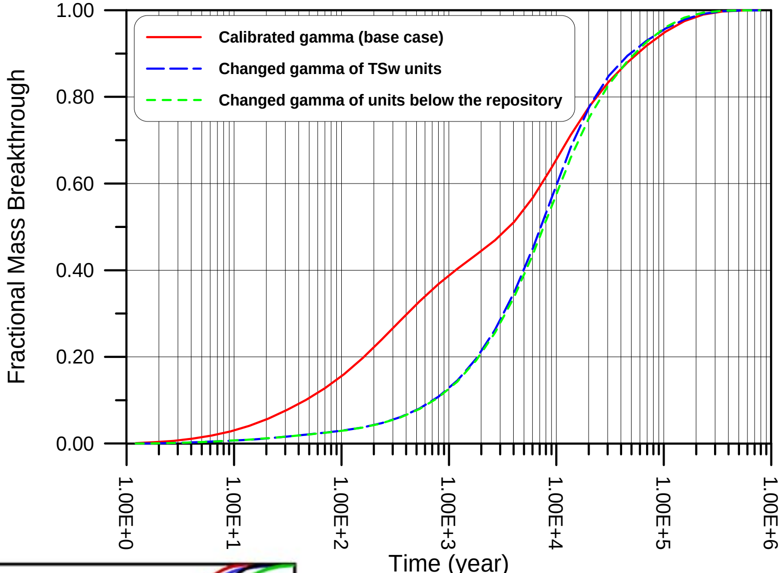
Transport Time of a Passive Tracer

Transport time for a passive tracer is sensitive to:

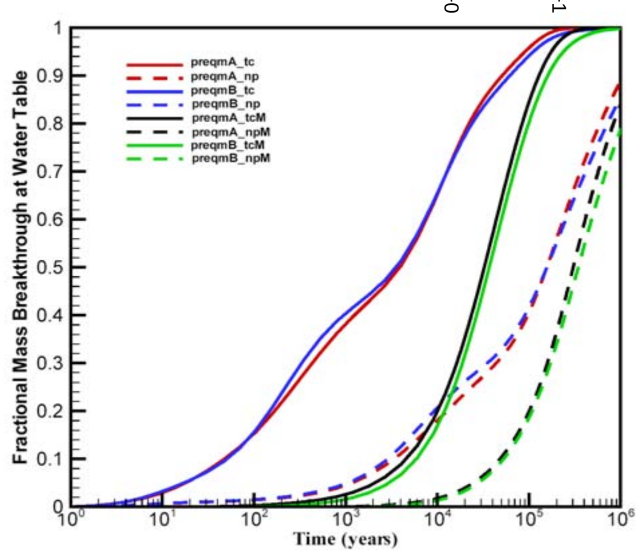
Infiltration rate (climate uncertainty)



Fracture-matrix interaction



Initiation in fracture or matrix continua



The data shown in these figures are based on a model that is appropriately conservative for TSPA analyses and not intended to represent expected breakthrough of radionuclides or groundwater travel time for unsaturated zone portion of the Yucca Mountain flow system.

Conclusions

- **Climate projections based on climate cycles are supported by paleoclimate data and correlations with earth orbital behavior**
- **Predicted net infiltration rates using a water balance model are in general agreement with independent estimates of flux through the UZ using geochemical and borehole temperature methods**
- **Representation of heterogeneity based on hydrogeologic units is generally appropriate for flow and transport at the mountain scale**
- **Dual-permeability method captures the main features of flow in fractured rock but may underestimate f-m interaction for radionuclide transport**
- **Unsaturated flow in fractures using the van Genuchten relationships appears to be adequate for low fracture saturations expected under ambient flow conditions. However, this conclusion is based mainly on modeling because data at low water saturations is not available**

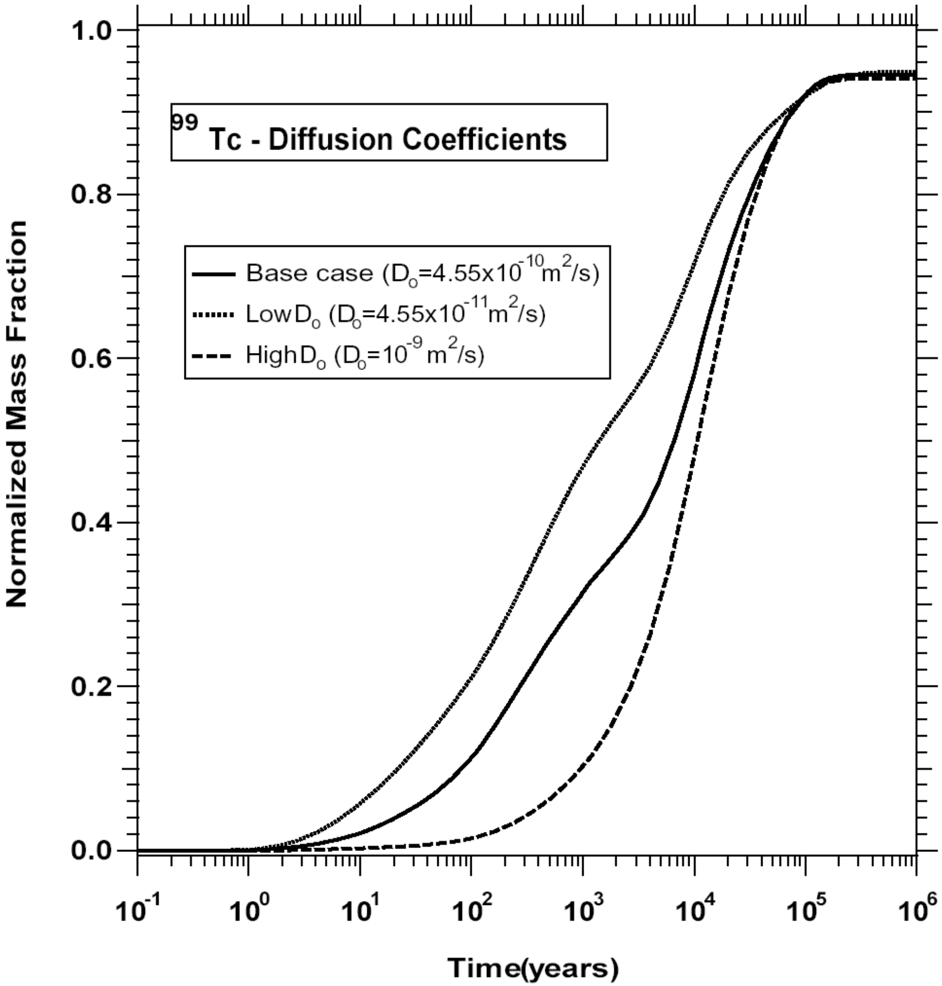
Conclusions
(Continued)

- Active fracture model accounts for reduced fracture matrix interaction and is qualitatively consistent with fracture coating data
- Episodic transient flow and fast flow paths appear to play a minor role based on simulation results and isotopic data
- Large-scale lateral flow in the PTn is consistent with chloride data in the Exploratory Studies Facility
- Matrix-dominated flow in the CHnv is consistent with hydrologic properties and flow observations at Busted Butte
- Matrix diffusion plays a significant role in transport through welded tuffs as shown in Alcove 1 and Alcove 8-Niche 3 tests
- Transport times are sensitive to infiltration, fracture-matrix interaction, and initial conditions (initiation in fractures or matrix)

Backup

Sensitivity to Matrix Diffusion

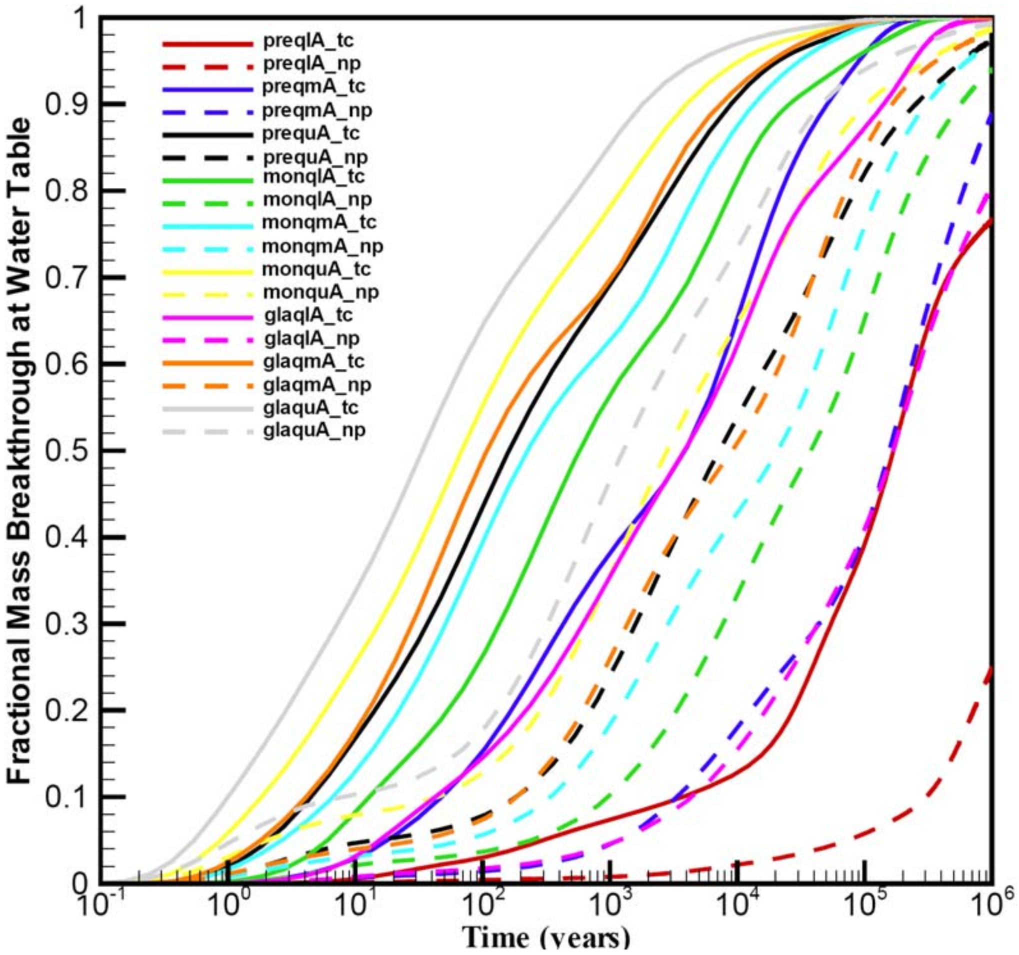
Transport is sensitive to the matrix diffusion coefficient



The data shown in this figure are based on a model that is appropriately conservative for TSPA analyses and not intended to represent expected breakthrough of radionuclides or groundwater travel time for unsaturated zone portion of the Yucca Mountain flow system.

Effects of Climate on Transport

Climate and climate uncertainty has a major impact on transport



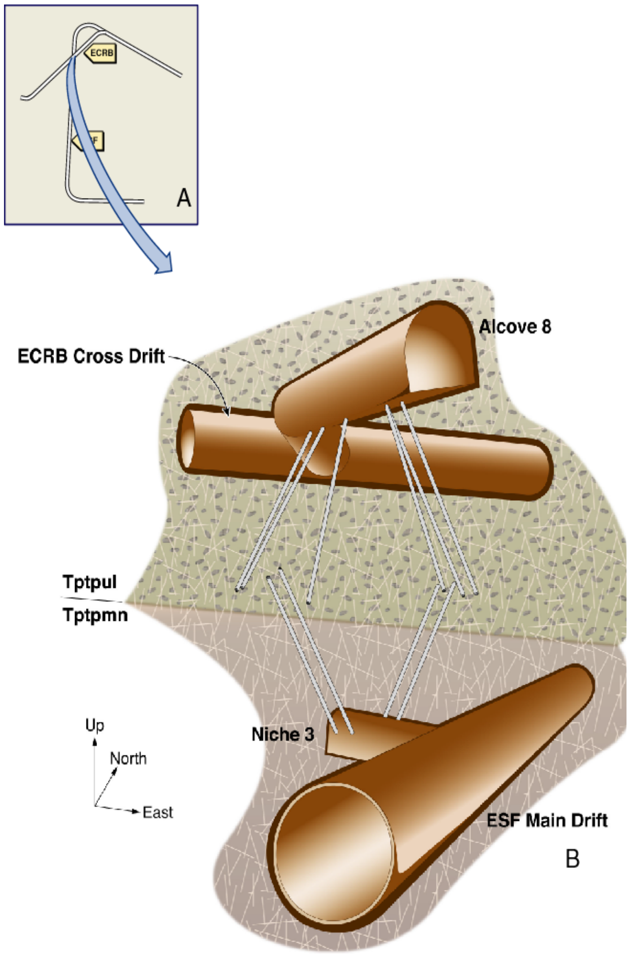
The data shown in this figure are based on a model that is appropriately conservative for TSPA analyses and not intended to represent expected breakthrough of radionuclides or groundwater travel time for unsaturated zone portion of the Yucca Mountain flow system.

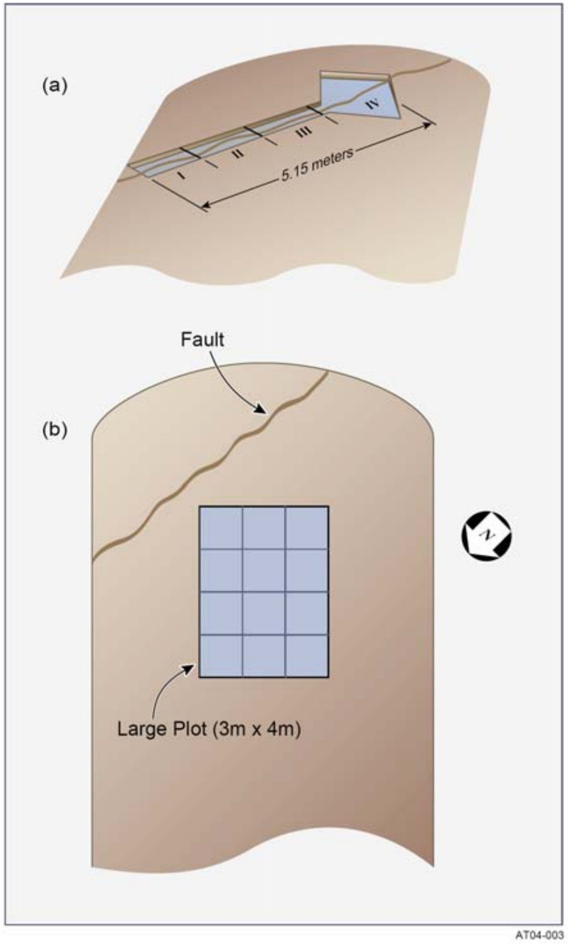
Transport Tests at Alcove 8-Niche 3

Transport tests are being conducted between Alcove 8 in the TSw upper lithophysal unit and Niche 3, 20 m below, in the TSw middle non-lithophysal unit.

Results are available from flow, seepage, and transport tests along a fault that extends between Alcove 8 and Niche 3.

Water uptake rates were on the order of 25 mm/day.



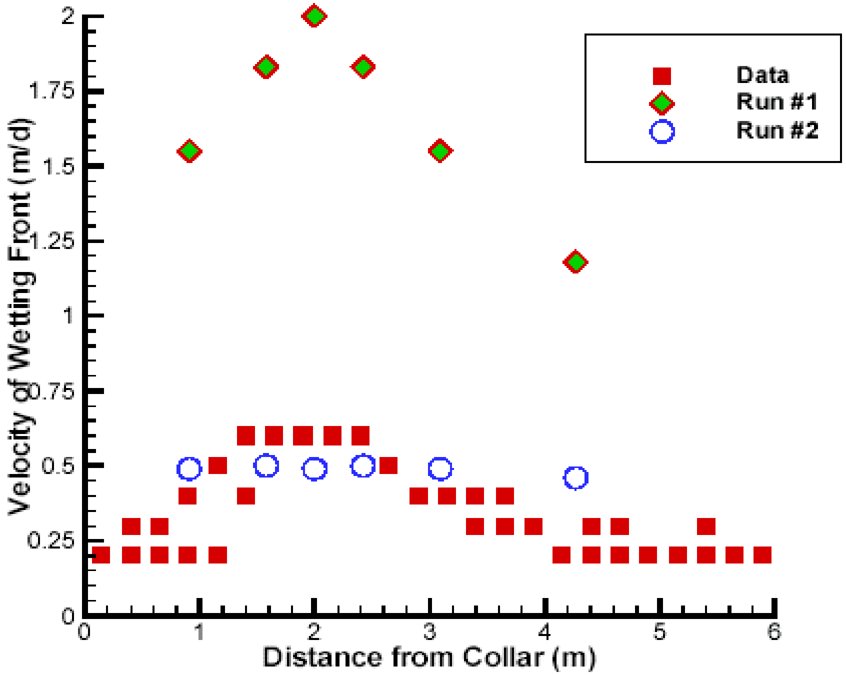


Transport Tests at Alcove 8-Niche 3

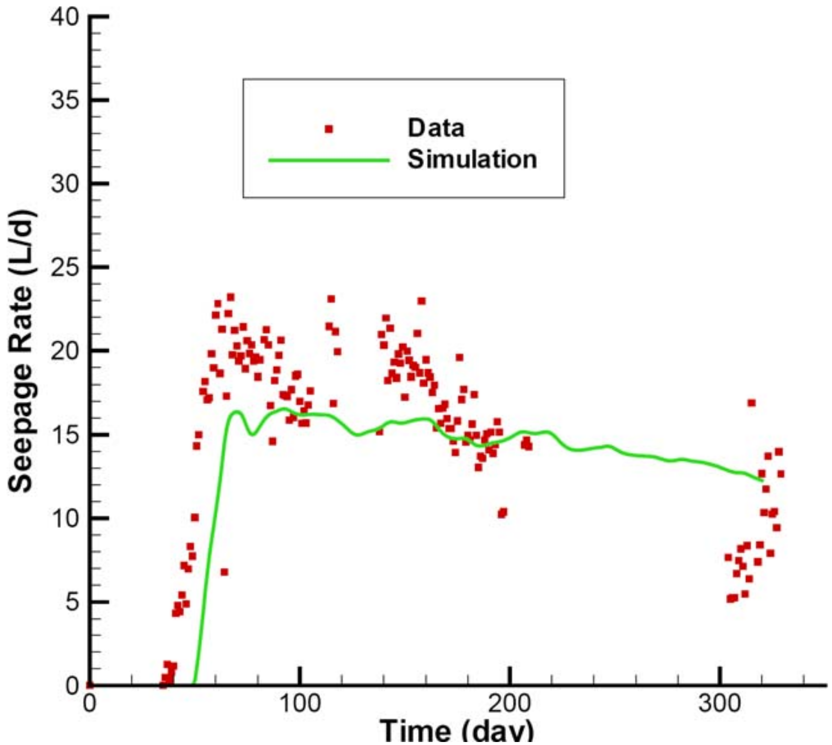
(Continued)

Fault and rock mass fracture properties in the test bed flow model are calibrated to water arrival times and seepage data.

Water travel velocity from fault testing



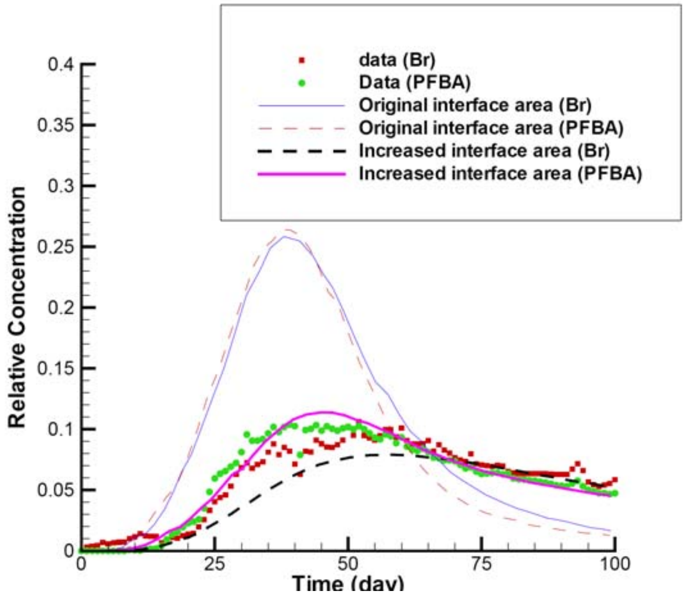
Seepage

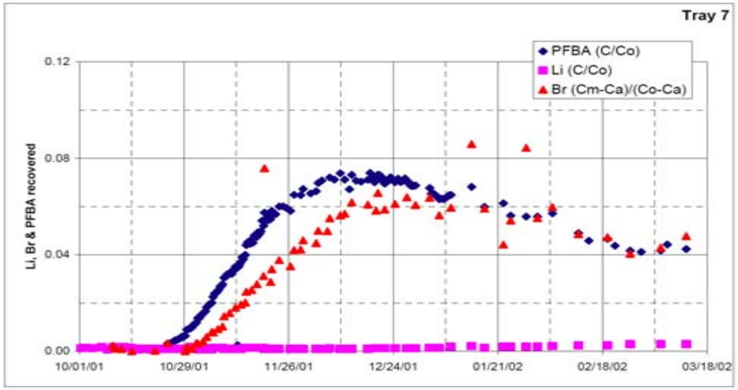


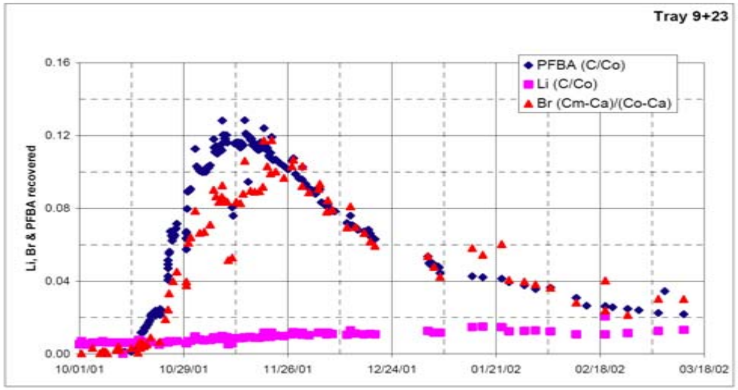
Transport Tests at Alcove 8-Niche 3

(Continued)

Lithium bromide and pentafluorbenzoic acid tracers were used in the transport tests. Diffusion coefficients for the two tracers differ by roughly a factor of 4.

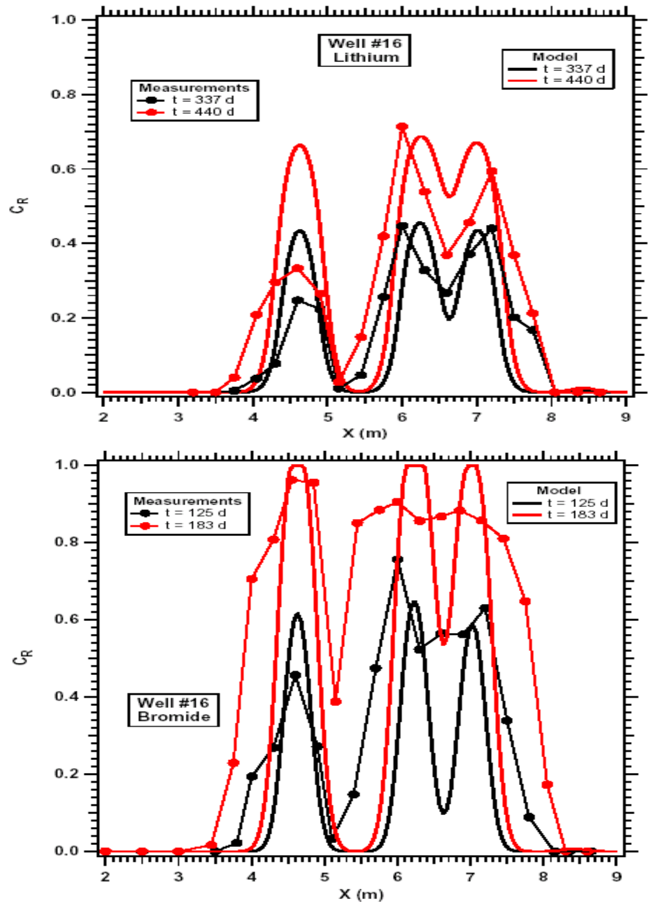


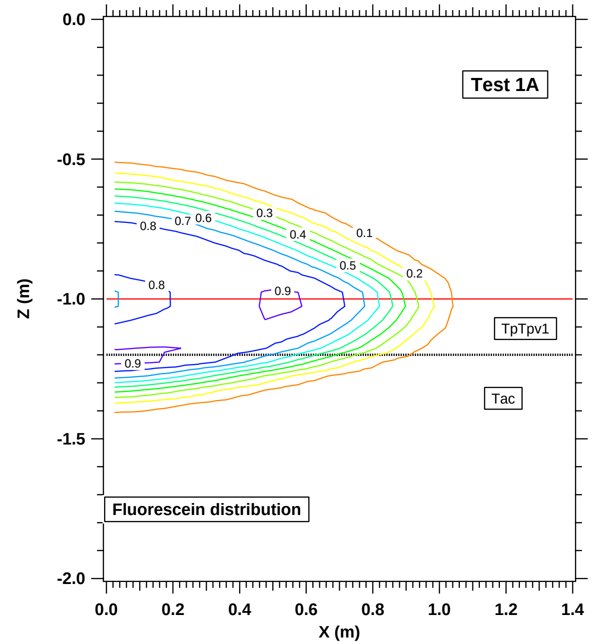




Results indicate that matrix diffusion is an important factor in transport.

Busted Butte Transport





Measured and predicted (calibrated) breakthrough curves for Li and Br

Matrix K_d initial estimates for Li are 3.5 x 10^{-5} (m^3/Kg) in TpTpv1 and 8.8 x 10^{-5} (m^3/Kg) inTpTpv2, Calibrated values are 5.5 x10^{-4} (m^3/Kg) and 9.3 x10^{-4} (m^3/Kg) respectively (1 m^3/kg=10^{-3} ml/g)