Migration of Solutes in Unsaturated Fractured Rock at Yucca Mountain: Mechanisms, Measurements, and Models

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Mechanisms

• Driving Forces
  - Aqueous phase solutes
    » Infiltration
  - Gas phase solutes
    » Temperature gradients
    » Pressure gradients

• Barries to Solute Migration
  - Aqueous phase solutes
    » Molecular diffusion
    » Sorption
  - Gas phase solutes
    » Diffusion into rock matrix from fractures
    » Reactions: Partitioning and fractionation with aqueous phases

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Measurements

- Infiltration - Flint et al., USGS
- CI-36 - Fabryka-Martin et al., LANL
- C-14 - Yang, USGS
- Kd - Triay et al., LANL
Lateral Flow in Calico Hills Induced by Non-uniform Infiltration

Infiltration = 1 mm/yr

Infiltration = 0.05 mm/yr

water table

Saturation Field

Normalized Cl-36 Concentration Field

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Estimated Variations in CI-36/Cl Ratio Over Last One-Million Years

Based on Estimates of Variations in Geomagnetic Field Intensity

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Effects of a Variable Source Concentration over Time

Constant CI-36 Concentration over time

Variable CI-36 Concentration over time

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Particle Arrival Times at Three Locations in Calico Hills Unit

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Carbon-14 Migration Studies

Initial Conditions
(figures)

Saturation Profile

Temperature Profile

Gas Velocity Vectors

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Radiometric Age - No Chemistry

Radiometric Age - Carbonate Chemistry for pH = 8.4

Radiometric Age - Carbonate Chemistry for pH = 8.4
Bottom Boundary Age Fixed at 10,000 Year Old Water

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Reduced Matrix/Fracture Connectivity

Breakthrough Curves for Infiltration = 4 mm/yr

1. **NO DIFFUSION**
- Fracture
- Matrix

2. **DIFFUSION = 1e-12 m²/d
- Fracture
- Matrix

3. **DIFFUSION = 1e-10 m²/d
- Fracture
- Matrix

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Carbon-14 Migration Studies

Computed Kd map for pH = 8.4

\[ K_d = \frac{[CO_2(aq) + HCO_3(aq) + CO_3^{2-}] \rho_{H2O}}{[CO_2(g)] \rho_{vapor}} \]

Computed map of Retardation Factors

\[ R = 1 + K_d \left( \frac{S_{H2O}}{1 - S_{H2O}} \right) \]

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Dual Permeability Flow and Transport Model Evaluation

Evaluate Sensitivity to:
- Infiltration Rate
- Diffusion
- Fracture/Matrix Connectivity

water table boundary

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Matrix and Fracture Saturations For Three Different Infiltration Rates

Elevation (m)

Matrix Saturation

Fracture Saturation

0.1 mm/yr
1.0 mm/yr
4.0 mm/yr

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Reduced Matrix/Fracture Connectivity

Breakthrough Curves for Infiltration = 1 mm/yr

**NO DIFFUSION**

**DIFFUSION = 1e-12 m²/α²**

**DIFFUSION = 1e-10 m²/α²**

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Decreased Matrix/Fracture Connectivity

Matrix and Fracture Saturations For Two Different Infiltration Rates

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Breakthrough Curves for Infiltration = 4 mm/yr

NO DIFFUSION

DIFFUSION=1e-12 m²/αs

DIFFUSION=1e-10 m²/αs

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Breakthrough Curves for Infiltration = 1 mm/yr

- NO DIFFUSION
- DIFFUSION = 1e-12 m²/yr
- DIFFUSION = 1e-10 m²/yr

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Summary

• Dipping stratigraphic beds may provide a reasonable pathway for Cl-36 to travel from regions of high infiltration to measurement locations

• New infiltration data from Flint and three-dimensional solute transport simulations should enhance our understanding of this process

• Gas phase C-14 transport simulations yield maximum and minimum bounds for the measurements taken in Yucca Mountain

• High Tritium signal still not explainable

• Model simulations indicate extreme conditions/parameters required to get rapid movement of solutes to depth with Dual Permeability Formulation

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Transport Barriers
Uniform Infiltration = 0.36 mm/yr
Source Above Thinner Section of Calico Hills

Case 1: No Retardation
30,000 years

Case 2: With Retardation in Calico Hills (Kd = 3)
30,000 years
400,000 years

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Transport Barriers
Uniform Infiltration = 0.36 mm/yr
Source Above Thicker Section of Calico Hills

Case 1: No Retardation
55,000 years

Case 2: With Retardation in Calico Hills (Kd = 3)
55,000 years
820,000 years

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