SAND2007-4228P

Geohydrology Applications: Tracer Testing in Fractured Rocks

KHNP Training Program

Module 4: Repository Siting and Characterization

June 28, 2007

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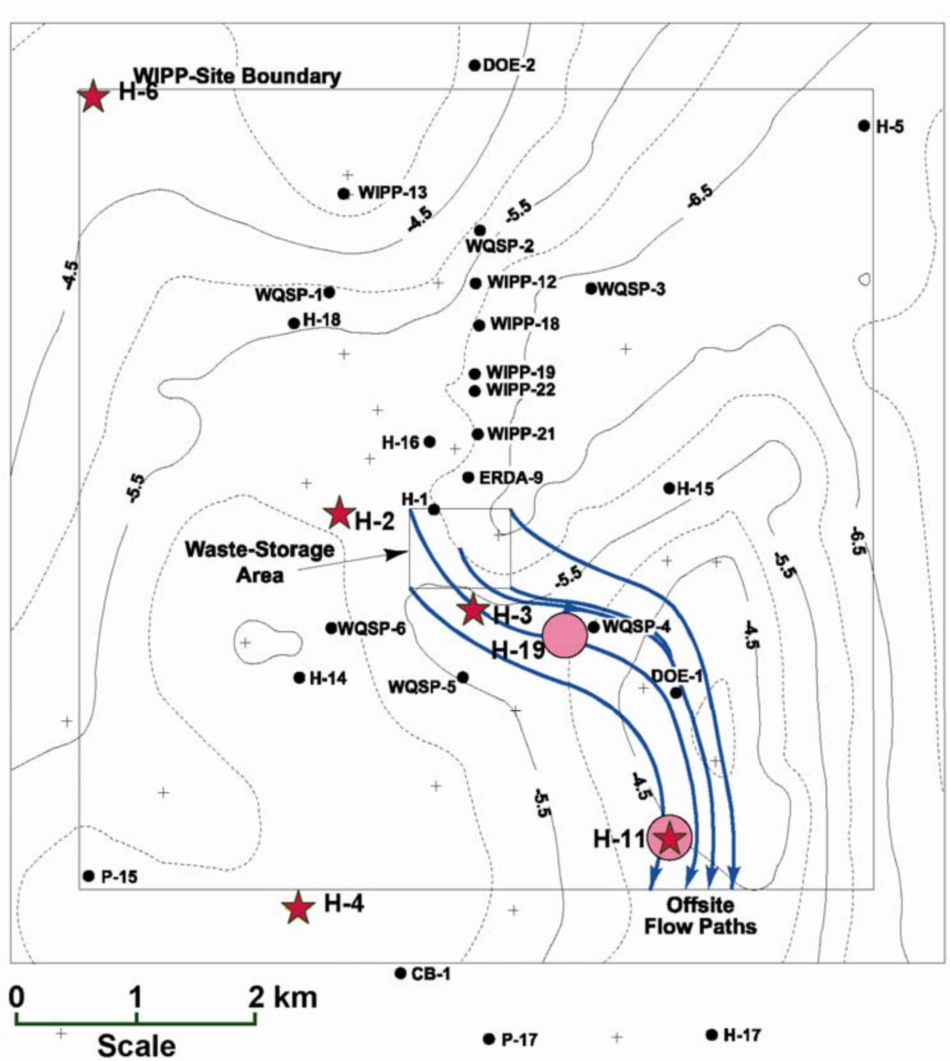
SAND 2007-

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.

Sandia Experience

- Conducting and analyzing tracer tests
- Analysis of tracer tests to develop parameters and conceptual models for PA

Tracer Tests at the WIPP Site



- **1980 – 1986 Tracer Tests**
  - 5 Locations
  - Two Types of Tests
    - Convergent-flow tests
    - Two-well recirculating (dipole) tests
- **1995-1996 Tracer Tests**
  - 2 Locations
  - Two Types of Tests
    - Convergent-flow tests
    - Single-well injection-withdrawal tests

★ Location of 1980-1986 Tracer Tests

● Location of 1995-1996 Tracer Tests

• Observation Well

+ Pilot-Point Location

Transmissivities in $\log_{10}$ m^2/s
Contour Interval 0.5 $\log_{10}$ m_2/s

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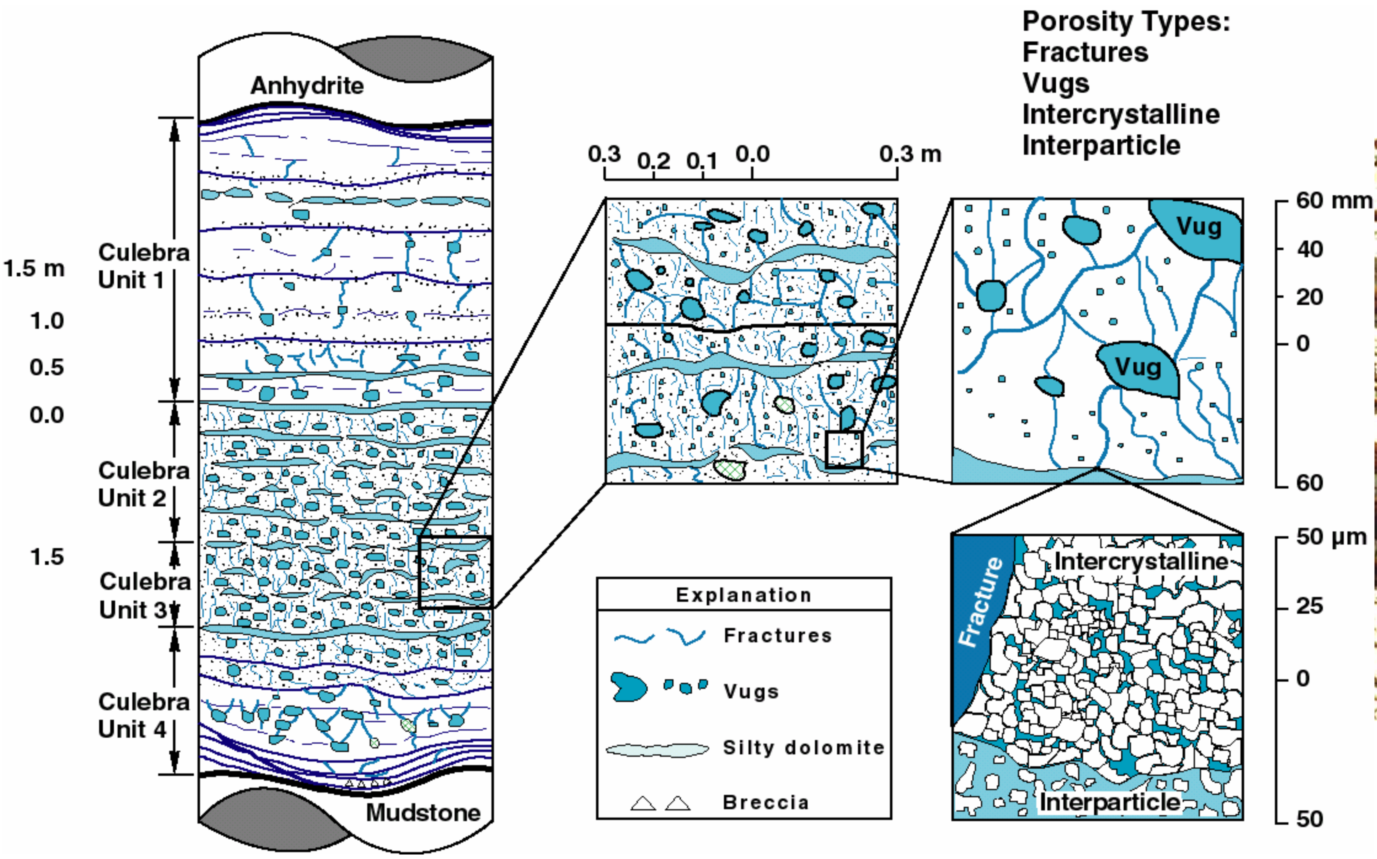
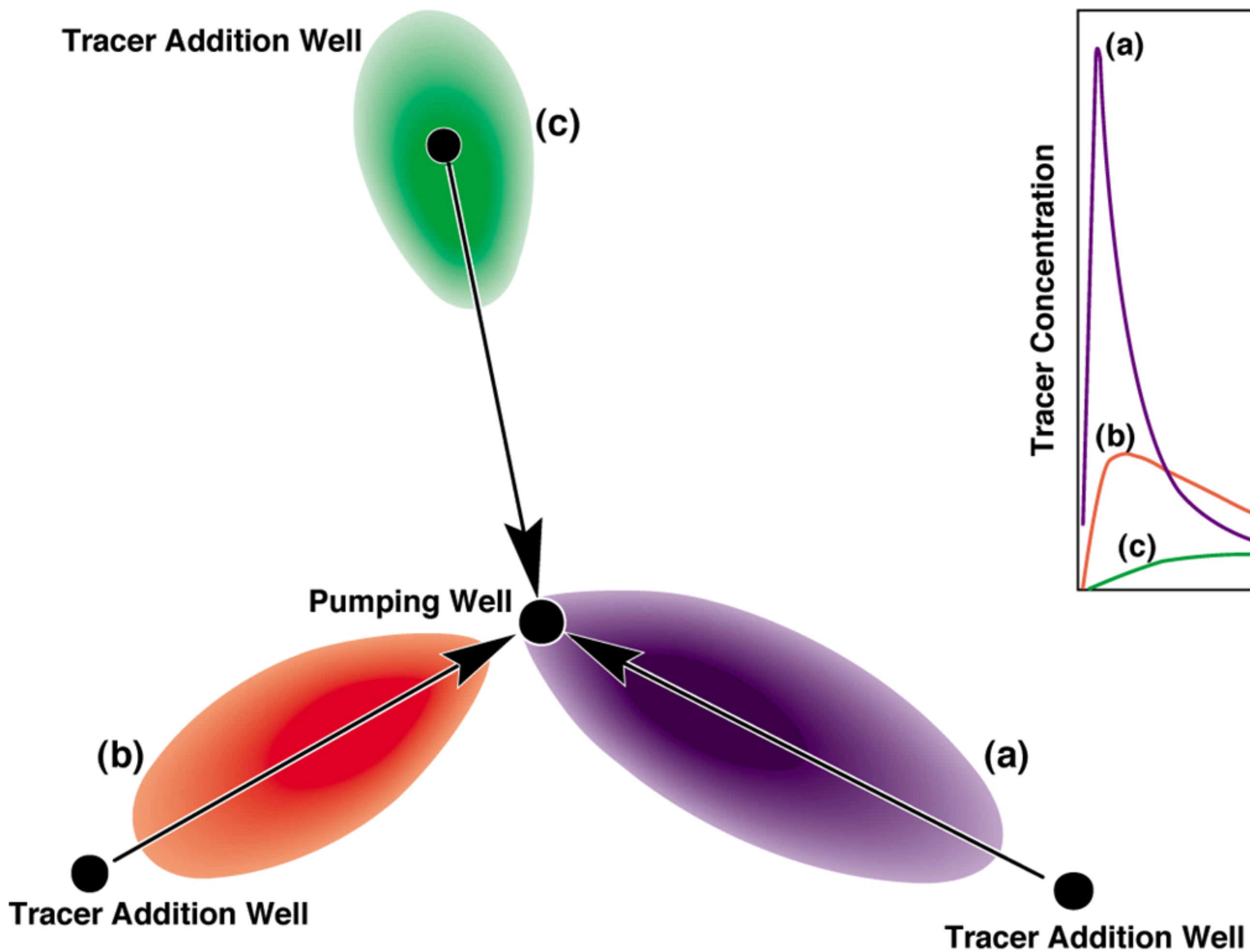
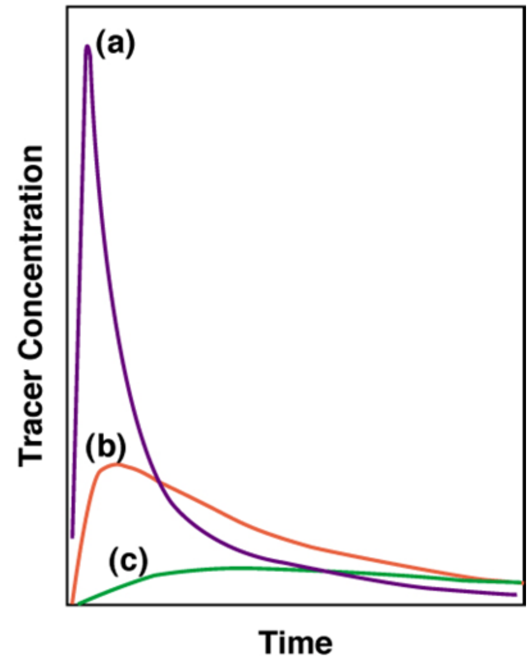
The Culebra Dolomite is a Heterogeneous Fractured Rock



Convergent-Flow Tracer Tests





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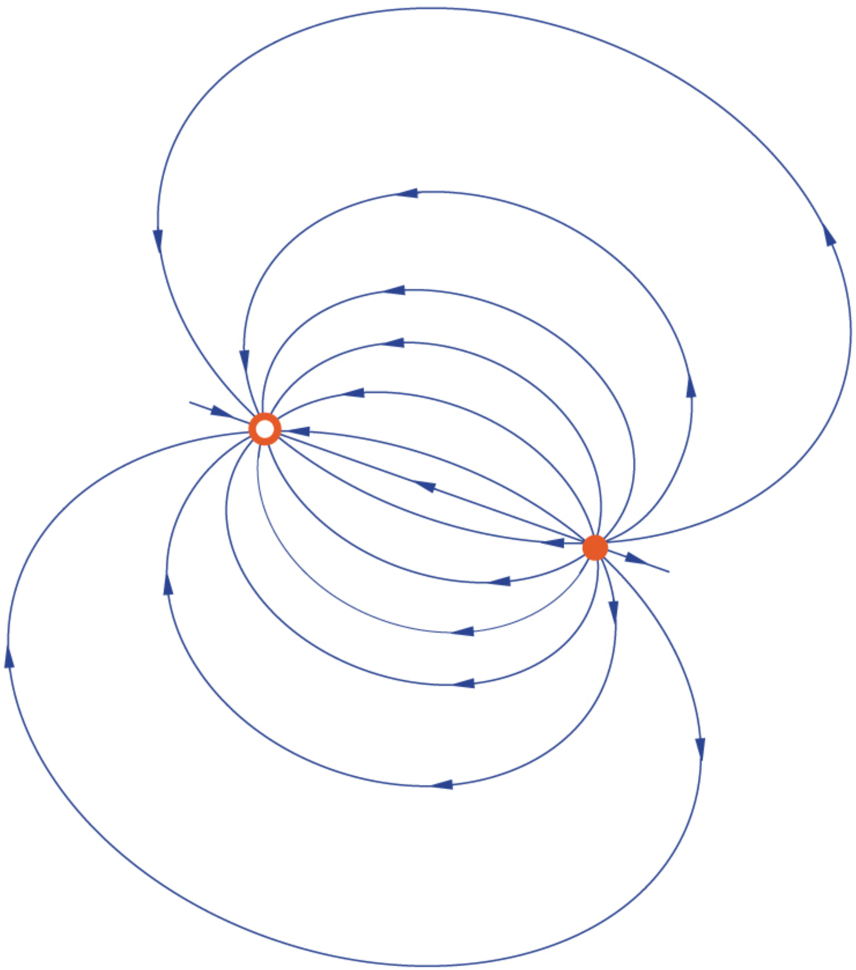
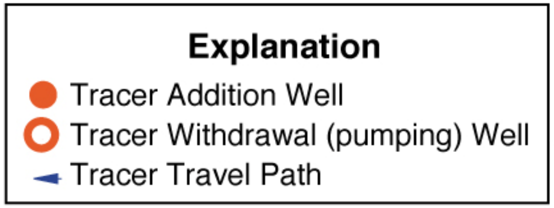
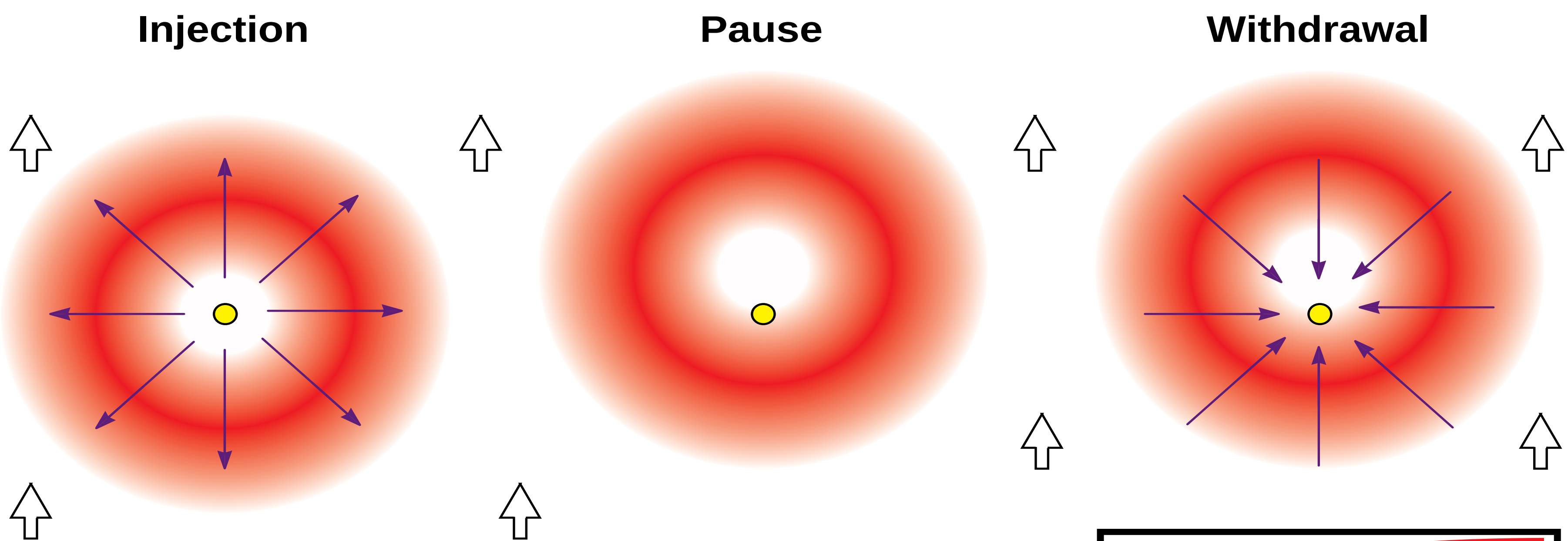
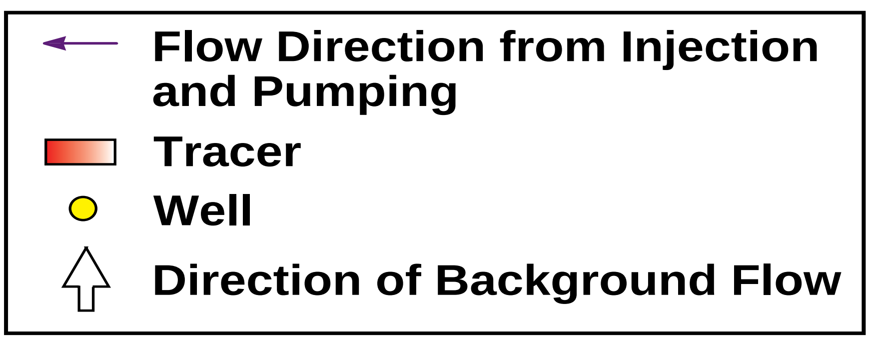
Dipole Tracer Tests

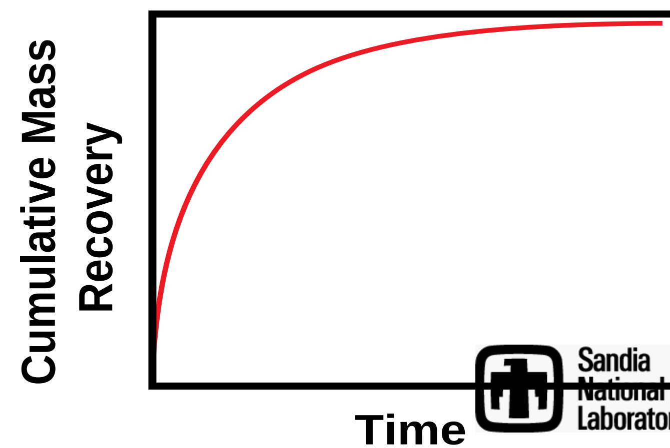




Single-Well
Injection-Withdrawal Tracer Tests







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Strengths and Weaknesses of Convergent-Flow Tests

- **Strengths:**
  - Best test for defining advective porosity
  - Provides most information on three-dimensional variation in transport properties (heterogeneity)
- **Weaknesses:**
  - High requirements (wells, equipment, tracers, analyses, time, money)
  - Relatively insensitive to multiple rates of diffusion

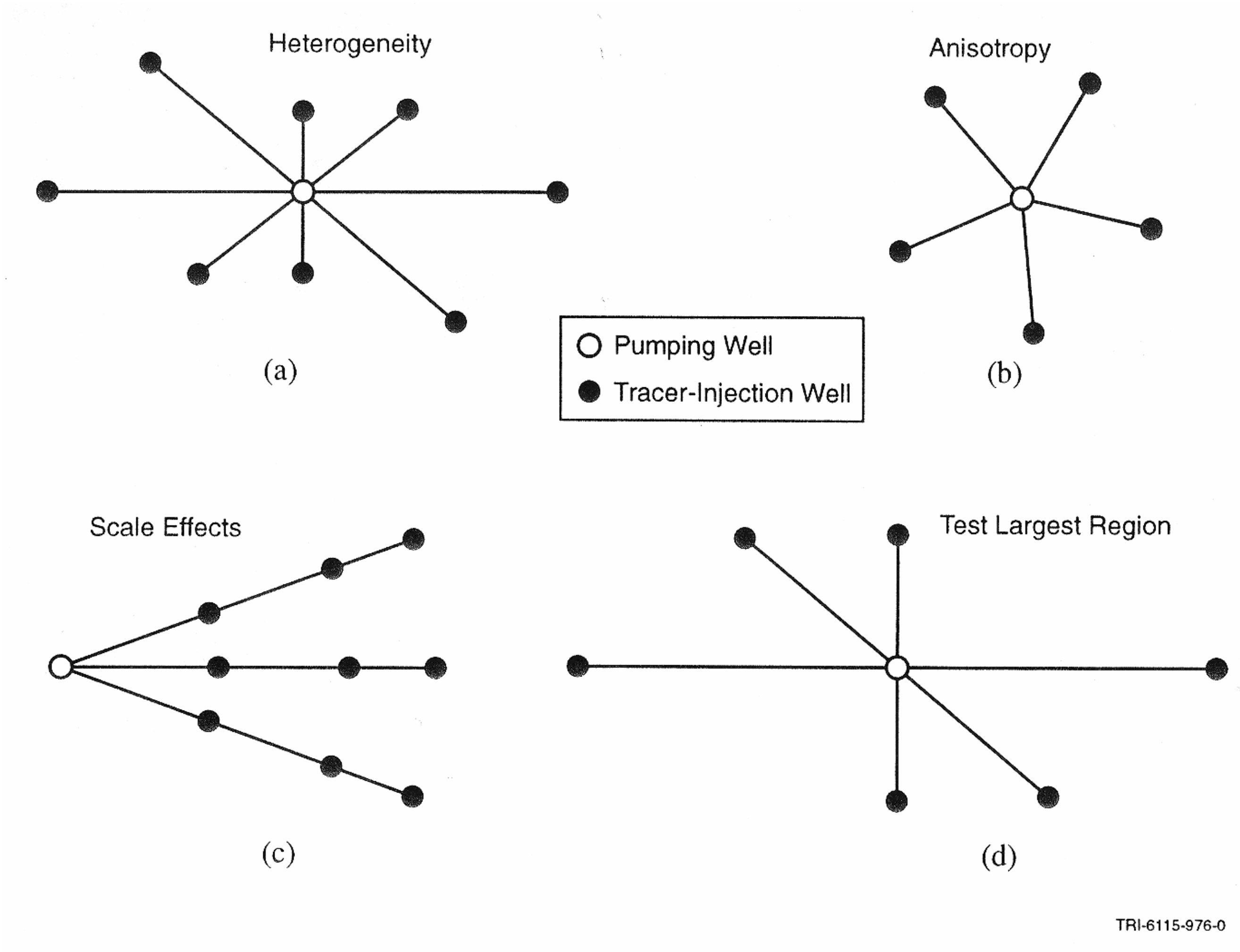
Strengths and Weaknesses of Dipole Tests

- **Strengths:**
  - Equipment requirements are relatively modest—injection and extraction pumps
  - Does not produce large amount of fluids to be disposed
- **Weaknesses:**
  - Provides little information on heterogeneity
  - Provides no clear signature of matrix diffusion

Strengths and Weaknesses of Single-Well Injection-Withdrawal Tests

- Strengths:
  - Best test for demonstrating multirate matrix diffusion
  - Low requirements (wells, equipment, tracers, analyses, time, money)
- Weaknesses:
  - Provides little information on heterogeneity
  - Insensitive to advective (transport) porosity

Design Considerations for Convergent-Flow Test Well Locations



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Design Considerations for Tracer Solutions

- Tracer solubility needs to be sufficiently high to allow detection after dilution by 4-5 orders of magnitude
  - Tracer concentration will decrease in formation due to dispersion and mixing
  - Tracer concentration will further decrease due to matrix diffusion and sorption (if applicable)
- Density contrast between tracer solution and formation water needs to be minimized
  - High-density solution will tend to sink to bottom of injection interval
  - Once in formation, high-density solution will tend to move vertically downward in addition to the desired horizontal movement

Groundwater Tracers Used

- NaI
  - aqueous diffusion coefficient 18.0×10^{-10} m^2/s
- Fluorobenzoates
  - aqueous diffusion coefficients 7.4 to 8.2×10^{-10} m^2/s
- Chlorobenzoates
  - aqueous diffusion coefficients 6.8 to 7.3×10^{-10} m^2/s

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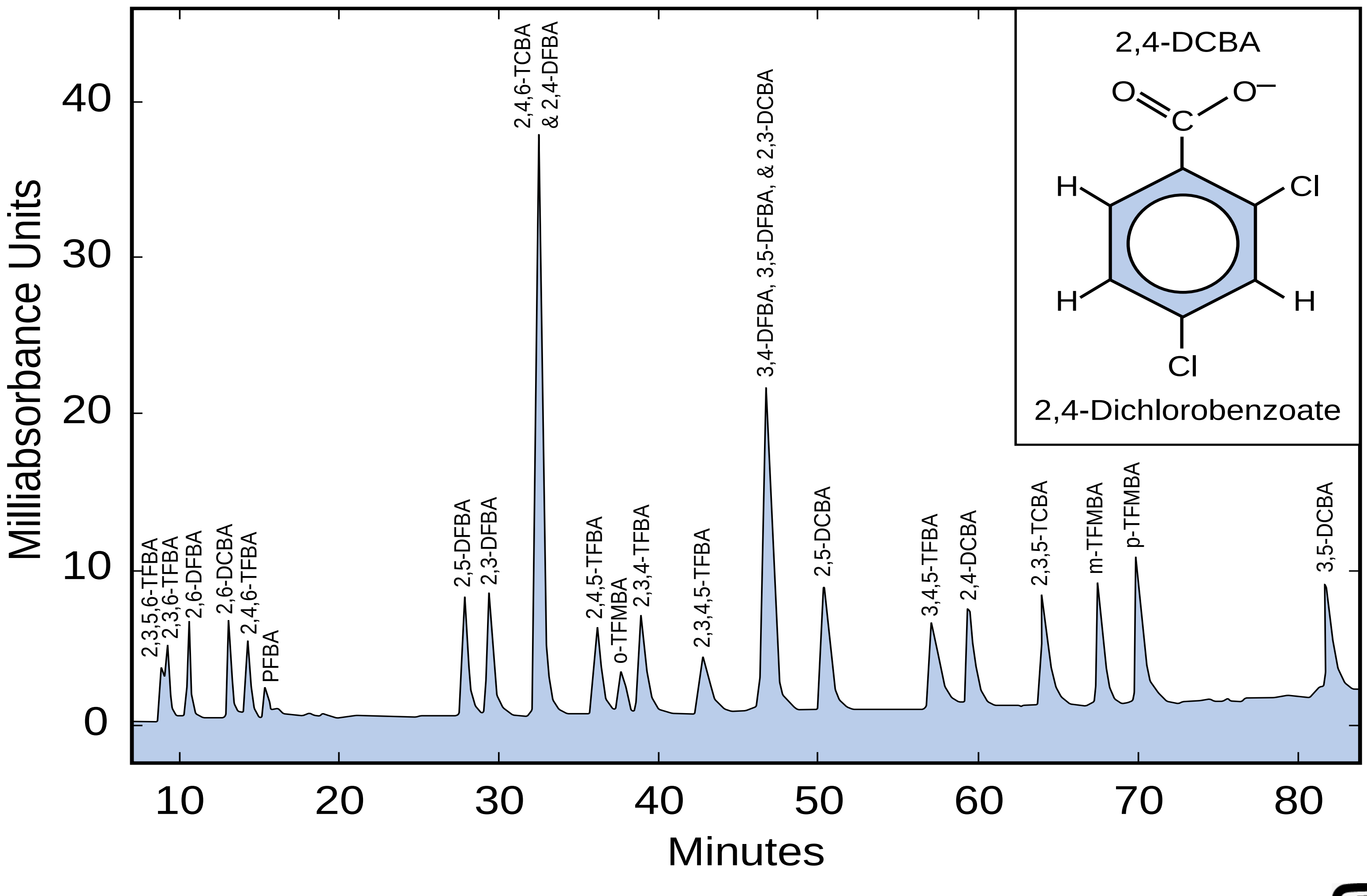
Benefits of Fluoro- and Chlorobenzoates as Groundwater Tracers

- Conservative
  - Tested with batch sorption experiments
- Suitable solubilities
- Low detection limits
- Available in ~20 isomers that can be separated chromatographically
  - Allows for use of numerous tracers along different flowpaths
- Low concentrations in natural groundwaters

Chromatogram for 20 Benzoates



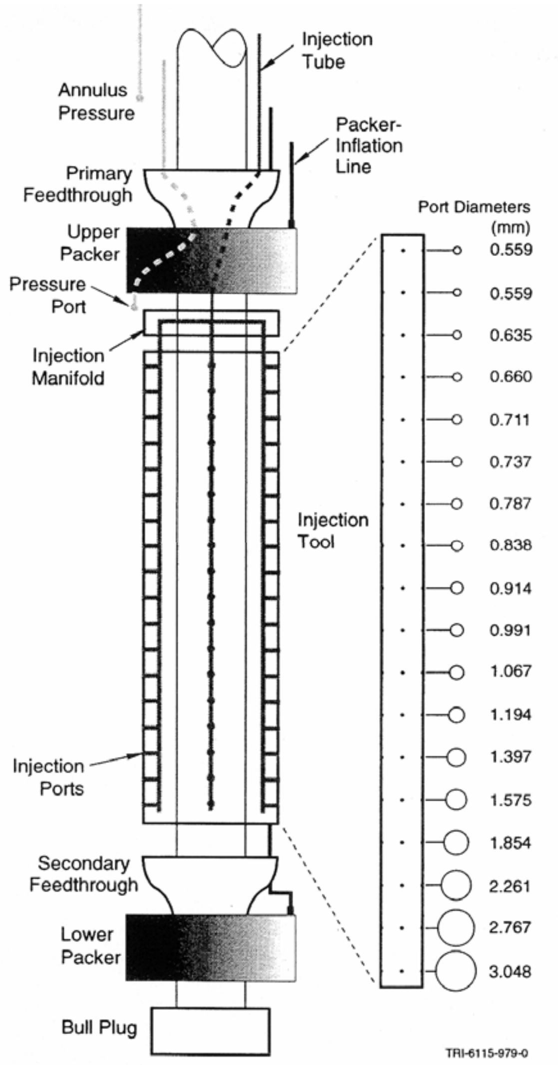
Design Considerations for Tracer-Injection Systems

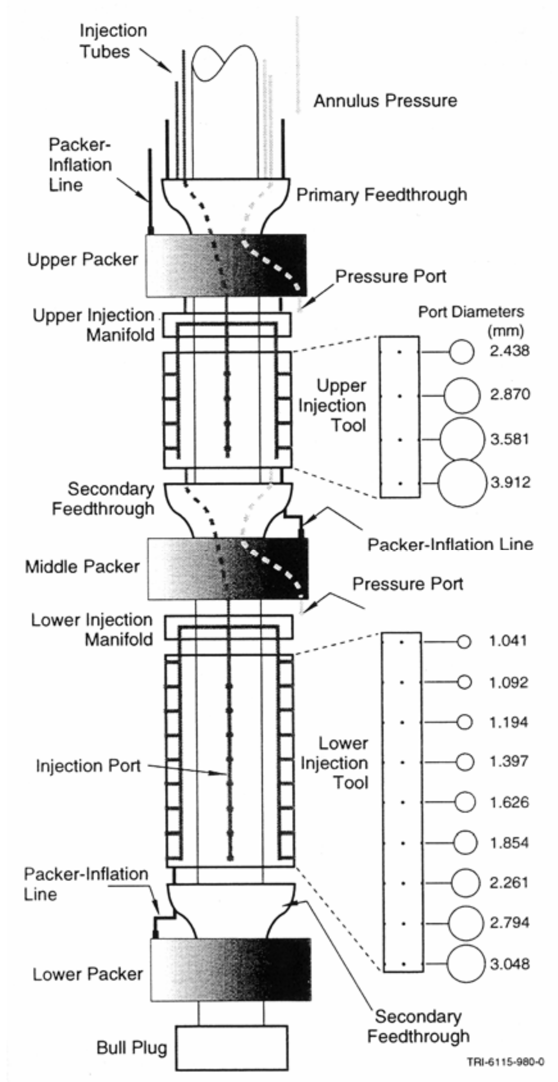
- **Deliver tracer uniformly over thickness of tested formation**
  - Need injection ports evenly distributed both vertically and horizontally (radially)
  - Injection ports need to be progressively sized (diameter increases with depth) to maintain uniform injection rate
- **Minimize interactions between borehole and tracers**
  - Solid tool volume should be large to minimize fluid volume in injection interval
  - Tracer needs to be chased (displaced) by untraced water so it enters the formation rapidly with minimal density-driven stratification

Tracer-Injection Systems

- 1.27-cm O.D. (outside diameter) tracer-injection line from surface to injection manifold at top of injection tool
- Injection manifold splits tracer into four lines of ports
- Ports are ~36 cm apart and increase from 0.56 mm at top to 3.05 mm at bottom for full-thickness tool, 2.44 to 3.91 mm for upper Culebra tool, and 1.04 to 3.05 mm for lower Culebra tool
- Packers set above and below Culebra for all wells, and in middle of Culebra for three wells
- Tool solid volume reduced downhole fluid volume from borehole volume of ~140 L to ~50 L
- Tubing volume ~16 L

Tracer-Injection Systems





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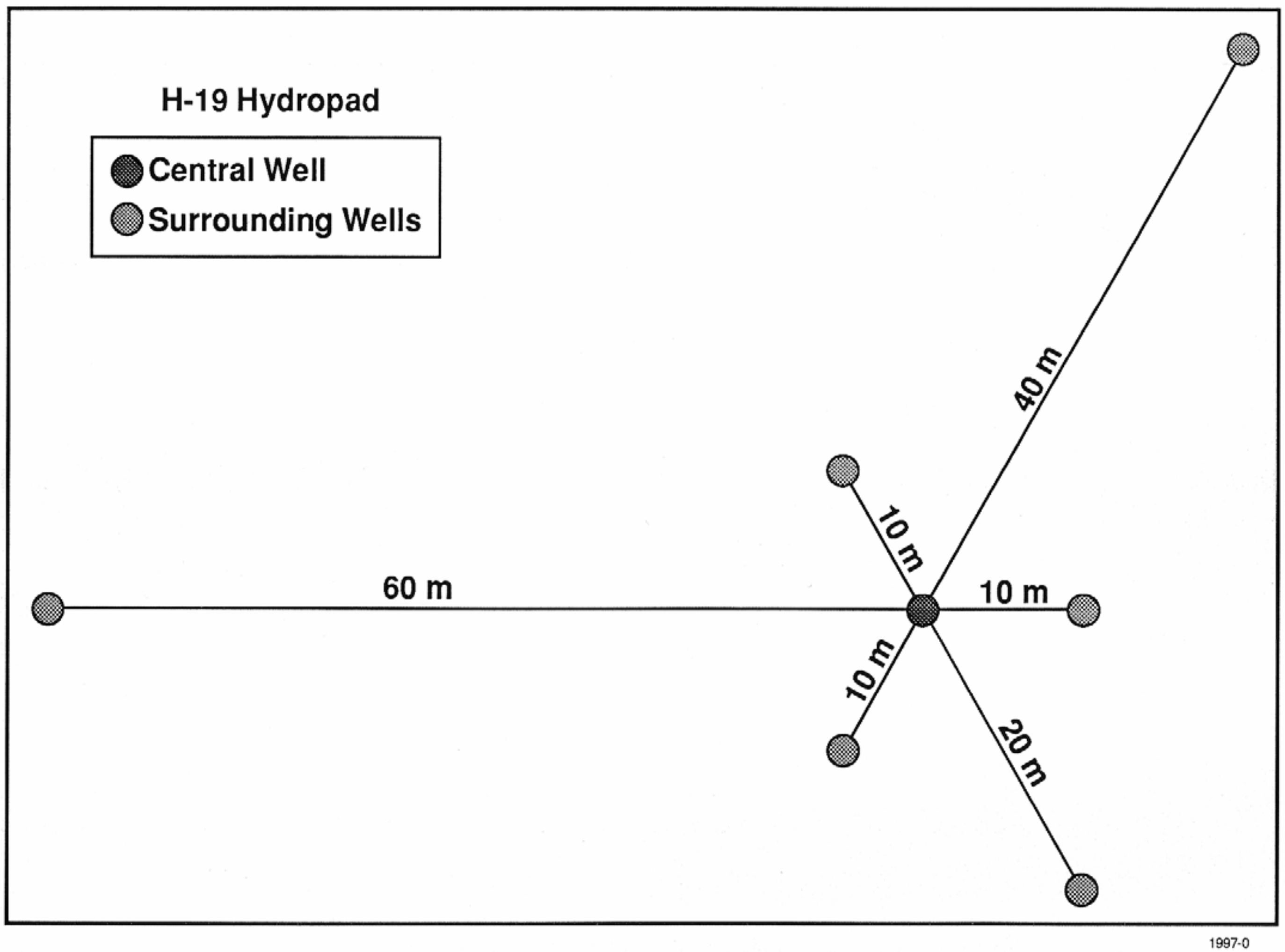
Tracer Injection

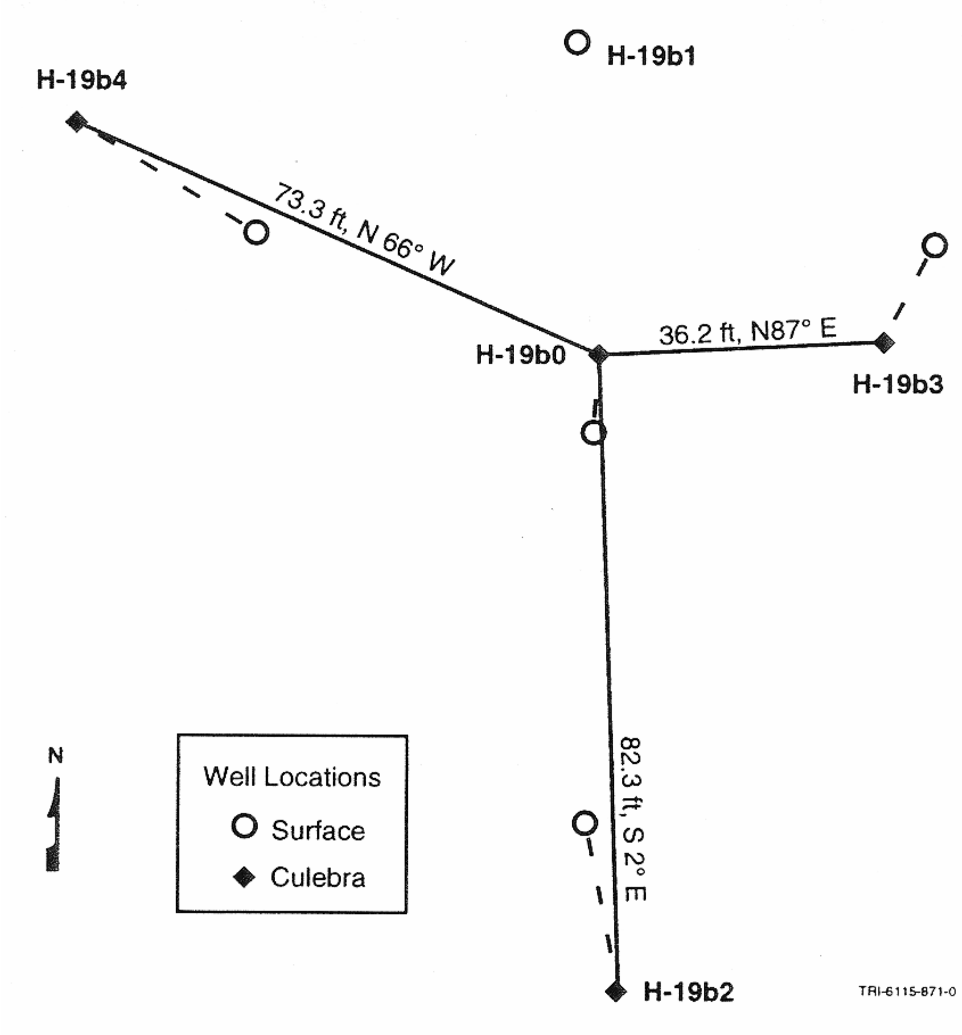
1995-96 Tracer Tests

- Performed in fractured Culebra dolomite
- SWIW and convergent-flow tests performed
- Convergent-flow tests involved three and six different flow paths—preliminary testing performed before locations for final three tracer-injection wells determined
- Employed tracers with different diffusion coefficients
- Tracers injected over full and partial thicknesses of Culebra
- Two different pumping rates used
  - Different velocities allow different times for diffusion

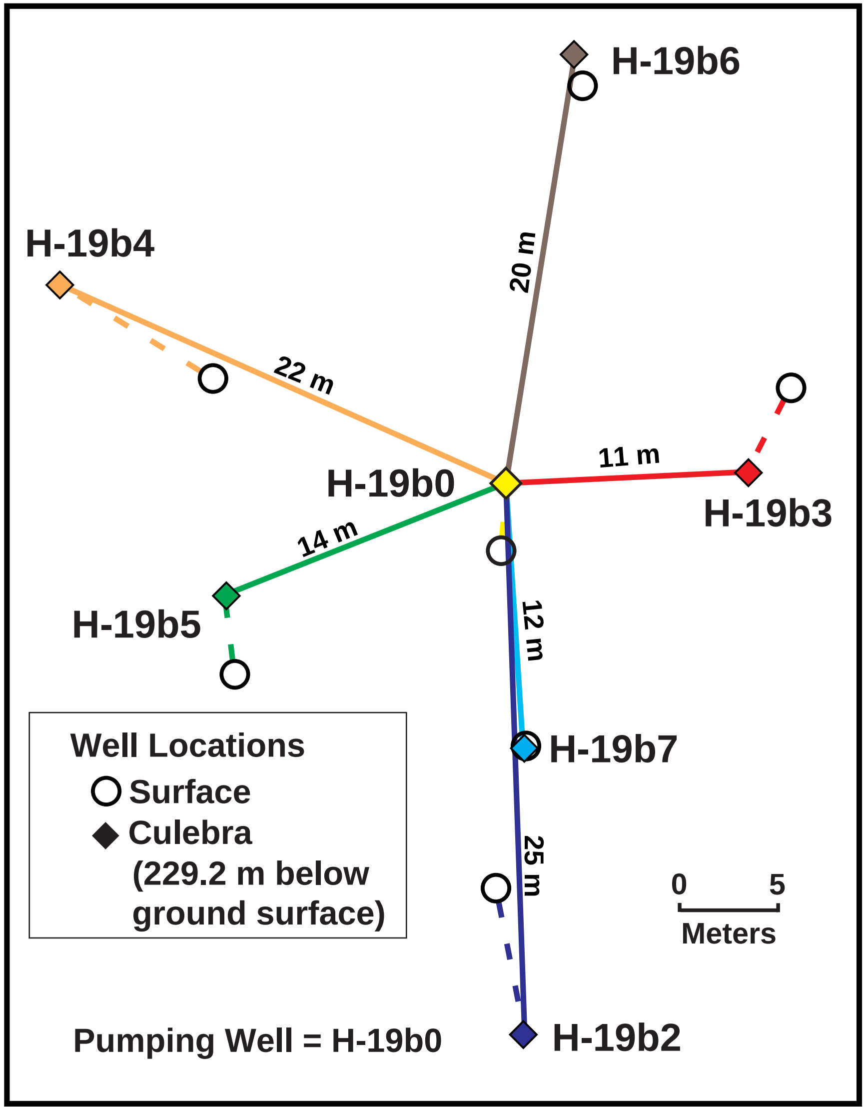
Original Design Concept for H-19 Wells



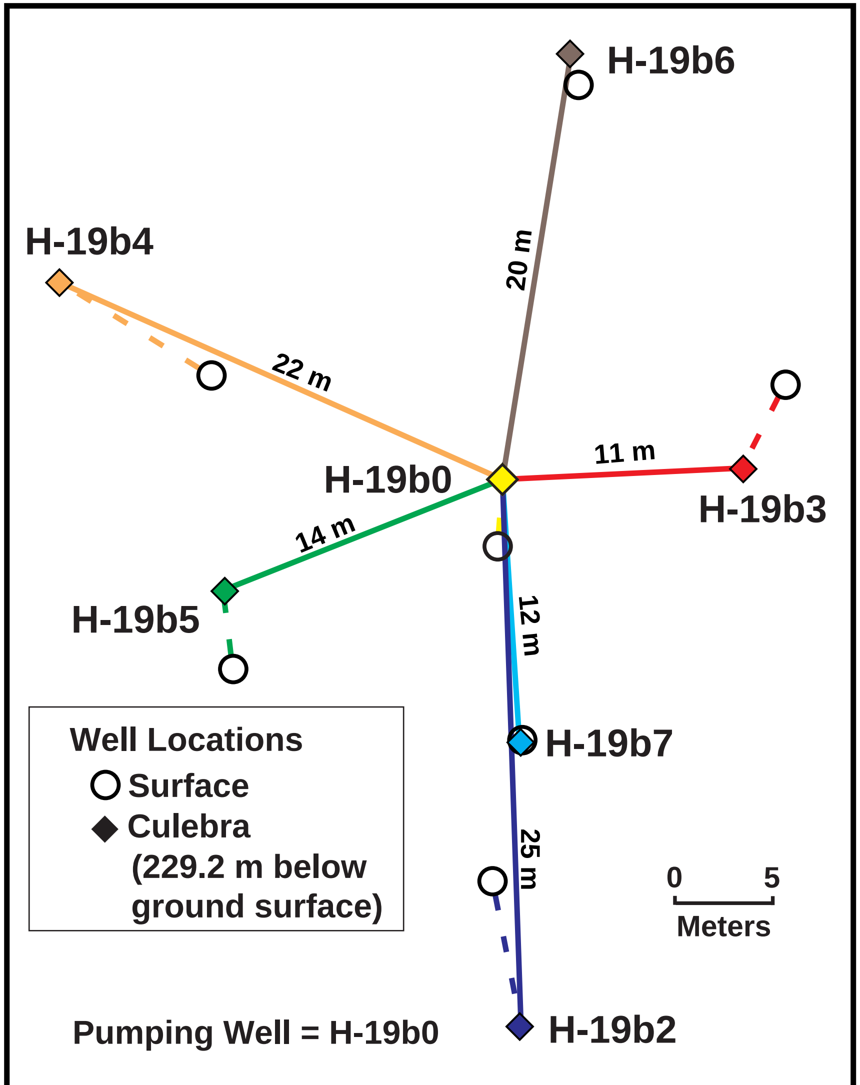
As-Built Locations of First Four H-19 Wells



Final Locations of Seven H-19 Wells



Tracer Testing at H-19 Hydropad



Hydropad designed to provide 6 injection wells and 1 pumping well.

Different tracers injected in each well.

Upper and lower Culebra isolated in three nearest wells and separate tracers injected.

Tracer Testing at H-19 Hydropad (2)

- SWIW tests preceded both convergent-flow tests
  - Tracers injected followed by chaser
  - Pause duration of 18 hr before beginning pumping to recover tracers
- Pumping continued for 5 days to create steady flow field (~constant inter-well gradients [1.3-3.7 m/m]) for convergent-flow tests
- Preliminary test performed at single pumping rate (0.24 L/s) with first three injection wells

Advantages of Preliminary Tests

- Allow testing of equipment
- Provide experience for field crew
- Allow estimation of properties for better placement of additional wells

SWIW Tracer Injection at H-19

- Preliminary test:
  - 1000 L of a 5 g/L tracer solution 1 injected over the entire Culebra
  - 1000 L of a 2 g/L tracer solution 2 injected over the entire Culebra
  - 1000 L of chaser solution used to displace tracer into formation
- Final test:
  - 850 L of a 6 g/L tracer solution injected over the lower Culebra only
  - 1700 L of chaser solution used to displace tracer into formation
- Tracer and chaser injection rates ranged from 0.12 to 0.13 L/s

Convergent-Flow Tracer Injection

- 200 L of a 10-g/L tracer solution injected in most cases
- Chaser volumes 2-3 times the borehole fluid volume used to displace tracer into formation
- Tracer and chaser injection rates ranged from 0.008 to 0.23 L/s

3 Rounds of Tracer Injection at H-19

- Round 1, Q = 0.27 L/s, injection over full Culebra in H-19b2, 3, 4, 6, and 7, injection over upper and lower Culebra separately in H-19b5, simultaneous injection of tracers with different diffusion coefficients in H-19b3
- Round 2, Q = 0.25 L/s, injection over full Culebra in H-19b5, injection over upper and lower Culebra separately in H-19b3 and 7
- Round 3, Q = 0.16 L/s, injection over full Culebra in H-19b3, 6, and 7, simultaneous injection of tracers with different diffusion coefficients in H-19b7

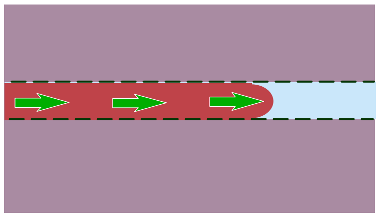
Time Corrections

- Tracer-injection time (t_0) needs to be corrected for travel time down tubing to injection interval
- Tracer-recovery times need to be corrected for travel time up tubing to sampling point
- Typical correction times 35-75 minutes

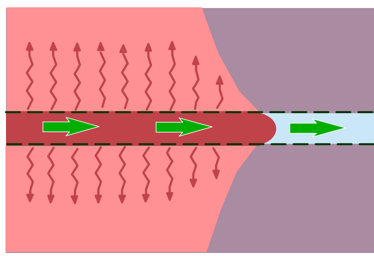
Analysis of Tracer Tests to Provide a Defensible Model for PA

Conceptual Model

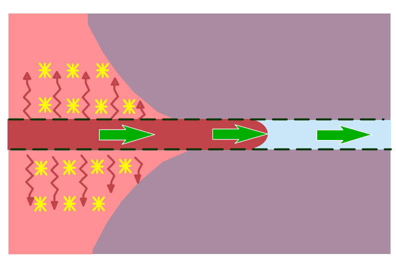
Single-Porosity Fracture-Only Transport

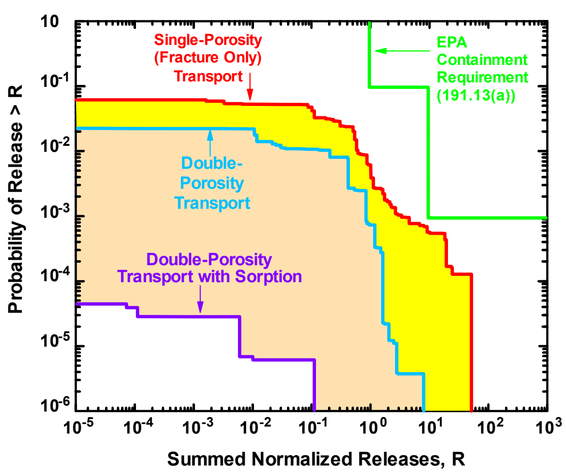


Double-Porosity Nonreactive Transport (Physical Retardation)



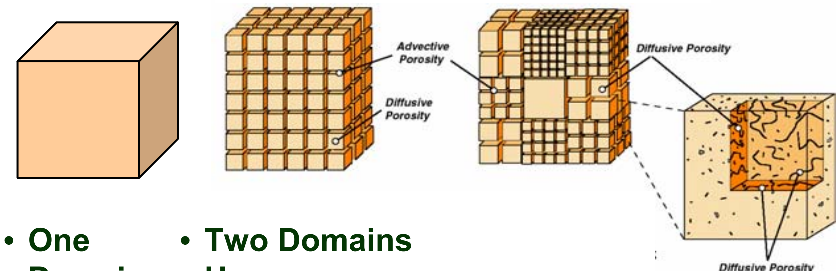
Double-Porosity Reactive Transport (Physical and Chemical Retardation)

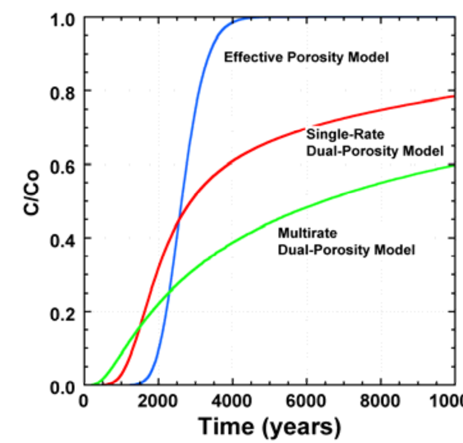




Numerical Implementation

Effective-Porosity Model	Conventional Single-Rate Diffusion	Multirate Diffusion
• One Domain	• Two Domains • Homogeneous Matrix and Fracture	• Two Domains • Heterogeneous Matrix and Fracture





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Numerical Interpretation of Tracer Tests

- Two-dimensional heterogeneous, single-porosity model
  - Test the appropriateness of single-porosity vs. double-porosity conceptualization
- One-dimensional, single-diffusion-rate, double-porosity model (STAMMT-R)
- One-dimensional, multiple-diffusion-rate, double-porosity model (STAMMT-R)

Damköhler Numbers

DaI = $\alpha(\beta^*+1)LR/v$

- α = mass-transfer coefficient (1/T)
- β^* = capacity coefficient
- L = advection travel length (L)
- R = retardation coefficient
- v = pore water velocity (L/T)

DaI > 100 -- “instantaneous” diffusion -- local equilibrium assumption (LEA)

DaI < 0.01 -- no diffusion -- transport only in advective porosity

Double-porosity behavior is observed when DaI is between 0.01 and 100

STAMMT-R

- Solute Transport and Multirate Mass Transfer in Radial Coordinates
  - One-dimensional (radial) simulator for SWIW and convergent-flow tests
  - Assumes power-law distribution of diffusion rate coefficients
  - Determines best-fit distribution of diffusion rates by optimizing on advective porosity, longitudinal dispersivity, mean of diffusion rate distribution, and standard deviation of diffusion rate distribution
  - Does not (currently) include sorption or radionuclide decay
- STAMMT-L (linear) version can be used for PA calculations of transport

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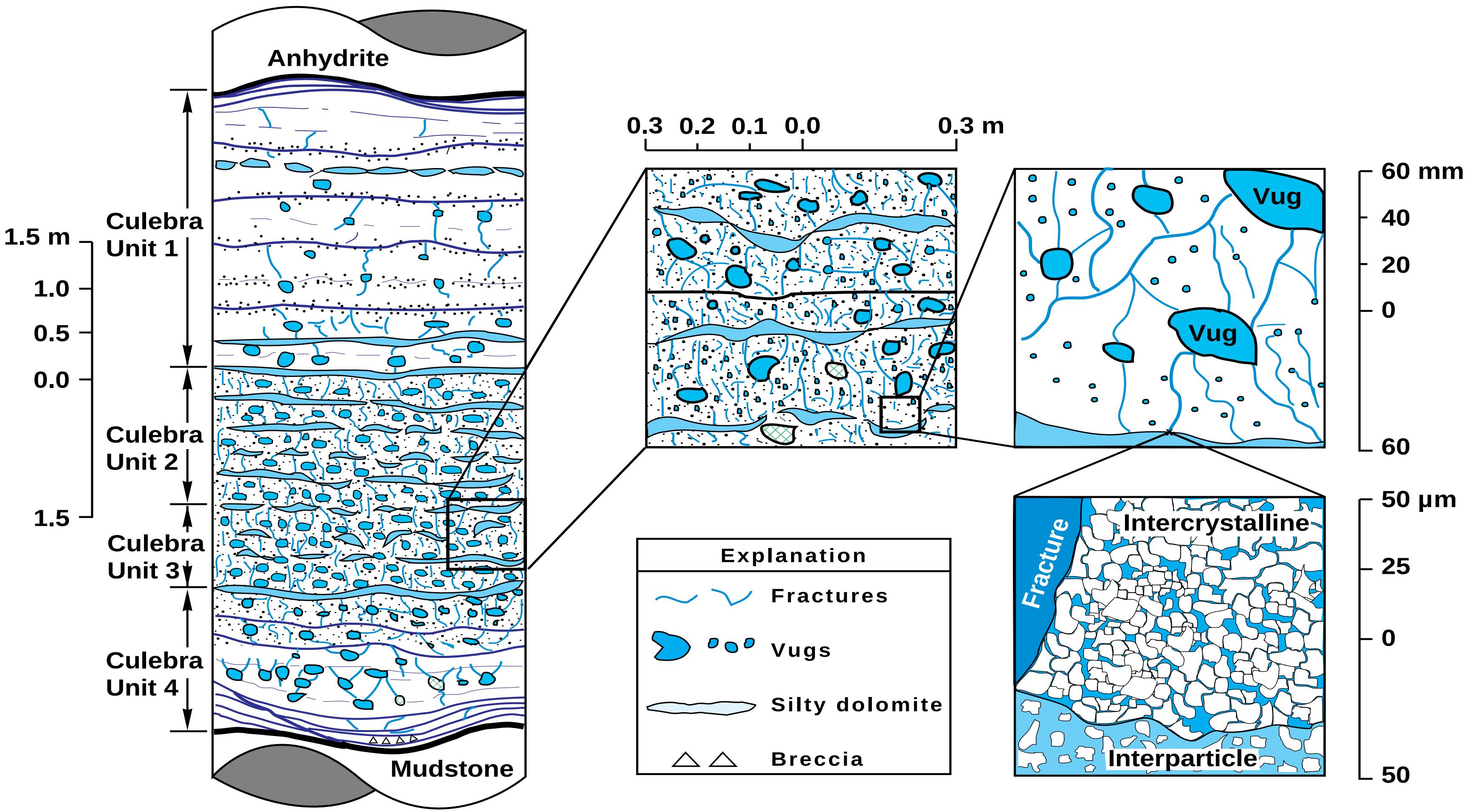
Multiple Scales of Culebra Porosity



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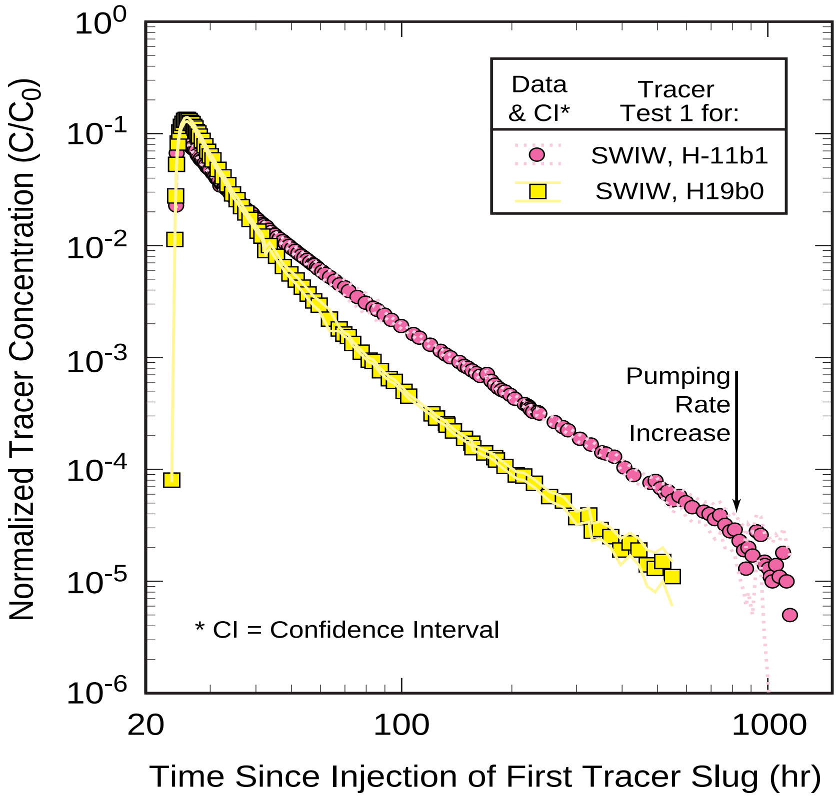
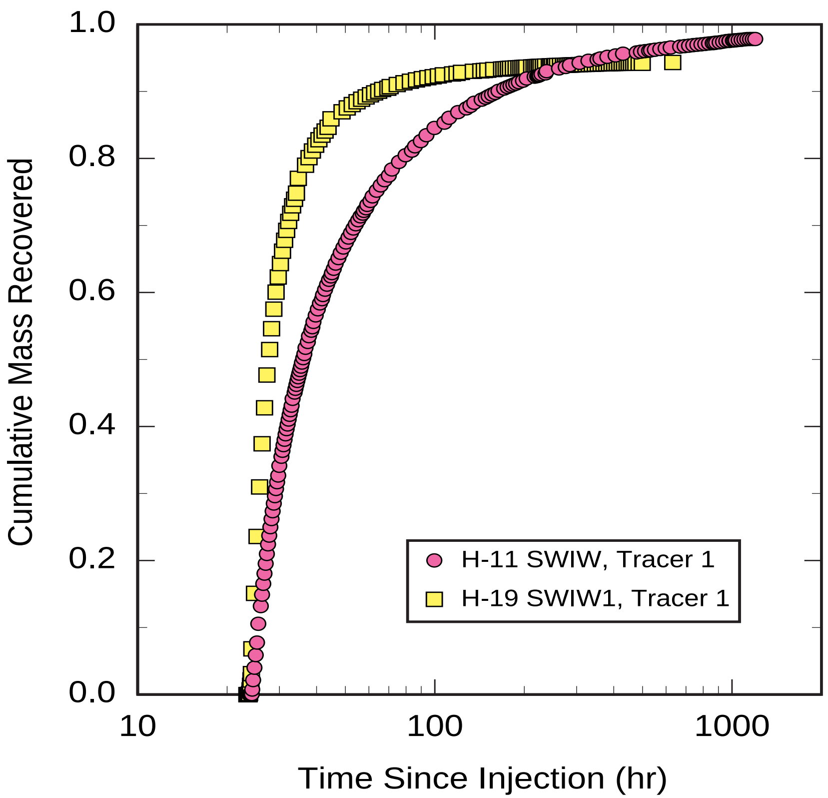
SWIW Test Results

- 94-98% mass recovered
- Log-log tracer-recovery curves do not exhibit the -1.5 slope expected from matrix diffusion (at a single rate)
- Observed slopes of -2.2 to -2.8 can be explained by multiple rates of matrix diffusion

SWIW Test Data





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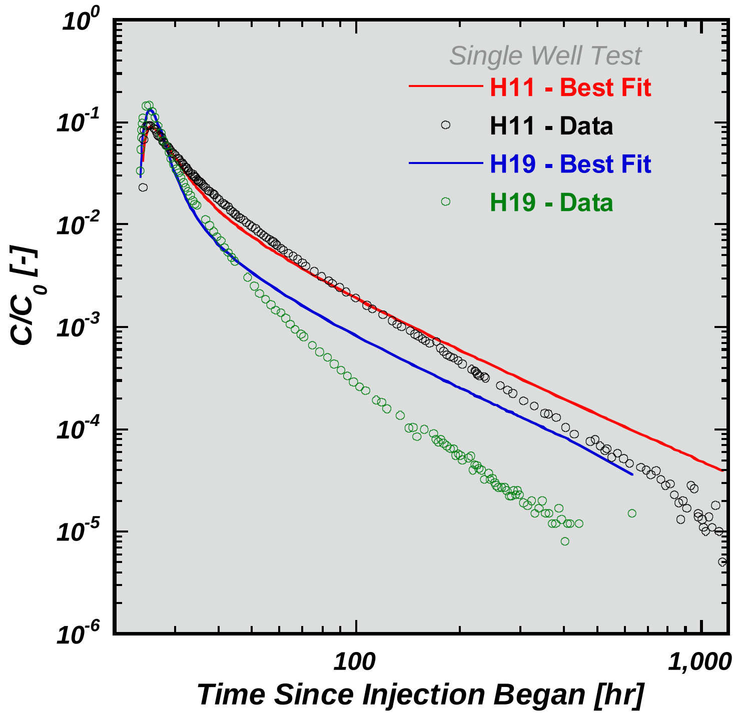
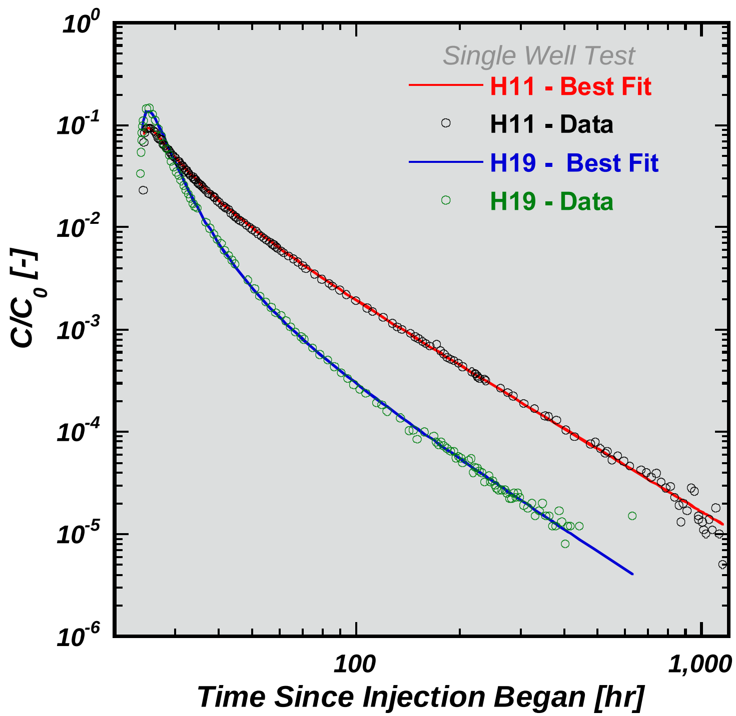
STAMMT-R Results for SWIW Tests

Single-Rate Model



Cannot Capture Tailing Behavior

Multirate Model



Provides Excellent Fits Throughout Time Range

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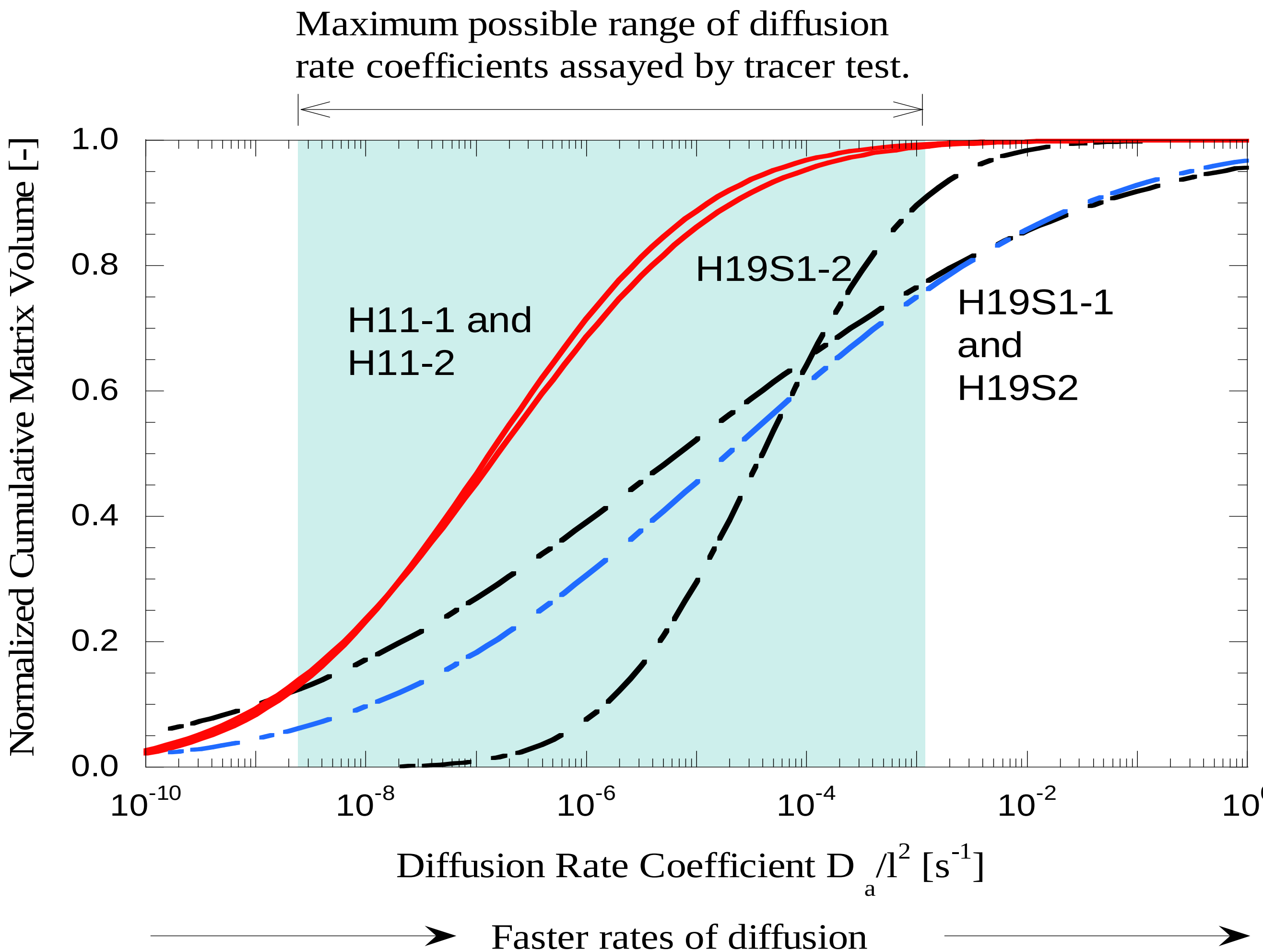
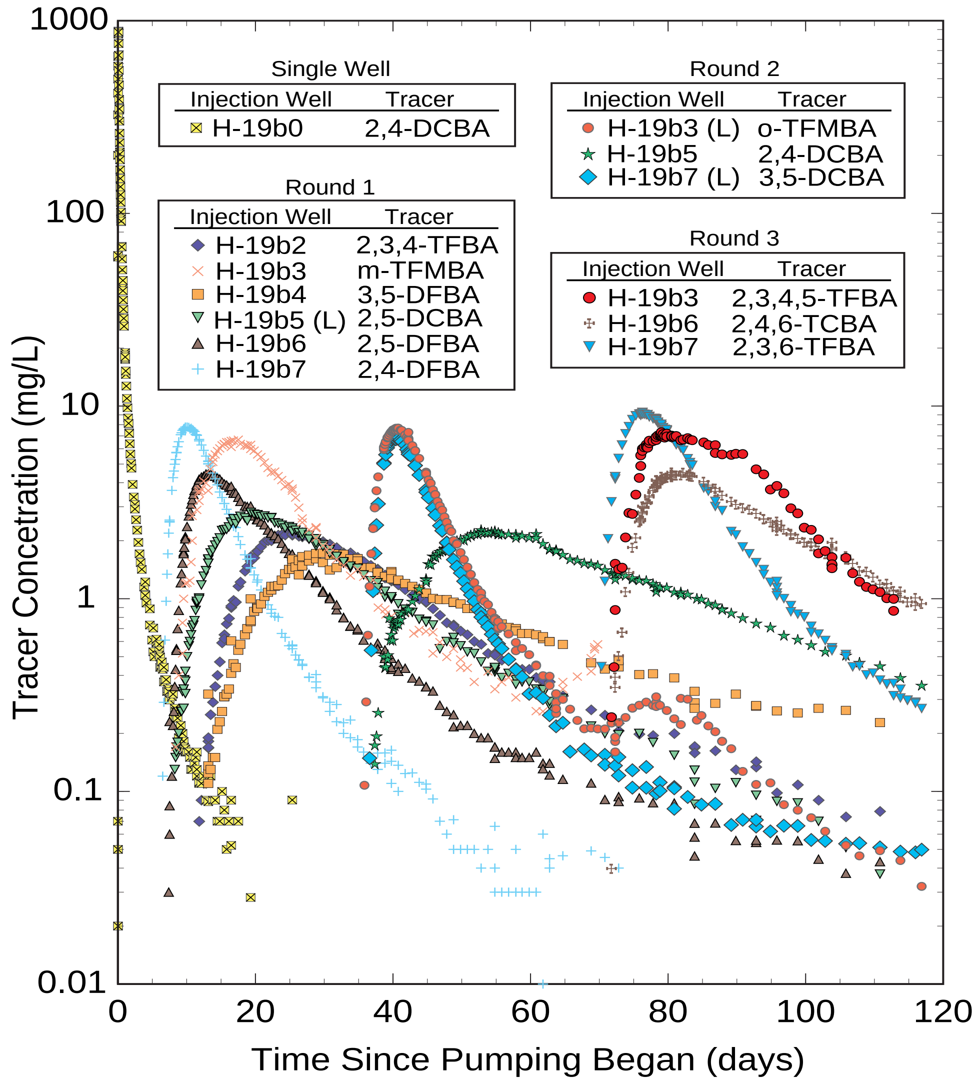
STAMMT-R Results for SWIW Tests



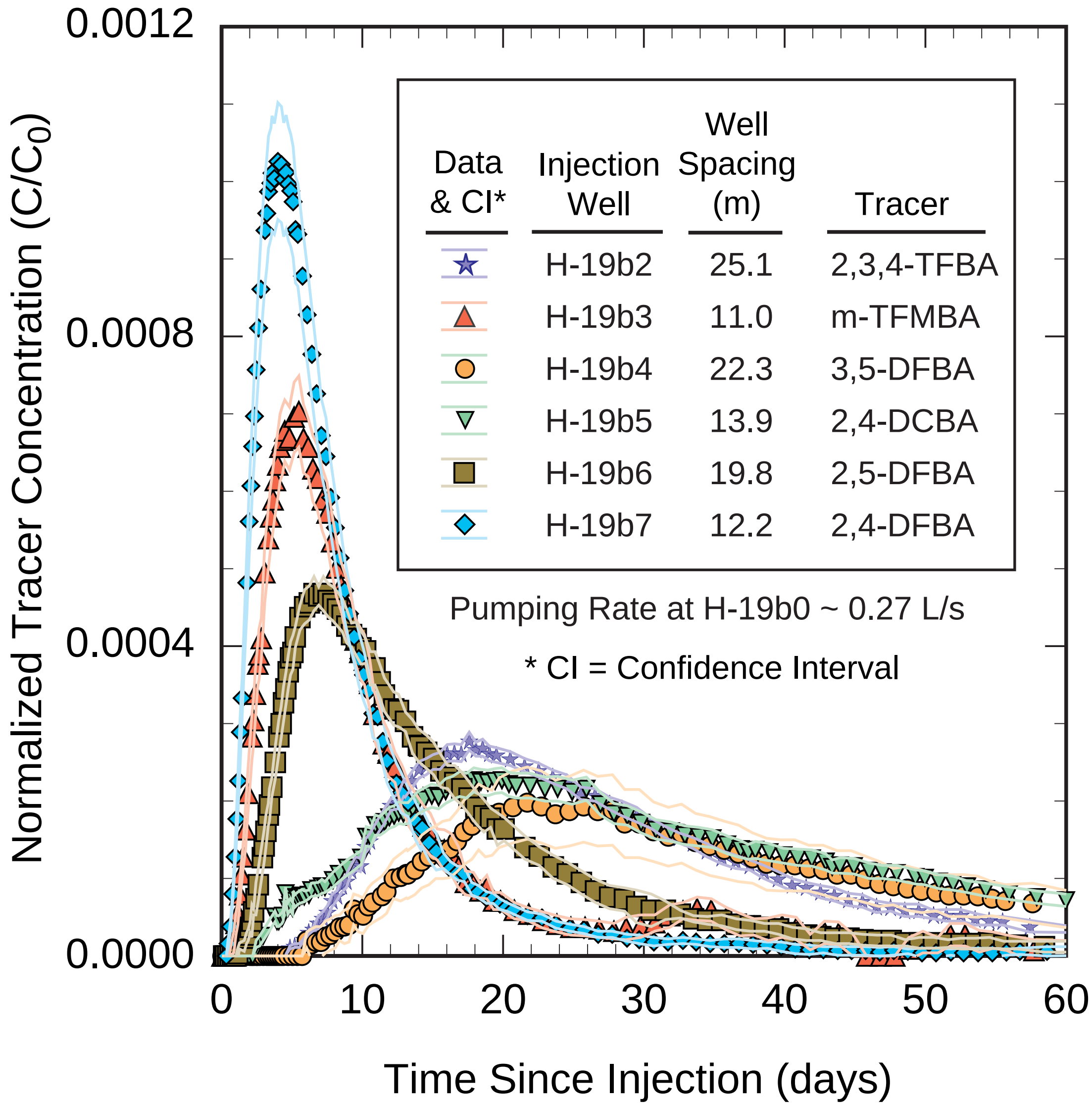
Convergent-Flow Final Test Results

- 74-103% mass recovered for full and lower Culebra intervals; 5-18% mass recovered for upper Culebra intervals
- Times to peak concentration do not show uniform relationship to travel path length
- Peak heights show little difference for pumping rate variations of less than a factor of two
- Multirate diffusion model fits breakthrough curves only slightly better than single-rate model

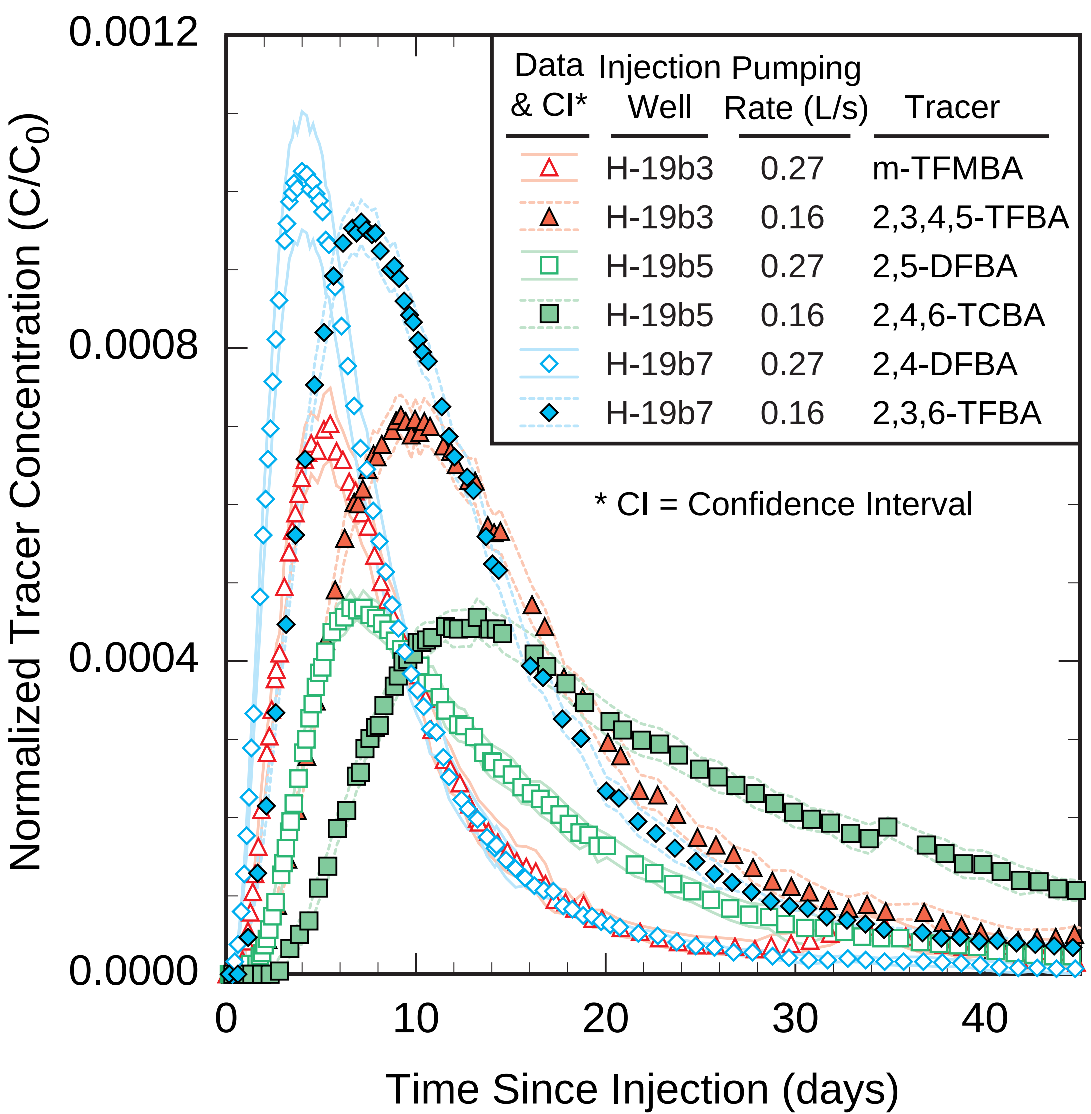
H-19 Tracer Test Data



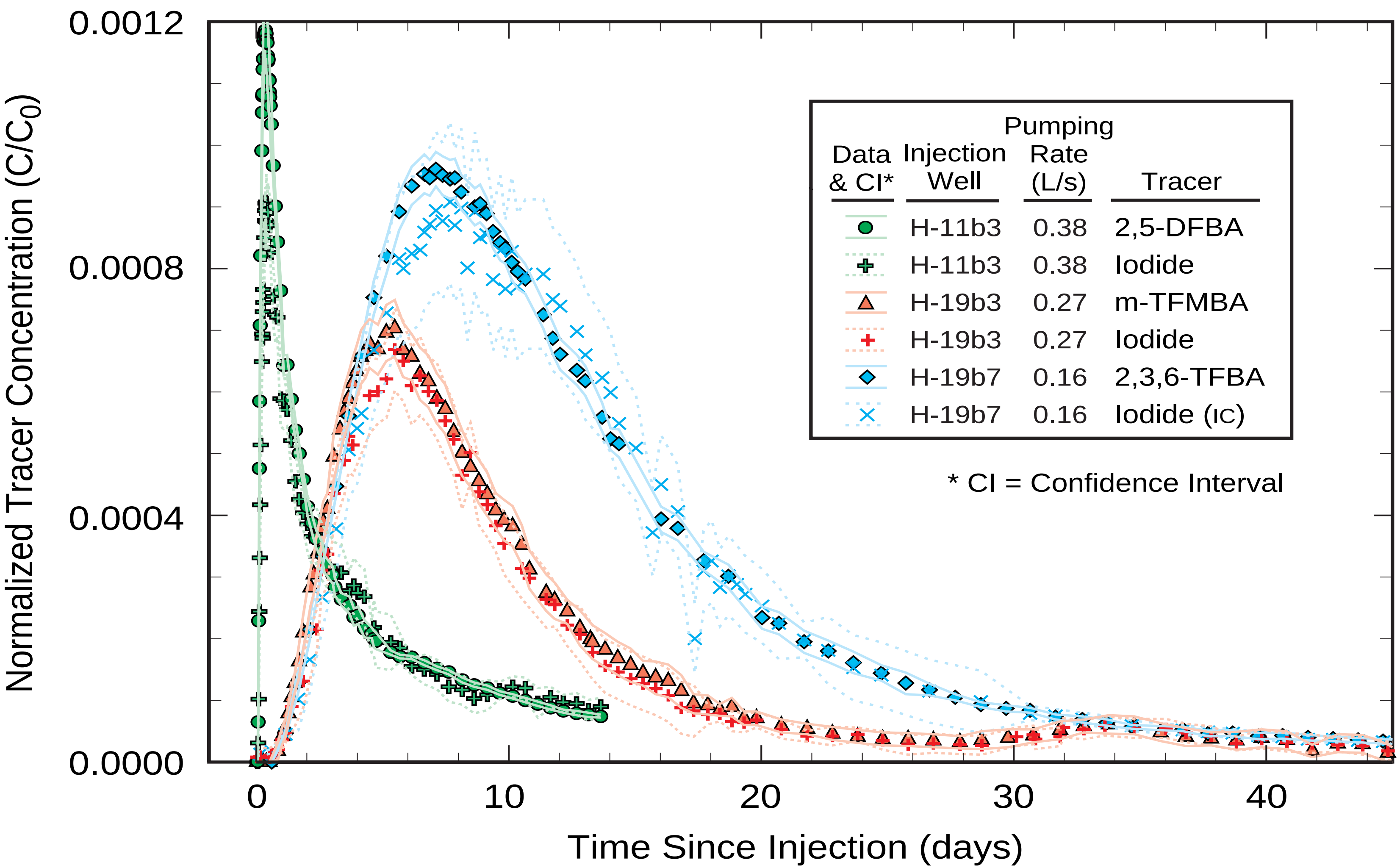
H-19 Breakthrough Curves (BTC's) for High Pumping Rate



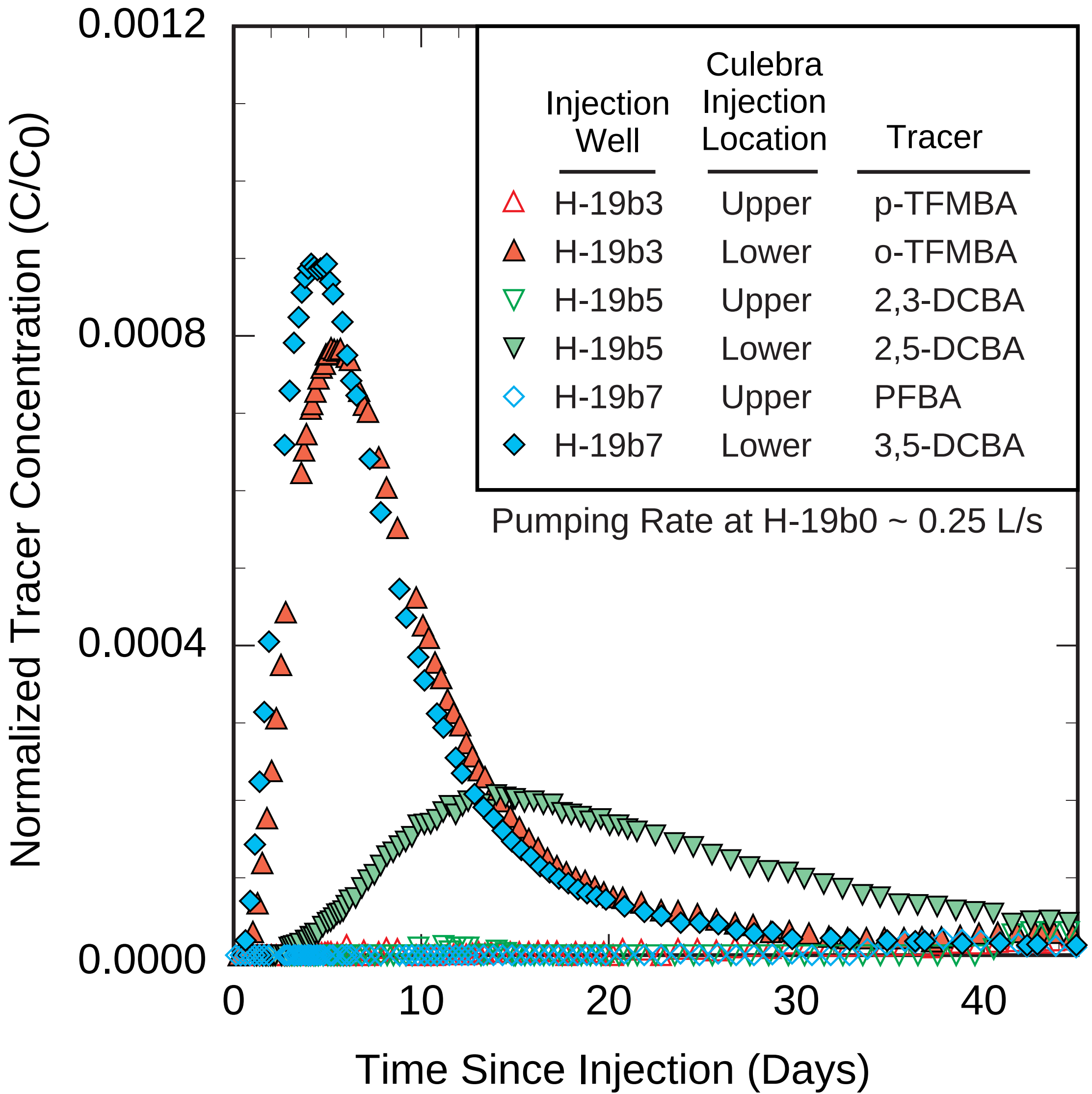
Comparison of BTC's for High and Low Pumping Rates



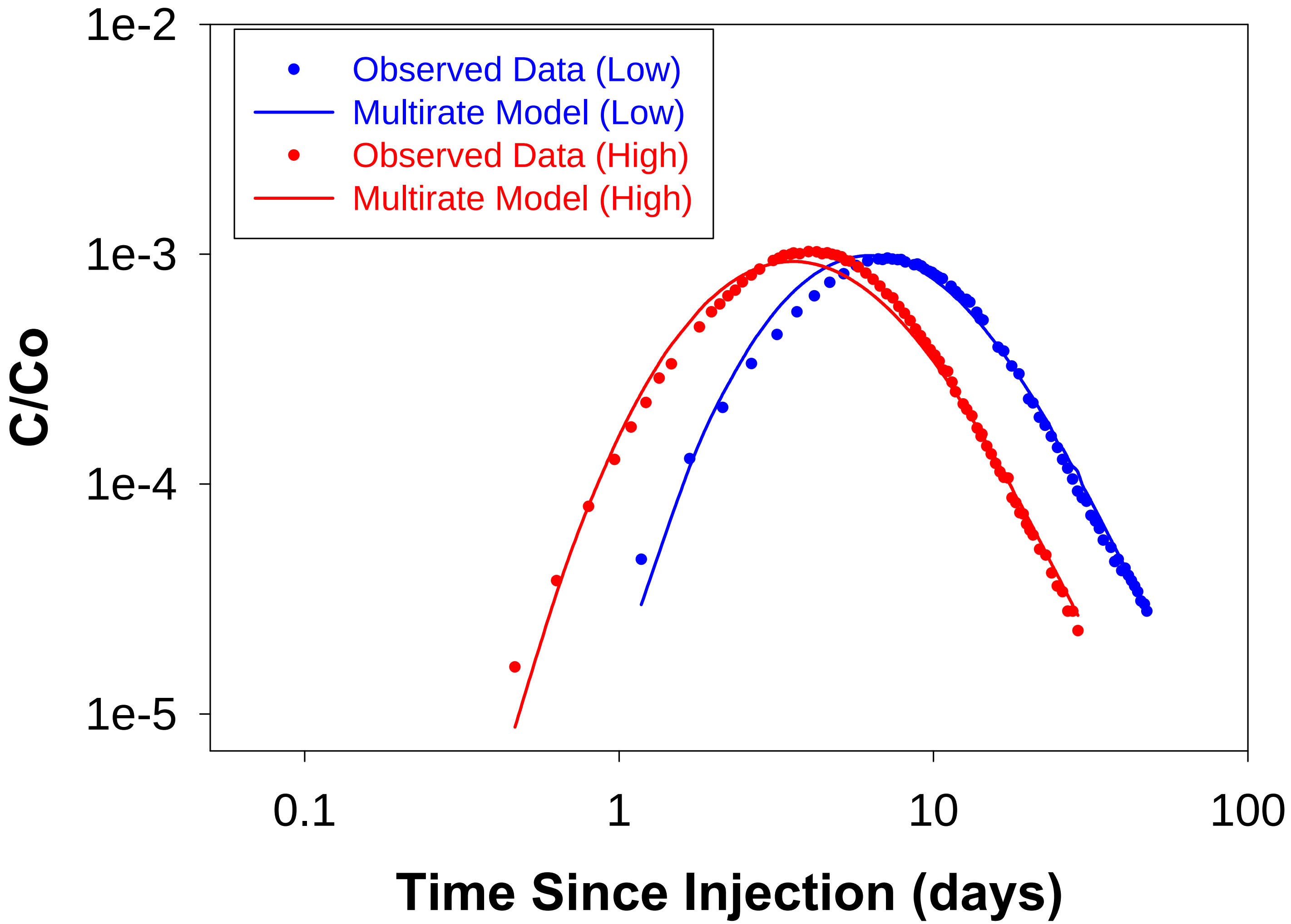
Comparison of BTC's for Tracers with Different Diffusion Coefficients



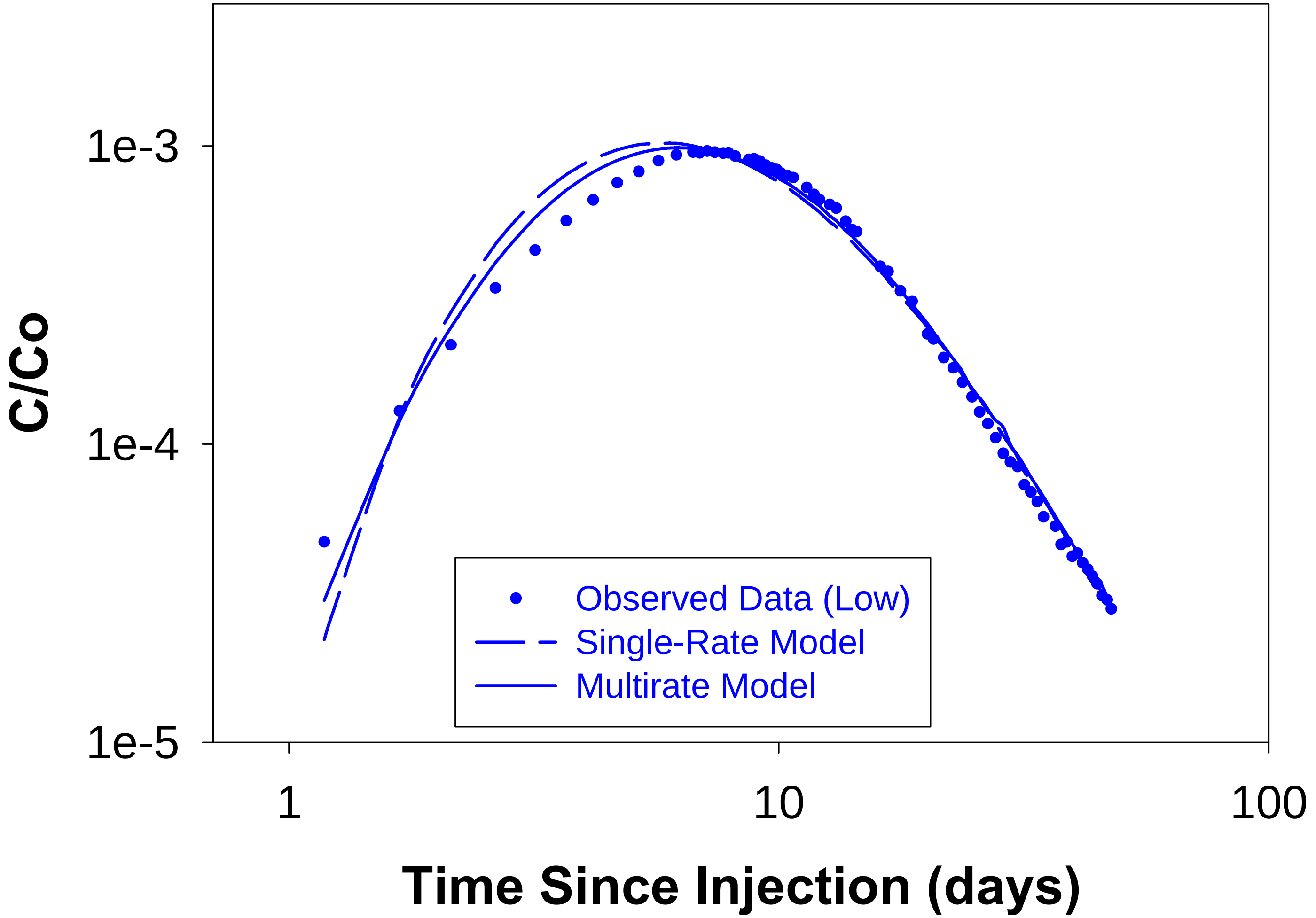
Comparison of BTC's for Injection Into Upper and Lower Culebra



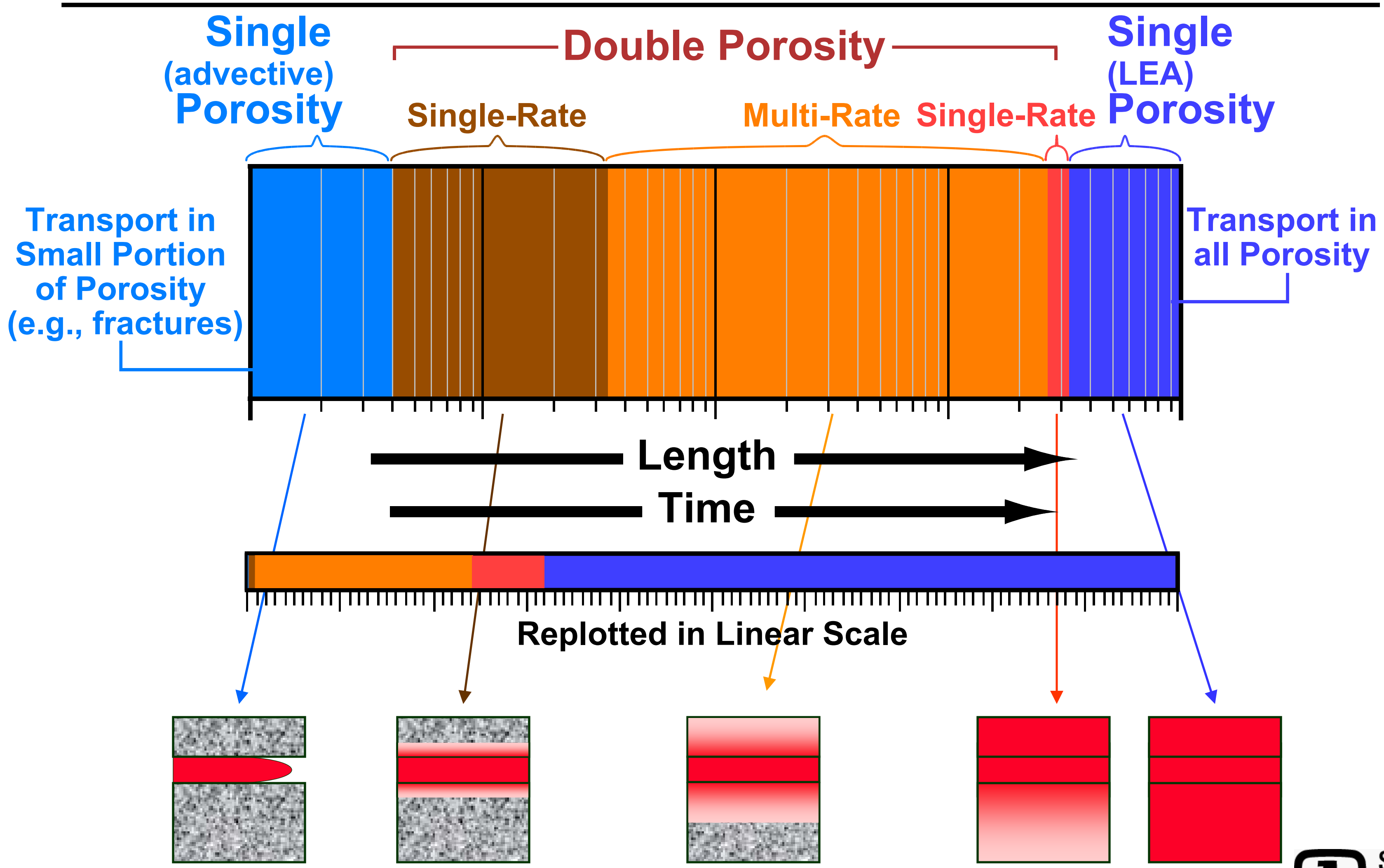
STAMMT-R Results for Convergent-Flow Tests



STAMMT-R Results for Convergent-Flow Tests



Expected Culebra Transport Behavior as a Function of Distance and Time



Integration of Tracer Tests into Site Licensing

Tracer Tests: 1980-1988

- 5 locations
- Types of tests
  1) Convergent-flow tests
  2) Dipole tests
- Analysis method:
  1) radial (1D) single-rate, double-porosity model

Tracer Tests: 1995-1996

- 2 locations
- Types of tests:
  1) Convergent-flow tests
  2) Single-well injection-withdrawal tests
- Analysis methods:
  1) 2D (heterogeneous) single-rate, double-porosity model
  2) radial (1D) single-rate, double-porosity model
  3) radial (1D) multirate, double-porosity model

Recognized need to reduce conceptual model and data uncertainty (1994)

Comments of Independent Reviewers

- Questioned matrix diffusion as mechanism for retardation
- Suggested alternative mechanisms:
  1) Channeling caused heterogeneity
  2) Delayed release of tracer from the injection wells

Use for Compliance and Certification

- Confirmed matrix diffusion as a mechanism for retardation
- Provided credible, defensible and realistic model
- Model reviewed and accepted by EPA-mandated Conceptual Model and Natural Barriers Peer Review Panels
- Provided basis for simplified PA model
- Provided important physical transport parameters for PA
- Provided rationale for parameters

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Recommendations for Tracer Testing

- Combine use of SWIW and convergent-flow tests:
  - SWIW tests sensitive to multiple rates of diffusion
  - Convergent-flow tests sensitive to advective porosity
- Vary pumping rates and tracer diffusion coefficients over as wide ranges as possible:
  - Use to discriminate matrix diffusion from heterogeneity
- "Validate" results by blind prediction of results expected for as-yet-untested flow path(s)
  - Convert tracer-injection well from first test(s) to pumping well for new test, and perform new tests with different orientation of hydraulic gradients

Avenues for Future Research

- **Better definition of injection source term:**
  - Concentration in injection wellbore as function of time
  - Relative percentages of tracer entering formation at different levels / fractures
- **Better definition of interwell velocities:**
  - First order: account for anisotropy in transmissivity (flow to pumping well is NOT uniformly distributed radially)
  - Second order: account for vertical heterogeneity (fast vs. slow layers)
- **Integrated analysis of multiple breakthrough curves:**
  - Determine single distribution of diffusion rates that provides best fits to ALL data simultaneously

Recent Sandia Tracer References

Meigs, L.C., and R.L. Beauheim, 2001. Tracer tests in a fractured dolomite 1. Experimental design and observed tracer recoveries, *Water Resources Research, 37(5),* 1113-1128.

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Haggerty, R., S.A. McKenna, and L.C. Meigs. 2000. On the late-time behavior of tracer test breakthrough curves, *Water Resources Research*, 36(12), 3467-3479.

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