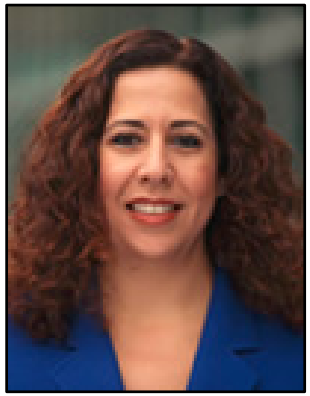
Characterization and Remediation in Fractured Rock Environments

August 20, 2015

SERDP DOD • EPA • DOE | ESTCP

Welcome and Introductions

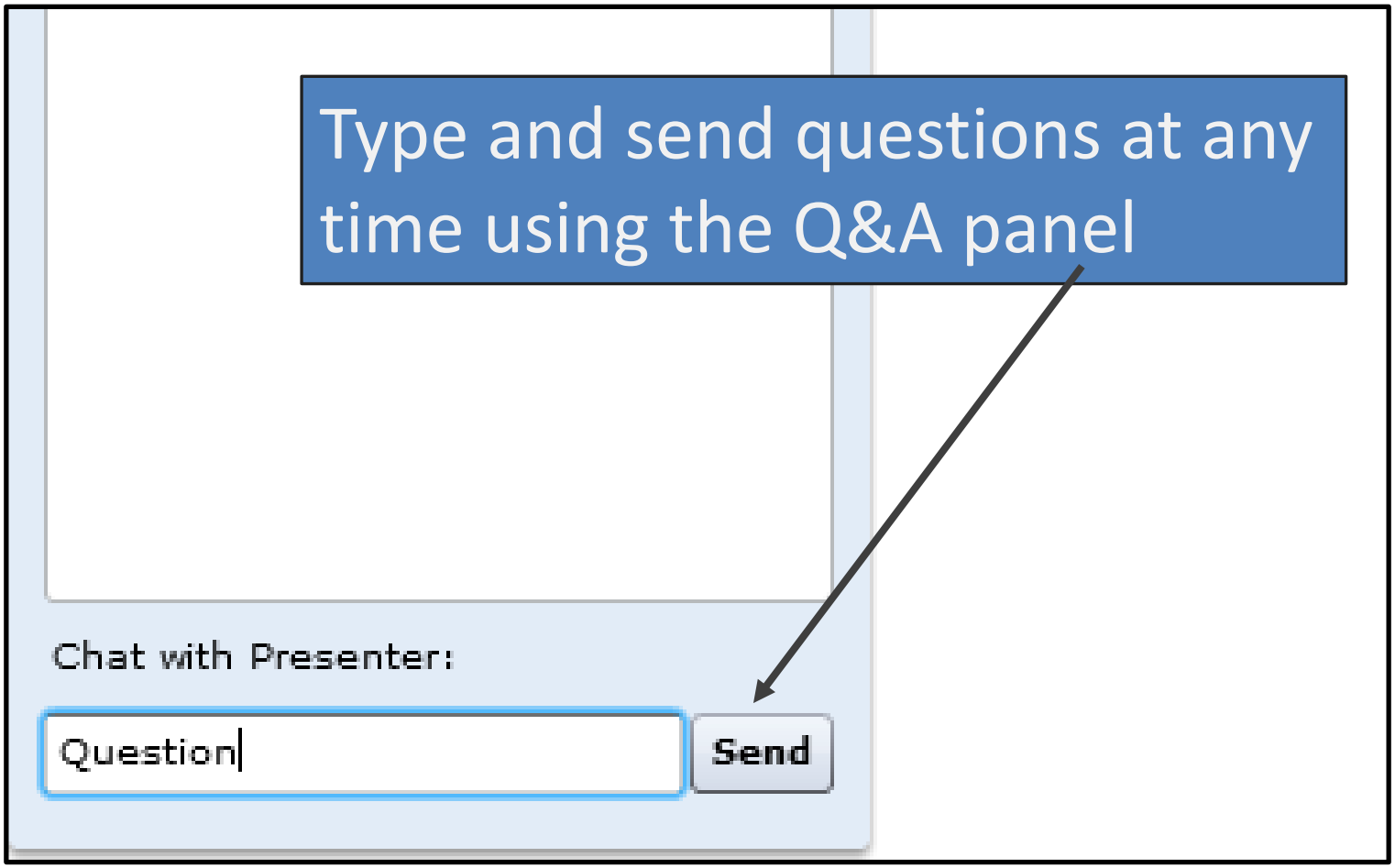


Rula Deeb, Ph.D.
Webinar Coordinator

Agenda

- **Webinar Logistics**
  Dr. Rula Deeb, Geosyntec (5 minutes)
- **Overview of SERDP and ESTCP**
  Dr. Andrea Leeson, SERDP and ESTCP (5 minutes)
- **Designing, Assessing, and Demonstrating Sustainable Bioaugmentation for Treatment of DNAPL Sources in Fractured Bedrock**
  Dr. Charles Schaefer, CDM Smith (25 minutes + Q&A)
- **Bioremediation of Co-Mingled Perchlorate and Explosives in Groundwater at an Active Military Range**
  Dr. Lee Slater, Rutgers University (25 minutes + Q&A)
- **Final Q&A session**

How to Ask Questions



In Case of Technical Difficulties

- Delays in the broadcast audio
  - Click the mute/connect button
  - Wait 3 to 5 seconds
  - Click the mute/connect button again
  - If delays continue, call into the conference line
    - U.S./Canada: 1-877-776-3503
    - International: 330-871-6014
    - Required conference ID: 82635620
- Submit a question using the chat box

SERDP and ESTCP Overview

Andrea Leeson, Ph.D.
Environmental Restoration Program Manager

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SERDP

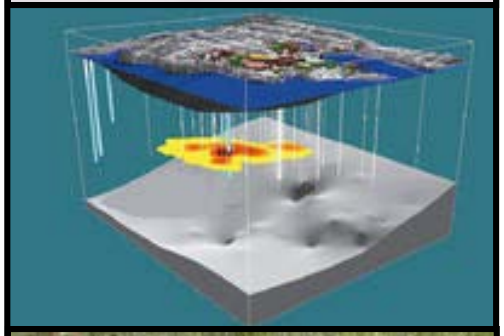
- Strategic Environmental Research and Development Program
- Established by Congress in FY 1991
  - DoD, DOE and EPA partnership
- SERDP is a requirements driven program which identifies high-priority environmental science and technology investment opportunities that address DoD requirements
  - Advanced technology development to address near term needs
  - Fundamental research to impact real world environmental management

ESTCP

- Environmental Security Technology Certification Program
- Demonstrate innovative cost-effective environmental and energy technologies
  - Capitalize on past investments
  - Transition technology out of the lab
- Promote implementation
  - Facilitate regulatory acceptance

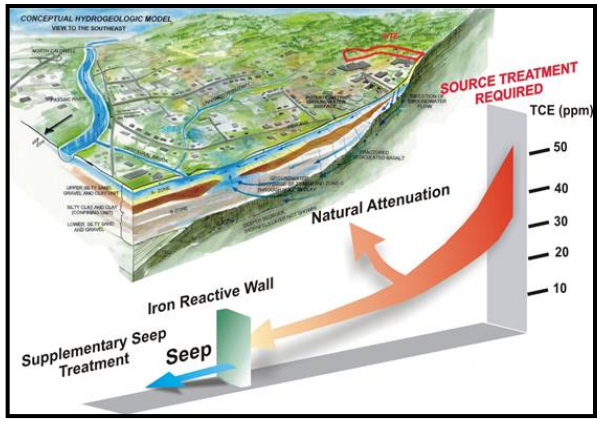
Program Areas

1. Energy and Water
2. Environmental Restoration
3. Munitions Response
4. Resource Conservation and Climate Change
5. Weapons Systems and Platforms



Environmental Restoration

- Major focus areas
  - Contaminated groundwater
  - Contaminants on ranges
  - Contaminated sediments
  - Wastewater treatment
  - Risk assessment



SERDP and ESTCP Webinar Series

DATE	Topics
September 17, 2015	Munitions Response: Water Geophysical Sensors
October 1, 2015	Hexavalent Chrome Elimination from Hard Chrome Surface Finishing
October 15, 2015	LED-ing the Way: Sophisticated and Energy Efficient Exterior Lighting Systems for DoD Installations
October 29, 2015	Assessment and Treatment of Contaminated Sediments
November 12, 2015	Munitions Response: Land Based Program Closeout
December 3, 2015	Emerging Contaminants: DoD Overview and State of Knowledge on Fluorochemicals and 1,4-Dioxane
December 17, 2015	Resource Conservation and Climate Change

http://serdp-estcp.org/Tools-and-Training/Webinar-Series

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Designing, Assessing, and Demonstrating Sustainable Bioaugmentation for Treatment of DNAPL Sources in Fractured Bedrock

Charles Schaefer, Ph.D.
CDM Smith

SERDP DOD • EPA • DOE | ESTCP

Contributors

- Graig Lavorgna, CB&I (Project Manager)
- Tim Ault, CB&I
- Mike Annable, Ph.D., P.E., University of Florida
- Erin White, University of Florida
- AECOM (Field support)

Agenda

- Background
- DNAPL architecture in fractured bedrock
- Bioaugmentation for removal of DNAPL sources

Motivation

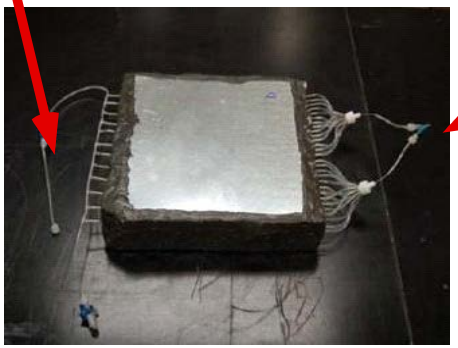
- DNAPL in bedrock is a substantial environmental challenge for the DoD
- Tools for assessing DNAPL in bedrock limited
- Can cost-effective in situ treatments be effectively applied?

Background

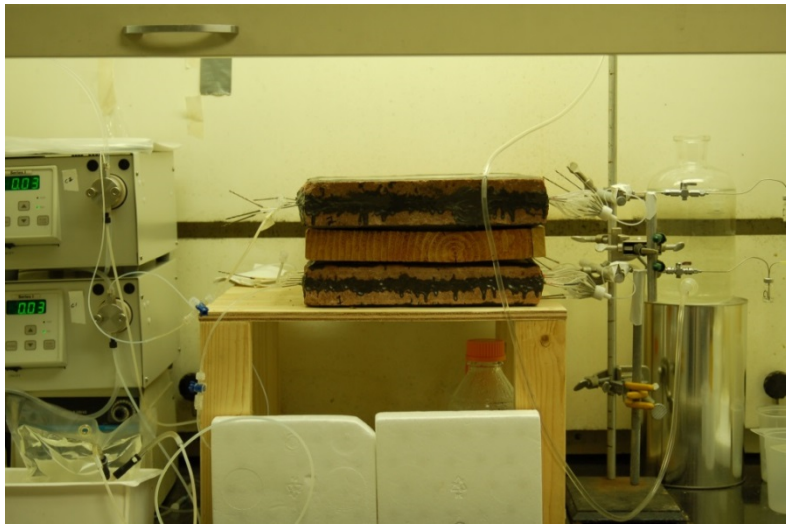
- Bioaugmentation for DNAPL treatment in unconsolidated media
  - Cape Canaveral (USEPA, 2004)
  - ITRC, 2007
- Bioaugmentation in fractured bedrock (DNAPL not present or assessed)
  - Edwards AFB (Mora et al., 2008)
  - Former Naval Air Warfare Center (Révész et al., 2014)
- Bench scale studies to assess bioaugmentation for DNAPL in Single Fractures (SERDP Project ER-1554)

Laboratory Studies

Influent manifold connected to HPLC pump. Typical flow of 0.1 mL/min.



Effluent collection



Bioaugmentation Effective for Enhancing DNAPL Dissolution

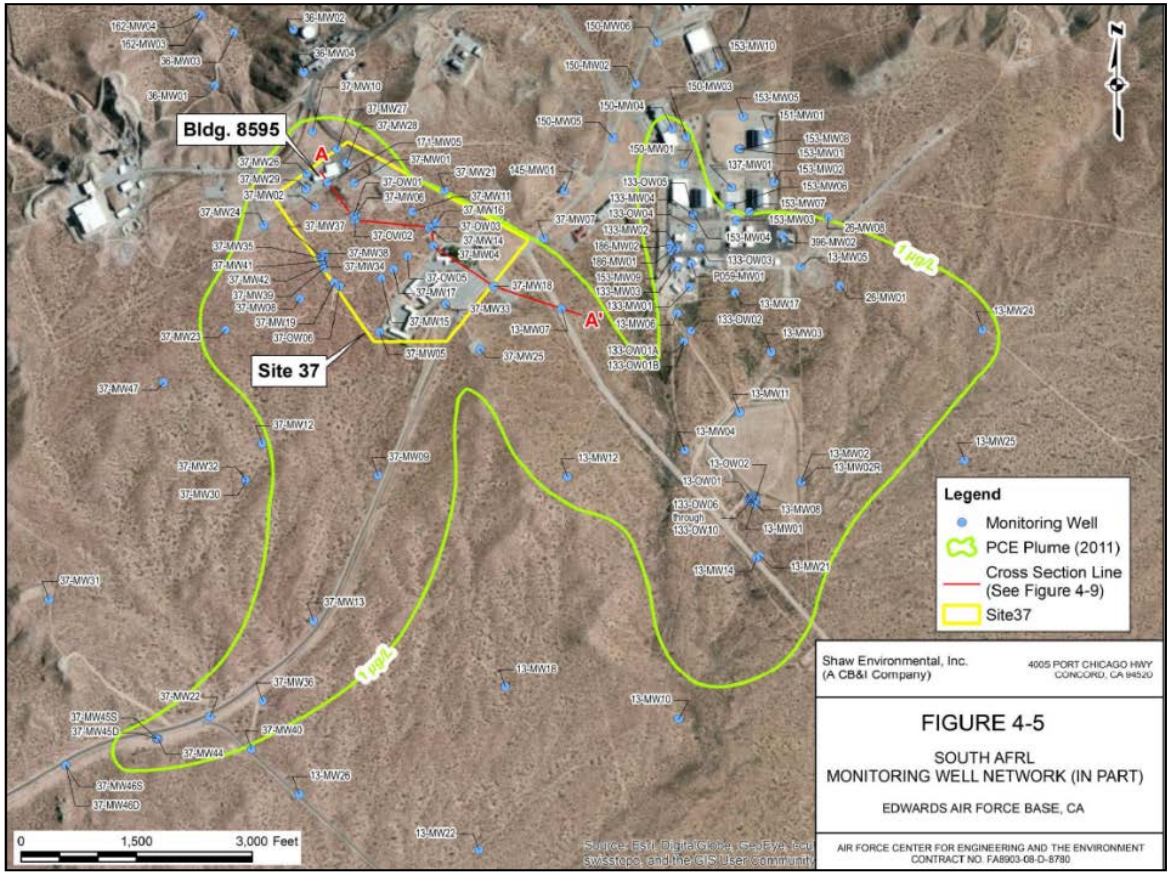
Key Application Issues

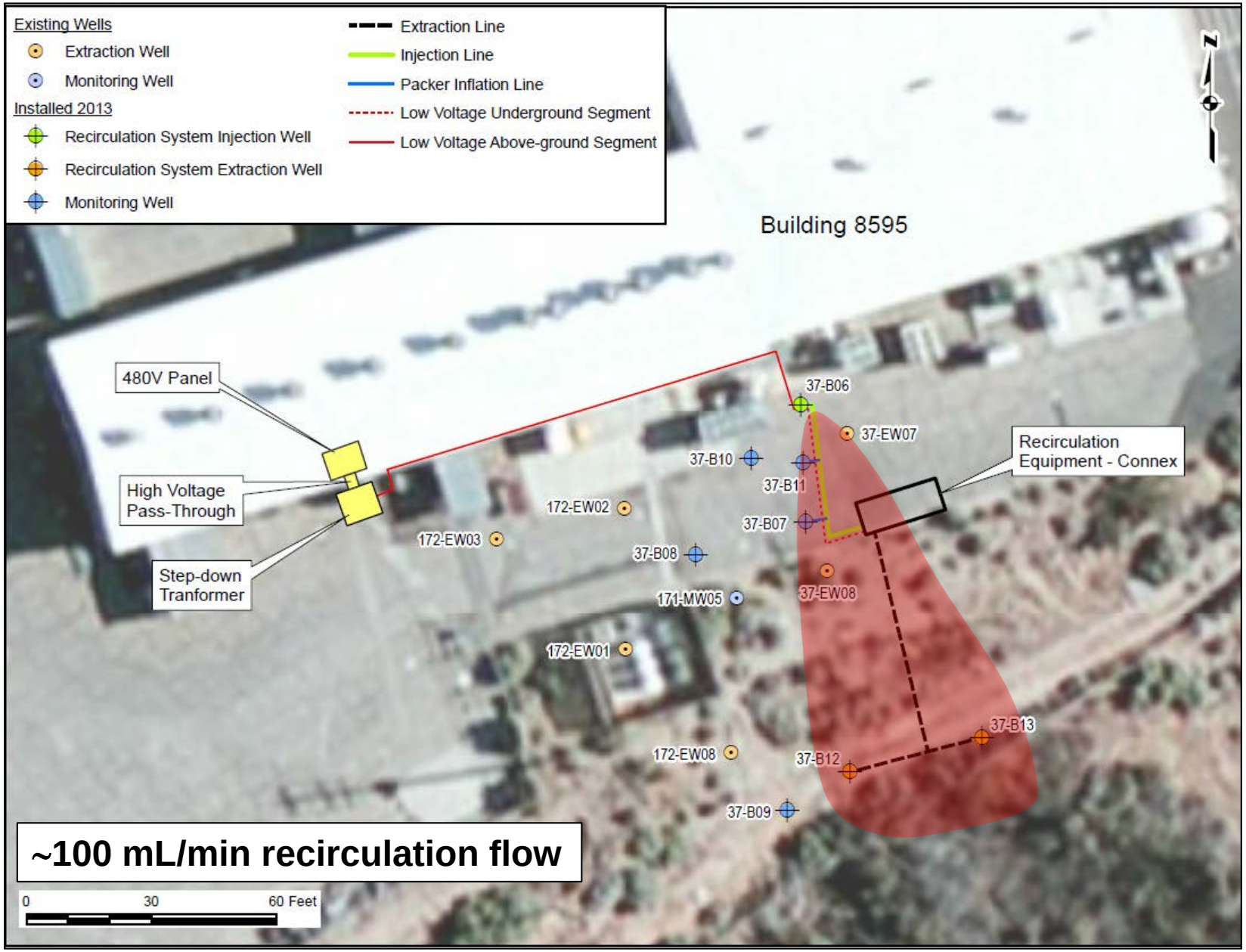
- Can DNAPL sources be effectively located and targeted?
- What is the DNAPL architecture in a complex fracture network?
  - CSM
  - Technology selection
  - Performance monitoring
- How do DNAPL sources impact the plume?
- Can bioaugmentation be effectively applied to treat DNAPL sources
  - Mass removal
  - Mass discharge

Demonstration Location
Edwards AFB

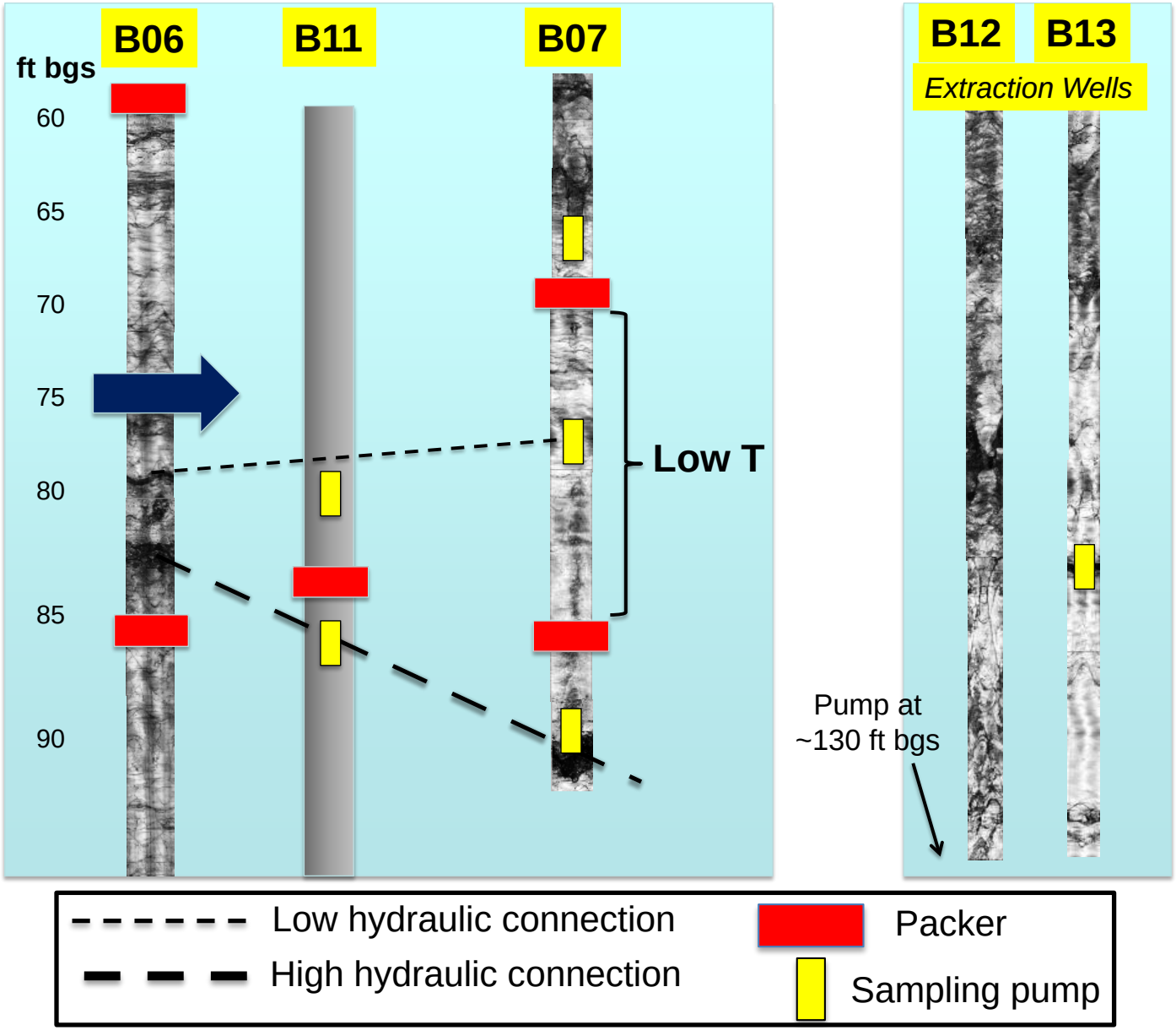
Site 37 characteristics

- Large plume (390 acres)
- Deep (>200 ft)
- Granite bedrock (quartz/feldspar)
- Low transmissivity
- Fracture flow
- PCE at >10% solubility
- No direct evidence of DNAPL (prior to this project)



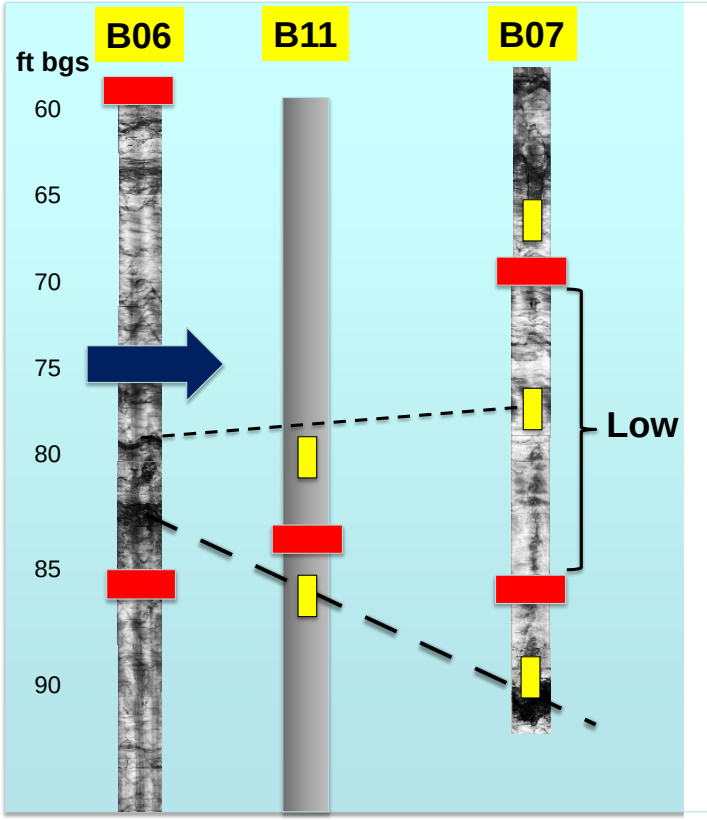


~100 mL/min recirculation flow


B06
B11
B07
B12
B13
Extraction Wells
ft bgs
60
65
70
75
80
85
90
Low T
Pump at
~130 ft bgs
Low hydraulic connection
High hydraulic connection
Packer
Sampling pump

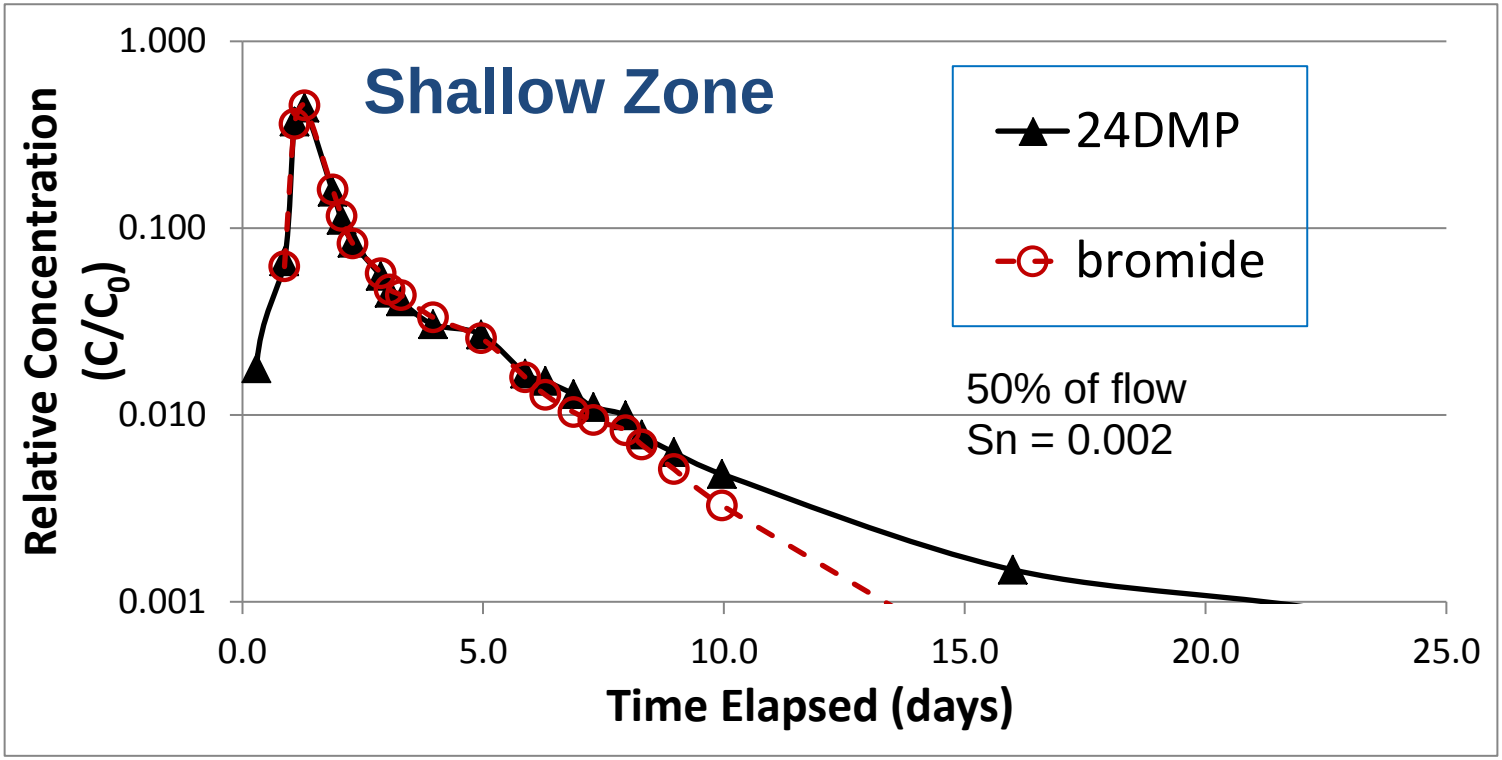
Partitioning Tracer Test

- Conservative tracer velocity used to estimate fracture porosity
  - Matrix effects minimal (4.9% matrix porosity)
- Mass of tracer eluted per fracture or fracture zone is proportional to the transmissivity
- Hydrophobic tracer retardation used to estimate DNAPL mass



PTT Results

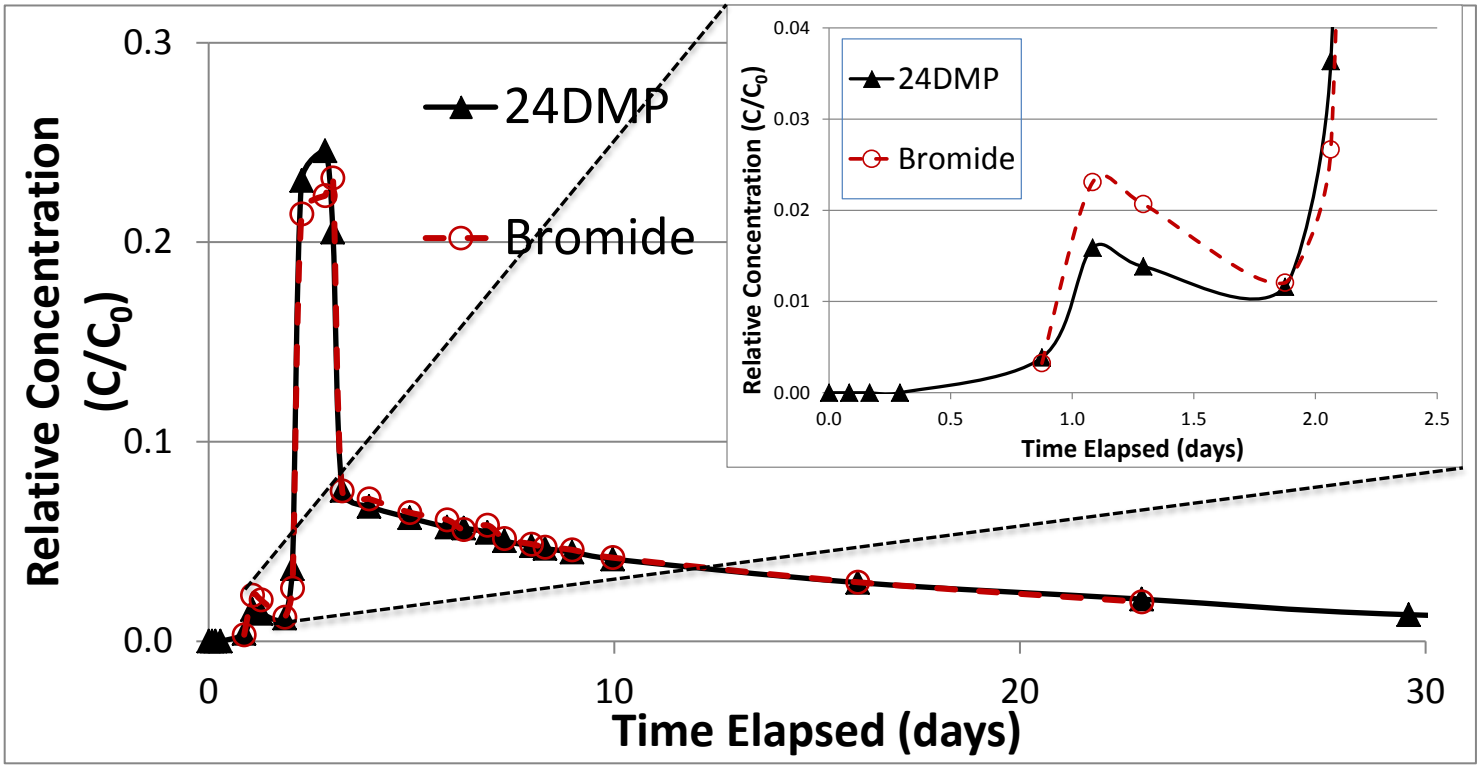
Method of moments used to analyze tracer data (University of Florida)



DNAPL <u>Along</u> <u>Fracture</u> <u>Flow</u> <u>Path</u> Identified and Quantified

PTT Results

Deep Zone – Multiple Fractures



Initial Peak (low T fracture)

- 1% of flow
- Sn = 0.007

Middle Peak

- 9% of flow
- Sn = 0.0

Late Peak

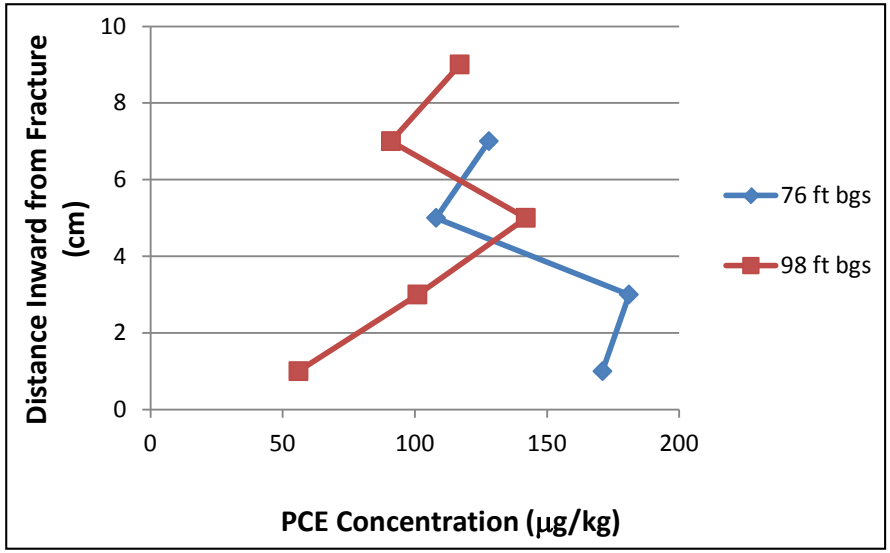
- 40% of flow
- Sn = 0.0004

So What Else Does This Tell Us?

- DNAPL distribution
  - DNAPL present in high T fractures, but also in low T zones
- Average fracture porosity
  - 0.005
- DNAPL mass
  - 1.5 kg in 15 ft radius around injection well interval
- DNAPL persistence under ambient conditions (dissolution only)
  - B11s – 44 years
  - B11d (low T) – 200 years
  - B11d (tail) – 13 years

PCE Mass Distribution and Flux

Rock Matrix vs. Fractures



Based on PTT DNAPL estimate

149 g PCE in rock matrix

PCE concentration profile suggests back-diffusion not occurring

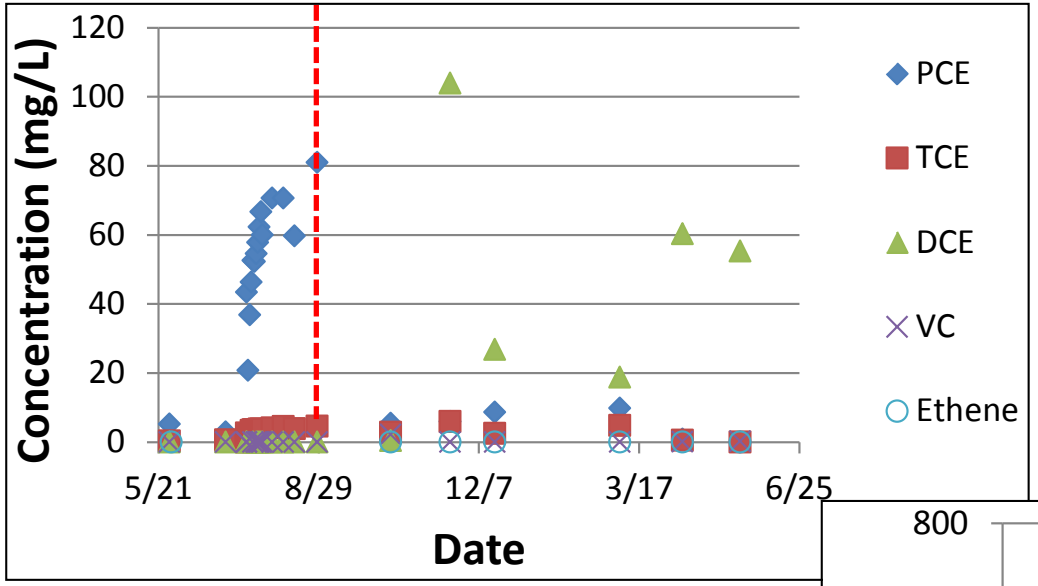
1,500 g PCE as DNAPL in fractures

Bioaugmentation (August 29, 2014)

Target DNAPL for removal and decrease mass discharge from source area

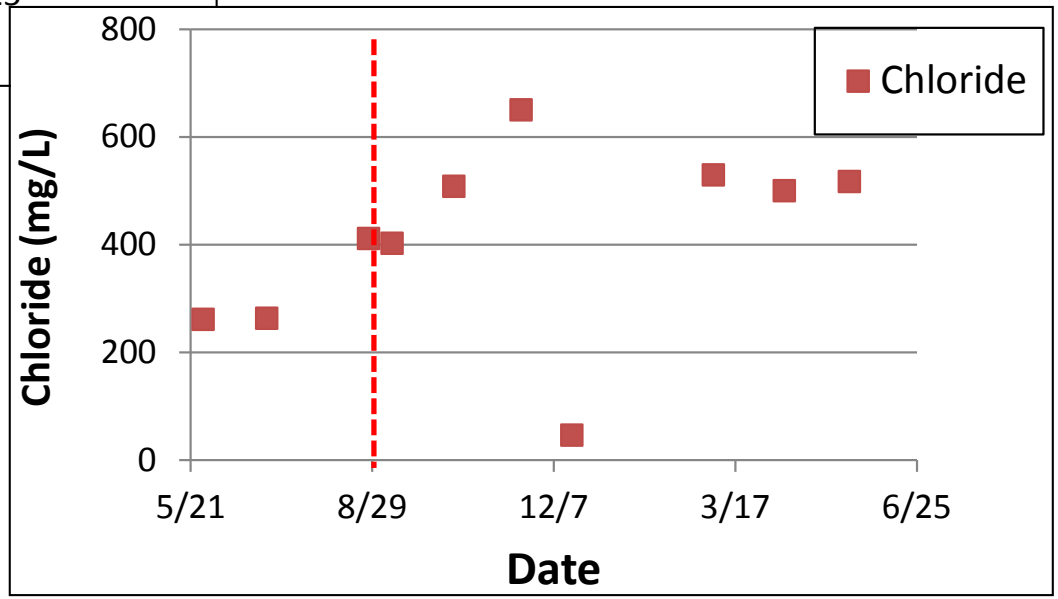
- Initial electron donor delivery
  - 59 L into B06 injection interval
    - 1,000 mg/L lactate
    - 100 mg/L DAP
    - 100 mg/L yeast extract
  - Recirculate groundwater overnight
- Bioaugmentation
  - 5 L of CB&I's SDC-9 culture into B06 injection interval
    - 10^{12} cells/L DHC
    - 38 L electron donor chase solution (lactate, DAP, yeast extract)

Results - B11S

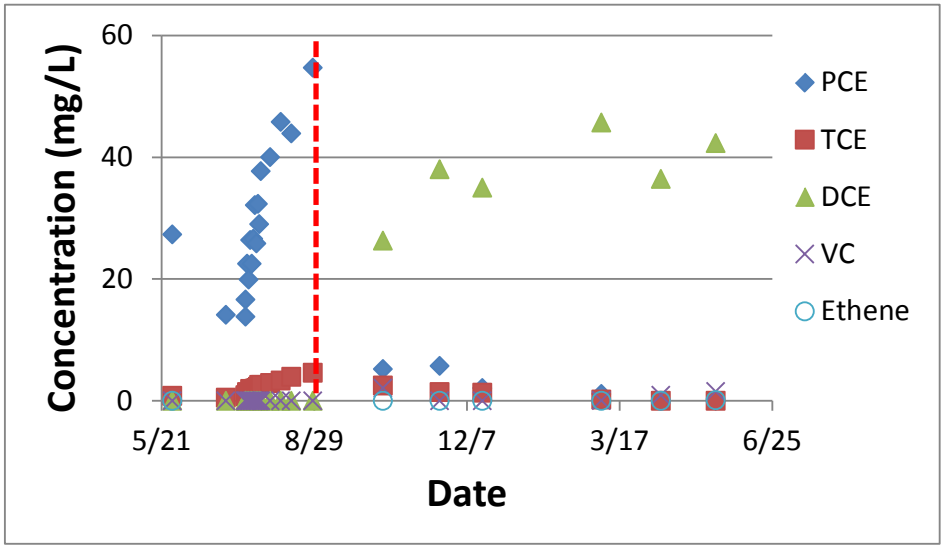


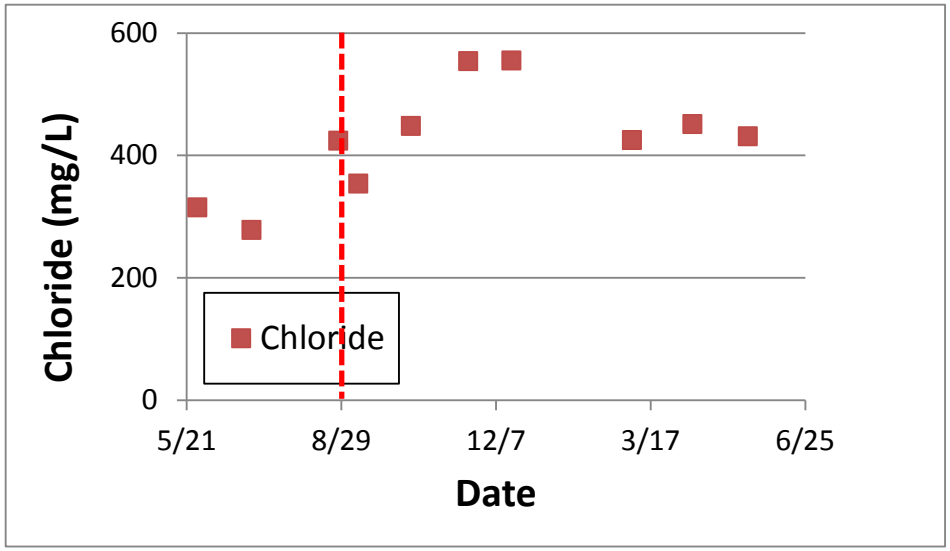
Elevated PCE levels in extraction wells

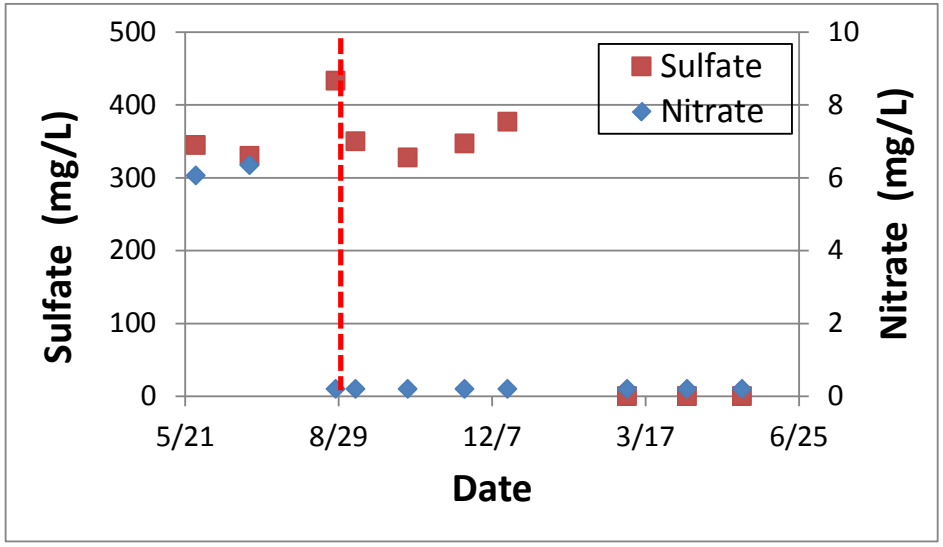
Chloride generation indicates substantial dechlorination of PCE

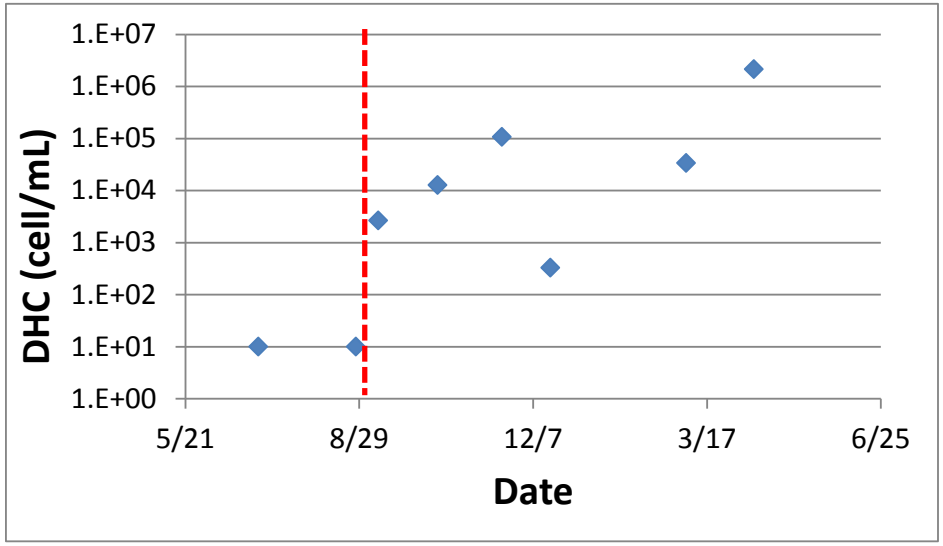


Results - B11D









Mass Removal

Dissolution Enhancement Factor (E) = $\frac{[PCE] + moles\ PCE\ transformed\ to\ DCE}{[\mathrm{PCE}]}$

(Based on chloride generation)

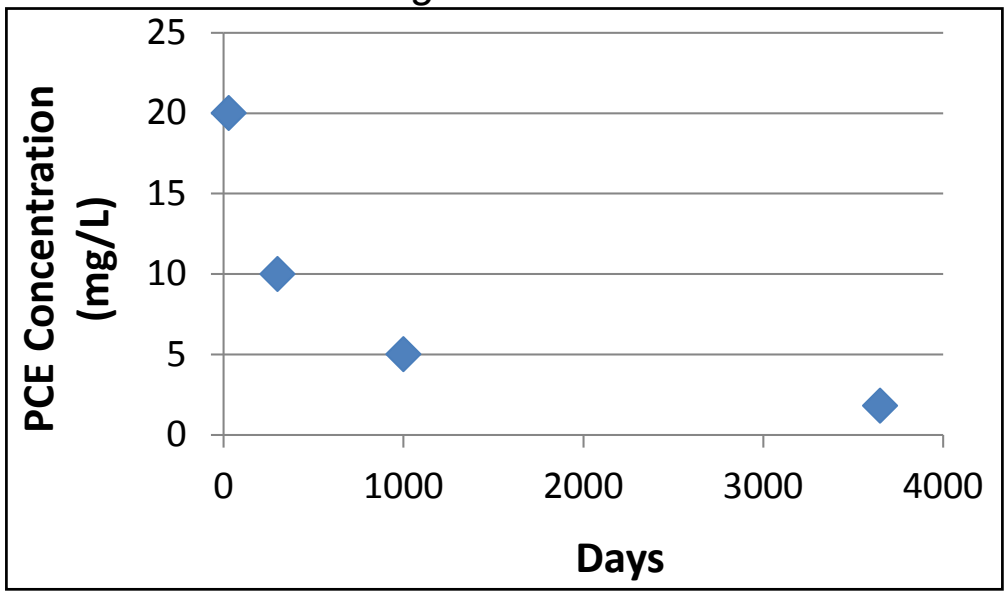
E ~ 5

Consistent with bench scale studies (Schaefer et al., ES&T, 2010)

Chloride generation data and DNAPL mass balance indicate DNAPL in transmissive fractures has been removed (8 months of treatment)

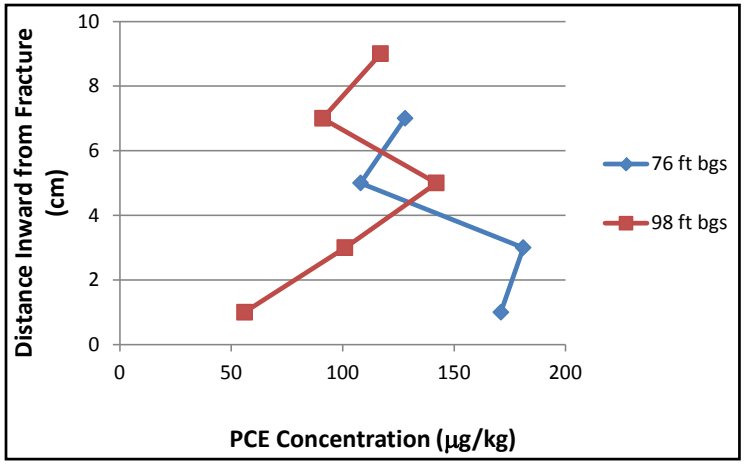
So How Does DNAPL Removal Help?

Simulated Decay in Source Area Concentrations Following DNAPL Removal



Back-diffusion flux from rock matrix unable to sustain elevated source area concentrations

Assumes no treatment into rock matrix



Persistent untreated DNAPL in low T zones could sustain low mass discharge

Next Steps

- Rebound monitoring
- Partitioning tracer test
- Potential rock core collection to assess PCE removal in rock matrix

Conclusions

- DNAPL mass and architecture can be determined in fractured bedrock
  - CSM
  - Target treatment
  - Performance monitoring
- DNAPL may account for the majority of contaminant mass and discharge from source
- DNAPL may reside in low T fractures
  - Plume persistence
  - Ability to treat / practical limit of remedial effectiveness
- Bioaugmentation may be a viable solution for treating DNAPL sources in fractured bedrock

For additional information, please visit

https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Persistent-Contamination/ER-201210

Speaker Contact Information

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Q&A Session 1

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Seeing Beyond Boreholes: A Geophysical Toolbox for Characterization and Monitoring of Amendment Delivery in Fractured Rock Aquifers

Lee Slater, Ph.D.
Rutgers University

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Additional Project Team Members

- Fred Day Lewis and John Lane (USGS, Office of Groundwater,Branch of Geophysics)
- Allen Shapiro (USGS, Reston, VA)
- Judy Robinson and Dimitrios Ntarlagiannis (Rutgers University Newark)
- Tim Johnson (Pacific Northwest National Laboratory)

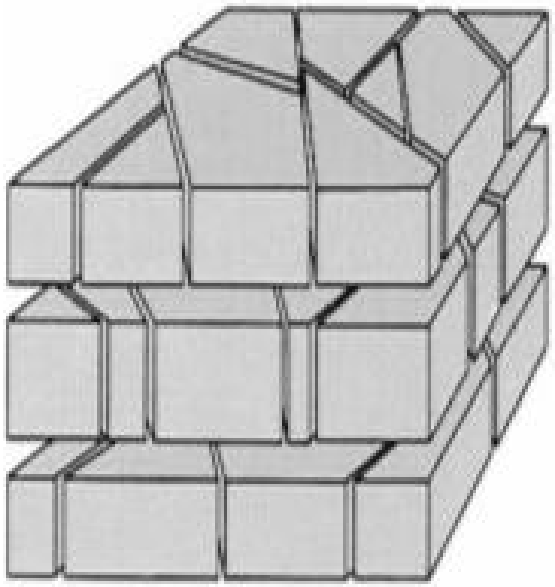
Agenda

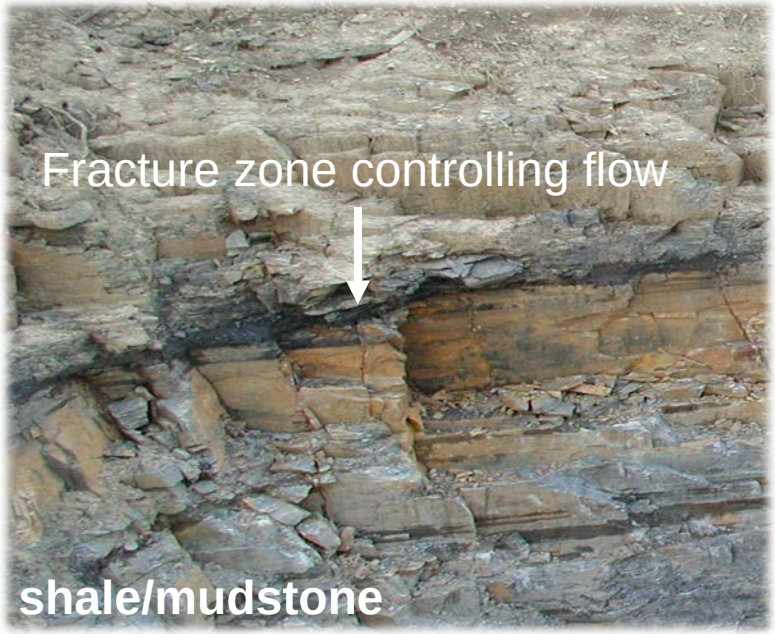
- Characterization/amendment injection challenges: the geophysical need
- Electrical Resistivity Tomography (ERT) overview and application at the Naval Air Warfare Center (NAWC), NJ
- Characterization/monitoring results and validation against supporting data
- DoD relevance and benefits of the technology

- Key message: Geophysical imaging technologies can be used to characterize heterogeneity, monitor amendment injection strategies and evaluate zone of influence

Characterization Challenges in Fractured Rock

- Highly heterogeneous media where discrete fracture networks or fractured zones determine flow and transport

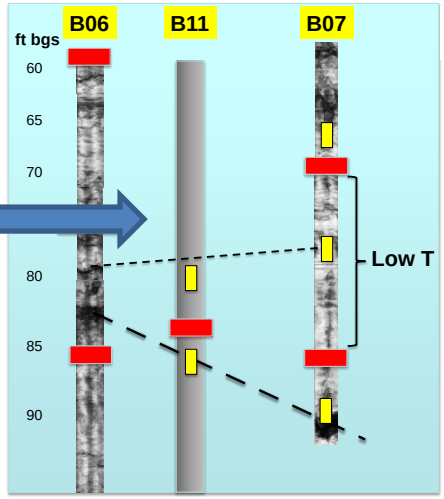




- Large permeability variation
- Expensive characterization from drilling alone

Amendment Injection Challenges

- Fate of amendment injections often poorly understood
- Problem accentuated in fractured rock
  - Surface area of fracture zones impacted by amendment?

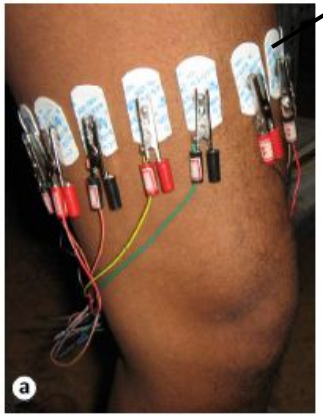


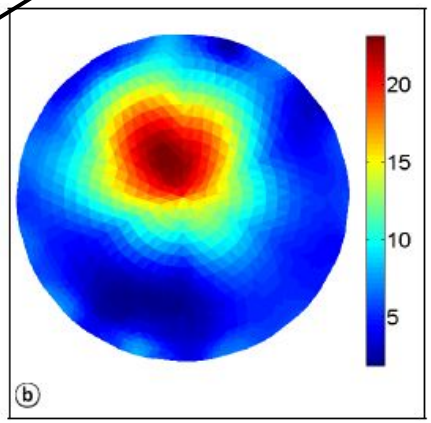
?

ER-201210
Schaefer

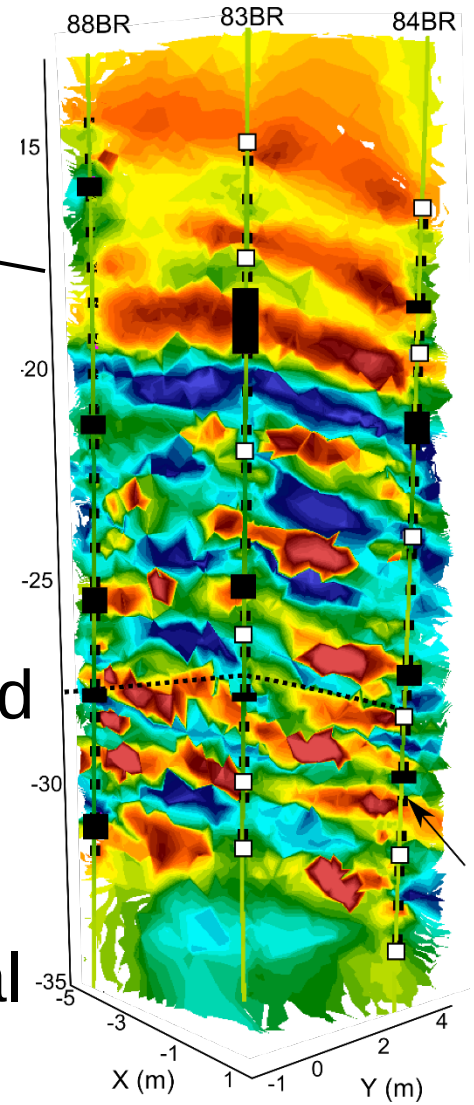
Method: Electrical Resistivity Tomography (ERT)

- Site remediation equivalent of medical tomography



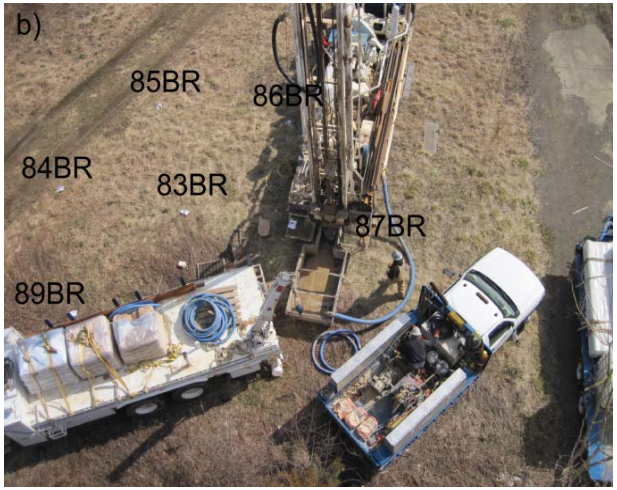


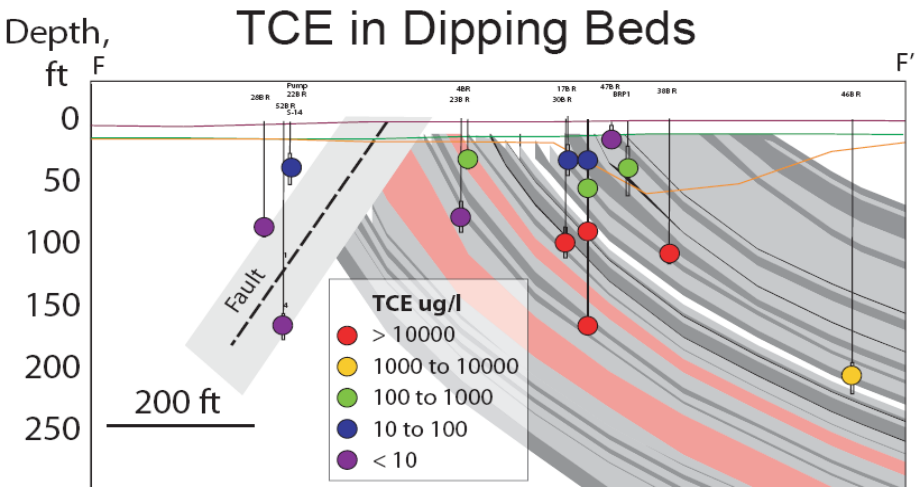
- Electrodes in boreholes are used to image volume bounded by boreholes
- Relies on electrical conductivity contrasts



Demonstration site: Naval Air Warfare Center (NAWC)

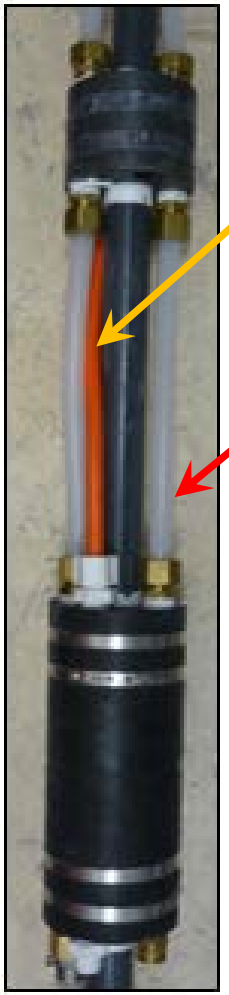
- Contaminant transport primarily in fractured zones
  - Prior problems with determining fate of amendments





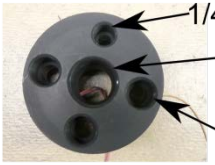
Technology Development

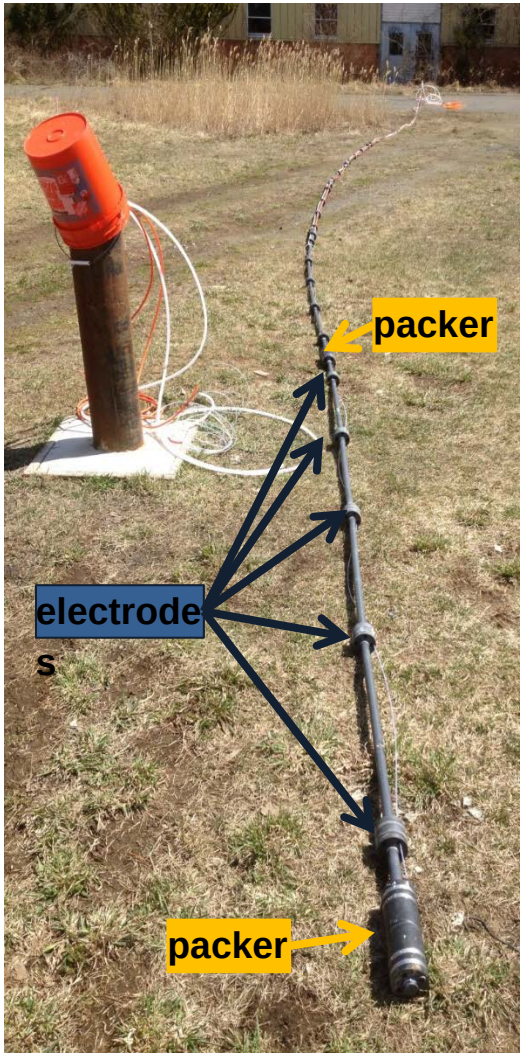
- First-of-a-kind integrated packer-electrode-sampling arrays



Airline to one or more packers (orange tubing)

Water sample line (white tubing) and smaller airline for bottom packers

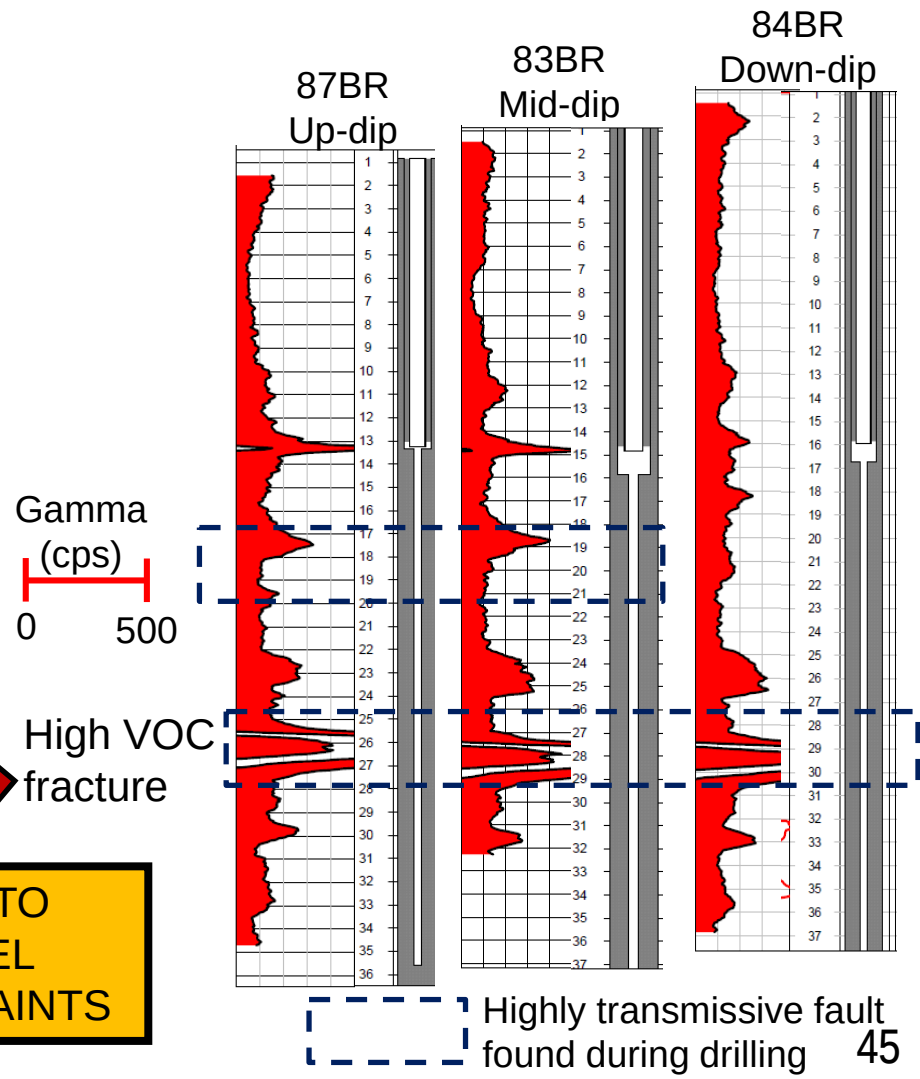




Borehole Logging Results

- Provides a wealth of information but only local to the borehole
- Information used to constrain the ERT inversion, e.g., to define local transmissive fracture zone locations and to define the specific conductance of the borehole

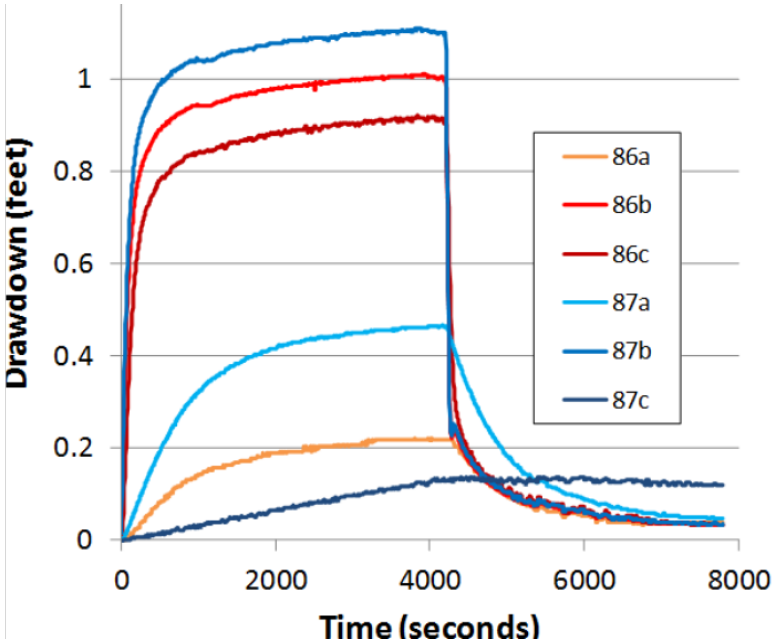
EXAMPLE NATURAL GAMMA LOGS

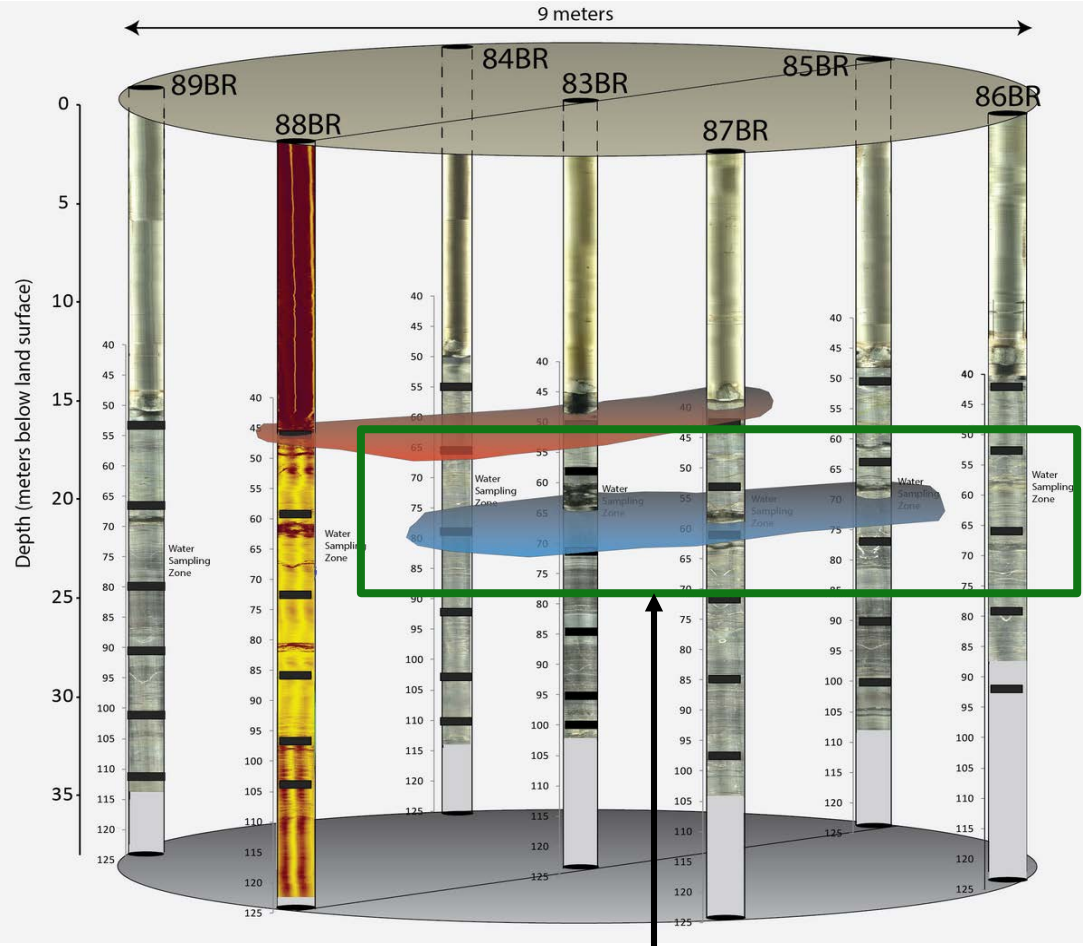


FEED TO MODEL CONSTRAINTS

Cross-hole Hydraulic Testing Results

- Identified well-connected fracture zone (later demonstrated to contain high contaminant concentrations)

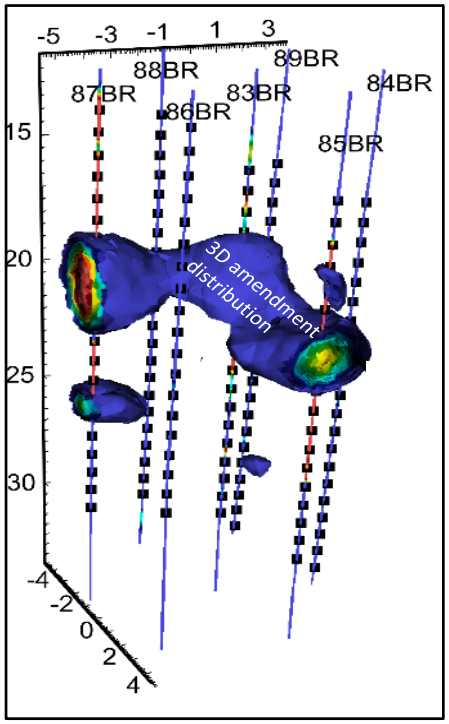




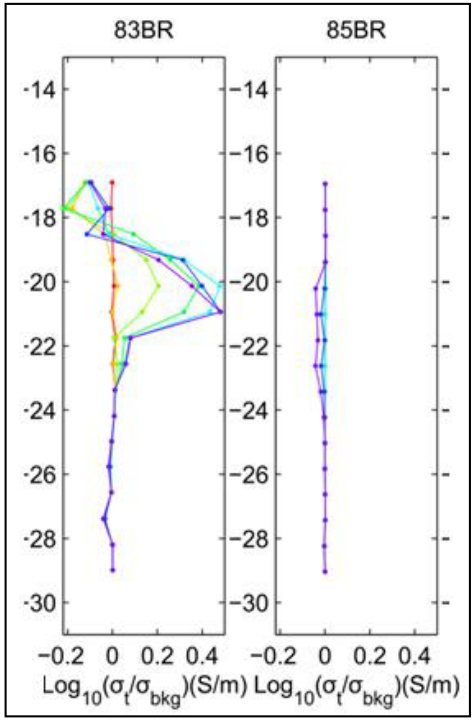
Targeted interval for amendment injection

Imaging Versus Vertical Profiling (VP)

- Different information types
  - VP (~10 seconds) captures local tracer breakthrough at wells
  - Imaging (~20 minutes) determines 3D character of breakthrough within rock mass



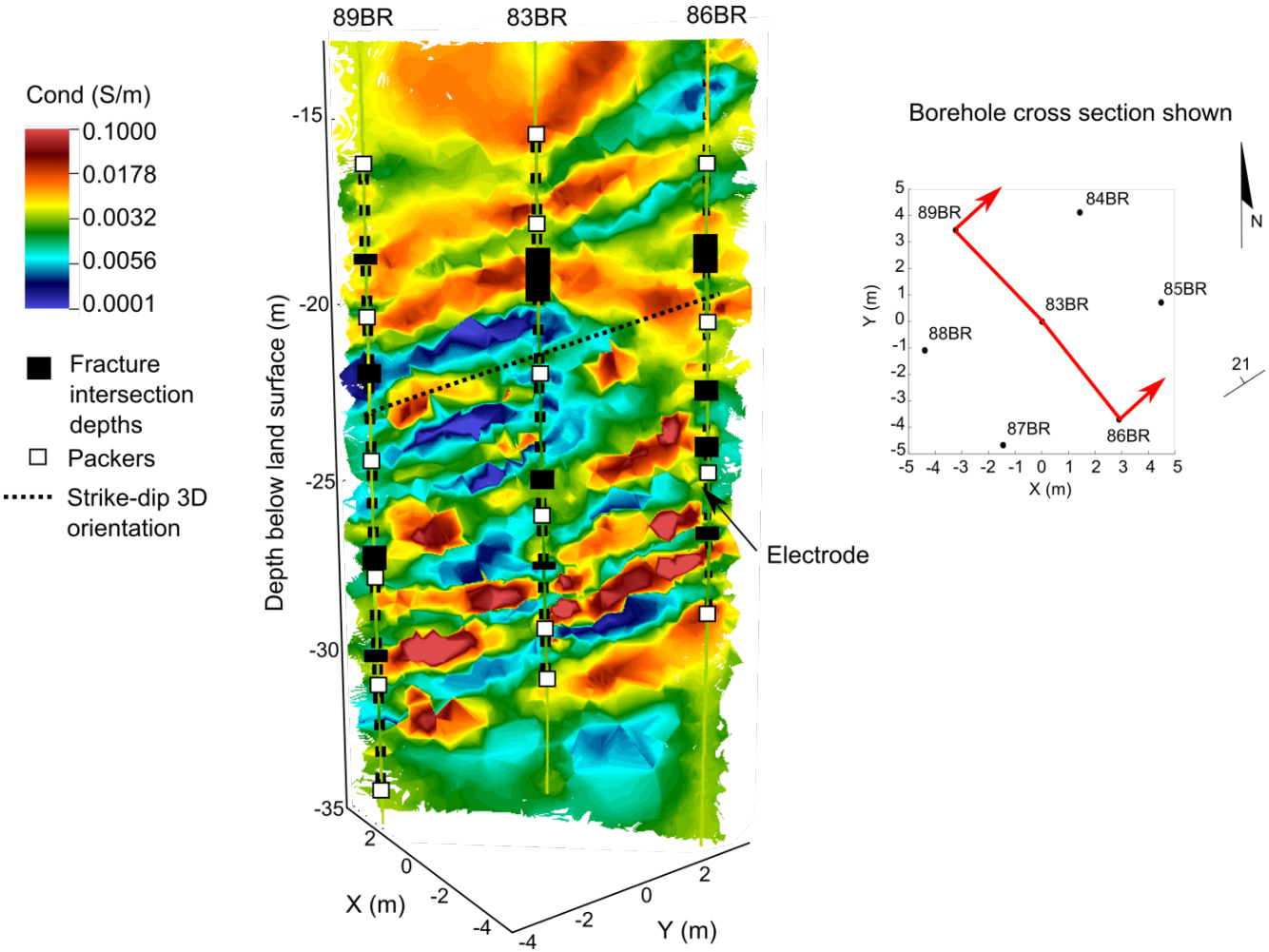
Imaging of amendment distribution



Rapid vertical pseudo specific conductance profiling

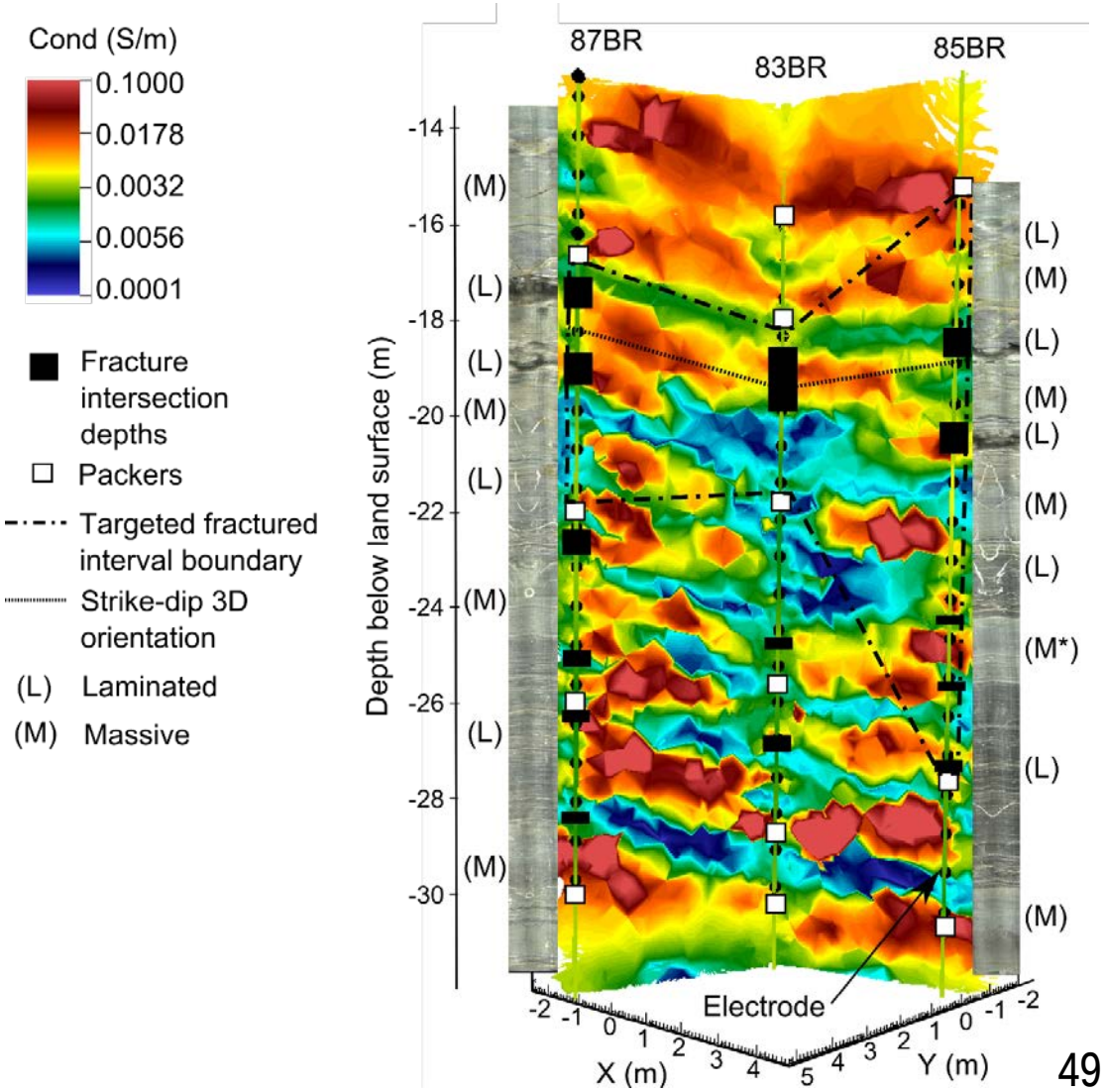
Characterizing the Rock Mass Beyond the Boreholes

- Electrical image of 1000 m^3 of fractured rock mass
- Identifies primary structures



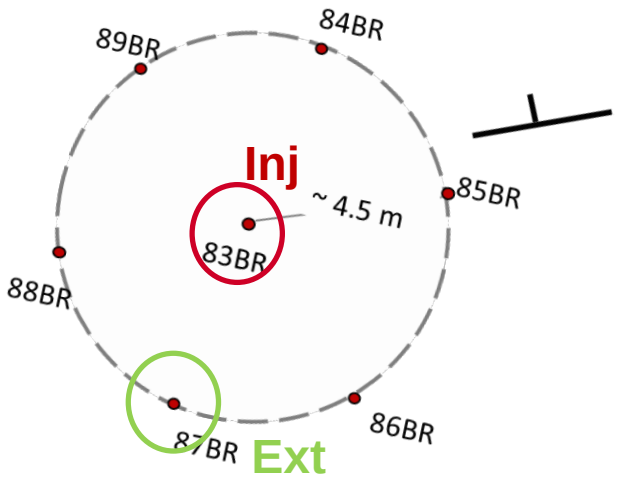
Validation

- Borehole logs and hydraulic testing support the geophysical zonation of structure
- Information at the boreholes is used to constrain the interpretation and also inform the imaging [not discussed here]

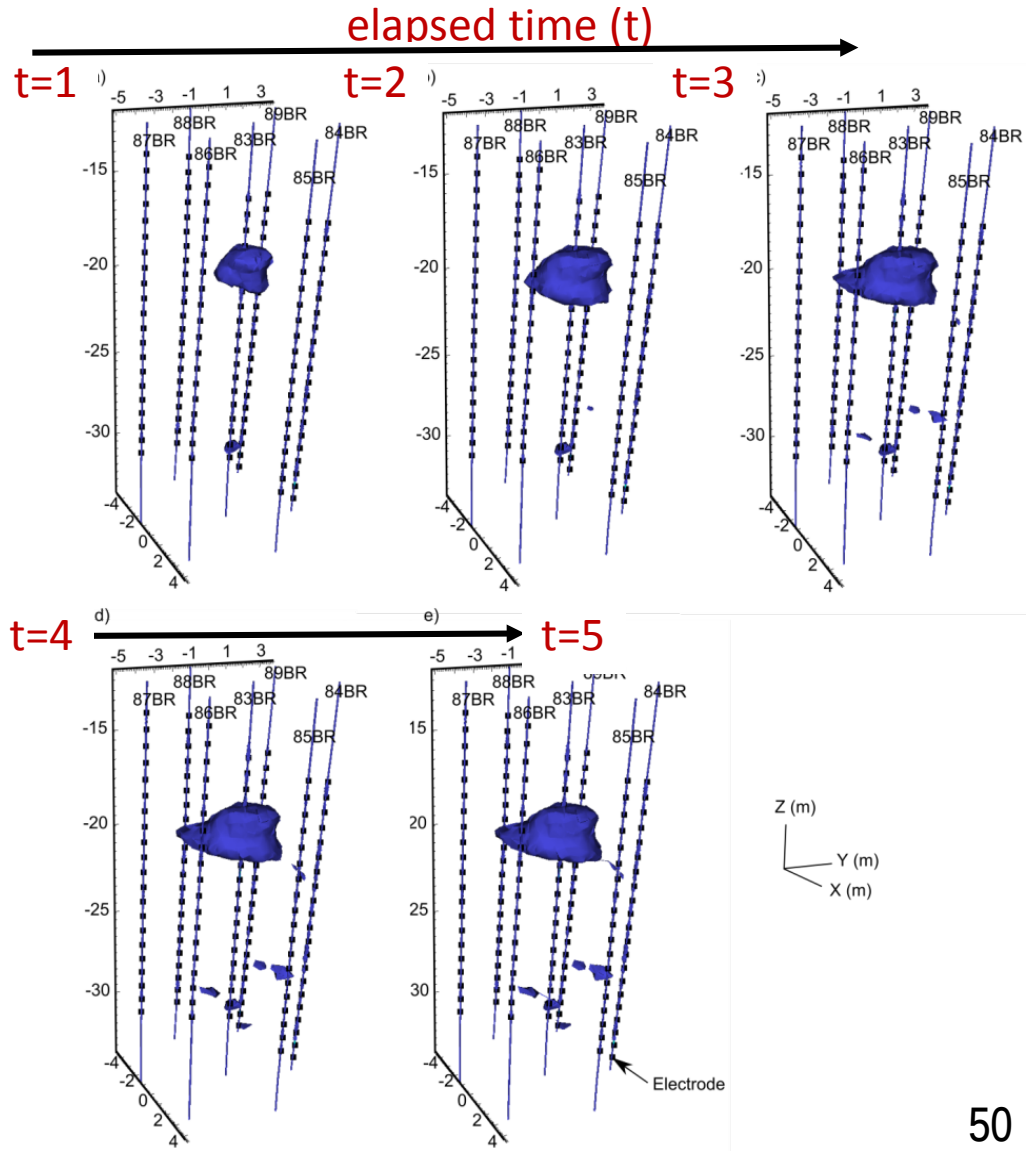


Monitoring Beyond the Boreholes

- Conductivity contrasts associated with tracer injection highlight tracer transport via preferred flow paths
- An ineffective tracer injection strategy

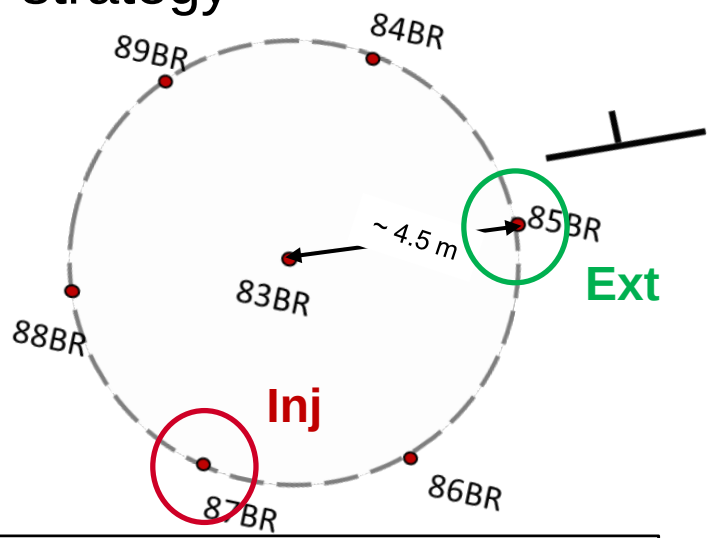


Inj = Injection; Ext = Extraction



Monitoring Beyond the Boreholes

- Conductivity contrasts associated with amendment injection highlight tracer transport via preferred flow paths
- **An effective** tracer injection strategy



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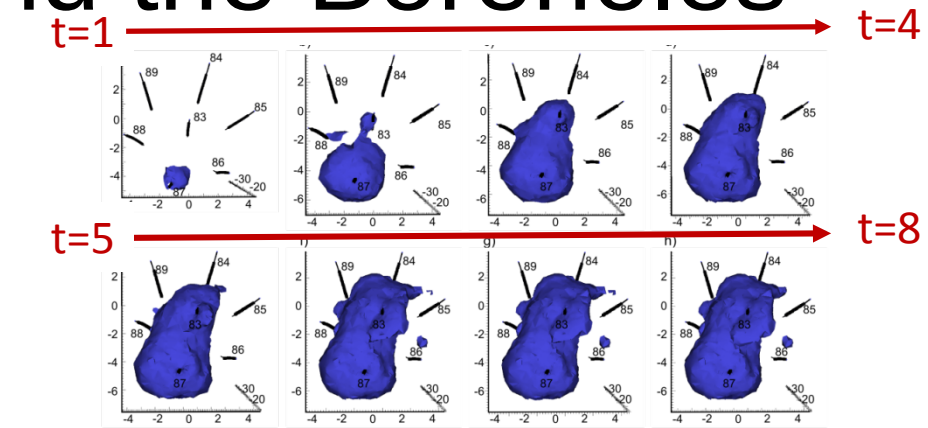
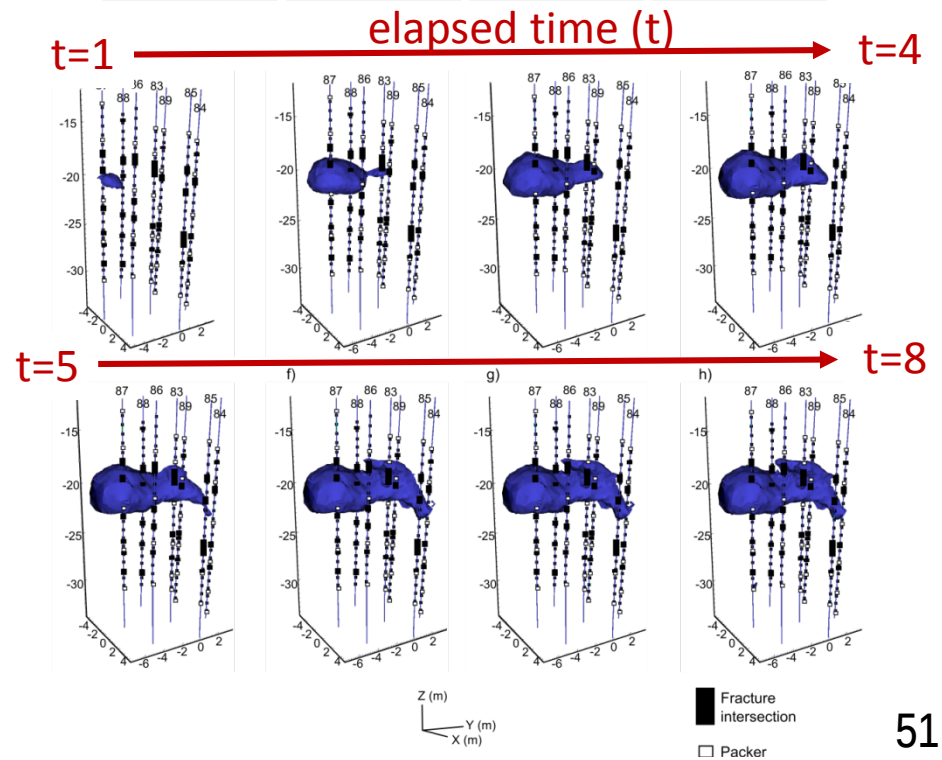
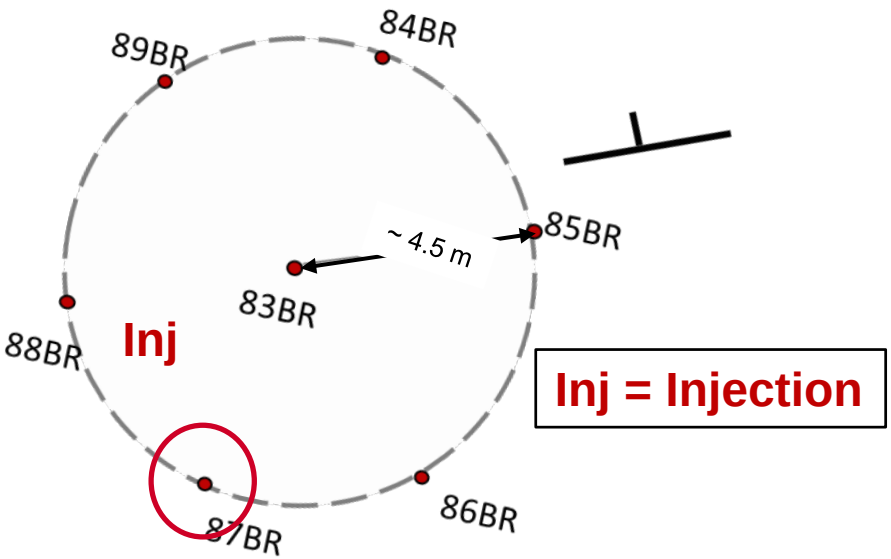
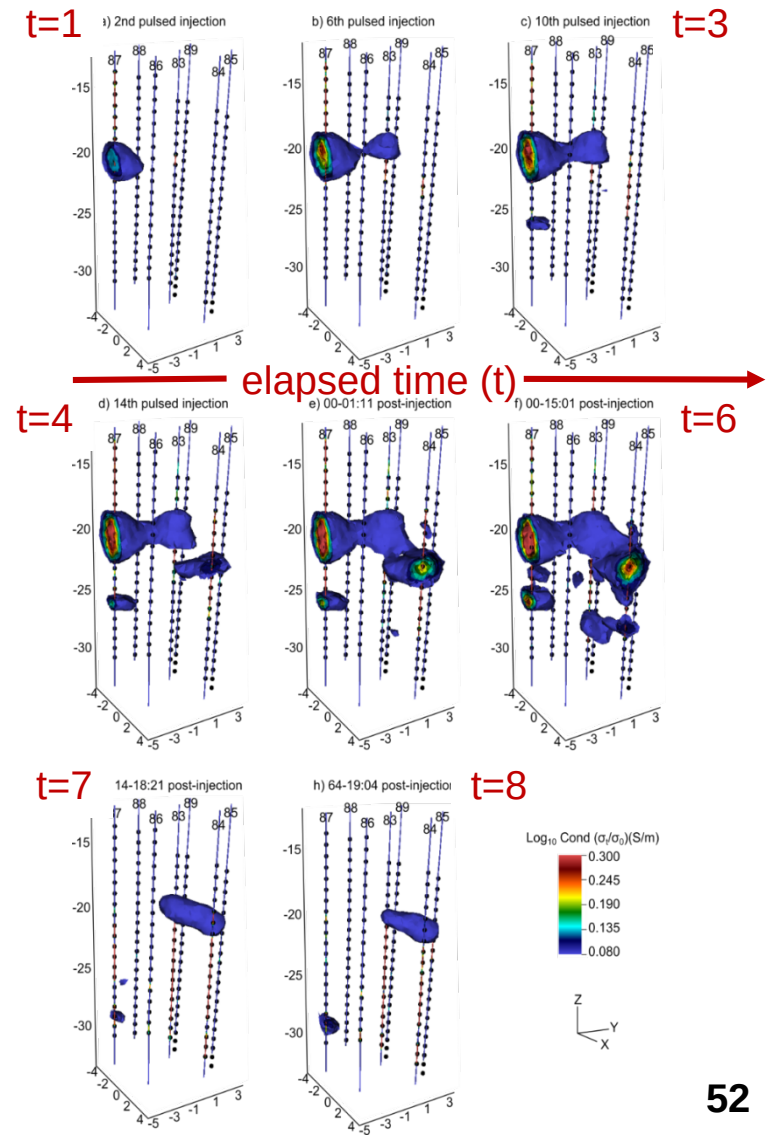




Monitoring Beyond The Boreholes

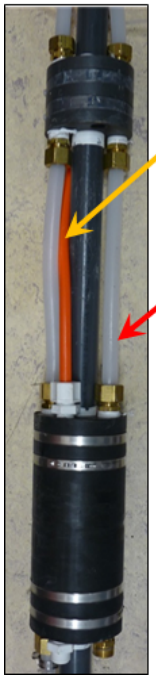
- Conductivity contrasts associated with amendment injection highlight tracer transport via preferred flow paths
- Amendment transport differs from tracer due to [1] different injection strategy; [2] different physical properties?
- Captures heterogeneous, channelized flow in the fracture zone

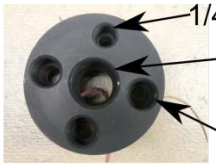


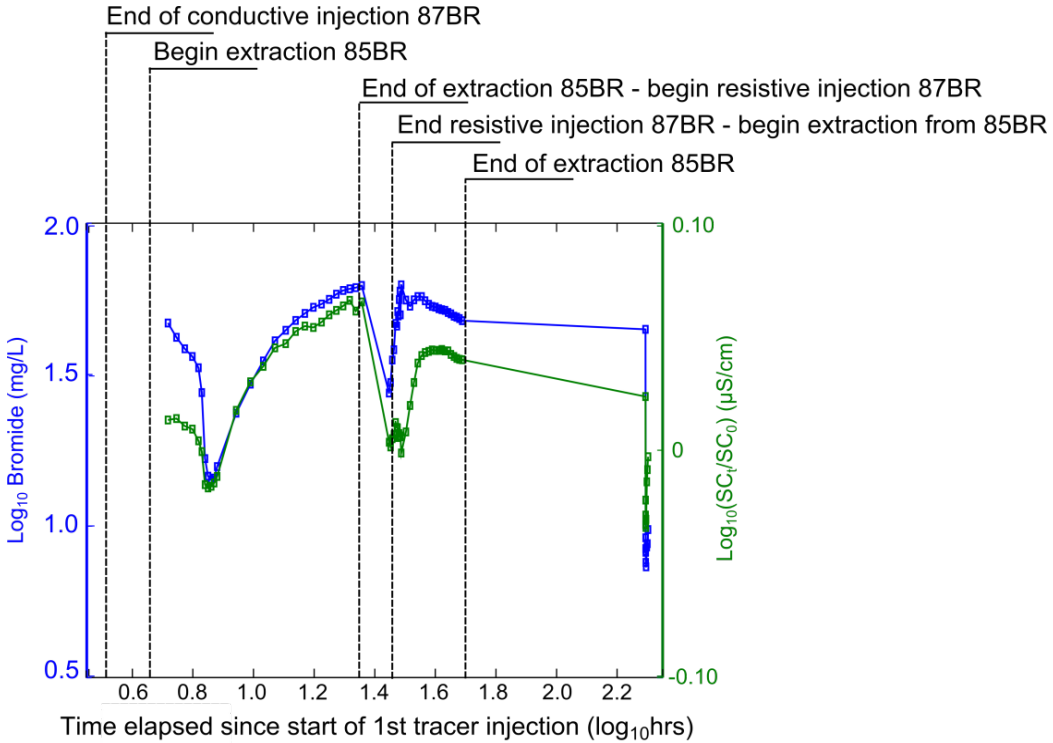


Validation

- Co-located specific conductance and ERT data lend confidence to the geophysical interpretation
- Integrated array assembly provides opportunity for effective validation



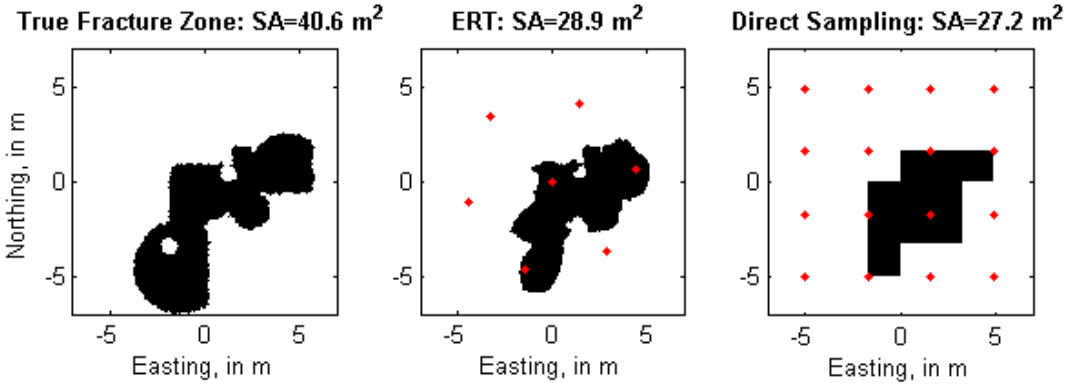


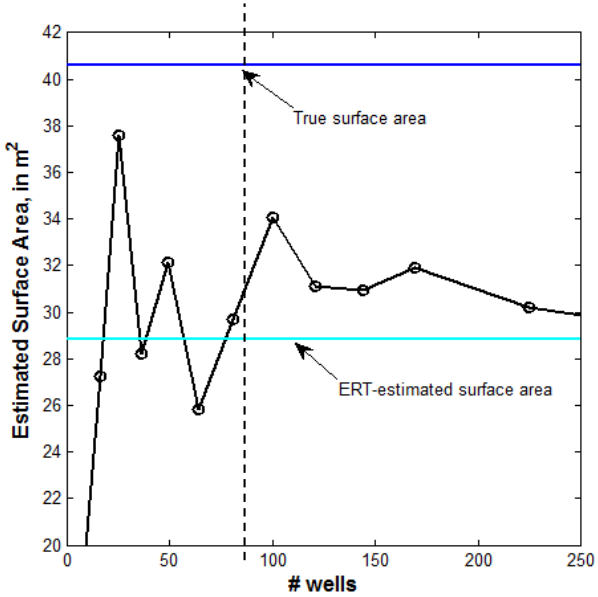


Cost Assessment

- Estimated fracture zone surface areas
  - Direct sampling requires 70+ wells to reliably perform better than information from 7 ERT wells

Hypothetical amendment-treated fracture zone including surface area calculation





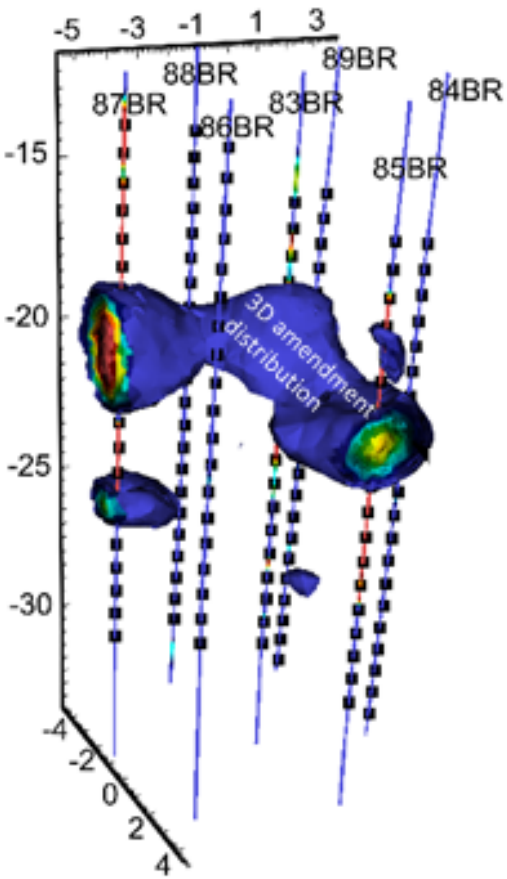
Conclusions

Take-away messages

- ERT: provides spatially continuous information on rock mass beyond boreholes
- Fate of amendment injections determined
- Tracer tests provide opportunities to optimize amendment strategy
- Geophysics cannot visualize contaminant concentration changes directly

Relevance and Recommendations

- Assess effectiveness (delivery, zone of influence) of multiple remediation strategies (e.g. bioremediation, thermal treatment, monitored natural attenuation (MNA), chemical addition) implemented at DoD sites



Recommendations

1. Minimum boreholes: 2 (2D) or 3 (3D)
2. Vertical length of open hole should be at least 1.5x borehole spacing
3. Geophysical expert on electrical inverse methods needed

Benefits

- Time and cost reductions
  - Characterization and monitoring cost savings: conventional sampling on a regular grid requires ~70 wells to reliably obtain surface-area estimates equal to those obtained from 3D ERT using 7 wells
- Expanded spatiotemporal information
  - Fills gaps in space and time that plague conventional data
- Cost savings
  - Early abandonment of amendment injections that are failing
- Minimally invasive sampling
  - Reduced opportunities for cross-contamination and human exposure
- Multi-use, multi-information
  - Turn sampling wells into sampling/geophysics wells: increase information content by a factor of 10x for a few $K of capital costs

For additional information, please visit

https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Persistent-Contamination/ER-201118/ER-201118/(language)/eng-US

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