Naval Facilities Engineering Command
ENGINEERING AND EXPEDITIONARY WARFARE CENTER

Demonstrating a Geophysics Strategy for Minimally Invasive Remediation Performance Assessment

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Presentation Overview

- Basic Theory
- Implementation Examples
- Limitations, Pitfalls, and How to Avoid Them
- Case Studies
- Wrap-Up

Definitions

Current: A flow of electric charge: the charge is most often carried by ions in the Earth

Potential: A measure of the electrical potential energy on a unit charge at any point in the Earth

Electrode: An electron conductor (usually a metal) that is used to make electrical contact with the Earth. Used for injecting current and for measuring potential.

Transfer resistance: The ratio of the *potential* measured to the *current* injected between electrodes

Conductivity: An intrinsic property of the Earth that quantifies ease at which current can flow. *Resistivity is the inverse of conductivity*.

Forward modeling: A numerical method used to simulate *transfer resistance* measurements

Inversion: A numerical method to estimate the most probable *conductivity* structure of the Earth matching simulated *transfer resistances* with observed *transfer resistances*

Imaging/Tomography: A method integrating *forward modeling* and *inversion* to produce a 2D, 3D, or 4D image of the *conductivity* of the Earth from *electrodes* placed along boundaries (commonly defined by the Earth surface and/or boreholes)

Previous Related RITS

- Distribution of In Situ Amendments (Spring 2014)

https://www.navfac.navy.mil/navfac_worldwide/specialty_centers/exwc/products_and_services/ev/erb/rits/pastrits.html

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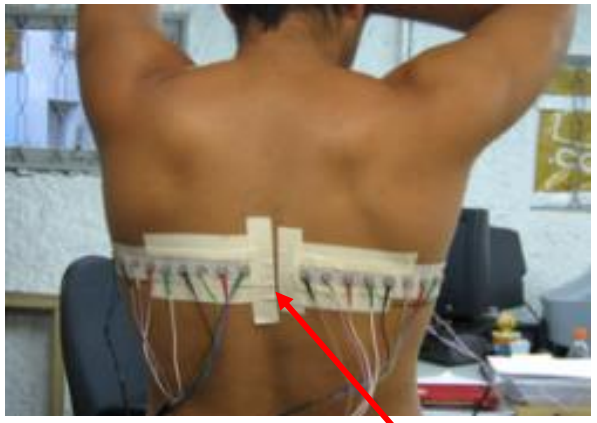
Objective: Familiarize the participants with geophysical imaging and how it works

What is Electrical Resistivity Tomography (ERT)?

Medical Imaging Analog: Electrical Impedance Tomography

Data Collection



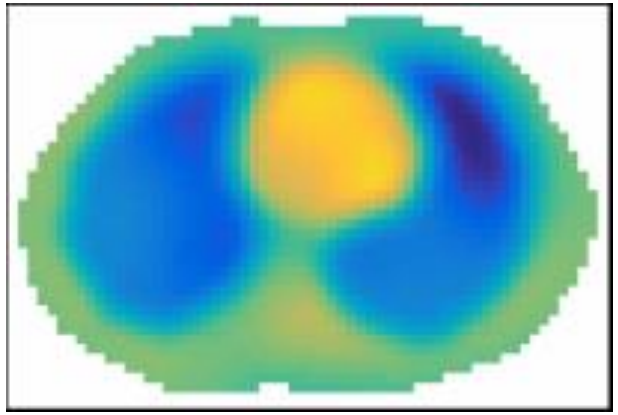
Courtesy Sarah Hamilton

Electrodes

Data Processing

(Inversion)

Tomographic Image



(http://www.marquette.edu/mscs/facstaff-hamilton.shtml
Source: Hamilton et al., 2012.

What is ERT? (cont.)

Subsurface Imaging: Electrical Resistivity Tomography

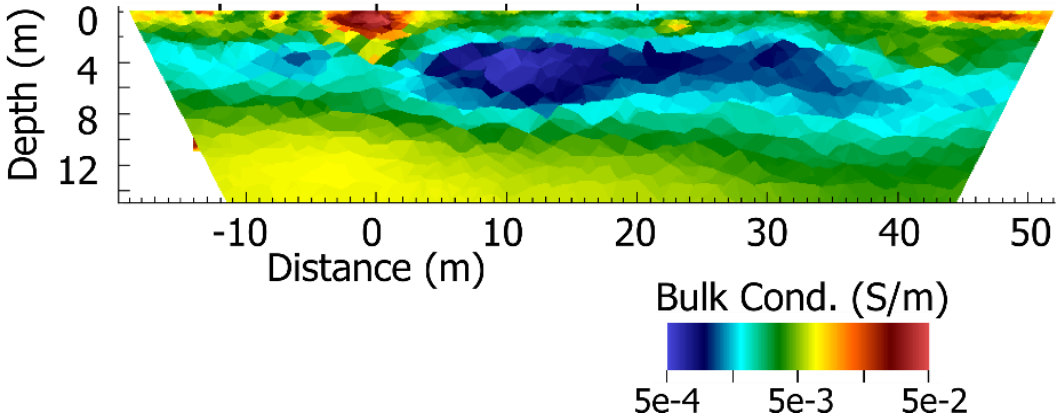
Data Collection

Surface electrode lines

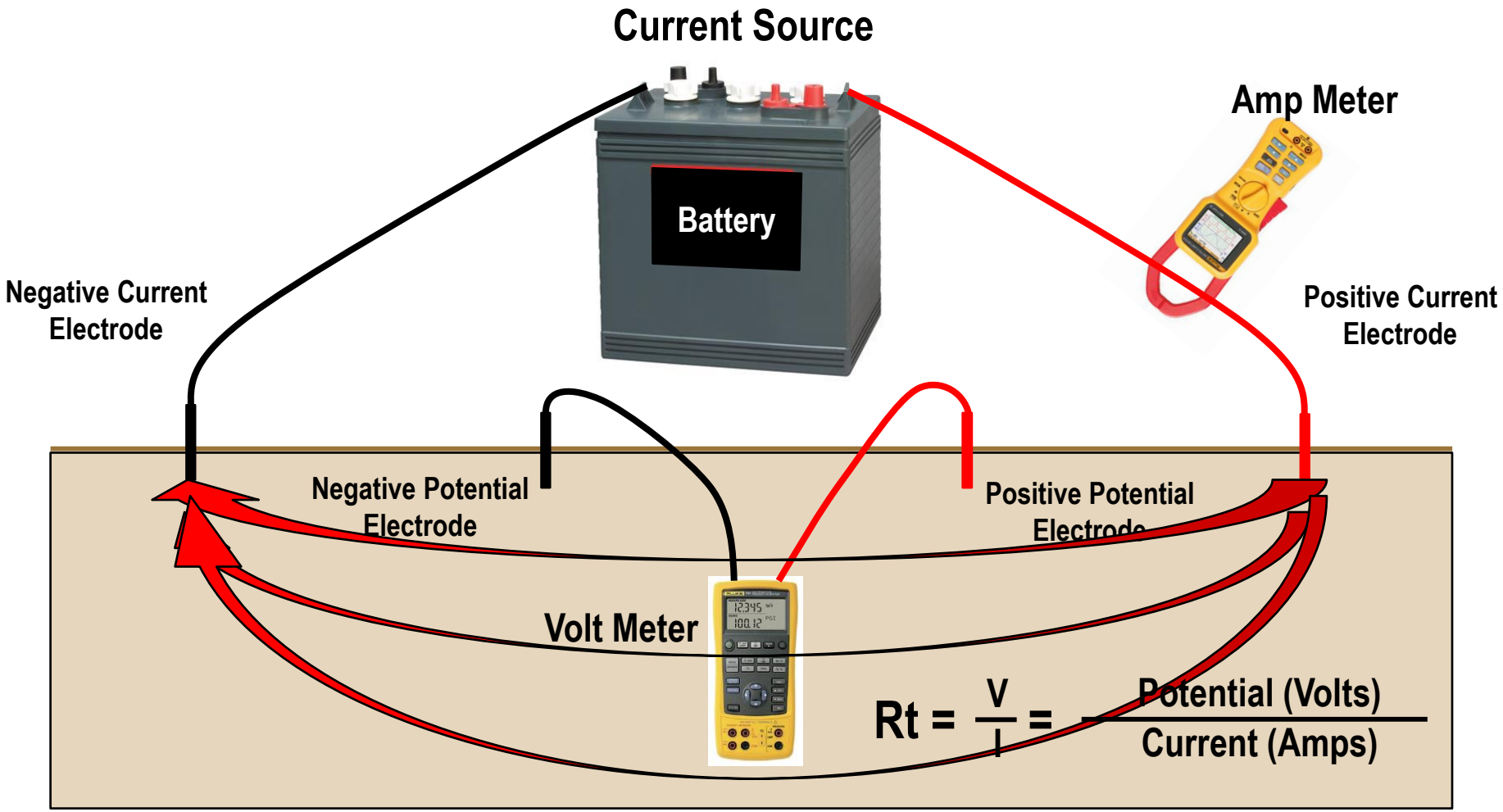
Data Processing

(Inversion)

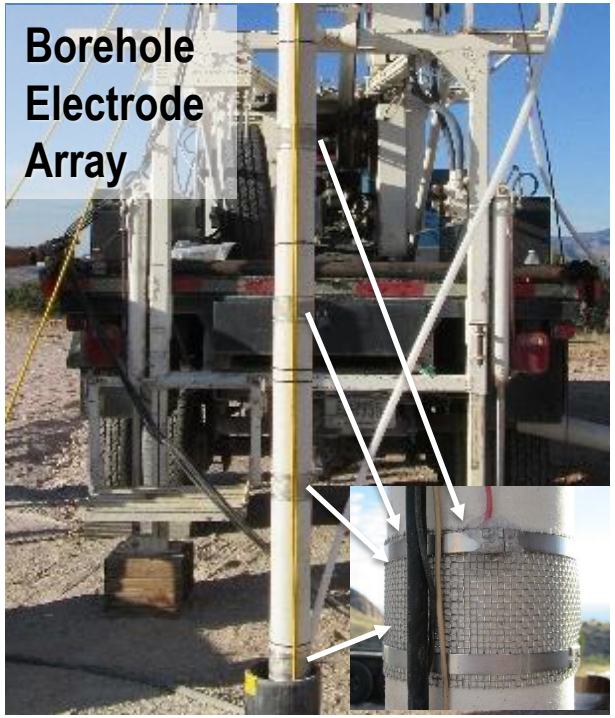
Tomographic Image

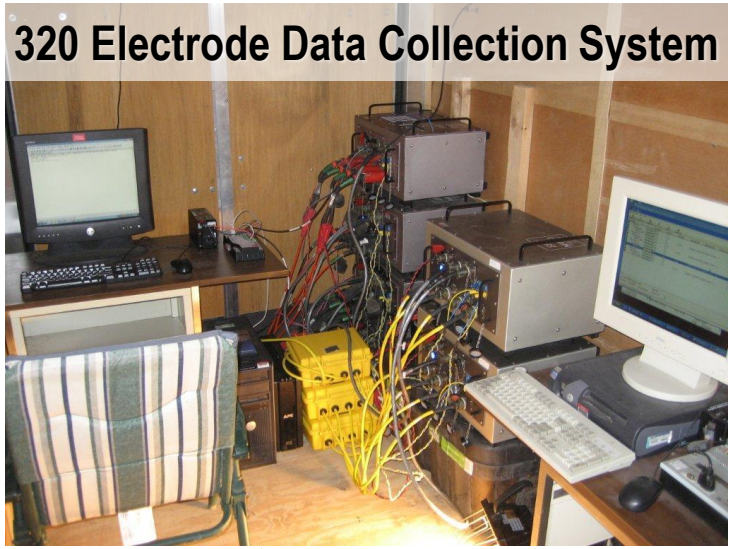


How Does ERT Work?
Data Collection Concept



How Does ERT Work?
Data Collection Hardware

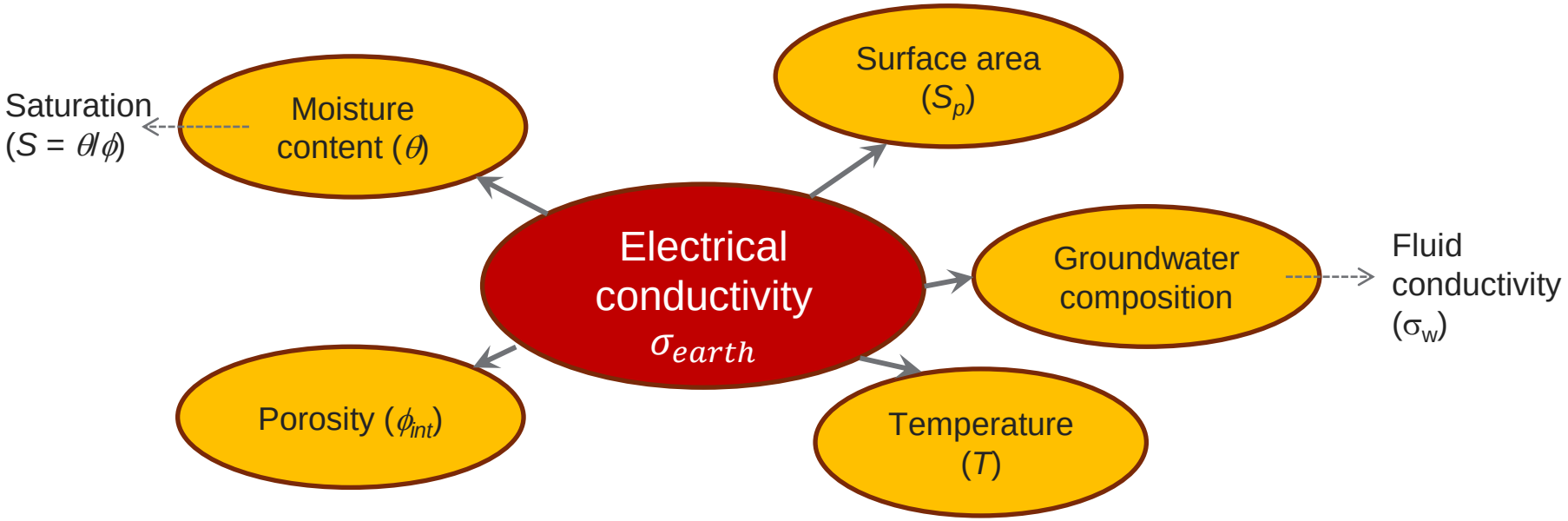




- Autonomous operation (facilitates monitoring)
- Multi-channel – many potential pairs per current injection (enables rapid data collection)
- Remote accessibility (facilitates autonomous imaging)
- No metal casing
- In-borehole electrodes okay in screened zone

What are we measuring and why do we care?

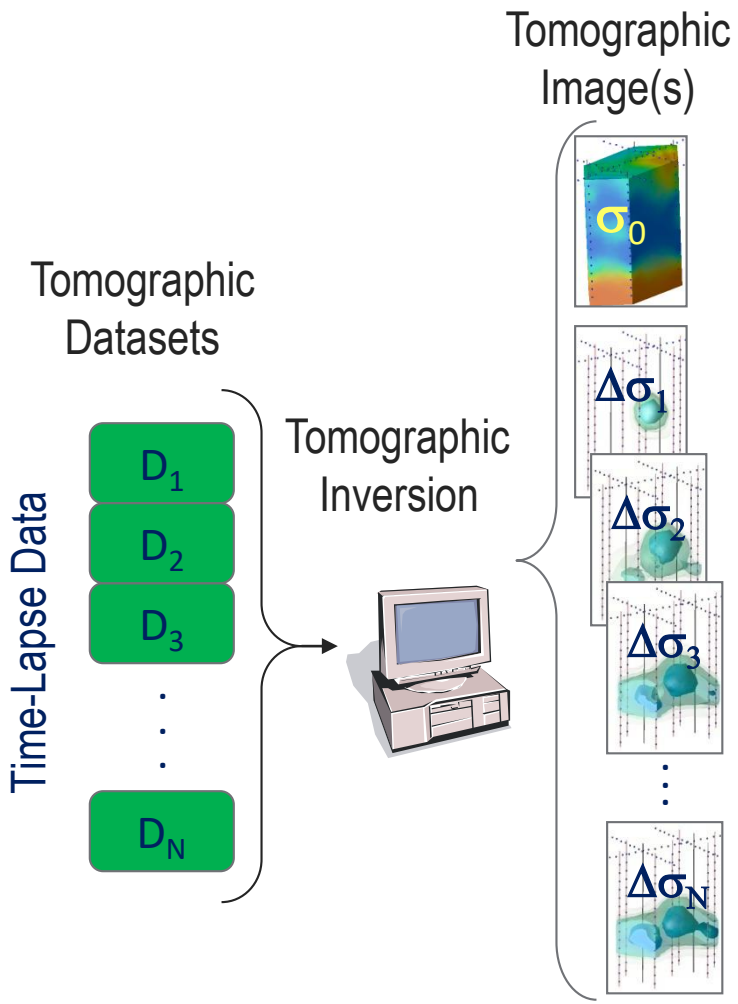
- ERT images the electrical conductivity distribution of the subsurface
- Electrical conductivity is governed by several properties important to remediation performance



$$\sigma_{earth} = \frac{1}{\rho_{earth}} = \sigma_w(T)\phi_{\text{int}}^m S_w^n + \sigma_{surf}(S_p, \sigma_w, S, T)$$

m and n are exponents related to pore space connectivity/tortuosity

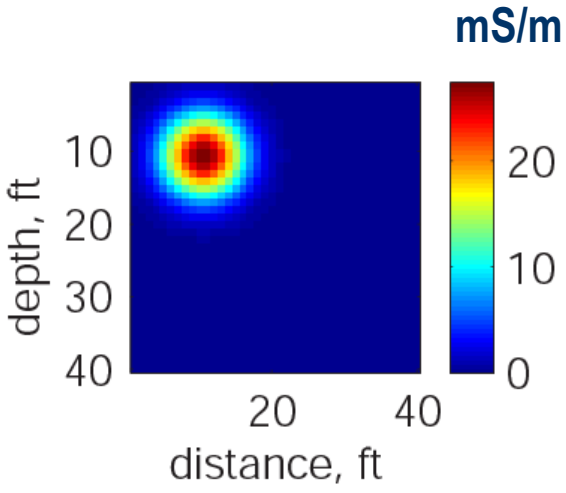
How Does ERT Work?
Data Processing



- Datasets are inverted to recover "images" of electrical properties
- Static images show absolute properties
- Time-lapse images show changes over time
- ERT images conductivity (σ_{earth}) or resistivity (ρ_{earth})

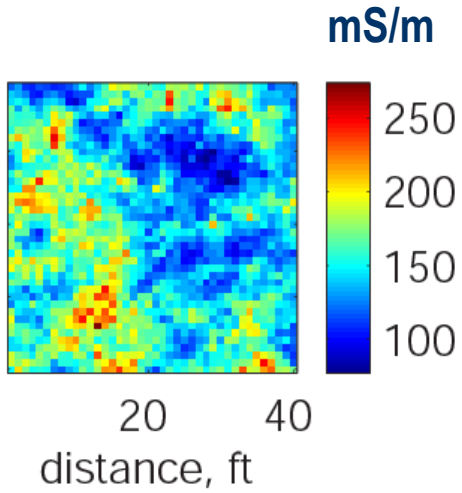
Time-Lapse Difference Imaging

Electrical Conductivity Anomaly (Plume)



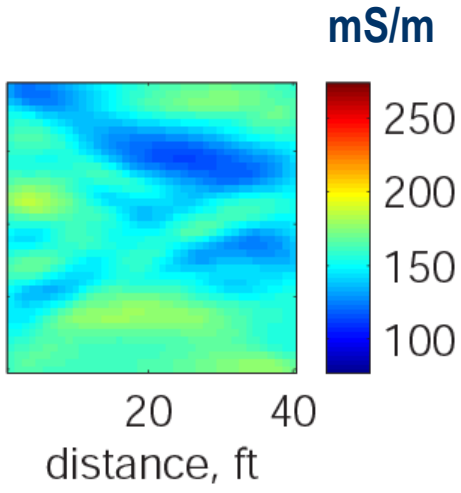
"The Needle"

Electrical Conductivity Cross Section



"The haystack + needle"

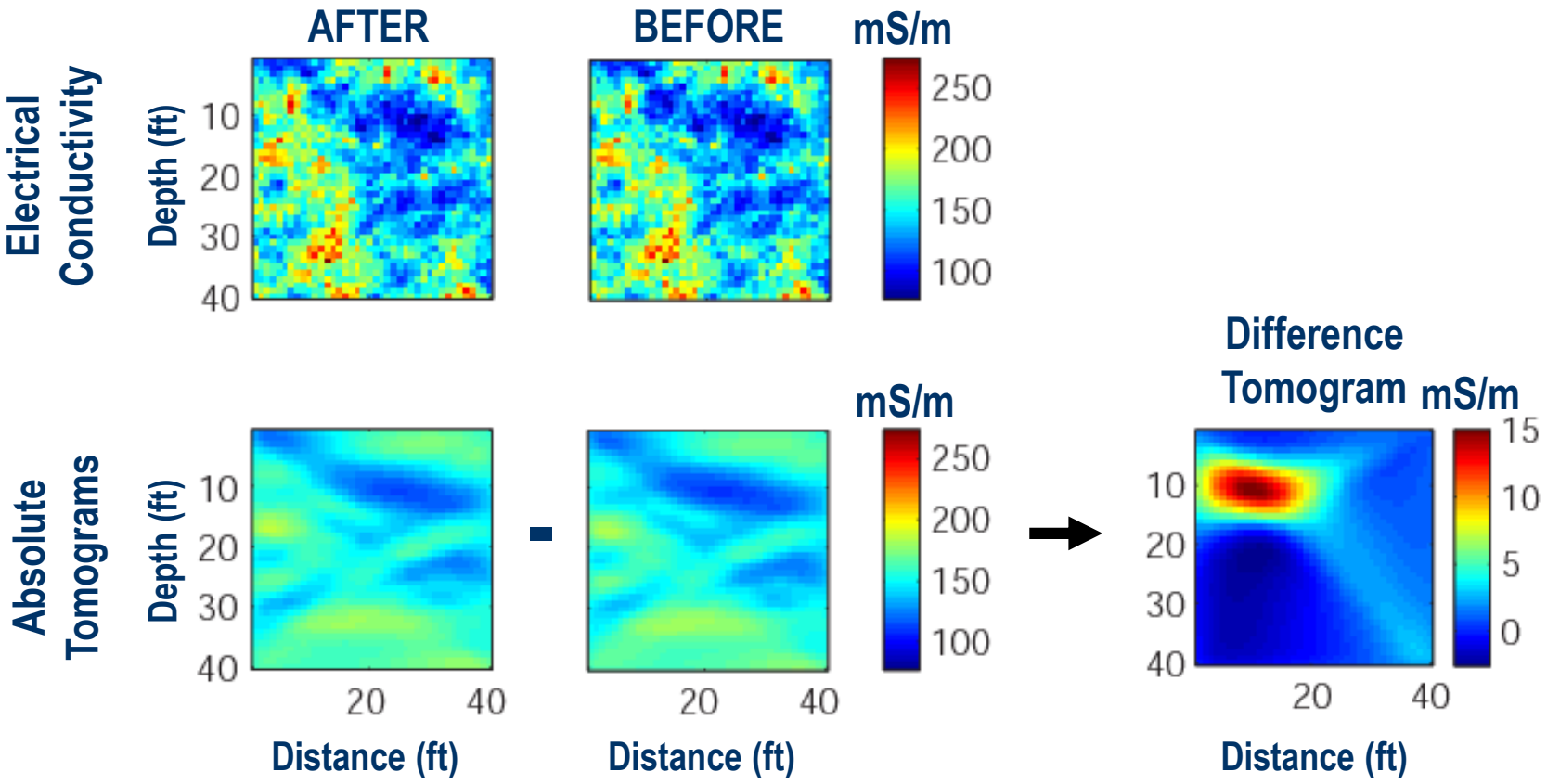
Electrical Conductivity Tomogram



"Blurry Haystack"

Key Point Plume is masked by geologic heterogeneity

Time-Lapse Difference Imaging (cont.)

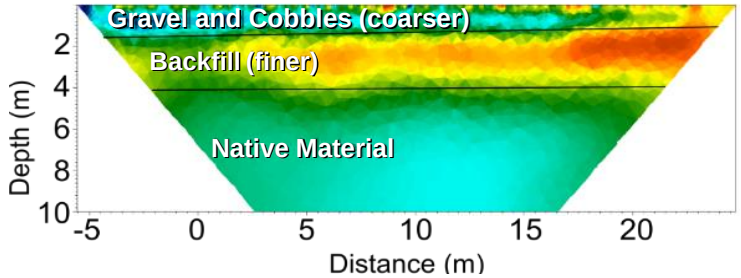


Key Point Plume is revealed by subtracting out pre-injection background, removing unrelated spatial contrasts; i.e., we removed the haystack

Key Points: ERT Can Be Used in Characterization, Remediation, and Monitoring Phases of Your Project

Characterization

- Identify primary geologic boundaries (2D and 3D)
  - Porosity, surface area, and saturation



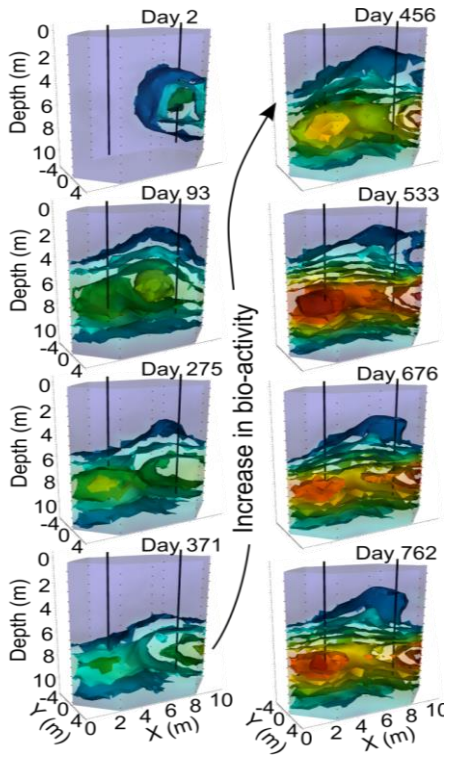
Static 2D ERT Image

Remediation

- Determine distribution and migration of remedial amendments (2D, 3D, 4D)
  - Amendment induced changes in fluid conductivity

Monitoring

- Determine when and where the subsurface is changing (2D, 3D, 4D)
  - Fluid conductivity, precipitation, saturation
- Autonomous, low cost
- With supplementary information (e.g., sample data), can identify what is changing …



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Objective: Familiarize participants with a range of example applications, requirements, costs, and auxiliary data requirements using brief field examples

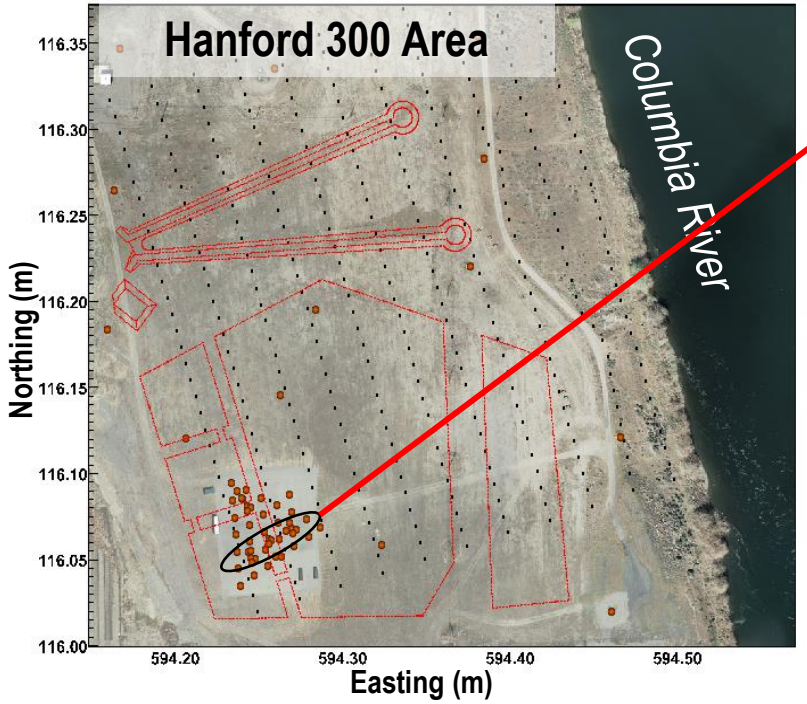
Geologic Characterization of a Shallow Sedimentary System: Hanford Site Near Richland, WA

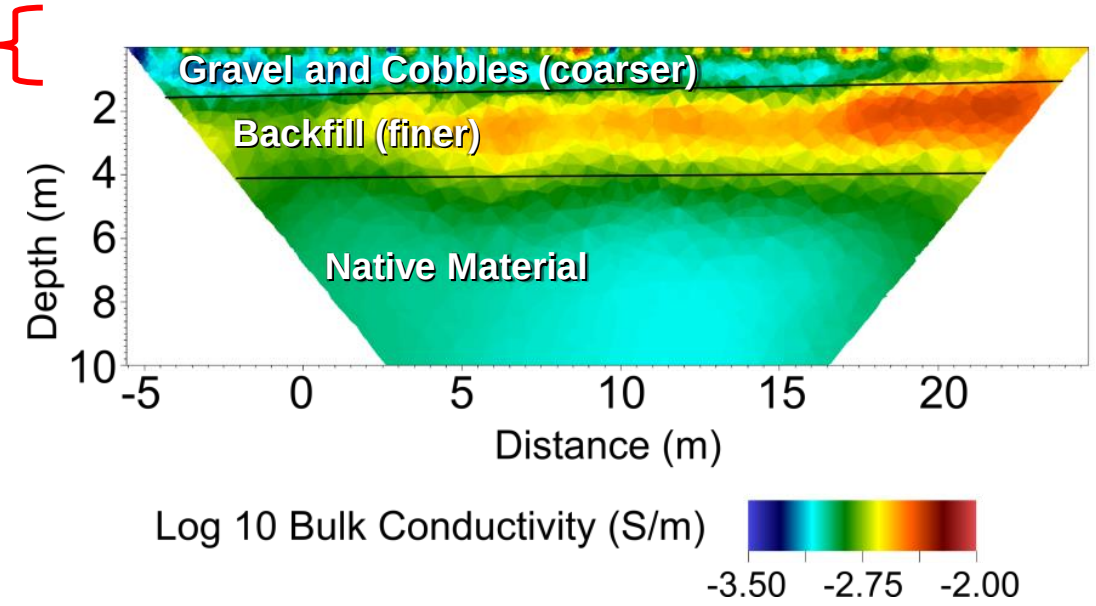
Supplementary Information

- Water table at ~10 m
- Previously excavated to ~4 m
- Coarse surface materials (cobbles, gravel)

Other

- Field time: about 6 man-hours
- Office time: about 3 man-hours
- 64 electrode array





What can this image tell us about the subsurface, in addition to the location of apparent strata boundaries?

Imaging Amendment Transport and Distribution in Fractured Rock Formations: Naval Air Warfare Center, Trenton NJ

Problem

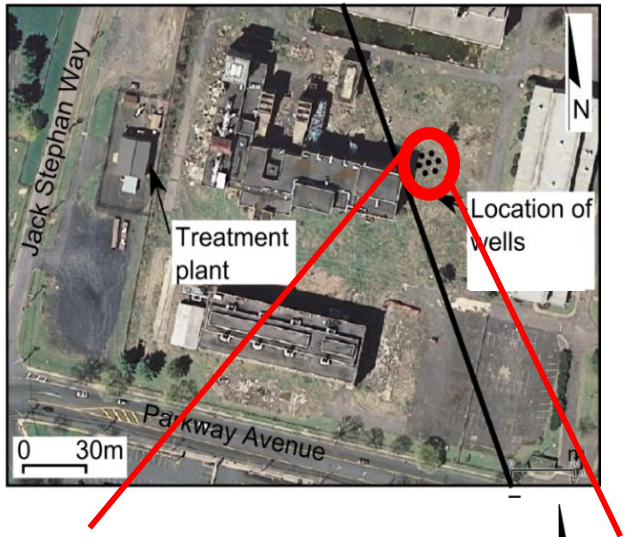
Understanding fluid flow in fractured rock systems is critical for remediation design, but notoriously difficult

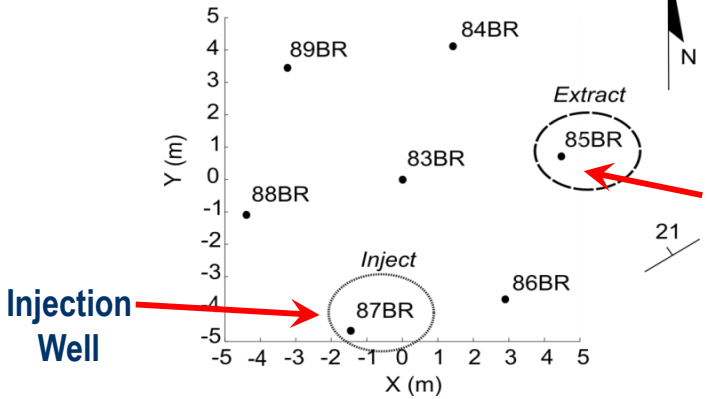
Objective

Demonstrate cross-hole 4D ERT imaging to monitor fluid transport within the fracture zone (ESTCP ER-201118: PI Lee Slater)

Supplementary Information

- Saturated fractured rock (low-grade coal/shale formation)
- Borehole televiewer logs; various geophysical logs to determine fracture contacts at borehole locations, strike, dip
- Saline tracer will increase bulk conductivity of occupied fracture(s)

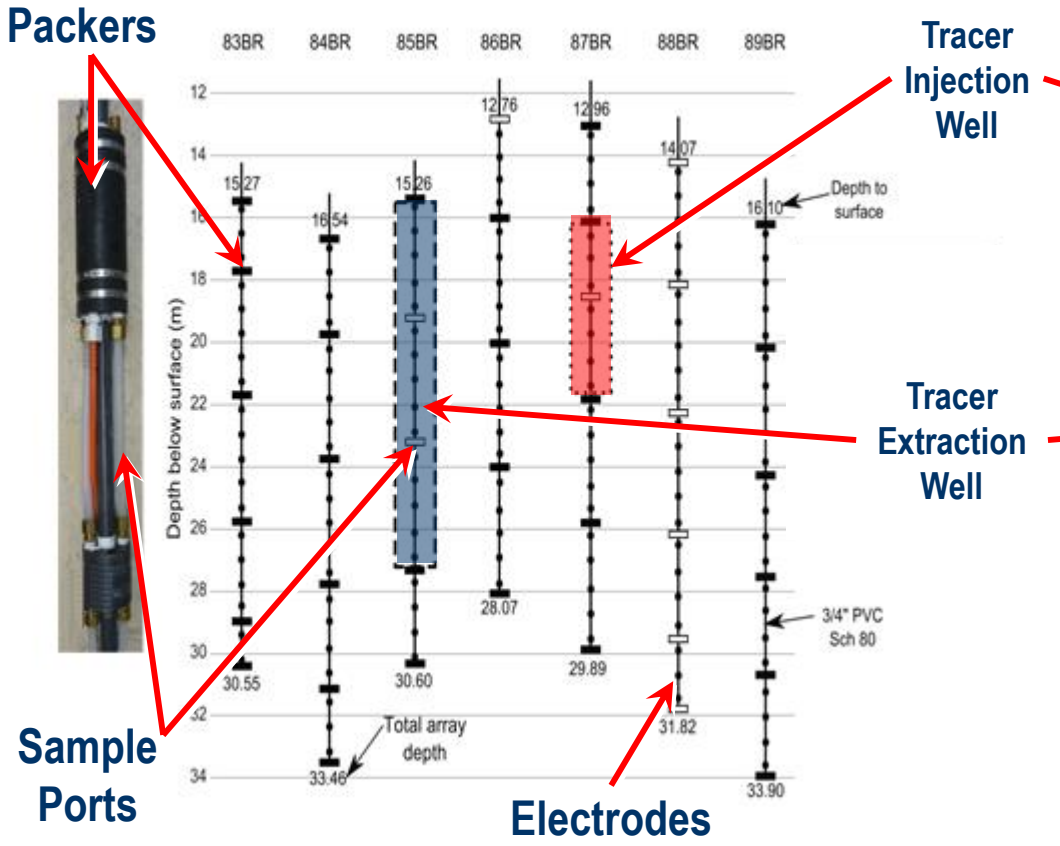




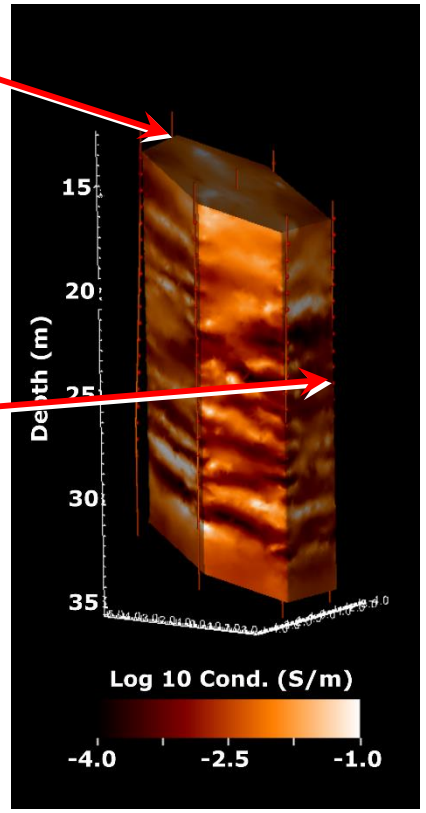
Source: Robinson et al., 2015. *Groundwater*.

Multi-Purpose ERT/Packer/Sampling System and Baseline ERT Image

System Layout



Baseline ERT Image



Source: Robinson et al., 2015. *Groundwater*.

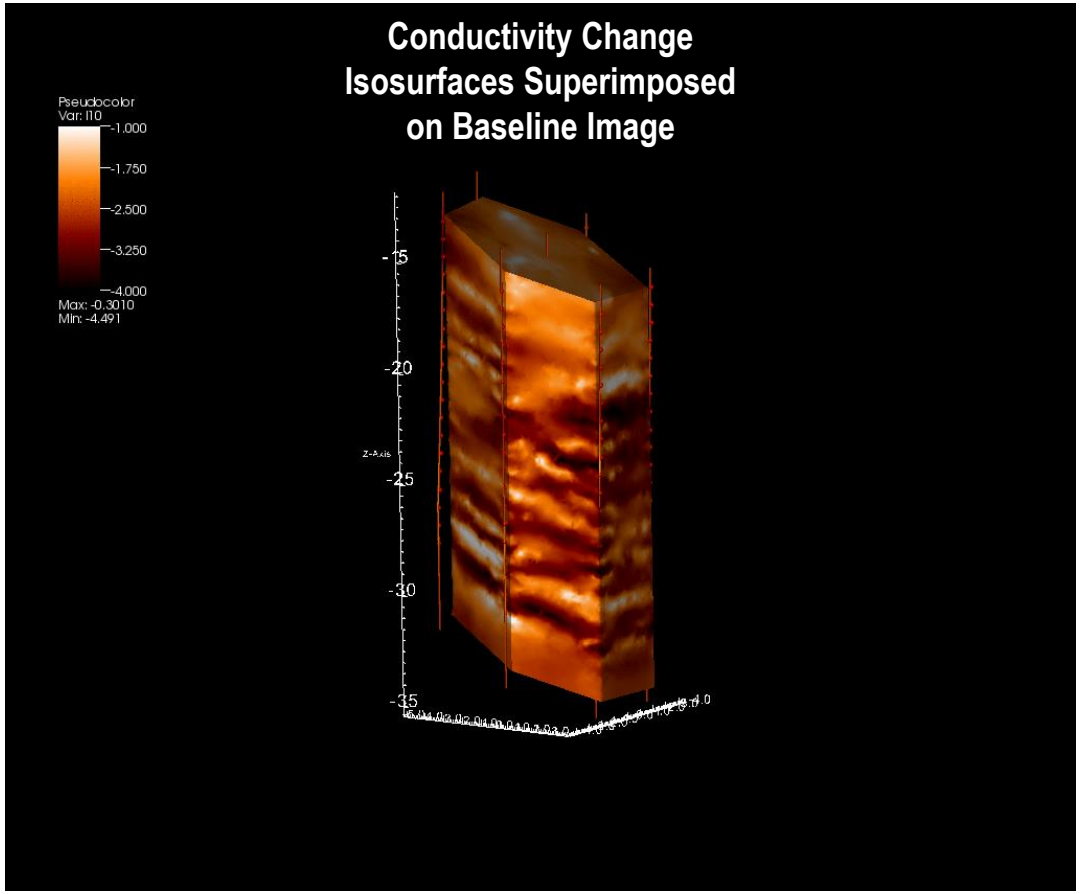
Time-Lapse Difference Imaging Results and Cost

Results

- Tracer distribution captured with time, verified via sampling
- Migrates through fracture zone captured in baseline image
- Demonstrates capability to monitor 3D fluid flow in fractured systems

Costs

- 7 integrated packer/electrode/sampling arrays
  - 96 hours + $5K materials
- Array installation: 32 hours
- Baseline characterization: 8 hours
- Time Lapse 8 frames: 16 hours
- Utilized existing boreholes



Source: Robinson et al., 2015. *Groundwater*.

4D Real-Time Imaging of Stage-Driven Groundwater/Surface Water Interaction: Problem and Objective (Hanford Site Near Richland, WA)

Problem

Former waste infiltration ponds and trenches caused an active uranium plume

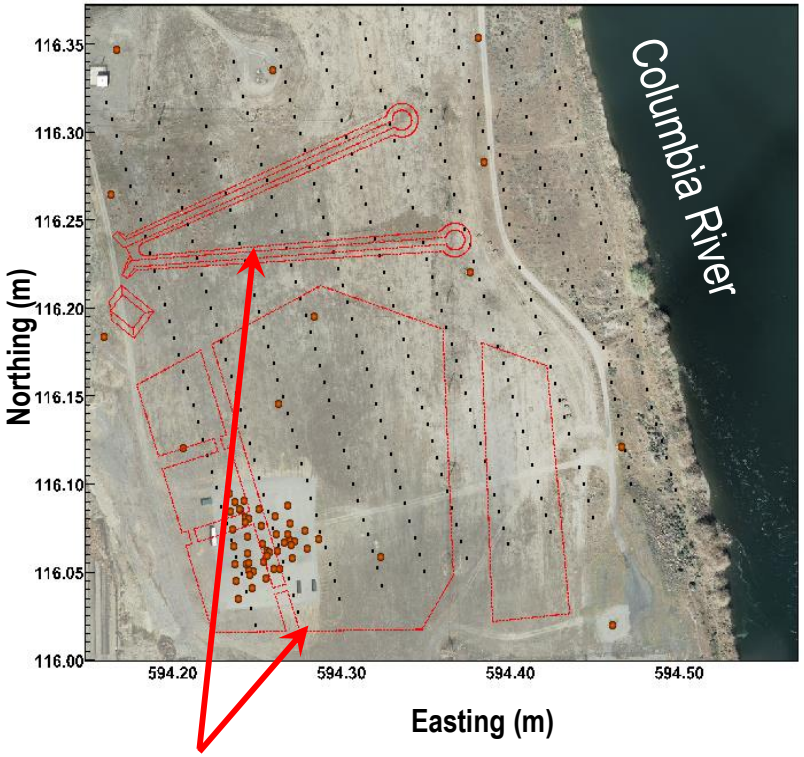
Supplementary Information

- River water chemistry enhances uranium desorption from sediments
- Stage variations and high permeability sediments result in active groundwater/surface water interaction
- River water specific conductance is approximately ½ of groundwater-specific conductance

Objective

Use time-lapse ERT to image stage driven river water intrusion patterns

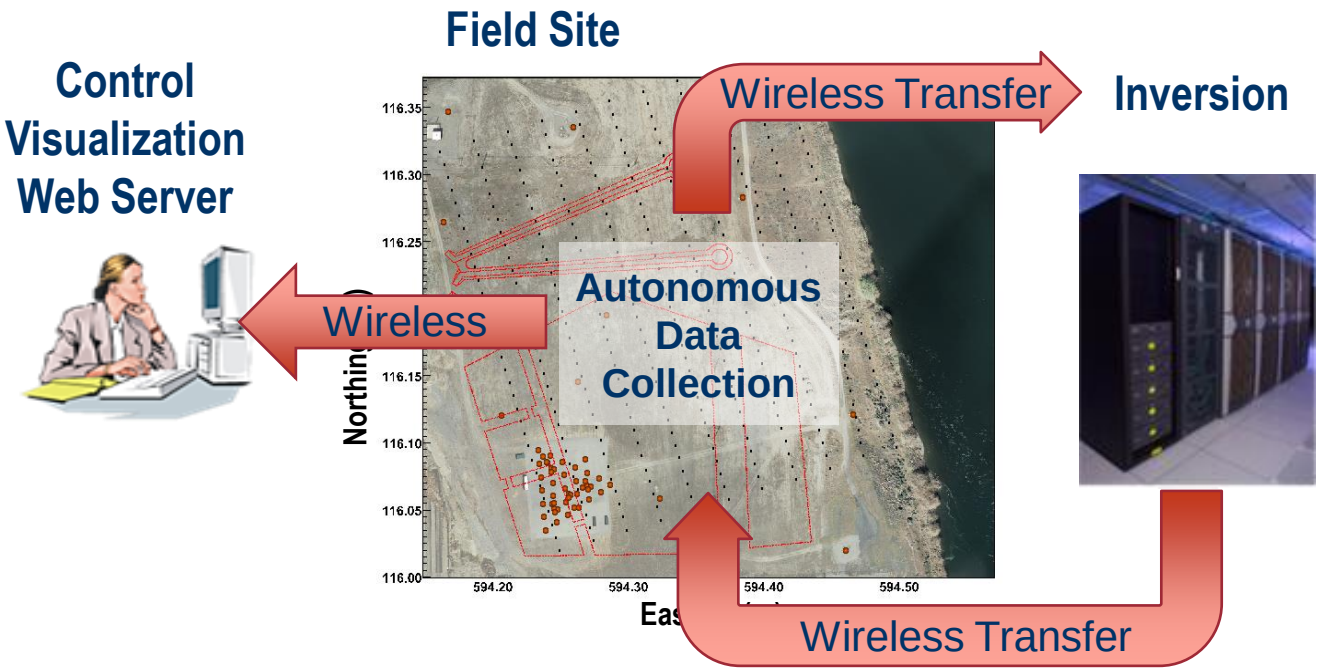
Hanford 300 Area



Former Waste Infiltration Galleries

Surface Electrodes

4D Real-Time Imaging of Stage-Driven Groundwater/Surface Water Interaction: Monitoring System



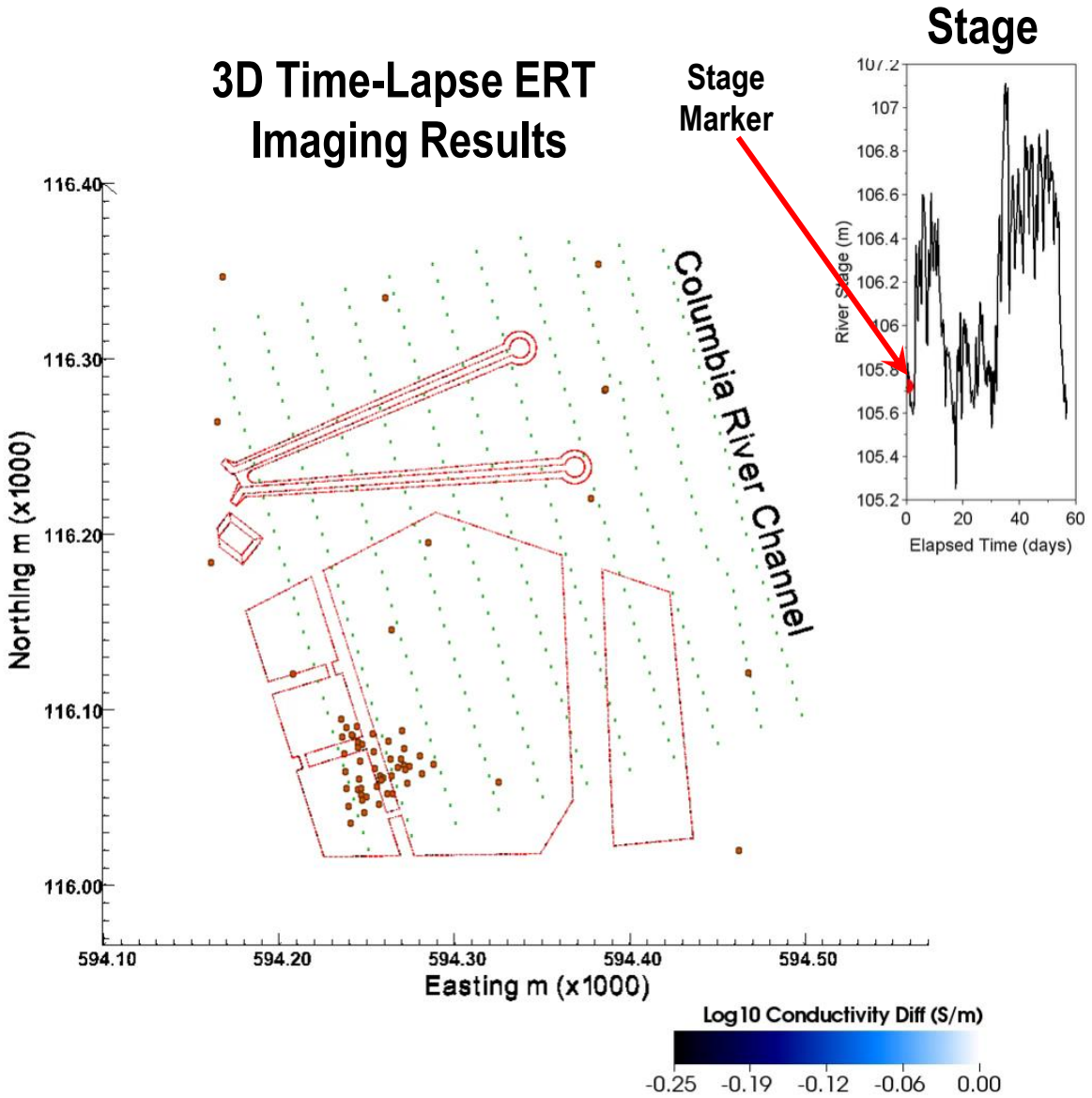
- 320 electrodes
- Field setup time: ~60 man hours
- Office setup time: ~40 man hours
- Capital cost: ~$100 K

- Survey time: ~ 6 hours (no labor required)
- Inversion time: ~ 5 minutes (no labor required)
- Monitoring duration: 6 months
- Fully autonomous operation

4D Real-Time Imaging of Stage-Driven Groundwater/River Water Interaction: Time-Lapse Difference Imaging Results (Hanford Site Near Richland WA)

Comments

- Baseline image at low stage (when aquifer is occupied by groundwater)
- Images show decrease in bulk conductivity caused by intruding river water
- Results show groundwater/river water interaction governed largely by high permeability paleochannel



Source: Johnson et al., 2015. *Water Resources Research.*

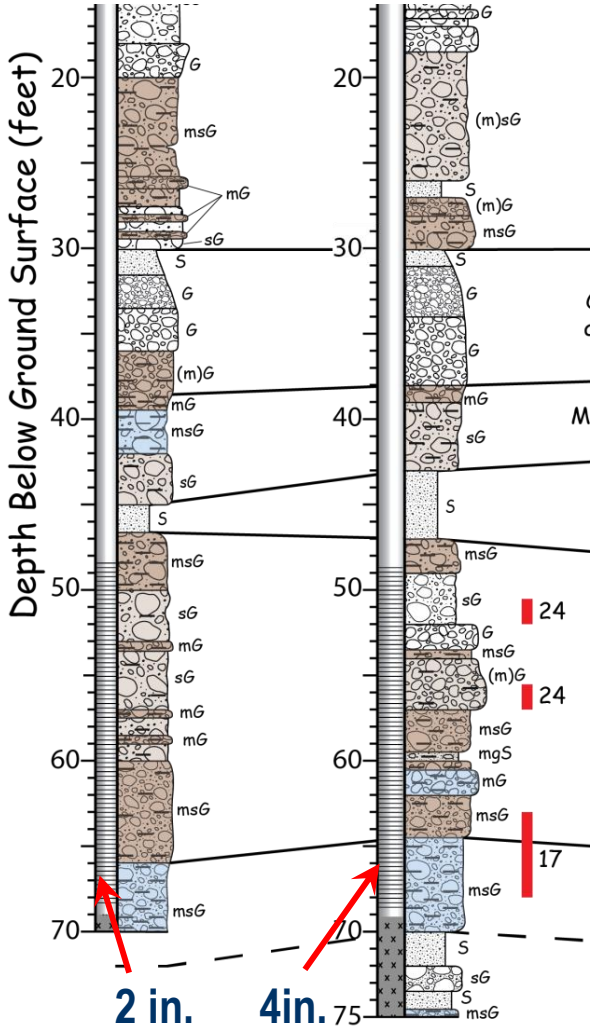
Evaluating the Performance of Shear Thinning Fluids for Accessing Low Permeability Zones: Problem

Problem

TCE contamination in low-permeability sediments
(Joint Base Lewis McCord Golf Course, Bremerton, WA)

Note: Shear thinning fluid viscosity decreases as shear stress increases (i.e., tends to be more viscous when pushed through high permeability sediments and less viscous when pushed through low-permeability sediments … enables penetration into low permeability sediments.
Examples: xanthan gum, guar gum)

TCE-Contaminated Muddy Gravels and Sands



Evaluating the Performance of Shear Thinning Fluids for Accessing Low Permeability Zones: Objective

Problem

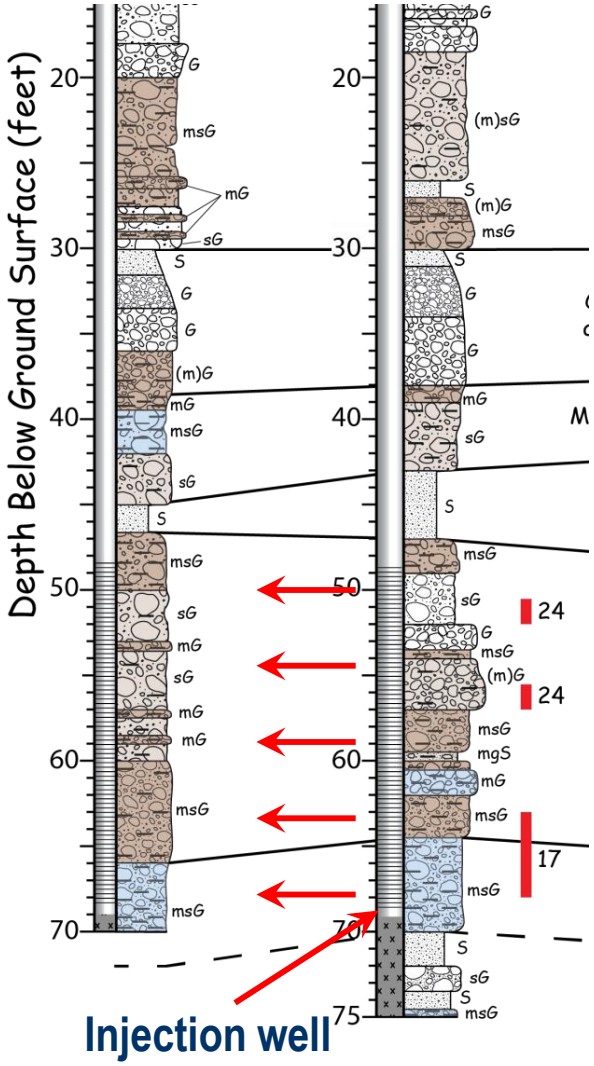
TCE contamination in low-permeability sediments
(Joint Base Lewis McCord Golf Course, Bremerton, WA)

Objective

Evaluate the use of shear thinning fluids for delivering remedial amendments to low-permeability zones

Procedure

1. Inject conservative tracer with water
2. “Rinse” with groundwater
3. Inject conservative tracer with shear thinning fluid
4. Compare



Source: Truex et al., 2011. *Groundwater Monitoring and Remediation*.

Evaluating the Performance of Shear Thinning Fluids for Accessing Low Permeability Zones: Approach

Problem

TCE contamination in low-permeability sediments
(Joint Base Lewis McCord Golf Course, Bremerton, WA)

Objective

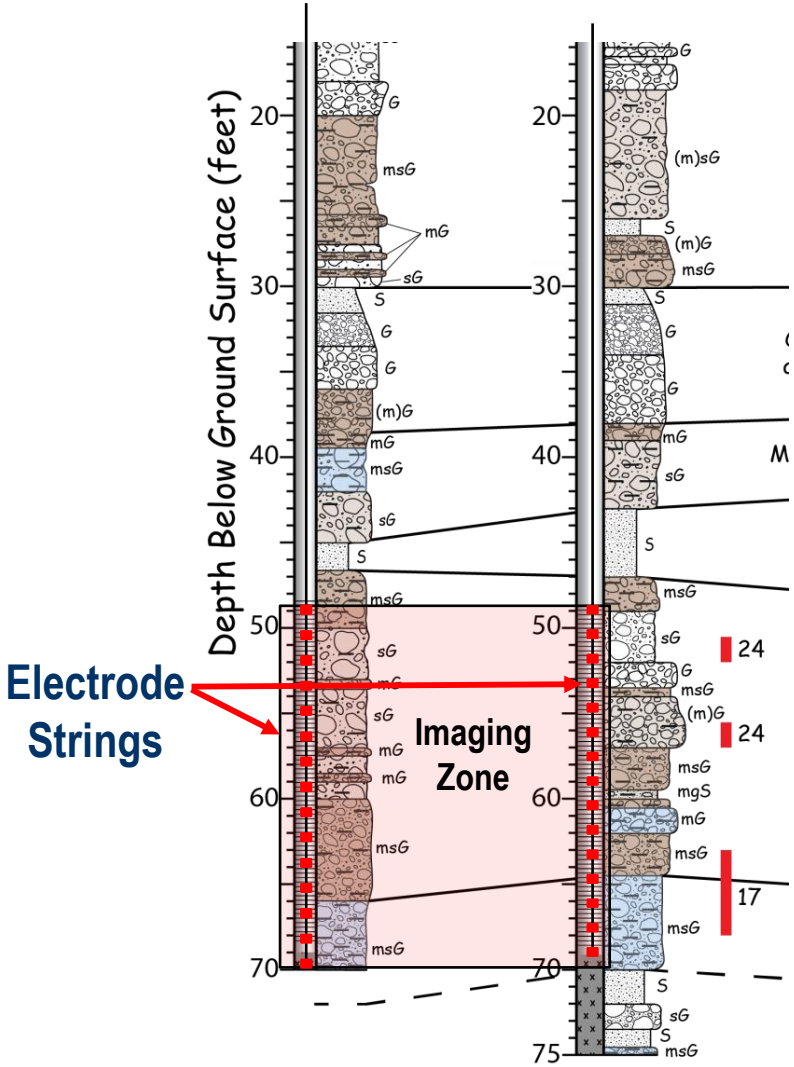
Evaluate the use of shear thinning fluids for delivering remedial amendments to low-permeability zones

Approach

Use ERT difference tomography to image amendment penetration with and without shear thinning fluid

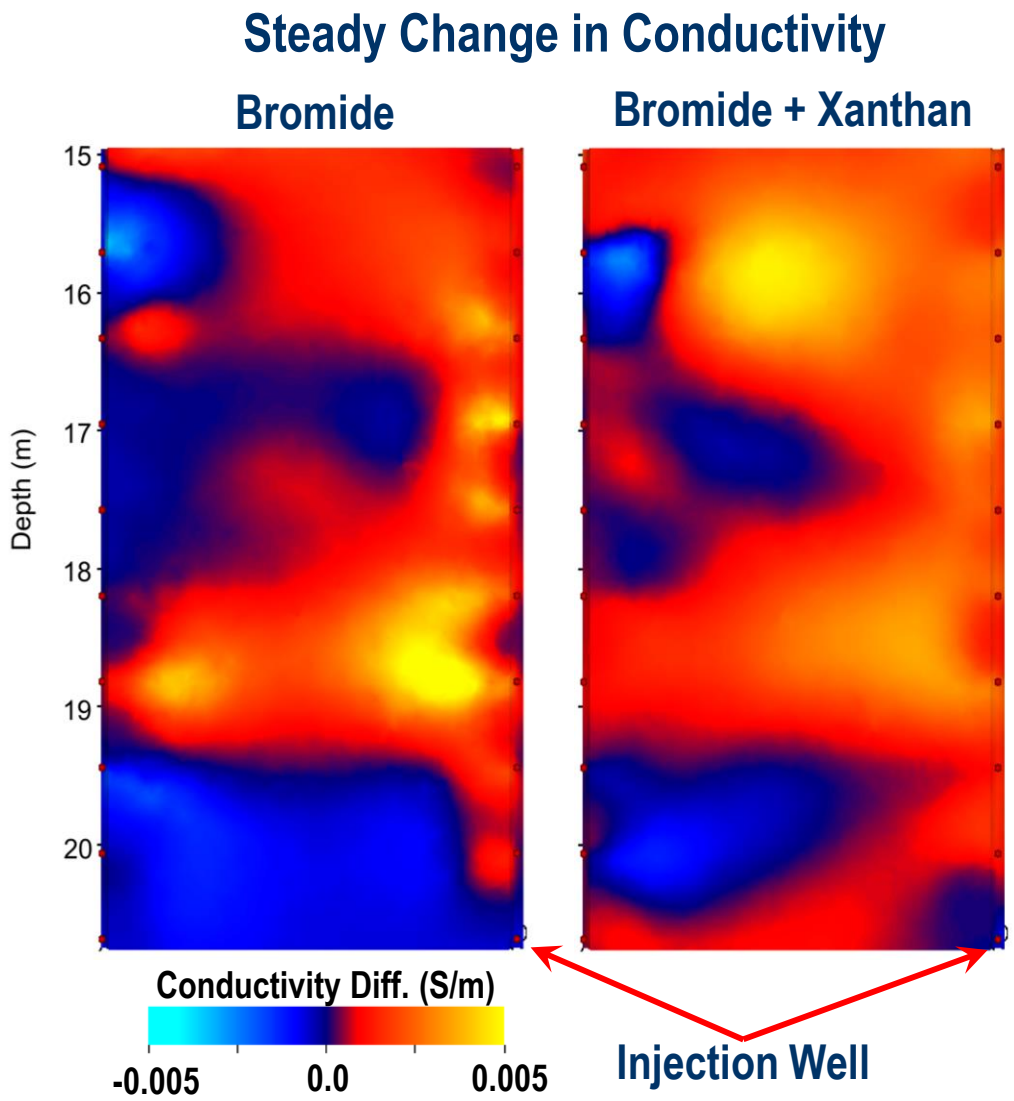
Question

- Why should difference imaging work?



Evaluating the Performance of Shear Thinning Fluids for Accessing Low Permeability Zones: Results

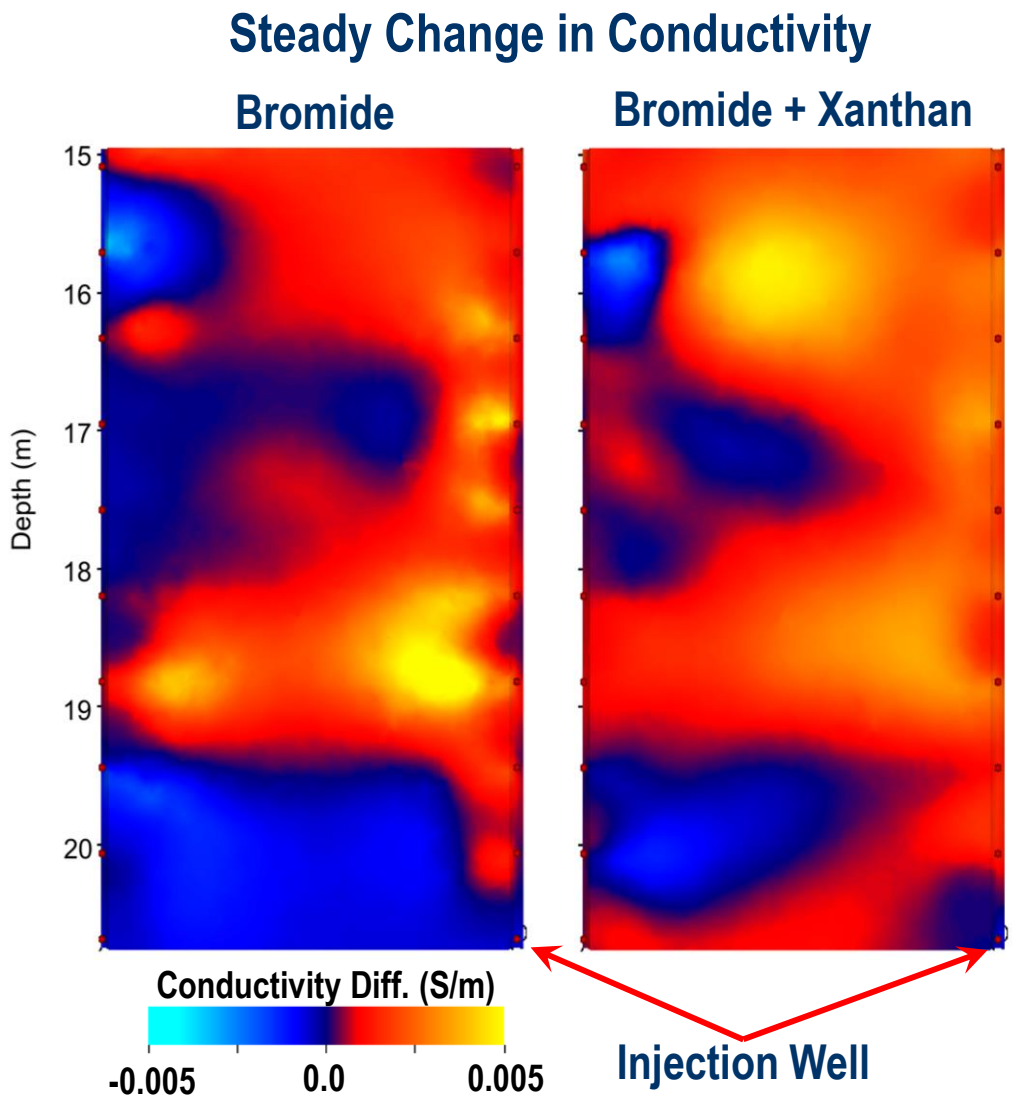
- Steady state = no further penetration with continued pumping
- Positive changes in conductivity indicate presence of bromide tracer
- Significantly improved penetration with shear thinning fluid (Xanthan)
- Results validated with monitoring well samples



Source: Truex et al., 2015. *Groundwater Monitoring and Remediation*.

Evaluating the Performance of Shear Thinning Fluids for Accessing Low Permeability Zones: Cost

- Used existing screen sampling wells
- ~4 hours field setup
- ~12 hours office time
- ~$25K for ERT instrument
- ~$ 5K for project-specific hardware (electrode cables, etc.)



Source: Truex et al., 2015. *Groundwater Monitoring and Remediation*.

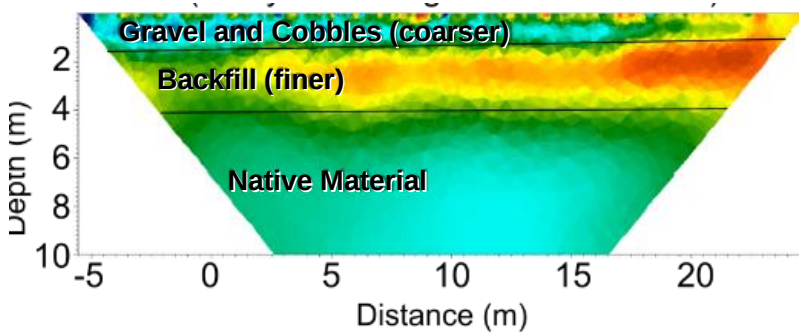
Key Points: What Can ERT Do for You?

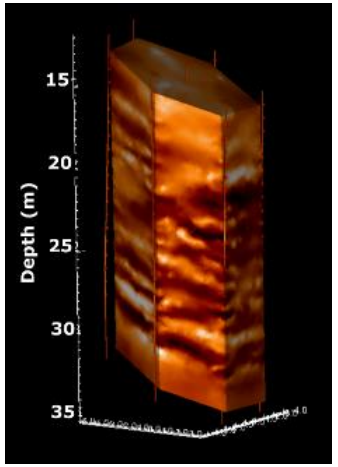
- Provide geologic boundaries for conceptual site model development
- Image when and where the subsurface is changing in 2D or 3D (e.g., amendment delivery)

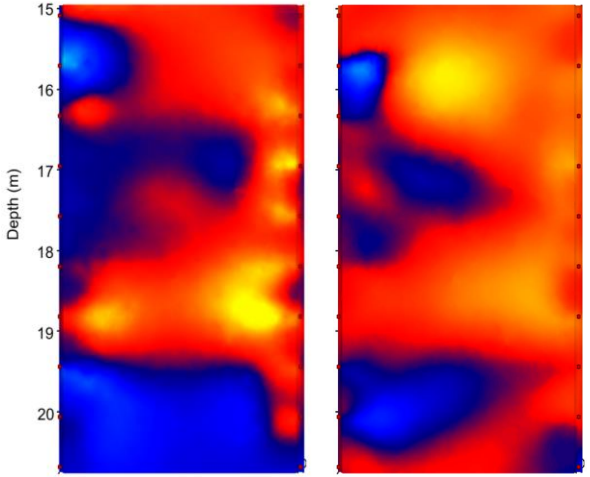
These capabilities are all accessible …

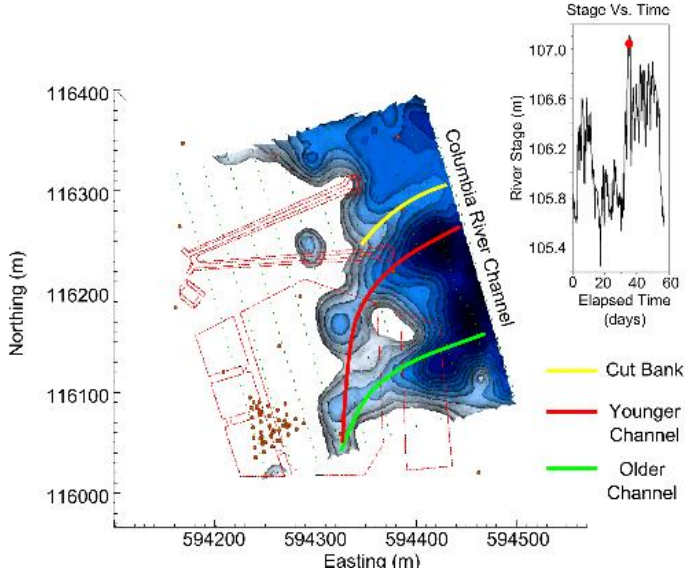
- *Except commercial real-time imaging*
- *Different contractors have different levels of capability*

How does the RPM ensure success?









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Objective: Familiarize participants with the limitations and pitfalls of geophysical imaging using field examples. Point to tools and resources that minimize risk.

Understanding Resolution and Implications: Developing Realistic Expectations

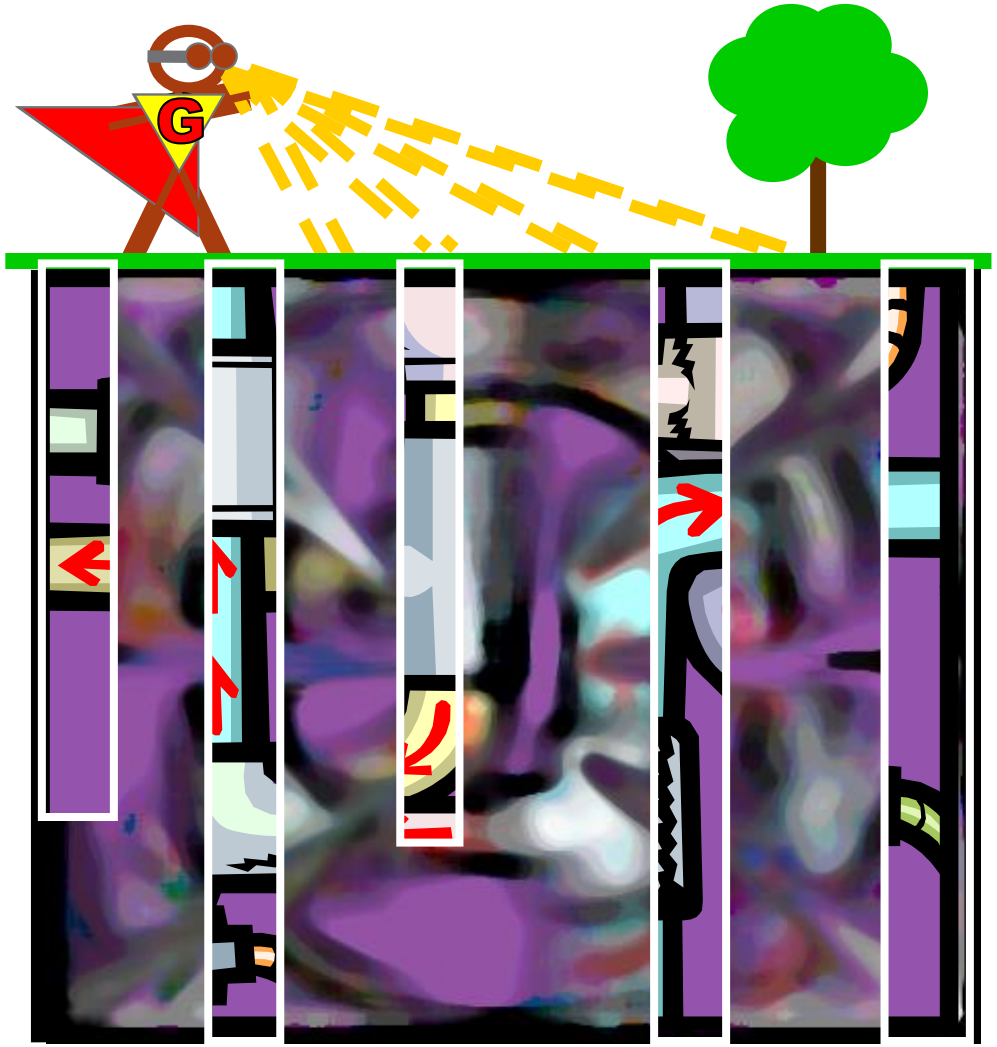
Pros

- Minimally invasive
- Relatively low cost
- Can cover a large area
- ‘Sees’ in between wells
- Good at the “when and where”

Cons

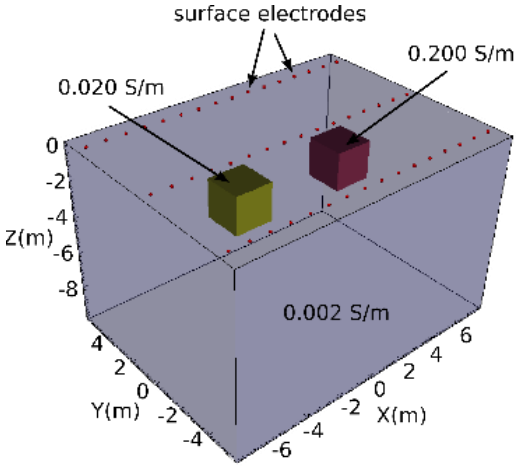
- Indirect – Correlation or interpretation is required
- Limited resolution
- Not good at the “what”

→ **Not an either/or proposition!**
Geophysics is most powerful when used in combination with conventional measurements!

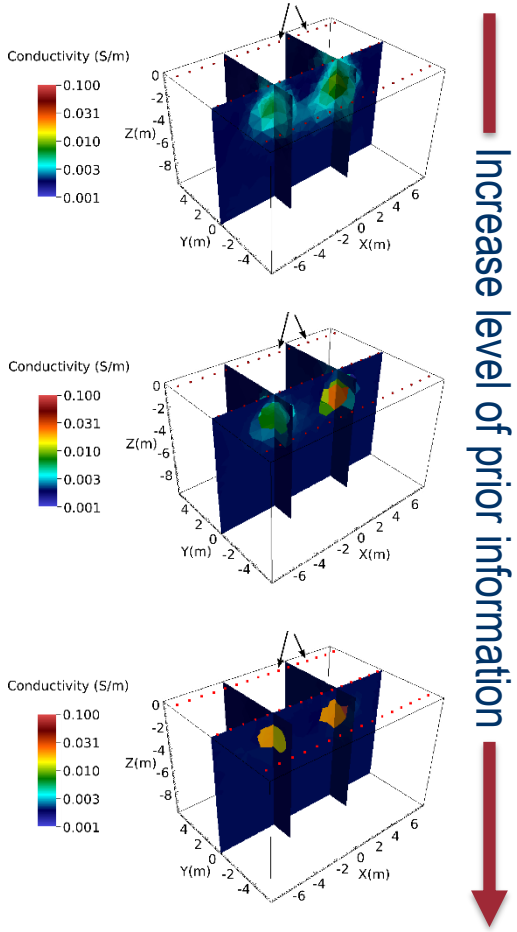


Understanding Resolution and Implications: Consequences of Limited Resolution

True Conductivity



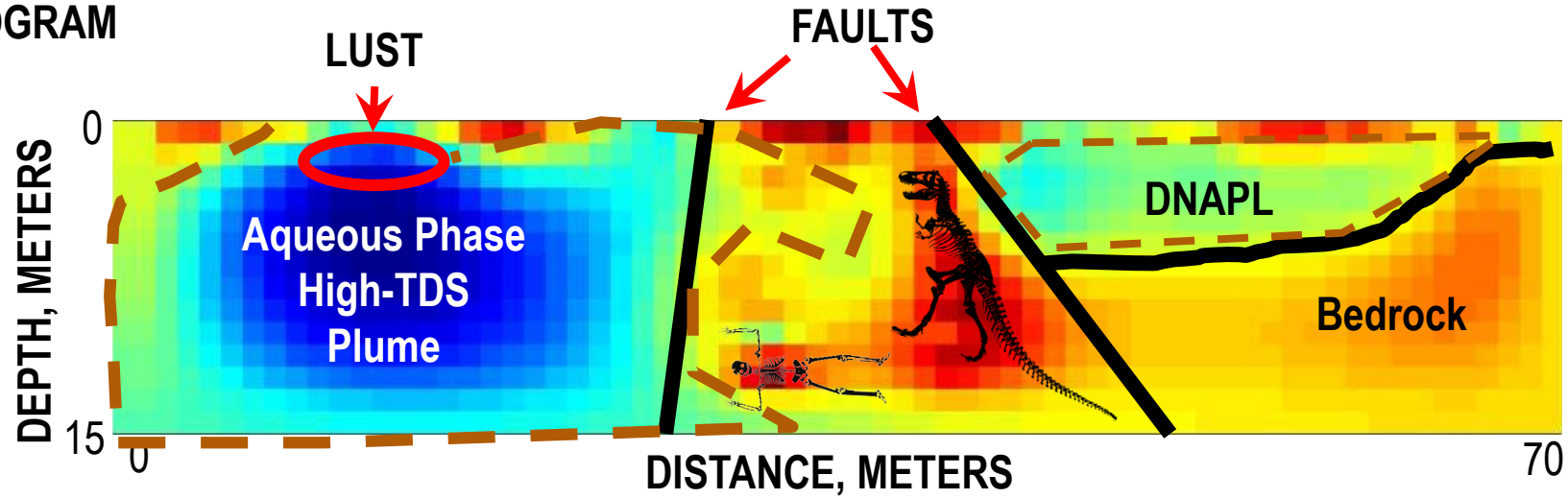
3D Images



- Images are smeared versions of reality
- Small-scale features unresolved
- Averaging (highs under-predicted, lows are over-predicted)
- Laboratory-scale measurements do not translate directly to field scale
- Resolution decreases with distance from electrodes
- Prior information can improve resolution (with great care!)

Recognizing Overinterpretation

TOMOGRAM



TRUTH

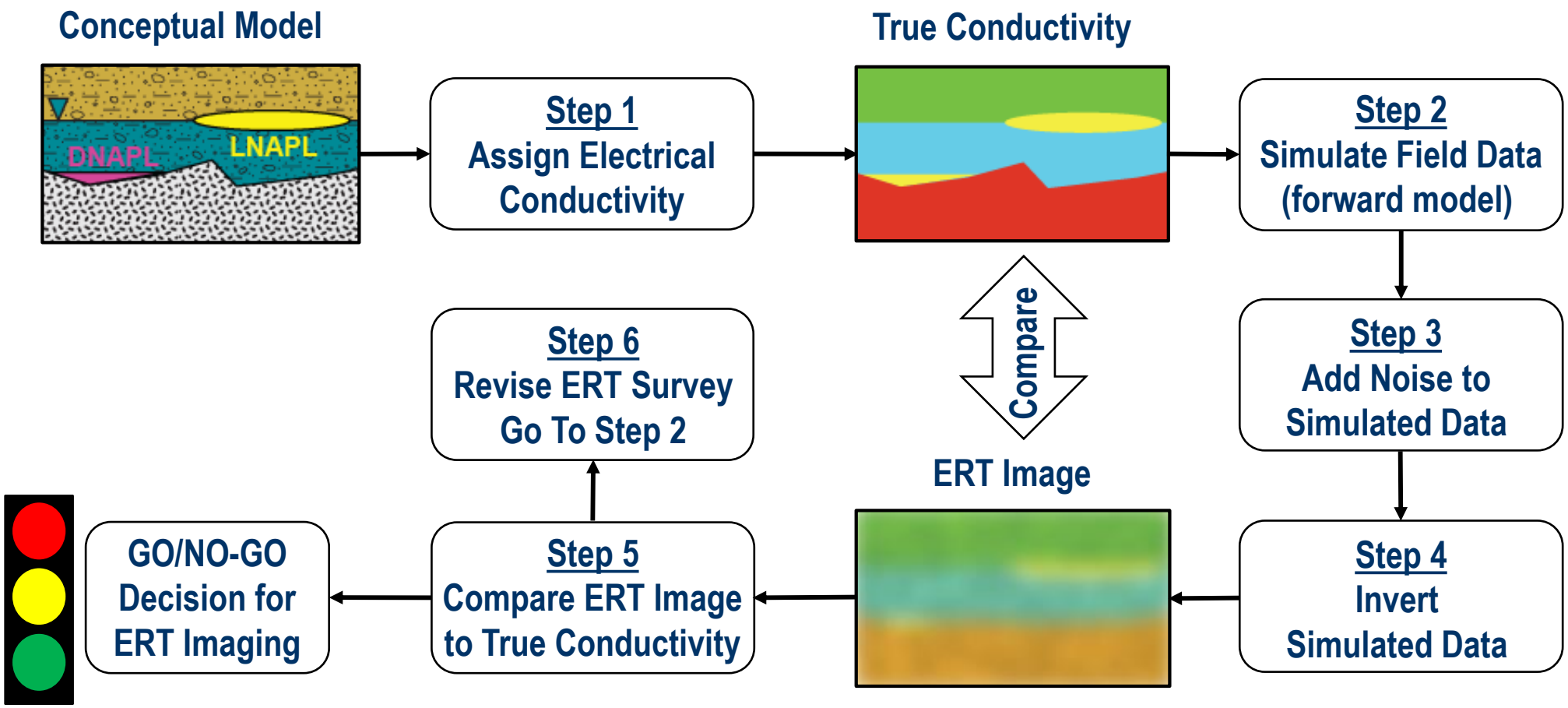
How to Avoid Pitfalls: The Feasibility Assessment

RED FLAGS:

- **Highly detailed images/small features far from electrodes**
  - Indicative of data overfitting
- **Quantitative interpretations**
  - Maps of contaminant concentrations
  - Maps of porosity, saturation, mineralogy
  - Maps of bioactivity
- **Interpretation without any supporting information**
- ***Sounds Complicated! How is the RPM to avoid the pitfalls?***

Key Point ***REQUIRE A FEASIBILITY ASSESSMENT FROM YOUR CONTRACTORS!***

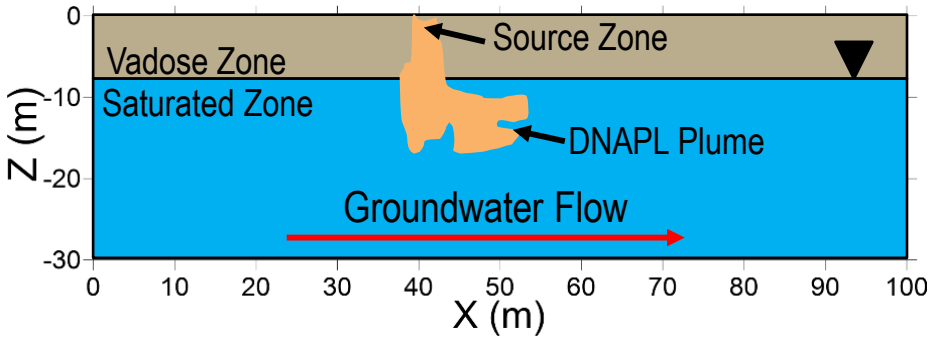
Pre-Modeling Feasibility Assessment Flowchart



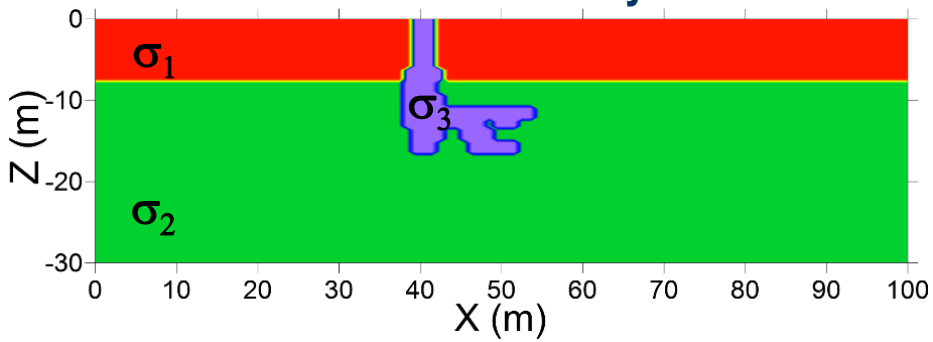
Example Feasibility Assessment: Imaging a DNAPL Plume

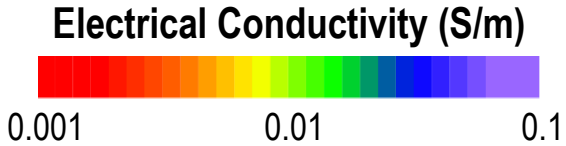
Step 1
Assign Electrical Conductivity

Conceptual Model



True Conductivity





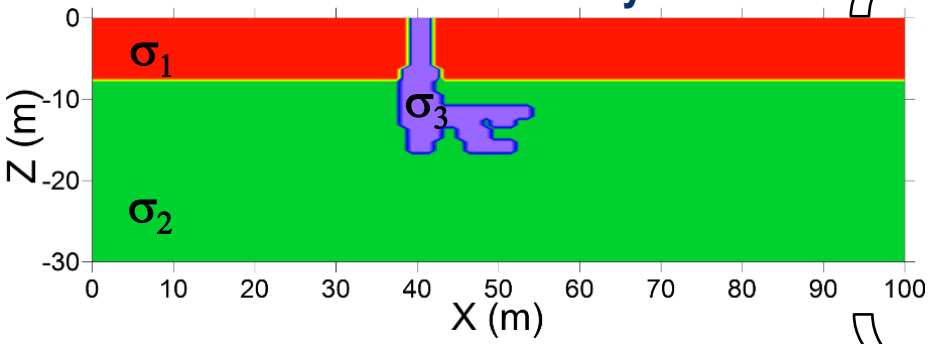
True conductivity estimated from

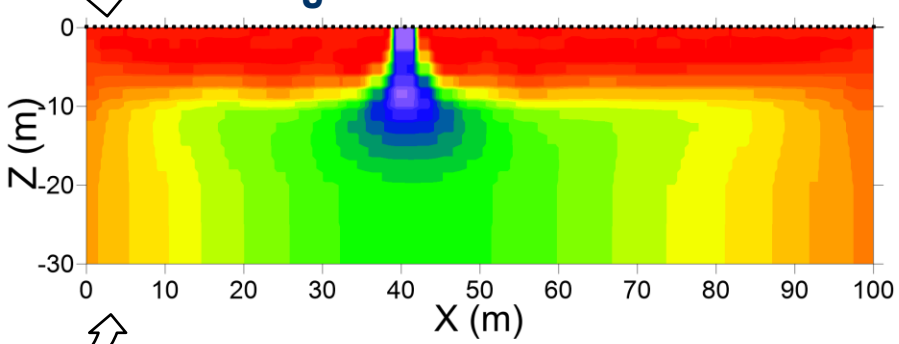
- Estimated saturation
- Estimated porosity
- Estimated native and DNAPL fluid conductivity

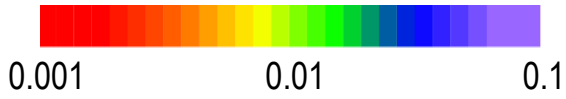
(See slide 9)

Example Feasibility Assessment: Imaging a DNAPL Plume (cont.)

Steps 2, 3, and 4

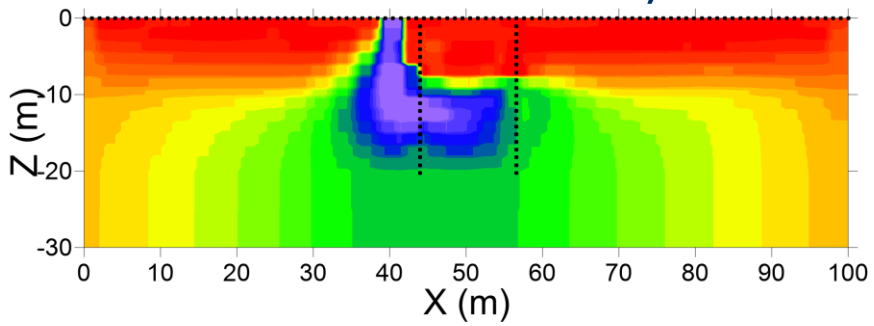






Step 5 (Compare)

Step 6 (revise survey, add borehole electrodes)



Step 7: Go/ No-Go Decision

- Does pre-modeling suggest the target is sufficiently resolvable with electrical imaging?

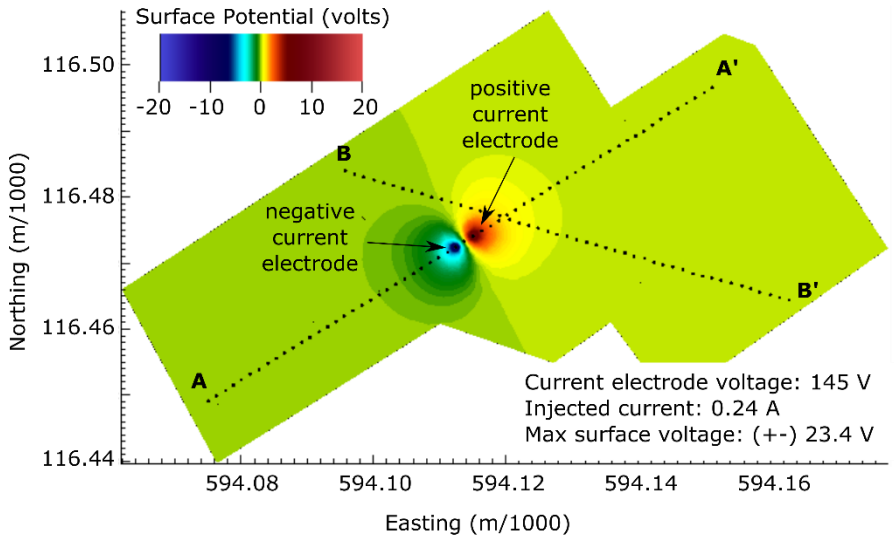
What Conditions Disqualify ERT From Consideration?

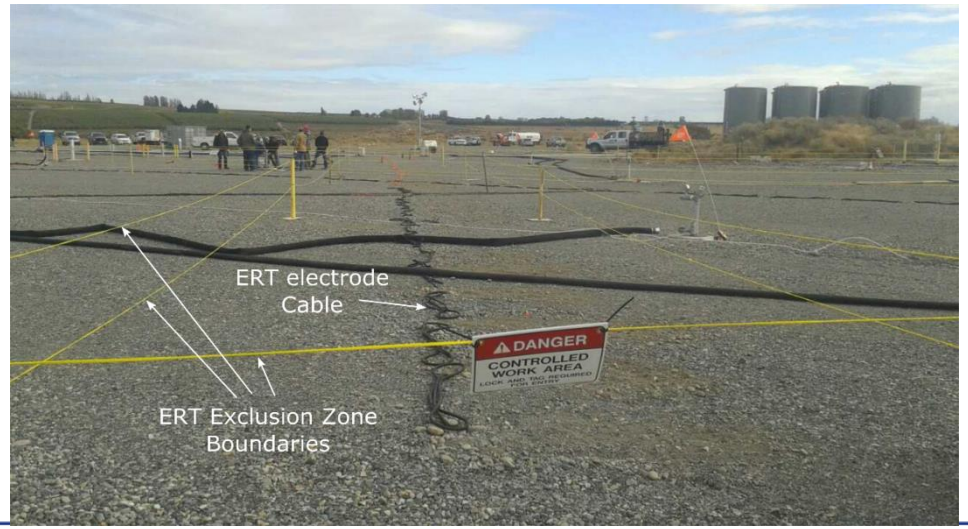
1. **Excessive grounded metallic infrastructure (pipes, well casing, tanks) within the target zone**
2. **Imaging target is too deep**
   - Too far from surface electrodes (rule of thumb: 25% of line length)
   - Too expensive/infeasible to install borehole electrodes
   - Can be assessed with feasibility study
3. **Excessive electrical noise (e.g., near cathodic protection cathodes)**
   - Can be assessed with simple field test
4. **Target feature or process has insufficient electrical conductivity contrast**
   - Can be assessed with feasibility study
5. **Any condition/requirement/expense that disallows adequate placement or electrical coupling of electrodes with ground**
   - “Adequate placement” determined with feasibility study

Safety Considerations

- ERT instruments are self-regulated
- Can apply several hundred volts to current electrodes, if needed
- Maximum ground voltages are lower than electrode voltages (typically order of magnitude)
- Electrical safety requirements vary by organization and circumstance, ranging from basic training to physical barriers to lockout/tagout
- *Safety requirements/assessments are project specific, but should always be addressed*

Surface Voltage





ERT in the Regulatory Context

There are currently no criteria for using ERT directly for regulatory decisions or compliance/performance metrics (and rightly so)

- It is an indirect measure of regulated metrics
- There are no standards for imaging or interpretation

However

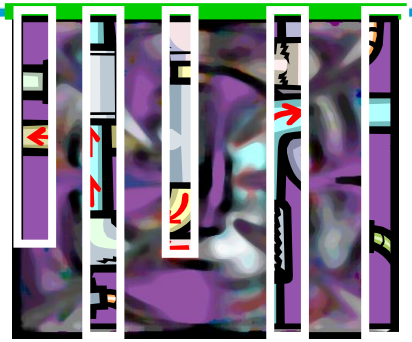
ERT can improve capability to meet regulatory goals

- Enables improved understanding → improved remediation design

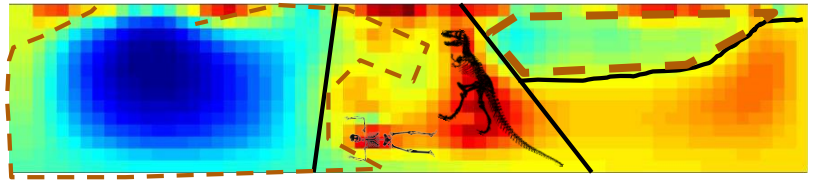
Example: ERT use is encouraged as a support tool by the Washington State Dept. of Ecology, EPA, and DOE on the Hanford Site, but is not accepted as a compliance metric

Key Points: Avoiding Pitfalls and Limitations

- Develop Realistic Expectations, Leverage Supporting Data

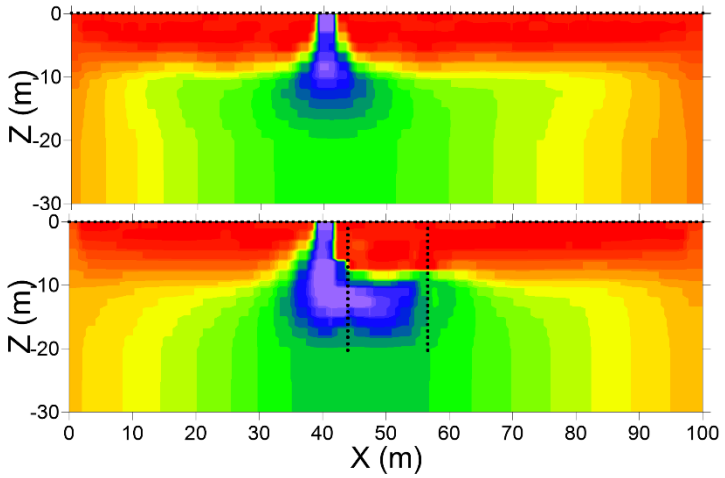


- Recognize Over-interpretation



and most of all …

- ***<u>REQUIRE A FEASIBILITY ASSESSMENT</u>***



Presentation Overview

- Basic Theory
- Implementation Examples
- Limitations, Pitfalls, and How to Avoid Them
- ► Case Studies
- Wrap-Up

- **Objective: Demonstrate the topics previously discussed using case studies**

Case 1: Monitoring Vadose Zone Amendment Delivery Surface-Based ERT Monitoring: Hanford Site 300 Area, WA

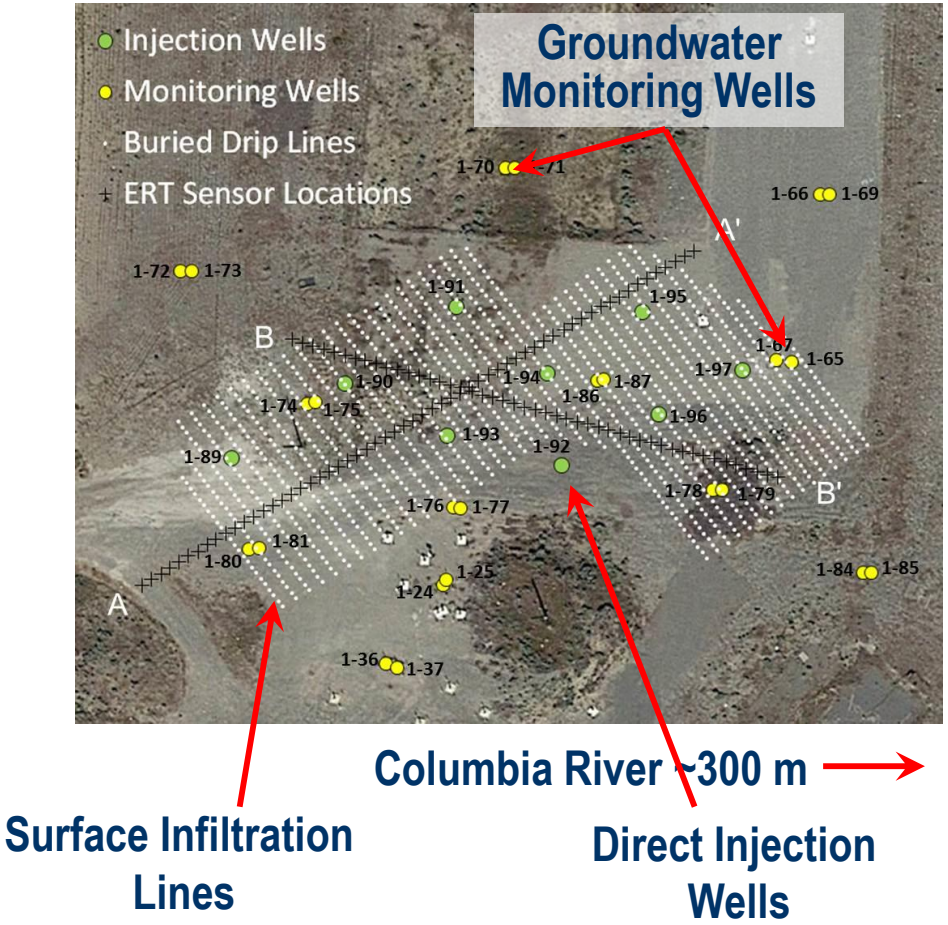
Background

- Uranium-contaminated vadose zone sediments
- Poly-phosphate amendment shown in laboratory setting to bind uranium to sediment
- Field-scale treatability test agreed upon by regulators and stakeholders

Approach

- Hanford cleanup contractors design amendment delivery system via direct injection and surface infiltration

Hanford 300 Area: North Pond



Case 1: Monitoring Vadose Zone Amendment Delivery Surface-Based ERT Monitoring: Hanford Site 300 Area, WA (cont.)

Problem

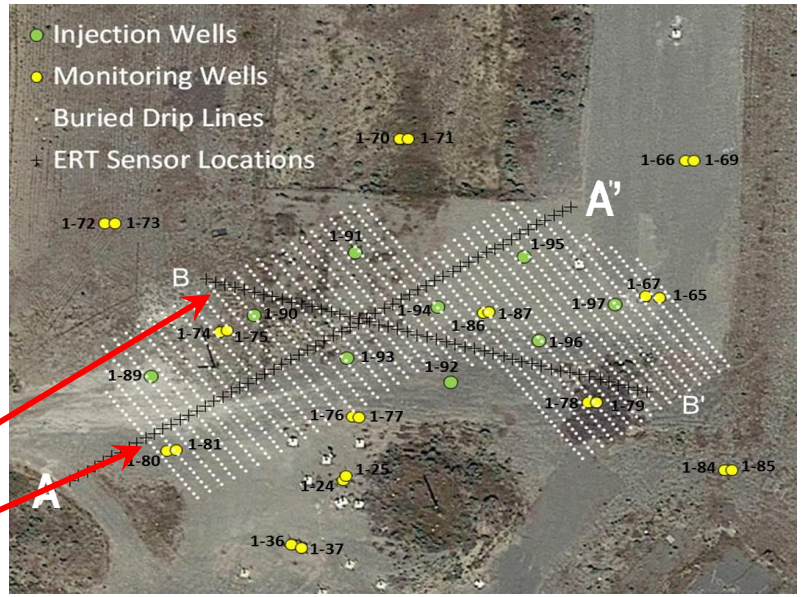
- Monitoring/verification of amendment delivery

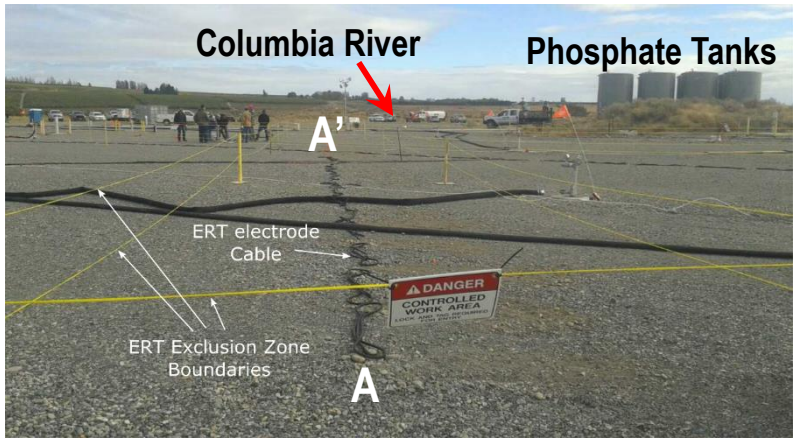
Supplementary Information

- Amendment increases saturation and pore fluid conductivity

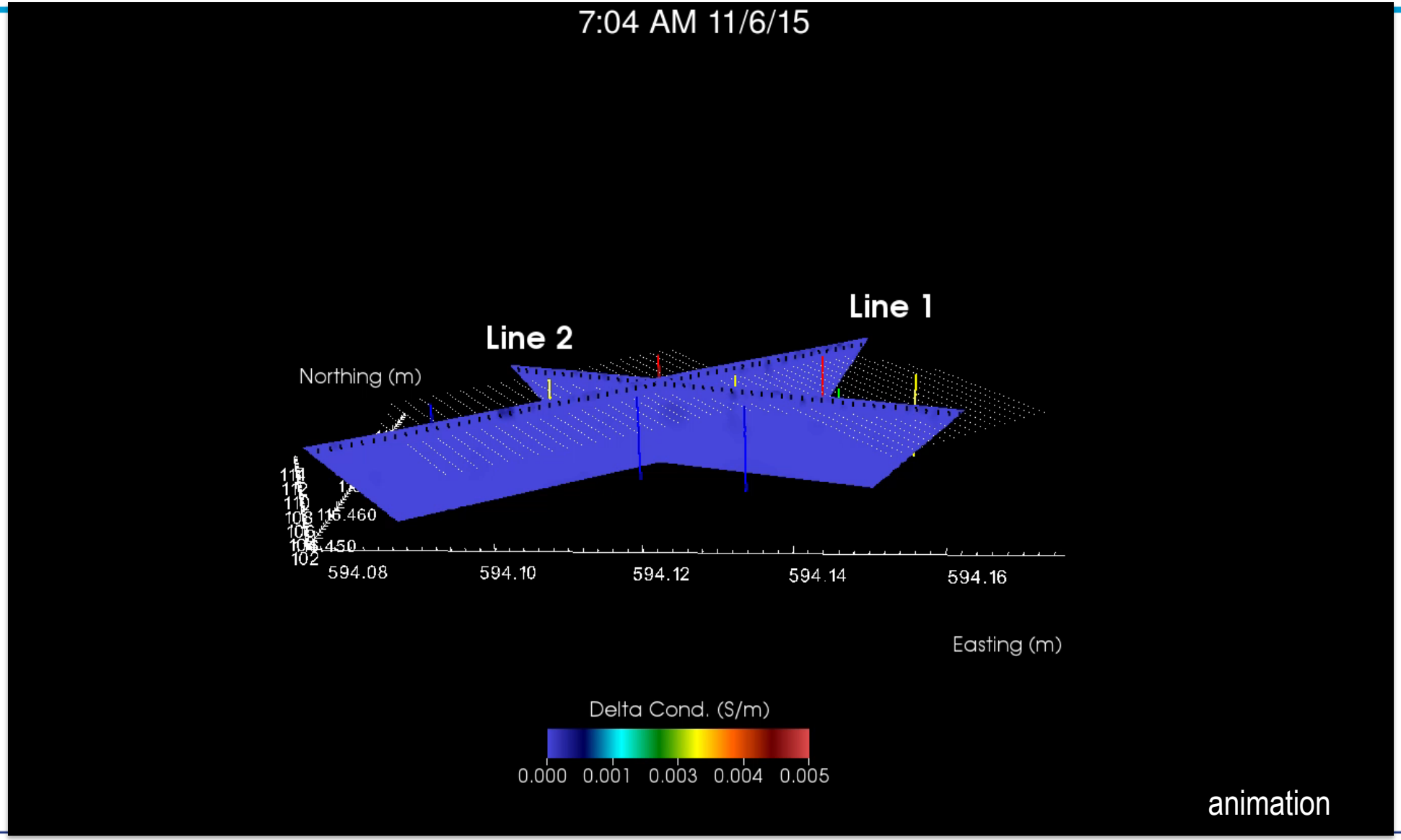
Objective

- Use time-lapse ERT monitoring to image amendment distribution over time
- Two surface ERT lines (@ 2.5 m)
- Real-time Web site delivery for duration of treatment





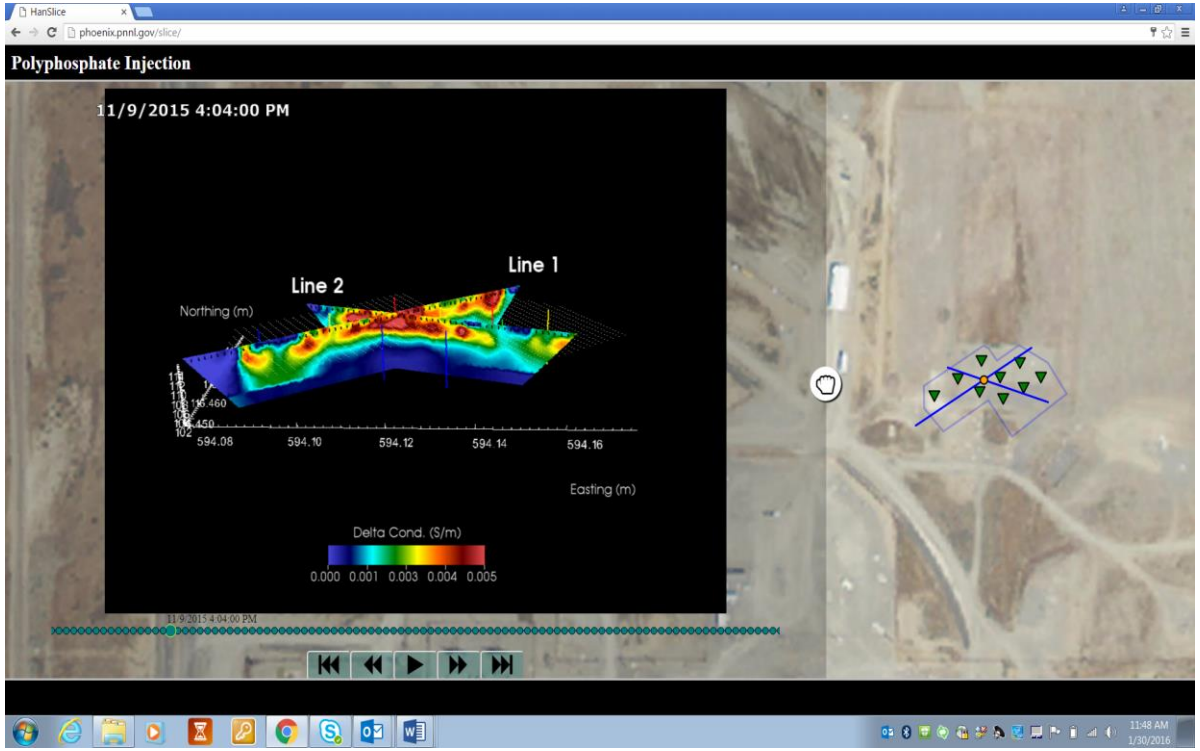
Case 1: Monitoring Vadose Zone Amendment Delivery with Real-Time Surface-Based ERT Monitoring: Imaging Results



Case 1: Monitoring Vadose Zone Amendment Delivery with Real-Time Surface-Based ERT Monitoring: Imaging Results (cont.)

- Images were delivered in 'real-time' (~12 minutes from start of survey to image) for 21-day duration
- Demonstrated capability to provide timely feedback
- Opportunity to optimize delivery process during application

Image Delivery Web Site Screenshot



Case 1: Monitoring Vadose Zone Amendment Delivery with Real-Time Surface-Based ERT Monitoring: Post Analysis

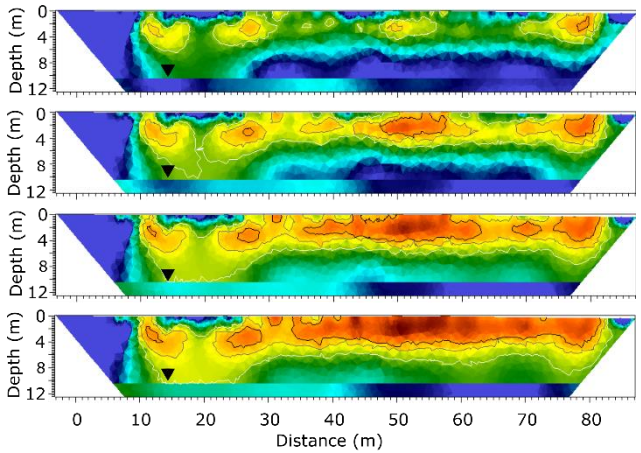
Performance Objective

- Determine when and where amendment arrived

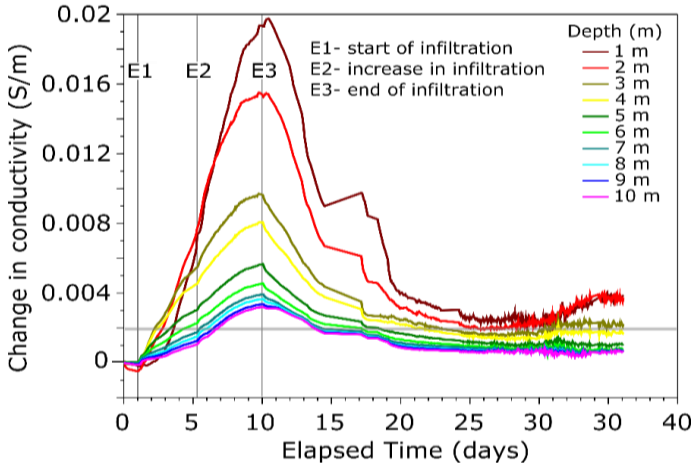
Approach

- Use ERT images to generate break through curves at each imaging pixel
- Choose conservative point on break through curve for arrival time
- Generate break through map of arrival times
- Generate map of average vertical amendment velocity

Daily ERT Images



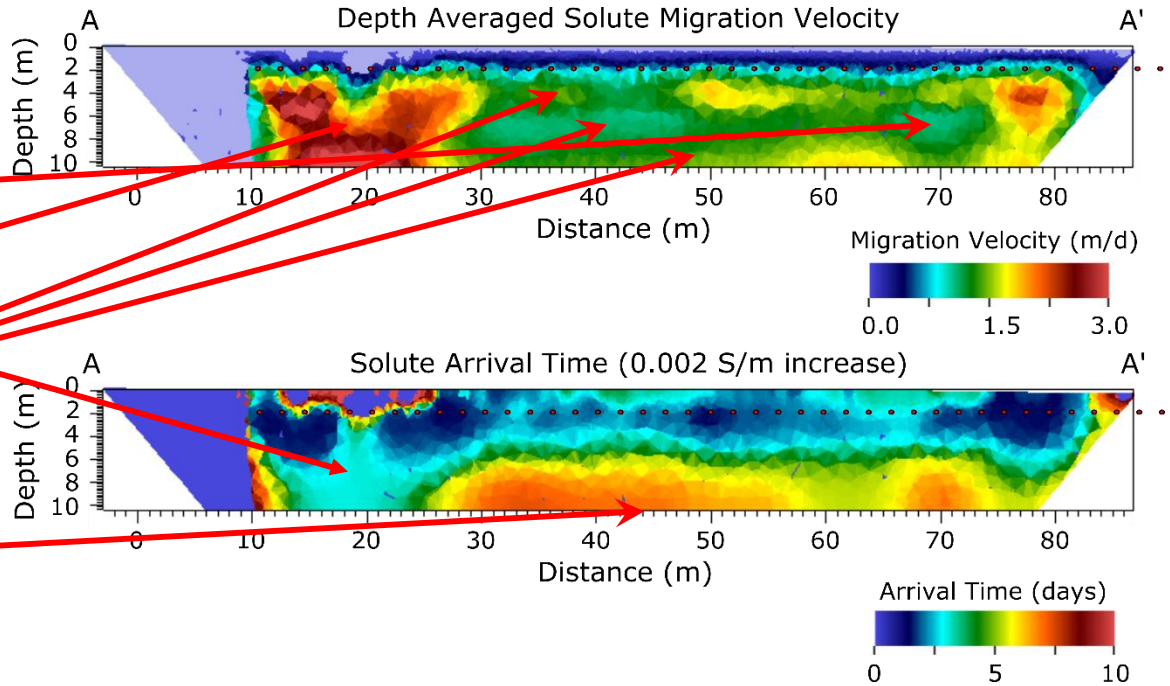
Example Break Through Curves



Case 1: Monitoring Vadose Zone Amendment Delivery with Real-Time Surface-Based ERT Monitoring: Post Analysis (cont.)

Conclusions

- Plugged/slow drip lines were compensated by neighbors
- High K, fast break through zone
- Heterogeneous permeability/flow velocity
- Sufficient infiltration time for complete treatment



NOTES

- Post-test core analysis: phosphate precipitated in upper vadose zone! Why didn't ERT see this?
- Solute reached water table, phosphate did not
- Excellent example of ERT impact + possible pitfall and need for supporting info

Source: Johnson and Thomle, 2016.

Case 1: Monitoring Vadose Zone Amendment Delivery with Real-Time Surface-Based ERT Monitoring: Project Cost

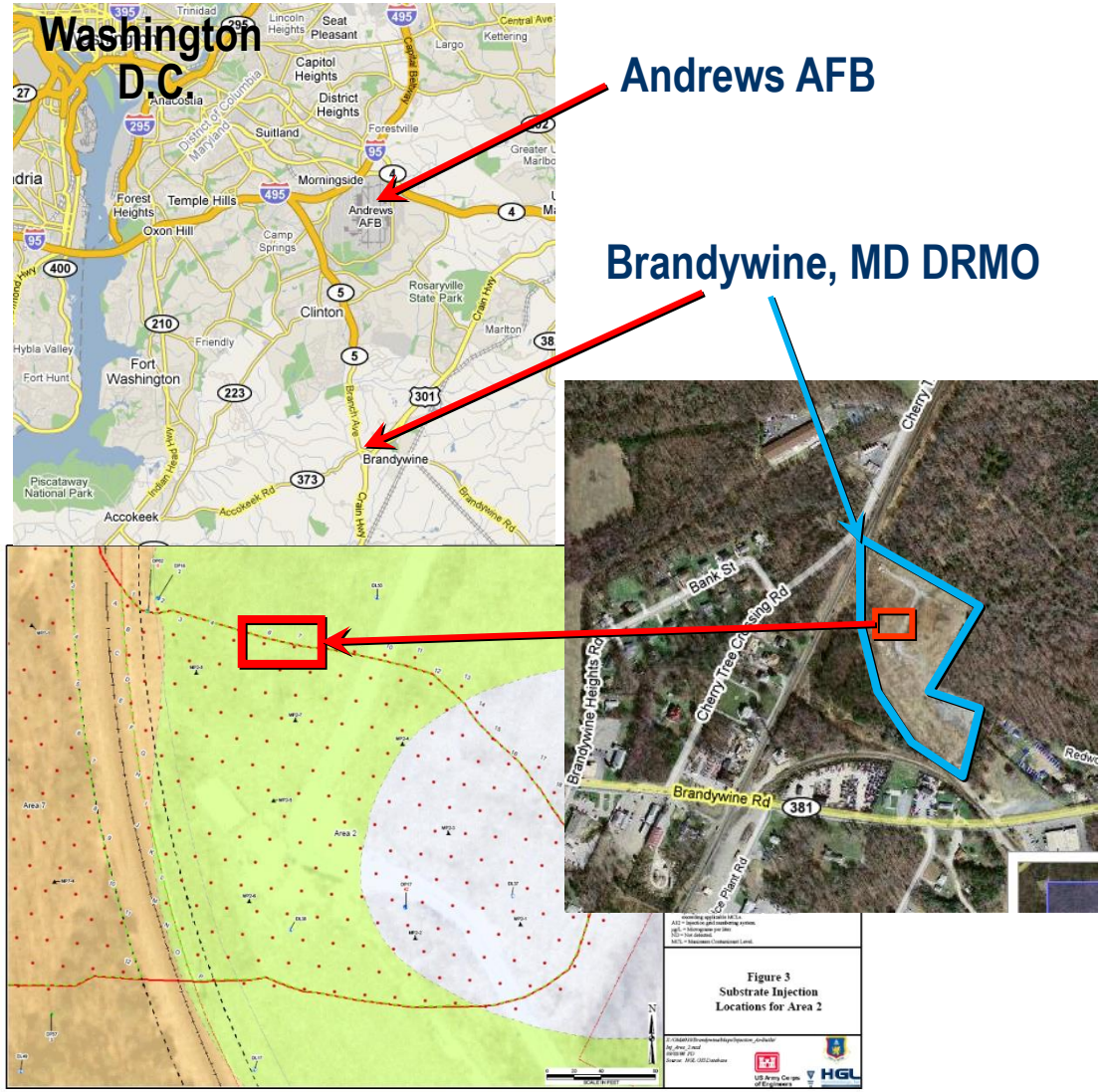
- Total Labor Cost: **~260 hrs**
  - Health and Safety Plan, Inspections, Lock Out Tag Out (LOTO) Training (30 hrs)
  - Test Plan (20 hrs)
  - QA Plan (20 hrs)
  - Field Instrumentation (60 hrs…due to electrode burial req's)
  - Web Site Construction (40 hrs)
  - Baseline Data Collection & Processing (6 hrs)
  - Time Lapse Data Processing (1 hr, autonomous)
  - Post Analysis (40 hrs)
  - Final Report (40 hrs)
- Equipment Cost: **~$50 K**
  - ~$45 K for 128-Electrode ERT System (non-exclusive cost … system useable for other projects)
  - ~$5 K for Materials (electrodes and cables)

Case 2: Bioremediation Performance Monitoring: ESTCP Projects ER-0717 and ER-201579-PR

Background

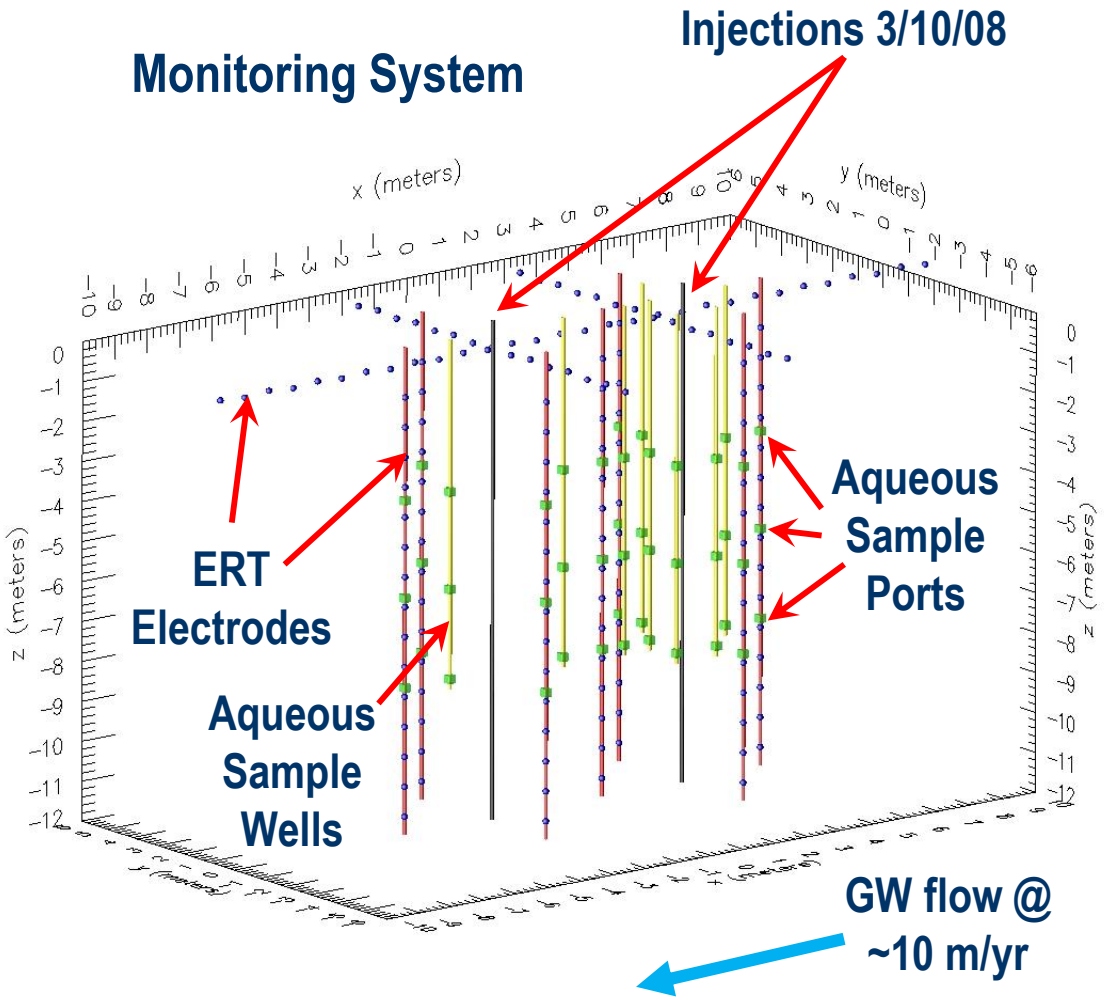
Brandywine, MD Defense Reutilization Marketing Office (DRMO) (Andrews AFB)

- TCE-contaminated groundwater
- Upper 12 m unconfined aquifer
- Spreading to residential neighborhood
- ROD – Enhanced bioremediation
- Amendment injections ~20 ft spacing (~1,000)
- ESTCP Dem/Val effort to monitor two injection points at boundary of treatment area



Case 2: Bioremediation Performance Monitoring: Monitoring and Validation System Infrastructure (Brandywine, MD)

- Highly instrumented subsurface monitoring system
- 8 3-port chemical sampling wells
- 7 ERT/chemical sampling wells
- 105 total borehole electrodes
- ER data autonomously collected once every two days for 2.5 years
- Strategically-timed comprehensive chemical sampling



Case 2: Bioremediation Performance Monitoring: Amendment and Injection Details (Brandywine, MD)

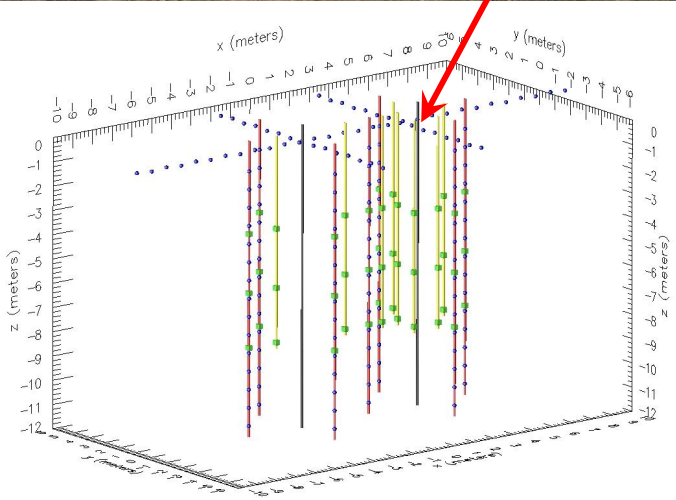
- Injections occurred via direct push in March 2008

Recipe

- 250 gallons of ABC (Anaerobic Biochem, mixture of lactates, fatty acids, and phosphate buffer)
- 3,200 gallons of water
- 466 lbs $NaHCO_3$
- Injectate conductivity 15 mS/cm, pH 8

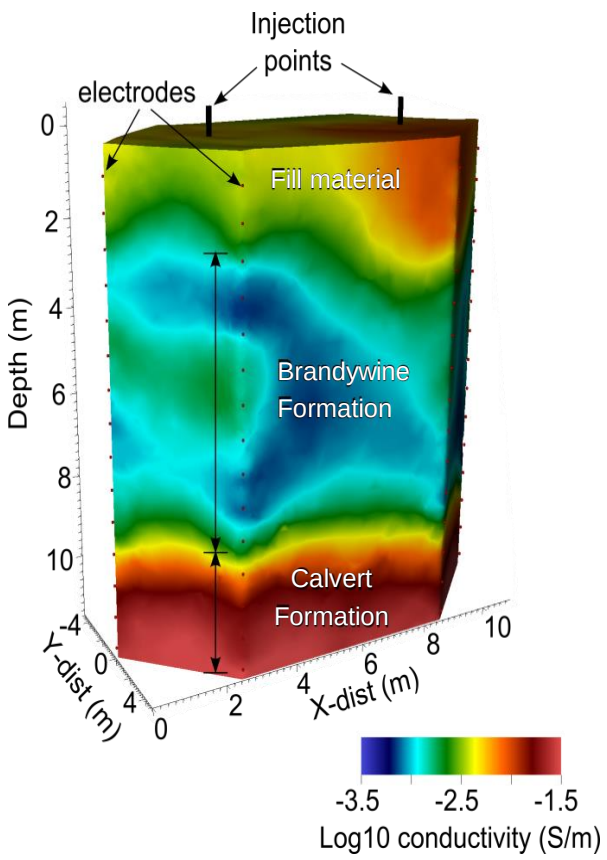
Procedure

- Direct push injection pipe to 34 feet bgs
- Inject 36 gallons of amendment @ 1 foot intervals
- Total ~ 950 gallons/location

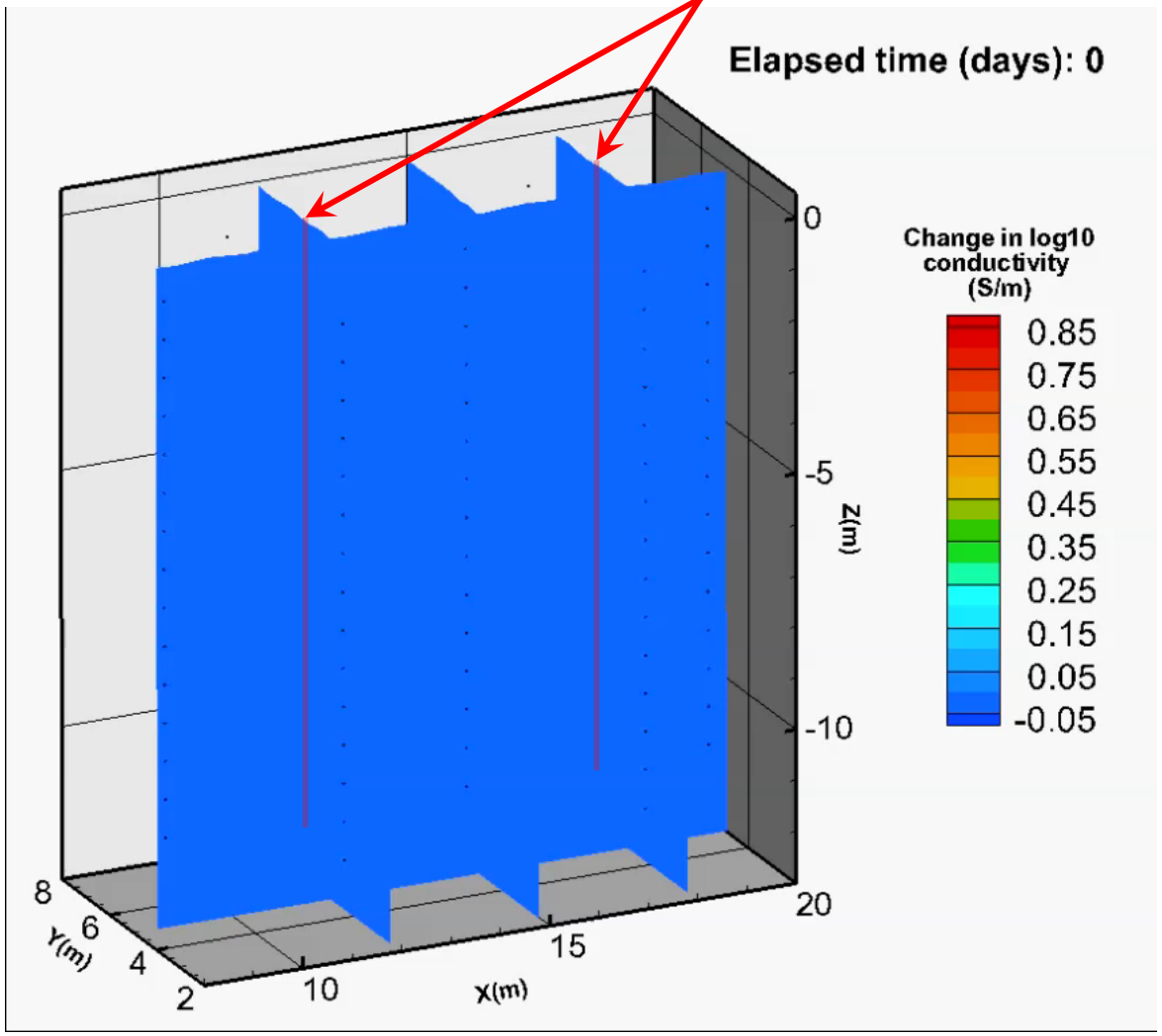


Case 2: Bioremediation Performance Monitoring: Imaging Results (Brandywine, MD)

Pre-Injection Baseline Image

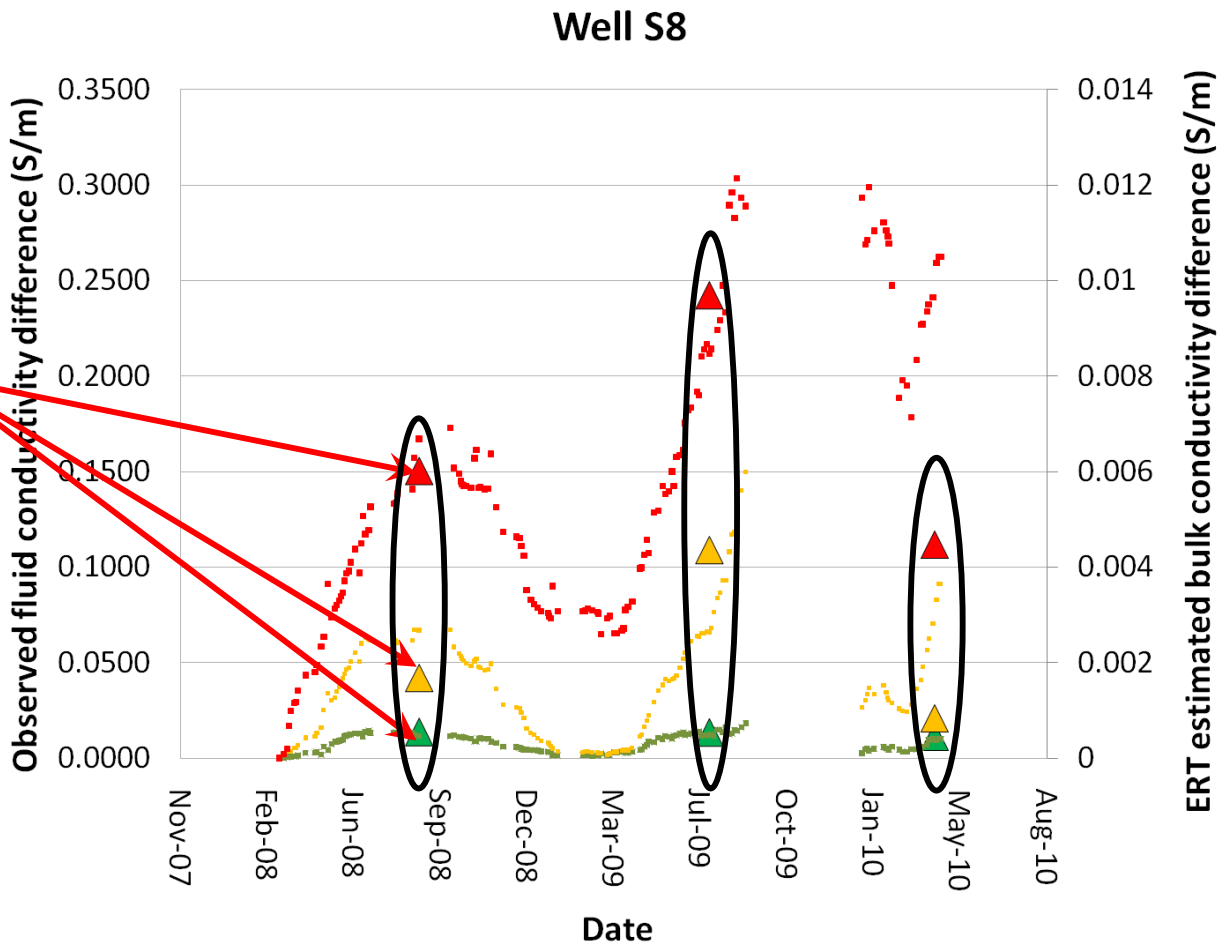


Injection Locations



Case 2: Bioremediation Performance Monitoring: Interpreting the Time-Lapse Images using Fluid Conductivity Measurements

Fluid specific conductance values collected at 3 depths and discrete sample times



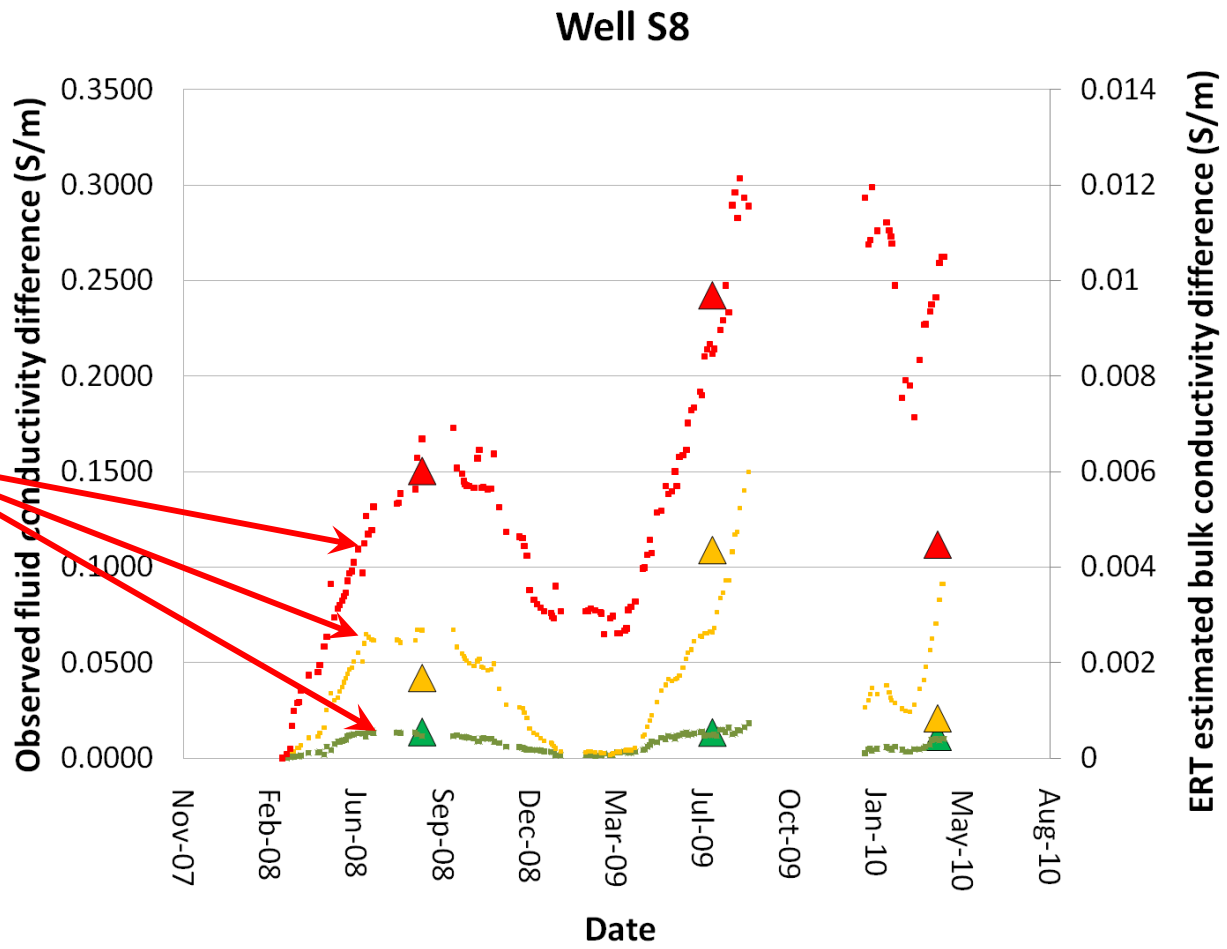
~3.5 m bgs

~6.0 m bgs

~8.5 m bgs

Case 2: Bioremediation Performance Monitoring: Interpreting the Time-Lapse Images using Fluid Conductivity Measurements (cont.)

Bulk conductivity difference time-series extracted from ERT images at sample port locations



~3.5 m bgs

~6.0 m bgs

~8.5 m bgs

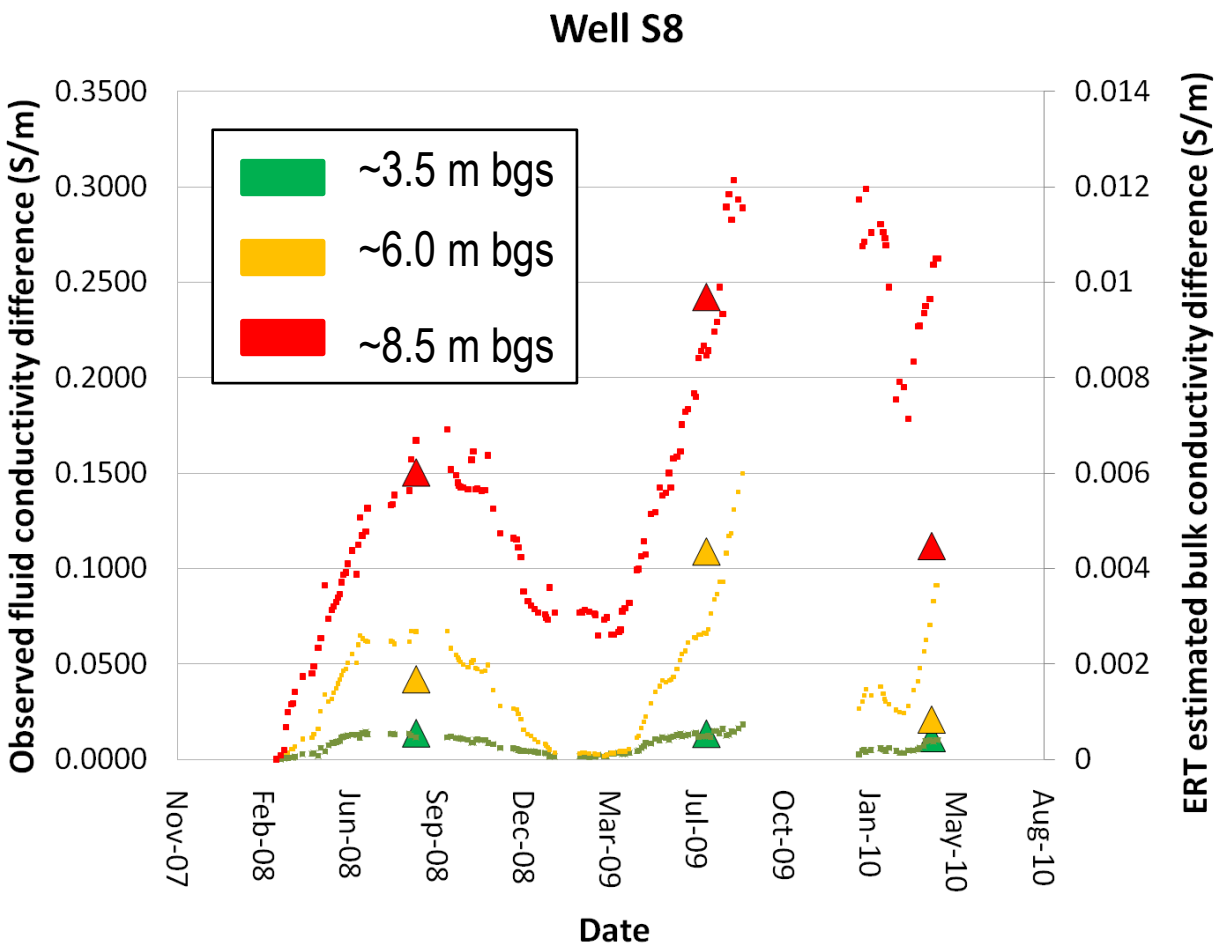
Case 2: Bioremediation Performance Monitoring: Interpreting the Time-Lapse Images using Fluid Conductivity Measurements (cont.)

Evidence

- Changes in bulk conductivity and fluid conductivity are highly correlated for first two sampling events (R^2 = 0.87 over all sample ports)
- Last event: increase in bulk conductivity, decrease in fluid conductivity…

Interpretation

- Change in solid phase properties between second and third sampling event
  a) Increase in porosity?
  b) Increase in surface area?
  c) Metallic mineral precipitation?



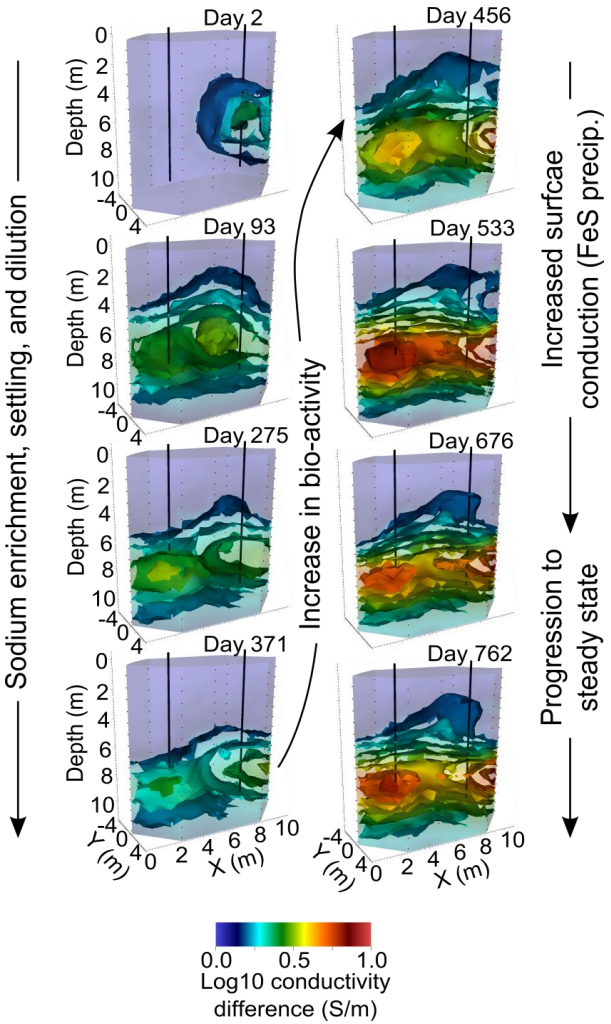
Case 2: Bioremediation Performance Monitoring: Interpreting the Time-Lapse Images using Fluid Conductivity Measurements (cont.)

Other Evidence Supporting Biomineralization

- Contractors note enhanced microbial activity in 5th quarter
- Sulfide precipitation part of reaction sequence
- Black particulate in several April 2010 samples
- Consistent with aqueous chemistry

Primary Implications and Impacts

- Amendment behavior autonomously monitored in 4D
- Solid phase alterations identified through comparison with fluid conductivity samples (simple and inexpensive)
- Demonstrated capability to image biomineralization…important diagnostic indicator for performance evaluation
- What about 'production' application at larger scales?

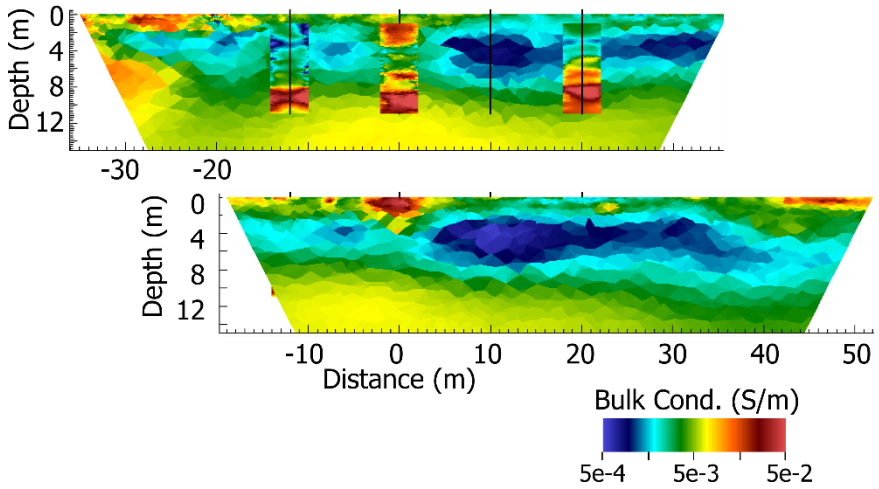


Johnson et al., 2015. *Groundwater*.

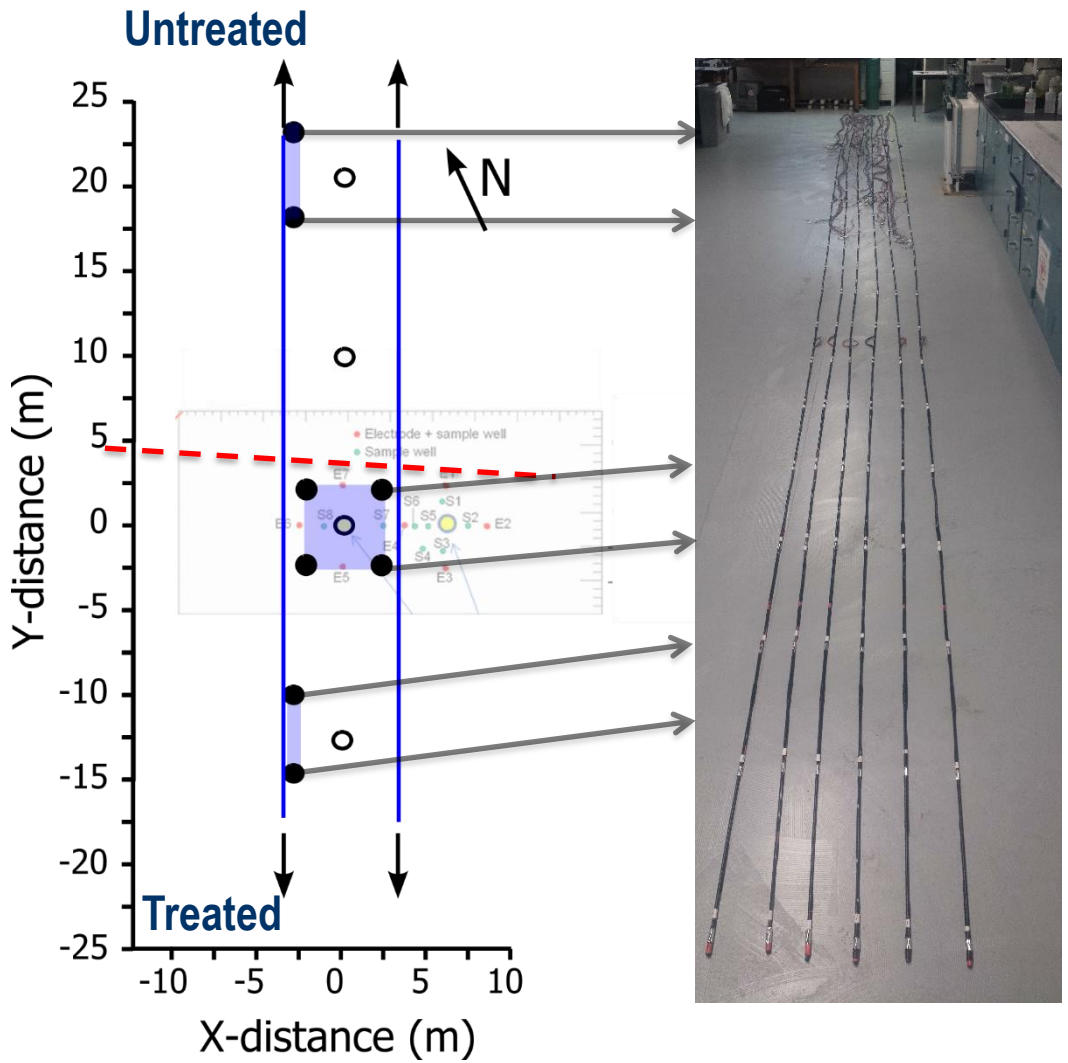
Case 2.5: Post-Remediation Assessment: ESTCP Project ER-201579-PR (Brandywine, MD)

Objectives

1. Identify the long-term geophysical footprint of active bioremediation at a VOC contaminated site
2. Determine the significance of the geophysical footprint with respect to solid phase mineral transformations and/or biofilms induced by the treatment process
3. Demonstrate the use of 1 and 2 above to map gradients in the geophysical footprints of biostimulation along a transect crossing the boundary of the treatment area at an active remediation site, and interpret those gradients in terms of long-term biogeochemical impacts

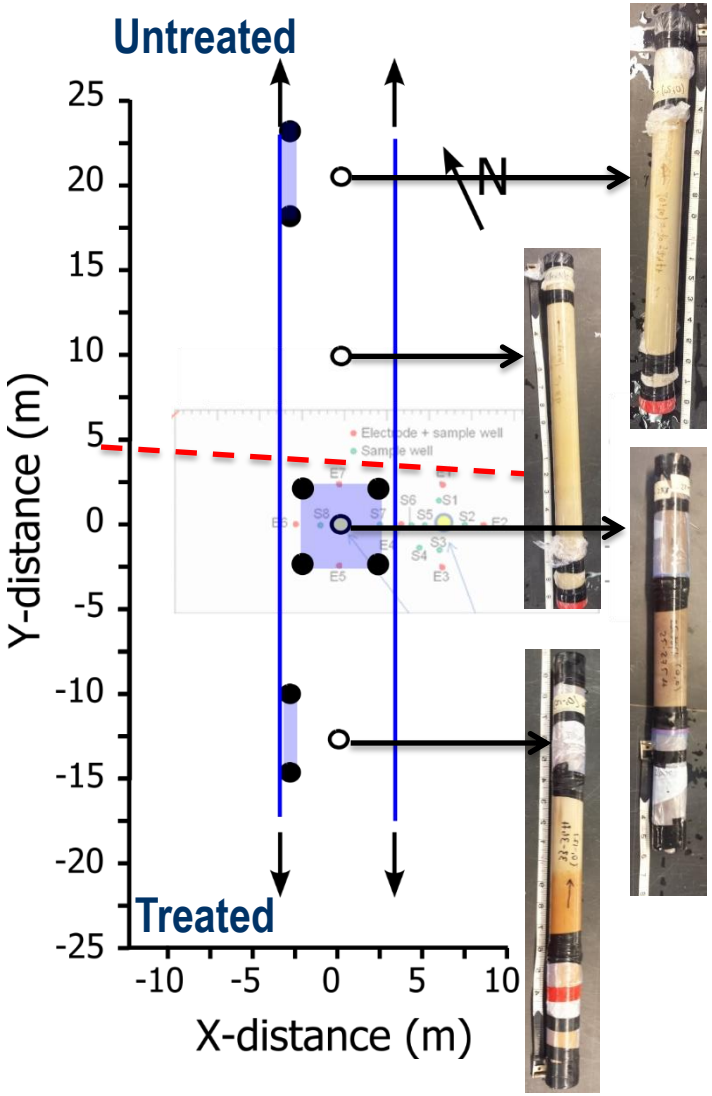


Case 2.5: Post-Remediation Assessment: Crosshole Imaging/Fluid Sampling Arrays (Brandywine, MD)



- Eight vertical arrays installed via direct push
- Each array includes 24 electrodes and 3 fluid sampling ports
- Enables 3D crosshole imaging directly in the ER0717 injection zone
- Enables 2D crosshole imaging inside and outside of the treatment area
- Enables depth-discrete pore fluid sampling inside and outside of treatment zone

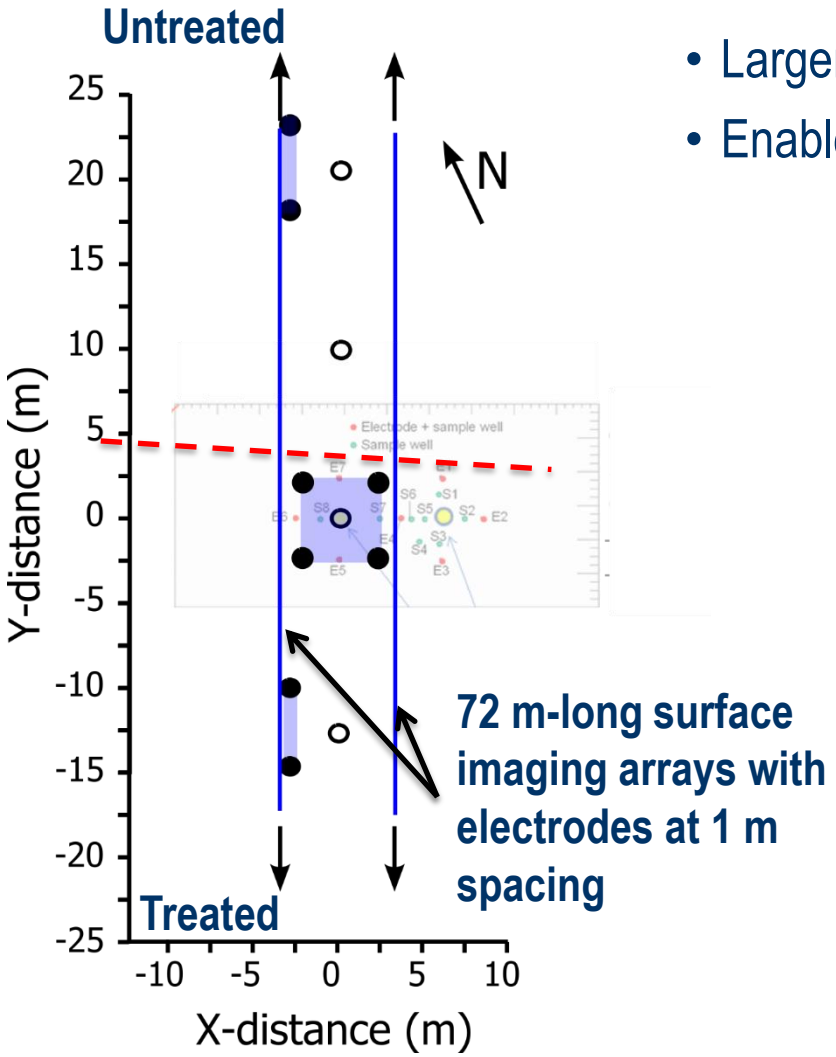
Case 2.5: Post-Remediation Assessment: Core Sampling/Logging Holes (Brandywine, MD)



Four continuous core boreholes completed with PVC

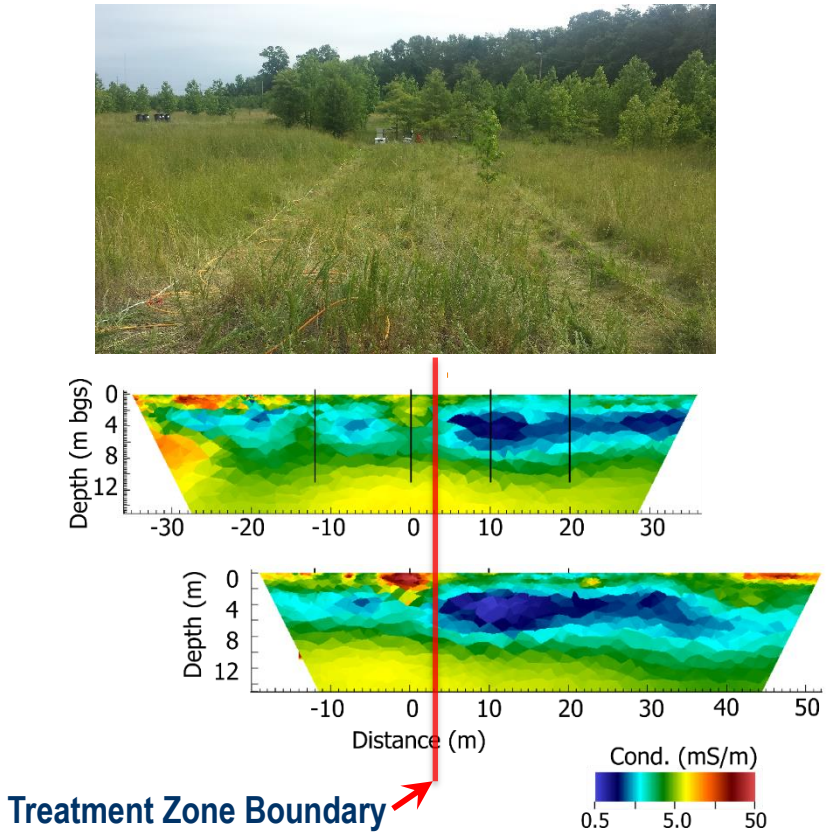
- Enables direct lab measurement of electrical geophysical properties
- Enables assessment of microbial communities and biogeochemical solid phase treatment zone
- Enables 1D geophysical logging profiles
- Critical to relate field-scale images to long-term biogeochemical impacts

Case 2.5: Post-Remediation Assessment: Surface Imaging Results (Brandywine, MD)

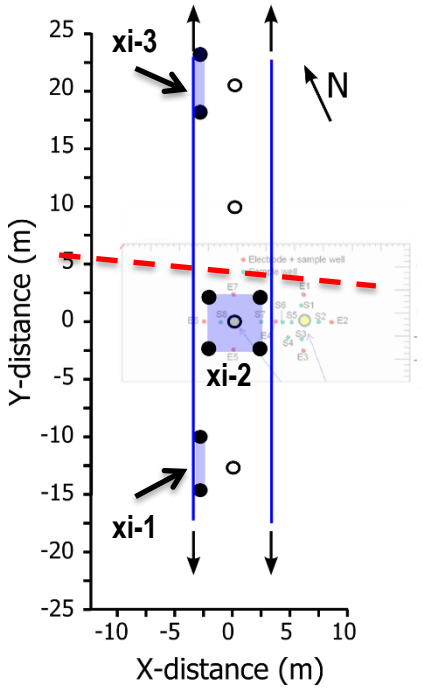


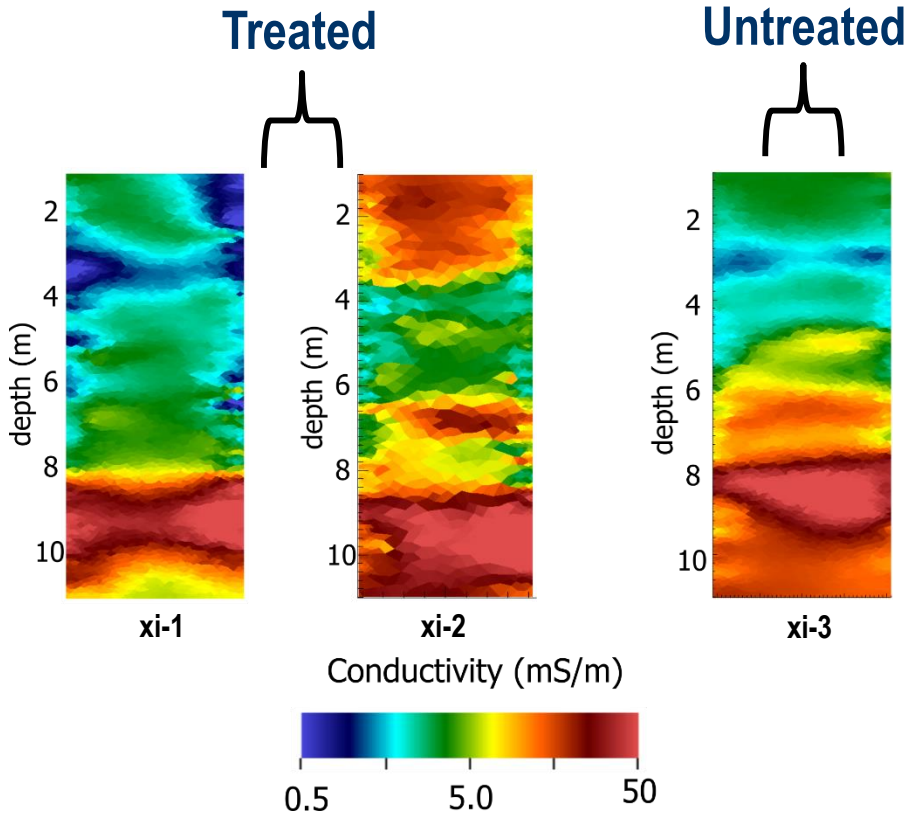
Surface ERT Arrays

- Larger scale, lower resolution, less expensive imaging
- Enables inspection of the treated-to-untreated transition zone



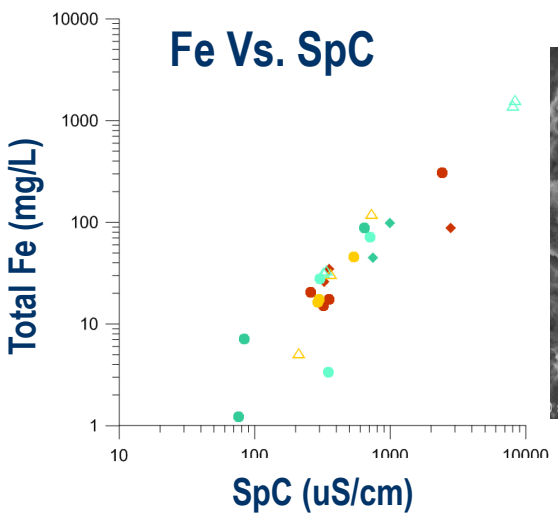
Case 2.5: Post-Remediation Assessment: Borehole Imaging Results (Brandywine, MD)



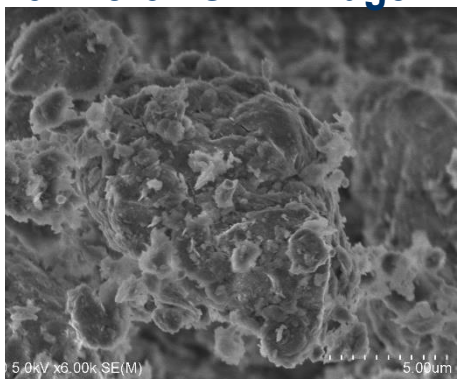


- **Highest conductivity occurs in the vicinity of the injection well (profile xi-2)**

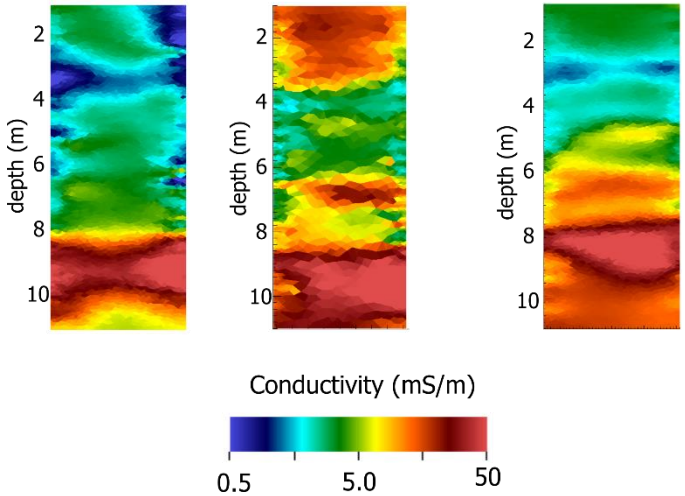
Case 2.5: Post-Remediation Assessment: Project Status (Brandywine, MD)



5 micron SEM Image



Lab Analysis



Field Images

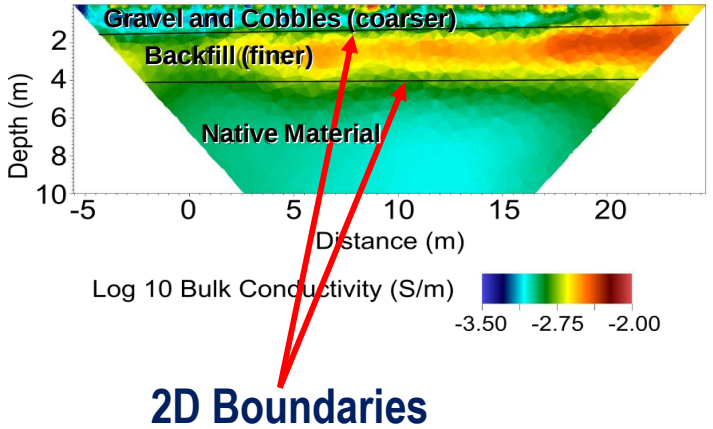
- Long-term geophysics footprint of bioremediated site exists and is identified
- Origin of geophysical signature in terms of solid phase mineral transformations and/or biofilms (in progress)
- Interpretation of images in terms of long-term biogeochemical impacts

Presentation Overview

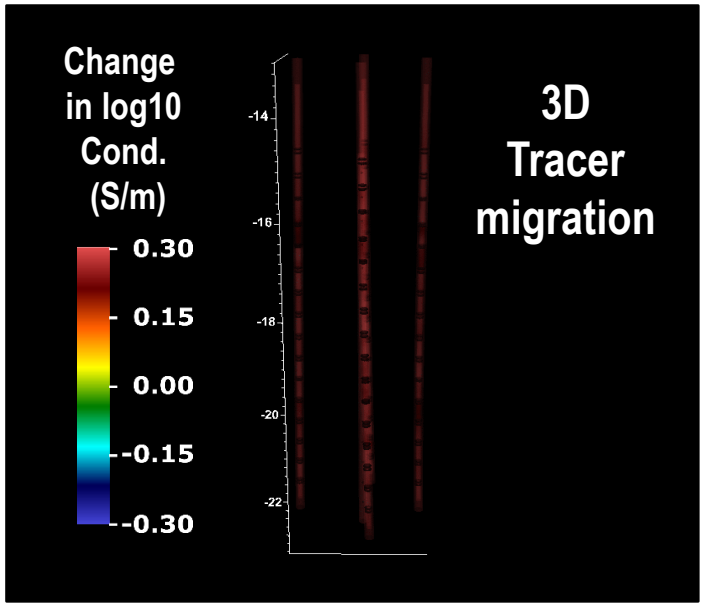
- Basic Theory
- Implementation Examples
- Limitations and Pitfalls
- Case Studies
- ► Wrap-Up

Take-Home Messages: What Can ERT Do For You?

- Characterization
  - Remotely, cost-effectively image primary geologic boundaries
- Amendment Emplacement
  - Time-lapse image how/where your amendment or tracer are migrating
- Monitoring
  - Determine when and where the subsurface is changing
  - Autonomous

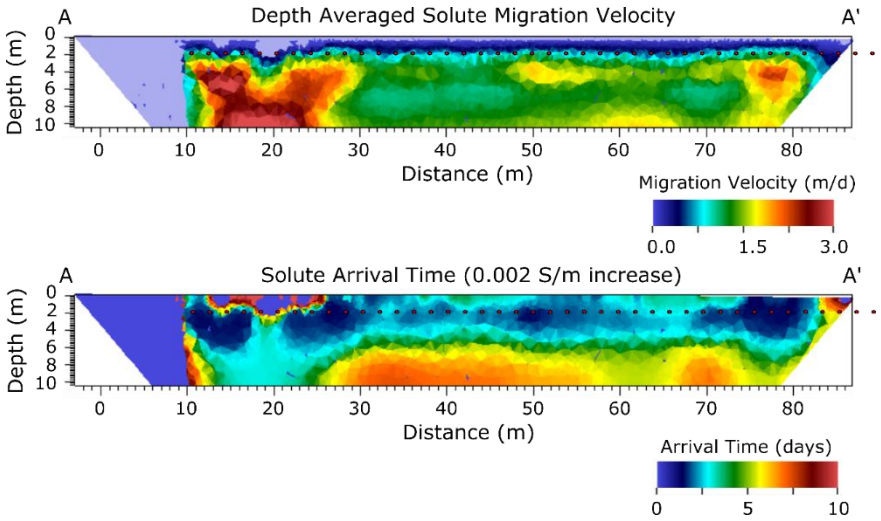


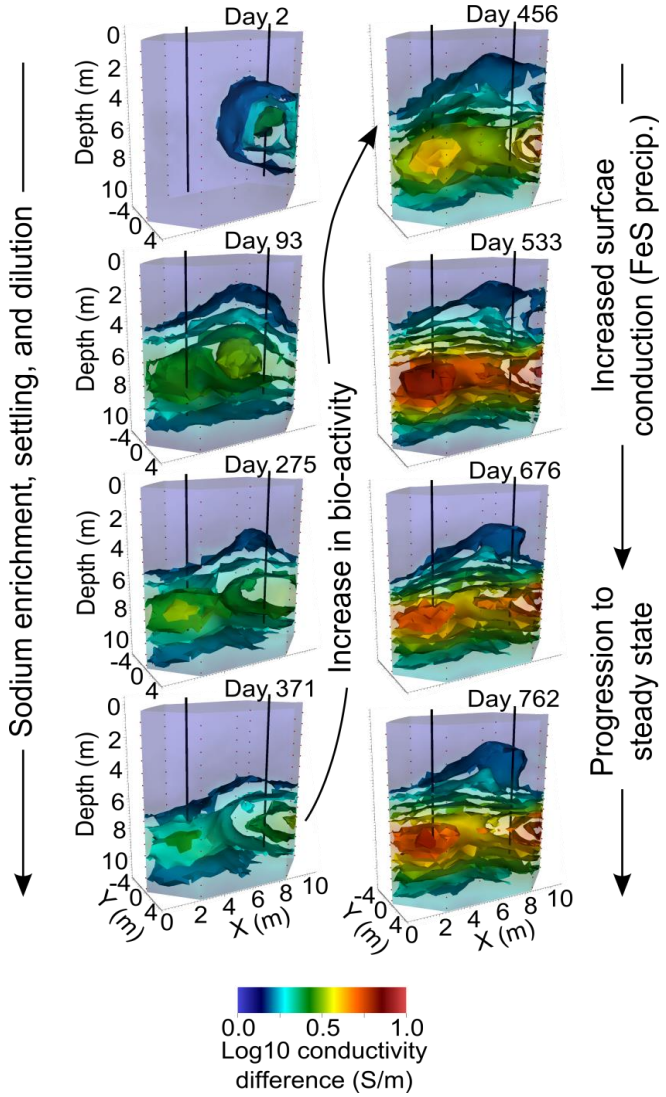
2D Boundaries



Take-Home Messages: What Else Can ERT Do for You?

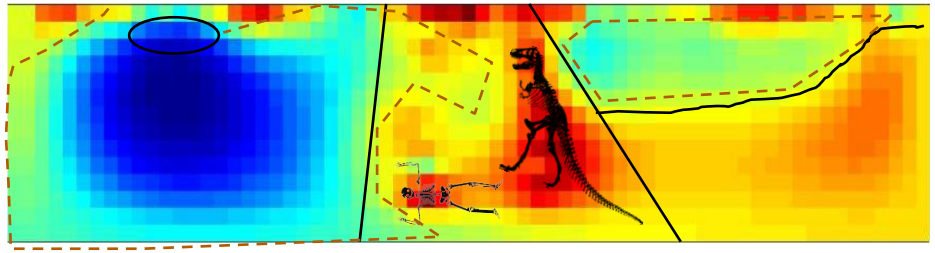
- Determine <u>what</u> is happening (with help)
  - Requires supplementary information
    - e.g., wellbore fluid chemistry, soil samples
  - Time-lapse imaging removes ambiguity (removes the haystack)



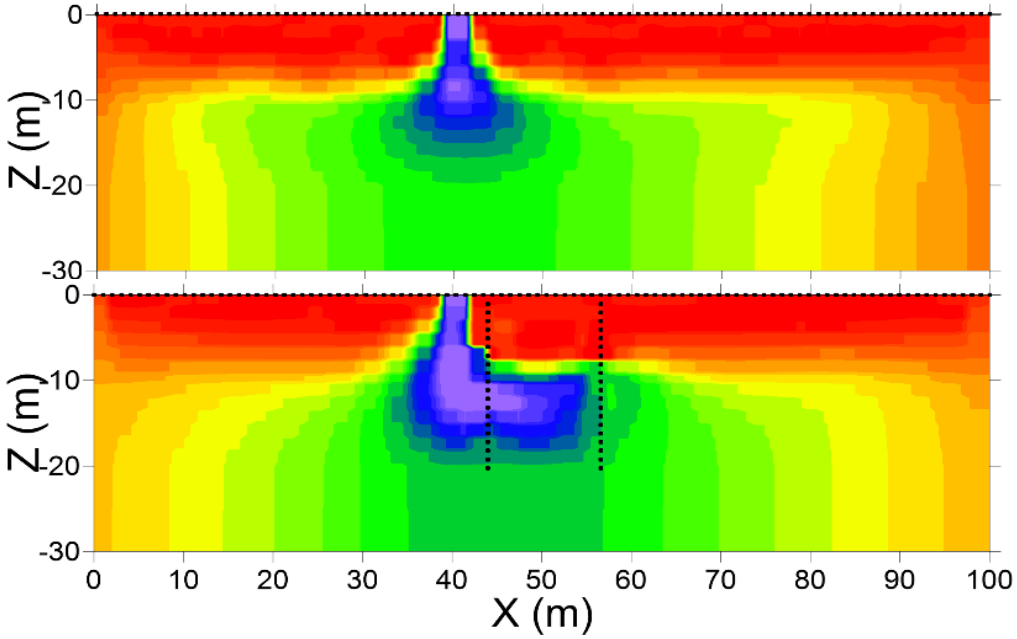


Take-Home Messages: How Can You Mitigate Risk of Failure?

- Understand capabilities to develop realistic expectations



- Always require a pre-modeling feasibility assessment from your contractors



Resources

- ESTCP Project Reports
- Rutgers/USGS ESTCP Webinars
  - https://www.serdp-estcp.org/Tools-and-Training/Webinar-Series/07-28-2016
  - https://www.serdp-estcp.org/Tools-and-Training/Webinar-Series/06-30-2016
- USGS Fractured Rock Geophysical Toolbox
  - http://water.usgs.gov/ogw/frgt
- PNNL ERT Imaging Software (E4D)
  - https://e4d.pnnl.gov

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Questions and Answers