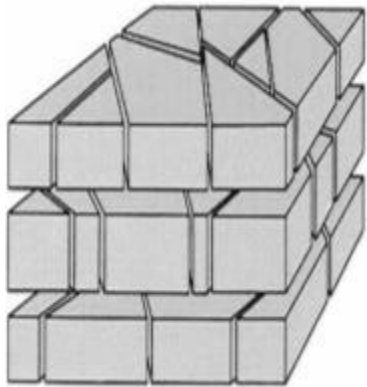


Introduction to Geophysical Methods for Fractured Rock

*EPA Region 10 Workshop
September 11-12, 2019*

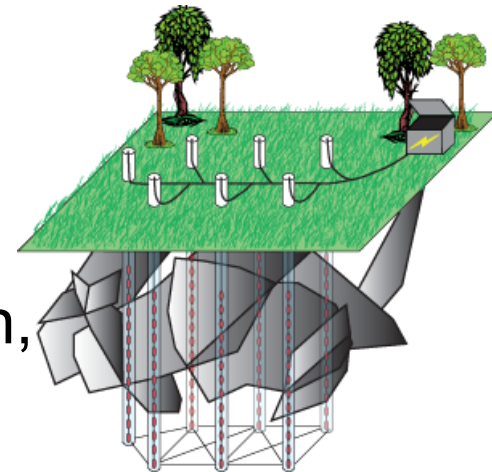


Frederick Day-Lewis,
USGS

Earth System Processes Division,
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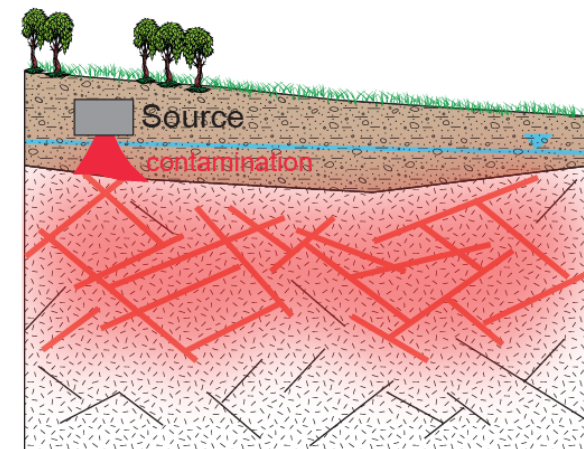
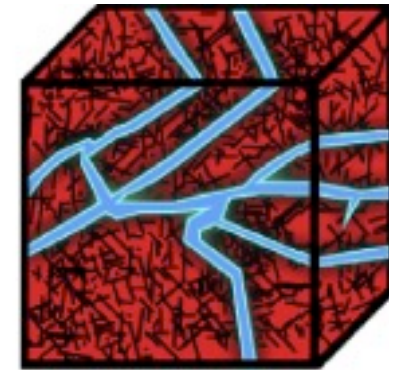
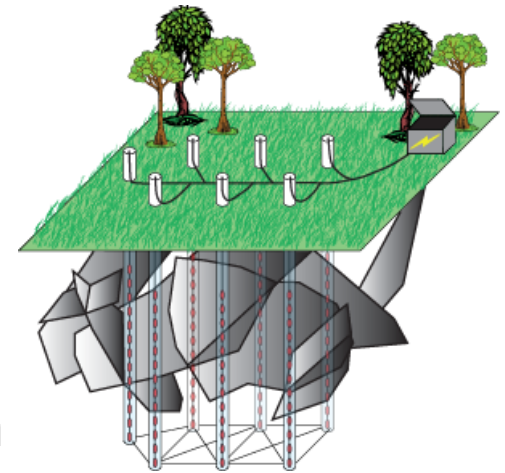
daylewis@usgs.gov

860.487.7402 x21

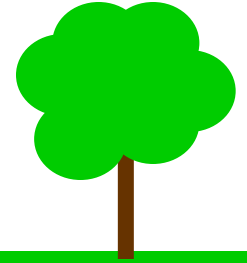


Outline

- Challenges in fractured rock
- Hydrologic and Geophysical Characterization - Why geophysics?
- The fractured rock geophysical toolbox
- Method selection
- Characterization vs. Monitoring
- Borehole logging methods
- Radar imaging methods
- Resistivity imaging methods
- Feasibility studies – pre modeling
- Summary



Challenges in Fractured Rock



Characterization Challenges:

- Permeability varies many (5+) orders of magnitude over short distances
- Fractures can act as flow conduits or barriers
- Drilling more expensive than in unconsolidated media
- Sampling and testing more complicated (packers)
- Requires joint interpretation of geology, geophysics, chemistry, groundwater and other types of information



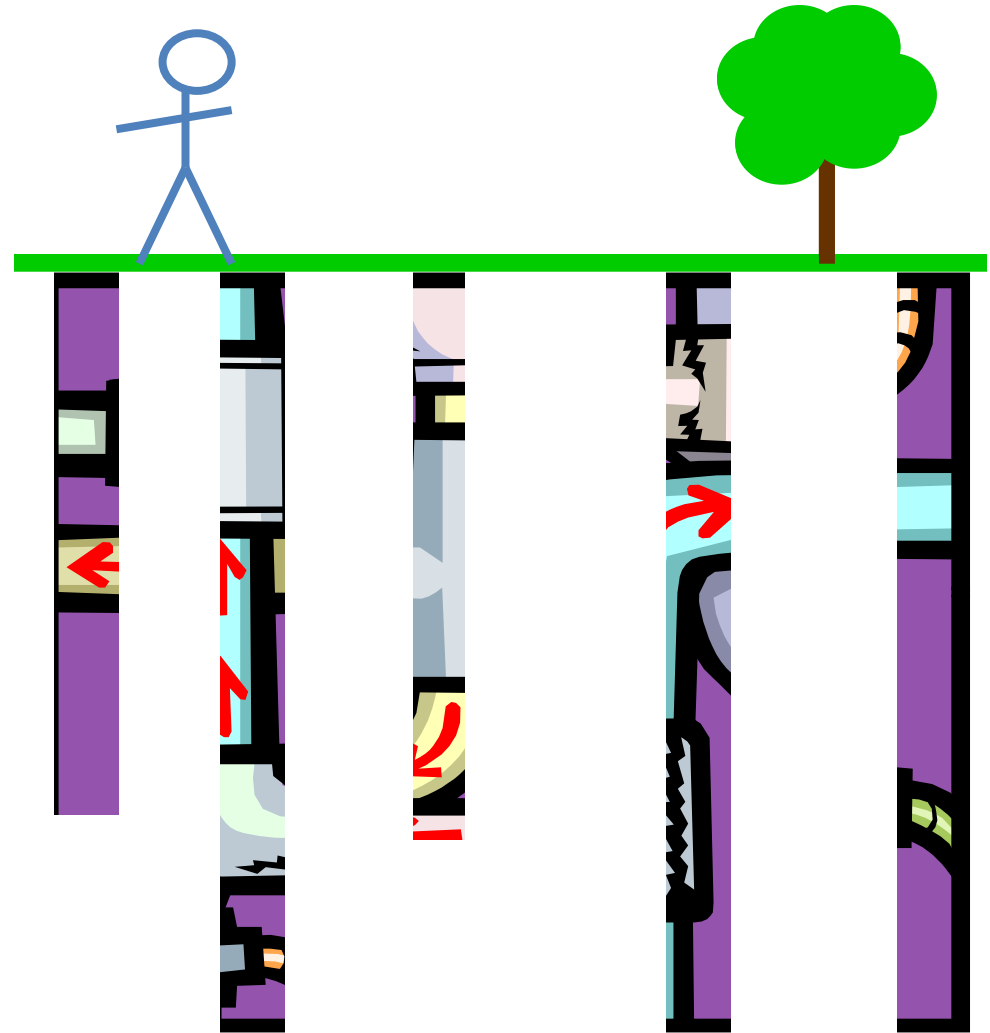
Hydrologic Characterization

- Hydrologic Data:

- Packer tests
- Pumping tests
- Tracer tests
- Coring
- Sampling

These are:

- Sparse and local
- Require boreholes
- Expensive

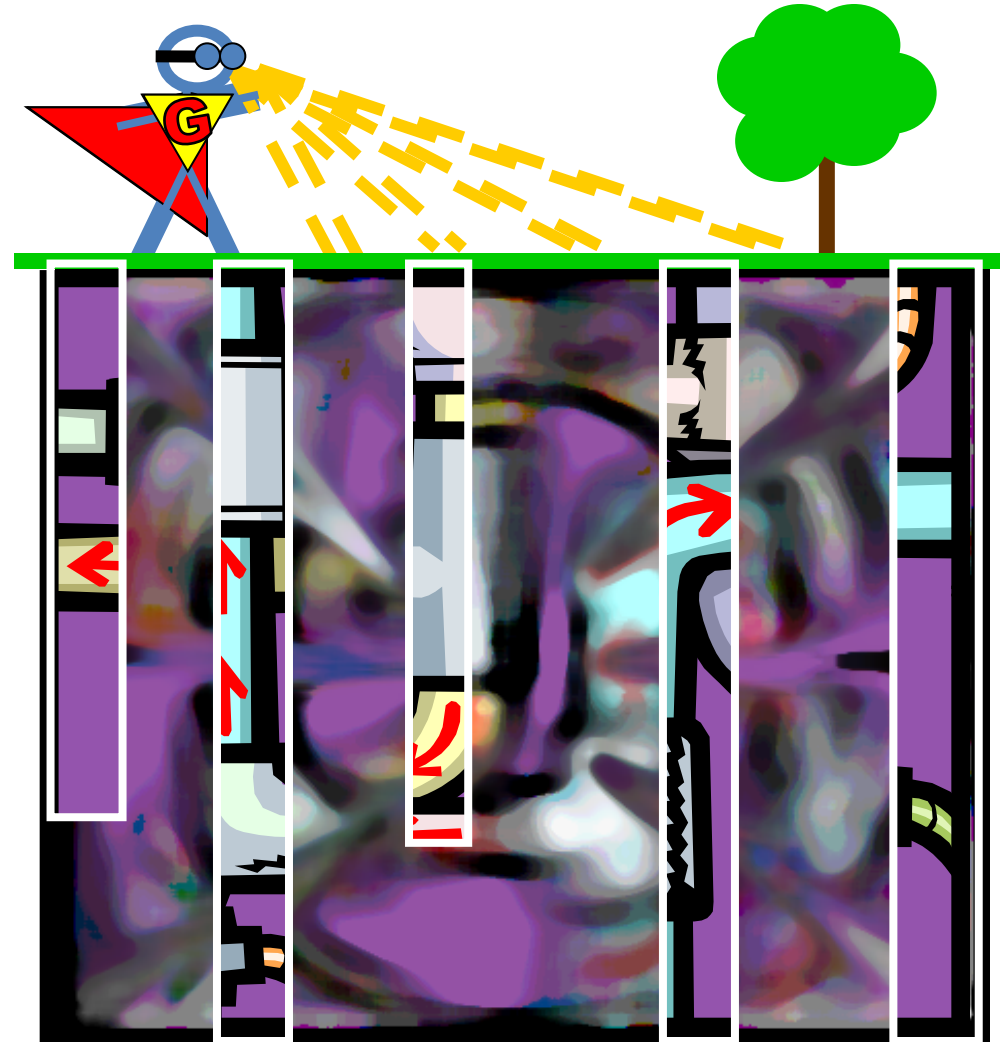


Geophysical Characterization

- Geophysical data:
 - Improved spatial coverage
 - Minimally invasive
 - Cost-effective

but...

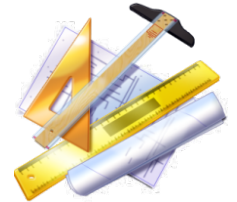
- Limited resolution
- Must be linked to parameter of interest
- Most powerful when interpreted jointly with other geophysical or hydrologic data



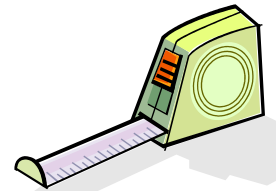
The Fractured Rock Geophysical Toolbox (FRGT)



Borehole geophysics
(high resolution,
near-hole
information)



Crosshole
resistivity & GPR
(information
between holes,
time-lapse
potential)



Conventional
hydrologic
measurements
(calibration and
groundtruth)

**NO SINGLE TOOL CAN WORK
FOR EVERY PROBLEM/SITE**

FRGT Method Selection Tool

Excel-based tool used to identify methods that:

- Address project goals
- Are likely to work at the given site

Goal: Provide project managers and regulators with tools for 'numerical gut checks' to help evaluate geophysical proposals and strategies for specific sites.

Status:

- Published at Groundwater
- Served from:
<http://water.usgs.gov/ogw/frgt>

The screenshot shows the 'FRGT METHOD SELECTION TOOL' spreadsheet. The title bar at the top reads 'FRGT METHOD SELECTION TOOL'. The spreadsheet content includes:

- Contact Info:** <http://water.usgs.gov/ogw/bgae>
- Last updated:** 02/26/2015
- Summary:** The Fractured Rock Geophysical Toolbox comprises a suite of geophysical methods for aquifer characterization and monitoring. This spreadsheet-based tool is designed to assist project managers and scientists in selecting tools that (1) satisfy study goals, and (2) are feasible for application at a given site, based on site characteristics as entered by the user.
- Installation:** Just use this spreadsheet. You may need to reset macro security to include the location of this file as a 'trusted site.' Go to 'Excel Options' under the 'Office Button.' The spreadsheet is designed for use in Excel 2010 or later.
- Input:** The user must enter a site description and study goals using on the FRGT MATRIX worksheet using the numeric up-downs and menus provided.
- Output:** The spreadsheet will indicate the degree to which methods will be useful for satisfying project goals and which methods are likely feasible given the characteristics of the site.
- Disclaimer:** In our experience no one tool or single method achieves all goals when working in fractured-rock aquifers. We encourage a multi-disciplined approach that uses methods that measure different subsurface properties, thereby improving the detection, characterization, and interpretation of the aquifer. This FRGT utility is intended to help select methods and to assess their appropriateness and the potential for success given the goals of your investigation.
- Results:** Results at any one site may vary depending on the actual tools and acquisition settings used. We recommend that when making tool selections you read the manuals or consult the vendors for the range

The spreadsheet interface includes a ribbon at the bottom with tabs for 'INTRODUCTION', 'FRGT MATRIX', and worksheets 'M1' through 'M9'. The status bar at the bottom shows 'Ready' and '80%' zoom.

Day-Lewis, F.D., Johnson, C.D., Slater, L.D., Robinson, J.L., Williams, J.H., Boyden, C.L., Werkema, D., Lane, J.W., 2016, A Fractured Rock Geophysical Toolbox Method Selection Tool, Groundwater.

Funding from ESTCP (ESTCP ER-200118 and ESTCP ER 201567T2 and from EPA.

FRGT Method Selection Tool

FRGT METHOD SELECTION TOOL



Fill in cells shaded aqua-blue (in column D). All other cells will be automatically updated.

- indicates method is recommended
- indicates method is not recommended
- indicates method is appropriate/effective
- indicates method is not appropriate/effective

Project and site parameters	
1. What is the depth to bedrock (m)?	15
2. What is the electrical resistivity of bedrock (ohm-m)?	100
3. What is the minimum spacing between wells (m)?	4
4. What is the well casing?	Open
5. What is the vertical extent of open holes (m)?	20
6. Is borehole fluid turbid/muddy (opaque)?	No
7. Borehole diameter (inches)	6
8. Cultural EM interference? (utilities, pipes, etc.)	Yes
9. Is it possible to disturb the ground for electrodes or geophysics?	Yes
10. What is native groundwater conductivity (micro-S/cm)?	100
11. What is the project cost threshold for a given method?	High

Goals	
A. Identify discrete fracture network characteristics	Yes
B. Identify lithologic contacts	Yes
C. Map depth to bedrock	No
D. Understand large-scale anisotropy, average fracture orientations	No
E. Estimate discrete fracture hydraulic properties	Yes
F. Estimate small-scale effective hydraulic properties	Yes
G. Estimate large-scale hydraulic properties	No
H. Identify interwell hydraulic connections	Yes
I. Time-lapse snapshots of amendment delivery	Yes
J. Continuous monitoring of degradation	No
K. Screening for iron/minerals	No

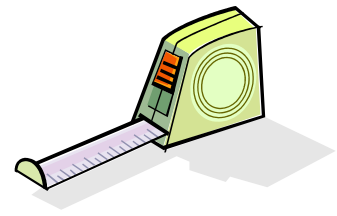
Assumptions	
- Wells are partially or completely fluid filled	

Comments	
- May require the use of a borehole liner.	

Methods	Appropriate for goals	Effectiveness at site	Relative cost	Method contributes to goal:											Made infeasible by site parameter:													
				A	B	C	D	E	F	G	H	I	J	K	1	2	3	4	5	6	7	8	9	10	11			
Surface methods																												
1. EM terrain conductivity (induction)	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
2. ERT	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
3. GPR	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
4. Resistivity - azimuthal	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
5. SP - azimuthal	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
6. Seismic refraction	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
7. Seismic reflection	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Medium	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
8. Time domain EM	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Cross-hole methods																												
9. ERT	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Medium	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
10. GPR	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	High	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
11. IP	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Medium	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
12. Seismic	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	High	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Borehole methods																												
13. ATV	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
14. Caliper	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
15. EM Induction	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
16. Flowmeter (single hole)	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
17. Flowmeter (cross-hole)	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
18. Gamma	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
19. IP and Normal Resistivity	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
20. Magnetic susceptibility	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
21. NMR	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Medium	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
22. OTV	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
23. Bader (borehole GPR)	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Medium	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
24. Video camera	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Hydrologic tests																												
25. Dilution/fluid replacement	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	High	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
26. Focused packer testing	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	High	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
27. Fluid resistivity & temperature	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Low	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
28. High resolution temperature	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	High	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
29. Open-hole hydraulic tests	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	Medium	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
30. Tracer tests	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	High	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	

This FRGT utility is intended to help select methods and to assess their appropriateness and the potential for success given the goals of your investigation. Actual performance of the geophysical and hydraulic tools may vary depending on the specific tool used and acquisition settings.

The Toolbox



Conventional:

- Hydraulic tests (single hole) → estimates of transmissivity for isolated intervals of boreholes (i.e., focused packer testing)
- Coring → lithology, fractures, contaminant mass
- Tracer tests → estimates of transport properties (hydraulic conductivity, effective porosity, dispersivity, exchange rates, etc.)



Geophysical:

- Flowmeter logging (single and crosshole) → estimates of transmissivity associated with single fractures or fracture zones; far-field heads
- Borehole geophysical logging (caliper, electromagnetic, gamma, neutron, nuclear magnetic resonance, induced polarization, fluid conductivity/ temperature, spontaneous potential, televiewer) → high-resolution measurements indicating lithology, fracture presence, etc.
- Crosshole resistivity tomography → electrical resistivity structure, tracer movement
- Borehole radar reflection → fracture location and orientation
- Borehole radar transmission tomography → electromagnetic structure, tracer movement



Method	Geophysical Property	Relevant Hydrologic Property/Parameter	Acquisition method(s)
Seismic refraction & reflection	Seismic velocities & reflectivity (bulk & shear moduli)	Depth to bedrock, water table, aquifer boundaries	Lab, borehole, crosshole, surface
DC Electrical Resistivity (ER)	Electrical resistivity	Water content, salinity, pore fluid, porosity, lithology	Lab, borehole, crosshole, surface
Induced polarization (IP)	Chargeability	Surface area of pores/grains, lithology	Lab, crosshole, surface
Spontaneous Potential (SP)	Spontaneous potential	Flow through porous medium, redox potential	Lab, borehole, crosshole, surface
Ground penetrating radar (GPR)	Dielectric constant, electrical conductivity	Water content, salinity, pore fluid, porosity, lithology	Lab, crosshole, surface
Electromagnetic (EM)	Electrical resistivity	Water content, salinity, pore fluid, porosity, lithology	Lab, borehole, crosshole, surface, airborne
Conventional borehole logging: caliper, gamma, sonic, etc.	Many	Many: fracture locations, clay content, lithology, etc.	Borehole
Advanced borehole logging: ATV/OTV, flowmeter, etc.	Many	Many: fracture locations, lithology, transmissivity, etc.	Borehole

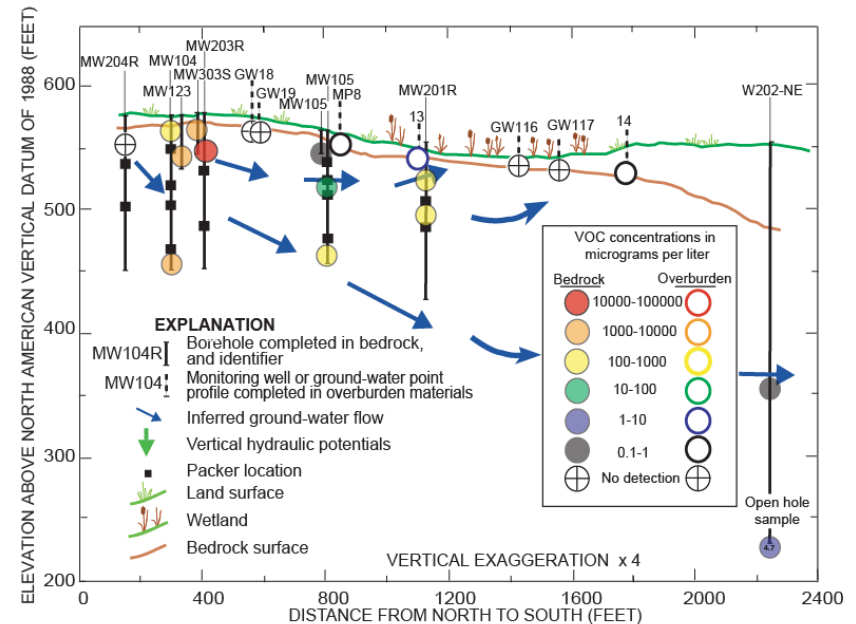
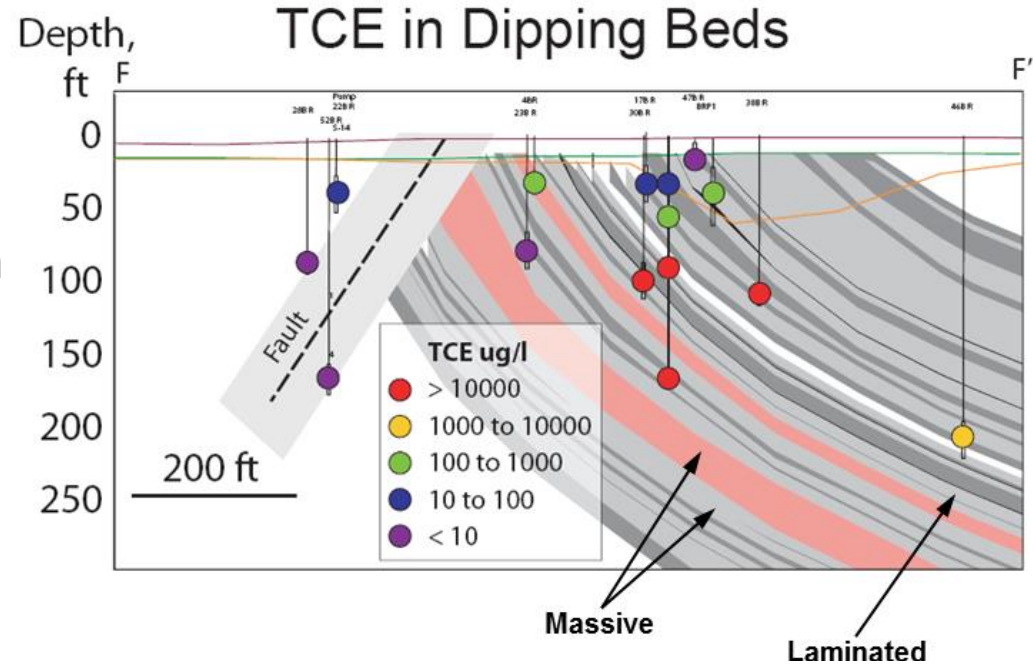
The Goal of Characterization

Conceptual Model / Hydrogeologic Framework:

- Aquifer architecture/plumbing network; i.e., the spatial distribution of major fractures or fracture zones
- Some understanding (statistical?) of the fractures not explicitly identified
- Some understanding (statistical?) of the properties of the matrix

Simulation Model / Attaching #'s to the Framework:

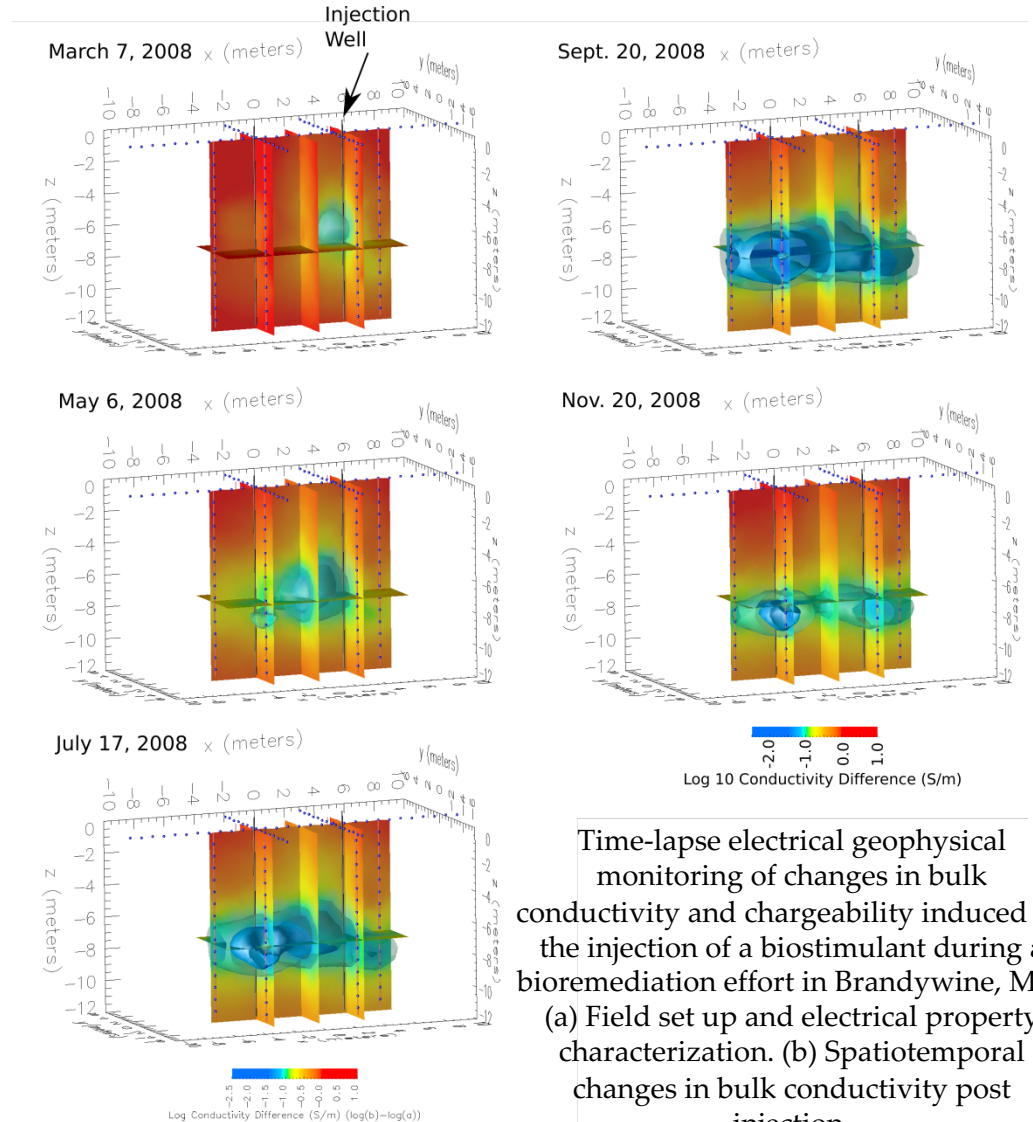
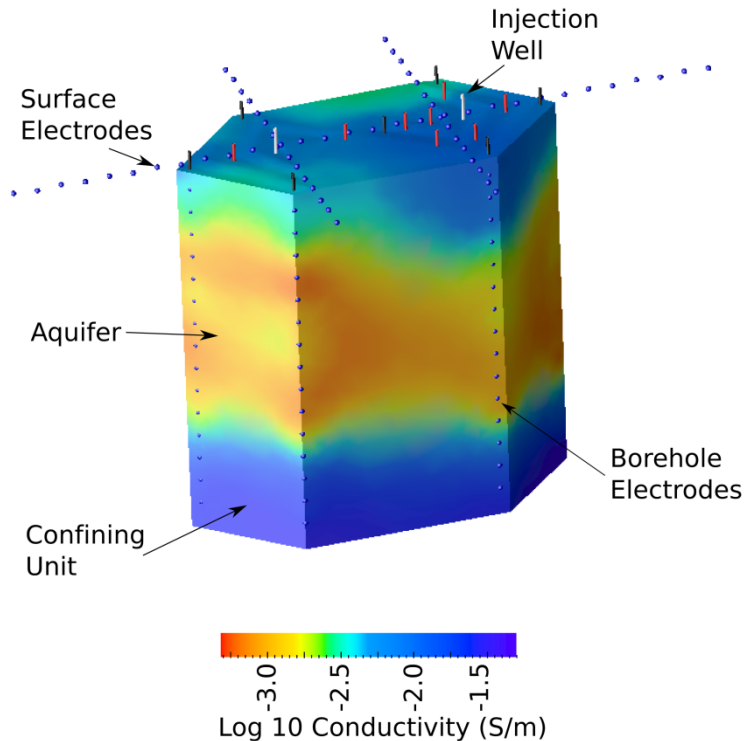
- A quantitative description of aquifer properties in 3D: Hydraulic conductivity, porosity, etc.; possibly for a discrete fracture network; e.g., MODFLOW, MT3D, FRACMAN, etc.



The Goal of Monitoring

Understanding of changes in:

- Contaminant mass
- Tracer concentration
- Biostimulation amendments
- Aquifer properties
- Example: Brandywine, MD

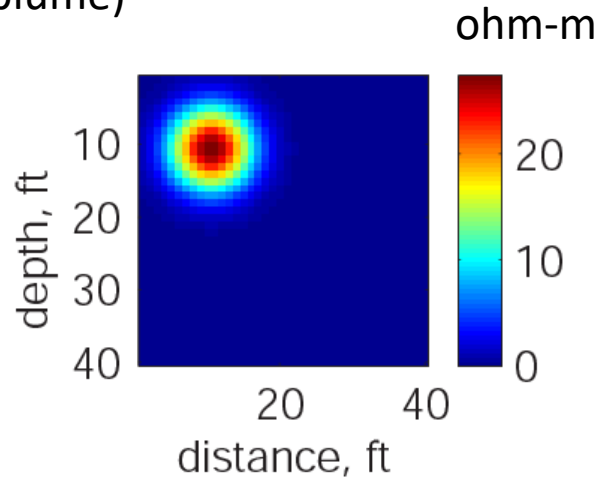


Time-lapse electrical geophysical monitoring of changes in bulk conductivity and chargeability induced by the injection of a biostimulant during a bioremediation effort in Brandywine, MD. (a) Field set up and electrical property characterization. (b) Spatiotemporal changes in bulk conductivity post injection.

A note on: Monitoring vs. Detection

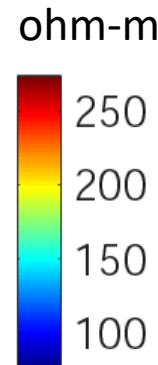
The Detection Problem: A 2-D Crosshole GPR example: finding a plume

Electrical Resistivity Anomaly
(plume)



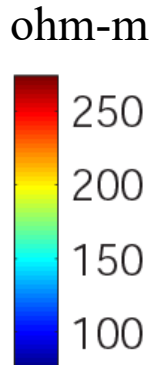
“The Needle”

Electrical Resistivity
Cross section



“The haystack + needle”

Electrical Resistivity
Tomogram

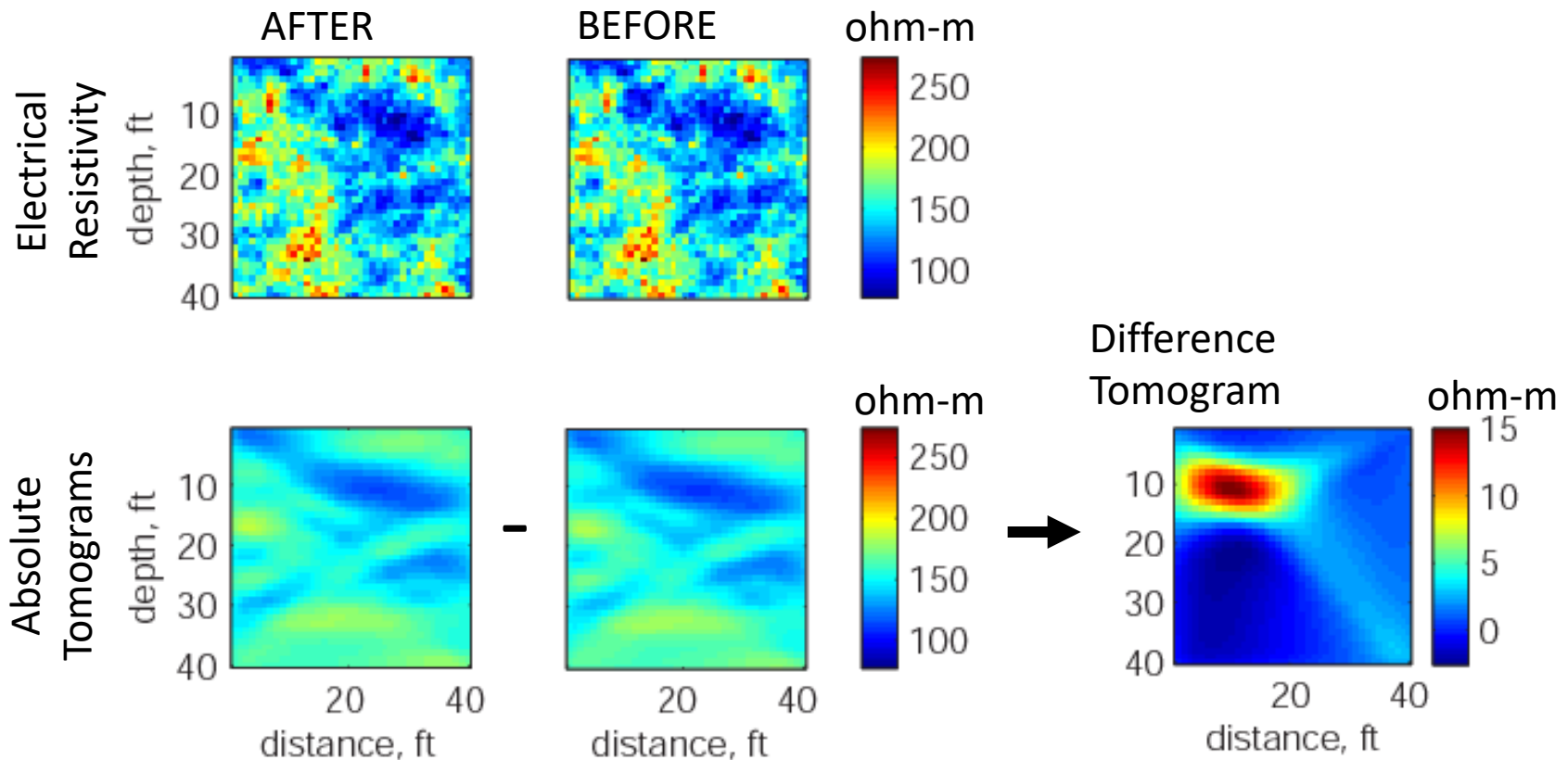


“Blurry Haystack”

→ *Plume is masked by geologic heterogeneity*

A note on: Monitoring vs. Detection

The Monitoring Problem: Difference against background



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

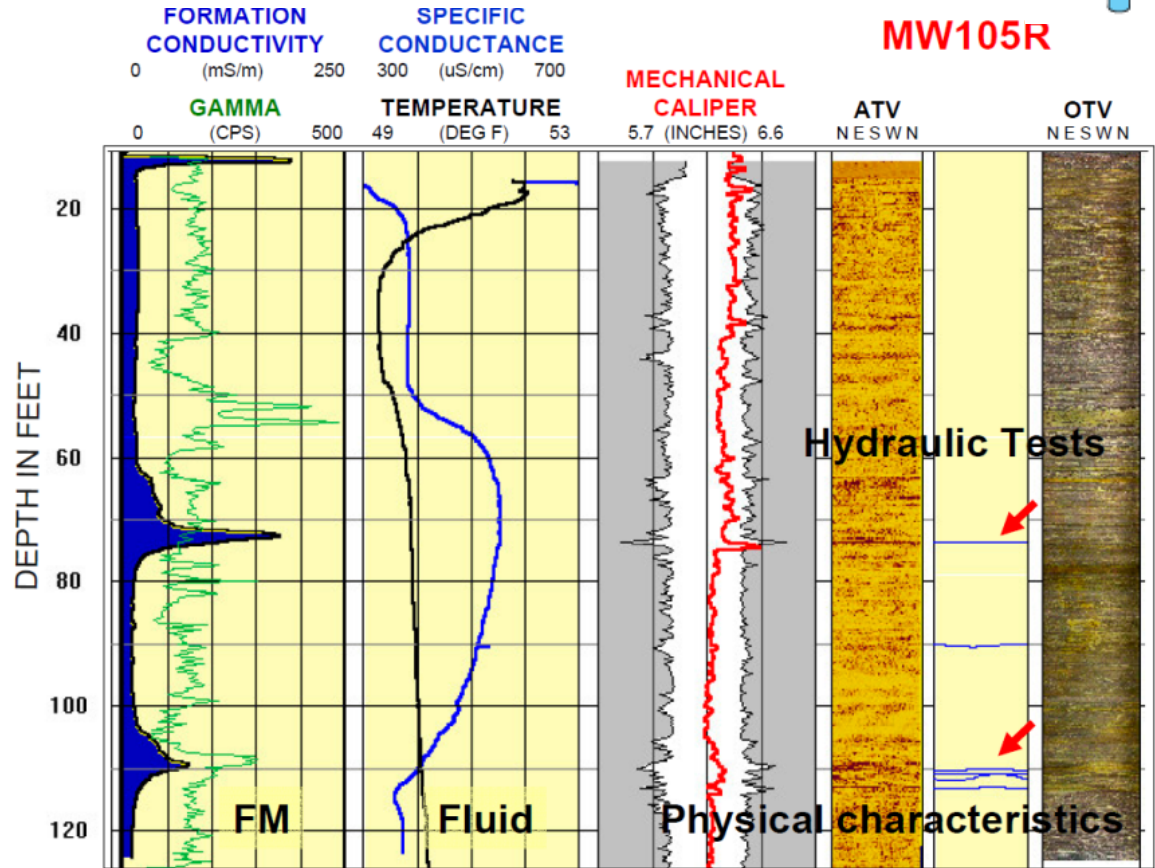
Borehole geophysical logging



Used for understanding:

- Well construction and integrity of the borehole
- Geology and structure
- Water (amount and chemistry)
- Hydraulically active fractures intersecting boreholes and between boreholes

The bulk of geophysical work in fractured rock is borehole logging



Example of borehole log panel from the U. Connecticut Landfill [23-24], in which major fractures appear in multiple logs at ~110 ft, 90 ft and 75' depths

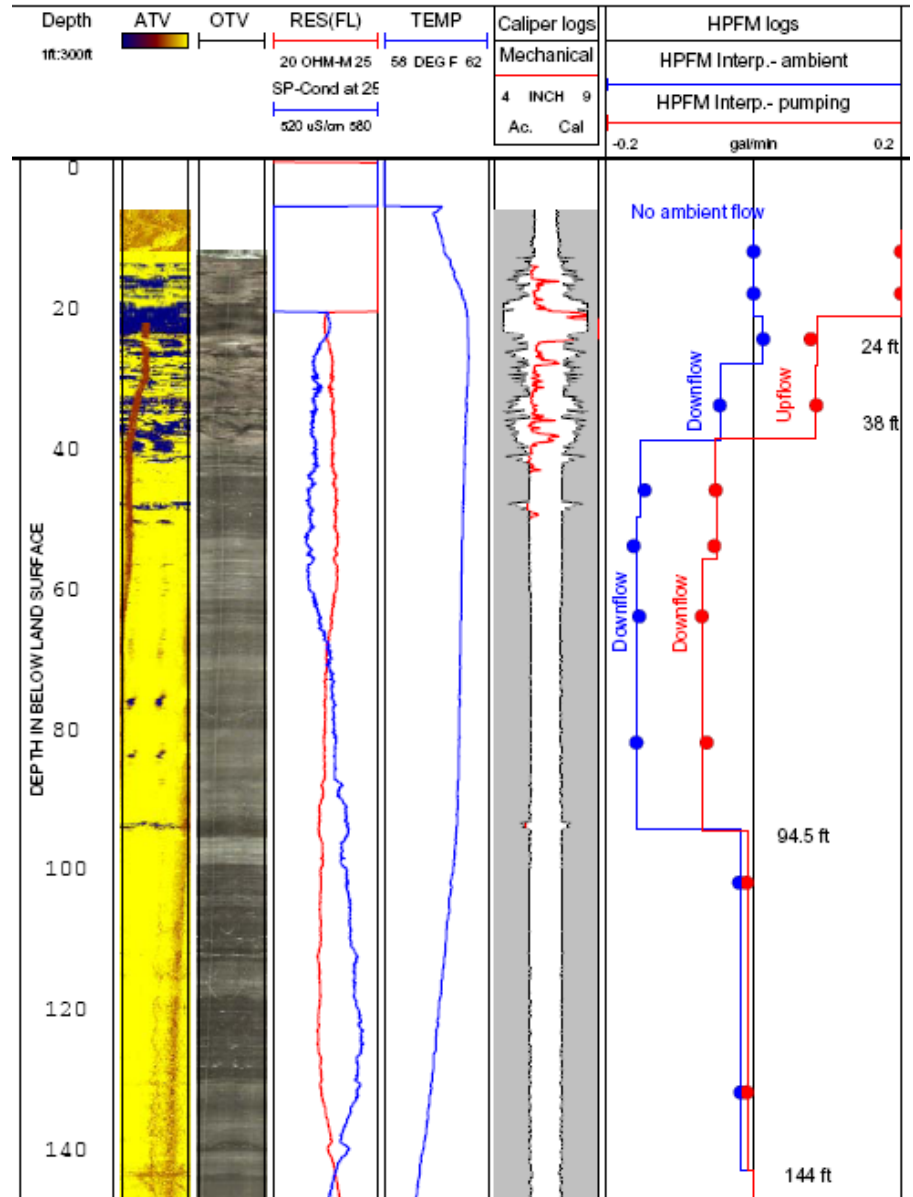
Flowmeter Logging

Used for understanding:

- Flow in boreholes
- Hydraulic context for interpretation of samples, or selection of sampling locations
- Far-field heads
- Fracture transmissivities

Methods: Single-hole, cross-hole, fluid differencing, dilution...

Overview of FLASH software
 [Day-Lewis et al., 2011,
 Ground Water]



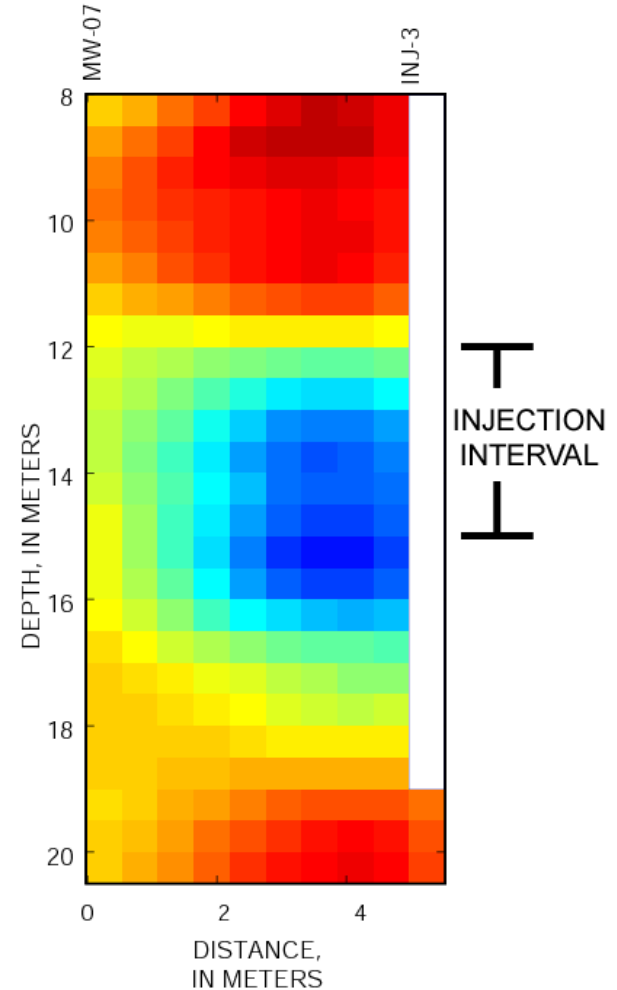
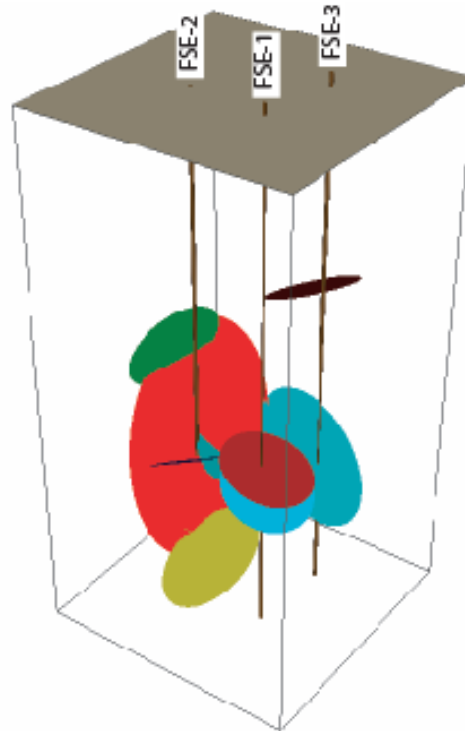
Radar Tomography and Reflection

Used for understanding:

- Electromagnetic structure
- Interpreted for lithology, fracture zones, physical property variations (transmission mode)
- Interpreted for individual fractures (reflection mode)

Use to monitor:

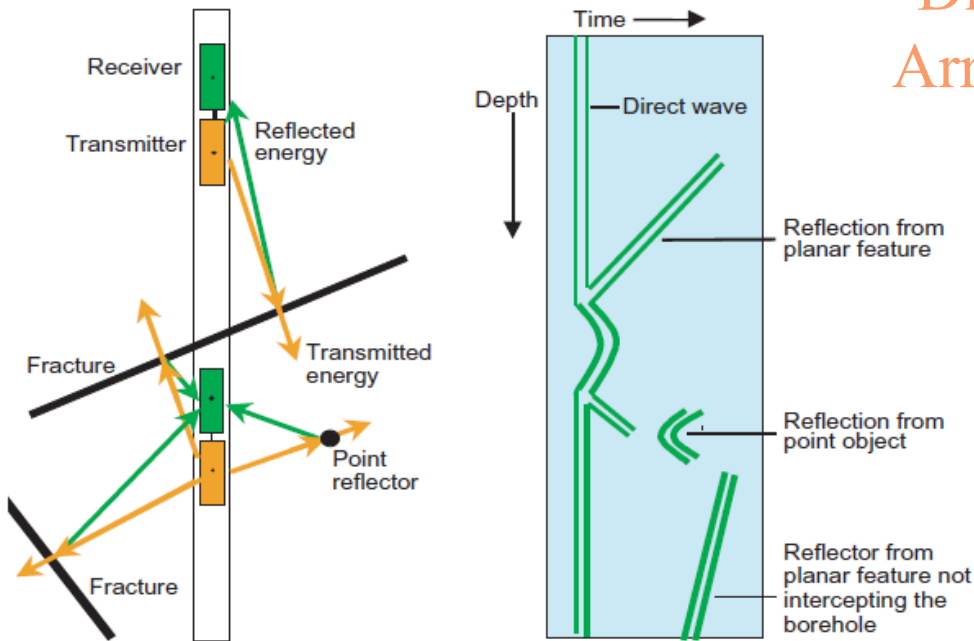
- Tracer experiments
- Remediation



Reflection-Mode Radar

Borehole Reflection Data:

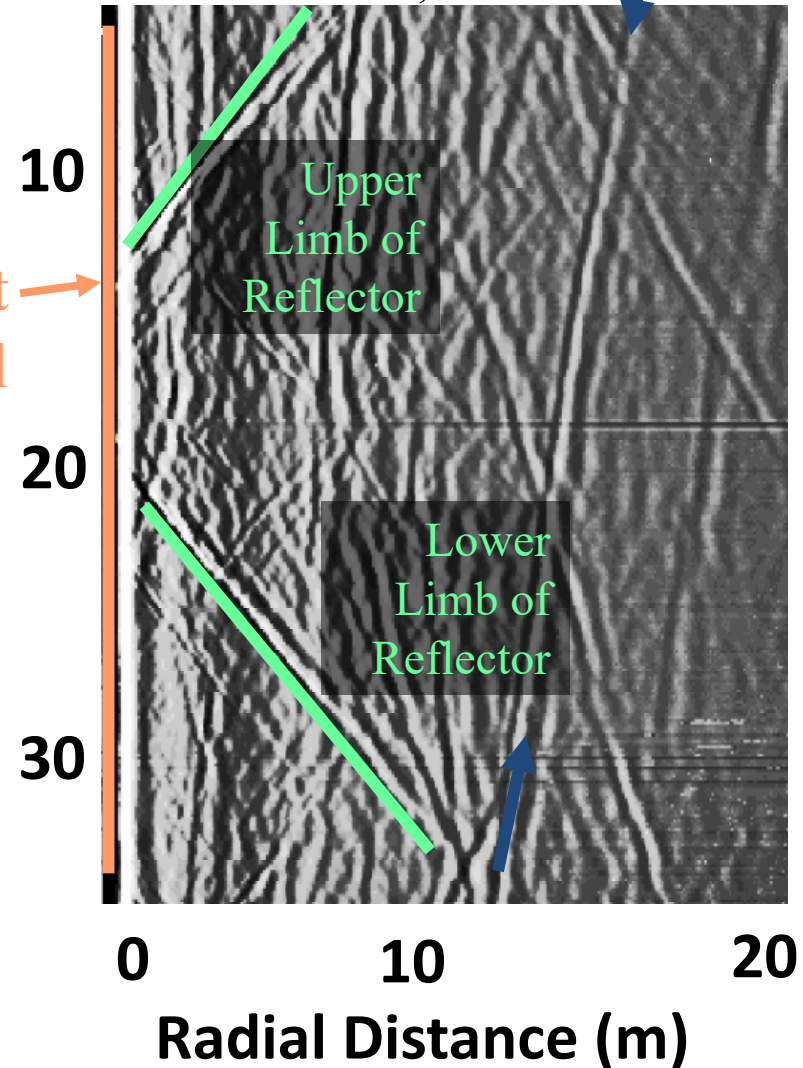
- Yield fracture location and orientation (w/ directional antennas)
- Can detect individual fractures



Direct
Arrival

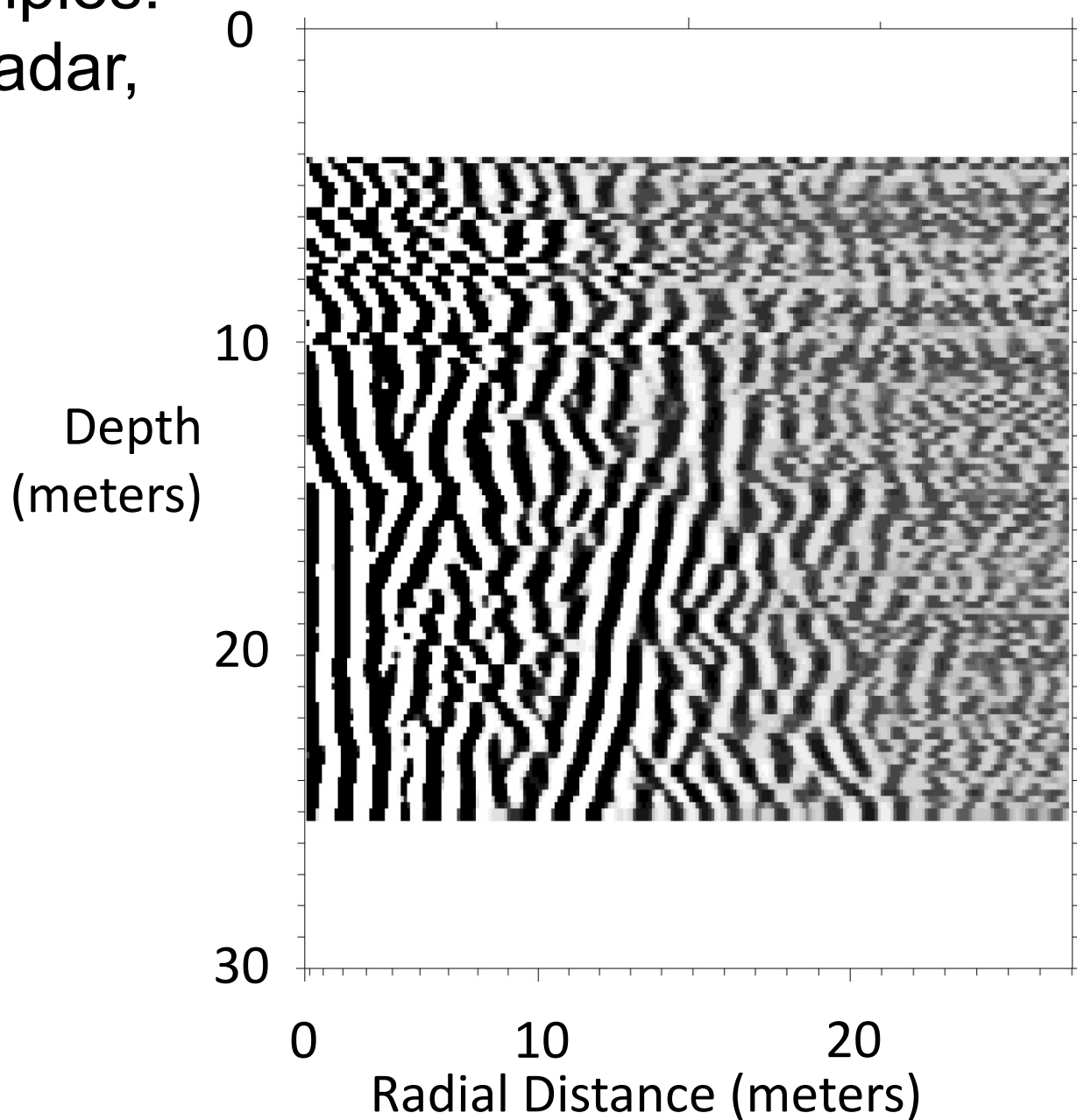
Reflector that does not
intercept the borehole

Malå, Sweden



Reflection Examples:

1. Reflection Radar, Bronx, NY

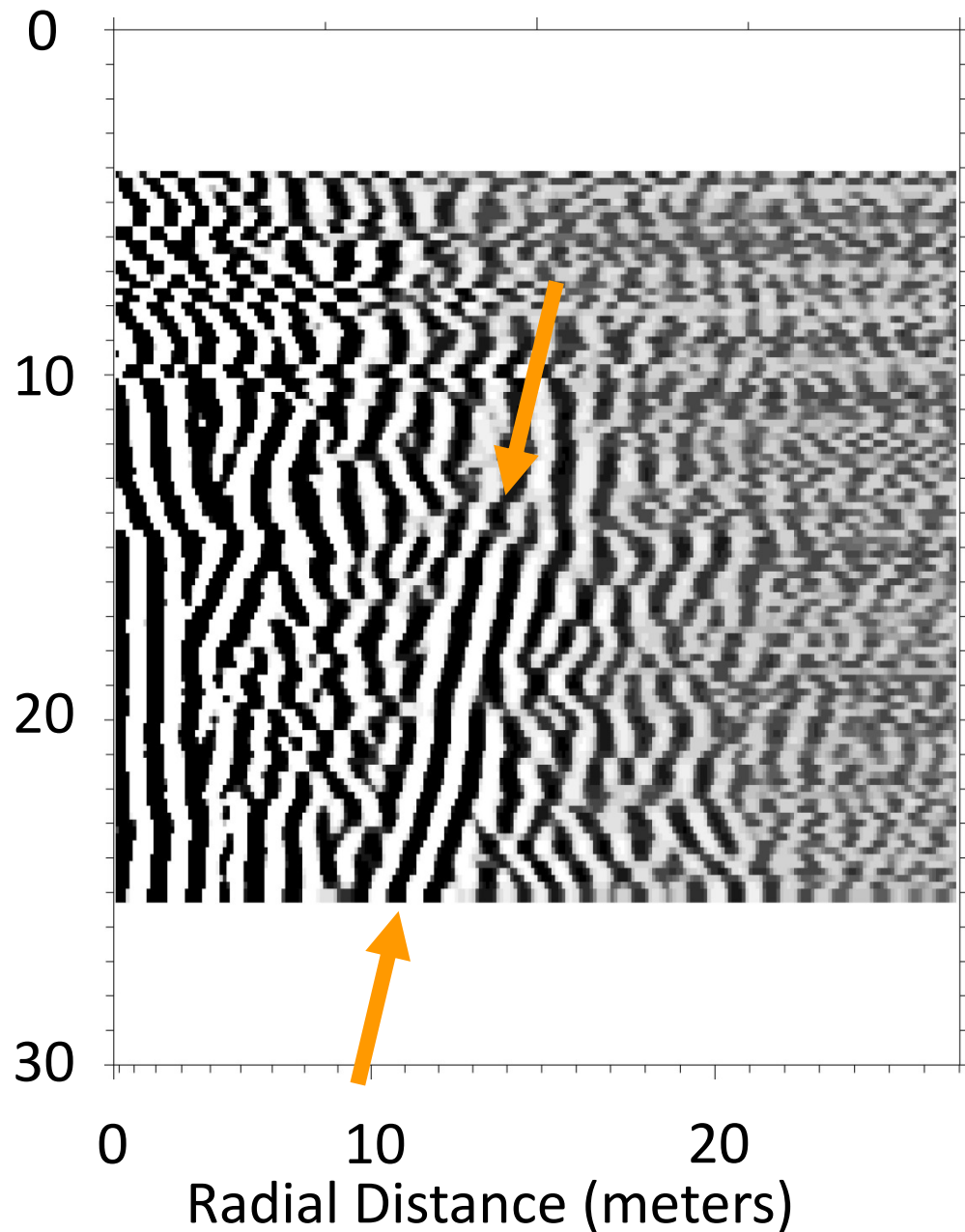


Borehole Radar Reflection Data Borehole B-1 Bronx, NY

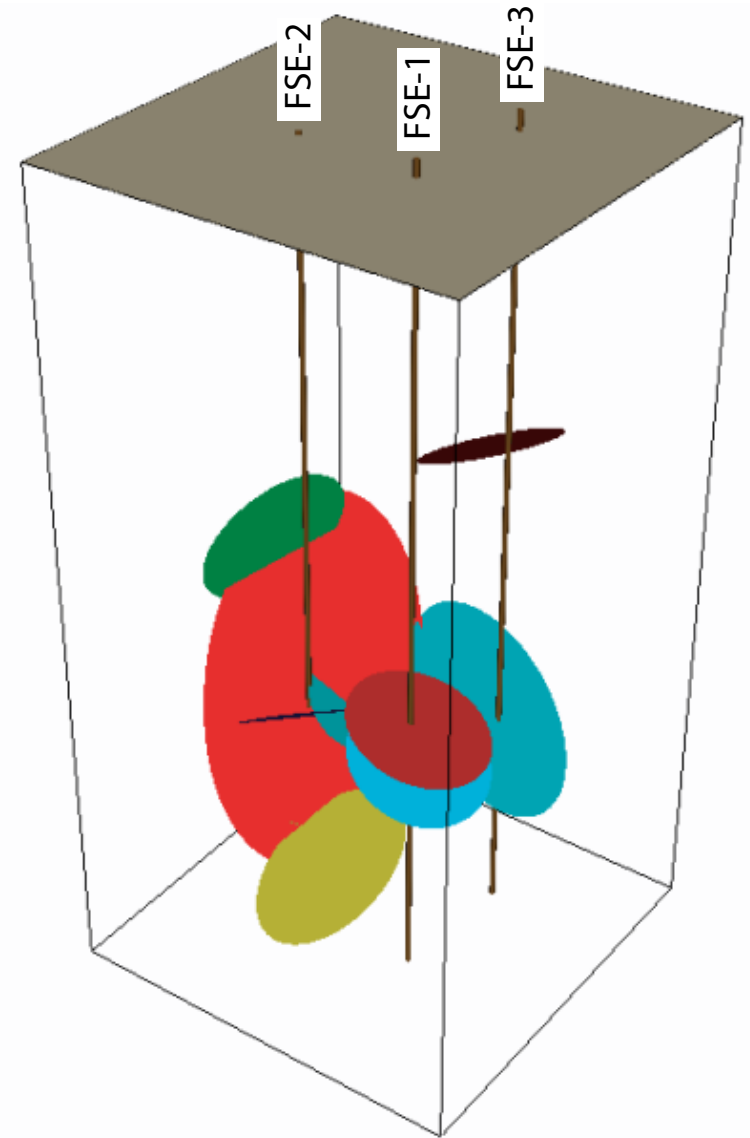
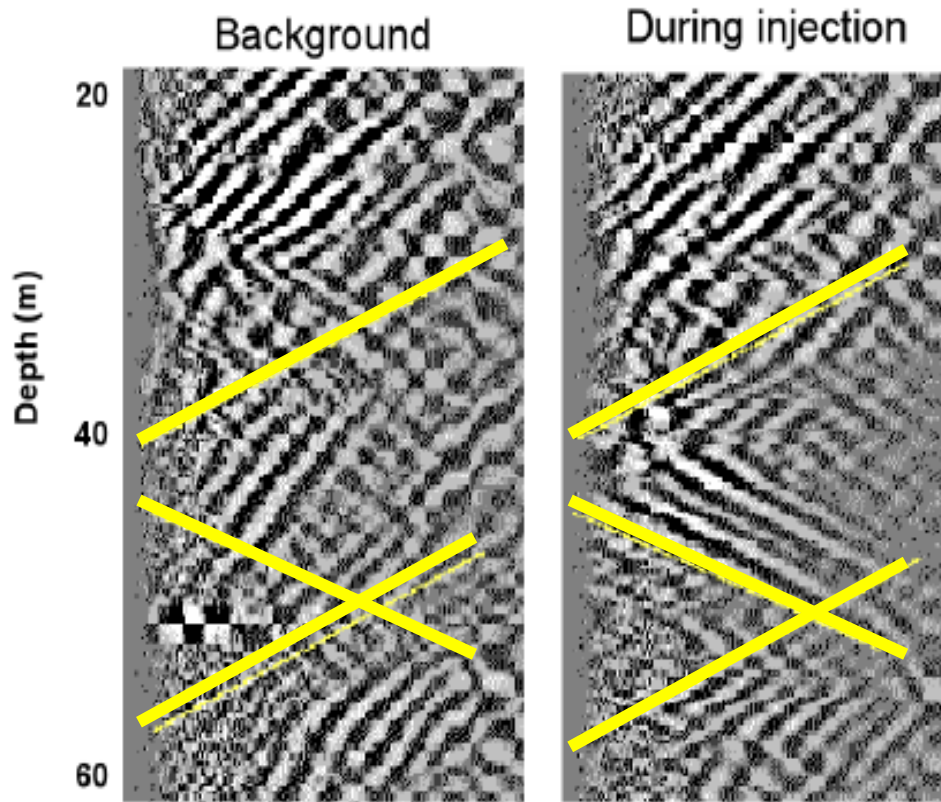
Depth
(meters)

Strike: $325^\circ \pm 10^\circ$
Dip: 76.5°

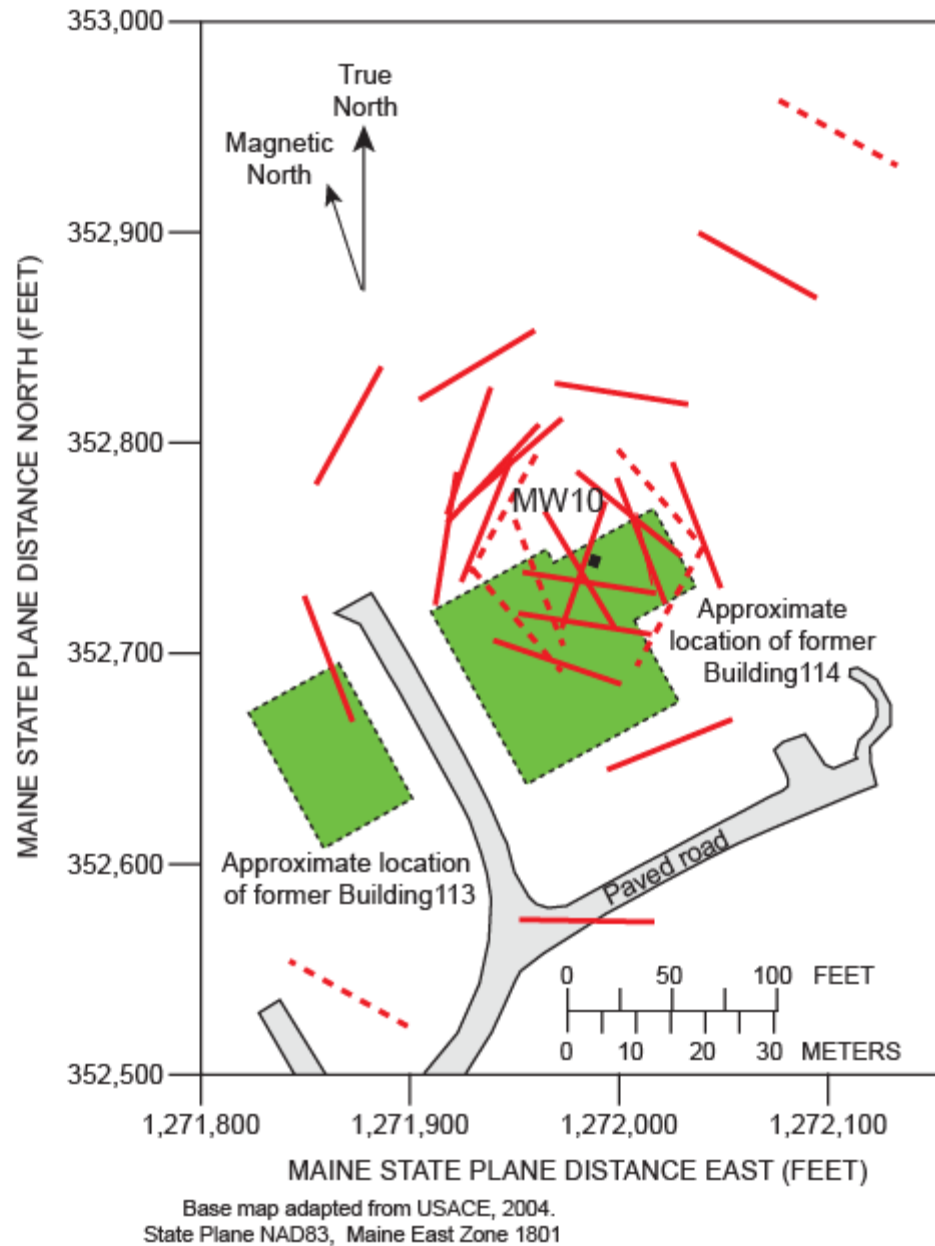
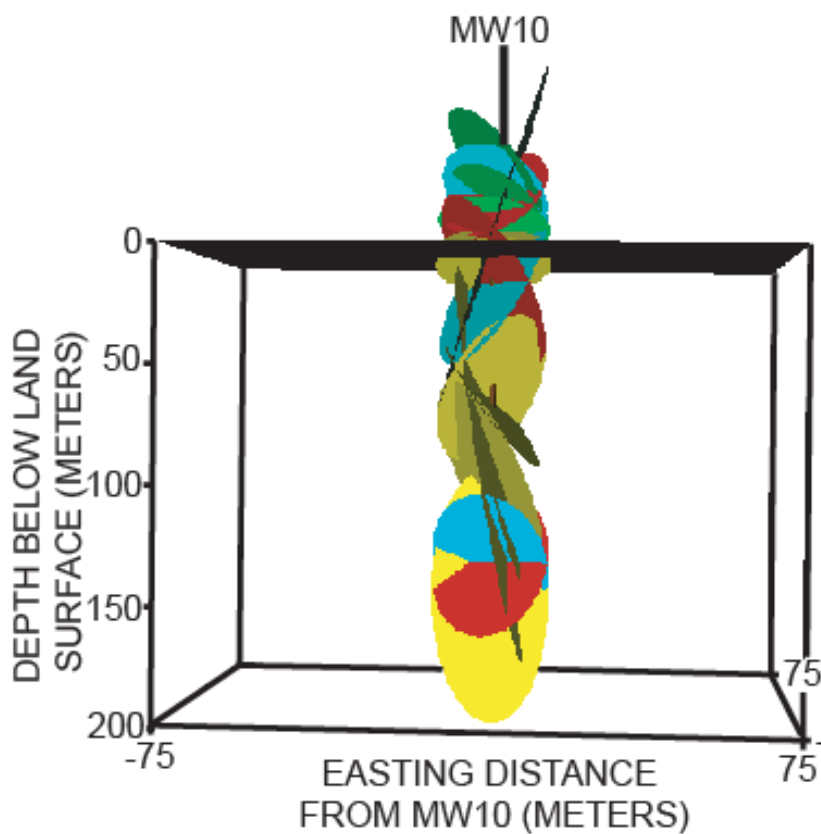
Approx. 11 meters from B-1



Reflection Example: 2. Mirror Lake, NH

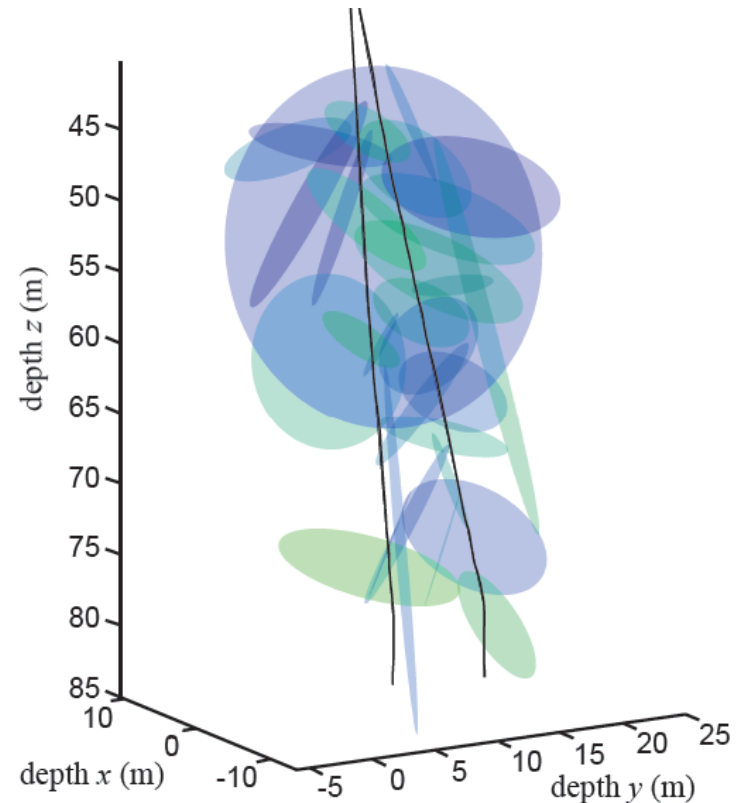
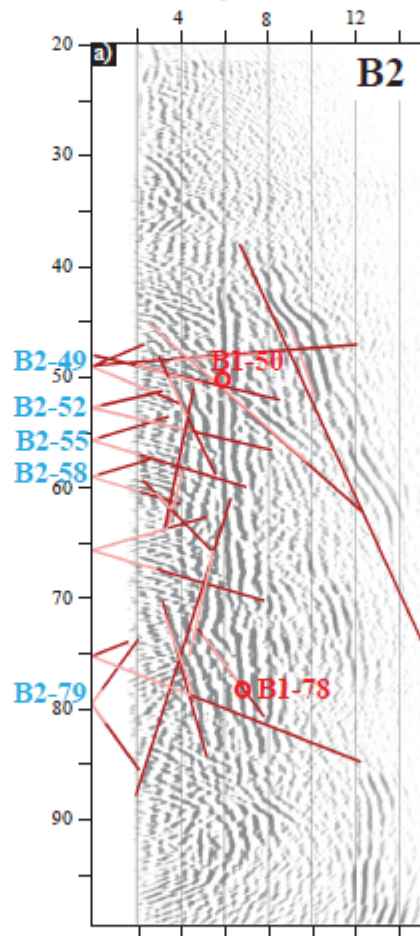


Reflection Example: 3. Machiasport, ME

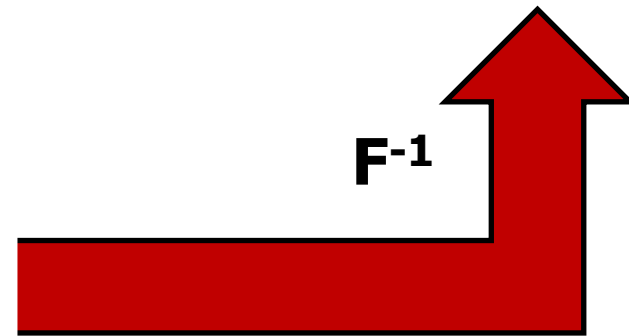
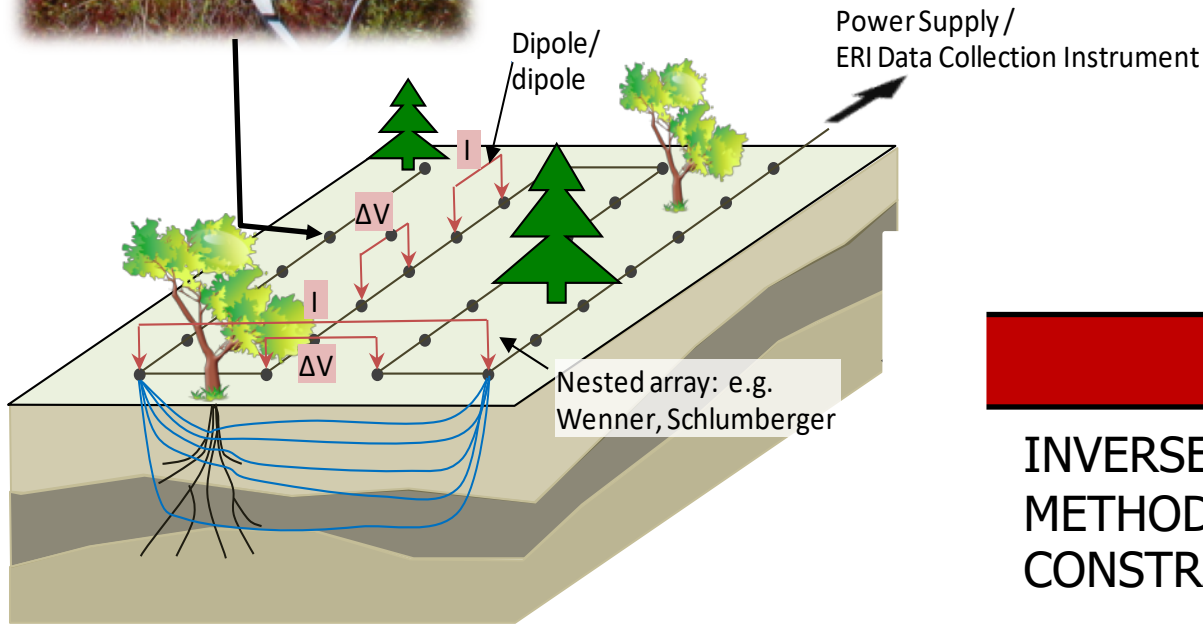
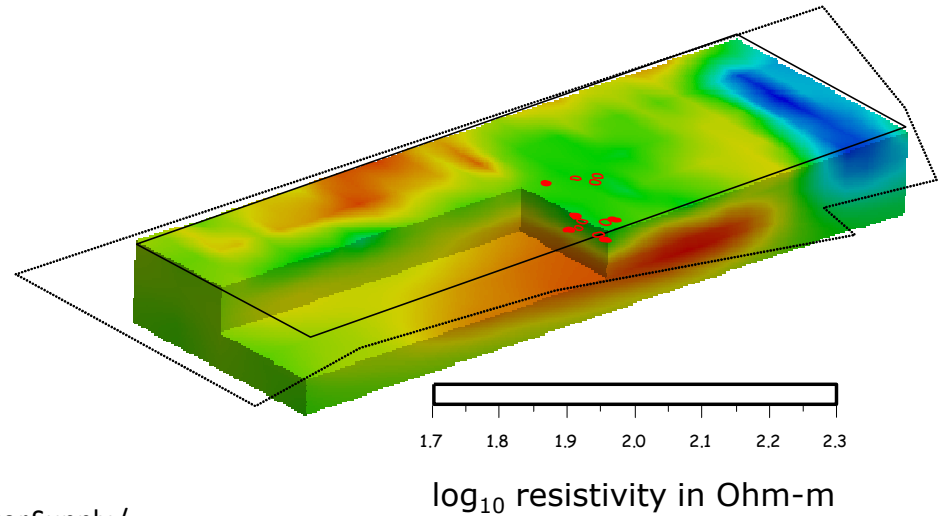


Recent Fractured Rock Data Integration

- Discrete fracture network realizations conditioned to borehole reflection mode radar and hydrologic data [C. Dorn, PhD, U. Lausanne] for Stang-er-Brune Site, France



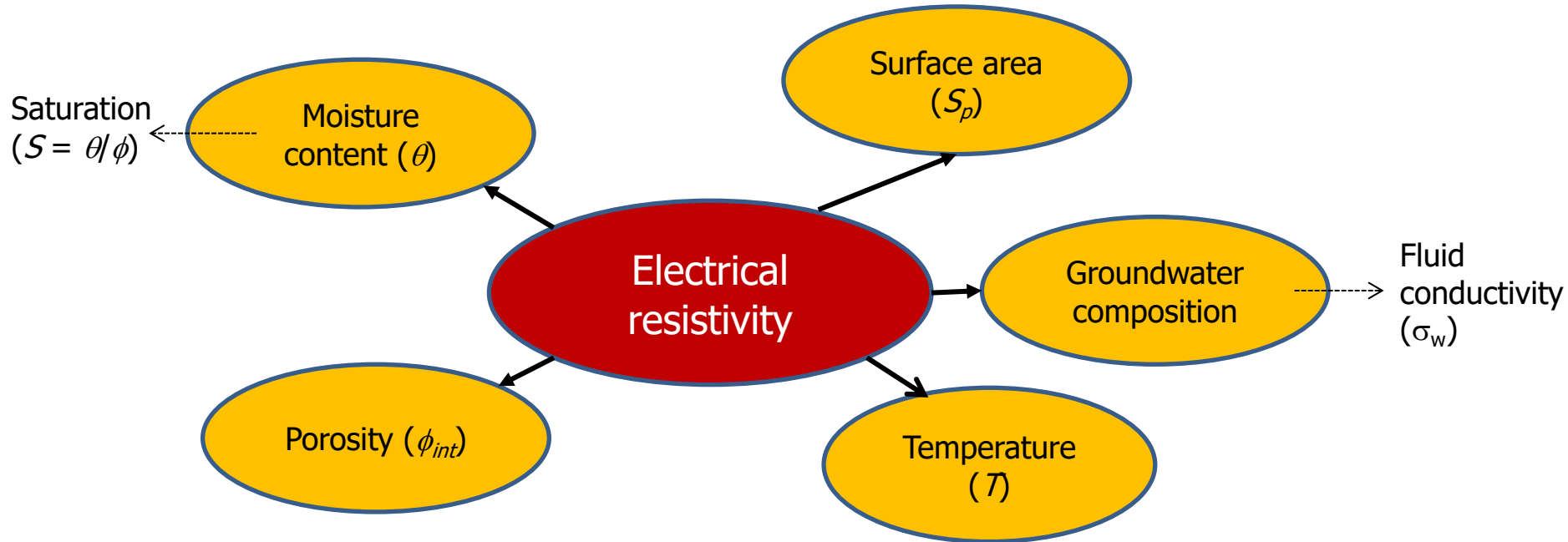
Electrical Resistivity



INVERSE PARAMETER ESTIMATION
METHODS WITH REGULARIZATION
CONSTRAINTS

Why resistivity?

A geophysical property dependent on many subsurface properties....



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

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

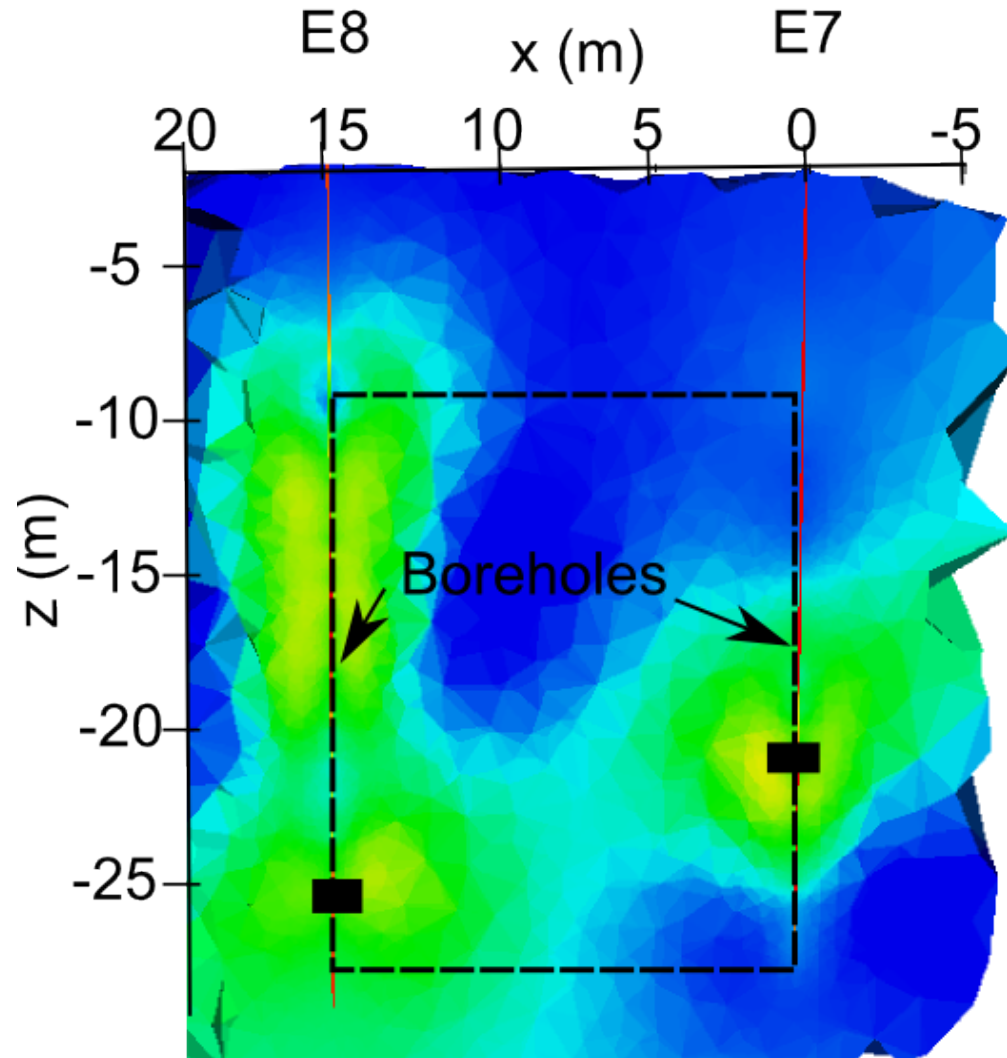
Resistivity Tomography

Used for understanding:

- 1D, 2D or 3D electrical-conductivity structure
- Lithology, fracture zones, physical property variations

Use to monitor:

- Tracer experiments
- Remediation



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

Problem

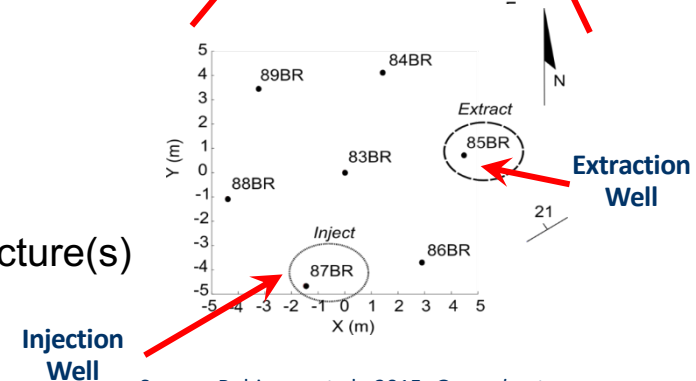
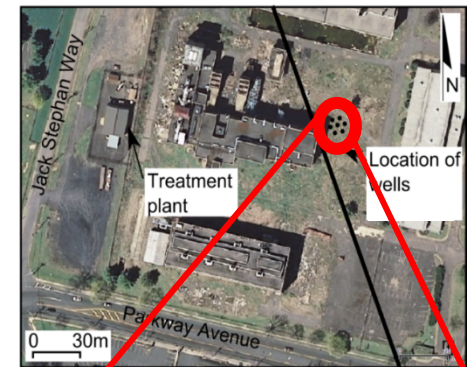
Understanding fluid flow in fractured rock systems is critical for remediation design, but notoriously difficult

Objective

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

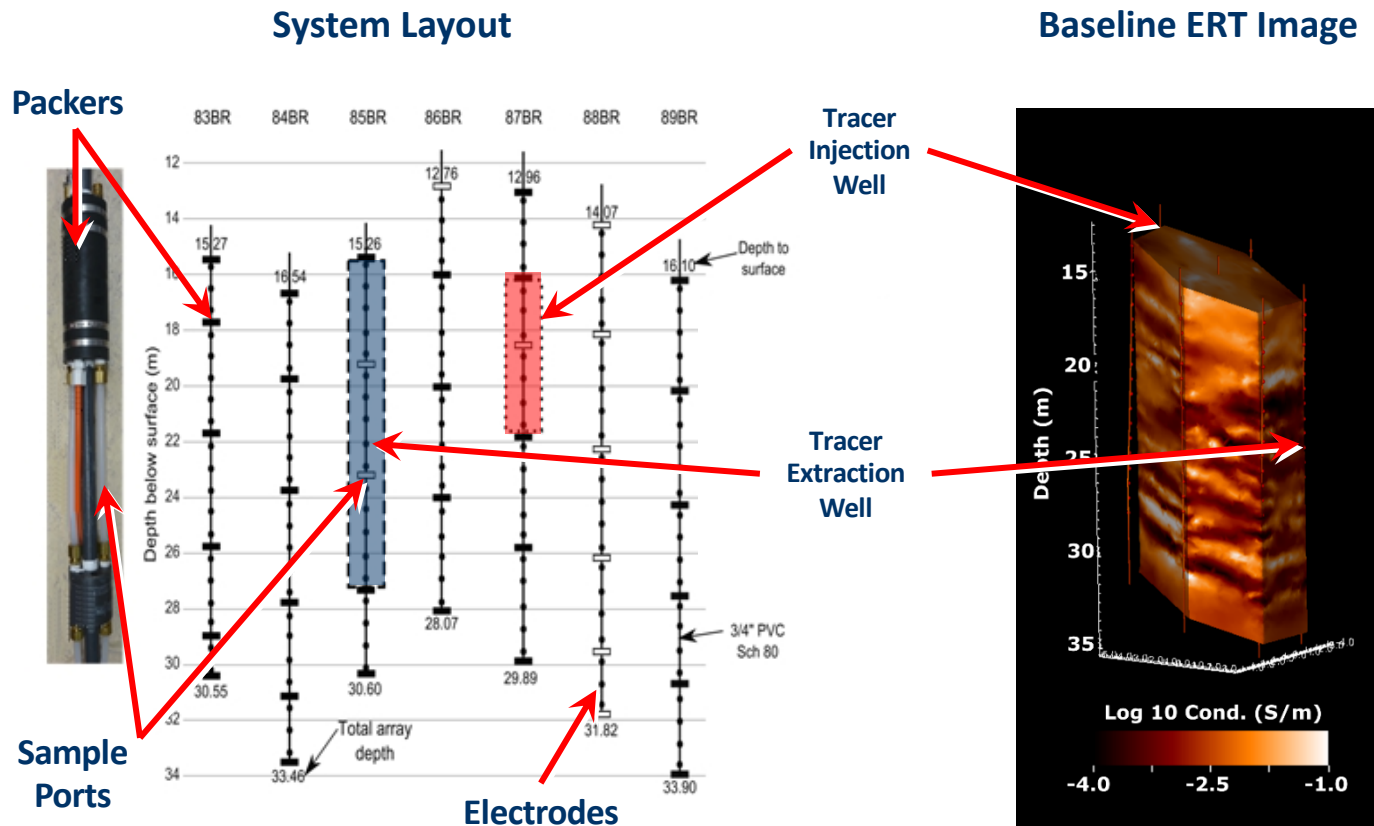
Supplementary Information

- 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



Source: Robinson et al., 2015.
Groundwater.

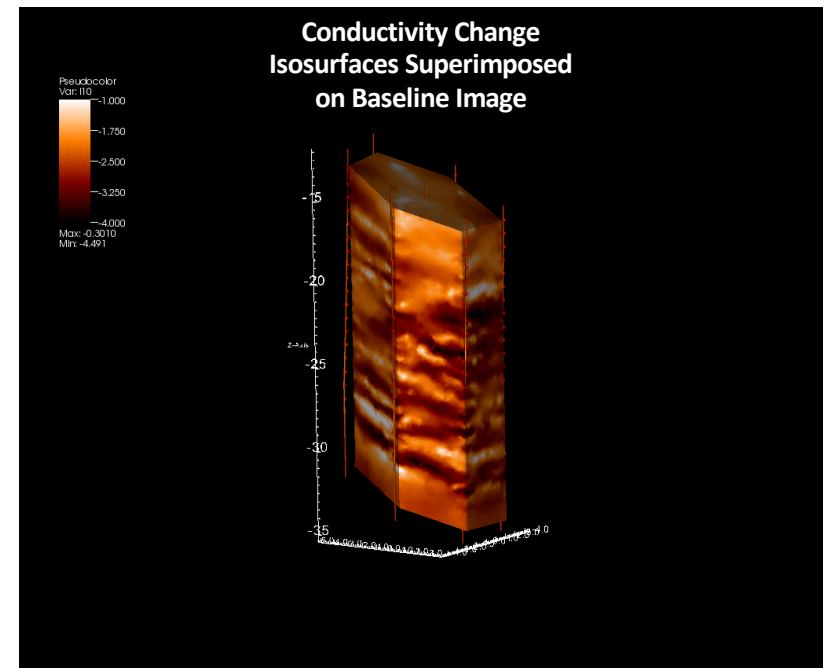
Time-Lapse Difference Imaging Results and Cost

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



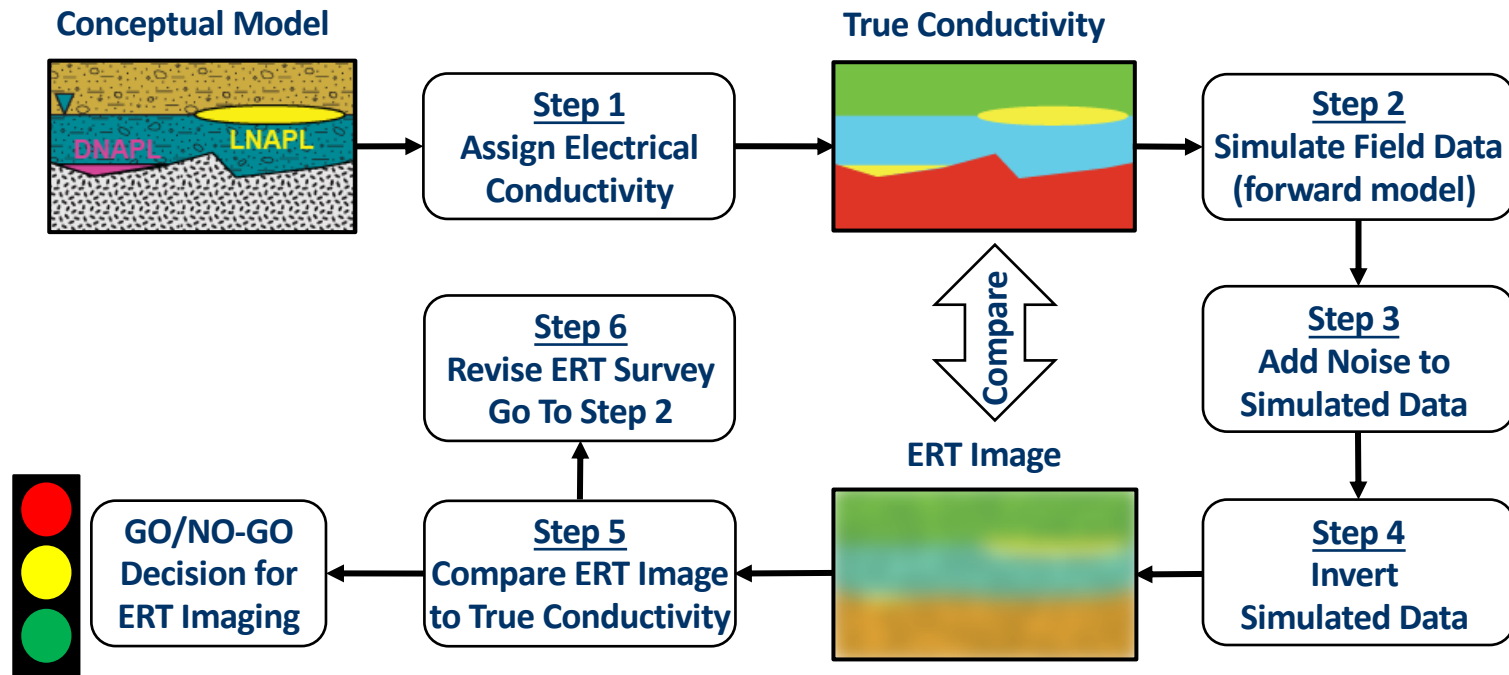
Source: Robinson et al., 2015.
Groundwater.

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 can we avoid pitfalls?*
 - ***REQUIRE A FEASIBILITY ASSESSMENT FROM YOUR CONTRACTORS!***

Pre-Modeling Feasibility Assessment Flowchart

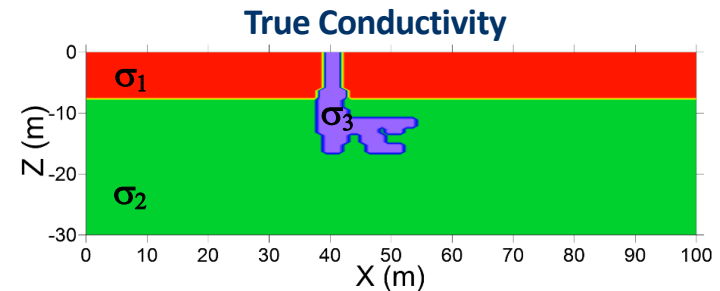
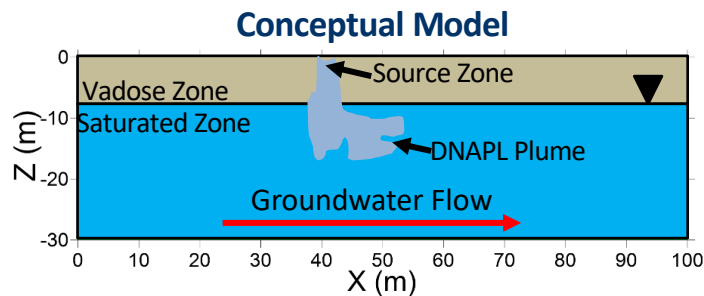


after Day-Lewis, F.D., Slater, L.D, Johnson, C.D., Terry, N., and Werkema, D., 2017, An overview of geophysical technologies appropriate for characterization and monitoring at fractured-rock sites, *Journal of Environmental Management*, <http://dx.doi.org/10.1016/j.jenvman.2017.04.033>

Example Feasibility Assessment: Imaging a DNAPL Plume

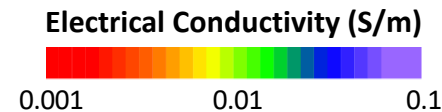
Step 1

Assign Electrical Conductivity



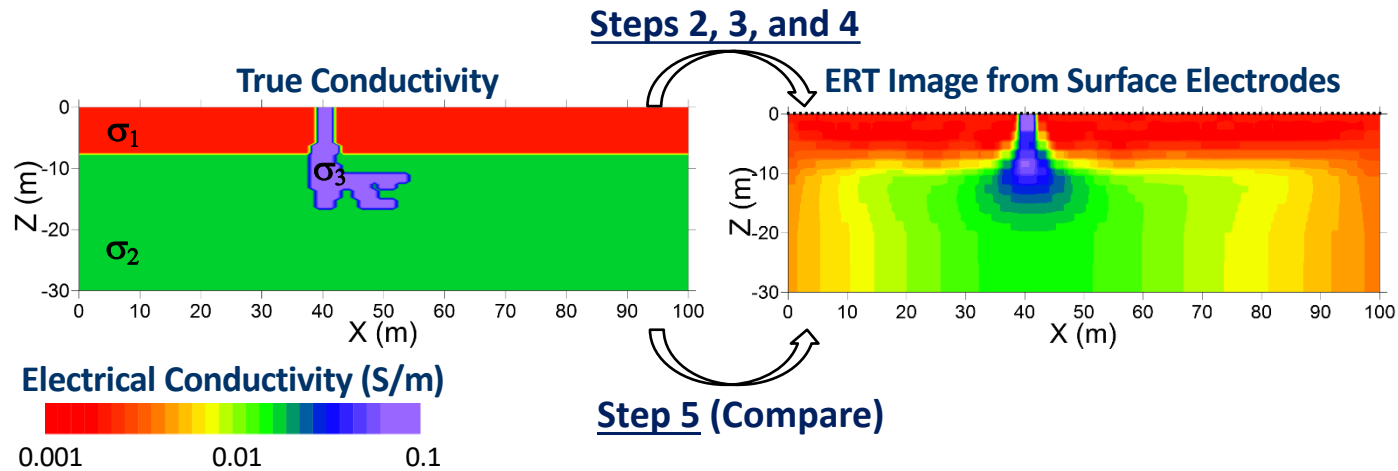
True conductivity estimated from

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



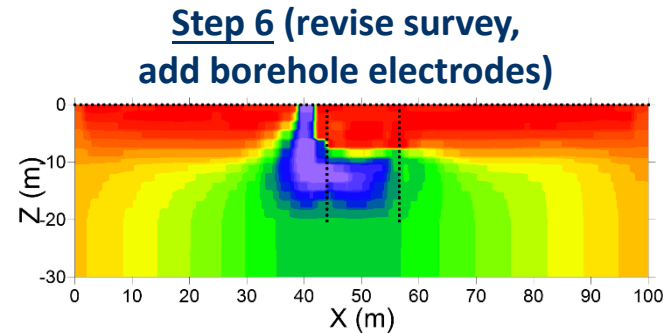
after Terry, N., Day-Lewis, F.D., Robinson, J., Slater, L.D., Halford, K., Binley, A., Lane, J.W., Werkema, D., in press, *The Scenario Evaluator for Electrical Resistivity (SEER) Survey Design Tool, Groundwater*.

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



Step 7: Go/ No-Go Decision

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



after Terry, N., Day-Lewis, F.D., Robinson, J., Slater, L.D., Halford, K., Binley, A., Lane, J.W., Werkema, D., in press, *The Scenario Evaluator for Electrical Resistivity (SEER) Survey Design Tool, Groundwater*.

SUMMARY

- Fractured rock a challenging environment to:
 - Characterize
 - Model
 - Monitor
- Method selection
 - FRGT-MST
- Characterization
 - Structure
 - Major features
- Monitoring
 - Changes in properties
 - Amendment emplacement
 - Remediation effects?
- Approaches
 - Borehole geophysics (more later)
 - Cross hole imaging
- Feasibility studies to mitigate risk of failure (SEER)

