Remote Sensing of Subsurface Bioremediation

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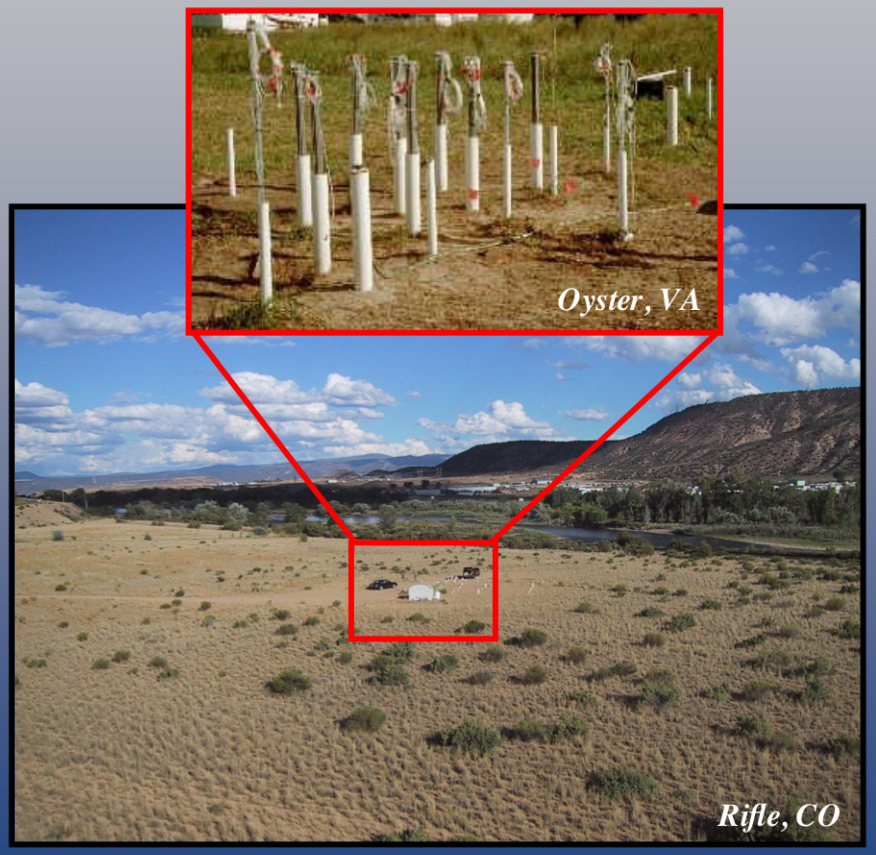
Objective

"Use of non-invasive geophysical methods to monitor the extent and stability of microbial transformations ***over large spatial scales***"

- ***Hypothesis***: microbial processes induce ***changes in mineralogy*** that can be detected using time-lapse geophysical methods

- ***Challenges***:
  - Competing metabolic processes
  - Mineral phase transformations
  - Non-contaminant mineral effects



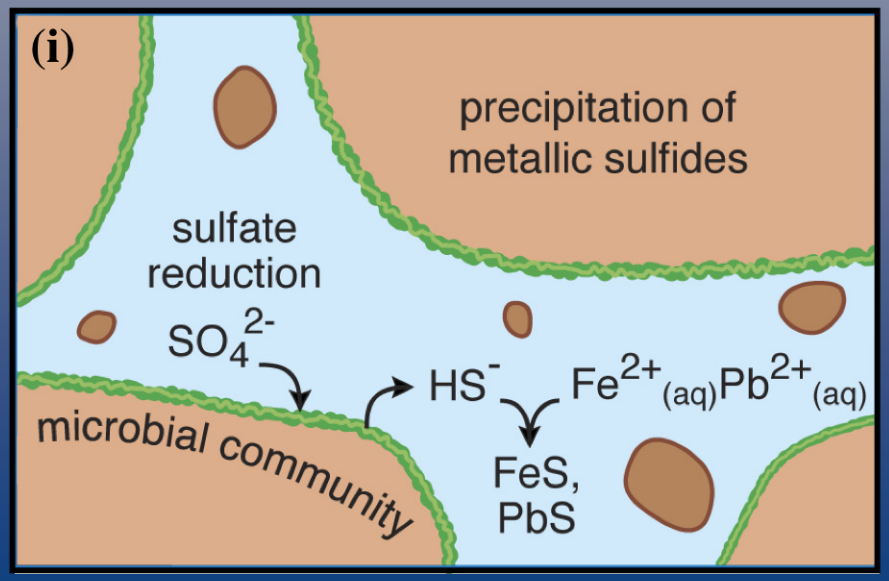
EMSP
Environmental Management Science Program

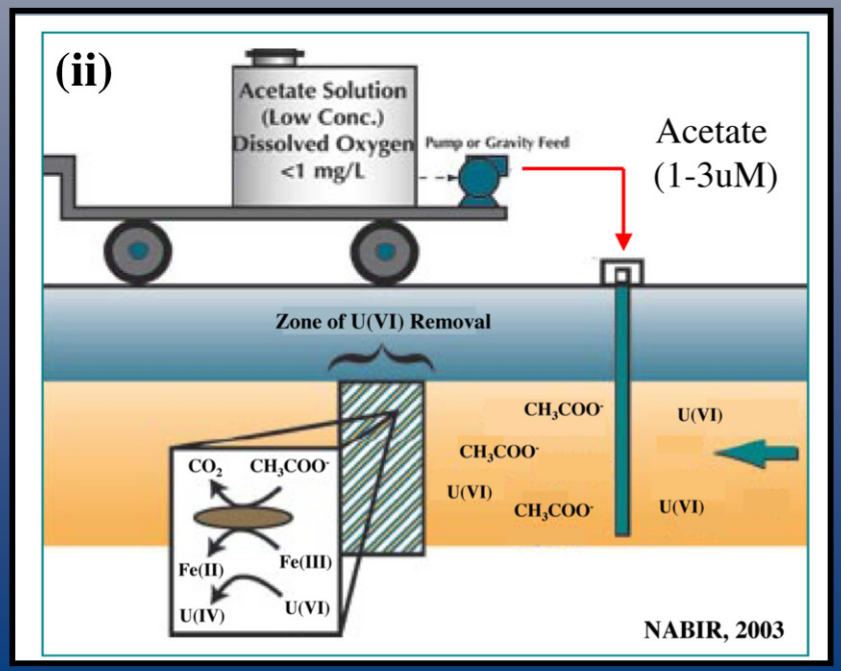
Stimulated Biomineralization

- Use of indigenous microorganisms to remediate toxic metals and radionuclides in groundwater
  - Delivery of substrates necessary to promote desired metabolism
  - Conversion from ***soluble*** to ***insoluble*** forms:

    (i) $Pb^{2+}(aq) + H_2S \rightarrow PbS(s) + 2H^+$

    (ii) $U^{6+}, Cr^{6+}(aq), \rightarrow UO_2, Cr_2O_3(s)$

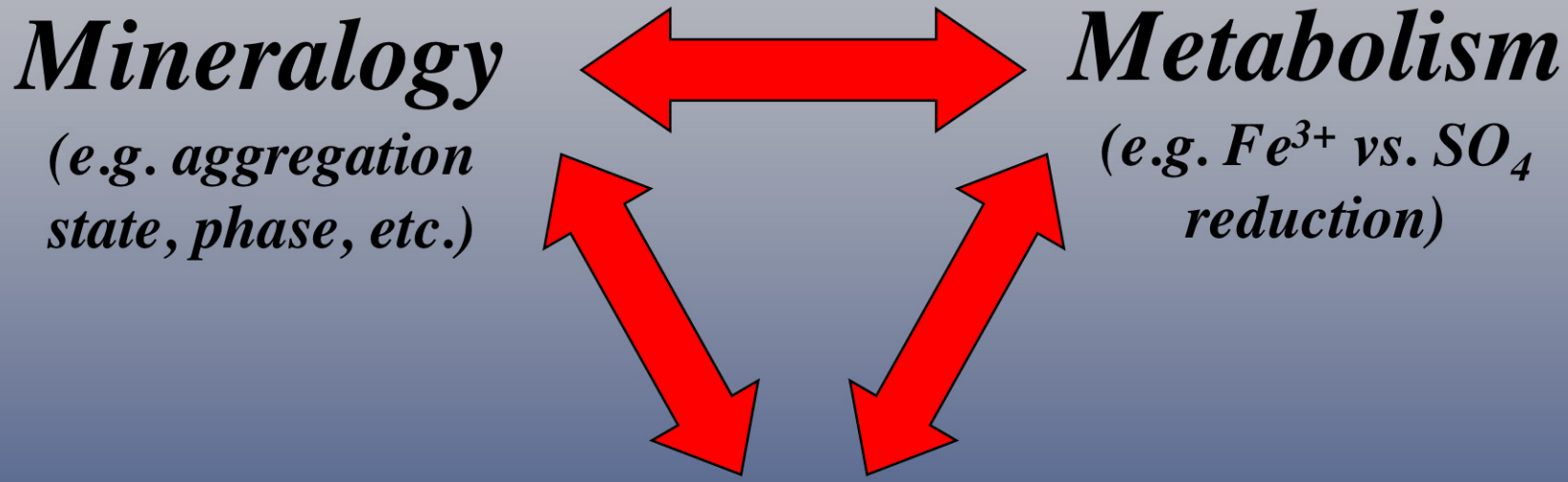




Geophysical Monitoring:

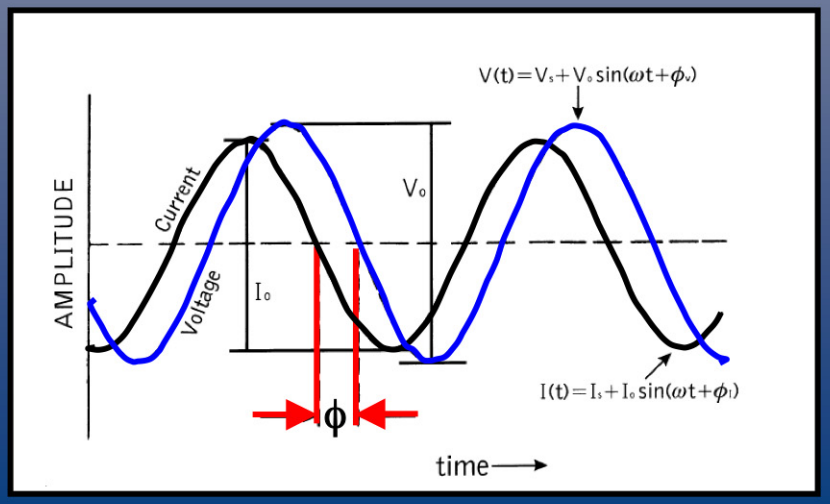
Possibilities and Pitfalls

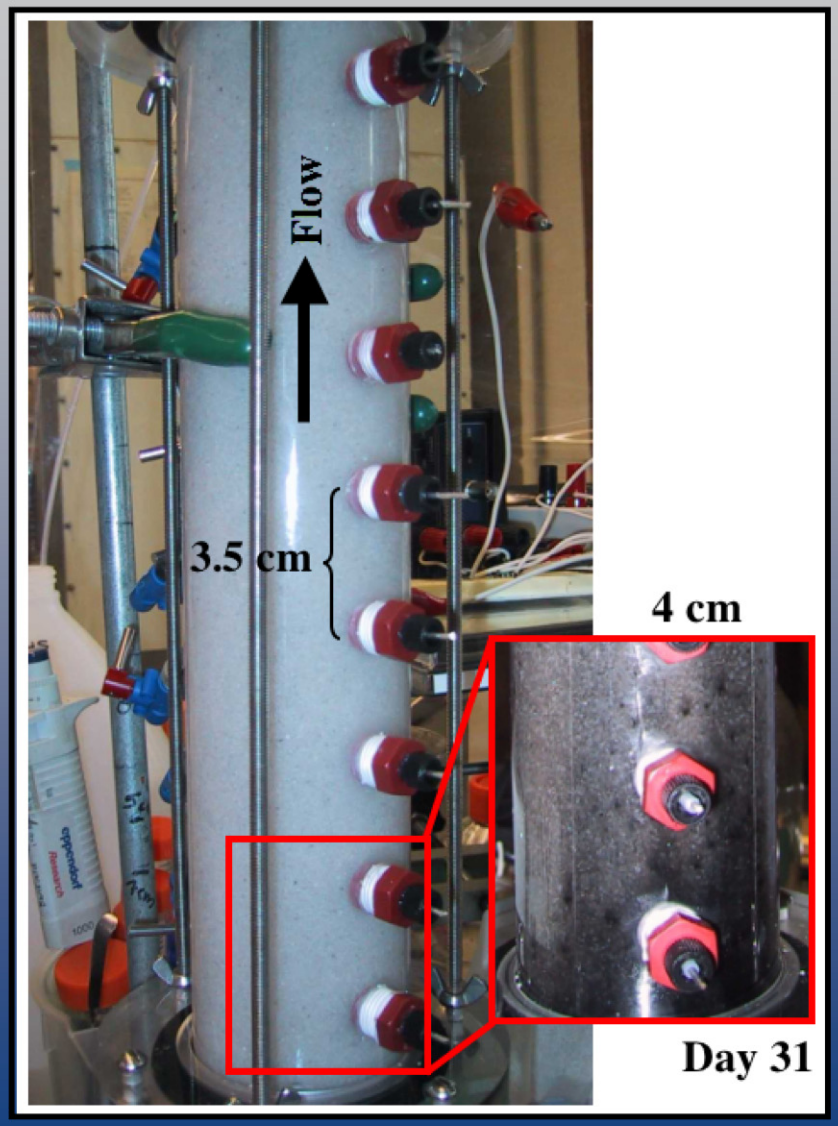
Successful interpretation requires an understanding of…



Lab Measurements of Microbe-Induced ZnS and FeS Precipitation

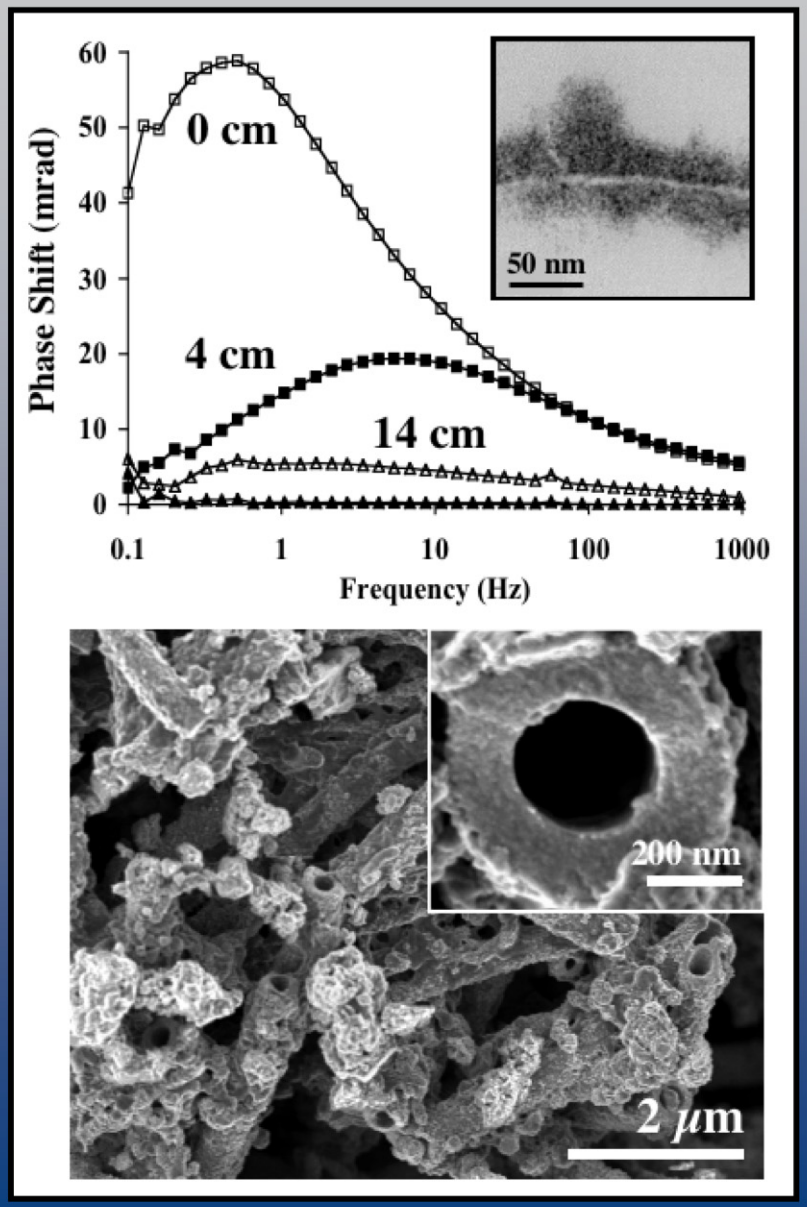
- ***Spectral Induced Polarization***
  - Low frequency (0.1-1000 Hz) electrical measurements
  - Measure ϕ and $|Z|$
  - Correlate changes with:
    - Active SRB metabolism
    - ZnS, FeS precipitates
    - ***Aggregation state, texture, and composition of precipitates***



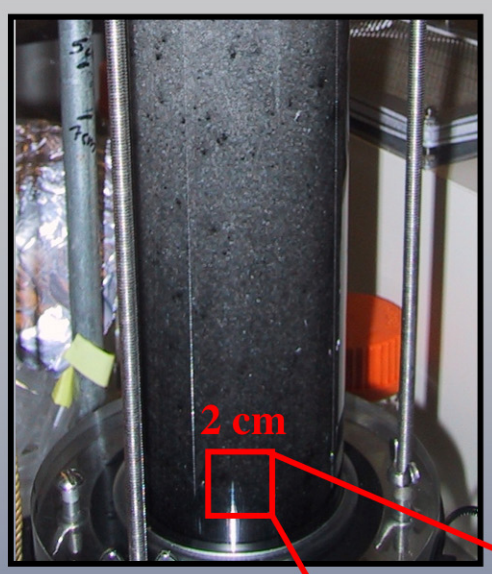


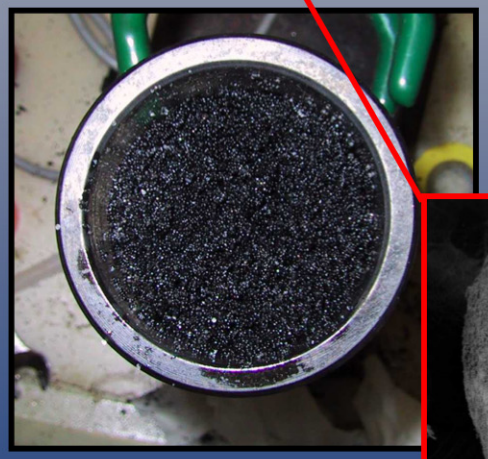
Lab Measurements of Microbe-Induced ZnS and FeS Precipitation

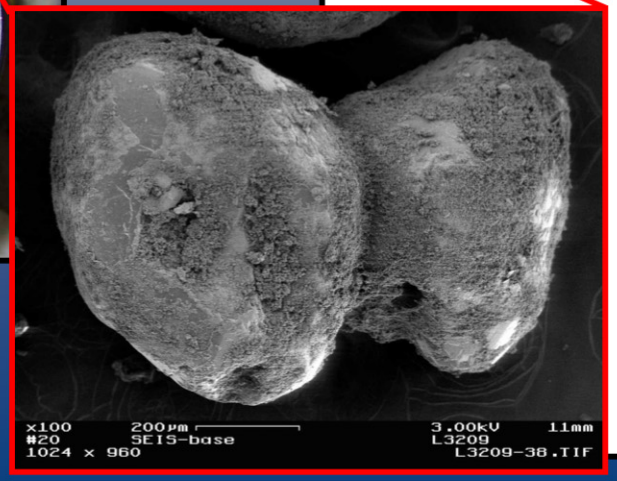
- ***Induced Polarization Results***
  - Phase shifts are spatially variable (*chemotaxis*)
  - Max. Phase Shift: ~60 mrad
    - ~2% (w/w) FeS/ZnS
  - ***Characteristic IP signature for sulfide precipitates***
    - ***Increasing phase response***
    - ***Diagnostic of sulfate-reduction***



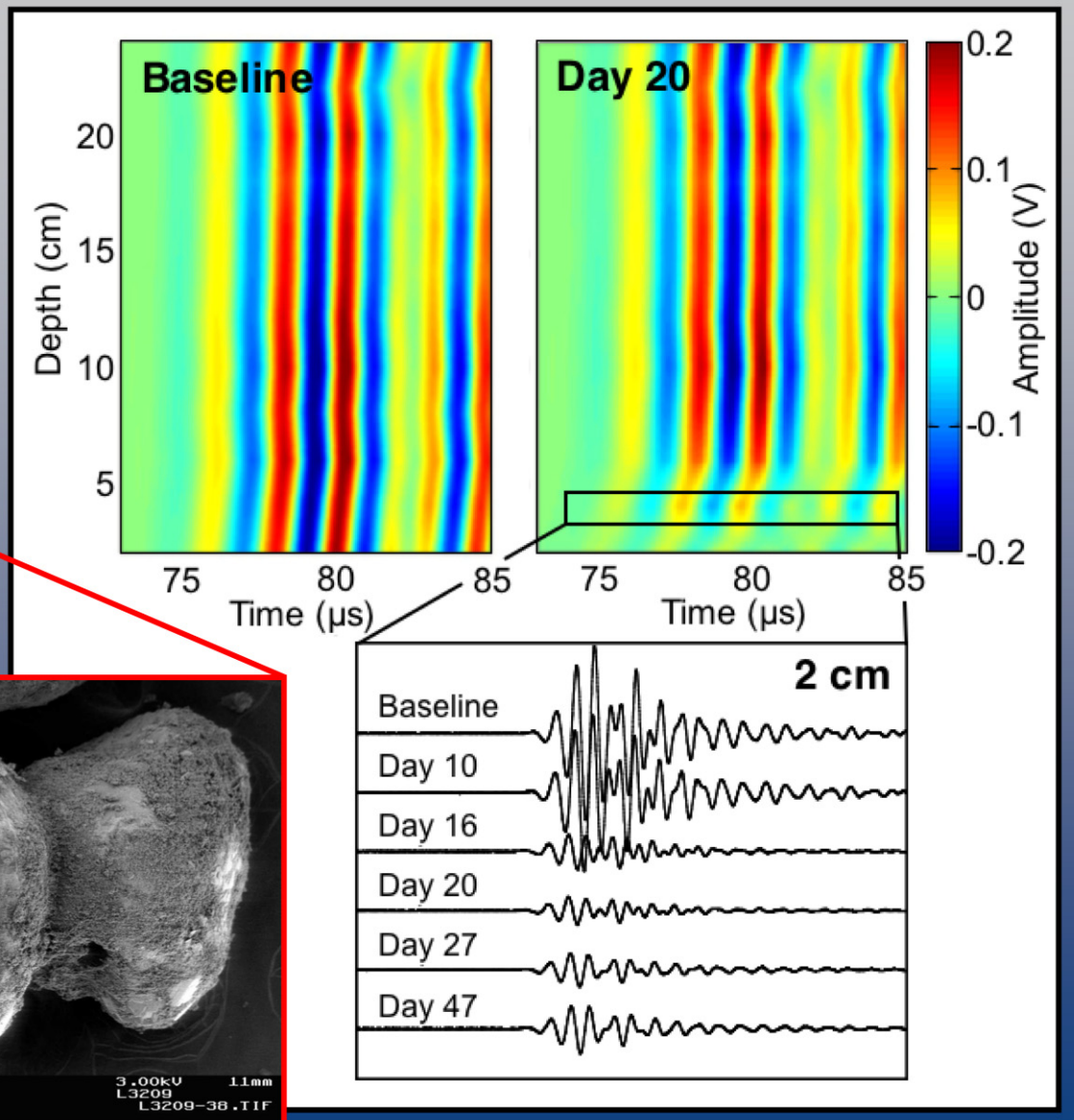
Lab Measurements of Microbe-Induced ZnS and FeS Precipitation



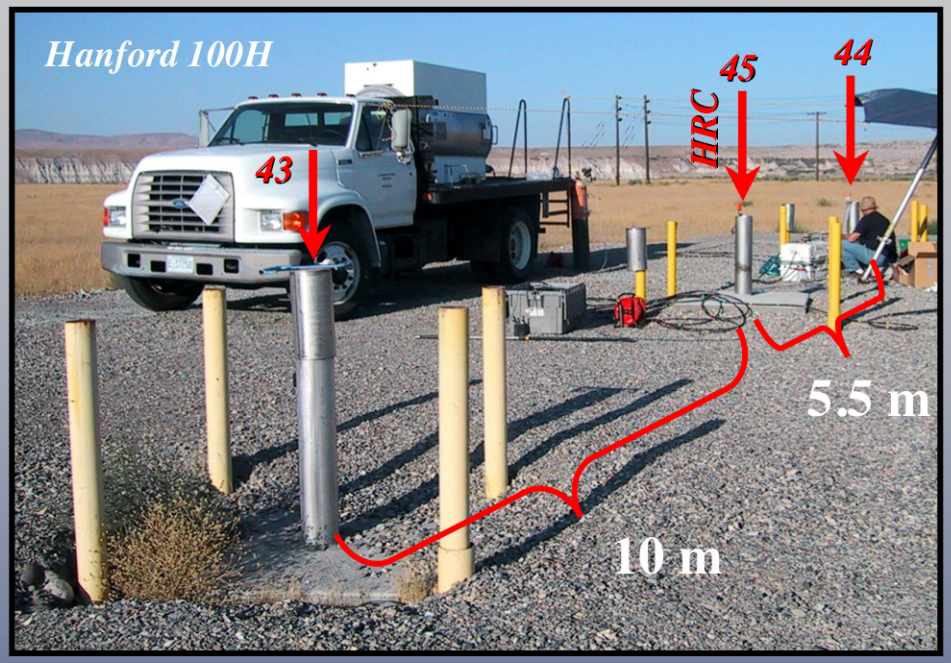


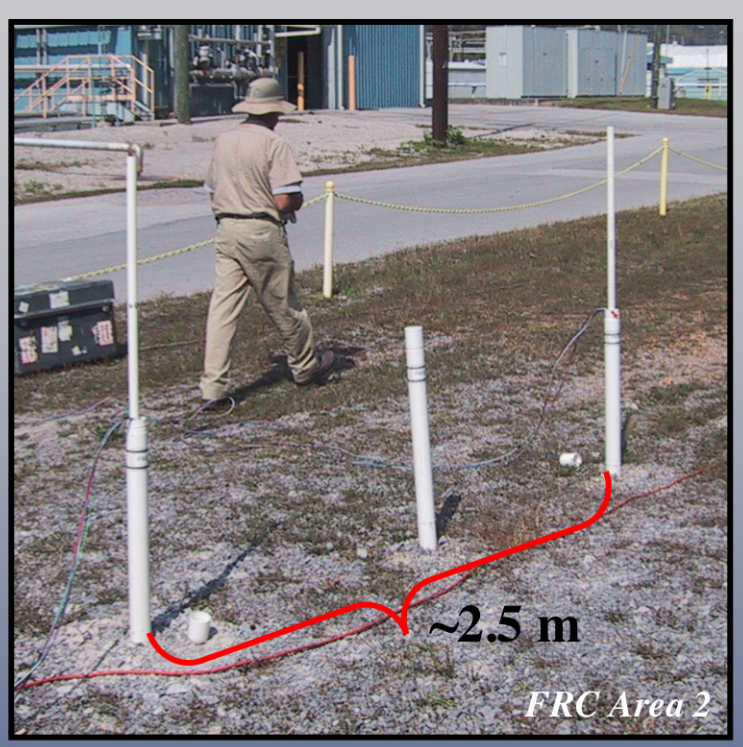


Acoustic Wave Monitoring



Field Experiments:

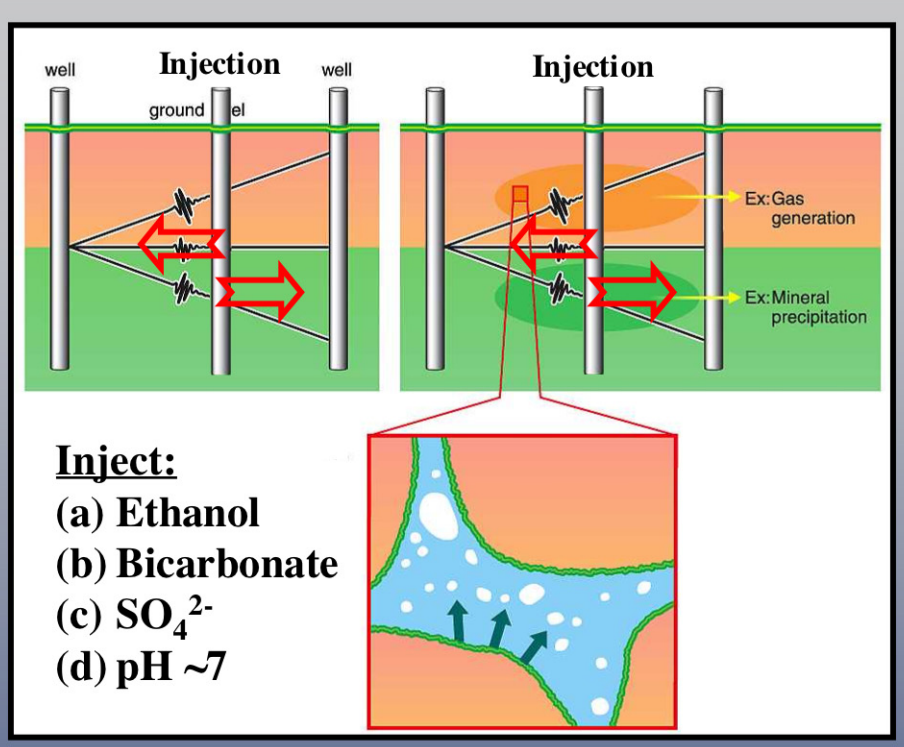


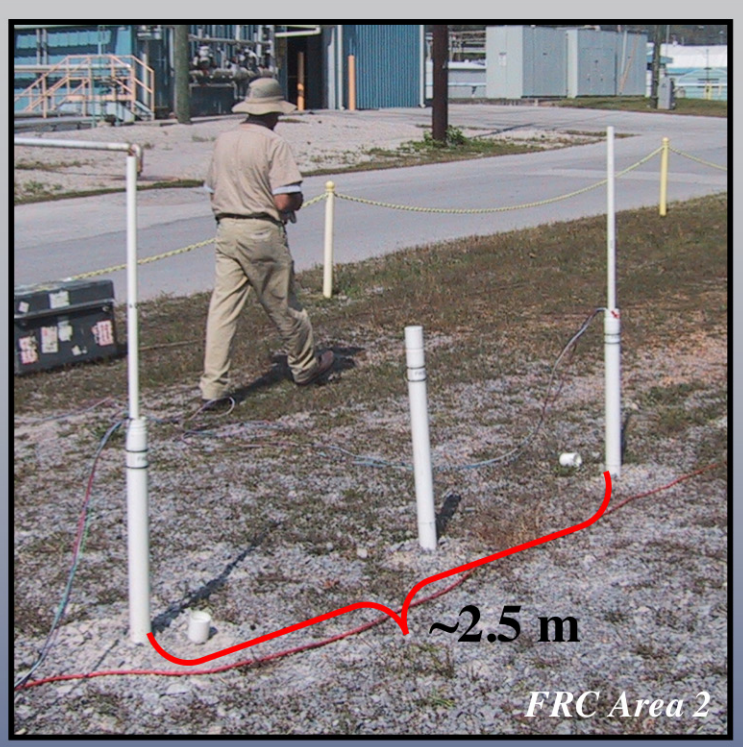


Geophysical Characterization and Monitoring:

- FRC (Area 1), Hanford 100H, Old Rifle UMTRA
- Radar, Seismic, Electrical methods
  - Highlight structural features
  - Monitor changes in aquifer properties:
    - Fluid conductivity, gases, and mineral precipitates
    - Asses spatiotemporal redox state

Field Monitoring: Push-Pull Testing at the FRC, TN

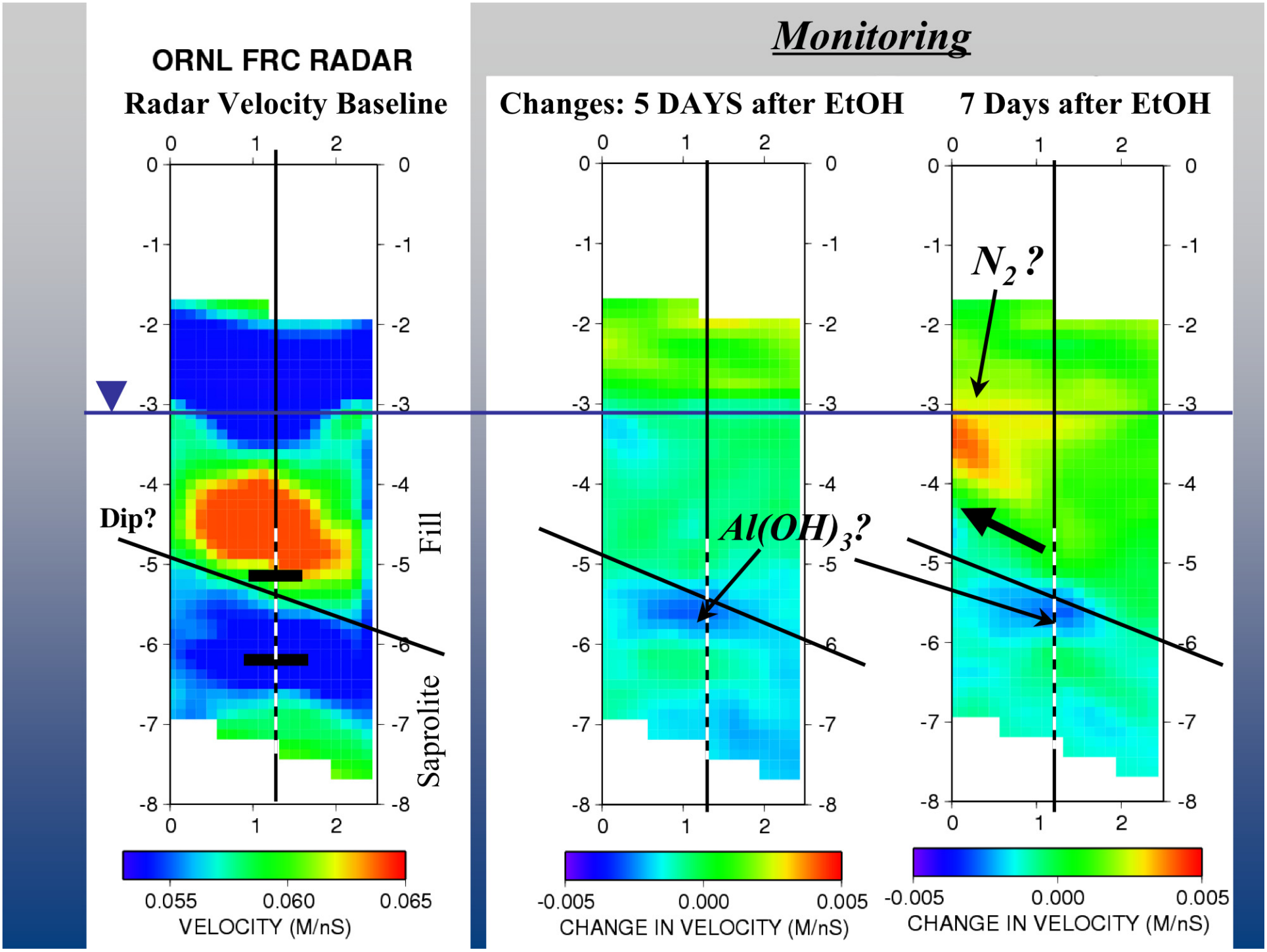




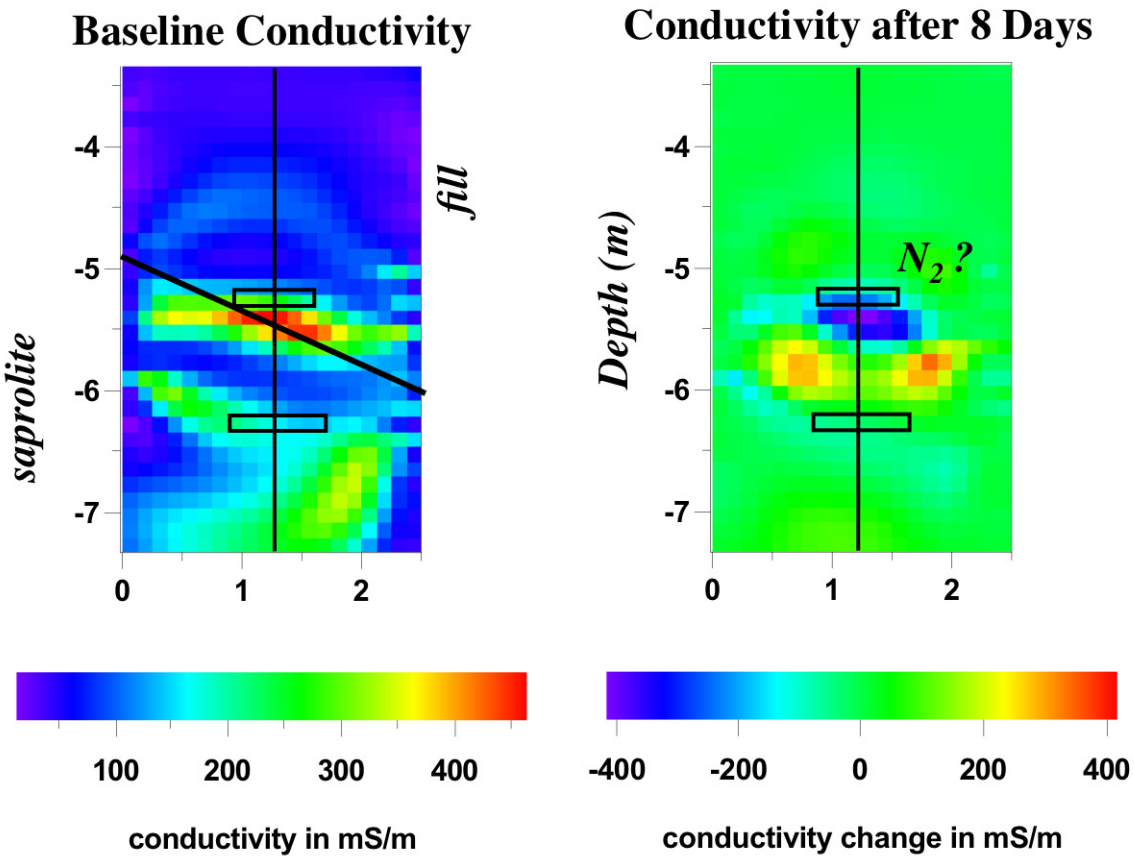
Geophysical Characterization and Monitoring:

- Cross-well Radar, Seismic, Resistivity
  - Highlight structural features
    - saprolite/fill boundary, fractures
  - Monitor changes in aquifer properties:
    - Fluid conductivity, gases, and mineral precipitates

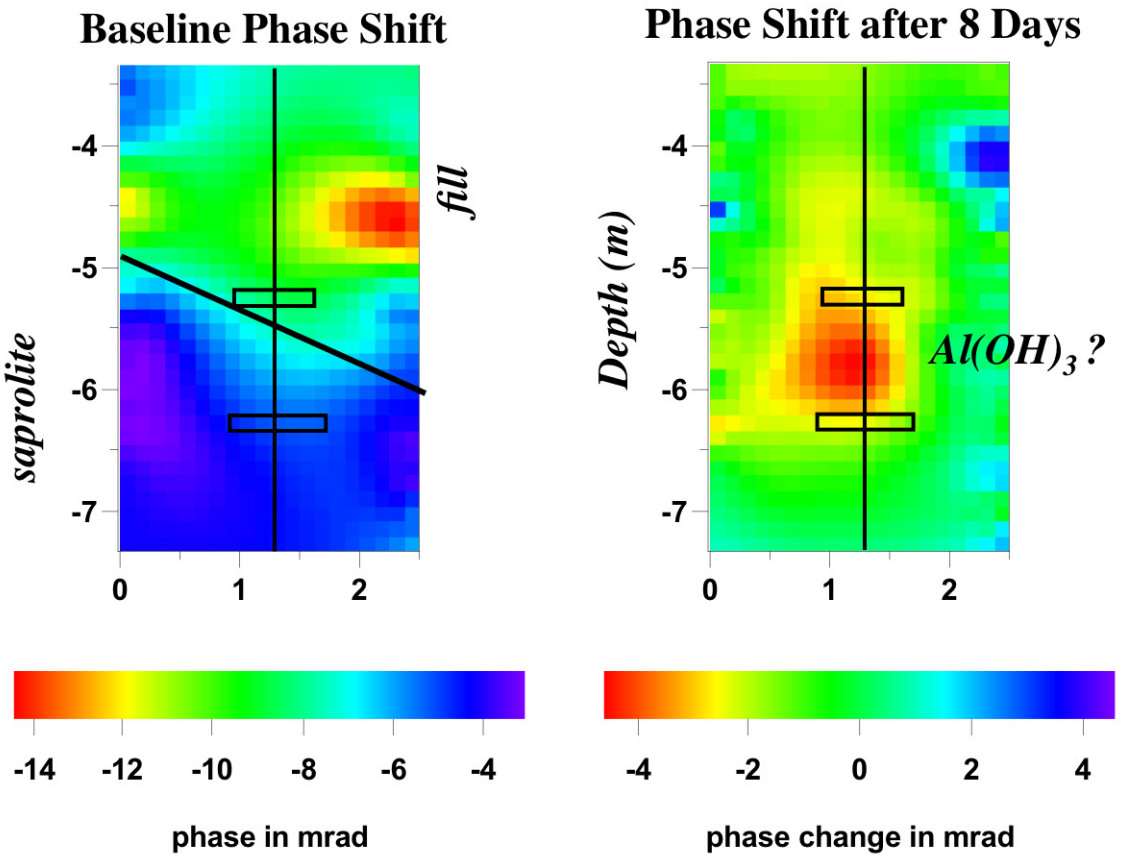
Monitoring


ORNL FRC RADAR
Radar Velocity Baseline
Changes: 5 DAYS after EtOH
7 Days after EtOH
Dip?
Fill
Saprolite
$Al(OH)_3$?
N_2 ?
0.055
0.060
0.065
VELOCITY (M/nS)
-0.005
0.000
0.005
CHANGE IN VELOCITY (M/nS)
-0.005
0.000
0.005
CHANGE IN VELOCITY (M/nS)

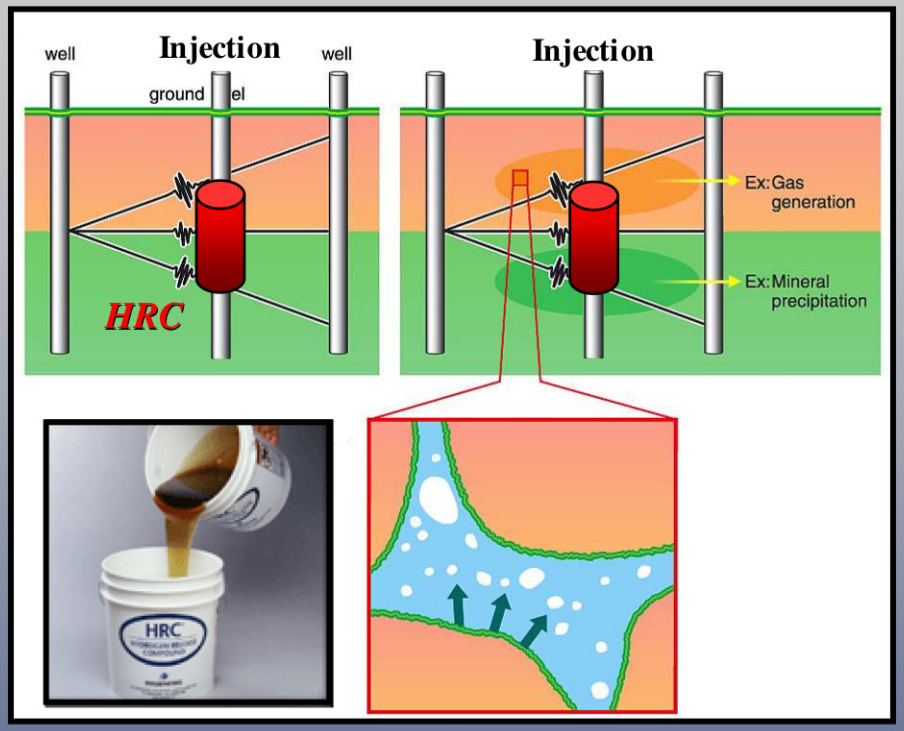
ERT Characterization & Monitoring

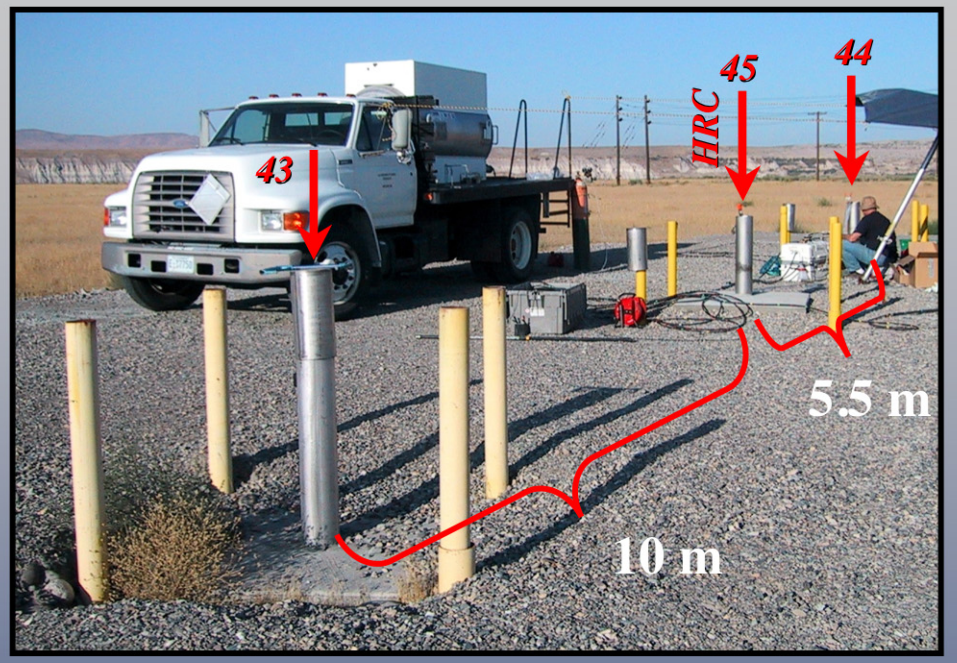


ERT Characterization & Monitoring



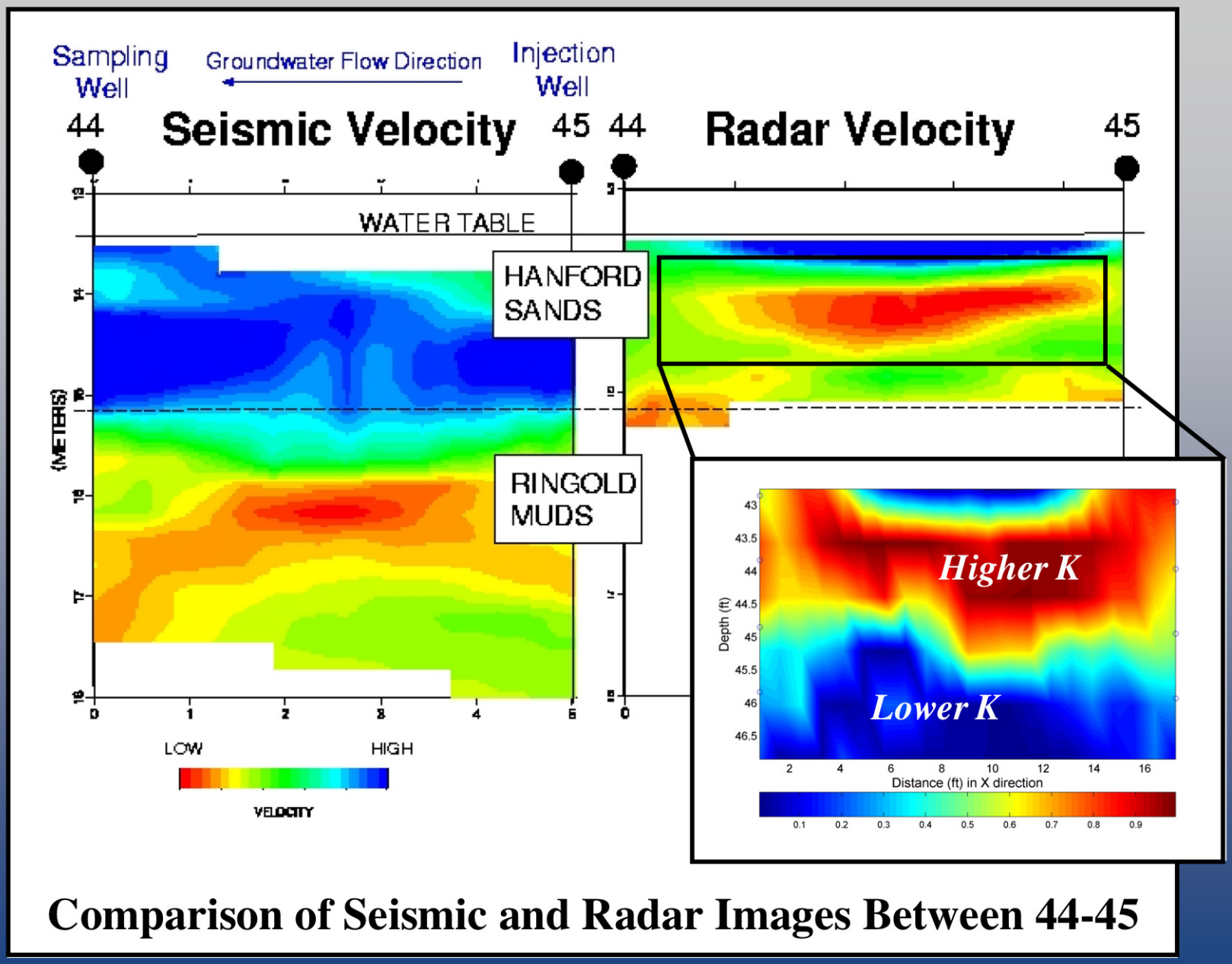
Field Monitoring: HRC Injection at Hanford 100H, WA





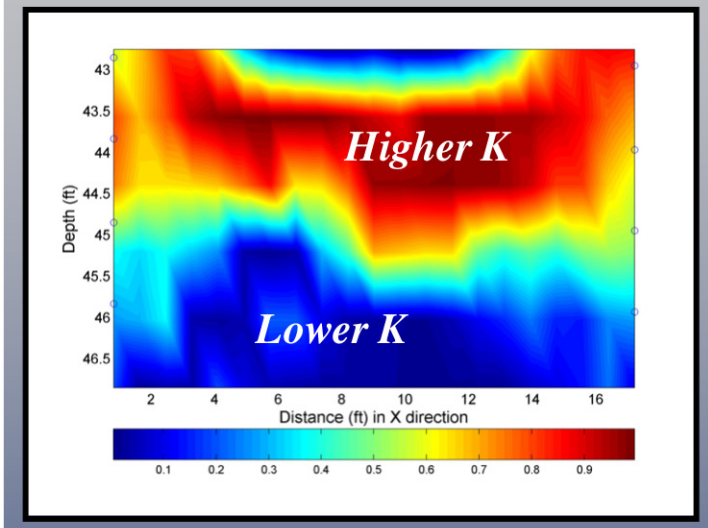
Geophysical Characterization and Monitoring:

- Borehole Radar and Seismic
  - Highlight structural features
    - High permeability sands
  - Monitor distribution of HRC (organic carbon amendment)



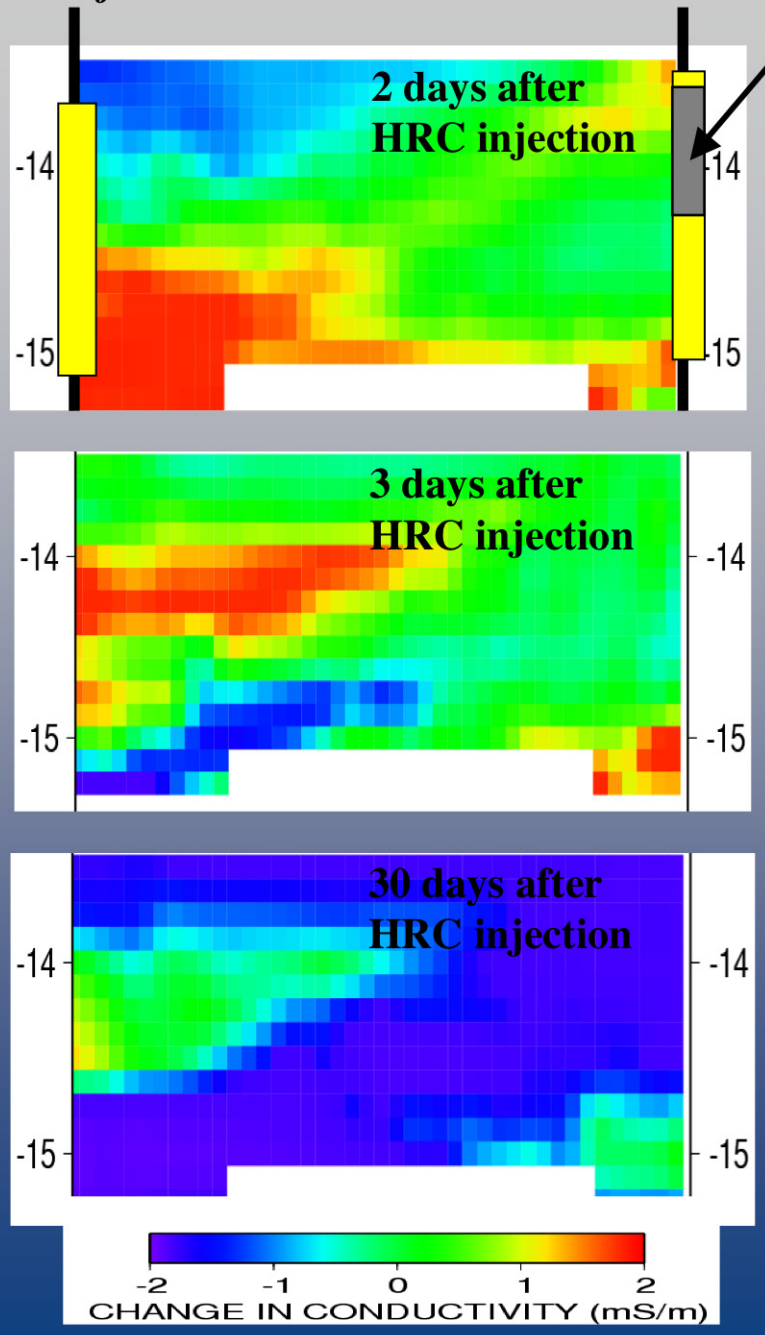
Comparison of Seismic and Radar Images Between 44-45

Once pumping effects reach injection well, HRC is mobilized into high perm zone



HRC Injection

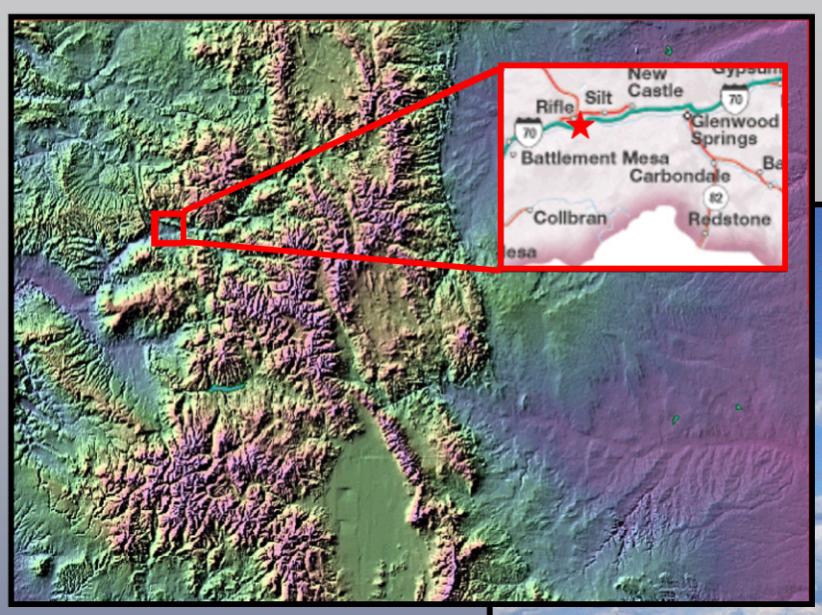
Pump location



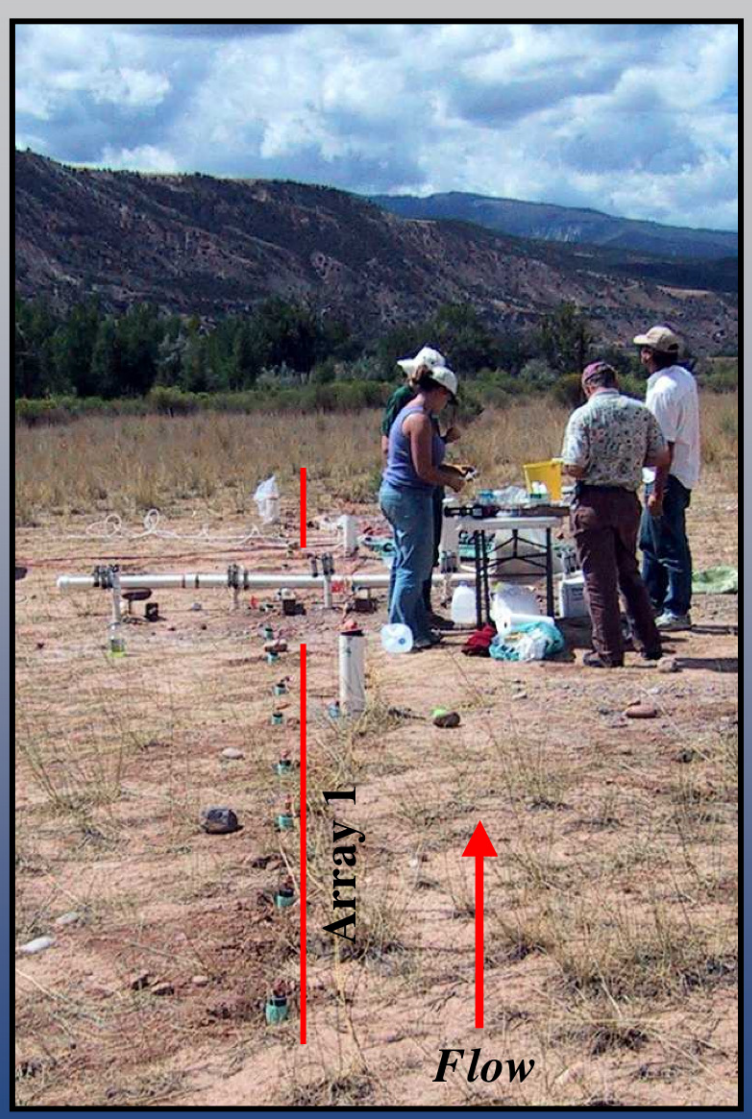
Change in Estimated Electrical Conductivity

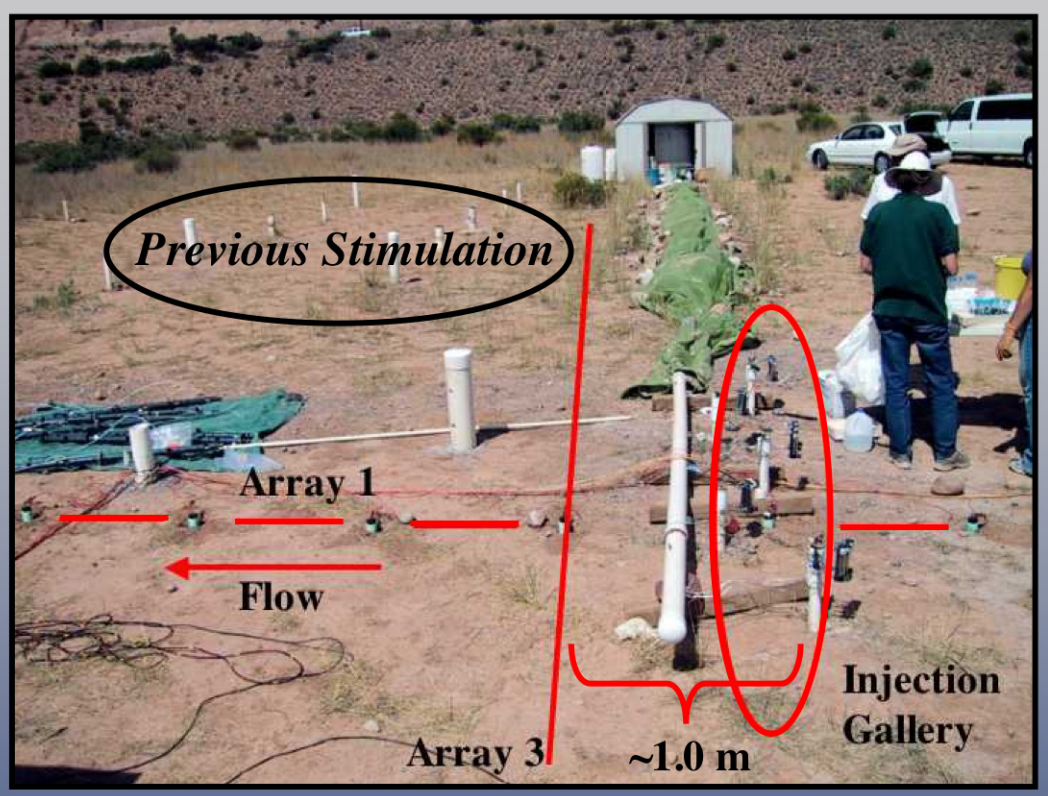
Groundwater Flow

Field Monitoring: U(VI) Remediation at Old Rifle Site, CO



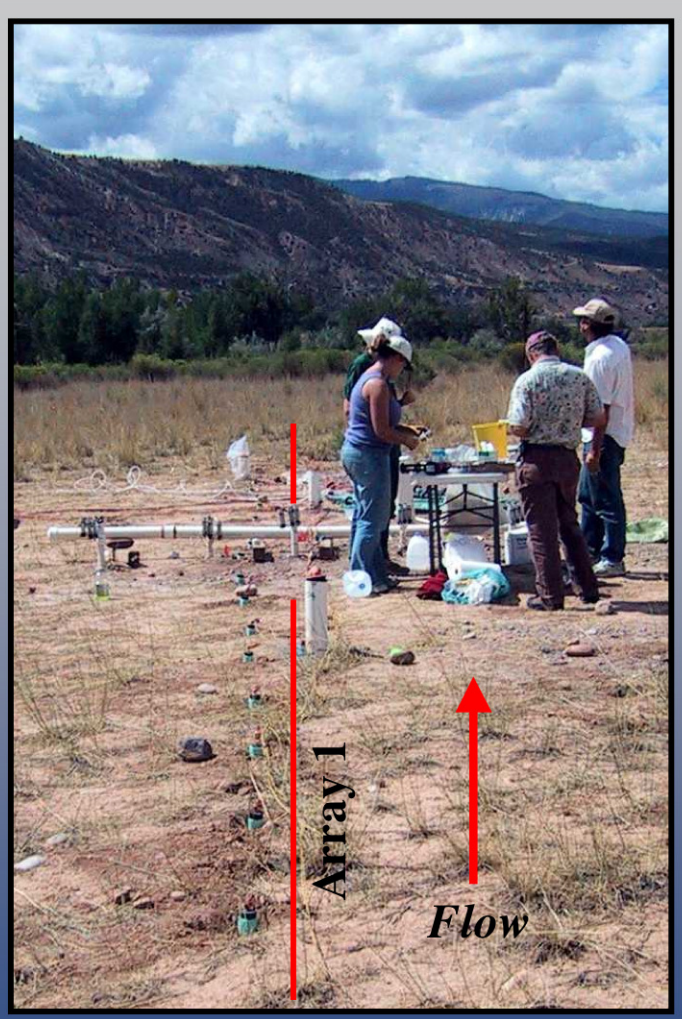
Field Monitoring: U(VI) Remediation at Old Rifle Site, CO

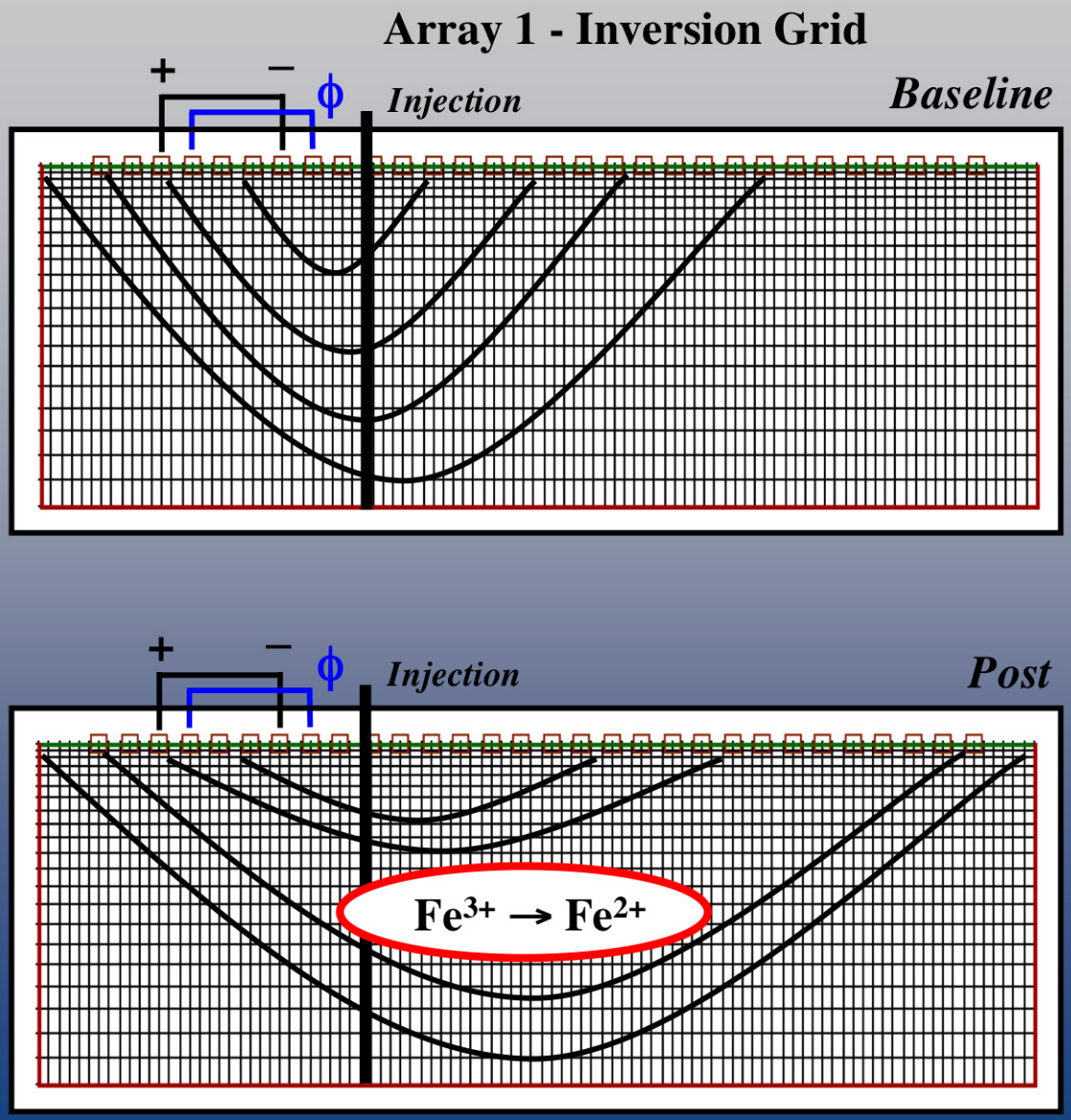




- ***Surface Spectral IP Survey:***
  - ***0.125, 1, and 8 Hz***
  - Electrode spacing: 1.0 m
  - Dipole-Dipole survey w/ 4.0 m dipole length
  - $Cu/CuSO_4$ electrodes

Field Monitoring: U(VI) Remediation at Old Rifle Site, CO

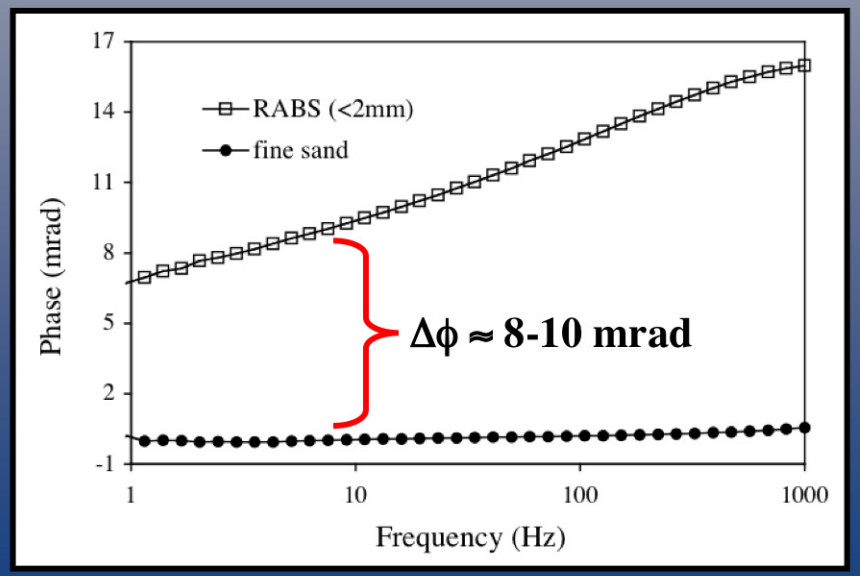


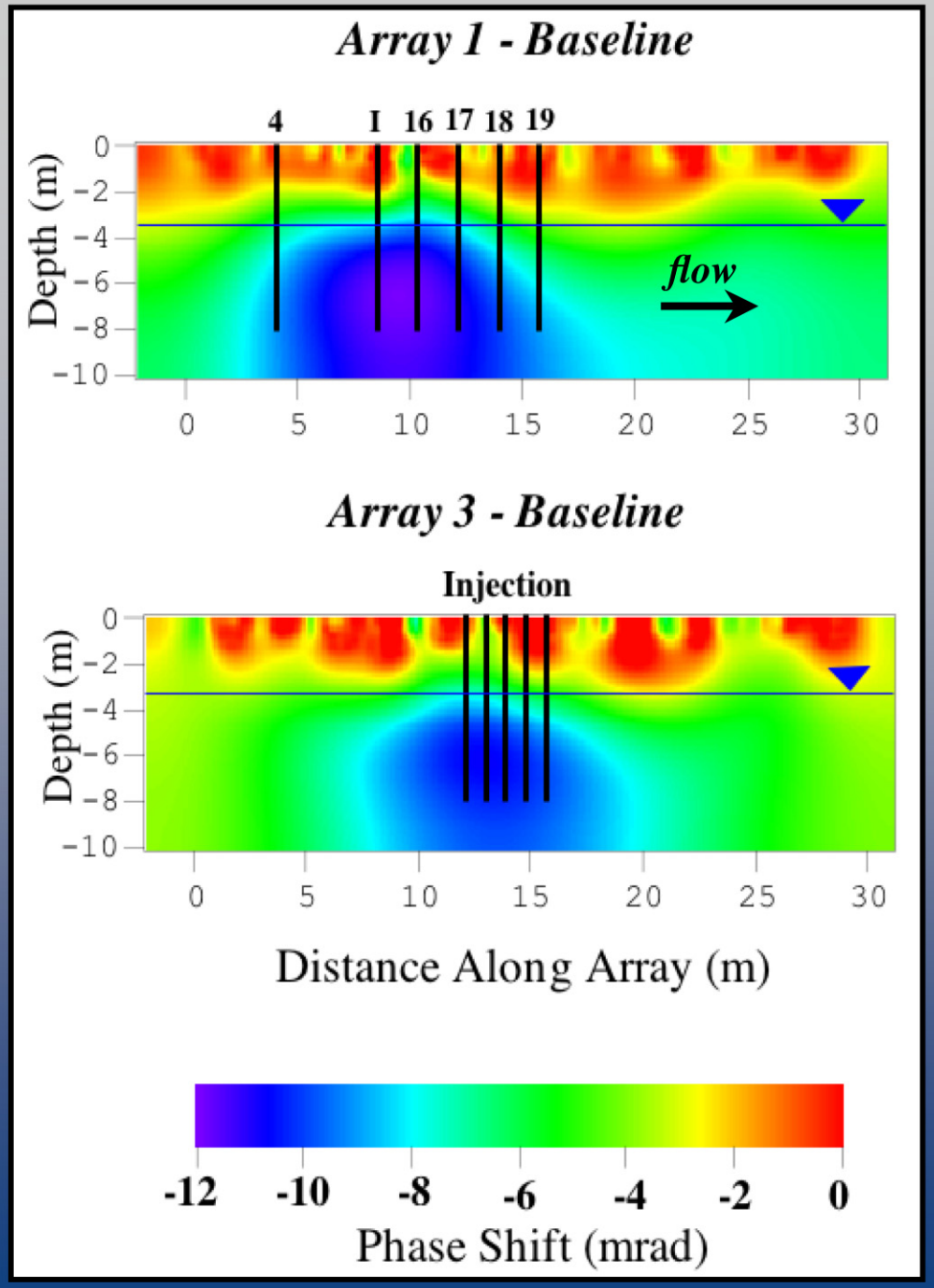


Baseline Results

- ***Pronounced phase anomaly***
  - Correlates with injection gallery
  - Phase shifts typical of clays
  - Clay-sized fraction likely dispersed during rotary sonic drilling
  - ***Bioavailable pool of Fe(III)?***
    - ***XRD analysis: vermiculite***

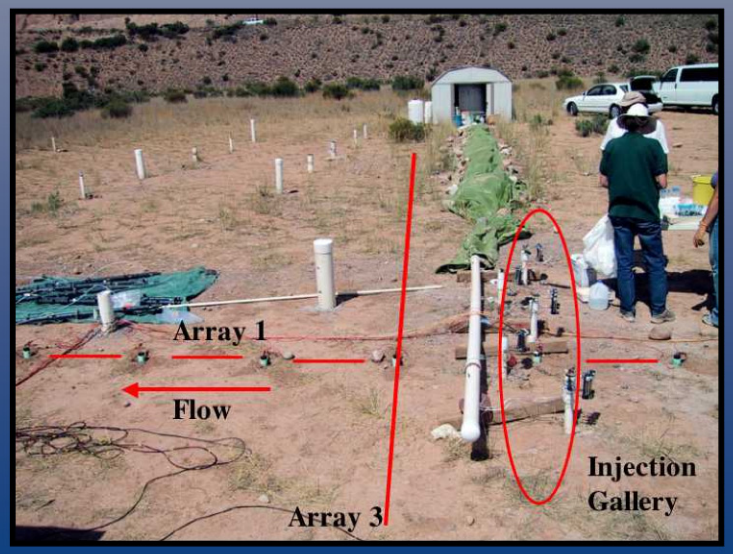
RABS Screened < 2 mm

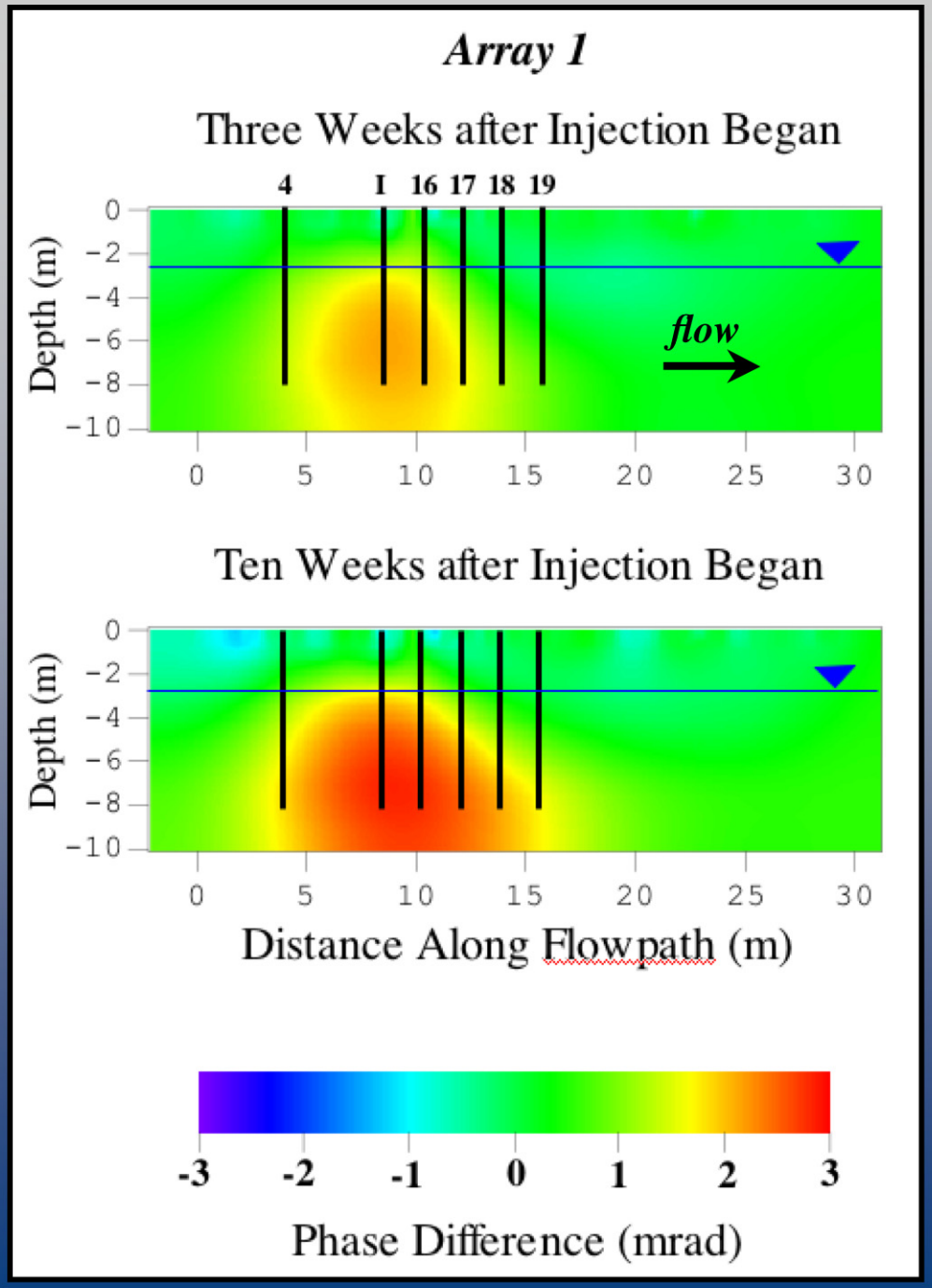




Array 1: Parallel to flow

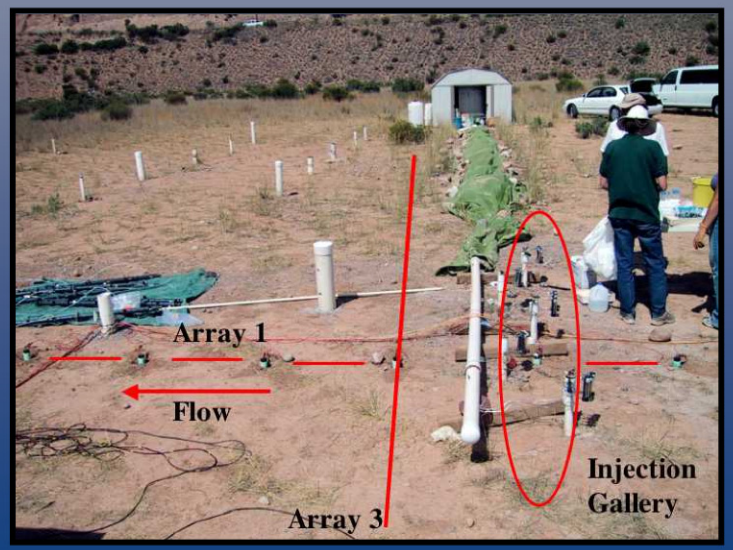
- ***Time-lapse IP results* (0.125 Hz):**
  - Phase shifts ***decrease*** w/time
  - Changes occur:
    - ***Below water table***
    - ***Near injection wells (I)***
      - *Some upgradient effects (diffusion, permeability reduction)*

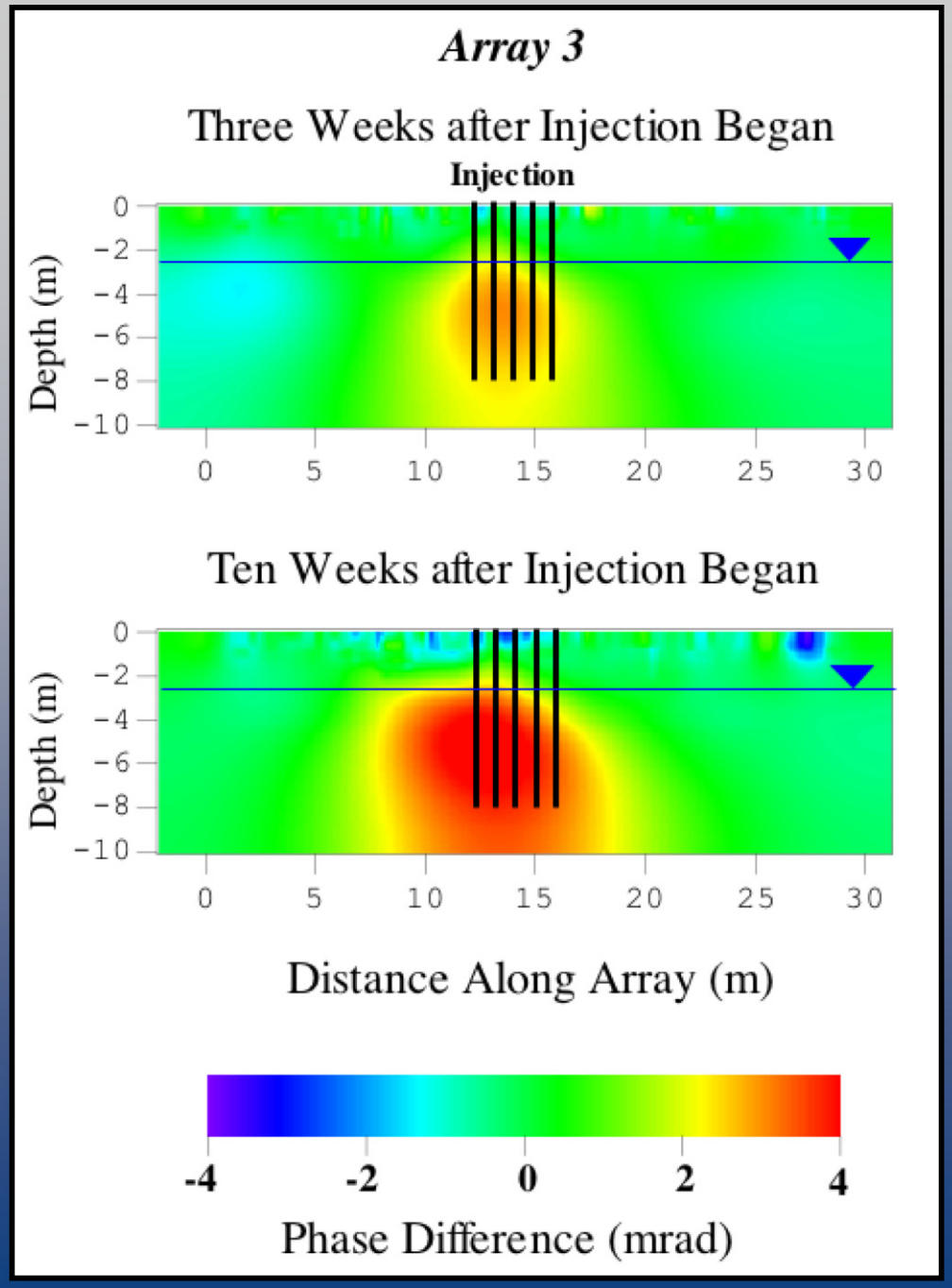




Array 3: Perpendicular to flow

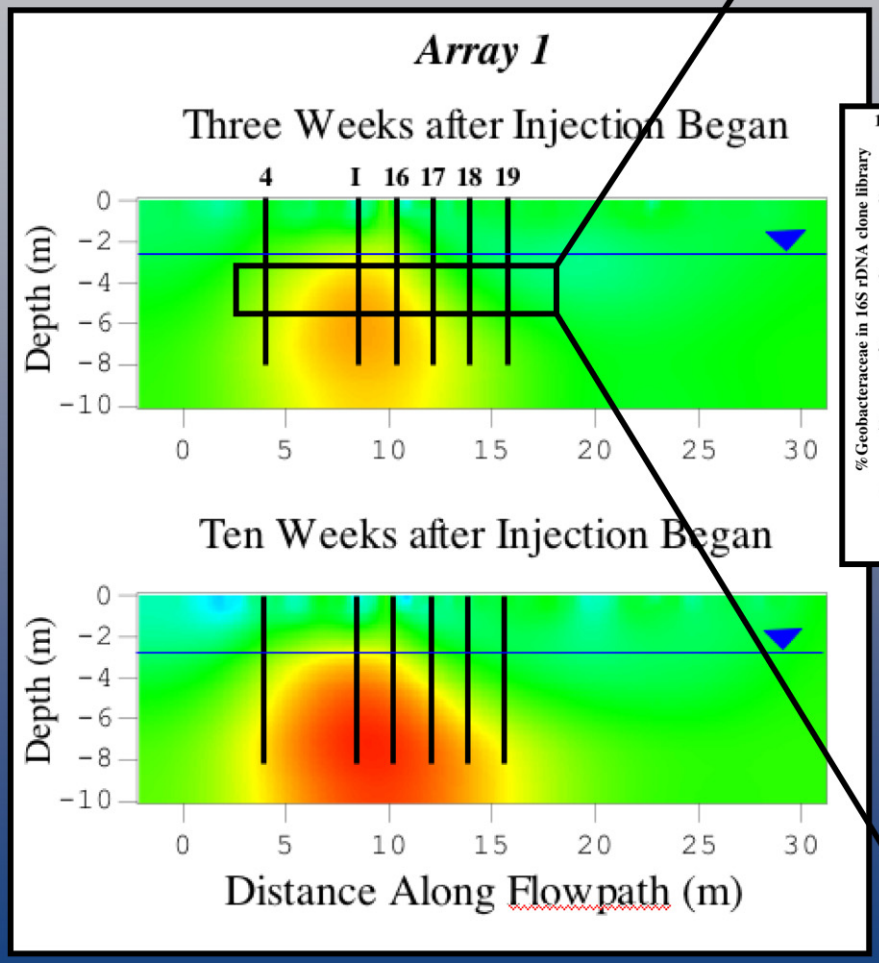
- ***Time-lapse IP results* (0.125 Hz):**
  - Phase shifts ***decrease*** w/time
  - Changes occur:
    - ***Below water table***
    - ***Near injection wells (I)***
      - *Lateral effects*

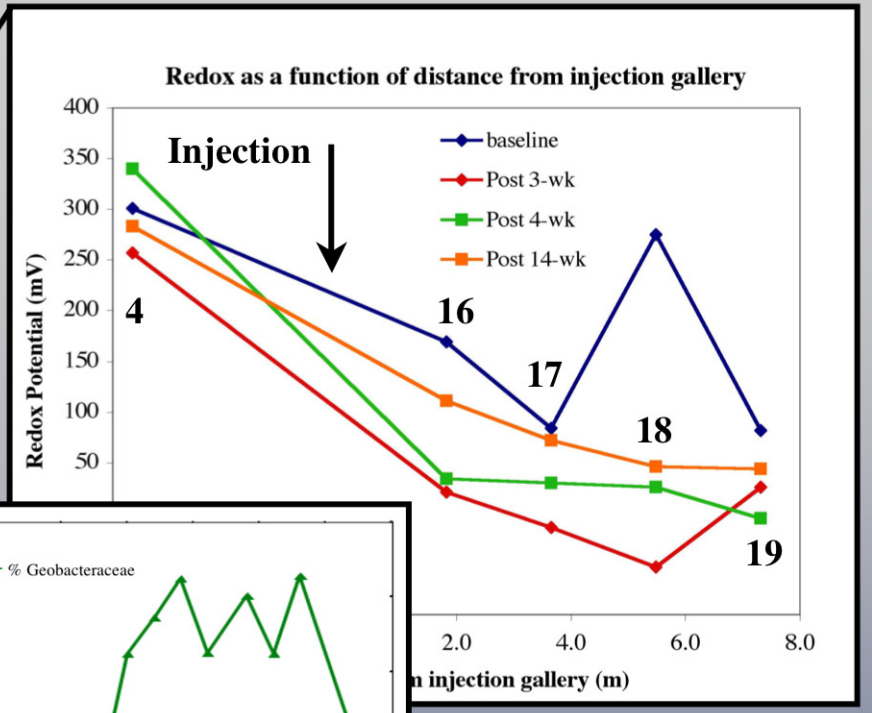


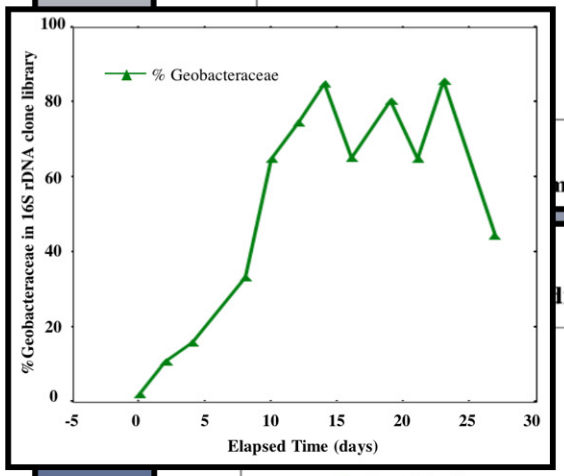


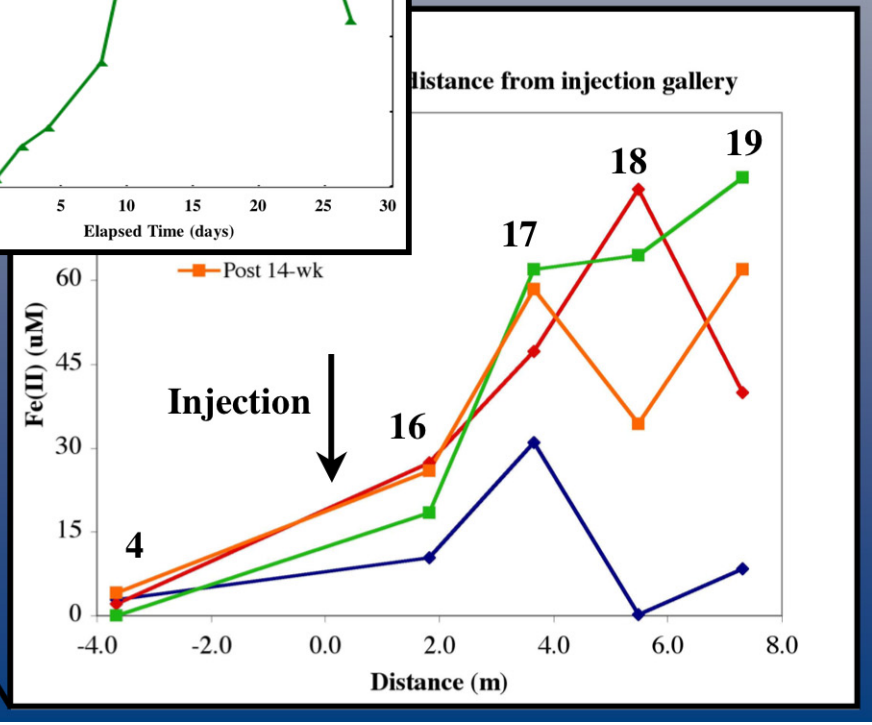
Geochemical Results

- ***Stimulated Fe(III)-reduction:***
  - Decreasing Redox potentials
  - Increasing Fe^{2+} concentrations
  - Increasing FeRB (*Geobacteraceae*)



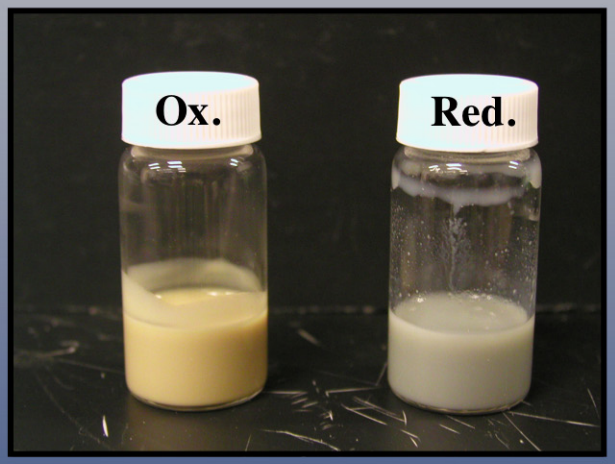




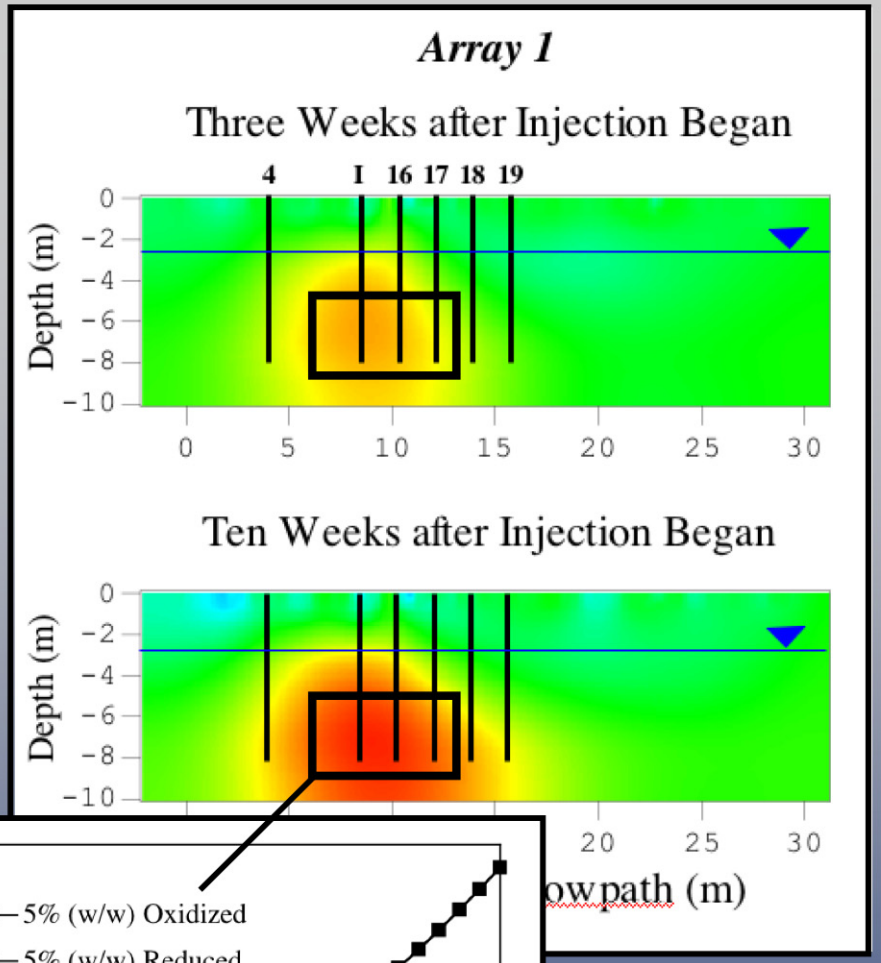


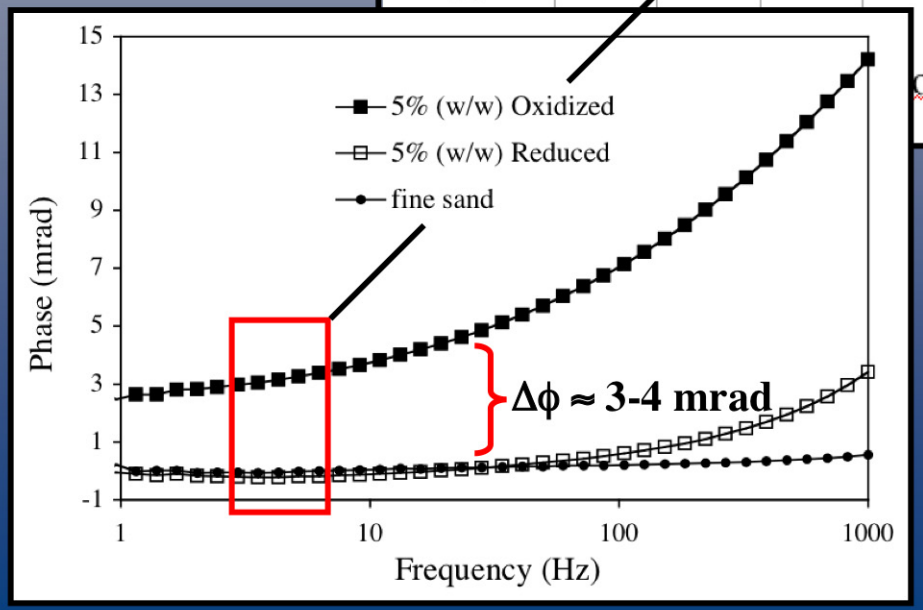
Proposed IP Mechanism

- ***Stimulated Fe-reduction:***
  - Mineralogical change/conversion
    - ***Fe(III)-clays → Fe(II)-clays***
    - Dissolution, clay collapse and decreasing surface area [*Kostka et al., 1999, 2002*]



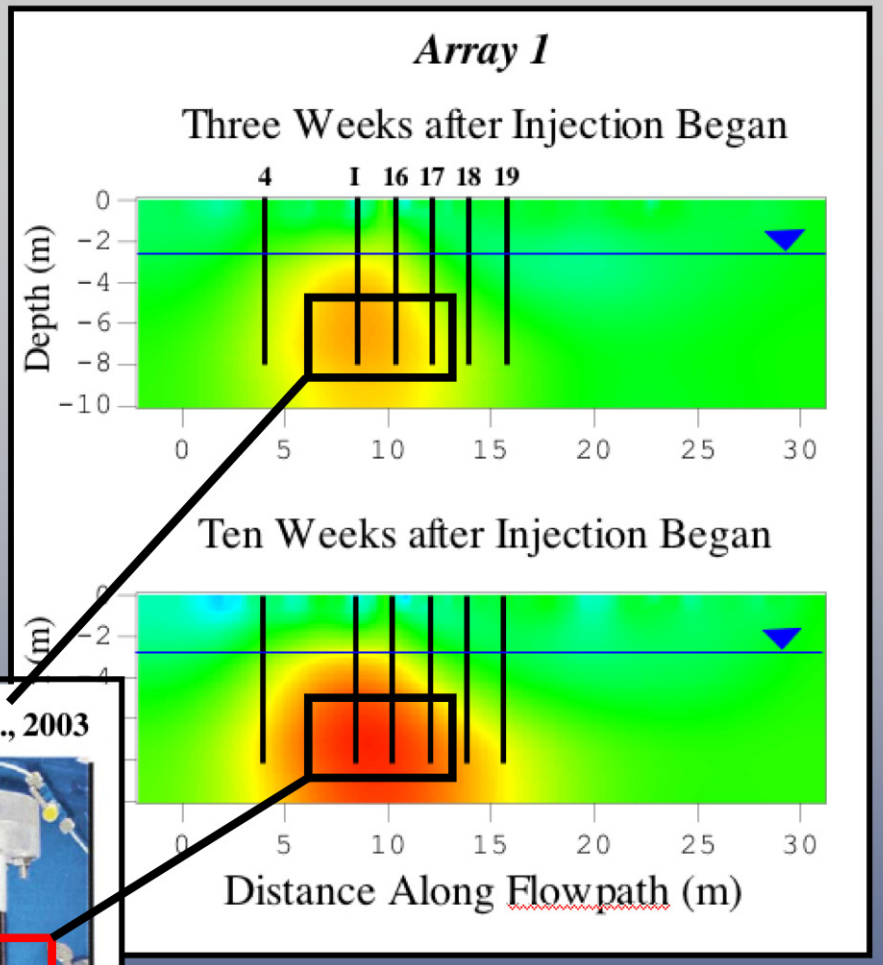
Panther Creek Bentonite
[Jim Amonette, EMSL]

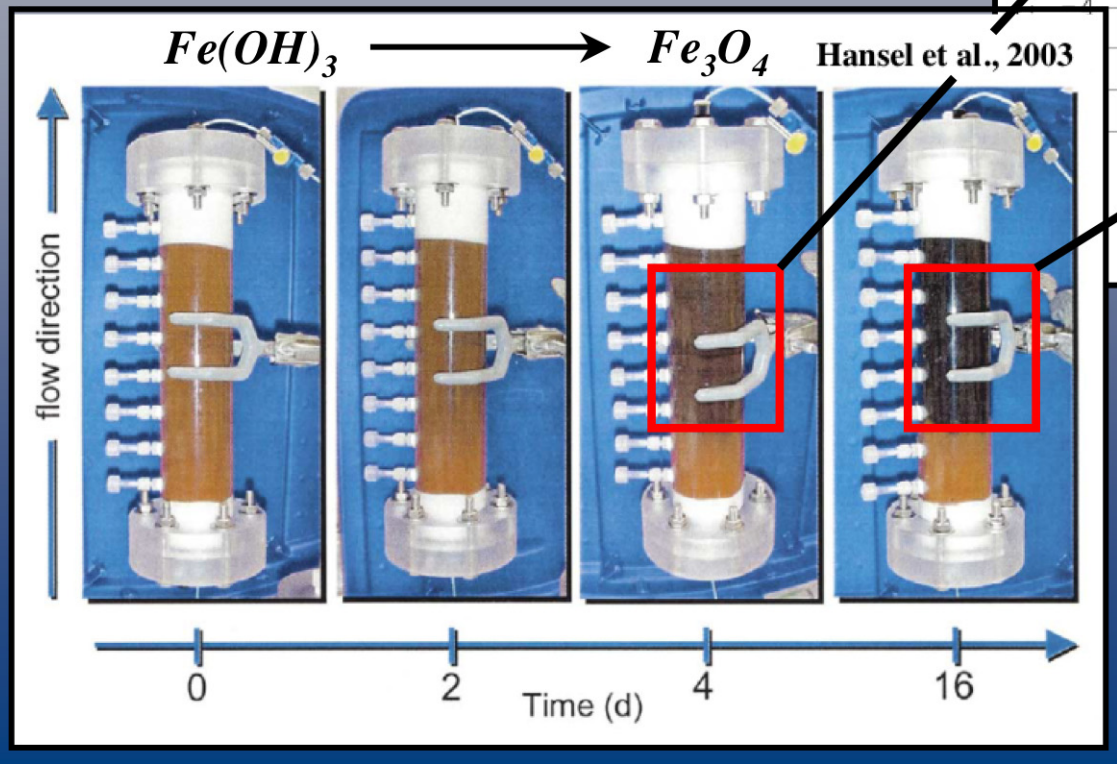




Proposed IP Mechanism

- ***Stimulated Fe-reduction:***
  - Mineralogical changes
    - $Fe(OH)_3 \rightarrow FeOOH \rightarrow Fe_3O_4$
    - Dissolution and decreasing surface area
    - Creation of less polarizable phases (e.g. magnetite)

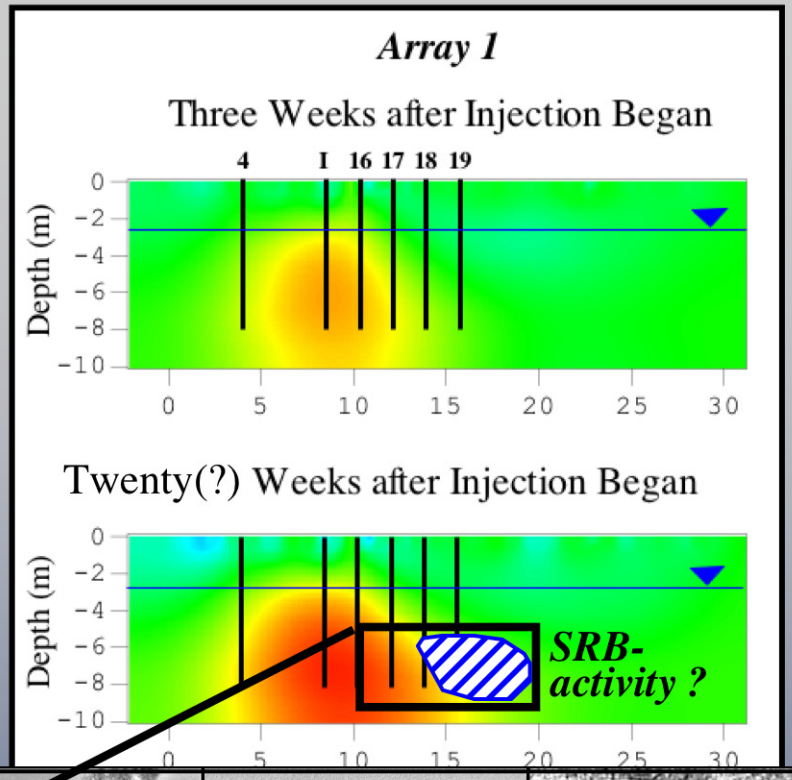




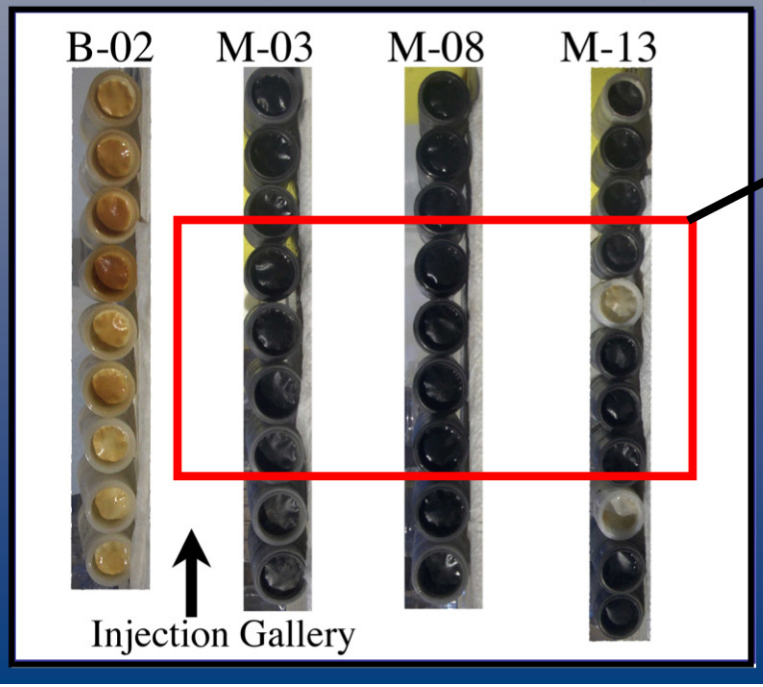
to be tested…

What's Next?

- ***Transition to sulfate-reduction:***
  - **Correlates w/ slight rebound in U(VI)**
  - FeS observed during previous experiment
    - Creation of ***polarizable*** phases
    - Morphology similar to column expt.'s
- ***Multiple metabolic pathways***
  - Distinct IP signals for FeRB and SRB!

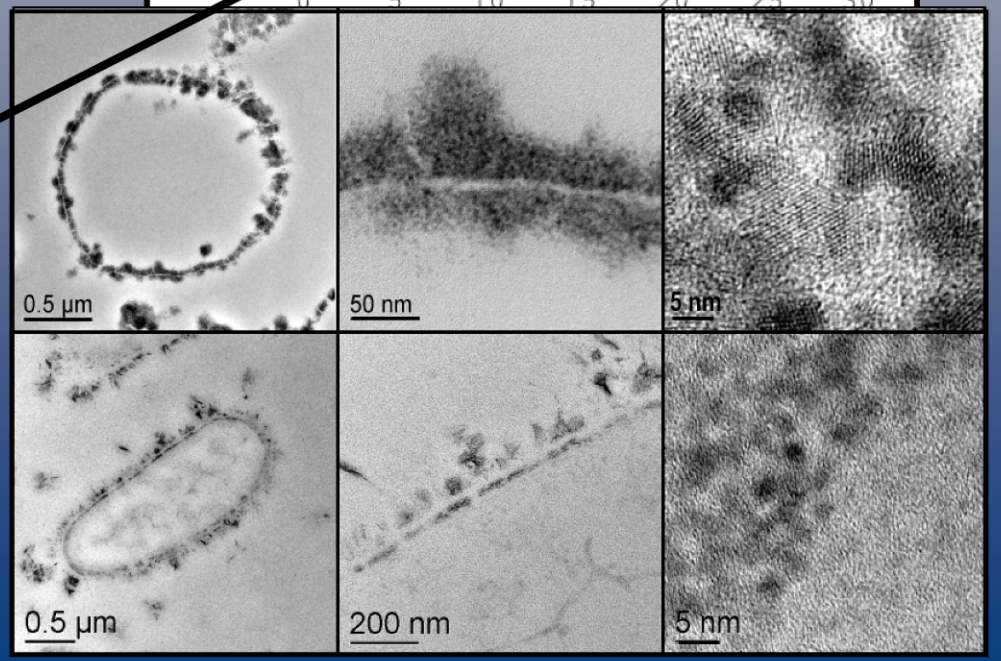


Oxidized and reduced MLS filters



Column test

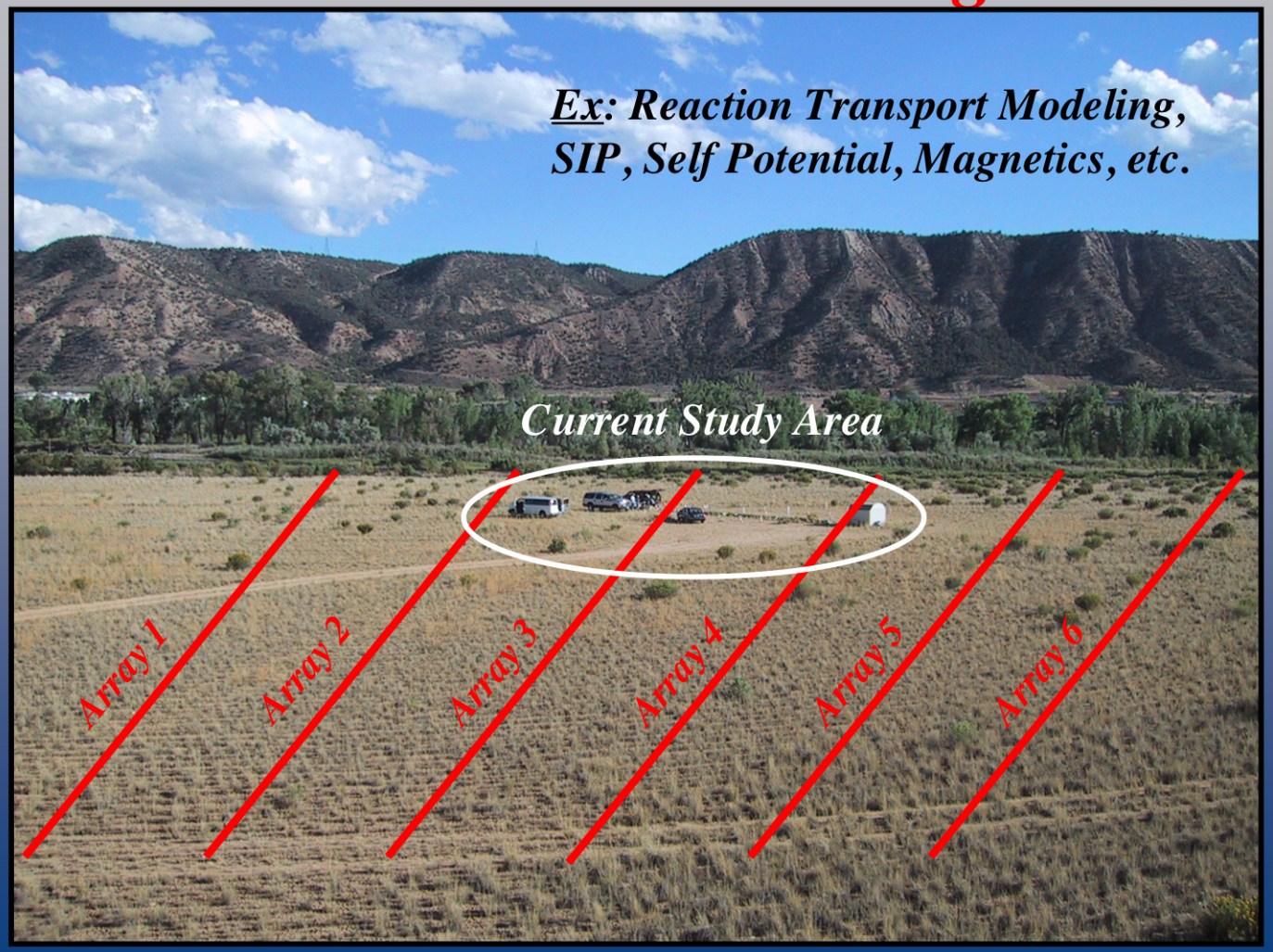
100H Expt.



What's Next and Why?

- *Large-scale monitoring (50-100 m):*
  - **Subsurface heterogeneity**
  - **Preferential flow**
  - **Scale of impact**

How do we handle scaling issues?



Summary

" Potential for using ***geophysical methods*** as a minimally invasive, ***field-scale*** approach for monitoring remediation processes "

- ***Understanding coupled mineralogical, metabolic, and hydrologic effects is critical***
- ***Ability to overcome borehole bias and monitor over large spatial scales***
- ***Potential for 'calibrating' reaction transport models***
- ***Permanently installed arrays for long-term monitoring***

Acknowledgments and Funding:

- **Laboratory and Field Work Funding**:
  - DOE's Office of Science, EMSP Program
- **Collaborators:**
  - Dave Watson (ORNL) for FRC logistics and access
  - Jack Istok and group (OSU) for Area 1 & 2 access
  - Phil Long (PNNL) and UMass for Rifle site access
  - DOE's Environmental Molecular Sciences Laboratory (EMSL)
    - Special thanks to Alice Dohnalkova and Jim Amonette (PNNL)
  - Lee Slater (Rutgers Univ.) for lab SIP assistance
  - Bill Daily (LLNL) - loan of field SIP system