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
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:
    1. $\text{Pb}^{2+} (\text{aq}) + \text{H}_2\text{S} \rightarrow \text{PbS} (\text{s}) + 2\text{H}^+$
    2. $\text{U}^{6+}, \text{Cr}^{6+} (\text{aq}), \rightarrow \text{UO}_2, \text{Cr}_2\text{O}_3$ (s)

![Diagram of microbial community and precipitation of metallic sulfides]

![Diagram of acetate solution and zone of U(VI) removal]
Geophysical Monitoring:
Possibilities and Pitfalls

Successful interpretation requires an understanding of...

Mineralogy
(e.g. aggregation state, phase, etc.)

Metabolism
(e.g. $\text{Fe}^{3+}$ vs. $\text{SO}_4$ reduction)

Heterogeneity
(e.g. high permeability, clay content, etc.)
Lab Measurements of Microbe-Induced ZnS and FeS Precipitation

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

![Graph](image.png)

$V(t) = V_0 + V_s \sin(\omega t + \phi)$

$I(t) = I_0 + I_s \sin(\omega t + \phi)$
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

2 cm
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

Inject:
(a) Ethanol
(b) Bicarbonate
(c) $\text{SO}_4^{2-}$
(d) pH ~7

-2.5 m

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
Saprolite Fill

ORNL FRC RADAR
Radar Velocity Baseline

Monitoring

Changes: 5 DAYS after EtOH

7 Days after EtOH

Dip?

Al(OH)₃?

N₂?
ERT Characterization & Monitoring

Baseline Conductivity

Conductivity after 8 Days

conductivity in mS/m

conductivity change in mS/m

saprolite

fill

Depth (m)

N2?
ERT Characterization & Monitoring

Baseline Phase Shift

Phase Shift after 8 Days

Depth (m)

phase in mrad

phase change in mrad

fill

saprolite

Al(OH)$_3$?
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

Higher K

Lower K

2 days after HRC injection

3 days after HRC injection

30 days after HRC injection

CHANGE IN CONDUCTIVITY (mS/m)
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/CuSO₄ electrodes
Field Monitoring: U(VI) Remediation at Old Rifle Site, CO

Array 1 - Inversion Grid

Baseline

Flow

Injection

Post

Fe$^{3+} \rightarrow$ Fe$^{2+}$
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

\[ \Delta \phi \approx 8-10 \text{ mrad} \]

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 $\rightarrow$ $Fe(II)$-clays
  - Dissolution, clay collapse and decreasing surface area
  [Kostka et al., 1999, 2002]

Panther Creek Bentonite
[Jim Amonette, EMSL]

Array 1
Three Weeks after Injection Began

Ten Weeks after Injection Began

Ox. Red.

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

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<th>B-02</th>
<th>M-03</th>
<th>M-08</th>
<th>M-13</th>
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Column test

100H Expt.

Injection Gallery
What’s Next and Why?

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

How do we handle scaling issues?

Ex: Reaction Transport Modeling, SIP, Self Potential, Magnetics, etc.

Current Study Area

Array 1 Array 2 Array 3 Array 4 Array 5 Array 6
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
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