Geophysical Characterization and Monitoring at the FRC

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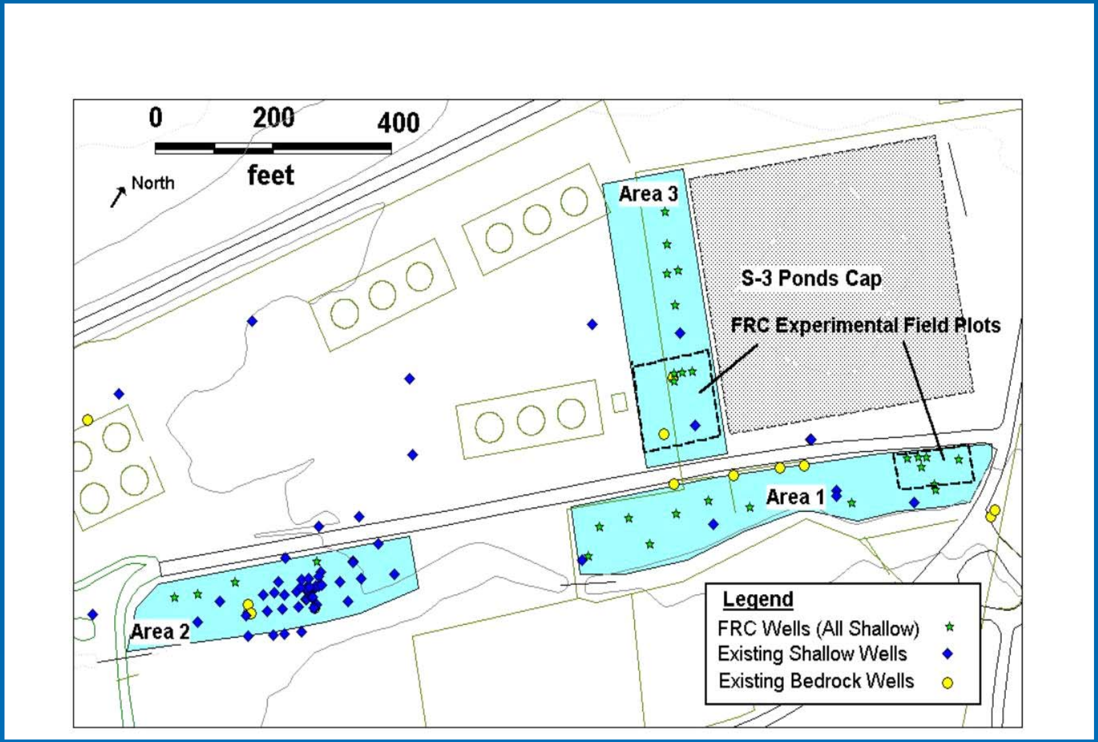


AREA 1: Monitor denitrification
AREA 2: Monitor sulfate reduction or redox zonation
AREA 3: Estimate fracture zonation using seismic tomographic data

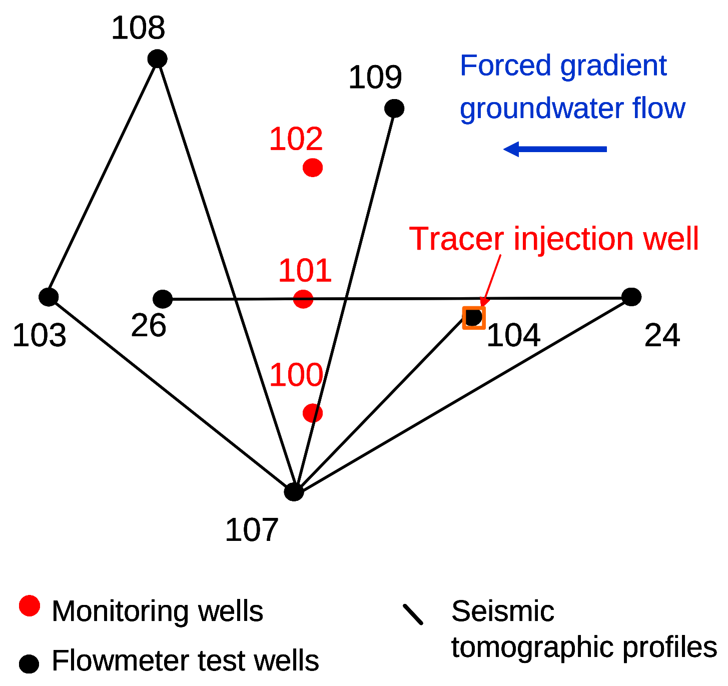
Approach: Integrated Laboratory and Field Experiments

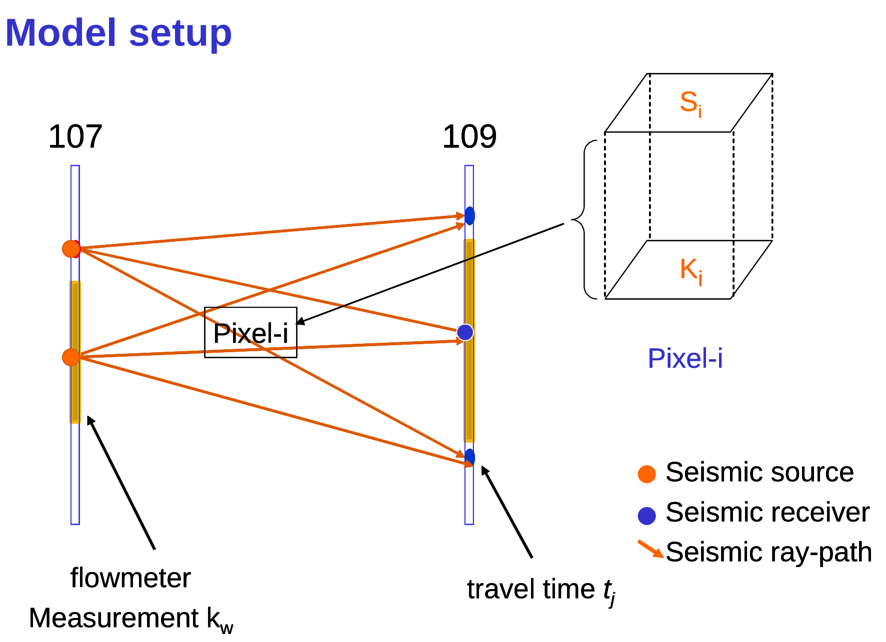
AREA 3: Fracture Zonation Estimation

Objective: Estimate the high hydraulic conductivity zone fracture zonation, which is the target zone for the Area 3 biostimulation experiment, using seismic tomographic data conditioned to flowmeter data.

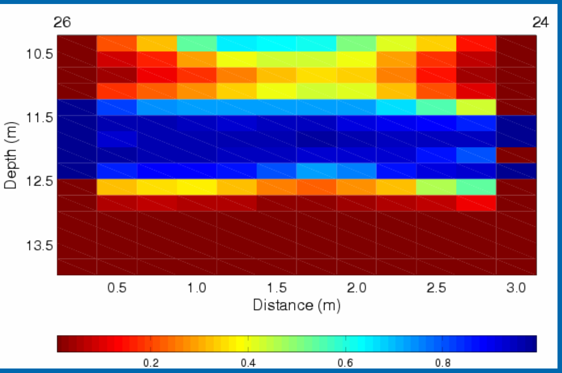
General Approach: Collect data along traverses across biostimulation area. Develop joint inversion approach using that data with Monte Carlo Markov Chain (MCMC) methods to estimate fracture zonation.

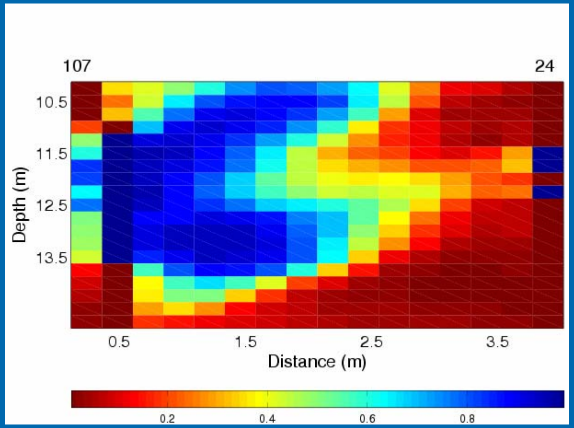
Wellbore and tomographic profile locations

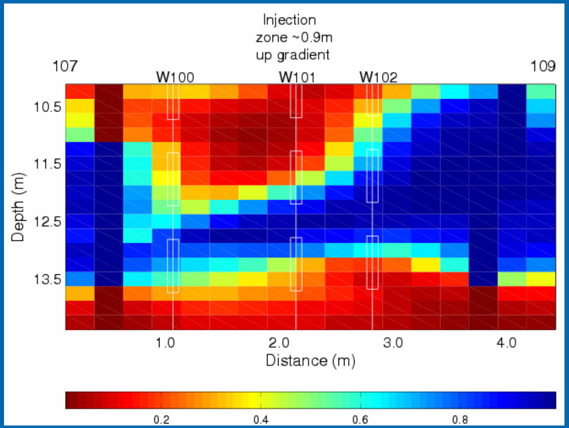




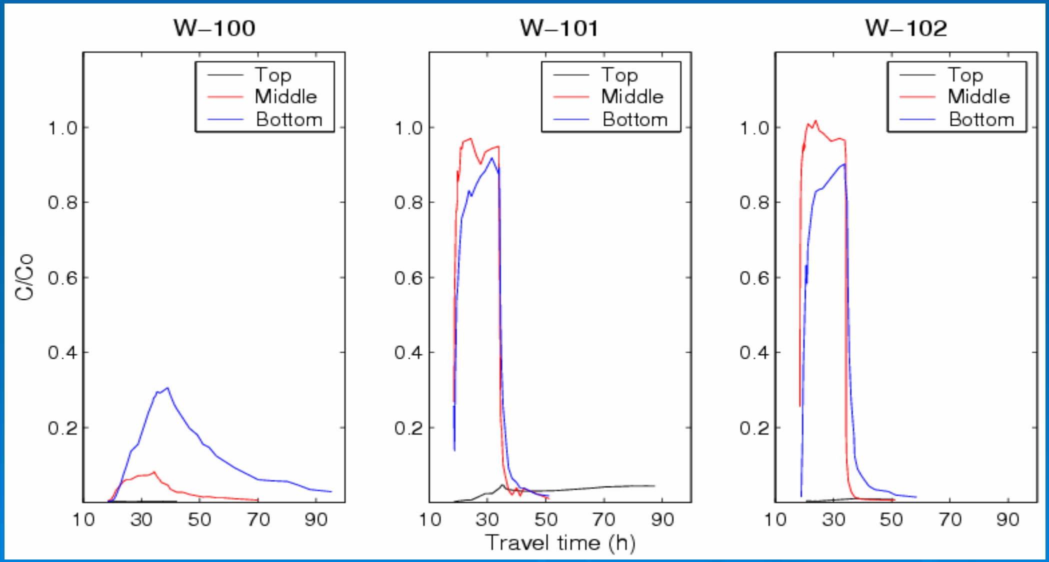
Estimation Results







Chen et al., Estimation of Fracture Zonation using Geophysical data at a Contaminated Field Site, to be submitted to WRR, 2005

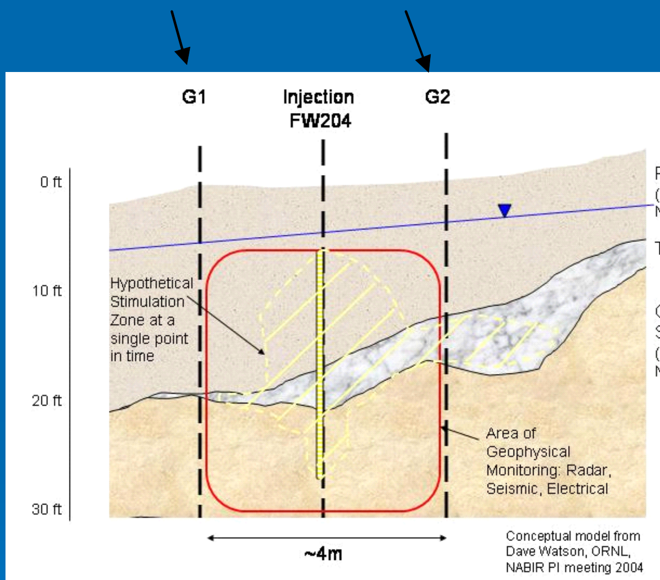


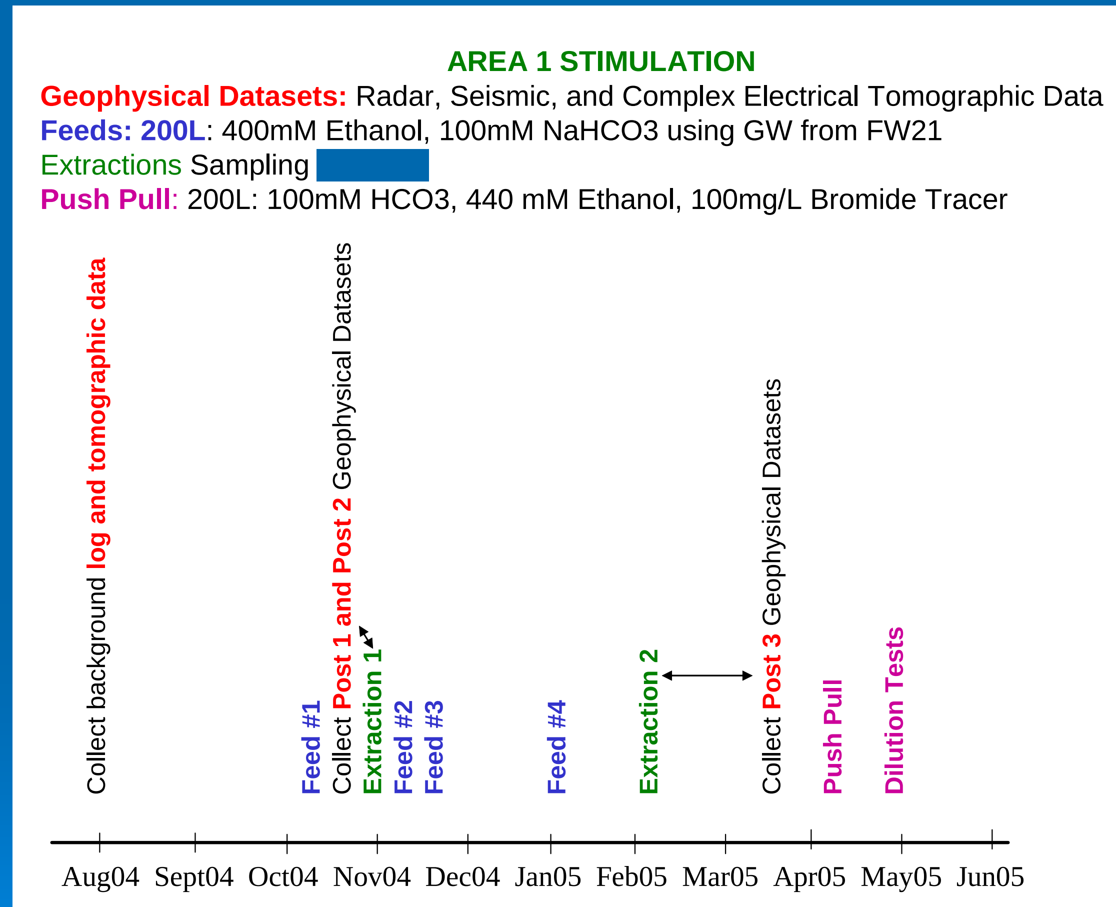
- Thickness and continuity of high K zone variable
- Geometry estimated using geophysical data qualitatively agrees with bromide tracer and U bioreduction observations.

AREA 1: MONITORING OF DENITRIFICATION

Objective: Monitor denitrification test in the presence of heterogeneity. This area contains high Nitrates and Aluminum (primarily within the saprolite).

Geophysical Monitoring Wells





Feeding included 400mM ethanol and 100mM NaHCO3

- Log and Tomographic data first used to identify Key Units
- Time-lapse geophysical data then used to monitor gas evolution

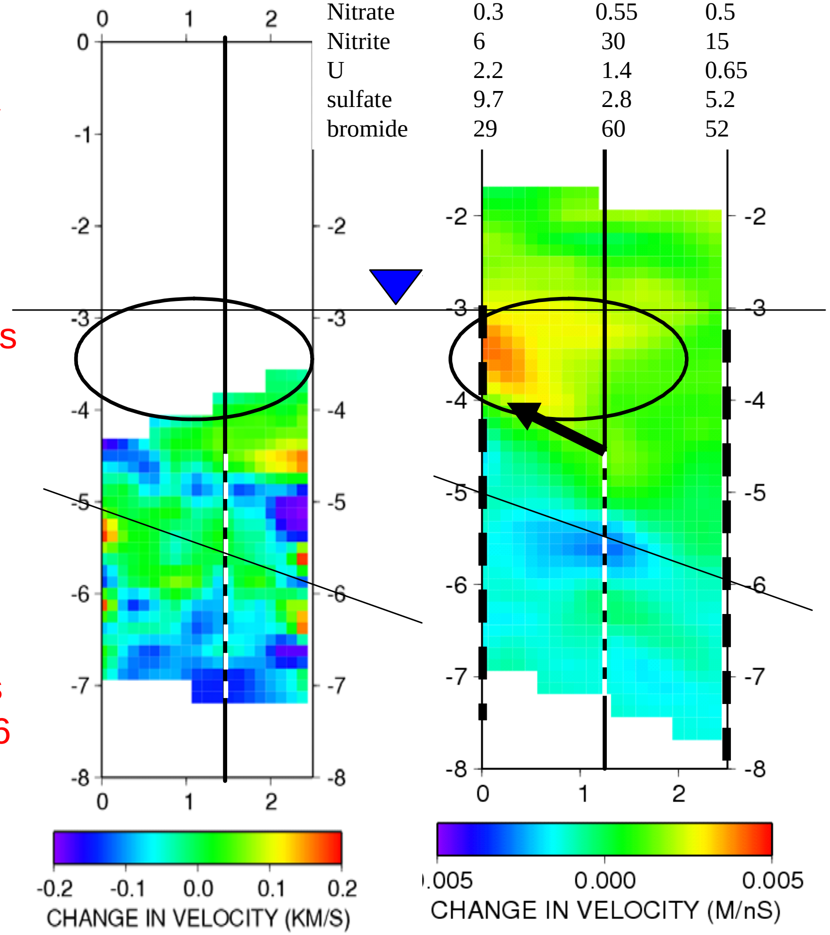
Changes in Seismic Velocity and Radar Velocity at 7 Days after Feed #1 compared to Geochemistry

Well	66	62	65
C/Co:		(Inj. Well)	
Ethanol:	0.17	0.35	0.0
Nitrate	0.3	0.55	0.5
Nitrite	6	30	15
U	2.2	1.4	0.65
sulfate	9.7	2.8	5.2
bromide	29	60	52

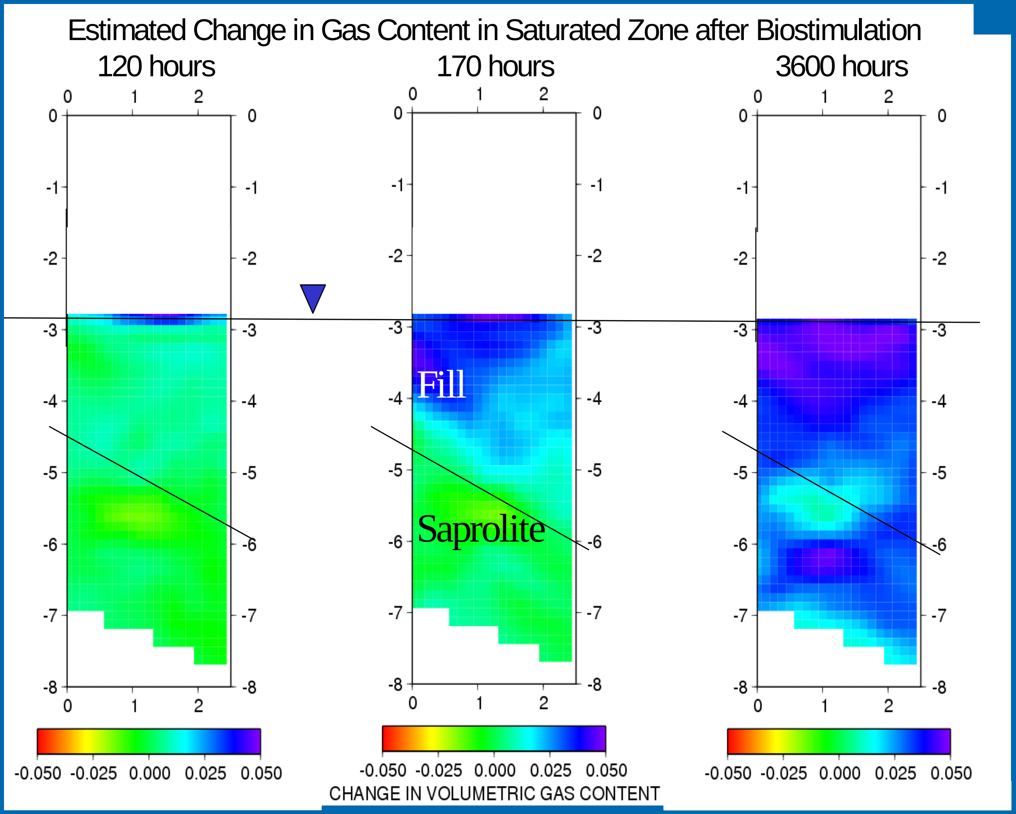
Seismic energy attenuated beneath water table in well 66

Radar Velocities Increased beneath water table in well 66

Geochemical data suggests that denitrification is active at well 66



Denitrification Monitoring Preliminary Results



Volume of gas evolved estimated using time-lapse radar data. The study suggests that

(1) The radar method is useful for showing the distribution and extent of denitrification;

(2) The evolved gas is influenced by heterogeneity, and

(3) that some of the evolved gas likely escaped from the saturated stimulation zone.

Volume estimates of evolved gas obtained using radar tomographic data:

After 120 Hours: $0.03m^3$

After 170 Hours: $0.2m^3$

After 3600 Hours: $0.6m^3$

Compare with stoichiometrically estimated volumes

AREA 2: MONITORING OF SULIDE PRODUCTION

Objective and Approach

Explore the potential of geophysical methods to remotely monitor the production of sulfides.

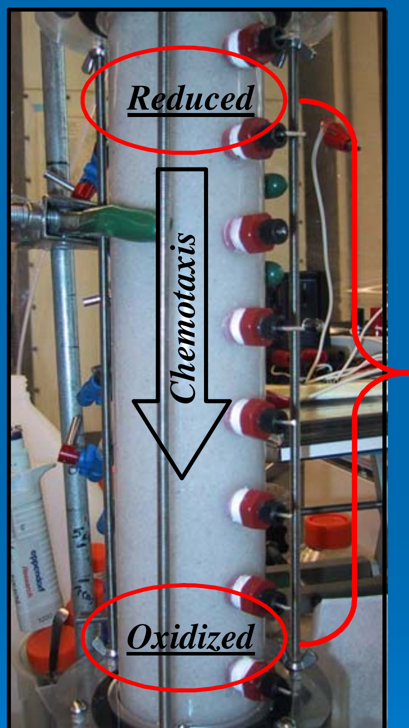
In contrast with Area 1, Area 2 has lower nitrates and aluminum and higher sulfate concentrations.

To investigate the production of **aqueous sulfide** during sulfate-reduction, we hypothesize that redox gradients are capable of generating subsurface voltage potentials that can be detected using SP methods.

To investigate the production of **sulfide precipitates**, we hypothesize that complex resistivity (induced polarization) measurements will be able to detect the evolution and possibly the aggregation state of sulfide precipitates, and that generation of precipitates will attenuate the seismic signal.

Laboratory Experimental Set up: IP and SP

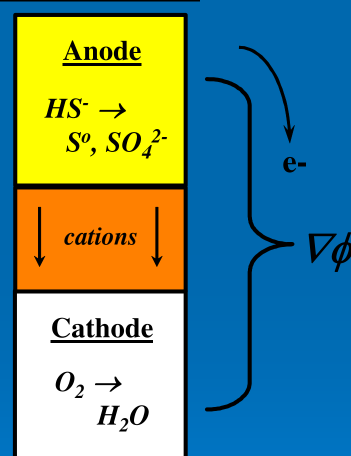
Self-Potential and IP Monitoring of Chemotaxis and Sulfate-Reduction



Self-Potential (SP): The generation of voltage potentials within earth materials, which can be measured between electrodes located along the surface or within boreholes.

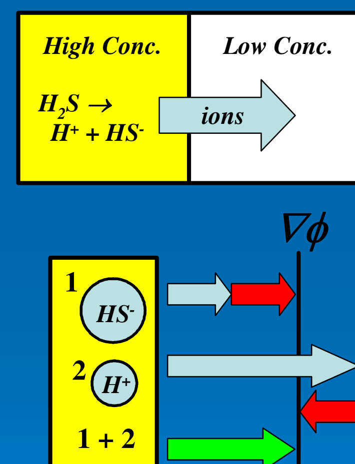
SP Mechanisms Relevant to Stimulated SRB:

Galvanic Cell *



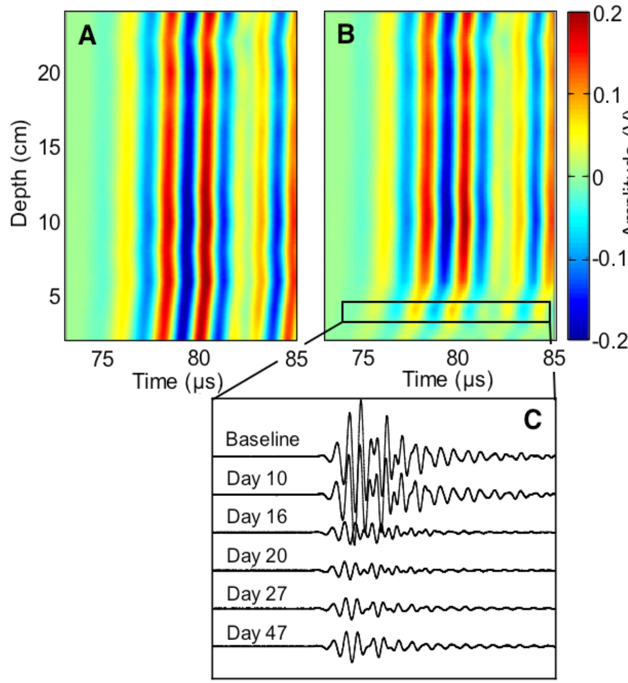
*primary mechanism

Liquid Junction

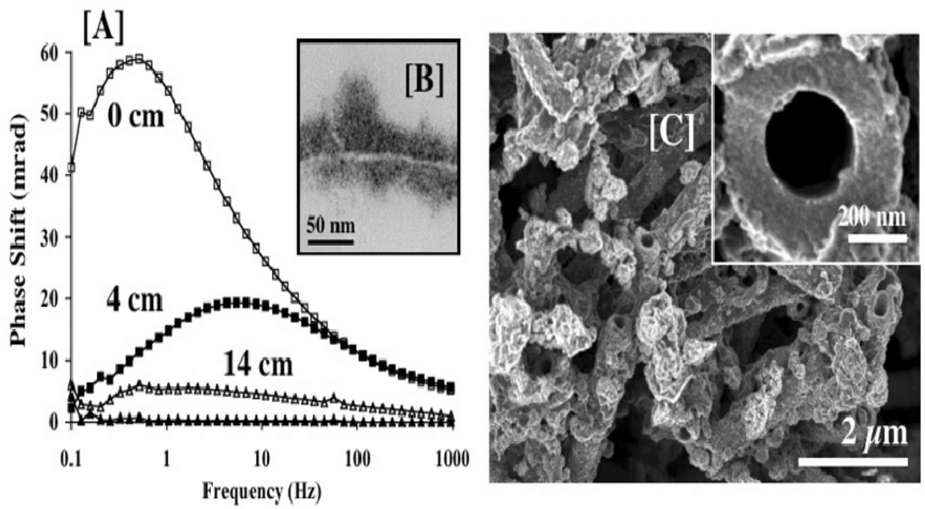


Induced Polarization (IP): Low frequency (0.1-1000 Hz) electrical measurements Measure ϕ and |Z| using low frequency (0.1-1000 Hz) electrical measurements between individual electrodes placed along column length. Correlate changes in phase with aggregation state and composition of precipitates associated with SRB.

Laboratory Studies suggest that both seismic and IP approaches should detect the onset and magnitude of biomineralization



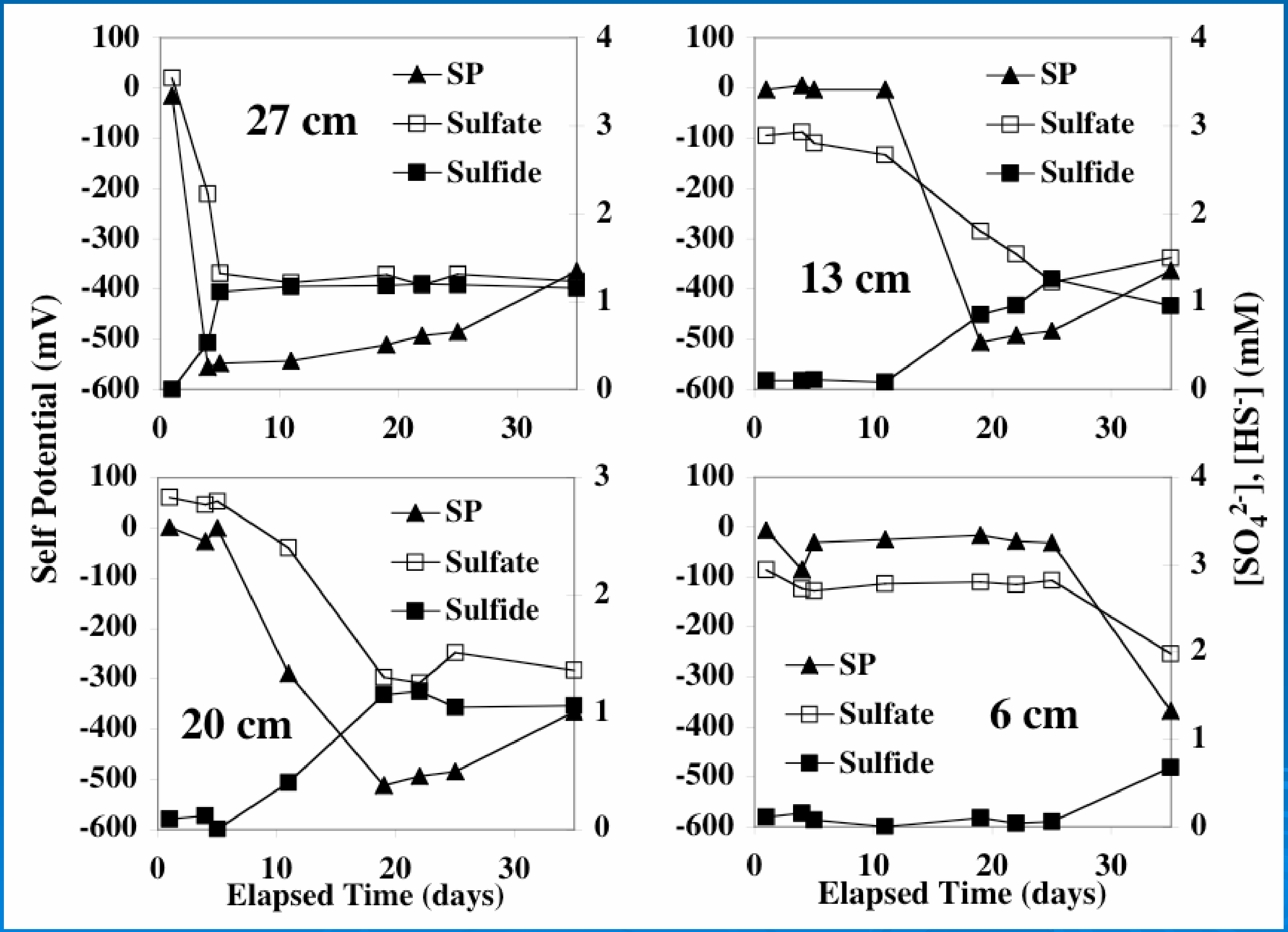
Changes in seismic waveforms near base of column as a function of time after inoculation.



[A] Maximum phase shift relative to baseline for four locations along the length of the column; [B] Cross sectional TEM image of a single *Desulfovibrio vulgaris* cell with membrane-bound ZnS and FeS precipitates. [C] SEM image of metal sulfide encrusted microbes and spherical aggregates; high-resolution SEM image of a fractured cell encrusted in compositionally mixed ZnS and FeS [inset]. Both [B] and [C] represent samples recovered from the 0 cm location in [A], which is nearest to the column inlet. These images and provide direct evidence of the products of biomineralization and their impact of complex resistivity signatures.

Williams, K.H. et al., Geophysical imaging of stimulated microbial biomineralization, Env. Science and Tech., 39, 7592-7600, 2005.

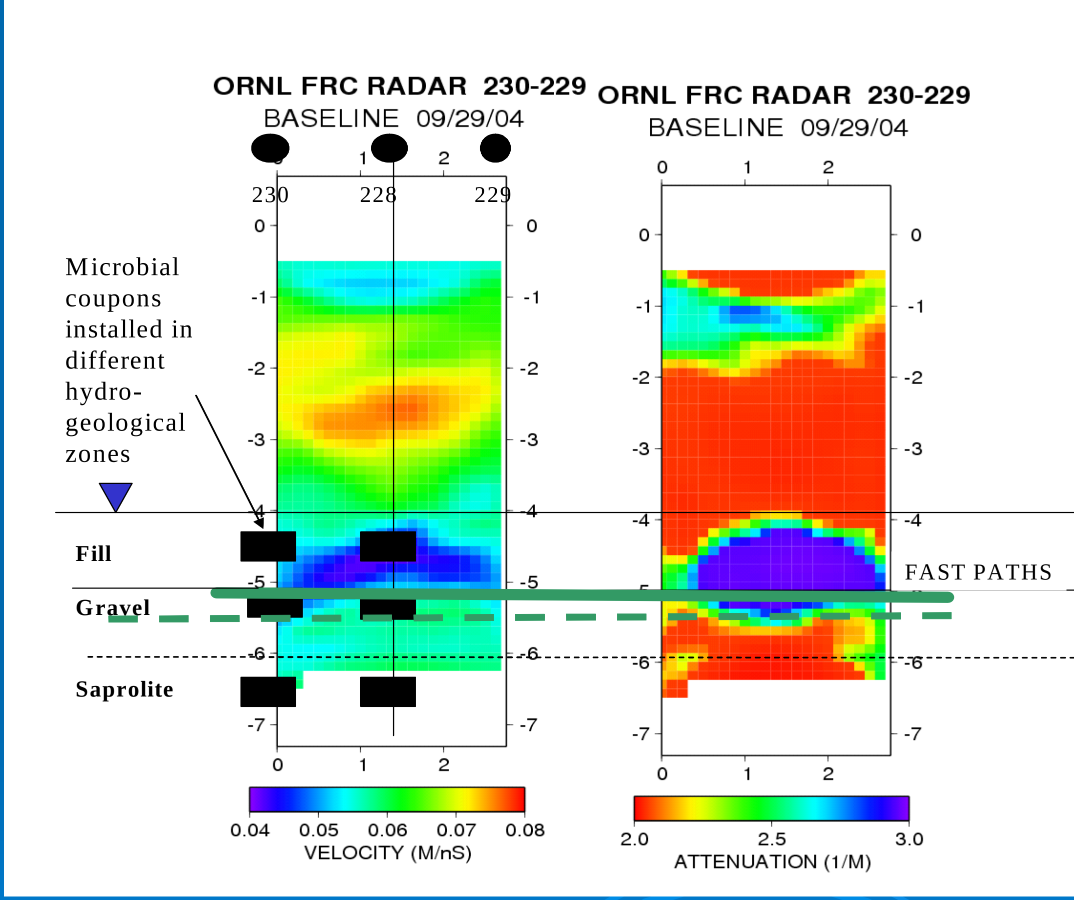
Laboratory SP results



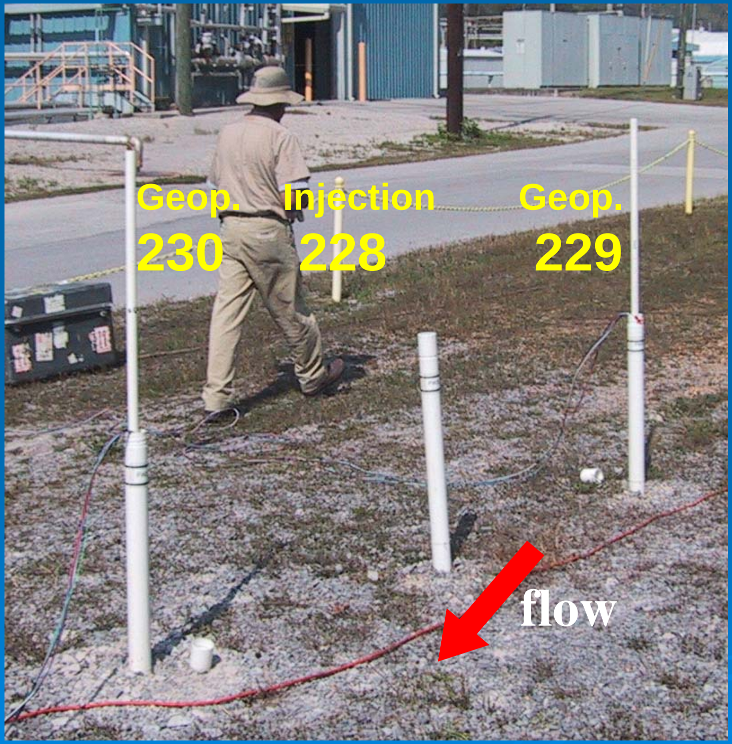
Changes in SP signature correspond to the onset of sulfate reduction and the production of sulfide.

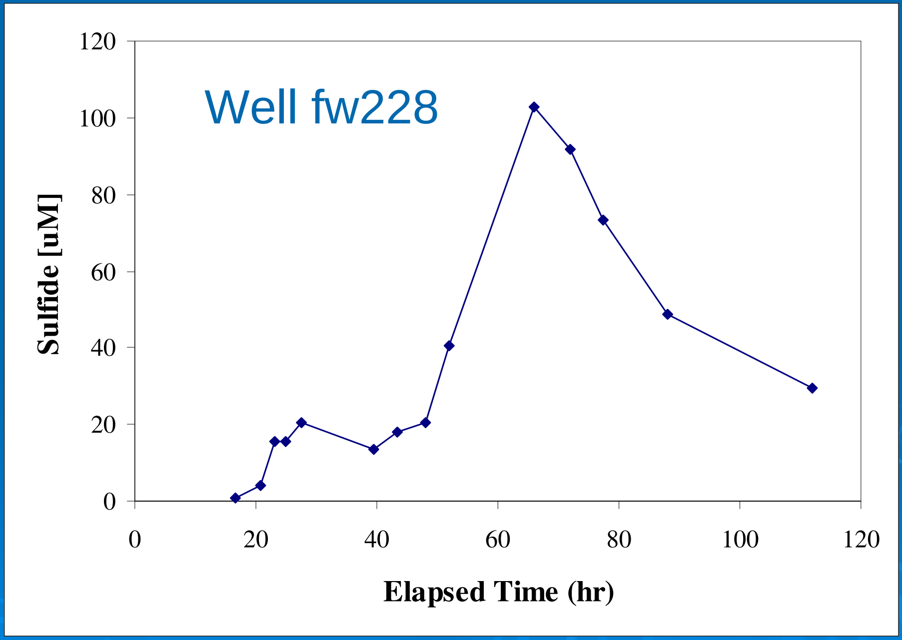
Area 2 Field Study

- Crosshole and Log data first used to Characterize the site;
- Amend with sulfate to protect against reoxidation- Stimulation was performed through the feeding of Well FW228 with 200L of GW835 water amended with 10mM bicarbonate, 20 mM sulfate and 40 mM ethanol.
- Time-lapse radar, seismic, IP and SP used to monitor sulfide production.



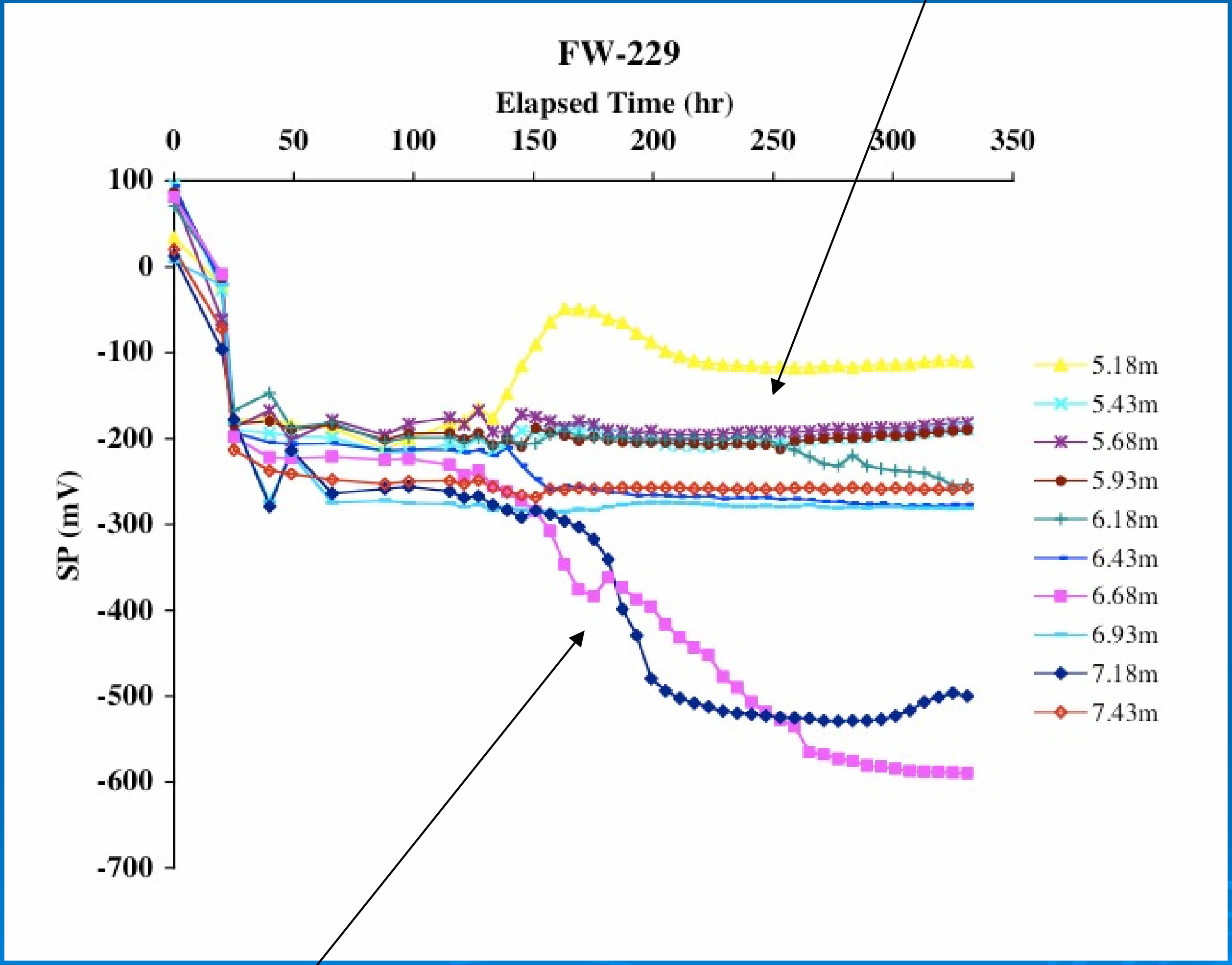
- SP monitoring was performed by placing the reference electrode near the injection well at the groundwater table (oxidizing conditions), and by lowering the SP electrodes in the outer geophysical wells as at 0.25m intervals over time (more reduced conditions);
- Aqueous sulfide concentrations were assessed in the injection well using colorimetric techniques.





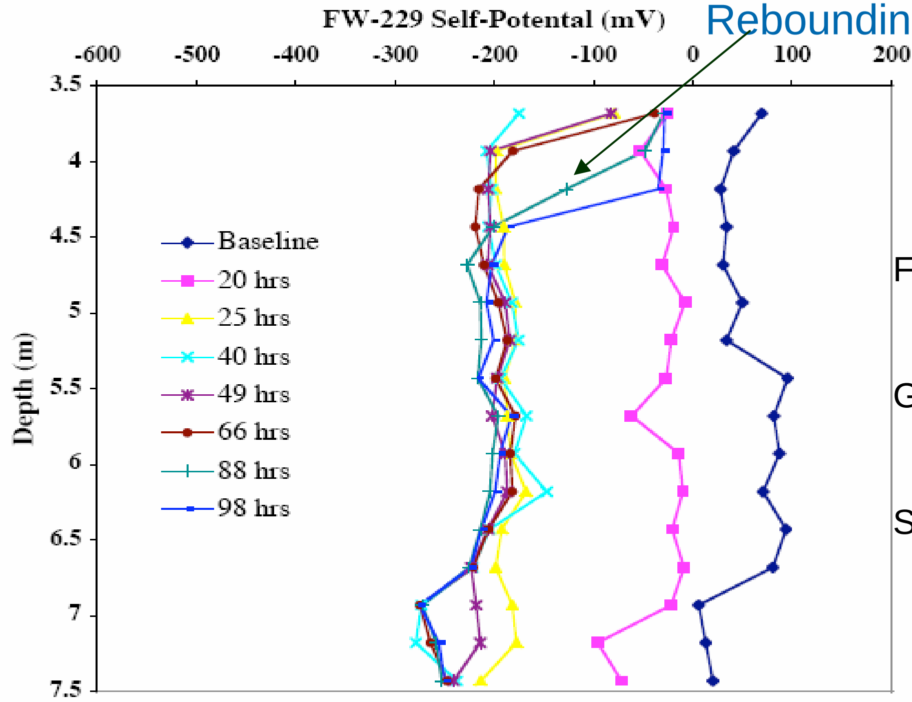
SP: Passive method

Early rebound in system at fill-gravel interface

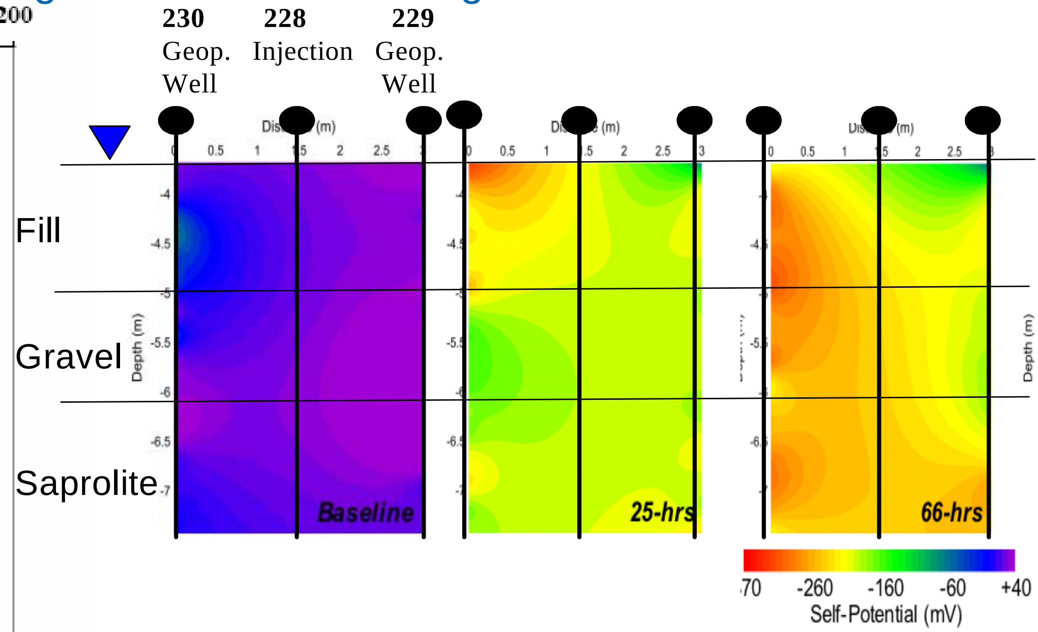


Late change in redox coniditions at gravel-saprolite interface

- SP values demarcate the region of the aquifer that is experiencing depressed redox conditions due to the sulfide production (goal of amending with sulfate), and the rebound of the system.
- Field SP observations are in line with laboratory experimental results.



Rebounding toward more oxidizing conditions near water table



•Although data collection/analysis is ongoing at this site, these preliminary images suggest that SP methods may hold potential for indicating onset and rebound of artificially depressed redox conditions.

•Time-lapse seismic, radar and IP still undergoing reduction

Summary

- Our results show that geophysical methods were useful for:
  - Mapping **Fracture zonation** that influences chemical tracer transport and the spatial distribution of U bioreduction (Seismic - Area 3);
  - Imaging the spatial distribution of **denitrification** (Radar - Area 1);
  - Imaging changes in **redox zonation** associated with sulfate reduction (Electrical - Area 2-in progress).
  - Reduction of methods to image sulfate precipitation is still n progress (Area 2)
- These studies suggest that **heterogeneity plays a role in system transformations during remediation**.

Ongoing Work / Future Needs

- Area 1: Quantitative comparison of Volumetric Gas estimates;
- Area 2: Complete analysis of extended SP data and tomographic data and integrate with geochemical data;
- Area 2: Assess change in microbial community as function of heterogeneity/stimulation;

Future Char and Monitoring Needs

- Detailed Characterization at 'new' sites
- Gross Characterization along watershed
- Deploy low-cost monitoring networks (i.e., copper electrodes to monitor artificially depressed redox conditions) as a way to assess system transformations and to indicate when to add additional stimulants (e.g., sulfate and ethanol).
- Use monitoring data to provide near real-time constraints to transport model

EMSP Environmental Management Science Program

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