Characterization and Monitoring at the FRC using Integrated Geophysical Data

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INTRODUCTION

Hydrogeological and biogeochemical heterogeneity in natural systems is great and is characterized by multiple spatial scales. Conventional wellbore sampling methods typically do not provide the information necessary for adequately characterizing and monitoring the subsurface at a high enough resolution for guiding remediation efforts. Here, we focus on the use of geophysical methods to characterize hydrogeological heterogeneity as well as to monitor transformations that occur during remediation in a high-resolution, minimally invasive manner.

Our work, which has been performed in conjunction with other NABIR field PIs, has focused on the acquisition of high resolution radar, seismic and complex electrical data as well as SP data at Areas 1, 2 and 3 of the FRC site, and the joint analysis of the geophysical data with hydrological and biogeochemical data. The primary objectives of our investigations have varied depending on the site:

AREA 1: Monitor denitrification in the presence of heterogeneity using geophysical approaches;
AREA 2: Monitor sulfate reduction or redox zonation in the presence of heterogeneity using geophysical approaches.
AREA 3: Estimate fracture zonation using seismic tomographic data and explore the influence of this zonation on the biostimulation results.

As will be described below, our studies suggest that geophysical methods hold potential for both characterizing and monitoring contaminated sites, and that physical heterogeneity likely plays a very significant role in the responses of the system to biostimulation. These studies have helped to understand the zone of influence of push-pull tests, and how heterogeneity influences amendment distribution and system transformations.

AREA 3: FRACTURE ZONATION ESTIMATION

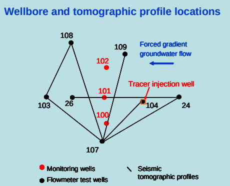
Objective: Estimate the high hydraulic conductivity zone fracture zonation (Figure 2), which is the target zone for the Area 3 biostimulation experiment using seismic tomographic data conditioned to flowmeter data.

Obstacle: Fracture zonation leads to geophysical anisotropy and the scale matching between borehole and crosshole data is exacerbated in fractured materials. Previously developed two-step Bayesian estimation approaches (Chen et al., 2001; Hubbard et al., 2001), which use estimates such as those shown in Figure 3 for hydraulic conductivity estimation, are not applicable at the complex, fractured FRC site.

General Approach: Collect data along traverses across biostimulation area, such as illustrated in Figure 3. Develop joint inversion approach using that data with Monte Carlo Markov Chain (MCMC) methods to estimate fracture zonation.

Figure 2 High K transition zone (Watson et al., 2003)

Figure 3



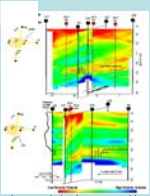


Figure 4: Seismic tomographic Imaging along strike and dip cross sections

MCMC Approach: The dependence between unknown variables and available are illustrated by this graphical model shown in Figure 5. The unknown zonation indicator at any location is related to the known indicator values at the two wells through spatial correlation. The unknown seismic slowness is related to the co-located unknown zonation indicator through unknown a petrophysical model with unknown parameters. We simultaneously estimate all those unknown variables by conditioning to the given seismic travel-time and borehole flowmeter data as is illustrated in Figures 6 and 7. Note that we use the seismic travel time data (or slowness data) rather than the inverted velocity data shown in Figure 4. We use a borehole flowmeter median value of 10^{-6} m/s as an indicator cutoff value: values higher than that were considered to be within the high hydraulic conductivity fracture zone.

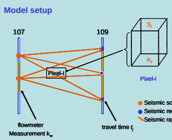


Figure 5

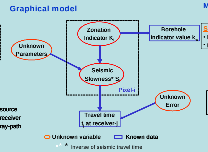


Figure 6

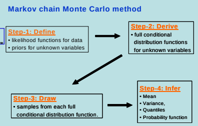


Figure 7

Results The probability of being in the high conductivity (K) fracture zone along the geologic dip and strike directions is illustrated by figures 8-10. These figures suggest that along the dip direction, the high K zone is spatially variable in thickness and is discontinuous towards the downdip direction.

Validation. Comparison of the heterogeneity estimates with tracer breaktthrough data (P. Jardine and T. Melhorn, ORNL) suggest that the estimates are reasonable and that the heterogeneity greatly influence transport at the site. Additionally, during the biostimulation experiment, U(VI) remained at background concentrations at MLS 100 (Wu et al., 2005), further supporting the interpretation that that the downdip area was hydraulically isolated from the injection zone.

Probability of being in the High K Zone

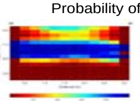


Figure 8

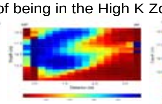


Figure 9

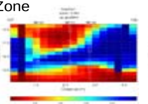


Figure 10

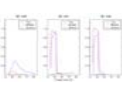


Figure 11

AREA 1: MONITORING OF DENITRIFICATION

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

Approach.

Related Laboratory Studies. Column-scale experiments such as those shown in Figure 14 were performed to assess the geophysical responses to gas generation. Using a three phase mixing model (gas, water, solids) with radar velocities, the volume of pore space filled with evolved N2 gas was estimated within 1% of that obtained using gravimetric measurements (Figure 15; Hubbard and Williams, 2004). Seismic methods indicated that the presence of gas in the pore space dramatically attenuates the signal (Figure 16; Williams 2003).

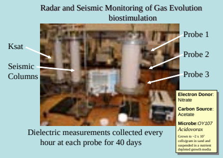


Figure 14

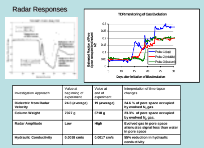


Figure 15

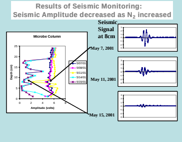


Figure 16

Data Acquisition This project involved acquisition of seismic, radar, and complex resistivity data between boreholes and the use of those time-lapse data with wellbore hydrological, geophysical, and geochemical data to infer the control of heterogeneity on the system response to stimulation. Well logging was initially performed in a central well to characterize the physical structure at the study site. The same central wellbore was used for stimulating the subsurface. Geophysical tomographic data were collected using two additional boreholes, which are located on either side of the injection well as is illustrated in Figure 17. Groundwater from a nearby well was amended with 440mM of ethanol and 100mM NaHCO3 following the schematic approach shown in Figure 18. The timing of the feeds, geophysical data acquisition, and push pull experiment is shown in Figure 19.

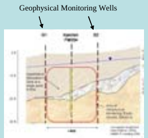


Figure 17

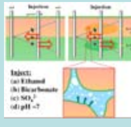


Figure 18

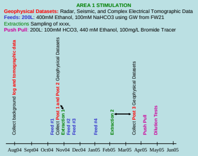


Figure 19

Characterization Both logs and tomographic data were used to provide baseline information about the zonation and variation of lithologic units at the Area 1 study site, which encompassed wells FW62, 65 and 66. Log data included polyelectric, temperature, acoustic televiewer, SP, gamma, borehole deviation and caliper logs. Tomographic data were collected using radar, seismic, and complex electrical methods. The location of the water table, fill zone, and saprolite interfaces were interpreted as is shown in Figure 20. Comparison of the data also illustrated the location of two small potential fracture zones as well as an electrically conductive interface between the fill and the saprolite.

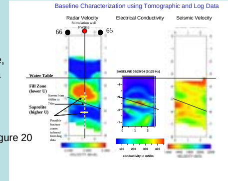


Figure 20

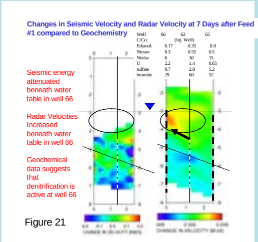


Figure 21

Time-Lapse Imaging and Interpretation As shown by figure 19, tomographic data were collected four different times during the course of the biostimulation experiment. Difference images were constructed to show the change in the geophysical properties relative to the time prior to stimulation. A comparison of the change in seismic and radar velocities relative to 'baseline' at 7 days after the first stimulation (feed) is shown in Figure 21. Also indicated on that image are concentrations of different species measured at extraction 1, which are relative to the injected concentrations associated with feed 1 (see Figure 19). This figure suggests that:

- Nitrate is being reduced quicker at updip well 66 relative to the injection well;
- A zone of high radar velocity and lost seismic signature is located just beneath the water table at the well 66 location.

Based on laboratory results (refer to Figures 13 and 14), we interpret the ***seismic and radar anomalies to be associated with the evolution of N2 gas, which migrates up dip and becomes trapped beneath the water table.*** As changes occur preferentially in the fill zones, these data also illustrates the ***influence of heterogeneity on system transformations***.

Estimation of Gas Produced using Geophysical and Geochemical Data

Geochemical datasets suggest that the reduction of Uranium at this site was proceeded by denitrification. For reduction of Uranium in the presence of nitrate, it is important to consider:

- To what extent and where does denitrification occur;
- Is the evolved N2 gas retained in the system or does it escape from the system.How does trapped gas impact the effectiveness of biostimulation?

Time-lapse radar velocity data were used to estimate the volumetric of evolved gas produced during this biostimulation experiment, which may include both N2 and CO2. Radar velocity measurements were used with a petrophysical mixing model to estimate evolved gas at 120, 170, and 3600 hours after stimulation as Is shown in Figure 22. By assuming horizontal isotropy, the 2D estimates were converted to 3D estimates of gas evolution. A comparison of the radar Estimates of gas production with geochemical measurements is shown in Figure 23. These figures suggest that: (1) The radar method is useful for showing the distribution and extent of denitrification; (2) The evolved N2 gas is influenced by heterogeneity, and (3) that some of the evolved gas likely escaped from the saturated stimulation zone.

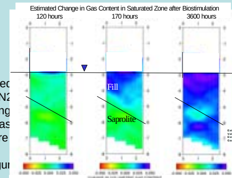


Figure 22

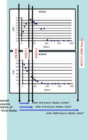


Figure 23

AREA 2: MONITORING OF SULIDE PRODUCTION

Objective:
Explore the potential of geophysical methods to remotely monitor the evolution of aqueous and solid sulfides, redox zonation, and the influence of heterogeneity on the evolution. 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.

Approach
Related Laboratory Studies.
Column scale studies were performed to assess the influence of evolved aqueous sulfides as well as the development of precipitates on geophysical responses. Figure 24 shows the column geometry that was used to measure both IP and SP responses. A separate column was used to assess the impact on the seismic signature. After poising the system to undergo sulfate reduction, *Desulfovibrio vulgaris* were added to the top of the column for the SP experiments and to the middle of the column for the IP and seismic measurements.

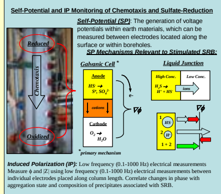


Figure 24

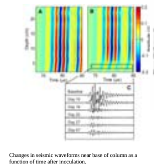


Figure 25

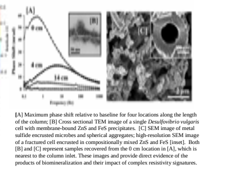


Figure 26

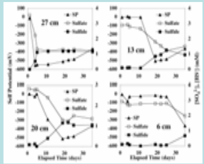


Figure 27

Figures 25 and 26 show the changes in seismic amplitude and phase response, respectively, associated with the onset and evolution of sulfide precipitation. As described by Williams et al. (2005) during column studies, high-frequency seismic wave amplitudes were reduced by nearly 84%, and significant changes in complex electrical conductivity measurements were observed. The decreased acoustic wave amplitudes may be explained by using a patchy saturation model, wherein wave-induced flow results from the heterogeneous formation of high bulk modulus sulfide precipitates within formerly fluid-filled pores. Changes in the IP response are attributed to alterations in subsurface mineralogy arising from stimulated microbial activity within the pore space, including precipitation reactions, aggregation dynamics, and solid-state mineral transformations. Figure 27 shows the changes in SP responses associated with the biostimulation experiment, and reveals that SP anomalies correspond to the onset of sulfate reduction and the production of sulfide.

These laboratory experiments suggest that geophysical techniques are capable of detecting the onset and evolution of microbe-induced aqueous and solid sulfides, and that frequency-dependent electrical measurements are sensitive to pore-space alterations in mineralogy.

Field Experiments
On March 21st, 2005, stimulation began at this site through the "feeding" of Well FW228 with 200L of GW835 water amended with 10mM bicarbonate, 20 mM sulfate and 40 mM ethanol. Geophysical data were collected prior and during this feeding. The next feeding of this well was performed in June and at the end of the summer of 2005, and the push-pull experiment was performed in September of 2005. Geochemical and time-lapse radar, seismic, complex electrical and SP, as well as well-log data were collected using wells FW228, FW229 and FW230. Figure 28 reveals the heterogeneity at the study site obtained using radar tomographic data together with wellbore data. This site has three distinct hydrogeological zones (fill, gravel zone, and saprolite), with two interpreted fast path zones.

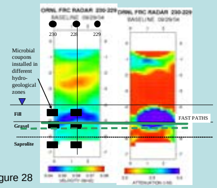


Figure 28

Figure 29

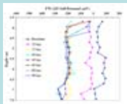


Figure 30

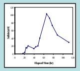


Figure 31

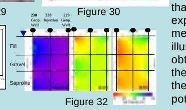


Figure 32

Detecting changes in Redox Conditions
SP monitoring was performed by placing the reference electrode in the injection well at the groundwater table, and by lowering the SP electrodes in the outer geophysical wells as at 0.25m intervals over time (Figure 29). Aqueous sulfide concentrations were assessed in the injection well using colorimetric techniques (Figure 31). Figure 30 illustrates the change in SP measurements in well 229, and reveals that SP decreases after the stimulation, in line with laboratory experimental results (see Figure 27). Sulfide concentrations were measured in well 228 over time (Figure 31). Finally, Figure 32 illustrates SP measurements variations over time and space, obtained from interpolating between the measurements collected in the two outer wells. Although data collection is ongoing at this site, these preliminary images suggest that SP methods may hold potential for tracking changes in redox conditions.

SUMMARY

Laboratory and Field geophysical results were integrated with hydrogeological and biogeochemical information to understand the capabilities of geophysical methods to characterize the subsurface at Areas 1,2 and 3 of the FRC and to monitor processes that occur during stimulation at areas 1 and 2. The studies revealed that geophysical data constrained by direct measurements are helpful for providing information about hydrogeological and zonation. Using time-lapse seismic, **radar, complex electrical, and SP data**, we were able to compare the heterogeneity with the spatial distribution of processes associated with biostimulation (evolution of gasses and sulfides). Our results show that geophysical methods were useful for: (1) **Mapping Fracture zonation that influences chemical tracer transport and the spatial distribution of U bioreduction (Area 3); (2) Imaging the spatial distribution of denitrification (Area 1);(3) Imaging changes in redox zonation associated with sulfate reduction (Area 2).** These studies suggest the potential of time-lapse geophysical methods for helping to understand system transformations during bioremediation and for guiding field efforts.

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