Characterization and Monitoring at the ORNL IFC using Geophysical Methods

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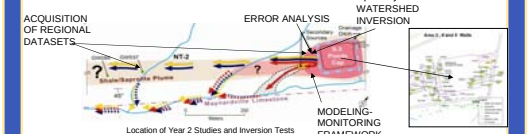
Abstract

Geophysical approaches are being developed and tested at the ORNL IFC to meet several key objectives:

1. **Watershed characterization** is being performed to define major flow paths, which is needed to parameterize a site-wide model and to provide a framework for interpretation of transient recharge data. Key watershed characterization studies include the:
- **Development of a watershed inversion approach** that can incorporate disparate and multi-scale datasets;
- Use of regional surface electrical and seismic lines to **delineate a geophysical anomaly** that may indicate an important conduit for watershed transport.

2. Geophysical methods are being used to **monitor processes associated with recharge.** Efforts this year have included:
- **Assessing the error** associated with time-lapse geophysical datasets;
- **Development of a joint hydrological-geophysical inversion** framework that permits the use of multiple datasets for exploring recharge processes, such as the infiltration of fresh water and subsequent changes in TDS.

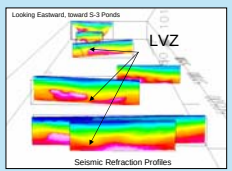
3. Laboratory equipment is being developed and tested to:
- Facilitate the geophysical **monitoring of transformations associated with subsurface manipulations**, such as the development of precipitates associated with pH manipulations.
- Results from laboratory studies will be used in conjunction with field experiments to address the potential of the geophysical methods for *in situ* monitoring of precipitate evolution as an indicator of U immobilization associated with pH adjustment.

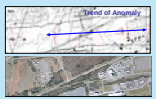


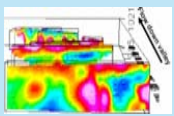
Location of Year 2 Studies and Inversion Tests

Watershed Characterization

REGIONAL DATASETS We have used surface geophysical methods to characterize and delineate a regionally extensive (low seismic velocity [LVZ] and high electrical conductivity) anomaly approximately parallel to geologic strike; drilling is in progress to explore the hydrogeological-geochemical properties associated with the anomaly and implications for regional flow.



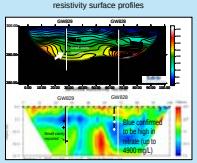




Co-located seismic refraction and electrical resistivity surface profiles

We have used a variety of methods and data sets (coring, driving in push probes, hydrological measurements, installing and sampling wells) to ground truth the surface geophysical measurements. These methods suggest that in addition to delineating gross flowpaths, the surface geophysical data should be useful for inferring nitrate distribution.

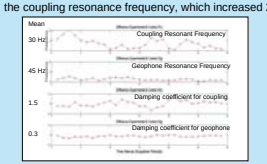
Efforts are also underway to integrate the geophysical measurements with more traditional datasets, such as digital elevation and geologic maps.

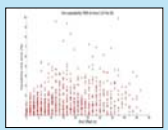


Monitoring Natural Recharge Processes

ERROR ANALYSIS OF TIME LAPSE SEISMIC REFRACTION TOMOGRAPHY

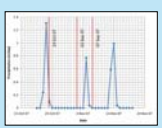
We investigated the difference in different diagnostic indicators between seismic refraction data collected over time relative to 'control' datasets. Such investigation will help us to understand inherent errors associated with acquisition and processing, which are not associated with the process that we are attempting to monitor (such cementation associated with pH manipulations). The study indicated that the most variable parameter as the coupling resonance frequency, which increased 20-30% after precipitation events.

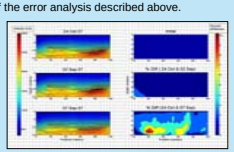




TIME LAPSE SURFACE SEISMIC REFRACTION IMAGING NEAR S-3 PONDS

We collected time-lapse seismic refraction data near the S-3 ponds to investigate apparent changes in seismic attributes under variable precipitation conditions. The inverted data suggests that there is an increase in seismic velocity with increasing precipitation in the high-hydraulic conductivity transition zone. We are currently interpreting these results in the context of the error analysis described above.





Monitoring Remediation Transformations

We are exploring geophysical responses to the evolution of Al precipitates associated with pH adjustments aimed at immobilizing U. To meet this objective, we have:

Developed specialized experimental cells that permit synchronous measurement of seismic *P*-wave velocity, complex resistivity, and TDR measurements at the column scale, which will be used to conduct pH-manipulation experiments;

Developed and tested **micro dynamic flow-through cells** for micro-tomographic imaging of **precipitates** at the Advanced Light Source. Preliminary results suggest that the resolution and contrasts will inform us about the evolution of precipitates at the micron scale. Dynamic micro-imaging will be used to formulate petrophysical and porosity-permeability relationships associated with precipitate development.

Summary

Progress in both numerical and multi-scale experimental studies has been made during this second year of the project. The geophysical component is/will:

1) Advance methods that permit quantitative use of geophysical datasets for watershed characterization and monitoring;

2) Provide insights into rates and mechanisms of geochemical and hydrological processes associated with natural episodic, seasonal, and annual recharge over field-relevant scales

3) Guide targeted treatment processes (such as pH manipulation);

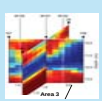
4) Provide insight into spatiotemporal distribution of treatment end-products as a function of local-scale heterogeneity;

5) Provide parameterization/validation to site models.

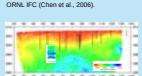
WATERSHED INVERSION

We are developing a Bayesian approach to systematically integrate multi-scale wellbore, crosshole, and surface datasets to provide the spatial distribution of lithofacies important for understanding flow at the watershed-scale. Our work is **motivated** by:

- Previous **hydrogeophysical work** performed at the IFC that indicated the utility of seismic travel time information for delineating local-scale fracture zones (Chen et al., 2006);
- Observation that **refraction velocities at the IFC correspond with the and depth of refusal** of push probes (Watson et al., Ground Water, 2005);
- Observation that there is a **low-seismic anomaly** that is spatially extensive, which is difficult to image using conventional refraction methods.
- The need to develop **watershed-scale characterization approaches** that can incorporate different datasets and provide information about uncertainty.

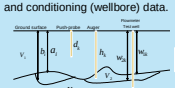


Estimation of the probability of being in a high hydraulic conductivity fracture zone, obtained through joint inversion of tomographic travel time and wellbore data and an MCMC method at the ORNL IFC (Chen et al., 2006).



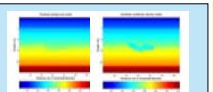
Comparison of surface seismic refraction, wellbore refusal depths, and crosshole datasets near the S-3 ponds IFC area.

COMPONENTS of Estimation Framework: (1) Numerical staggered-grid finite difference **forward model** to simulate seismic full waveform propagation; (2) **Bayesian framework** for incorporating refraction traveltime and wellbore datasets, where we obtain estimates using Markov chain Monte Carlo sampling methods; (3) **Parallel computing environment** that allows us to run models with a large number of source-receiver pairs, unknowns, and conditioning (wellbore) data.



Bayesian Estimation Framework

$$f(A,R,V \mid T,D,H,W) \propto f(T \mid A,R,V) f(D \mid A) f(H \mid A,B) f(W \mid A,B) f(A) f(B) f(V)$$

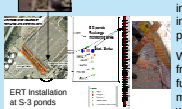


EARLY RESULTS using synthetic models have indicated the sensitivity of the refraction method to the location of the anomaly. Ongoing efforts are focused on comparing results from the new inversion approach (a) with and without conditioning wellbore data and (b) relative to conventional seismic refraction results.

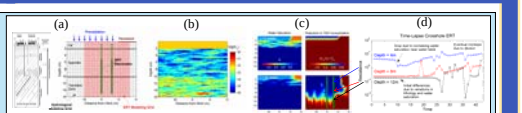
COUPLED MONITORING-MODELING

- We have developed a coupled, local-scale hydrological-geophysical modeling framework using the TOUGH2 family of codes for integrating disparate datasets.
- We have permanently installed ERT sensors near the S-3 Pond for tomographic imaging.
- The framework and time-lapse datasets will be used to explore the sensitivities of the electrical resistance tomographic datasets to variations in moisture in the vadose zone and recharge-associated variations in total dissolved solid (TDS) in the saturated zone.
- Extension of the approach with surface geophysical datasets and along the plume gradient is expected to provide insights into rates and mechanisms of geochemical and hydrological processes associated with natural episodic, seasonal, and annual recharge over field-relevant scales

Observed trend of precipitation and nitrate (TDS) concentration



ERT installation at S-3 ponds



EARLY RESULTS. The above figure shows (a) coupled hydrological-ERT model set-up, (b) geostatistically generated permeability distribution, (c) water saturation and reduction in TDS concentration at two times, and (d) simulated ERT data as a function of time (for current injection and voltage measurement dipoles centered at three respective depths, as indicated). The TOUGH2 hydrological model captures time-varying recharge due to precipitation and runoff near the S-3 pond (regional flow will also be included).

We are in the process of incorporating field hydrological and ERT data into the modeling framework and comparing the forward-inverse simulations with wellbore measurements. The fully developed model will be used to explore the sensitivity of ERT data to changes in moisture and TDS, and to develop an understanding of rates and mechanisms associated with infiltration and mixing at the 'field scale'.

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