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Monitoring of In Situ Chemical Oxidation (ISCO) Treatment with Time-Series Geophysical Surveys, Savage Superfund Site, Milford, NH

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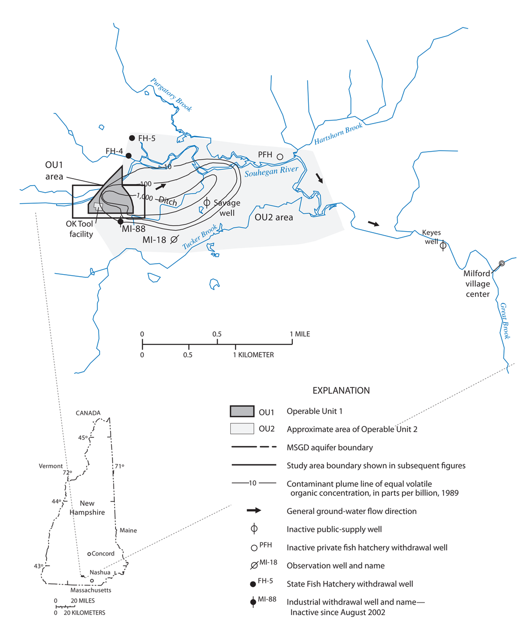
INTRODUCTION

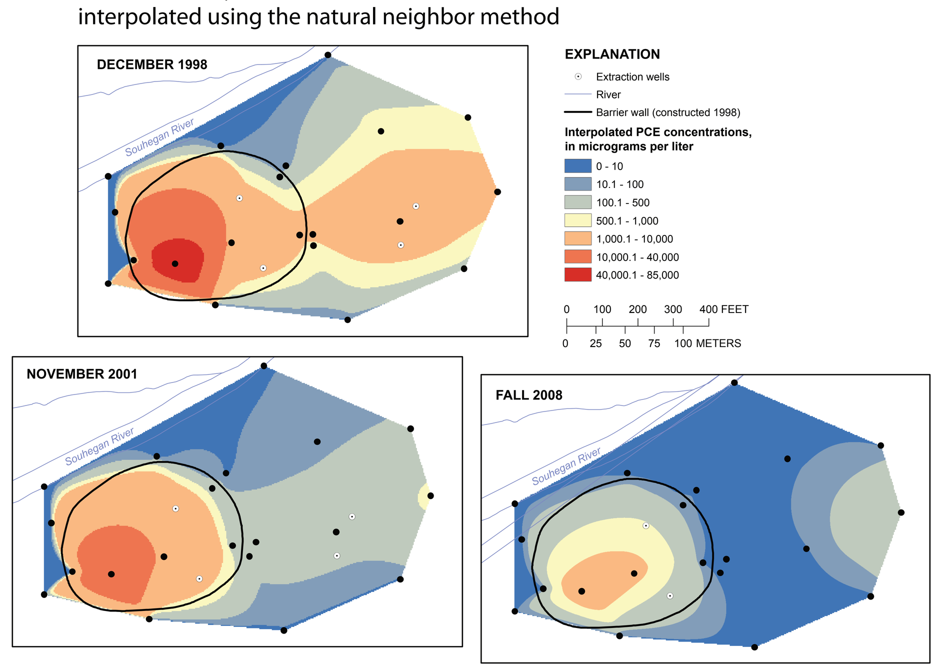
In situ chemical oxidation (ISCO) treatment with an electrically conductive injectate, like sodium or potassium permanganate, provides a strong electrical signal for tracking of injectate transport using time-series geophysical surveys including direct current (D.C.) and electromagnetic (EM) methods. Geophysical surveys can enhance the monitoring coverage provided by conventional well sampling and they are non-invasive and can efficiently cover large areas.



Background

- Tetrachloroethylene (PCE) plume
- Sand, gravel, and cobble river-valley aquifer of glacial deposition
- Muncipal well, called the Savage well, found to be contaminated in 1983
- Study area is Operable Unit 1 (OU1), located at the western edge of the river valley

Tetrachloroethylene (PCE) concentrations from 1998, 2001, and 2008 interpolated using the natural neighbor method



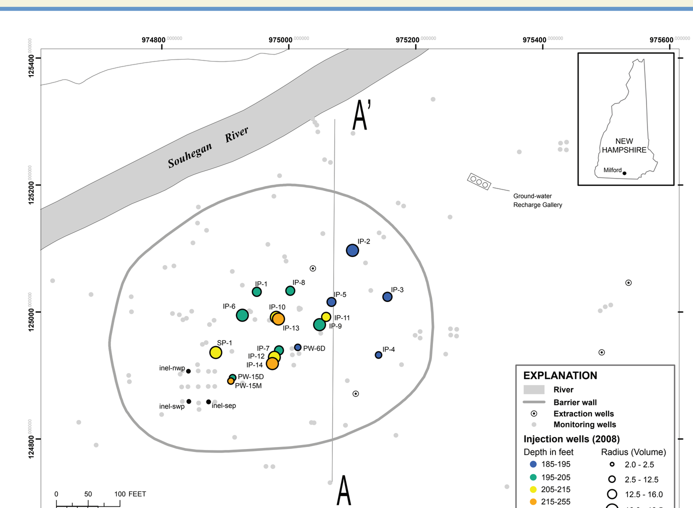
Description of OU1 Study Area

- Remediation started in 1999
- System includes a low permeability slurry barrier wall that encircles DNAPL or residual PCE sources
- Interior (barrier) extraction wells extract about 30 gal/min to maintain inward gradients across the barrier
- Exterior extraction wells turned off in 2007 after PCE concentrations decreased to 10 micrograms per liter in large areas outside the barrier
- Interior PCE concentrations still high, above 1,000 micrograms per liter in 2008

Hydrogeologic Setting

The subsurface geology of the aquifer has been mapped into primarily 11 hydrostratigraphic units and consists of several well-sorted sandy layers with some gravel separated by poorly sorted cobble layers with a fine-grained matrix. The cobble layers likely represent deposition in a cyclic topset glaciodeltaic environment close to the glacial ice front. The lowermost overburden unit is a basal till that ranges in thickness from 0 to greater than 3 m (~10 ft) and mantles the bedrock surface. The hydraulic conductivity of the well-sorted sandy units typically is greater than that of the poorly sorted cobble units and the basal till. Hydraulic conductivity ranges by approximately two orders of magnitude from 1.5 to greater than 150 m/d (5 to 500 ft/d) between the till and the sandy units. Hydrostratigraphic controls on contaminant distribution and remediation have been shown to be an important factor in mapping recalcitrant PCE concentrations in OU1.

ISCO TREATMENT



2008 ISCO Treatment

- Sodium permanganate 3% solution
- Pulse injection into 21 partially penetrating screen wells
- Total mass 10,818 kg
- Average concentration 4,270 mg/L
- Deep injection from 18 m to 27.5 m depth below land surface (cover bedrock and till surface)

GEOPHYSICAL DATA COLLECTION AND ANALYSIS

Methods

- Direct-Current Resistivity Surveys
  - Two Dimensional Field Surveys
  - Sediment Resistivity Lab Tests
- Electromagnetic (EM) Surface Surveys (Frequency Domain)
- Borehole Electromagnetic (EM) Induction Logging
- Borehole Neutron Density, Natural Gamma Ray and Fluid Logging

Direct-Current Resistivity Surveys

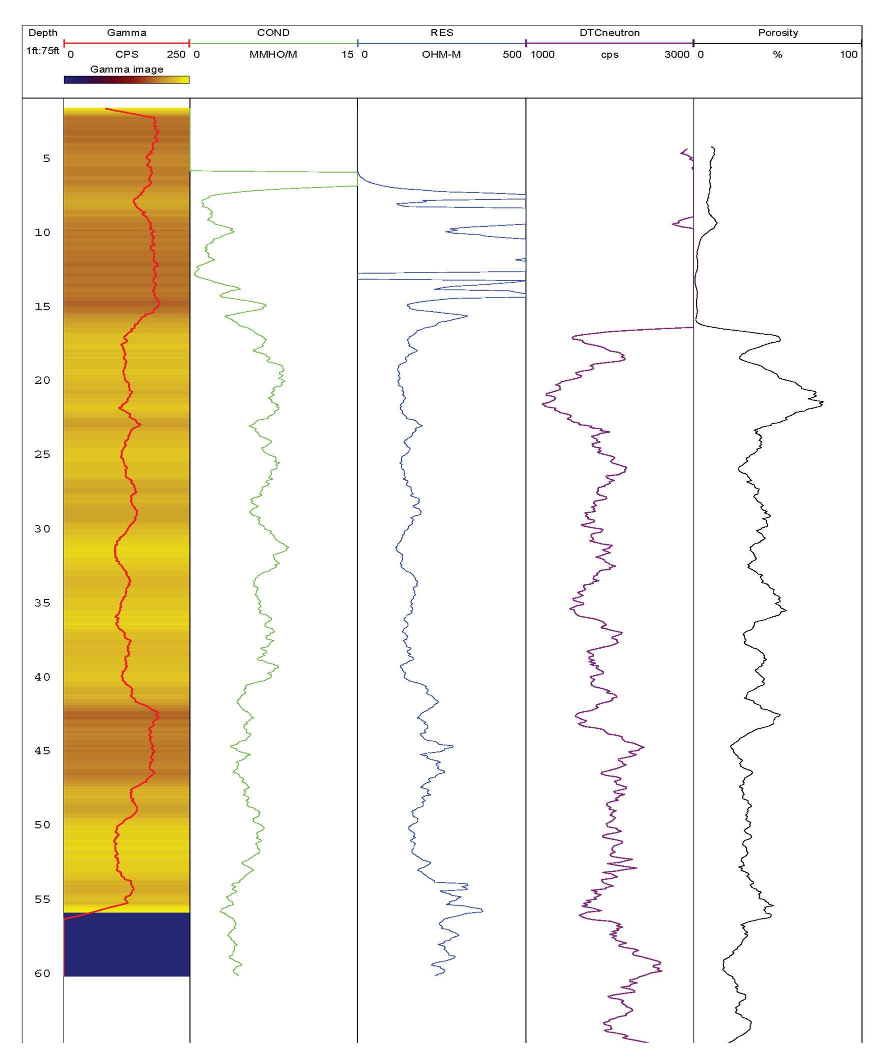
DC-resistivity surveys measure the electrical resistivity of the subsurface or test box core material to characterize lithology and water quality.

Two Dimensional Field Surveys

Dipole-dipole array, two dimensional (2D) DC resistivity survey results were processed to create cross sections of resistivity values with depth. Apparent resistivity data from the surveys represent a crude average affected by structure and lithology changes. These values are corrected for topography and reverse modeled to produce resistivity cross sections (estimated resistivity at a point) for interpretation. Multiple repeated surveys allow for identification of temporal change in bulk "electrical properties" from permanganate injections.

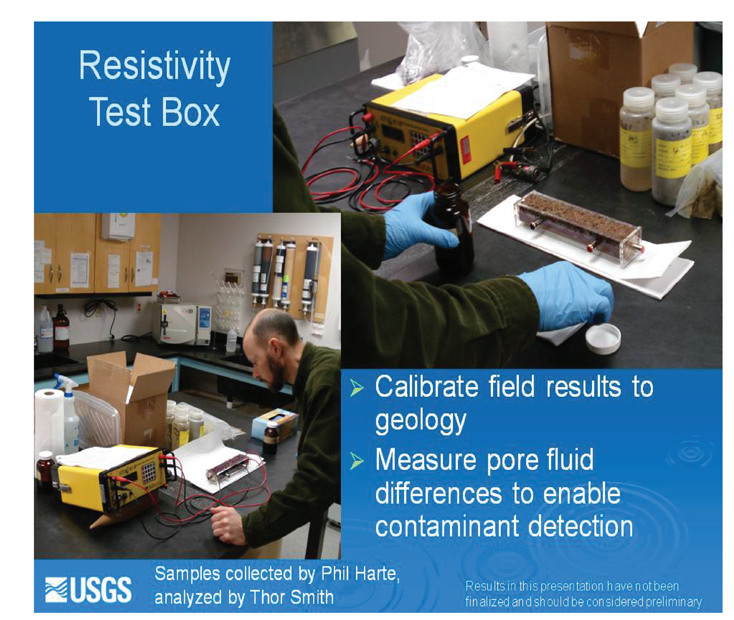
Borehole Geophysical Logging

The hydrostratigraphy and important physical parameters such as porosity can be mapped with use of borehole geophysical logging. The use of borehole electromagnetic induction logging in time series mode with multiple temporal measurements allows for an evaluation of temporal change in bulk "electrical properties" from permanganate injections.



Sediment Resistivity Lab Tests

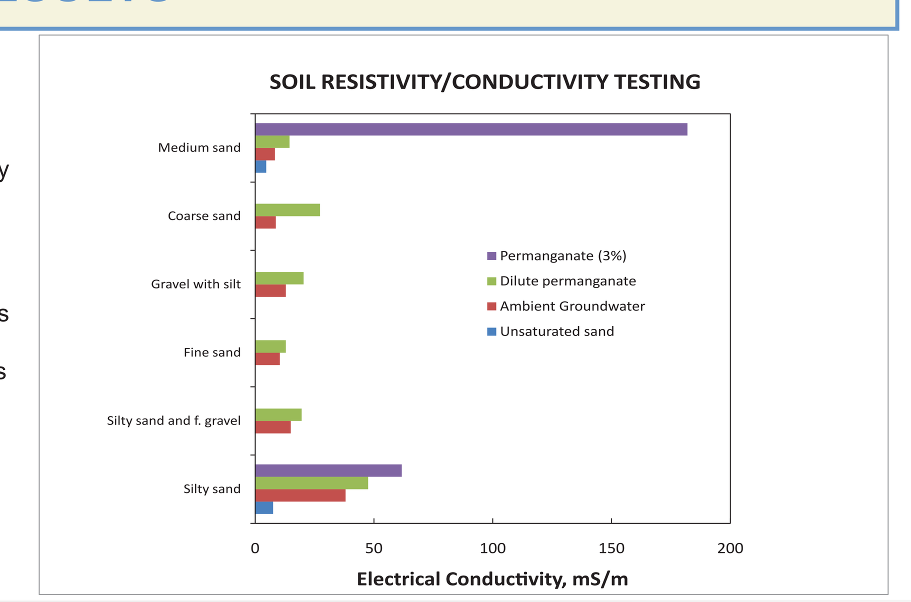
Sediment resistivity was lab tested to help calibrate resistivity values encountered during field measurements of surface D.C. resistivity and borehole EM induction logging. Temporal changes in resistivity were measured as a result of exchanging various pore fluids and saturation levels. Pore-fluid conditions that were tested include unsaturated, saturated with ambient groundwater, dilute (10% of original 3 % solution) concentration of sodium permanganate) and full strength (3% permanganate) concentration of sodium permanganate. The pore fluids selected represent conditions likely encountered during time-series monitoring of the permanganate injection.



RESULTS

Resistivity Sediment Tests

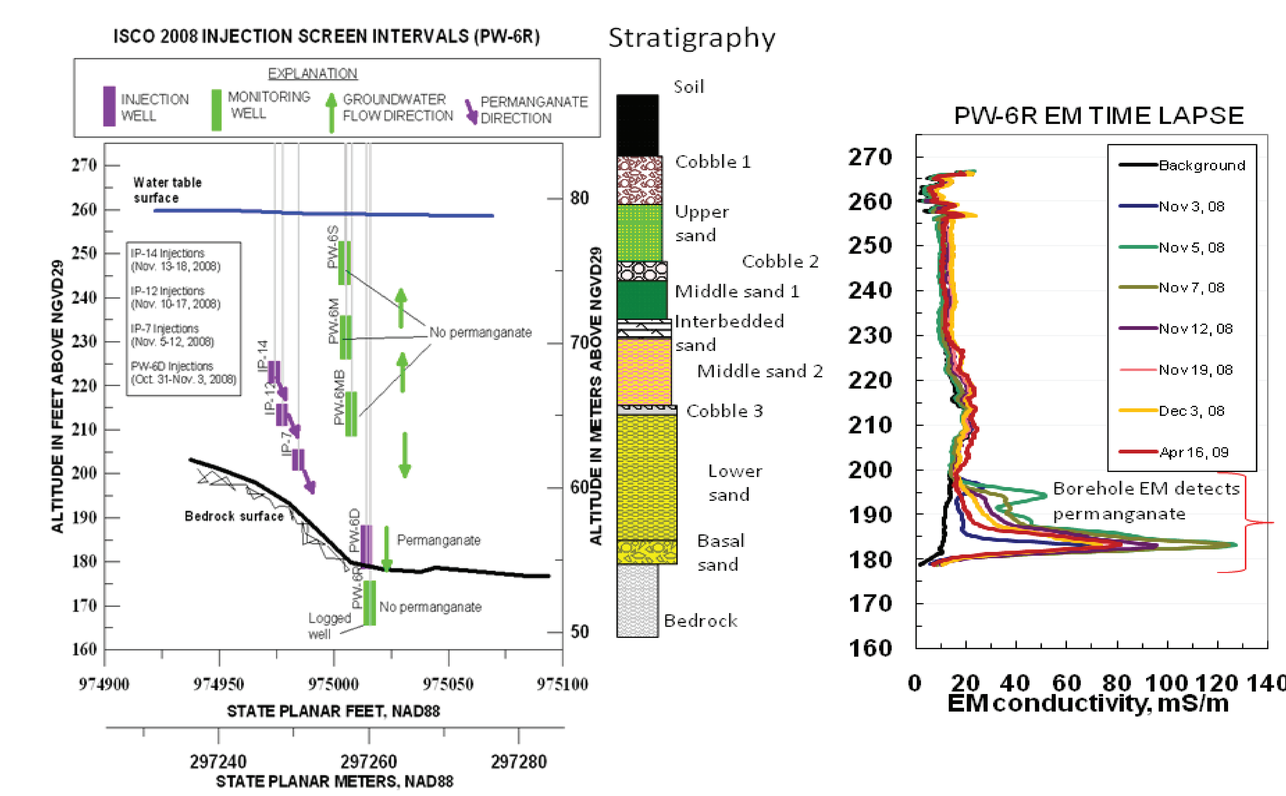
The results from the laboratory testing of sediment resistivity, inverted to calculate conductivities, show that the highest permeability units will experience the greatest increase in conductivity due to injection of permanganate. A greater than 50 % increase was measured for the permeable samples when permanganate was added. In contrast, only a 20% increase was measured for the low permeability units. Part of the reason for the small change in conductivities when permanganate is introduced into low permeability units is the initial high conductivity of its sediments. Another important reason is the difficulty in completely exchanging the pore spaces of the low permeability units with permanganate.



RESULTS

Borehole Electromagnetic Induction Logging

Time-lapse EM borehole logging in observation wells showed that sodium permanganate injectate from the injection wells is initially transported laterally within 1 to 1.5 m (3 to 5 ft) thick layers and then spreads vertically downward, due to density differences between the injectate (specific gravity of about 1.1 %) and groundwater. Because the EM log can measure outside the solid polyvinyl chloride (PVC) wall of the well, it can detect the spread of the injectate through the full penetration of the well and not just the screen interval.



Borehole EM Logging (PW-6R example)

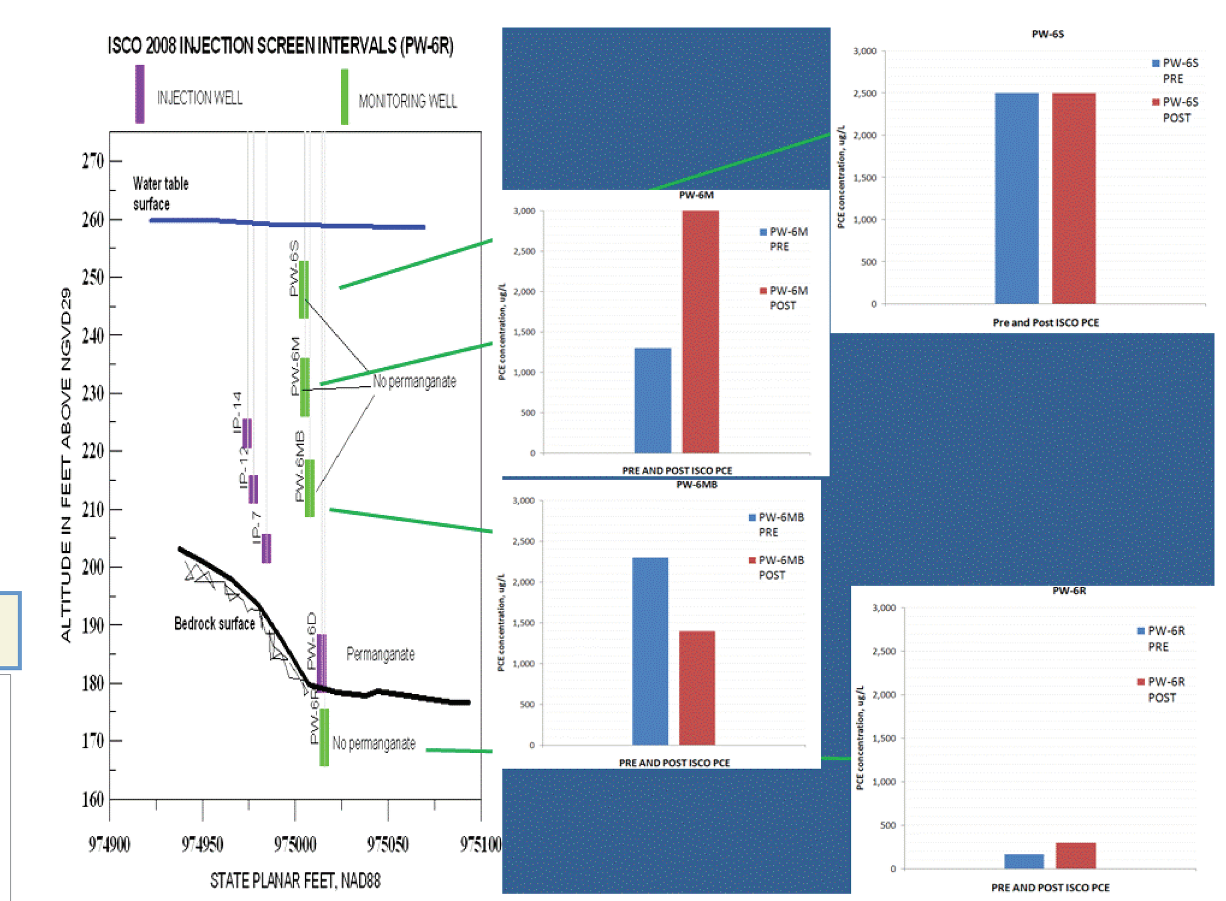
- Borehole EM log detects permanganate above bedrock surface in a cased section of the well
- Bedrock water sample shows no permanganate in bedrock confirming pooling ontop of bedrock surface
- Permanganate not detected in wells above bedrock surface confirming density effects

Archie Law Correction

- EM conductivity can be converted to pore-water conductivity by use of Archie's Law
- In this example, an EM conductivity of 127 mS/m is equivalent to pore water saturated with 2% permanganate solution

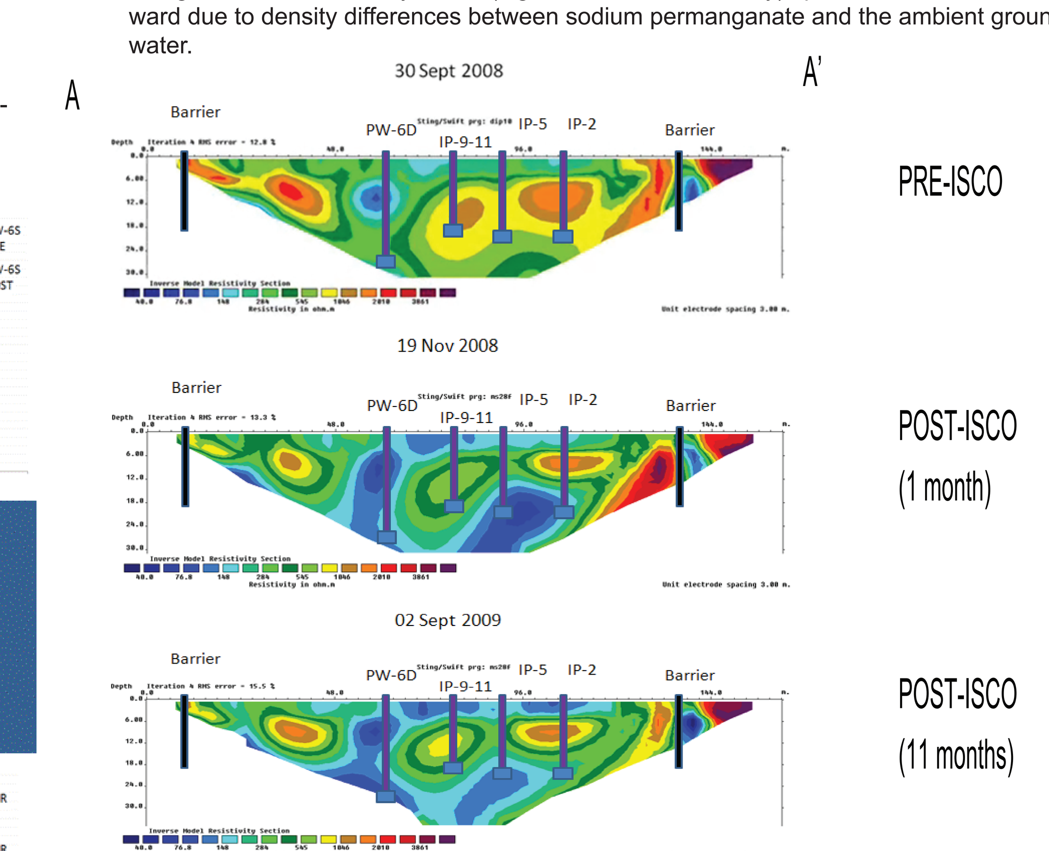
PCE Change

PCE concentrations in monitoring wells pre- and post-injection, shown by blue "pre" and red "post" bar graphs, corroborate findings from EM logging indicating that because of density flow, permanganate spread primarily downward and not lateral. Observation wells screened near the till/bedrock surface had the greatest decrease in PCE concentrations. In general, observation wells above the till/bedrock surface showed small decreases in PCE concentration. Here we see the shallower, intermediate depth wells (PW-6MB and PW-6M) showing contrasting PCE temporal changes.



Two Dimensional D.C. Resistivity Surveys

Repeated D.C. resistivity surveys through the middle of the interior barrier area identified temporal changes in bulk electrical resistivity from the injection and spread of permanganate. Low resistivity zones (high electrical conductivity) spread and moved downward due to density differences between sodium permanganate and the ambient groundwater.



CONCLUSIONS

Collectively, the time-series geophysical monitoring program showed that due to density contrasts between sodium permanganate and groundwater, injected permanganate was transported laterally and downward. No geophysical responses occurred at an elevation higher than the adjacent injection well screen elevation. Most EM conductivity responses were recorded near basal stratigraphic contacts like the top of till and bedrock.

Conceptually, the injection of permanganate at OU1 can be viewed as spreading like an inverted cone-shaped cloud until it hit the till or bedrock surface. The monitoring program also showed the difficulty at several injection wells to penetrate into low permeability units when the injection well screens crossed units of contrasting geological heterogeneity and permeability.

The geophysical monitoring program provided enhanced mapping capability. At sites with geologic heterogeneity and where injection and(or) monitoring wells are partially penetrating with relatively short screens, conventional well sampling may miss the spread of permanganate. A time-series geophysical monitoring program allows for the delineation of the spread of permanganate so that a better assessment can be made of target zone treatment.

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