Enhanced Bioremediation of Chlorinated Solvents in Fractured Bedrock Aquifers

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Background/Objectives. Fractured bedrock aquifers can be extremely heterogeneous which not only results in complex dissolved plume behavior but can also hinder bioremediation efforts that rely on subsurface injection of amendments to promote microbial activity or abiotic degradation. Simply put, injected amendments may bypass or have limited contact time with impacted zones due to transport differences within primary and secondary rock porosity and other subsurface heterogeneities. With thorough characterization of site hydrology, routine performance monitoring, and an adaptive site management approach however, bioremediation can be successful in fractured bedrock aquifers. The current studies describe pre-injection hydrogeologic characterization (pumping and dye tests), focus on implementation of enhanced anaerobic bioremediation and combined bioremediation/in situ biogeochemical reduction, and illustrate the importance of post-injection performance monitoring and remedy optimization.

Approach/Activities. The study sites are former industrial facilities where the fractured bedrock aquifers have been impacted by chlorinated solvents including trichloroethene (TCE), trichloroethanes (TCA), 1,2-dichloroethane (DCA), and degradation products. At Site A, pumping tests (step drawdown, constant rate, and recovery) were used to estimate hydraulic characteristics including transmissivity, conductivity, effective porosity and groundwater velocity. In addition, dye tracer studies (Eosine and Fluorescein) were conducted concurrently with injection of electron donor and abiotic stimulants and immediately following the injections. For both sites, groundwater monitoring included analysis of contaminant concentrations, VFA production and geochemical parameters such as dissolved iron, sulfate and methane. Baseline and post-injection groundwater monitoring also included qPCR and QuantArray quantification of key organohalide-respiring bacteria (e.g., *Dehalococcoides*) and functional genes (e.g. vinyl chloride reductases) to evaluate performance of biostimulation.

Results/Lessons Learned. At Site A, pumping and slug tests indicated that hydraulic conductivity was on the order of 1×10^{-3} in the fractured sandstone aquifer. The initial dye tracer study revealed substantial interconnections between fractures and was used to estimate the radius of influence of amendment injections. While detected, abundance of *Dehalococcoides* (10^1 cells/mL) and *Dehalobacter* (10^2 cells/mL) were low and vinyl chloride reductase gene copies were near detection limits during baseline sampling. In the spring of 2016, a combination of electron donor, sulfate, and ferrous iron was injected at Site A. Based on the detection of the dye in downgradient wells, the observed radius of influence was extensive and the monitoring network was expanded. While additional groundwater sampling events will be conducted, initial performance monitoring confirmed substantial increases in populations of halorespiring bacteria. At Site B, vertical connectivity was limited rendering the air sparging infeasible, but horizontal fractures were significant which led to groundwater velocities on the order of 5 to 70 m/year. As with Site A, concentrations of organohalide-respiring bacteria were initially low. Following electron donor injection, *Dehalococcoides* increased dramatically and remained at concentrations greater than 10^5 cells/mL for over three years. Overall, the results of the case studies conclusively demonstrate that with thorough characterization and performance monitoring in situ bioremediation is not only feasible but effective in fractured bedrock aquifers.