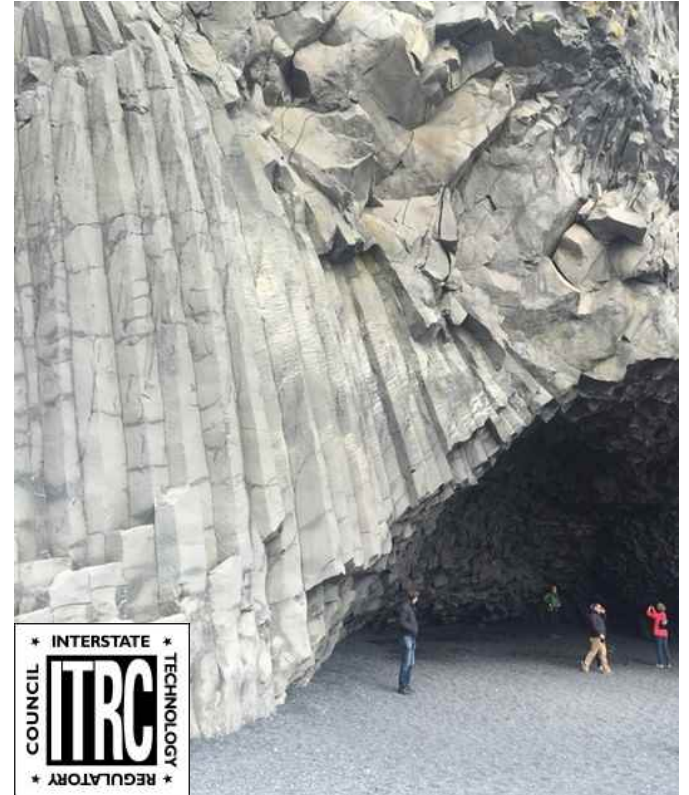




Optimizing Remediation in Bedrock: Lessons from Successful Injection Projects

Paul M. Dombrowski, P.E.

- Incomplete understanding of groundwater flow and contaminant transport
- Difficulties in site characterization
- Cost of investigation / remediation
- Unrealistic remedial objectives
- Selected remedy is ineffective

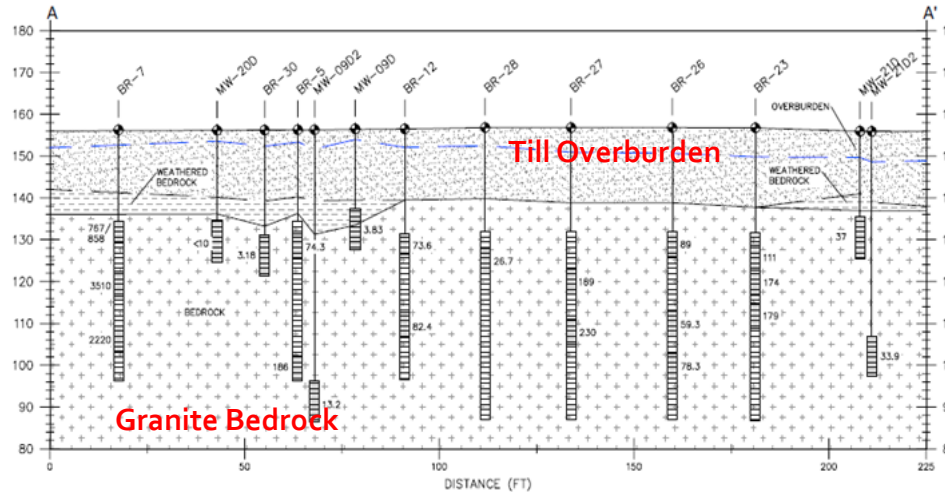


Characterization and Remediation of Fractured Rock (FracRx-1) <http://fracturedRX-1.itrcweb.org>

- **Remedial design based on conceptual site model**
 - Where is the contamination?
 - Where is it traveling?
 - How did it get there?
 - What are proposed amendments?
 - How do geologic features impact above questions?
- **Objective: maximize contact between contaminants and remediation reagents**
- **Injected amendments likely to follow path similar to groundwater flow**

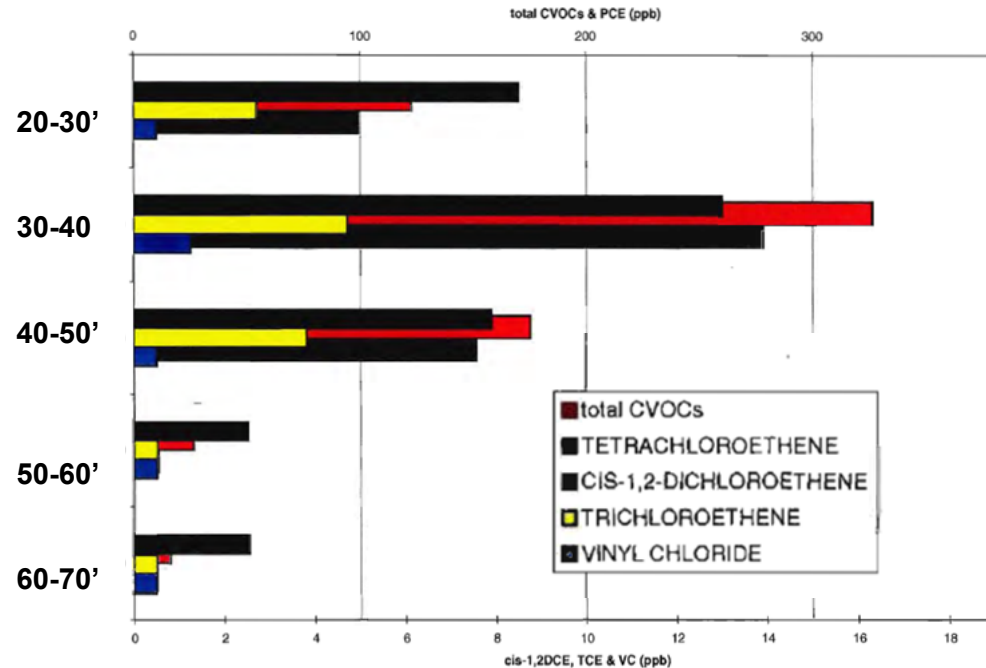


- Site previously contained a 500-gallon UST to store waste oil generated during vehicle maintenance (removed in 1991)
- Petroleum hydrocarbons, LNAPL, and PCE measured in soil & groundwater
 - Focused excavation addressed LNAPL
 - CVOCS detected in bedrock 25 – 120' bgs
- **Site Geology**
 - 15-20 Feet Till (sandy upper till & dense basal till)
 - Granite Bedrock



■ Initial Bedrock Investigation (1997-2000)

- Outcrop fracture survey
- Bedrock Core Extraction
- Borehole Geophysics (2 locations)
- Fracture Permeability Test
 - 4.3×10^{-5} to 2.6×10^{-4} cm/s
- Interconnectivity Testing
- Bedrock Porosity (0.17%)
- Bedrock Packer Sampling



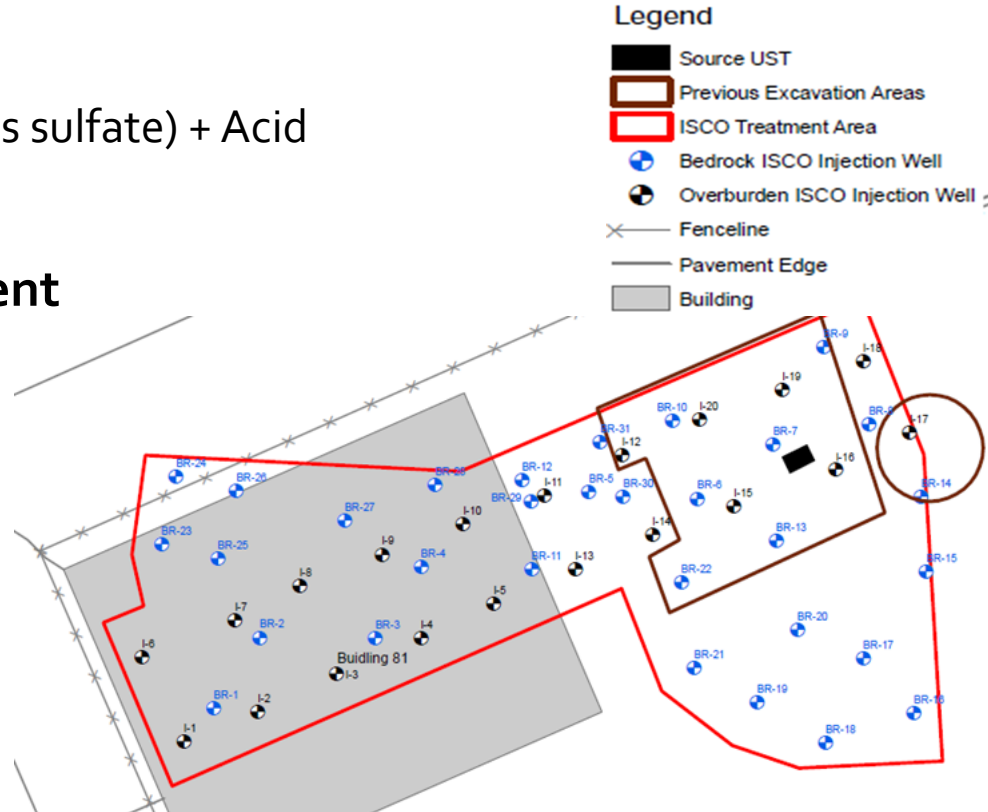
■ Fenton's Reagent

- H₂O₂ (5-15%) + Iron Catalyst (ferrous sulfate) + Acid
- Produce Hydroxyl Radicals (OH•)

■ Considerations for Fenton's Reagent

- Acidified to Keep Fe in Solution
- Exothermic reaction
- Pressure build up in subsurface

- **20 overburden injection wells**
- **31 bedrock injection boreholes**

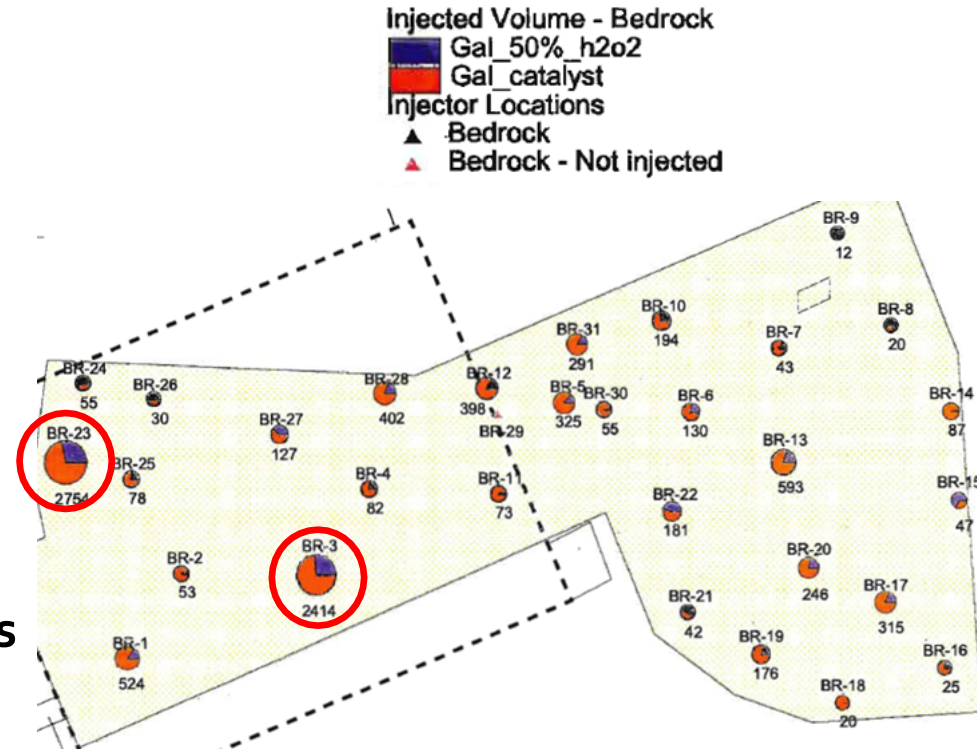


- **2 Injection Events**

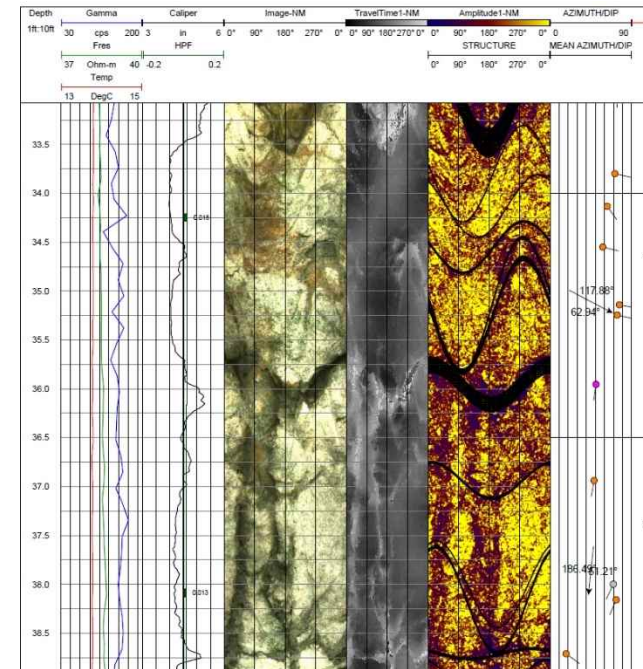
- October 2000 (H₂O₂ to 16 BR points)
 - March 2001 (H₂O₂ to 21 BR points)

- **60% of H₂O₂ injected in 2 points**

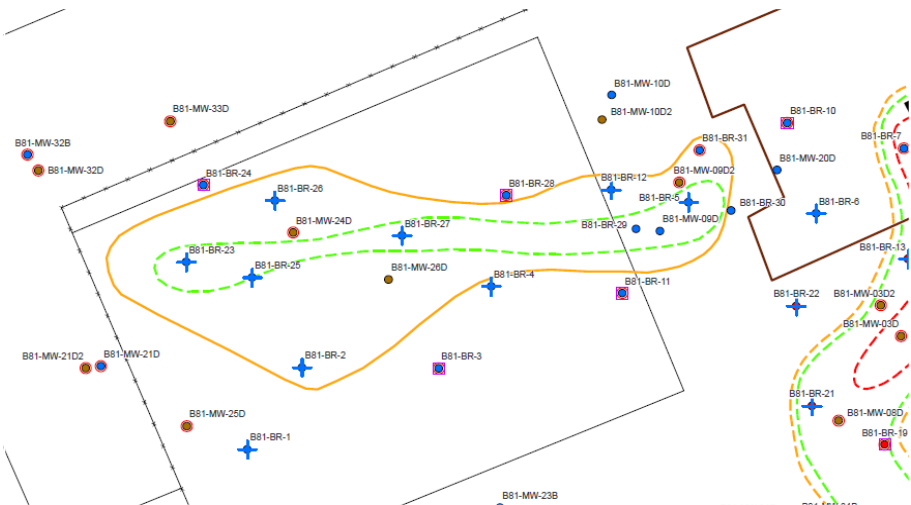
- **Most monitoring wells did not show influence or change in CVOCs**



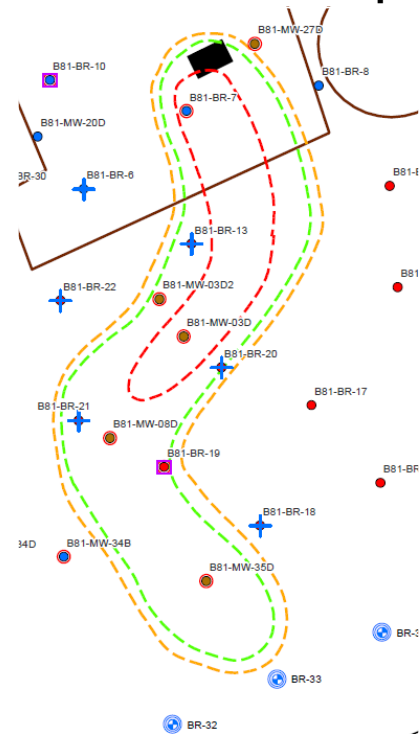
- **Record of Decision:**
 - Enhanced Reductive Dechlorination (10+ years post ISCO)
- **Objective: Understand Each Borehole**
- **Borehole geophysics at all boreholes where possible (~20)**
 - caliper, fluid temperature, fluid resistivity, natural gamma, optical and acoustic televiewer, and heat pulse flow meter
 - installed new wells/boreholes
- **Packer sampling of water bearing fractures**
- **Interconnectivity Testing**
- **Two different plumes identified**
 - RI/ROD only had one plume



West Bedrock Plume: Shallow <50 ft



South Bedrock Plume: Deep >50 ft



- Geochemical signatures differed between plumes
- ROD treatment zones missed one plume & only included a portion of the other
- Treatment Zones modified

- **Large droplet EVO (SRS®-FRL) with added sodium lactate (QRS®-SL)**
 - Slow-release & fast-release electron donors
 - Bioaugmentation
- **17 Open Boreholes for Injection**
 - Volumes specified for each borehole & each fracture zone
 - 73 separate fracture zones
 - Inflatable packers used to target fractures 21- 120' bgs
 - Injection choreography with points sequenced based on connectivity testing

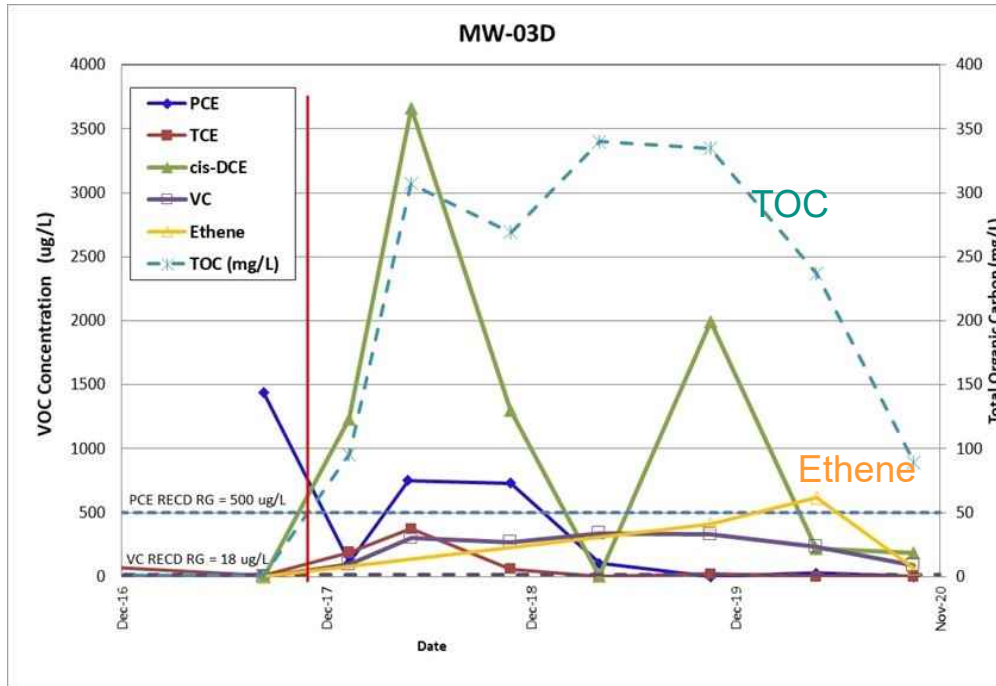


Enhanced Reductive Dechlorination

- Injected over 9,500 gallons (EVO + Lactate & Chase Water) with 37 L DHC
 - Average 0.6 gallons per minute
 - Inject into 3 -4 boreholes simultaneously
 - 21-day injection event
 - Same volume as 2 ISCO events
 - Each injection borehole received design volume

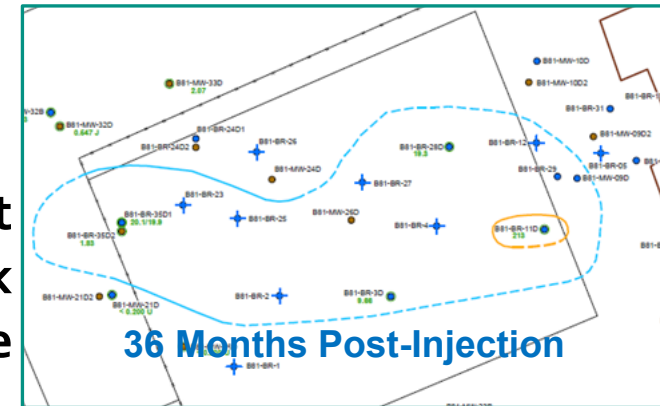
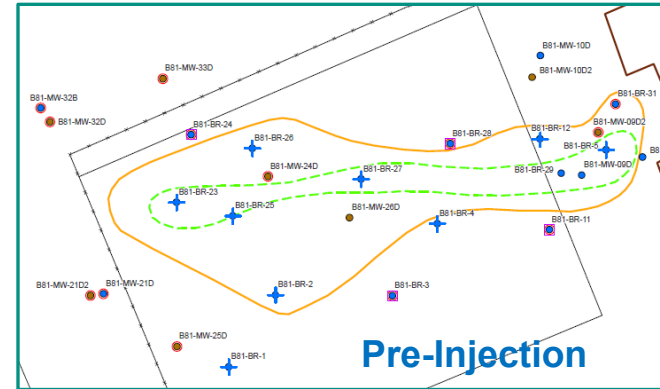
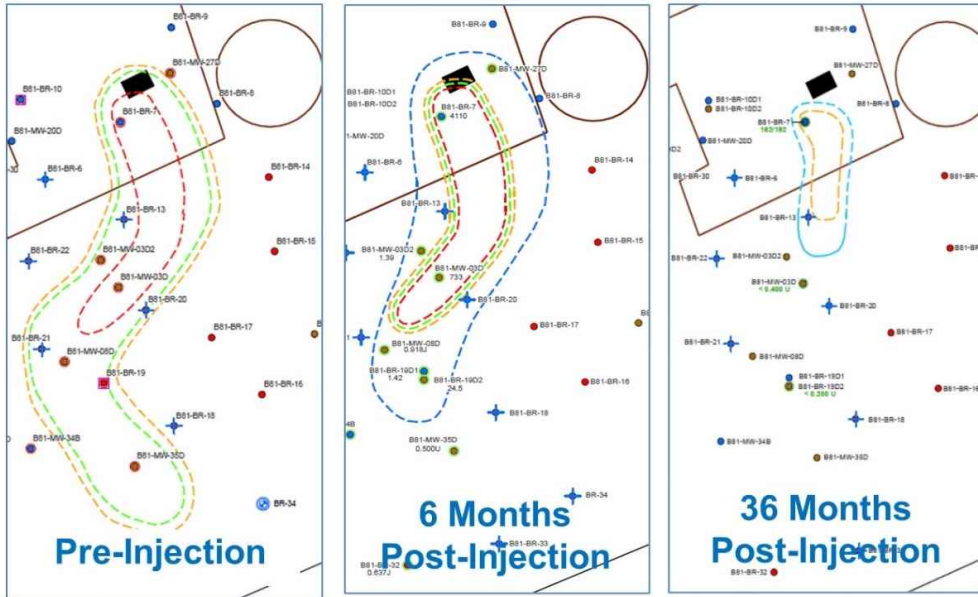


- 3 years post injection - Elevated ethene + DHC present



Post-Injection DHC Counts (cell / liter)			
Well	1 year	2 years	2.5 - 3 years
BR-35D2	<2.6E+03	4.0E+04	3.0E+04
MW-33D	2.0E+05	8.0E+04	1.0E+04
BR-11D	6.0E+04	6.0E+04	1.0E+05
BR-31	2.0E+05	2.0E+04	n/s
BR-3D	<1.3E+04	1.0E+06	4.0E+04
BR-19D2	5.0E+06	1.0E+06	1.0E+05
BR-37D2	4.0E+04	8.0E+03	n/s
MW-35D	4.0E+04	5.0E+04	n/s
BR-07	n/s	2.0E+07	1.0E+05
MW-03D	2.0E+08	4.0E+07	6.0E+05
MW-03D2	n/s	2.0E+03	n/s

South Bedrock Plume

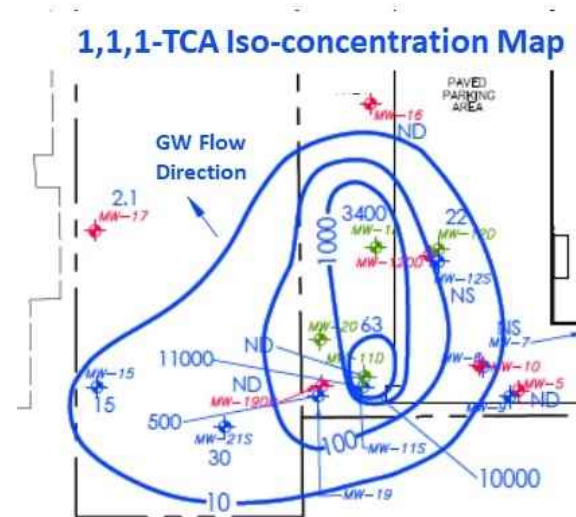


- Groundwater 5 ug/L PCE Contour
- Groundwater 55 ug/L PCE Contour
- Groundwater 110 ug/L PCE Contour
- Groundwater 500 ug/L PCE Contour

**West
Bedrock
Plume**

- Former manufacturing site
- CVOC impacted bedrock
 - sandstone, shale, siltstone, mudstone
 - groundwater flow primarily in secondary porosity
- CVOCs observed to the west & southwest

ug/L	MW-11	MW-18
1,1,1-TCA	17,000	6,000
1,1-DCE	21,000	25,000
TCE	23,000	17,000
cis-DCE	14,000	39,000



- **Reduce Source Area CVOC concentrations**
 - Below 1% NAPL solubility
- **Establish natural attenuation conditions**
 - Reducing trend for CVOC concentrations
 - Wells in injection area/source area
 - Wells downgradient of injection area (50 to 200 feet)



- **Enhanced In-Situ Dechlorination**

- ISOTEC fine-tuned the design
- Low pressure injection of liquid amendments to preferentially delivery to existing fractures

EISD Remediation	
Area Treated (sq ft)	17,000
Injection Interval (ft bgs)	25 - 55
Injection Locations	12
Injection Volume (gal)	34,000

- **Sequential injection of multiple EISD amendments**

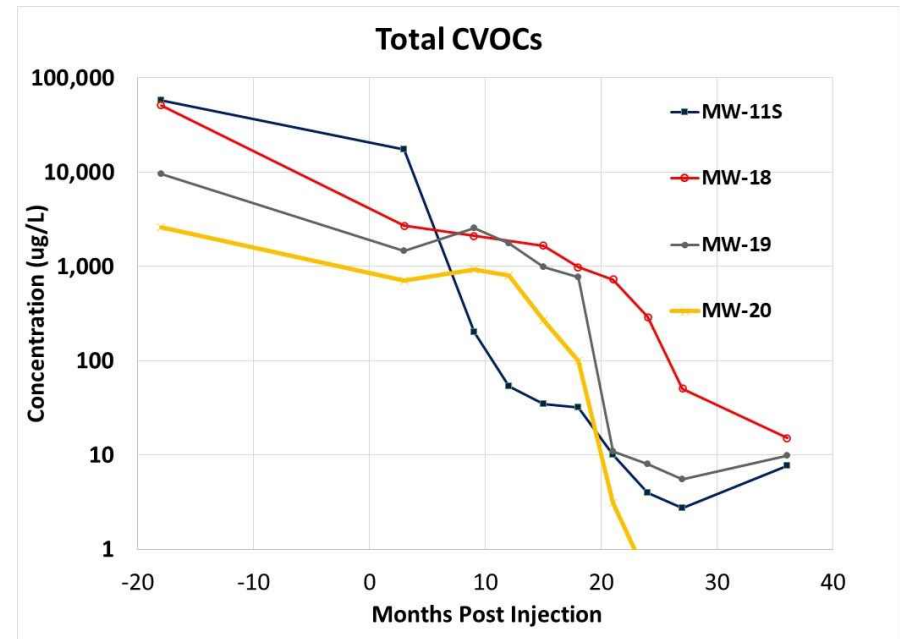
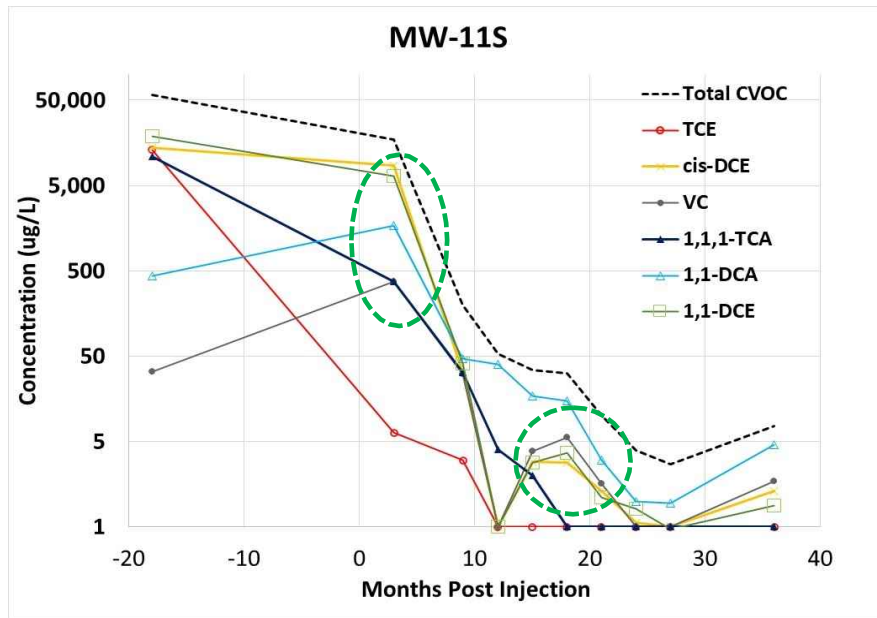
- Sodium Lactate (QRS™-SL-Plus with NutriPlus™): accelerate reducing conditions
- Small Droplet EVO (SRS-SD®): allow migration of organic carbon
- Large Droplet EVO with ZVI (SRS®-ZVI): keep EVO with ZVI in source area
- Blended Bioaugmentation culture with DHC & DHB
- pH Buffers

- **ISOTEC's scope included installation of 10 new injection boreholes**
 - Recommended geophysical assessment
 - Client decided not to proceed
- **Next best thing = hire an experienced driller**
 - ISOTEC field scientist and driller in constant dialogue on rates of advancement, exertion of rig, "feel" of the bedrock
 - Injection was limited in intervals where driller said "not many fractures" or "pretty hard down there"
 - Injection at lower pressures observed in intervals where driller noted more potential fractures

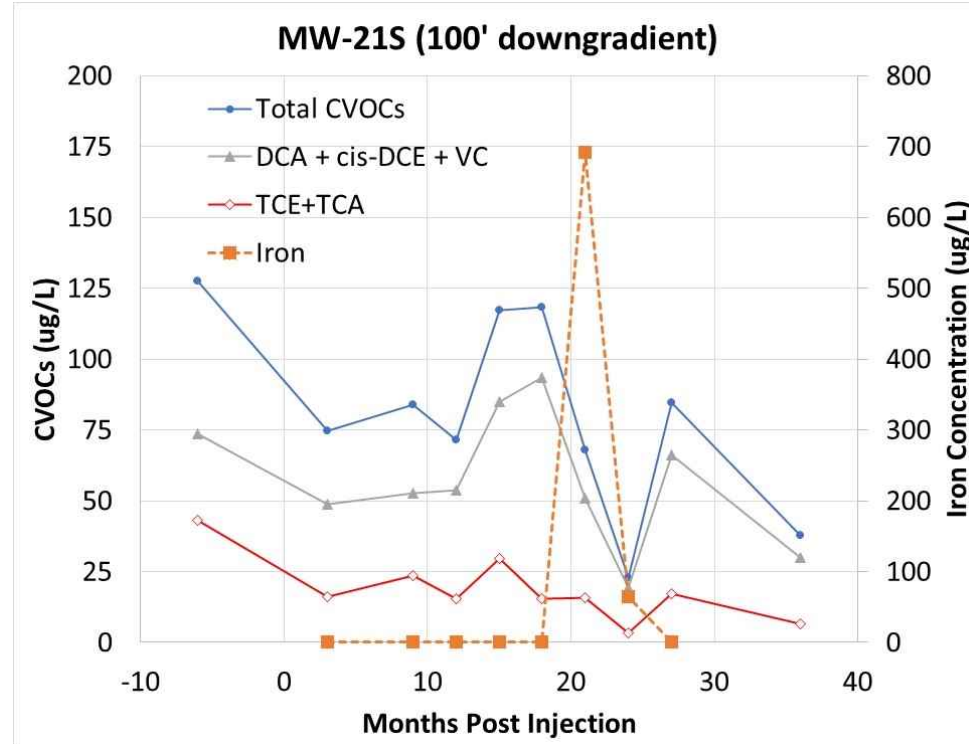


- 3 years of post injection
 - rapid reduction of CVOCs
 - abiotic & biotic

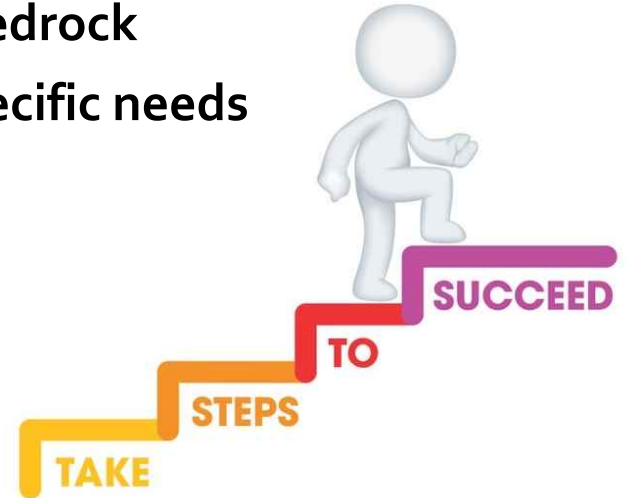
- >99% reduction in total CVOCs in all source area wells



- Reductive dechlorination lines of evidence observed 90-200 feet from injection area ~2 years after injection
 - increases in dissolved iron
 - decrease in sulfate
 - detection of lesser chlorinated VOCs
 - decrease in total CVOC concentration



- **Successful remediation can be performed in bedrock**
- **Tailor remedial design and reagents to site-specific needs**
 - Conceptual Site Model
 - Harness advantages using multiple reagents
 - Fast-acting + persistent reagents
- **Geology assessment**
 - Geophysics
 - Geologic logging





ISOTECH Field Crews for adaptability & safety-first culture
Tom Musser
Prasad Kakarla, P.E.
Mike Temple



Dick Raymond
Mike Lee, Ph.D.
Michael Free



Curt Weeden



Chemical Oxidation



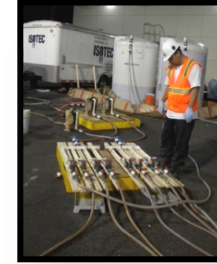
Bioremediation



Activated Carbon Injectates
(BOS 100® & BOS 200®)



Soil Mixing
(Chemical Reagents &
Stabilization)

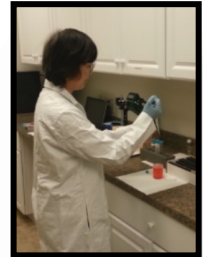
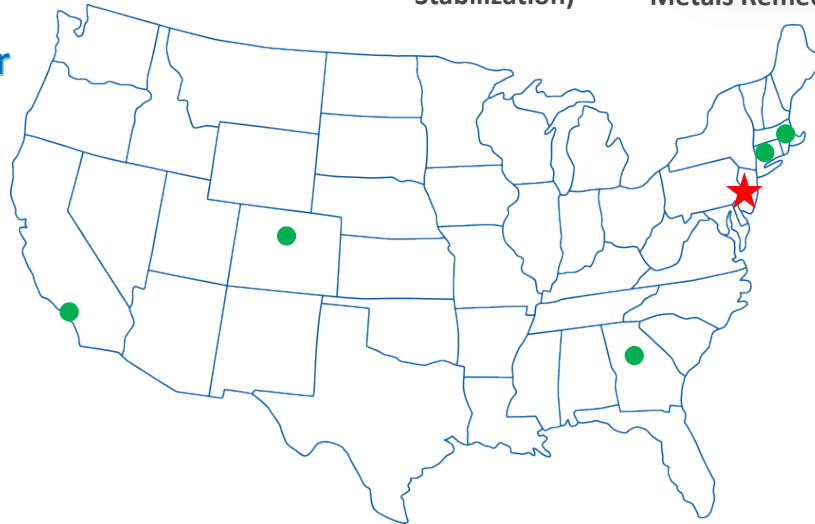


Metals Remediation



Bedrock Injections

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Treatability
Laboratory