# LEVERAGING THE CSM TO DEVELOP SUCCESSFUL BEDROCK REMEDIATION APPROACHES

## Concepts and Case Studies

Julie Konzuk, Leah MacKinnon – Geosyntec Consultants
Chapman Ross - FRx

# Presentation Outline

- Introduction to your speakers
- Problem statement
- Typical CSMs for bedrock sites
- Where geology meets engineering: concepts and considerations
- Case studies
- Take home messages

# Your Speakers Today

## Leah MacKinnon, Geosyntec

- MASc Civil Engineering
- 20+ years experience in remedial design and implementation at fractured bedrock sites, including US northeast, southeast and mid-west
- Experience with aerobic and anaerobic bioremediation, chemical oxidation, MPE, MNA and thermal applications in sedimentary, metamorphic, and crystalline bedrock environments

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## Julie Konzuk, Geosyntec

- PhD Civil Engineering / Contaminant Hydrogeology
- 20+ years experience in remedial design and implementation at fractured bedrock sites
- Experience with bioremediation, chemical oxidation, ZVI PRB, and thermal applications in sedimentary, metamorphic, crystalline, and basalt bedrock environments

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## Chapman Ross, FRx

- MS Environmental Engineering
- 20+ years experience in remedial design and implementation at fractured bedrock sites
- Experience with bioremediation, chemical oxidation, ZVI, and physical removal
- Experience with advanced injection methods for overburden and bedrock, including hydraulic fracturing and high-pressure jet injection

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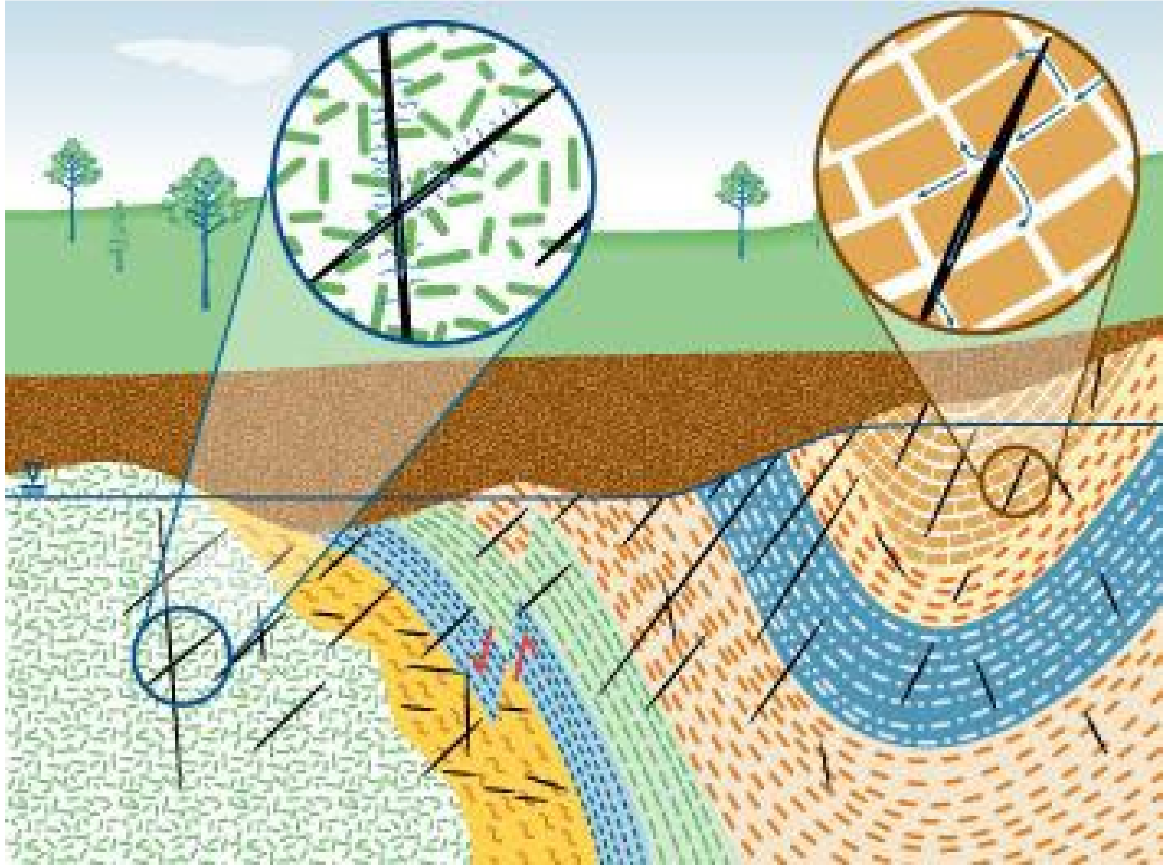
# Problem Statement

“**Fractured rock sites can be intimidating**, because remediating contaminated groundwater in fractured rock has not been widely conducted or studied” [ITRC 2017]

**The lack of a common framework, understanding**, or expectations regarding remediation objectives, assessment, and realistic endpoints hinder effective engineering” [NAS 2015].

**Here we aim to dispel the belief that fractured bedrock sites are too complex to remediate.**



https://fracturedrx-1.itrcweb.org/

# TYPICAL CONCEPTUAL SITE MODELS FOR FRACTURED BEDROCK SITES

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# Fracturing Features and Control on Contaminant Fate and Transport

## Type 1 – Single Porosity (fracture)

- ✓ Transport and storage in fractures

## Type 2 – Dual Porosity

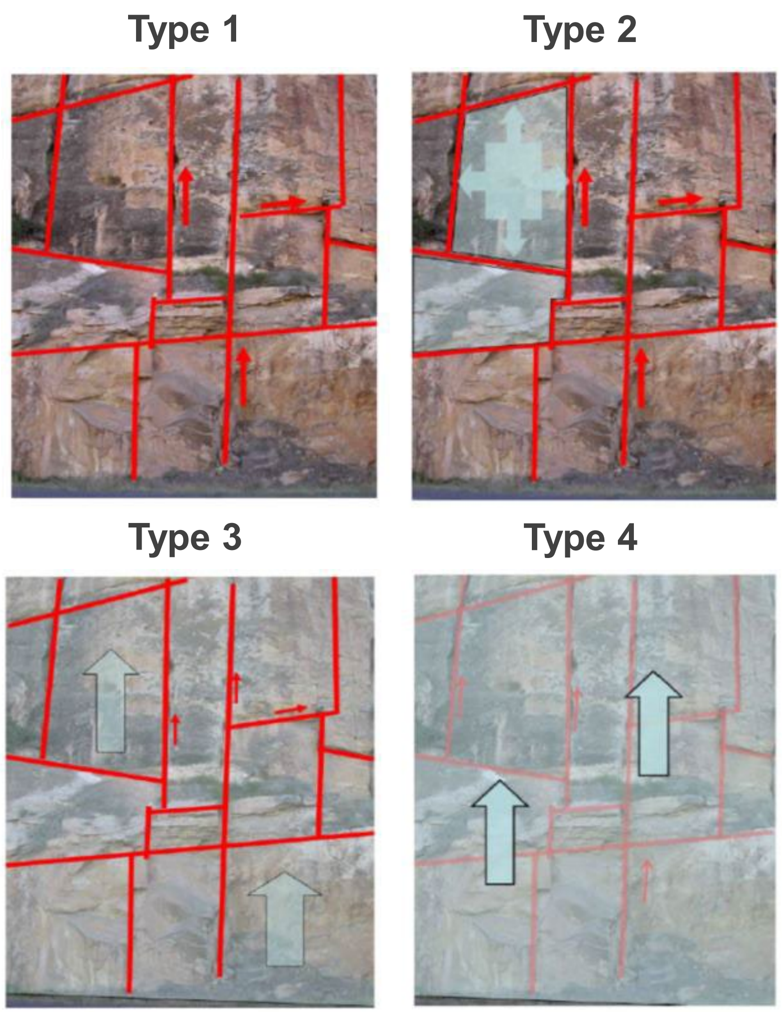
- ✓ Transport in fractures and storage in matrix

## Type 3 – Dual Permeability

- ✓ Transport and storage in fractures and matrix

## Type 4 – Single Porosity (matrix)

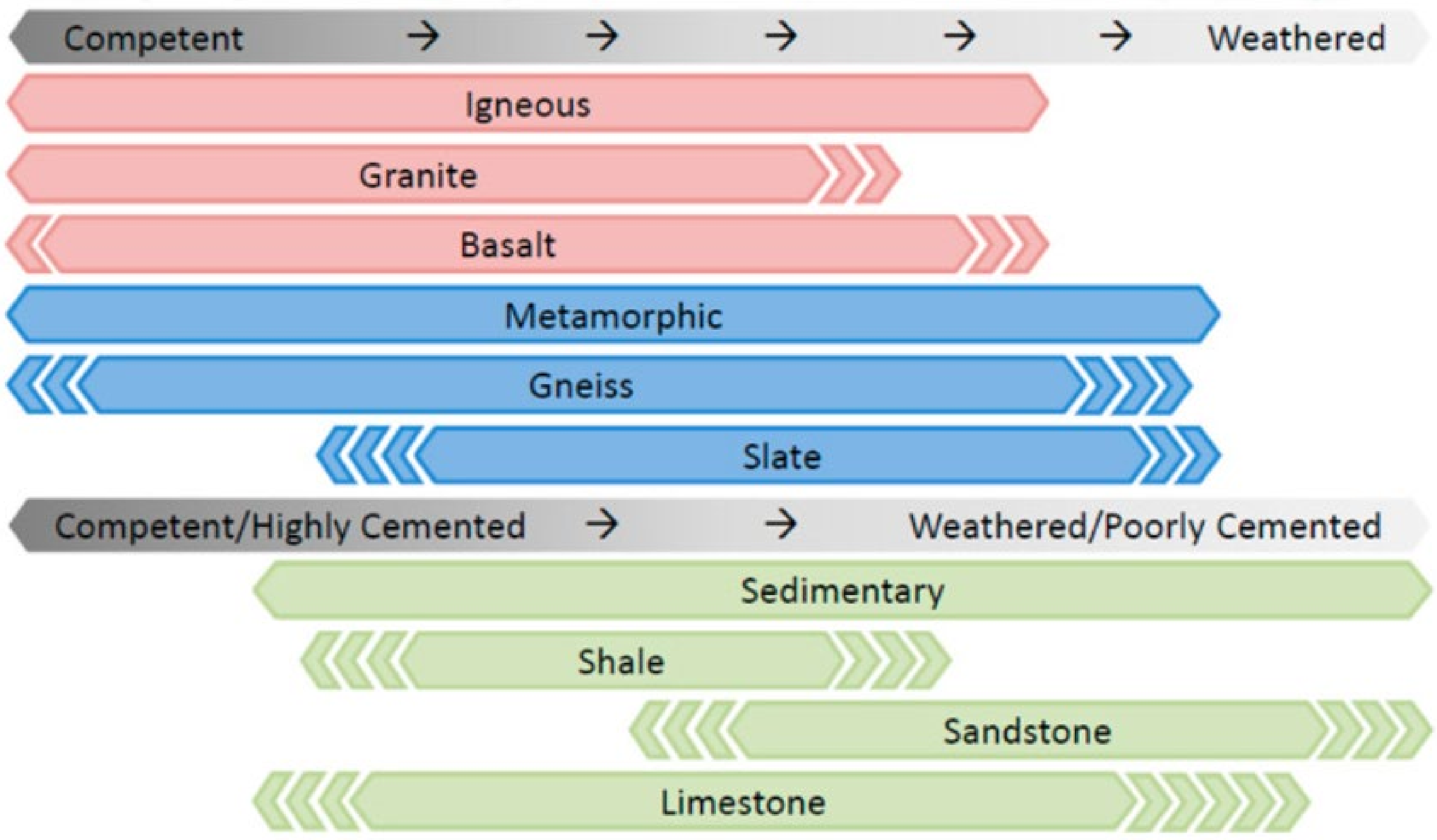
- ✓ Transport and storage in matrix with negligible influence from fractures




Adapted from National Academy of Sciences (2015)

# The Spectrum of Rock Types

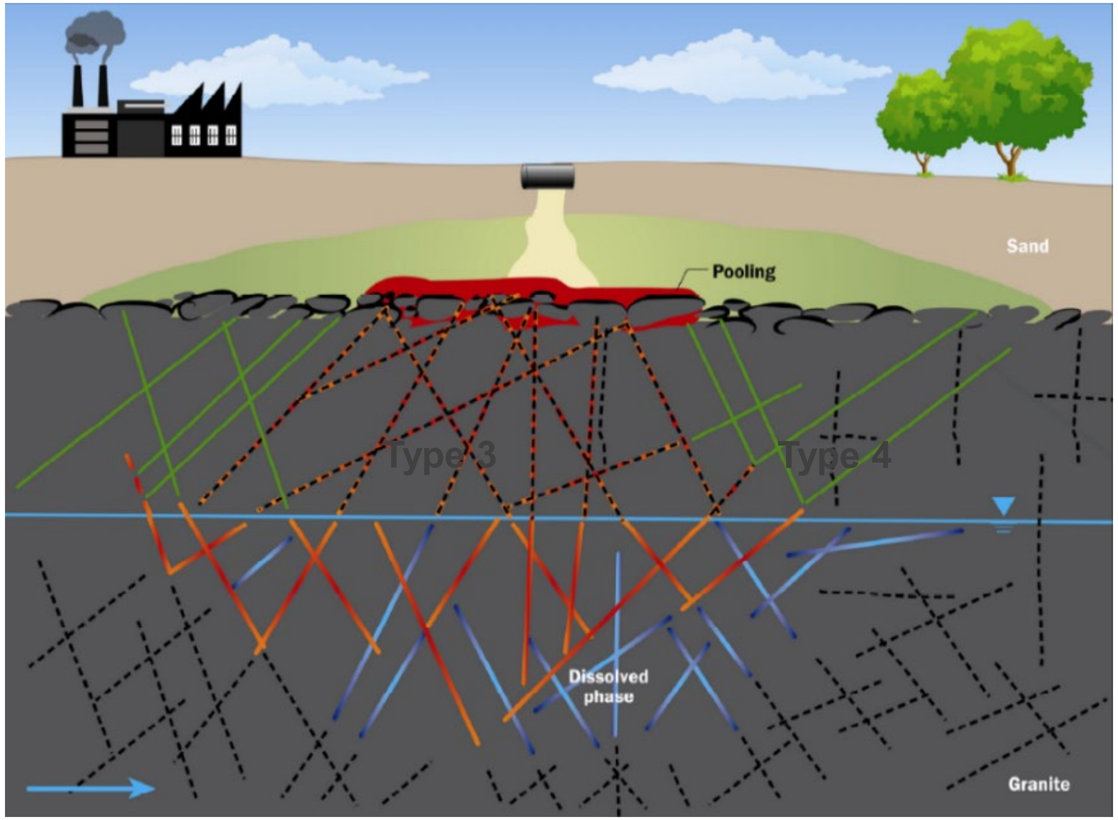
Type 1 → Type 2 → Type 3 → Type 4




From ITRC, 2018. *LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies*. LNAPL-3. Washington, D.C.: Interstate Technology & Regulatory Council. LNAPL Update Team.

# Conceptualization of Type 1 Bedrock Regime Single Porosity (Fracture)

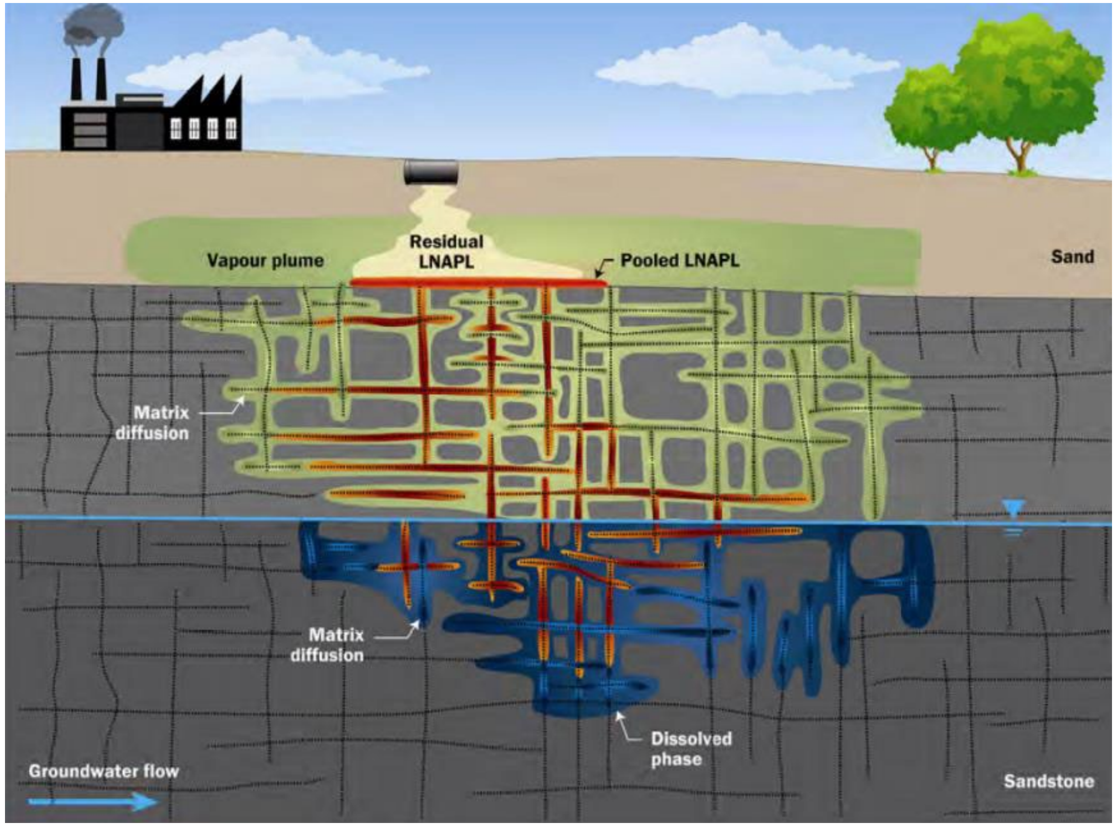
- **Examples** crystalline rocks
  - Igneous, metamorphic
- **Flow Regime** fracture porosity dominates flow and storage, matrix porosity non-existent or negligible
- **Contaminant Storage & Transport**
  - NAPL and aqueous sources largely reside in low-T fractures
  - Plume transport through complex network of high-T fractures
- **Common Challenges** Unpredictable transport pathways due to variable fracture density, orientation, and transmissivity




From CLAIRE (2015)

# Conceptualization of Type 2 Bedrock Regime Dual Porosity

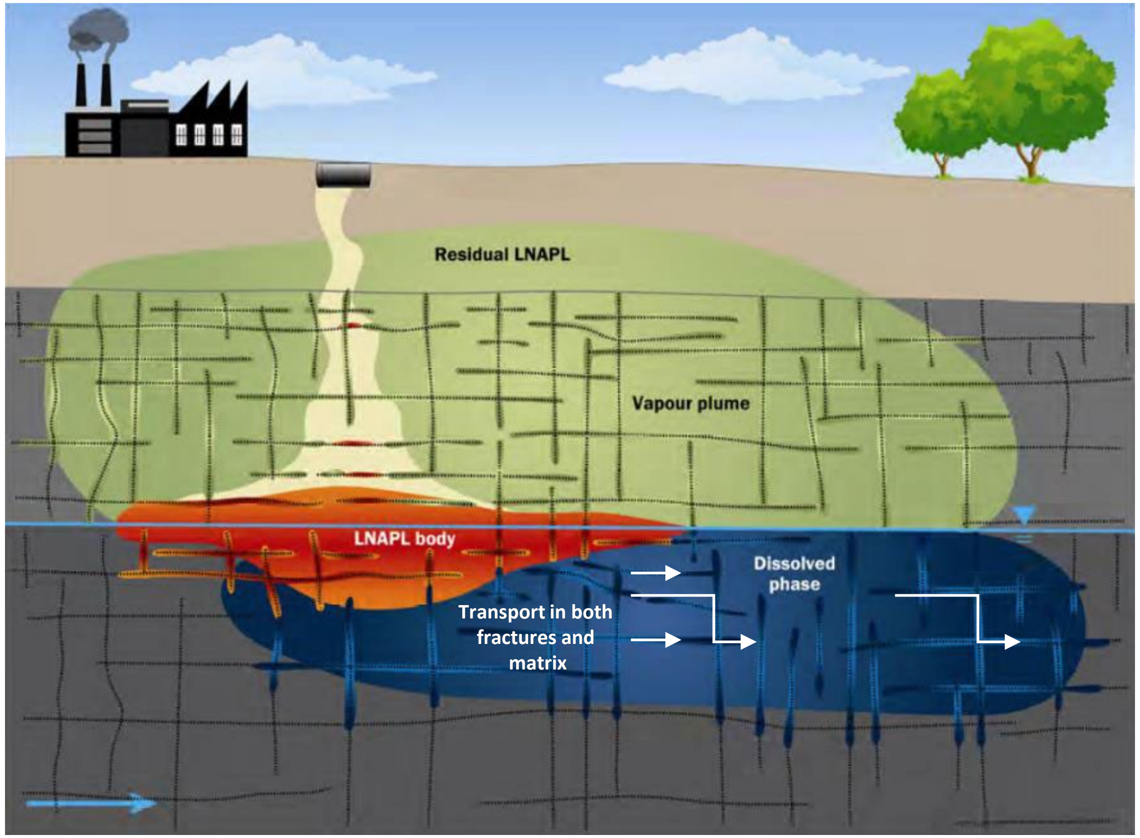
- **Examples** sedimentary rocks
  - Sandstone, siltstone, limestone
- **Flow Regime**
  - Fracture porosity along bedding planes
  - Joint sets dominate flow
  - Negligible flow through matrix
- **Contaminant Storage & Transport**
  - NAPL and aqueous sources stored in matrix porosity via diffusion
  - Plume transport through bedding plane fractures and x-cutting joints
- **Challenges**
  - Matrix storage difficult to access
  - Steeply dipping joint sets may not be apparent in rock core




From CLAIRE (2015)

# Conceptualization of Type 3 Bedrock Regime Dual Permeability

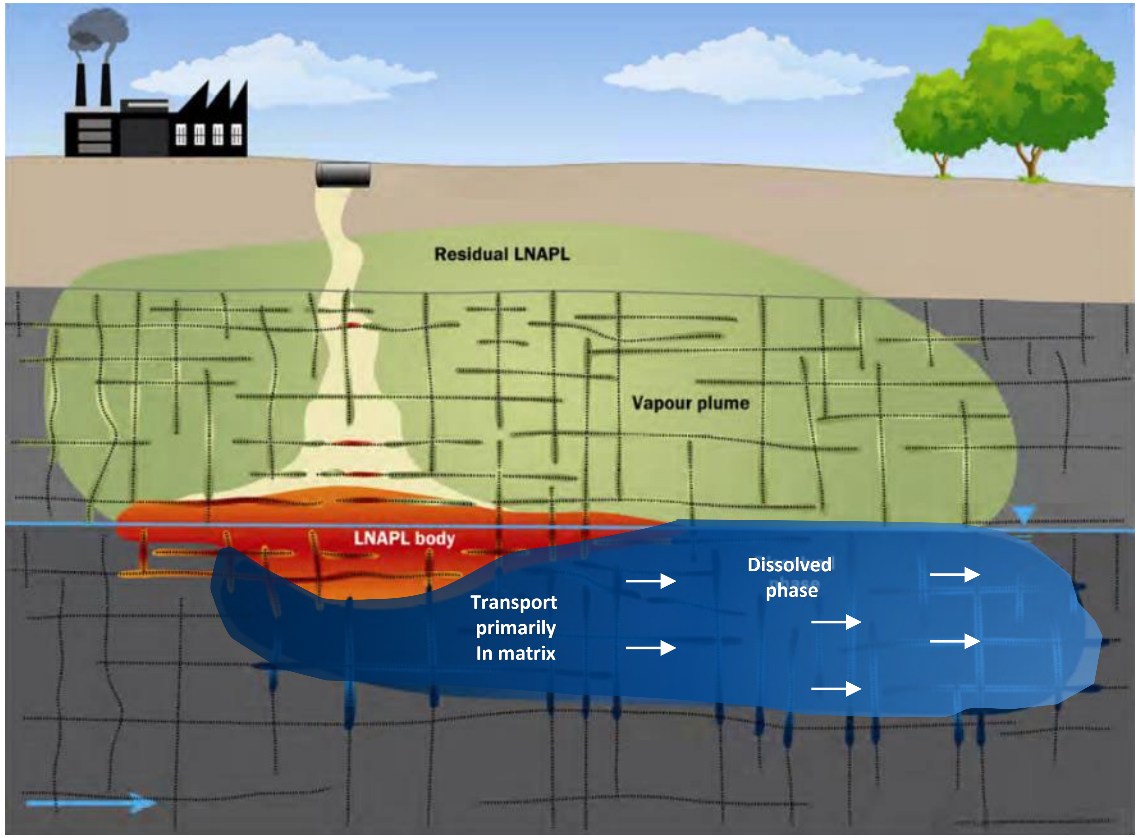
- **Examples**
  - Permeable sedimentary rocks (sandstone)
  - Partially weathered crystalline rocks
- **Flow Regime** fracture and matrix porosity both contribute to flow
- **Contaminant Storage & Transport**
  - NAPL and aqueous sources stored in matrix and fracture porosity
  - Plume transport through matrix predominates with variable contribution from fractures
- **Challenges** Penetrative storage of NAPL and aqueous sources




Adapted From CLAIRE (2015)

# Conceptualization of Type 4 Bedrock Regime Single Porosity (Matrix)

- **Example**
  - weakly fractured highly porous sandstone
- **Flow Regime** matrix porosity dominates flow and storage, fracture porosity non-existent or negligible
- **Contaminant Storage & Transport**
  - NAPL and aqueous sources stored in matrix
  - Plume transport largely follows Darcy flow
- **Challenges**
  - Penetrative distribution of contaminants
  - Potential source accumulation near contact with underlying, less weathered or competent bedrock




Adapted From CLAIRE (2015)

# Take Home Messages

Each bedrock site is unique. Ultimately remedial success requires a good understanding of the conceptual site model.

The degree of diffusion / sorption occurring, accessibility of source mass and matrix/fracture porosity

Groundwater and contaminant migration pathways (matrix, fractures)

Interconnection between contamination migration pathways

# WHERE GEOLOGY MEETS ENGINEERING: CONCEPTS AND CONSIDERATIONS

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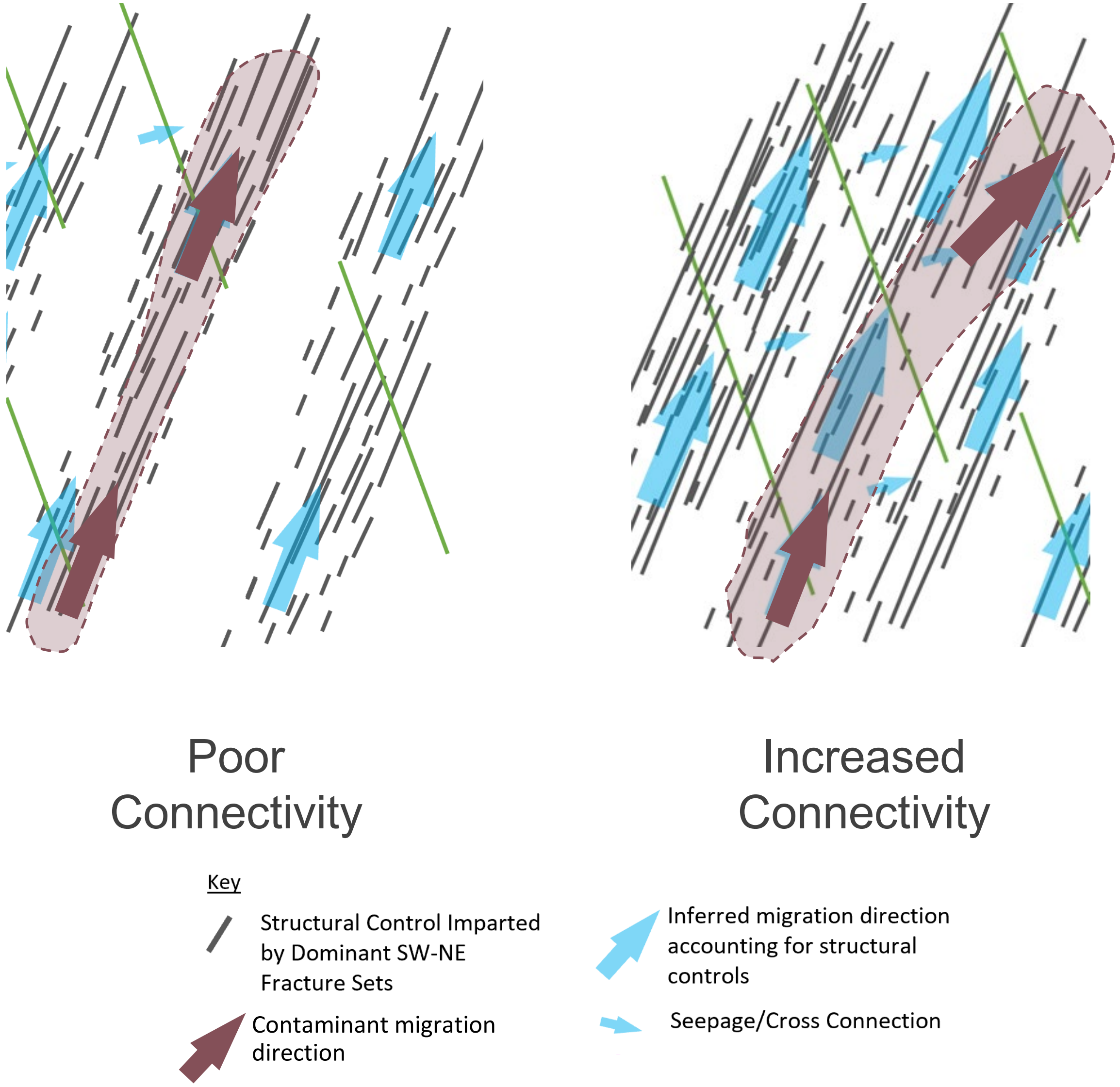
# Key Concepts and Considerations that may Drive Remedial Approach / Success

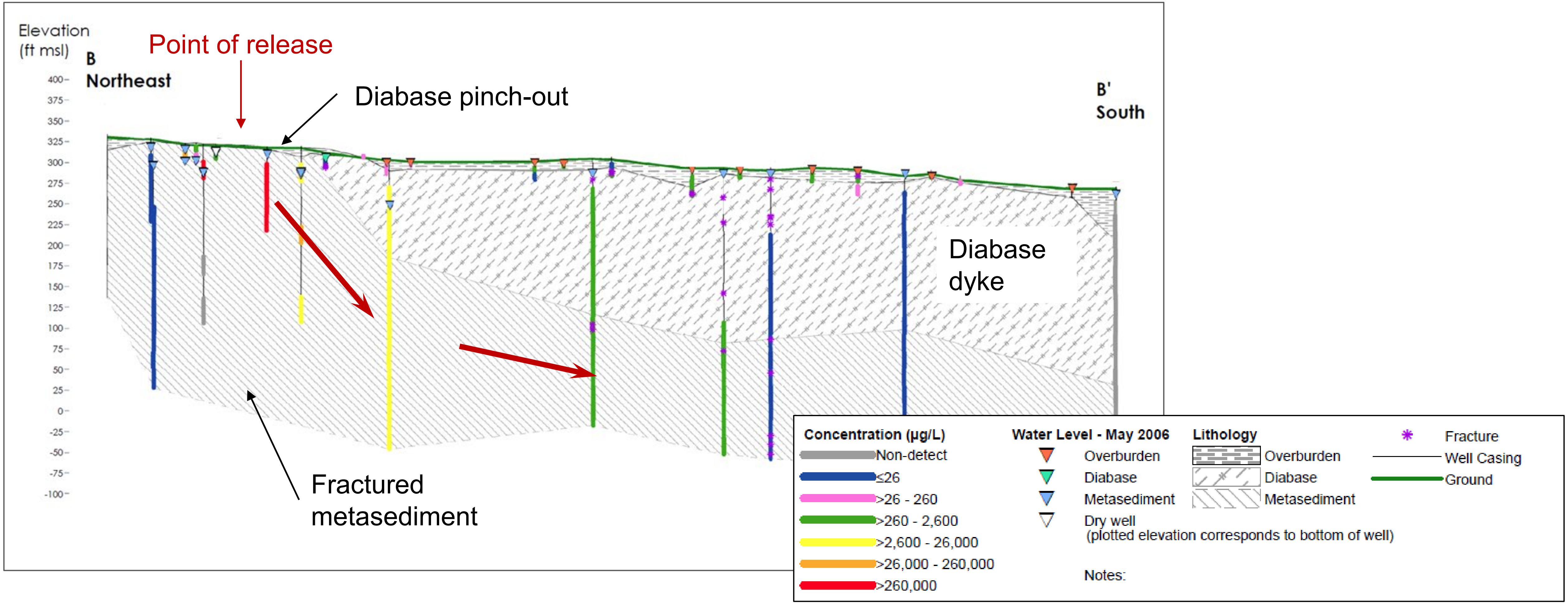
- Influence of bedrock structure on migration of contaminants and amendments
- Influence of bedrock structure on success of remedial implementation
- Potential for mobilization of contaminant mass and/or altered flowpaths
- Opportunities to overcome limitations in bedrock porosity
- Accessibility of source mass (primary and secondary)
- Defining performance criteria and endpoints

# Influence of Bedrock Structure on Migration of Contaminants and Amendments in Bedrock

In most bedrock settings, contaminant and amendment migration behavior is dominated by the fracture structure and degree of interconnections.

In poorly connected fracture environments, contaminant pathways can be missed, and amendment may bypass contaminated zones.

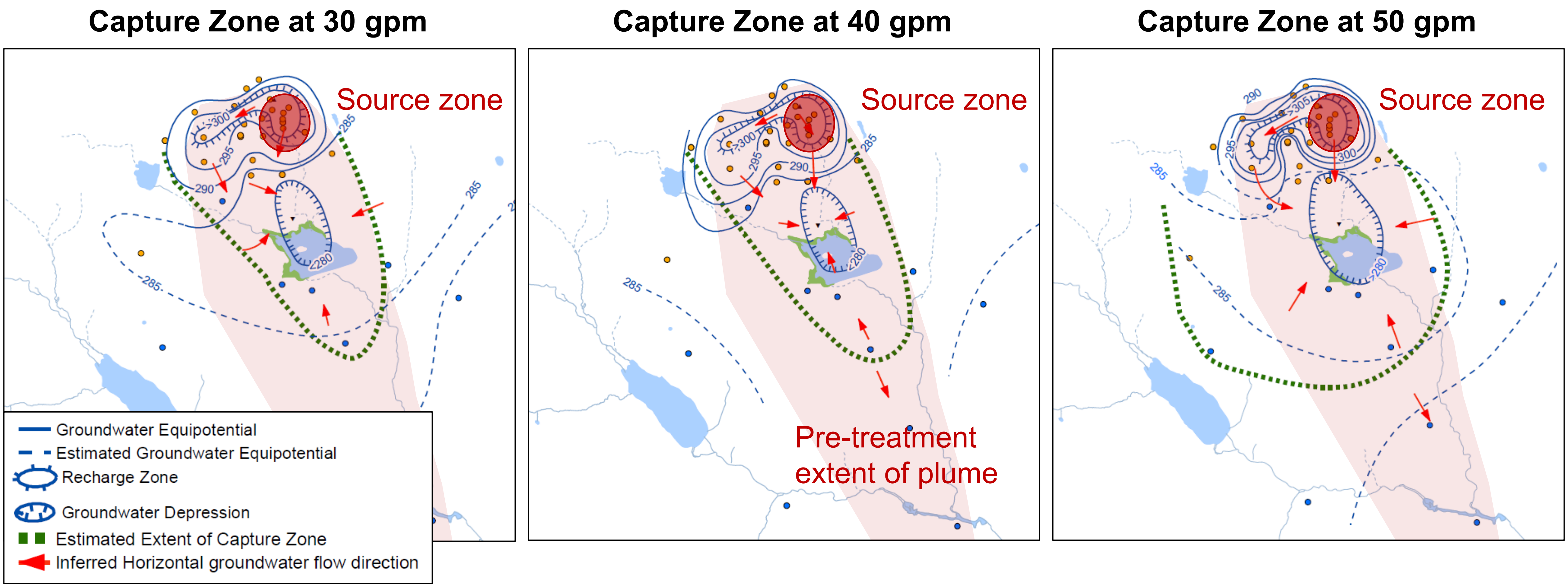





**Site Example #1**

Metasediment (discretely fractured) and diabase (non-water bearing) bedrock (Type 1): **CSM**

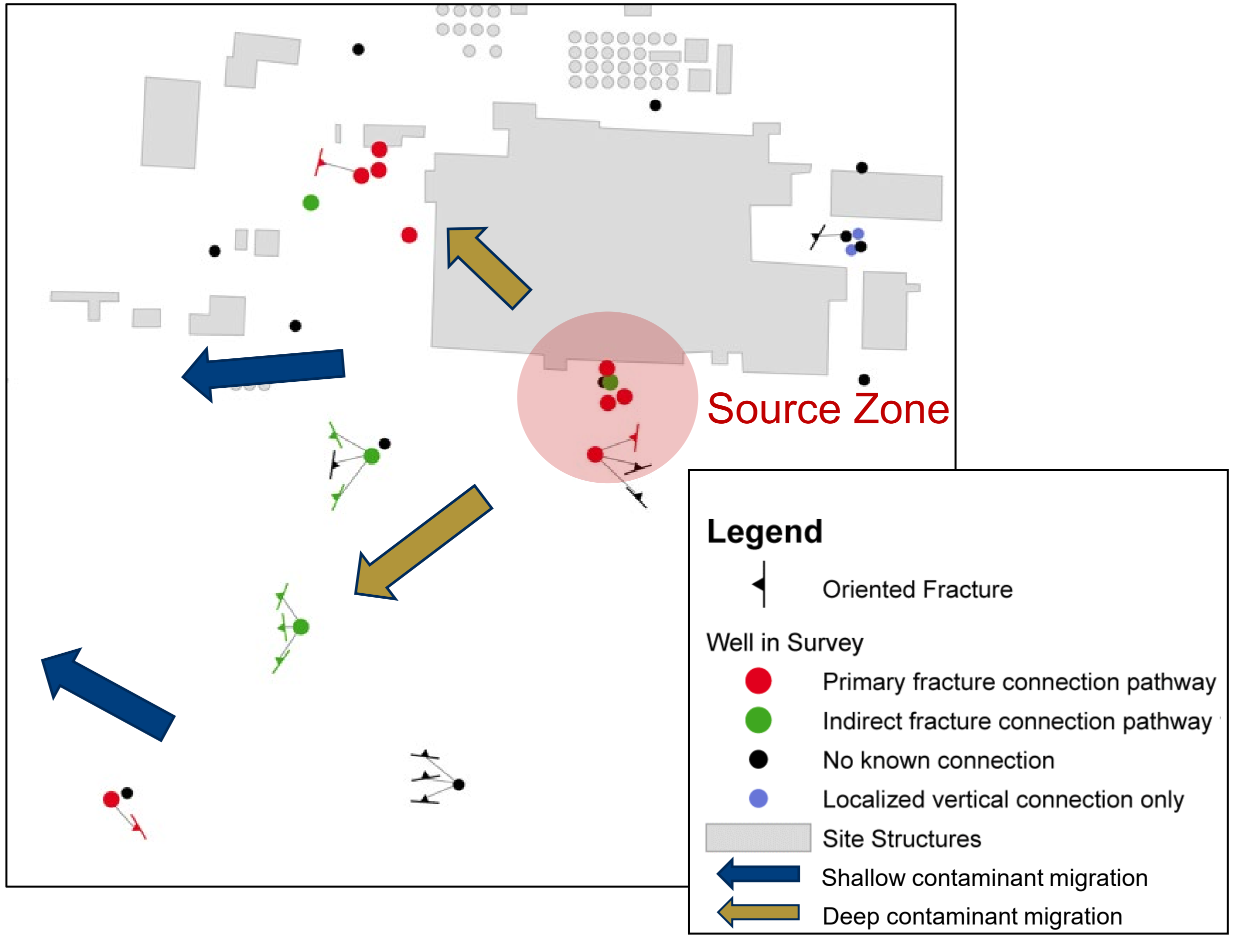
- Intrusion of diabase dyke created impermeable barrier
- Contaminant migrated into deep bedrock where dyke pinched out
- Migrated away from source downwards beneath dyke and to west and south

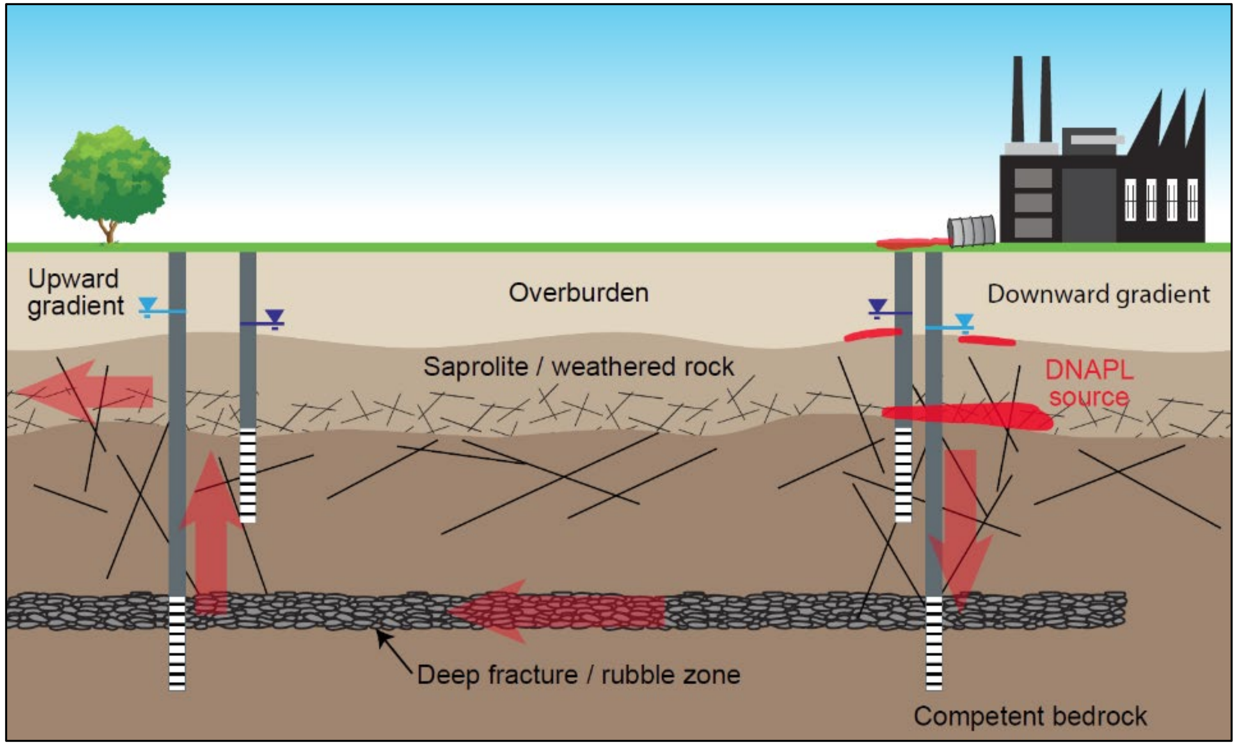



**Site Example #1**

Metasediment (discretely fractured) and diabase (non-water bearing) bedrock (Type 1): **Remedial Solution**

- Large-scale pumping test undertaken to map capture zones at varying rates
- Tracer testing confirmed fractures connected to source, aiding monitoring network design
- Remedial design: biorecirculation system combining hydraulic control with treatment in situ
- After 3 years of biorecirculation, achieved 75% reduction in concentrations and reduction in plume size back to capture zone

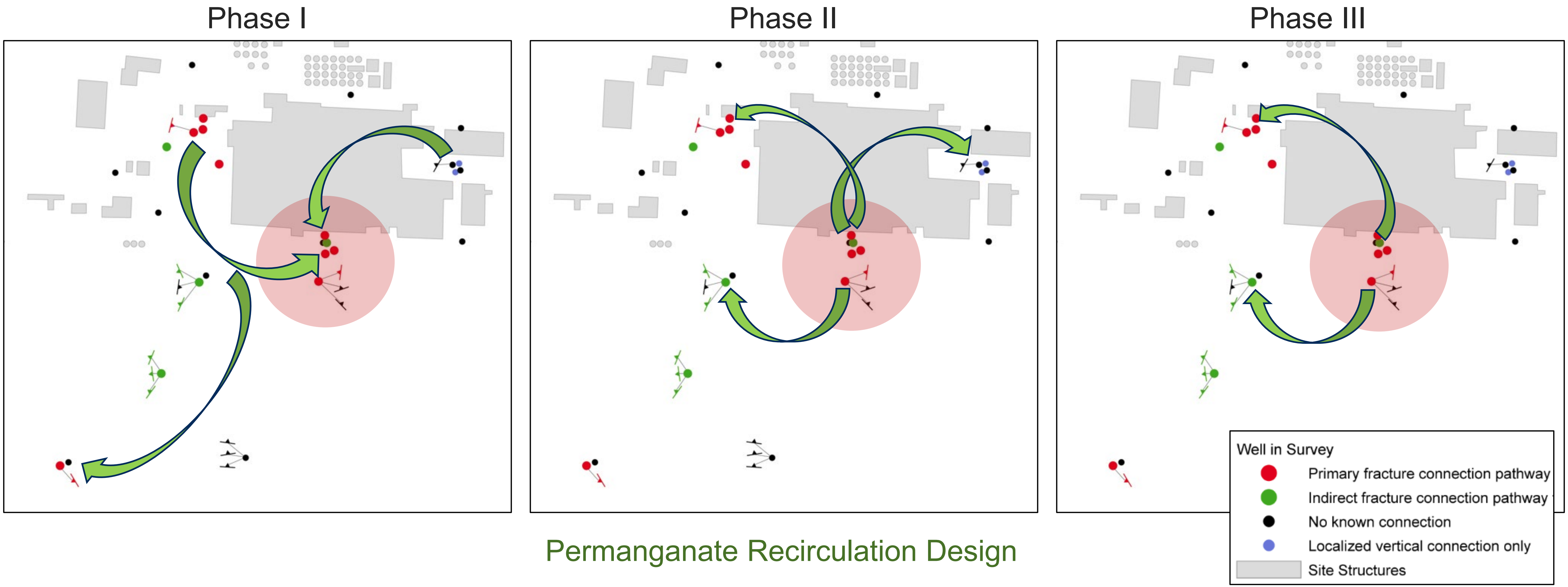



**Site Example #2**

Saprolite overlying weathered and competent metagabbro bedrock (Type 1/2): **CSM**

- Connected pathways mapped through large-scale pumping, borehole geophysics, and pressure pulse connectivity testing
- Downward migration near source along sub-vertical pathways
- Migration along deep horizontal fracture/rubble zone
- Upward migration in downgradient area




Permanganate Recirculation Design

**Site Example #2**

Saprolite overlying metagabbro bedrock (Type 1/2)

**Remedial Solution**

- Part of source mass inaccessible (beneath plant)
- Objective was to treat source mass and higher concentration core of plume
- Large-scale recirculation system flushed permanganate beneath building through weathered bedrock and deep fracture zone in varying configurations
- Deep zone effectively treated, rebound observed in shallower intervals (second source identified)

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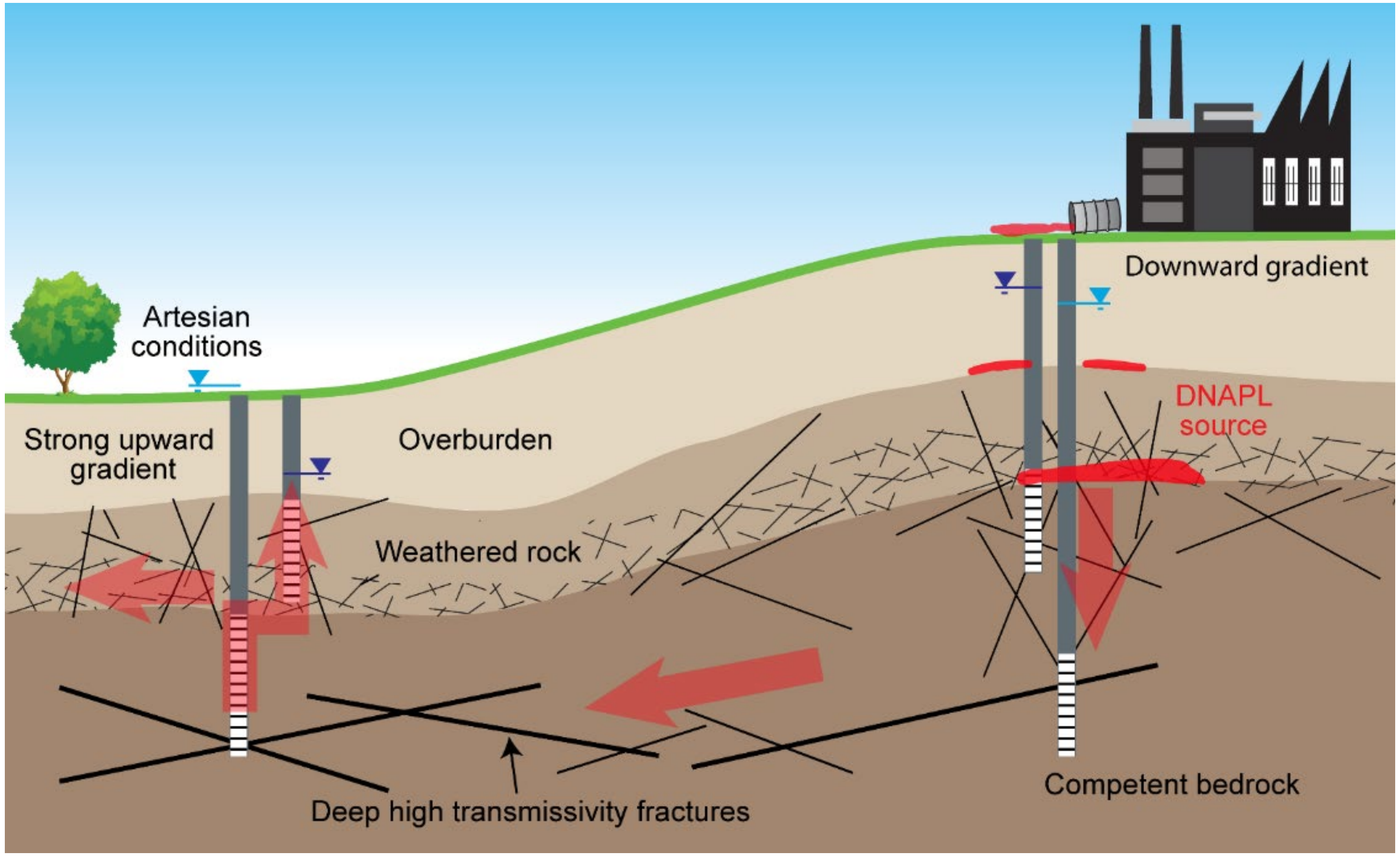
# Drilling Can Alter Aquifer Properties in Unpredictable Ways

Mobilization of mass and creation of new pathways can occur when fracture pathways are interconnected during drilling.

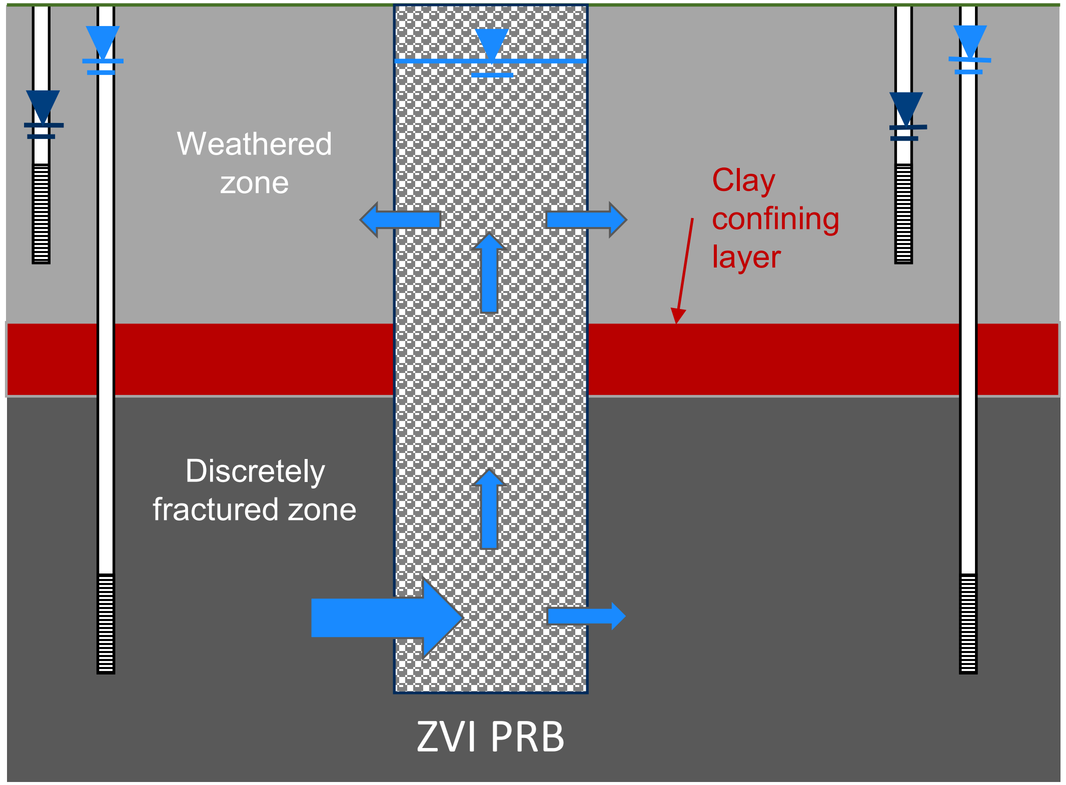


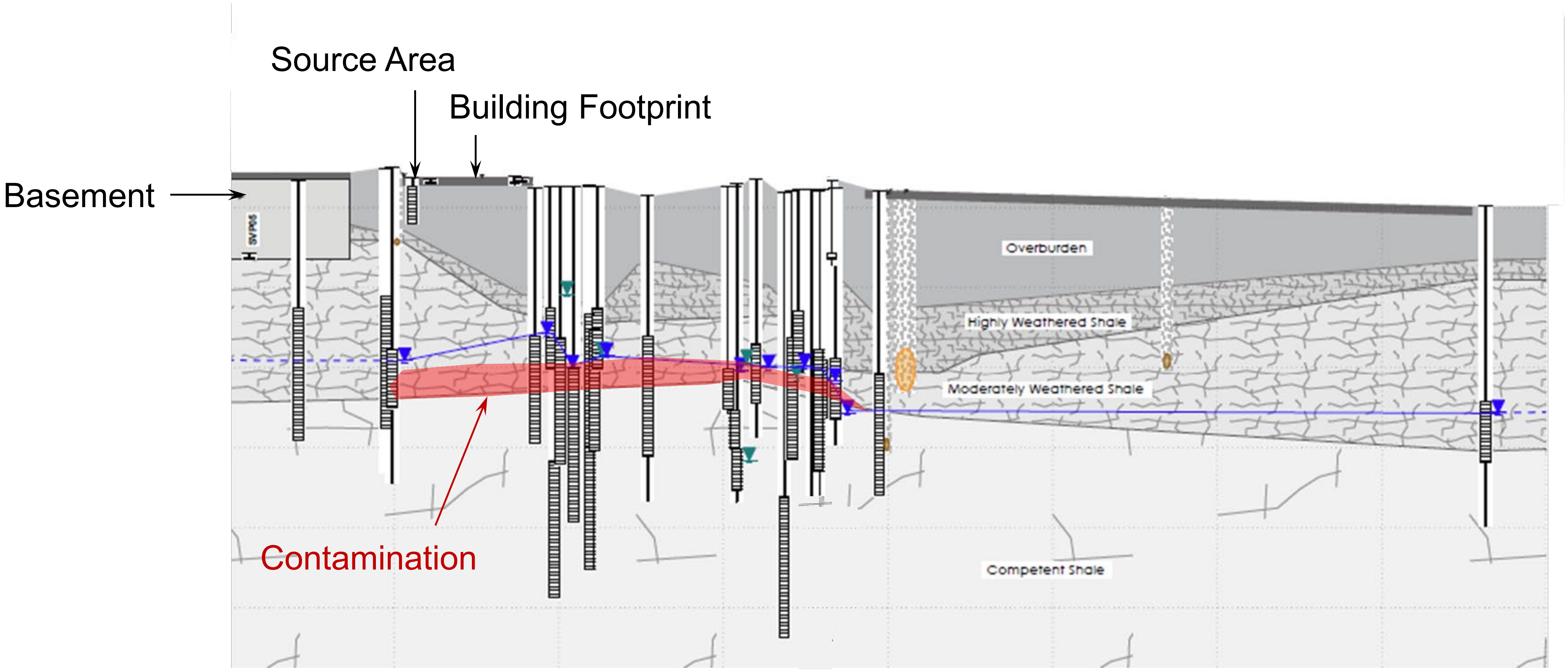
# Remediation Activities Can Alter Aquifer Properties in Unpredictable Ways

Contaminant migration pathways can be altered in unexpected ways as a result of remediation.

This can happen for a number of reasons:

- Connection of confined flow zones and equalization of hydraulic pressures
- Clogging of fractures due to precipitate formation
- Degassing of generated gases.





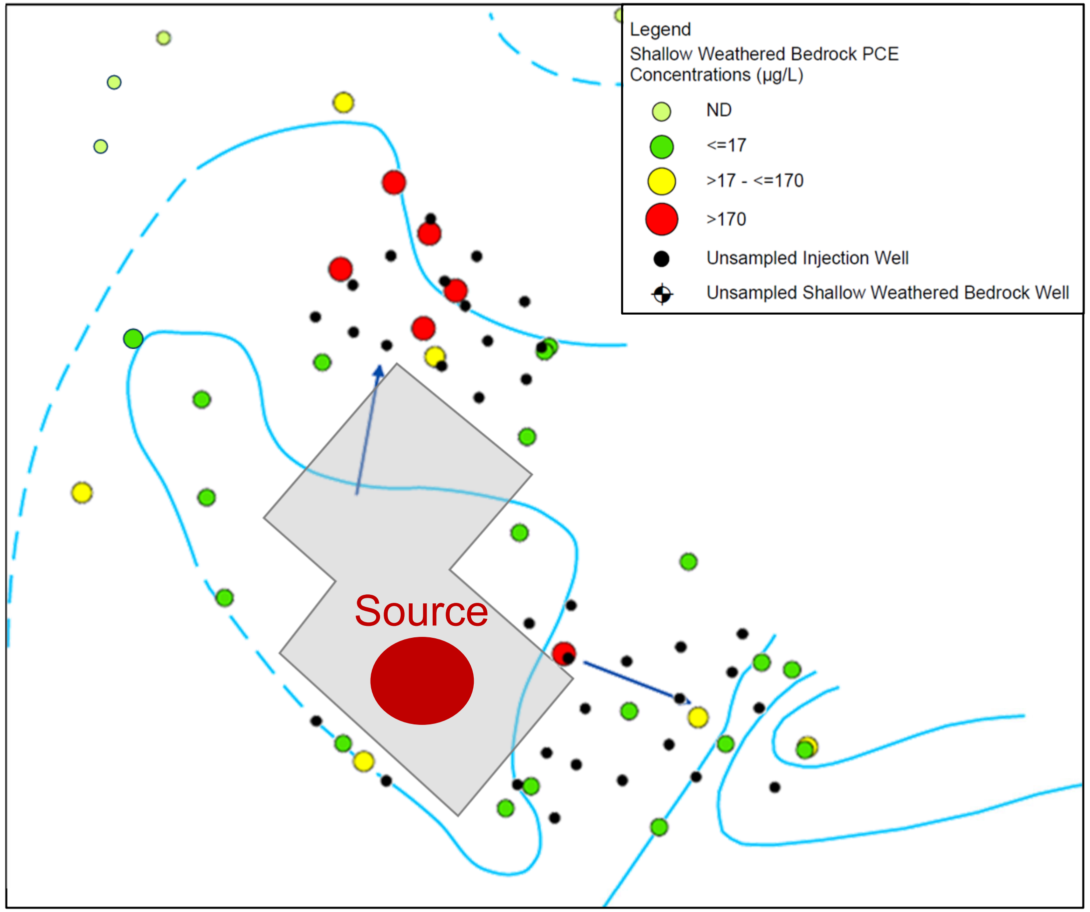

**Site Example #3**

Weathered shale (Type 3):

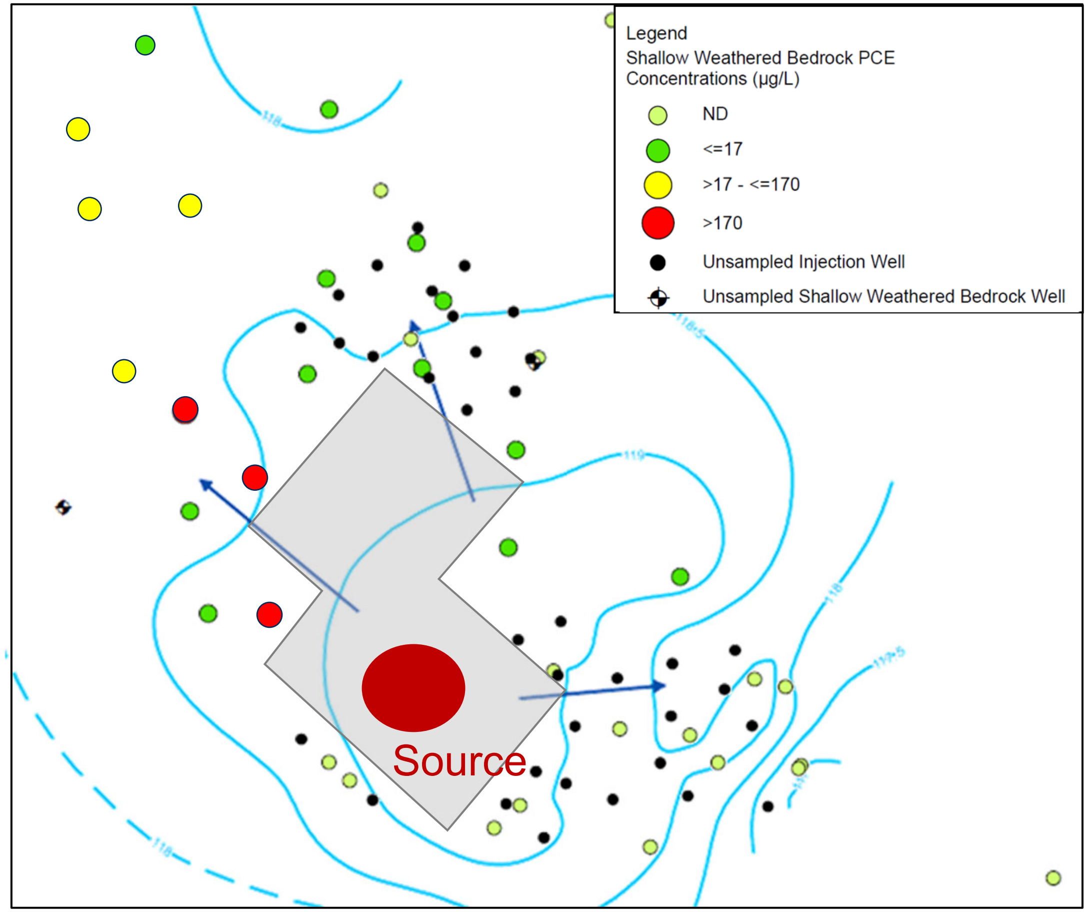
**CSM**

- Contamination migrates through thin weathered shale interval on top of competent bedrock
- Source area underlies building (inaccessible)
- Limited natural attenuation, slow plume expansion in two directions

Pre-Remediation Conditions




Two Years Post Remediation




**Site Example #3**

Weathered shale (Type 3):

**Remedial Solution**

- Venting of subslab soil vapors to remove vadose zone mass
- Bioremediation of groundwater implemented using long-term donors, with successful treatment to near detection limits of original plume in 2 years (source was inaccessible)
- Migration of mass from source changed direction potentially due to FeS precipitation and/or methane degassing, lining of leaky sewer

# Key Concepts and Considerations that may Drive Remedial Approach / Success

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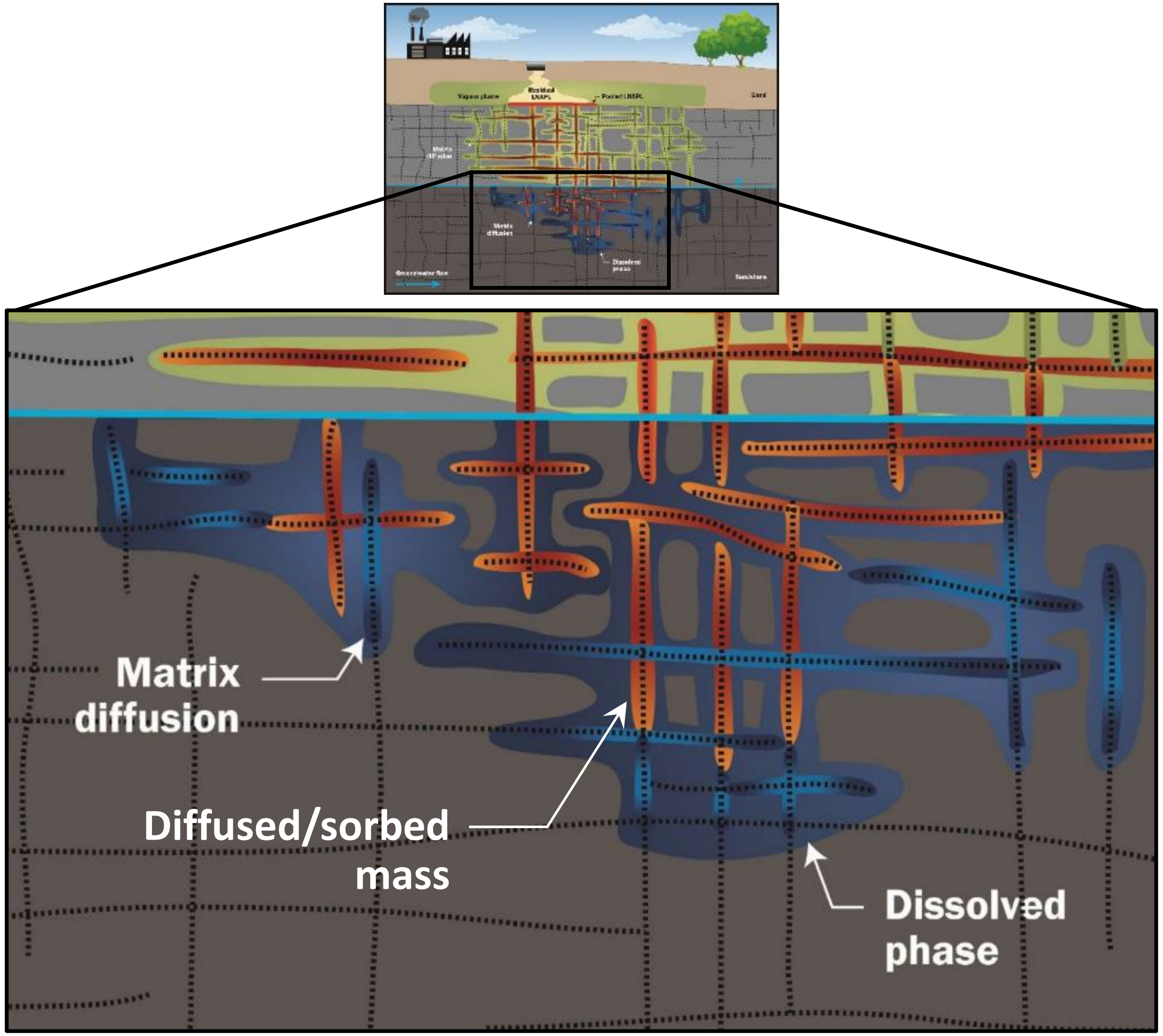
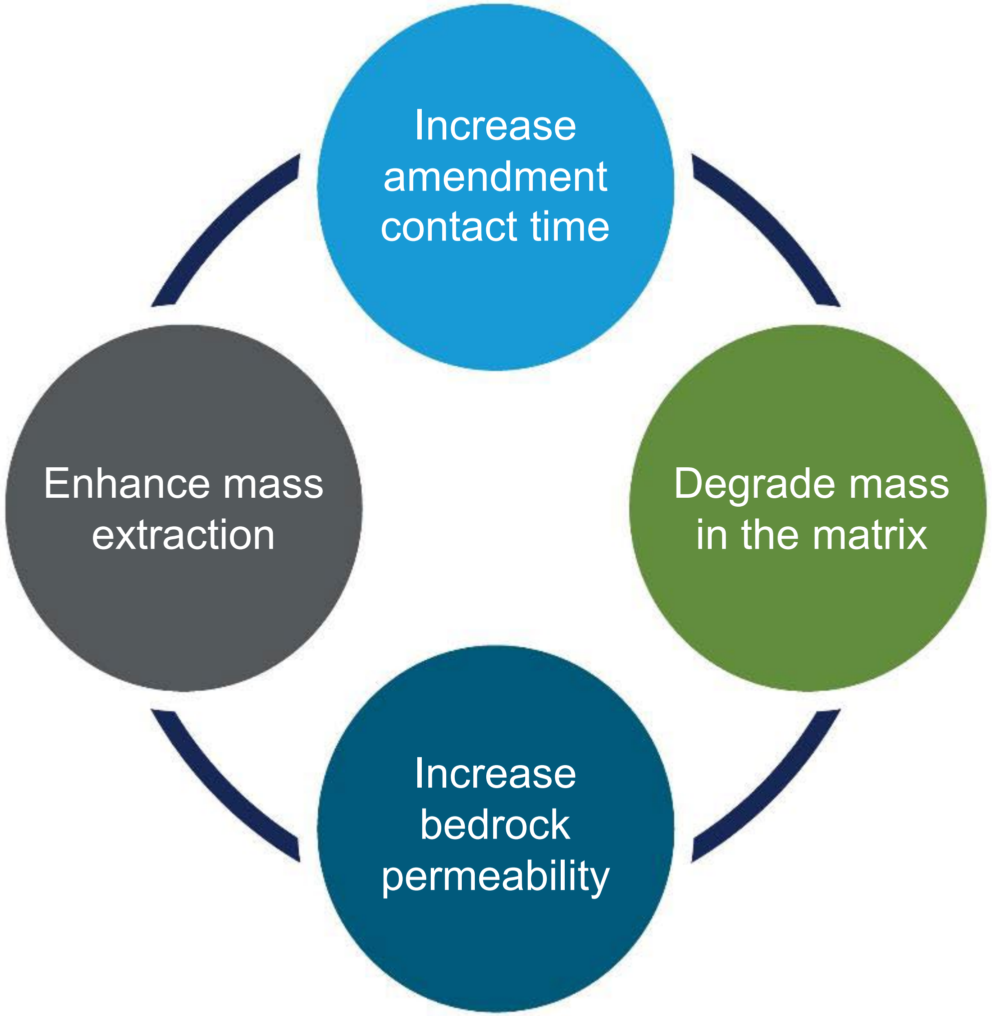
# Accessibility of Source Mass

Inaccessible source mass is more commonly encountered in bedrock settings.  Over time, mass diffuses into the matrix (**Types 2 through 4** sites) or gets trapped in dead end fractures (**Types 1 through 4** sites).

Back-diffusion of mass from the matrix and dead-end fractures will sustain the plume over a longer timeframe than the original source persists.



# Tools to Improve Treatment of Mass in Bedrock Matrix



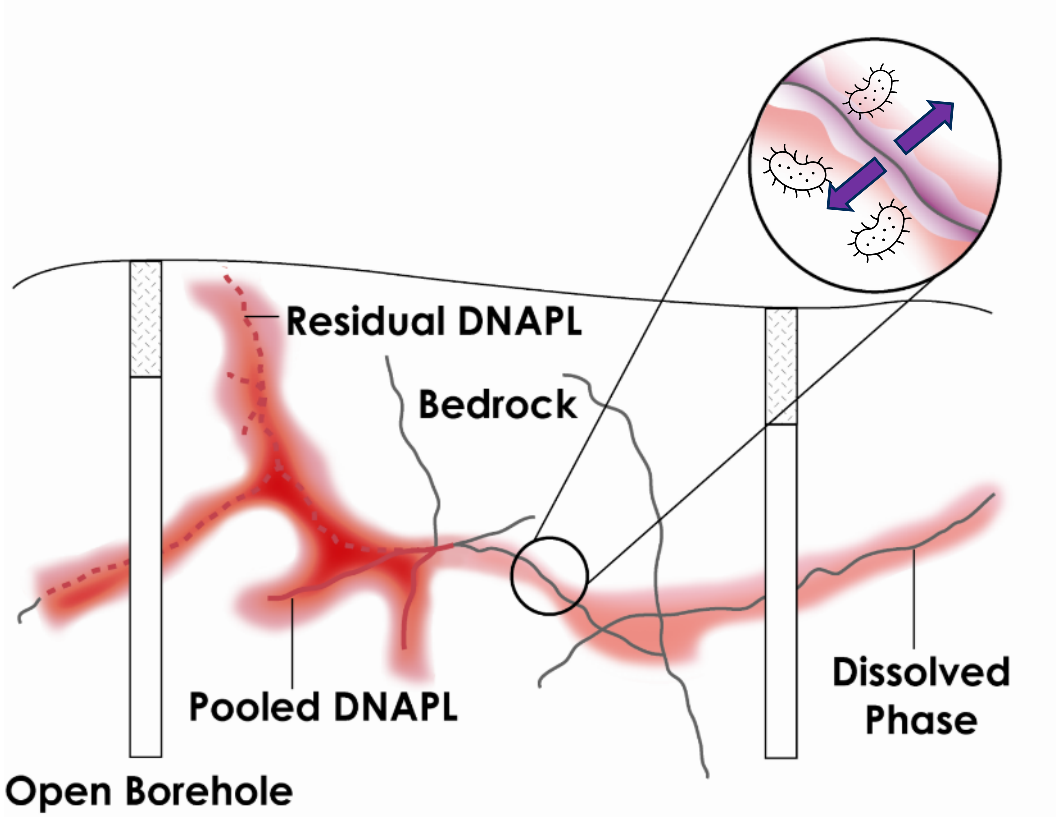

- Inject solid amendments into fractures to increase treatment longevity
- Recirculate amendments

- Heat bedrock to pyrolyze mass in situ
- Degrade mass in matrix - use low solubility / low reactivity reagents to diffuse amendment into matrix

- Use hydraulic fracturing or jet injection to dilate existing fractures or create new ones
- Target injection/extraction of specific fracture intervals using straddle packers

- High-vacuum extraction
- Create a concentration gradient at the matrix interface to enhance back-diffusion

# Biodegradation Sustains Long Term Treatment




Amendments and bacteria can penetrate the matrix for some rock types, stimulating treatment in the matrix. Reduced minerals also form during treatment stimulating abiotic degradation.

After electron donors are consumed, endogenous cell decay and reduced minerals sustain treatment and reduce occurrence of rebound for years.

Sustained treatment: Implications for treatment timescales associated with source-depletion technologies


Article in Remediation Journal 21(2):27 - 50 · March 2011

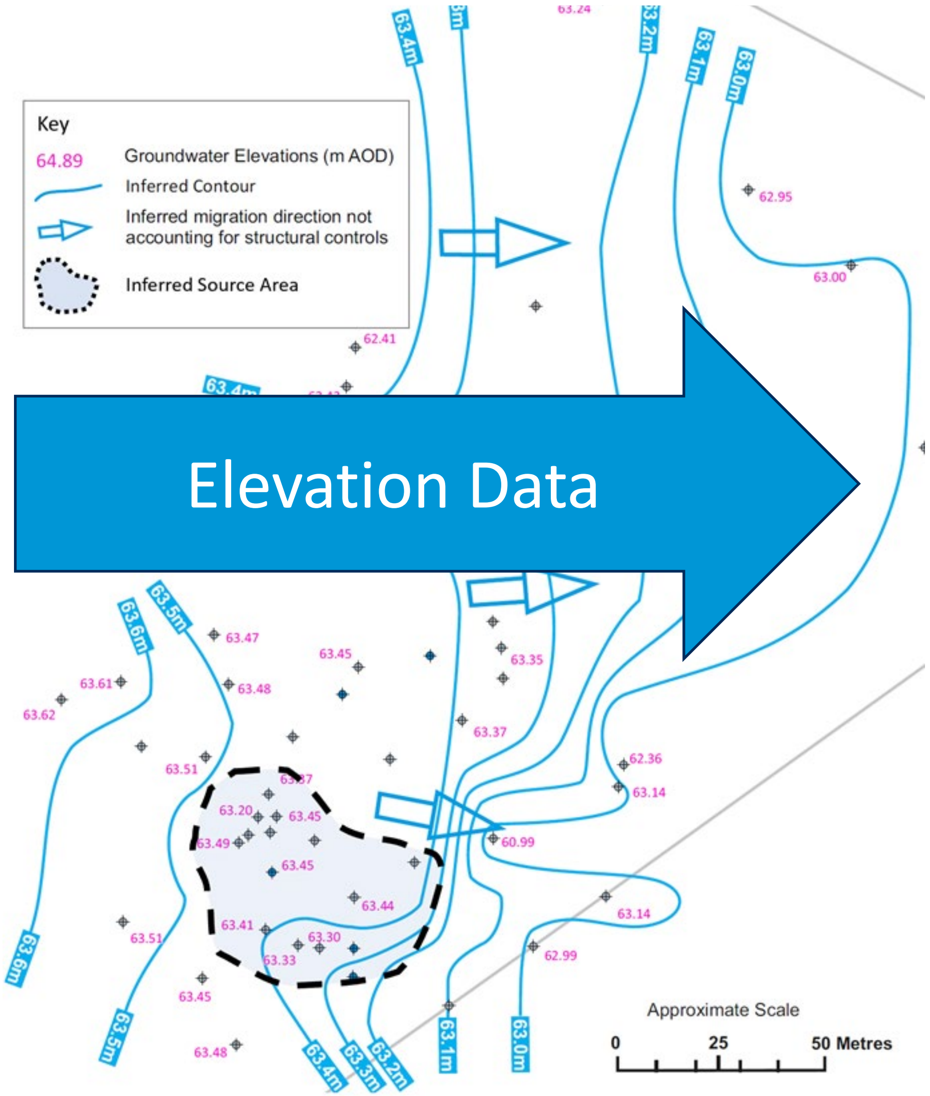
DOI: 10.1002/rem.20280

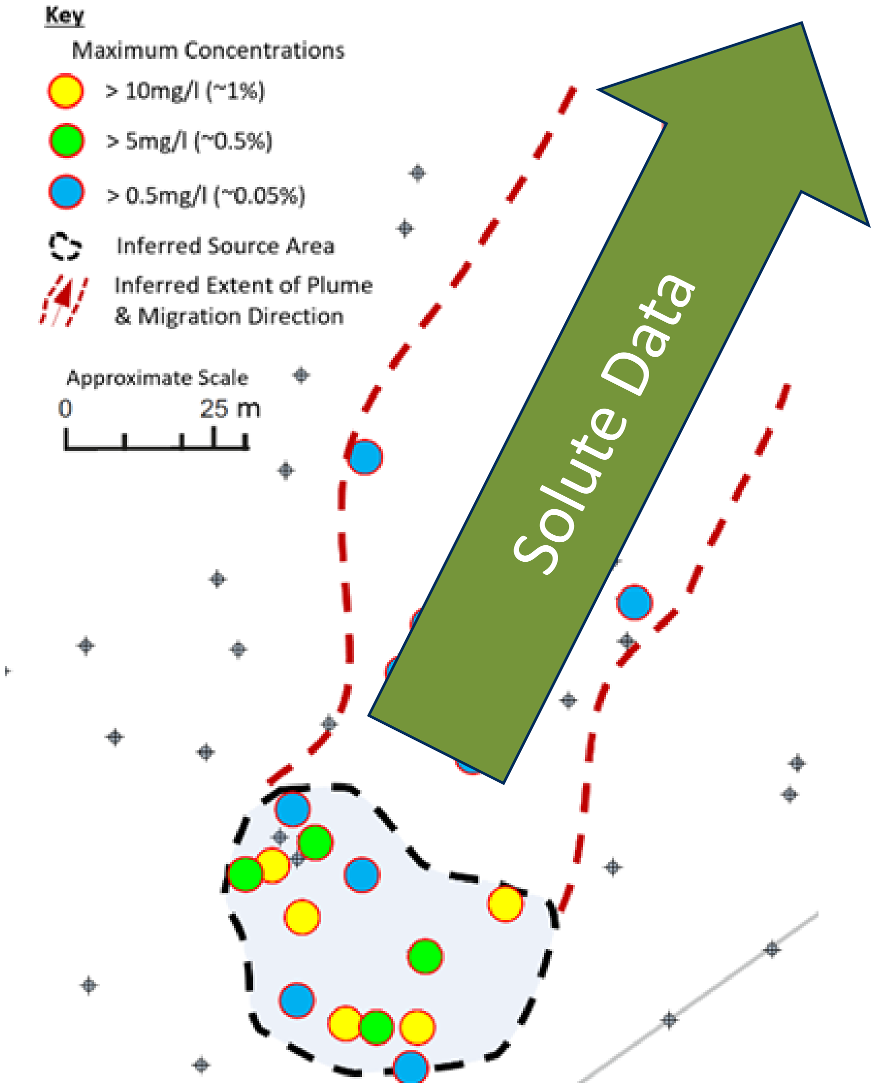

Support of Source Zone Bioremediation through Endogenous Biomass Decay and Electron Donor Recycling


David T. Adamson and Charles J. Newell
GSI Environmental, Inc., Houston, Texas, USA



ABSTRACT Enhanced bioremediation strategies employ intensive electron donor amendments that can be successful in generating high biomass concentrations within the targeted area, and this technology is increasingly being applied within source zones to address non-aqueous phase contaminants. An unintended consequence is potential electron donor recycling via the

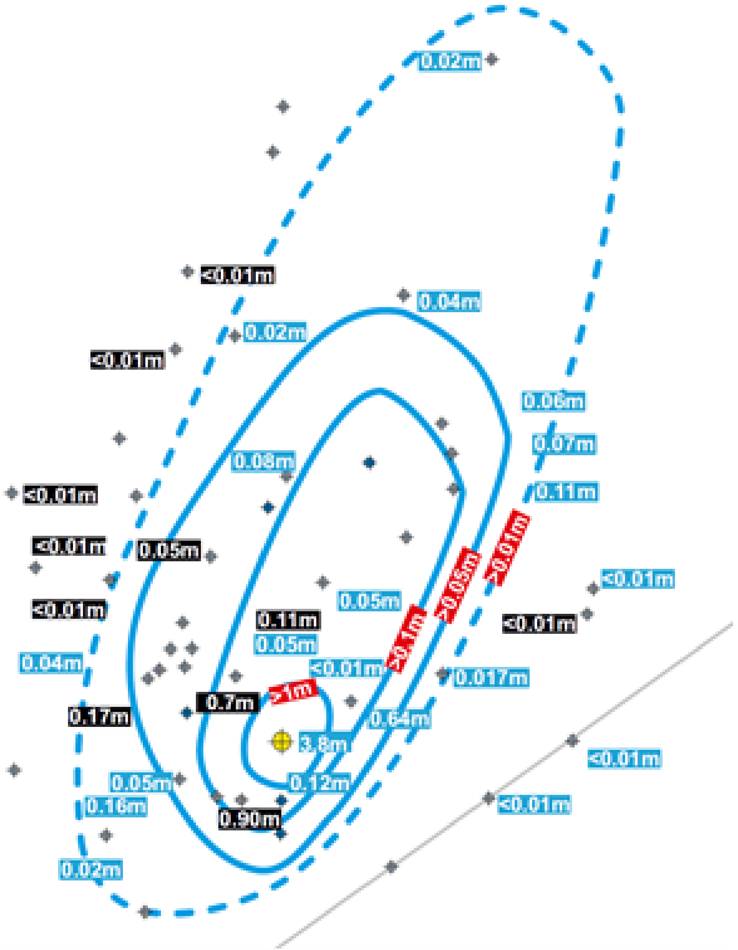


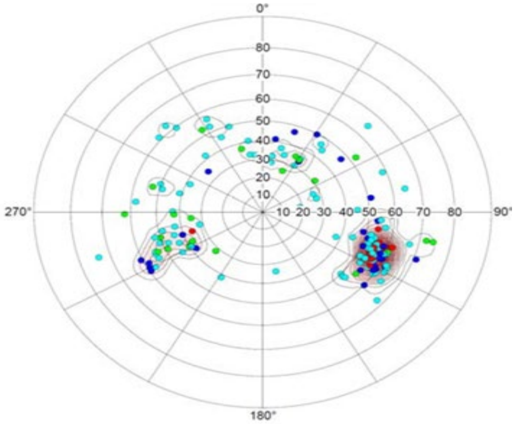



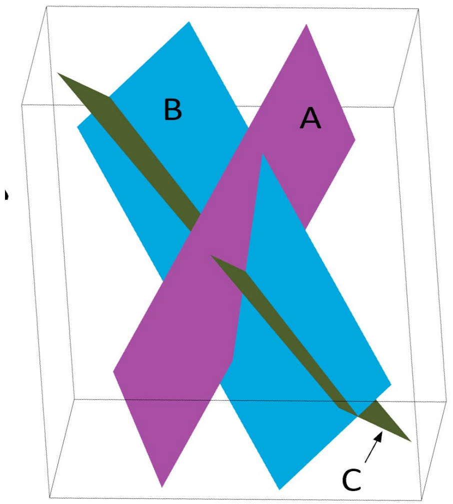

**Site example #4**

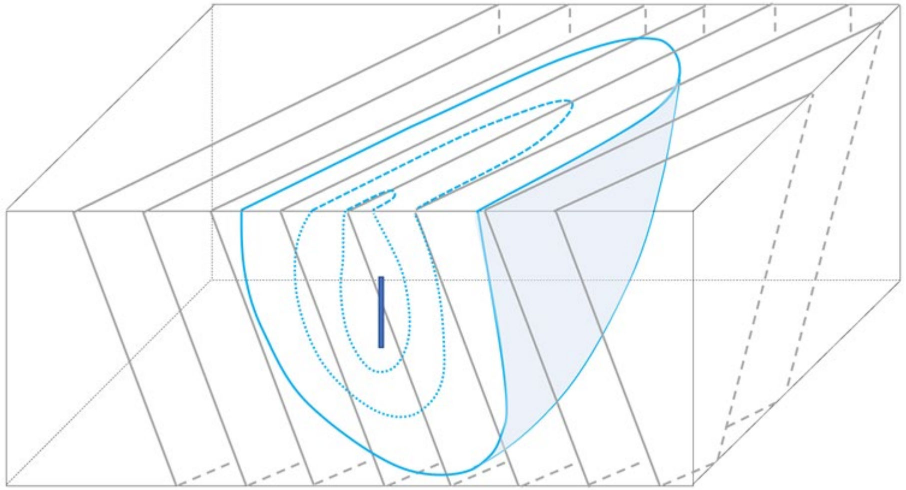
Addressing CE Source in Limestone Bedrock Matrix (Type 1): **CSM**

- Example of a fractured limestone system, groundwater gradient is to the east, but the plume is to the northeast of the source area
- Why? How does this effect the remedial design?



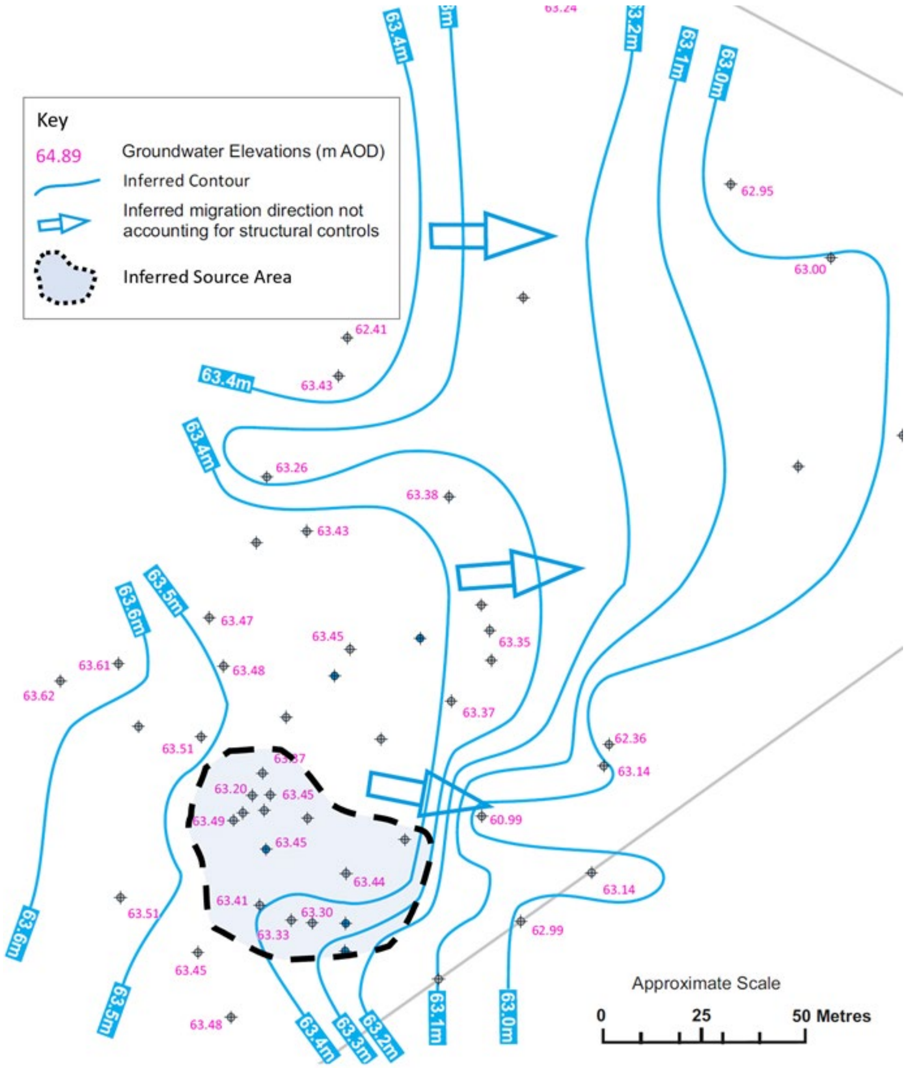



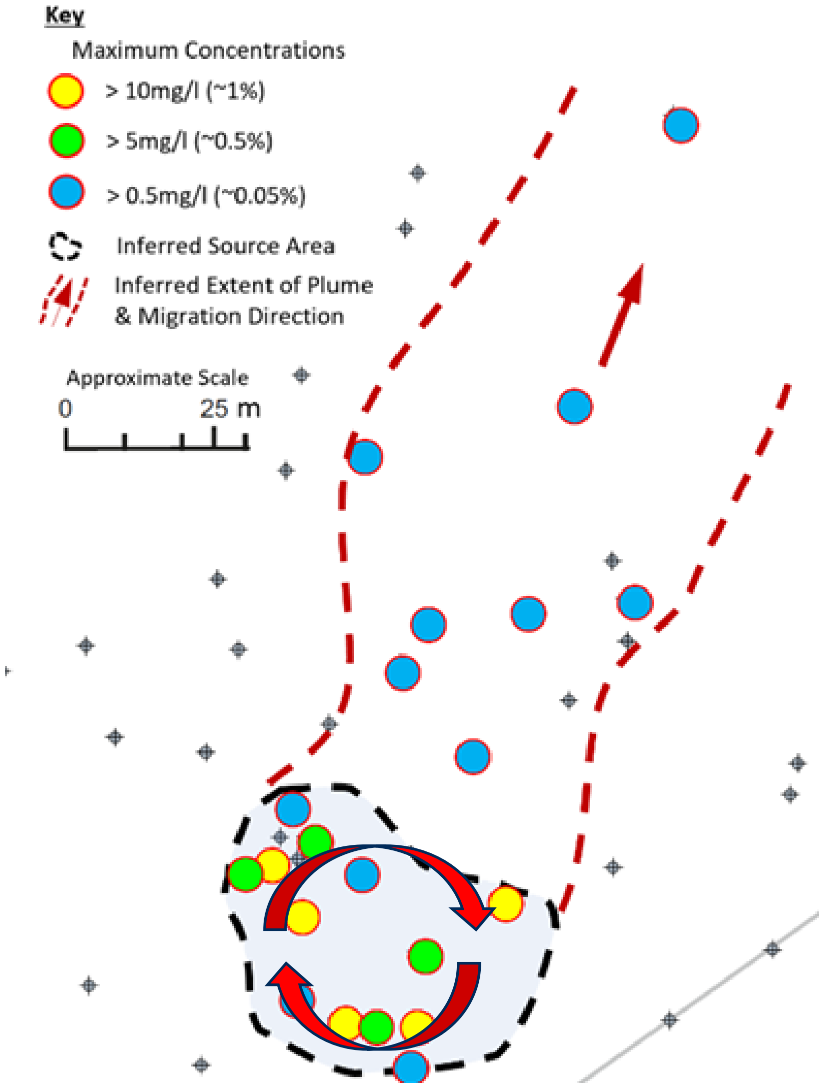



**Site Example #4**

Addressing CE Source in Limestone Bedrock Matrix (Type 1): **CSM**

- Groundwater flow in limestone bedrock aligns with major fracture sets, including steeply dipping fractures
- Smaller fractures likely




**Site Example #4**

Addressing CE Source in Limestone Bedrock Matrix (Type 1): **Remedy Solution**

- EISB remedy using
  - Long term electron donor
  - Recirculation in source area using packered injection wells for focused delivery into smaller fracture sets

# Key Concepts and Considerations that may Drive Remedial Approach / Success

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# Achieved Outcomes

| Site | Rock | Weathered / Competent | Rock Type | COC Distribution (Fracture / Matrix) | | Contact Enhancement Approaches (Fracturing, Hydraulic Control, Vacuum, Long-Term Amendments) | | | | Remedial Technology | Treatment Timeframe (yrs) | Treatment Outcome |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | F | M | F | HC | V | LTA | | | |
| SC #1 | Crystal. | W, C | 1 | • | | | • | | | ISCO | 2-3 | Deep bedrock treated to below MCLs, rebound in shallow bedrock |
| NC #1 | Crystal. | W, C | 1 | • | | | • | • | | SVE | 5 | SVE removed source under building |
| NC #2 | Crystal. | W, C | 1 | • | | | • | | | EISB | 2 | Shallow recirc treated to below criteria in shallow and deep bedrock |
| MW #1 | Limestone/ Karst | W, C | 1/2 | • | • | | • | • | • | Thermal then EISB | 2 (Thermal) 1 (EISB) | Successful treatment of source and attenuation of deeper plume |
| SC #2 | Crystal./ Saprolite | W, C | 1/3 | • | • | • | | | • | ISCO and ZVI | 10 | Source depleted, 100 ppb plume reduced in area by 70% |
| EUR #1 | Granite | C | 2 | • | • | | | • | | Thermal | <2 | Achieved remedy objectives for VI |
| AU #1 | Basalt | W, C | 2 | • | | • | • | | • | EISB and SVE | 8 | 90% reduction mass discharge |
| MW #2 | Shale | W, C | 2/3 | • | • | • | | | • | EISB | 10 | 99% mass reduction, NFA granted |
| CO #1 | Claystone / Sandstone | W, C | 2/3 | • | • | • | • | | • | ISCO in source, P&T and EISB in plume | 2 years source >10 yrs (plume) | Source mass reduced 90%, treatment in plume ongoing |
| UK #1 | Limestone | C | 2 | • | ? | | | | • | EISB | ongoing | Ongoing, mass treatment evident |
| UK #2 | Limestone | W, C | 2 | • | | | • | • | | ISCO and HVE | <3 | Source treated and plume shrunk |
| ON #1 | Shale | W, C | 3 | • | • | | | | • | EISB | 2 | Near ND in treatment area, source mass flux bypassing treatment areas |
| PA #1 | Shale/ Siltstone | C | 3 | • | • | | • | | | ISCO and P&T | 3 (ISCO) P&T ongoing | ISCO showed mass treatment, but rebound, transition to P&T |

# Take Home Messages

Remediation of contaminated bedrock sites is achievable.

Success is dictated by the ability to contact the mass and a good understanding of the flow regime.

- Flow patterns can be unpredictable – mapping the aquifer hydraulics is one key to remedy success
- Connecting isolated hydraulic units may create new pathways or have unpredictable results
- Where mass transport is fracture dominated, consider hydraulic control (extraction, recirculation) for remedies
- Where source mass is in matrix, consider technologies that can penetrate matrix (bio, thermal, fracturing) or treat / enhance back-diffusion

# CASE STUDIES

## USING HYDRAULIC FRACTURING TO ENHANCE AMENDMENT DISTRIBUTION IN BEDROCK FOR CHEMICAL OXIDATION, CHEMICAL REDUCTION, AND BIOREMEDIATION TREATMENTS

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# Key Concepts and Considerations – Case Study #1

- Influence of bedrock structure on migration of contaminants and amendments
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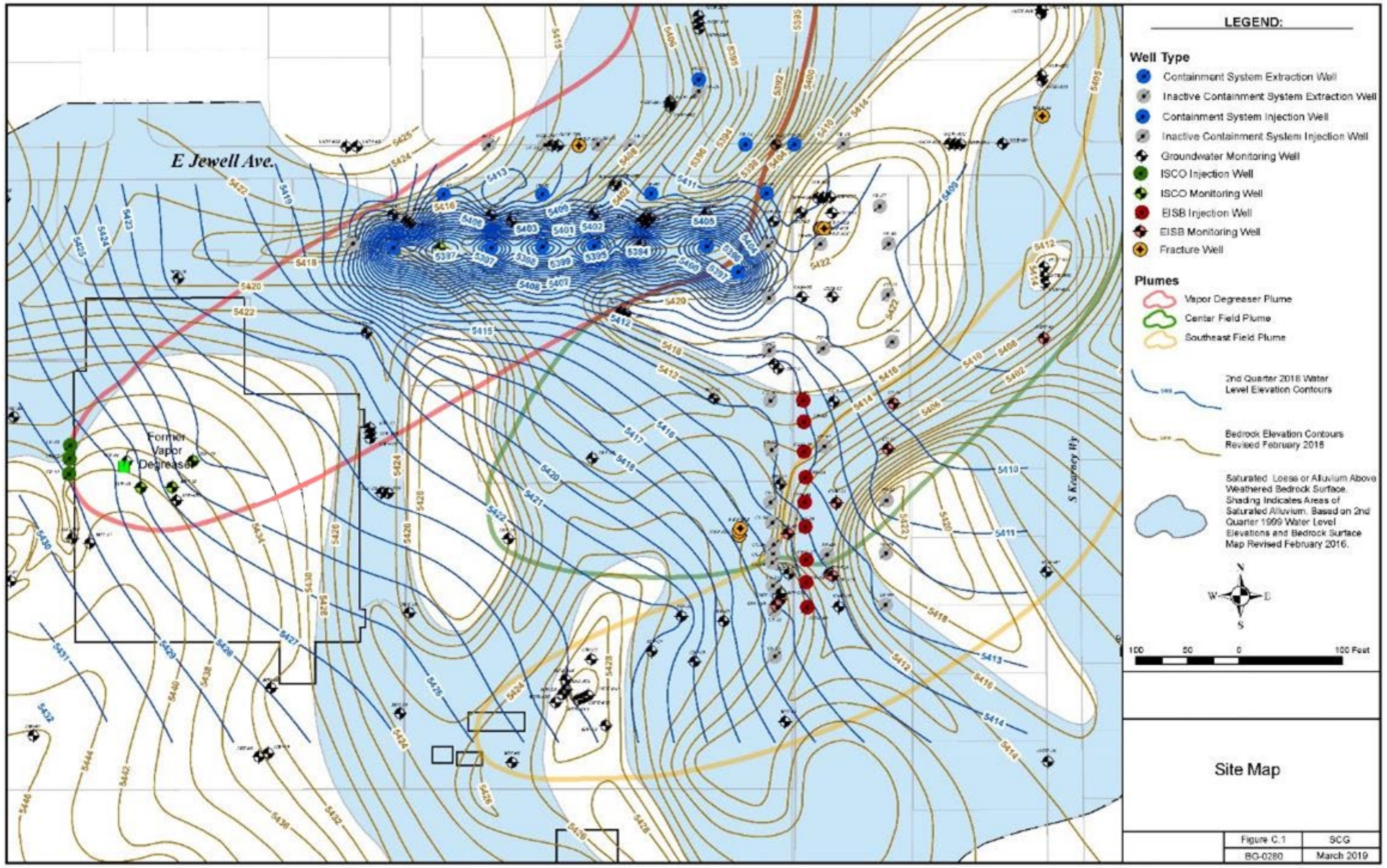
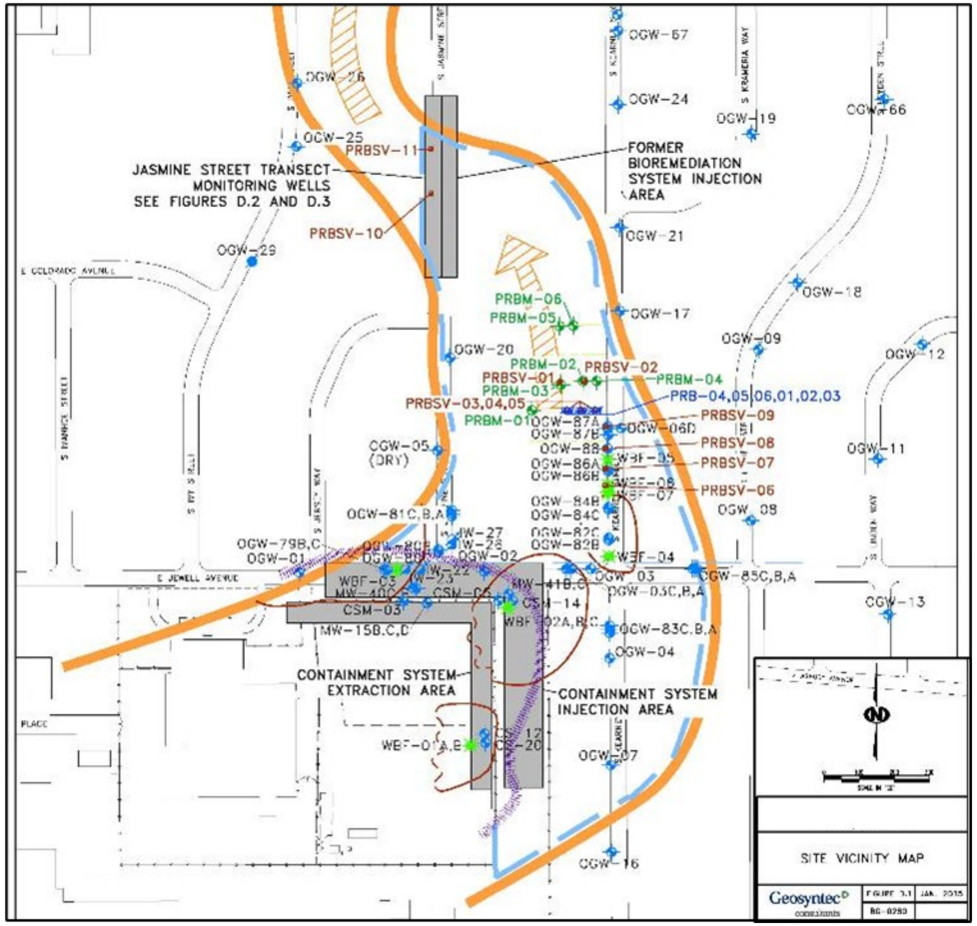



**Case Study #1 – Colorado**

CVOCs and 1,4-dioxane in alluvium and weathered bedrock (Type 2/3): **Remedial Solution**

- Multiple source areas, extended CVOC plume, sensitive receptors
- Two target zones: alluvium, weathered claystone and sandstone transitioning to competent siltstone
- Plume treatment: Hydraulic containment, ERD, ERD with sand fractures
- Source treatment: ISCO via sand fractures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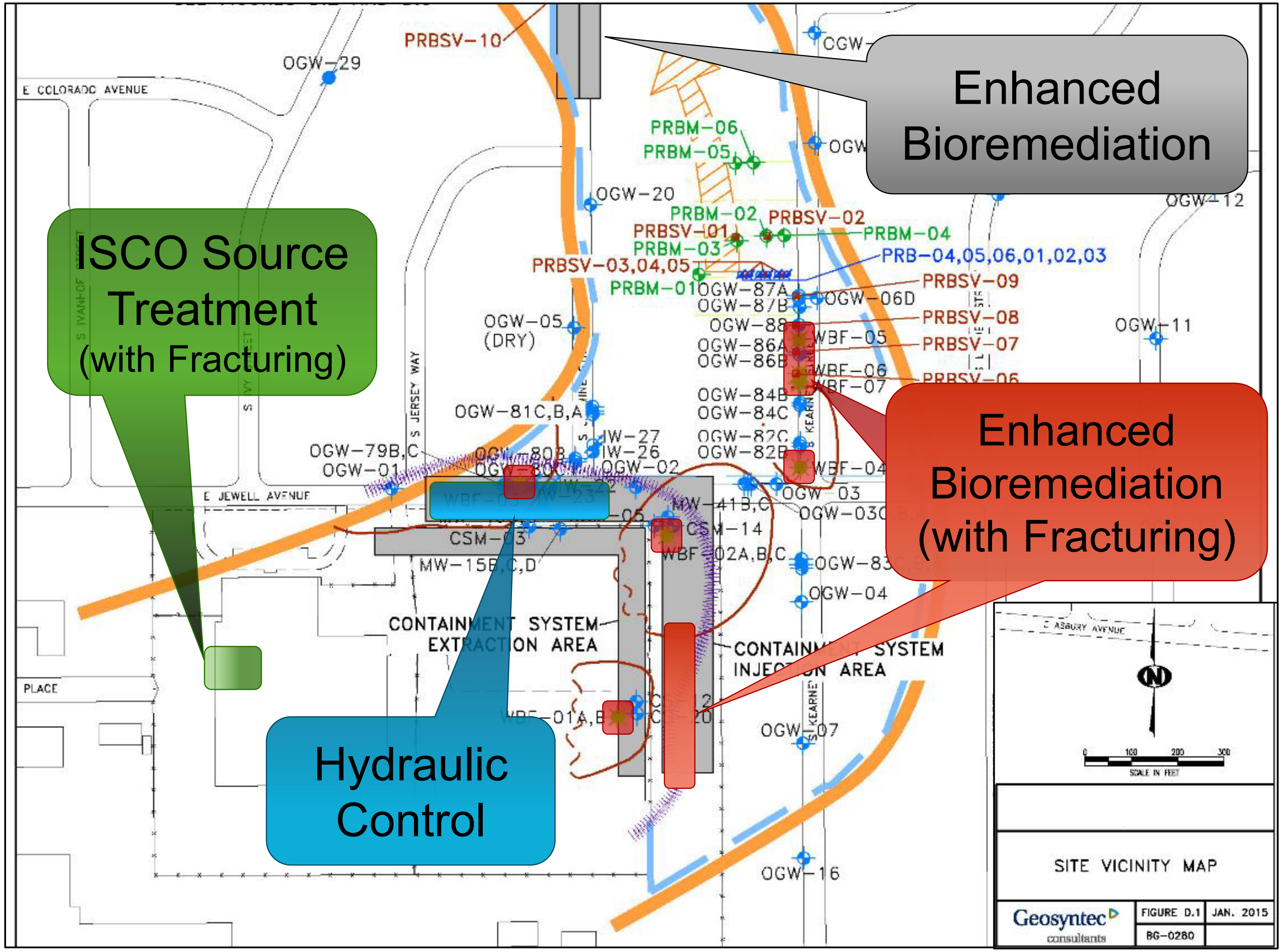
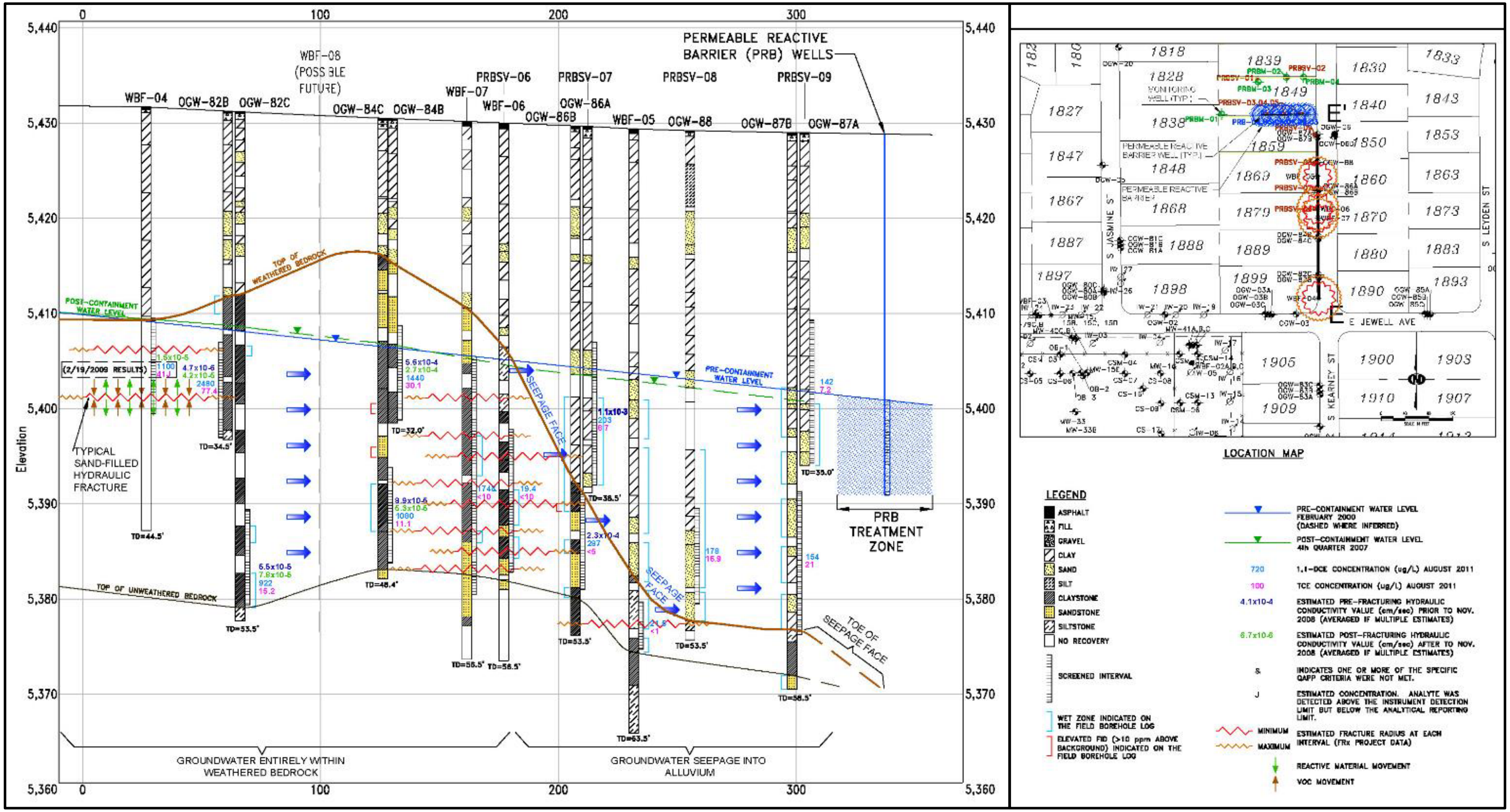
- Plume treatment: Hydraulic containment, ERD, ERD with sand fractures
- Source treatment: ISCO via sand fractures

# Case Study #1 – History of Remediation

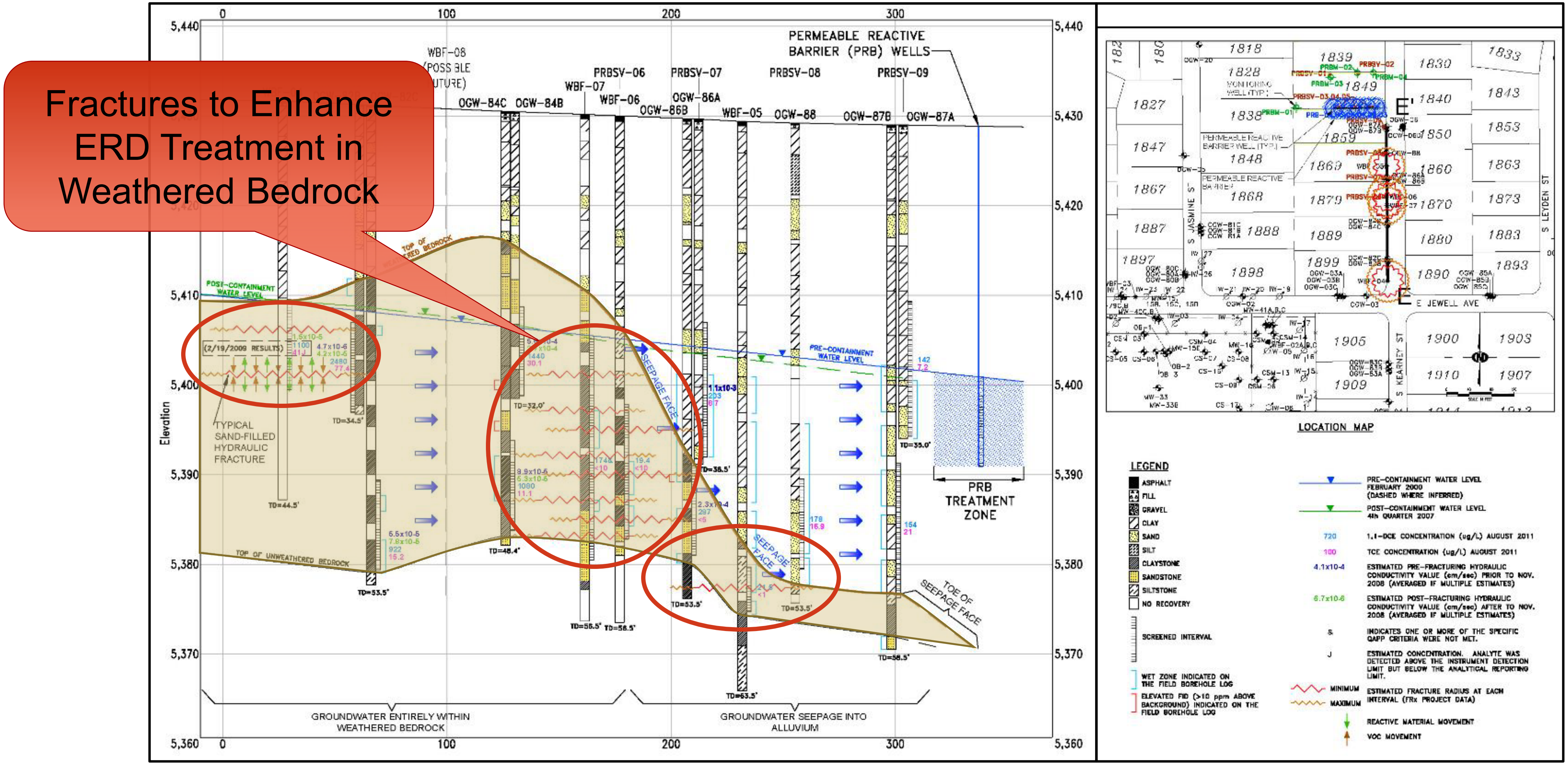
- 2000 – Pump & treat at property boundary for hydraulic control
- 2002 – Enhanced reductive dechlorination (ERD) for offsite plume
- 2008 – ERD Biobarrier at property boundary (9 alluvium wells; 11 fractures at 7 weathered bedrock wells)
- 2009 – ERD Biobarrier at property boundary (7 fractures at 3 weathered bedrock wells)
- 2016 – Residual source treatment with ISCO



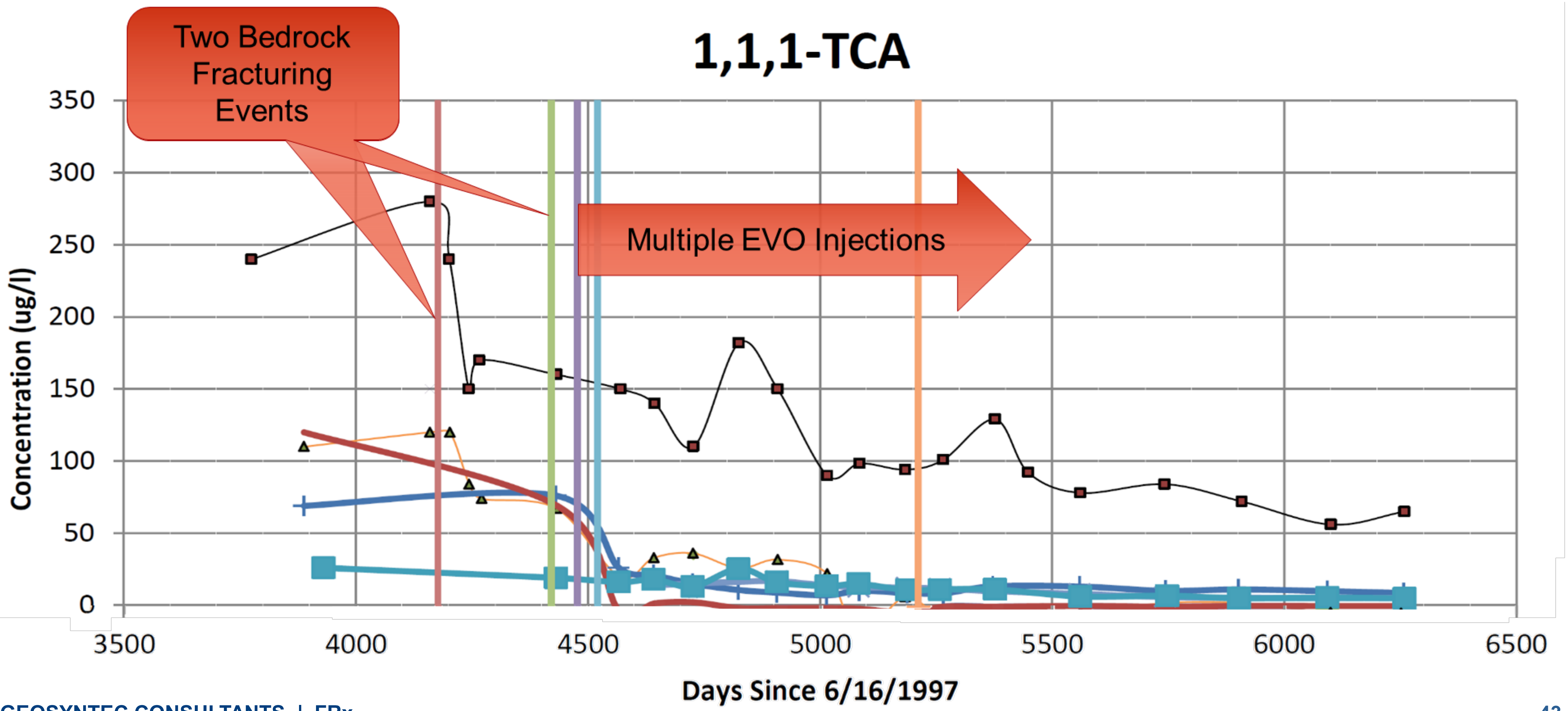
# Case Study #1 – Plume Treatment Remedial Design



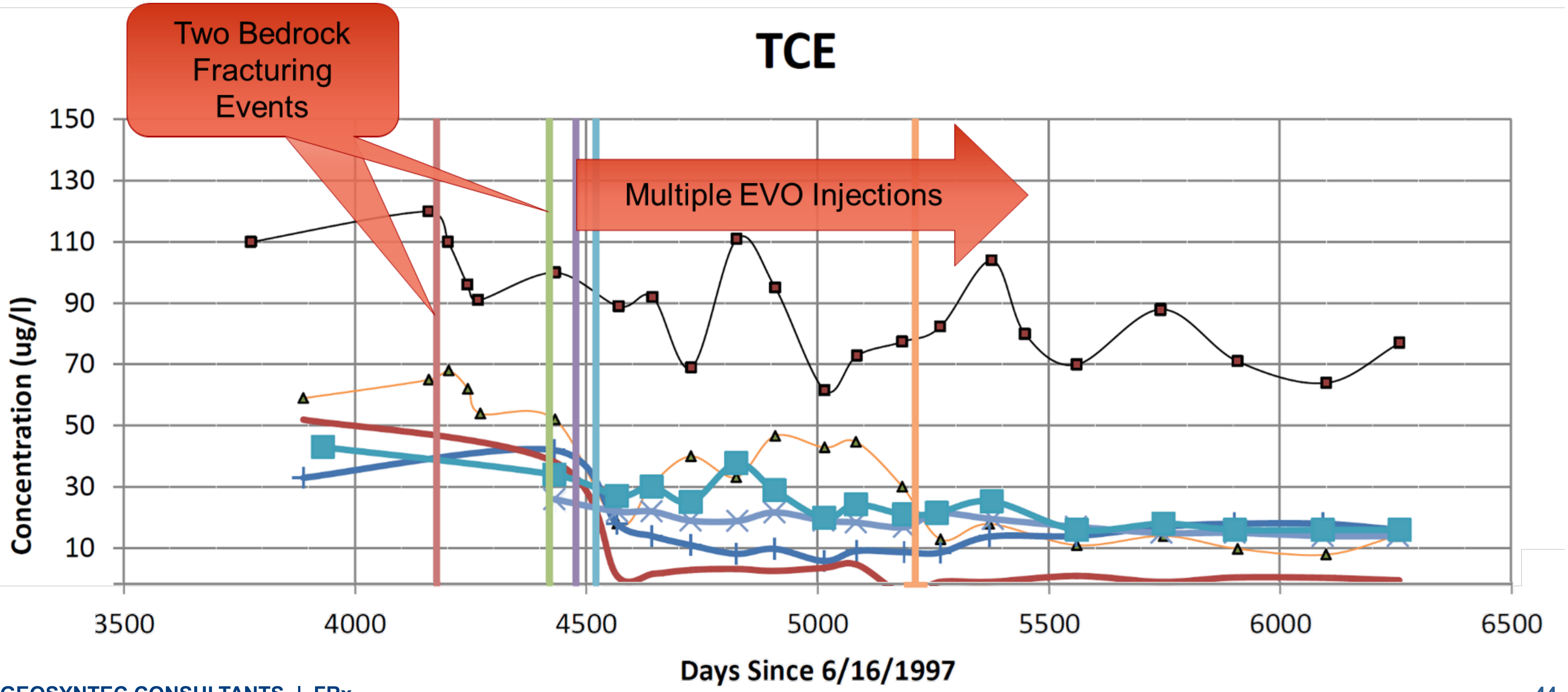
# Case Study #1 – Plume Treatment Remedial Design



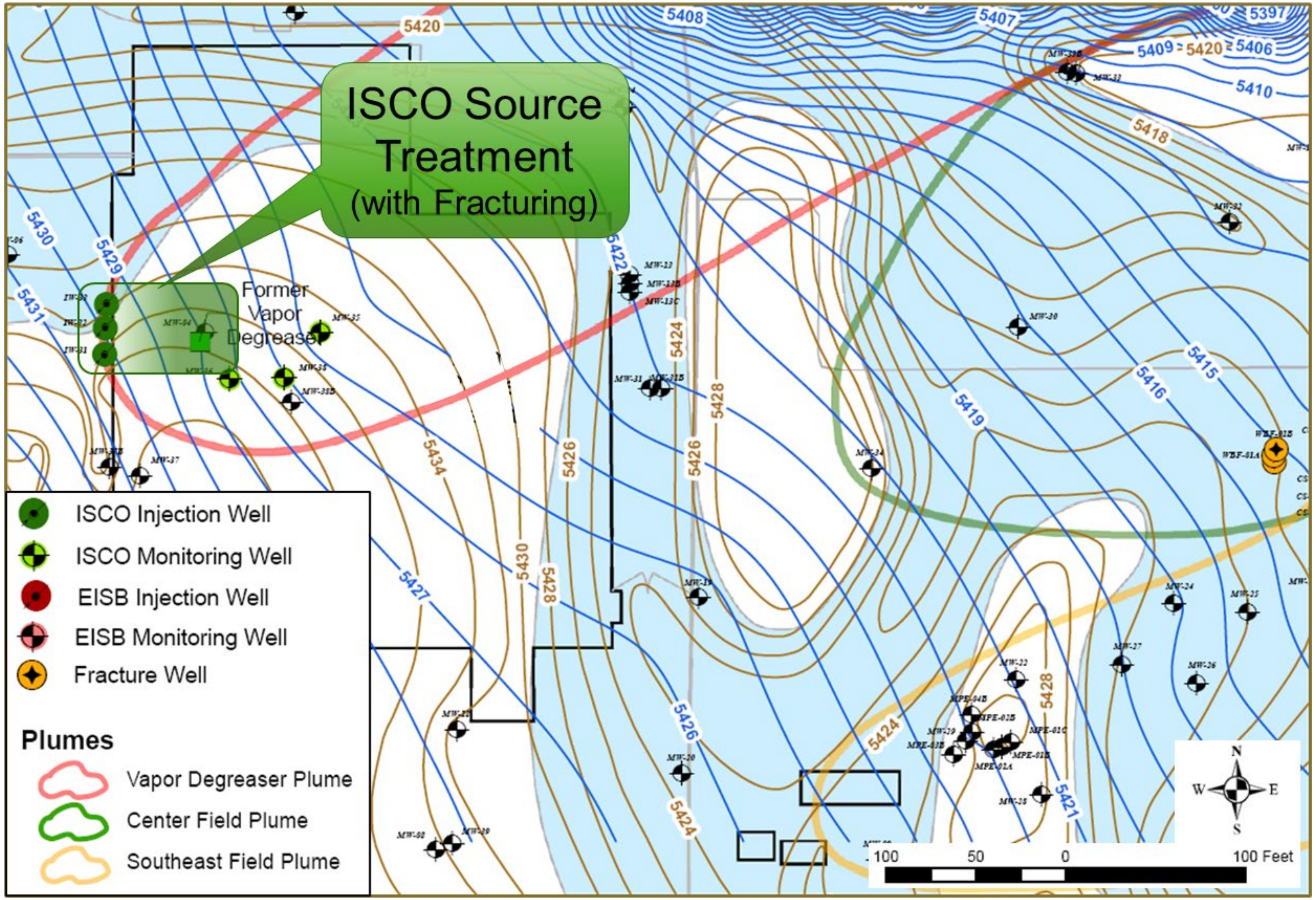
# Case Study #1 – Plume Treatment – 1,1,1-TCA Results



# Case Study #1 – Plume Treatment – TCE Results



# Case Study #1 – Source Treatment Remedial Design



# Case Study #1 – Source Treatment Implementation

- Target zone 25 to 38 feet bgs beneath building
- Hydraulic fracturing via angled wells to access source (Oct 2016)
  - 3 angled wells (60°) to 85 linear feet TD, or 42.5 feet bgs
  - 5 sand-filled fractures per well, 15 fractures total

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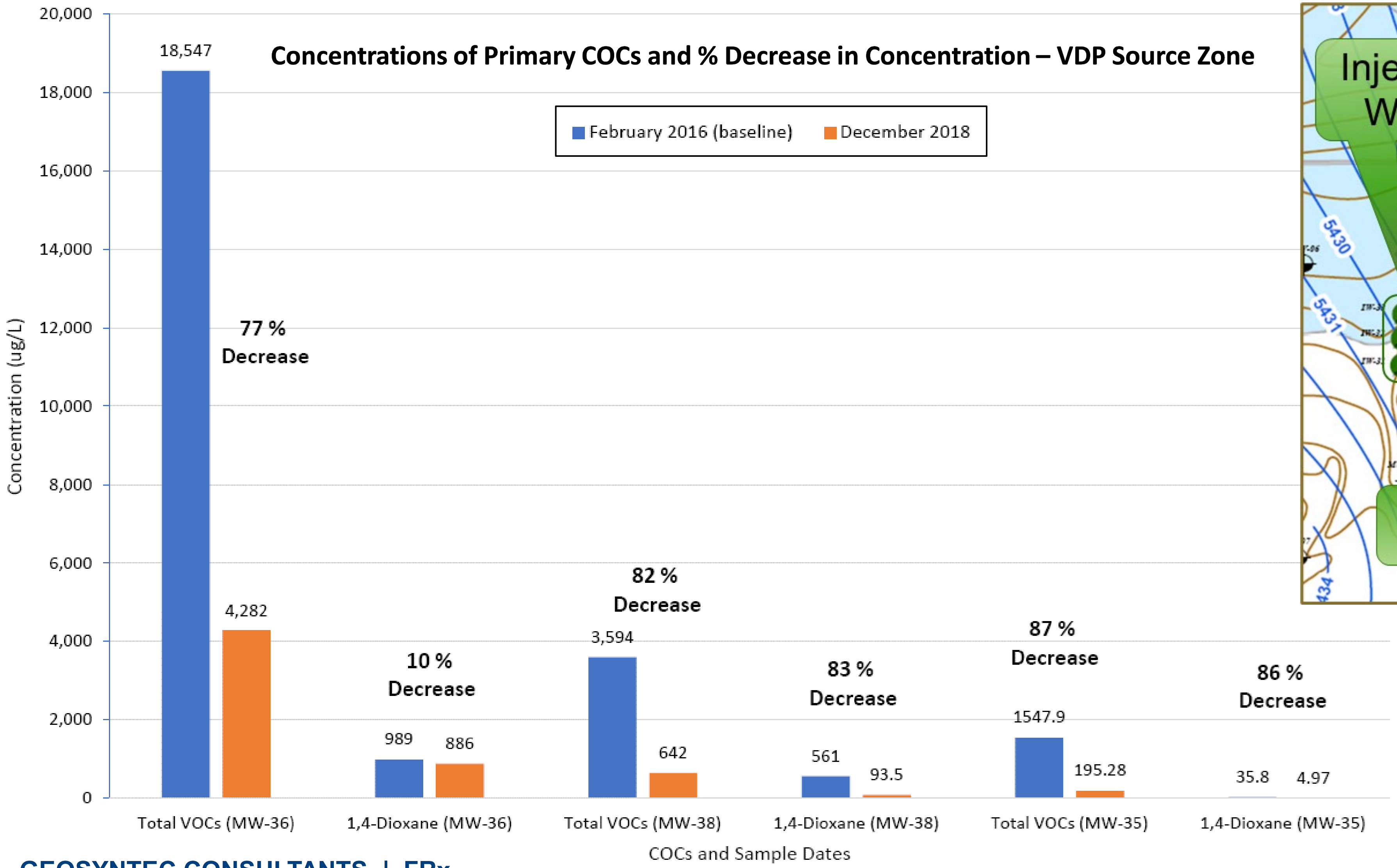
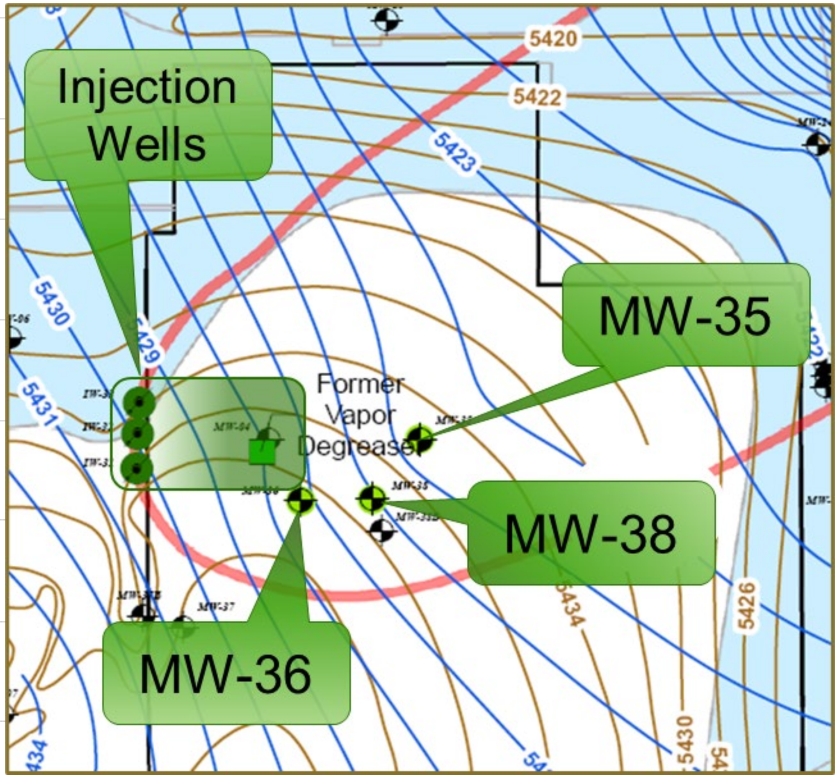
  - 5 sand-filled fractures per well, 15 fractures total
- Dual oxidant mixture to treat CVOCs + 1,4-dioxane
  - ISCO approach using innovative permanganate-persulfate mixture
  - Oxidant formulation and dosing determined by treatability testing
- Dosing and Delivery Metrics
  - Sodium Persulfate: 6,447 pounds @ 75 g/L
  - Sodium Permanganate: 538 gallons @ 26 g/L
  - Total oxidant solution: 10,976 gallons
  - Flow & Pressure: 4-6 gpm typical @ 5-15 psi

# Case Study #1 – Source Treatment Results



# Take Home Messages – Case Study #1

Successful distribution of ERD and ISCO amendments through sand-filled fractures in weathered bedrock provided treatment of CVOCs and 1,4-dioxane.

Novel ISCO chemistry used to treat CVOCs and 1,4-dioxane in weathered bedrock source zone.

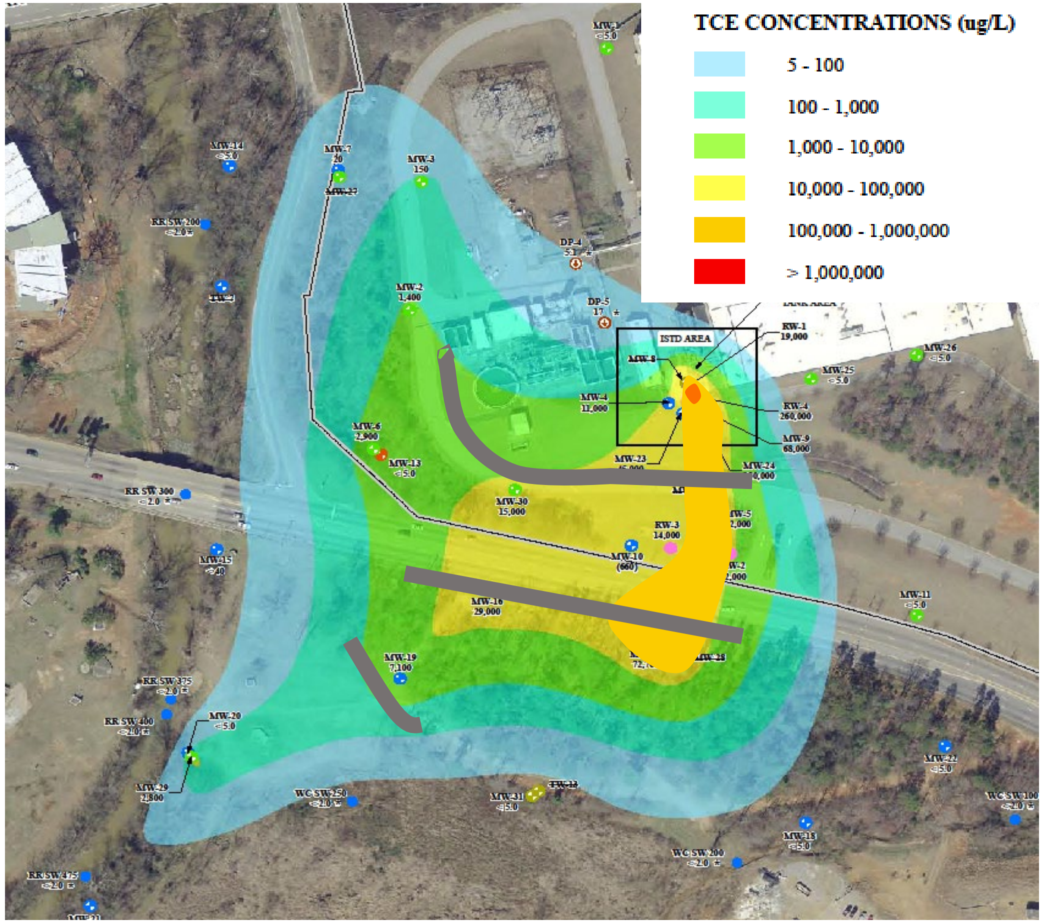
77-86% decrease in total VOCs

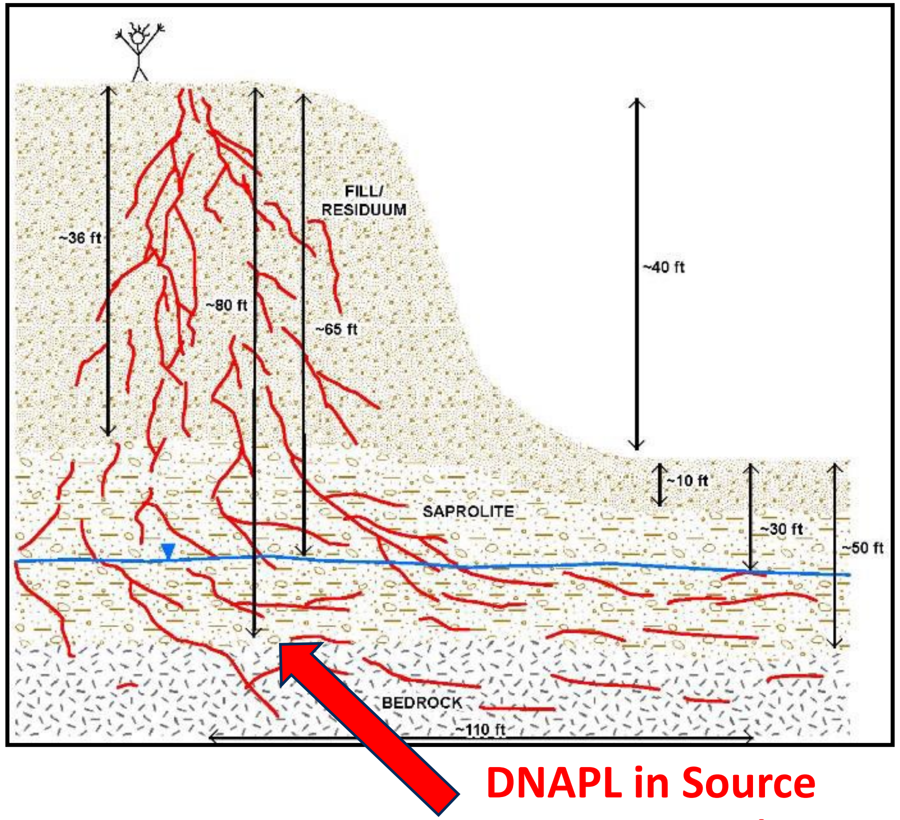
10-87% decrease in 1,4-dioxane

Sand-filled fractures enhanced amendment distribution in weathered rock where traditional methods failed.

# Key Concepts and Considerations – Case Study #2

- Influence of bedrock structure on migration of contaminants and amendments
- Influence of bedrock structure on success of remedial implementation
- Potential for mobilization of contaminant mass and/or altered flowpaths
- Opportunities to overcome limitations in bedrock porosity
- Accessibility of source and plume mass
- Defining performance criteria and endpoints



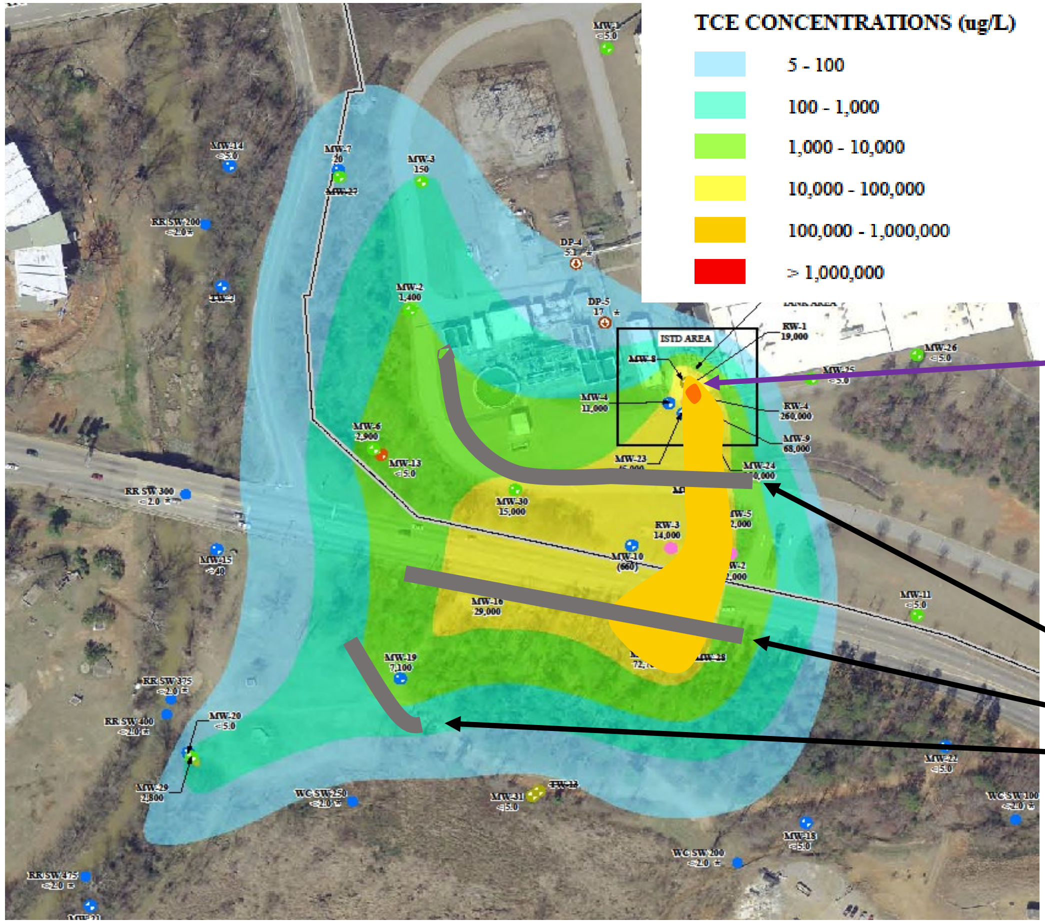




**DNAPL in Source**
**(max 1,200 mg/L TCE)**

## Case Study #2 – South Carolina

TCE in saprolite (Type 3) transitioning to competent bedrock (Type 1): **Remedial Solution**

- DNAPL source area, 15-acre TCE plume
- Three target zones: saprolite, partially weathered rock (PWR), and fractured metamorphic bedrock
- Source treatment: Potassium permanganate slurry injection
- Plume treatment: PRBs via mZVI slurry injection




## Source Treatment

### ISCO with Permanganate

Grid configuration of injection wells
Rapid source depletion

## Plume Treatment

### ISCR with ZVI

PRB configuration of injection wells
Long-term treatment

**Case Study #2 – South Carolina**

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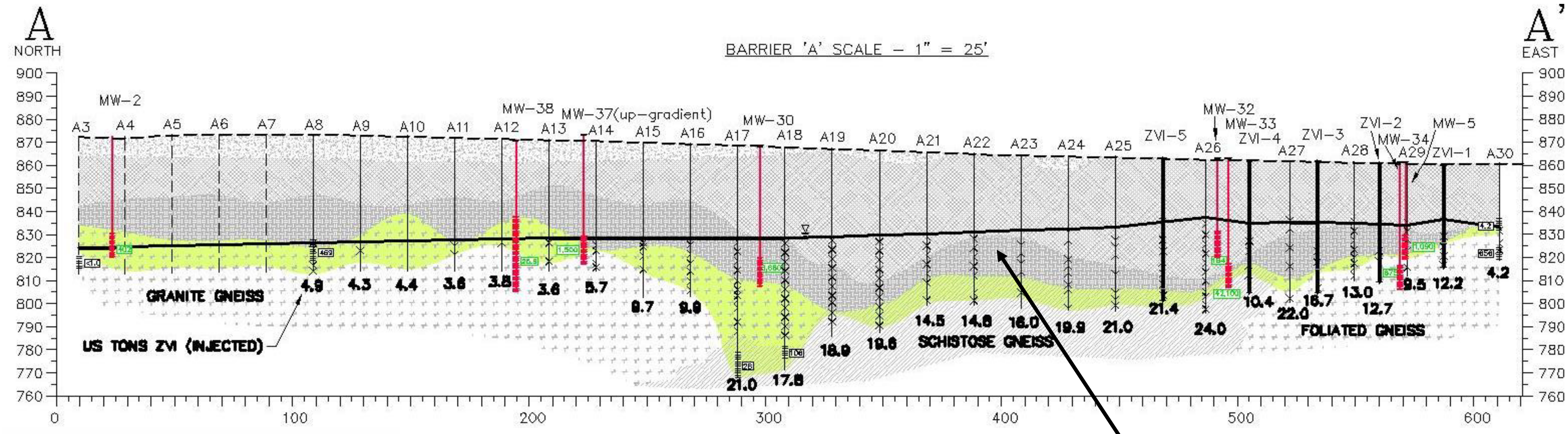
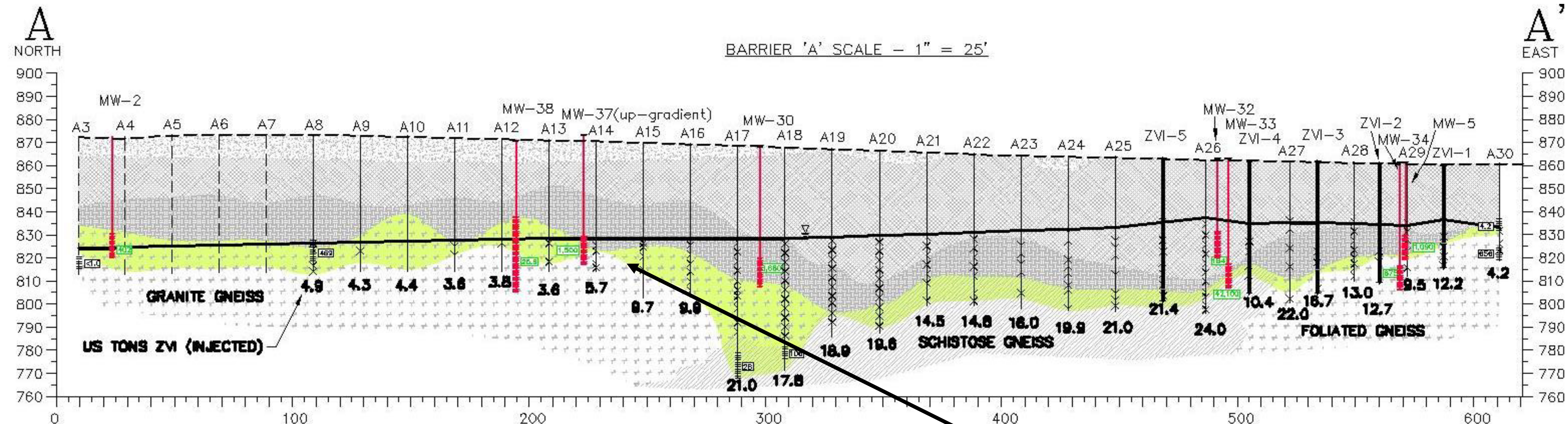
# Case Study #2 – Target Zones in Piedmont Geology

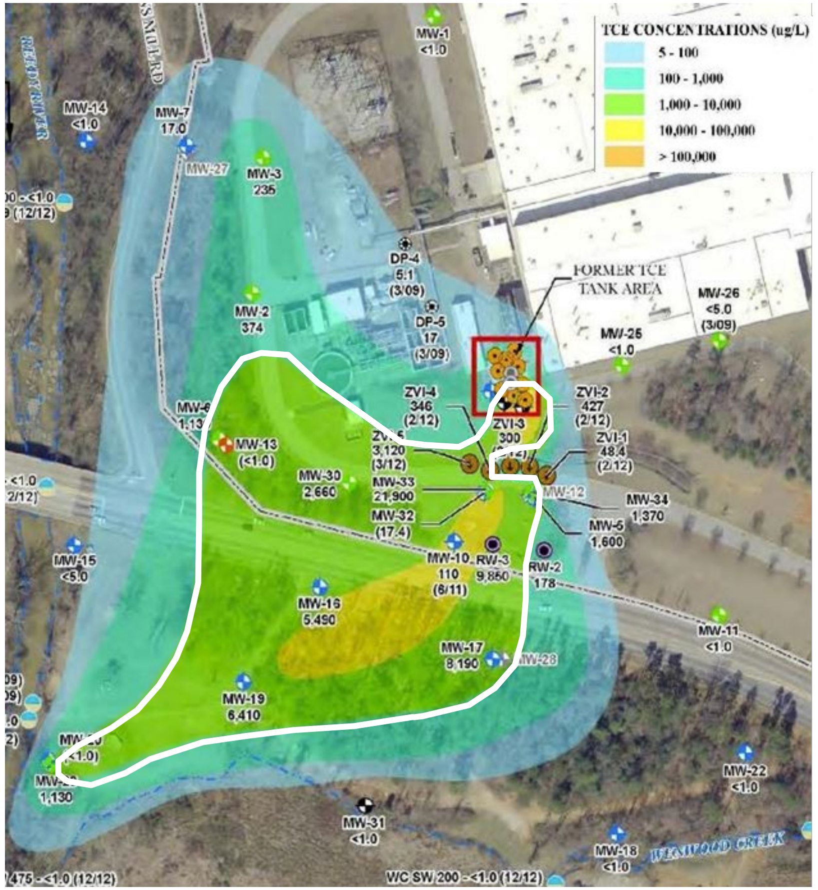



# Case Study #2 – Target Zones in Piedmont Geology

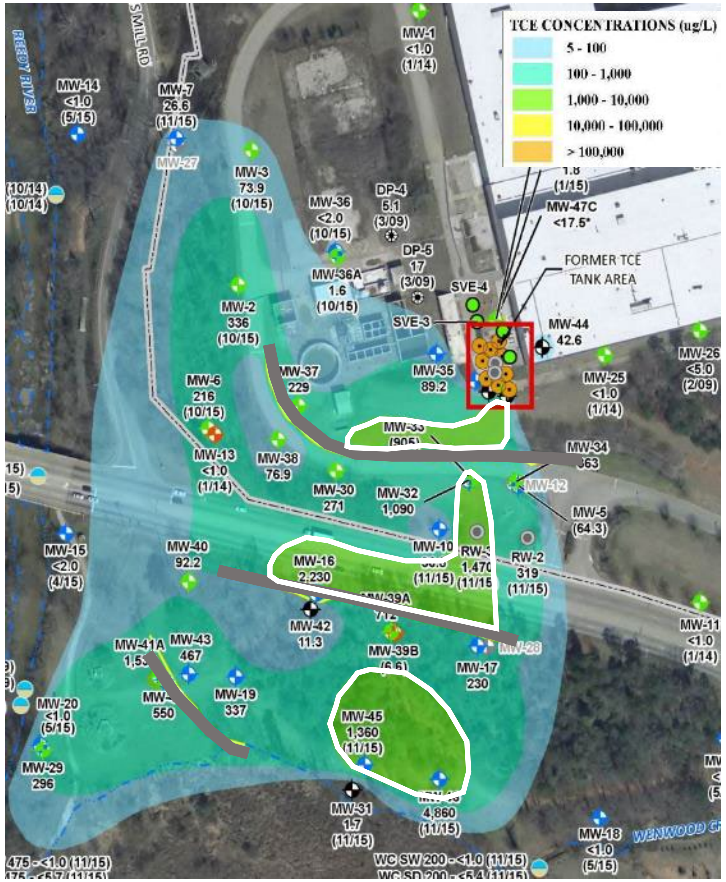



**Weathered Crystalline Bedrock**

# Case Study #2 – Plume Treatment – 1,000 μg/L

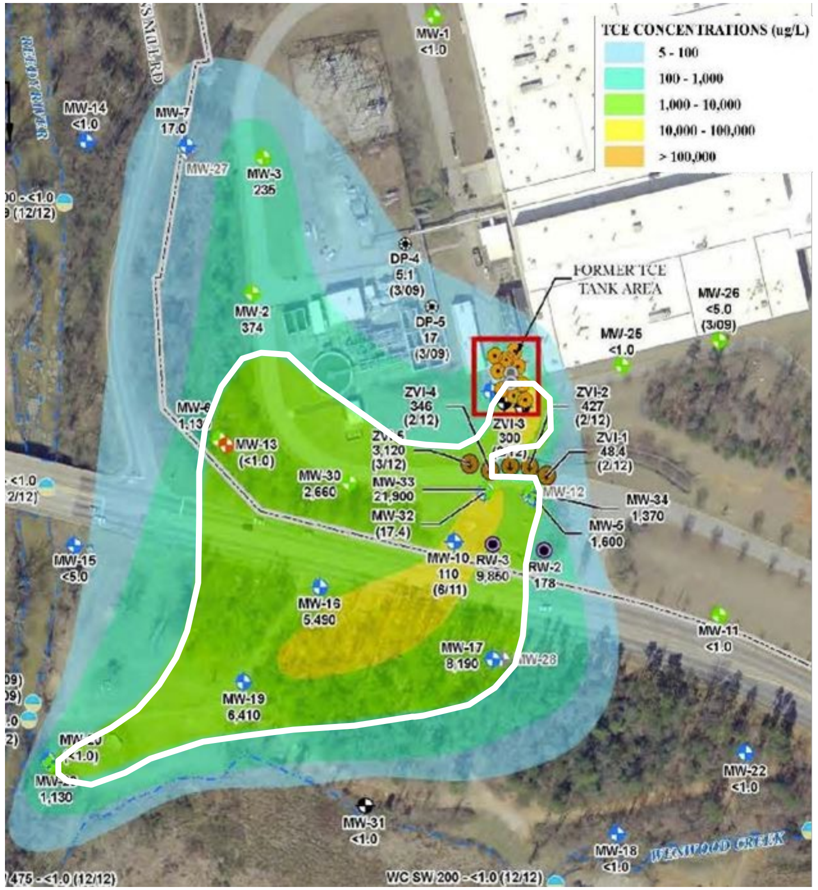


**Pre-Injection Q1 2013**

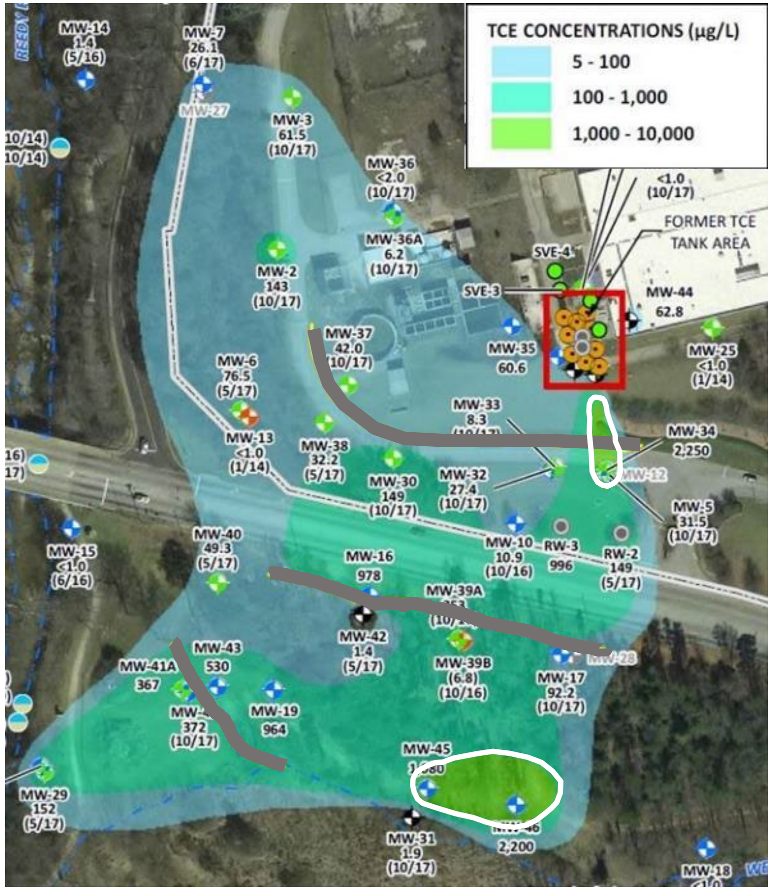


**Post-Injection Q1 2016**

# Case Study #2 – Plume Treatment – 1,000 μg/L

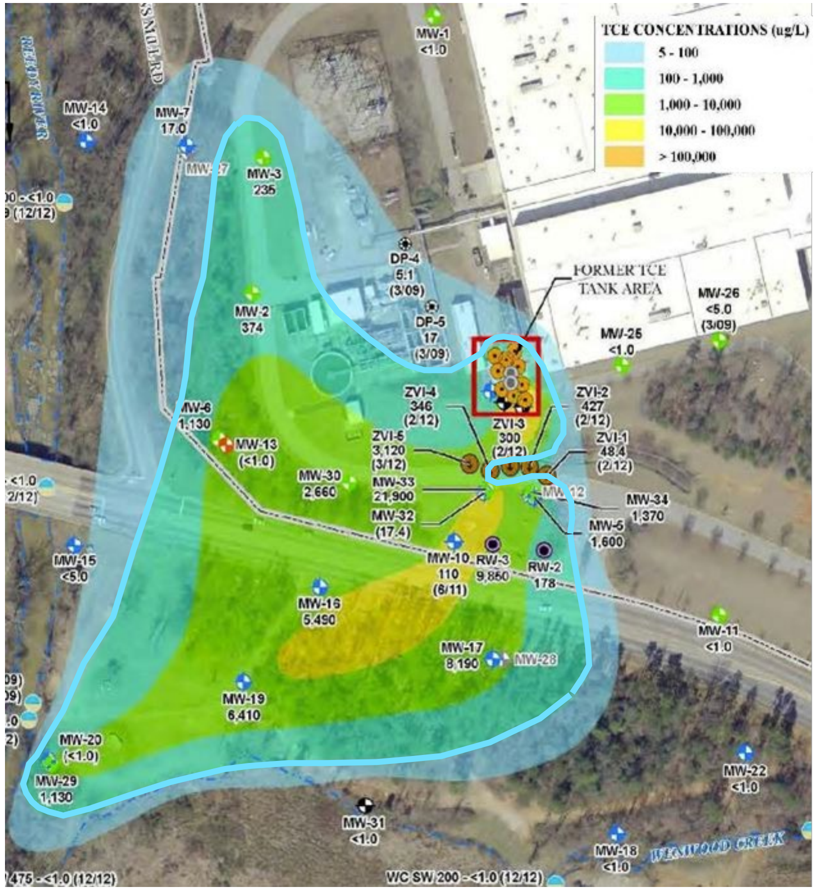



**Pre-Injection Q1 2013**

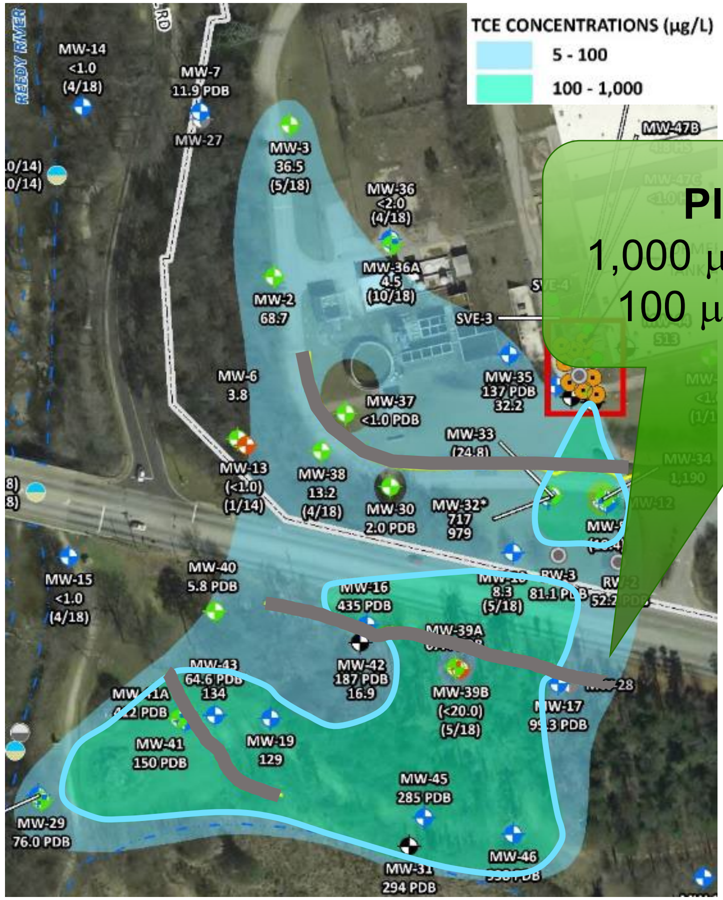



**Post-Injection Q1 2018**

# Case Study #2 – Plume Treatment – 100 $\mu g/L$




Pre-Injection Q1 2013




**Plume Area 2020**
1,000 $\mu g/L$ decreased >99%
100 $\mu g/L$ decreased 70%

Post-Injection Q2 2019

# Take Home Messages – Case Study #2

DNAPL in Piedmont geology presents unique challenges. Overcoming them requires firm CSM, creative remedial approach, and effective access to COCs in multivariate units.

- Firm CSM in saprolite > PWR > crystalline bedrock profile is paramount
- Combined ISCO-ISCR has proven effective and durable
- Hydraulic fracturing of solid reagents provides access to varied target units

# Acknowledgements

Geosyntec consultants

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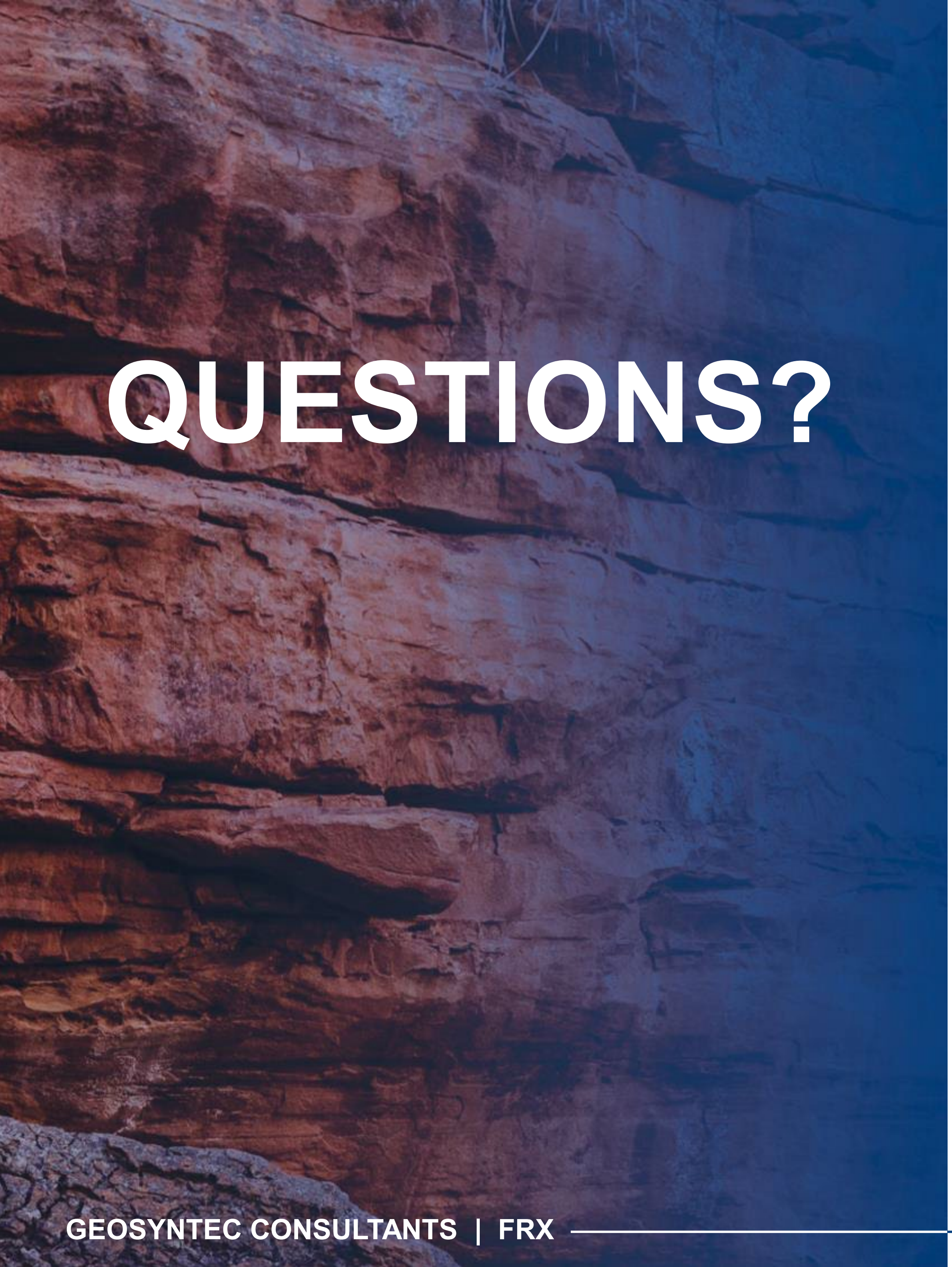
George Maalouf and Stan Golaski at Rogers & Callcott Environmental



# QUESTIONS?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