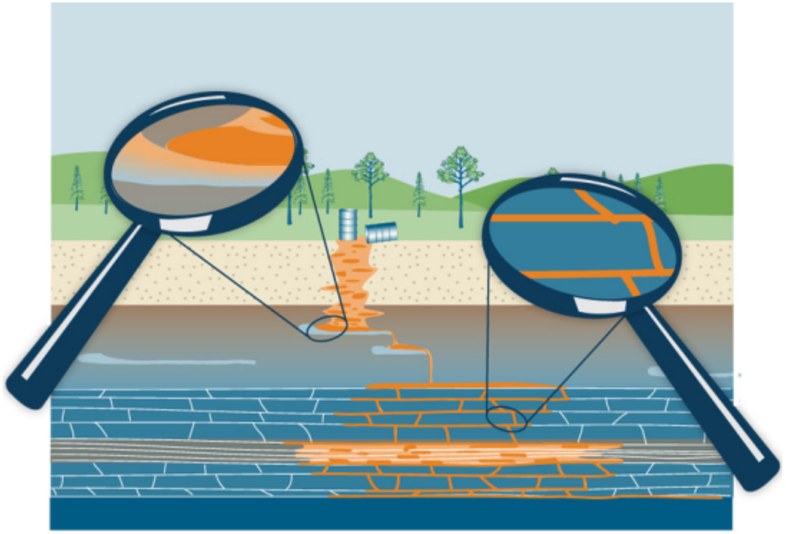
Characterization and Remediation of Fractured Rock



Tuesday, May 15, 2018
Kauffman Foundation Conference Center

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Overview of the Training - Purpose

1. To provide a basic high-level introduction to the unique challenges of investigation and remediation in fractured rock
2. To capitalize on recent advances and successes captured in the new ITRC guidance document
3. To demonstrate that bedrock challenges, historically written off, are surmountable

Courtesy Dan Bryant

Overview of the Training - Agenda

- **Introduction**
- Fractured Rock CSM Considerations
- Fluid Flow in Bedrock
- Contaminant Fate and Transport
- Fractured Rock Characterization
- Remedy Development for Contaminated Fractured Rock
- Monitoring
- Summary

The Problem with Fractured Rock Remediation

- Not achieving cleanup goals
- Spending time and money, but substantial risk remains
- Often considered too complex
- Often defaults to containment and long-term monitoring
- Conventional approaches reflect an outdated understanding of fracture flow that does not incorporate advances in the sciences and technologies of site characterization and remediation

Common Site Challenges

- Incomplete understanding of complexity of groundwater and contaminant flow in fractured rock
- Difficulties in site characterization
- Cost of investigation
- Unrealistic remedial objectives
- Selected remedy is not satisfactory

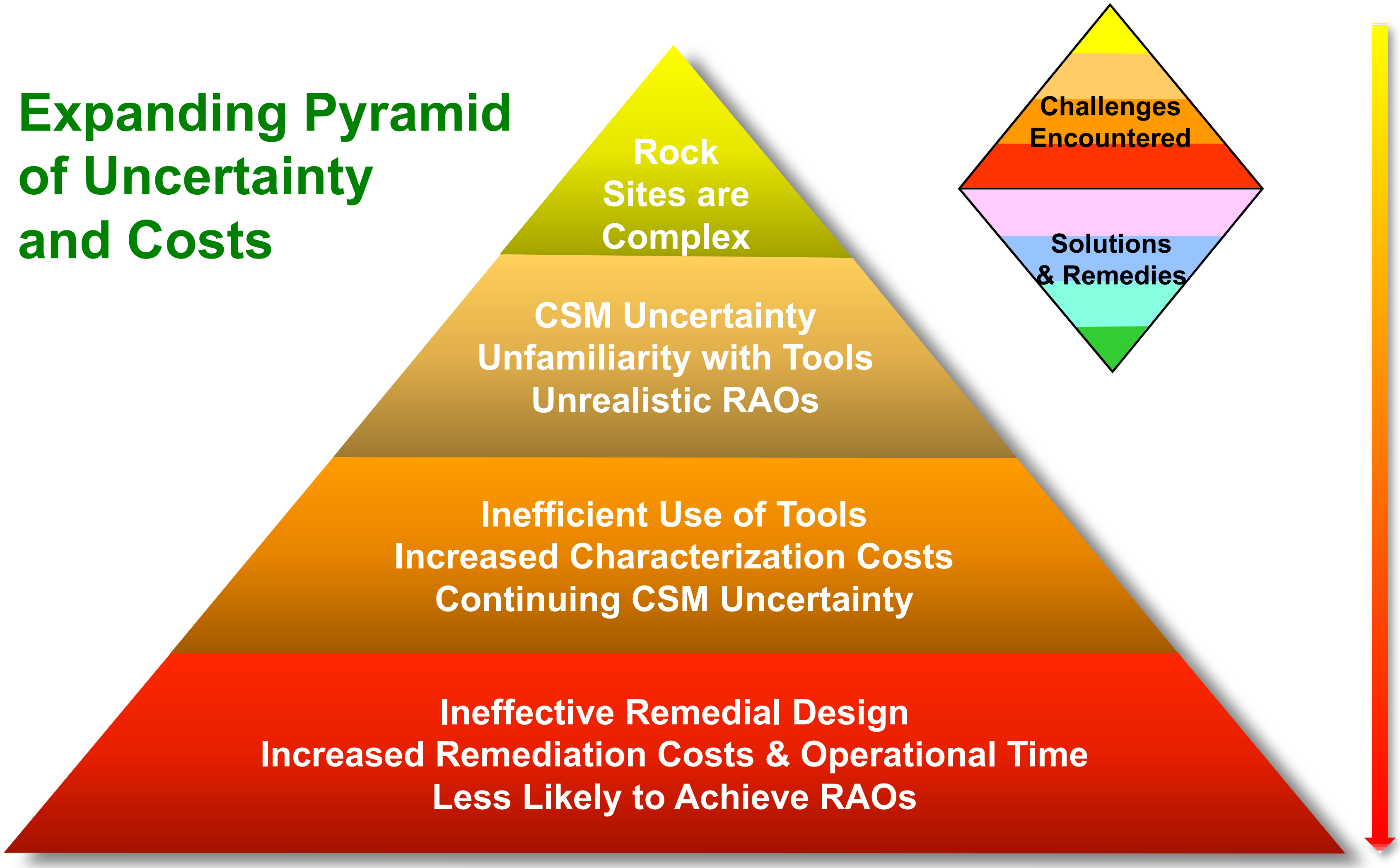
Courtesy Dan Bryant

Dispelling the Fractured Rock Site Myth Can These Site Really Be Cleaned Up?

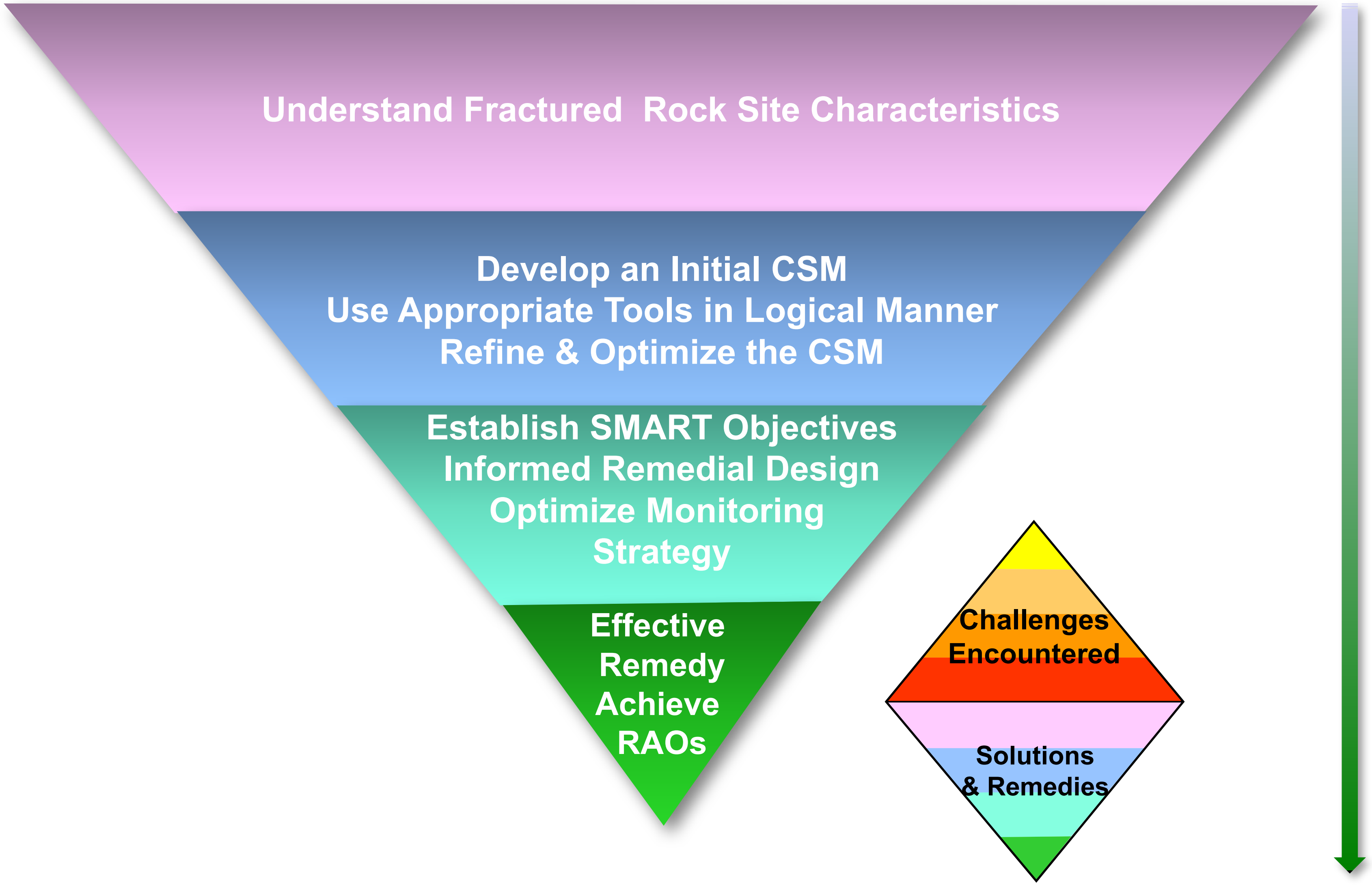
Courtesy Dan Bryant

The Nature of the Problem

Expanding Pyramid of Uncertainty and Costs



The Nature of the Solution



A Better Way….. Based on the Latest Research Specific to Fractured Rock

ITRC Technical and Regulatory Guidance:

Characterization and Remediation of Fractured Rock

http://fracturedRX-1.itrcweb.org

Characterization and Remediation of Fractured Rock: The Solution

ITRC Technical and Regulatory Document

- Role of geology in controlling contaminant fate and transport
  - Similarities and Differences Between Unconsolidated Material CSMs and Bedrock CSMs
- Role of Geologic terranes
- Hydrogeology
  - Fluid flow/fate and transport in fractures and matrix
- Chemistry

What will you gain from the ITRC Fractured Rock short course?

Characterization:

- How to Develop the Hydrogeologic Framework/CSM
- How to maximize information collected from each location, given that hard rock environments are more expensive and complicated than the unconsolidated subsurface
- Improved understanding of options and procedures for efficient characterization and remediation of fractured rock
- Proper selection and application of tools
- Will help define the level of characterization necessary to move forward with effective remediation

What will you gain from the ITRC Fractured Rock short course?

Characterization:

- Better understanding of the fractured environment
- More confidence in approaching fractured rock sites
- Better understanding of how to apply investigation and remediation tools to fractured rock sites
- Better understanding of the complexities faced when dealing with fractured rock

What will you gain from the ITRC Fractured Rock short course?

Remediation

- Better understanding
- More confidence in approaching fractured rock sites
- Better understanding of how to apply investigation data to developing remedial strategies at fractured rock sites
- Better understanding of the complexities of remediation in fractured rock

What will you gain from the ITRC Fractured Rock short course?

Monitoring

- Efficient/effective performance and compliance monitoring
- Built-in decision frameworks for technology transitions

Overview of the Training

- Introduction
- **Fractured Rock CSM Considerations**
- Fracture Characteristics of Geologic Terrane
- Fracture Flow & Contaminant Fate and Transport
- Fractured Rock Characterization
- Remedy Development
- Monitoring
- Summary

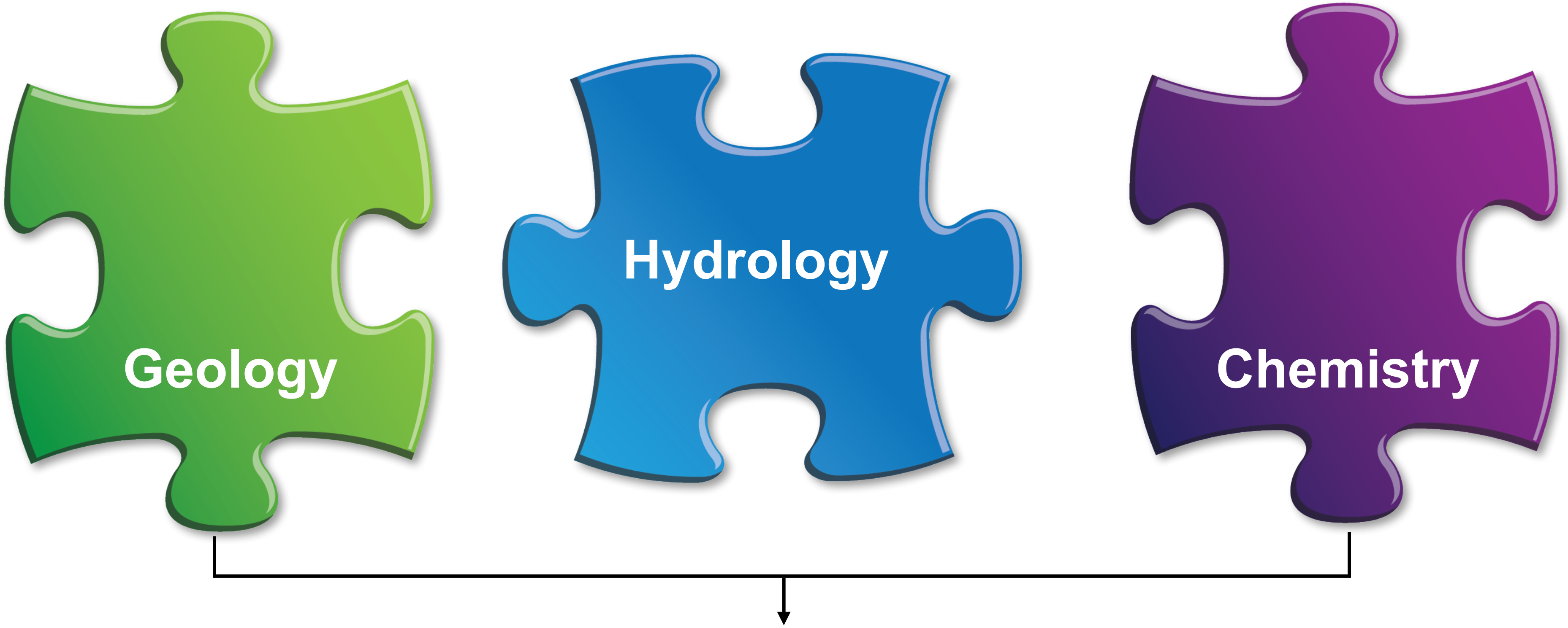
Poll Question

- Are Conceptual Site Models at fractured rock sites fundamentally differently from unconsolidated sites?
  - Yes
  - No

Fractured Rock CSM Considerations

- Definition of CSM
  - A representation of a fractured rock hydrogeologic system
  - Describes and explains key characteristics of groundwater flow, contaminant transport, and storage in the rock matrix and fractures
- Purpose
  - Characterize potential contaminant migration routes and risks to receptors and implement an effective remedial action accordingly.

Building a Quality Conceptual Site Model – You Need the Right Pieces



Fate & Transport

- Key to your success a team of expertise: hydrogeology, structural geology, geophysics, geochemistry, and engineering

Fractured Rock CSM Considerations

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Fractured rock sites require a team of specialists

Physical characteristics

- Lithology
- Structure
- Anisotropy
- Heterogeneity

Hydrologic properties

- Matrix Flow
- Fracture Characteristics

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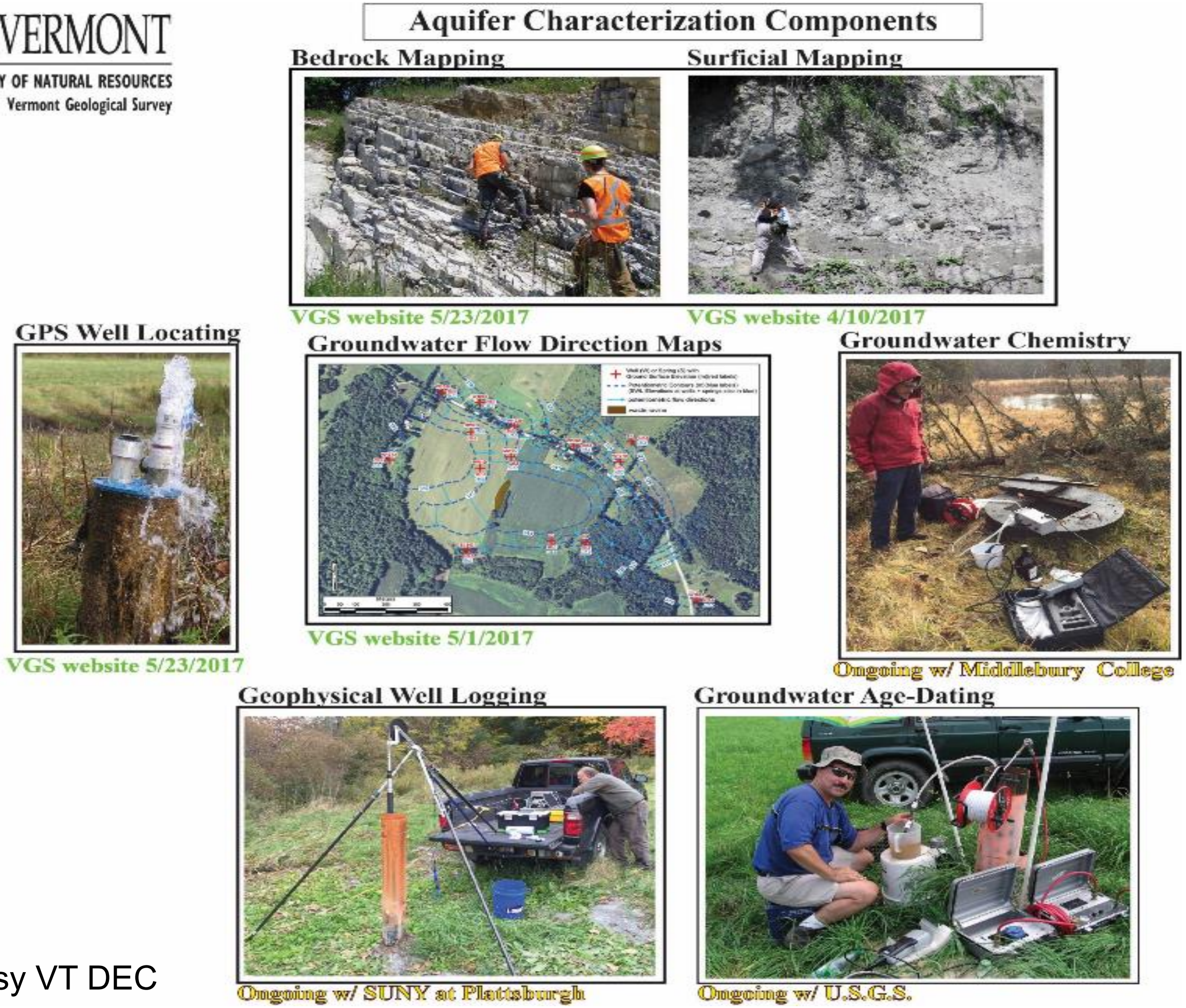
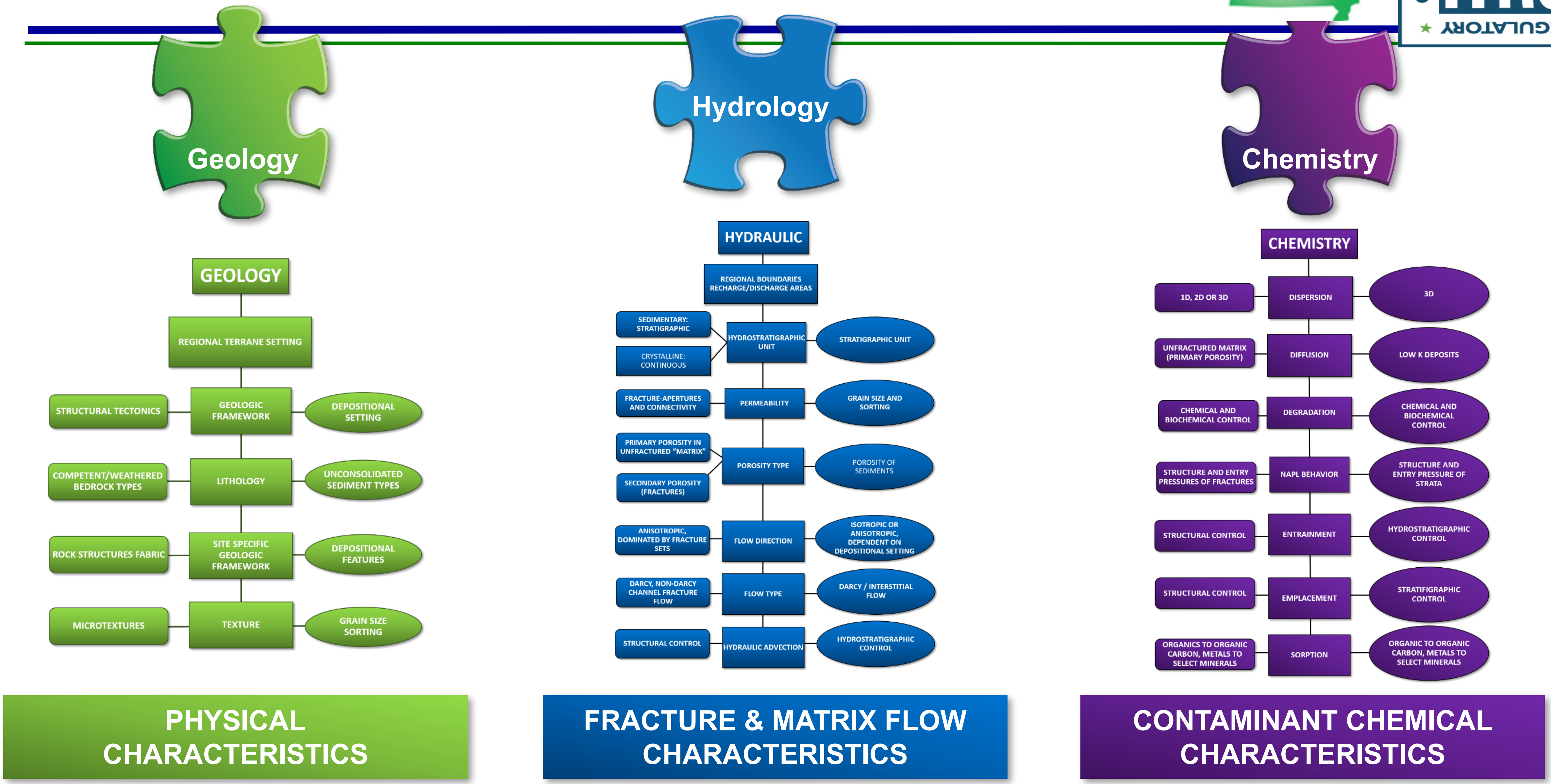
Vermont Geological Survey



Courtesy VT DEC

What you need to know about Fractured Rock



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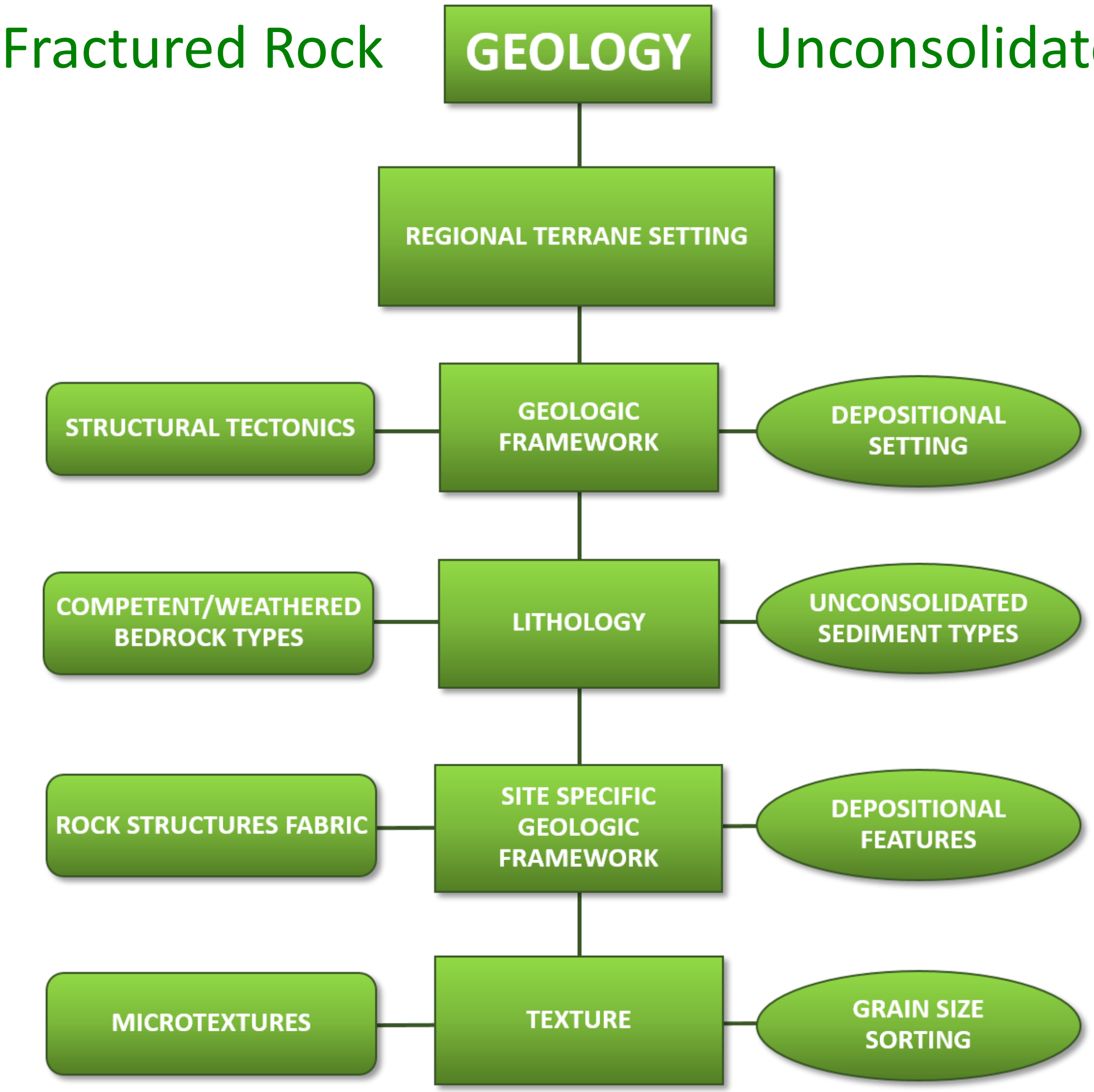
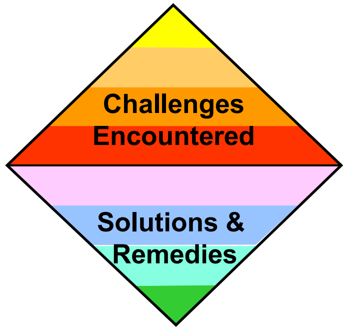
Geologic Characteristics that affect flow



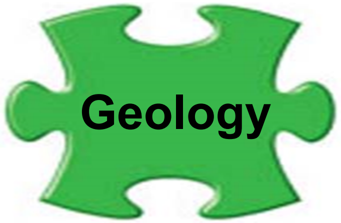


Terrane Analysis - Overview

Geology

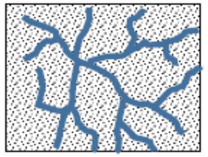
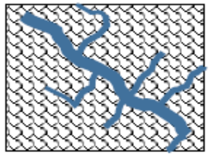
- Provides context for investigations
  - lithologic, stratigraphic, tectonic, structural, and physiographic characteristics
- Reveals patterns, features, and boundary conditions that influence fluid flow
- Provides broad-scale hydrogeologic framework and initial CSM
- Guides detailed investigation, remediation, and risk management measures

Terrane Analysis - Elements



1. Regional physical setting (e.g., physiographic provinces)
2. Bedrock lithology and stratigraphy
3. Structural geology and tectonic setting
4. Anisotropy and heterogeneity
5. Hydrology
6. Location of potential receptors
7. Historical Land Use

Table 2-1
Terrane Analysis Matrix – Excerpt (Sedimentary Rocks)

Potential Receptors (e.g., groundwater supply wells, surface water bodies)	Regional Physical Setting (physiographic provinces)	Lithology		Structure	Anisotropy	Heterogeneity	Hydrology
		Non-Crystalline	Sedimentary[1]	 Horizontal Beds	Isotropic in horizontal plane. Impedes (does not prohibit) vertical migration of NAPL.	Potential heterogeneity associated with complex depositional history and environments, local-scale folding, and differential weathering. Homogeneous for uniform depositional history / environment.	 Isotropic flow to dendritic drainage network.
				 Inclined Beds	Preferential fluid migration along strike (into /out of page) under static equilibrium. Down-dip migration of DNAPLs. Fluctuation of LNAPL up and down dip with changes in water table elevation. Down-dip pumping induced flow. Down-dip emplacement of contaminants through "vadose" zone via surface release. Down-dip infiltration and recharge.		 Anisotropic flow to trellis drainage network.
				 Vertical Beds			
				 Folding / Faulting		Potential heterogeneity associated with complex structural deformation, fracturing, and depositional history and environment.	

1) Sedimentary rocks include clastic, chemical, and biological rocks that exhibit bedding. This matrix does not apply to karst or solution features associated with chemical sedimentary rocks. (See Appendix B for a more detailed description of Karst features.)

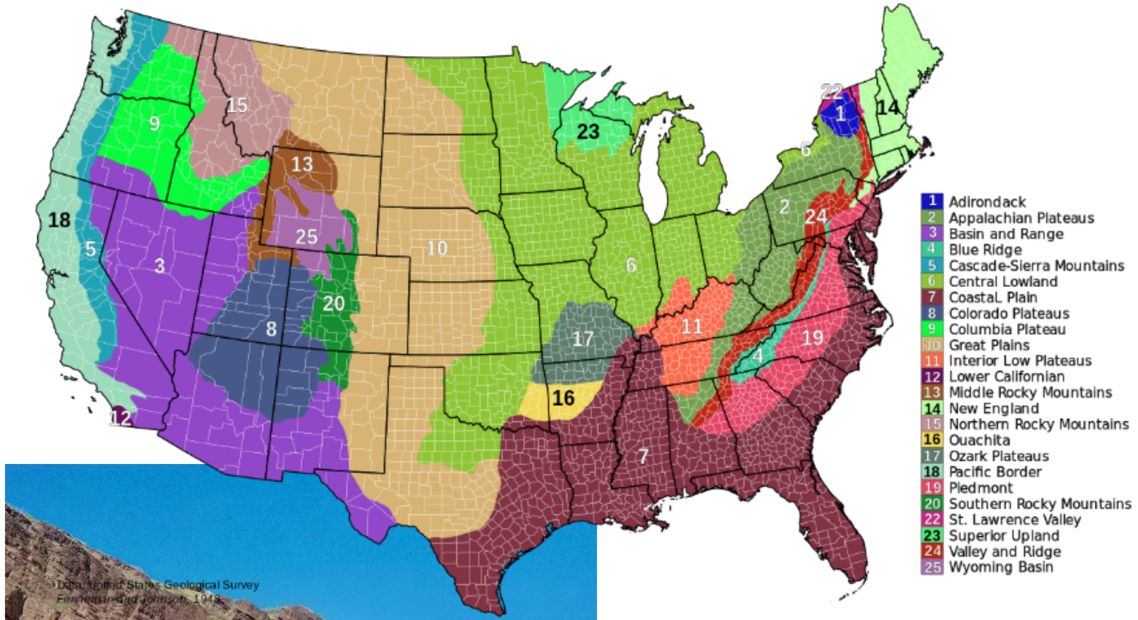
ITRC FracRx-1 Appendix B

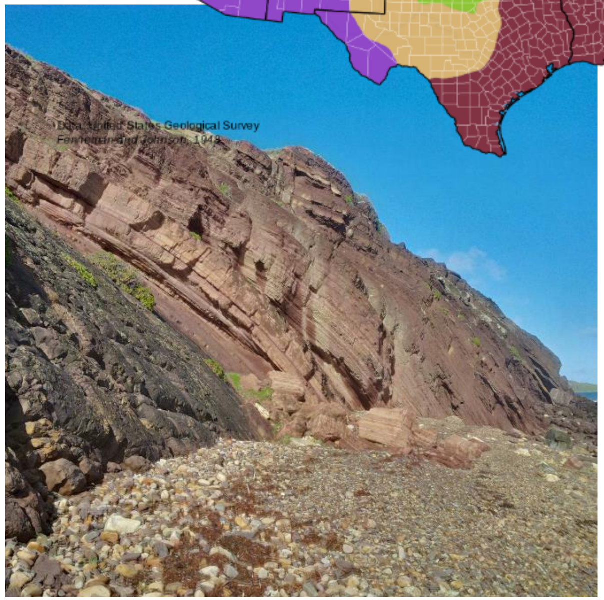
Terrane Analysis - Elements

Geology

1. **Regional physical setting (e.g., physiographic provinces)**
   - Characterized by major rock types
     - Igneous, sedimentary, metamorphic
   - Structural attributes
   - Topography
   - Drainage feature
2. **Bedrock lithology and stratigraphy**
   - primary porosity (matrix)
   - secondary porosity (fractures)
   - fracture characteristics

Geophysical Provinces of the Conterminous United States





Terrane Analysis - Elements

Geology

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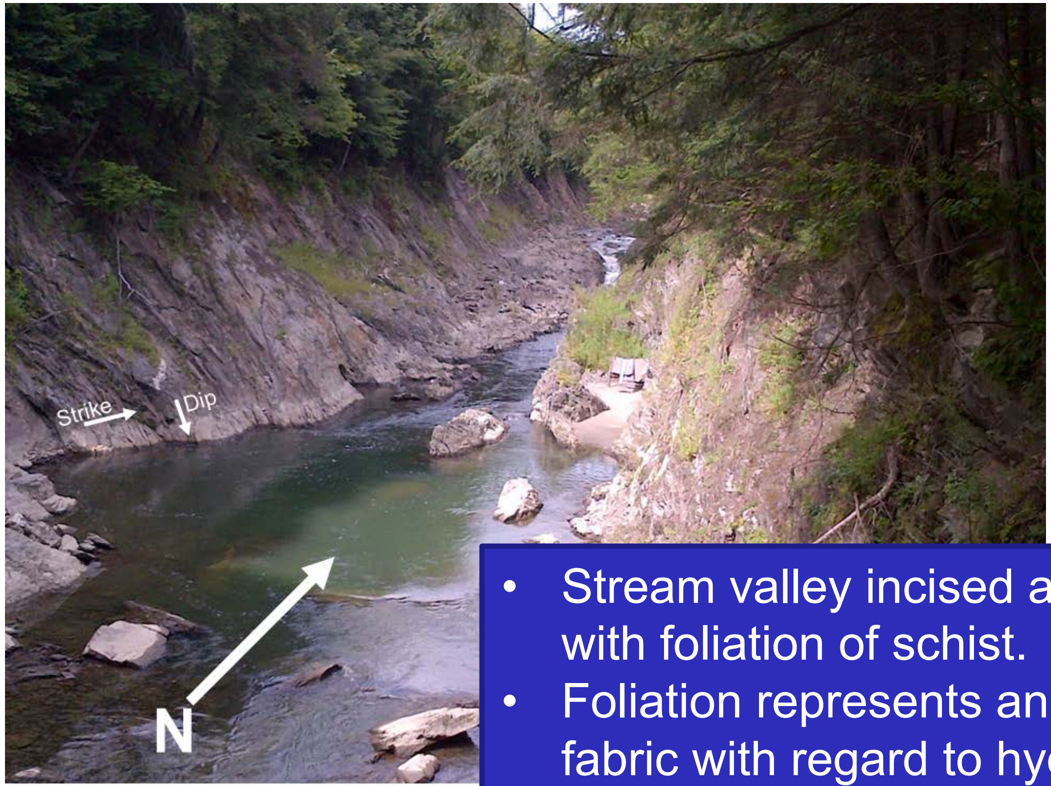
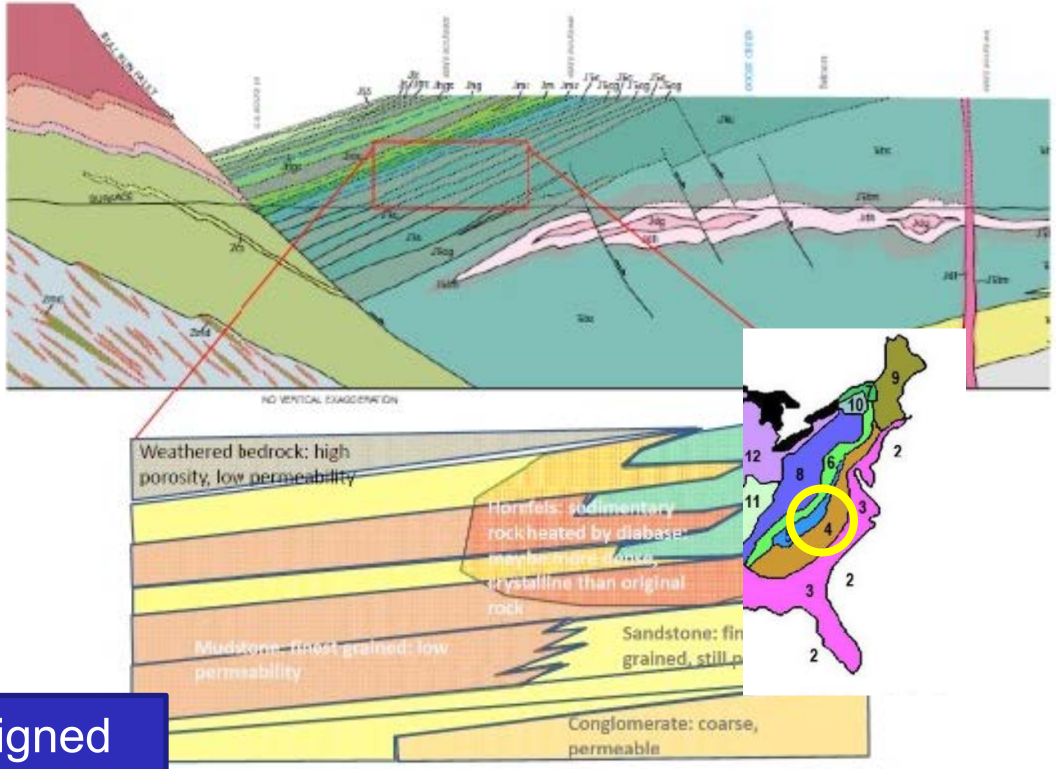
3. Structural geology and tectonic setting
4. Anisotropy and heterogeneity
5. Hydrology



- Stream valley incised and aligned with foliation of schist.
- Foliation represents anisotropic fabric with regard to hydrogeology.



Courtesy Jeff Hale

Terrane Analysis - Elements

Geology

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6. Location of Potential Receptors
7. Historical Land Use (Industrial Archeology)

Courtesy VT DEC

Not really part of terrane analysis, but the terrane may influence type of historical development and therefore, possible sources.

Terrane Analysis - Example

Geology

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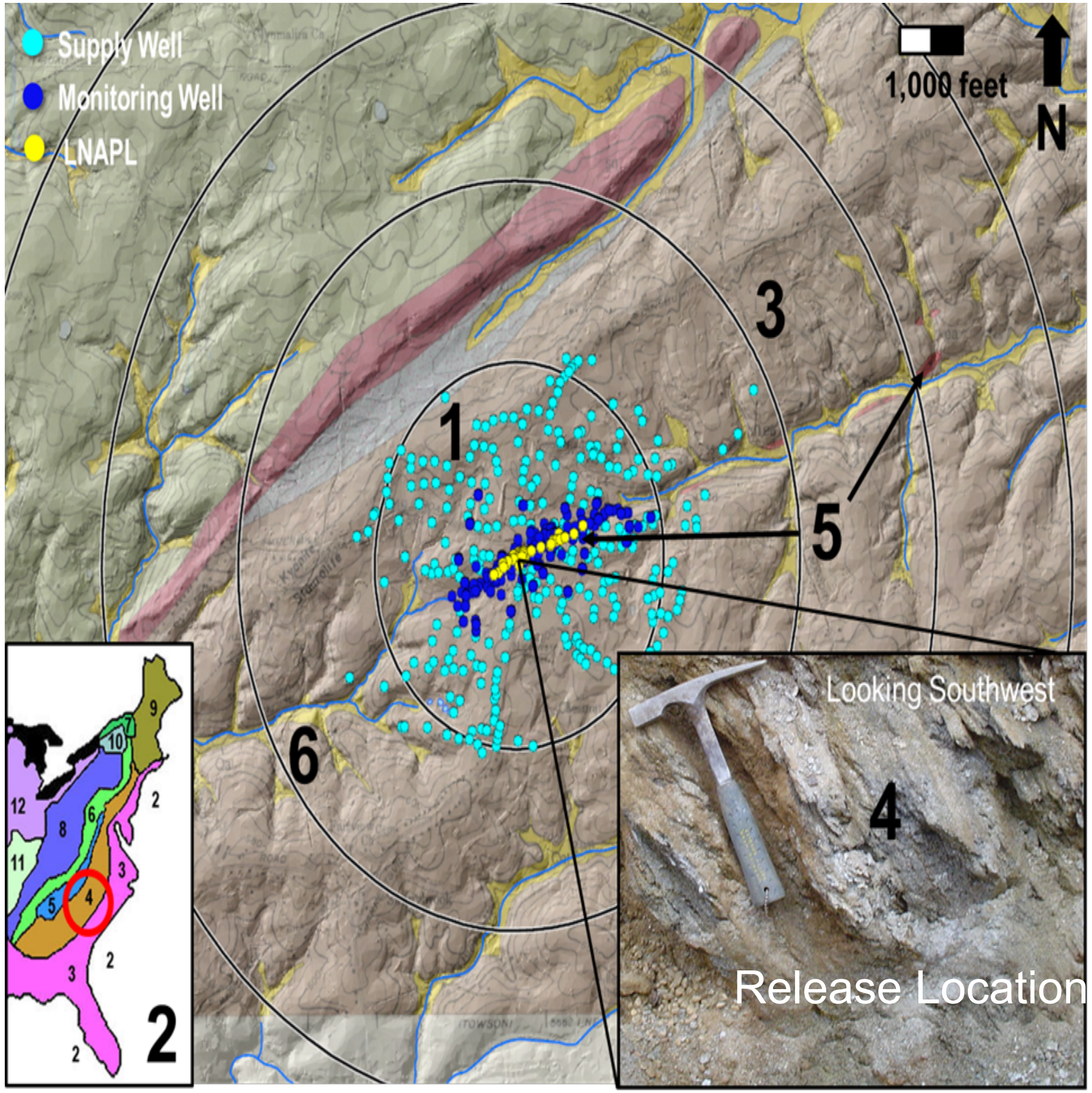
1. Piedmont Physiographic Province
2. Metamorphic rocks (gneiss and schist)
3. Foliation (NE Strike, NW Dip, regional fabric)
4. Anisotropy influenced contaminant migration and emplacement
5. Trellis drainage pattern of local streams = groundwater discharge locations
6. Supply wells and streams



Courtesy Jeff Hale

Overview of the Training

Geology

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- Introduction
- Fractured Rock CSM Considerations
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Fluid Flow in Fractured Rock

Hydrology

- Where is the fluid?
- Are there multiple phases?
- How does it move?

Fractured Rock	HYDRAULIC	Unconsolidated
	REGIONAL BOUNDARIES RECHARGE/DISCHARGE AREAS	
SEDIMENTARY: STRATIGRAPHIC; CRYSTALLINE: CONTINUOUS	HYDROSTRATIGRAPHIC UNIT	STRATIGRAPHIC UNIT
FRACTURE-APERTURES AND CONNECTIVITY	PERMEABILITY	GRAIN SIZE AND SORTING
PRIMARY POROSITY IN UNFRACTURED "MATRIX"; SECONDARY POROSITY (FRACTURES)	POROSITY TYPE	POROSITY OF SEDIMENTS
ANISOTROPIC, DOMINATED BY FRACTURE SETS	FLOW DIRECTION	ISOTROPIC OR ANISOTROPIC, DEPENDENT ON DEPOSITIONAL SETTING
DARCY, NON-DARCY CHANNEL FRACTURE FLOW	FLOW TYPE	DARCY / INTERSTITIAL FLOW
STRUCTURAL CONTROL	HYDRAULIC ADVECTION	HYDROSTRATIGRAPHIC CONTROL

Challenges Encountered / Solutions & Remedies

Hydrogeology of Fractured Rock

Flow and transport in rock is inherently different than unconsolidated media

- ► Flow characterized by:
  - dual-porosity (fluid exchange between matrix and fractures)
  - secondary porosity (primarily fractures)
  - very large variations in transmissivity

Courtesy Dan Bryant

Bedrock Properties Controlling Flow

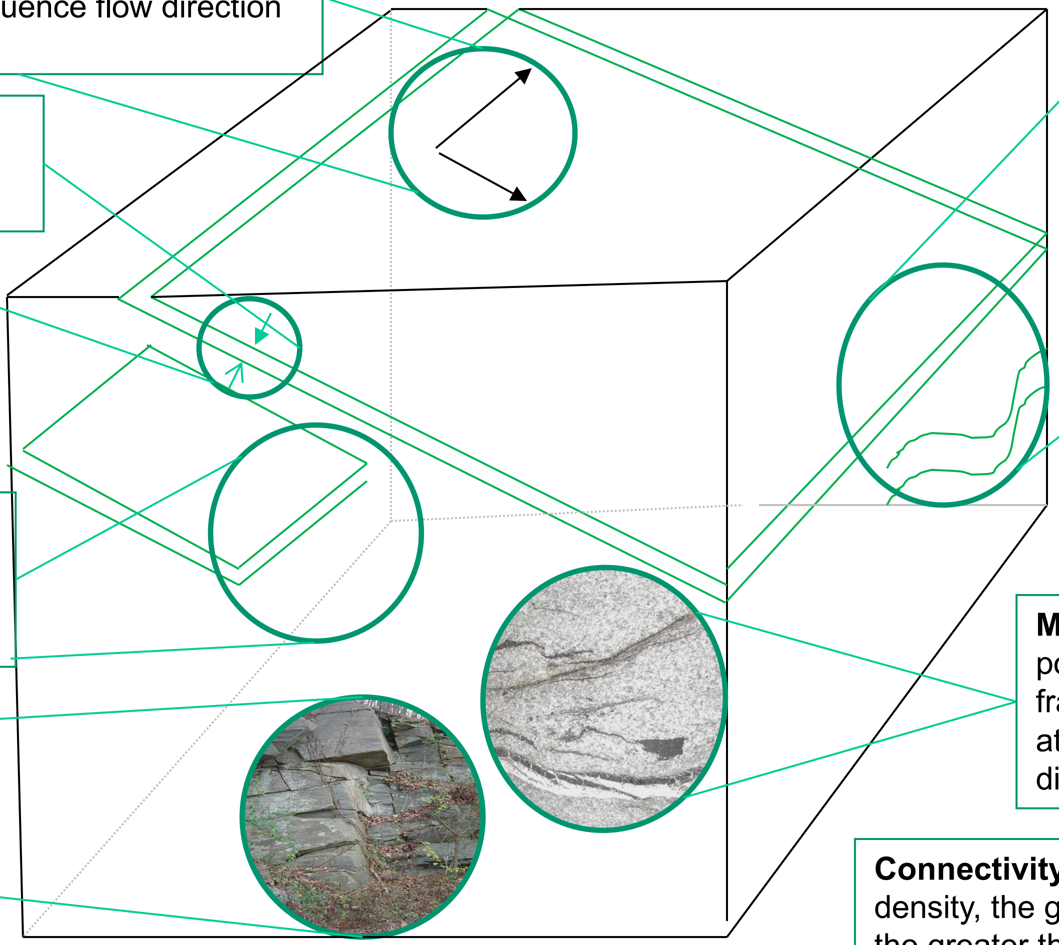
Orientation: direction (strike) and slope (dip) of fracture influence flow direction inside a fracture

Aperture: a 10 fold increase in a fracture width = a 1000 fold increase in flow potential

Infilling: debris, weathering products, cementation or biofilm in a fracture or on the fracture wall will affect flow

Length: the longer the fracture, the further unimpeded flow is likely to occur and the more likely fractures will interconnect

Fracture Density: the greater the number of fractures in a unit volume, the higher the fracture connectivity and capacity for flow and storage



Planarity or waviness: open flat fractures provide unimpeded flow while wavy fractures may lock open, or may form dead ends where fracture surfaces touch

Roughness: a smoother fracture surface results in less frictional resistance to flow and fewer surfaces for solids or microbes to attach to

Matrix: The rock type, grain size, porosity, cementation and micro-fractures affect how much flow occurs at the micro scale and the importance of diffusion and back diffusion.

Connectivity: The greater the fracture density, the greater the fracture length, the greater the potential for fractures to be connected

ITRC FracRx-1 Figure 3-2

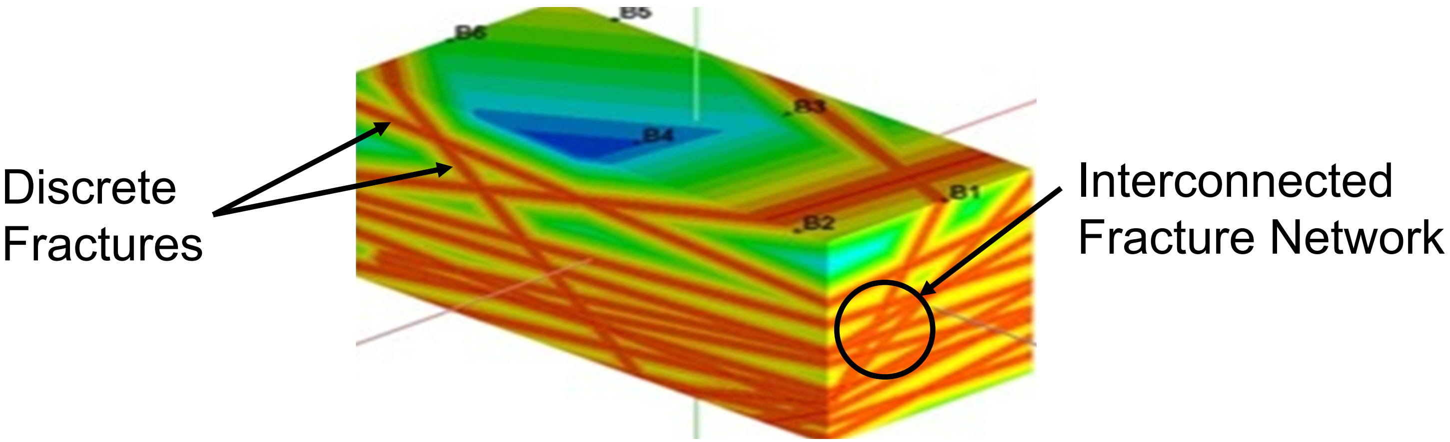
Primary Considerations for Flow in Sedimentary vs Crystalline Rock

- Influence of fractures
- Bedding or layering
- Fracture systems
- Mechanical and chemical weathering

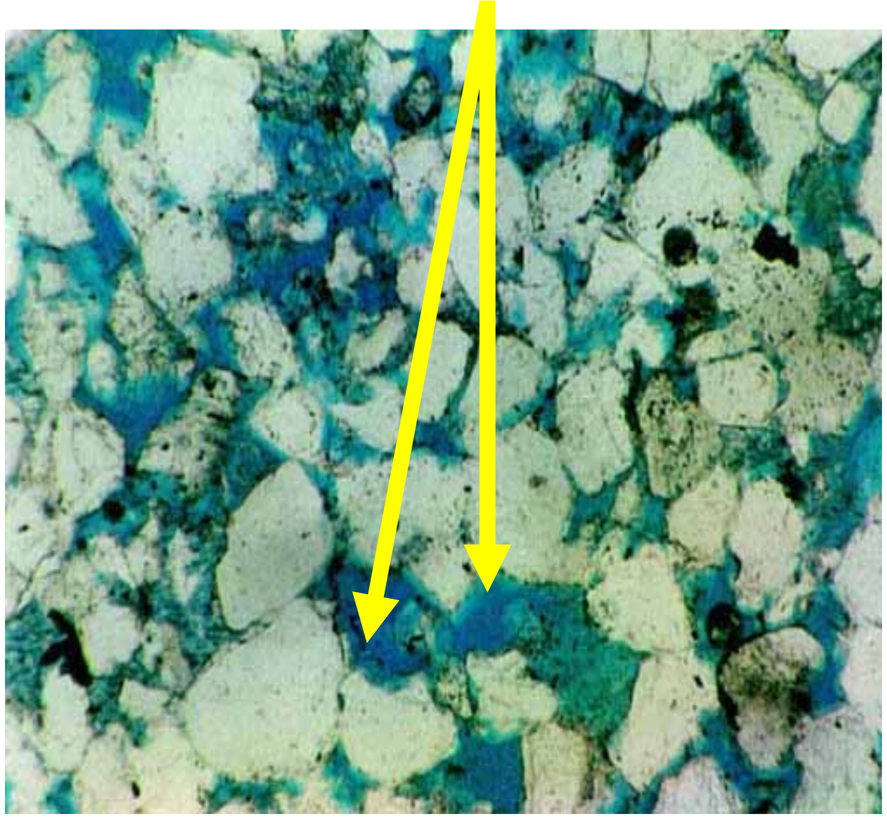
Courtesy Melissa Boysun
Courtesy Johannes Mark

Flow types drive investigation approach

- Matrix porosity flow
- Interconnected fracture network flow
- Discrete fracture flow
- Discrete Fracture Network (DFN)
- Equivalent Porous Medium (EPM)



Matrix Porosity Flow



From PGA Ltd.

Bedrock Characteristics Affecting Flow

Hydrology

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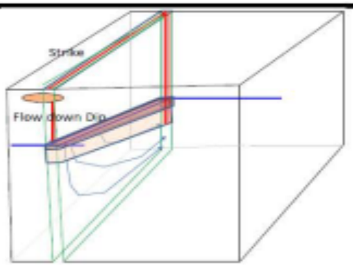
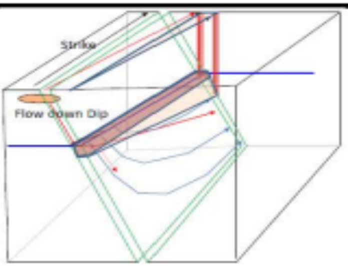
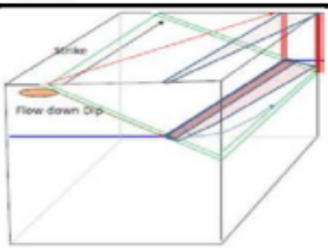
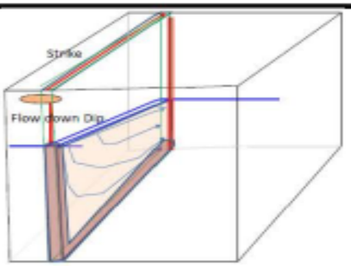
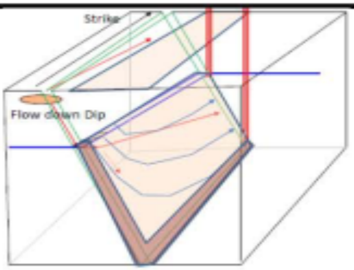
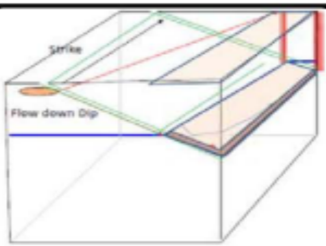
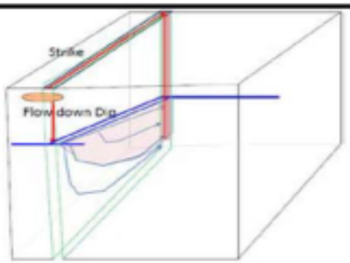
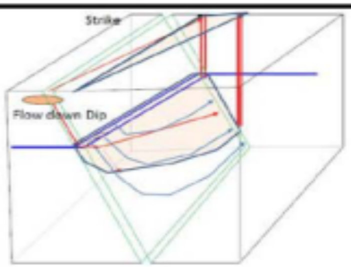
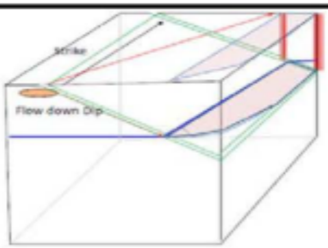
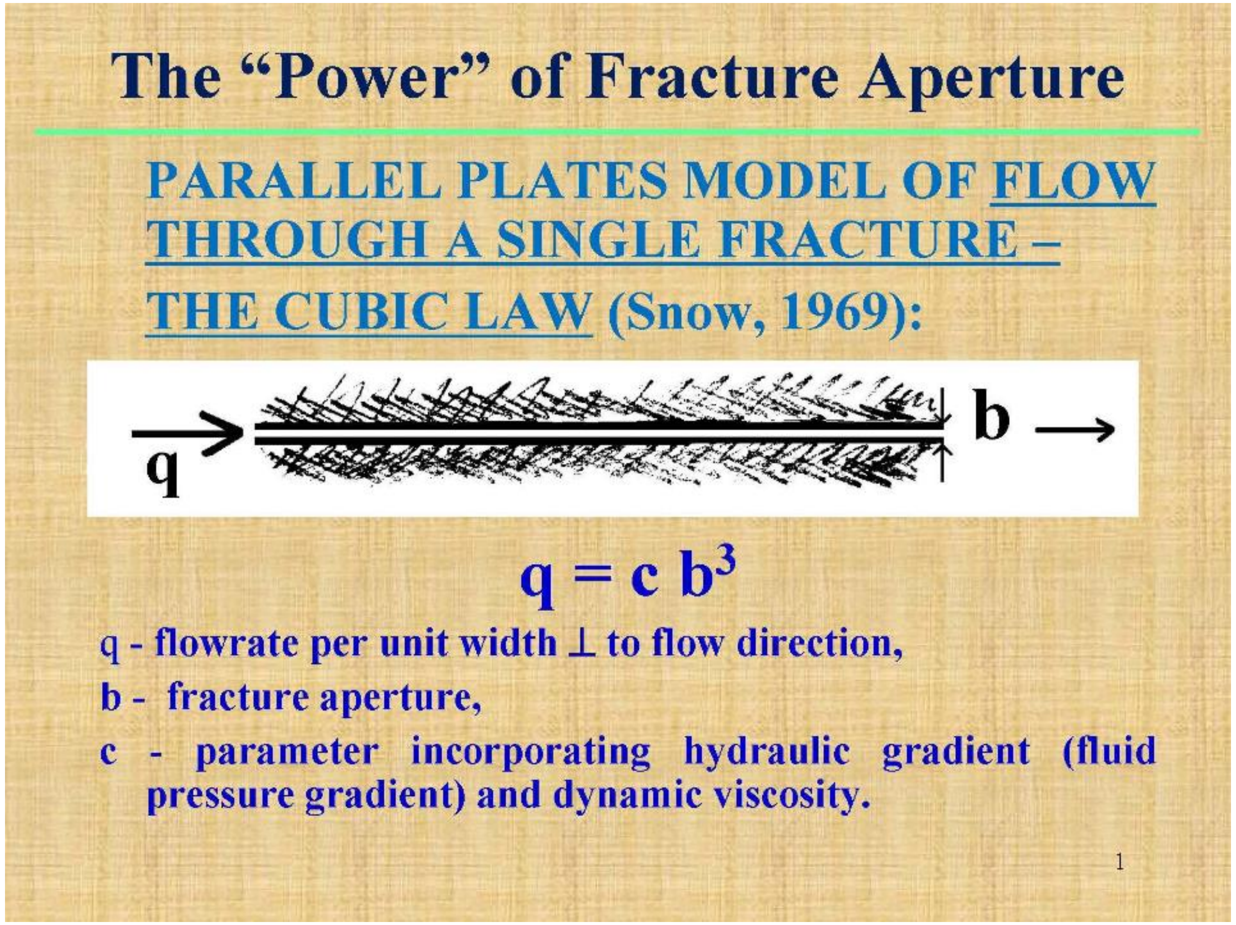
	Vertical fracture		Steeply Dipping Fracture		Gently dipping fracture	
	Contaminant and water flow is restricted to the orientation of the fracture. Wells near the source should find the plume but need to be positioned based on anticipated strike.		Flows down dip and then follows strike, giving an apparent horizontal displacement of the source and "apparent" source in groundwater		The low angle of dip results in the apparent plume direction being significantly displaced from strike direction and the apparent source is displaced from the "apparent" source on the groundwater table.	
Light /LNAPL, t tends to concentrate near the groundwater table.		Conventional screen intercepting water table can be effective in identifying LNAPL		Contaminated zone may be easily missed by wells not intercepting the precise zone of the fracture holding the LNAPL		Boreholes drilled near the source will miss the plume
Dense/ DNAPL flows to the full depth of the fracture and then along the orientation of the fracture		Shallow wells away from source area likely to miss DNAPL and higher dissolved phase		The movement of the DNAPL through the fracture results in a widely dispersed dissolved phase plume		The movement of the DNAPL through the fracture results in a widely dispersed dissolved phase plume
Dissolved phase follows the flow path through the plane of the fracture, deepening with distance from the source		Wells near the source area may miss the plume. Wells screened at the water table may miss the core of the dissolved phase plume		Dissolved phase follows the flow path through the plane of the structure. Wells need to be designed based on structure and likely head induced flow		Dissolved phase plume likely to be spread horizontally but confined to a narrow depth zone.

Bedrock Characteristics Affecting Flow

- Fracture Aperture
- Fracture Infilling
  - The mean aperture size controls specific discharge
  - May have significant variability along a fracture based on infilling (sediment, chemical precipitation, NAPL)



Intersection of Scale and Fracture Flow Properties

Hydrology

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- ▶ Macroscopic
- ▶ Mesoscopic
- ▶ Microscopic

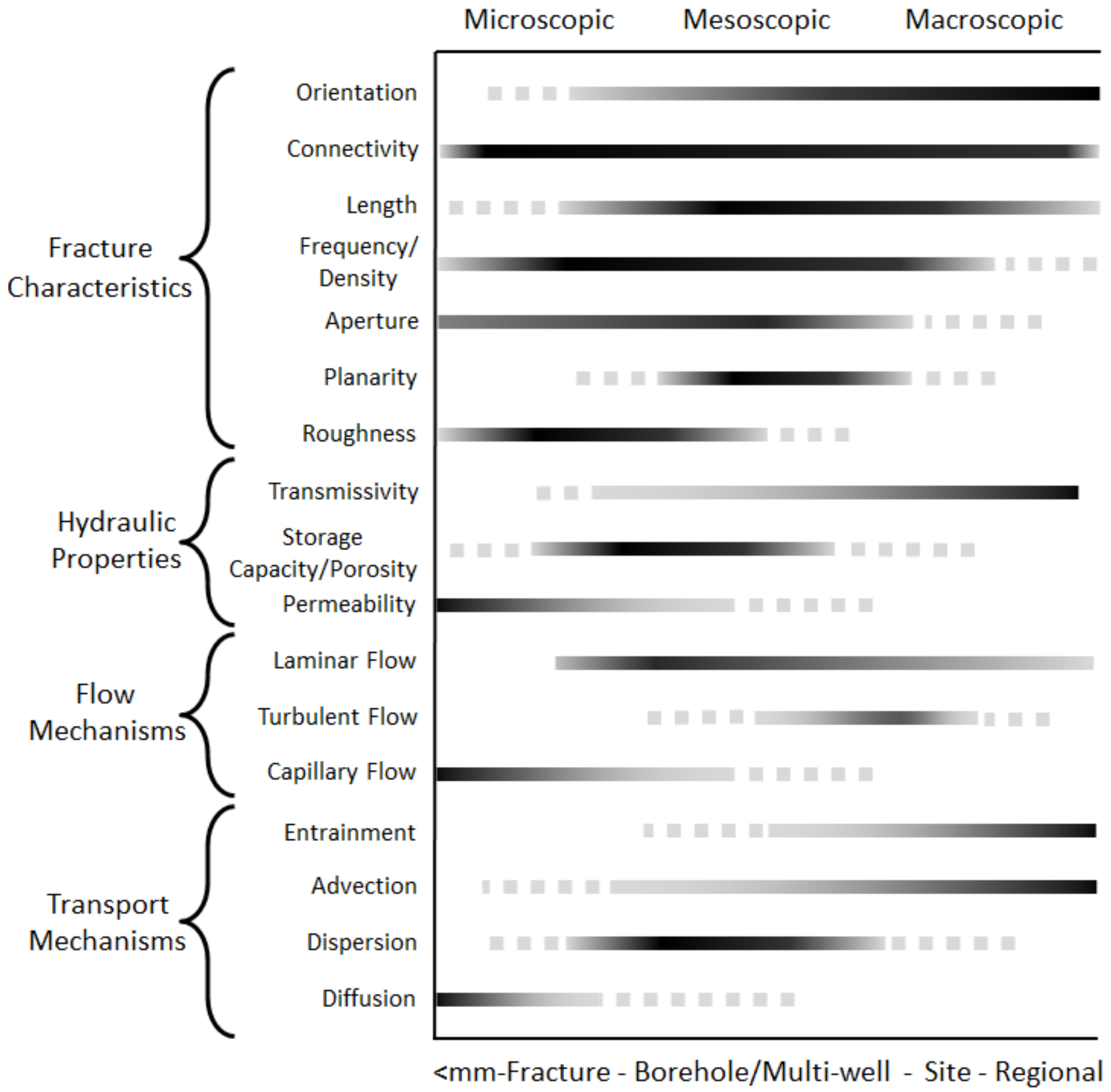


Figure 3-1

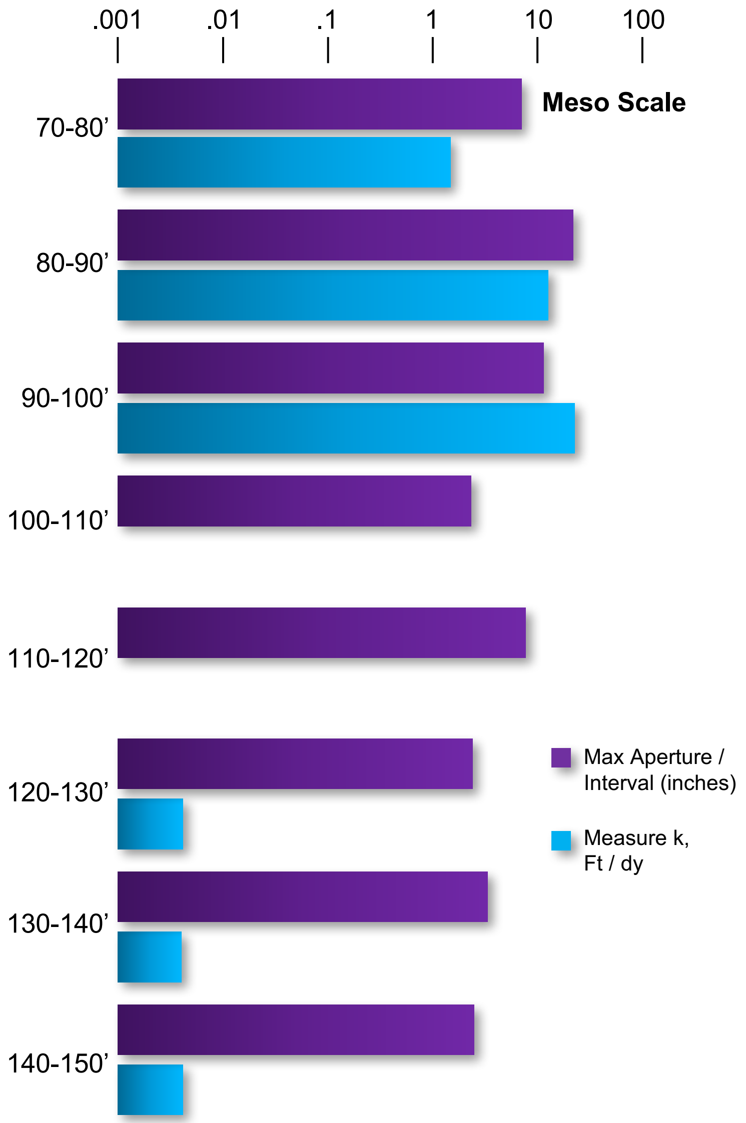
Macroscopic Flow: The Big Picture

- Occurs and Regional or Site-wide Scale
- Regional factors influence flow
  - Faults
  - Rivers
  - Changes in lithology
- Remote Sensing and Terrane Analysis to evaluate interaction of multiple structures
  - Orientation, length, connectivity
  - Karst is considered as a whole
  - Overall flow behaving as continuous Darcian flow system
- Knowing how structures interact helps direct investigation at smaller scales

From Figure 3-13

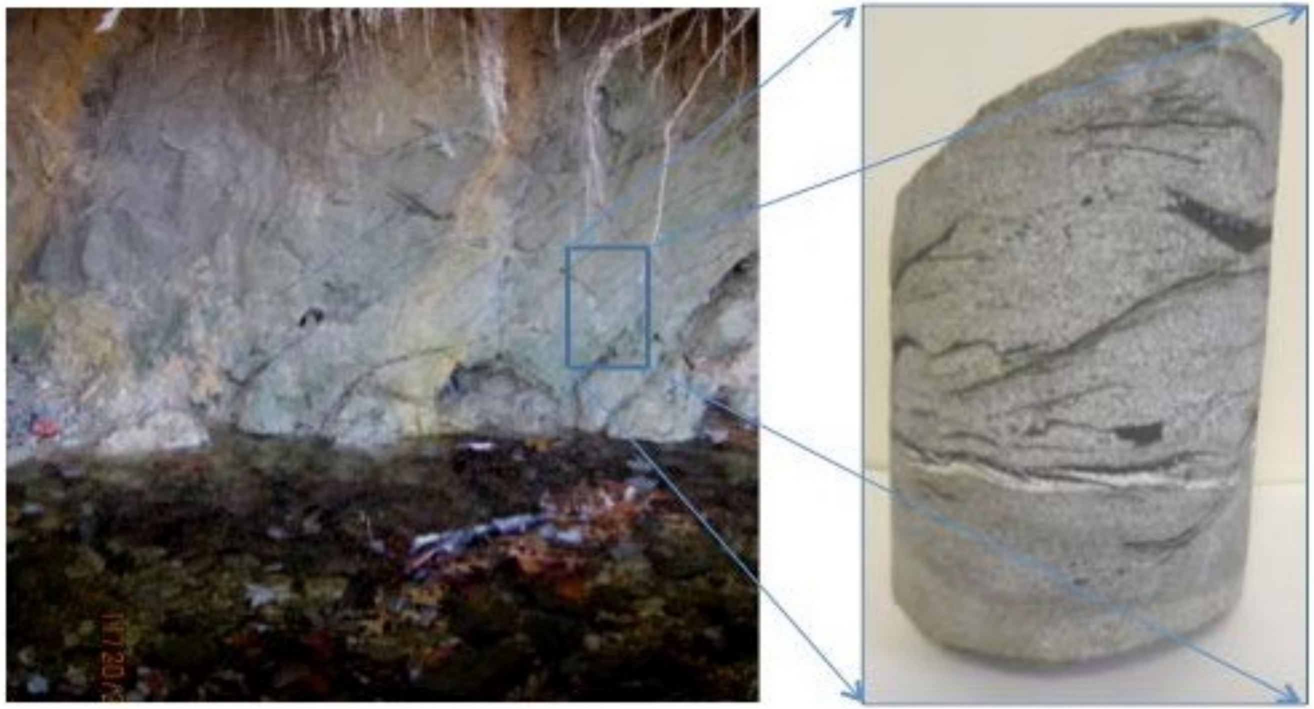
Mesoscopic Flow: Where we Learn the Most

- Plume delineation, flow between multiple wells/boreholes
  - Orientation, aperture, density, length, and connectivity
  - Influence of matrix characteristics
- Boreholes and Outcrops
  - Fracture analysis
  - Hydraulic testing
- Flow in fracture sets
  - Impact of turbulent flow may become evident
  - Advection, entrainment, dispersion
- Primary scale of investigation
  - Majority of investigation and characterization techniques



Microscopic Flow: Tools for Fine-Tuning your Site Understanding

- Individual fractures to matrix interaction
- Microscopic and individual fracture analysis
  - Individual fracture characteristics
  - Core samples
- Flow between fractures & matrix
  - Changes the morphology of the fracture (Roughness & planarity)
  - Aperture increases or decreases by infilling and dissolution
  - Diffusion and capillary flow
- Interface between fracture and matrix and matrix storage effects F&T



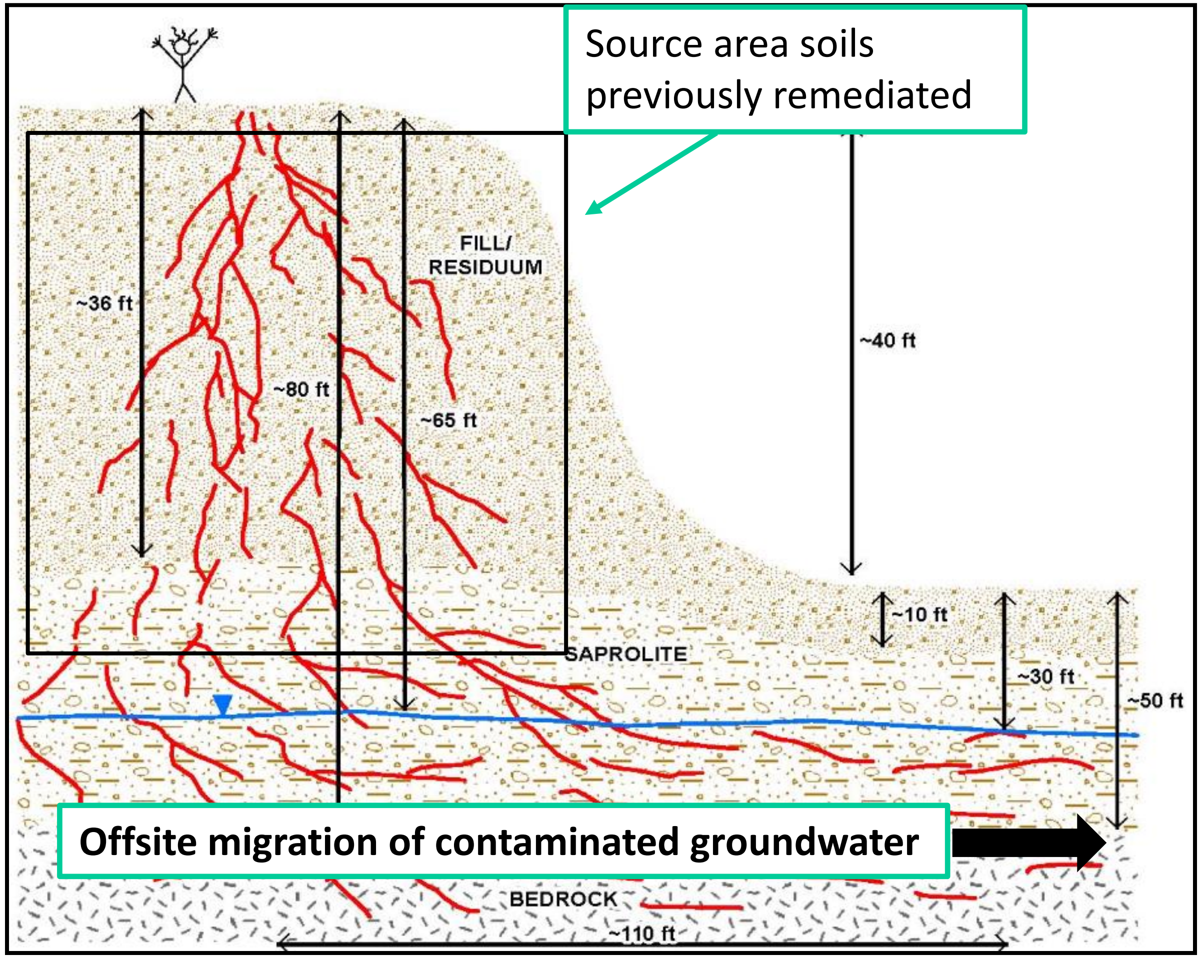
Courtesy Jeff Hale

We may not get down to this scale very often

How Fluid Dynamics Changes Flow

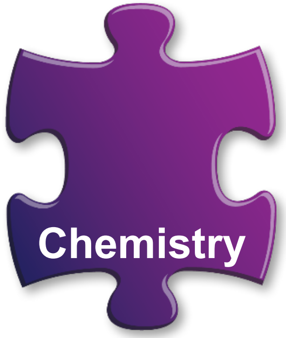
- Pressure and Density Gradients
- Laminar vs Turbulent
  - Darcy vs non-darcy flow
  - Scale dependence
- Multi-fluid systems
  - Wetting vs non-wetting phases
  - Effects of density contrast

Figure 6-2. Cross-sectional schematic illustrating potential pathways and risks at the Former Industrial Site.

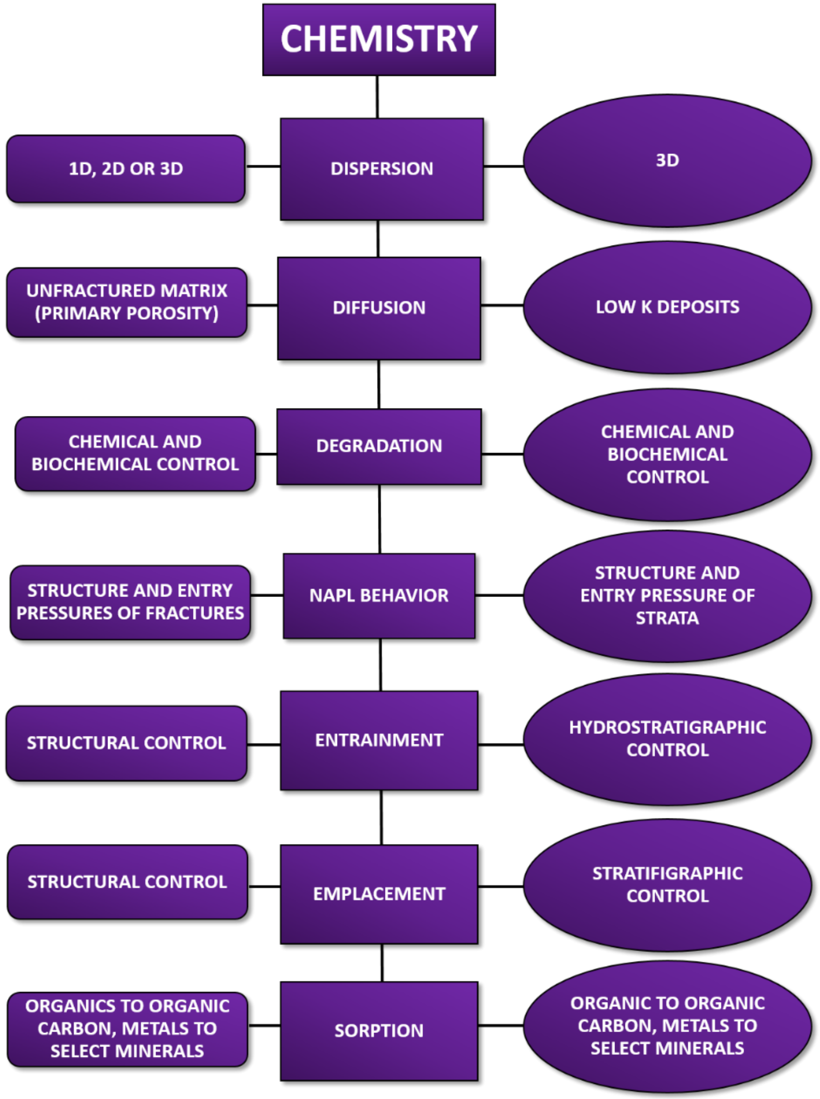


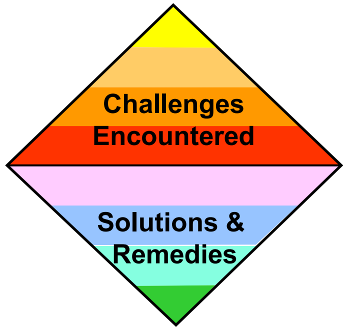
Courtesy Dan Bryant

Chemical Characteristics Affect Fate & Transport



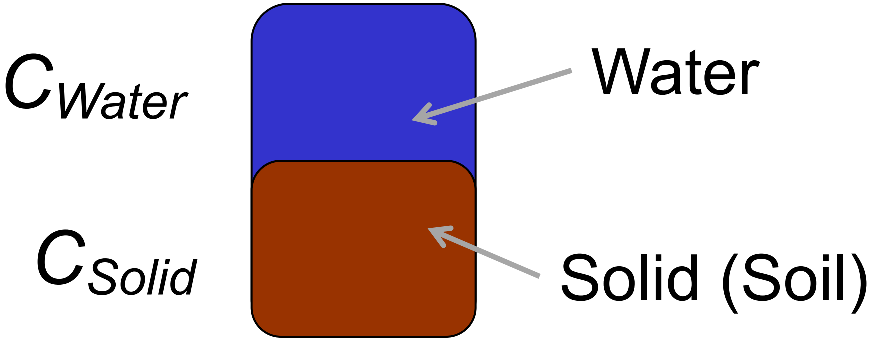
- Physical State
- Solubility
- Diffusion and Dispersion
- Volatility
- Henry's Law Constant H
- Vapor Pressure
- Boiling Point
- Water/Air Partition Coefficient K_w





Chemical characteristics that affect fate and transport

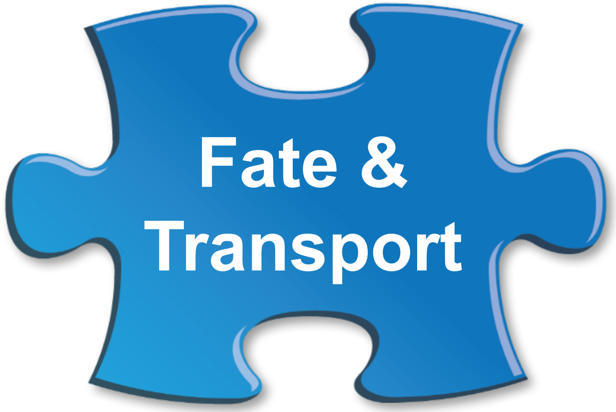
- Octanol/Water Partition Coefficient K_{ow}
- Organic Carbon Adsorption Coefficient K_{oc}
- Soil-water Partition Coefficient K_d
- Degradation/Chemical Half-Lives
- Photolysis
- Chemical Degradation
- Retardation Factor
- Biodegradation



$$C_s = C_w * f_{oc} * K_{oc}$$

How to Integrate this with your CSM

- Better understanding of where the fluid is and where it's going
- Started to look at how multiple phases interact
- Incorporated flow and fracture data from multiple scales

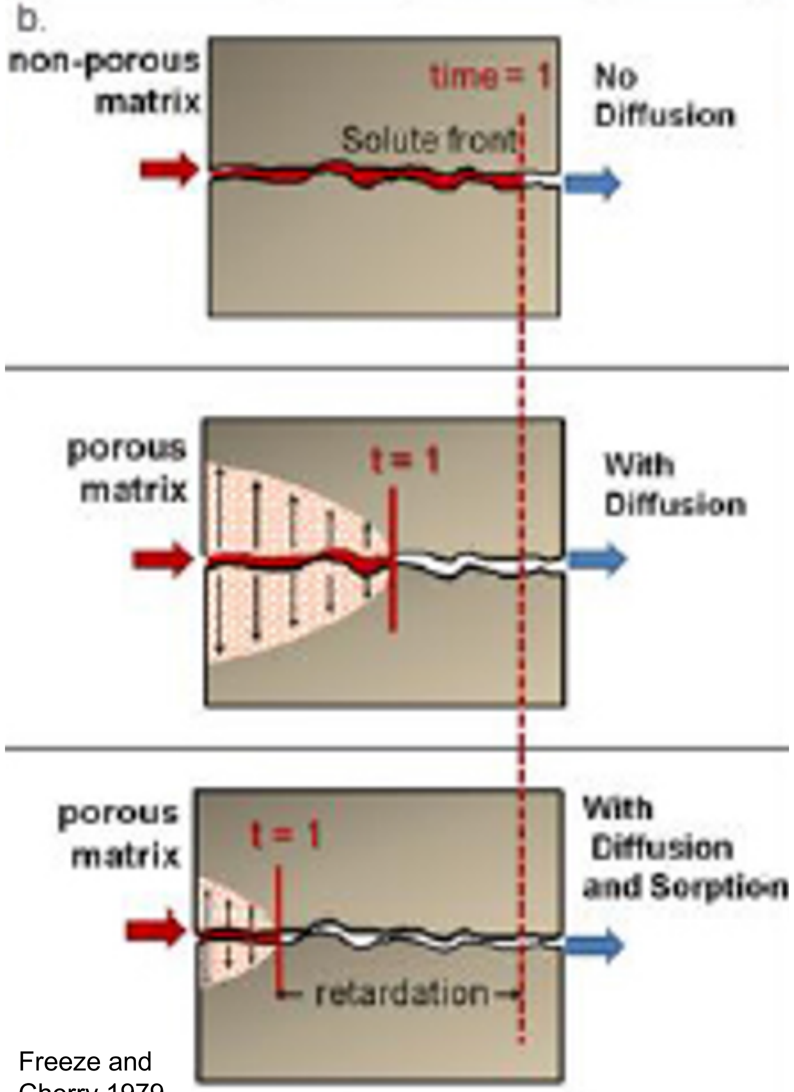


- Fate and Transport - last piece of puzzle before creating initial CSM
- Understanding fate and transport in fractured rock
  - Unique properties of the contaminant
  - Characteristics of the rock
- Consider fate and transport mechanisms involved

Contaminant Fate and Transport in Saturated Fractured Rock

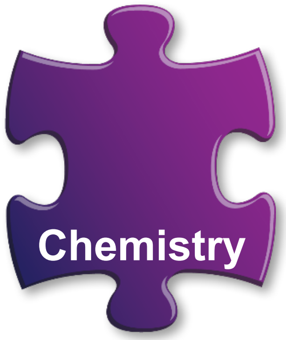
- Common Fate and transport mechanisms
  - Density driven vertical migration
  - Dissolution
  - Advection through fractures
  - Matrix diffusion/Back Diffusion
  - Sorption/retardation
  - Natural attenuation
    - Example: Abiotic transformation

Fate & Transport



Freeze and Cherry 1979

Identification of Contaminant Properties



Chemical	Liquid Density	Vapor Pressure	Solubility	Henry's Constant	Koc	Reactivity
	g/cm^3 (water = 1 g/cm^3)	mm HG (volatile >= 1 mm HG)	mg/L	atm-m^3/mole	L/kg	
-						
trichloroethene (TCE)	1.46	58 @ 20 C	1100	0.0103 (EPA)	166	abiotic biogeochemical transformation

- Identify properties of contaminant (example, TCE)
- Consider example of sedimentary bedrock such as shale
  - Potential for bedding planes
  - Vertical fractures
  - Potential for primary (matrix) porosity

ITRC FracRx-1Table 4-1

Identification of Potential Fate and Transport Mechanisms

Chemical	Liquid Density	Vapor Pressure	Solubility	Henry's Constant	Koc	Reactivity
	g/cm^3 (water = 1 g/cm^3)	mm HG (volatile >= 1 mm HG)	mg/L	atm-m^3/mole	L/kg	
-						
trichloroethene (TCE)	1.46	58 @ 20 C	1100	0.0103 (EPA)	166	abiotic biogeochemical transformation

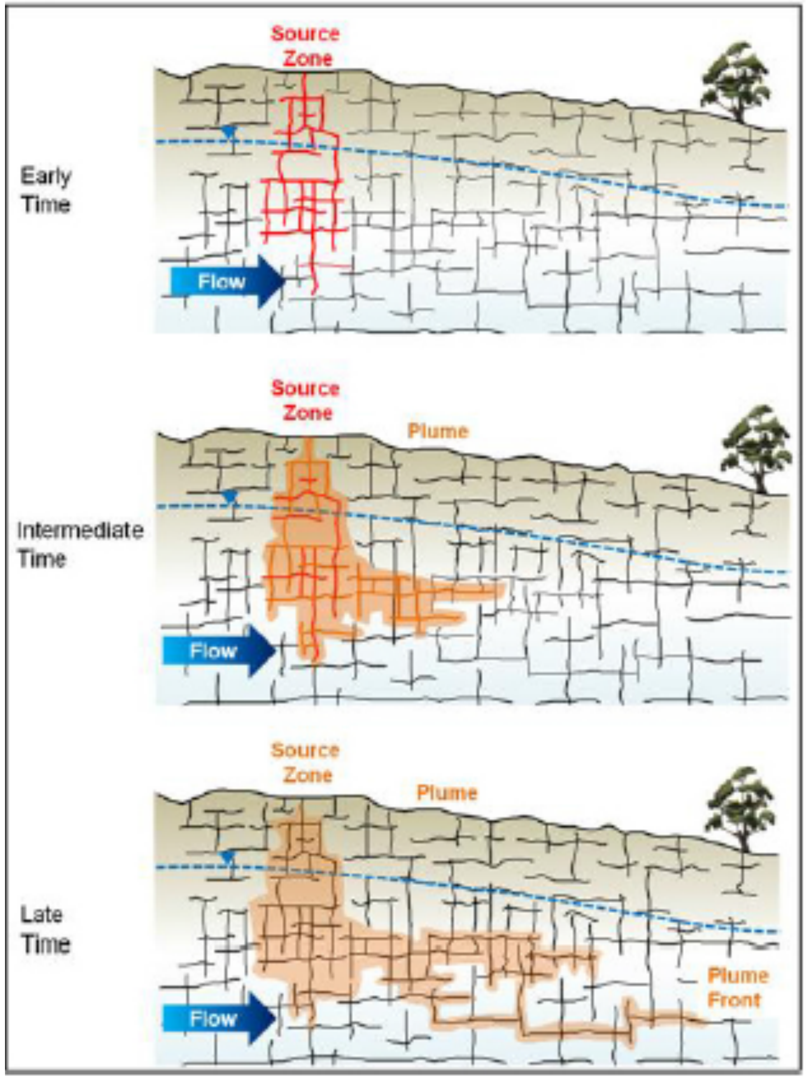
Fate and Transport Mechanisms Likely

- (blue) Based on density, likely to sink in saturated zone
- (light green) Potential for partitioning to vapor phase
- (purple) Potential for dissolved plume and matrix diffusion
- (tan) Potential retardation along fracture walls and/or within rock matrix pc
- (pink) Abiotic transformation potential

Contaminant Fate and Transport in Saturated Fractured Rock

Fate & Transport

- Example DNAPL release
- Vertical migration into saturated zone
- Dissolution and advection/retardation within fractures
- Matrix diffusion/back diffusion
- Consider soil gas survey
- Consider potential for natural attenuation (abiotic transformation)

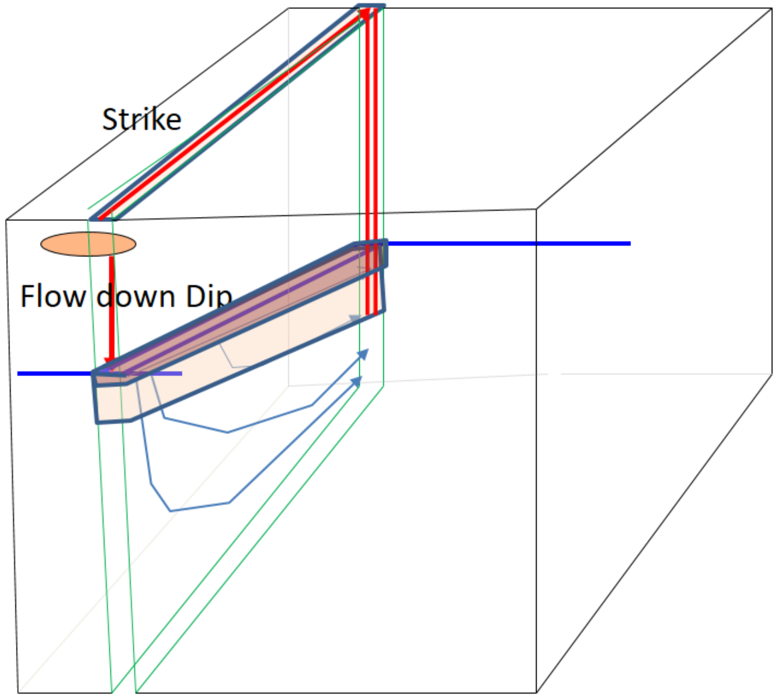


Parker et al. 2012

Strike and dip influence on flow

Fate & Transport

- Light/LNAPL with Vertical Fracture
  - Migrates downward along dip in unsaturated fractured rock
  - Migrates along strike in saturated fracture rock
- Conventional screen intercepting water table can be effective
- Dipping of fracture can increase difficulty of identifying LNAPL
  - Consider other lines evidence (water table, fracture architecture)

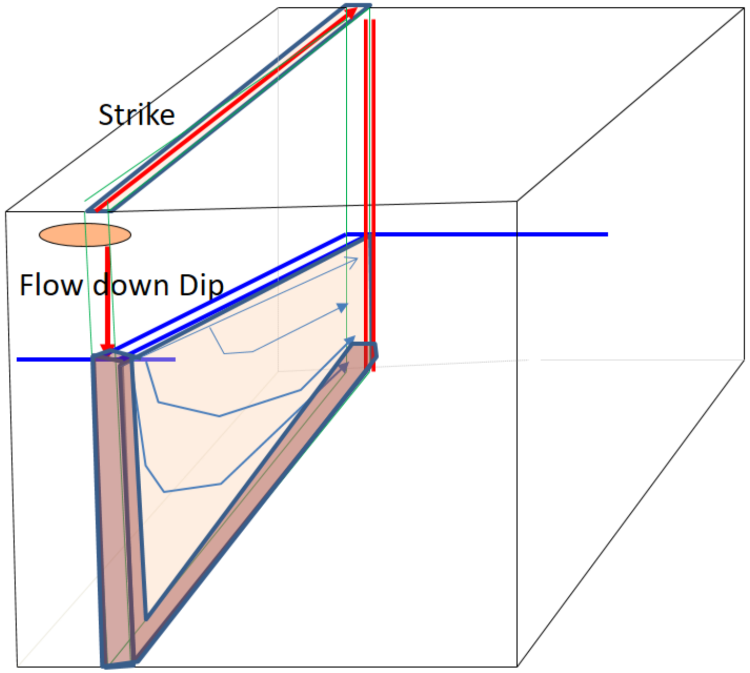


Courtesy Alex Wardle

Strike and dip influence on flow

Fate & Transport

- Dense/DNAPL with Vertical Fracture
  - Migrates downward along dip in unsaturated fractured rock
  - Migrates downward along dip in saturated fracture rock
- Shallow well away from source area likely to miss DNAPL and higher dissolved plume
- Dipping of fracture can increase difficulty of identifying DNAPL but may help in locating the dissolved plume (see document for additional detail)



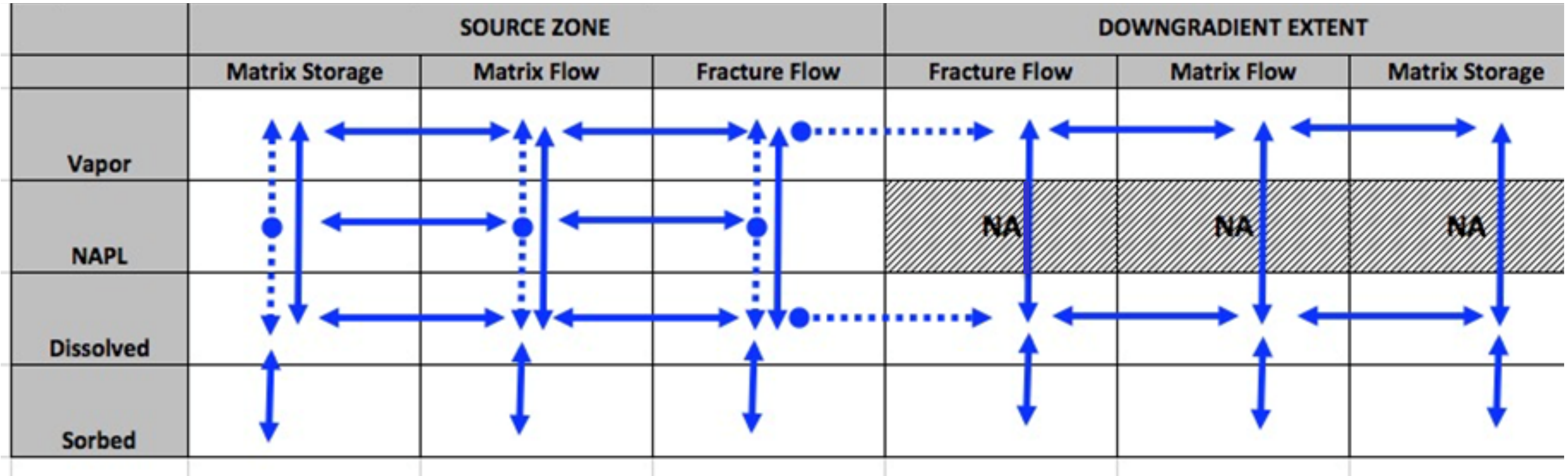
Courtesy Alex Wardle

Introduction – 21 Compartment Model

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor*						
NAPL*				NA	NA	NA
Dissolved						
Sorbed						

ITRC FracRx-1 Table D-1

Hydrogeology of Fractured Rock



Arrows are a qualitative representation of flux

Solid arrows are reversible fluxes; dashed arrows are irreversible fluxes

Modified from ITRC FracRx-1 Table D-1

21 Compartment Model – Sandstone

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Low	Medium	Medium	Medium	Medium	Low
NAPL	Low	Low	High	NA	NA	NA
Dissolved	Low	Medium	Medium	Medium	Medium	Low
Sorbed	Low	Low	Medium	Medium	Medium	Low

DNAPL spill site underlain by fractured uncemented sandstone

Fate & Transport

21 Compartment Model – Shale Bedrock

Fate & Transport

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Low	NA	Medium	Medium	NA	Low
NAPL	Low	NA	High	NA	NA	NA
Dissolved	Low	NA	Medium	Medium	NA	Low
Sorbed	Low	NA	Medium	Medium	NA	Low

DNAPL spill site underlain by fractured shale bedrock

21 Compartment Model - Granite

	SOURCE ZONE			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor	Negligible	NA	Medium	Medium	NA	Negligible
NAPL	Negligible	NA	High	NA	NA	Negligible
Dissolved	Negligible	NA	Medium	Medium	NA	Negligible
Sorbed	Negligible	NA	Low	Low	NA	Negligible

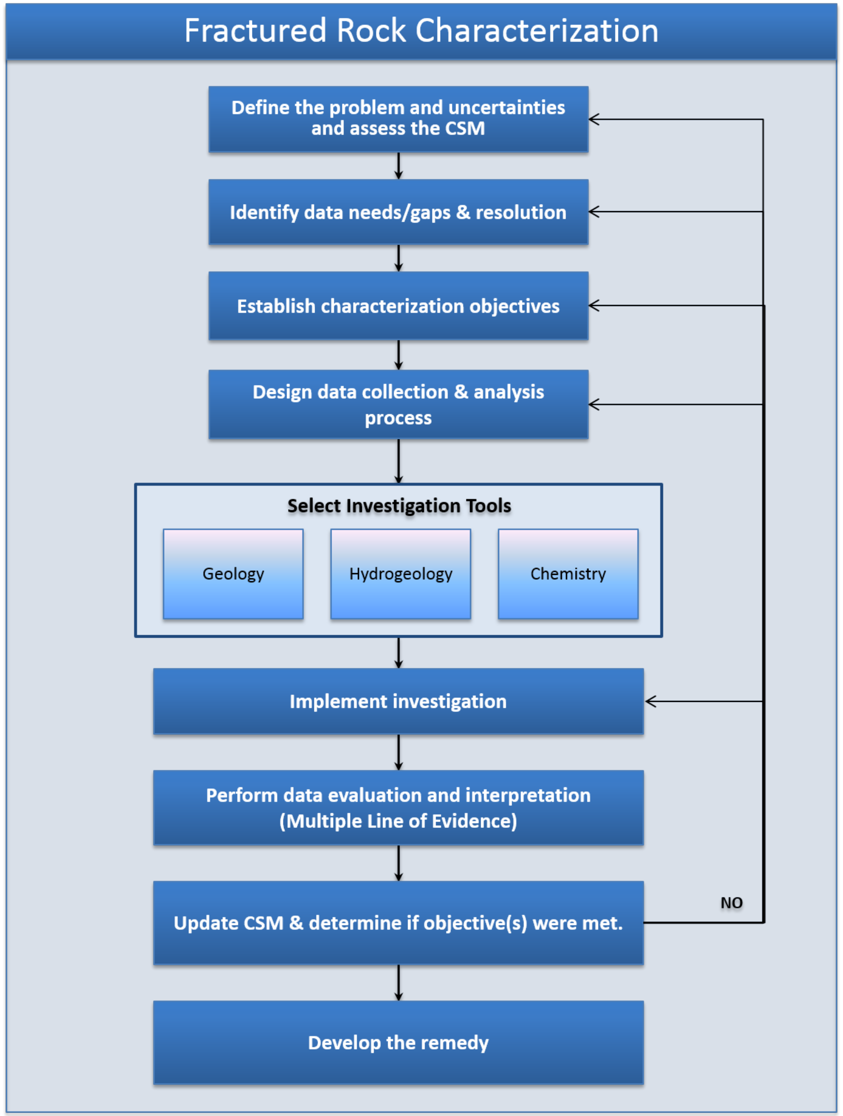
DNAPL spill site underlain by fractured granite bedrock

Overview of the Training

- Introduction
- Fractured Rock CSM Considerations
- Fracture Characteristics of Geologic Terrane
- Fracture Flow & Contaminant Fate and Transport
- **Fractured Rock Characterization**
- Remedy Development
- Monitoring
- Summary

Characterization of Fractured Rock Flow Path

1. Develop Problem Statement
2. Develop Preliminary Conceptual Site Model
3. Identify Significant Data Gaps
4. Formulate-Revise Characterization Objectives
5. Select Investigation Tools
6. Develop and Implement Work Plan
7. Evaluate and Interpret Results
8. Update CSM
9. Develop the Remedy



Modified from ITRC ISC-1, 2015, Figure 4-1

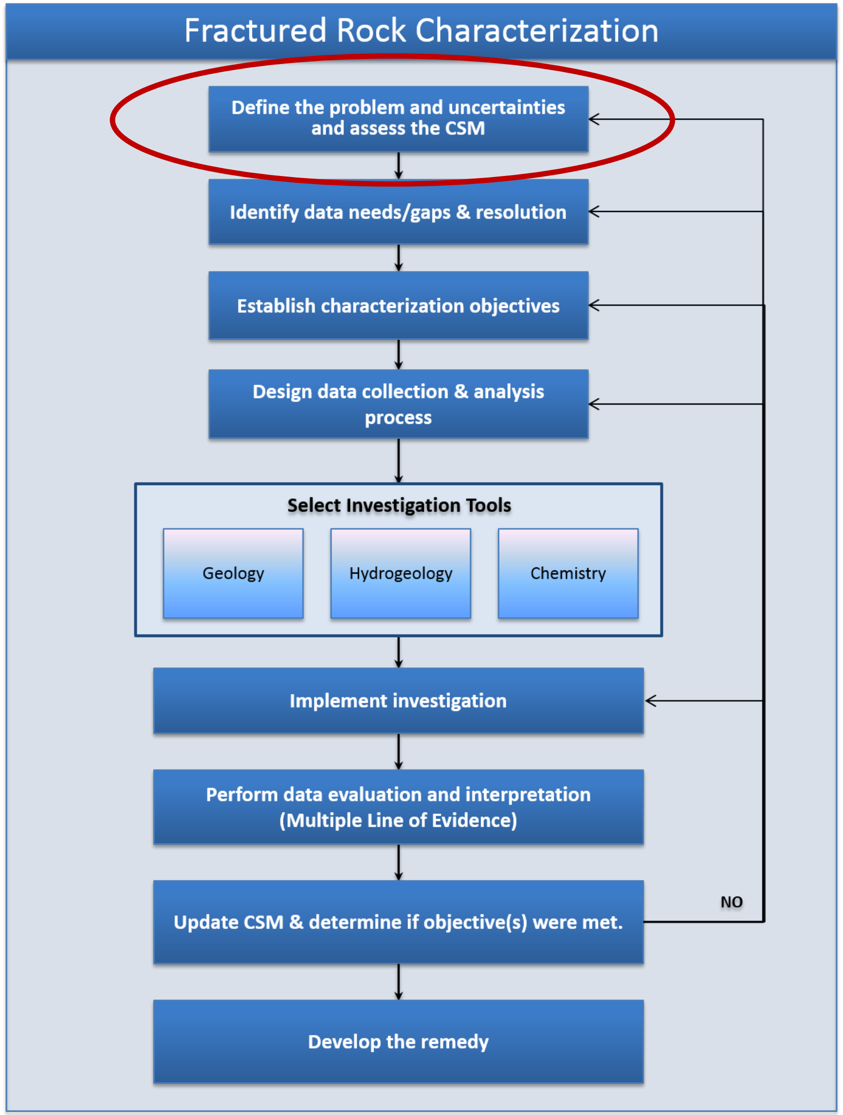
Step 1: Develop a Problem Statement

"a problem well stated is a problem half solved"

(Charles F. Kettering, 1876-1958)

Step 1: Develop a Problem Statement

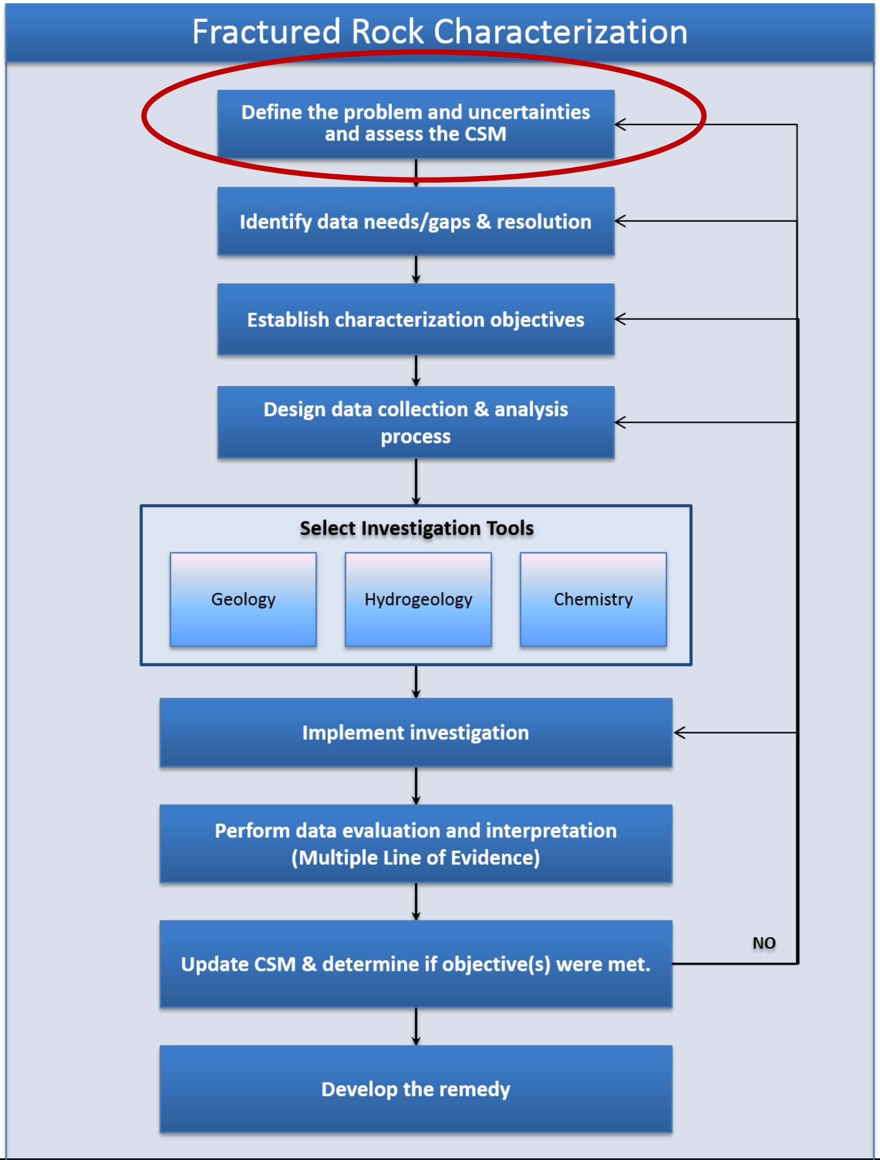
- Assess existing CSM
- Define problem
- Define uncertainties



Modified from ITRC ISC-1, 2015, Figure 4-1

Step 2: Develop or Refine a Fractured Rock Conceptual Site Model (CSM)

- Research easily available sources of existing information:
  - topographic maps
  - geologic maps
  - nearby well logs
  - nearby bedrock outcrops
  - nearby information on other sites
  - existing characterization data
  - regional water quality data
  - media reports of contamination



Modified from ITRC ISC-1, 2015, Figure 4-1

Step 2: Develop or Refine a Fractured Rock CSM

The CSM is a *living document that should:*

- reflect the best interpretation of available information at any point in time.
- be updated continuously as new data are collected at any stage of the remedy
- continually improved if new data are inconsistent - additional evaluations should take place.

Refine an Existing CSM:

- At many sites, significant investigation may have occurred
- The scope of the earlier investigations and type of data however may not be up to present day standards
- There may be an existing incorrect or incomplete CSM

This does not mean the existing data can't be incorporated into your initial CSM

Step 2: Develop or Refine a Fractured Rock CSM

MISSOURI WASTE CONTROL COALITION

INTERSTATE TECHNOLOGY REGULATORY COUNCIL ITRC

Key Elements to Consider

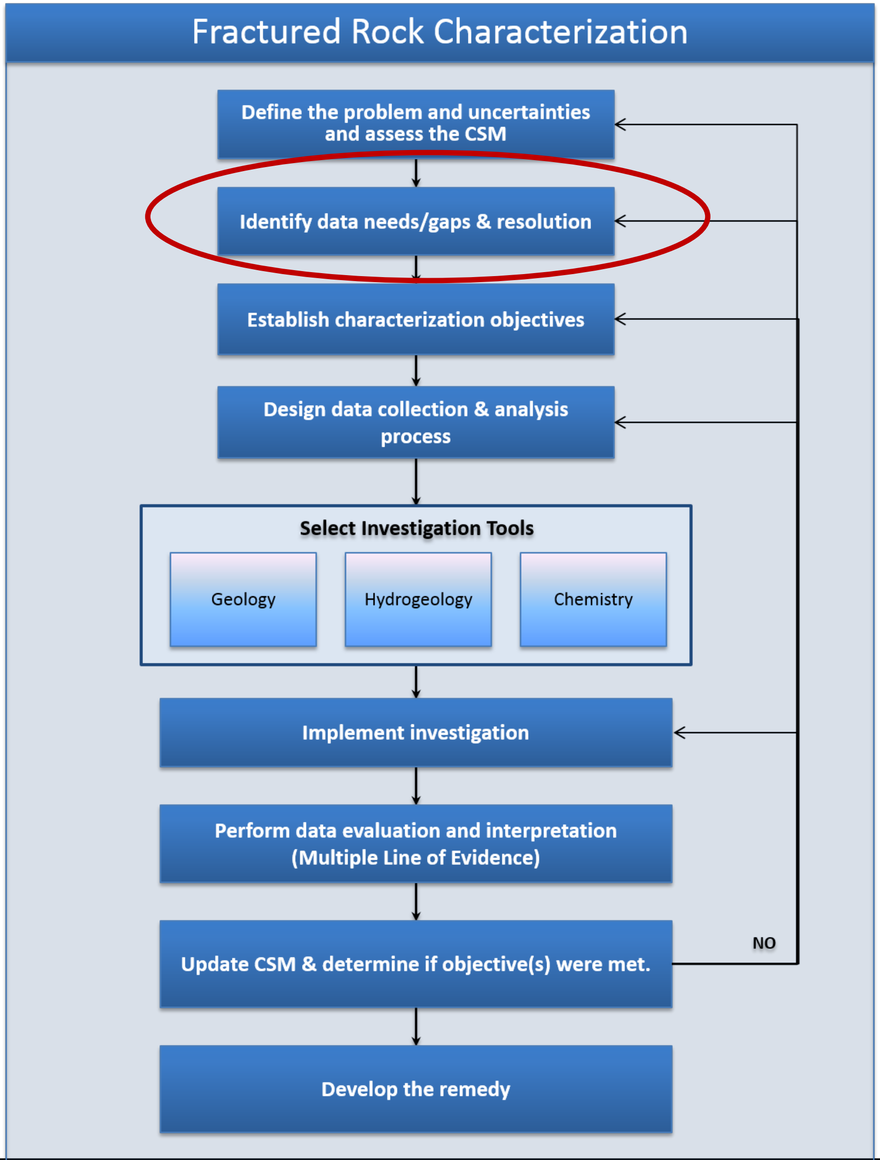
- ***Terrane analysis -***presents key elements that should be evaluated, from a physiographic province scale to finer site scale, to compile an "initial CSM".
- MUST include the unconsolidated materials above the bedrock.
- Contaminants in fractured bedrock must investigate the full extent of, and fate and transport of contaminants in all media.

Specific Elements

- Regional physical setting (e.g. physiographic province)
- Structural geology and tectonic setting
- Lithology and stratigraphy/mechanical stratigraphy
- Anisotropy and heterogeneity

Step 3: Identify Significant Data Gaps

- Translate uncertainties into data needs
- Determine resolution needed to assess controlling heterogeneities



Modified from ITRC ISC-1, 2015, Figure 4-1

Step 3: Identify Significant Data Gaps

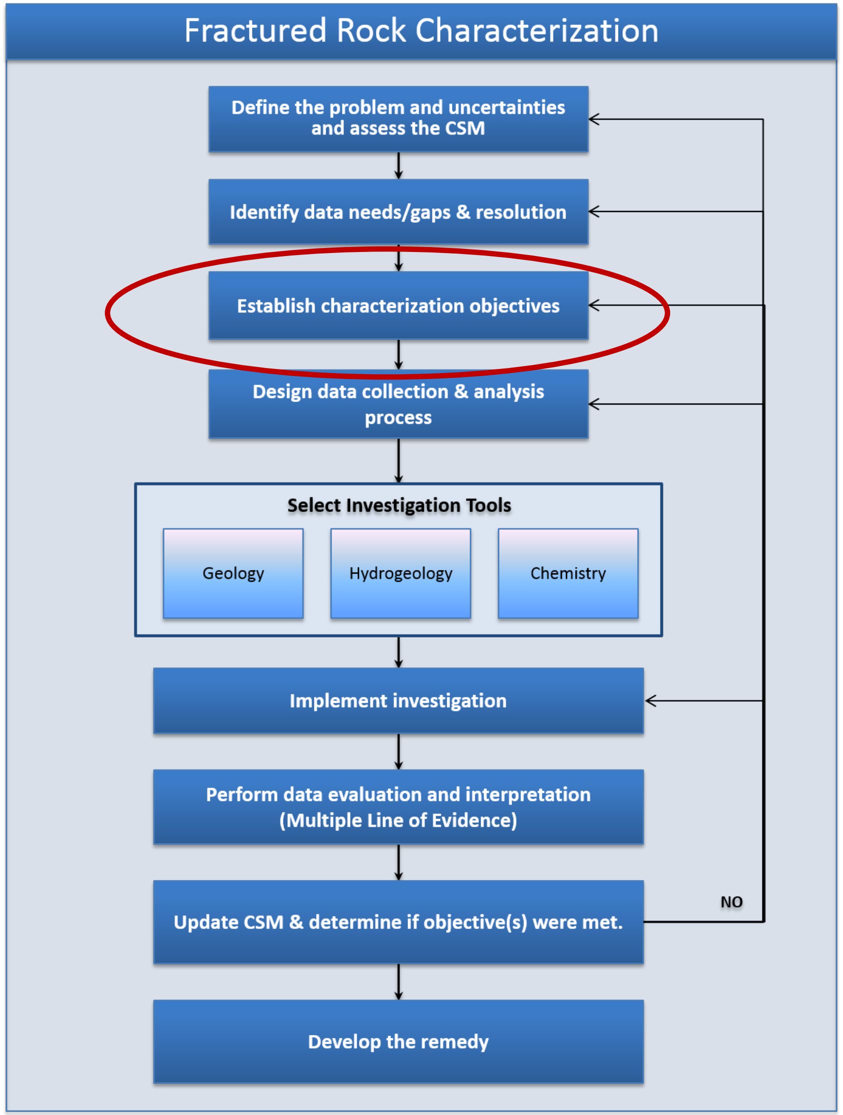
- **Fractured rock CSMs will unavoidably have data gaps throughout the process**
  - the lateral and vertical extent of contamination
  - the direction the contamination is moving
  - identification of imperiled receptors
  - the rate at which the contamination is moving
  - what areas should be targeted for sampling.

- Missing information limits the formulation of a scientifically defensible interpretation of environmental conditions and/or potential risks in a bedrock hydrogeologic system. A data gaps exists when:
  - it is not possible to conclude with confidence whether or not a release has occurred
  - evaluation of all data, in proper context, does not/cannot support the CSM
  - if more than one interpretation of existing data set

Each data gap can be transformed into one or more specific characterization objectives

Step 4: Formulate-Revise Characterization Objectives

1. Develop Problem Statement
2. Develop Preliminary Conceptual Site Model
3. Identify Significant Data Gaps
4. **Formulate-Revise Characterization Objectives**
5. Select Investigation Tools
6. Develop and Implement Work Plan



Modified from ITRC ISC-1, 2015, Figure 4-1

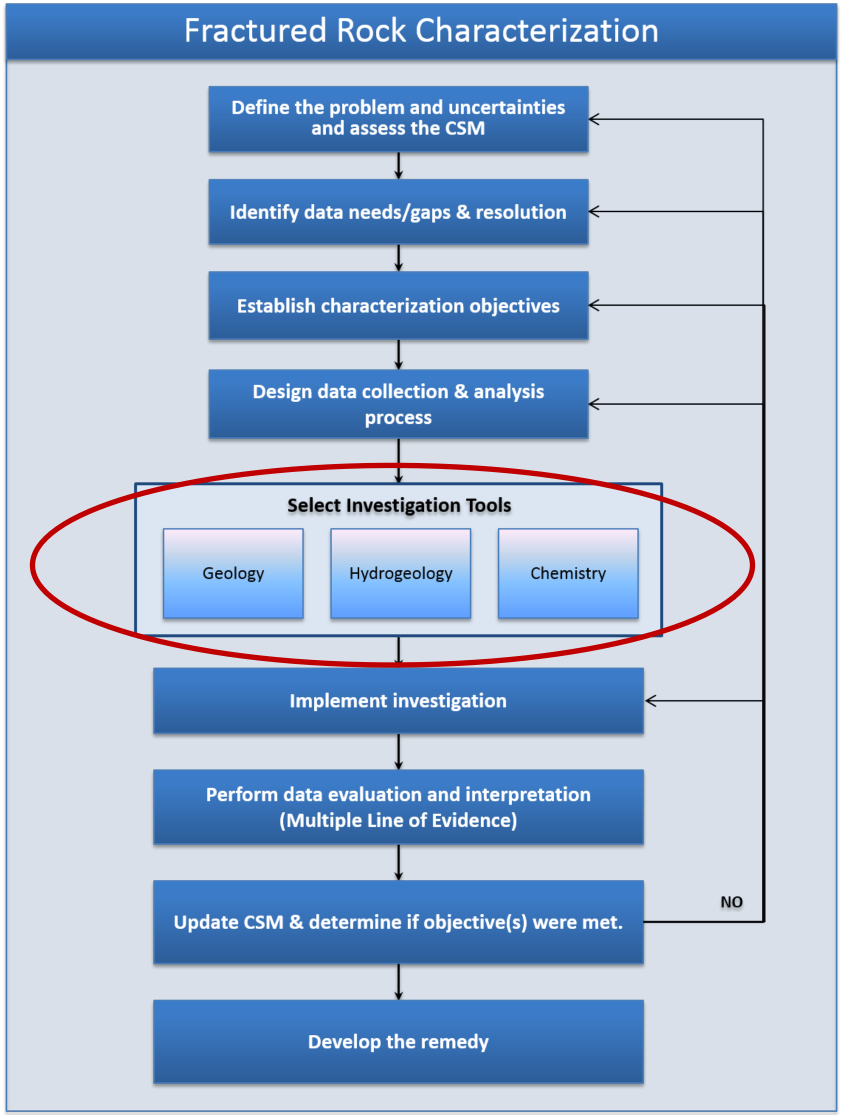
Step 4: Formulate-Revise Characterization Objectives

- Data collection objectives (DQOs)- determine specific data needs and to select tools to be used in the investigation
- DQOs should be clear, focused, specific, & consider:
  - fracture orientation,
  - spacing and aperture,
  - hydraulic head,
  - and flow velocity

- **Characterization Objective**: Determine the lateral and vertical extent of dissolved phase VOCs.
- **Data Gap:** The vertical and lateral extent is unknown.
- **Data Collection Objective**: Gather data on: fracture location, orientation, connectivity and VOC concentration in the source, plume and towards receptors.

Step 5: Select Investigation Tools

1. Develop Problem Statement
2. Develop Preliminary Conceptual Site Model
3. Identify Significant Data Gaps
4. Formulate-Revise Characterization Objectives
5. **Select Investigation Tools**
6. Develop and Implement Work Plan



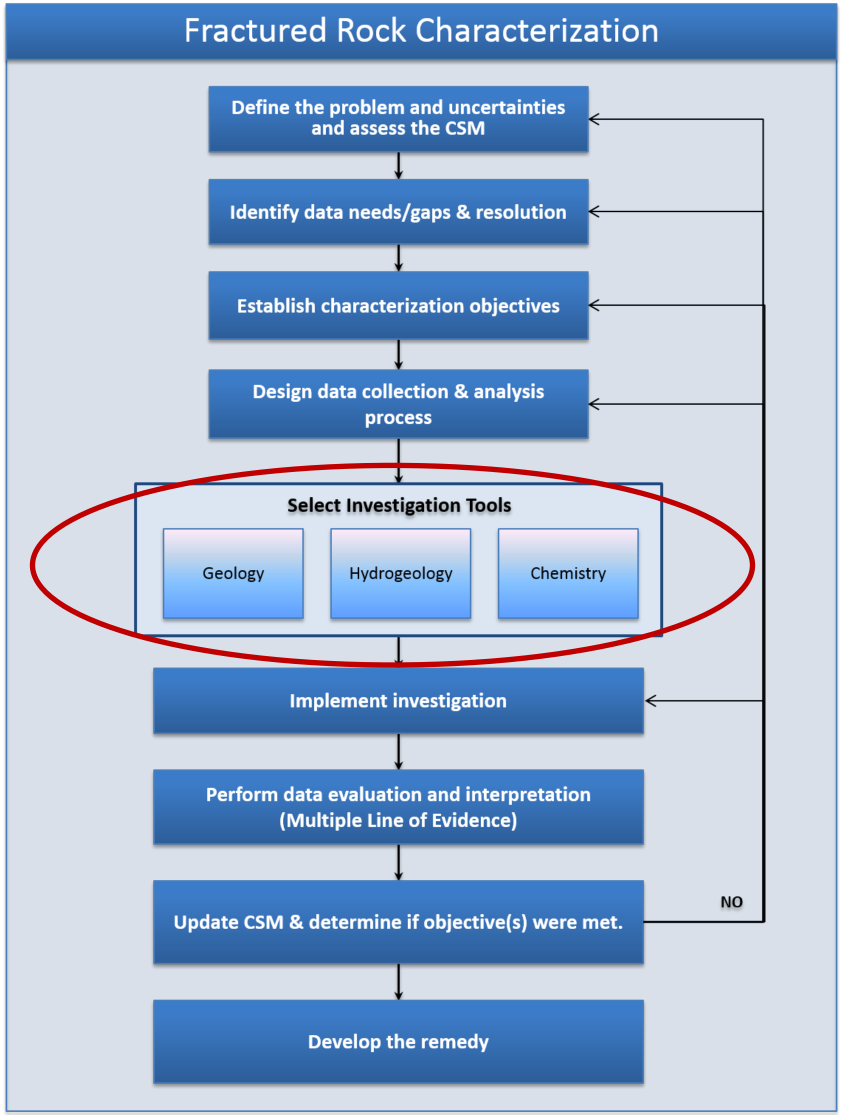
Modified from ITRC ISC-1, 2015, Figure 4-1

Step 5: Select Investigation Tools

Tools Matrix:

An interactive matrix that helps in selecting appropriate tools to meet your characterization objectives

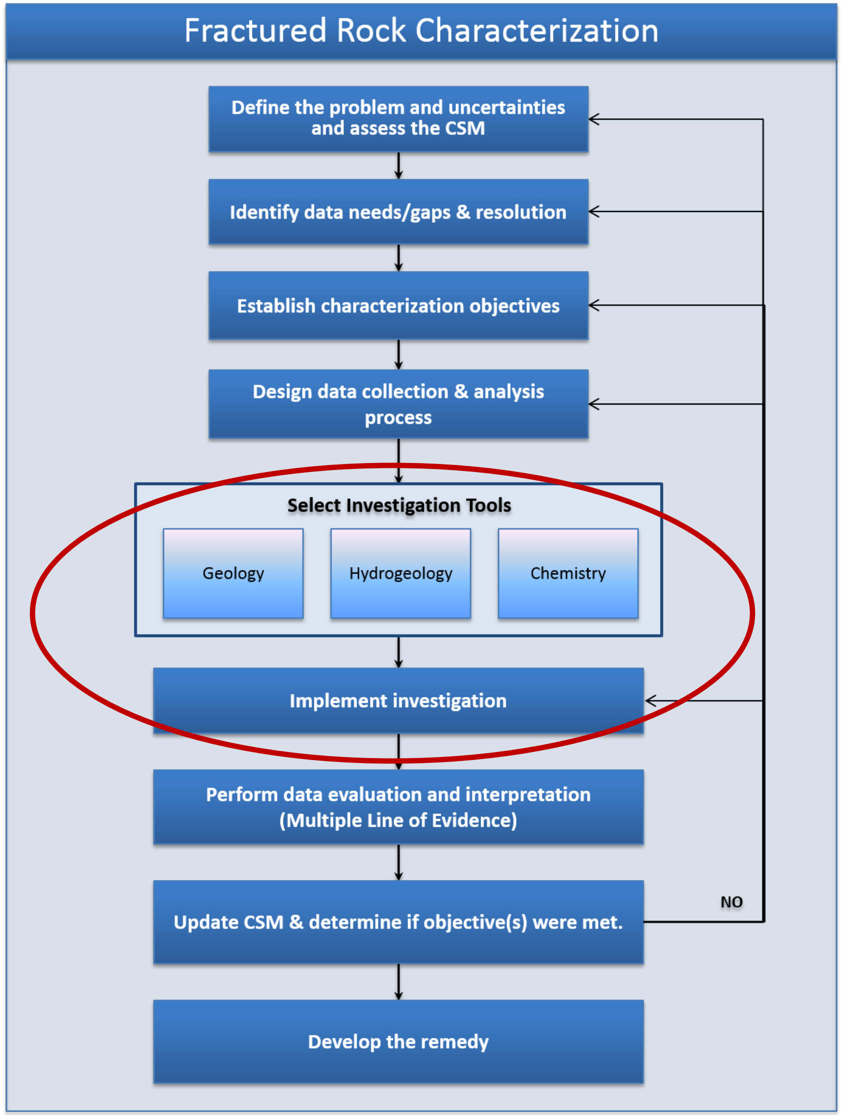
- Tools segregated into categories and subcategories, selected by subject matter experts
- A living resource intended to be updated periodically



Modified from ITRC ISC-1, 2015, Figure 4-1

Step 6: Develop & Implement Work Plan

1. Develop Problem Statement
2. Develop Preliminary Conceptual Site Model
3. Identify Significant Data Gaps
4. Formulate-Revise Characterization Objectives
5. Select Investigation Tools
6. **Develop and Implement Work Plan**

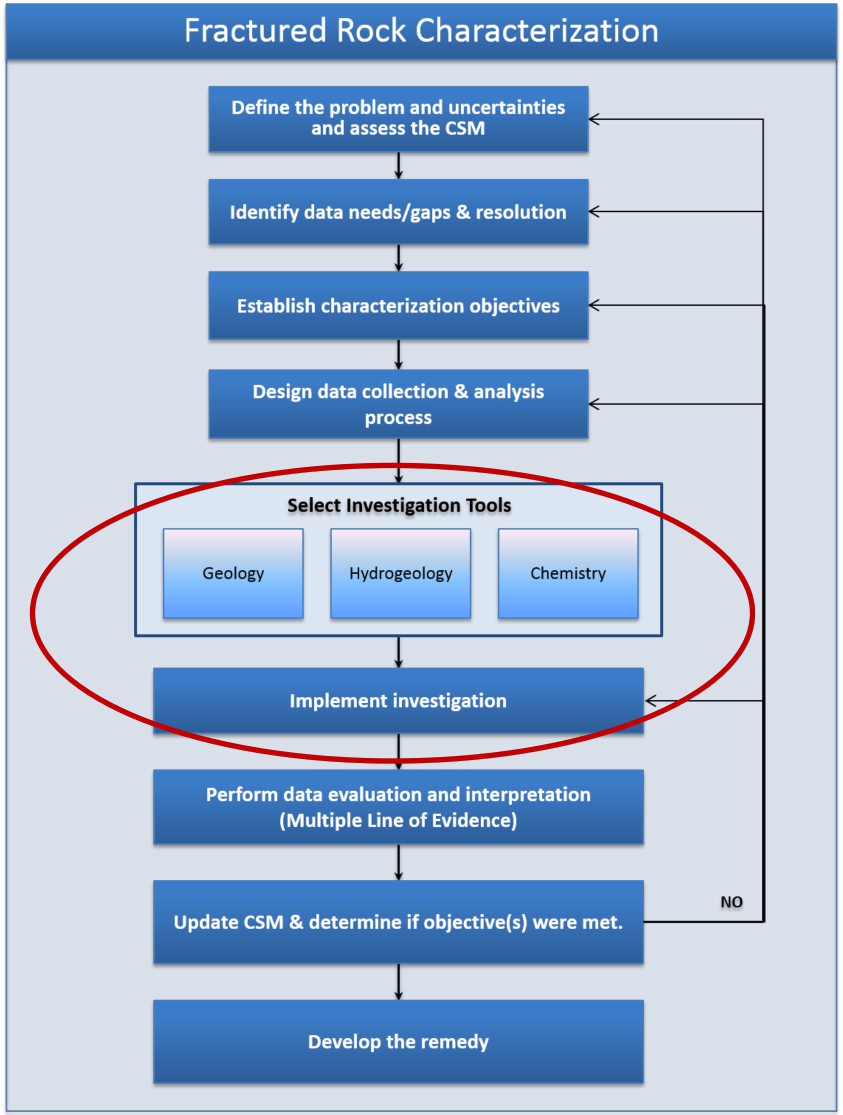


Modified from ITRC ISC-1, 2015, Figure 4-1

Step 6: Develop & Implement Work Plan

Develop and Implement Work Plan

- Select Tools
- Drill bedrock boreholes targeting surface geophysical anomalies
- Collect Rock Cores as necessary
- Test boreholes for hydrologic characteristics and contaminant distribution (packer testing/packer sampling, heat pulse flow meter, multi-well aquifer pump testing, etc.)
- Test groundwater



Modified from ITRC ISC-1, 2015, Figure 4-1

Step 6: Develop & Implement Work Plan

Develop a Work Plan

A typical fractured rock characterization work plan should:

- Emphasize characterization and data collection objectives
- Present a data collection process
- Include the tools selected
- Be forward-looking to discuss what procedures/software/models will be used for data evaluation and interpretation
- Include data evaluation process

Step 6: Develop & Implement Work Plan

Develop a Work Plan

A dynamic work plan can involve

- Real time data assessment
- Frequent (up to daily) calls or data uploads between the field team and project stakeholders to review field activities and data, to make decisions next steps for efficiently completing the characterization.
- Continuously or frequently updating the CSM

Step 6: Develop & Implement Work Plan

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INTERSTATE TECHNOLOGY REGULATORY COUNCIL ITRC

Implement the Site Investigation

- Once the work plan has been developed and approved by stakeholders, the next step is to implement the Site investigation.

- Portions of the Site investigation may run concurrent to the initial phases of Data Management, Interpretation and Presentation.

- If real time or near-real time data are being generated during the investigation, these results can be evaluated as they are generated to help guide further data collection activities.

Step 6: Develop & Implement Work Plan

We stress that characterization activities must be designed to not spread contamination!

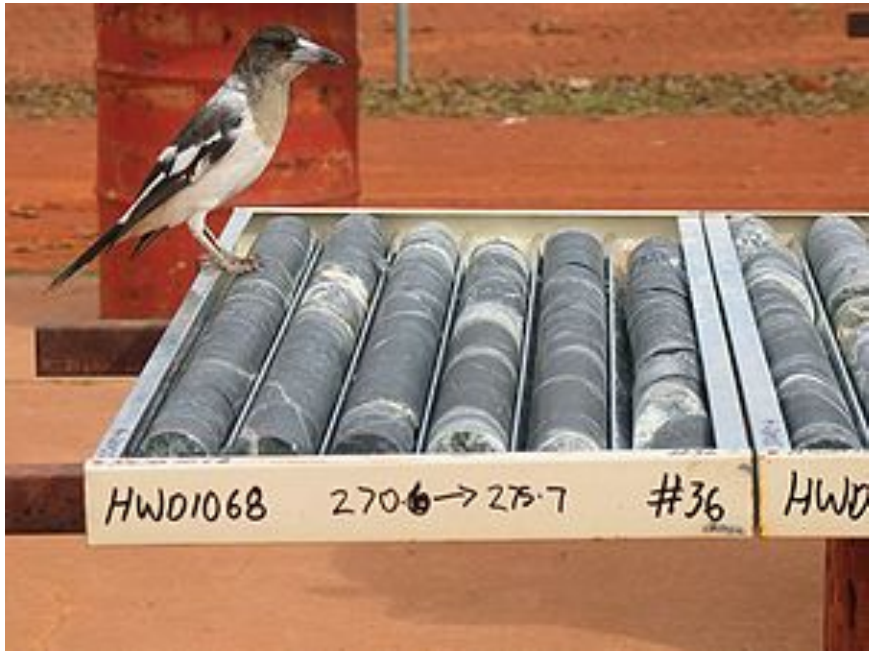
- Do not leave open holes where flow can occur between previously unconnected fractures.

Step 6: Develop & Implement Work Plan

Develop a Work Plan

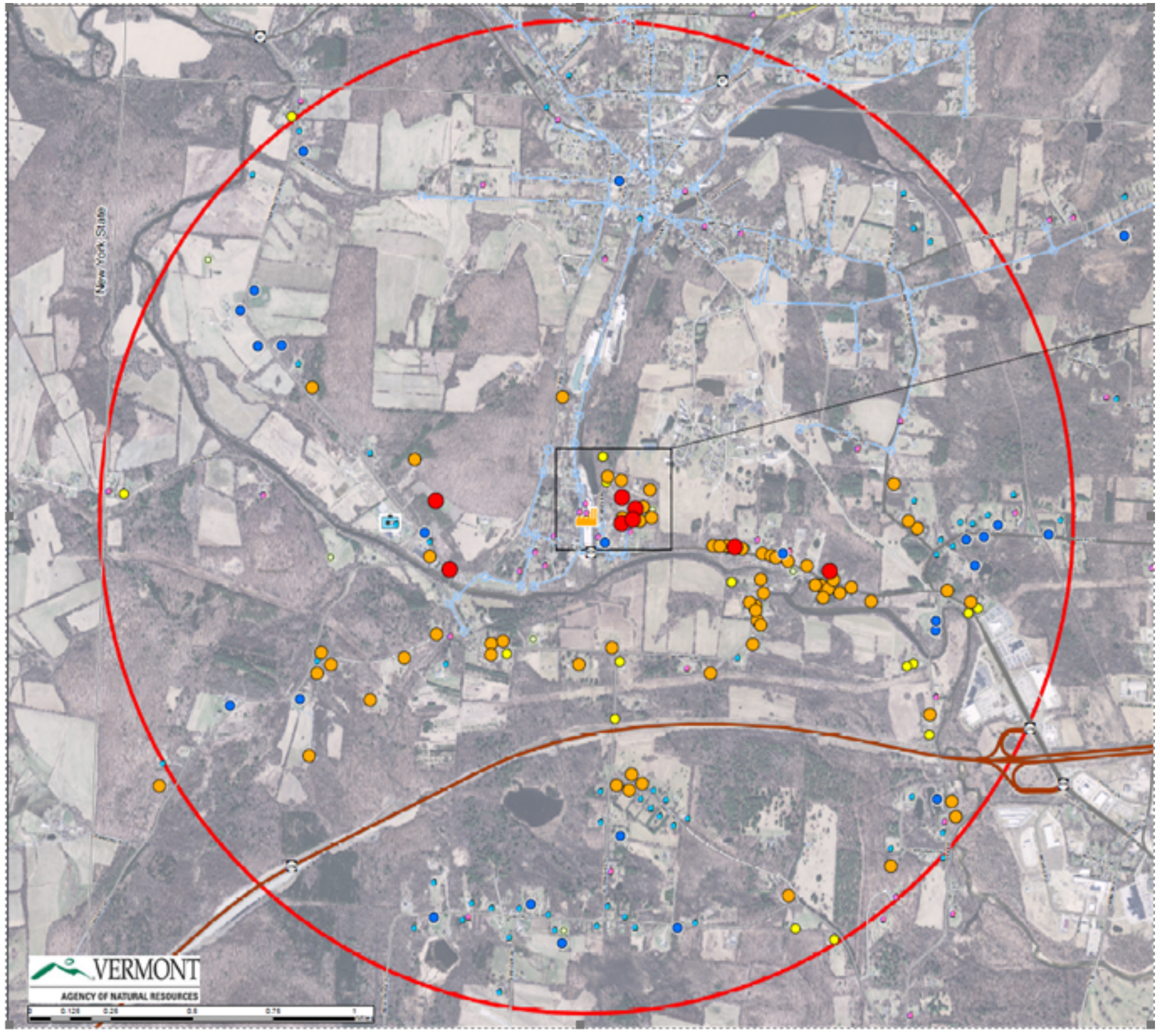
ITRC endorses a dynamic field approach to site characterization to the extent practical at fractured rock sites

- The work plan should be flexible to allow changes to the work scope based on real-time results obtained during the investigation activities.
- The work plan should outline the process for documenting field changes or adjustments during implementing the site investigation



Fractured Rock Characterization Process: Bennington, VT

Step 1: the Initial Site Specific Problem Statement



PFOA found in several domestic water wells near a former fabric waterproofing factory.

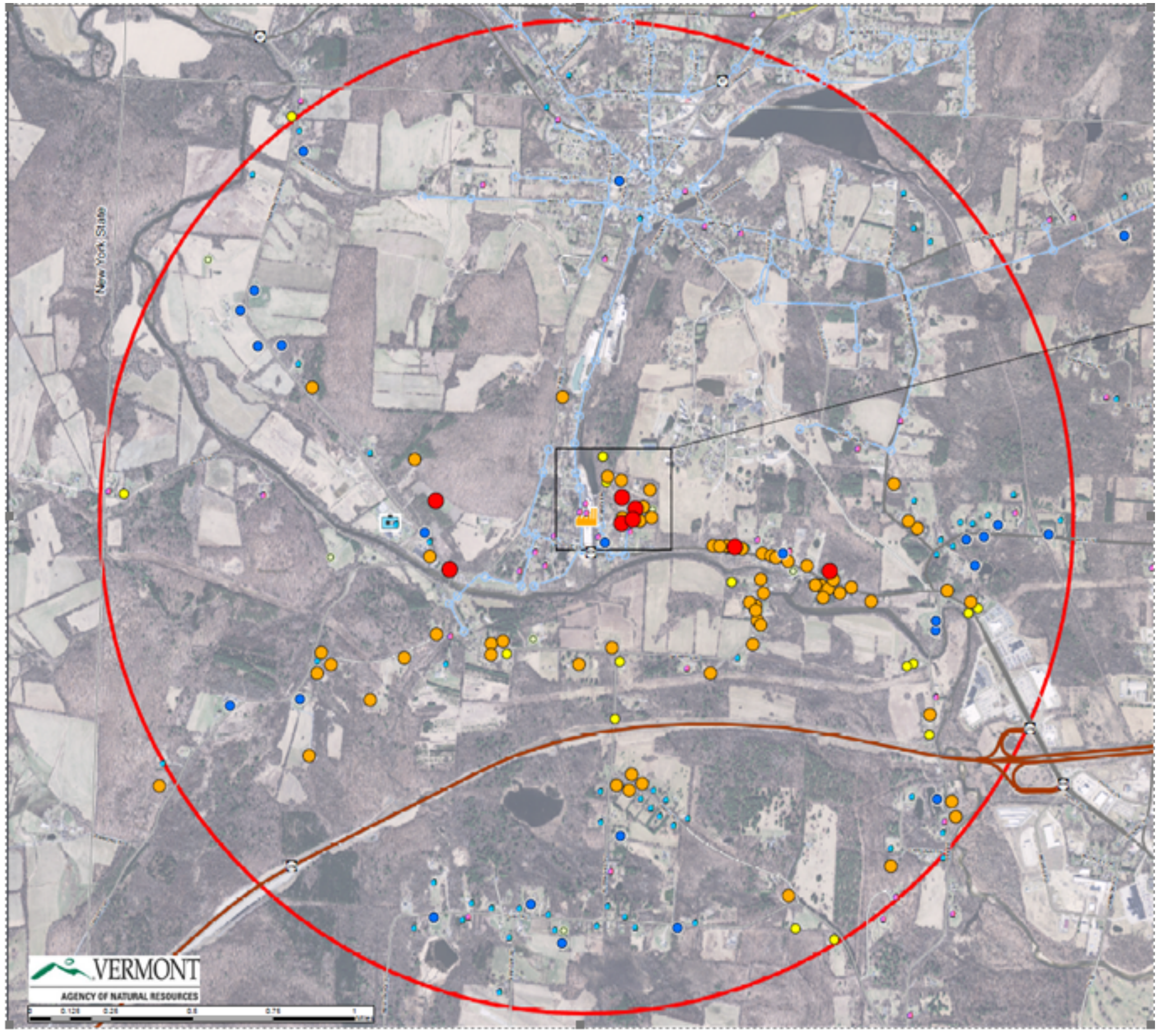
There is a documented significant problem with PFOA contamination caused by a similar factory in a neighboring state.

How large a problem is this in Bennington?

Courtesy VT DEC

Fractured Rock Characterization Process: Bennington, VT

The Site Specific Problem Statement Grows



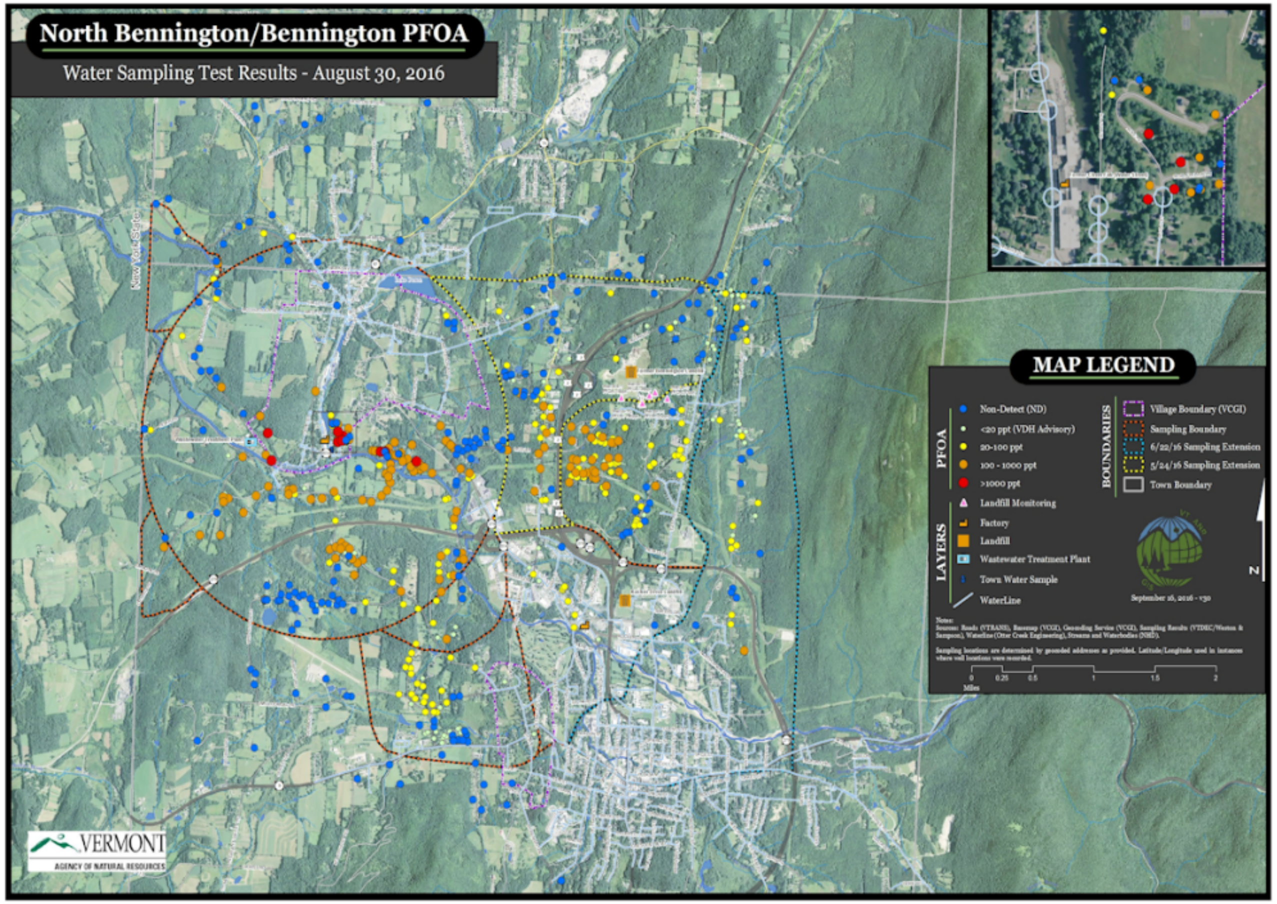
50 wells sampled

- 22 results : ND
- 9 results : 0-20 ng/l
- 8 results : 20-100 ng/l
- 11 results : > 100 ng/l

Courtesy VT DEC

Fractured Rock Characterization Process: Bennington, VT

The Site Specific Problem Statement Grows More

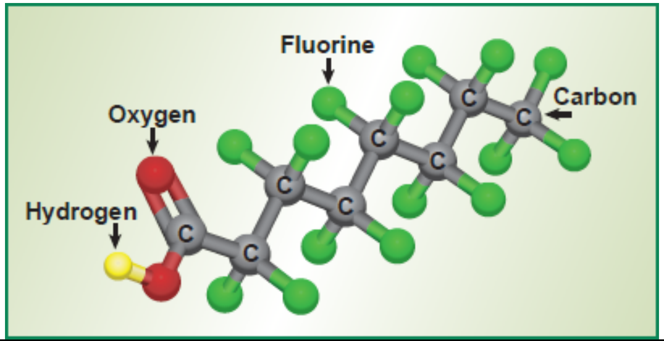


Courtesy VT DEC

- 541 samples collected from private wells

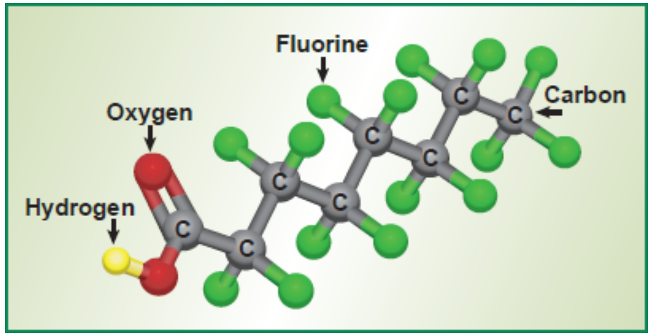
  >60% of all wells had some level of PFOA

- 199 results : ND (37%)
- 76 results : 0-20 ppt (14%)
- **266 results : >20 ppt (49%)**

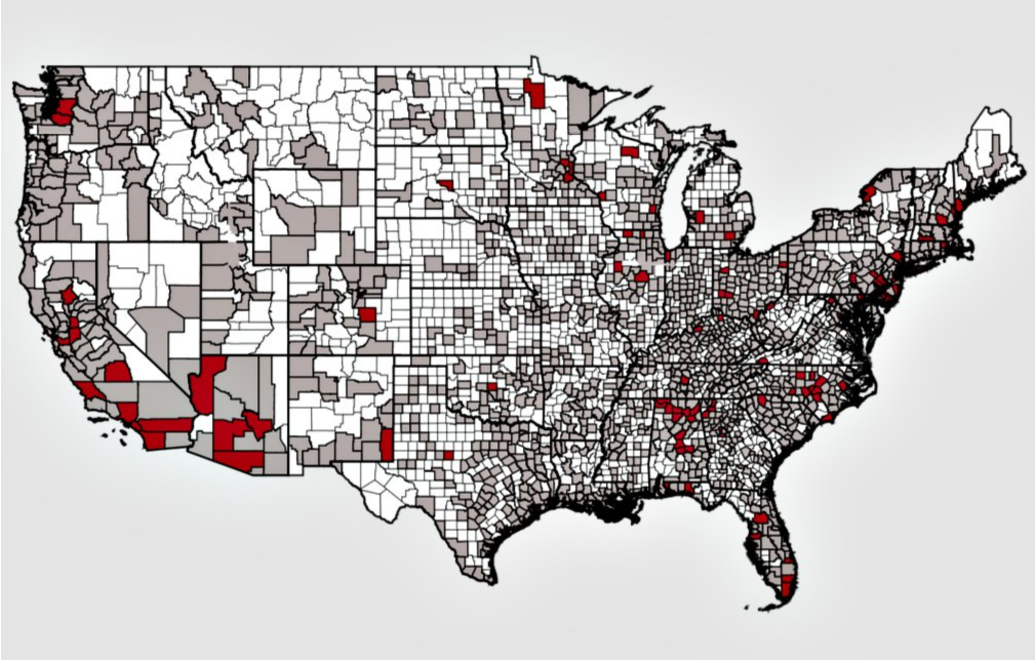


Step 2: Develop or Refine a Fractured Rock CSM

Bennington, VT

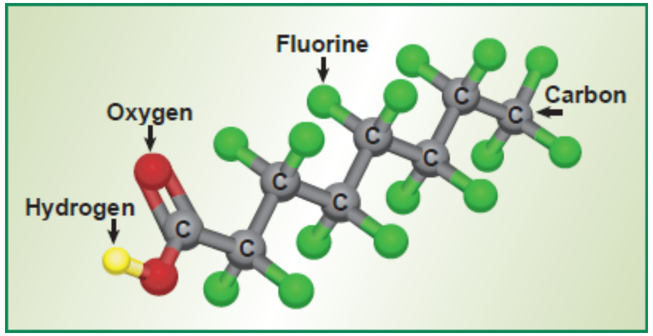


Initial CSM: Type of Waterproof fabric produced

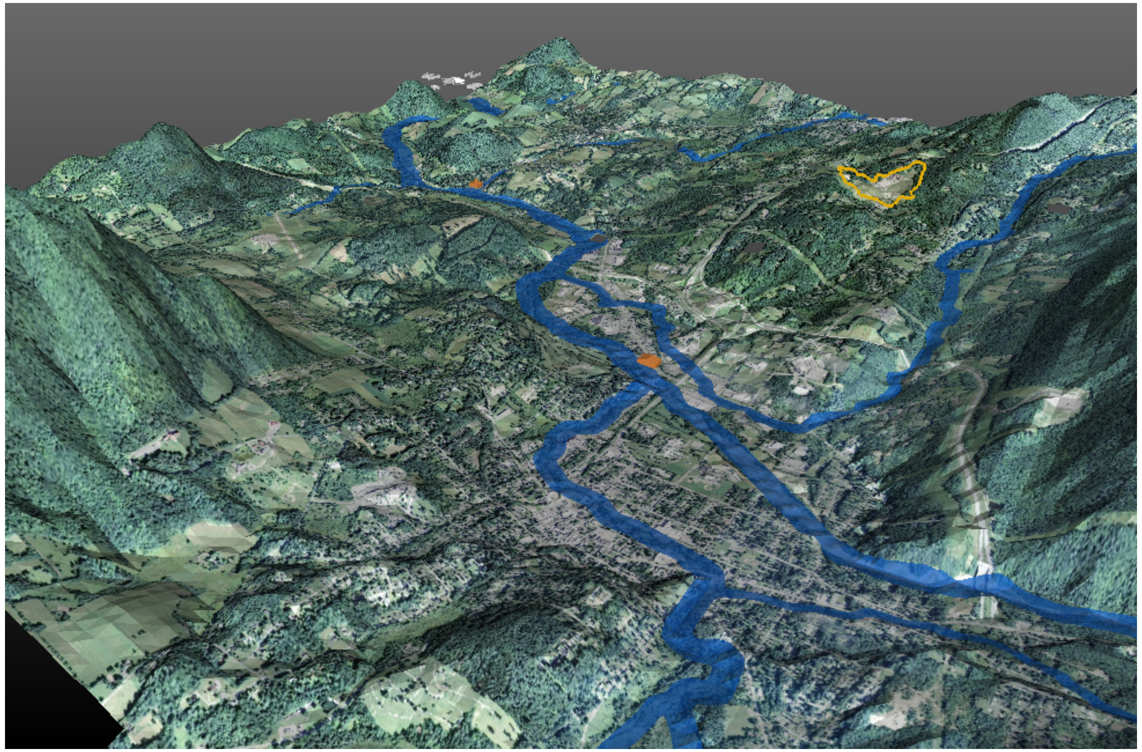


Step 2: Develop or Refine a Fractured Rock CSM

Bennington, VT



Initial CSM: Topography and potential sources



Courtesy VT DEC

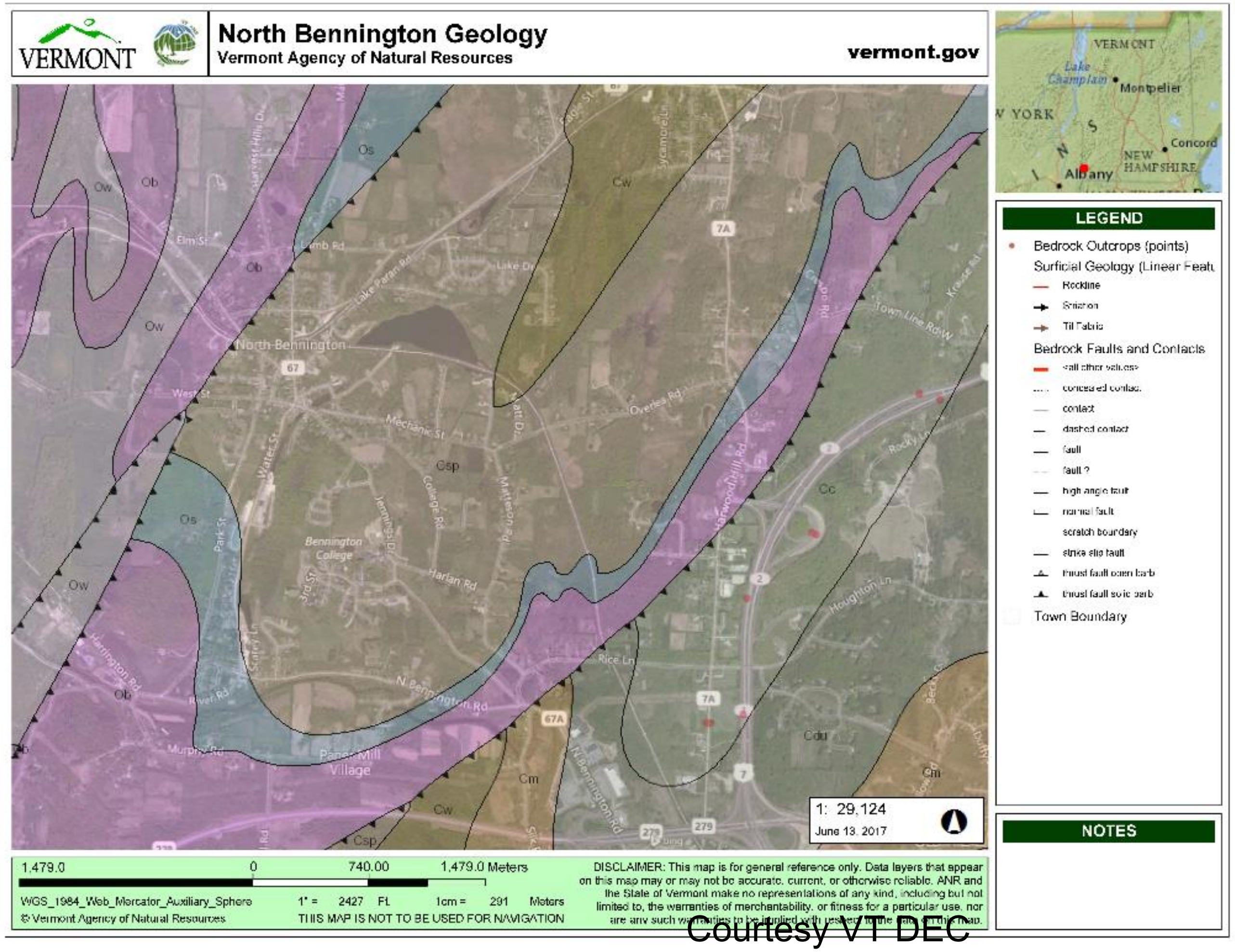
Aerial Deposition?

Surface/Floor Drain releases?

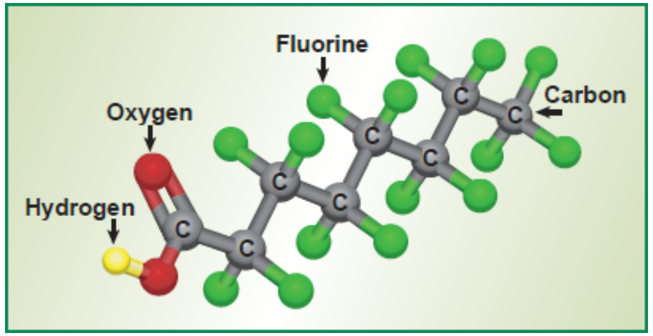
Spreading composted sanitary waste sludge?

Step 2: Develop or Refine a Fractured Rock CSM

Bennington, VT



Courtesy VT DEC



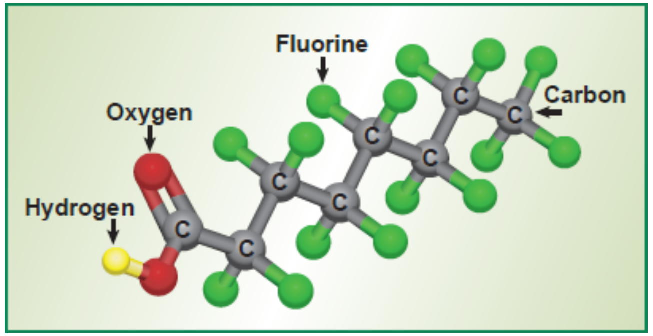
Initial CSM: Bedrock Geology

Several thrust faults

Primarily carbonate rocks in area of contamination

Step 3: Identify Significant Data Gaps

Bennington, VT PFOA Data Gaps example



What was the PFOA release mechanism

- Aerial Deposition?
- Surface/Floor Drain releases?
- Spreading composted sanitary waste sludge?
- Where was this spread?

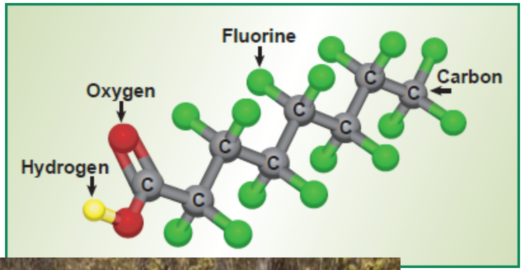
What is the local geology, structure, rock types, major faulting, brittle structure fractures, fracture connectivity, and how does it affect flow and transport?

Is the PFOA in the environment affecting agricultural products?

What is the mass in the soil?
Is it in surface water?
Is it in fish?

Steps 4, 5, & 6 : Develop & Implement Work Plan

Bennington, VT

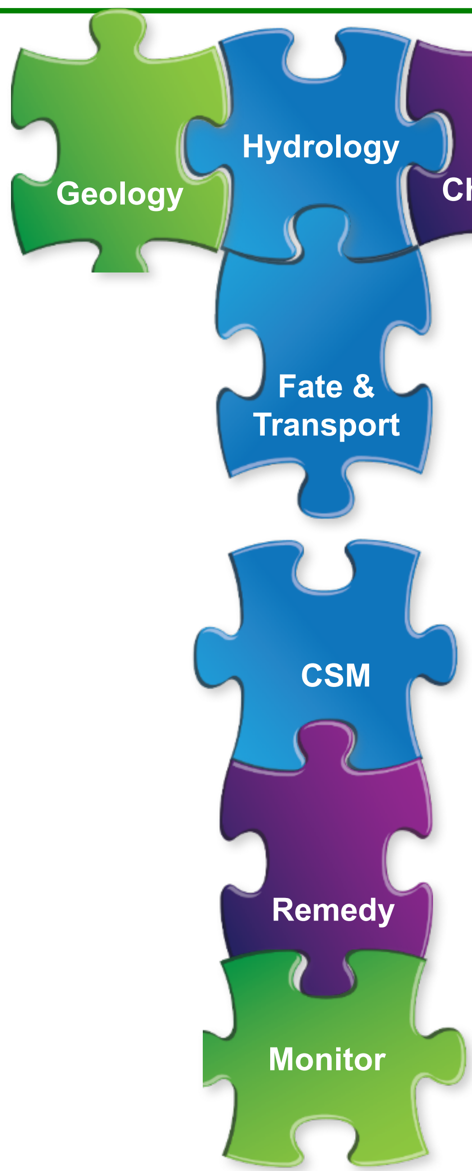


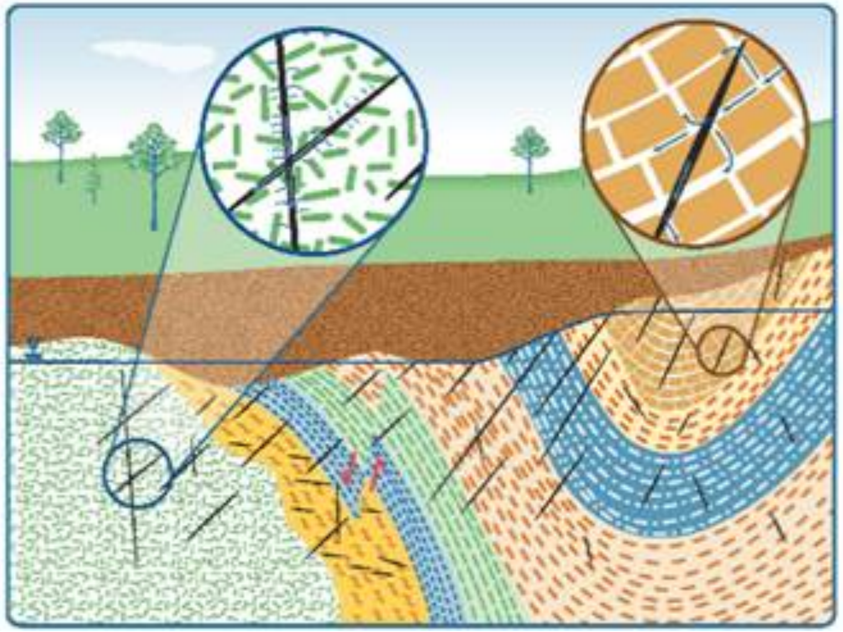
Area-Wide Geologic and Aquifer Characterization Activities

- Geologic and Surficial Mapping by Vermont Geological Survey with support from academic institutions
- Geophysical Logging 12 wells
- Groundwater Geochemistry
- Geochronology (dating) water in wells
- Area-wide groundwater flow direction integrating information from wells, topographic maps, and geologic maps

Courtesy VT DEC

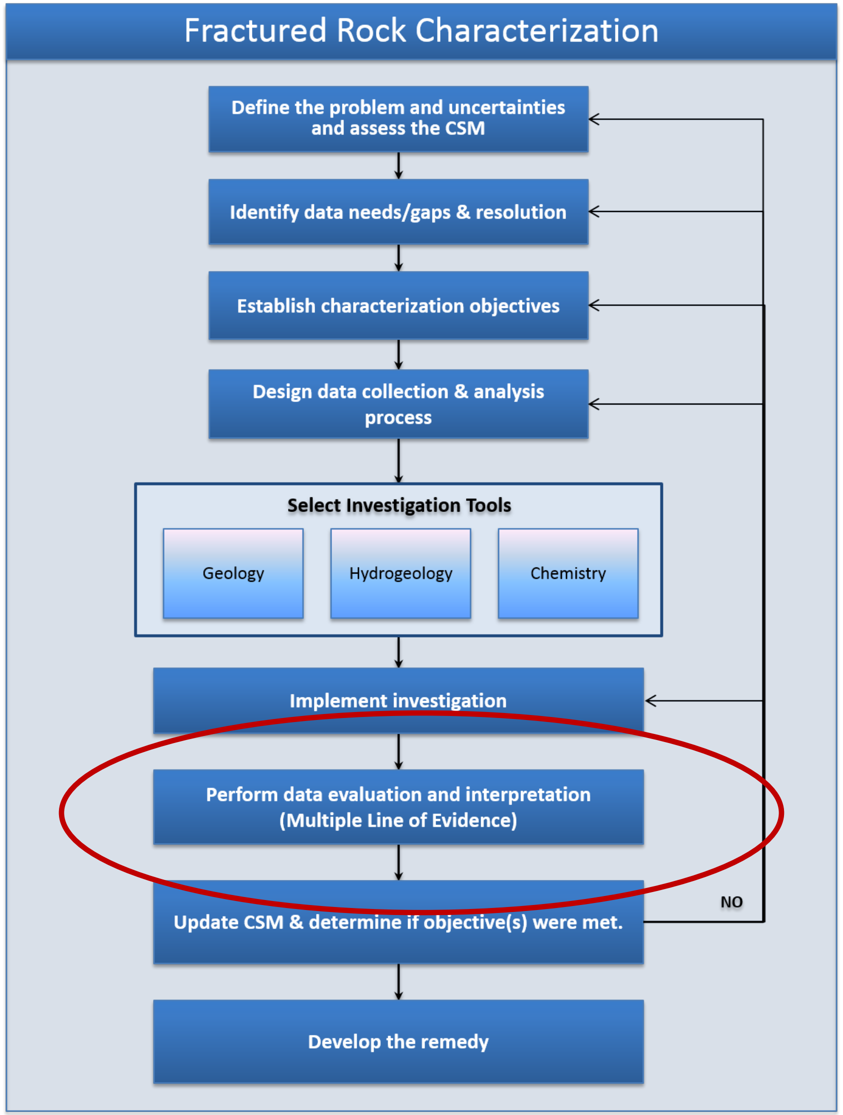
Q&A Break


Geology
Hydrology
Chemistry
Fate & Transport
CSM
Remedy
Monitor



Step 7: Evaluate and Interpret Results

7. **Evaluate and Interpret Results**
8. Update CSM
9. Develop the Remedy



Modified from ITRC ISC-1, 2015, Figure 4-1

Step 7: Evaluate and Interpret Results

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Data Management, Interpretation, and Presentation

- The objective of the data management, interpretation and presentation is to provide a framework for how to
  - interpret,
  - synthesize,
  - manage, and
  - apply data

Critical Early Data for Fractured Rock Sites:

- fracture orientation, aperture, frequency by orientation and depth
- relationship to lithology, infilling, alteration
- hydraulic activity

Needed to help direct the collection of borehole data (e.g., drill cutting or core characterization) and identify packer testing intervals.

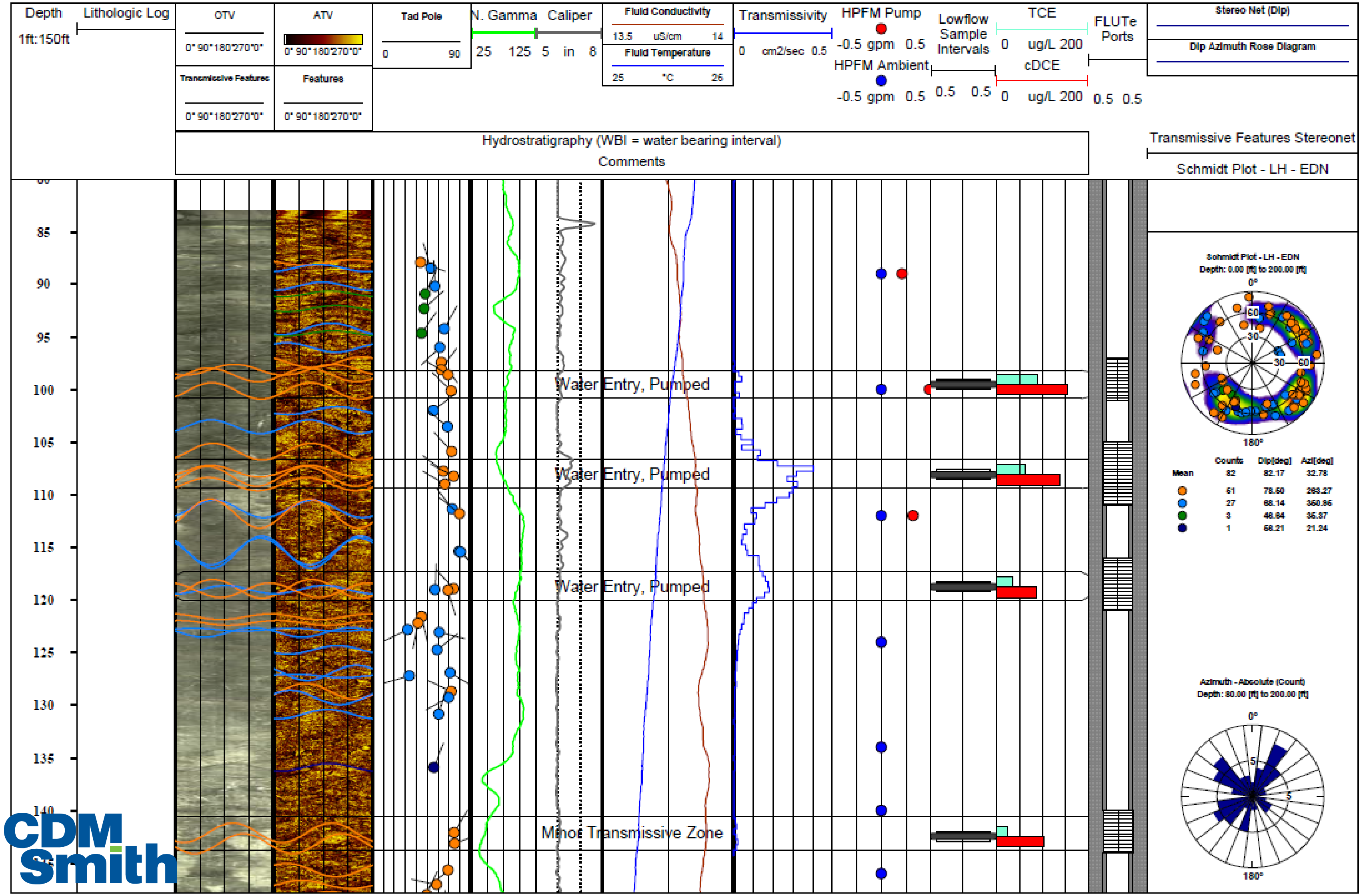
Step 7: Evaluate and Interpret Results

- **Data deliverables, including raw data should include:**
  1. Geophysical logging data from instruments
  2. Integrated borehole logs
  3. Pump test results
- **Manage and Interpret Data with:**
  - 1. Data visualization software
  - 2. Database management software
  - 3. Archive data storage systems

- **Types of data include:**
- *Borehole Geophysics*
  - *Borehole Caliper*
  - *Optical and Acoustic Televiewer*
  - *Fluid Resistivity (induction resistivity) and Temperature Profiling*
  - *Heat-Pulse Flow Meter (HPFM)*
  - *Natural Gamma*
- *Hydraulic Testing and Fracture Connectivity*
  - *Borehole Packer*
  - *Transmissivity Profile*
  - *Reverse-Head Profile*
- *Rock Matrix and Fracture Contamination*
  - *Rock matrix/chip analysis*
  - *Groundwater analysis*

Step 7: Evaluate and Interpret Results

Composite Borehole Geophysics Log

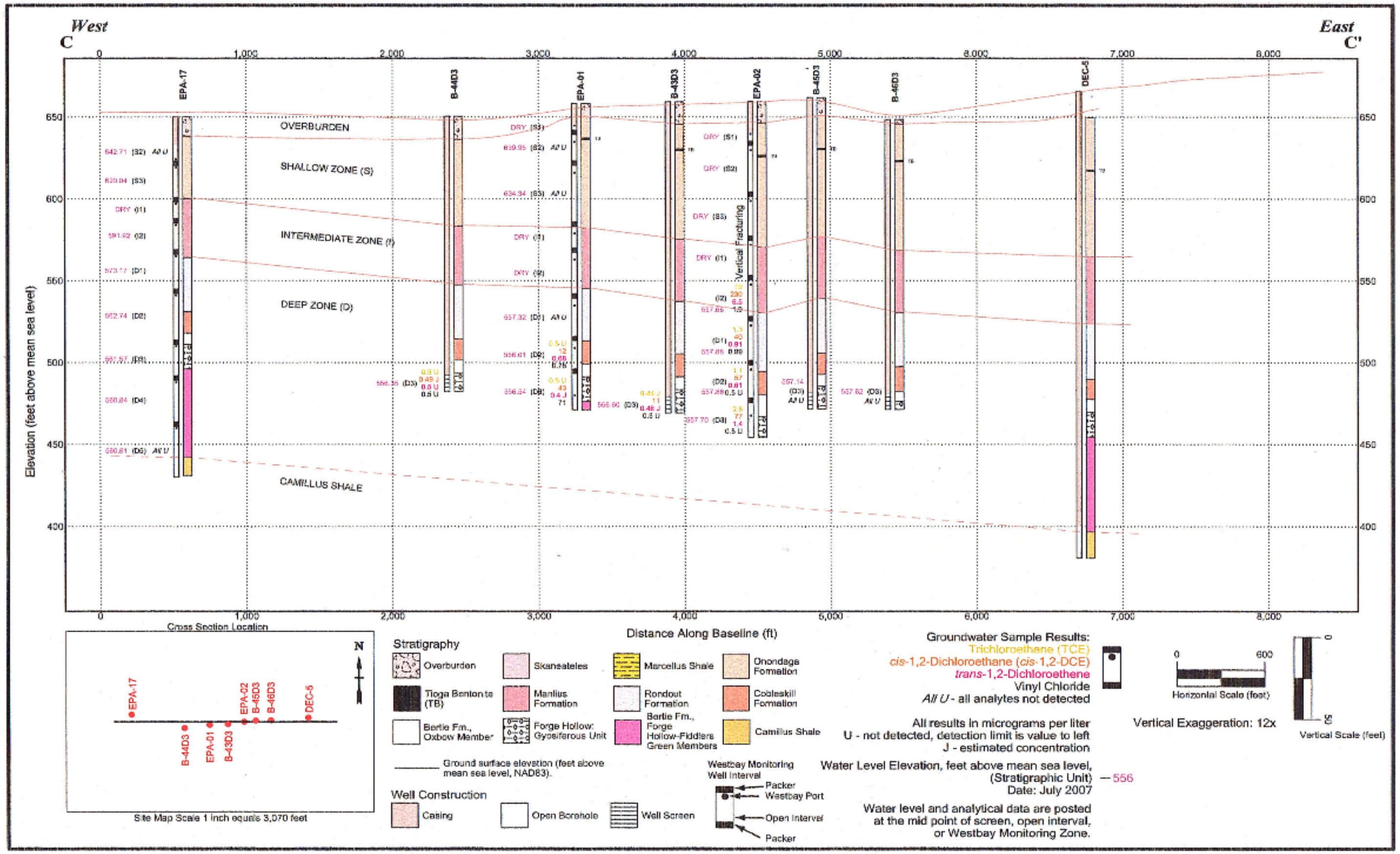


Courtesy John Dougherty

Step 7: Evaluate and Interpret Results

Data Management, Interpretation, and Presentation

Cross-Sections



Step 7: Evaluate and Interpret Results

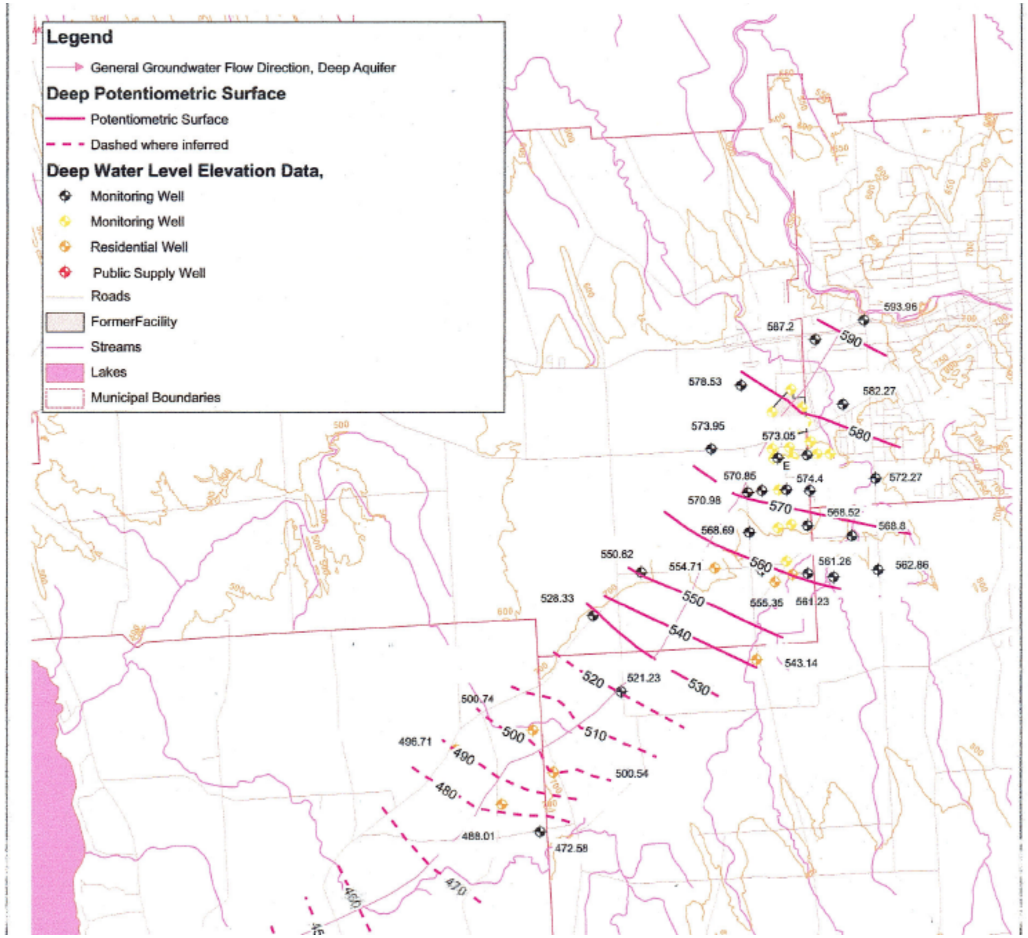
Features for Inclusion on Cross-Sections

Physical Features	Geology	Hydrogeology/Hydrology	Contamination
Monitoring Locations	Bedrock Geology	Flow Direction	Source Locations
Utility Trenches	Fracture Orientation	Extraction Wells	Matrix Concentrations
Grade Elevation	Fracture Type	Water Table	Plume Boundaries
Scale and Vertical Exaggeration	Bedding Units (if applicable)	Piezometric Water Level if Different than Water Table Hydrogeologic Units and Lower Boundary Surface Discharge and Recharge bodies Receptors	Plume Speciation and Concentration Contours
	Top of Bedrock Surface	Preferential Migration Pathways Interconnectivity	NAPL

Step 7: Evaluate and Interpret Results

Data Management, Interpretation, and Presentation

Plan View



ITRC FracRx-1
Figure 5-5

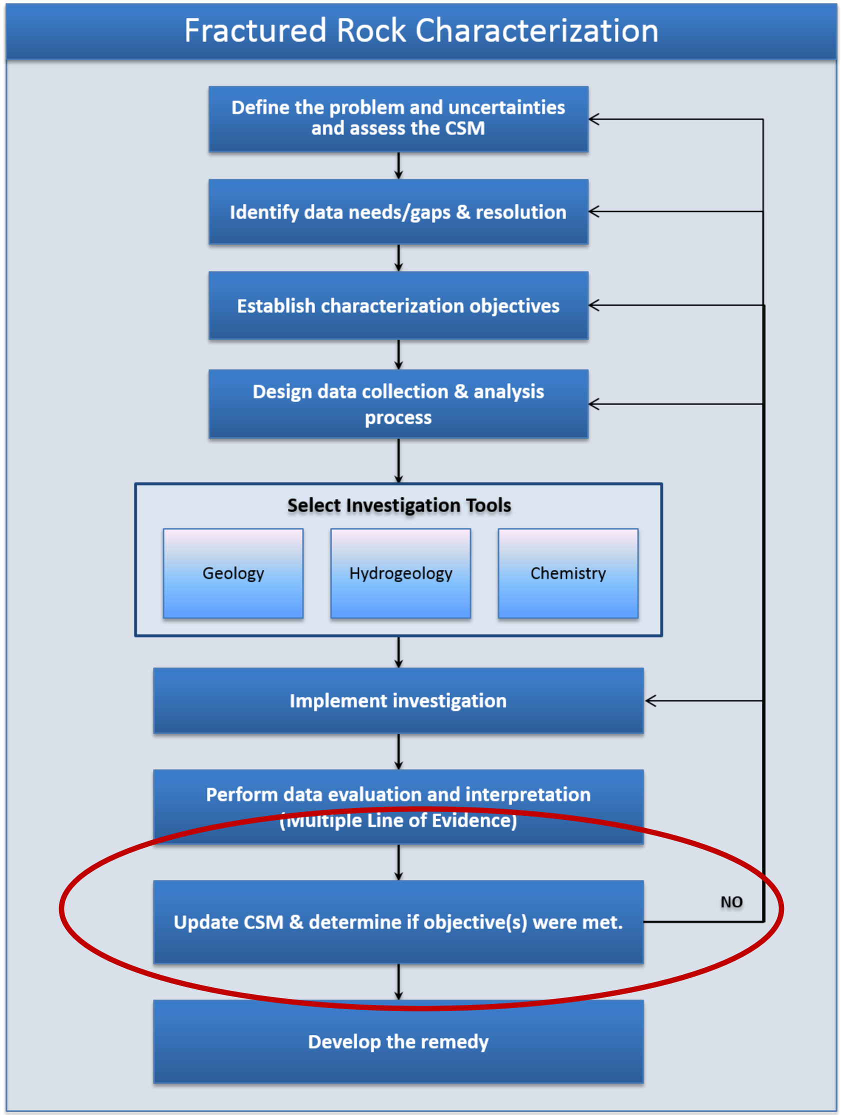
Step 7: Evaluate and Interpret Results

Features for Inclusion on Plan View

Features that should be considered for inclusion on a plan view representing a CSM			
Physical Features	Geology	Hydrogeology/Hydrology	Contamination
Monitoring Locations	Topography (surface)	Water sheds	Source Locations
Utility Trenches	Lineaments	Piezometric Contours and Flow Direction	Plume Boundaries and Contaminant Contours
Property Boundaries	Top of Weathered Bedrock Elevation Contours	Extraction Wells in Each Aquifer	Plume Speciation
Human and Ecological Receptors	Faults	Surface Discharge or Recharge Bodies	NAPL Presence
	Top of Competent Bedrock Elevation Contours	Subcropping and Fracture Planes	

Step 8: Update CSM

7. Evaluate and Interpret Results
8. Update CSM
9. Develop the Remedy



Step 8: Update CSM

Update CSM

- ▶ This should be occurring continuously as new data are available

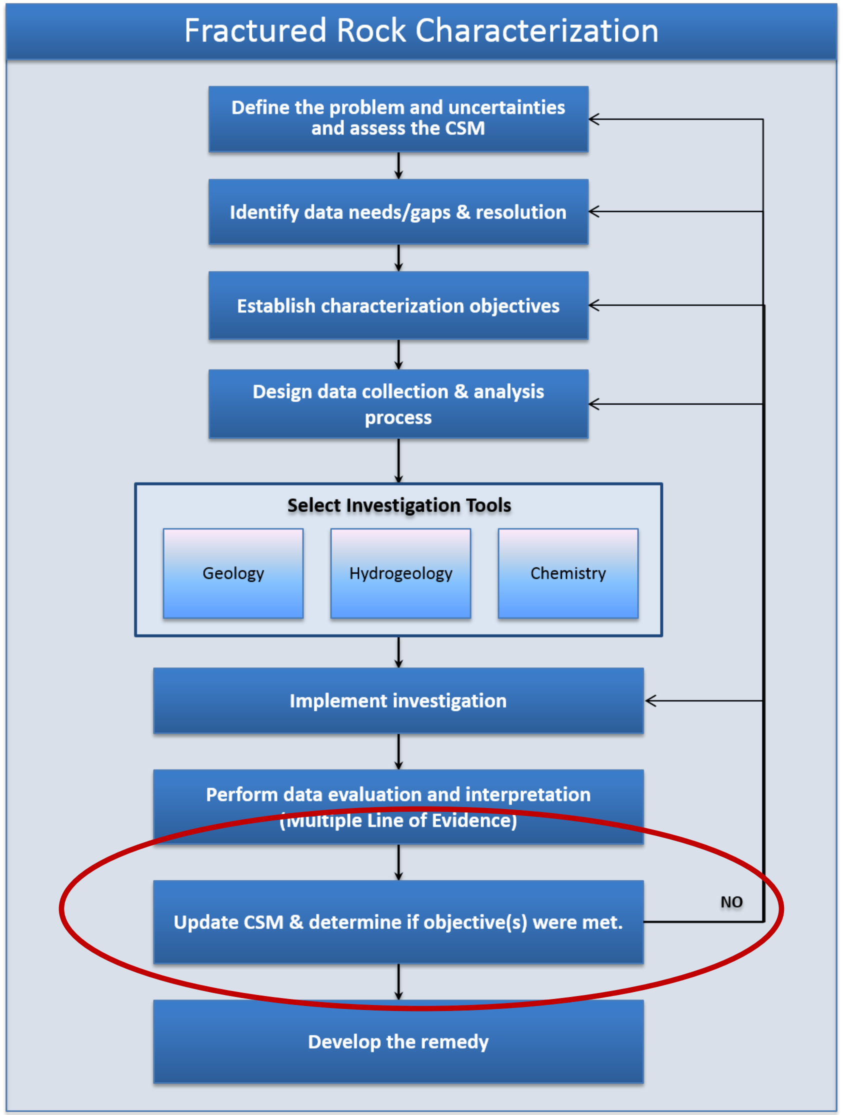
Are Characterization Goals Met?

No?

- Repeat previous steps as needed to achieve characterization goals

Yes?

- Proceed to Remedy Development

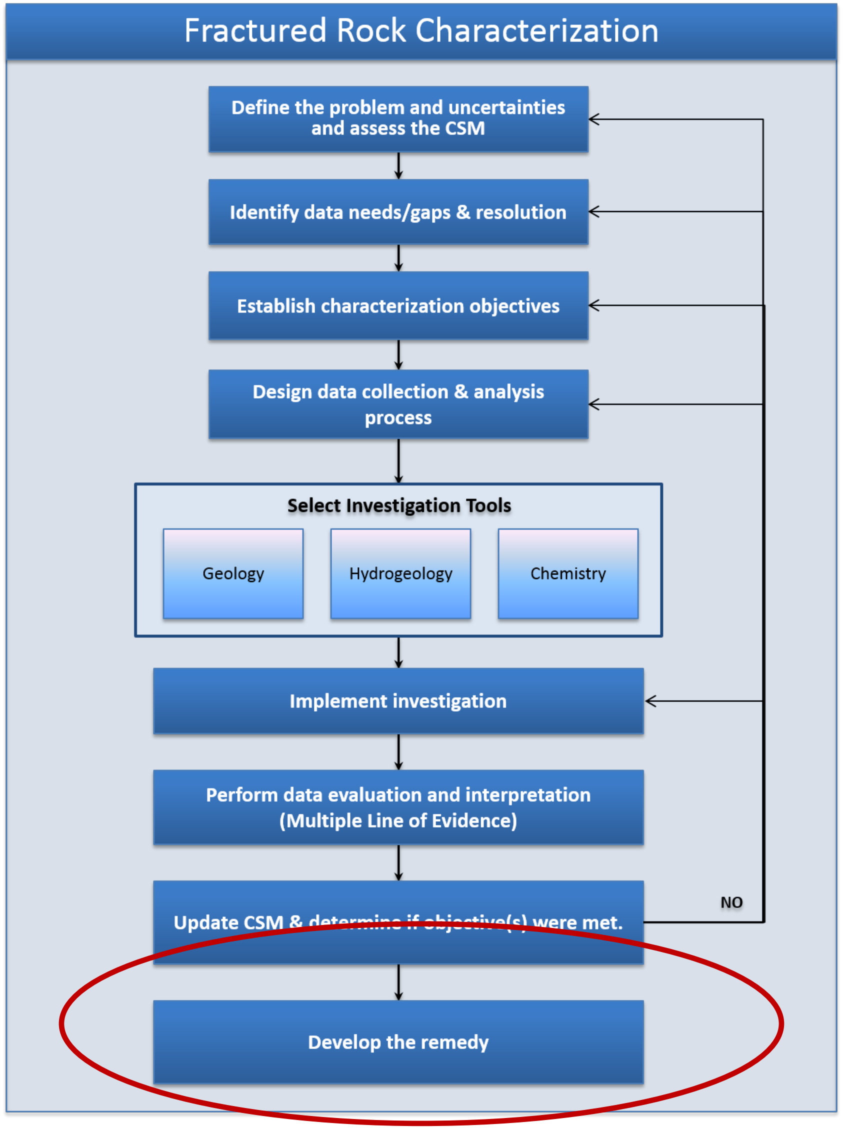


Overview of the Training

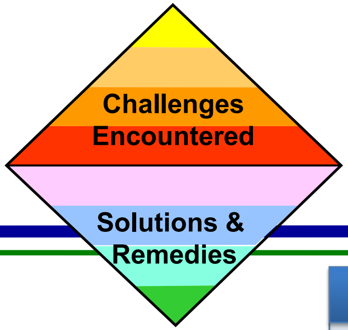
- Introduction
- Fractured Rock CSM Considerations
- Fracture Characteristics of Geologic Terrane
- Fracture Flow & Contaminant Fate and Transport
- Fractured Rock Characterization
- **Remedy Development**
- Monitoring
- Summary

Step 9: Develop the Remedy

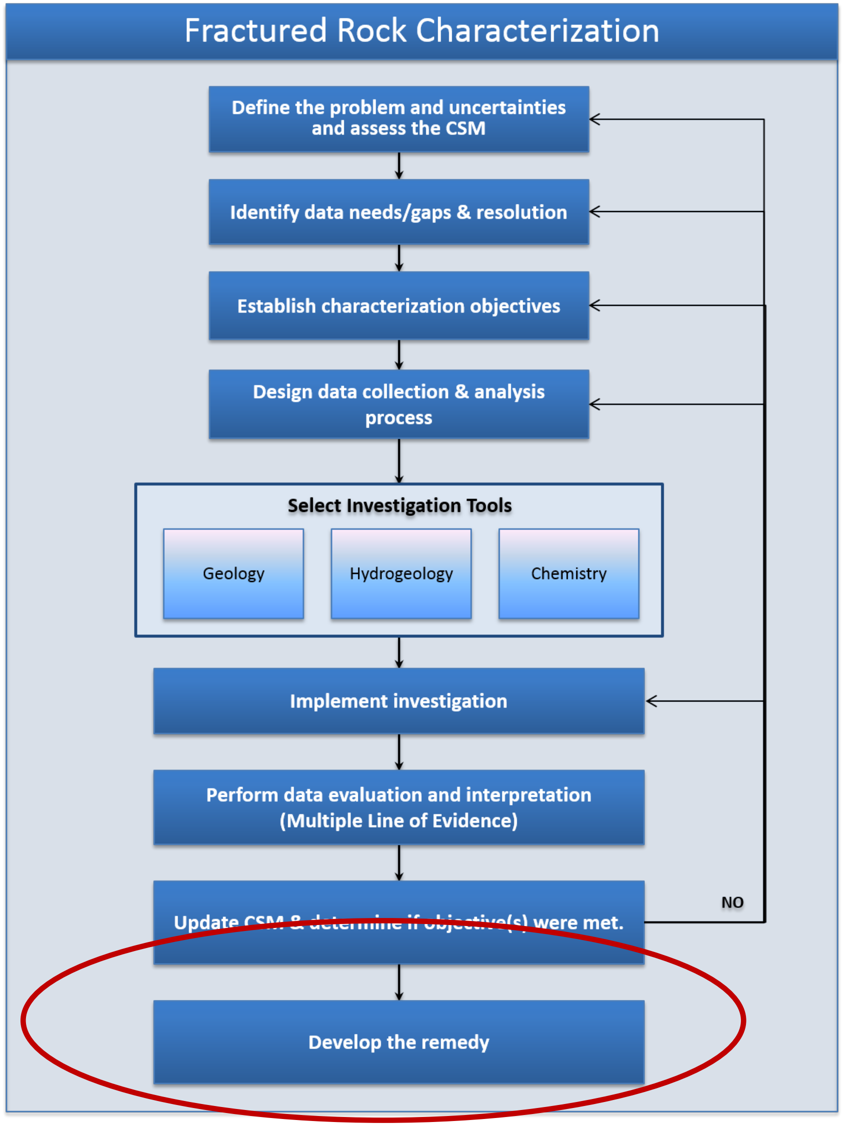
7. Evaluate and Interpret Results
8. Update CSM
9. **Develop the Remedy**



Step 9: Develop the Remedy



- Attaining presumptive levels (e.g., MCLs) generally more challenging than in overburden
- **Focus on "SMART" Remedial Action Objectives (RAO's)** and risk reduction
- Consider remedies that have reasonable timeframes and costs, and that:
  - Address most critical risks
  - Foster partial cleanups
  - Address community concerns
  - Progress towards complete restoration



Step 9: Develop the Remedy

Absolute RAO's vs. Functional RAO's

Absolute Objectives- based on broad social values

- Protect human health and the environment
- Conserve natural resources
- Address adverse community impacts (e.g., beneficial use impacts to groundwater)
- Minimize the burden of past practices on future generations

Functional Objectives- steps taken to achieve absolute objectives

- Specific actions to reduce:
  - Risk
  - Extent
  - Longevity
  - Regulatory
  - Community
  - Economic
  - Sustainability
  - Example: reduce loading to the aquifer by treating, containing or reducing source

Step 9: Develop the Remedy

Functional RAO's Should be SMART

SMART means:

- Specific
  - Objectives should be detailed and well defined
- Measureable
  - Parameters should be specified and quantifiable
- Attainable
  - Realistic within the proposed timeframe and availability of resources
- Relevant
  - Has value and represents realistic expectations
- Time-bound
  - Clearly defined and short enough to ensure accountability

- "SMART" RAOs and risk reduction may consider:
  - Groundwater discharge to surface water
  - Vapor discharge
  - Mass flux zones
  - Source zones
- Acknowledge uncertainty
- Develop contingency plan

Step 9: Develop the Remedy

Functional RAO's Time Frame

- Time frame should accommodate
  - Accountability
  - Natural variation of contaminant concentration and aquifer conditions
  - Reliable predictions
  - Scientific understanding and technical ability
- **Team suggests 20 years or less for Functional Objectives**

Site management and active remediation timeframe may continue for much longer

Step 9: Develop the Remedy

Special Considerations in Bedrock

Properties	Difference at Fractured Rock sites	Impact
Transmissivity/ mass storage	Wider spectrum of hydraulic transmissivity and contaminant mass storage domains	Injection and extraction based remedies can be more difficult to implement
NAPL	NAPL has much less water interfacial area	NAPL more difficult to remove/contact and can sustain plumes longer
Groundwater flow direction/flux	Groundwater flow is more uncertain, especially on local scales	Preferential flow can impact amendment distribution; passive remedies (e.g. barriers) can be more difficult
Abiotic/biotic reactions	Wide range of biotic and abiotic interaction with fracture surfaces and rock matrix	Need to understand rock types and whether matrix is reactive toward contaminants; can enhance MNA at some sites

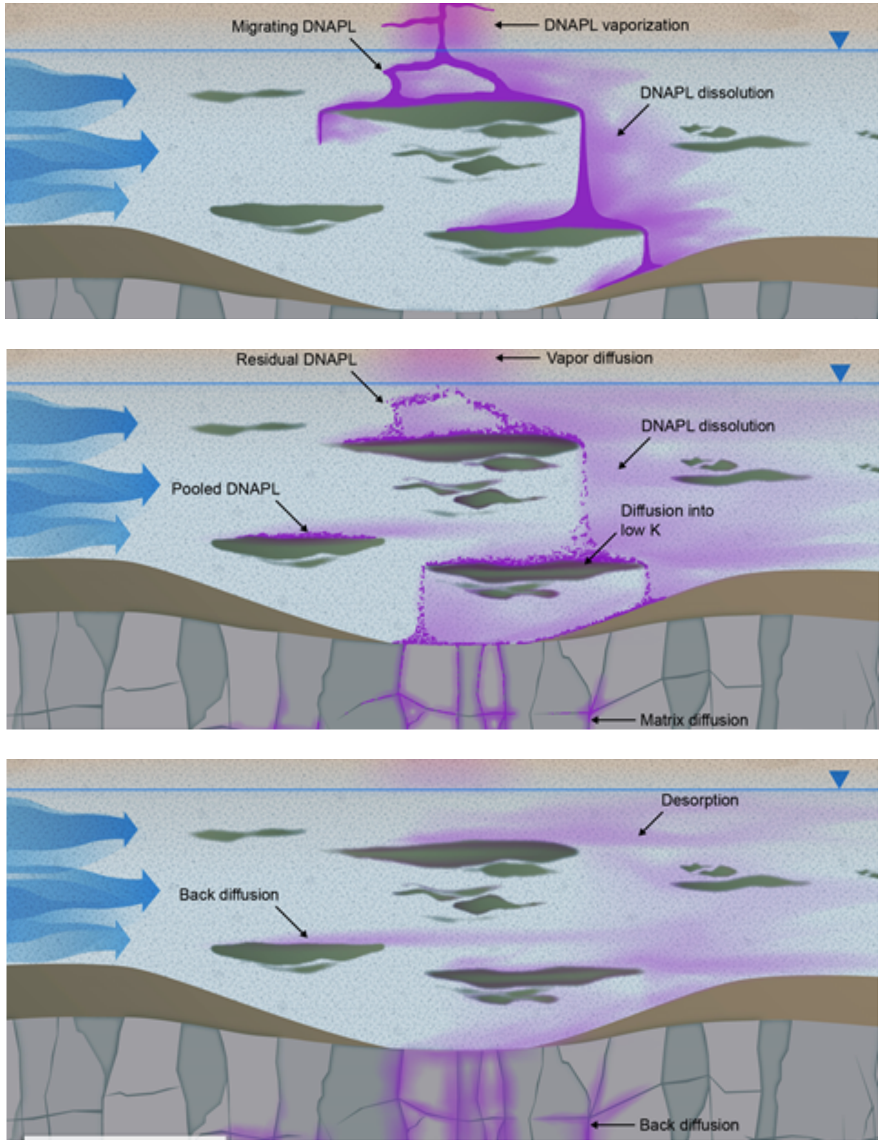
Step 9: Develop the Remedy

Rock Type Influences Remedy Selection

- Begin technology screening with consideration of general rock types
  - Rock type affects fate, transport, storage, geochemistry characteristics, and therefore remediation
    - Differences in hydraulic characteristics
    - Differences in organic carbon content
    - Abiotic transformation reactions

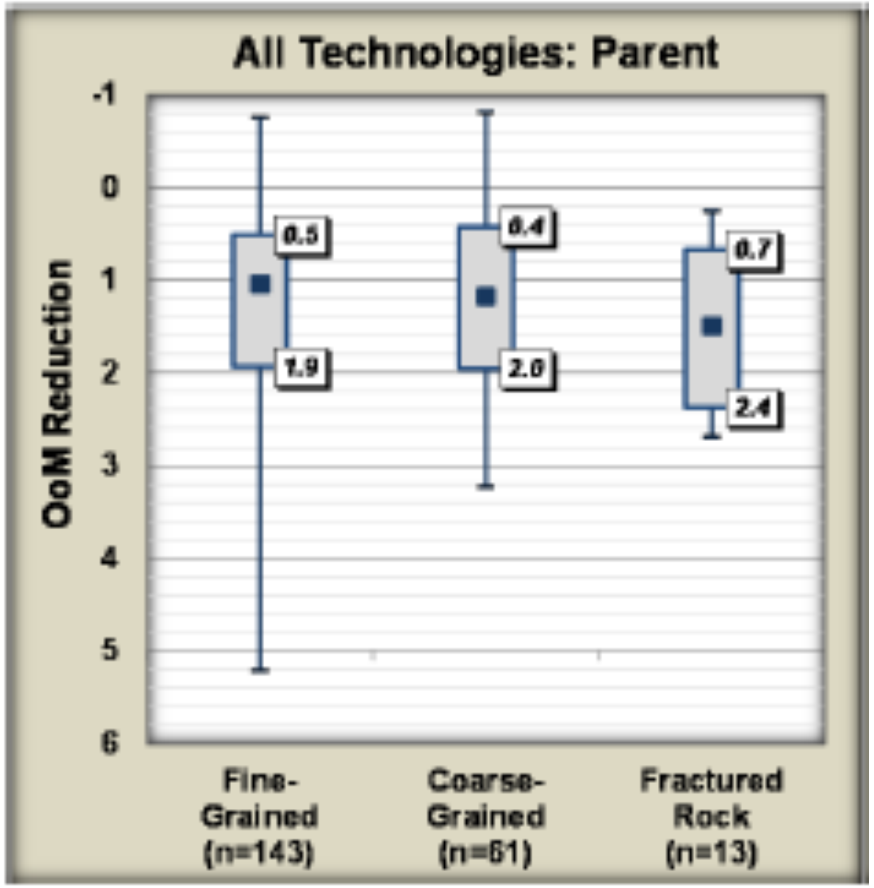
Contaminant Characteristic Considerations

- Highly soluble contaminants may exhibit strong matrix diffusion
  - Subsequent back diffusion following remediation of contamination within secondary porosity
- NAPLs may be transported great distances
  - Horizontal and/or vertical transport in fracture network
- Water-contaminant-rock interactions very different on fracture surfaces than in rock matrix



Performance at Fractured Rock Sites

- Overall fractured rock sites could be treated but required more detailed CSMs.
- In some instances, remediation is easier if target vertical/fracture intervals are identified.



Technology Screening Matrix (Table 6-2)

Table 6-2. Remediation Technology Screening Matrix for Fractured Bedrock Environments

Representative Rock Types / Origin				21-Compartment Model Elements			Physical					Containment		Chemical / Biological					
				Porosity		Matrix Storage	Removal	Thermal	Air Sparge	Vapor & Multiphase Extraction	Surfactant Flushing	Pump & Treat	Permeable Reactive Barrier	ISCO		ISCR		ISB	
				Primary	Secondary									Short-lived oxidant	Long-lived oxidant	Short-lived reductant	Long-lived reductant	Short-lived carbon substrate	Long-lived carbon substrate
Sedimentary Rocks	Chemical	Coal	Bituminous	H	L	H	Y	U	U	Y	U (?)	Y	N	N	N	N	N	N	Y
			Anthracite	L	L	L	Y	U	U	Y	U (?)	Y	N	N	N	N	N	N	Y
		Carbonates	Limestone (including Karst)	H	L or H	H	Y	Y	U	Y	U (?)	Y	Y	N	Y	N	Y	N	Y
			Dolomite & Recrystallized Limestone	L	L or H	L	Y	Y	U	Y	U (?)	Y	Y	Y	Y	N	Y	Y	Y
	Clastics		Cemented Sandstone, Conglomerate, & Other Coarse-Grained Rocks	L	H	L	Y	Y	U	Y	Y (?)	Y	Y	Y	Y	Y	Y	Y	Y
			Uncemented Sandstone, Conglomerate, & Other Coarse-Grained Rocks	H	L	H	Y	Y	U	Y	N (?)	Y	N	N	Y	N	N	N	Y
			Shale & Mudstone	H	H	H	Y	Y	U	Y	Y (?)	Y	Y	N	Y	N	Y	N	Y
Igneous & Metamorphic Rocks	Extrusives		Tuff / Scoria / Pumice	H	L	H	U	U	U	Y	N (?)	Y	N	N	Y	N	N	N	Y
			Basalt / Rhyolite	L	H	L	U	U	U	Y	Y (?)	Y	Y	Y	Y	Y	Y	Y	Y
	Intrusives		Granites & Other Crystalline Intrusives	L	H	L	U	U	U	Y	Y (?)	Y	Y	Y	Y	Y	Y	Y	Y
	Metamorphics		Foliated Metamorphsics (e.g., Gneiss & Schist)	L	H	L	U	U	U	Y	Y (?)	Y	Y	Y	Y	Y	Y	Y	Y
			Unfoliated Metamorphics (e.g., Quartzite, Amphibolite)	L	L	L	U	U	U	Y	N (?)	Y	N	N	Y	N	N	N	Y
Treatment Zone and Phase Considerations	Vadose Zone		NAPL				Y	Y	N	Y	Y (?)	N	N	Y	Y	N	N	N	N
			Matrix Storage				Y	Y	N	Y	N (?)	N	N	N	Y	N	N	N	N
			Vapor phase				Y	Y	N	Y	N (?)	N	N	N	Y	N	N	N	N
	Saturated Zone		NAPL				U	Y	N	N	Y (?)	N	N	Y	Y	Y	Y	Y	Y
			Matrix Storage				U	Y	N	N	N (?)	N	N	N	Y	N	Y	N	Y
			Dissolved phase				U	Y	N	N	N (?)	Y	Y	Y	Y	Y	Y	Y	Y
			Vapor phase				U	Y	N	N	N (?)	Y	Y	Y	Y	Y	Y	Y	Y

* This table is for general technology screening only. Technology selection must be based upon careful review of site-specific conditions.

H = High

L = Low

Y = Yes, generally applicable remediation technology

U = Unlikely to be applicable remediation technology

N = No, generally not applicable remediation technology

Technology Screening Matrix

MISSOURI WASTE CONTROL COALITION

INTERSTATE TECHNOLOGY REGULATORY COUNCIL ITRC

Rock Type defines physical properties that influence effectiveness

Porosity		Matrix Storage
Primary	Secondary	
H	L	H
L	L	L
H	L or H	H
L	L or H	L
L	H	L
H	L	H
H	H	H
H	L	H
L	H	L
L	H	L
L	H	L
L	L	L

"H" = "High"
"L" = "Low"

Table 6-2. Remediation Technology …reening Matrix for Fractured Bedrock Environments

Representative Rock Types / Origin				Porosity: Primary	Porosity: Secondary	Matrix Storage	Physical: …moval	Physical: Thermal	Physical: Air Sparge	Physical: Vapor & Multiphase Extraction	Physical: Surfactant Flushing	Containment: Pump & Treat	Containment: Permeable Reactive Barrier	ISCO: Short-lived oxidant	ISCO: Long-lived oxidant	ISCR: Short-lived reductant	ISCR: Long-lived reductant	ISB: Short-lived carbon substrate	ISB: Long-lived carbon substrate
Sedimentary Rocks	Chemical	Coal	Bituminous	H	L	H	Y	U	U	Y	U (?)	Y	N	N	N	N	N	N	Y
Sedimentary Rocks	Chemical	Coal	Anthracite	L	L	L	Y	U	U	Y	U (?)	Y	N	N	N	N	N	N	Y
Sedimentary Rocks	Chemical	Carbonates	Limestone (includ… Karst)	H	L or H	H	Y	Y	U	Y	U (?)	Y	Y	N	Y	N	Y	N	Y
Sedimentary Rocks	Chemical	Carbonates	Dolomite & Recrystallized Limestone	L	L or H	L	Y	Y	U	Y	U (?)	Y	Y	Y	Y	N	Y	Y	Y
Sedimentary Rocks	Clastics		Cemented Sandsto… Conglomerate, & O…r Coarse-Grained Ro…	L	H	L	Y	Y	U	Y	Y (?)	Y	Y	Y	Y	Y	Y	Y	Y
Sedimentary Rocks	Clastics		Uncemented Sands…, Conglomerate, & O…r Coarse-Grained Ro…	H	L	H	Y	Y	U	Y	N (?)	Y	N	N	Y	N	N	N	Y
Sedimentary Rocks	Clastics		Shale & Mudston…	H	H	H	Y	Y	U	Y	Y (?)	Y	Y	N	Y	N	Y	N	Y
Igneous & Metamorphic Rocks	Extrusives		Tuff / Scoria / Pum…	H	L	H	U	U	U	Y	N (?)	Y	N	N	Y	N	N	N	Y
Igneous & Metamorphic Rocks	Extrusives		Basalt / Rhyolite	L	H	L	U	U	U	Y	Y (?)	Y	Y	Y	Y	Y	Y	Y	Y
Igneous & Metamorphic Rocks	Intrusives		Granites & Othe… Crystalline Intrusi…	L	H	L	U	U	U	Y	Y (?)	Y	Y	Y	Y	Y	Y	Y	Y
Igneous & Metamorphic Rocks	Metamorphics		Foliated Metamorph…s (e.g., Gneiss & Sch…	L	H	L	U	U	U	Y	Y (?)	Y	Y	Y	Y	Y	Y	Y	Y
Igneous & Metamorphic Rocks	Metamorphics		Unfoliated Metamorphics (e.g., Quartzite, Amphibolite)	L	L	L	U	U	U	Y	N (?)	Y	N	N	Y	N	N	N	Y
Treatment Zone and Phase Considerations	Vadose Zo…		NAPL				Y	Y	N	Y	Y (?)	N	N	Y	Y	N	N	N	N
Treatment Zone and Phase Considerations	Vadose Zo…		Matrix Storage				Y	Y	N	Y	N (?)	N	N	N	Y	N	N	N	N
Treatment Zone and Phase Considerations	Vadose Zo…		Vapor phase				Y	Y	N	Y	N (?)	N	N	N	Y	N	N	N	N
Treatment Zone and Phase Considerations	Satu…ted Zone		NAPL				U	Y	N	N	Y (?)	N	N	Y	Y	Y	Y	Y	Y
Treatment Zone and Phase Considerations	Satu…ted Zone		Matrix Storage				U	Y	N	N	N (?)	N	N	N	Y	N	Y	N	Y
Treatment Zone and Phase Considerations	Satu…ted Zone		Dissolved phase				U	Y	N	N	N (?)	Y	Y	Y	Y	Y	Y	Y	Y
Treatment Zone and Phase Considerations	Satu…ted Zone		Vapor phase				U	Y	N	N	N (?)	Y	Y	Y	Y	Y	Y	Y	Y

* This table is for general tech…logy screening only. Technology selection must be based upon careful review of site-specific conditions.
H = High
L = Low
Y = Yes, generally appli…ble remediation technology
U = Unlikely to be ap…cable remediation technology
N = No, generally …t applicable remediation technology

Range of technologies in screening matrix

Physical					Contaminant		Chemical / Biological						
Removal	Thermal	Air Sparge	Vapor & Multiphase Extraction	Surfactant Flushing	Pump & Treat	Permeable Reactive Barrier	In-situ Chemical Oxidation		In-situ Chemical Reduction		In-situ Bioremediation		
							Short-lived oxidant	Long-lived oxidant	Short-lived reductant	Long-lived reductant	Short-lived carbon substrate	Long-lived carbon substrate	

Table 6-2. Remediation Technology Screening Matrix for Fractured Bedrock Environments

Representative Rock Types / Origin				Hydrogeology			Physical						Containment		Chemical / Biological						
				Transmissivity (Flow)		Matrix Storage	Removal	Thermal	Air Sparge	Vapor & Multiphase Extraction	Surfactant Flushing[1]	LNAPL Recovery	Pump & Treat	Permeable Reactive Barrier	In-Situ Chemical Oxidation		In-Situ Chemical Reduction		In-Situ Bioremediation		MNA
				Matrix	Fracture										Short-lived oxidant	Long-lived oxidant	Short-lived reductant	Long-lived reductant	Short-lived carbon substrate	Long-lived carbon substrate	
Sedimentary Rocks	Chemical	Coal	Bituminous	H	L	H	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
			Anthracite	L	L	L	Y	U	U	Y	U	Y	Y	N	N	N	N	N	N	Y	Y
		Carbonates	Limestone (including Karst)	H	L or H	H	Y	Y	U	Y	U	Y	Y	Y	N	Y	N	Y	N	Y	Y
			Dolomite & Recrystallized Limestone	L	L or H	L	Y	Y	U	Y	U	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
	Clastics		Cemented Sandstone, Conglomerate, & Other Coarse-Grained Rocks	L	H	L	Y	Y	U	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
			Uncemented Sandstone, Conglomerate, & Other Coarse-Grained Rocks	H	L	H	Y	Y	U	Y	N	Y	Y	N	N	Y	N	N	N	Y	Y
			Shale & Mudstone	H	H	H	Y	Y	U	Y	Y	Y	Y	Y	N	Y	N	Y	N	Y	Y
Igneous & Metamorphic Rocks	Extrusives		Tuff / Scoria / Pumice	H	L	H	U	U	U	Y	N	Y	Y	N	N	Y	N	N	N	Y	Y
			Basalt / Rhyolite	L	H	L	U	U	U	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Intrusives		Granites & Other Crystalline Intrusives	L	H	L	U	U	U	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Metamorphics		Foliated Metamorphsics (e.g., Gneiss & Schist)	L	H	L	U	U	U	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
			Unfoliated Metamorphics (e.g., Quartzite, Amphibolite)	L	L	L	U	U	U	Y	N	Y	Y	N	N	Y	N	N	N	Y	Y
Treatment Zone and Phase Considerations			Vadose Zone	NAPL			Y	Y	N	Y	Y	N	N	N	Y	Y	N	N	N	N	N
				Matrix Storage (sorbed mass)			Y	Y	N	Y	N	N	N	N	N	Y	N	N	N	N	Y
				Vapor phase			Y	Y	N	Y	N	N	N	N	N	Y	N	N	N	N	Y
			Saturated Zone	NAPL			U	Y	N	N	Y	Y	N	N	Y	Y	Y	Y	Y	Y	N
				Matrix Storage (sorbed mass)			U	Y	N	N	N	N	N	N	N	Y	N	Y	N	Y	Y
				Dissolved phase			U	Y	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
				Vapor phase (dissolved gas)			U	Y	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y

* This table is for general technology screening only. Technology selection must be based upon careful review of site-specific conditions.

1. Surfactant use in bedrock presents a high degree of uncertainty and was not recommended as a fractured bedrock remediation technology in previous ITRC guidance (ITRC, 2003). However, some case studies have demonstrated success with fractured bedrock sites in some scenarios.

H = High
L = Low

Y = Yes, generally applicable remediation technology
U = Unlikely to be applicable remediation technology
N = No, generally not applicable remediation technology

Technology Screening Matrix

MISSOURI WASTE CONTROL COALITION

INTERSTATE TECHNOLOGY REGULATORY COUNCIL ITRC

General technology applicability

Table 6-2. Remediation Technology Screeni

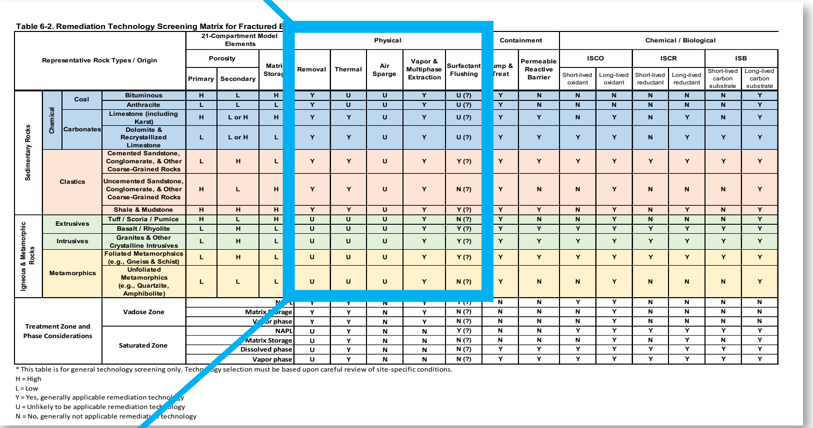
Representative Rock Types / Origin				Physical: Removal	Physical: Thermal	Physical: Air Sparge	Physical: Vapor & Multiphase Extraction	Physical: Surfactant Flushing
Sedimentary Rocks	Chemical	Coal	Bituminous	Y	U	U	Y	U (?)
			Anthracite	Y	U	U	Y	U (?)
		Carbonates	Limestone (including Karst)	Y	Y	U	Y	U (?)
			Dolomite & Recrystallized Limestone	Y	Y	U	Y	U (?)
	Clastics		Cemented Sandstone, Conglomerate, & Other Coarse-Grained Rocks	Y	Y	U	Y	Y (?)
			Uncemented Sandstone, Conglomerate, & Other Coarse-Grained Rocks	Y	Y	U	Y	N (?)
			Shale & Mudstone	Y	Y	U	Y	Y (?)
Igneous & Metamorphic Rocks	Extrusives		Tuff / Scoria / Pumice	U	U	U	Y	N (?)
			Basalt / Rhyolite	U	U	U	Y	Y (?)
	Intrusives		Granites & Other Crystalline Intrusives	U	U	U	Y	Y (?)
	Metamorphics		Foliated Metamorphsics (e.g., Gneiss & Schist)	U	U	U	Y	Y (?)
			Unfoliated Metamorphics (e.g., Quartzite, Amphibolite)	U	U	U	Y	N (?)

Example: Physical Removal

Y = Generally applicable

N = Not generally applicable

U = Unlikely applicable



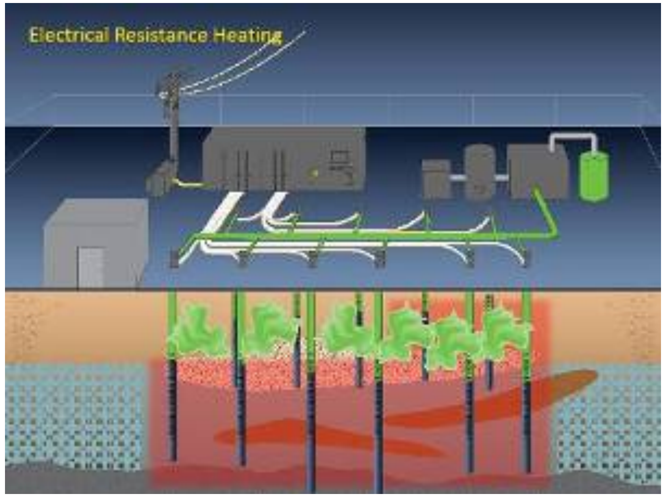
Physical Technologies

Removal

- Limited to unsaturated, “soft” or weathered rock
- Good for high matrix storage and primary porosity

Thermal Methods

- Includes steam-enhanced extraction (SEE), electrical resistance heating (ERH), thermal conduction heating (TCH)
- Different methods have individual advantages and disadvantages for different types of rock
  - e.g., steam would be more effective in crystalline rock than ERH as ERH passes electric current through water so is more effective in rock with higher primary porosity

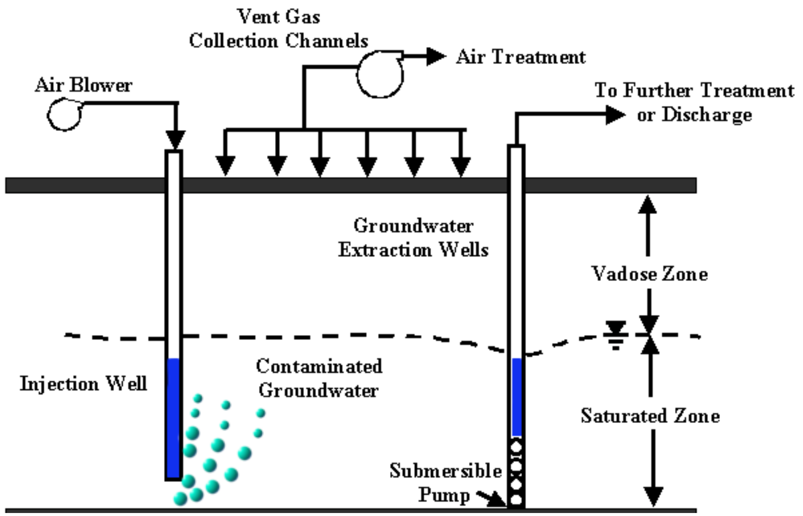


[1]Kingston et al, 2010

Physical Technologies

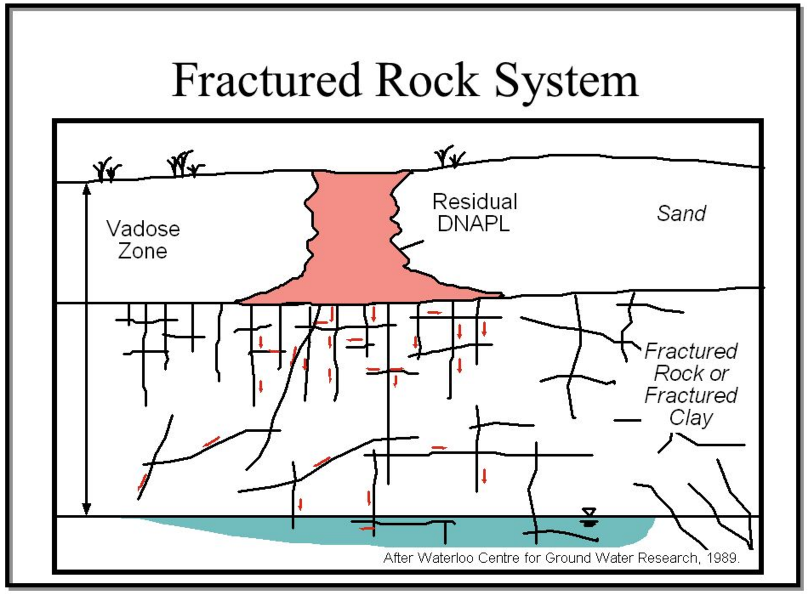
Air Sparge

- May be limited by bubble blockage in fractures
- Will be limited as it can dewater fractures very quickly



Vapor and Multiphase Extraction

- Both commonly applied in bedrock
- Design more challenging due to discrete fracture control of vapor and fluid migration
- Commonly coupled with other technologies
  - Component of thermal methods
  - Coupled with peroxide ISCO for of gas control



Physical Technologies

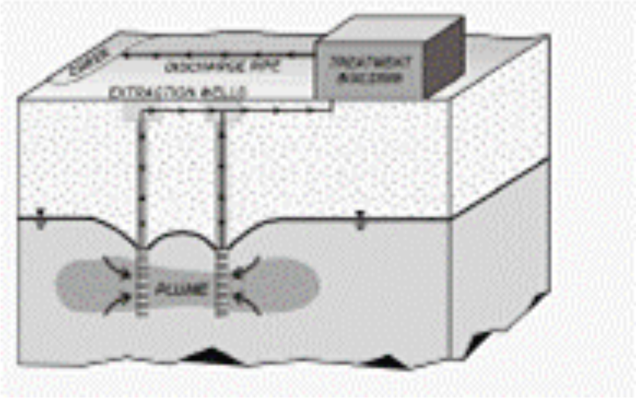
- Surfactant / Cosolvent Flushing
  - Challenging due to heterogeneous fluid flow
    - Preferential migration through transmissive, large-aperture fractures
    - Little or no contact with NAPL in less-transmissive fracture zones, primary porosity, or matrix storage

ITRC (2003) recommended against application of surfactants or cosolvents in fractured rock aquifers.

Containment Technologies

Pump and Treat

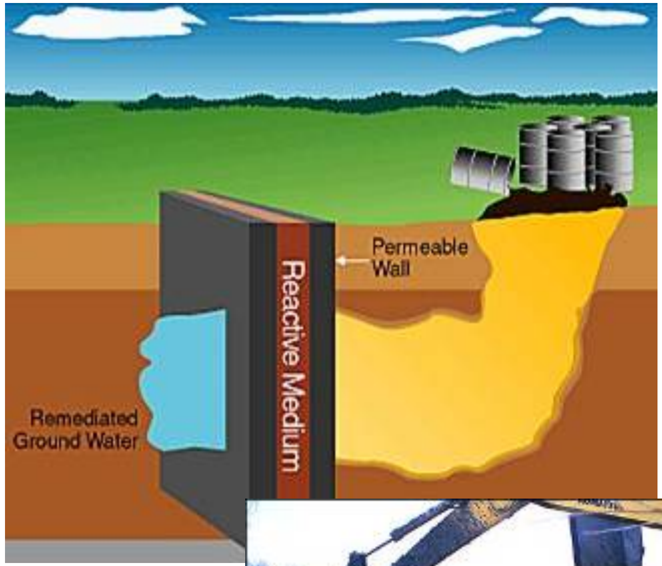
- Widely applied, but special rock considerations
  - Primary and secondary porosity domains
  - Fracture orientations
  - Multiple intersecting fracture sets
  - Dead-end fractures
  - Communication with overburden or weathered bedrock
  - Contaminant diffusion into secondary porosity



- Generally an inefficient technology for mass removal, more effective for containment, can be optimized with flexible extraction network

Containment Technologies: Permeable Barriers

- Accurate fracture identification and depth resolution are critical
  - Target transmissive, water-bearing fractures
  - Careful coring and logging to identify depths
  - May be ineffective if a transmissive fracture is missed
- Injected media may affect fluid flow
- PRBZ technologies most applicable to sites with significant secondary porosity

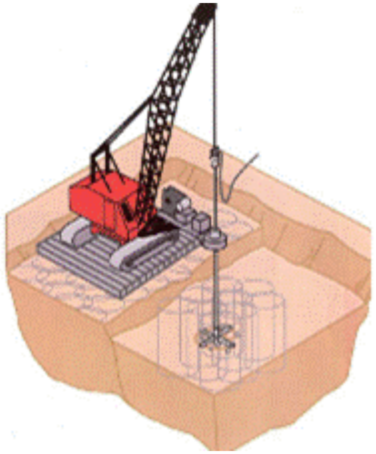


[1]Liang et al., 2010
[2]U.S EPA, 1998

Chemical and Biological Technologies

In-Situ Chemical Oxidation (ISCO) and In-Situ Chemical Reduction (ISCR)

- Geologic oxidant or reductive demand is generally lower than in unconsolidated materials
  - Distribution to transmissive secondary porosity rather than primary porosity
- Fracture orientation and density-driven flow
- If oxidant lifetime is short, back diffusion from primary porosity can create rebound
- Long-lived oxidants diffusively penetrate rock
- NAPLs tough to get at



[1]Krembs et al., 2010
[2]Olsen and Sale, 2009

Chemical and Biological Technologies

Bioremediation and Monitored Natural Attenuation

- Widely applied technologies taking advantage of natural phenomena
- Reagent distribution challenges like ISCO & ISCR
- Consideration of microbial distribution between groundwater and primary porosity, and biofilms
- Ability of microbes to migrate into and survive within primary porosity is not well known.
- MNA is often the transitional technology following active remediation

Combined Remedies

- Remedial paradigm has shifted to accept that combined remedies is almost always necessary
  - Emphasize strengths, minimize weaknesses
  - ISCO may kill bugs necessary for bio or MNA, while thermal may enhance bug activity
- Rock often requires development and/or modification of standard overburden approaches
- Spatial and/or temporal separation
- Requires careful designs to consider both positive and negative interactions between technologies
- The 21-Compartment Model may help develop and communicate combined remedy strategies

Chemical Technology – A Case Study

MISSOURI WASTE CONTROL COALITION

INTERSTATE TECHNOLOGY REGULATORY COUNCIL ITRC

TCE and Hex Chrome Bedrock Site

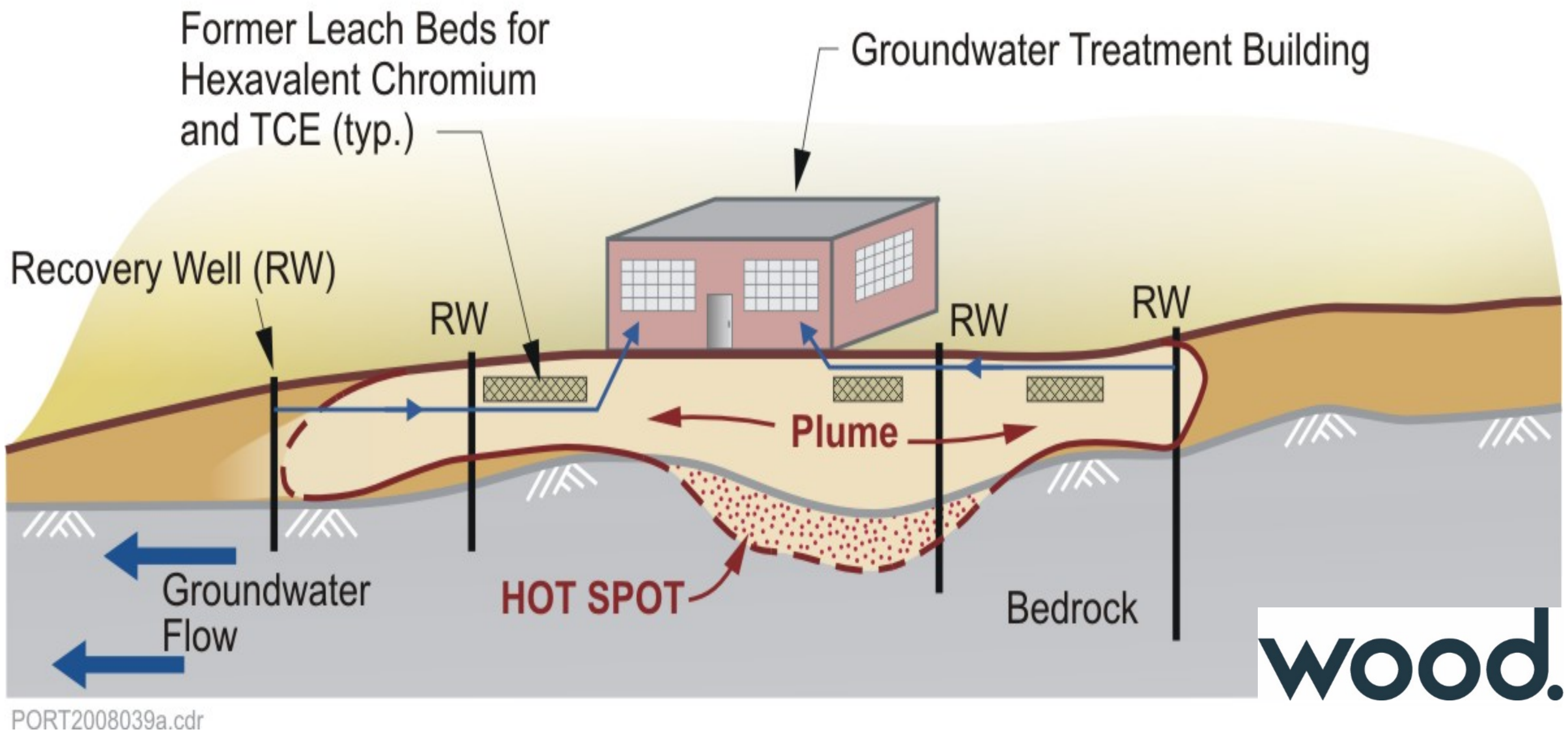
Circuit Board Manufacturing

Classic Back Door Disposal

Lessons Learned in Undesirable Side-Effects

Chemical Technology – Case Study

CSM

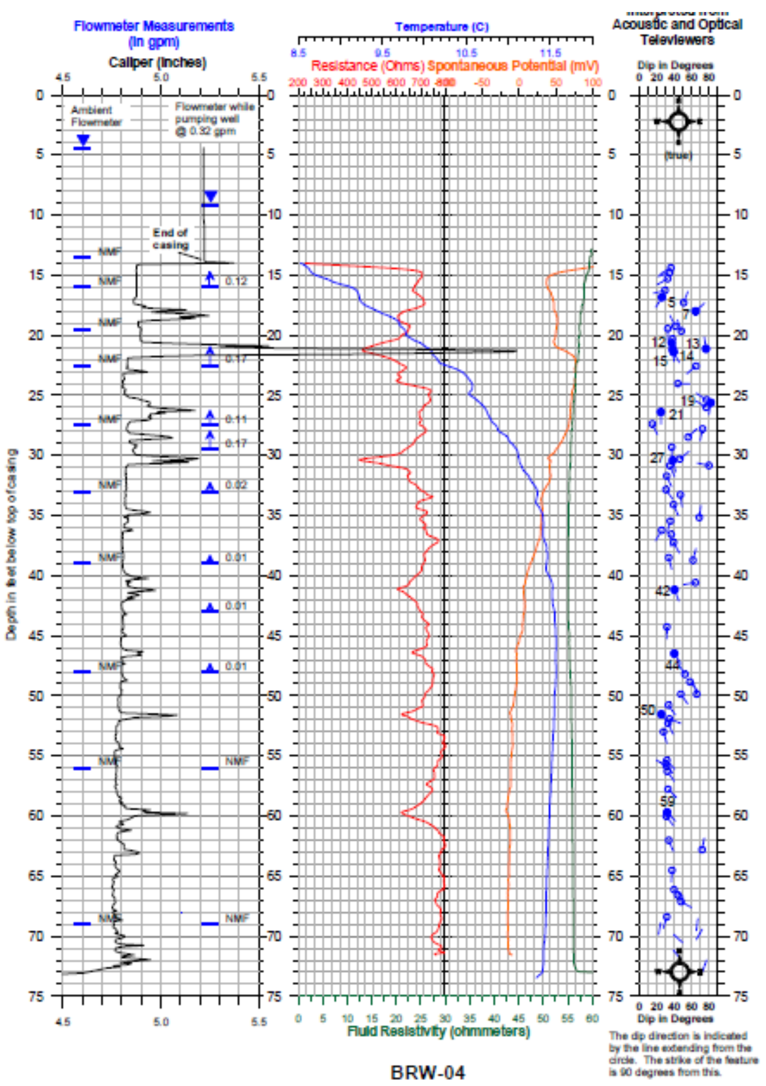


Wastewater discharged to several leach beds

Waste TCE dumped out the back door

Early CSM simplified distribution to shallow bedrock

Chemical Technology – Case Study



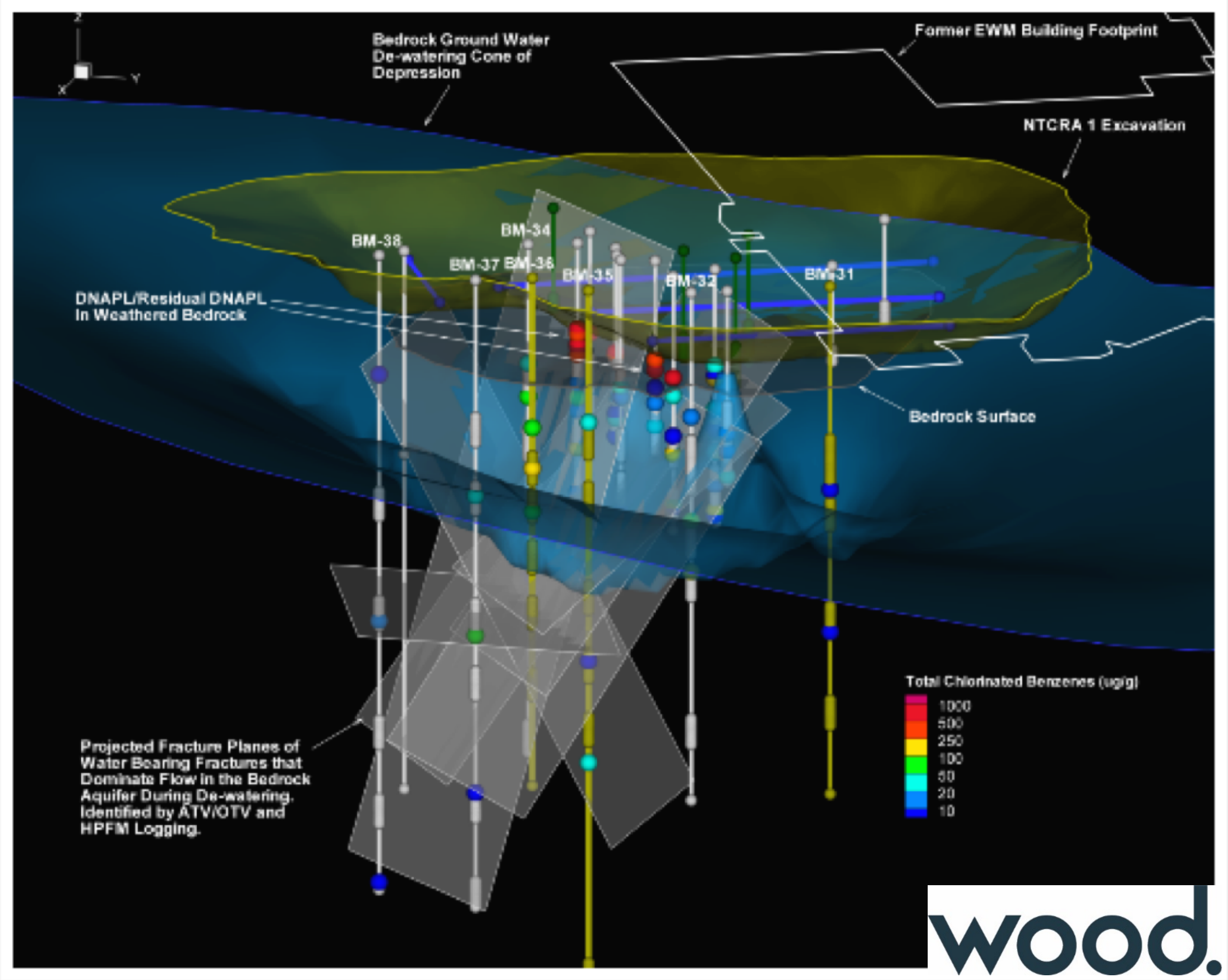
Borehole Geophysics to map structures

High-resolution sampling to map TCE source

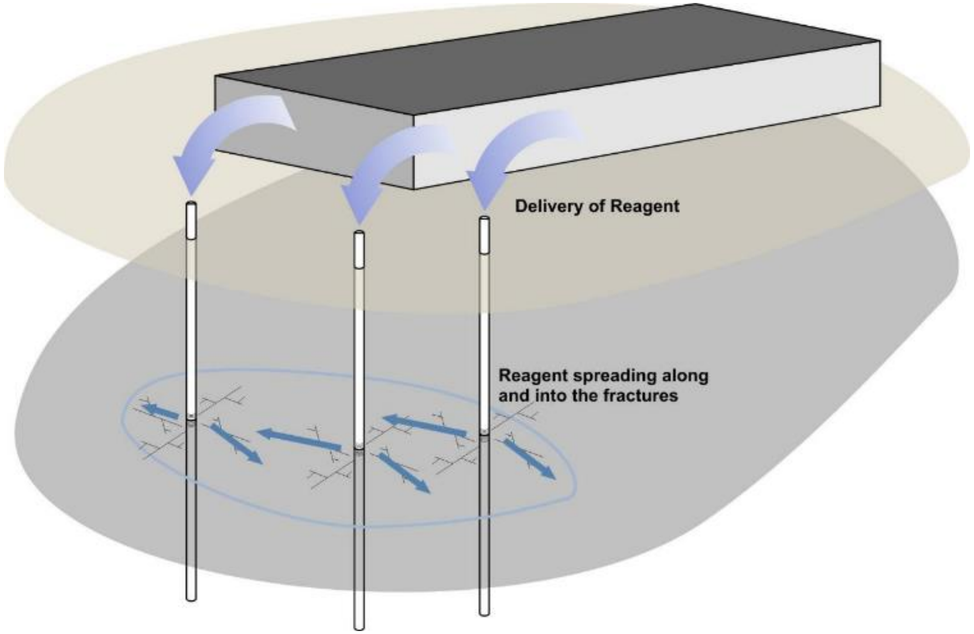
Chemical Technology – Case Study

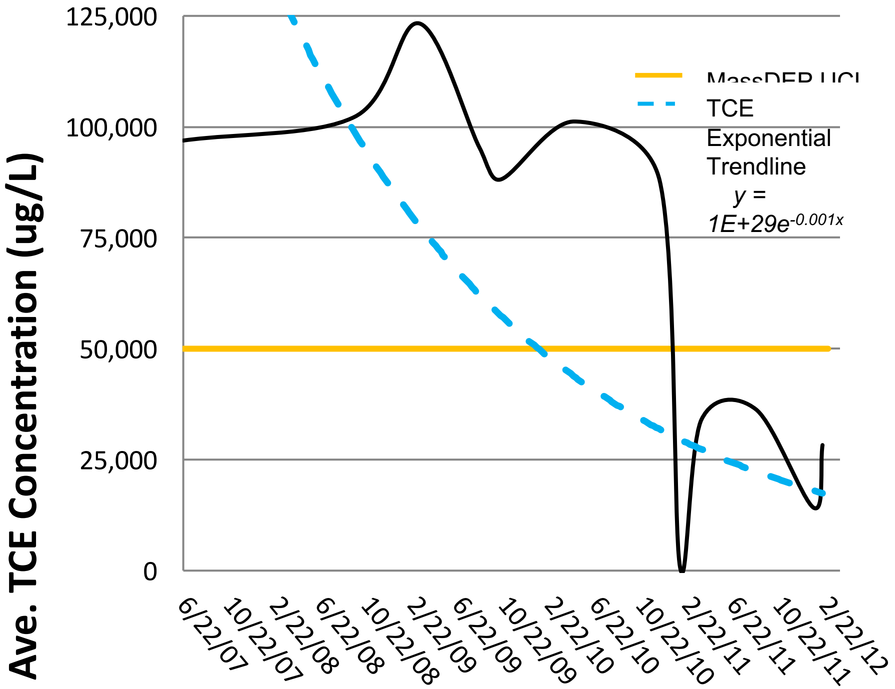
Borehole geophysics to:

- **Define fracture network**
- **Identify hydraulically significant fractures**
- **Map fractures between boreholes**
- **Design tracer test**
- **Design injection strategy**



Chemical Technology – Case Study





Sodium persulfate first delivered via trenches

Major increase in Cr+6

Changed delivery to deep wells

Added ISCR to mitigate oxidation

TCE Reduction > 2 Orders of Magnitude

Bench and Field Pilot Test Considerations

- **Bench and field pilot tests provide relevant data**
  - Treatability, rock-chemistry interaction, reagent distribution, and overall effectiveness
- **Relevant differences from overburden include**
  - The rock surface area exposed to groundwater, contaminants, and reagents is very different
    - Using crushed rock for bench tests may not be an appropriate surrogate for full-scale treatment.
  - Fracture-controlled groundwater flow can be much faster than in granular overburden – implications for reaction kinetics

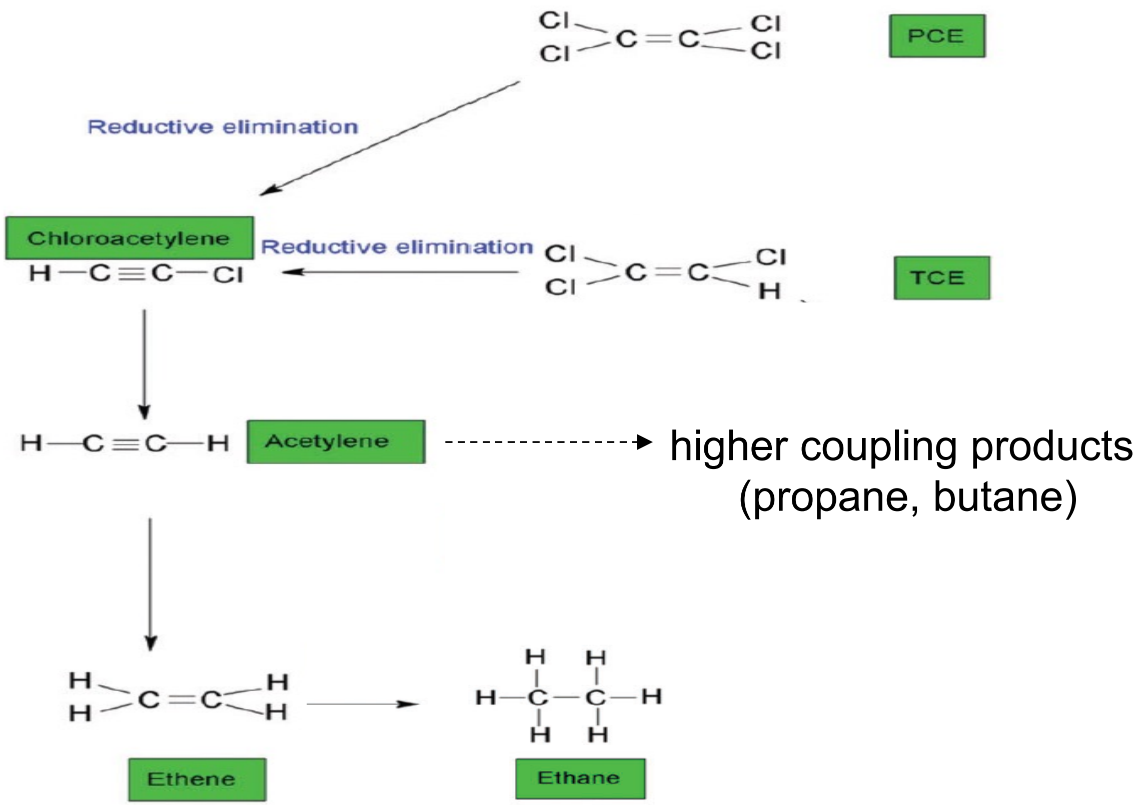
Overview of the Training

- Introduction
- Fractured Rock CSM Considerations
- Fracture Characteristics of Geologic Terrane
- Fracture Flow & Contaminant Fate and Transport
- Fractured Rock Characterization
- Remedy Development
- **Monitoring**
- Summary

Abiotic Dechlorination via Ferrous Minerals

Ferrous Minerals

Anaerobic Conditions

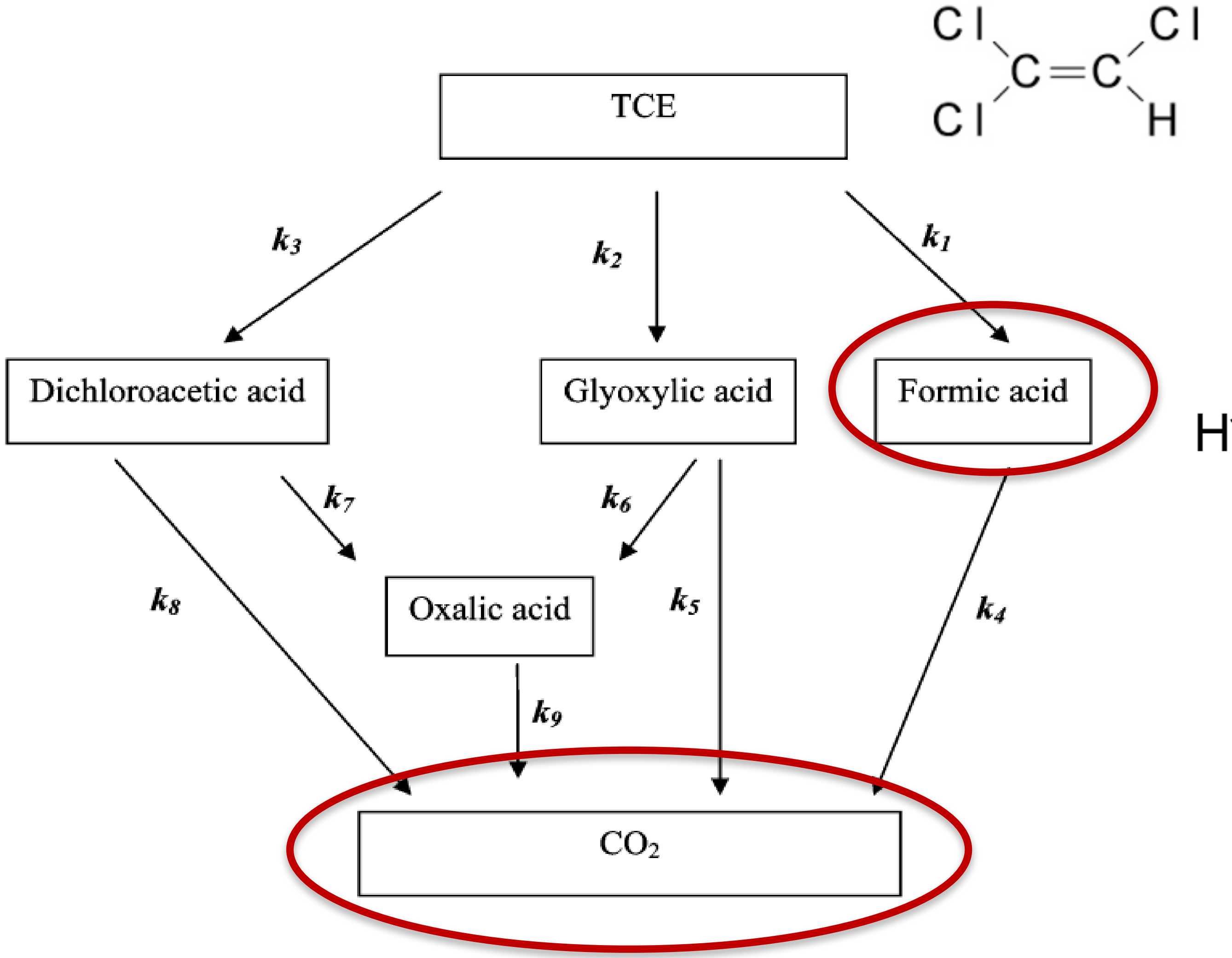


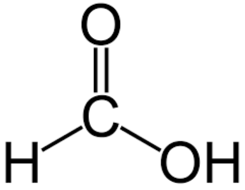
- **FeS**
- **Pyrite (FeS_2)**
- **Magnetite (Fe_3O_4)**
- **Green rusts**

Modified from He et al., *GWMR,* 2015 and Elsner et al., *ES&T,* 2008; slides courtesy C. Schaefer

Abiotic Dechlorination via Pyrite Minerals

Aerobic Conditions



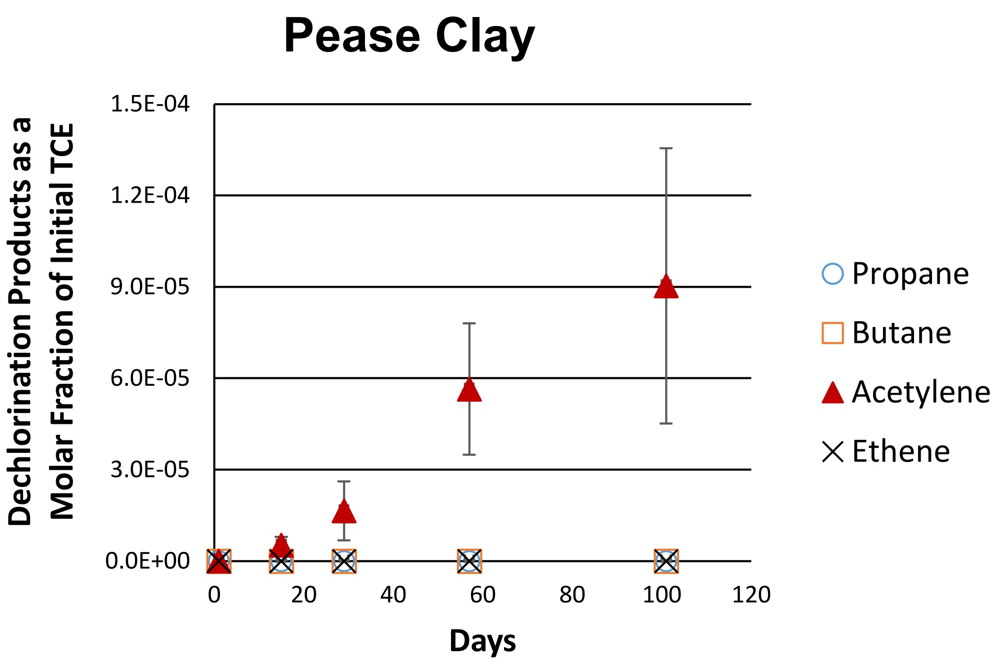


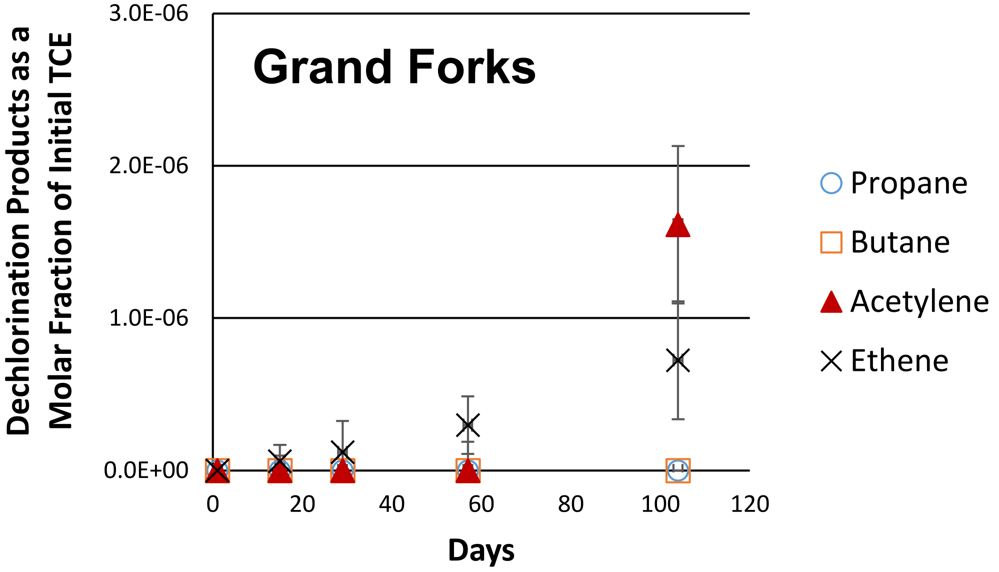
from Pham et al., *ES&T,* 2009

Test Soils

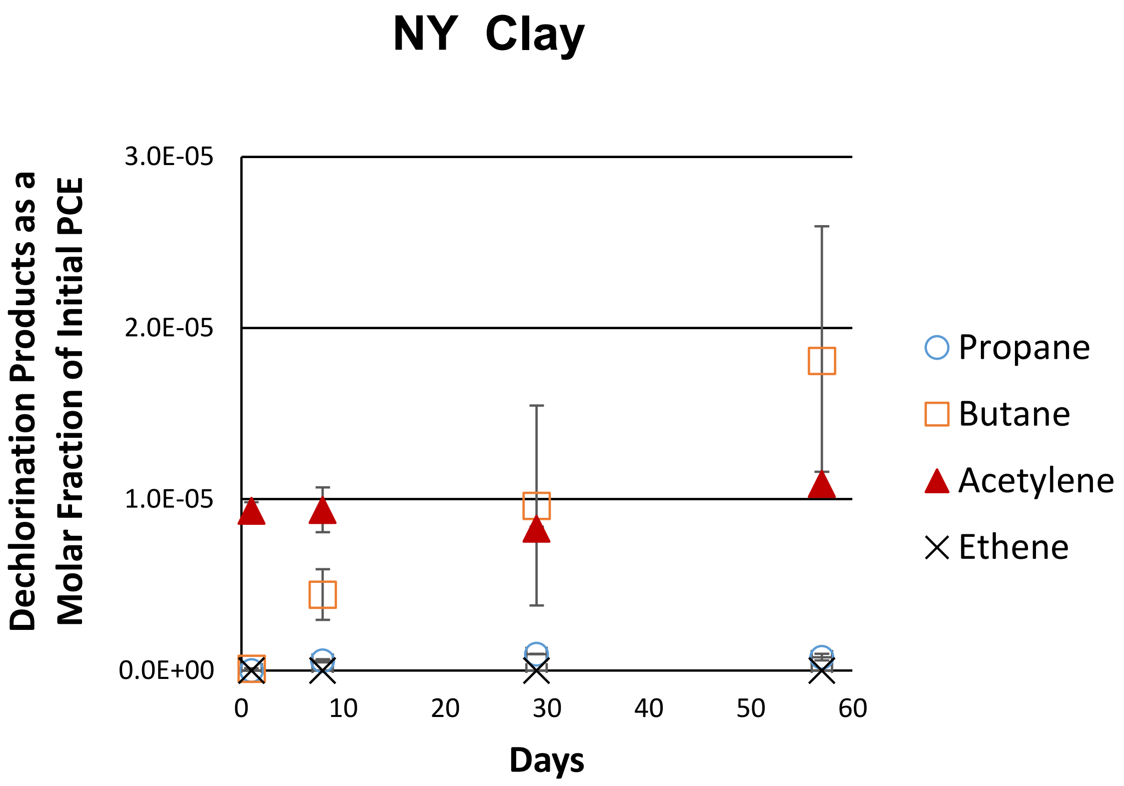
Soil	Ferrous Iron (mg/kg)	Magnetic Susceptibility (m^3/kg)	Ferrous Minerals Present (XRD analysis)
PR Clay	4.3	1.1×10^{-5}	Antigorite
NY Clay	4200	6.7×10^{-7}	Chlorite, Riebeckite
Pease Clay	2570	3.9×10^{-7}	Chlorite, Siderite, Ankerite
Pease Sand	45	6.1×10^{-7}	Magnetite, Siderite, Ankerite
Grand Forks	160	3.5×10^{-7}	Chlorite, Siderite, Ankerite

Results: Anaerobic Transformation Products



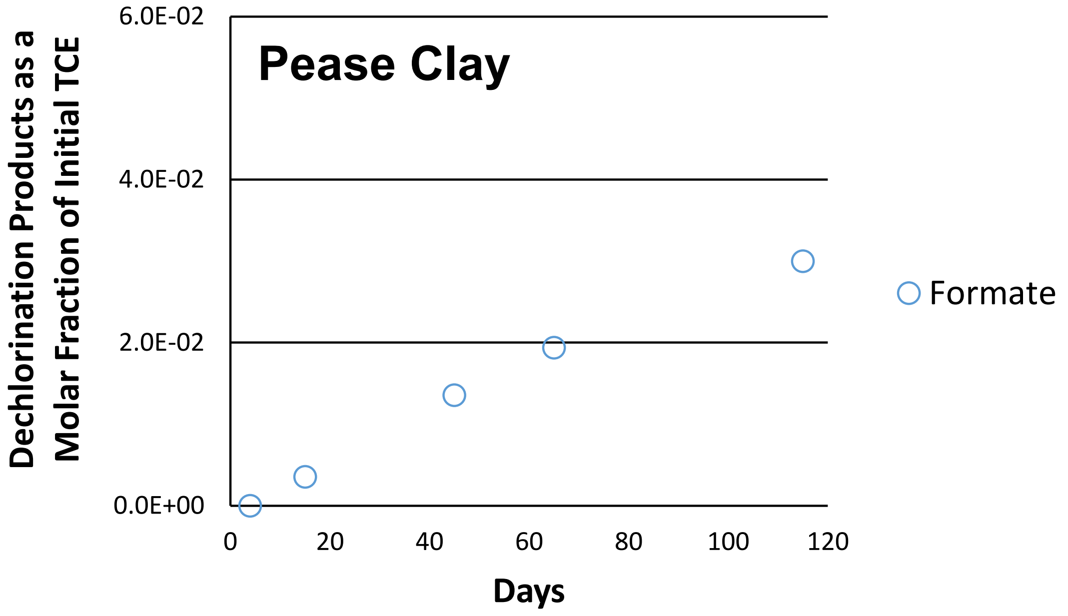


Results: Anaerobic Transformation Products

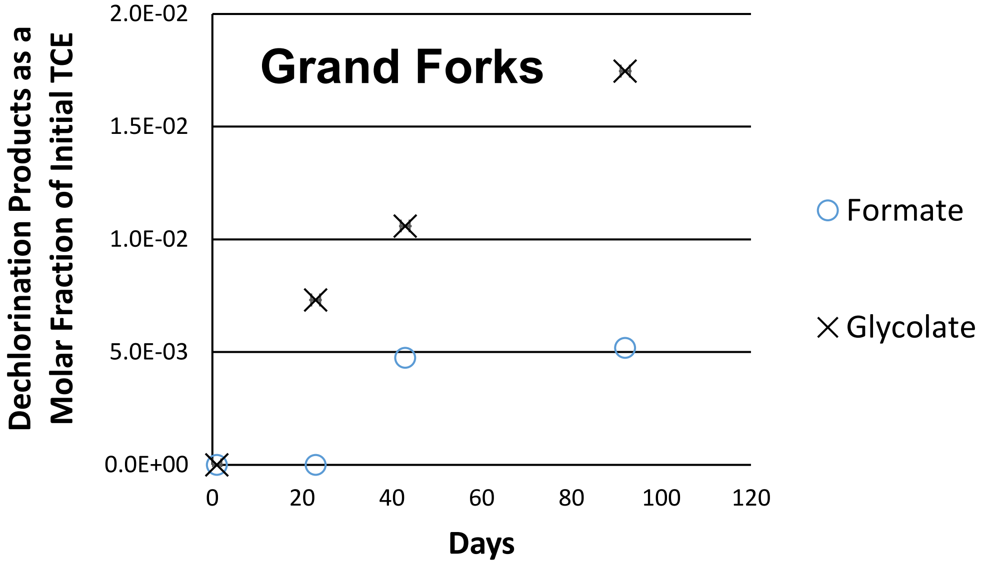


Propane observed as TCE abiotic transformation product in prior studies using bedrock

Results: Aerobic Transformation Products



CO_2 generation from TCE was below detection



First-Order PCE/TCE Transformation Rate Constants

Anaerobic

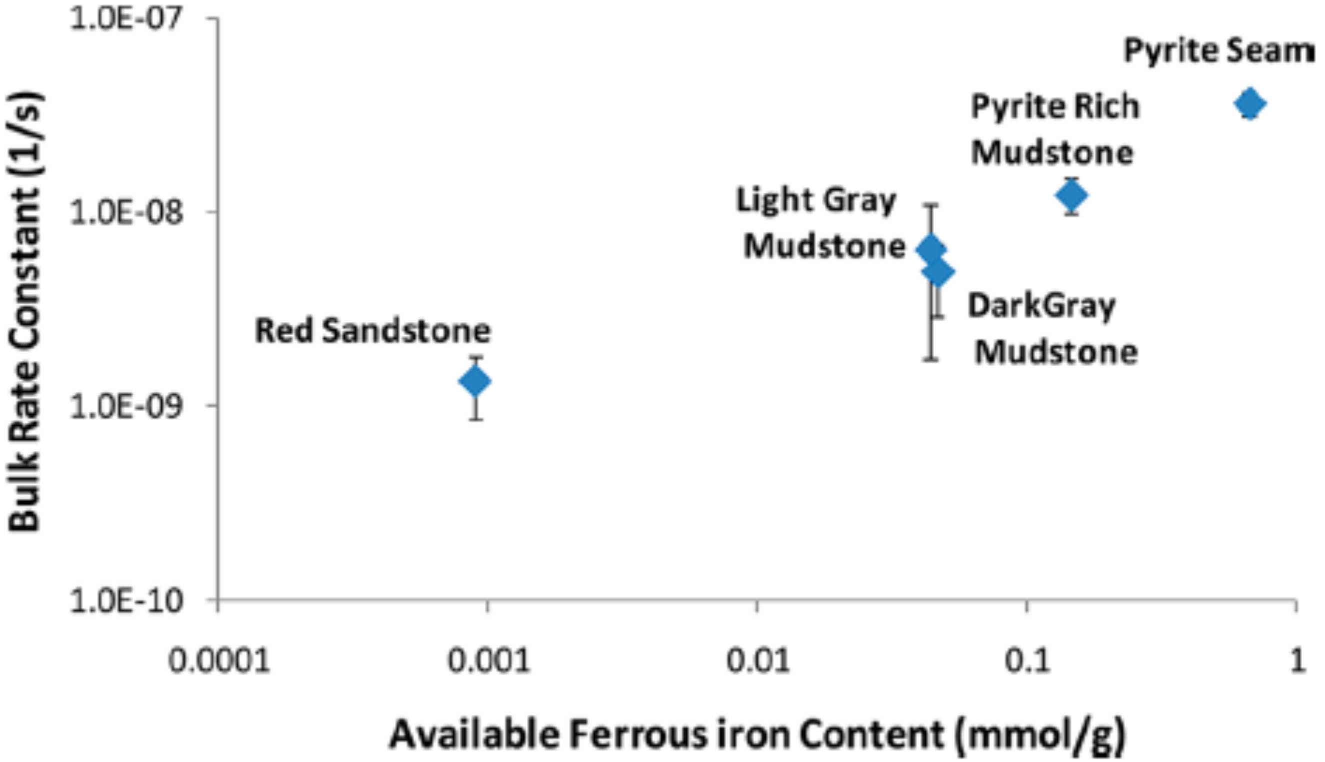
Soil	k (day^{-1})	R^2
PR Clay	~0	-
NY Clay	8.3 ± .41 x 10^{-7}	0.98
Pease Clay	8.9 ± .02 x 10^{-7}	0.97
Pease Sand	~0	-
Grand Forks	1.7 ± .40 x 10^{-8}	0.76

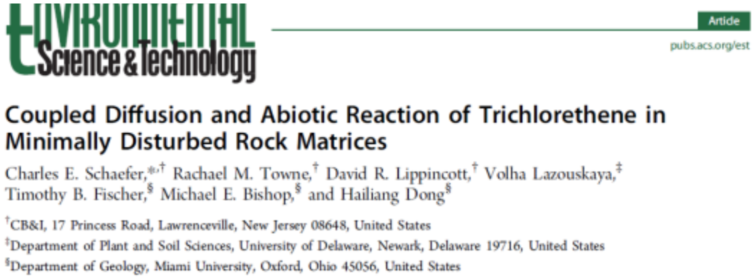
Aerobic rate constants are much greater than the anaerobic rate constants

Aerobic

Soil	k (day^{-1})	R^2
Pease Clay	2.8 ± .07 x 10^{-4}	0.99
Pease Sand	~0	-
Grand Forks	2.7 ± .24 x 10^{-4}	0.93

Rate Constants Related to Ferrous Iron Content




Environmental Science & Technology
Article
pubs.acs.org/est

Coupled Diffusion and Abiotic Reaction of Trichlorethene in Minimally Disturbed Rock Matrices

Charles E. Schaefer,*,† Rachael M. Towne,† David R. Lippincott,† Volha Lazouskaya,‡ Timothy B. Fischer,§ Michael E. Bishop,§ and Hailiang Dong§
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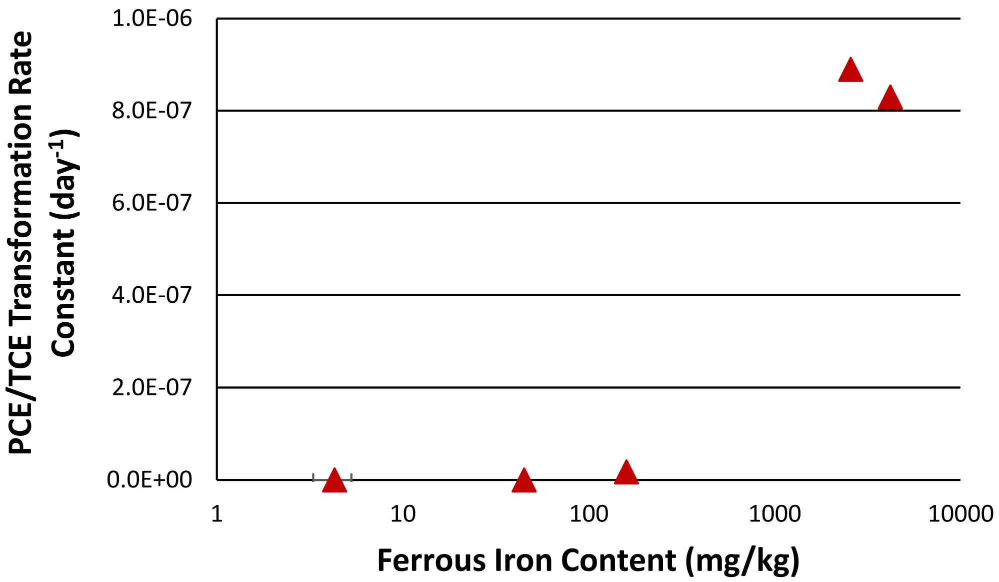
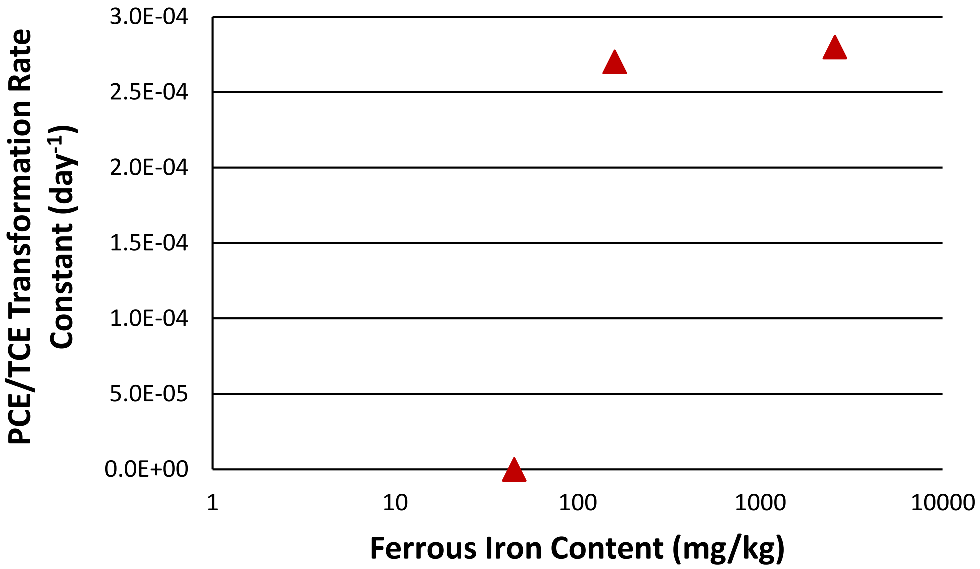
Rate Constants Related to Ferrous Iron Content

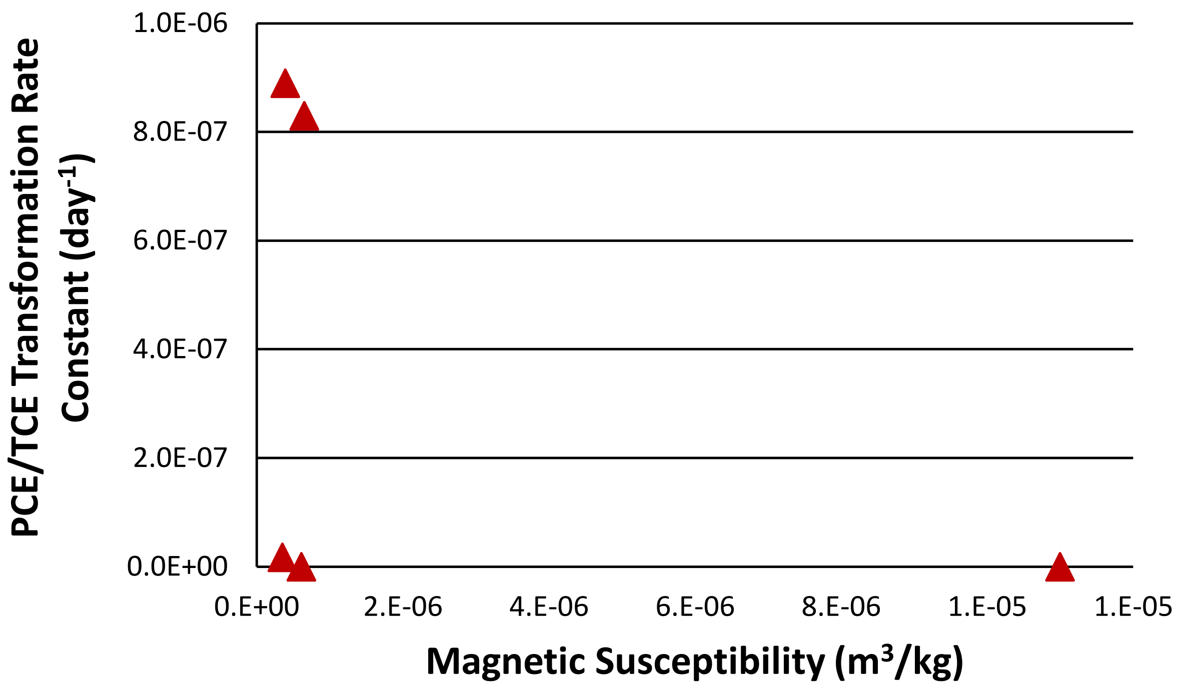
Anaerobic



Aerobic



How About Magnetic Susceptibility?

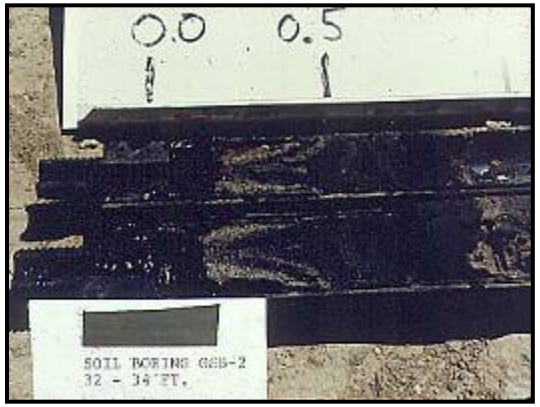


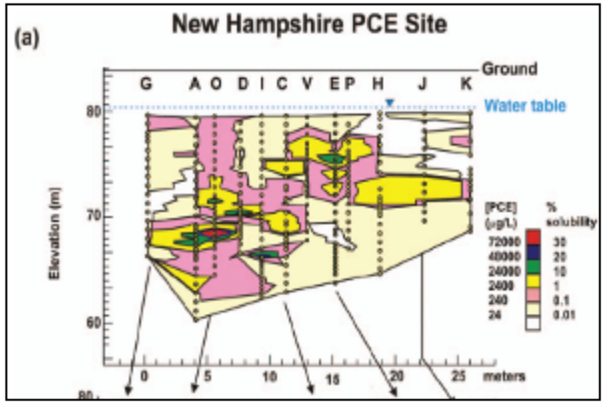
Characterization and Remediation of Fractured Rock: Monitoring

Objective:

Develop a groundwater monitoring strategy for your fractured rock site taking into account:

- Results of the site characterization,
- Informational needed to ensure that the selected remedial strategy attaining site-specific cleanup goals





Characterization and Remediation of Fractured Rock: Monitoring

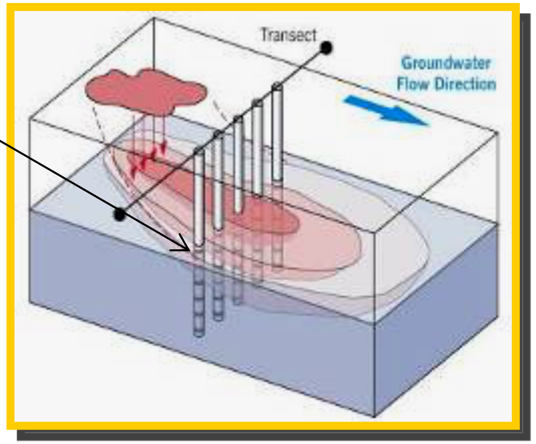
Monitoring has several important functions:

- Determining baseline conditions
- Establishing trends
- Understanding the fate and transport of contaminants
- Assessing the performance of a remedial system
- Demonstrating compliance with ROAs and standards

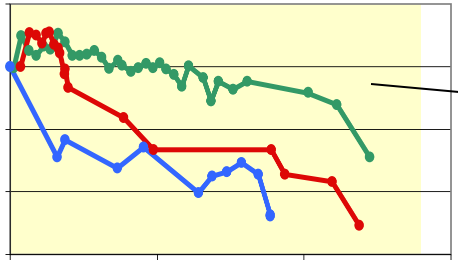
Monitoring efficiently and effectively is the challenge

Type of Monitoring

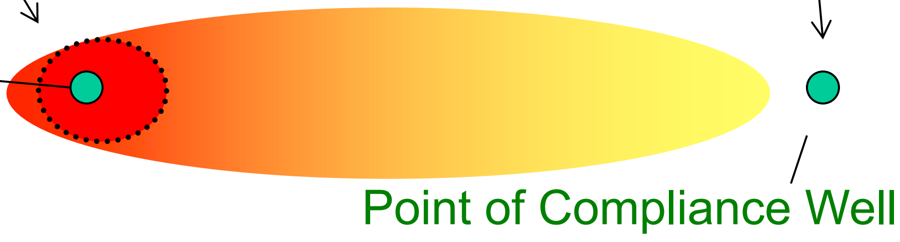
- **Performance Monitoring**
  - At end of the day, did it work?
  - Compare to SMART functional objectives



- **Process Monitoring**
  - We turned it on – is it working correctly?
  - Data used to optimize system



- **Compliance Monitoring**
  - How are we compared to regulatory limits?
  - Is everyone safe?



Media to Monitor

- Subsurface gas
  - Monitory migration and/or degradation of contaminants in the fractured rock.
- Groundwater
  - Monitor concentrations of dissolved contaminants and water level elevation data are needed to monitor groundwater flow.
- Surface Water
  - Monitor groundwater discharge, surface water quality and impact to groundwater
- Aquifer Matrix Materials
  - Groundwater or subsurface vapor monitoring data are indicators of conditions in the aquifer matrix materials

All of these media have associated exposure Pathways:

- Vapor intrusion/IAQ
- Drinking water
- Consumption of water and organisms
- Benthic community
- Terrestrial and aquatic receptors

Characterization and Remediation of Fractured Rock: Monitoring

Monitoring Network Design

- Characteristics of the rock type(s) at the site
  - Igneous, sedimentary, metamorphic.
- Fracture network and bedding orientation and lateral extent
  - Need data from multiple wells.
- Role of hydrogeochemical zoning
  - Minerals may release metals into solution
- Receptors
  - Identify, confirm, monitor potential/confirmed human and ecological receptors
- Overburden and other media
  - Most sites present a combined bedrock/overburden environmental challenge
  - Other media provide clues to bedrock behavior

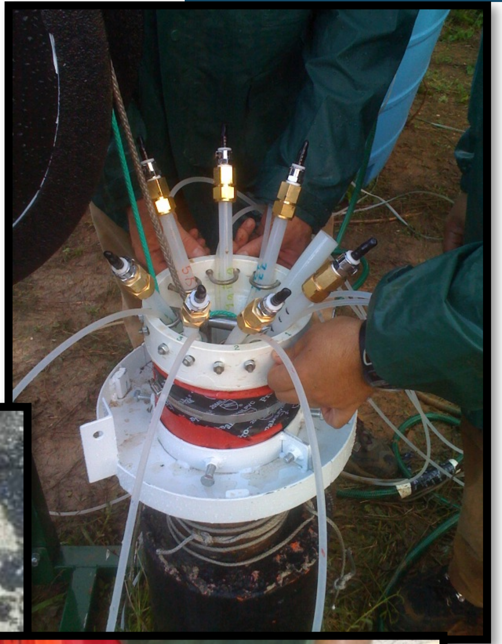
Monitoring Locations

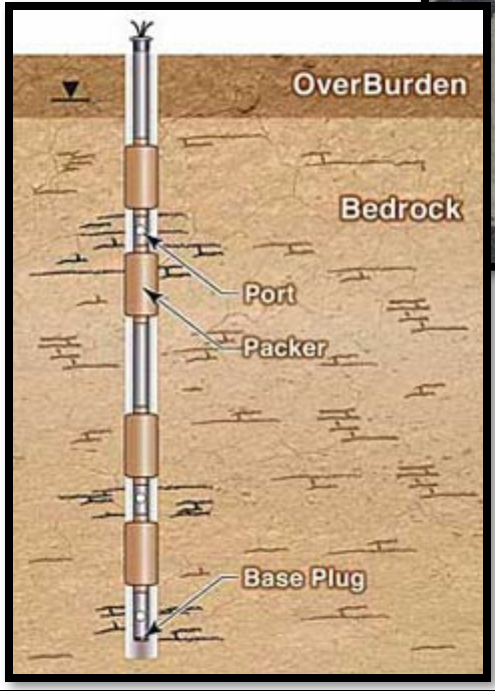
- Selection of monitoring locations is based on:
  - Fracture network
    - Where are the most transmissive features and what is there orientation?
  - Groundwater gradient and flow direction
    - Where is groundwater, and hence contaminants, flowing?
    - Is flow being refracted by the fracture network or is an equivalent porous media model acceptable?
  - Geochemistry
    - Focus monitoring on fracture zones with site related contaminants.

Characterization and Remediation of Fractured Rock: Monitoring

Monitoring Locations

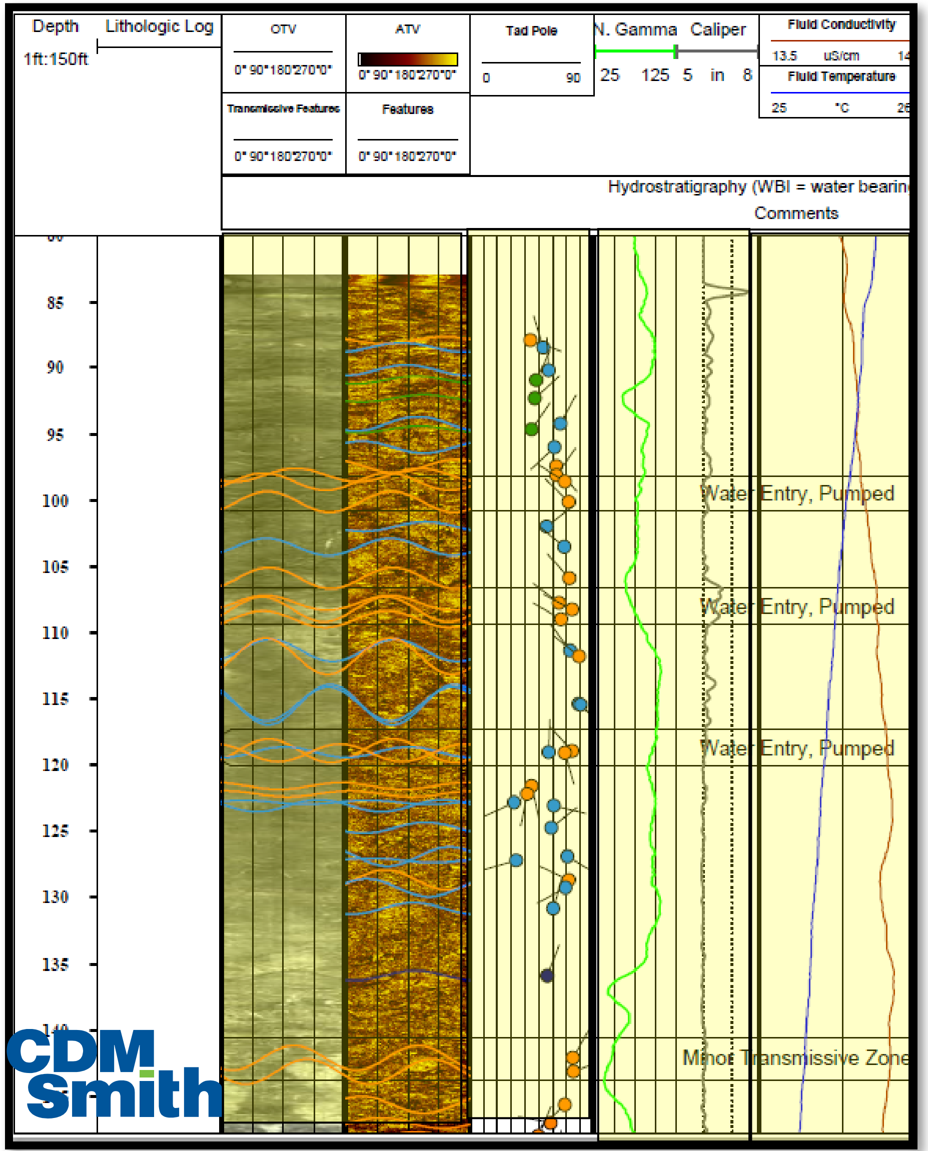
- Source zone wells
- Impacted zone wells
- Up gradient and cross gradient wells
- Flow path wells
- Distal portions and boundaries of the plume
- Sentinel wells.





Borehole Geophysical Logging: Step 1

- **ATV and OTV logs** -characterize lithology and structure.
- **Tad pole plot-** is structure data derived from feature orientation determined from the ATV and OTV.
- **Gamma**- lithology & key stratigraphic features such as marker beds.
- **Caliper**- borehole diameter and is used to process other logs (gamma).
- **Fluid conductivity and temperature-** provide information on fluid entry and exit points in the borehole.



Borehole Geophysical Logging: Step 2

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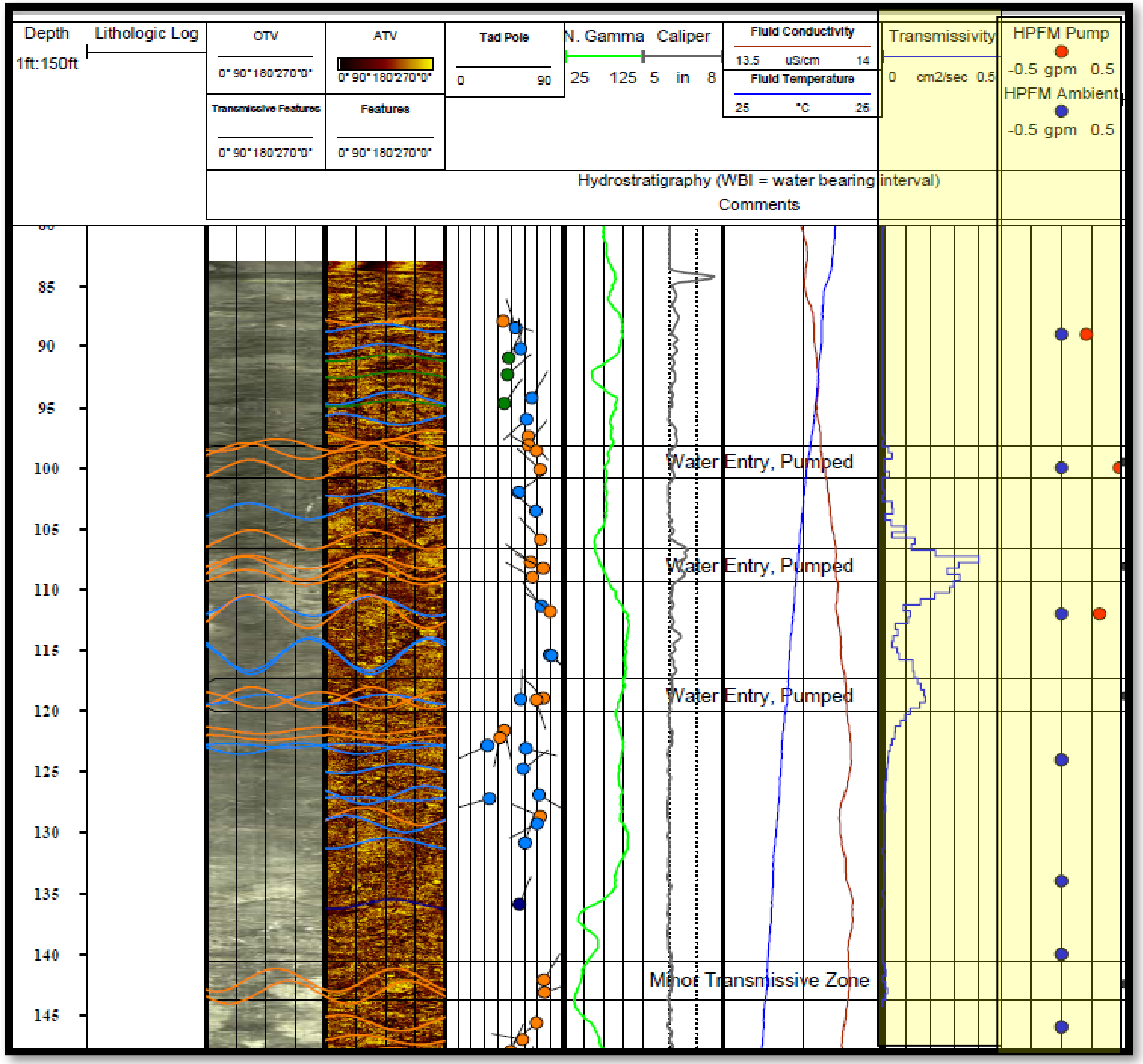
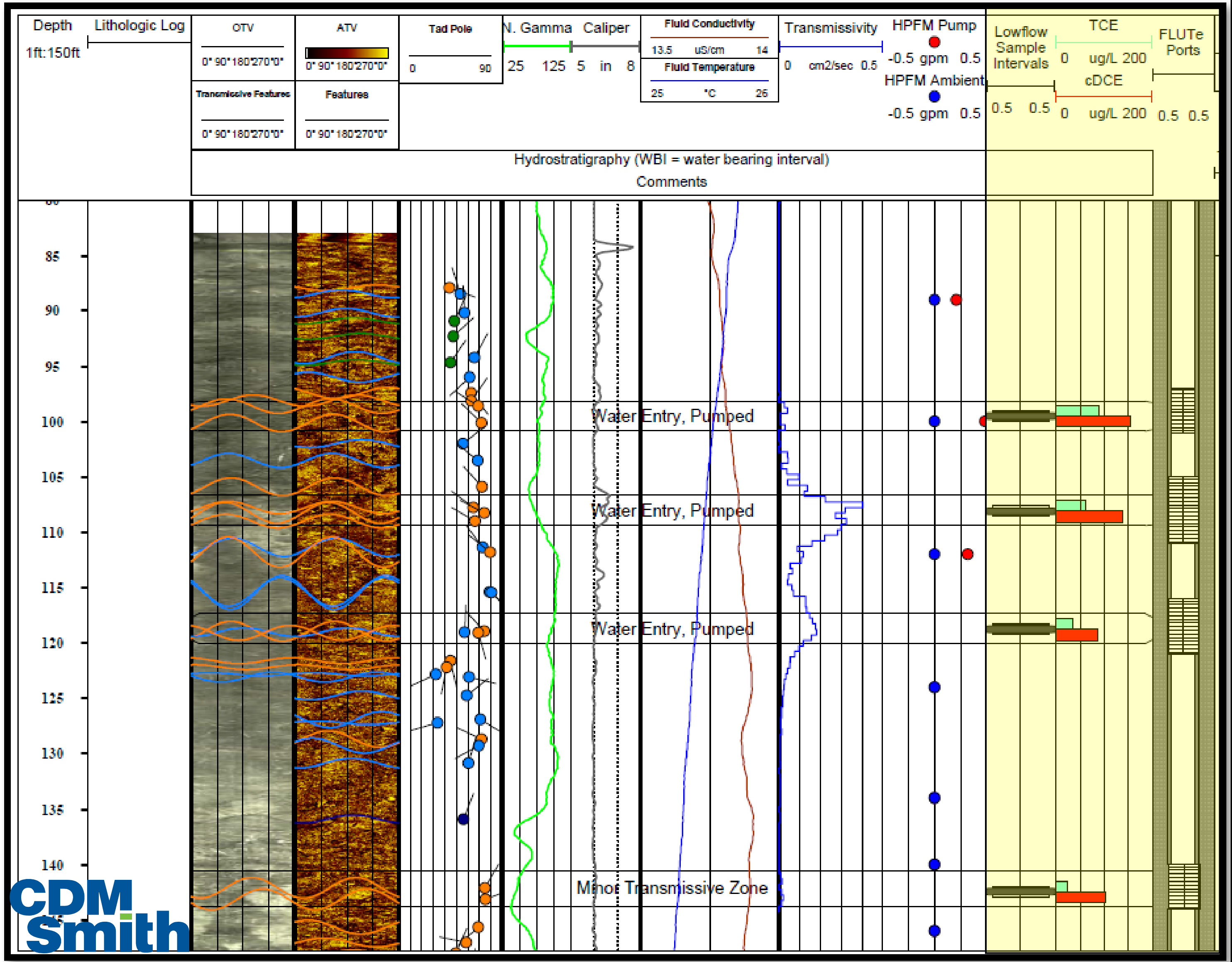
INTERSTATE TECHNOLOGY REGULATORY COUNCIL ITRC

- FLUTe liner drop test generates a profile of transmissivity in the borehole.
- Heat Pulse Flow Meter- evaluates vertical flow



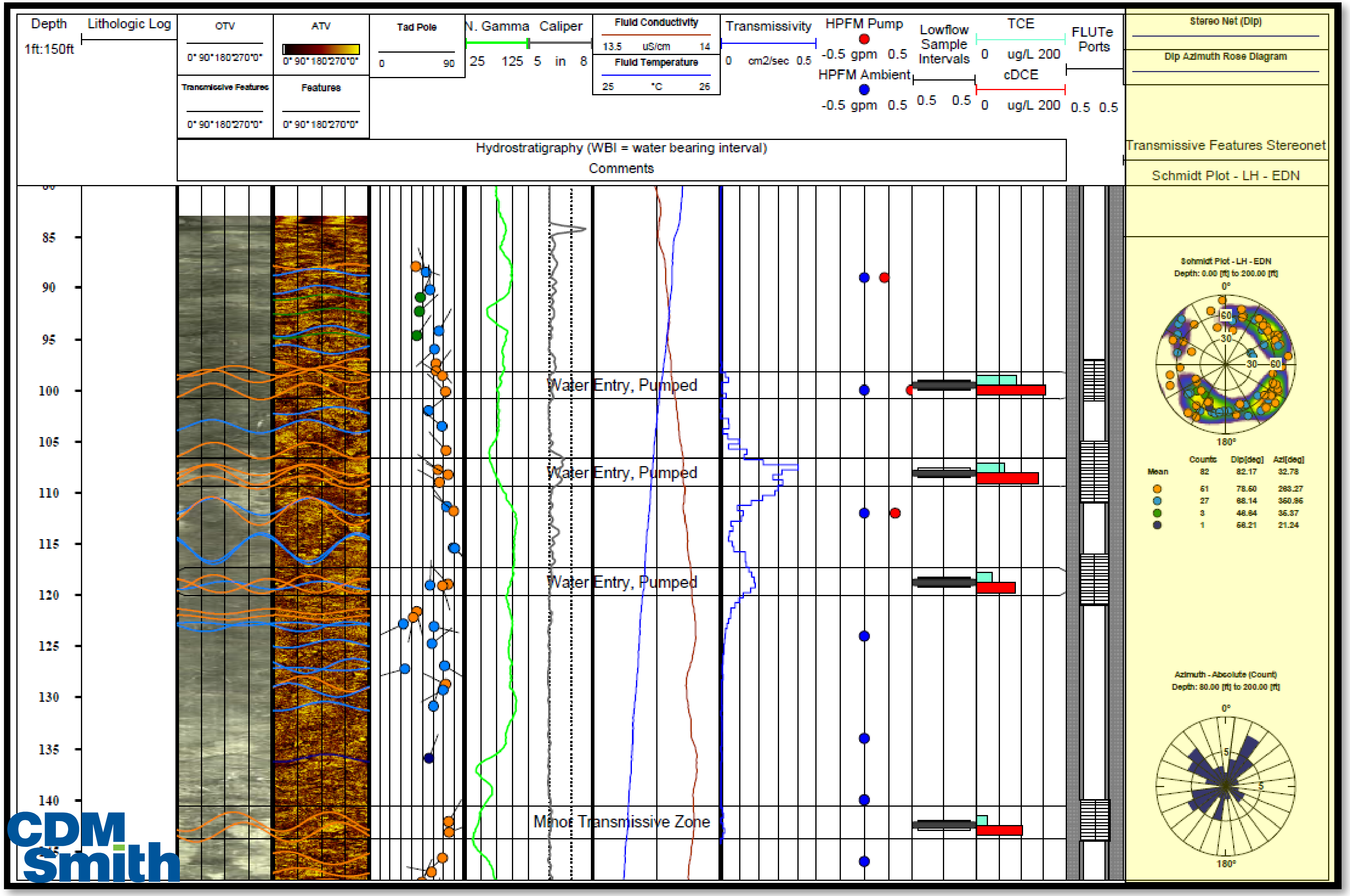
Borehole Geophysics: Step 3

- A grab sampler or packer system- develop a vertical profile of contaminant distribution in the transmissive zones.
- Packer tests can also be run to collect data so that the transmissivity of the interval can be estimated.
- All the results are used to design the multiport well.



Borehole Geophysics: Step 4

- Feature orientation data from the ATV and OTV logs is used to create stereo nets and rose diagrams.
- Multiple boreholes provides site wide data on the orientation of transmissive features and the hydrostratigraphy at the site.



Monitoring Evaluating the Remedy

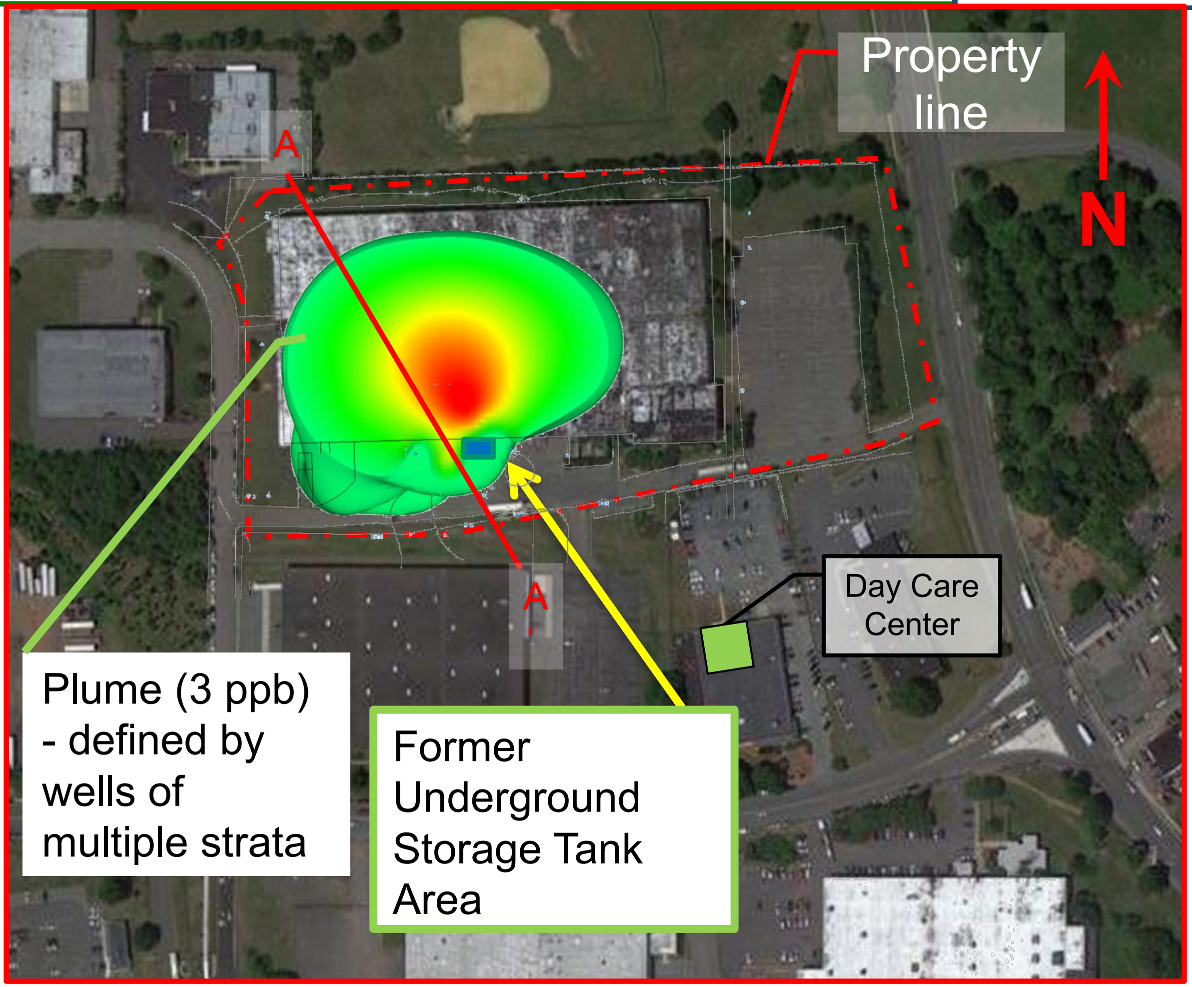
- USEPA guidance "Groundwater Remedy Completion Strategy. Moving Forward with an End in Mind" suggests four elements to an effective remedy evaluation
  - Remedy operation
  - Remedy progress toward groundwater RAOs and associated clean up levels
  - Remedy attainment of RAOs and cleanup levels
  - Other site factors

Case Study

Advanced Diagnostic Tools to Support Monitored Natural Attenuation for DNAPL Plume in Bedrock

Site Operational & Remedial Action History

- Pharmaceutical manufacturing - 1976 to 2005
- Discharge of dichloromethane (DCM)
- DCM reached bedrock groundwater at 25 to 70 feet depth
- Shallow rock wells exhibit highest concentrations - at solubility in source
- Groundwater quality standard - 3 µg/L
- Pump and treat system operation from 1995 to 2009



Surrounding area is industrial to the west and south. Commercial and residential areas to the east. Sensitive receptor to the south.

Site Remedial Strategy

1 … ng

2

3

4 … e.

5

6

Must Demonstrate:

1. a ***stable source*** that is ***contained*** with MNA and

2. contaminants are being ***completely degraded to innocuous end products***.

- Require robust CSM to support passive groundwater remedy

Advanced Characterization Tools

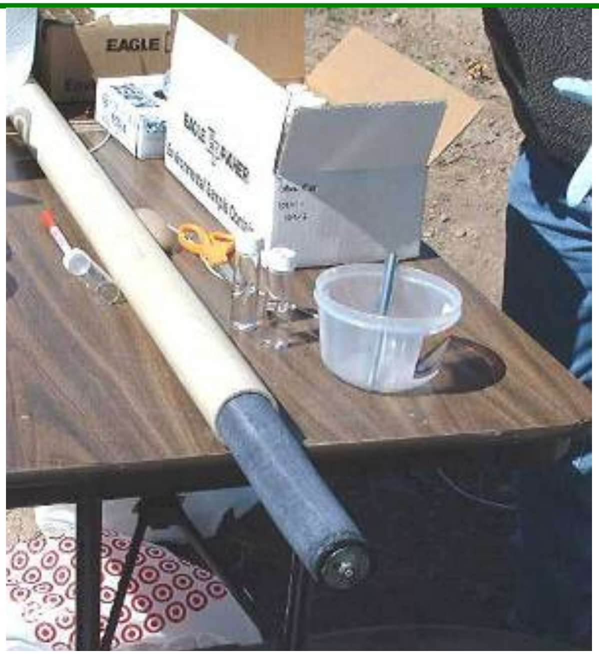
Informational Need	Characterization Tool
Source Zone Architecture and Impact of Diffusion	Rock core analysis and diffusion modeling
Contaminant and Groundwater Flux in Transmissive Fracture Zones	Passive Flux Meter (PFM) and Hydraulic and Contaminant Transport Modeling
Contaminant Biodegradation in the Source and Plume	Compound Specific Isotope Analysis (CSIA)
	Microbial MetaOmics

Rock Core Analysis Program

1. Collected 277 bedrock matrix core samples
   a) Initially focus on historical GW treatment zone
   b) Sampled depths from 2 to 25 meters BGS
   c) Analyzed DCM concentration in all cores
      - Analyzed a subset for bulk density, porosity, and organic carbon to calculate porewater concentrations
2. Delineated source area and high concentration plume horizontally and vertically
   a) Advanced along bedding plane from the historical UST leak (original source)
   b) Consistent with regional fractured bedrock strike and dip

Passive Flux Meter Deployment

- "One stop shop" for both flow and concentration
- Obtain high resolution profiles of groundwater velocity and contaminant flux within boreholes.
- Map fracture zones with high contaminant mass flux.
- Integrated with rock matrix data to evaluate matrix diffusion.



Sampling

Vendor: http://www.enviroflux.com/

1. Contaminant adsorbed onto passive flux meter over time to get Concentration

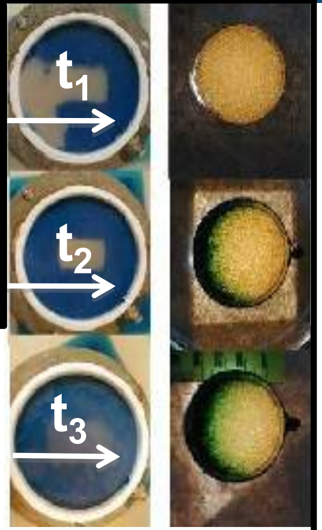
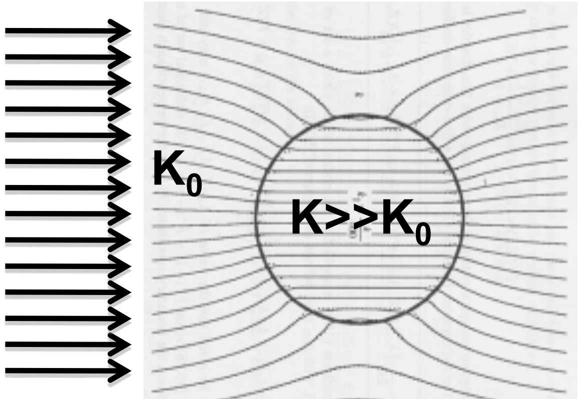
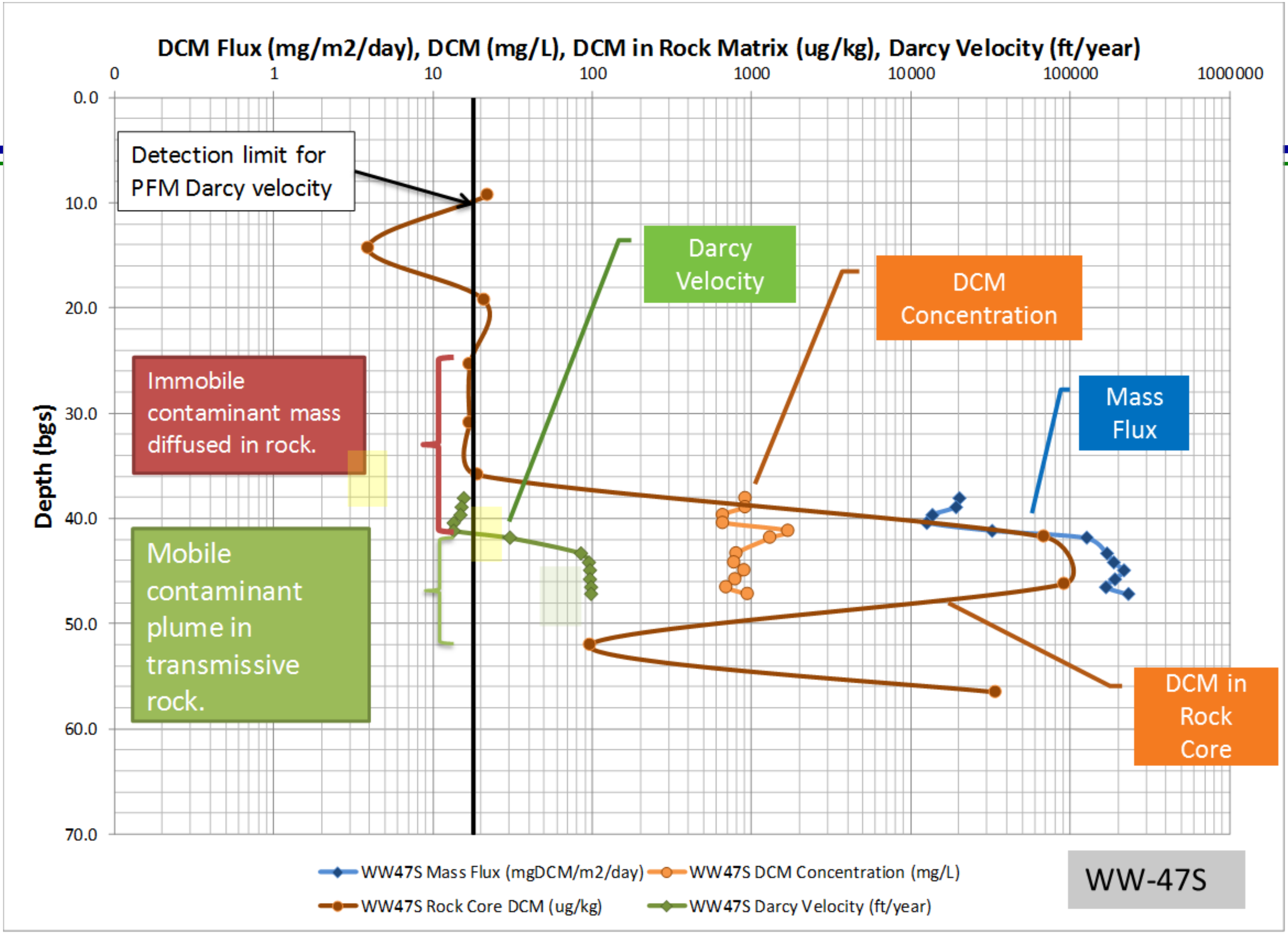


Photo: Dye intercepted in a meter

2. Tracer desorbs from passive flux meter to get Flow (Q)



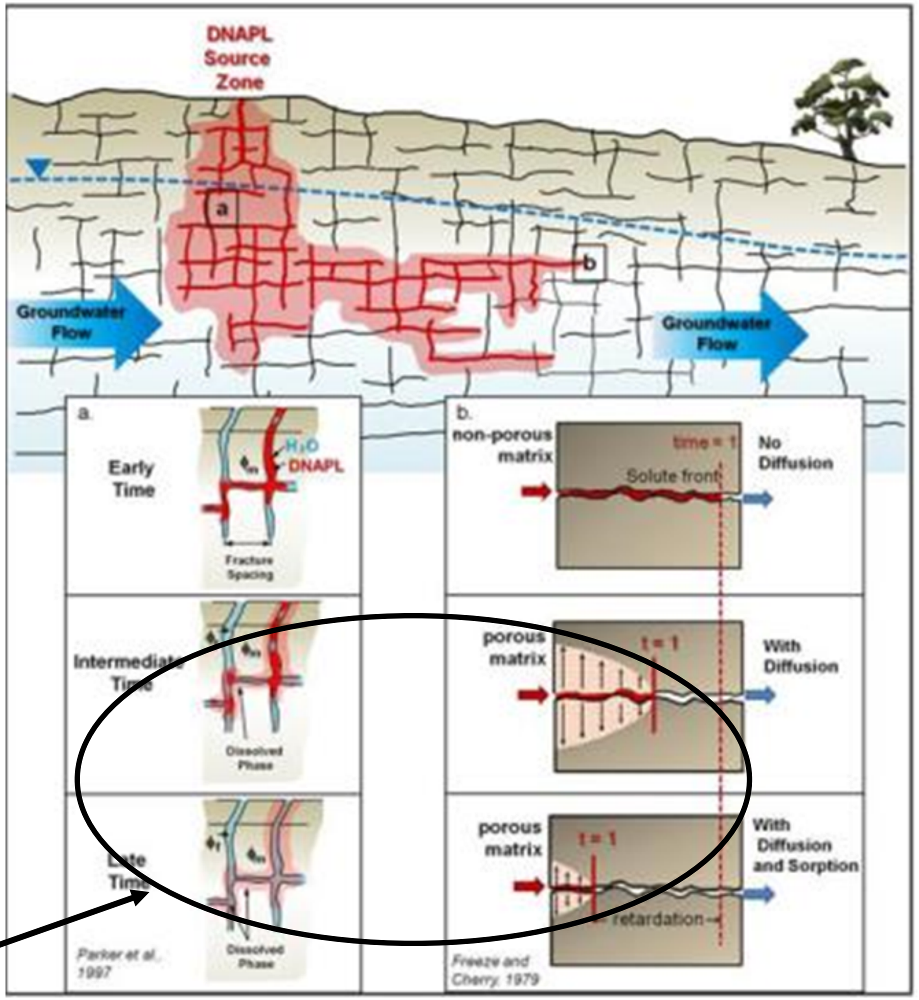
Groundwater Flowlines


DCM Flux (mg/m2/day), DCM (mg/L), DCM in Rock Matrix (ug/kg), Darcy Velocity (ft/year)
0
1
10
100
1000
10000
100000
1000000
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
Depth (bgs)
Detection limit for PFM Darcy velocity
Darcy Velocity
DCM Concentration
Mass Flux
Immobile contaminant mass diffused in rock.
Mobile contaminant plume in transmissive rock.
DCM in Rock Core
WW47S Mass Flux (mgDCM/m2/day)
WW47S DCM Concentration (mg/L)
WW47S Rock Core DCM (ug/kg)
WW47S Darcy Velocity (ft/year)
WW-47S

Conceptual Site Model Summary

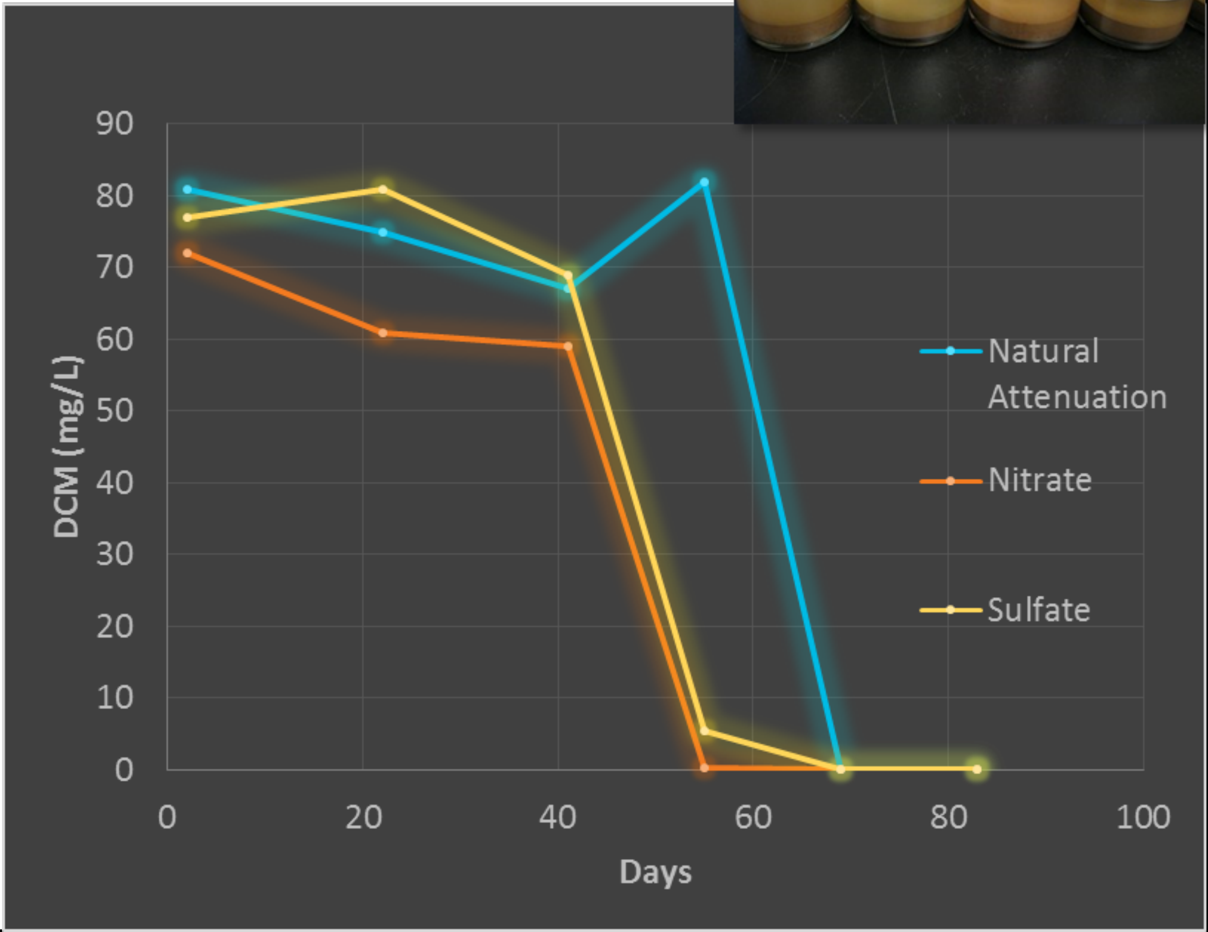
- Early:
  - DNAPL in fractures
  - Dissolves in groundwater
  - Diffuses into rock matrix
- Intermediate:
  - No mobile DNAPL remains
  - Back diffusion of DCM out of matrix into groundwater
- Late:
  - Plume migration and attenuation

Site is here



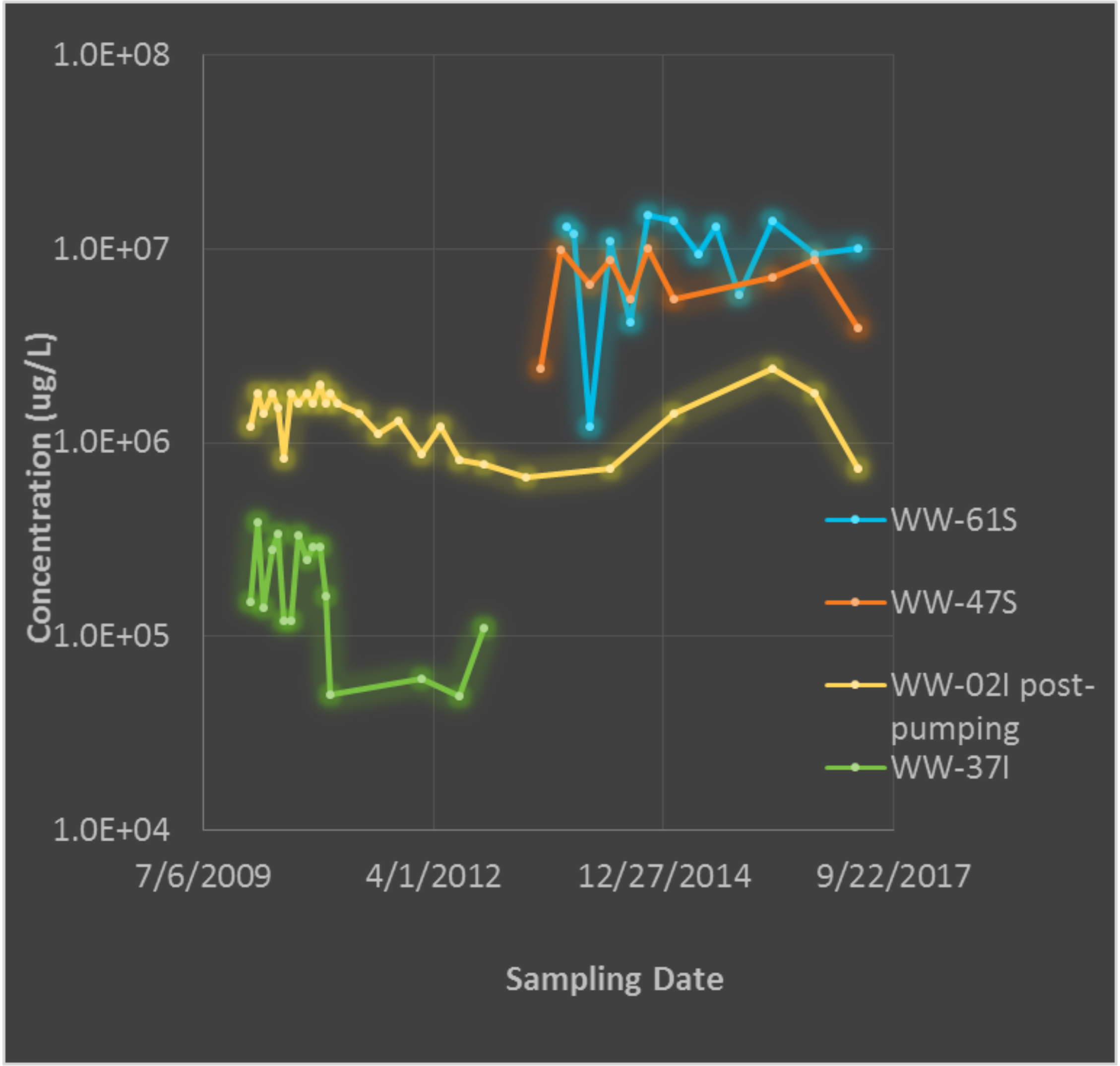
Preliminary Technology Evaluation

- 2005 **bench test** - very high intrinsic biodegradation rates - ***estimated half life of 2.2 days***
- **2009-current** - shut down P&T and evaluate rebound and MNA



Trend Analysis and Modeling

- Statistical analysis of concentration data showed stable or decreasing trends at all key monitoring wells
- BioChlor Modeling showed inclusion of a very short DCM half-life (e.g. 1-2 days) best matched plume conditions

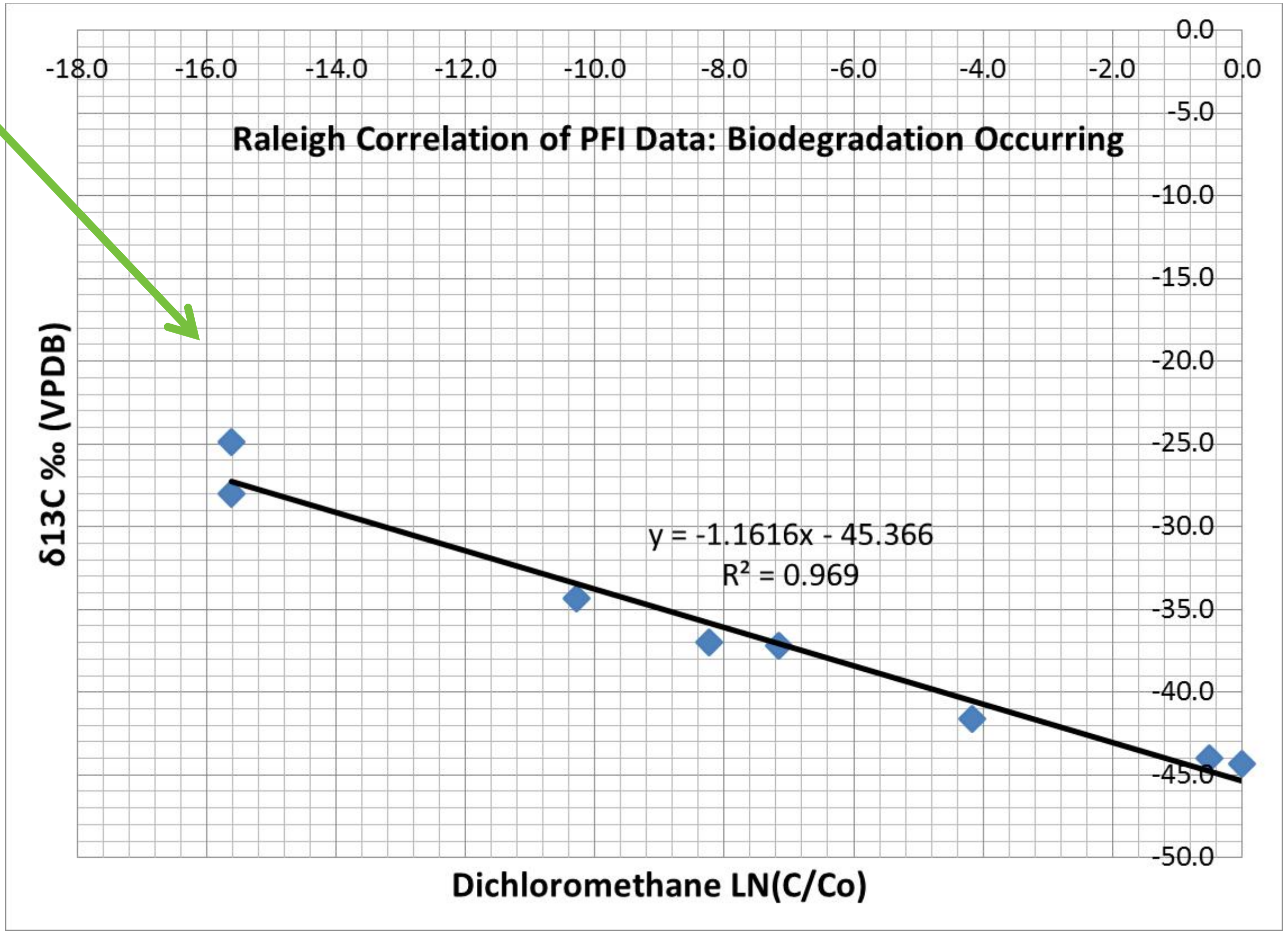


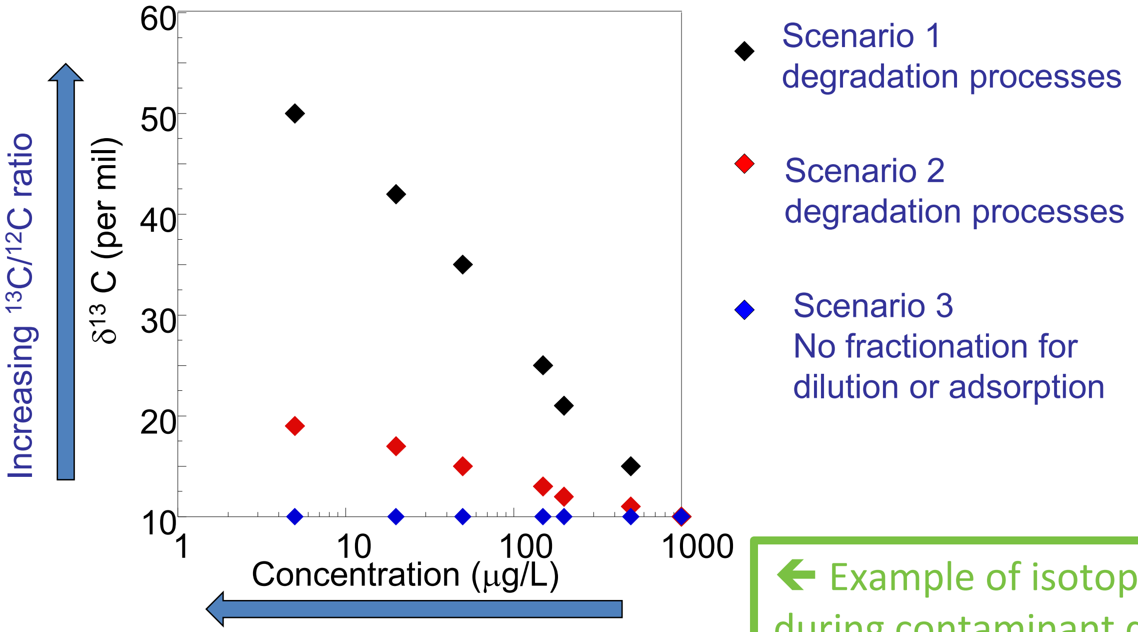
CSIA: Carbon Isotope Results

- Stable isotopes of carbon (C^{13}/C^{12}) analyzed from 8 wells
- Use Rayleigh model :

$$\delta^{13}C = \ln(C/C_0)*\varepsilon + \delta^{13}C_0$$

- ***Biodegradation occurring at the Site***





← Example of isotopic enrichment during contaminant degradation

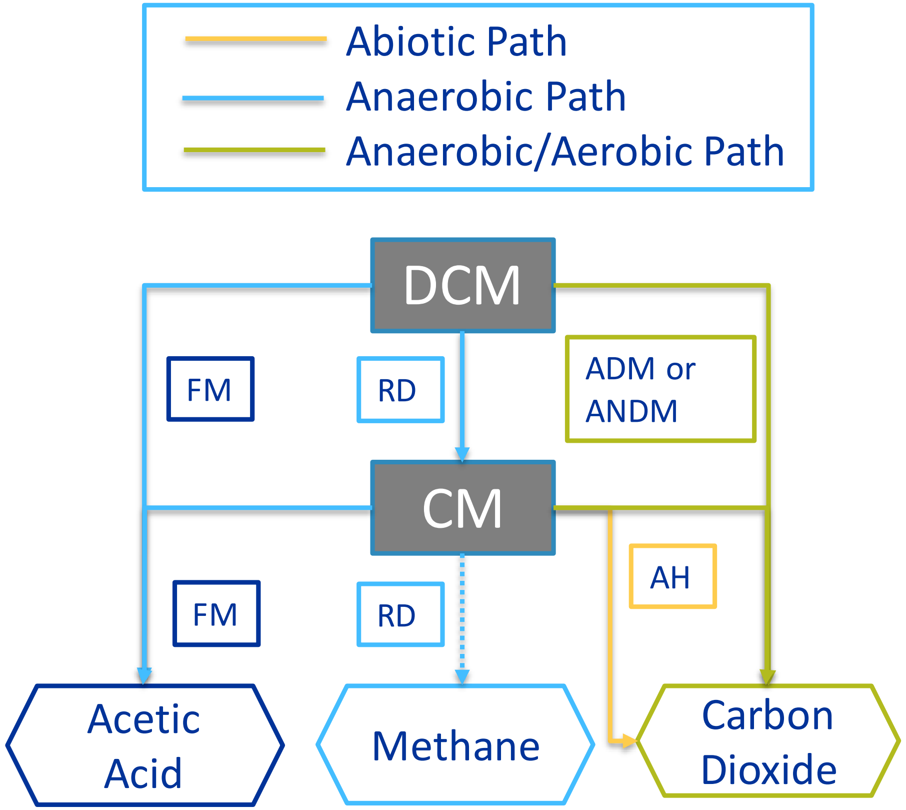
Biodegradation Rate Estimates

CSIA-derived Half Life Estimates

Sample ID	µg/L	Aerobic-Oxic[1]	Anaerobic-Fermentation[2]
		DCM Half Life Mean (days)	
WW-61S	12000000	Source Well	
WW-47S	7200000	105	40
WW-37I	186000	13	5
WW-01I	3200	5	2
WW-33I	9300	5	2
WW-46I	414	4	2
WW-48I	2	2	1
WW-58D	2	3	1

1 Methods in EPA 2008

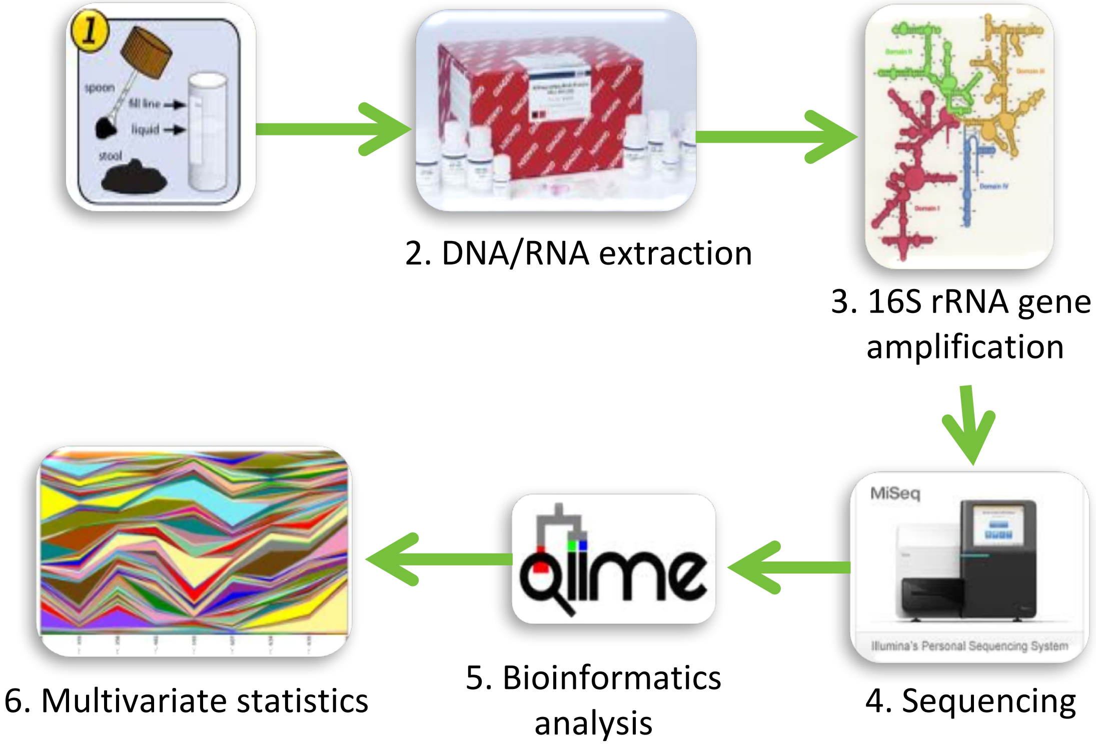
2 Used Epsilon factors from Trueba-Santiso et. al 2017



ADM- Aerobic Direct Metabolism
AH- Abiotic Hydrolysis
ANDM- Anaerobic Direct Metabolism
FM- Anaerobic Fermentation
RD- Reductive Dechlorination (Hydrogenolysis)

Meta-Omics DNA and RNA Analysis

1. Groundwater samples were collected quarterly between October 2013 and October 2014.
2. Samples were filtered and DNA and RNA was extracted.
3. This DNA was then subjected to Illumina-tag PCR and sequencing of the 16S rRNA gene.
4. 16S rRNA analysis and metatranscriptomics were conducted on 26 and 11 groundwater samples, respectively.

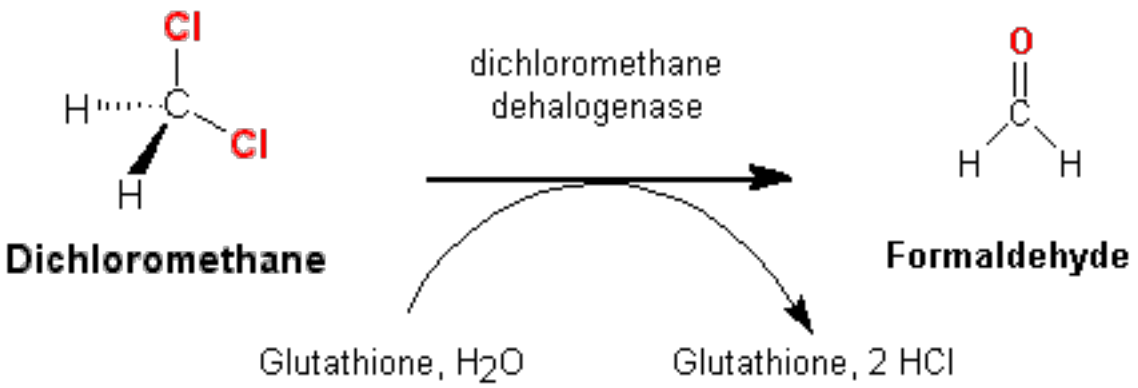


Microbiological Functional Gene Analysis

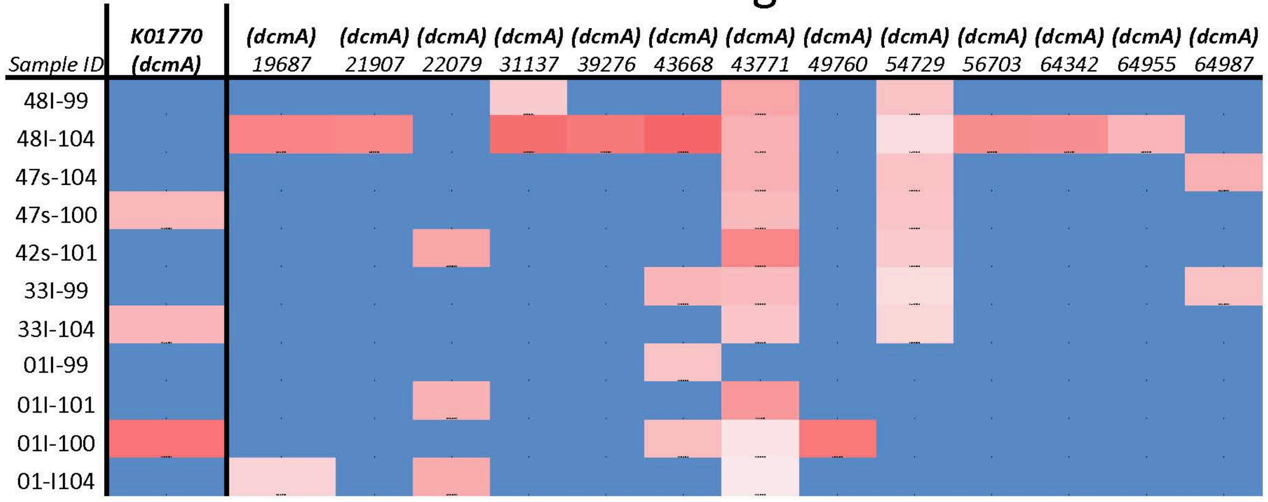
MISSOURI WASTE CONTROL COALITION

INTERSTATE TECHNOLOGY REGULATORY COUNCIL ITRC

1. Dichloromethane dehalogenase (dcmA) is central in dehalogenation of dichloromethane in aerobic environments.
2. Known gene dcmA was not highly expressed ***but***
3. 14 novel dehalogenases were identified and have different expression patterns across differentially contaminated groundwater samples



Bacteria are actively expressing the main gene involved in aerobic DCM degradation



Biodegradation Rate and Gene Expression

CSIA-derived Half Life Estimates			
Sample ID	µg/L	Aerobic-Oxic[1]	Anaerobic-Fermentation[2]
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1 Methods in EPA 2008

2 Used Epsilon factors from Trueba-Santiso et. al 2017

- *Aerobic degradation rates were correlated to both the known dcmA and novel dehalogenase transcripts:*
  - *expression of the novel dehalogenases shared the highest correlation with degradation rates (Spearman rho: 0.48-0.72)*
  - *previously identified/known dcmA genes (Spearman rho: -0.31)*

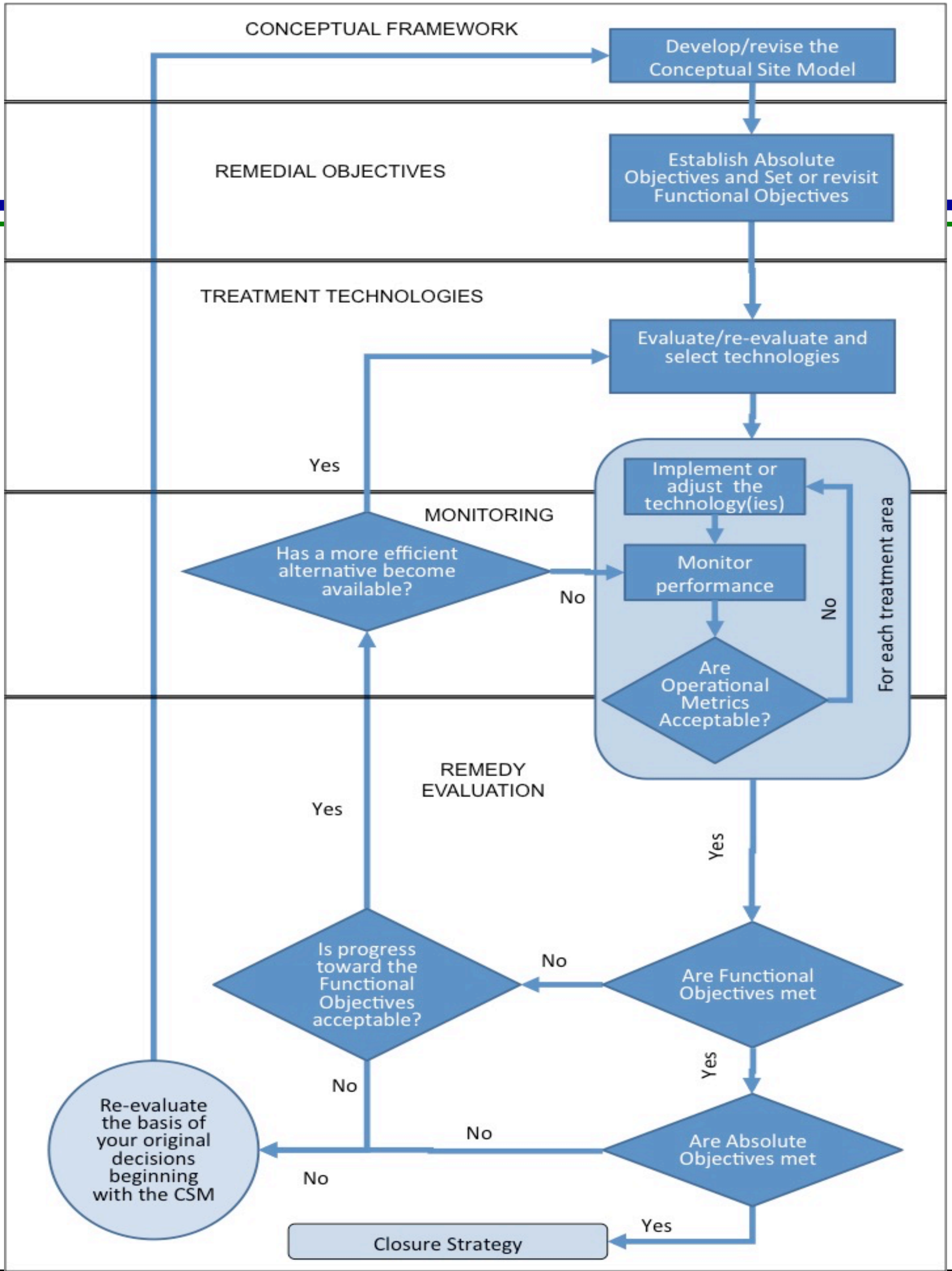
Summary

1. Rock Coring and Fluxmeters evaluated source architecture and relationship to contaminant mass transport
2. Modeling verified high degradation rates required to “explain” stable and controlled plume
3. CSIA used to evaluate DCM biodegradation mechanism and rate
4. Metagenomics Results:
    1. Identified DCM degrading genes/organisms consistent with CSIA conclusions (Sn2 dehalogenase-mediated degradation)
    2. Also identified anaerobic DCM-degrading Desulfosporosinus and Propionibacterium
5. Metatranscriptomics Results:
    1. Dehalogenases were the most expressed genes in the profiles (consistent with CSIA and metagenomics)- found 14 novel dcmA genes
    2. Tetahydrofolate cofactors associated with Desulfosporosinus actively expressed
6. Collectively demonstrated source is controlled and plume is attenuation for acceptance of the remedy

Overview of the Training

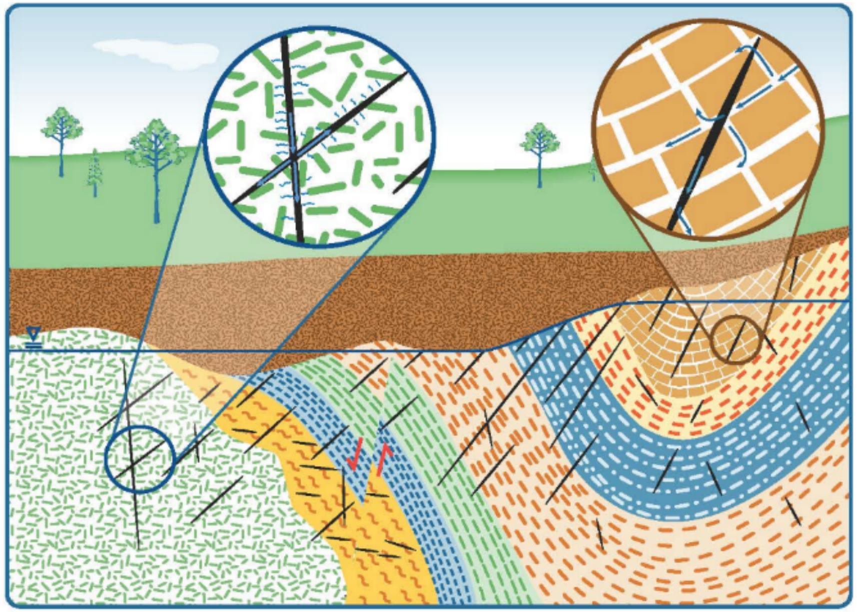
- Introduction
- Fractured Rock CSM Considerations
- Fracture Characteristics of Geologic Terrane
- Fracture Flow & Contaminant Fate and Transport
- Fractured Rock Characterization
- Remedy Development
- Monitoring
- **Summary**

Final Flow Chart



(Because it is an ITRC document)

ITRC Characterization and Remediation of Fractured Rock



Characterization and Remediation of Fractured Rock Document and Internet Training