Starting Soon: Characterization and Remediation of Fractured Rock

- Characterization and Remediation of Fractured Rock (FracRx-1) http://fracturedRX-1.itrcweb.org
- Download PowerPoint file
  - Clu-in training page at http://www.clu-in.org/conf/itrc/FracRx/
  - Under "Download Training Materials"
- Download flowcharts for reference during the training class
  - https://clu-in.org/conf/itrc/FracRx/ITRC_TrainingHandout_FracRx-Figure1-1.pdf

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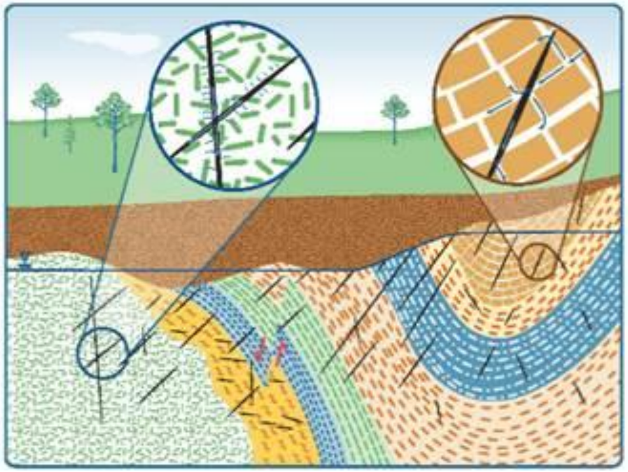
Welcome – Thanks for joining this ITRC Training Class

Characterization and Remediation of Fractured Rock



ITRC Guidance: Characterization and Remediation of Fractured Rock (FracRx-1)

Sponsored by: Interstate Technology and Regulatory Council (www.itrcweb.org)
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Meet the ITRC Trainers

Dave Scheer
Minnesota PCA
St. Paul, MN
dave.scheer@state.mn.us

John Dougherty
CDM Smith
Edison, NJ
Doughertyjn@cdmsmith.com

Tamzen Macbeth
CDM Smith
Helena, Montana
macbethtw@cdmsmith.com

Melissa Boysun
ERM
Zurich, Switzerland
melissa.boysun@erm.com

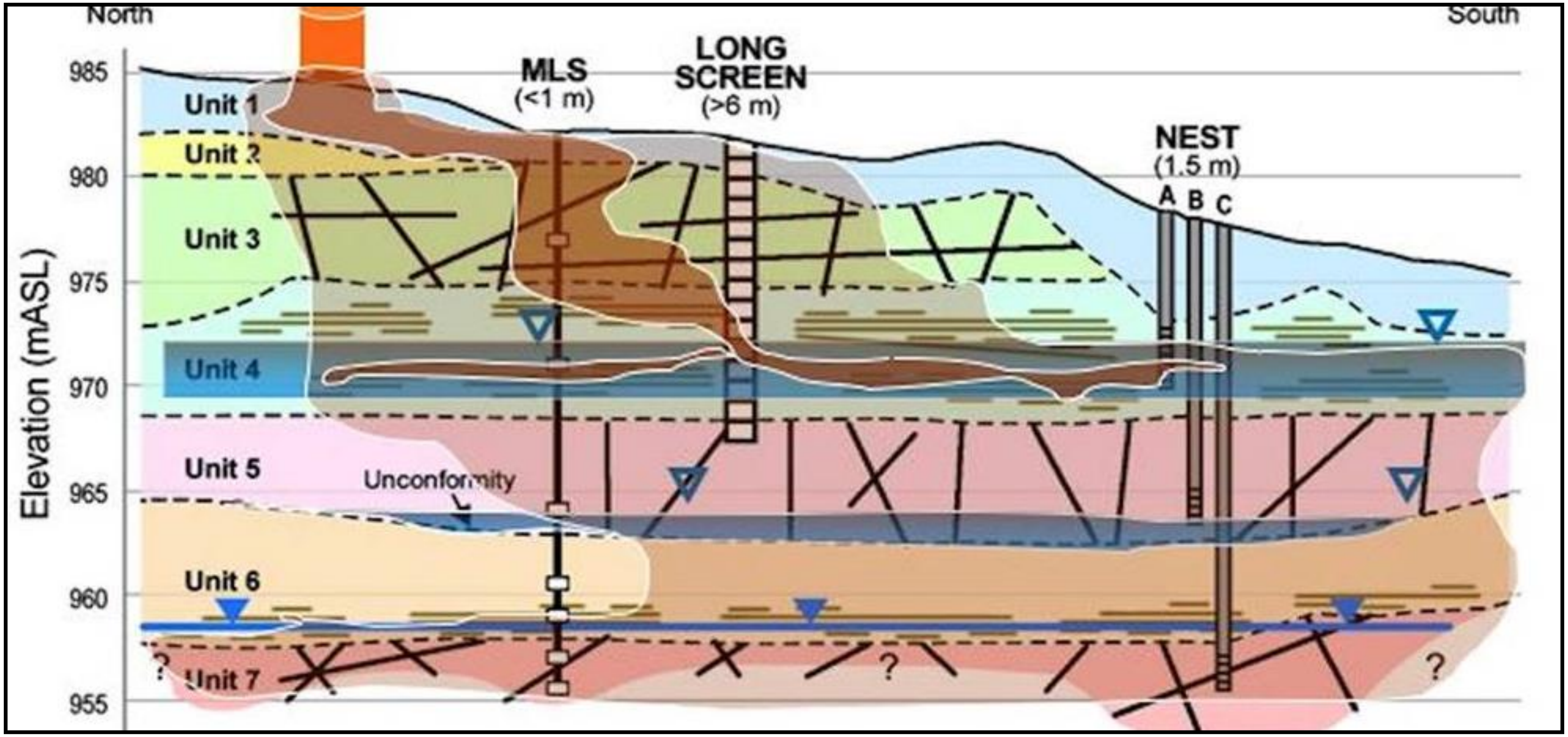
Dan Bryant
Woodard & Curran
East Windsor, NJ
dbryant@woodardcurran.com

Ted Tyler
Cardno
Mesa, AZ
ted.tyler@cardno-gs.com

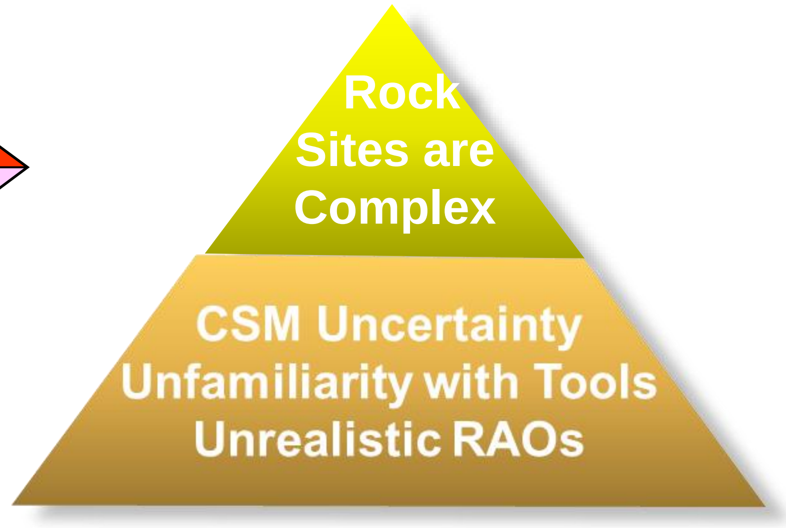
Read trainer bios at https://clu-in.org/conf/itrc/FracRx/#tabs-2

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

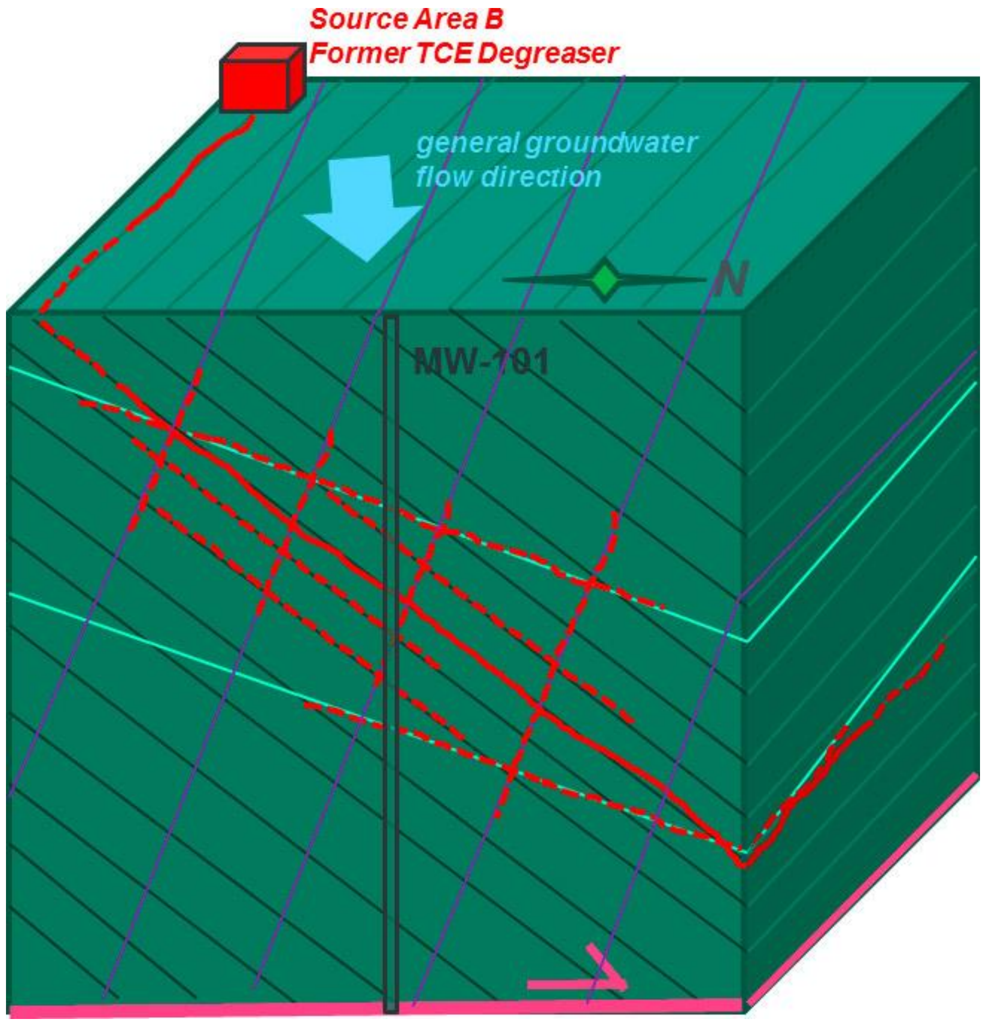
Difficult, But Not Impossible



The Problems and Site Challenges with Fractured Rock Remediation

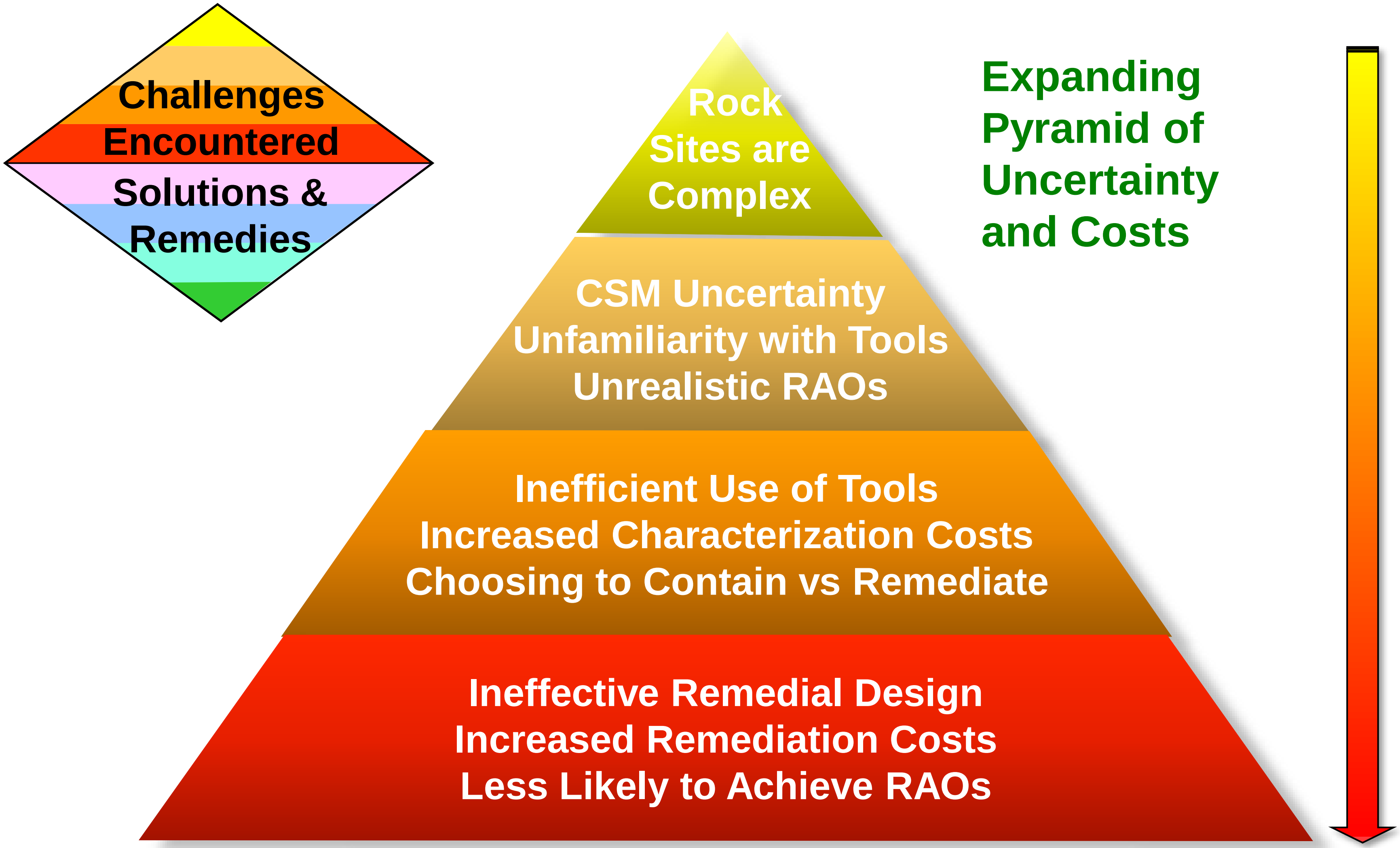


Challenge: Rock Sites are Complex



ITRC FracRx-1 Figure 11-3

The Problems and Site Challenges with Fractured Rock Remediation



RAO - remedial action objective

The Nature of the Solution
Solutions and Remedies

Understand Fractured Rock Site Characteristics

RAO - remedial action objective
CSM - conceptual site model

Solution: Understand Fractured Rock Characteristics

Figure B-4. Inclined sandstone bedding

Figure B-7 Foliated schist in outcrop.

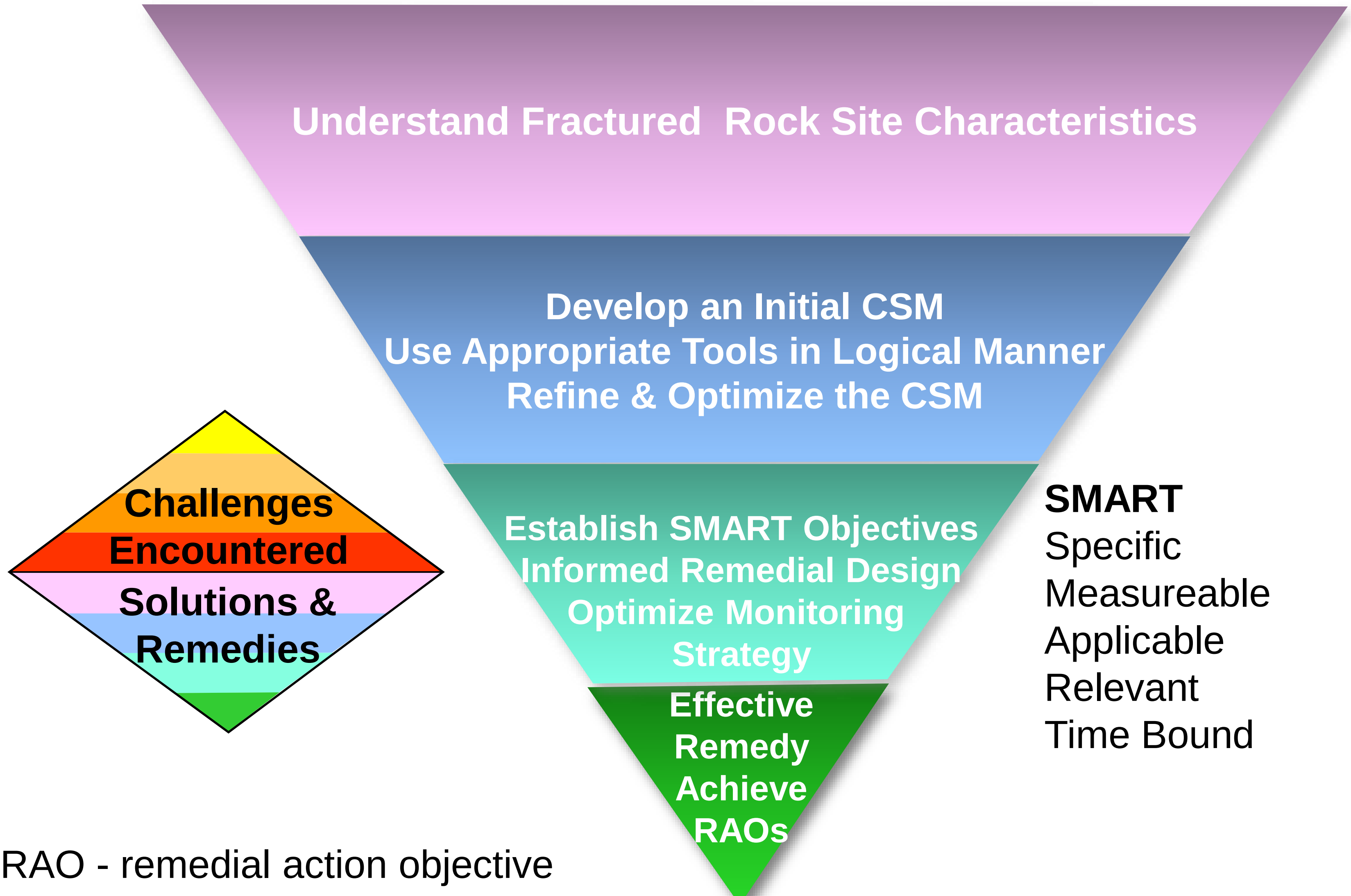
The Nature of the Solution
Solutions and Remedies

RAO - remedial action objective
CSM - conceptual site model

Solution: The Tool Table

Tool	Data Quality	Sub surface		Zone	
		Bedrock	Unconsolidated	Unsaturated	Saturated
Geophysics					
Surface Geophysics					
Ground Penetrating Radar (GPR)	QL - Q	✓	✓	✓	✓
High Resolution Seismic Reflection (2D or 3D)	QL - Q	✓	✓		✓
Seismic Refraction	QL - Q	✓	✓	✓	✓
Multi-Channel Analyses of Surface Waves (MASW)	QL - Q	✓	✓	✓	✓
Electrical Resistivity Tomography (ERT)	QL - SQ	✓	✓	✓	✓
Very Low Frequency (VLF)	QL	✓	✓	✓	✓
ElectroMagnetic (EM) Conductivity	QL	✓	✓	✓	✓
Downhole Testing					
Magnetometric Resistivity	QL	✓	✓		✓
Induction Resistivity (Conductivity Logging)	QL - Q	✓	✓	✓	✓
Resistivity (Elog)	QL - SQ	✓			✓
GPR Cross-Well Tomography	QL - Q	✓	✓	✓	✓
Optical Televiewer	QL - Q	✓	✓	✓	✓
Acoustic Televiewer	QL - Q	✓			✓
Natural Gamma Log	QL - Q	✓	✓	✓	✓
Neutron (porosity) Logging	QL - Q	✓	✓		✓
Nuclear Magnetic Resonance Logging	QL - Q	✓	✓	✓	✓
Video Log	QL - SQ	✓	✓	✓	✓
Caliper Log	QL - Q	✓	✓	✓	✓
Temperature Profiling	QL - Q	✓	✓		✓
Full Wave Form Seismic	Q - QL	✓			✓

The Nature of the Solution
Solutions and Remedies



SMART
Specific
Measureable
Applicable
Relevant
Time Bound

RAO - remedial action objective
CSM - conceptual site model

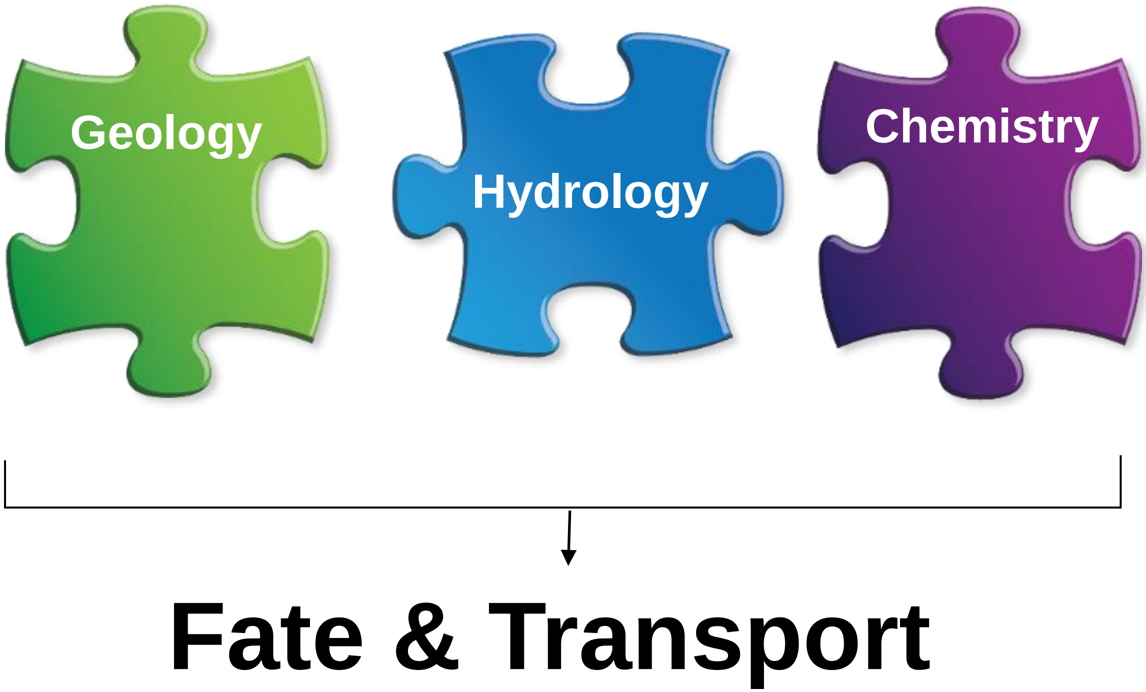
A Better Way….. Based on the Latest Research Specific to Fractured Rock

ITRC Technical and Regulatory Guidance:

Characterization and Remediation of Fractured Rock

http://fracturedRX-1.itrcweb.org

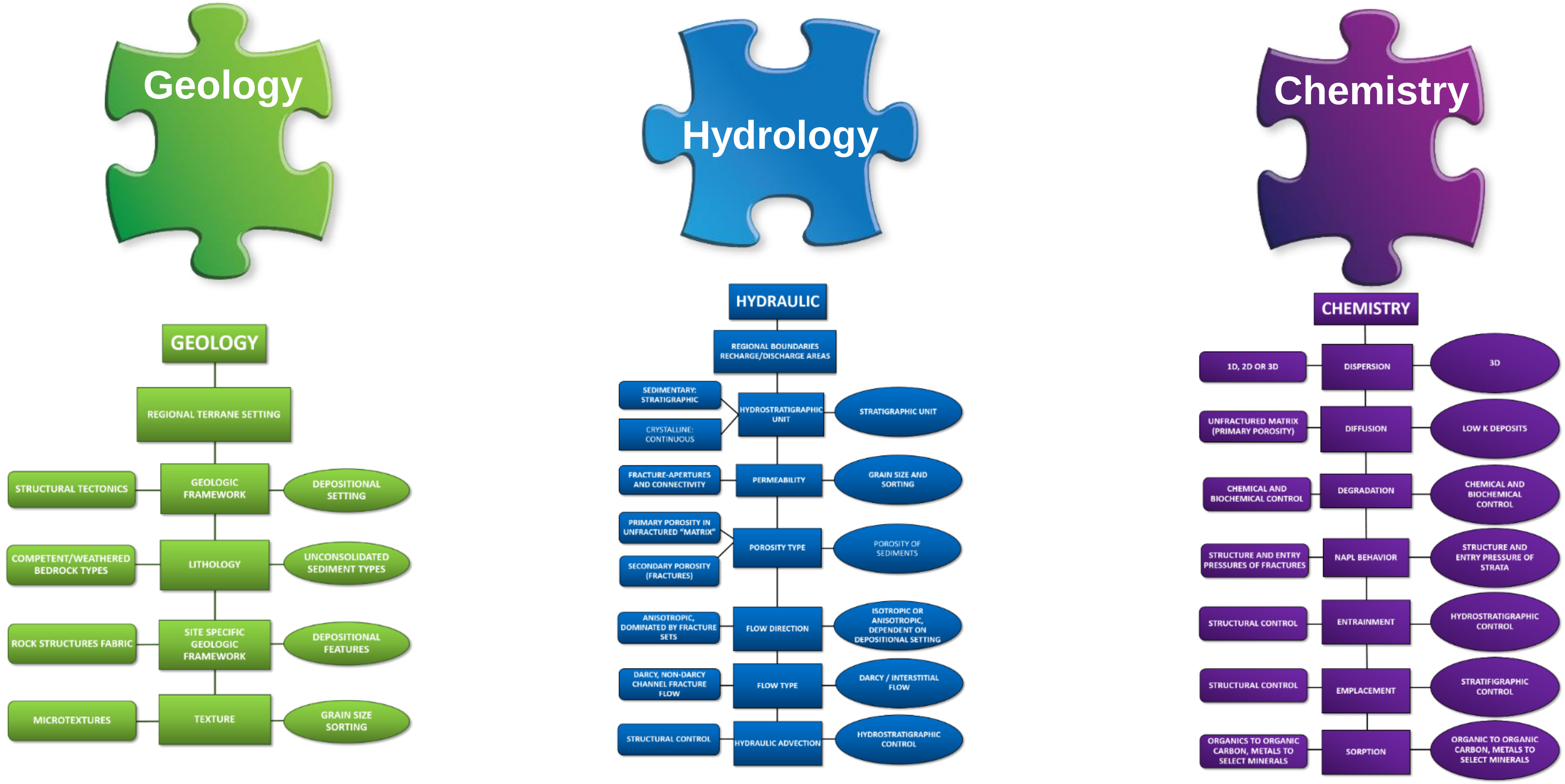
Building a Quality Conceptual Site Model – You Need the Right Pieces



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

What You Need to Know About Fractured Rock

See Training Handout

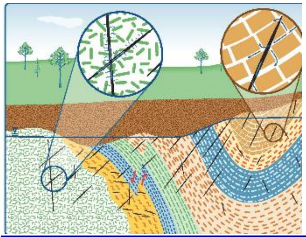


PHYSICAL CHARACTERISTICS

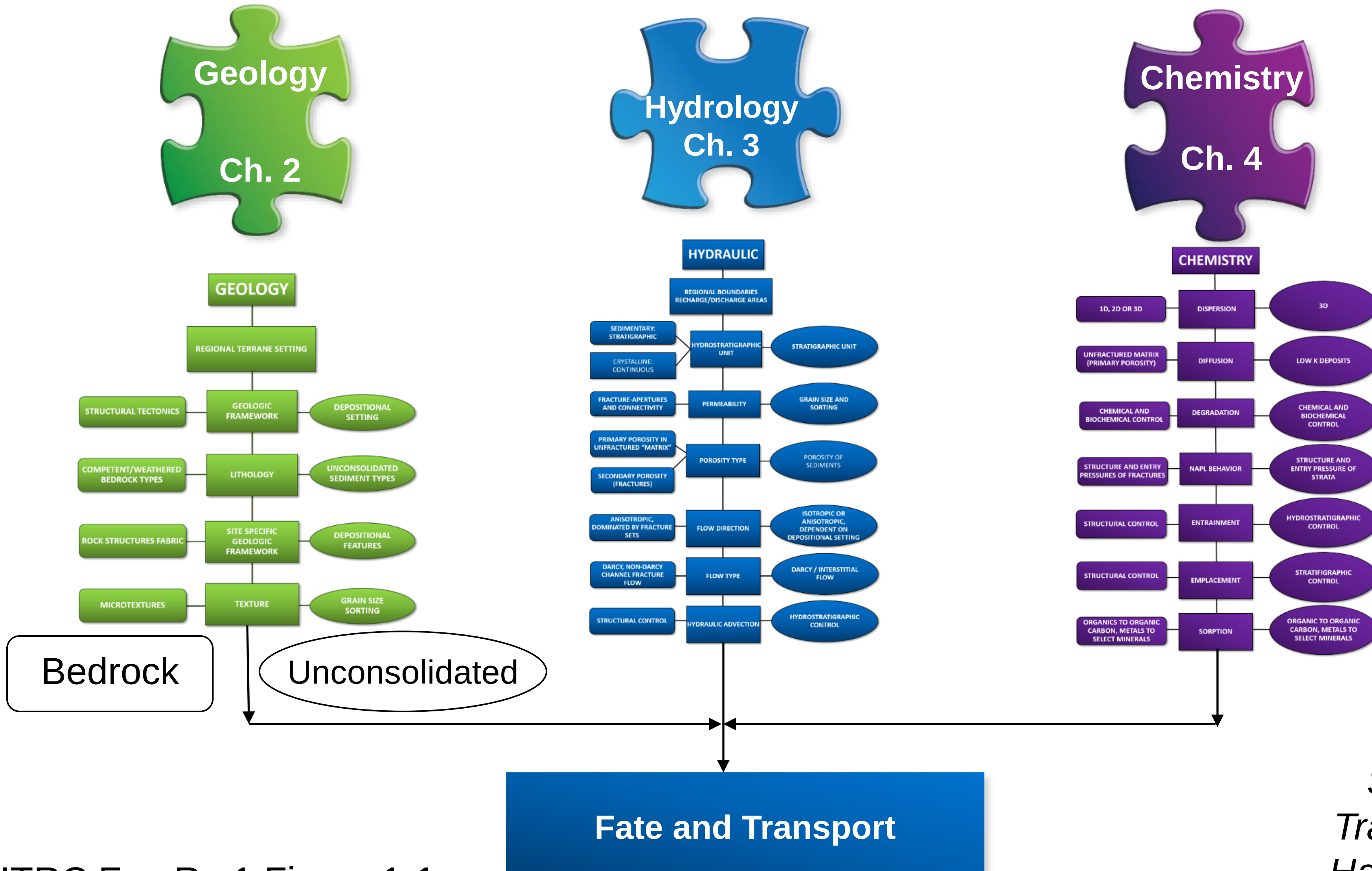
FRACTURE & MATRIX FLOW CHARACTERISTICS

CONTAMINENT CHEMICAL CHARACTERISTICS

ITRC FracRx-1 Figure 1-1



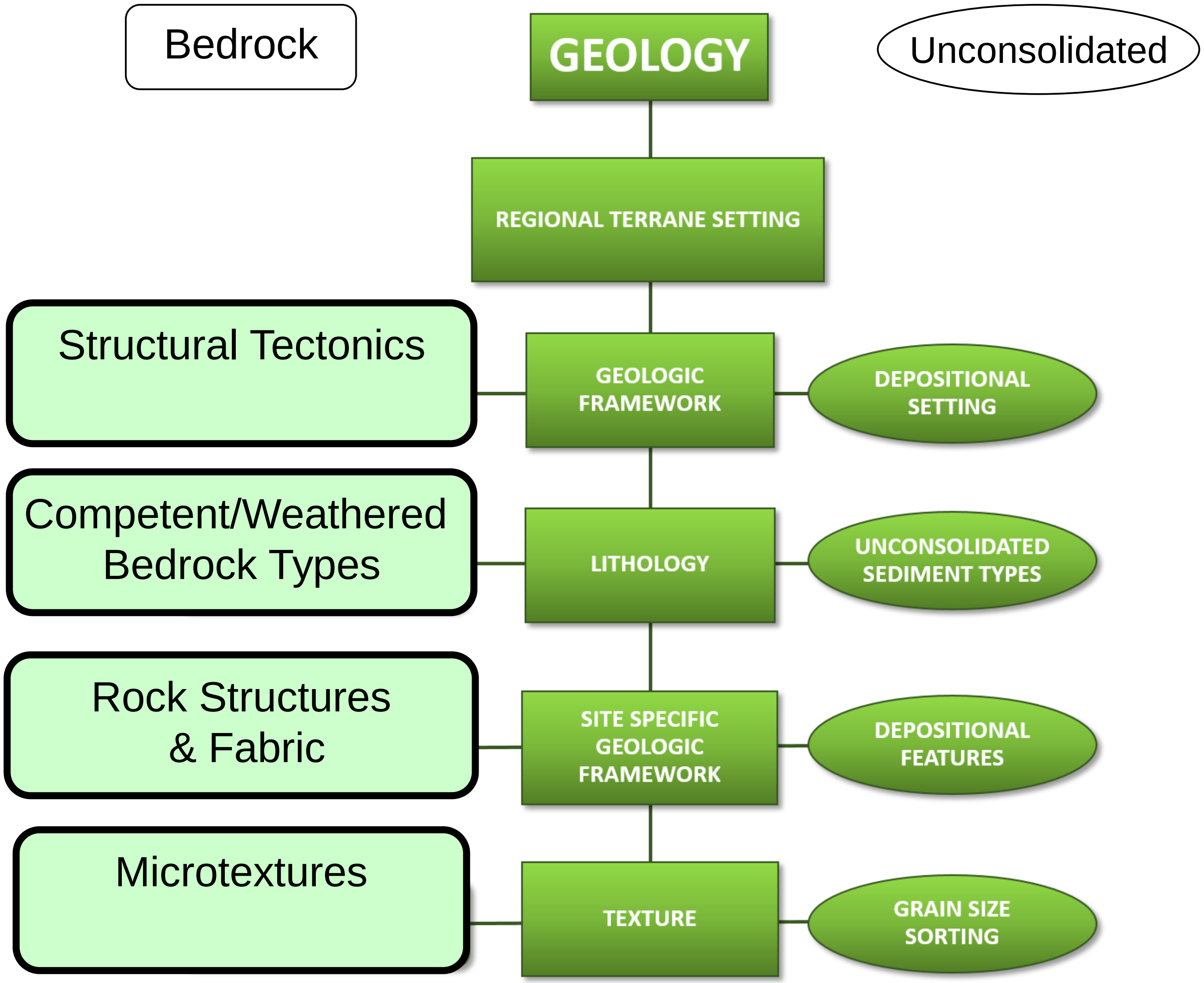
Similarities and Differences Bedrock vs. Unconsolidated



ITRC FracRx-1 Figure 1-1

See Training Handout

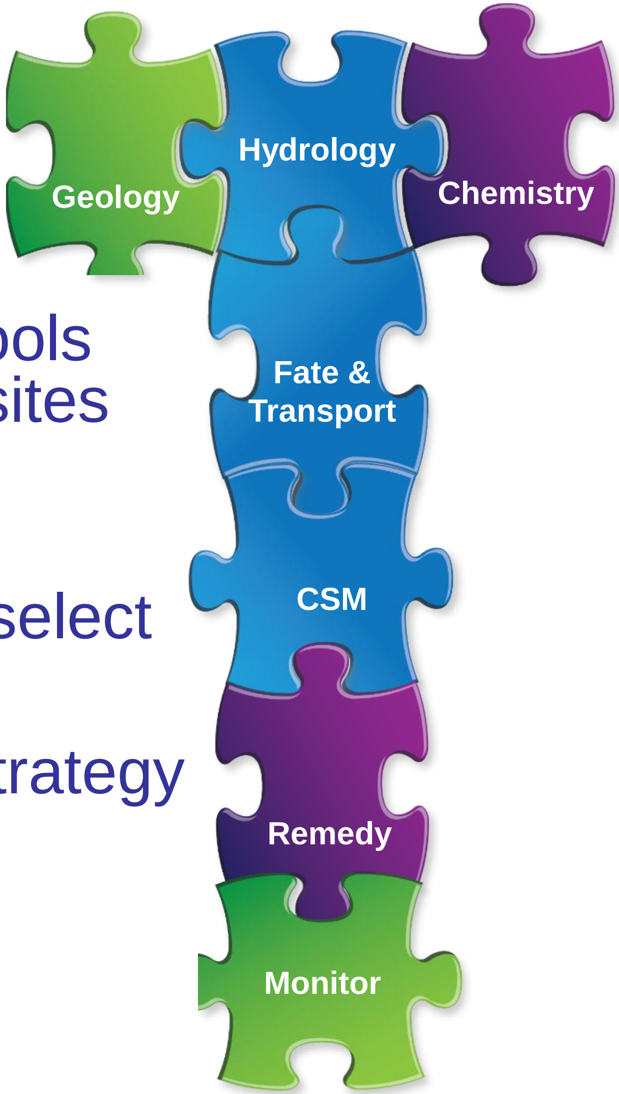
Geologic Characteristics that Affect Flow



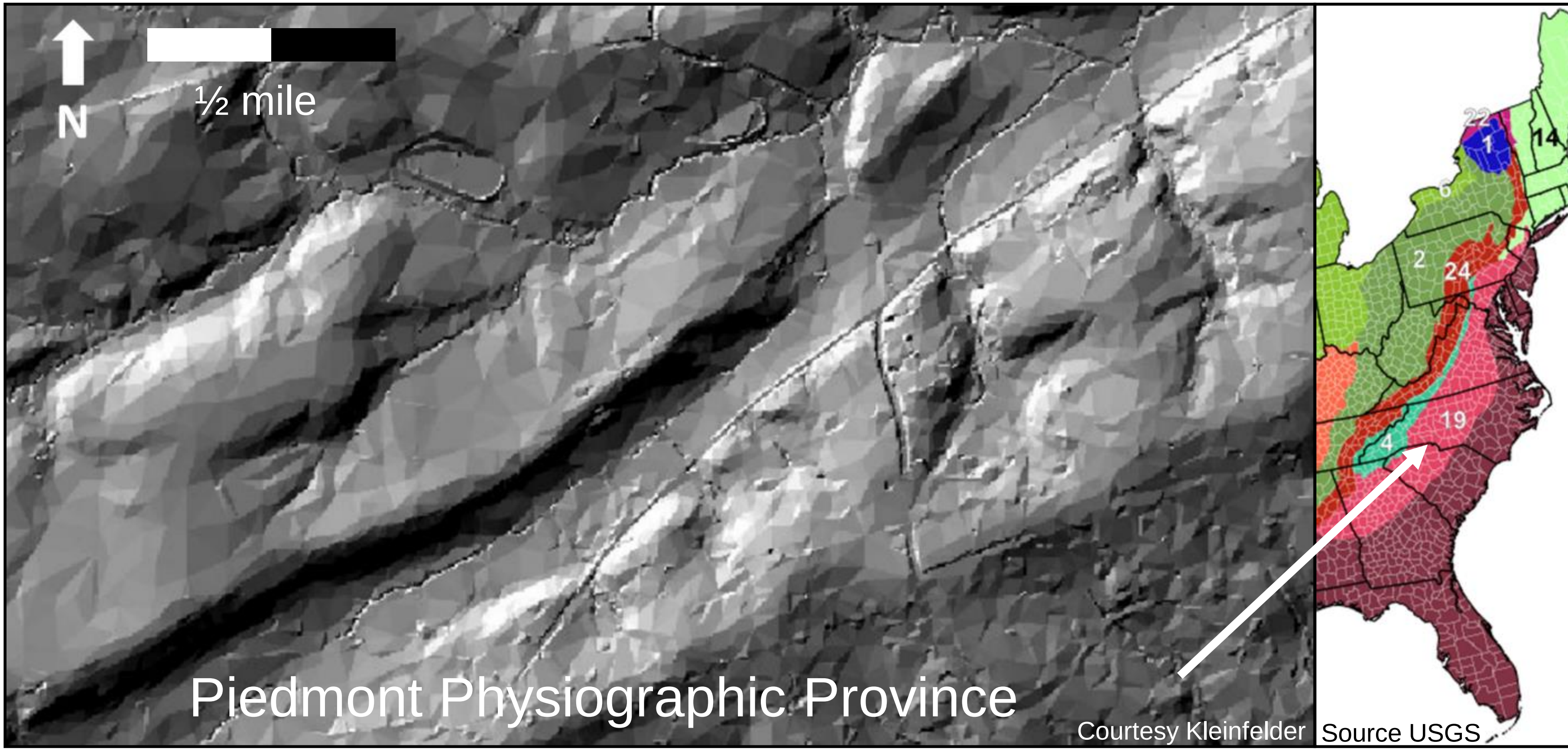
ITRC FracRx-1
Figure 1-1

Today's Road Map – Connects to ITRC Guidance

- Identify similarities and differences between characterizing fractured rock and unconsolidated media sites (**Chapters 2 - 4**)
- Recognize the skills, approaches, and tools available to characterize fractured rock sites and develop CSMs (**Chapter 5**)
- Apply improved approaches to develop Remedial Action Objective (RAOs) and select remedies (**Chapter 6**)
- Describe development of a monitoring strategy for fractured rock sites (**Chapter 7**)

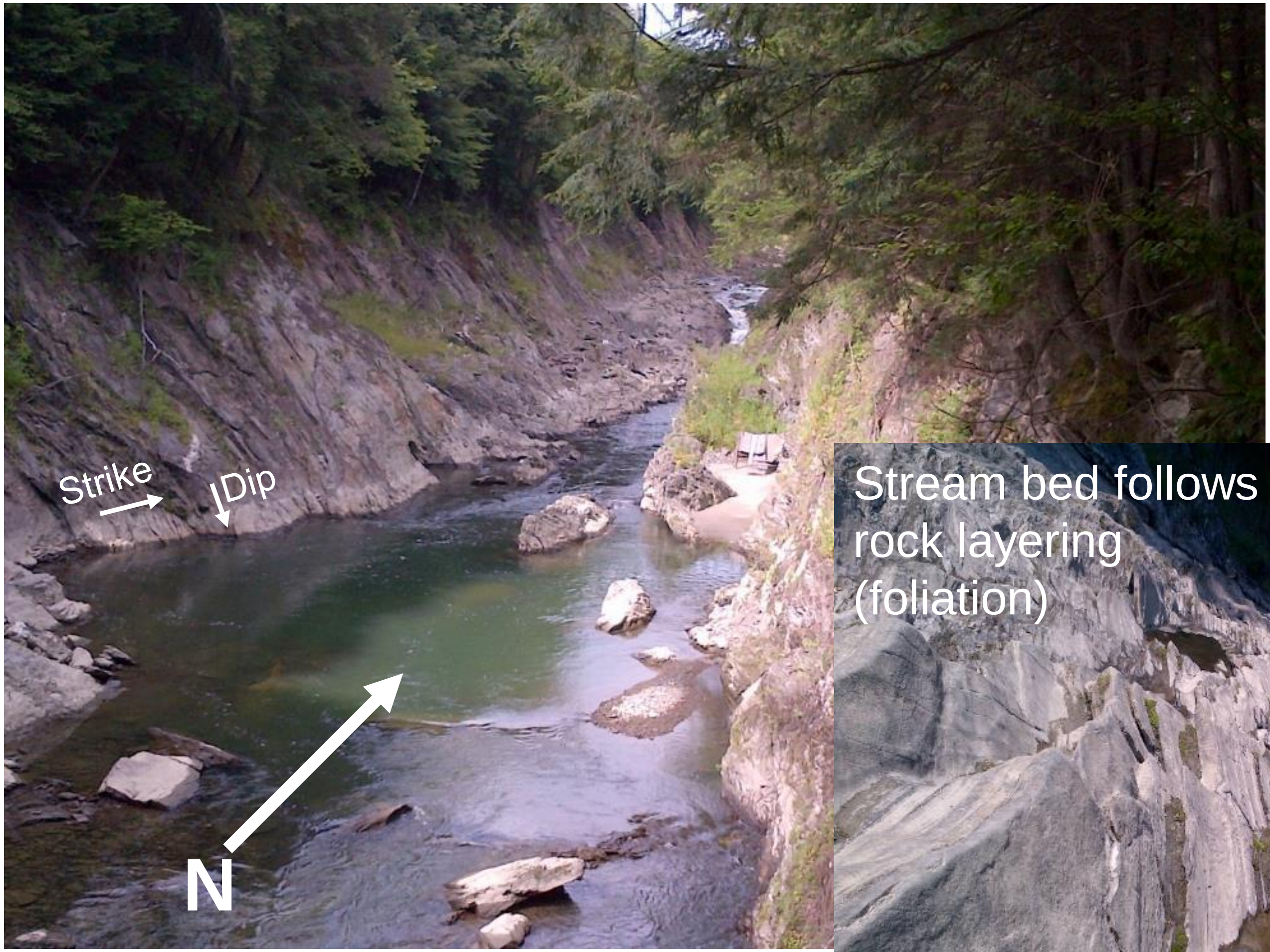


Terrane Analysis – Regional Setting



Note NE-SW trend in landscape and arrangement of physiographic provinces: initial clue to bedrock and groundwater flow characteristics.

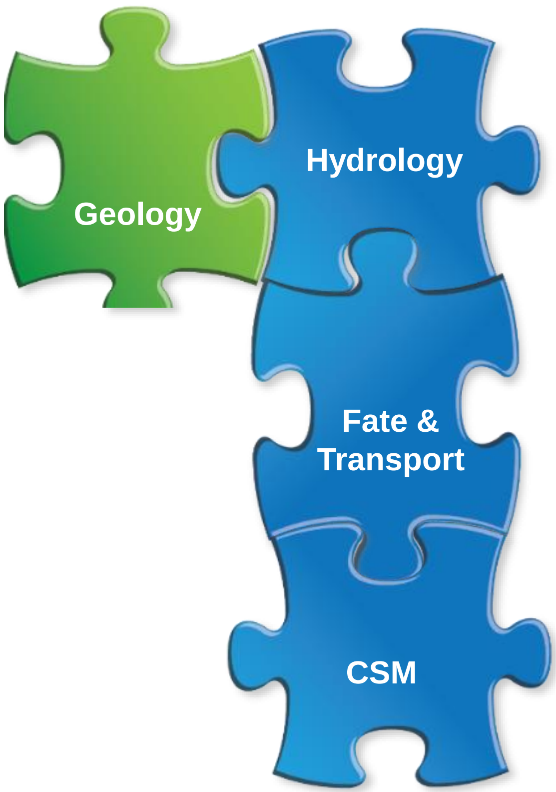
Terrane Analysis – Lithology, Structure, Anisotropy, Hydrology



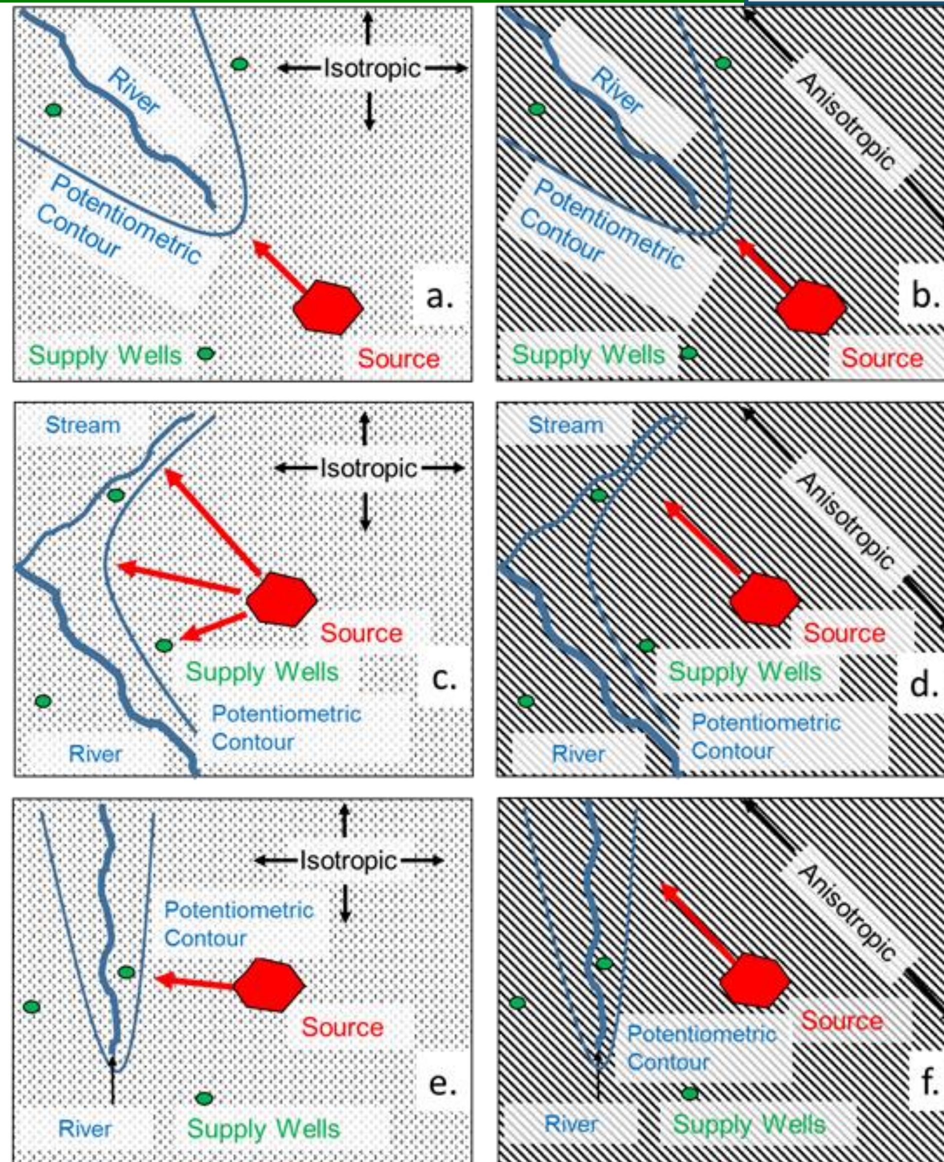
Rock type, layering, and structure impart directional component to hydrology and groundwater flow.

Courtesy Jeff Hale

Terrane Analysis – Initial CSM

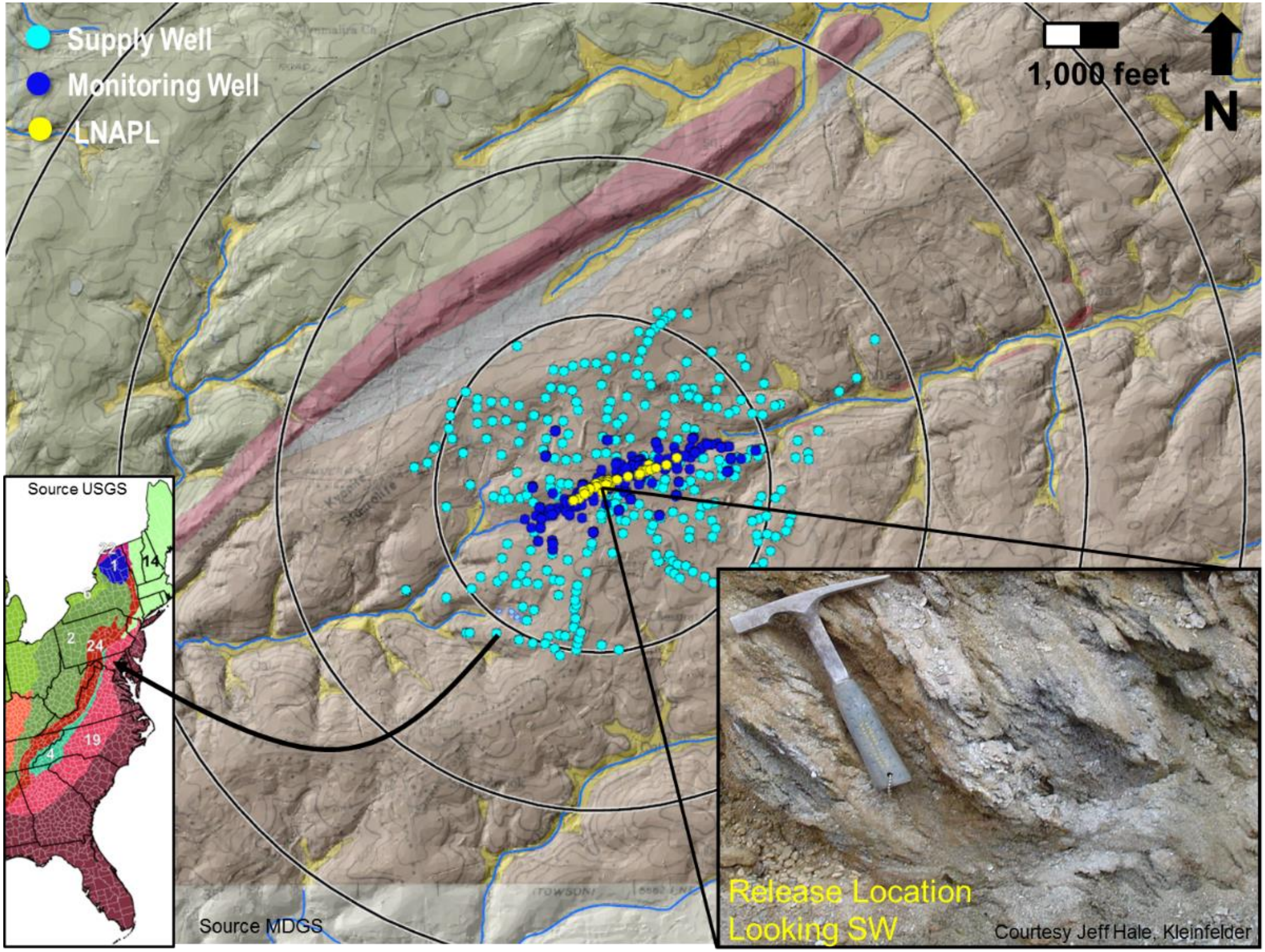


Assemble source, hydraulic gradient, bedrock influence, hydrology, and receptors for initial CSM.



Source Jeff Hale, prepared for ITRC

Terrane Analysis – Complete Example

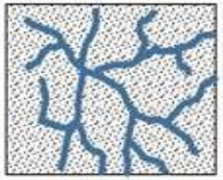
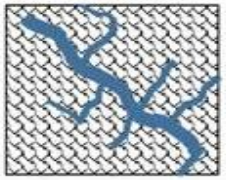


Terrane Analysis – Elements

- Receptors
- Regional Setting
- Lithology
- Structure
- Anisotropy
- Heterogeneity
- Hydrology

The Terrane Analysis Matrix (Appendix B) is a tool that breaks down terrane analysis into its basic elements with helpful tips.

ITRC FracRx-1 Appendix B

1	2	3		4	5		6
		Lithology		Structure	Anisotropy	Heterogeneity	Hydrology
Potential Receptors (e.g., groundwater supply wells, surface water bodies)	Regional Physical Setting (physiographic provinces)	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.	

Source J. Hale, prepared for ITRC; Photos J. Hale et al., Kleinfelder

Terrane Analysis – The Challenge of Karst

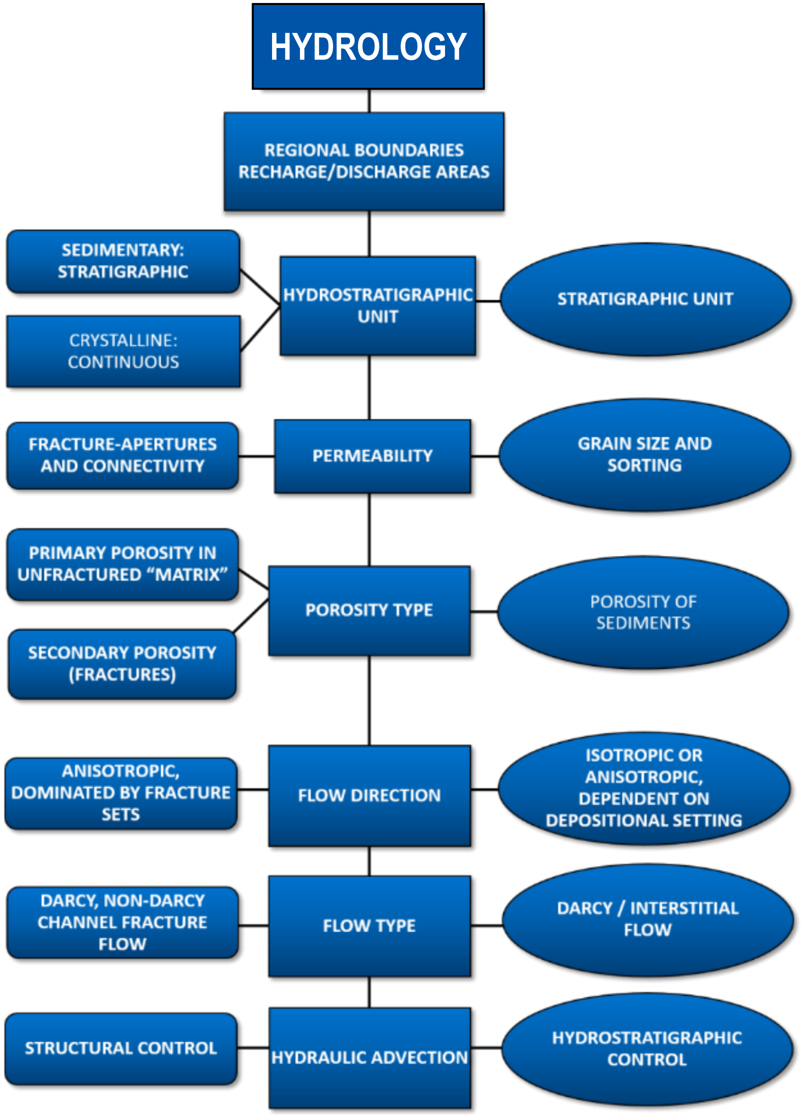
Karst landscapes develop when fractured, soluble bedrock interacts with surface water or groundwater to develop macroscale secondary porosity features such as voids, conduits, sinkholes, and caves.

- Appendix A in the document discusses Karst issues in detail

Hydrology of Fractured Rock – The Basic Questions

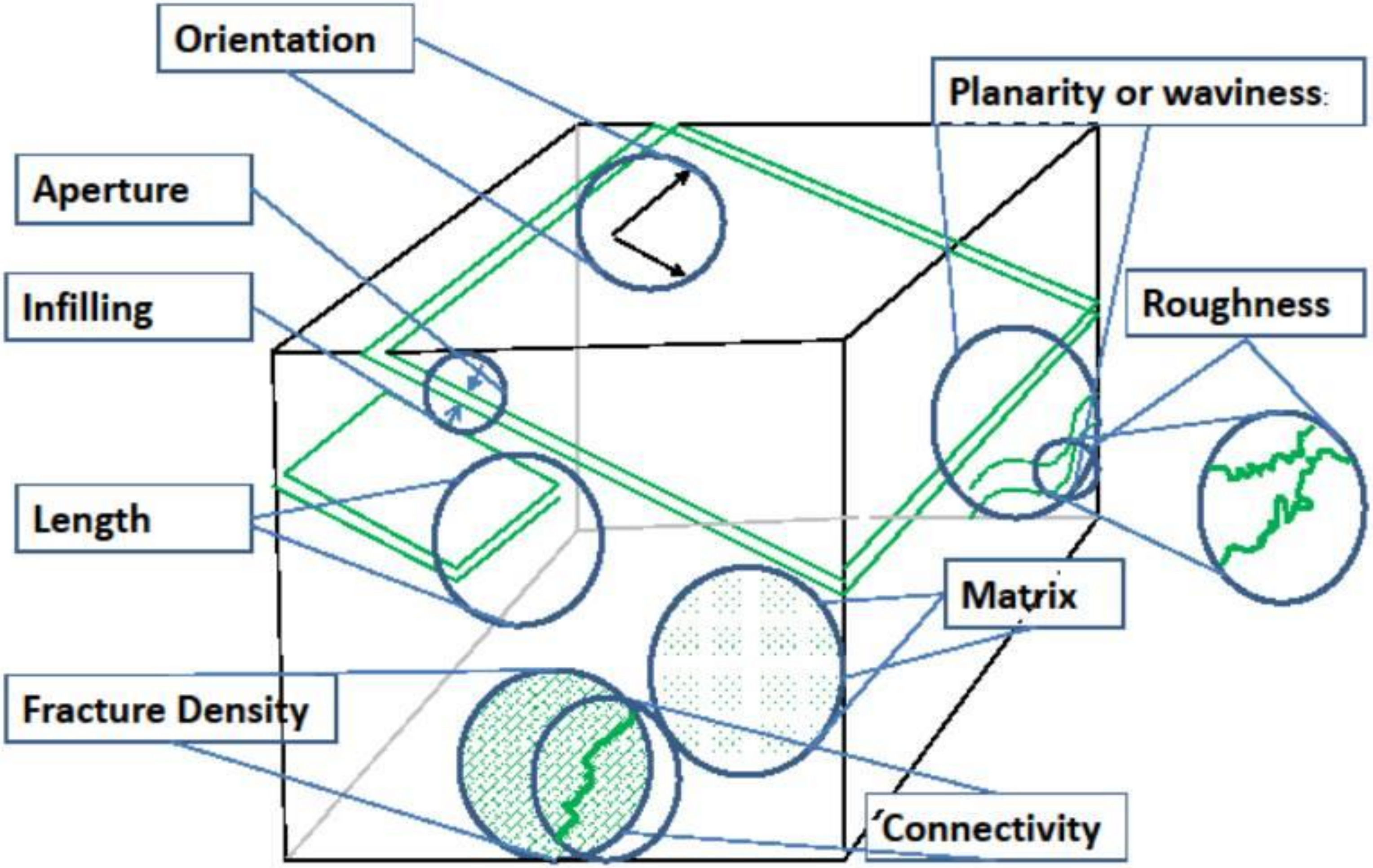
Poll Question

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



ITRC FracRx-1 Figure 1-1

What Bedrock Characteristics Control Fluid Flow?



ITRC FracRx-1 Figure 3-2

Primary Considerations for Flow in Sedimentary vs Crystalline Rock

Hydrology

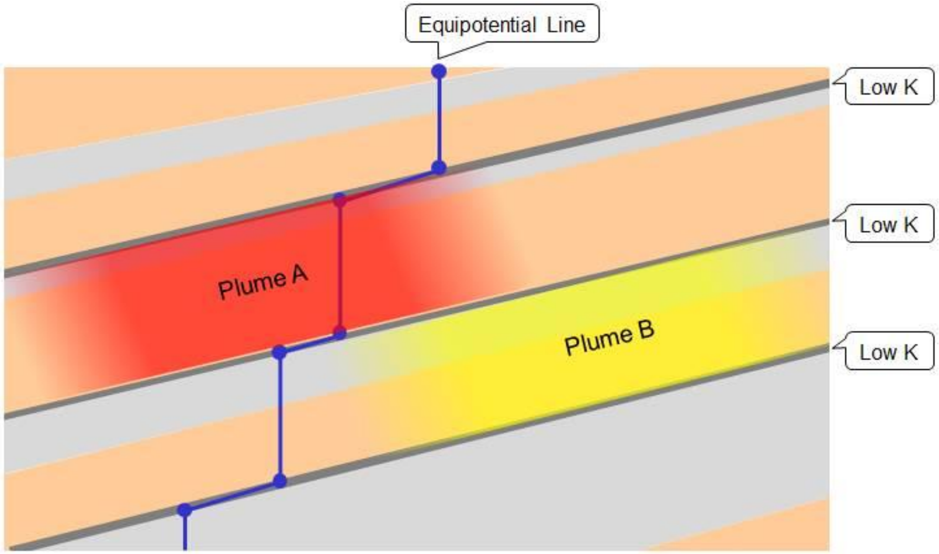
- Influence of fractures
- Bedding or layering
- Fracture systems
- Mechanical and chemical weathering

Courtesy Melissa Boysun

Primary Considerations for Flow in Sedimentary vs Crystalline Rock

Hydrology

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



Courtesy Johannes Mark

Primary Considerations for Flow in Sedimentary vs Crystalline Rock

Hydrology

- Influence of fractures
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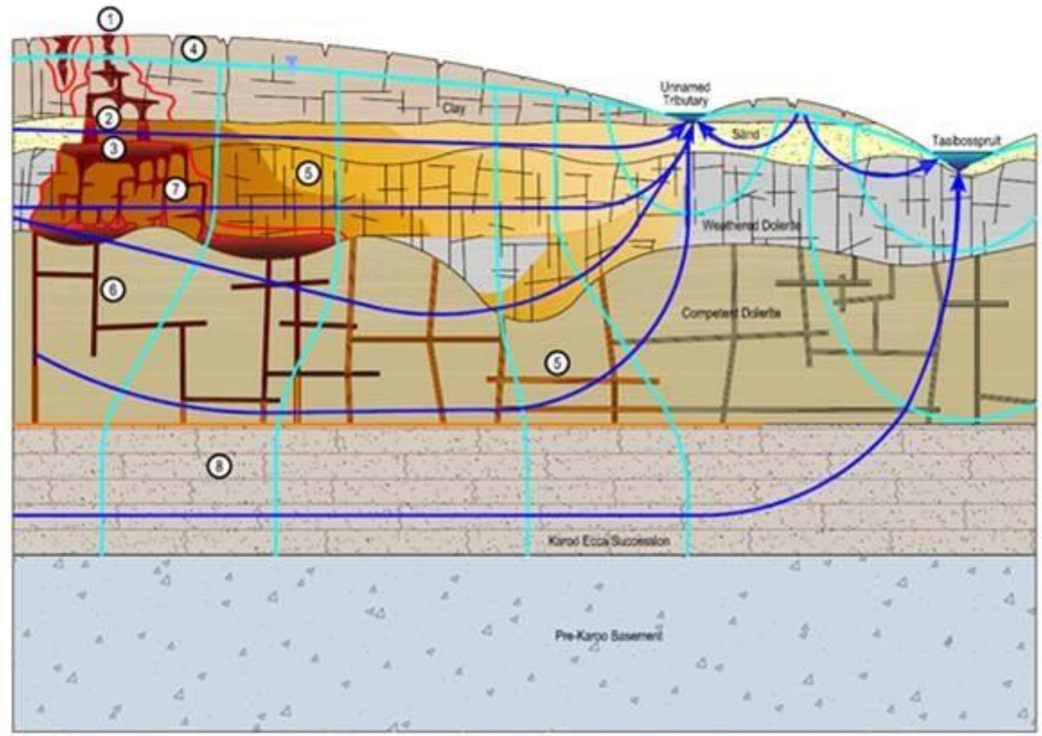
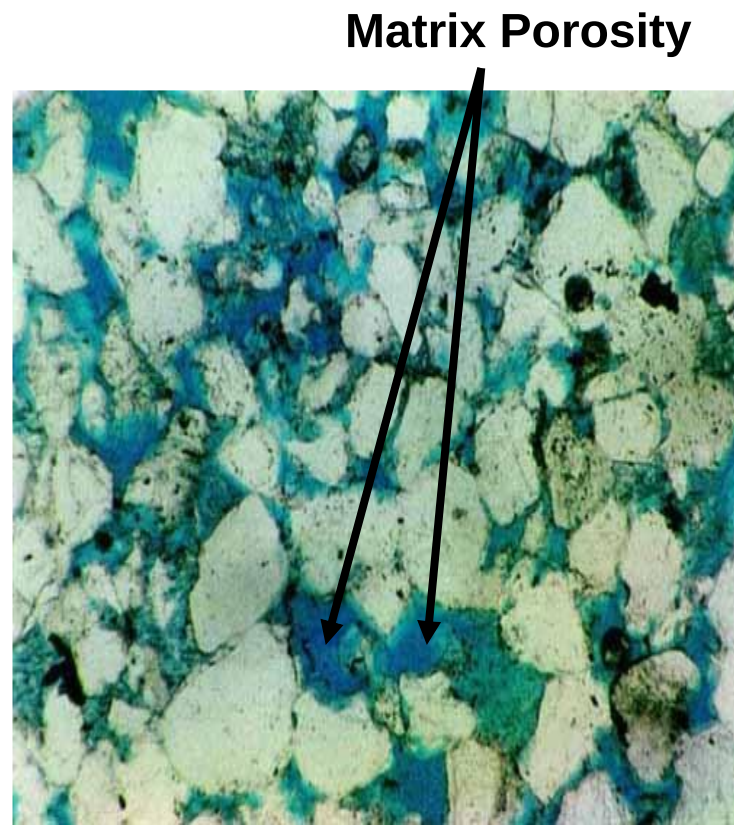
- Mechanical and chemical weathering



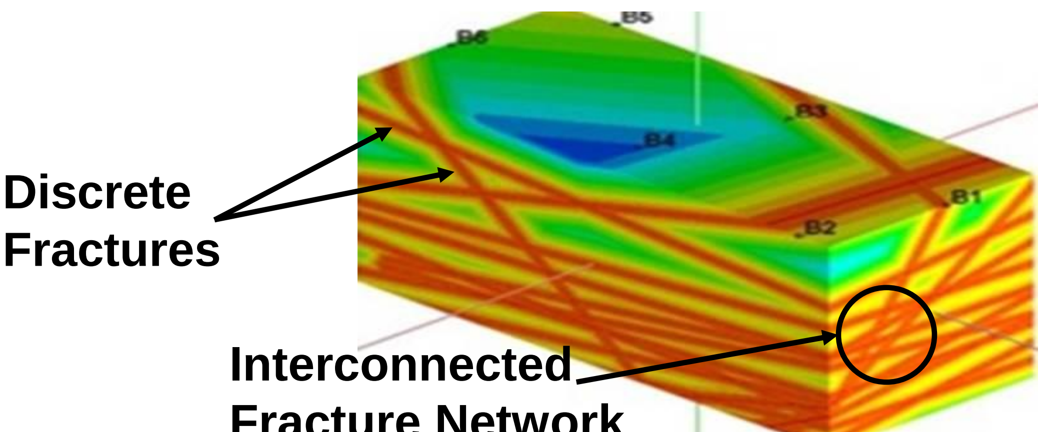
Courtesy Johannes Mark

Flow in Bedrock Drives the Approach to the Investigation

- Matrix flow
- Discrete fracture flow
- Interconnected fracture network flow



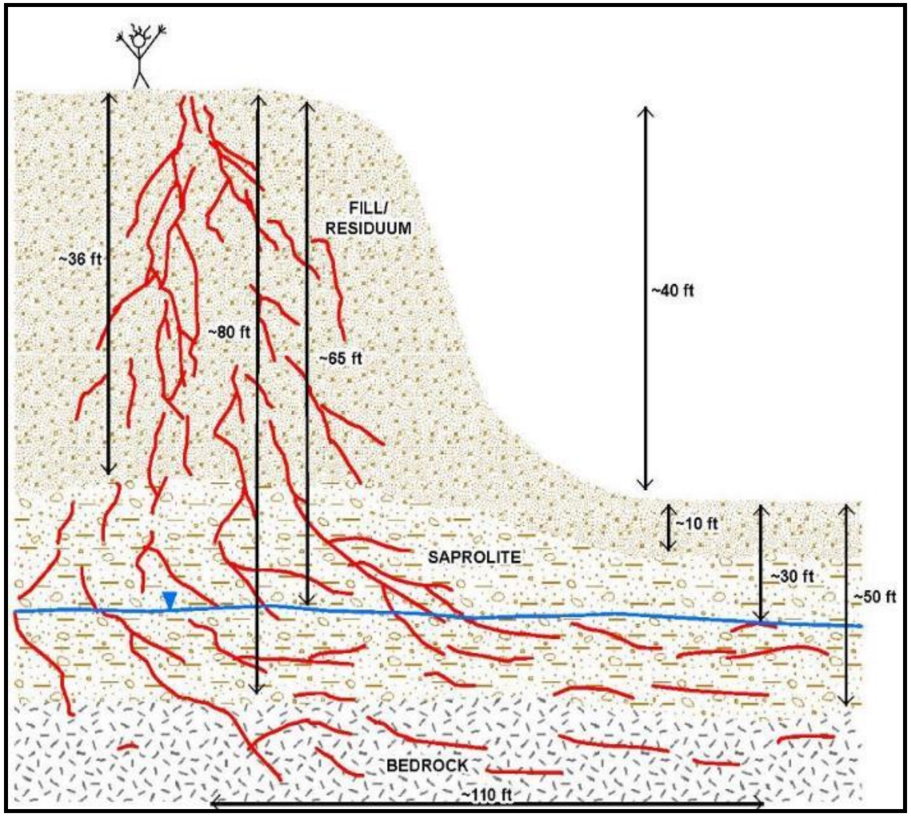
From PGA Ltd.



Fluid Dynamics

Hydrology

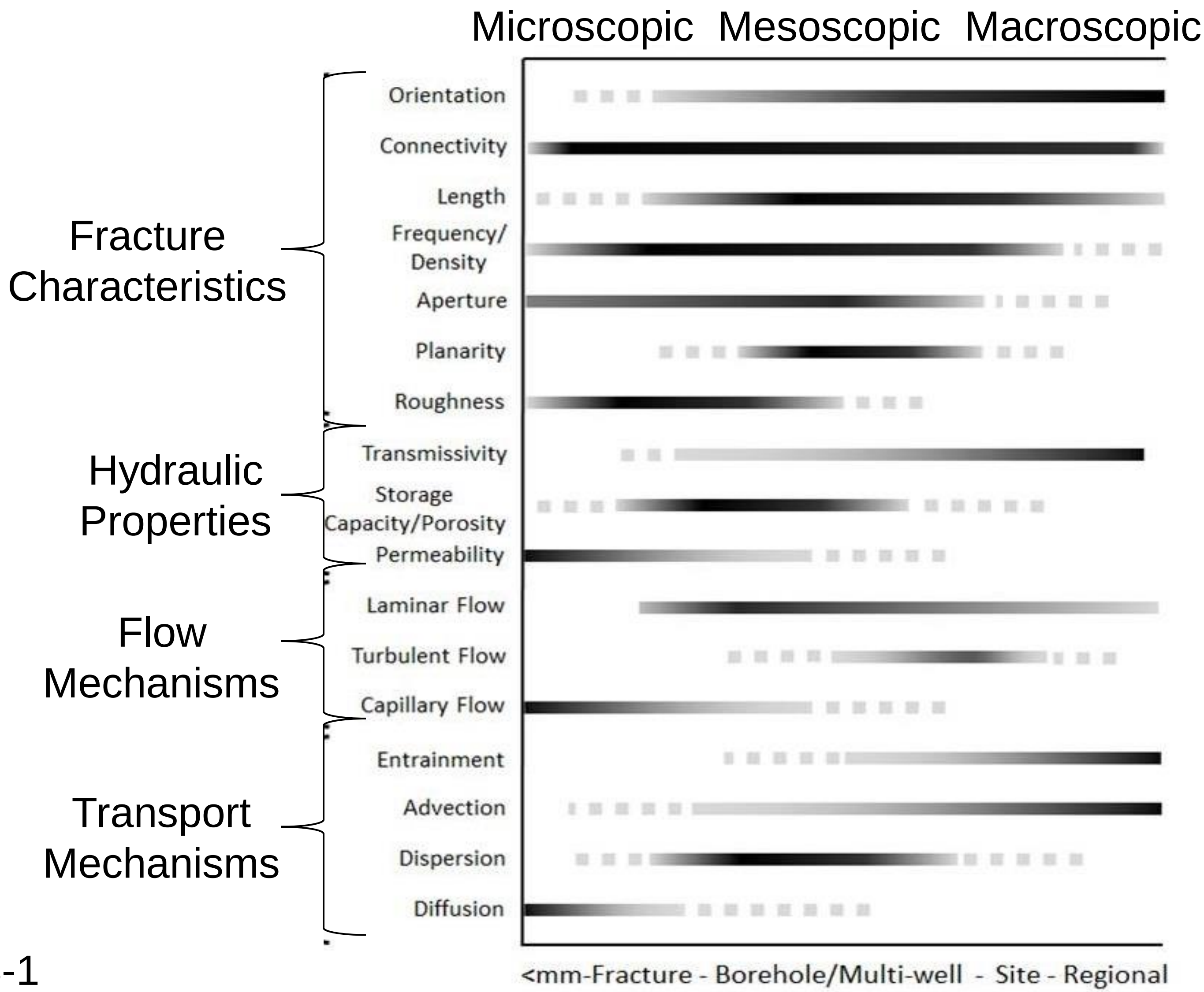
- Pressure and density gradients
- Laminar vs turbulent
  - Darcy vs non-darcy flow
  - Scale dependence
- Multi-fluid systems
  - Wetting vs non-wetting phases
  - Effects of density contrast



Courtesy Dan Bryant

Intersection of Scale and Fracture Flow Properties

- Macroscopic
- Mesoscopic
- Microscopic



ITRC FracRx-1 Figure 3-1

Macroscopic Flow: The Big Picture

- Occurs at regional or site-wide scale
- Regional factors beyond the site that could influence flow
  - Faults
  - Rivers
  - Tides
  - 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

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
  - Advection, entrainment, dispersion
- Primary scale of investigation
  - Majority of investigation and characterization techniques

Microscopic Flow: Tools for Fine-Tuning your Site Understanding

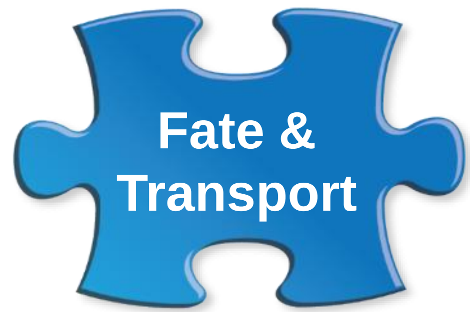
- Individual fracture, to matrix interaction
- Microscopic and individual fracture analysis
  - Investigate individual fracture characteristics
  - Core samples
  - Aperture increases by dissolution, or decreases by infilling
- Flow between fractures and matrix
- Interface between fracture and matrix and matrix storage effects F&T

Courtesy Jeff Hale

We may not get down to this scale very often

How to Integrate this with your CSM

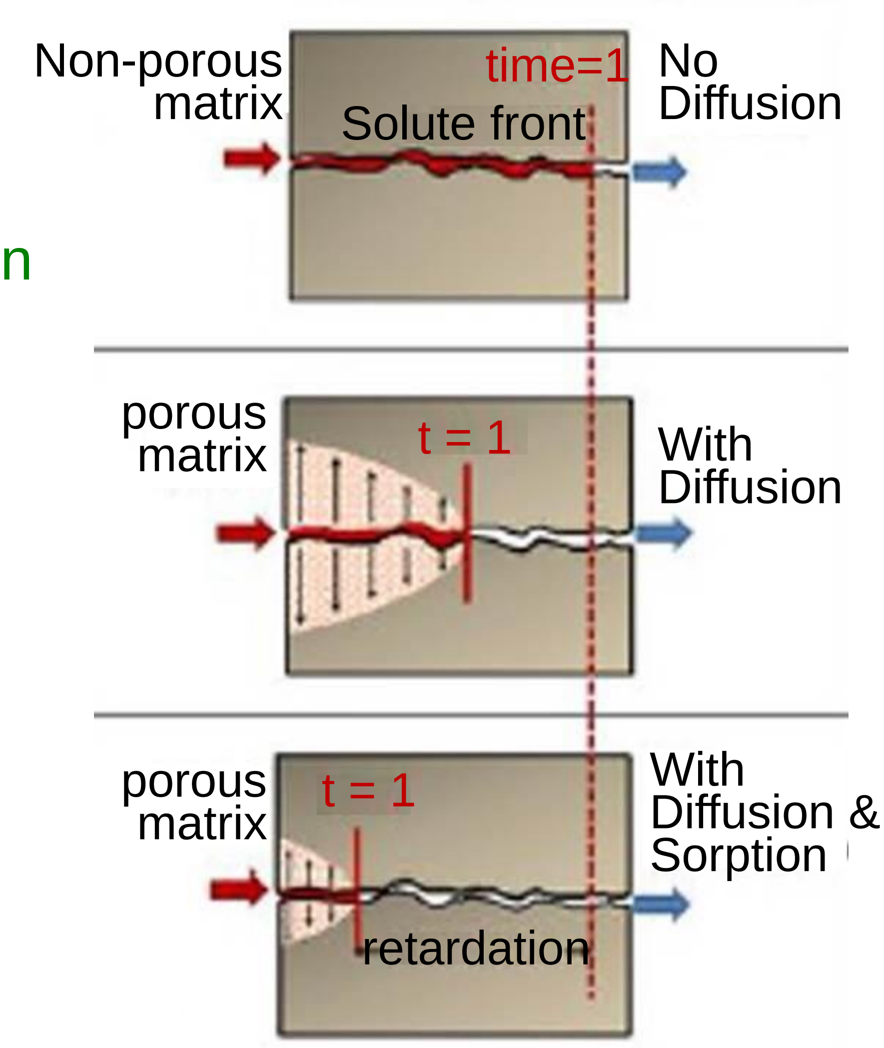
- Better understanding of where the fluid is and where it's going
- Started to look at how multiple phases interact
- Incorporated flow and fracture data from multiple scales



- 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 and advection
  - Matrix diffusion/back diffusion
  - Sorption/retardation
  - Degradation
    - Example: abiotic and biotic transformation

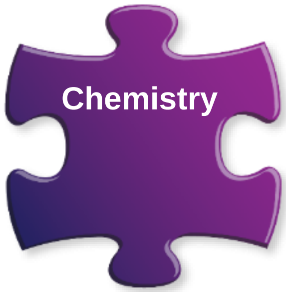


Freeze and Cherry 1979

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 how these properties affect flow in bedrock:
  - Flow through bedding planes
  - Flow through vertical fractures
  - Flow through 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

- Based on density, likely to sink in saturated zone
- Potential for partitioning to vapor phase
- Potential for dissolved plume and matrix diffusion
- Potential retardation along fracture walls and/or within rock matrix
- Abiotic transformation potential

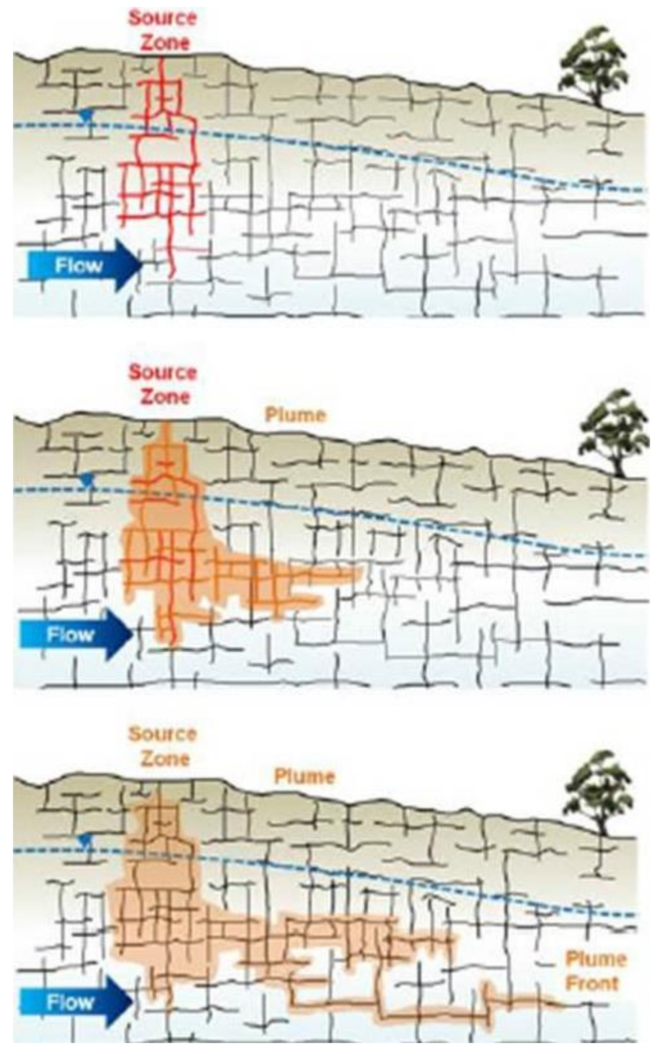
Contaminant Fate and Transport in Saturated Fractured Rock

- Example dense non-aqueous phase liquid (DNAPL) release
- Vertical migration into saturated zone
- Dissolution and advection within fractures
- Matrix diffusion/back diffusion, and potential sorption
- Consider potential for abiotic and/or biotic transformation

Early Time

Intermediate Time

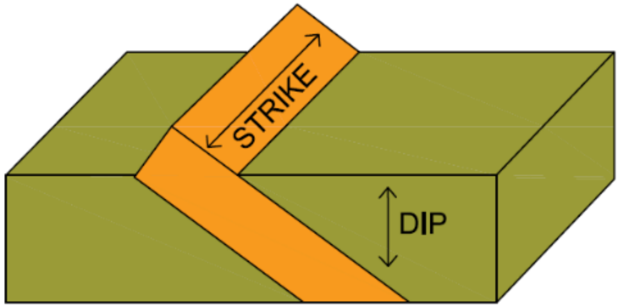
Late Time



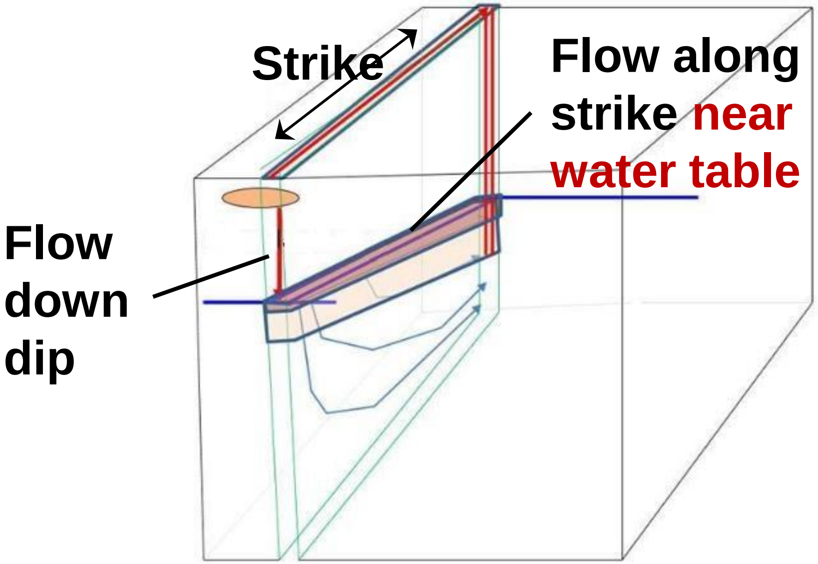
Parker et al. 2012

LNAPL in Fractured Rock

- Light non-aqueous phase liquid (LNAPL) migration in vertical fracture
  - Down dip in unsaturated zone
  - Along strike in saturated zone
- Dip of fracture can also affect difficulty of identifying LNAPL
  - Steeper fractures are less likely for a well to intersect
- In a horizontal fracture, hydraulic gradient could influence migration



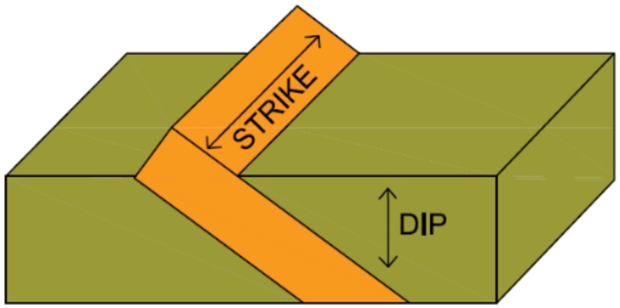
Courtesy Ted Tyler



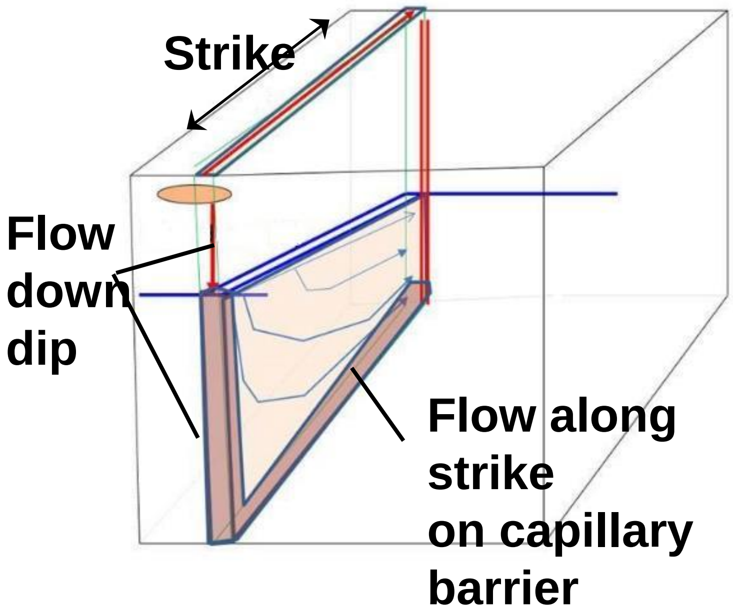
Courtesy Alex Wardle

DNAPL in Fractured Rock

- DNAPL migration in vertical fracture
  - Down dip in unsaturated zone
  - Down dip and potentially along strike in saturated zone
- Shallow well away from source area likely to miss DNAPL and highest dissolved concentrations
- Fracture dip can increase difficulty of identifying DNAPL but may help in locating the dissolved plume (see document for additional detail)
- In a horizontal fracture, hydraulic gradient could influence migration



Courtesy Ted Tyler



Courtesy Alex Wardle

Fate & Transport

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						

Fate & Transport

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

Key:
- Orange = high concentration
- Yellow = moderate concentration
- Green = low concentration

Fate & Transport

ITRC FracRx-1 Table D-3a

21 Compartment Model – Shale Bedrock

	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

Key:

- Orange = high concentration
- Yellow = moderate concentration
- Green = low concentration

Fate & Transport

ITRC FracRx-1 Table D-5a

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	NA
Dissolved	Negligible	NA	Medium	Medium	NA	Negligible
Sorbed	Negligible	NA	Medium	Medium	NA	Negligible

DNAPL spill site underlain by **fractured granite bedrock**

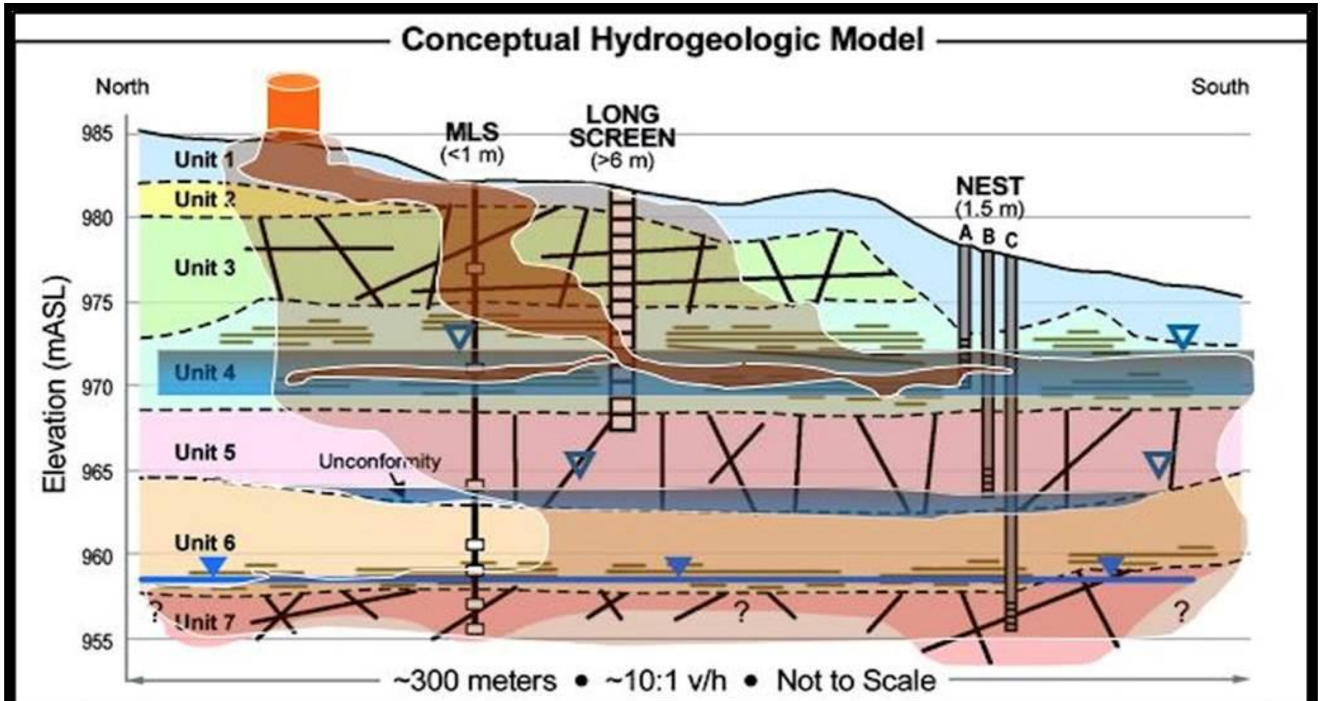
Key:

- Orange = high concentration
- Yellow = moderate concentration
- Green = low concentration

Fate & Transport

ITRC FracRx-1 Table D-5b

Combined 21 Compartment Model and Conceptual Hydrogeologic Model



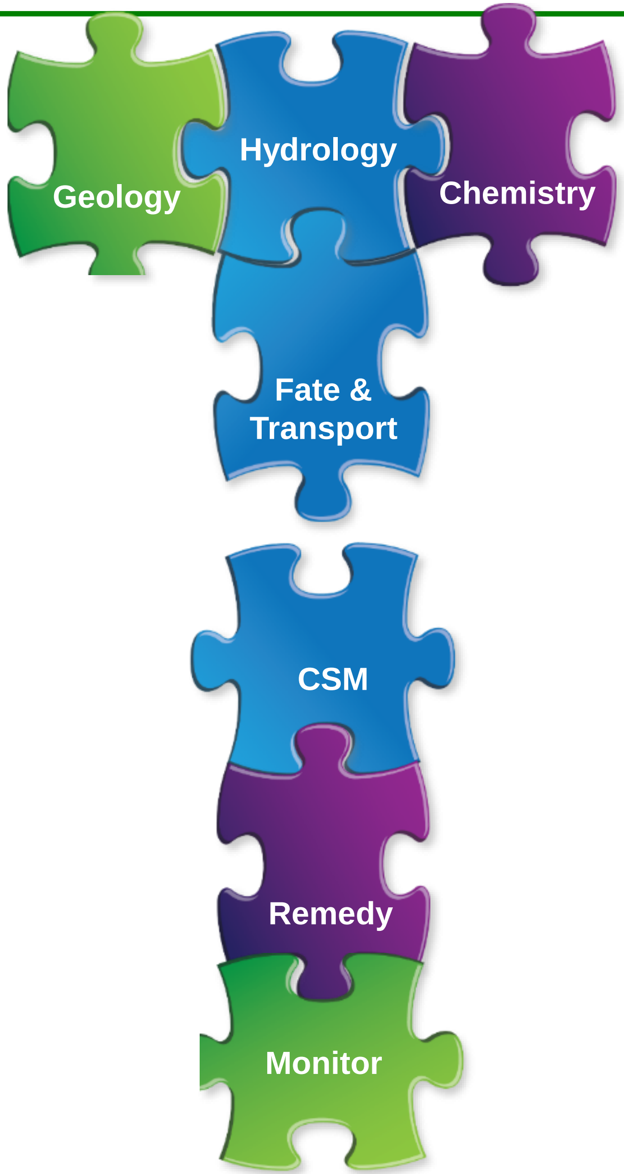
	Source Zone			DOWNGRADIENT EXTENT		
	Matrix Storage	Matrix Flow	Fracture Flow	Fracture Flow	Matrix Flow	Matrix Storage
Vapor		low			low	
NAPL		low		NA	NA	NA
Dissolved		low			low	
Sorbed		low			low	

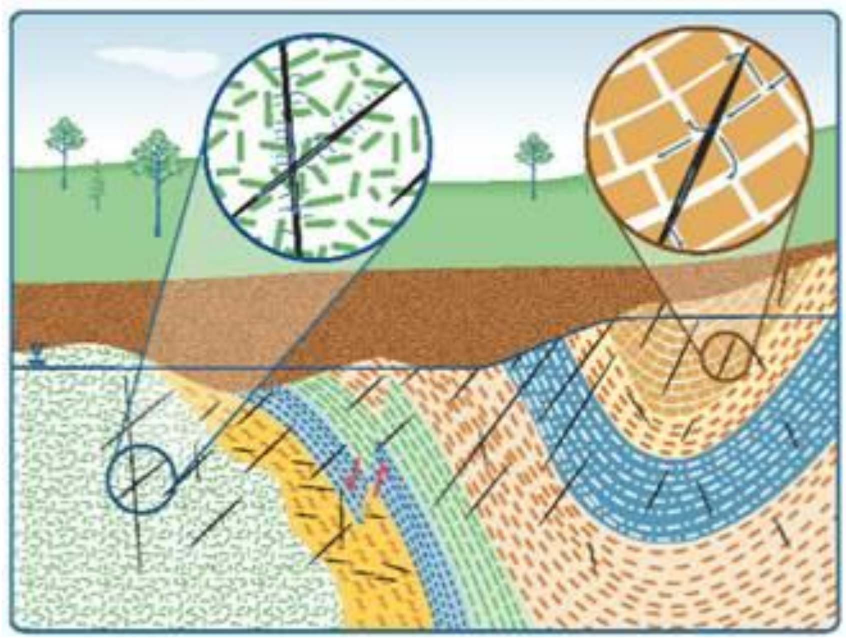
CSM Source: Jim Studer, InfraSUR

Fate & Transport

Q&A Break

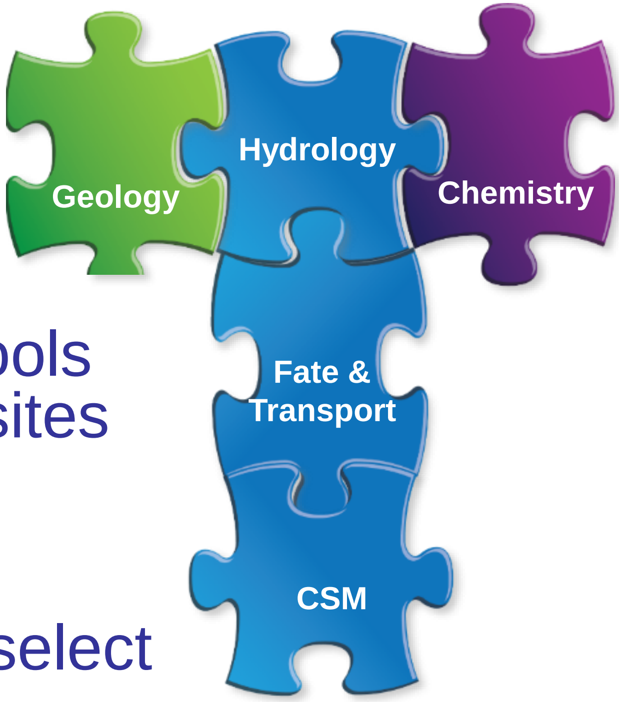
Follow ITRC





Today’s Road Map – Connects to ITRC Guidance

- Identify similarities and differences between characterizing fractured rock and unconsolidated media sites. (Chapters 2 - 4)
- Recognize the skills, approaches, and tools available to characterize fractured rock sites and develop CSMs (Chapter 5)
- Apply improved approaches to develop Remedial Action Objective (RAOs) and select remedies (Chapter 6)
- Describe development of a monitoring strategy for fractured rock sites (Chapter 7)



Developing a Fractured Rock CSM (Conceptual Site Model)

- Not a comprehensive start-to-finish “cookbook” for building a fractured rock CSM
- Discusses key elements unique to those sites
- Follows Integrated Site Characterization process developed in 2015 ITRC Guidance

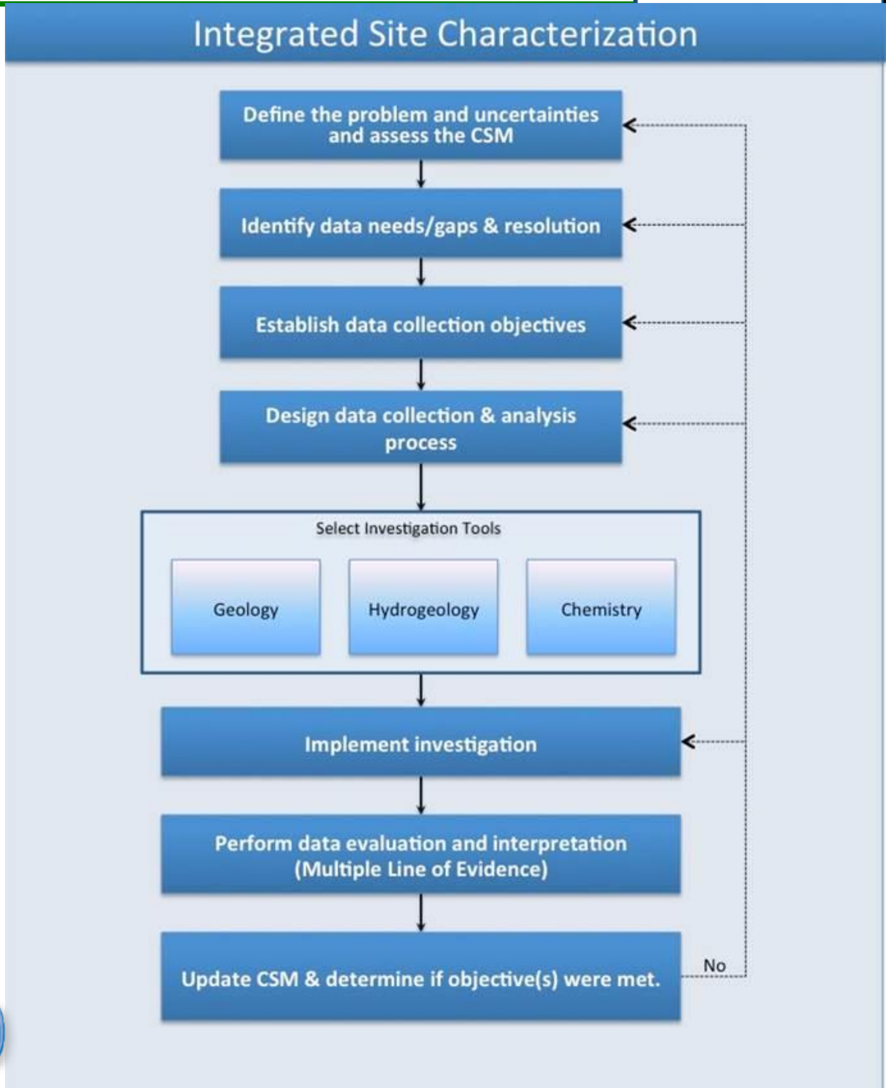


Figure 4-1 Integrated Site Characterization

ITRC ISC-1, 2015, Figure 4-1

Developing a Fractured Rock CSM – Key Elements

- Iteratively develop and assess the CSM (Section 5.1)
- Clearly define the problem statement (Section 5.2)
- Identify significant data gaps and needs, and resolution requirement (Section 5.3)
- Establish data quality objectives (Section 5.4)
- Select tools and techniques (Section 5.5)
- Carefully interpret, manage and present the data (Section 5.7)

Developing a Fractured Rock CSM – Process Summary

Initial Characterization Objectives

↓

Data Gap Resolution

What are specific Characterization Objectives?

↓

Data Collection Objectives

What do you need?

↓

Tools Table

How do you get there?

"Significant" Data Gaps

- Missing or incomplete information, which limits the formulation of a scientifically defensible interpretation of environmental conditions and/or potential risks in a bedrock hydrogeologic system.
- Likely to exist if more than one CSM can be supported by the data
- Reference: http://www.ct.gov/deep/lib/deep/site_clean_up/guidance/Site_Characterization/Final_SCGD.pdf

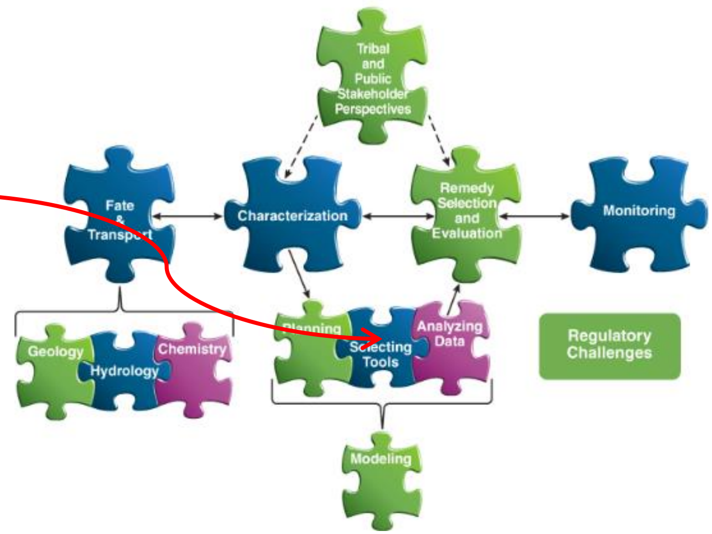
Examples of Objectives

- **Characterization Objective:** Determine the lateral and vertical extent of dissolved phase VOCs
- **Data Gap:** Vertical and lateral extent of dissolved phase VOCs is unknown
- **Data Collection Objective:** In areas beneath the source, and between the source and receptor(s), gather data:
  - Fracture locations
  - Fracture orientations
  - VOC concentrations

Tools Matrix Format and Location

- The tools matrix is a downloadable excel spreadsheet
- Tools segregated into categories and subcategories

The Fractured Rock Puzzle



Tool
Geophysics
Surface Geophysics
Downhole Testing
Hydraulic Testing
Single well tests
Cross Borehole Testing
Vapor and Soil Gas Sampling
Solid Media Sampling and Analysis Methods
Solid Media Sampling Methods
Solid Media Evaluation and Testing Methods
Direct Push Logging (In-Situ)
Discrete Groundwater Sampling & Profiling
Multilevel sampling
DNAPL Presence
Chemical Screening
Environmental Molecular Diagnostics
Microbial Diagnostics
Stable Isotope and Environmental Tracers
On-site Analytical

Tools Table can be downloaded on the opening page of ITRC FracRx-1

Orientation to the Tools Matrix

- Contains over **100** tools
- Sorted by:
  - Characterization objective
    - Geology
    - Hydrogeology
    - Chemistry
  - Effectiveness in media
    - Unconsolidated/Bedrock
    - Unsaturated/Saturated
- Ranked by data quality
  - Quantitative
  - Semi-quantitative
  - Qualitative

Tool	Data Quality	Sub surface		Zone	
		Bedrock	Unconsolidated	Unsaturated	Saturated
Geophysics					
Surface Geophysics					
Ground Penetrating Radar (GPR)	QL - Q	✓	✓	✓	✓
High Resolution Seismic Reflection (2D or 3D)	QL - Q	✓	✓		✓
Seismic Refraction	QL - Q	✓	✓	✓	✓
Multi-Channel Analyses of Surface Waves (MASW)	QL - Q	✓	✓	✓	✓
Electrical Resistivity Tomography (ERT)	QL - SQ	✓	✓	✓	✓
Very Low Frequency (VLF)	QL	✓	✓	✓	✓
ElectroMagnetic (EM) Conductivity	QL	✓	✓	✓	✓
Downhole Testing					
Magnetometric Resistivity	QL	✓	✓		✓
Induction Resistivity (Conductivity Logging)	QL - Q	✓	✓	✓	✓
Resistivity (Elog)	QL - SQ	✓			✓
GPR Cross-Well Tomography	QL - Q	✓	✓	✓	✓
Optical Televiewer	QL - Q	✓	✓	✓	✓
Acoustic Televiewer	QL - Q	✓			✓
Natural Gamma Log	QL - Q	✓	✓	✓	✓
Neutron (porosity) Logging	QL - Q	✓	✓		✓
Nuclear Magnetic Resonance Logging	QL - Q	✓	✓	✓	✓
Video Log	QL - SQ	✓	✓	✓	✓
Caliper Log	QL - Q	✓	✓	✓	✓
Temperature Profiling	QL - Q	✓	✓		✓
Full Wave Form Seismic	Q - QL	✓			✓

Tools Table can be downloaded on the opening page of ITRC FracRx-1

Tools Matrix Functionality

Click any box for a description or definition

E.3 Geology

Geologic data provide a means to describe the physical matrix and structure of the subsurface and to classify the sedimentary, igneous, or metamorphic environment. Data related to lithology and distribution of strata and facies changes are generated through a variety of qualitative and quantitative collection tools and methods.

Initial methods and tools used to characterize site geology include site walkovers to help gain a preliminary understanding of the site prior to a major field mobilization, which can involve the use of both intrusive and nonintrusive tools. Outcroppings offer insight into structural features of the bedrock, and much information can be obtained through basic geologic mapping techniques (for example, measuring strike and dip of planar features and plotting on a stereonet).

Following a surface investigation, the next step in site characterization commonly involves collecting a continuous core of sediments and bedrock. Data provided by this core sampling may include lithology, grain size and sorting, crystalinity, geologic contacts, bedding planes, fractures and faults, depositional environment, porosity, and permeability. Generally, numerous boreholes are drilled to determine the vertical and horizontal variability of the site-specific geology. The depositional environment and facies changes should also be mapped as much as possible, and these data may be combined with surface and borehole geophysical data to interpolate conditions between the holes. Downhole geophysical tools and direct-push tools – for example, membrane interface probe (MIP), hydraulic profiling tool (HPT), and Waterloo profiler – can provide detailed information on the geology and contaminant distribution at a site.

Effective site geology characterization requires that personnel are trained and experienced in field geology and are able to accurately assess the collected data. It is also important that the team use consistent investigative methods – for example, characterizing soil or rock type using the same, agreed upon classification system. The team must determine the level of data resolution necessary to adequately characterize a specific site and whether surface and borehole geophysical data are of sufficient resolution.

Unfortunately, collection efforts at contaminated sites often yield insufficient geologic data, leading to a high degree of uncertainty in subsurface interpretation. Historically, there has been a tendency to oversimplify conceptual site models (CSMs), which has led to the misperception that physical (geologic) conditions of the site can be engineered around – that is, limitations in site characterization data can be compensated by overdesigning remediation systems. However, remedy performance success rates have been poor under such circumstances, whereas investing in adequately detailed site characterization has provided a positive return on investigation in terms of improved remedy success rates and reduced life cycle costs.

Oversimplification of CSMs is particularly relevant to glaciated regions with complex depositional environments. In the northeast and Midwest, many glaciated sites contain both bedrock and glacial aquifers that have DNAPL issues. Under such conditions, hydrogeological and geological expertise specific to glacial environments and their depositional characteristics is required for developing an accurate and complete CSM, and is key to the success of a DNAPL remedy.

Detailed Tool Descriptions

Click on any tool

- Additional reference material
- Description
- Applicability
- Limitations

Click

Tool	Data Quality	Sub surface		Zone	
		Bedrock	onsolidated	nsaturated	Saturated

Tool/References	Description	Data Quality and Applicability/Advantages	Limitations/Difficulty
Ground Penetrating Radar • Annan 2005 • Bayer et al. 2011 • Beres et al. 1999 • Bradford 2006 • Bradford and Deeds 2006 • Bradford, Dickins, and Brandvik 2010 • Bradford and Babcock 2013 • Clement, Barrash, and Knoll 2006 • Guerin 2005 • USEPA 2004	Ground penetrating radar (GPR) creates a cross-sectional imaging of the ground based on the reflection of an electromagnetic (EM) pulse from boundaries between layers of different dielectric properties. The quality depends on soil and water conditions as penetration is reduced by clay, water, and salinity. GPR is useful in resolving stratigraphic layers; however, independent confirmation of lithology is required. GPR generates a 2D profile, but it can be run with multiple lines in a grid pattern to generate a pseudo-3D image. Penetration and resolution of features depend on antenna frequency and material conductivity and interferences, and are generally limited to 20 meters (m) deep. GPR can identify internal structures between material-bounding reflectors (e.g., cross-bedding) in some cases. GPR can be used to locate geologic material or property contacts associated with dielectric property contrasts (e.g., proxy for porosity in some water-saturated clastic sediments) as well as subsurface infrastructure (e.g., pipes, tanks, cavities).	Data Quality • varies with antennas and subsurface EC • relatively sharp boundaries • qualitative to quantitative depending on field conditions, prior knowledge/subsurface calibration, experimental quality, appropriate modeling Applicability/Advantages • relatively fast to acquire, and processing methodology well established • primarily used in materials with low EC (sand, gravel, or rock except shales) • can be run repeatedly in time-lapse mode to track changes in moisture (above water table) or EC or dielectric properties (plume or spill bodies, including several experiments tracking presence and changes in dense nonaqueous phase liquid [DNAPL] in sandy aquifers)	• minimal penetration in electrically conductive (silts and clay-rich or conductive pore water) units • interpretation of features and depths semiquantitative without independent reference (well or cone penetrometer [CPT])

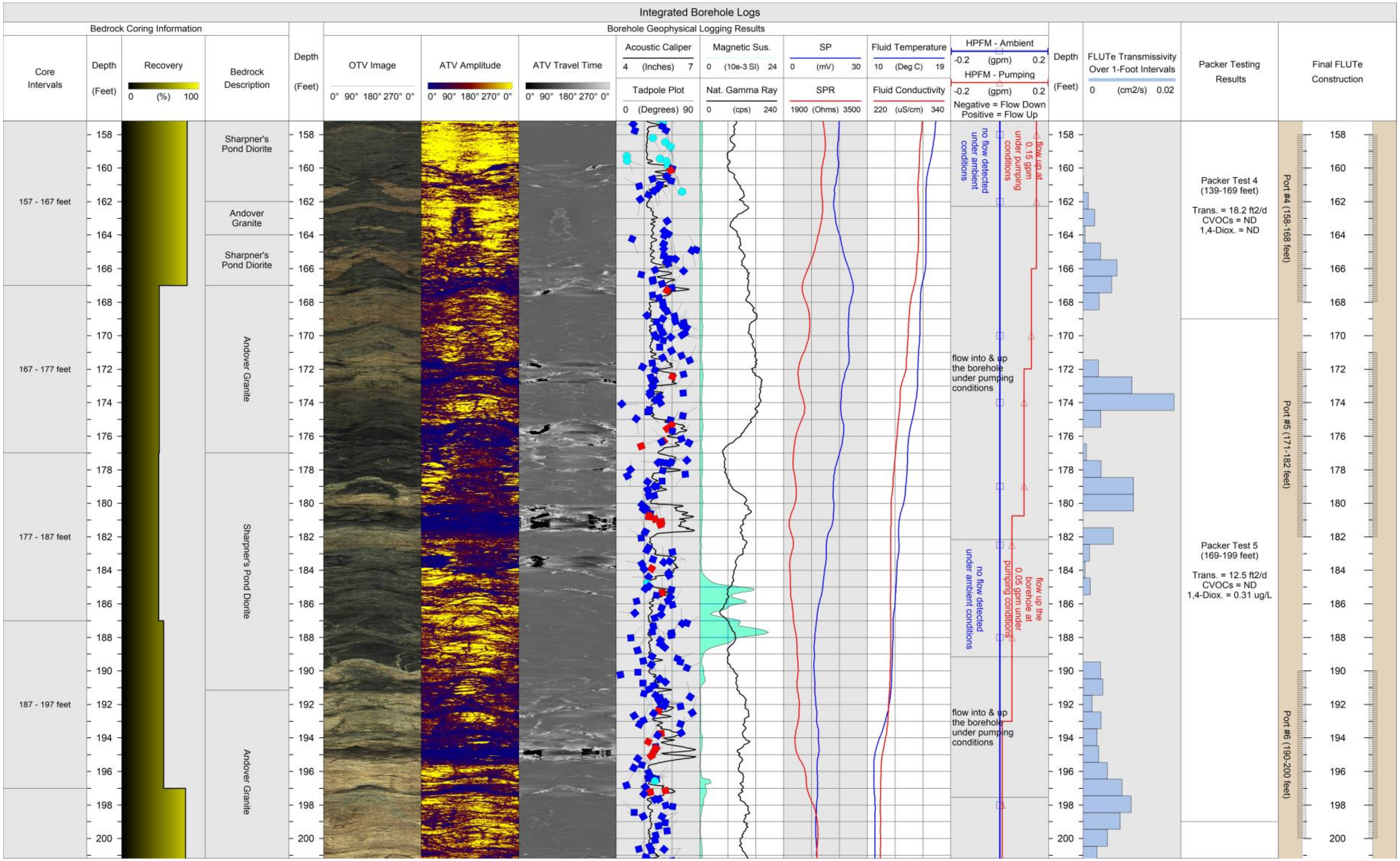
Shaded Boxes Denote Tool Meets Objective

Tools collect these types of information

Tool	Data Quality	Sub surface Zone: Bedrock	Sub surface Zone: Unconsolidated	Sub surface Zone: Unsaturated	Sub surface Zone: Saturated	Geology: Lithology	Geology: Lithology Contacts	Geology: Porosity	Geology: Permeability	Geology: Dual Permeability	Geology: Faults	Geology: Fractures	Geology: Fracture Density	Geology: Fracture sets	Geology: Rock Competence	Geology: Mineralogy
Geophysics																
Surface Geophysics																
Ground Penetrating Radar (GPR)	QL - Q	✓	✓	✓	✓	green	green	green			green					
High Resolution Seismic Reflection (2D or 3D)	QL - Q	✓	✓		✓	green	green				green	green	green		green	
Seismic Refraction	QL - Q	✓	✓	✓	✓	green	green				green				green	
Multi-Channel Analyses of Surface Waves (MASW)	QL - Q	✓	✓	✓	✓	green	green				green					
Electrical Resistivity Tomography (ERT)	QL - SQ	✓	✓	✓	✓	green	green	green			green				green	
Very Low Frequency (VLF)	QL	✓	✓	✓	✓		green				green	green				
ElectroMagnetic (EM) Conductivity	QL	✓	✓	✓	✓	green	green				green					
Downhole Testing																

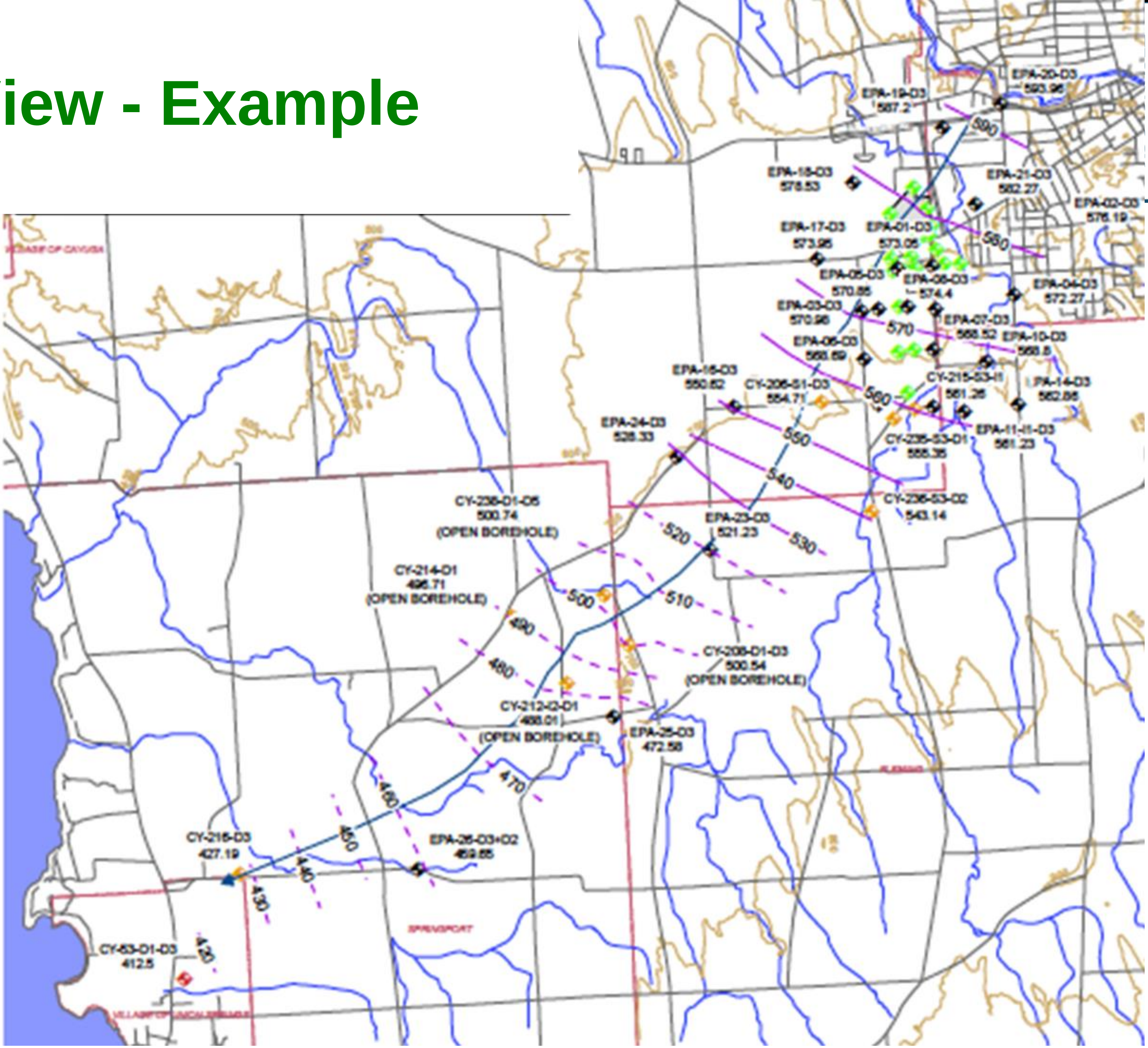
Green shading indicates that tool is applicable to characterization objective

Integrated Borehole Log - Example



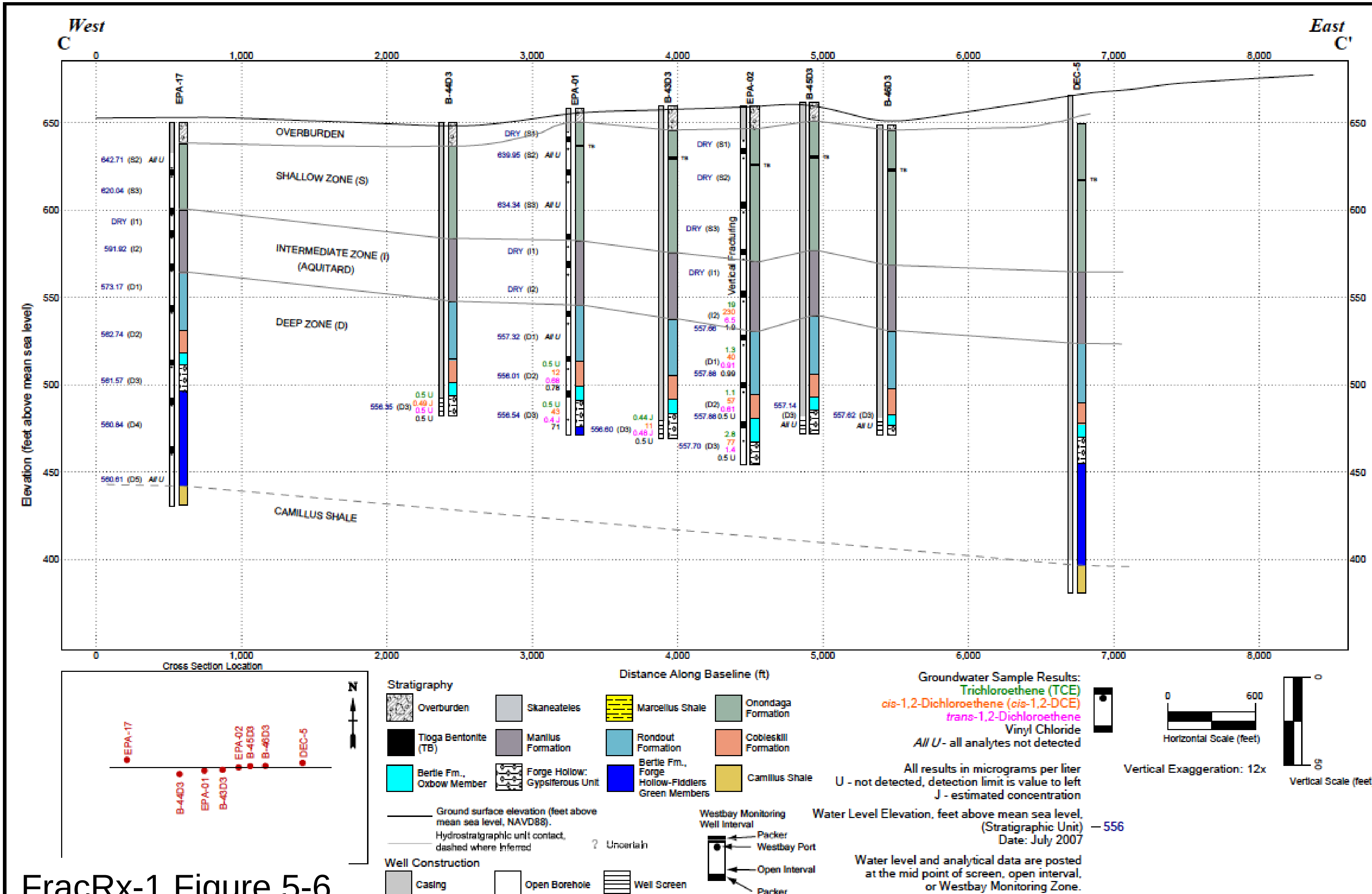
Courtesy Rob Garfield, Hager-Richter Geoscience

Plan View - Example



ITRC FracRx-1
Figure 5-5

Cross Section – Example



FracRx-1 Figure 5-6

Characterization of Fractured Rock Generic Flow Path

ITRC ISC-1, 2015

Develop and Implement Work Plan

- Select tools
- Drill bedrock boreholes
- 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.)
- Sample and analyze groundwater

Develop a Workplan

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 may be used for data evaluation and interpretation
- Include data evaluation process

Develop a Workplan

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

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

Implement a Site Investigation

- 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

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**.

Site Characterization
SRSNE Case Study Learning Objectives

Using this case study site as an example…

- See how regional (“macroscopic) structure influences site-scale (“mesoscopic”) structure
- Recognize the usefulness of measuring and analyzing in-situ bedrock fracture orientation data
- Understand how fracture orientations affect
  - Modeled groundwater flow directions (anisotropy)
  - Observed plume geometry
  - DNAPL migration
- See the hydraulic and fate-and-transport parameters that were quantified to understand the fracture system and the matrix

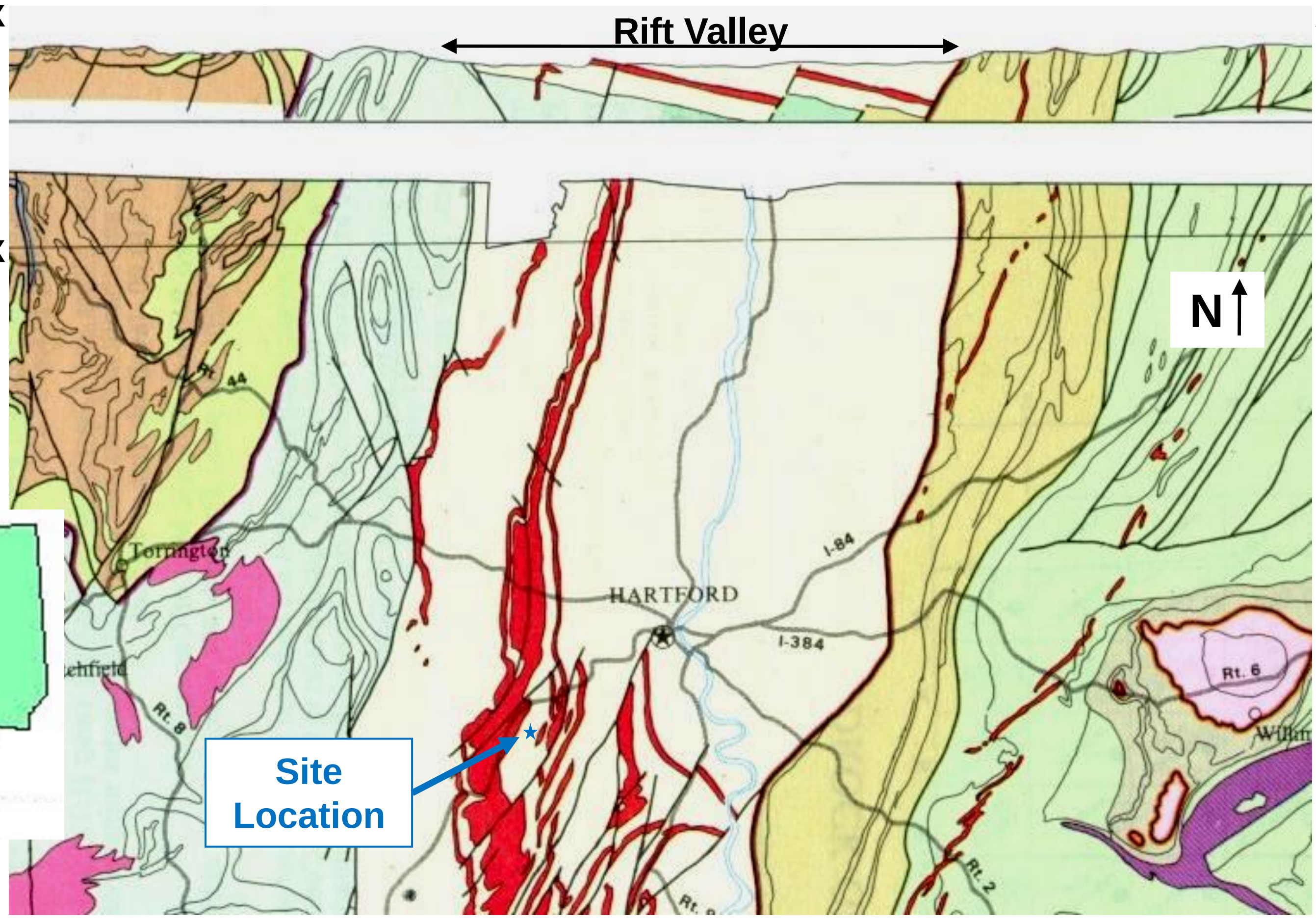
Site Characterization - Case Study

Regional Setting - Connecticut Rift Valley

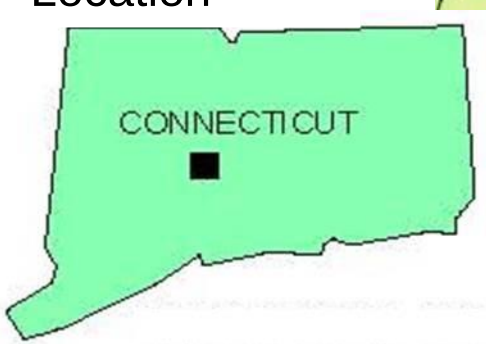
Solvents Recovery Service of New England, Inc. (SRSNE) Superfund Site

Geologic Cross Section

Geologic Map



Quadrangle Location



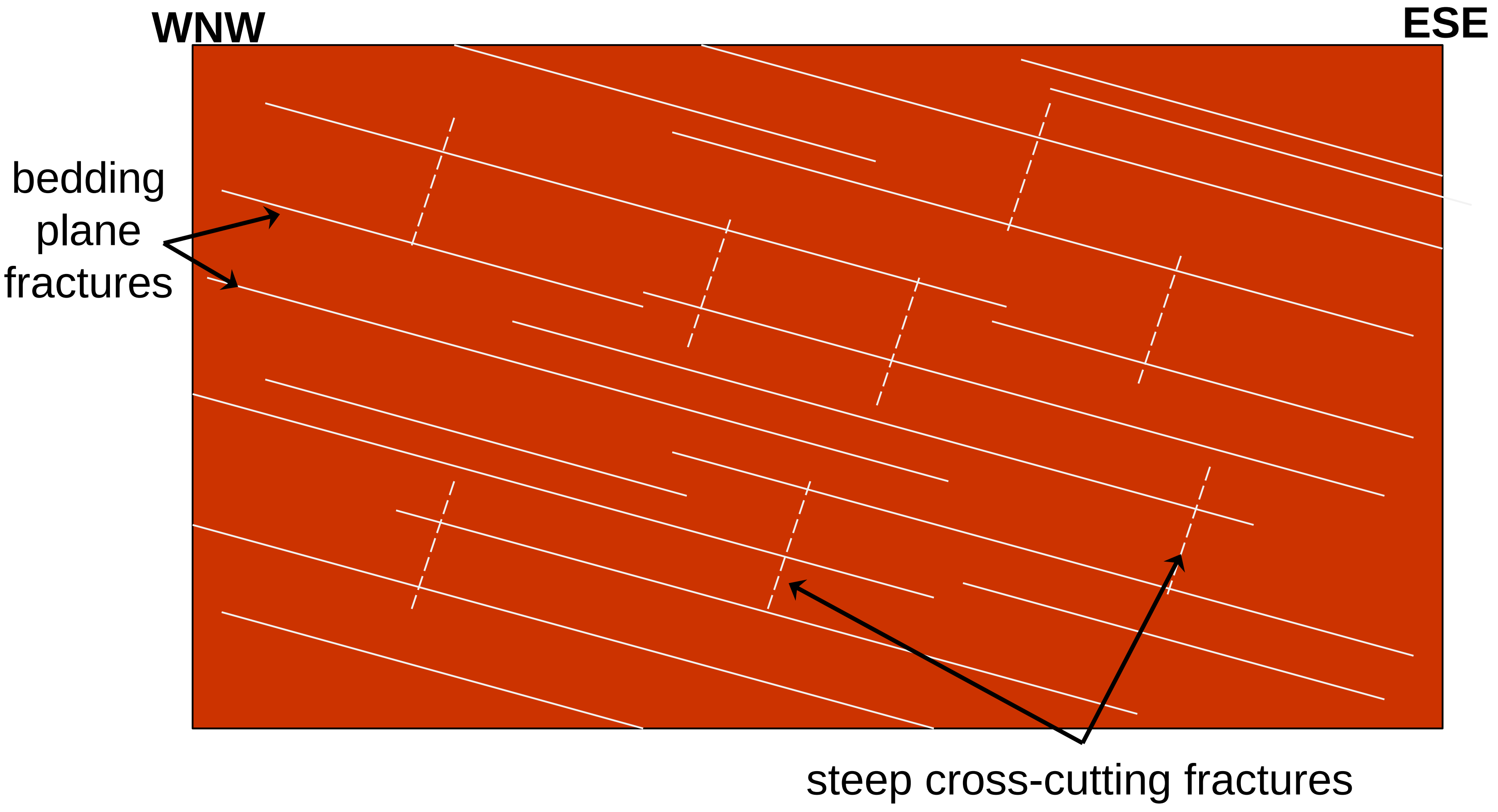
Courtesy Michael Gefell

10 km (approximately)

Source: Basemap from Connecticut Geological and Natural History Survey, 1990. White-colored map area = sedimentary rocks ("red beds")

Bedrock Conceptual Model

Cross Section Perpendicular to Inferred Strike of Fractures (Primary Groundwater Flow Direction)



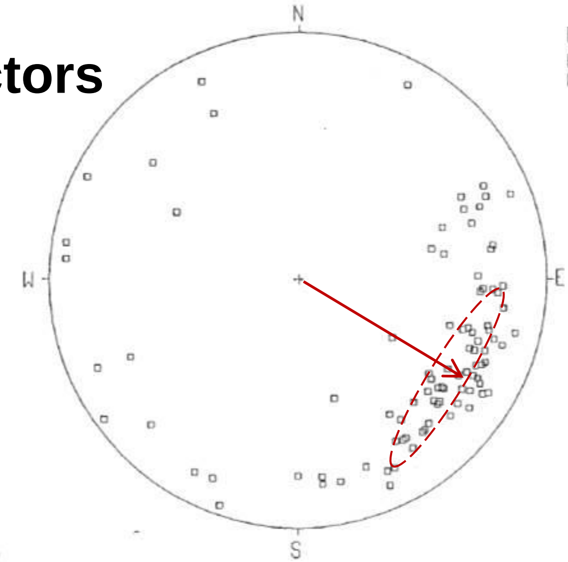
Courtesy Michael Gefell

In Situ Fracture Orientation Data

“Raw” data - not corrected for magnetic declination.

True orientations are 14˚ counterclockwise of these.

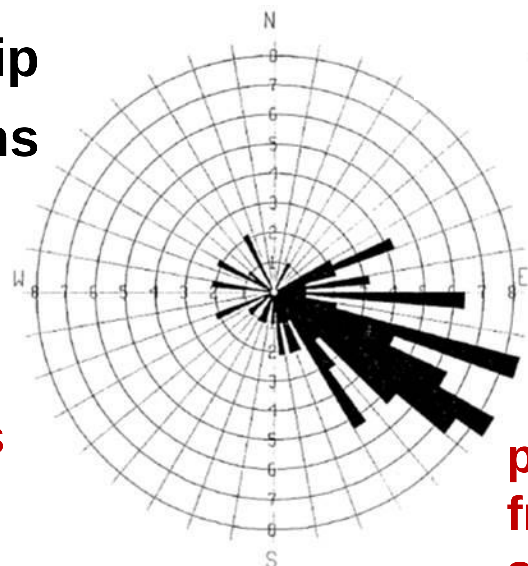
Dip Vectors



most dip vectors oriented toward ESE

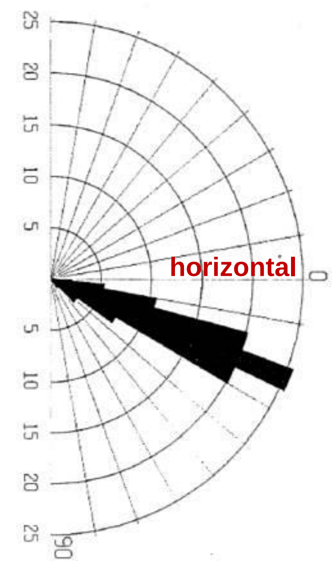
Dip Directions

note wide variety of secondary dip directions (minor cross-cutting fractures)



primary fracture set

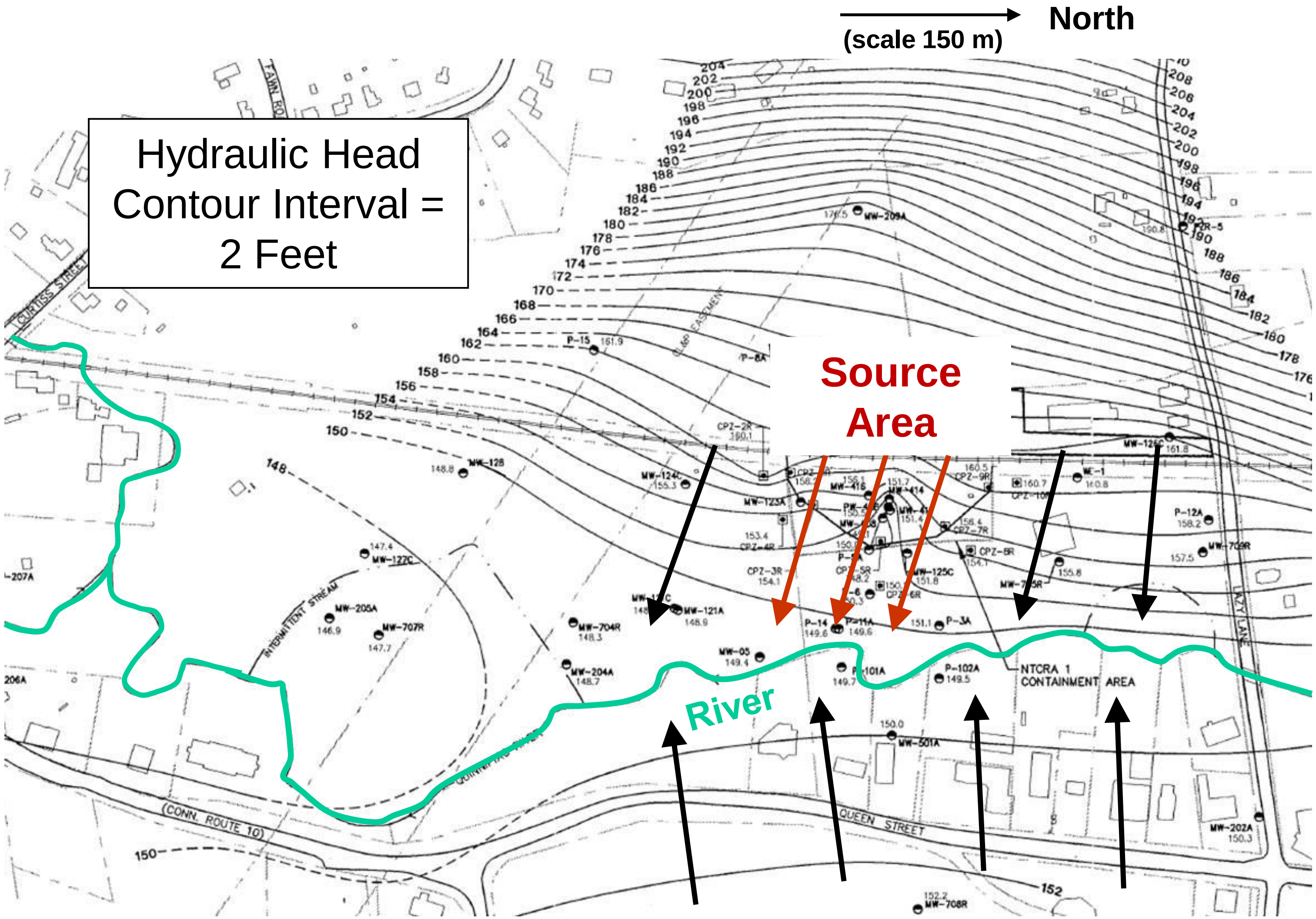
Dip Angles



consistent fracture dip for primary fracture set

Courtesy Michael Gefell

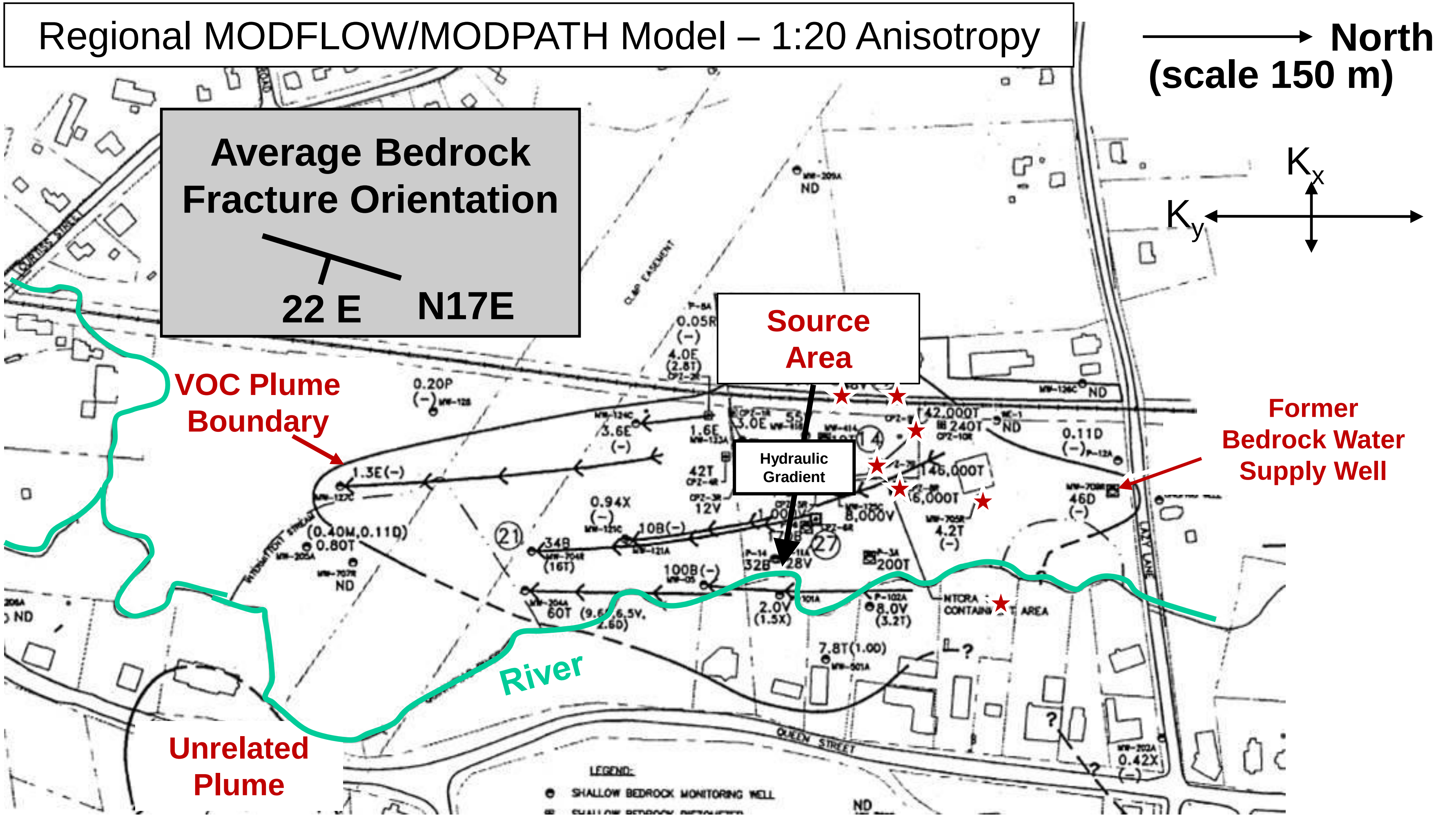
Plan View Hydraulic Gradient in Bedrock



Courtesy Michael Gefell

Modeled Anisotropy - Calibrated to Plume in Bedrock

Regional MODFLOW/MODPATH Model – 1:20 Anisotropy

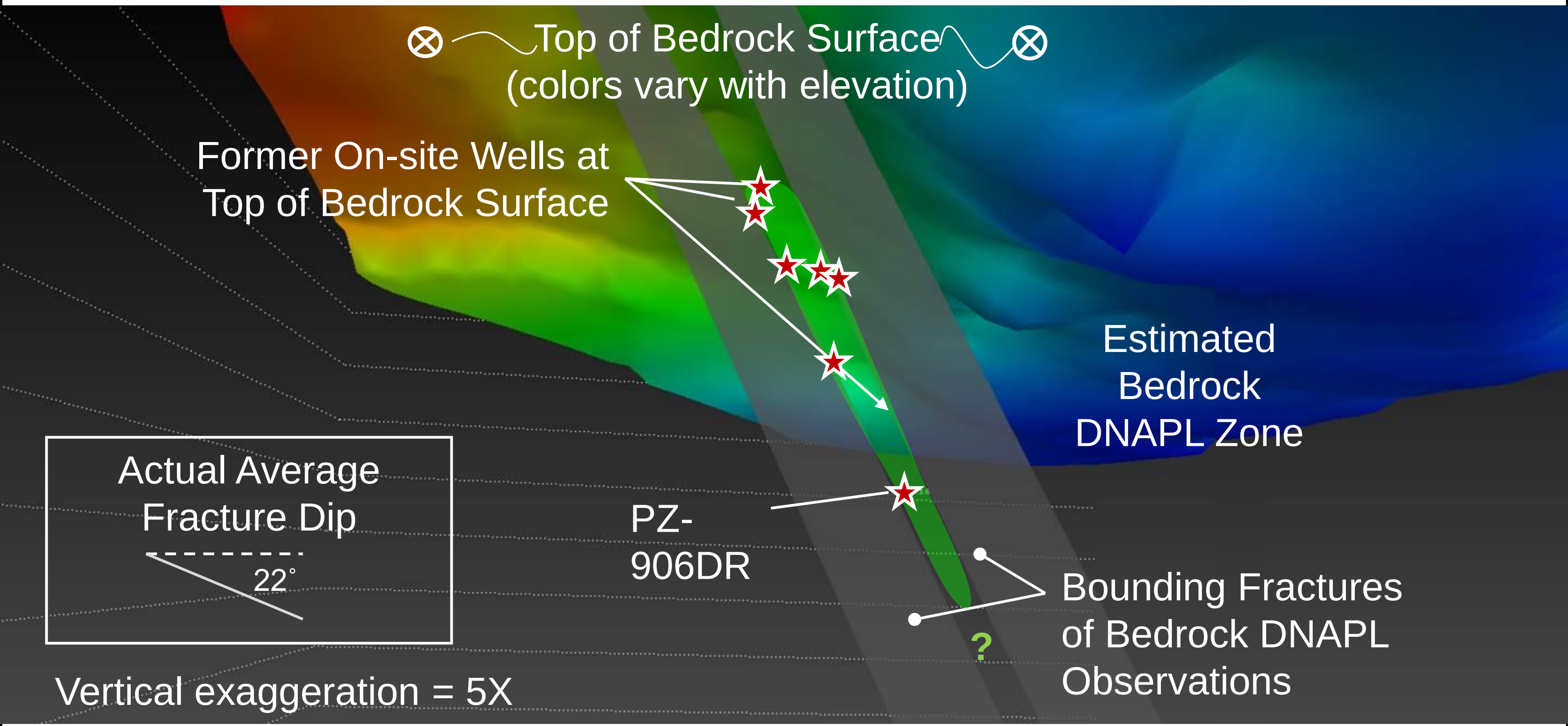


★ = DNAPL/Sheen Encountered in Bedrock

Courtesy Michael Gefell

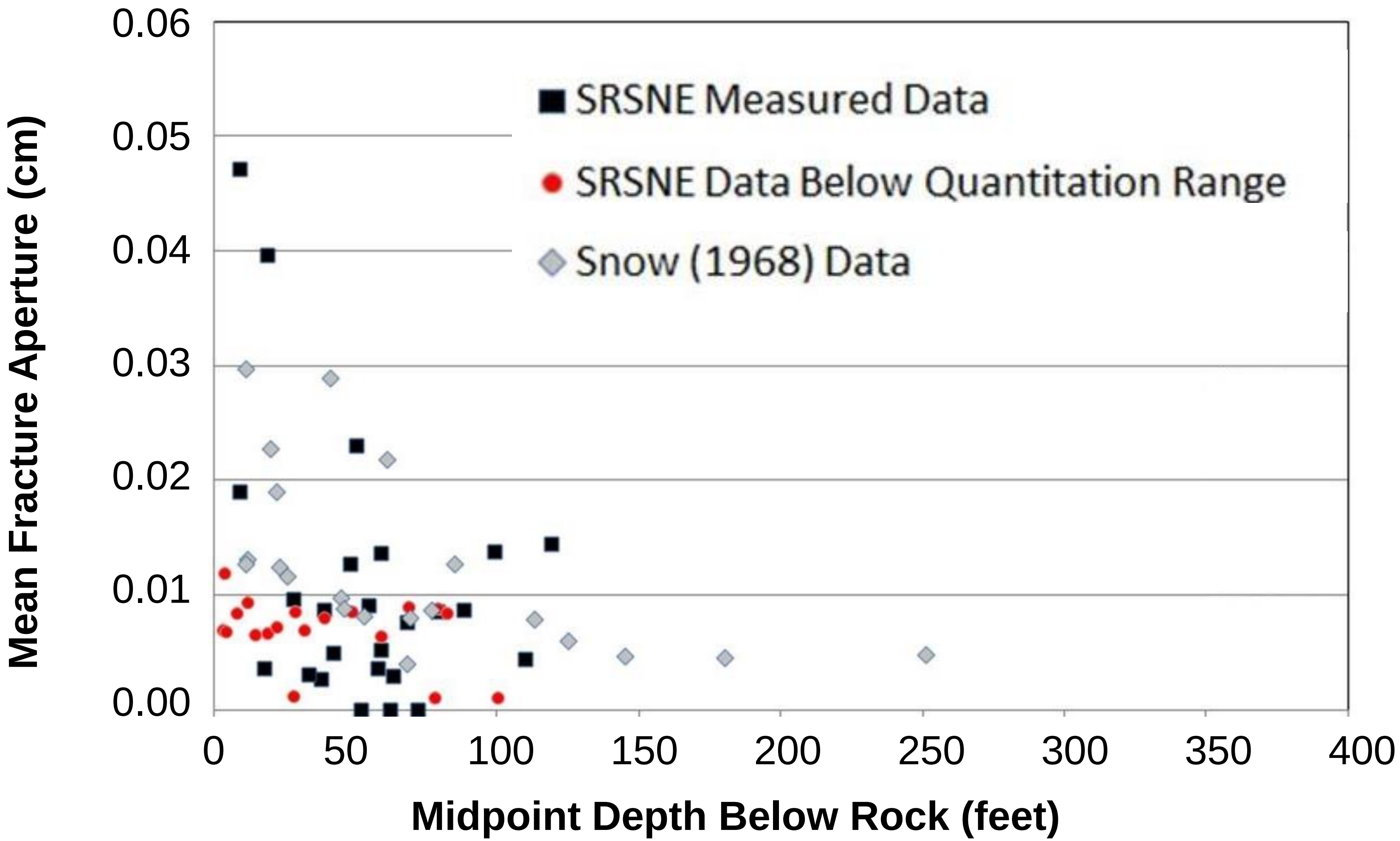
3-D Model of DNAPL Observations in Bedrock

Looking North-Northeast Along Strike of Fractures



Courtesy Michael Gefell

Fracture Hydraulic Aperture vs. Depth below top of Bedrock



Courtesy Michael Gefell

Site Specific Average Data for Fate and Transport Evaluation

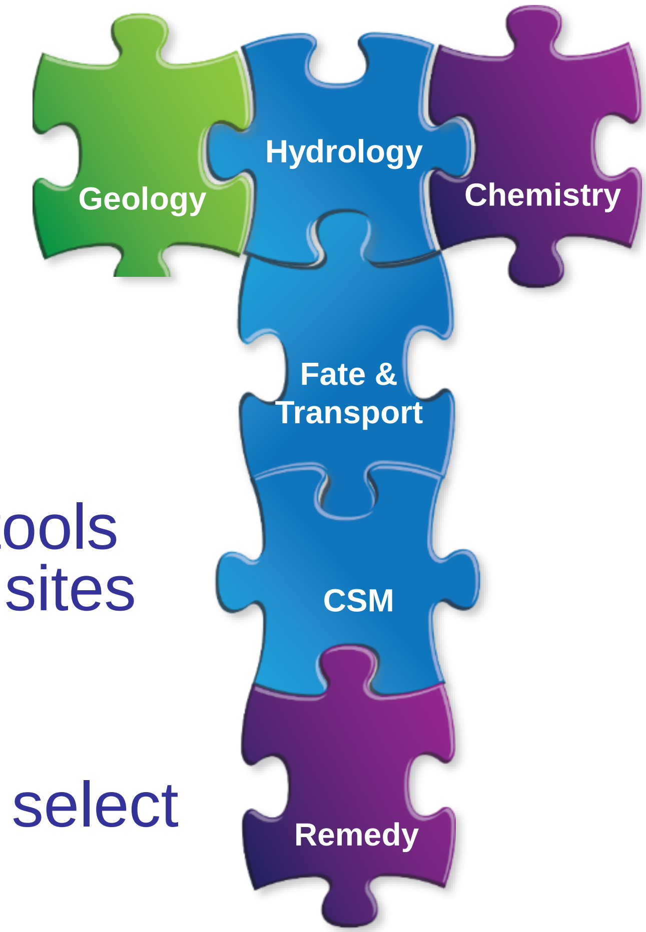
- Bulk permeability = 10^{-4} cm/s
- Matrix porosity = 8%
- Fraction organic carbon = 0.5%
- Fracture aperture = 97 microns
- Fracture spacing = 155 cm
- Fracture porosity = 0.006%

Courtesy Michael Gefell

Courtesy Michael Gefell

Today's Road Map – Connects to ITRC Guidance

- Identify similarities and differences between characterizing fractured rock and unconsolidated media sites. (Chapters 2 - 4)



- Recognize the skills, approaches, and tools available to characterize fractured rock sites and develop CSMs (Chapter 5)
- Apply improved approaches to develop Remedial Action Objective (RAOs) and select remedies (Chapter 6)
- Describe development of a monitoring strategy for fractured rock sites (Chapter 7)

Section 6: Remedy Selection

- Attaining prescriptive levels (e.g., MCLs) generally more challenging than in overburden
- Focus on “SMART” RAOs 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

SMART
Specific
Measureable
Applicable
Relevant
Time Bound

Establish Remedial Action Objectives (RAOs)

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

SMART
Specific
Measureable
Applicable
Relevant
Time Bound

Remediation Objectives, Section 3 of ITRC Guidance:
Integrated DNAPL Site Strategy (IDSS-1, 2011)

Special Considerations in Bedrock

Properties	Difference at Fractured Rock sites	Impact
Hydraulic conductivity/ mass storage	Wider range of hydraulic conductivity and contaminant mass storage domains	Injection and extraction based remedies can be more difficult to implement successfully
NAPL	NAPL distribution may be even more complex than in porous media	NAPL more difficult to remove/contact
Groundwater flow direction/flux	Groundwater flow is more complex, especially on local scales	Preferential flow can complicate amendment distribution; passive remedies (e.g. barriers) can be more difficult to install
Abiotic/biotic reactions	Wide range of biotic and abiotic interaction with fracture surfaces and rock matrix	Need to understand rock types and whether matrix degrades or immobilizes contaminants; can enhance MNA at some sites

ITRC FracRx-1, Summary of Section 6.2

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 fractures
- 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

Technology Screening Matrix

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

Representative Rock Types / Origin			Hydrogeology: Transmissivity (Flow) – Matrix	Hydrogeology: Transmissivity (Flow) – Fracture	Hydrogeology: Matrix Storage	Physical: Removal	Physical: Thermal	Physical: Air Sparge	Physical: Vapor & Multiphase Extraction	Physical: Surfactant Flushing[1]	LNAPL Recovery	Containment: Pump & Treat	Containment: Permeable Reactive Barrier	Chemical / Biological: In-Situ Chemical Oxidation – Short-lived oxidant	Chemical / Biological: In-Situ Chemical Oxidation – Long-lived oxidant	Chemical / Biological: In-Situ Chemical Reduction – Short-lived reductant	Chemical / Biological: In-Situ Chemical Reduction – Long-lived reductant	Chemical / Biological: In-Situ Bioremediation – Short-lived carbon substrate	Chemical / Biological: In-Situ Bioremediation – Long-lived carbon substrate	Chemical / Biological: MNA
Sedimentary Rocks	Chemical – Coal	Bituminous	H	L	H	Y	U	U	Y	U	Y	Y	N	N	N	N	N	N	Y	Y
		Anthracite	L	L	L	Y	U	U	Y	U	Y	Y	N	N	N	N	N	N	Y	Y
	Chemical – 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

ITRC FracRx-1, Table 6-2

Technology Screening Matrix

21-Compartment Model Elements by Rock Type

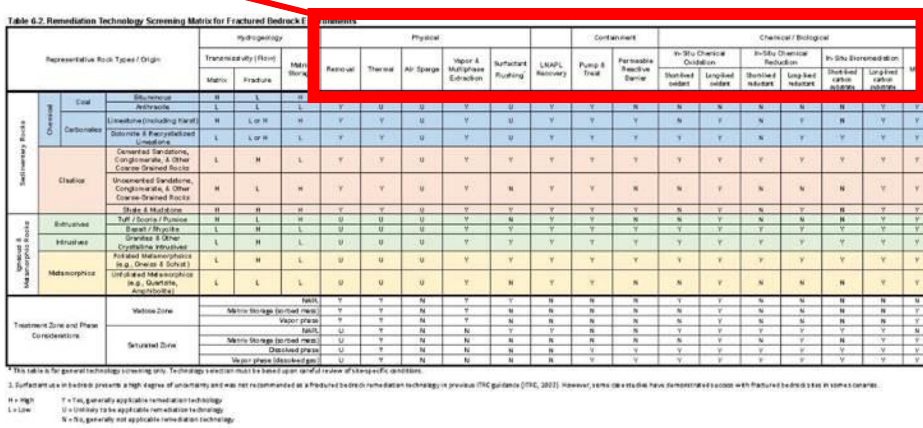
Representative Rock Types/Origin				Transmissivity (Flow): Matrix	Transmissivity (Flow): Fracture	Matrix Storage
Sedimentary Rocks	Chemical	Coal	Bituminous	H	L	H
Sedimentary Rocks	Chemical	Coal	Anthracite	L	L	L
Sedimentary Rocks	Chemical	Carbonates	Limestone (including Karst)	H	L or H	H
Sedimentary Rocks	Chemical	Carbonates	Dolomite & Recrystallized Limestone	L	L or H	L
Sedimentary Rocks	Clastics		Cemented Sandstone, Conglomerate, & Other Coarse-Grained Rocks	L	H	L
Sedimentary Rocks	Clastics		Uncemented Sandstone, Conglomerate, & Other Coarse-Grained Rocks	H	L	H
Sedimentary Rocks	Clastics		Shale & Mudstone	H	H	H
Igneous & Metamorphic Rocks	Extrusives		Tuff/Scoria/Pumice	H	L	H
Igneous & Metamorphic Rocks	Extrusives		Basalt/Rhyolite	L	H	L
Igneous & Metamorphic Rocks	Intrusives		Granites & Other Crystalline Intrusives	L	H	L
Igneous & Metamorphic Rocks	Metamorphics		Foliated Metamorphsics (such as Gneiss & Schist)	L	H	L
Igneous & Metamorphic Rocks	Metamorphics		Unfoliated Metamorphics (such as Quartzite, Amphibolite)	L	L	L

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

ITRC FracRx-1, Table 6-2

Range of Technologies

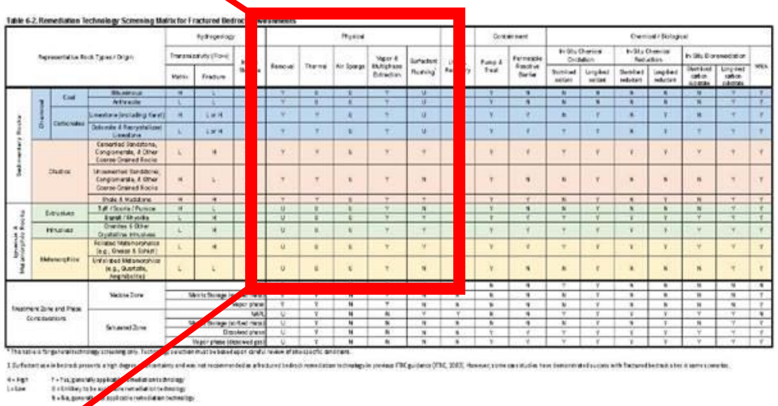
Physical					Contaminant		Chemical / Biological					
							In-situ Chemical Oxidation		In-situ Chemical Reduction		In-situ Bioremediation	
Removal	Thermal	Air Sparge	Vapor & Multiphase Extraction	Surfactant Flushing	Pump & Treat	Permeable Reactive Barrier	Short-lived oxidant	Long-lived oxidant	Short-lived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



General Technology Applicability

Example: Physical Removal
Y = Generally applicable
N = Not generally applicable
U = Unlikely applicable

Physical				
Removal	Thermal	Air Sparge	Vapor & Multiphase Extraction	Surfactant Flushing[1]
Y	U	U	Y	U
Y	U	U	Y	U
Y	Y	U	Y	U
Y	Y	U	Y	U
Y	Y	U	Y	Y
Y	Y	U	Y	N
Y	Y	U	Y	Y
U	U	U	Y	N
U	U	U	Y	Y
U	U	U	Y	Y
U	U	U	Y	Y
U	U	U	Y	N



ITRC FracRx-1, Table 6-2

Physical Technologies

- Removal
  - Limited to unsaturated, “soft” or weathered rock
  - Good for high matrix storage and primary porosity
- Thermal methods
  - Different methods have individual advantages and disadvantages for different types of rock
- Air sparge
  - Distribution pathways likely to be very limited compared to those in porous media

Physical Technologies
Vapor and Multiphase Extraction

- Both commonly applied in bedrock
- Design more challenging due to discrete fracture control of vapor and fluid migration in bedrock
- Commonly coupled with other technologies
  - Usually component of thermal methods
  - Commonly coupled with peroxide ISCO for off 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/cosolvents in fractured rock aquifers

Containment Technologies
Pump and Treat

- Widely applied, but special rock considerations
  - Communication with overburden or weathered bedrock
  - Fracture orientations and anisotropy
  - Multiple intersecting fracture sets
  - Capture-zone geometry more complex than in porous media, estimate using:
    - Modeling
    - Hydraulic head measurements
    - Groundwater contaminant concentrations

Containment Technologies
Permeable Reactive Barrier Zones

- 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

Chemical and Biological Technologies
In-Situ Chemical Oxidation & Reduction

In-Situ Chemical Oxidation (ITRC ISCO-2, 2005) & Reduction (ISCR) (ITRC IDSS-1, 2011)

- Reagent distribution is critical consideration
  - Distribution through transmissive secondary porosity rather than primary porosity or matrix storage domains
- Fracture orientation and density-driven flow
- Oxidant demand generally low (fracture surfaces)
- Long-lived oxidants diffusively penetrate rock
- NAPLs have much less interfacial surface area or trapped in less-transmissive fractures
- ZVI for permeable reactive barrier applications

Chemical and Biological Technologies
Bioremediation and Monitored Natural Attenuation

- Also widely applied
- 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

Combined Remedies

- Remedial paradigm has shifted to accept that combined remedies are almost always necessary
  - Emphasize strengths, minimize weaknesses
- 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

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:
  - Rock surface area exposed to groundwater, contaminants, and reagents is very different
    - Generally don't use crushed rock for bench tests.
  - Fracture-controlled groundwater flow can be much faster than in granular overburden

Remedy Selection
SRSNE Case Study Learning Objectives

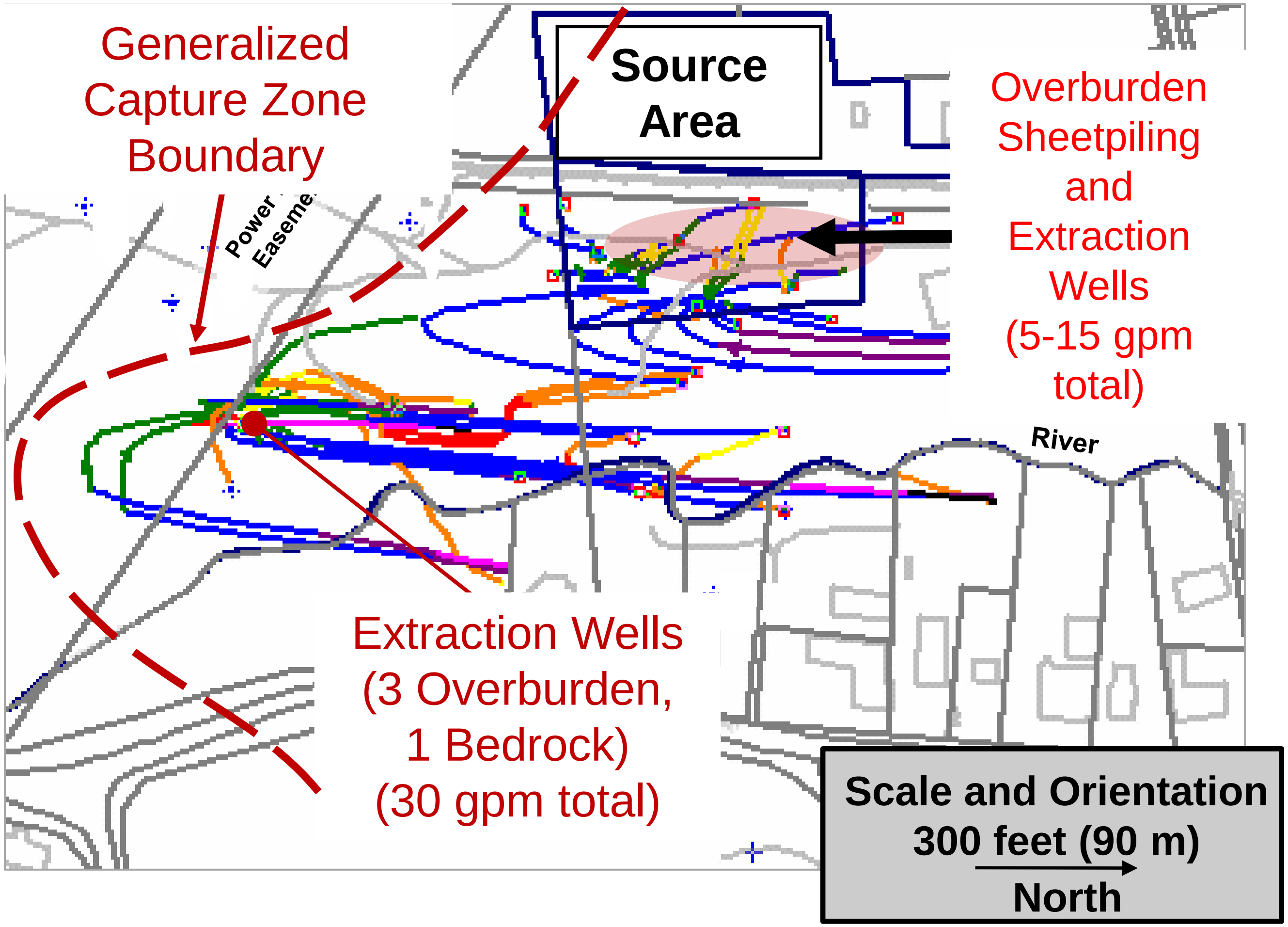
Using this case study site as an example…

- See how hydraulic containment was modeled to support the remedial design for VOC-affected bedrock groundwater
- Understand the multiple lines of evidence that are used to confirm that the existing remedy is protective

SRSNE Case Study - Remedy Selection

Bedrock GW Remedy: 1 - Plume Containment

- Regional, 3-D flow model
- 20:1 bedrock anisotropy in plan view
- Capture zone confirmed by:
  - Hydraulic heads
  - Groundwater sampling results



Courtesy Michael Gefell

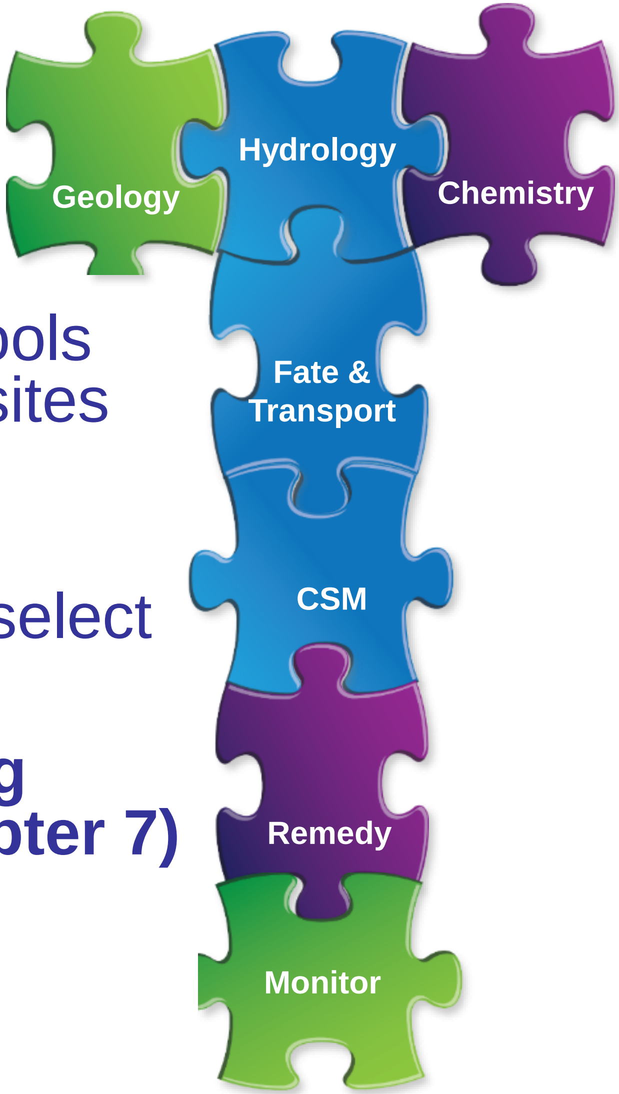
SRSNE Case Study Remedy Selection

Bedrock GW Remedy: 2 – Monitored Natural Attenuation

- MNA parameters monitored every 2 years at select wells inside and outside of capture zone
- VOC, 1,4-dioxane and tetrahydrofuran (THF) concentration trends and attenuation half-lives updated in annual MNA reports
  - Concentrations decreasing, even downgradient of bedrock DNAPL zone
- Quantitative polymerase chain reaction (qPCR) analysis demonstrated degraders present for CVOCs, BTEX, 1,4-dioxane and THF

Today's Road Map – Connects to ITRC Guidance

- Identify similarities and differences between characterizing fractured rock and unconsolidated media sites. (Chapters 2 - 4)
- Recognize the skills, approaches, and tools available to characterize fractured rock sites and develop CSMs (Chapter 5)
- Apply improved approaches to develop Remedial Action Objective (RAOs) and select remedies (Chapter 6)
- **Describe development of a monitoring strategy for fractured rock sites (Chapter 7)**



Monitoring: Objective

- Develop a groundwater monitoring strategy for your fractured rock site taking into account:
  - Results of the site characterization
  - Information needed to ensure that the selected remedial strategy attaining site-specific cleanup goals

Monitoring: Types

- Compliance monitoring
  - Assess compliance with regulatory requirements and protection of human health and the environment
- Operational monitoring
  - Assess whether a remediation system is meeting or approaching its functional objectives
- Progress/Performance monitoring
  - Assess the effectiveness of a remedial in achieving functional objectives

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

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 and low pH
- Location of potential sensitive receptors
  - Monitoring must evaluate the potential for exposure to receptors
- Characteristics of other media
  - May provide insight into extent of fracture network

Monitoring: Locations

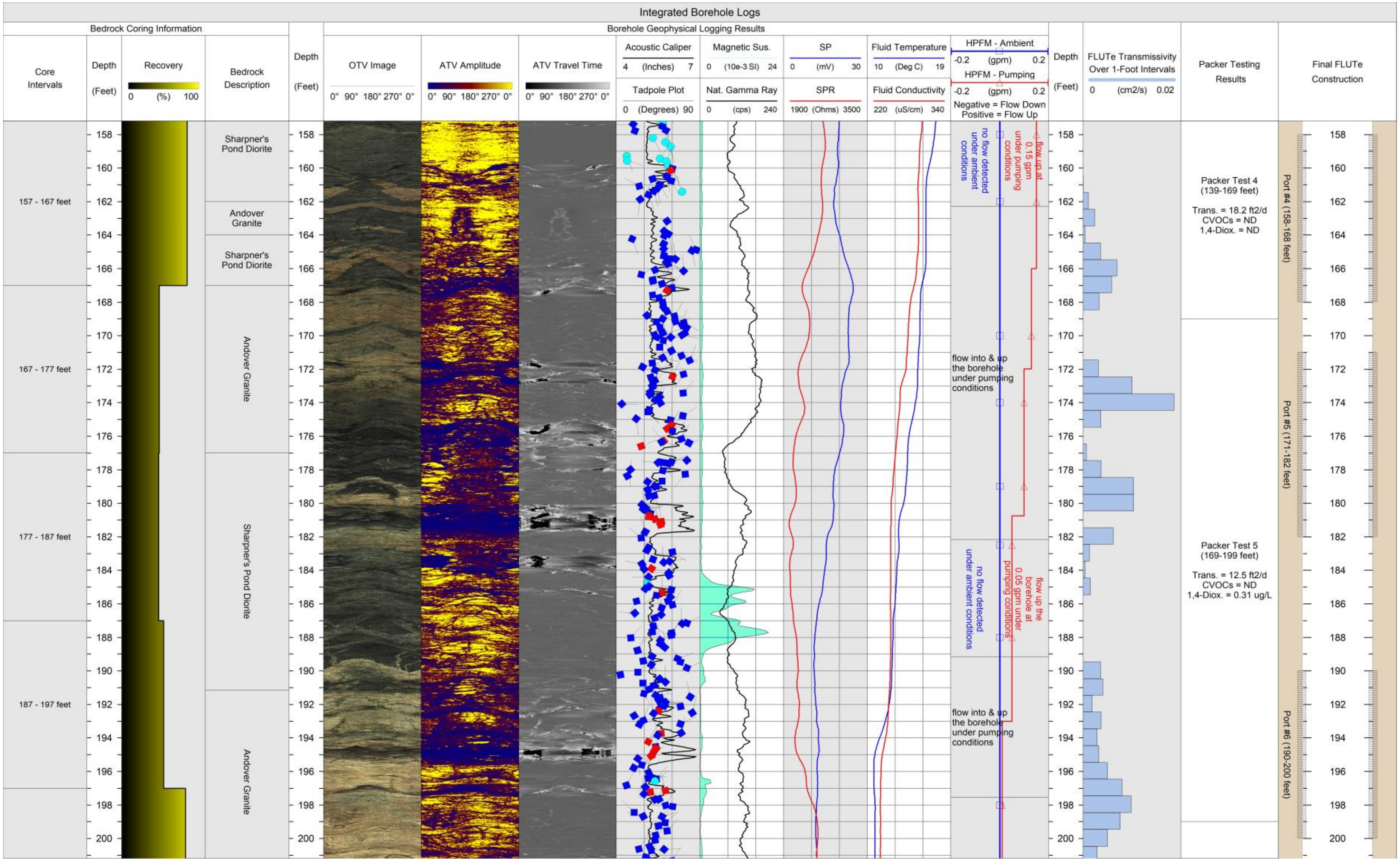
Selection of monitoring locations is based on:

- 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.

Monitoring: Locations

- Source zone wells
- Impacted zone wells
- Distal portions and boundaries of the area of impact
- Up gradient and cross gradient wells
- Sentinel wells

Monitoring: Well Design Considerations



Courtesy Rob Garfield, Hager-Richter Geoscience

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
  1. Remedy operation
  2. Remedy progress toward groundwater RAOs and associated clean up levels
  3. Remedy attainment of RAOs and cleanup levels
  4. Other site factors

Monitoring Strategy: Greenville Case Study

- Former Industrial Site in Greenville, South Carolina illustrates development of a remediation monitoring strategy
- Media to monitor
  - Groundwater and surface water
- Monitoring network design
  - Weathered rock zone grades into competent bedrock consisting of metamorphic gneiss with little matrix porosity
  - Fractures in the bedrock were predominantly sub-horizontal
  - Water-bearing fracture zones could be readily identified

Monitoring Strategy: Greenville Case Study (Continued)

- Monitoring network design (cont'd)
  - 15 monitoring wells in the source area and 37 monitoring wells in the impacted zone and adjacent areas in saprolite and bedrock
  - Included upgradient, cross gradient, and sentinel wells
  - Wells installed upgradient and down gradient of ZVI barriers to monitor remedy progress
  - Additional cross gradient wells were installed to confirm the treatment area boundaries
  - Periodic surface water sampling is conducted down gradient \ of the impacted zone

Monitoring Approach
SRSNE Case Study Learning Objectives

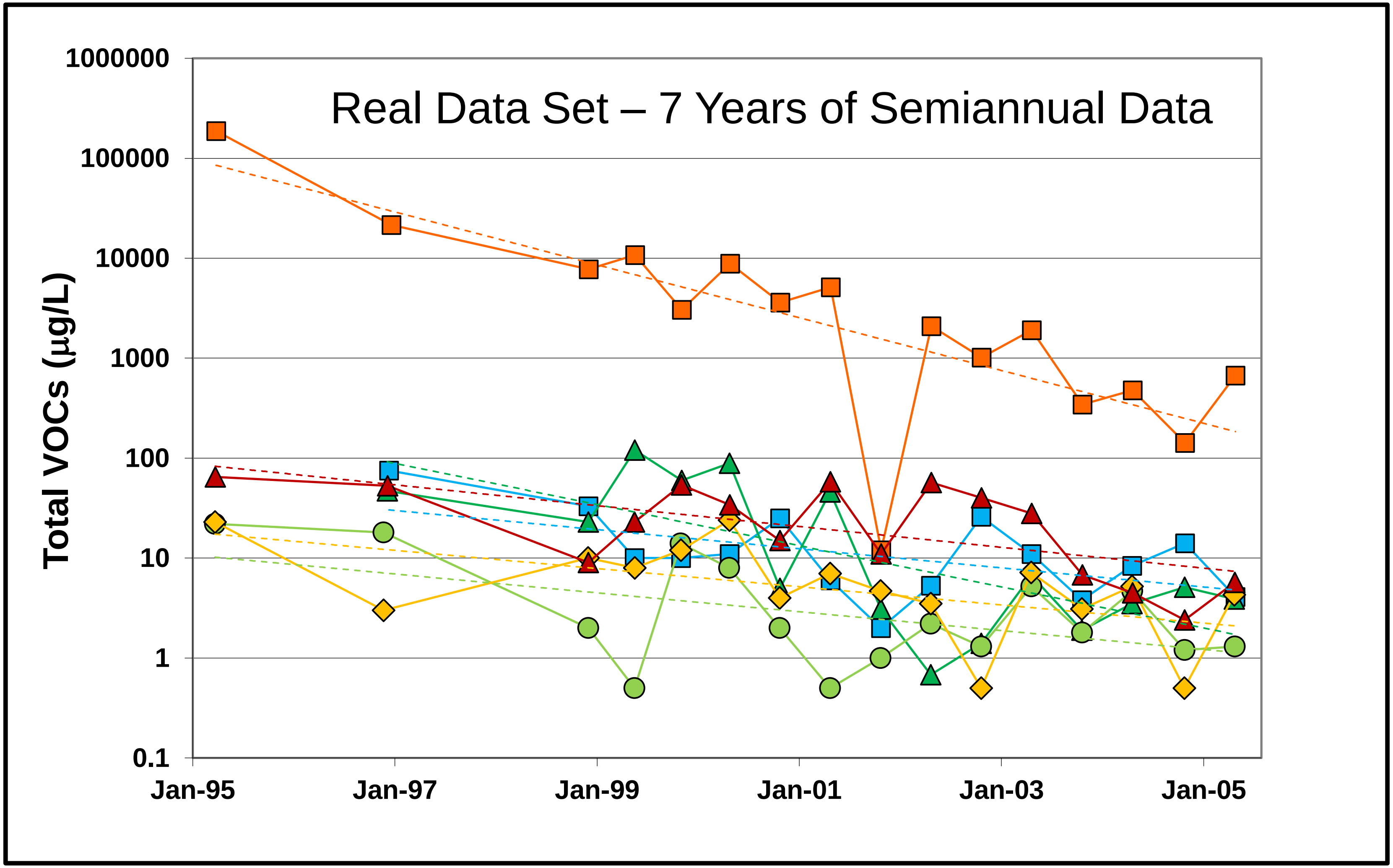
Using this case study site as an example…

- ► See how the monitoring network for this site was designed
- ► Recognize methods that can be used to reduce monitoring cost, while remaining protective
- ► Appreciate how historical data can be used to support reducing the monitoring frequency

SRSNE Case Study Groundwater Monitoring Approach

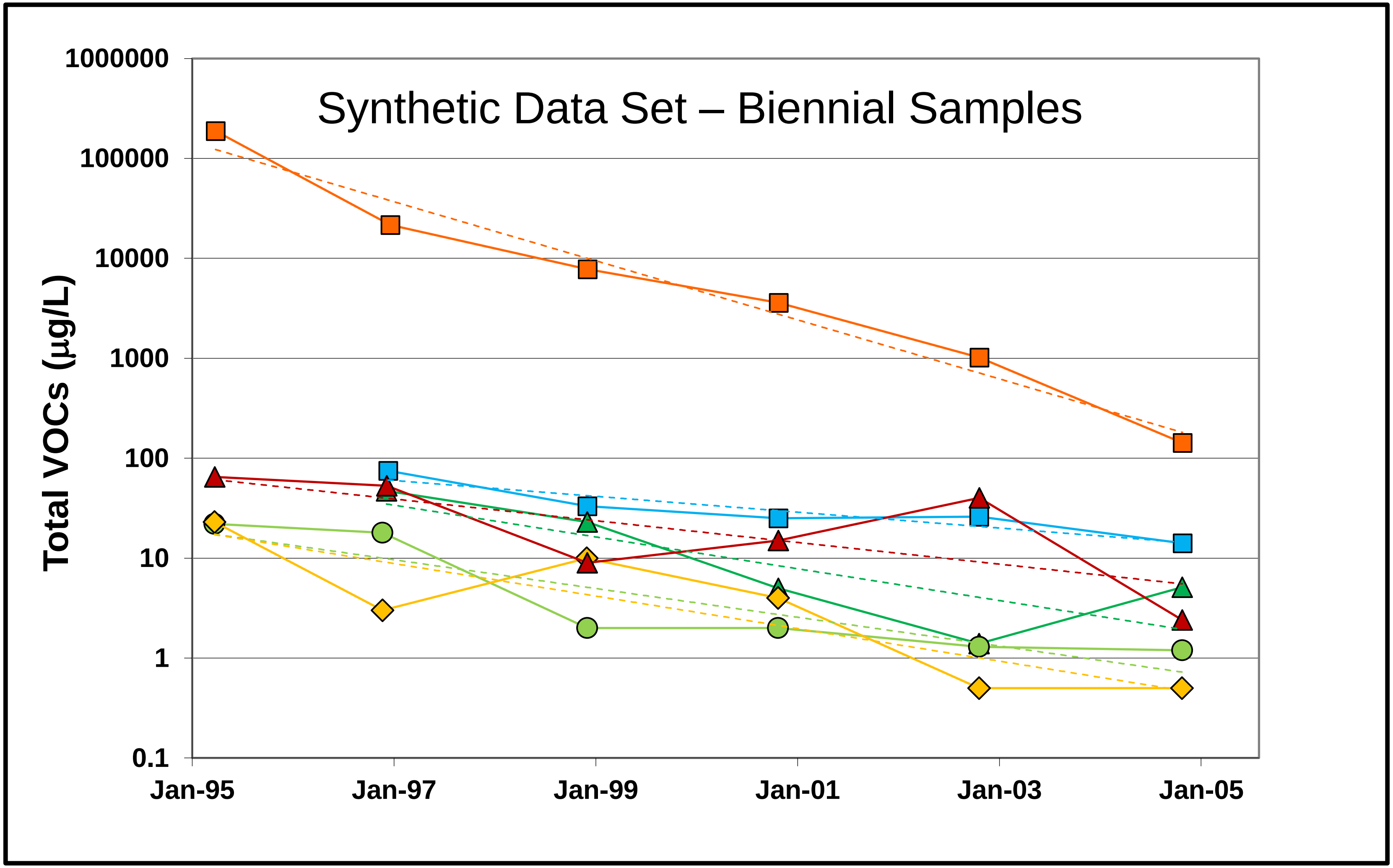
- Bedrock monitoring wells installed in two general depth zones – screen depths based on core inspection, packer tests, and/or geophysical logs:
  - Shallow bedrock – top 30 feet of bedrock
  - Deep bedrock – 60 to 125 feet below top of rock
- Annual, sampling for VOCs (biennial for MNA parameters) at subset of monitoring wells
  - No-purge sampling at wells with higher concentrations reduced sampling cost by half relative to low-flow
- Comprehensive network sampled by low-flow every 5 years for VOCs and 1,4-dioxane
- Long-term sampling frequency is based on historical trend statistics, and frequency-scenario testing

Historical TVOC Concentration Trends Example for 6 Wells



Courtesy Michael Gefell

Frequency Scenario Testing
Example for Same 6 Wells



Courtesy Michael Gefell

Reducing Sampling Frequency

- Mann-Kendall, Sen's Slope and Linear Regression Trend Test Results (number of wells with trend at 90% C.I.)

Frequency	Decreasing	No Trend	Increasing
Semi-Annual	18-19	6-7	0
Biennial	15	10	0

- Regulator approved reduced sampling during RD/RA
  - 23% no sampling, water levels only
  - 52% every 5 years
  - 16% of wells annual
  - 3% biennial
  - 6% variable (in source zone – remediation monitoring)

Overall Course Summary

Courtesy Dan Bryant

Dispelling the Fractured Rock Site Myth

These Sites Really Can Be Cleaned Up!

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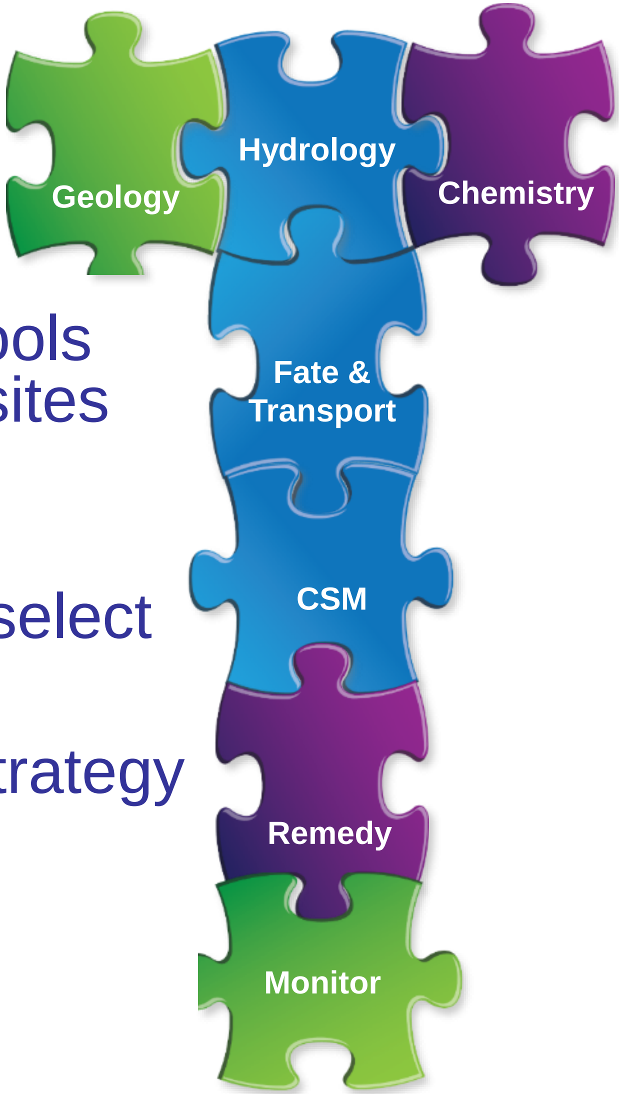


Use Tools Matrix for Characterization and Remedy Selection

- The tools matrix is a downloadable excel spreadsheet located in Appendix A
- Tools segregated into categories and subcategories, selected by subject matter experts
- A living resource intended to be updated periodically

Tool
Geophysics
Surface Geophysics
Downhole Testing
Hydraulic Testing
Single well tests
Cross Borehole Testing
Vapor and Soil Gas Sampling
Solid Media Sampling and Analysis Methods
Solid Media Sampling Methods
Solid Media Evaluation and Testing Methods
Direct Push Logging (In-Situ)
Discrete Groundwater Sampling & Profiling
Multilevel sampling
DNAPL Presence
Chemical Screening
Environmental Molecular Diagnostics
Microbial Diagnostics
Stable Isotope and Environmental Tracers
On-site Analytical

Our Goal is to Grow Your Skills and Knowledge to:

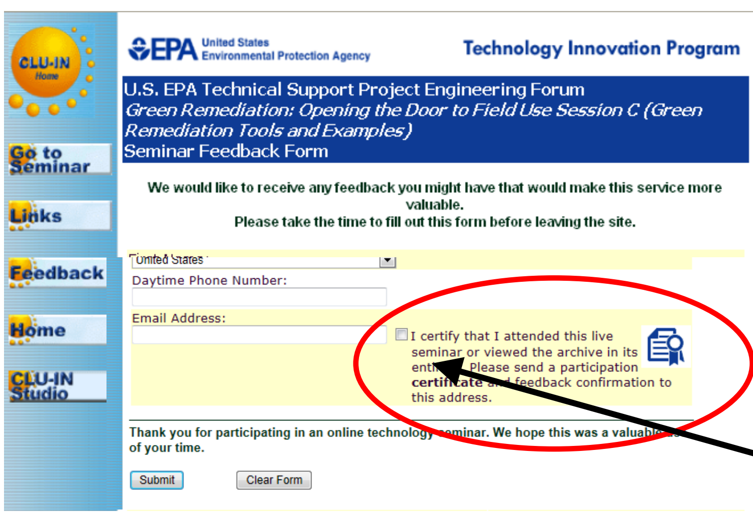
- Use ITRC's Fractured Rock Document to guide your decision making so you can:
  - Develop quality Conceptual Site Models (CSMs) for fractured rock sites (based on the state of the science)
  - Set realistic remedial objectives
  - Select the best remedial options
  - Monitor remedial progress and assess results
- So your site teams can make confident and effective decisions ……going beyond containment and monitoring - - to actually remediating sites

Thank You

Follow ITRC

Poll Question

- 2nd question and answer break
- Links to additional resources
  - https://clu-in.org/conf/itrc/FracRx/resource.cfm
- Feedback form – *please* complete
  - https://clu-in.org/conf/itrc/FracRx/feedback.cfm



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