Designing and Monitoring Remediation in Fractured Rock Aquifers: Challenges and Progress

Allen M. Shapiro
U.S. Geological Survey
Reston, Virginia, USA

Collaborators

USGS

Paul Bradley
Frank Chapelle
Gary Curtis
Dan Goode
Paul Hsieh
Tom Imbrigiotta
Julie Kirshtein
Pierre Lacombe
Kinga Révész
Jorie Schulz
Mary Voytek

Geosyntec consultants

Mary DeFlaun
Scott Drew

Even with the complexities of fractured rock aquifers, remediation technologies are being implemented. . .

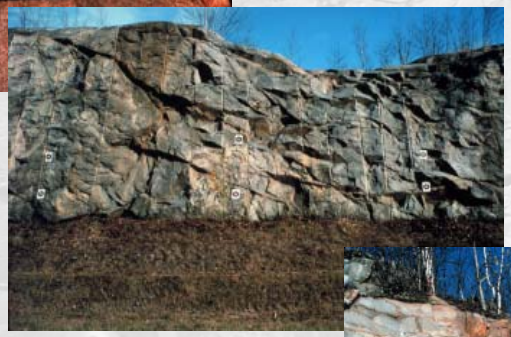
Drilling bedrock boreholes (mudstone)
Naval Air Warfare Center, West Trenton, NJ

Steam injection apparatus (limestone)
Loring Air Force Base, Aroostook County, ME

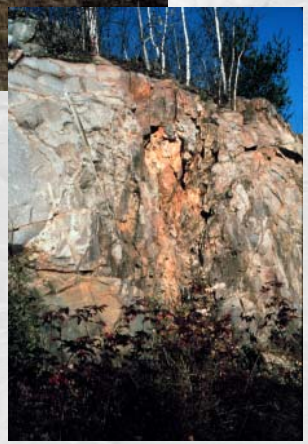
Geologic complexity of fractured rock aquifers

- *Hierarchy of void space*
- *Complex fracture connectivity*
- *Large range of hydraulic properties*

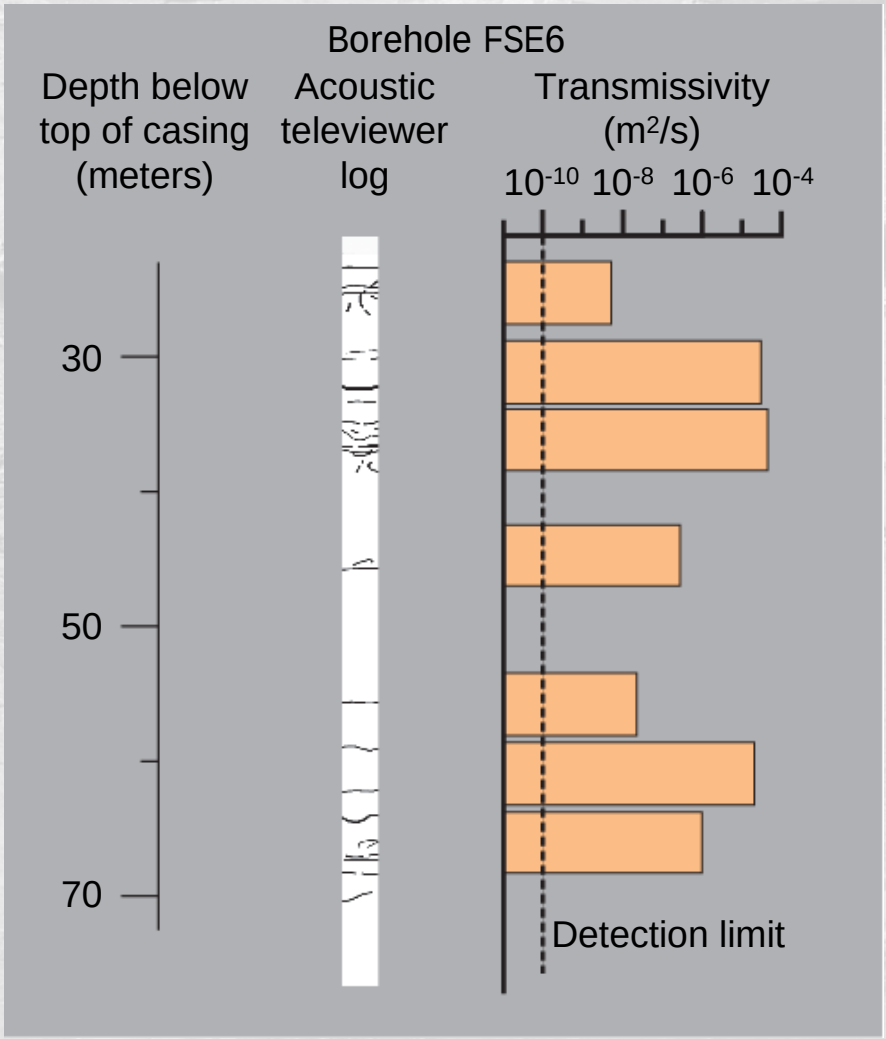
Matrix porosity



Fractures



Fault zones



Granite and schist, Mirror Lake, NH

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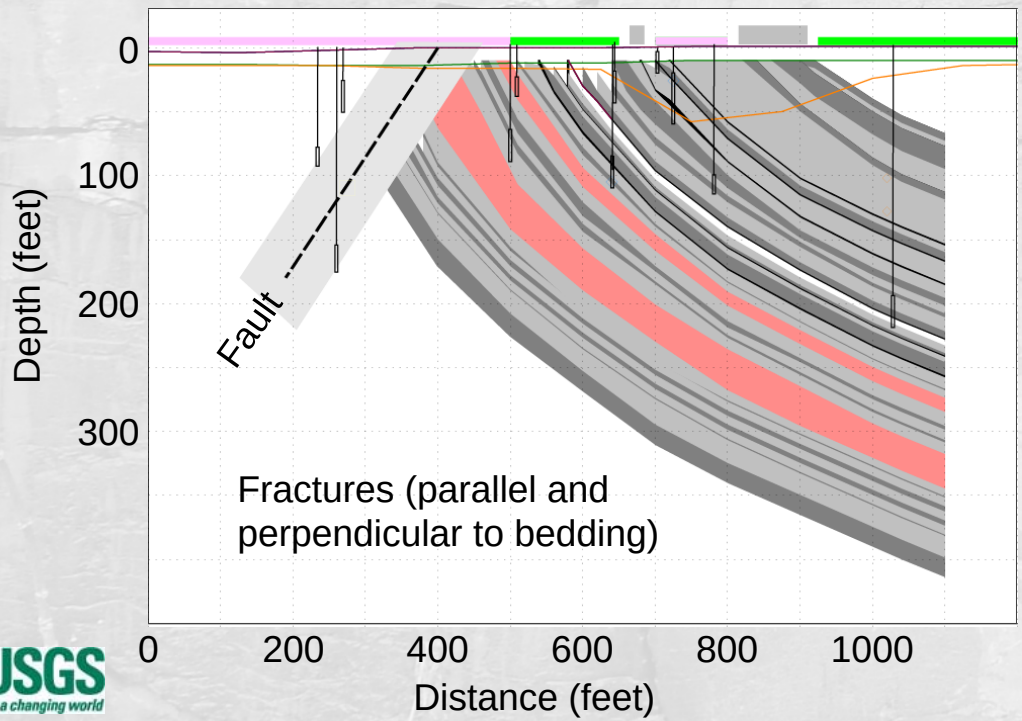
Even relatively "simple" fractured rock environments are subject to significant complexity in the characterization of contaminant transport

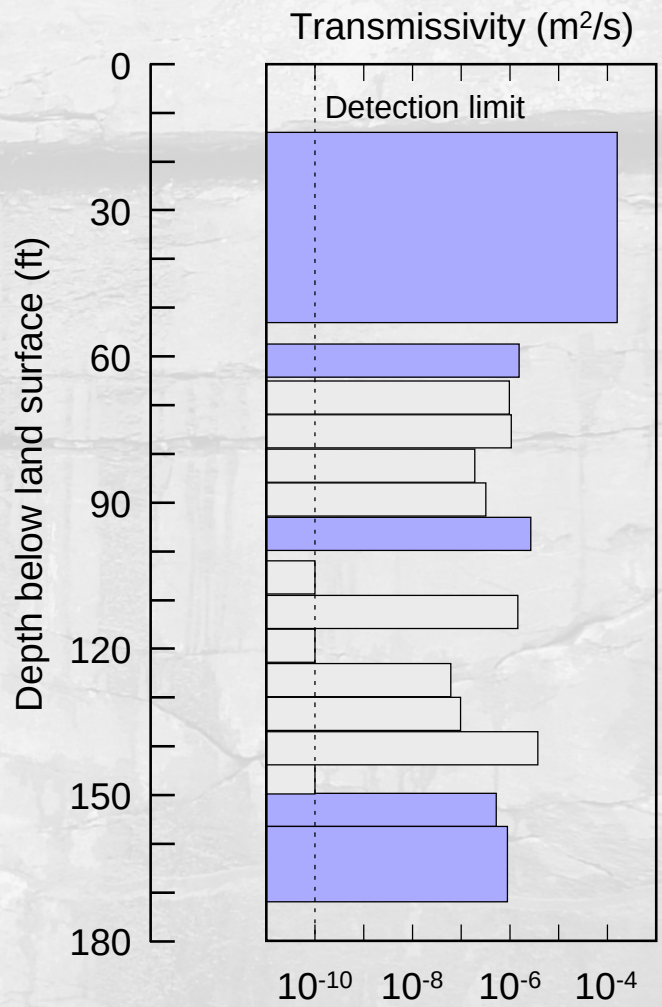
- *Hierarchy of void space*
- *Complex fracture connectivity*
- *Large range of hydraulic properties*

Matrix porosity

Lockatong Mudstone, West Trenton, NJ



Naval Air Warfare Center
Borehole 68BR



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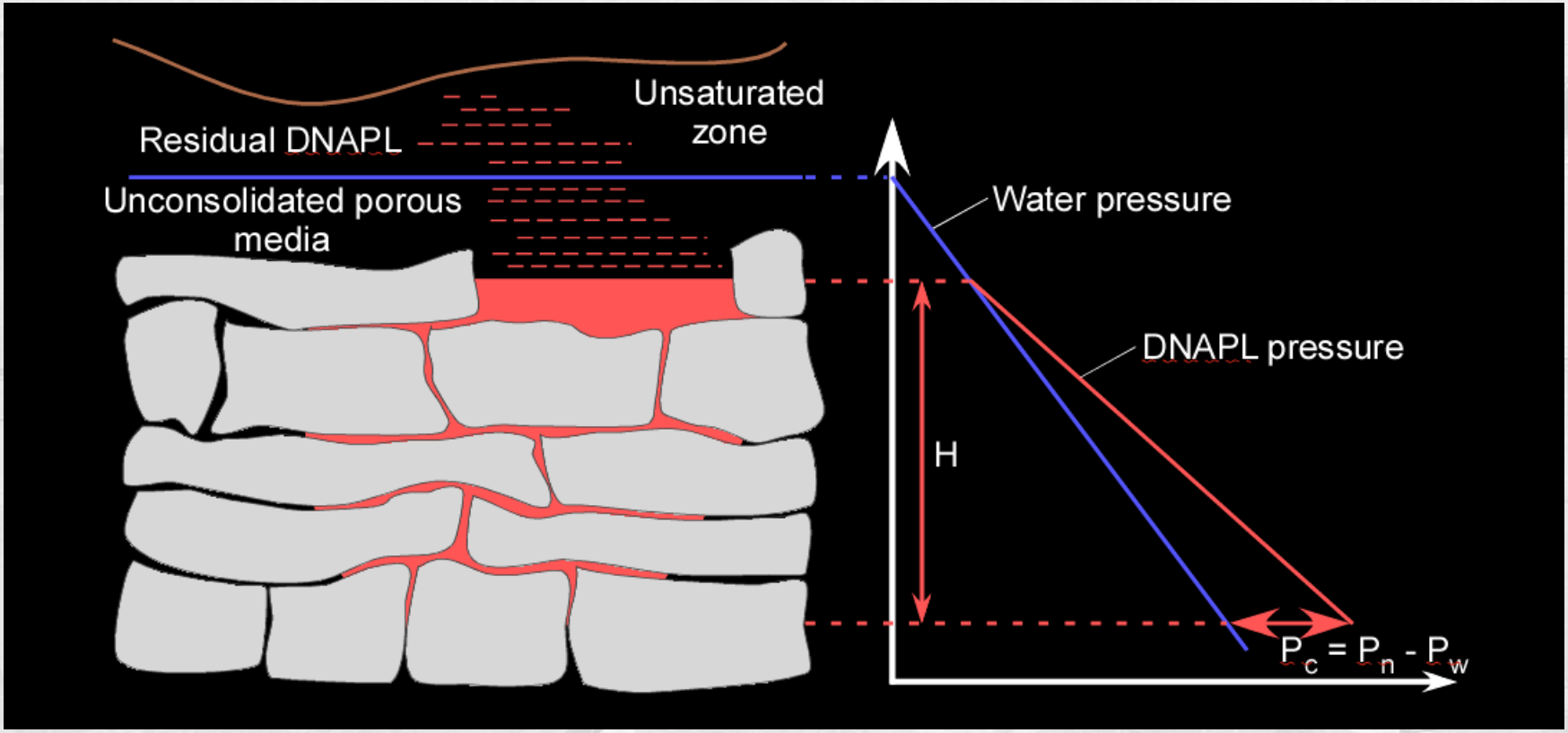
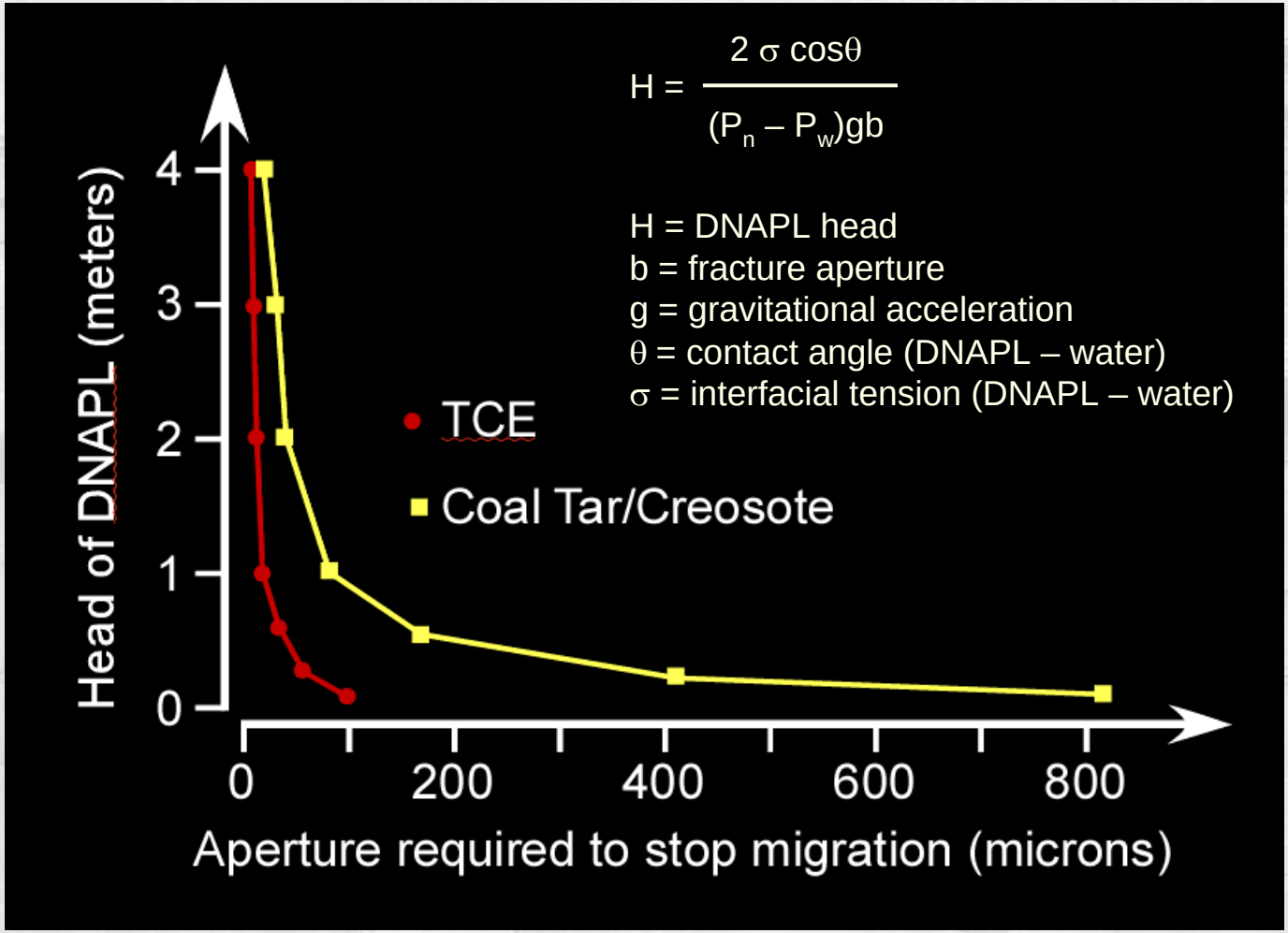
In fractured rock, where is the DNAPL ?

Small “pool” heights of DNAPL force DNAPL into small aperture fractures



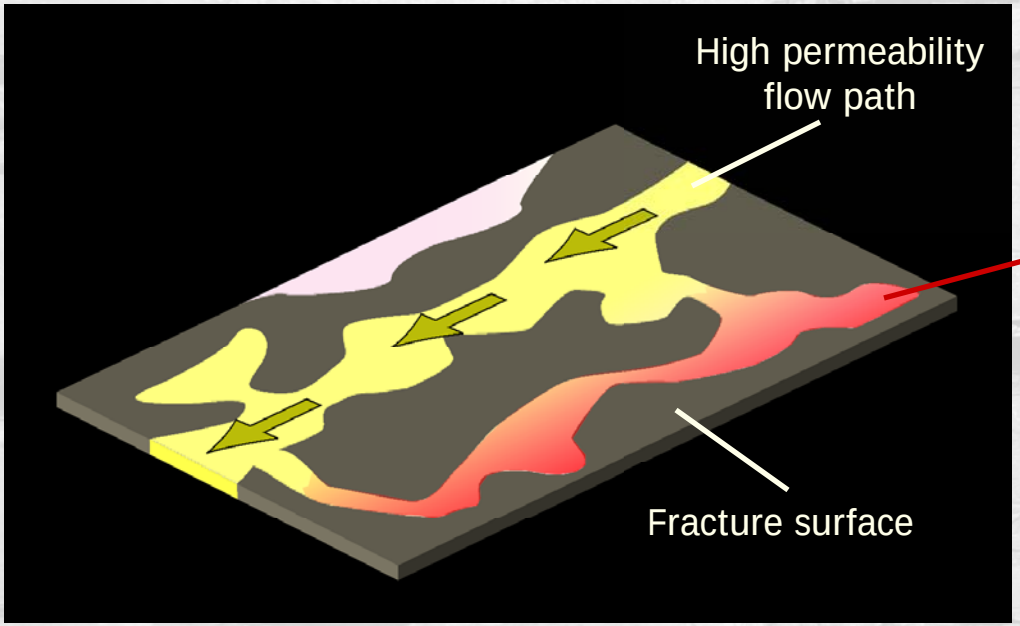
Small "pool" heights of DNAPL force DNAPL into small aperture fractures



- *9 micron (9×10^{-6} meters) fracture aperture needed to stop 1 meter "pool" height of TCE*

- *Diameter of human hair ~50 microns*

In fractured rock, where is the DNAPL, and where is the dissolved phase DNAPL ?



DNAPL forced into small aperture sections of fractures

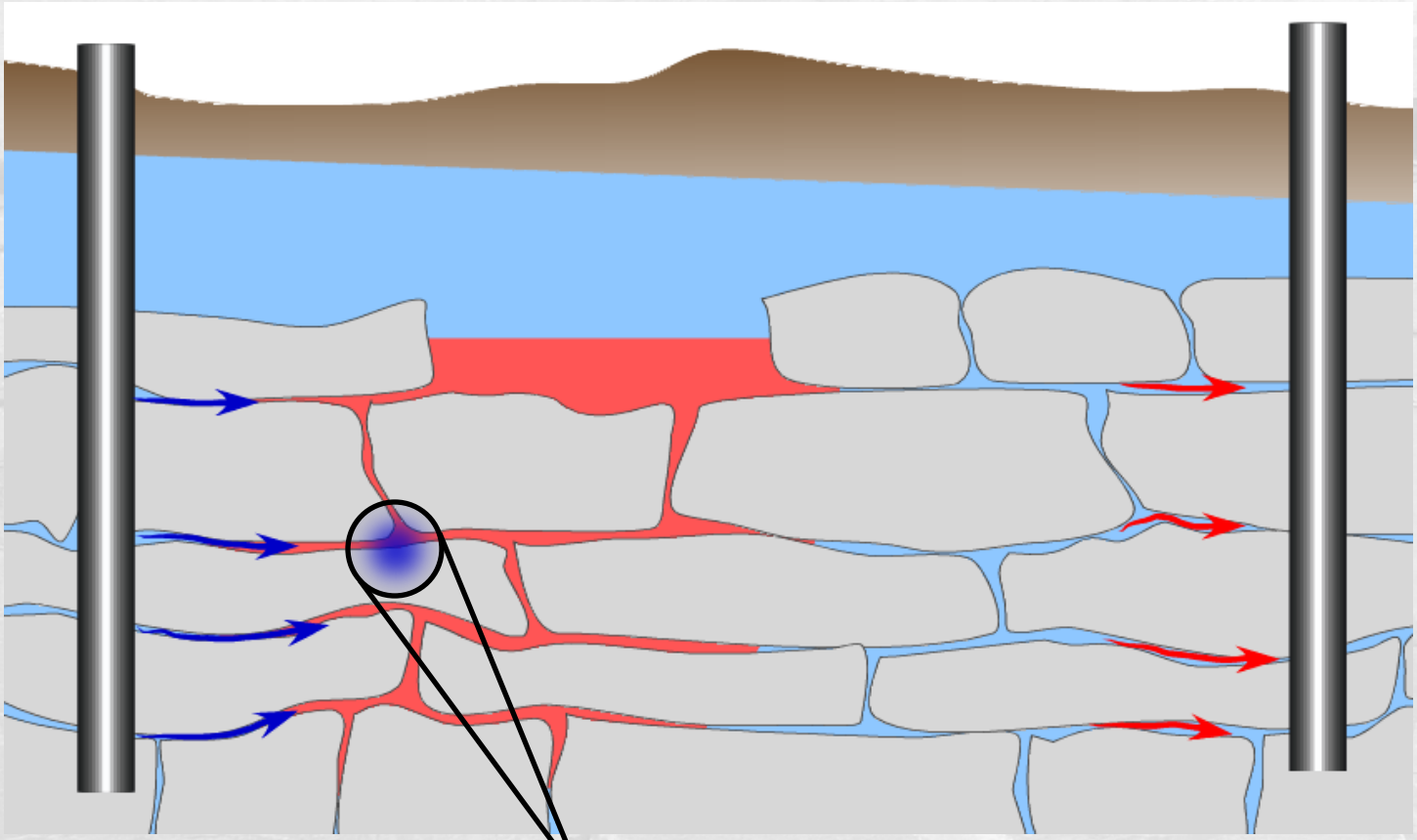
Complex topology of fracture surfaces

Chemical diffusion into matrix porosity

Most remediation technologies are inconsistent with the geologic complexities of fractured rock aquifers

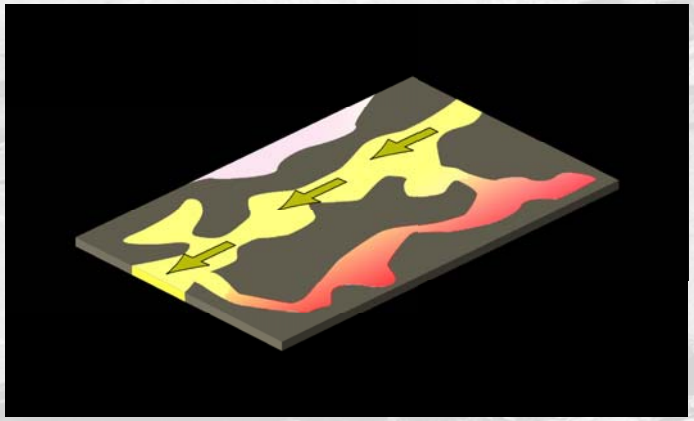
Influent flushing solution (e.g., steam, alcohol, surfactants, chemical oxidizers, microbial agents, etc.)

Contaminated fluids pumped to on-site or off-site treatment



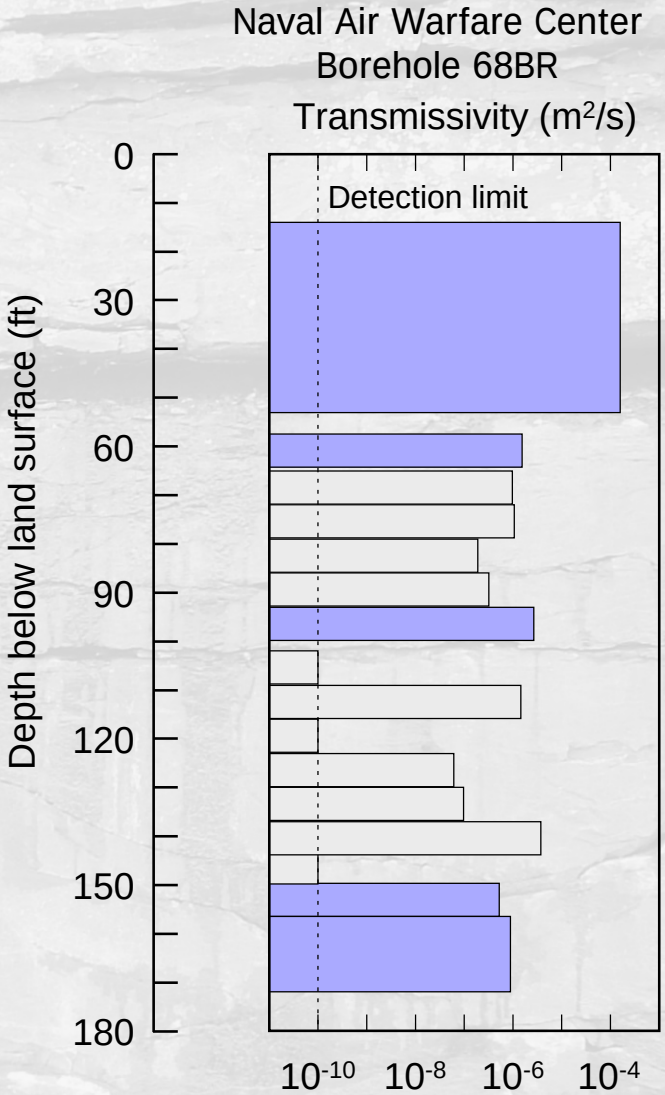
Chemical and/or microbial reactions with DNAPL and its dissolved phase, or increase mobility and/or solubility of the DNAPL

Most remediation technologies require contact with the DNAPL or its dissolved phase



High-permeability flow paths bypass small aperture fractures

Dissolved phase contaminants in rock matrix



Remediation technologies will be effective in the most permeable fractures

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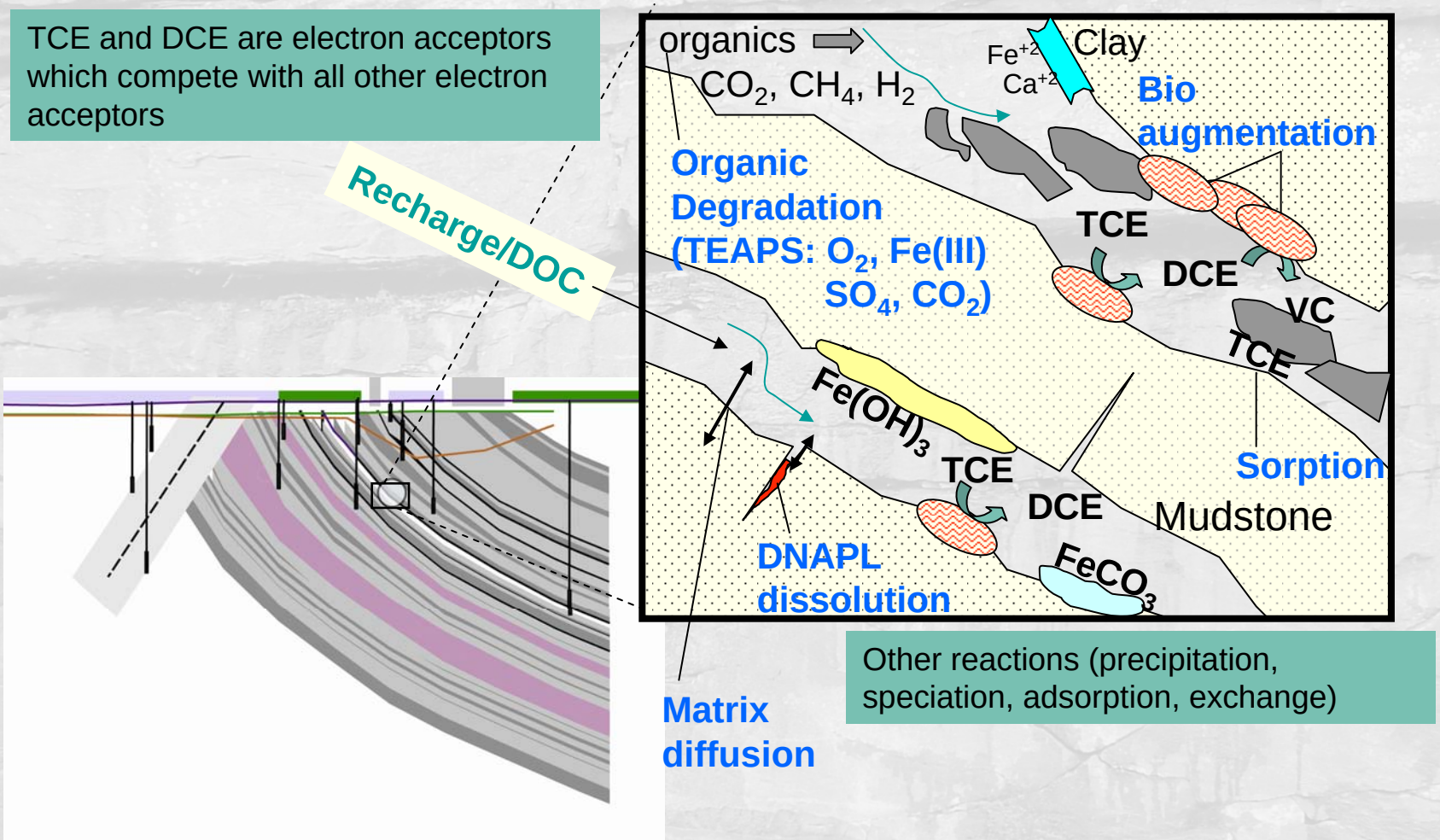
Even with all the complexities associated with fractured rock. . . reducing contaminant mass in permeable fractures may be a part of addressing project objectives

TCE and DCE are electron acceptors which compete with all other electron acceptors



Other reactions (precipitation, speciation, adsorption, exchange)

Reactive transport models will be critical in evaluating the cost/benefit of applying remediation technology in fractured rock

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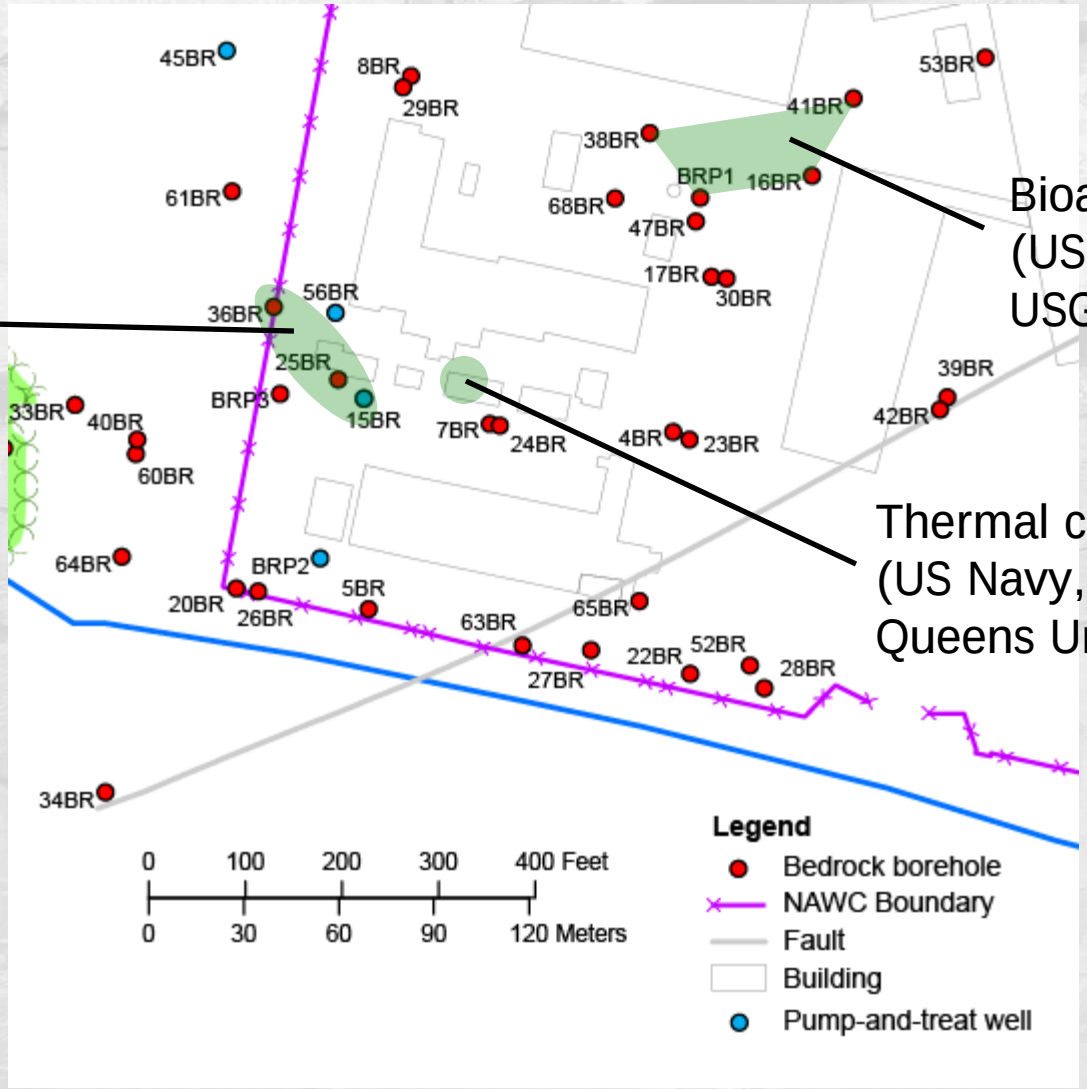
Designing and monitoring remediation at the Naval Air Warfare Center, West Trenton, NJ

Bioaugmentation (US Navy, USGS, Geosyntec, 2008)



Bioaugmentation (US Navy, Geosyntec, USGS 2005)

Thermal conductive heating (US Navy, TerraTherm, Queens Univ., USGS, 2009)

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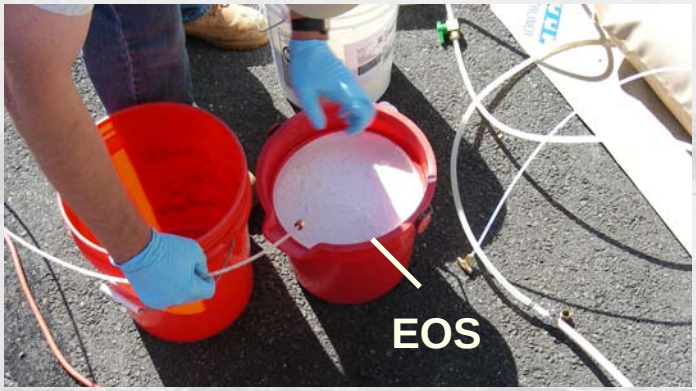
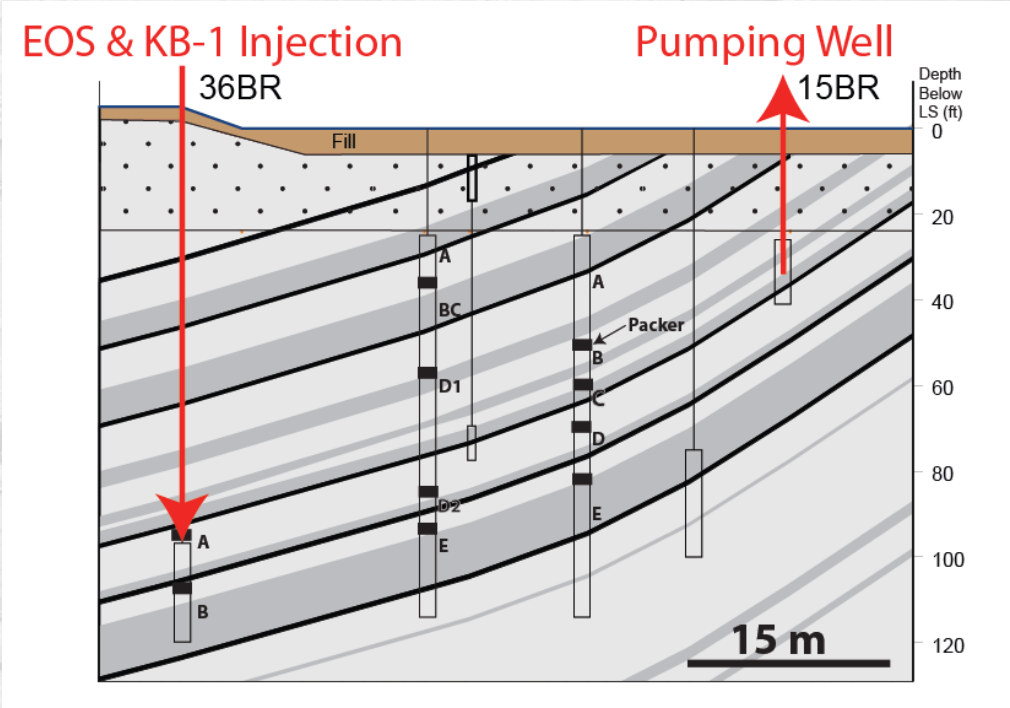
In situ bioaugmentation





October 15, 2008

- Water pumped from 36BR-A into 2 bladders (bladders pre-flushed with argon to keep formation water anaerobic)
- One bladder dosed with EOS and Vitamin B12
- Injection of ~50 gallons EOS solution
- Injection of 20 L microbial consortium KB-1
- Injection of ~100 gallons EOS solution
- Injection of ~100 gallons formation water (anaerobic)

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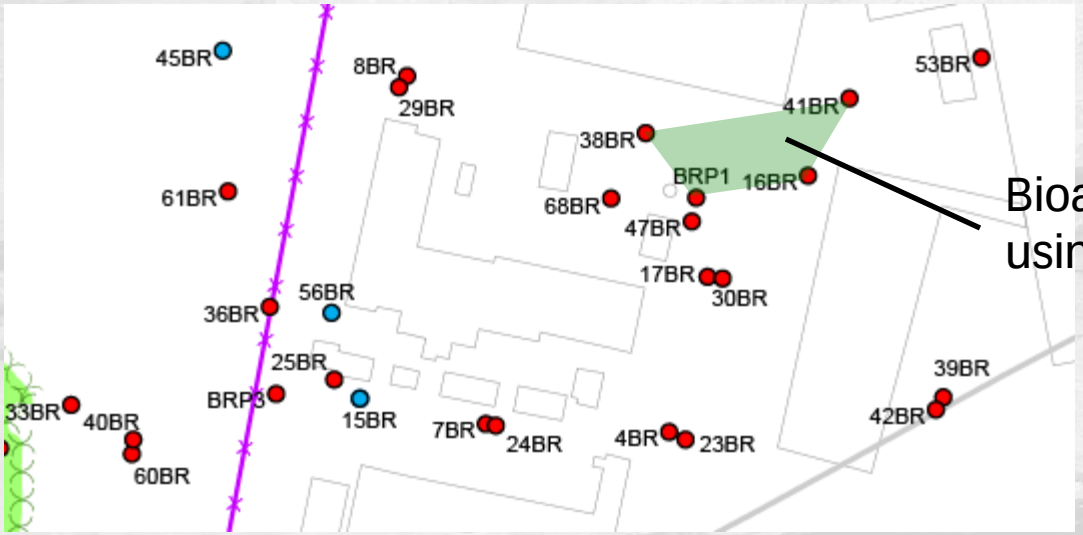
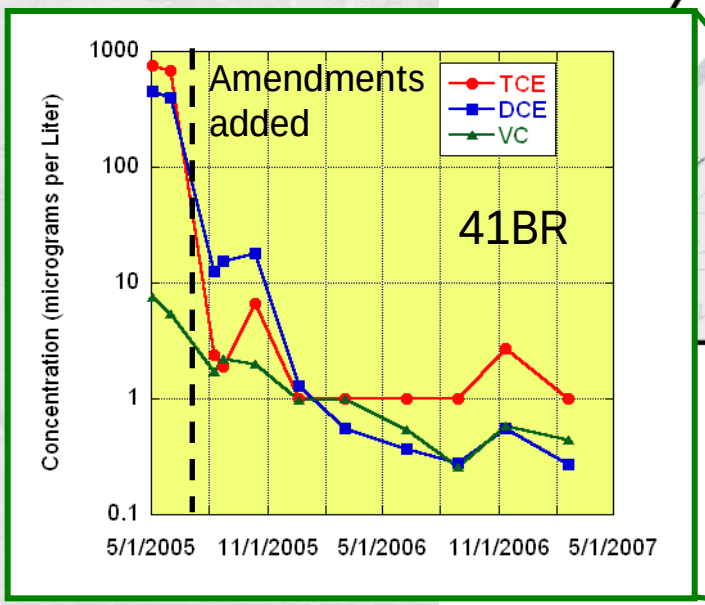
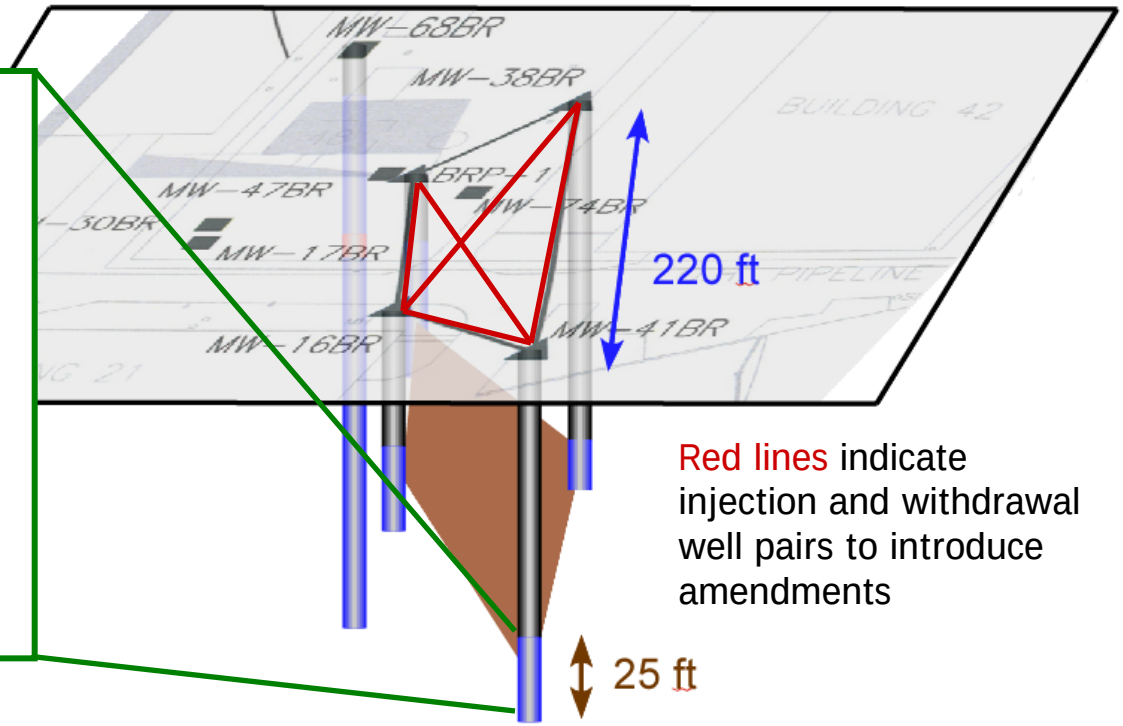


Bioaugmentation pilot study (2005) using EOS and KB-1





Red lines indicate injection and withdrawal well pairs to introduce amendments

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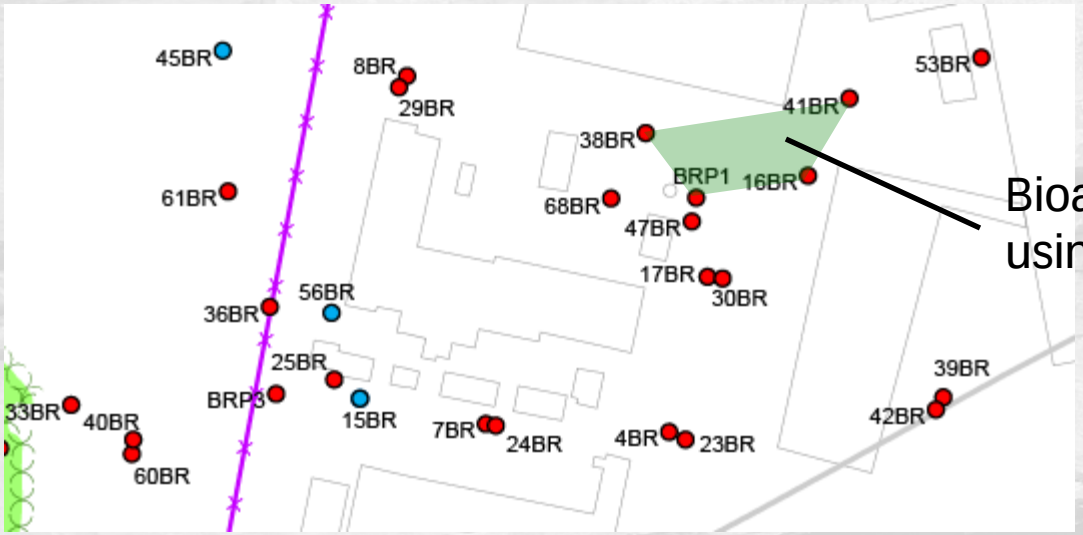
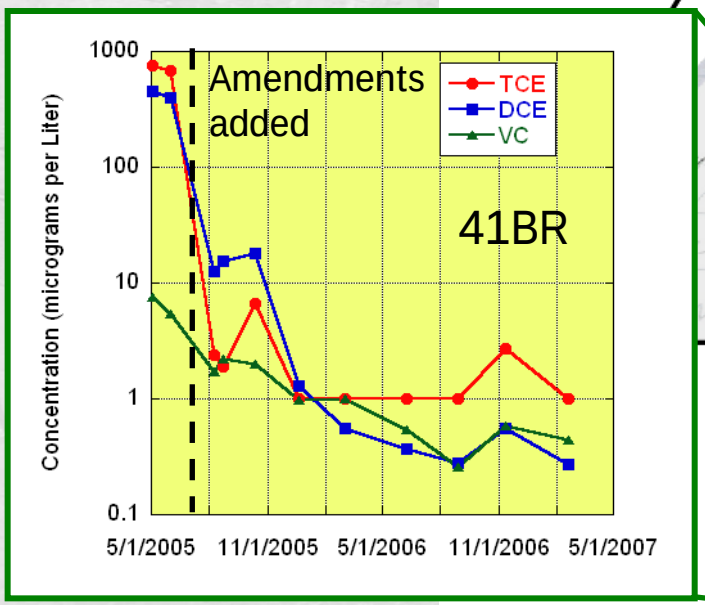
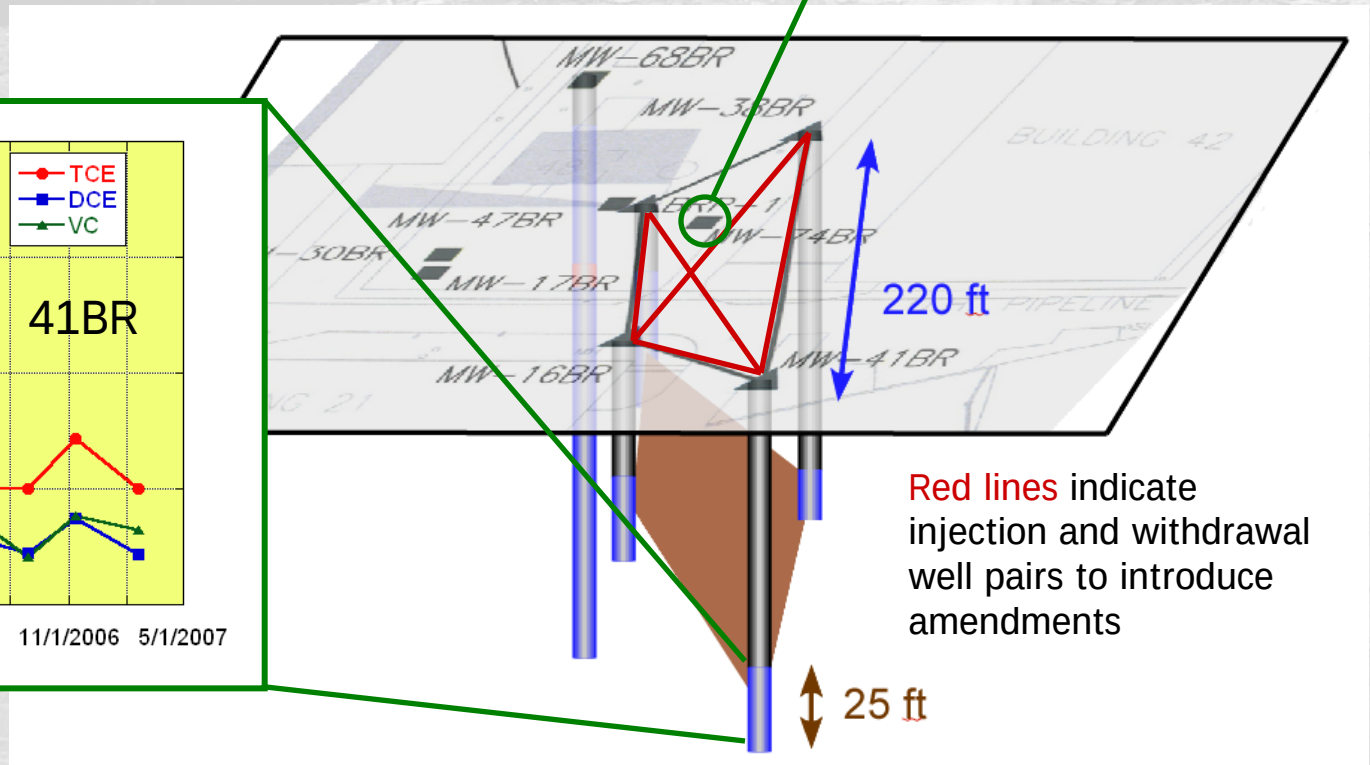


Bioaugmentation pilot study (2005) using EOS and KB-1

TCE 10 ppb
DCE 96 ppb
VC 54 ppb

Borehole drilled in 2007 showed no significant signs of remediation





Red lines indicate injection and withdrawal well pairs to introduce amendments

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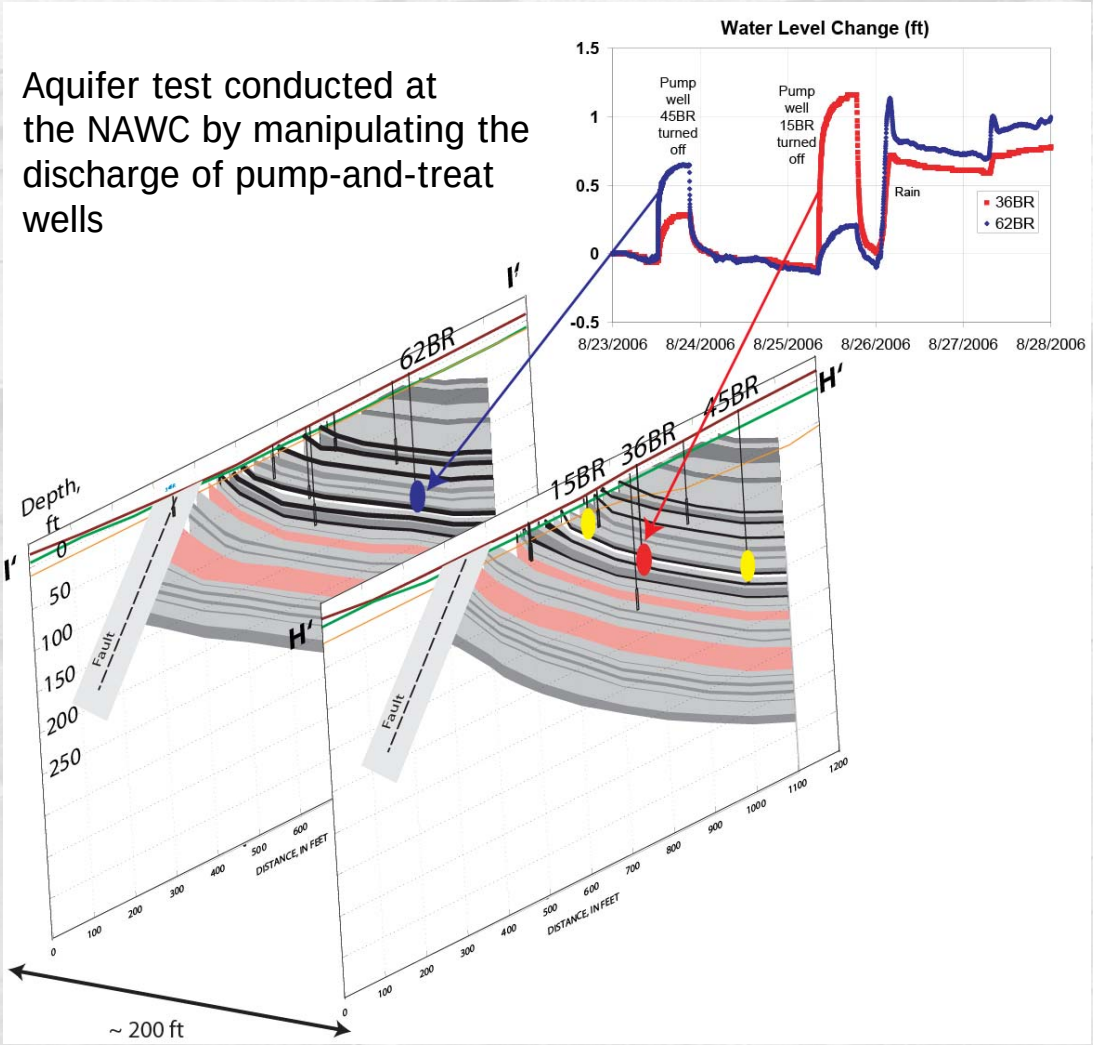
Interpreting the contaminant concentrations at points of ground water discharge

Aquifer test conducted at the NAWC by manipulating the discharge of pump-and-treat wells



Responses to pumping indicate potential contaminant pathways, but do not indicate the residence time and chemical mixing

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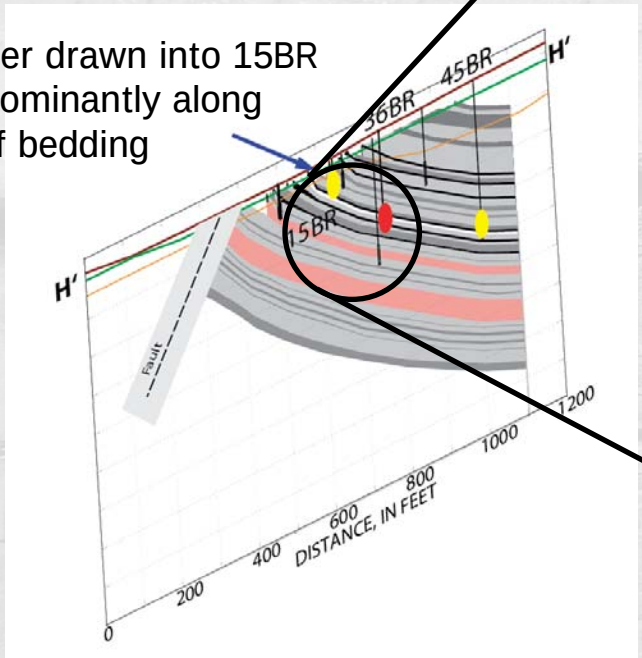
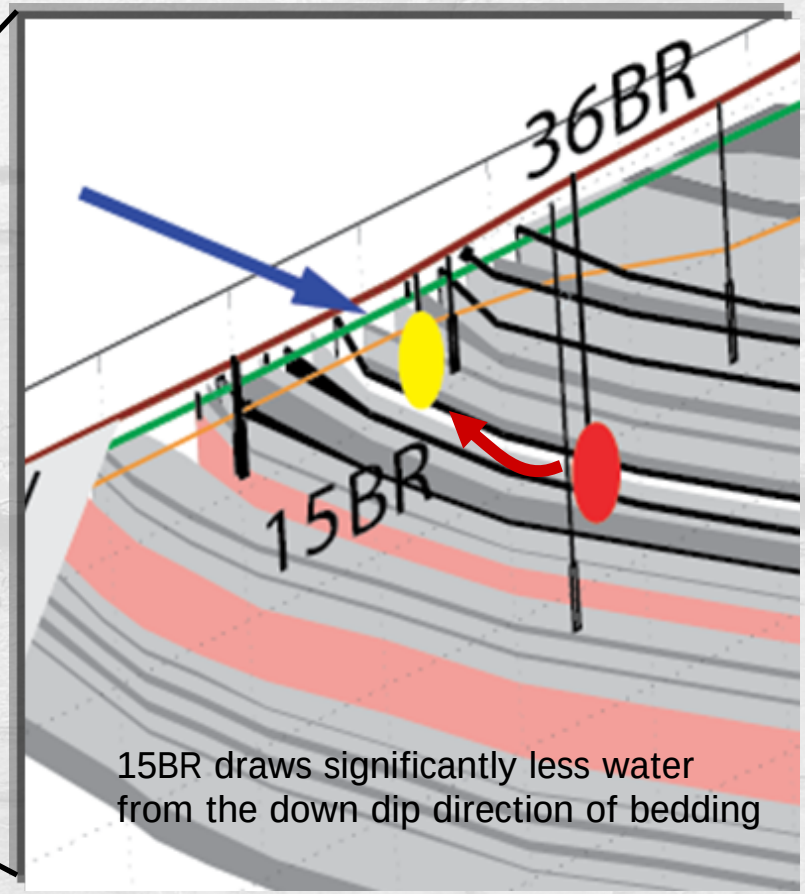
Ground water flow and transport models have been developed that represent the results of *in situ* hydraulic and tracer experiments

Ground water drawn into 15BR comes predominantly along the strike of bedding





15BR draws significantly less water from the down dip direction of bedding

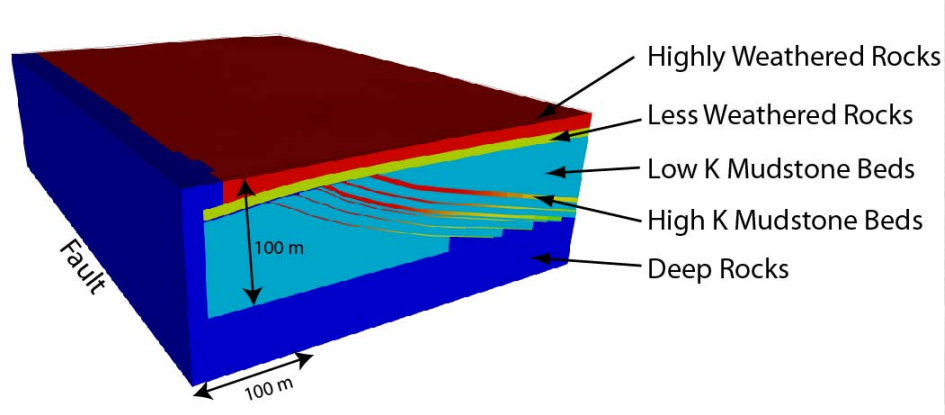


Diagram of bedding used in the ground-water flow model of the mudstone at the NAWC

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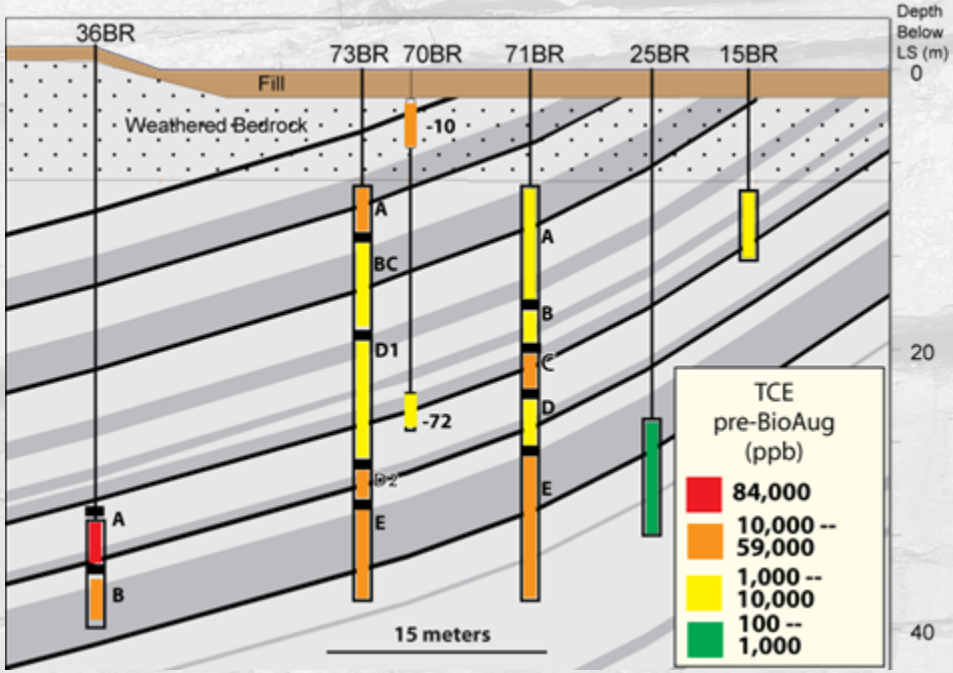
Interpreting the contaminant concentrations at points of ground water discharge



- *Remedial design is improved through direct evidence of ground water residence times and chemical mixing*
- *Designing the monitoring of remediation is improved through the understanding of the geologic framework, flow regime, and direct evidence of chemical transport*
- *Multilevel monitoring boreholes (70BR, 71BR, and 73BR) were installed prior to the bioaugmentation experiment*

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From complexities of fractured rock, we should anticipate. . .

- Complex distribution of DNAPL (free and dissolved phase), with contaminant mass in small aperture fractures and the primary porosity of the rock

- Remediation technology will be most effective in most permeable fractures

- Designing containment and remediation requires understanding of geologic framework, ground water flow regime, and chemical residence time and mixing

- Monitoring at manipulated boreholes, pumped boreholes, and intermediate locations

A few final thoughts. . .

- We have had great success in developing tools for characterizing ground water flow and chemical transport in fractured rock. . .our success makes it possible to design and implement containment and remediation strategies. . .

- Expectations of remediation success must be tempered by the reality of the complexities of fractured rock. . .