Developing a CSM to Inform Application of Bioremediation in Fractured Rock

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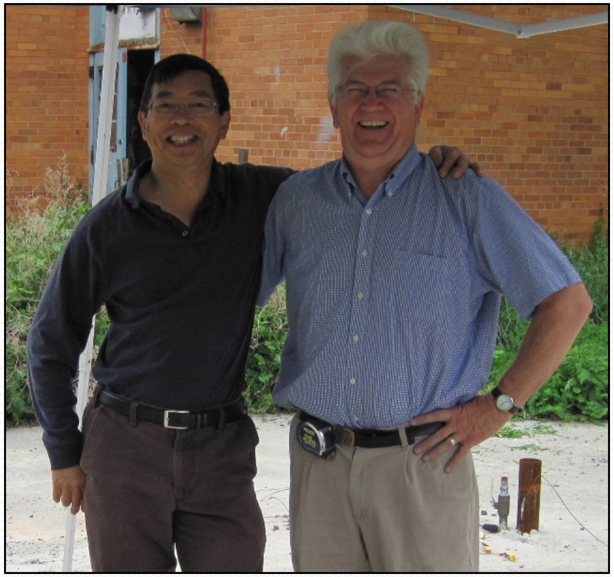
USGS NAWC Team



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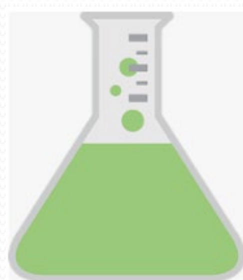

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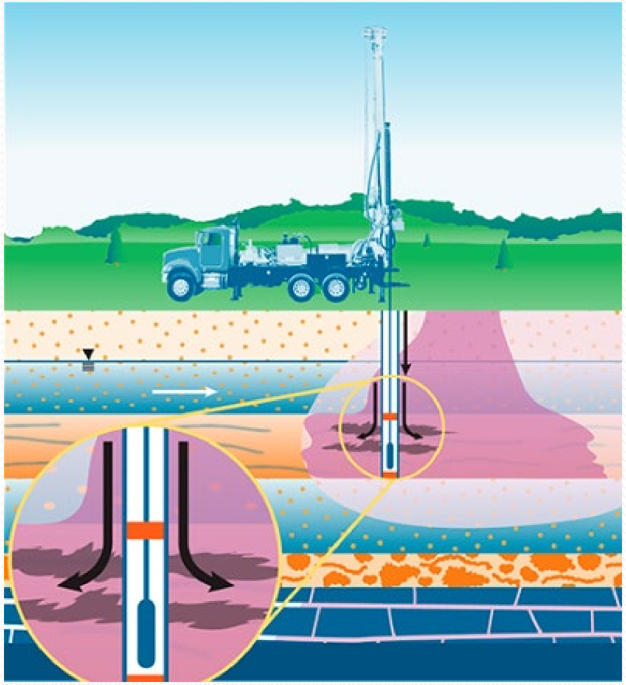
Outline

- Motivation: Importance of Hydrogeologic Conceptual Site Model to In-Situ Remediation
- Former Naval Air Warfare Center (NAWC) Site
- Development and Evolution of CSM to Inform Bioremediation Design and Expectations
- Bioremediation Results
- Summary

In-Situ Remediation of Fractured Rocks: Importance of Hydrogeologic CSM

- In-situ remediation typically involves injection of amendments to stimulate biological or chemical contaminant degradation and transformation processes.
- **Distribution of hydraulic properties** controls groundwater fluxes and the spread of amendments during and after injection.



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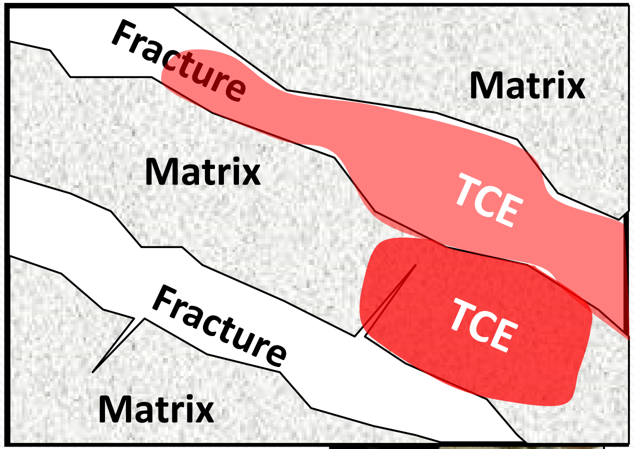
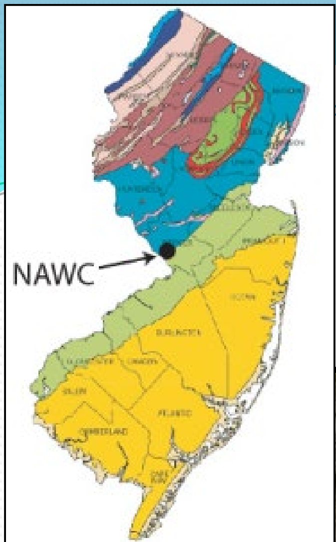
In-Situ Remediation of Fractured Rocks: Importance of Hydrogeologic CSM

- Understanding the hydrogeology is thus critical for designing injection strategies that spread amendments to locations of contamination in fractures and the rock matrix.

- While amendments might not enter the rock matrix, enhanced degradation in adjacent fractures leads to enhanced diffusion out of matrix.



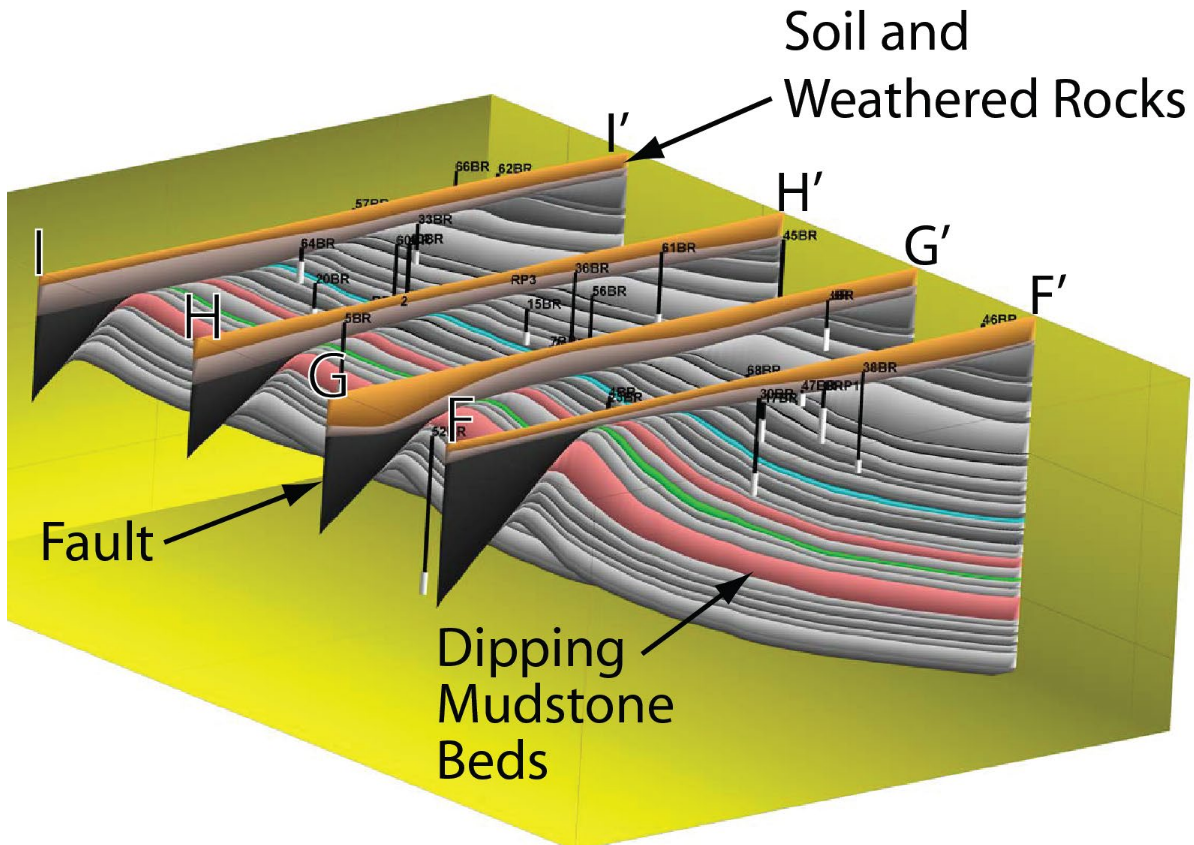


Former Naval Air Warfare Center (NAWC) West Trenton, New Jersey

- Focus site for USGS research on contaminant fate, transport, remediation under Toxic Substances Hydrology Program, 2005-2018.
- Dipping fractured sedimentary rocks.
- Groundwater highly contaminated with trichloroethene (TCE) and its degradation products DCE and vinyl chloride.

Geologic Framework

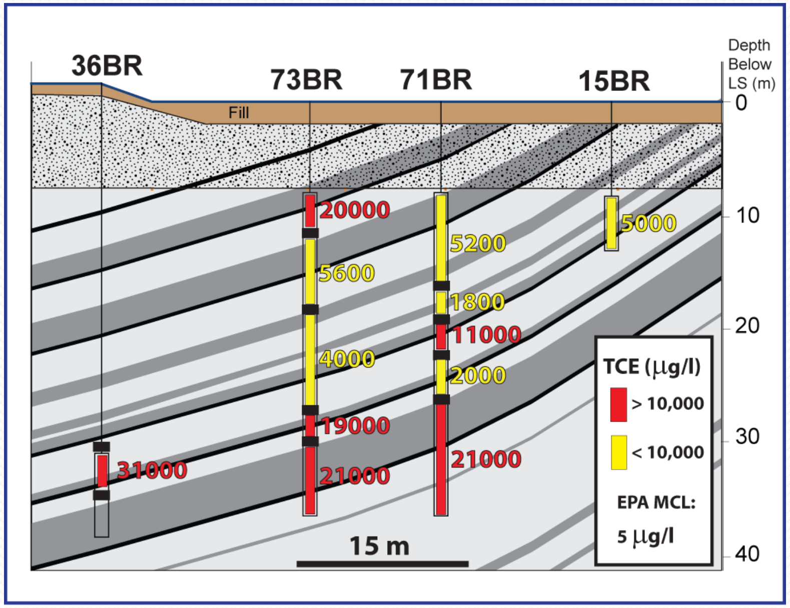
- Lockatong Formation of Newark Basin.
- Competent dipping mudstone beds overlain by weathered rocks & soil/saprolite.
- Individual mudstone beds mapped across NAWC site.
- Dominant flow paths along bedding-plane-parting fractures.

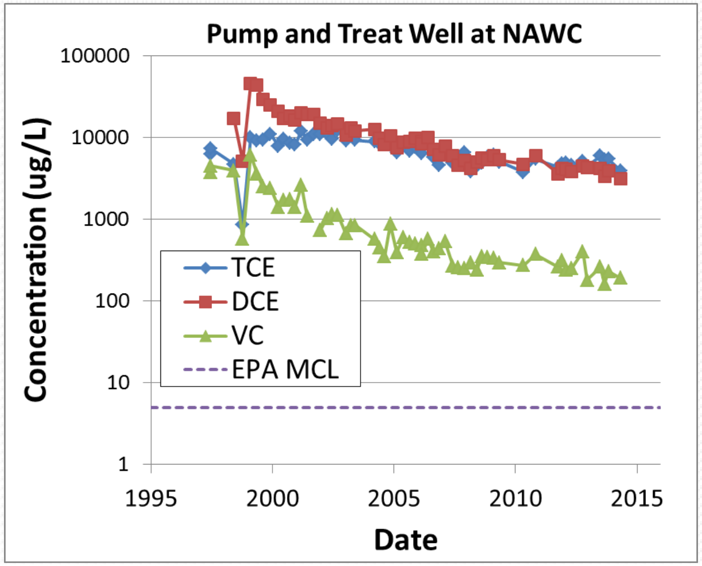


Highly weathered rock

Competent mudstones: fissile, laminated, massive

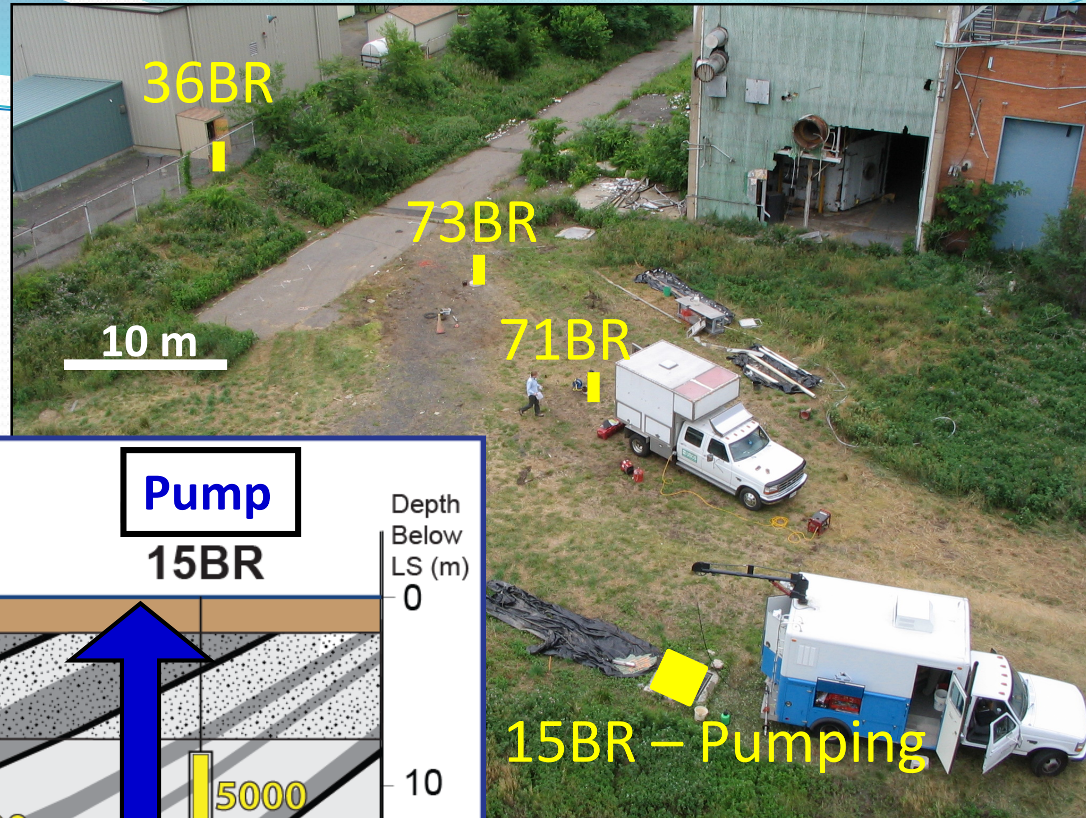
Contamination in NAWC Rocks

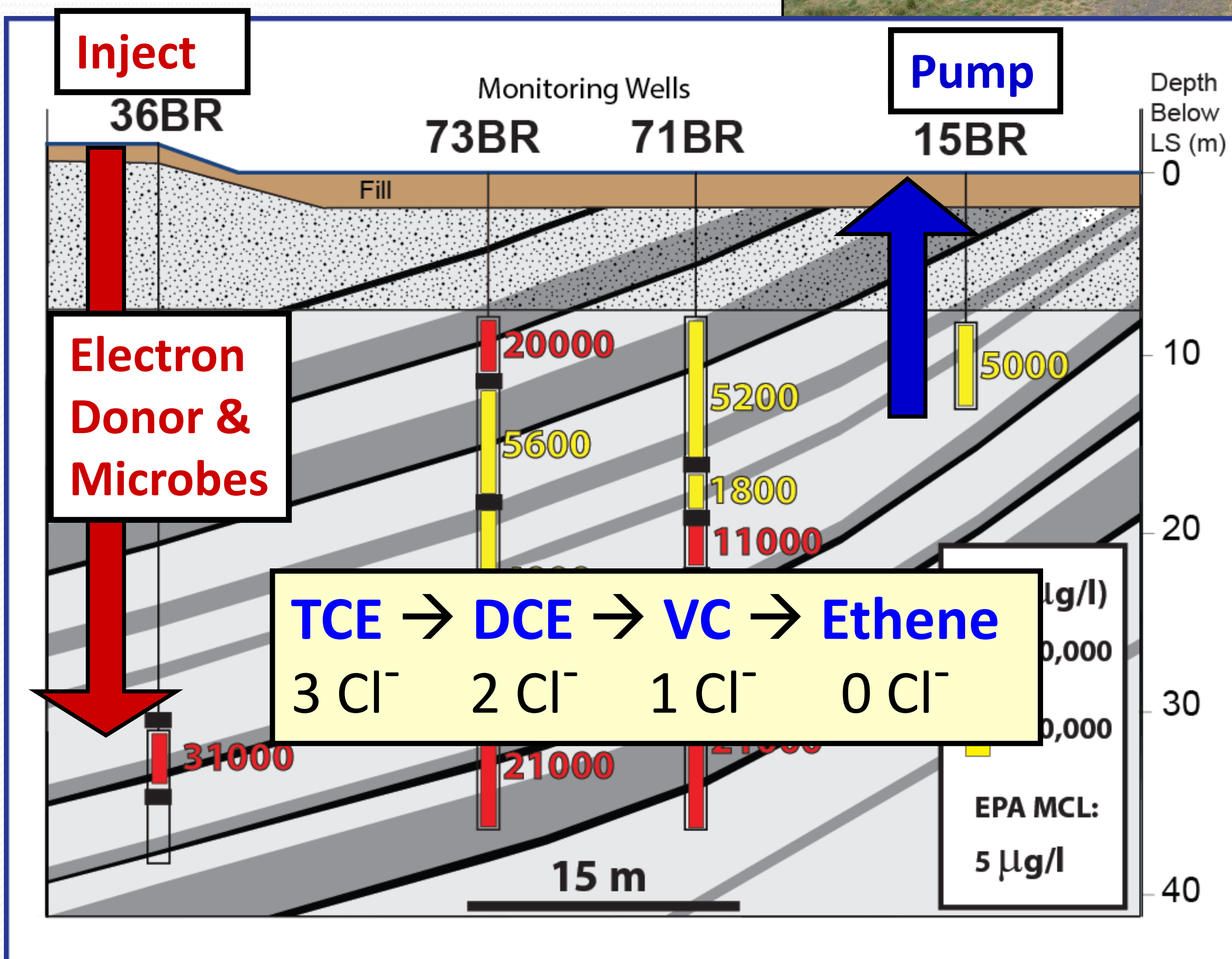




- Extremely high concentrations of TCE and DCE: Orders of magnitude above U.S. EPA standards.
- Extremely persistent: Contaminant concentrations remain high despite 20+ years of pump & treat.

Bioremediation Area





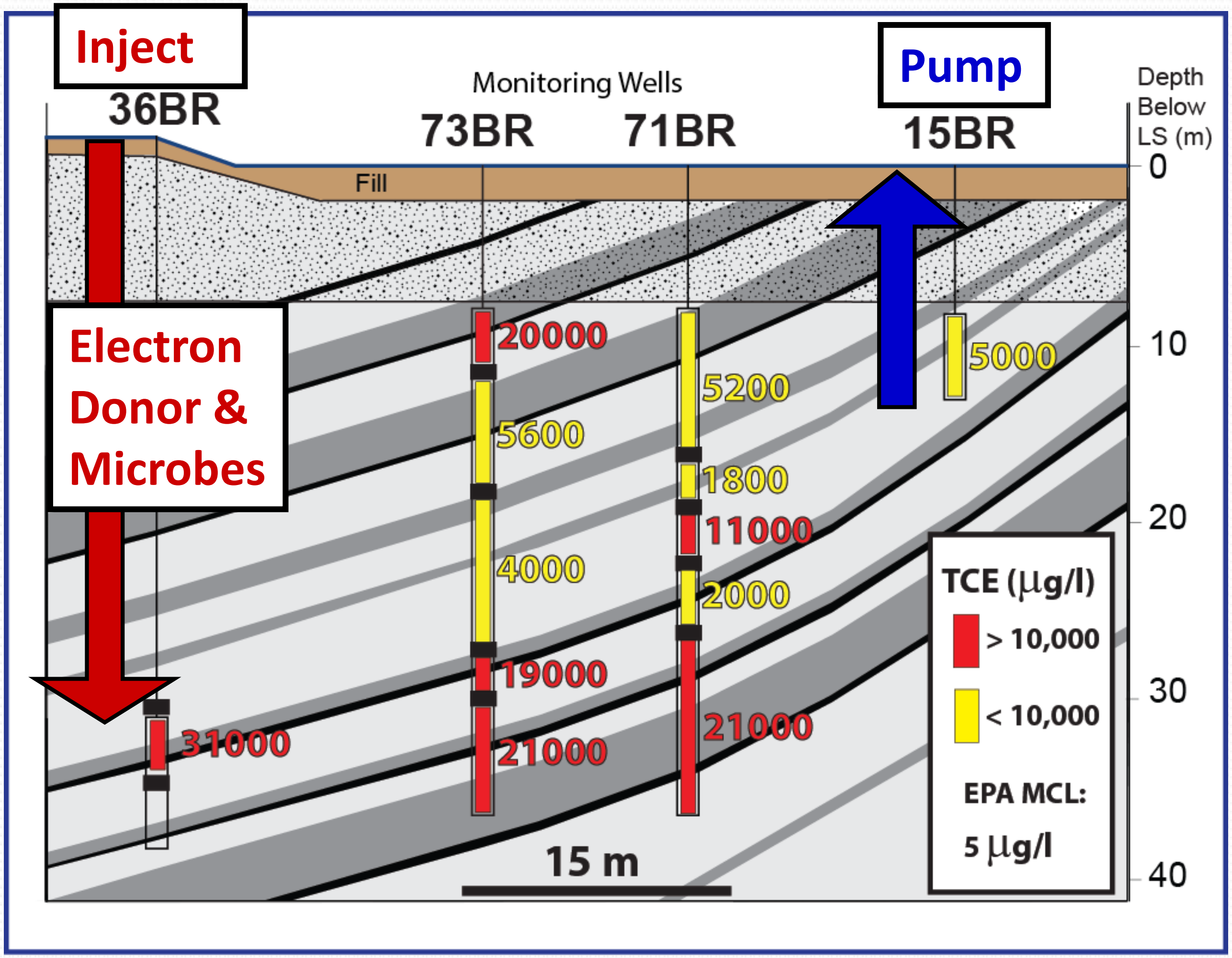
Overall objective:

Improve understanding of controls on bioremediation effectiveness in fractured rocks.

Bioremediation Design and Expectations

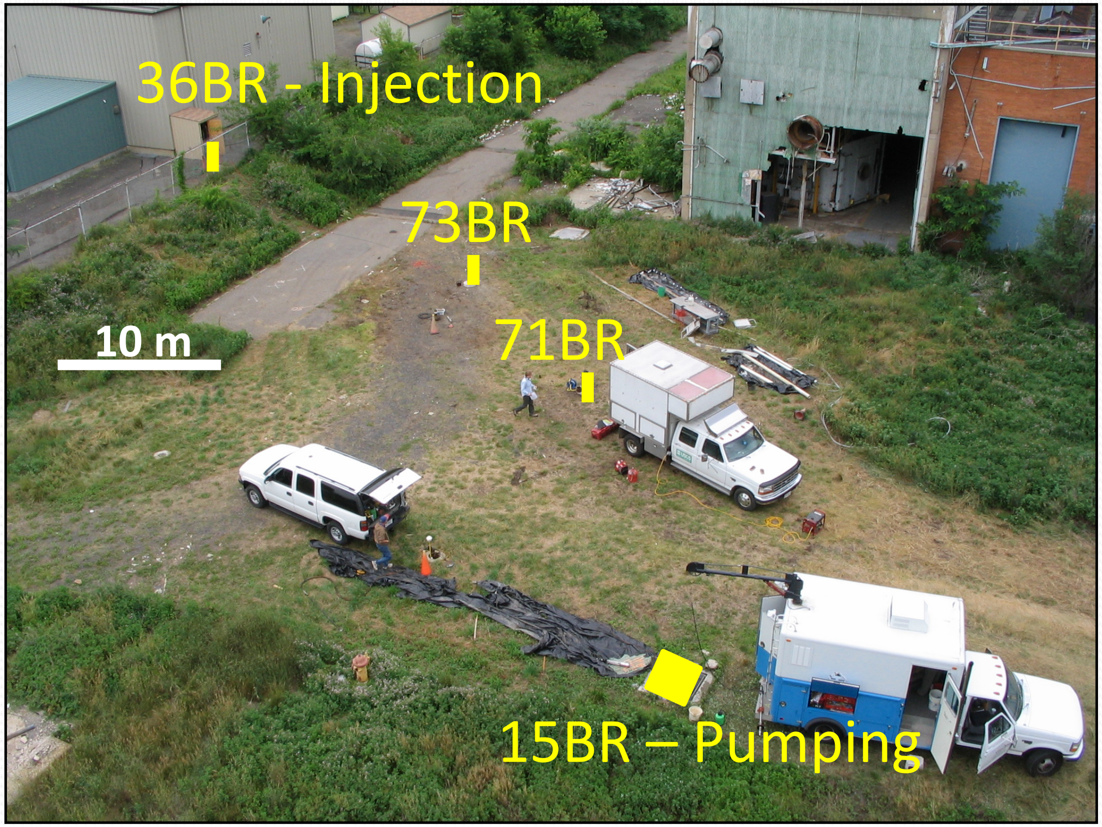
Questions related to hydrogeology:

- Amendment volume to inject?
- Pumping rate at extraction well?
- Where to expect treatment?



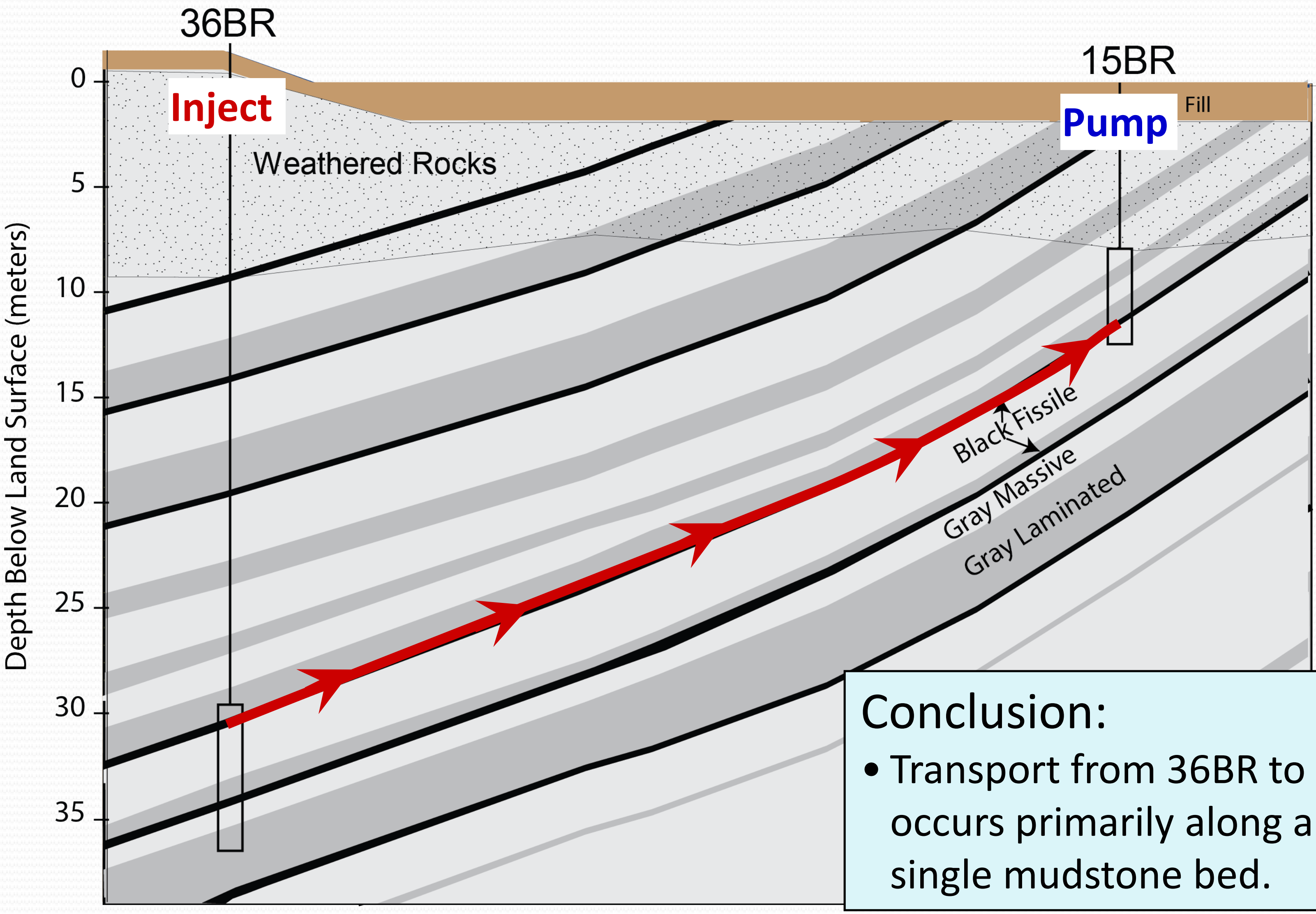
Hydrogeologic Investigation to Guide Bioremediation Design

- Geologic interpretation
- Single- & cross-hole hydraulic tests
- Cross-hole tracer test
- Flow & transport modeling



Results will be shown along transect between 36BR and 15BR. In reality, flow and transport are 3D.

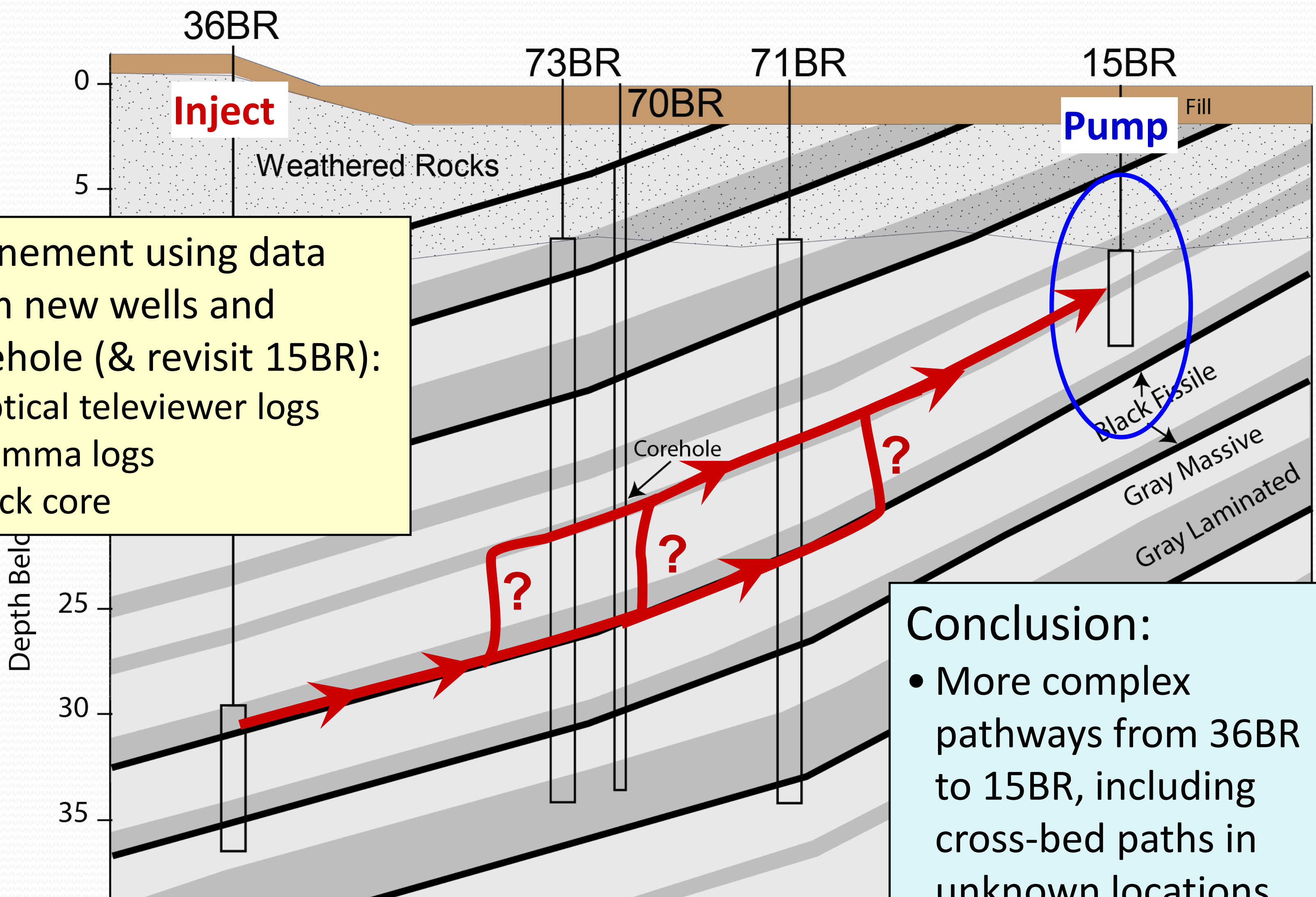
Initial Geologic Interpretation



Conclusion:

- Transport from 36BR to 15BR occurs primarily along a single mudstone bed.

Refined Geologic Interpretation



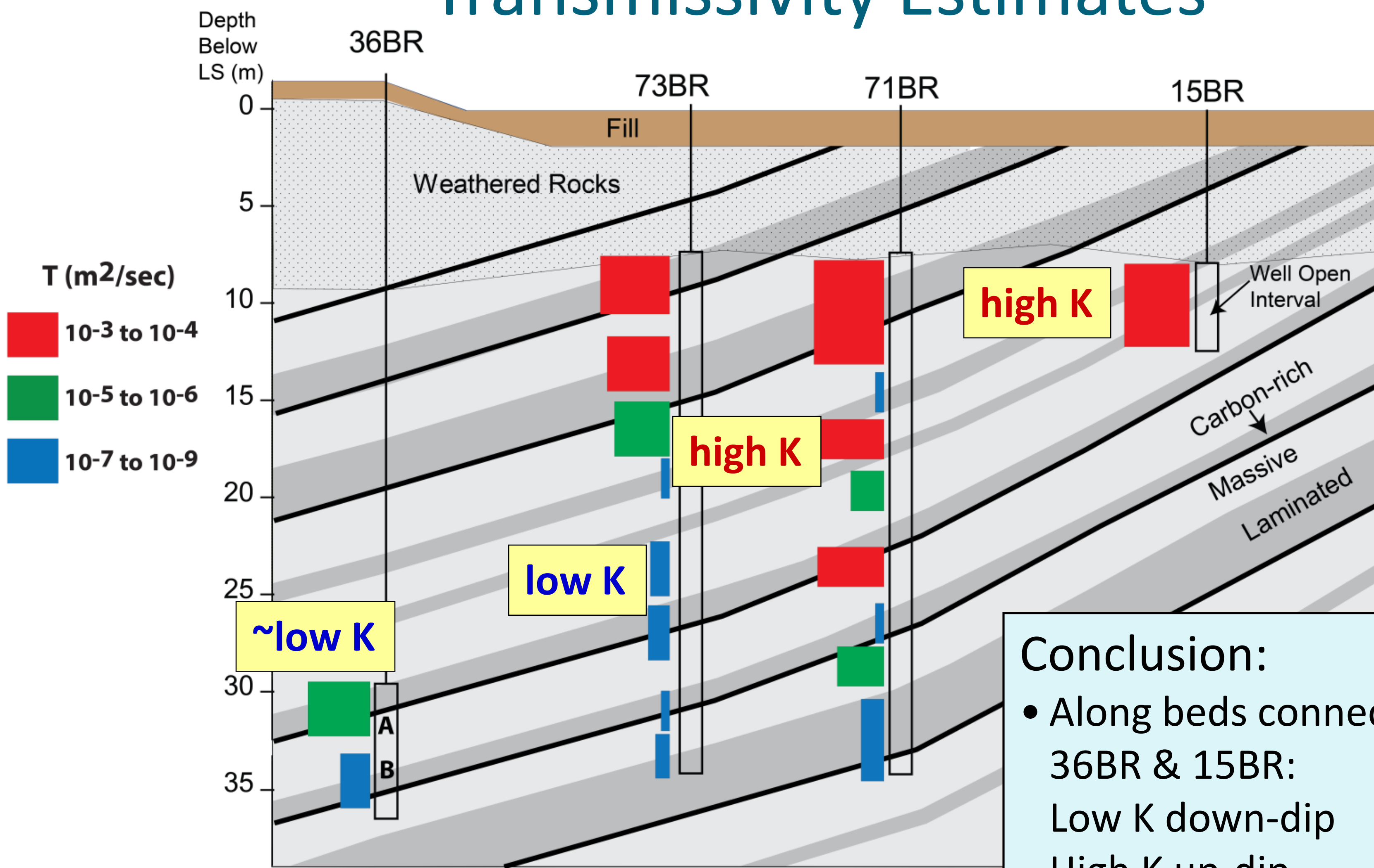
Refinement using data from new wells and corehole (& revisit 15BR):

- Optical televiewer logs
- Gamma logs
- Rock core

Conclusion:

- More complex pathways from 36BR to 15BR, including cross-bed paths in unknown locations.

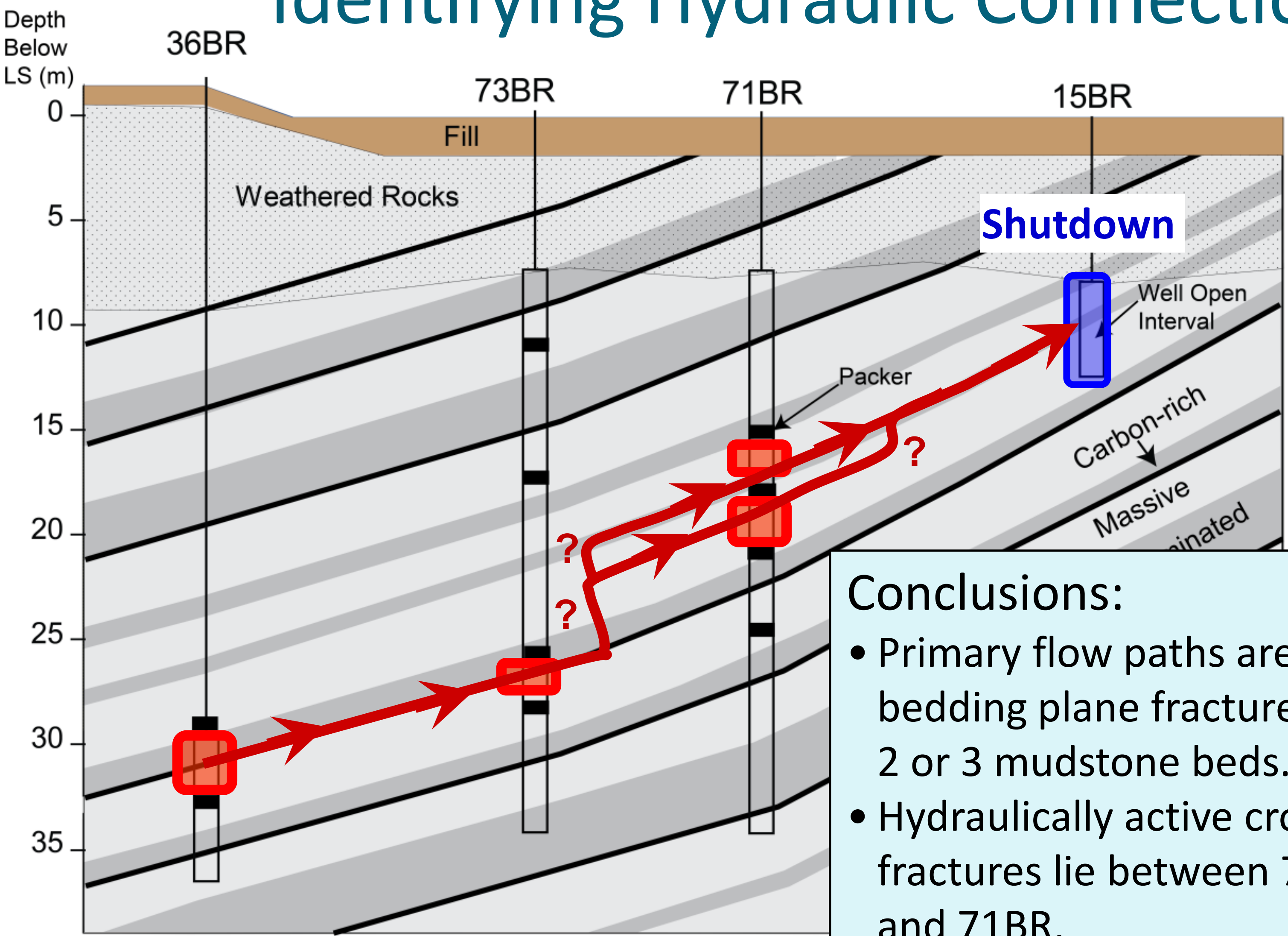
Single-Hole Hydraulic Testing: Transmissivity Estimates



Conclusion:

- Along beds connecting 36BR & 15BR:
  Low K down-dip
  High K up-dip

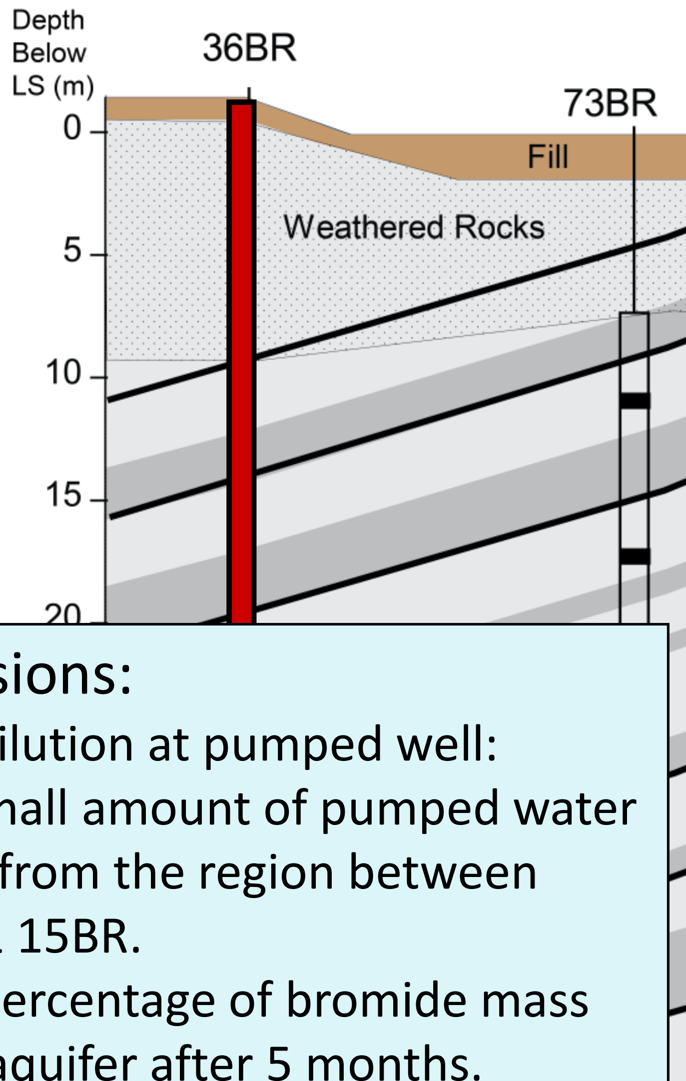
Cross-Hole Aquifer Testing: Identifying Hydraulic Connections

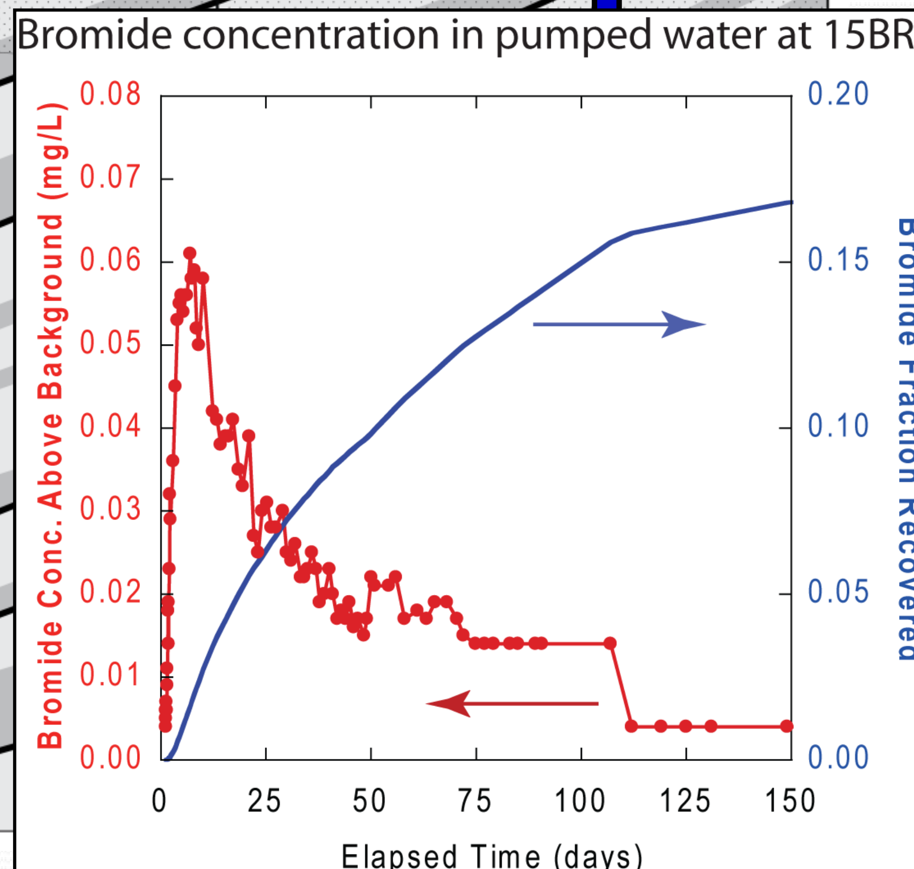


Conclusions:

- Primary flow paths are along bedding plane fractures in 2 or 3 mudstone beds.
- Hydraulically active cross-bed fractures lie between 73BR and 71BR.

Cross-Hole Tracer Testing: Transport Properties



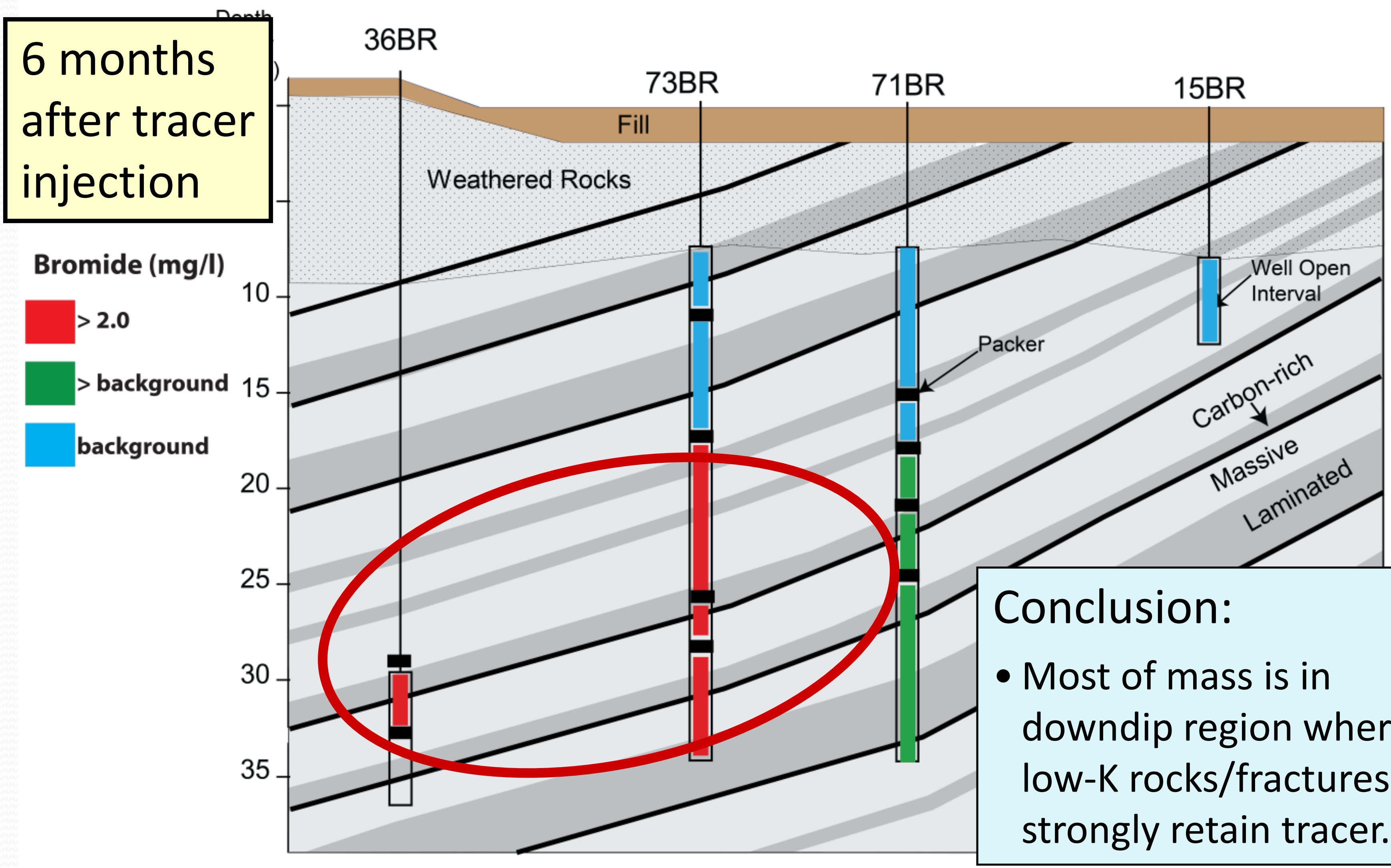


Conclusions:

- Huge dilution at pumped well: Only small amount of pumped water comes from the region between 36BR & 15BR.
- Large percentage of bromide mass still in aquifer after 5 months.

Strong Tracer Retention

6 months after tracer injection

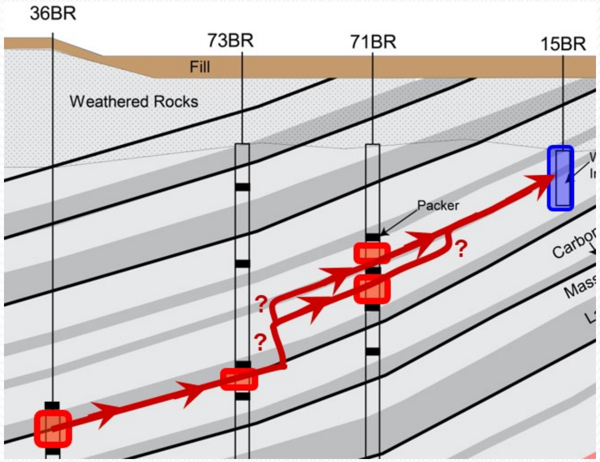


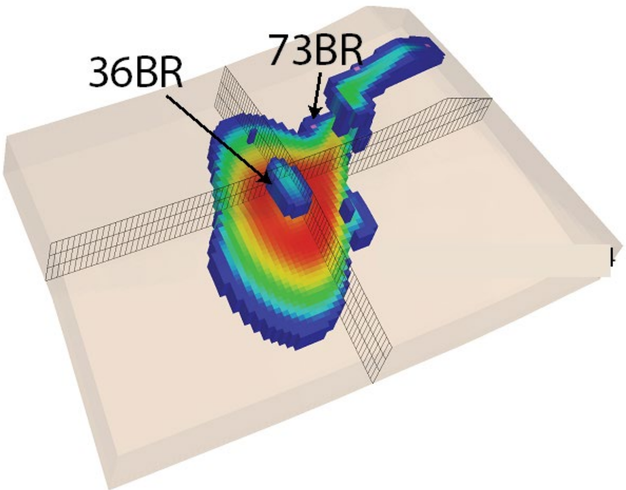
Conclusion:

- Most of mass is in downdip region where low-K rocks/fractures strongly retain tracer.

Further Advancing the CSM: Flow and Transport Modeling

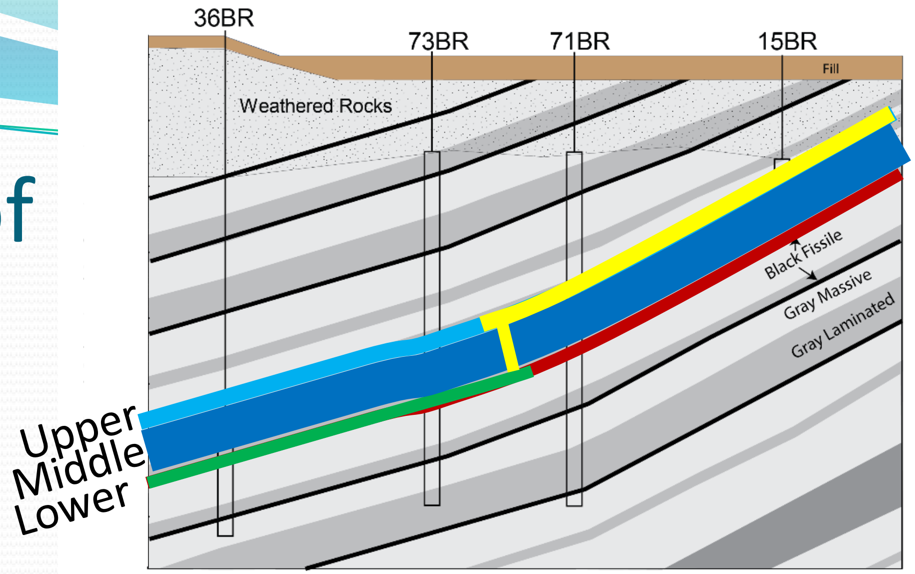
- Field characterization: *Qualitative* info about flow and transport paths and tracer behavior.
- No info about distribution and magnitude of groundwater fluxes between 36BR and 15BR, which *strongly control amendment transport*.
- Flow modeling provides fluxes.
- Bromide transport modeling uses these fluxes and simulates temporally varying distribution of the tracer.
- Simulated tracer transport informs expected advective transport of amendments.

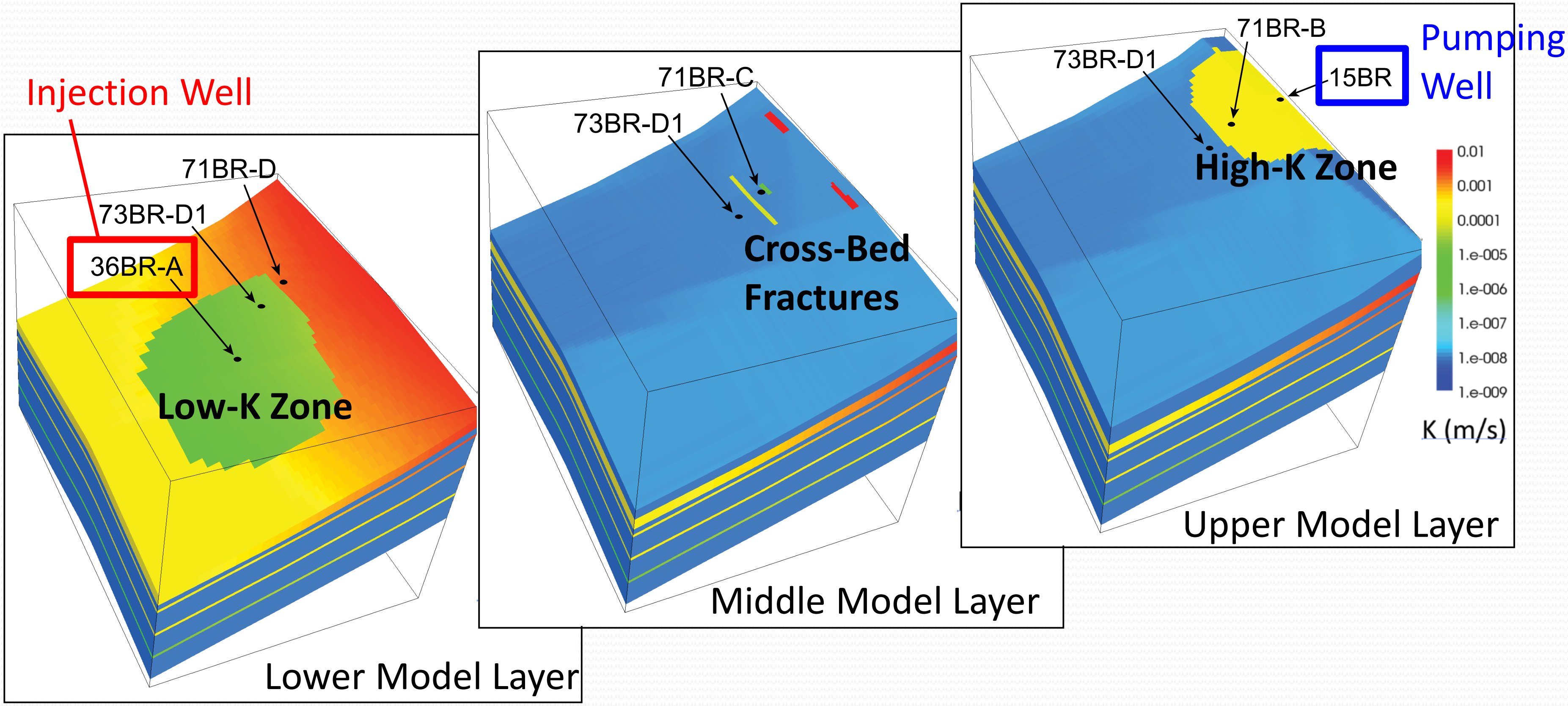




Model Representation of Hydraulic Conductivity

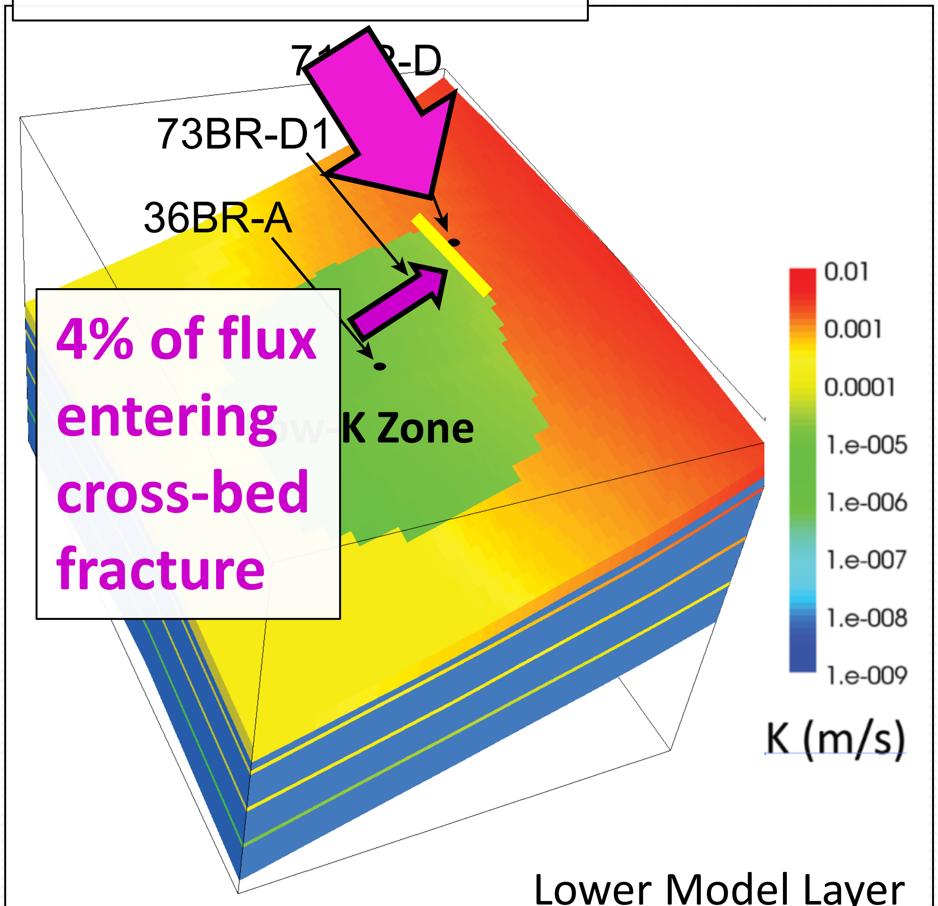
Informed by geology and hydraulic & tracer testing



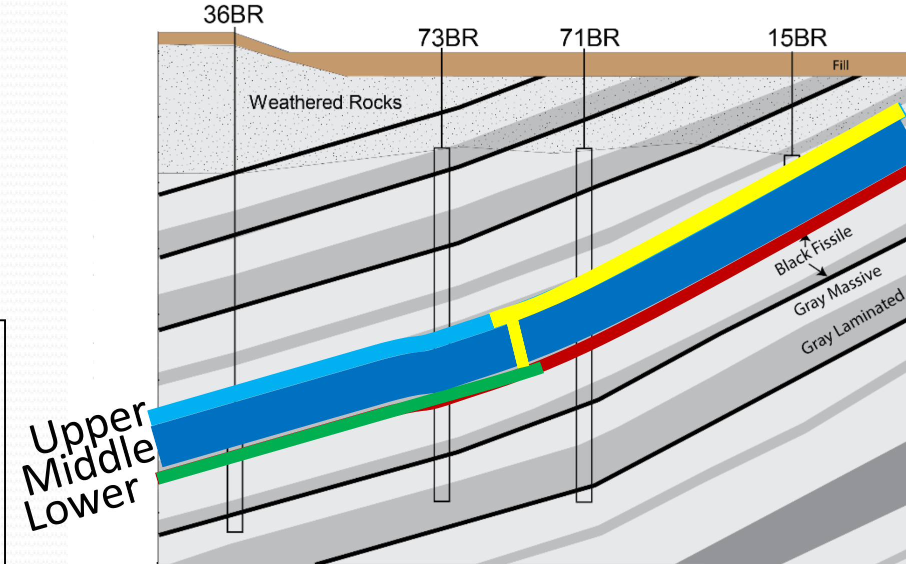


Groundwater Fluxes

96% of flux entering cross-bed fracture



4% of flux entering cross-bed fracture

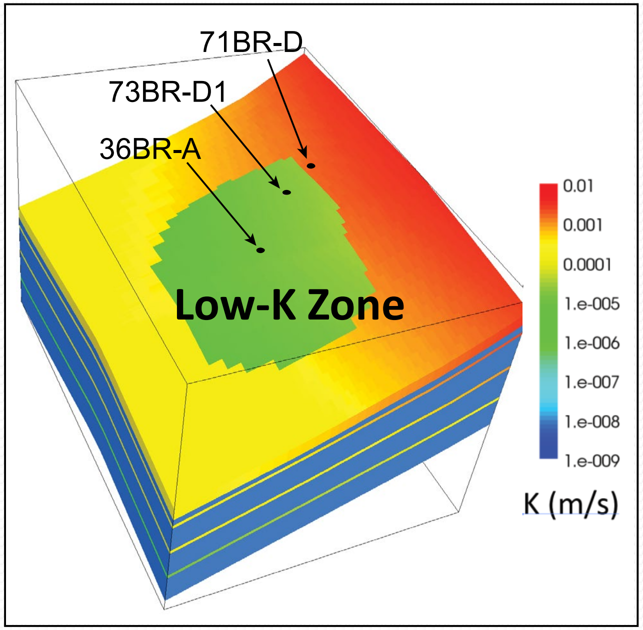


Conclusion:

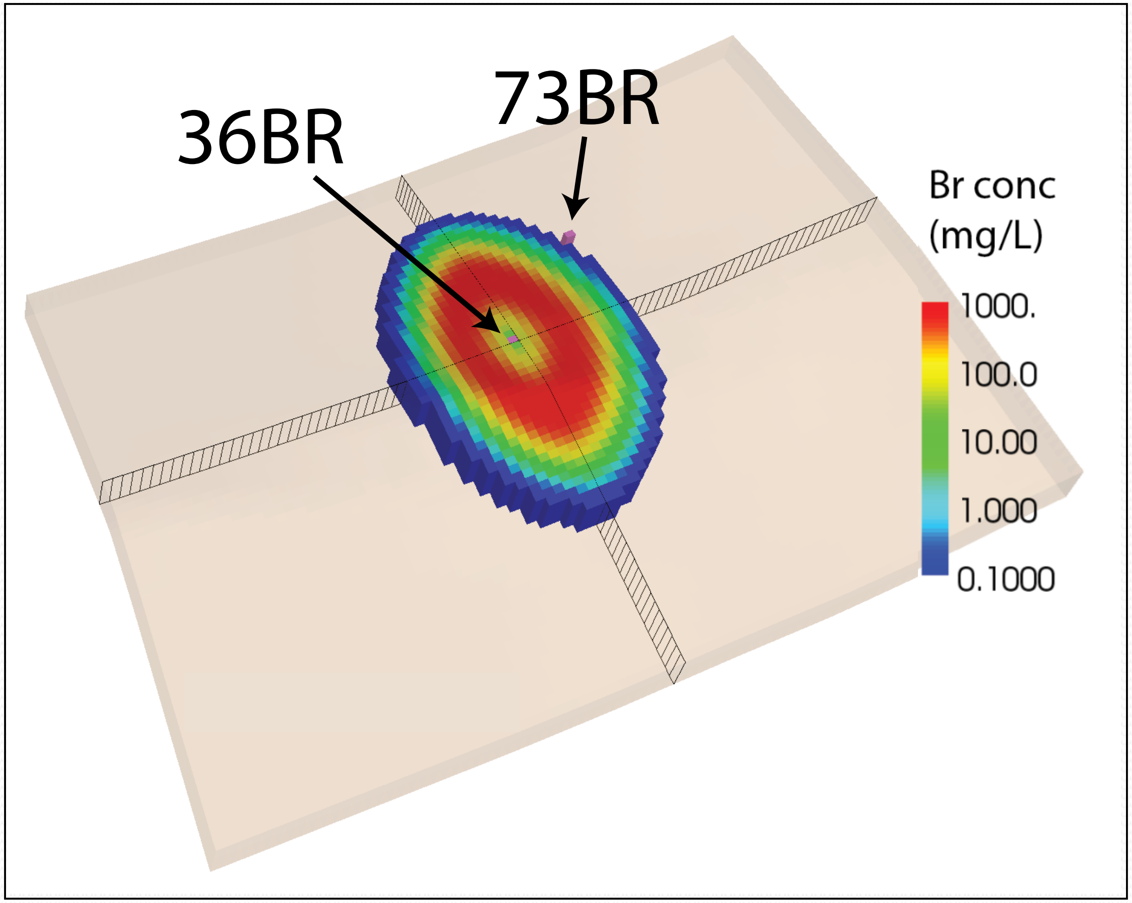
- Most of gw flux entering cross-bed fracture is from the high-K region

Simulated Bromide Tracer Test: Insight Into Expected Amendment Transport

1.5 hrs: End of injection

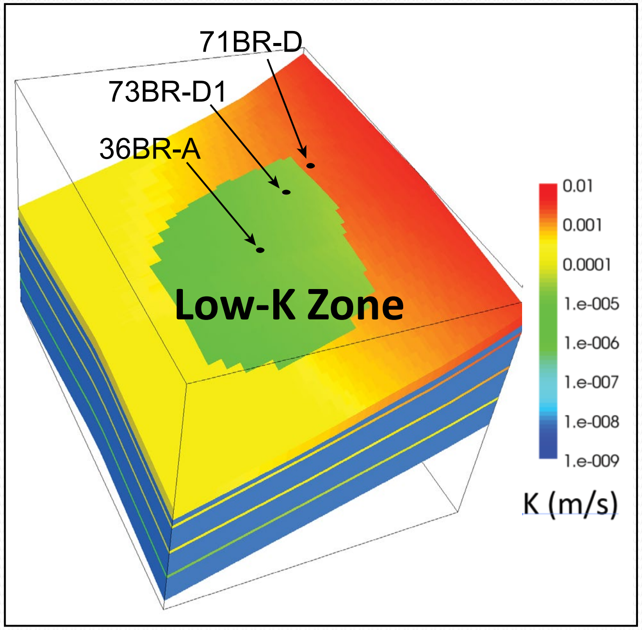


K Distribution



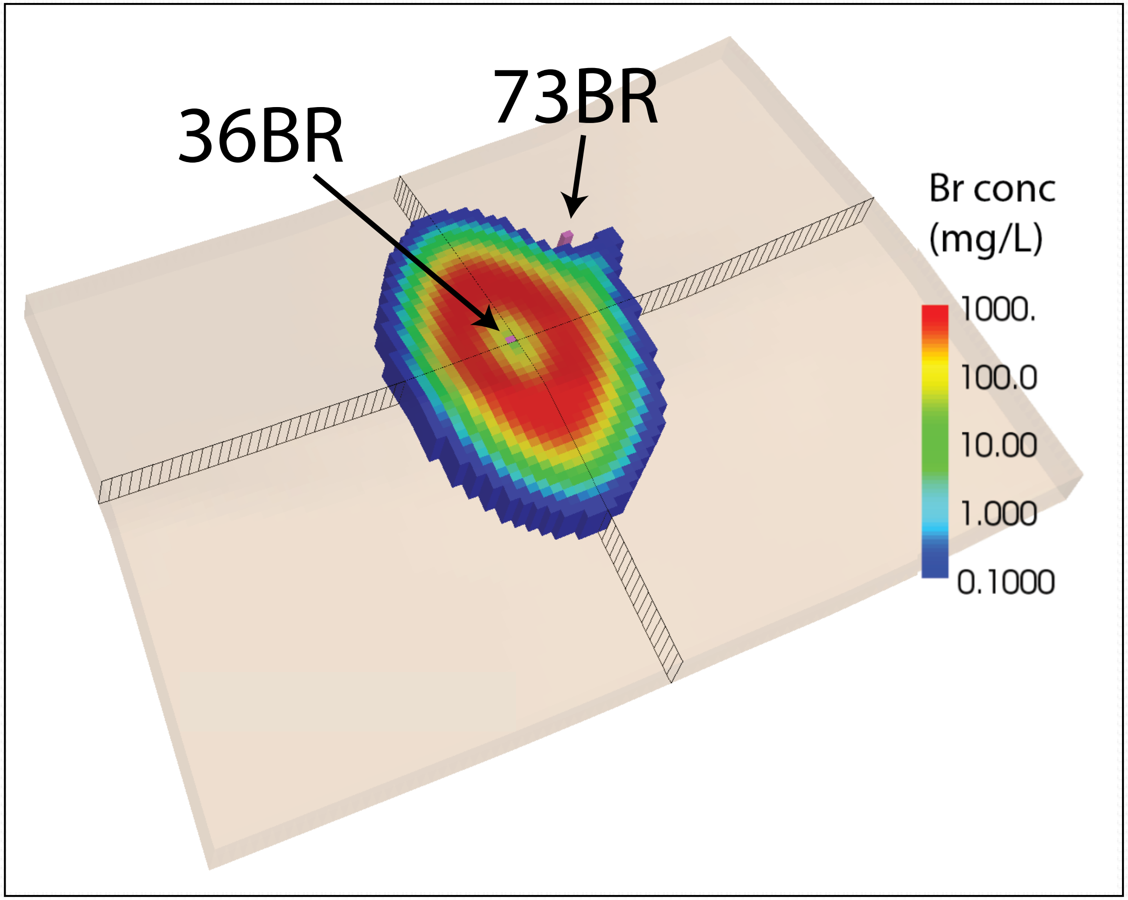
Bromide Transport

Simulated Bromide Tracer Test: Insight Into Expected Amendment Transport



K Distribution

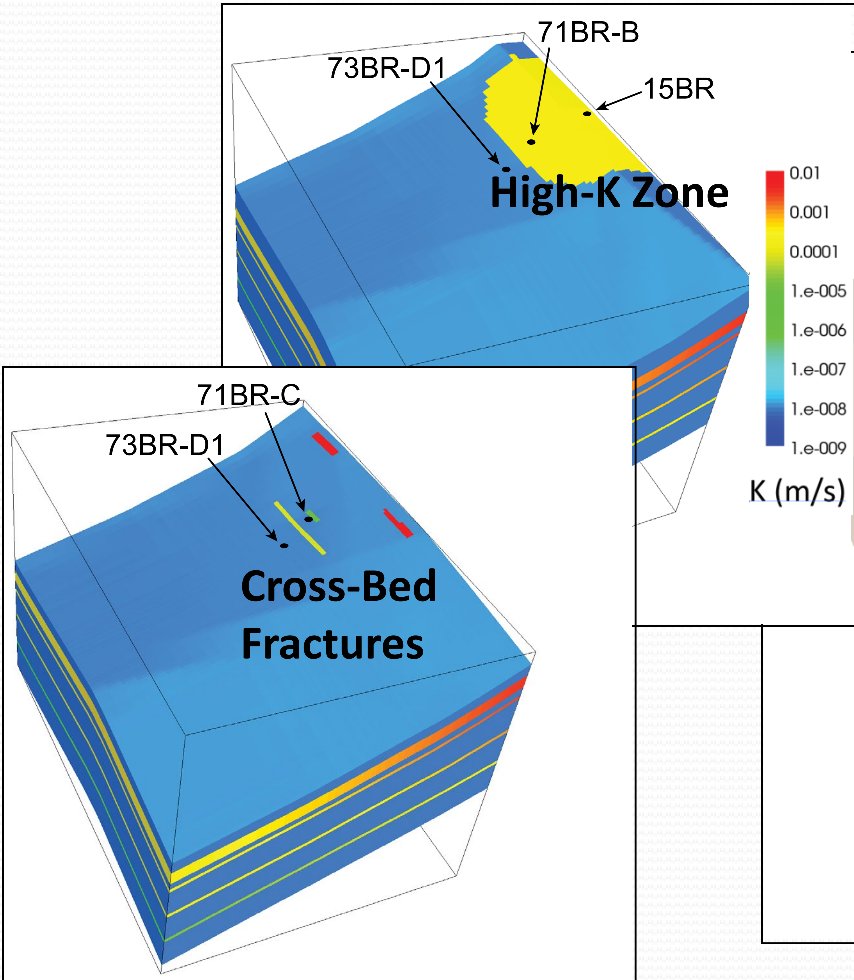
10 hrs: Similar solute distribution

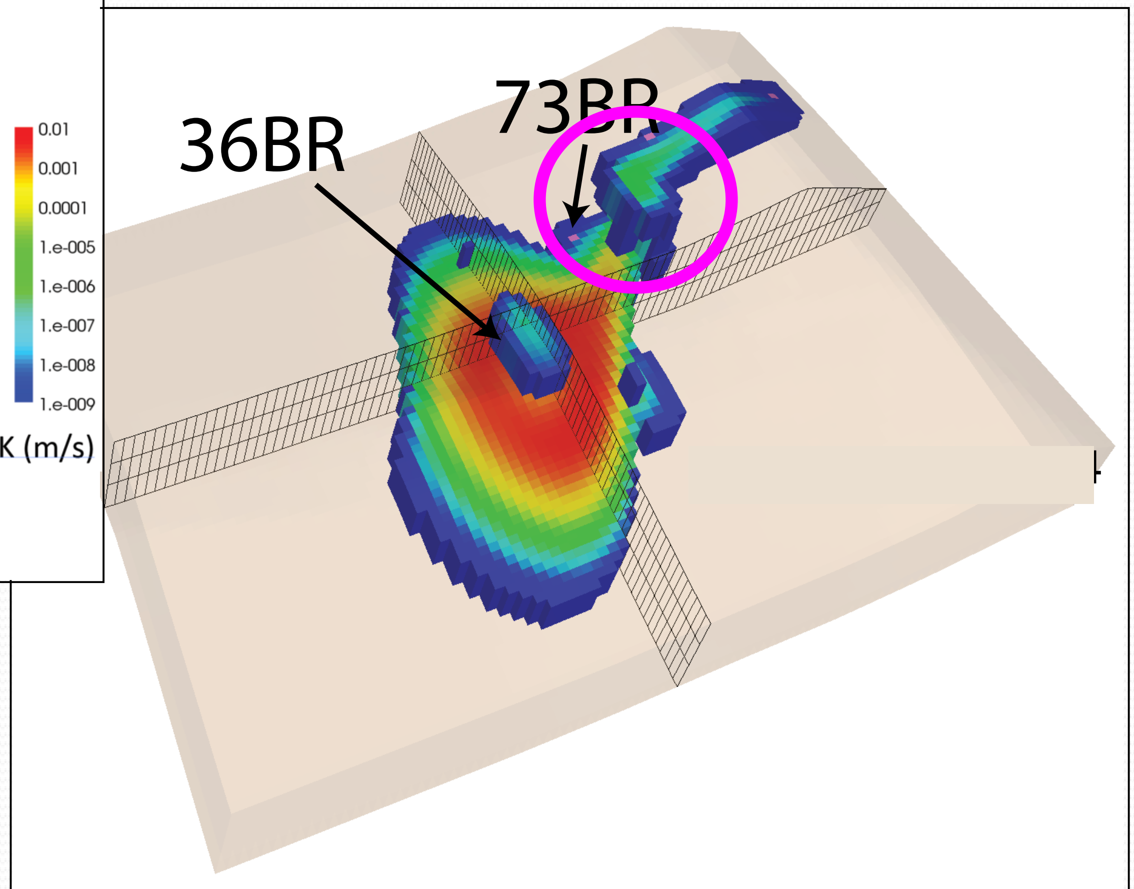


Bromide Transport

Simulated Bromide Tracer Test: Insight Into Expected Amendment Transport

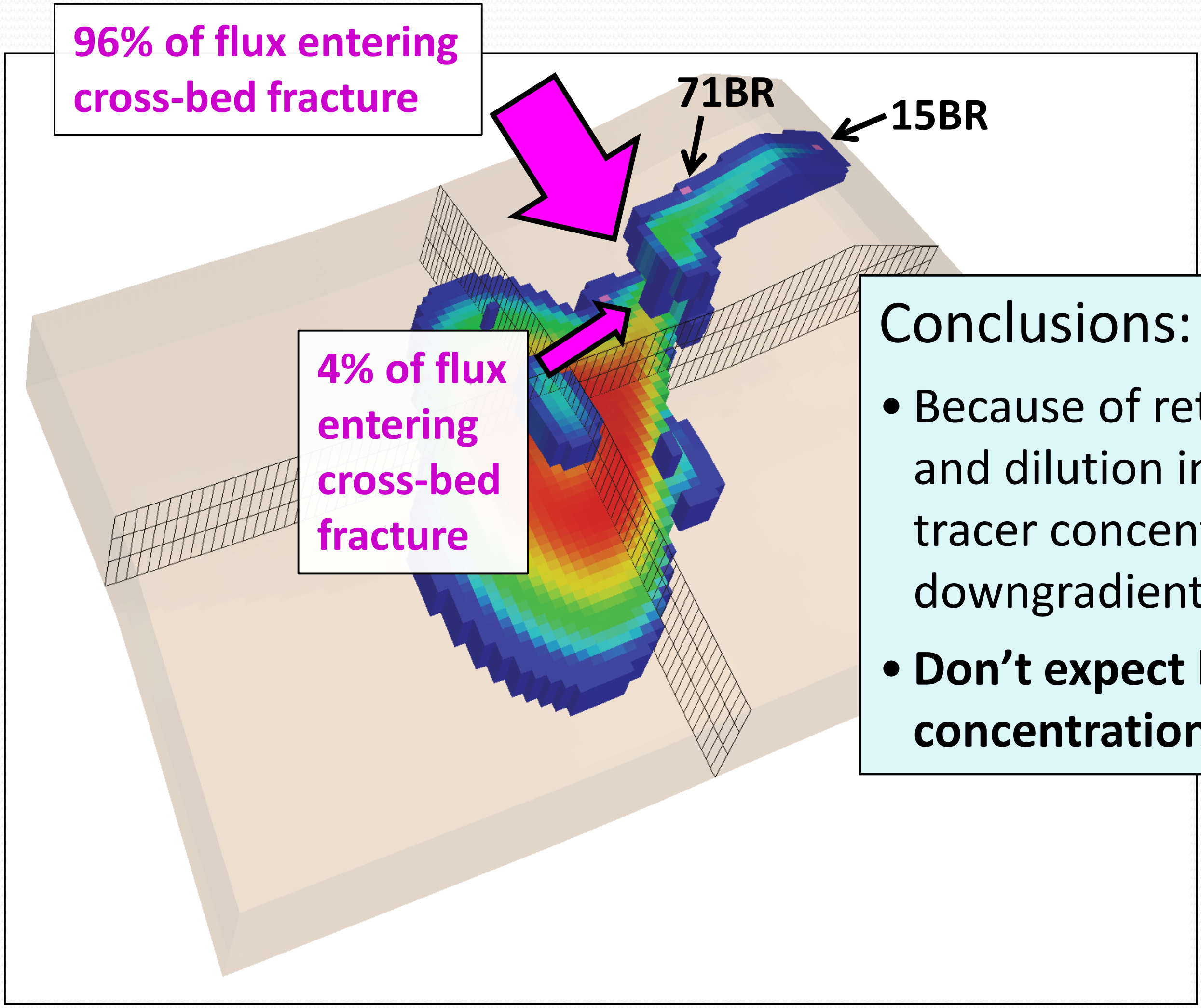
100 hrs: Solute migrates thru cross-bed fracture and to pumping well





Bromide Transport

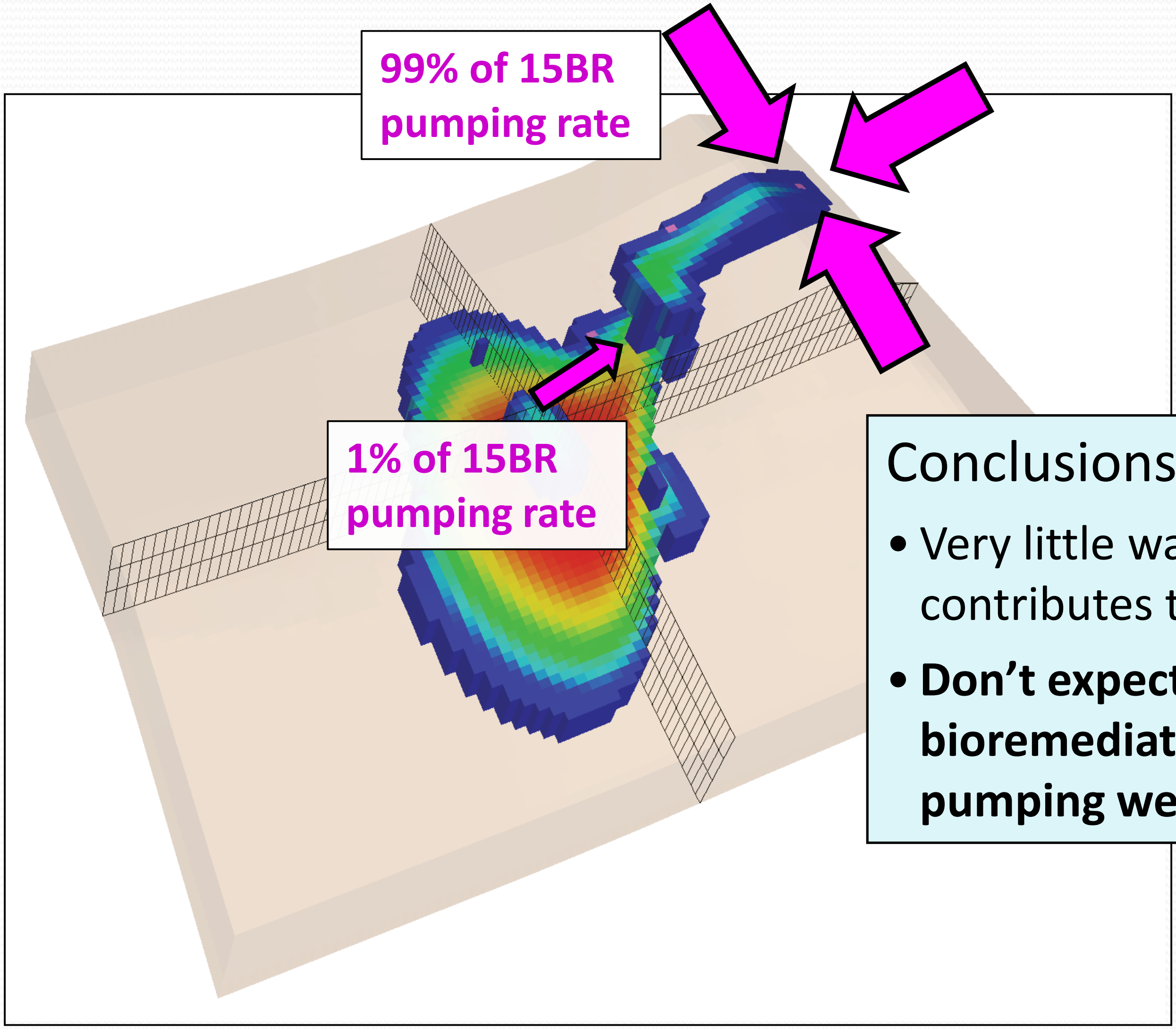
Role of GW Fluxes



Conclusions:

- Because of retention in low-K zone and dilution in cross-bed fracture, tracer concentrations are lower downgradient of this fracture.
- **Don’t expect high amendment concentrations at well 71BR.**

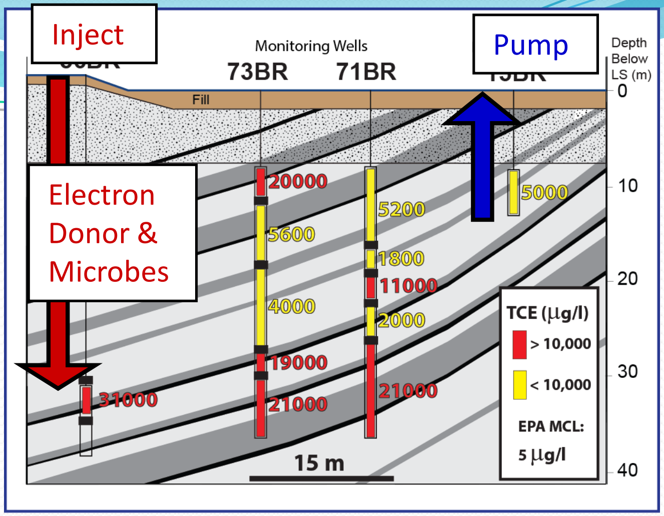
Role of GW Fluxes



Conclusions:

- Very little water from low-K zone contributes to pumped volume.
- **Don't expect to observe bioremediation effects at pumping well.**

Bioremediation Design and Expectations

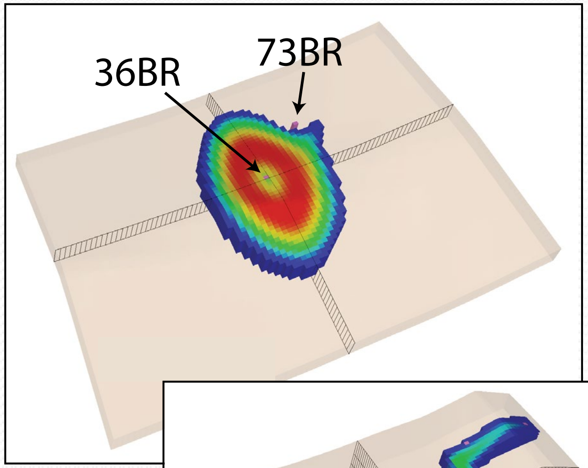


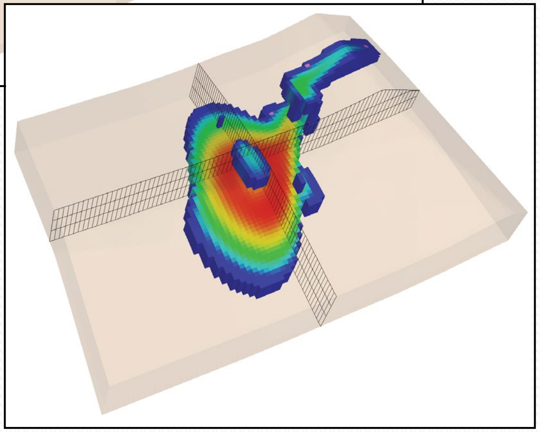
Answers from conceptual site model:

- **Amendment volume to inject?**
  Inject enough volume to spread amendments widely over low-K zone. Ambient flow field will not produce much spreading in this zone.

- **Pumping rate at extraction well?**
  No need to reduce rate. Large quantities of amendments will not be pumped out, because of strong retention in low-K zone.

- **Where to expect treatment?**
  In low-K zone. Because of dilution, don't expect substantial bioaugmentation effectiveness at 71BR and 15BR.





Bioremediation

- Final pre-bioremediation characterization activity: Push-pull tracer test in 36BR that showed 650 liters injectate volume is needed to spread amendments to 73BR (near edge of low-K zone).
- October 2008: Injected 670 liters amendments plus borehole flush water into 36BR:
  - 470 liters EOS^{TM} solution
  - 20 liters KB-1^{TM}
  - 180 liters borehole flush water

Injection bladders

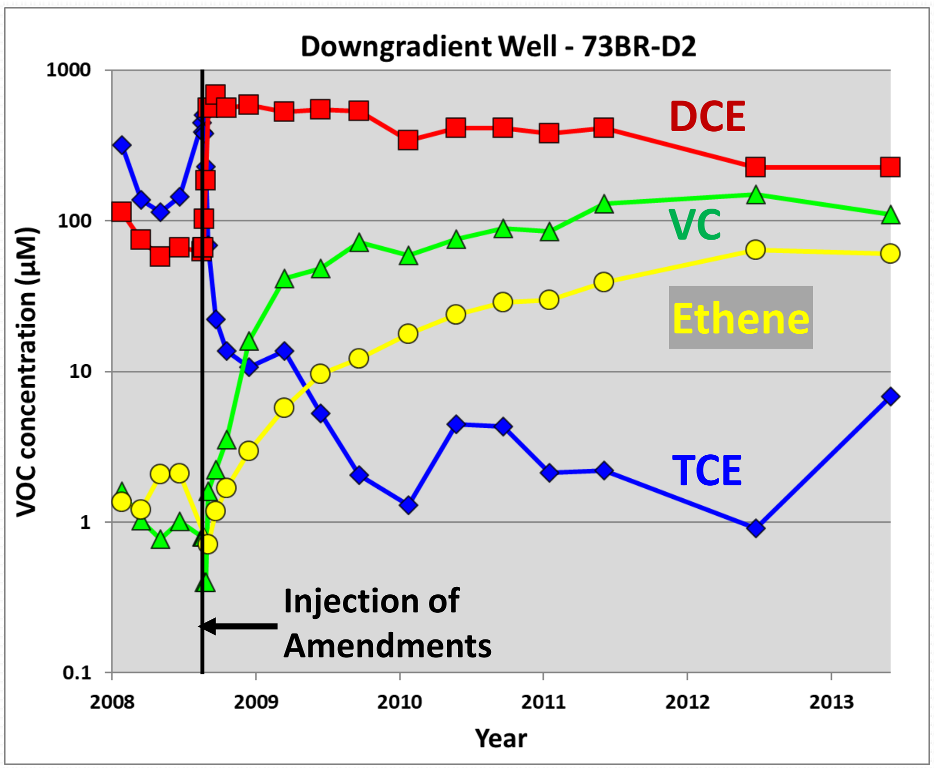

EOS^{TM} – Emulsified soybean oil

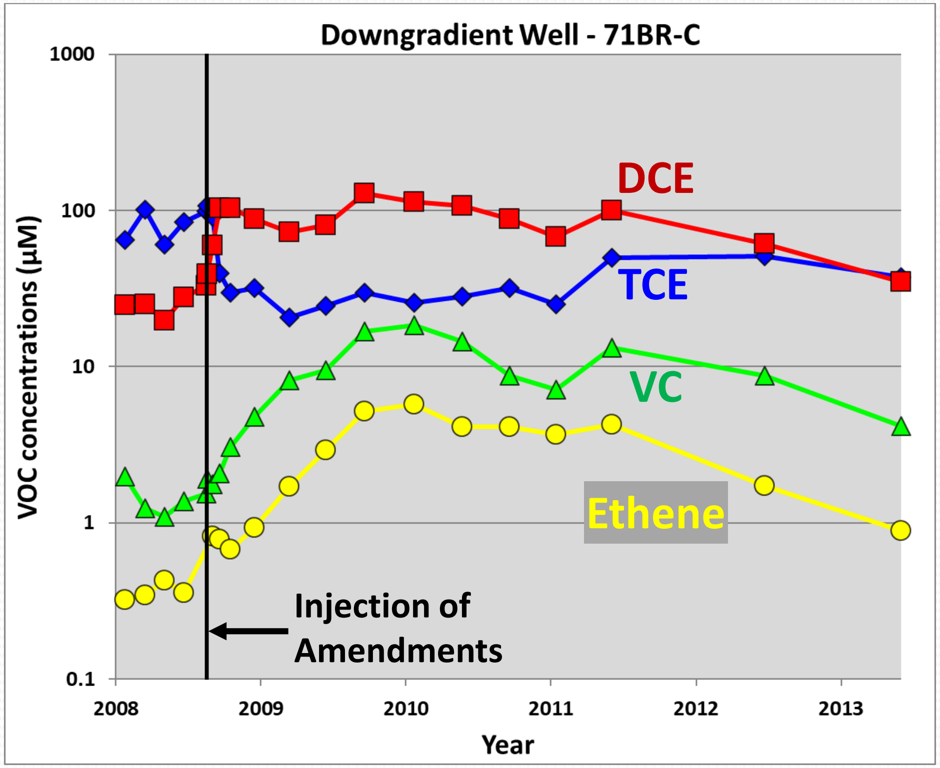

KB-1^{TM} – Microbial consortia containing complete dechlorinators

Bioremediation Effects 2008 - 2013

In low-K zone:

- TCE quickly degraded
- DCE produced and remains high
- Rates of degradation to VC & ethene are moderate





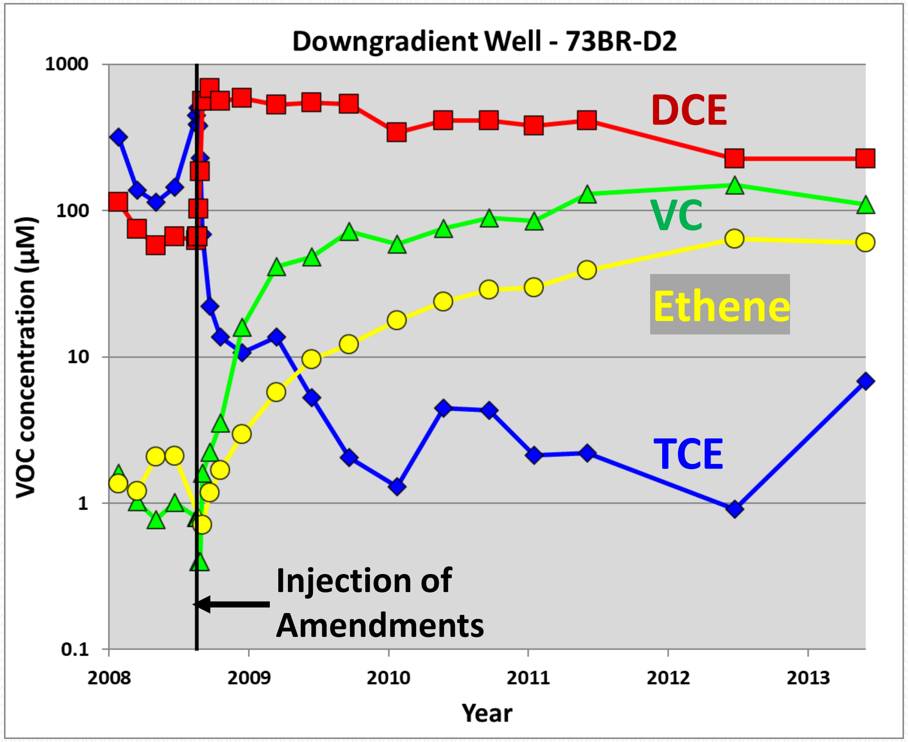
Downgradient of low-K zone at 71BR:

- TCE degradation & DCE production to a lesser degree
- Minor VC & ethene production

At 15BR: No concentration changes post-injection.

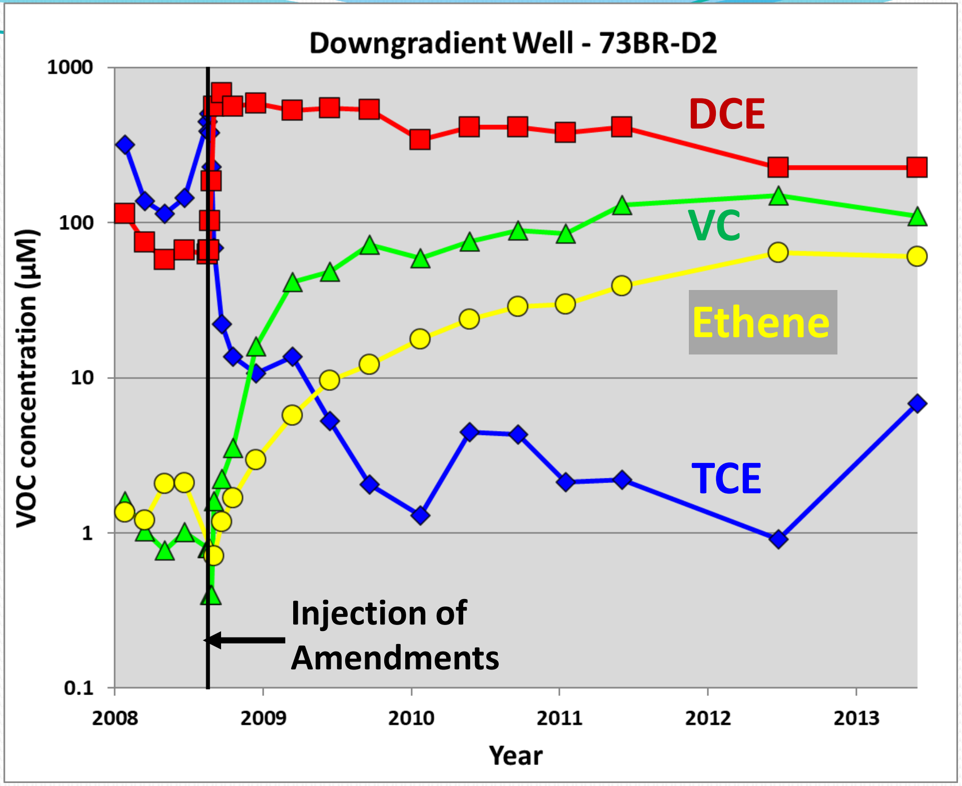
Expectations Vs Reality

- Expected more complete treatment of VOCs in low-K zone.
- Amendments were spread into this zone, and included microbes capable of completely degrading TCE to ethene.
- However, degradation of DCE and vinyl chloride is incomplete.



Cause of High DCE

- High DCE Production Rate:
  - Bioremediation rapidly degrades TCE in fractures, producing DCE.
  - Reduced TCE in fractures increases TCE diffusion out of rock matrix.
  - New TCE in fractures also rapidly degrades to DCE.

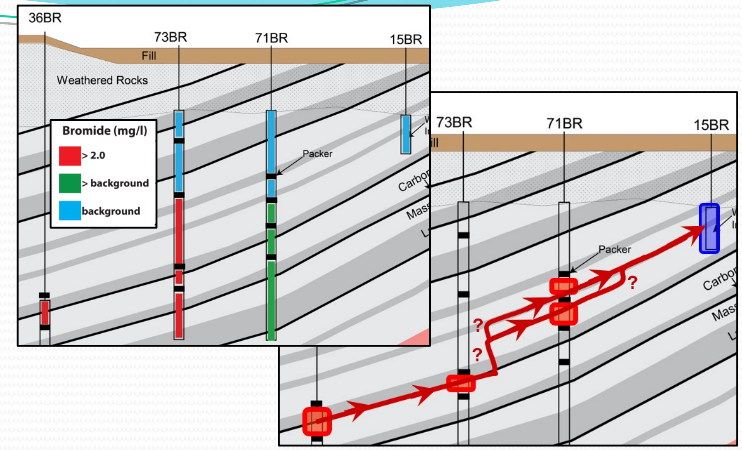


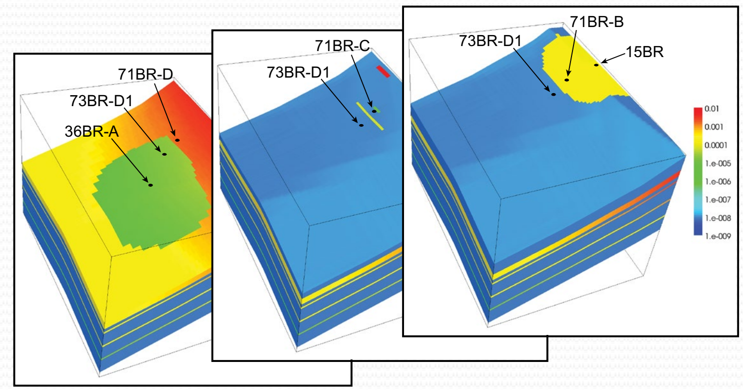
- Moderate DCE Degradation Rate:

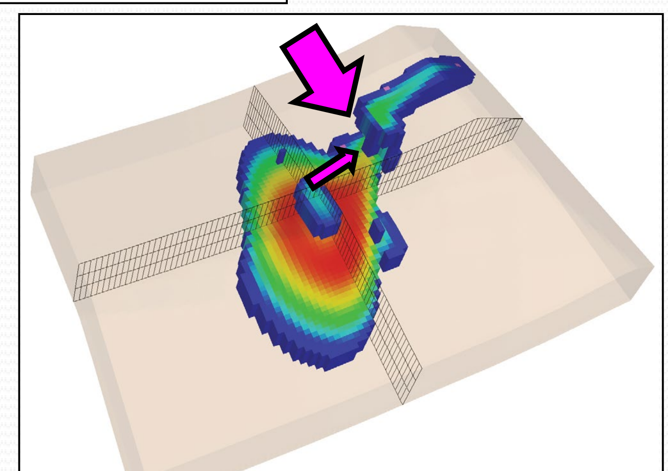
  (work by J. Underwood, D. Akob, M. Lorah)
  - Microbial community analyses show that partial dechorinators and other microbes dominate the post-injection population, rather than native and injected microbes capable of transforming DCE to VC to ethene.
  - Analyses suggest that the population of complete dechlorinators remained suppressed because of competition and toxicity effects.

Summary

- Hydrogeologic characterization and modeling to understand controls on amendment transport is one key component of a CSM for designing in-situ bioremediation, by providing information about:
  - Transport pathways
  - Injection volume
  - Expected spatial variability of amendment effectiveness

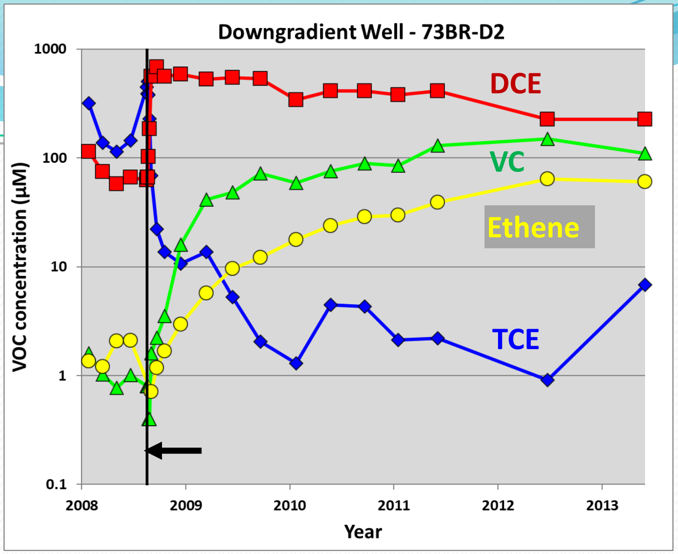


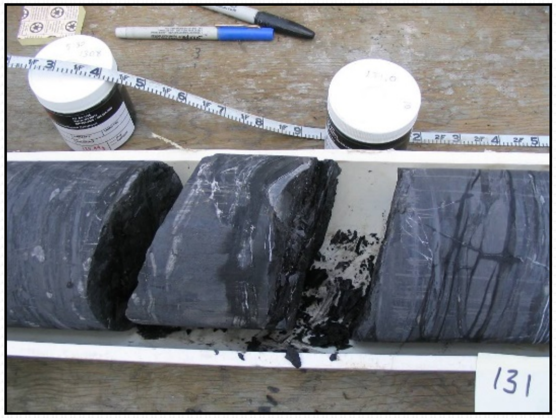




Summary

- Additional important components of CSM for designing bioremediation and setting expectations about treatment:
  - Biogeochemical conditions and processes that will affect evolution of microbial community after introduction of electron donor and microbial culture.
  - Effect of potentially large contaminant mass in rock matrix (or sediments where diffusion processes dominate) on biodegradation processes.





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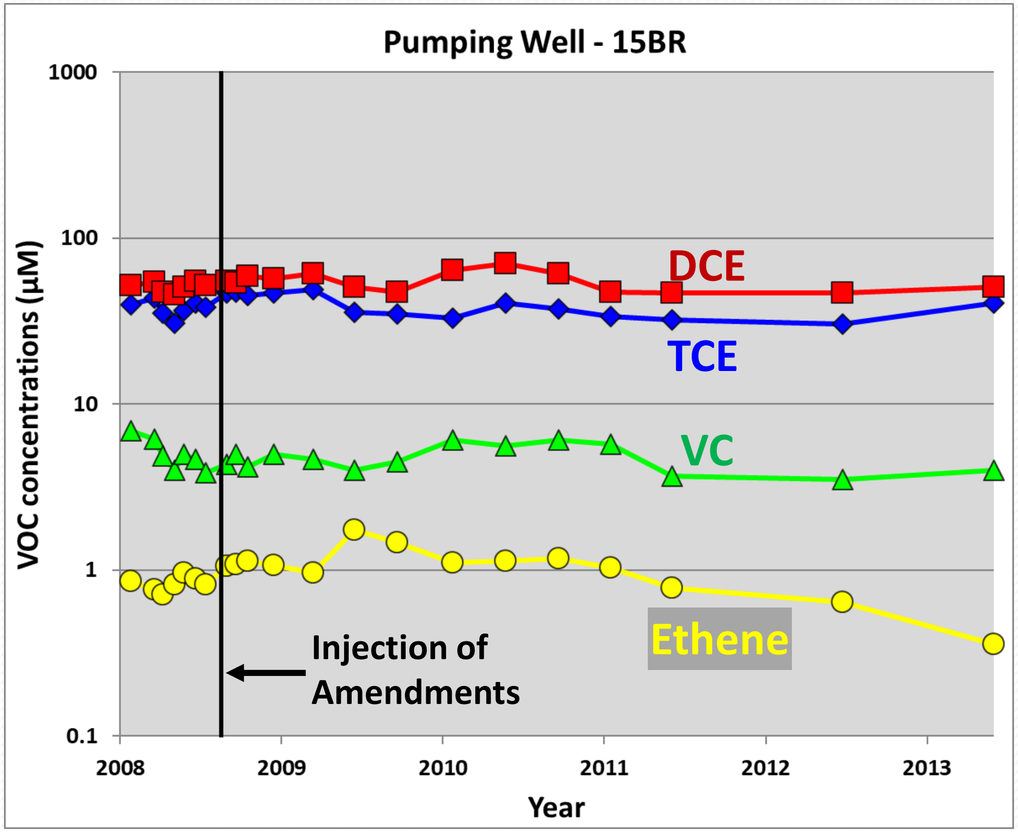
Extra Slides

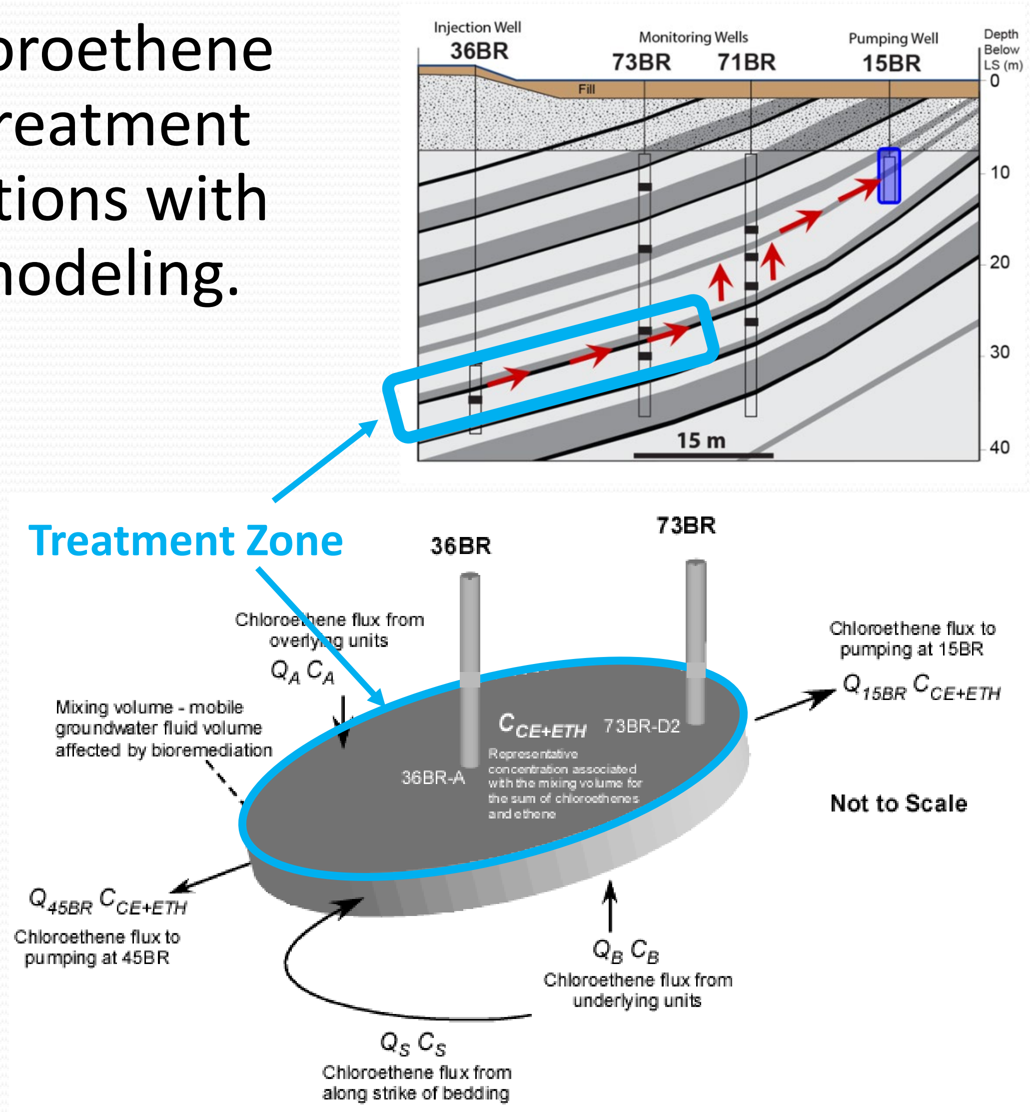
Treatment at Pumped Well 2008 - 2013

VOC concentrations at 15BR show no effect of bioremediation



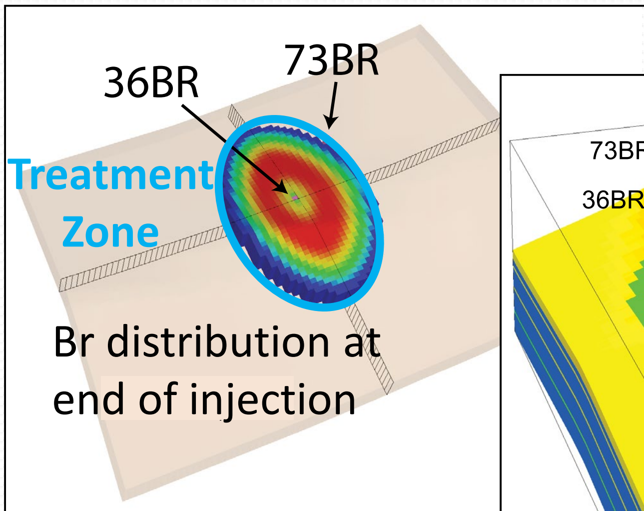
Mass Balance Analysis Approach

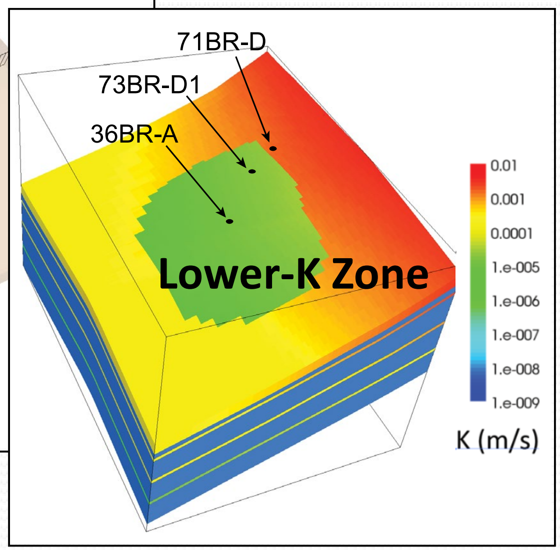
- Perform a rudimentary chloroethene (CE) mass balance for the treatment zone, using scoping calculations with inputs from groundwater modeling.
- Goal: Estimate CE mobilization rate out of the rock matrix.
- Mobilized CE can be from variety of sources in the matrix: DNAPL dissolution, desorption, diffusion of aqueous CE

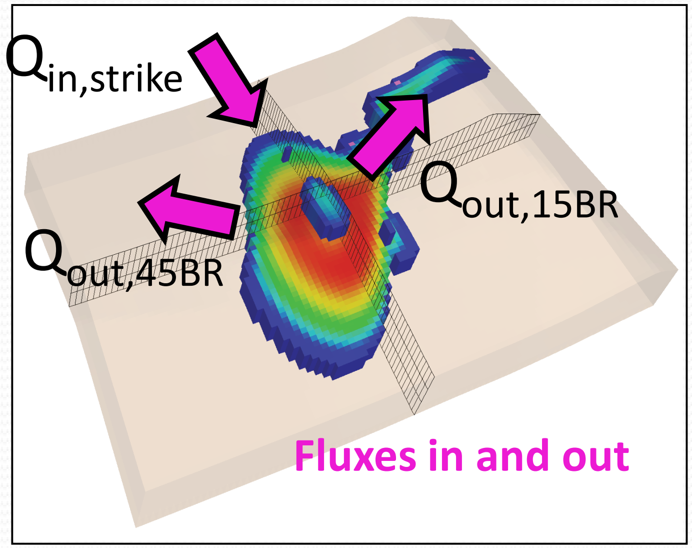


Scoping Calculations Inputs

- Size of treatment zone and fluxes in and out of treatment zone obtained from groundwater flow and transport models.







- CE concentrations in treatment zone obtained from samples collected in 36BR and 73BR.

Scoping Calculations

- Chloroethene + Ethene (CE+Eth) mass balance for treatment zone (TZ):

Change of CE+Eth flux in TZ fractures	=	CE+Eth flux into TZ	-	CE+Eth flux out of TZ	+	CE+Eth mobilization rate (from rock matrix)

- Calculation is for molar sum of all CE species + Ethene.
- Assume:
  - Steady flow: GW flux into TZ = GW flux out of TZ
  - Mobilization rate is net rate of all processes affecting CE transport in rock matrix: e.g., diffusion, sorption, abiotic degradation
  - CE+Eth spatially constant within TZ; calculation done using two possible values

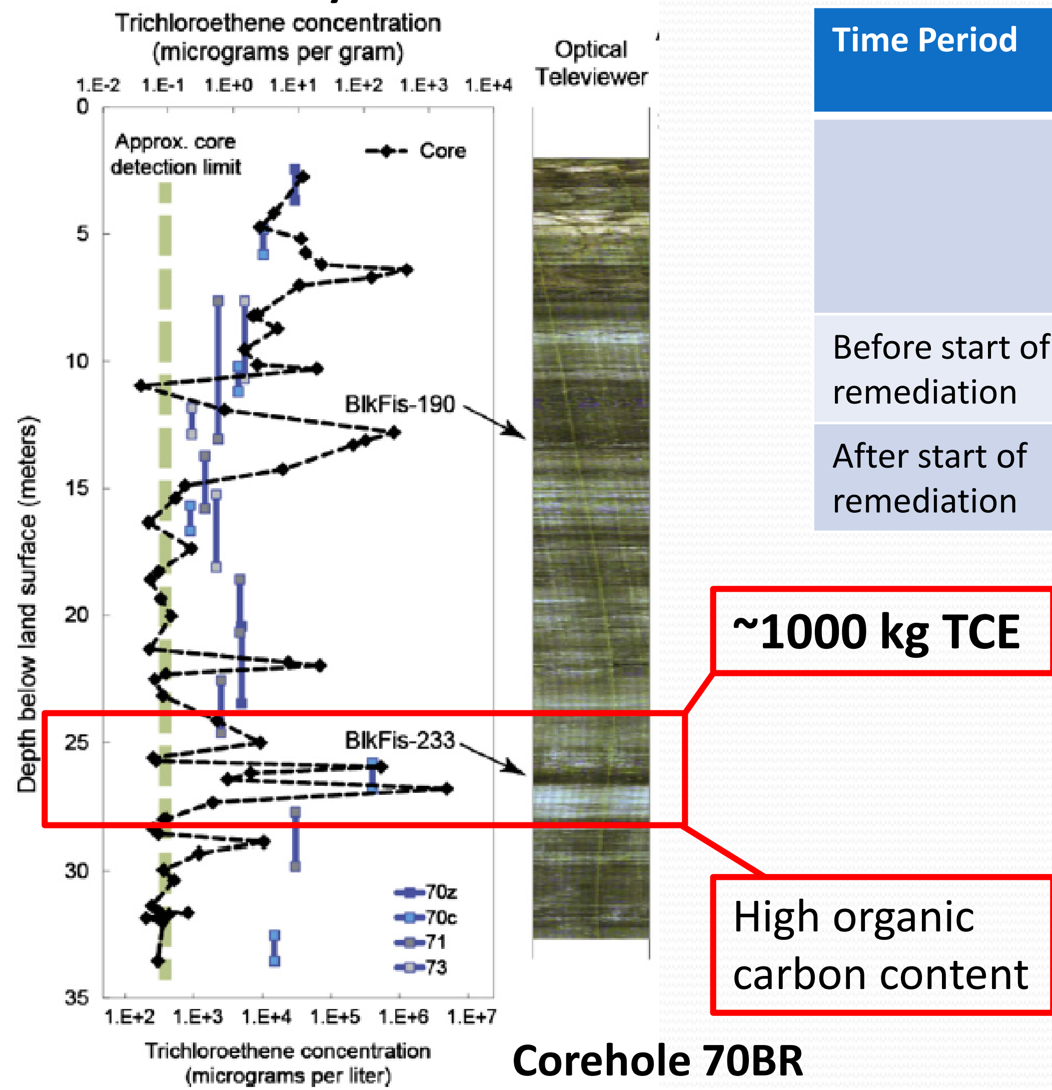
Results: CE Mobilization Rate

Estimates of CE Mobilization Rate
Before and After Bioremediation

Time Period	CE Mobilization Rate (kg TCE/yr)	
	C_{CE+ETH} defined from 36BR-A	C_{CE+ETH} defined from 73BR-D2
Before start of remediation	7.3	4.2
After start of remediation	44.6	34.0

Bioaugmentation causes rate to increase by a factor of 6 to 8, due to increased concentration gradients between rock matrix and fractures

Estimate of CE in Rock Matrix (BlkFis-233) from CE analyses of Rock Core



Corehole 70BR

Estimates of CE Mobilization Rate Before and After Bioremediation

Time Period	CE Mobilization Rate $V_F F_{CE+ETH}$ (kg TCE/yr)	
	C_{CE+ETH} defined from 36BR-A	C_{CE+ETH} defined from 73BR-D2
Before start of remediation	7.3	4.2
After start of remediation	44.6	34.0

Prior to remediation, 100's of years to mobilize CE mass in rock matrix. . .

After remediation, likely decades to mobilize CE mass, but multiple remediation treatments would be required. . .

The economics of each alternative would need to be evaluated