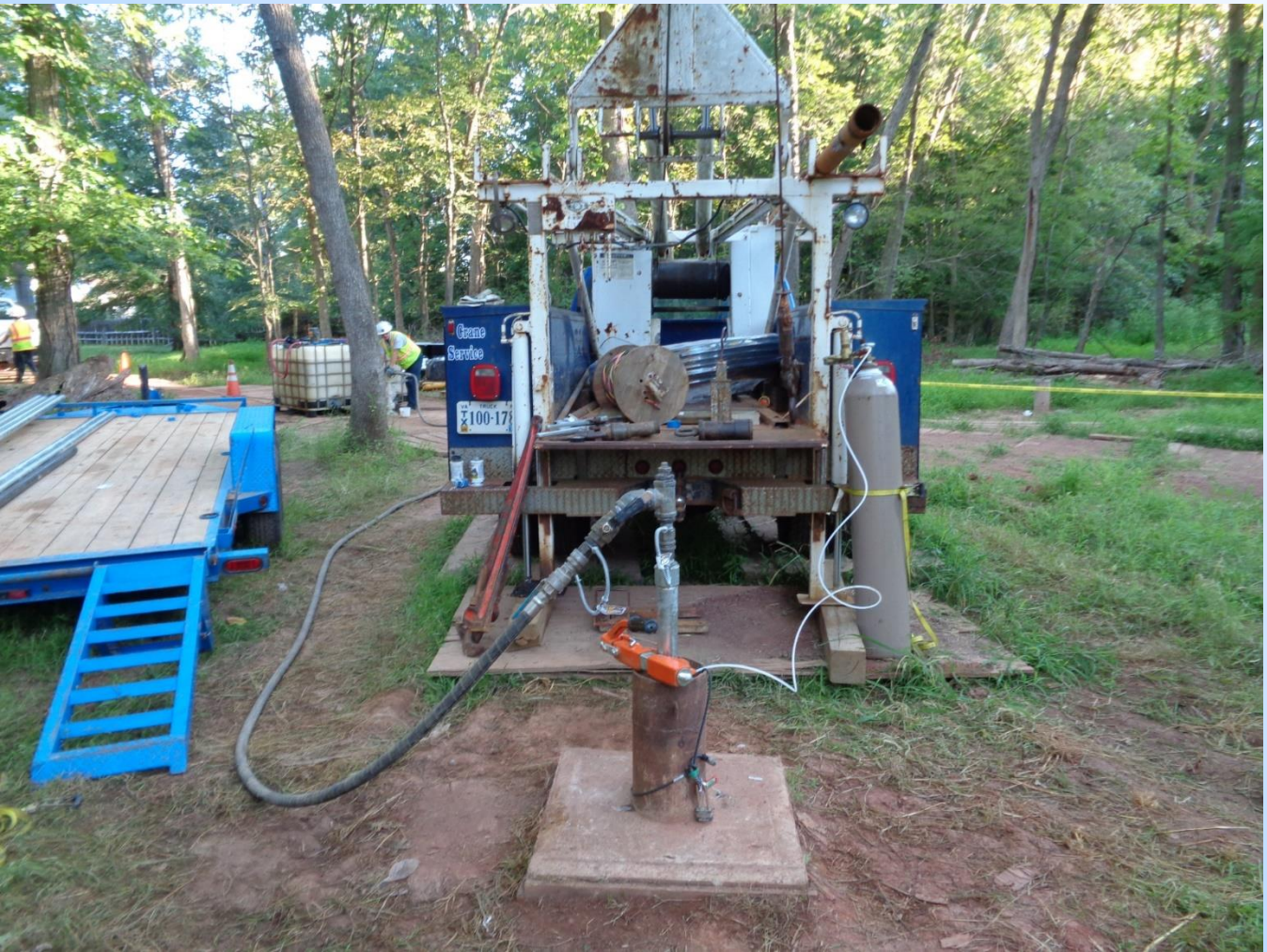
In-Situ Enhanced Biological and Chemical Reduction Pilot Study of TCE in Complex Fractured Bedrock



Prepared for:

The Fourth International Symposium on Bioremediation and Sustainable Environmental Technologies

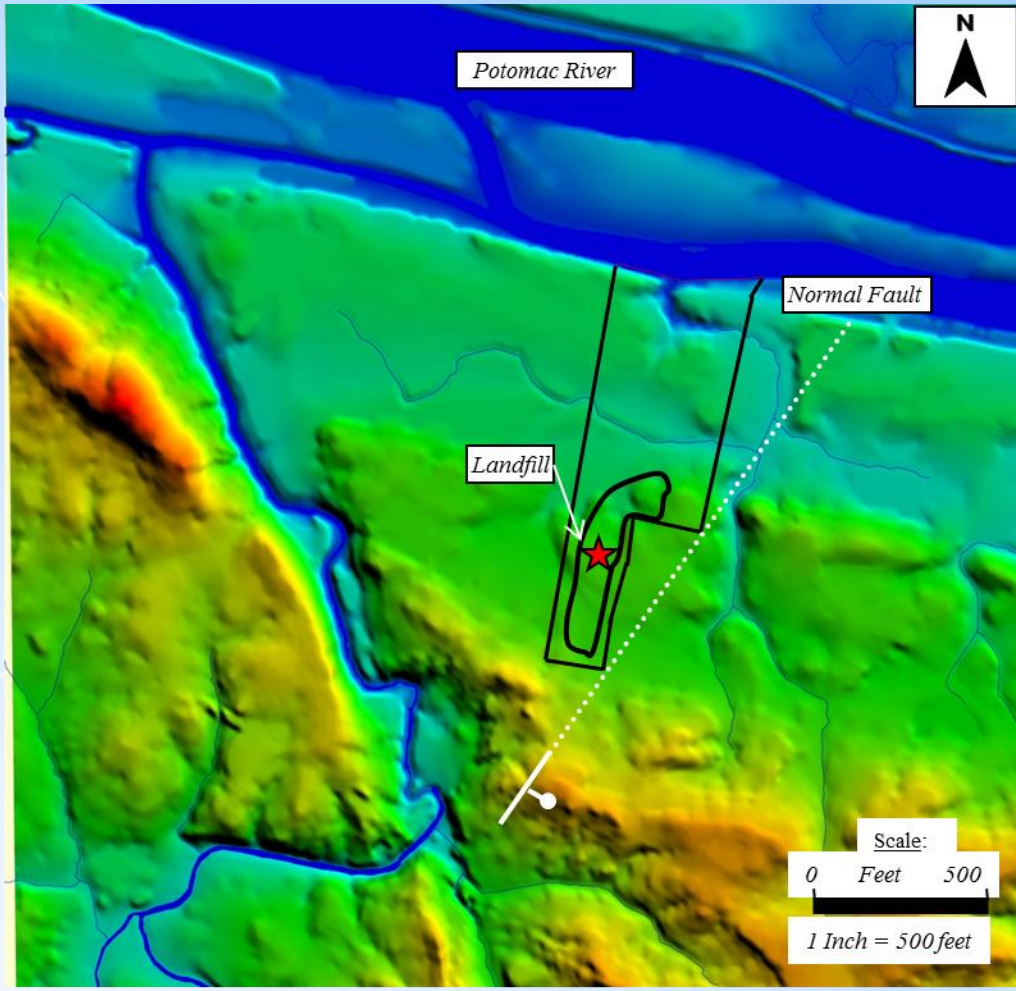
May 2017

Prepared by:

EA Engineering, Science, and Technology, Inc., PBC

Former VA Landfill Superfund Site, EPA Region 3

- RI/FS and Treatability Studies
- Contaminants of Concern: TCE
- Project Highlights
  - 25-acre former disposal facility in Loudoun County
  - Aged TCE release from landfill into subsurface within fractured siltstone bedrock
  - TCE detected in residential drinking water wells in adjacent subdivision
  - Maintenance response for whole house water treatment in homes with contaminated wells
  - RI/FS to be completed in 2017



-Base Map from USGS 10-meter Digital Elevation Model (DEM) Data, Global Mapper Overlay, Sterling Quadrangle, 1968

Conceptual Site Model

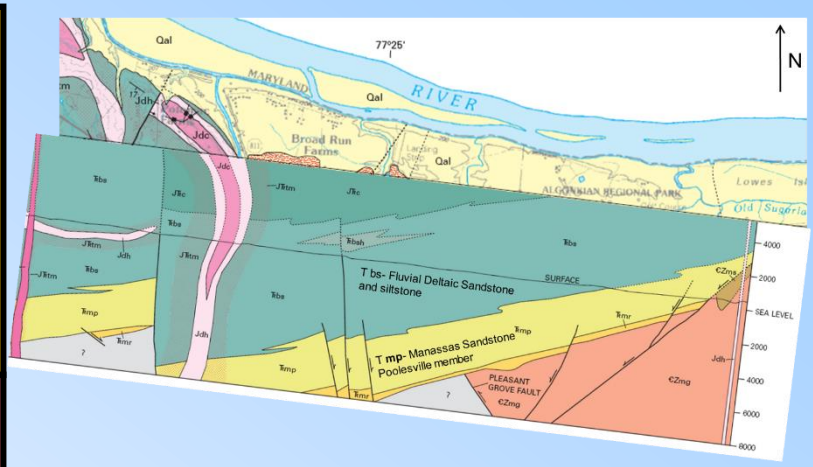
- **Hydrogeology**
  - Water table present at bottom of overburden
  - Hydraulically interconnected overburden and bedrock
  - Bedrock primary porosity roughly 2-4%
  - Bedrock secondary (fracture) porosity = 1-15%
  - Groundwater flow direction north
  - Average hydraulic gradient = 10^{-3}

Generalized Geologic Profile

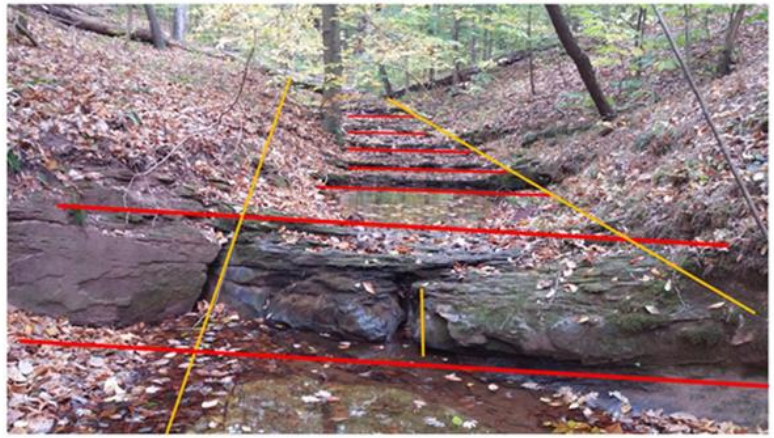
Quaternary Terrace Deposit Overburden (Unconsolidated clayey and sandy silt – 20 ft)

Triassic Balls Bluff Siltstone deposited within Triassic Rift Basin (Consolidated, thinly bedded, fractured bedrock – 5000 ft). Normal faulting caused by tensional tectonic forces

Geologic Map and Cross Section

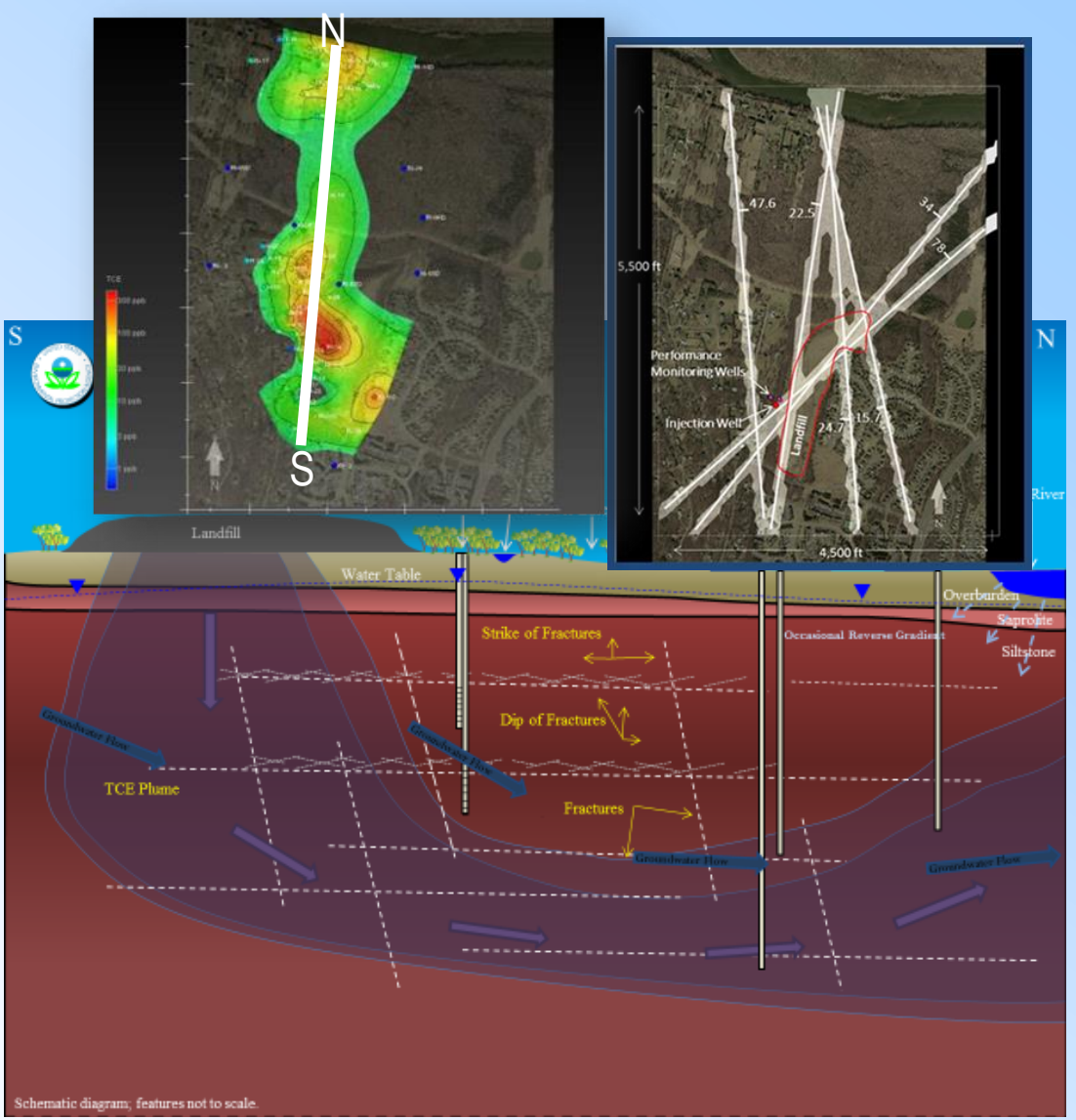


Source: Geologic Map of Loudoun County, 2006



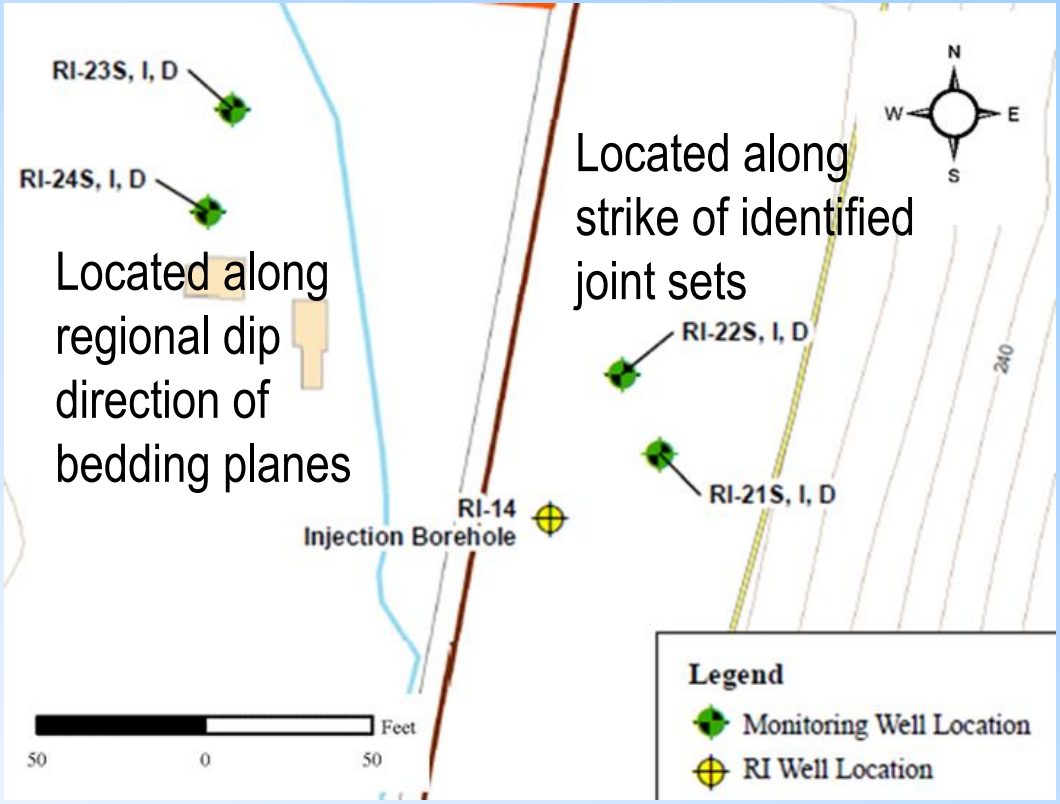
Conceptual Site Model (cont'd)

- **Contaminant Distribution**
  - TCE emanating from landfill area
  - Max dissolved TCE concentration: 500 µg/L
  - TCE distribution effected by tension fault/fractures and bedding plane partings
  - Plume extending roughly 1 mile and up to 450 ft bgs
  - Naturally aerobic conditions



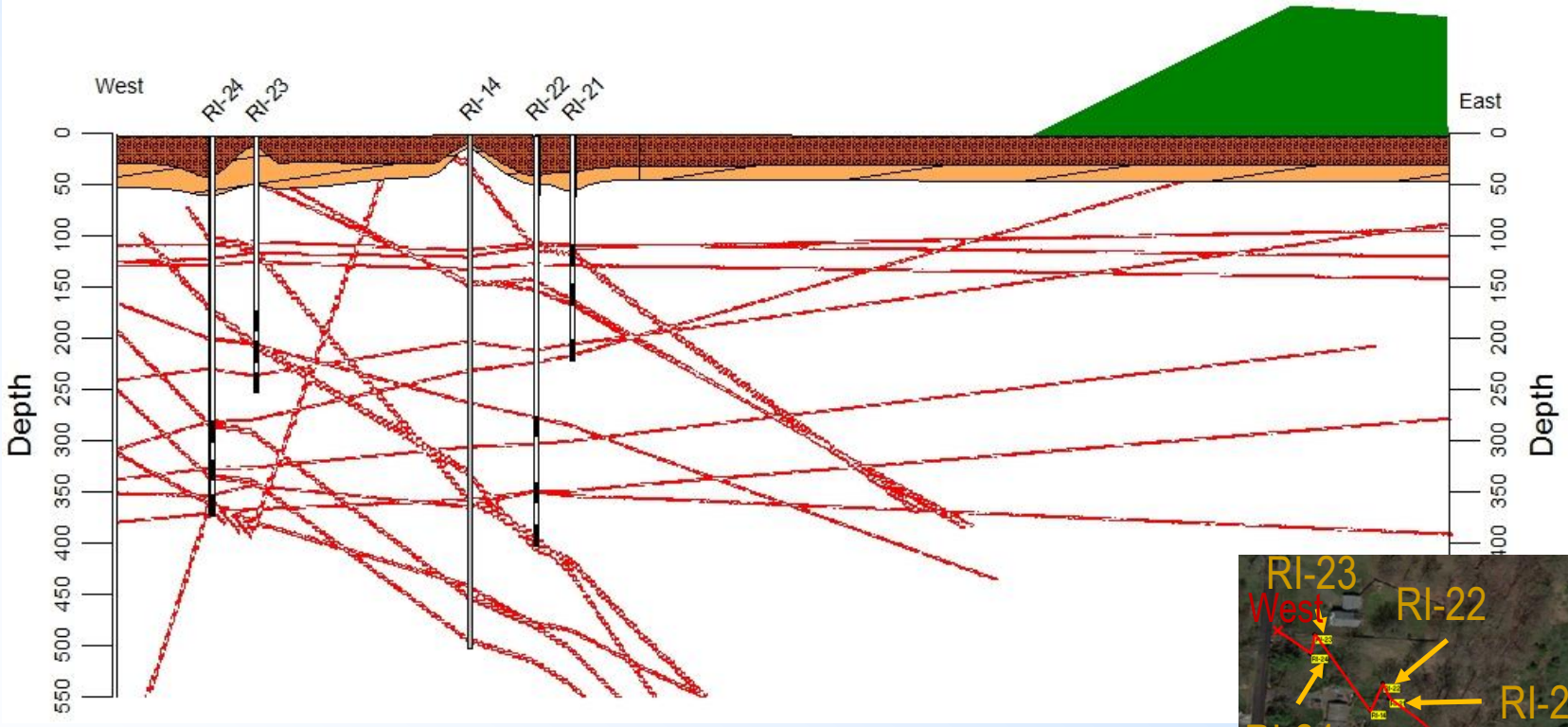
In Situ Bioremediation Treatability Study

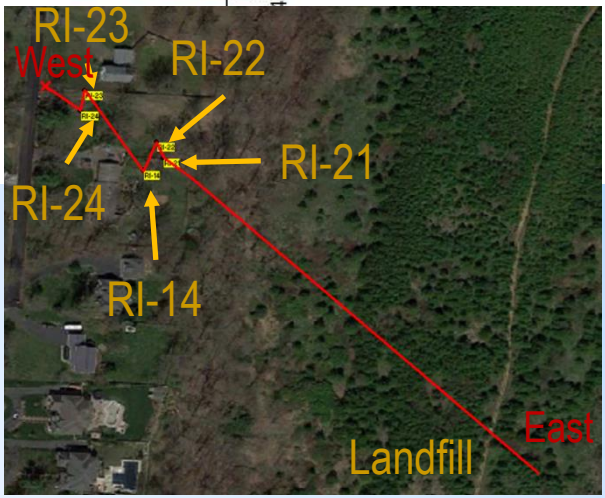
- Evaluate effectiveness of distributing bioremediation amendments in fractured bedrock
  - Differences in distribution within vertical zones distinguishable by fracture characteristics
  - Relative influence of fracture joint sets versus bedding plane partings on reagent delivery
- Assess the biological breakdown of TCE in light of the trends of reagent delivery



Monitoring Well ID	RI-21	RI-22	RI-23	RI-24
Distance from RI-14 (feet)	35	45	125	142

Hydrostratigraphic Section

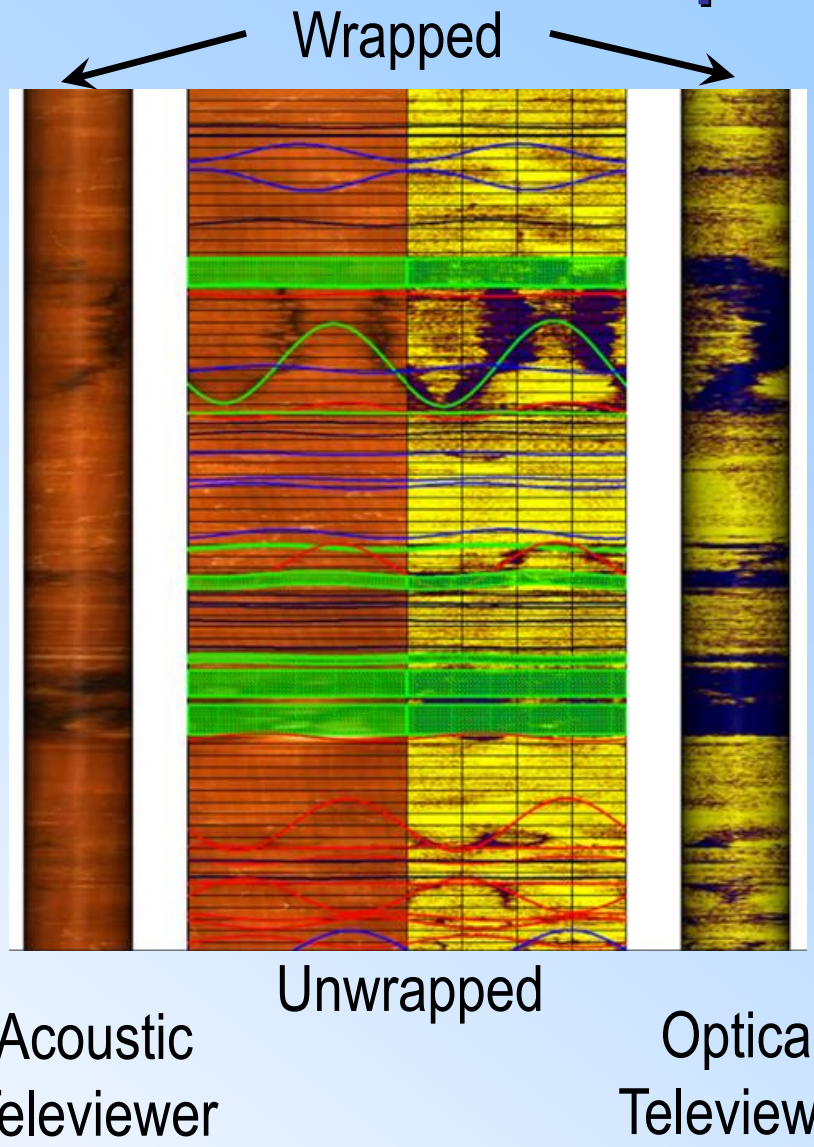




- Groundwater flow and reagent delivery controlled by bedding plane partings and joint sets
- Bedding plane partings likely more laterally extensive than joint sets

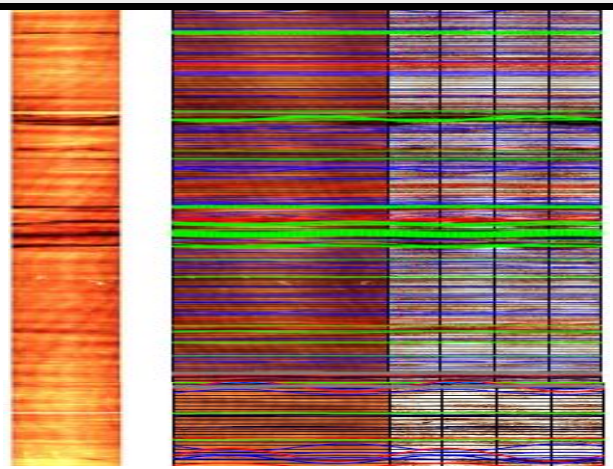
Hydrogeology and Fracture Assessment Techniques

Field Activity	Assessment Objective
Fracture Trace Analysis	Fractures and faults
Boring Advancement	Stratigraphy and contamination to solid matrix
Soil and Rock Classification	Rock texture
Monitoring Well Installation	Groundwater flow direction and contaminant plume morphology
Down-Hole Geophysics with Acoustic and Optical Televiewer, and Heat Pulse Flowmeter	Fracture spacing, density, orientation, and identification of vertical groundwater movement
Borehole Flowmeter Readings	Groundwater vertical gradients
Nested Well Installation	Vertical plume delineation and groundwater flow direction
Packer Isolation Slug Tests	Hydraulic Conductivity and yield
Packer Isolation Vertical Profiling	Vertical plume delineation
Multi-Point Fracture Analysis	Fracture/fault interconnectivity
3-D Plume Visualization	Aid to conceptual site model
Conceptual Site Model	Contaminant distribution interpretation



Analysis of Fracture Density from Televiewer Data

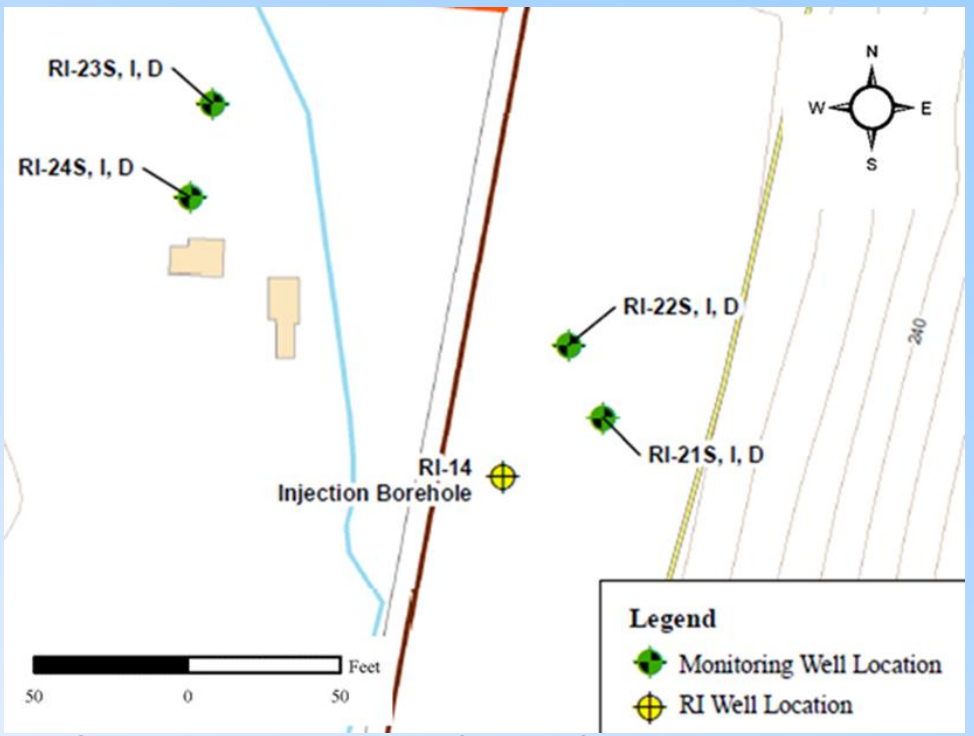
RI-21	Fracture Type						
Interval (ft bgs)	Open	Closed	Other	Open/Total	Aperature (in/10)	Closed/Total	Televiewer (Green: Open, Blue: Closed, Red: Other)
62-82	1	12	4	0.06	135.85	0.71	
82-102	0	10	10	0.00	0.00	0.50	
102-122	4	7	7	0.22	66.08	0.39	
122-142	2	10	7	0.11	25.06	0.53	
142-162	7	10	8	0.28	371.76	0.40	
162-182	6	8	3	0.35	49.09	0.47	
182-202	3	7	6	0.19	6.21	0.44	
202-222	3	6	10	0.16	158.74	0.32	
222-242	2	4	8	0.14	61.02	0.29	
AVG	3.1	8.2	7.0	0.17	97.09	0.45	



- Green = higher ratio of open fractures; brown = higher ratio of closed fractures.
- Interpreted fracture types tallied for standardized intervals to predict generalized trends of fracture density.
- Density of open/closed fractures qualitatively indicates potential for groundwater and reagent flow within aquifer zones. However, this approach does not quantify the relative influence of discrete or individual fractures on volumetric flow.

General Aquifer Zones Based on Fracture Density

AVG closed/Total					
Interval (ft bgs)	RI-24	RI-14	RI-22	RI-21	Interval (ft bgs)
53-62		0.80	0.33		53-62
62-82	0.31			0.60	62-82
82-102					82-102
102-122		0.40	0.08	0.39	102-122
122-142	0.18			0.46	122-142
142-162			0.38		142-162
162-182		0.42			162-182
182-202	0.28				182-202
202-222			0.16	0.40	202-222
222-242		0.35			222-242
242-262	0.13				242-262
262-282					262-282
284-304	0.23	0.66			284-304
304-308			0.53		304-308
308-328					308-328
330-350					330-350
350-370	0.12		0.29		350-370
370-390		0.39			370-390
390-410					390-410
410-430					410-430
430-441					430-441
441-461					441-461
461-481					461-481
481-501					481-501



- Green = higher ratio of open fractures; brown = higher ratio of closed fractures.
- Ratio of closed to total fractures per interval resolves major aquifer units comprised of bedding planes and fracture joint sets.
- Orientation of aquifer zones consistent with bedding plane dip and illustrates the model for a regional groundwater flow regime.

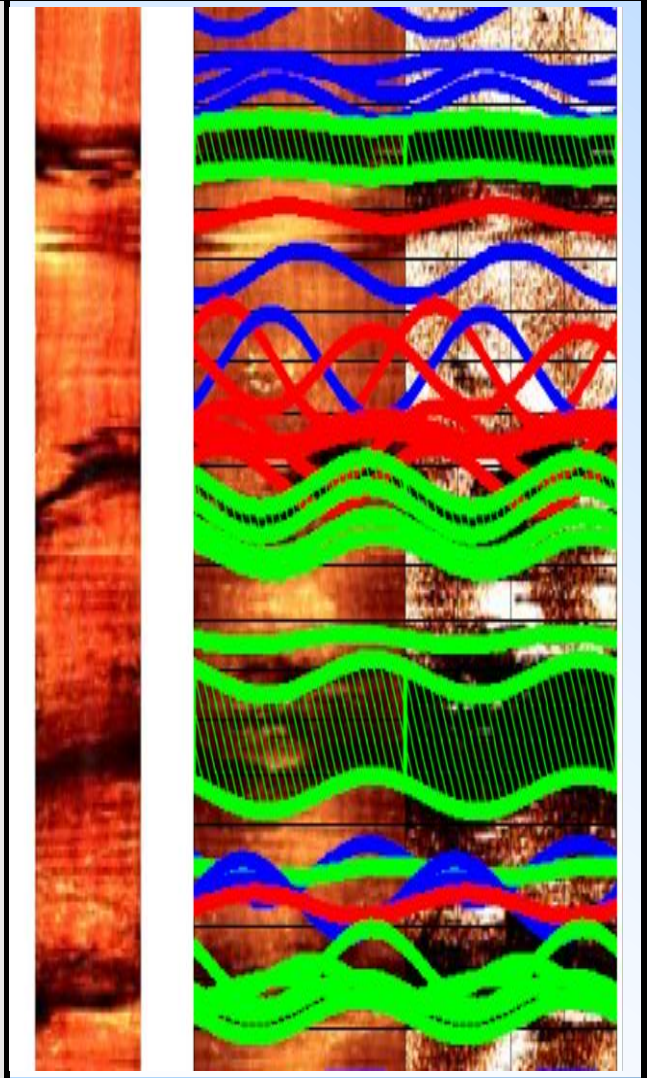
Correlation of Fracture Density and Transmissivity

AVG closed/Total Versus Transmissivities

Interval (ft bgs)	RI-24		RI-14		RI-22		RI-21		Interval (ft bgs)
	Closed/Total	T (ft2/day)	Closed/Total	T (ft2/day)	Closed/Total	T (ft2/day)	Closed/Total	T (ft2/day)	
53-62									53-62
62-82	0.31		0.80		0.33		0.60		62-82
82-102									82-102
102-122			0.40		0.08		0.39	10.7	102-122
122-142	0.18								122-142
142-162					0.38		0.46	30.3	142-162
162-182		14.4	0.42	62.1					162-182
182-202	0.28			72.9					182-202
202-222								1.2	202-222
222-242		15.4		30.7					222-242
242-262	0.13	14.5	0.35	184.3	0.16		0.40		242-262
262-282				19.8		16.2			262-282
284-304		17.1		106.1					284-304
304-308	0.23								304-308
308-328		15.6	0.66		0.53				308-328
330-350						1.2			330-350
350-370		7.7		84.6					350-370
370-390	0.12			415.6					370-390
390-410				123.8		5.6			390-410
410-430				71.3					410-430
430-441			0.39	109.8	0.29				430-441
441-461				28.6					441-461
461-481									461-481
481-501									481-501

- Aquifer zone Transmissivities (T) calculated from packer testing and pressure responses during reagent delivery
- Blue = generally good correlation between fracture density and T
- Red = generally poor correlation between fracture density and T

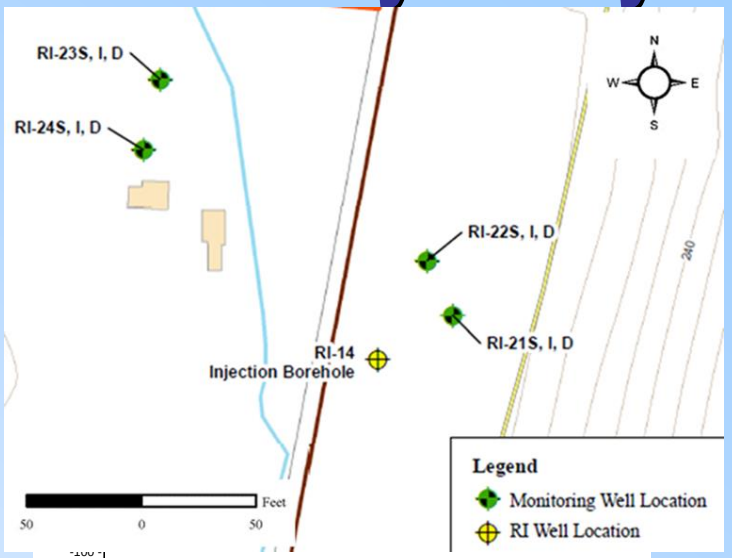
Fracture Aperture Size and Dip Direction

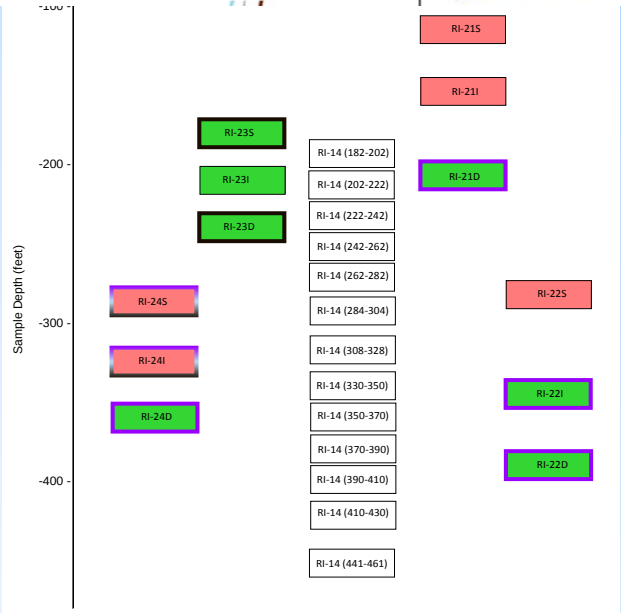
	Televiewer (Green: Open, Blue: Closed, Red: Other)	Depth (ft bgs)	Aperature (in/10)	Dip Direction	Aperature (in/10)
RI-21I		145.24	0	west	121.82
		145.42	0	west	
		145.93	0	west	
		146.81	121.82	west	
		148.13	0	west	
		149.25	0	east	
		151.04	0	west	
		151.09	0	west	
		151.13	0	east	
		152.32	0	east	
		152.52	0	east	
		152.56	0	west	
		153.28	0	west	
		153.63	42.19	east	290.07
		154.37	0	east	
		154.76	0	east	
		156.43	0	east	
		158.26	207.75	east	
		160.93	0	east	
		160.96	0	east	
		161.44	0	west	
		161.46	0	west	
		161.58	0	west	
		162.82	0	east	
		163.17	0	east	
		163.24	0	west	
		163.55	40.13	east	
		165.06	0	east	

- Aperture size and dip direction reveal potential exceptions to regional flow regime
- Orange = west dipping (generally bedding planes)
- Green = east dipping (generally joint sets).
- Dip direction/aperture size of discrete fractures partially explain anomalous trends with respect to groundwater flow direction, reagent delivery, and ultimate treatment performance.

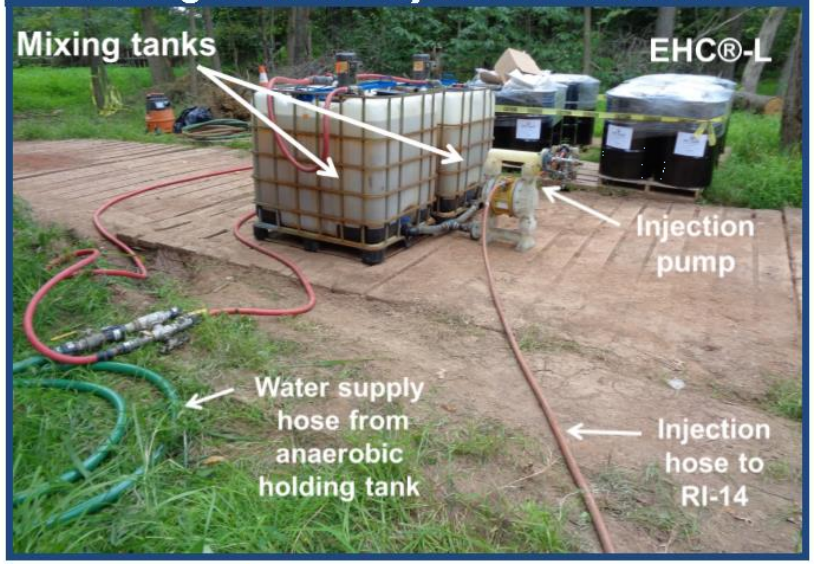
In Situ Bioremediation (ISB) Treatability Study

- **Biostimulation**
  - Injected lecithin-rich emulsion and chelated Fe^{+2}
  - Reagent concentration was 5000 mg/L
  - 40K gal of reagent injected into 13 zones of RI-14
  - 25% reagent to achieve 6720 lb injected
  - Volume injected per zone 800-6.5K gal per zone to achieve ROIs of approximately 100 ft
- **Bioaugmentation**
  - 15 L of SDC-9™
  - Pre-mixed with reagent in field following lactate amendment to pre-condition water
  - Injected into RI-14 simultaneously with reagent at pressures of 10 to 30 psi

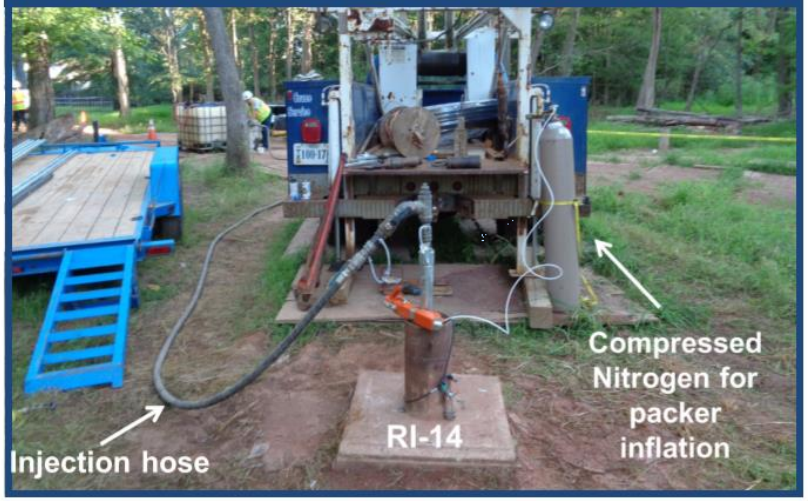




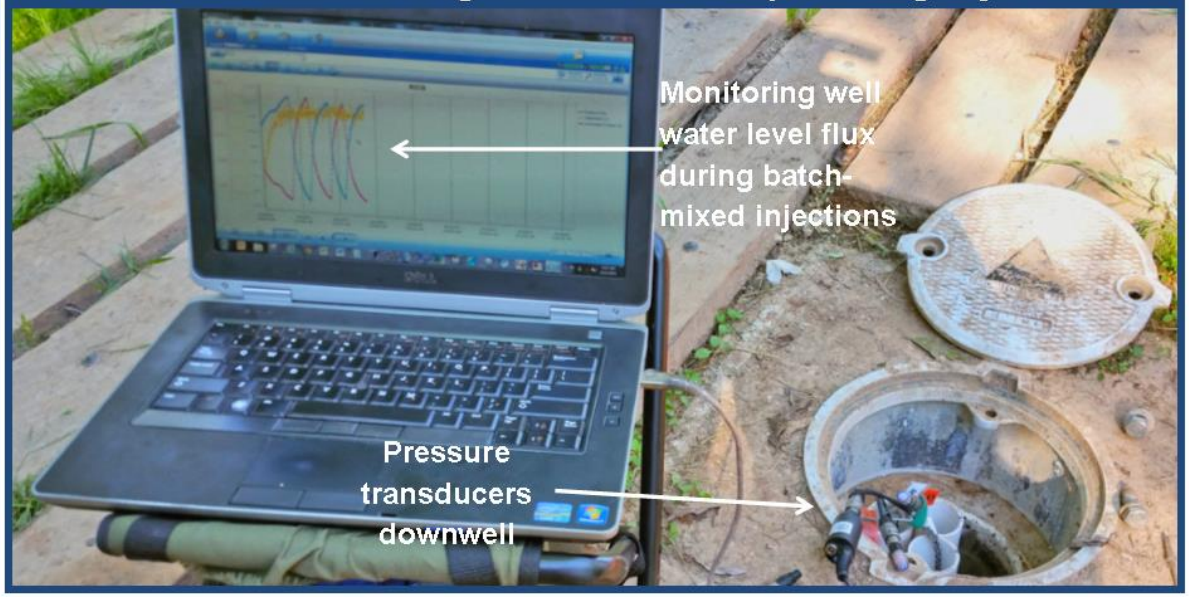
Mixing area for injection substrate



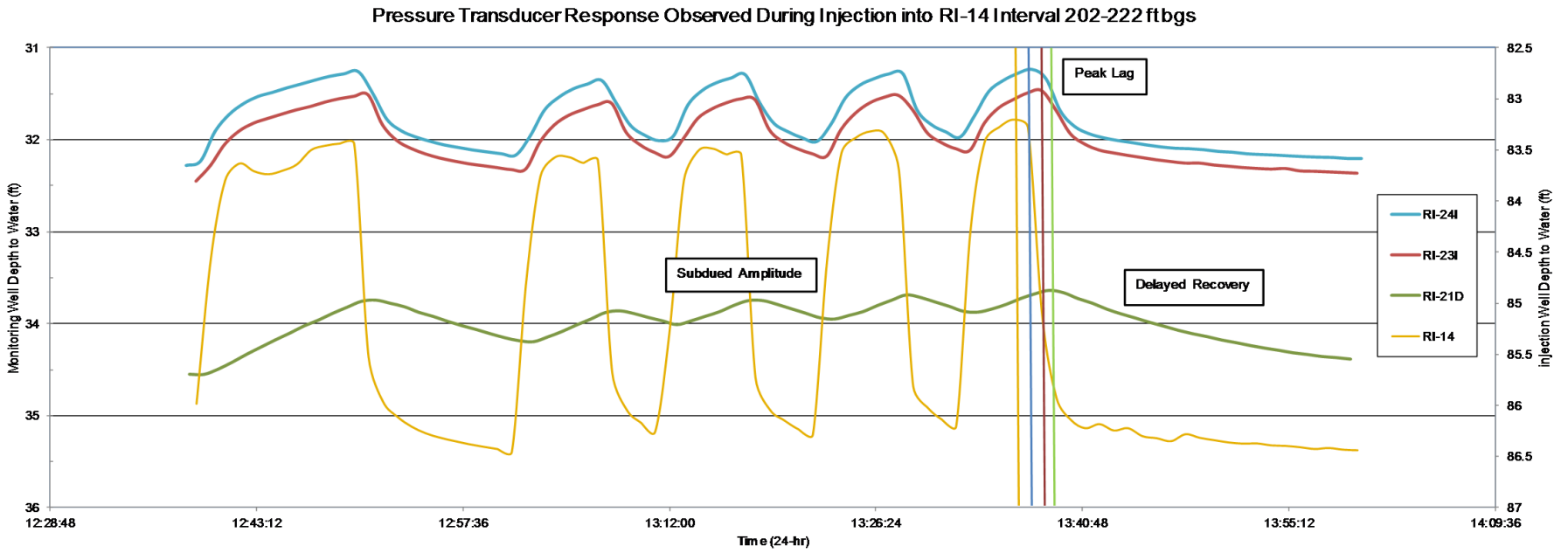
Packer assembly lowered in RI-14 Injection apparatus installed



Real-time monitoring of connectivity during injections

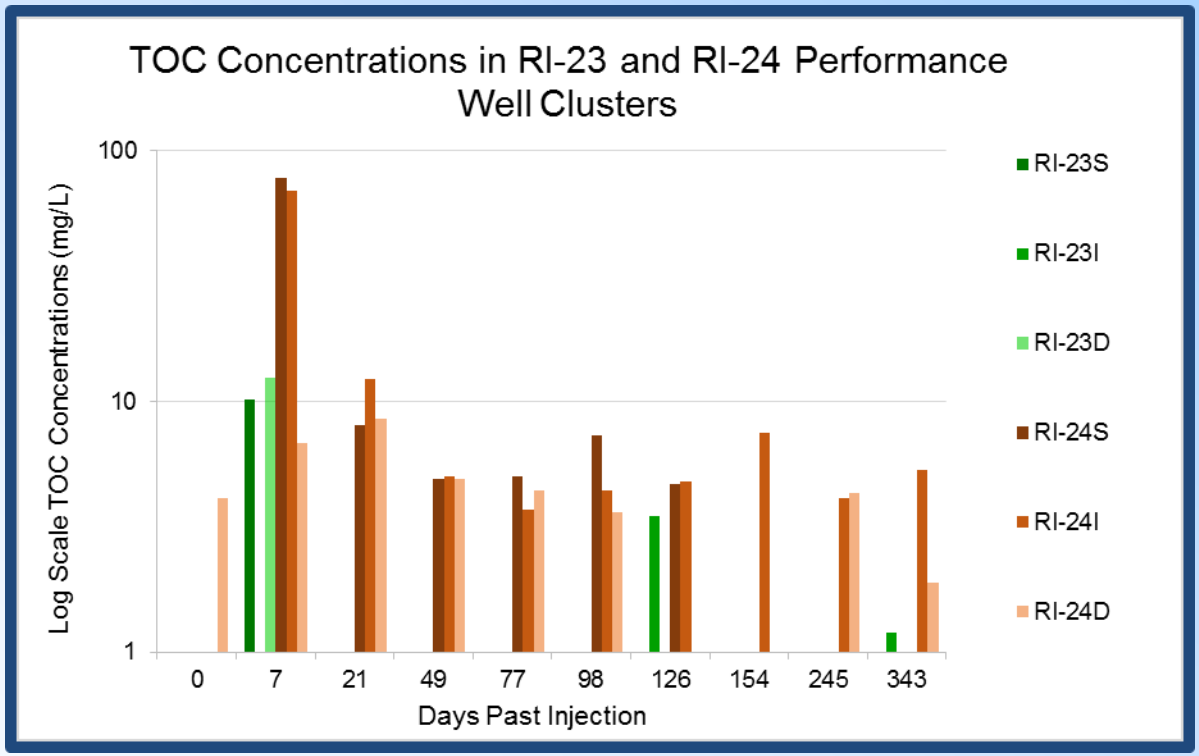


Pressure Response Characteristics



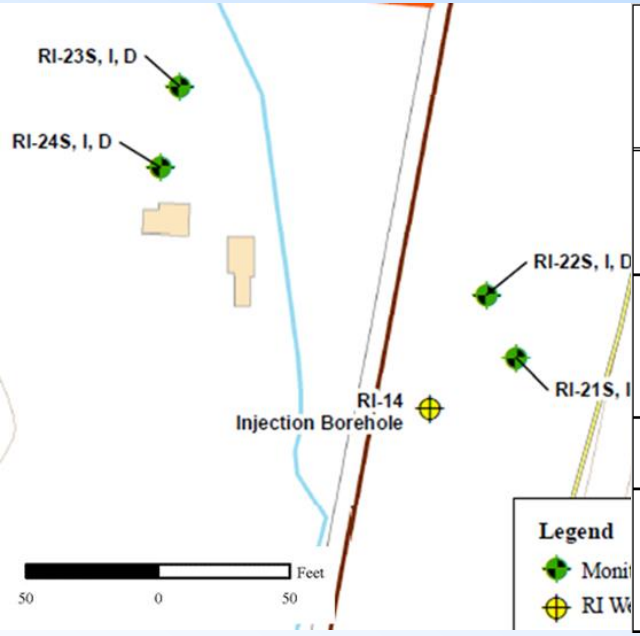
- Pressure response characteristics such as amplitude, peak lag, and rate of recovery used to assess interconnectedness to RI-14 injection zones.
- Fracture joint sets/large aperture fractures demonstrated larger amplitude, rapid peak and recovery curves.
- Conversely, the bedding planes/small aperture fractures demonstrated subdued amplitude, greater peak lag, and delayed recovery.

Reagent Delivery Characteristics



- As a tracer for determining reagent delivery, TOC identified non-uniformly in the pilot study area.
- Factors such as fracture aperture size and orientation contributed to the extent of delivery as well as sustained presence in performance monitoring wells.

ISB Treatability Performance Summary

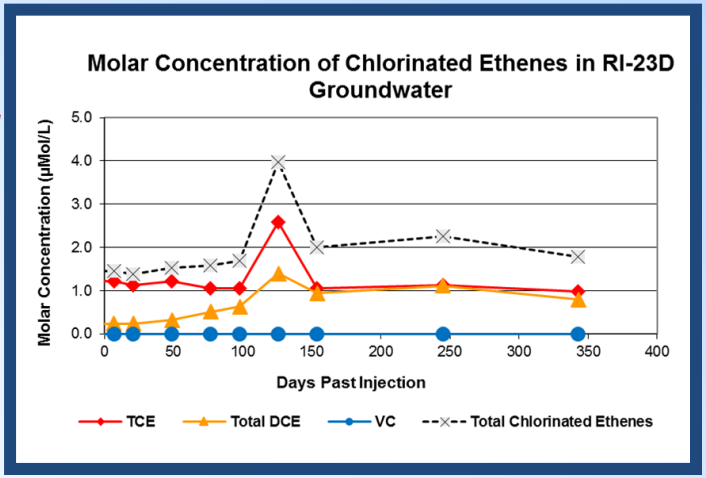


Structural Features Influencing Delivery	TOC Delivery + Presence	TCE Dechlorination to VC or Ethene/Ethane	Well ID	Relative Transmissivity	Overall Performance
Joint Sets/Large Aperture Fractures	Spike + Decline	No	RI-23S	High	Poor
			RI-23D	High	
Bedding Planes/Small Aperture Fractures	Some + Sustained	Yes	RI-21D	Low	Good
			RI-22I	Low	
			RI-22D	Medium	
			RI-24D	Medium	
Combination	Spike + Sustained	Yes	RI-24S	High	Best
			RI-24I	High	
No Significant Influence	Little to None	No	RI-21S	Medium	Worst
			RI-21I	High	
			RI-22S	High	
			RI-23I	High	

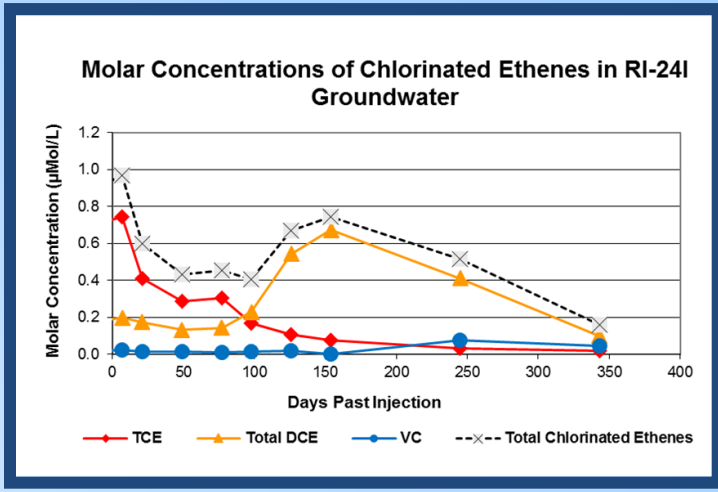
- Performers with large aperture fractures and/or influenced by joint sets, TOC immediately observed but not sustained. Larger aperture fractures allow better delivery of reagent. However, larger fractures susceptible to reagent dilution due to higher volumetric groundwater flow.
- Performers with smaller aperture fractures and/or influenced by bedding planes, TOC delivered and sustained for longer period of time. Reagent trapped allowing for longer residence time of TOC, and therefore sustained TCE reductive dechlorination.
- Best performers displayed a combination of these features and high T enabling both better delivery and sustained presence of TOC (and microbes) over the timeframe of the pilot study.

ISB Performance

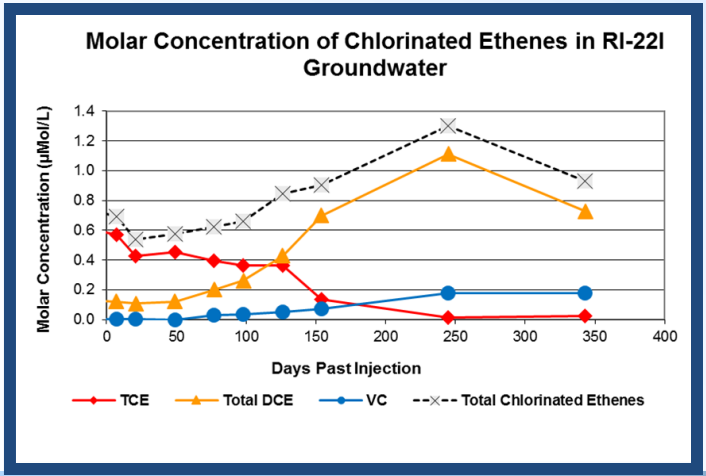
Joint Sets/ Large Aperture Fractures



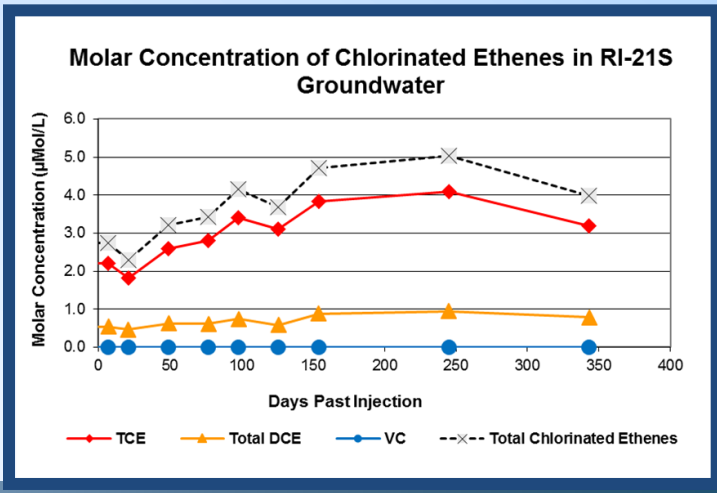
Joint Sets/Bedding Planes Combination



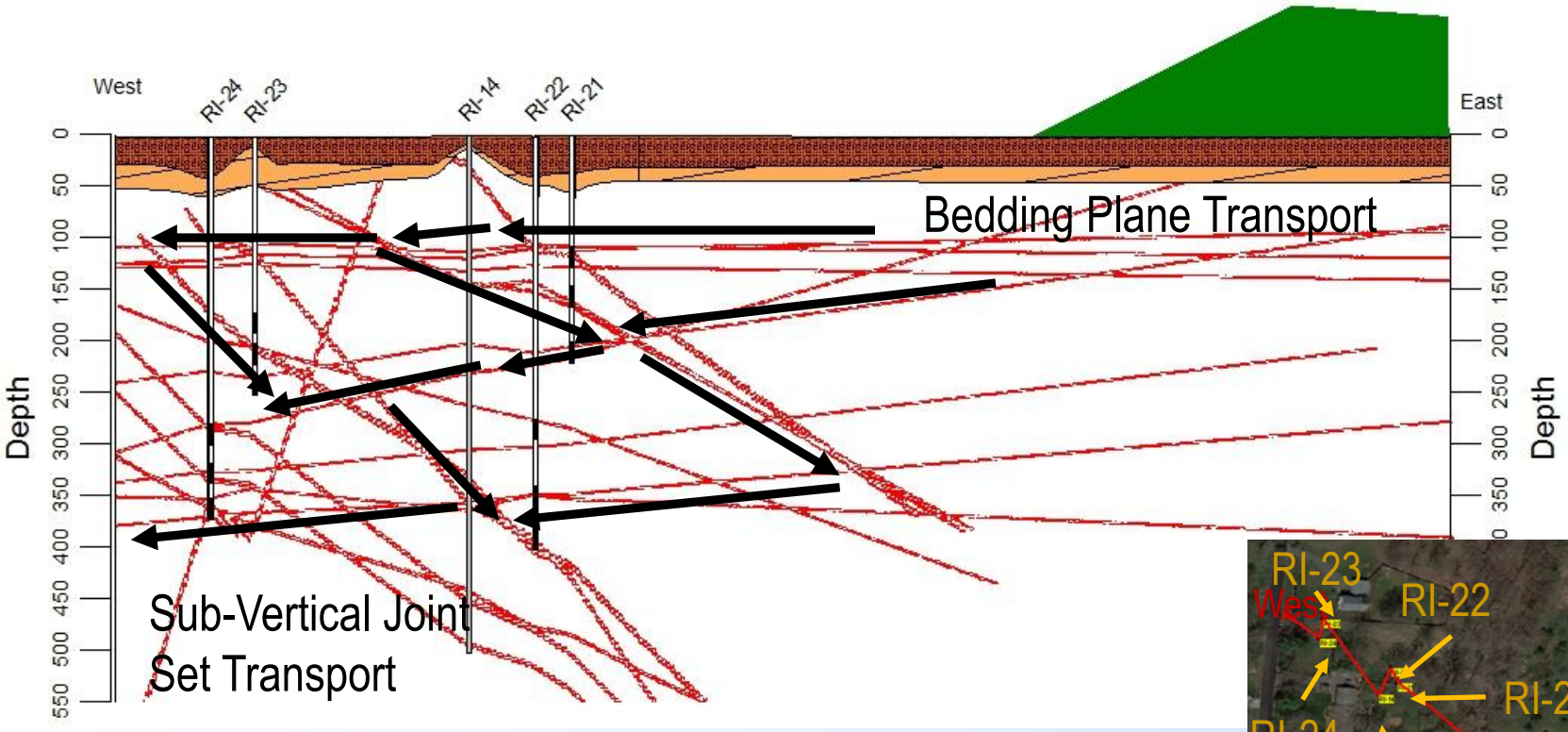
Bedding Planes/ Small Aperture Fractures

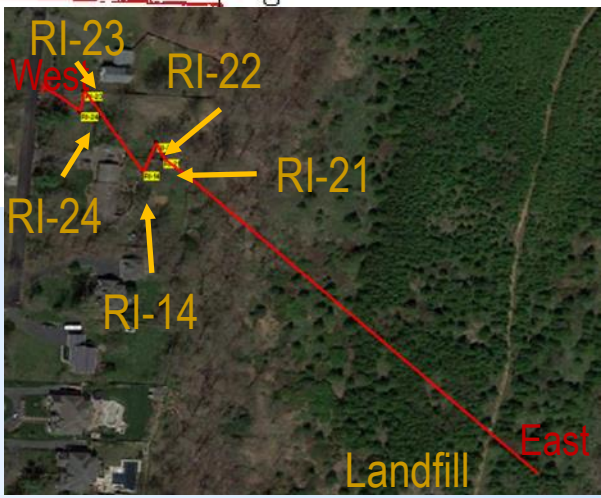


No Significant Influence

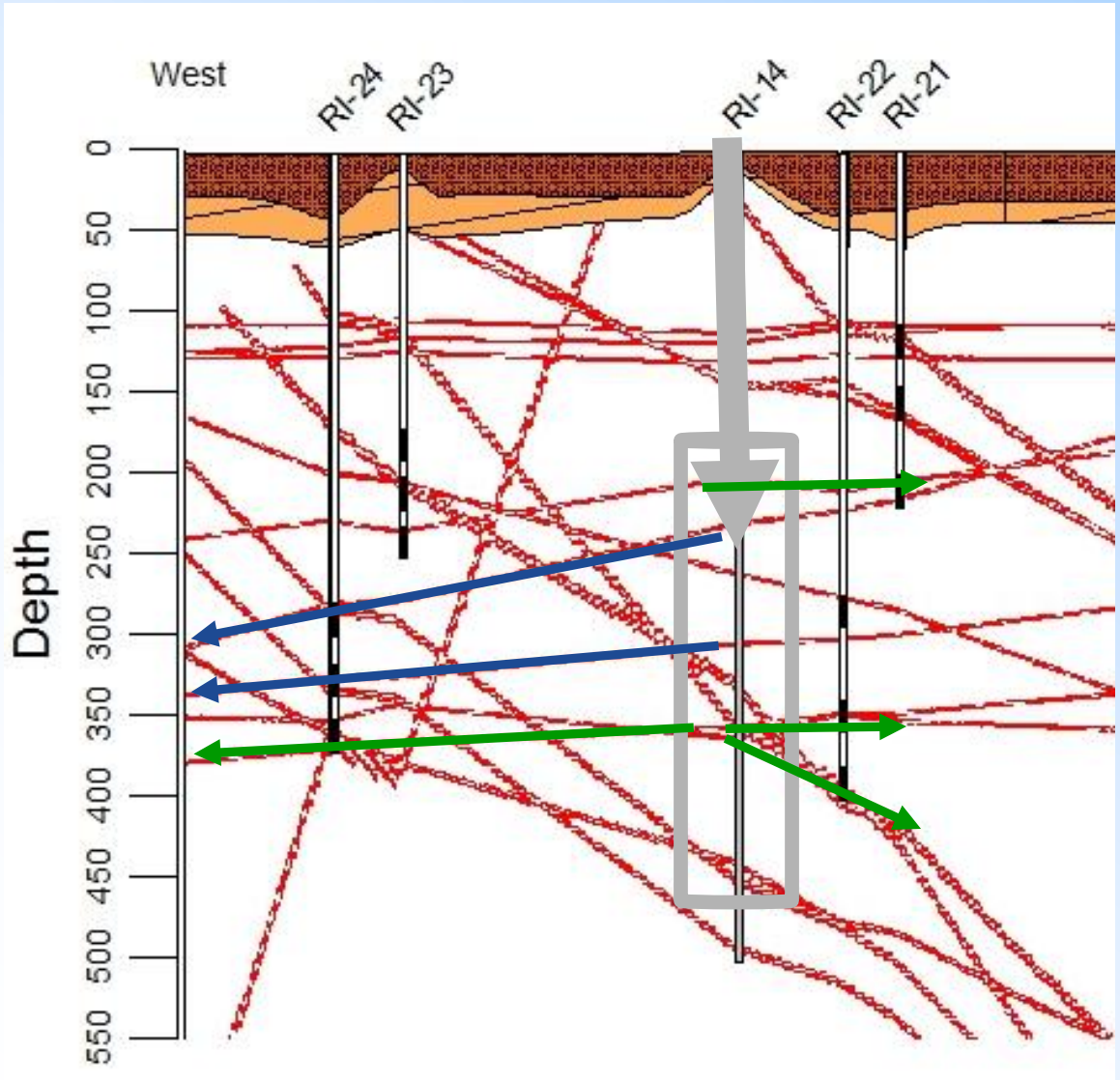


Site Understanding Using Leaky Multi-Unit (LMA) Model





Site Understanding Using Leaky Multi-Unit (LMA) Model



- Blue = best overall delivery and performance
- Green = good overall delivery and performance

Conclusions

- Fracture interconnectivity and reagent delivery can be challenging to resolve and predict in complexly fractured bedrock.
- Fracture density zonation and orientation trends confirmed that this site fits the hydrogeologic model of an LMA system with bedding plane partings and sub-vertical fracture flow paths.
- This framework useful in predicting delivery of reagent through generalized potential flow pathways.
- However, the role of discrete fractures & their characteristics such as aperture, transmissivity, precise orientations MUST be analyzed to explain outcomes that vary from predicted patterns that influence reagent delivery and ISB performance.

Acknowledgements

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