How to Remediate a Hexavalent Chromium and Volatile Organic Plume in a Single Application using Injection Flow Through Barriers

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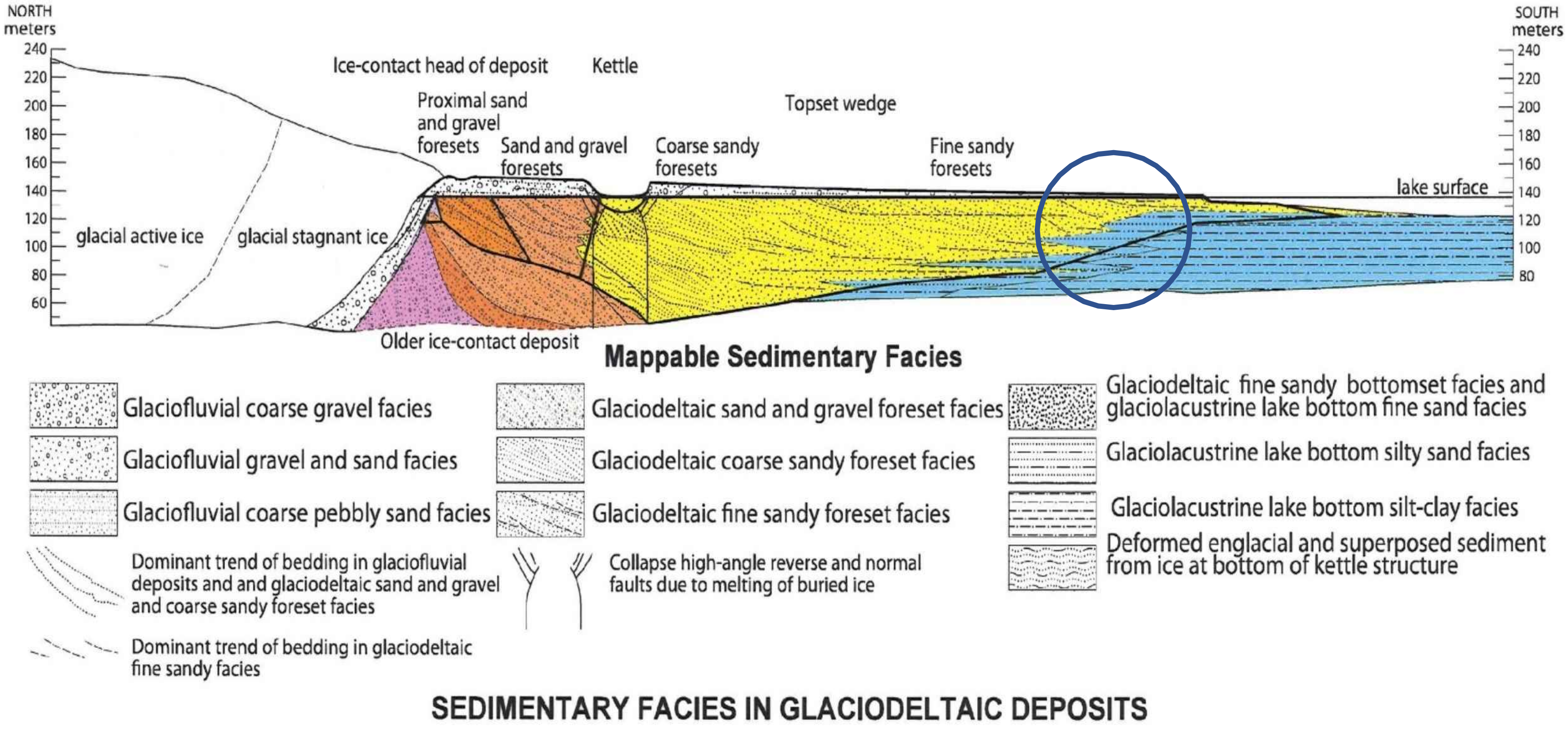
Critical Information Needed

- Why regional deposition and groundwater flow matters
- Heterogeneity considerations on the remedial design
- Benefits of full-scale pilot studies before remedy selection, final design and field implementation
- Look at ways to optimize the remedy

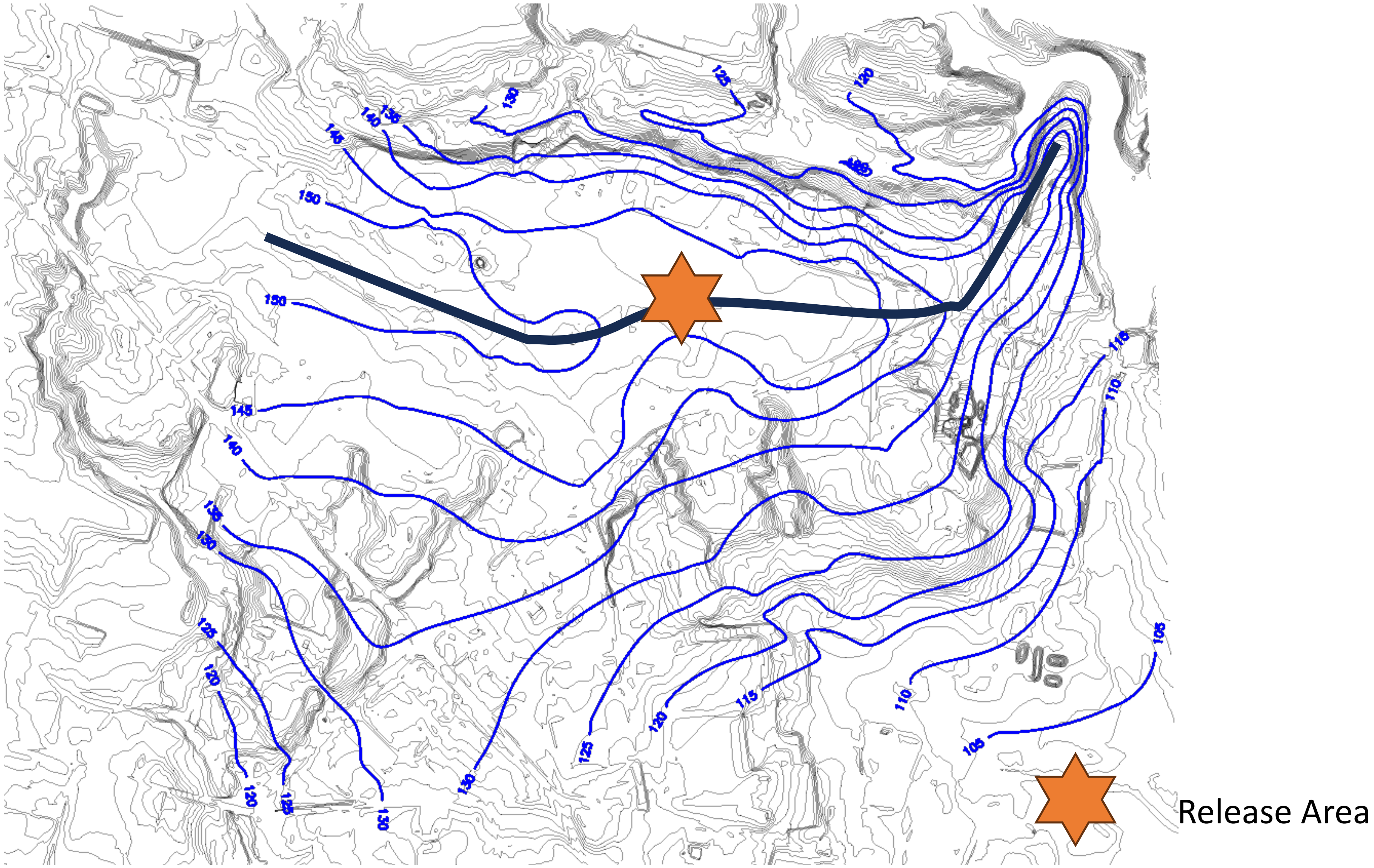
Iterative Process

Regional Sedimentary Facies

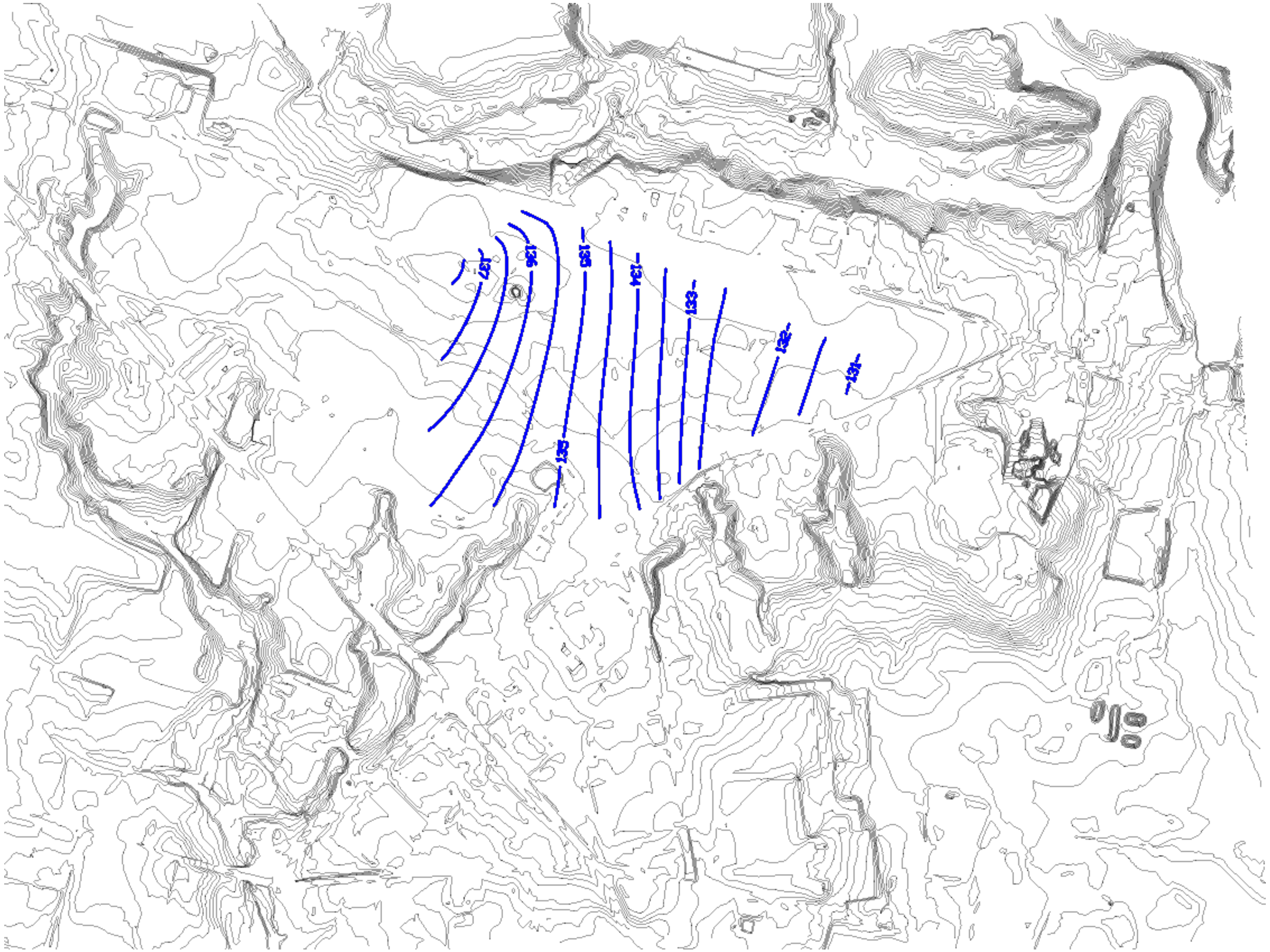


Conceptual model of mappable sedimentary facies within glaciodeltaic deposits (Stone, 2015), extended at the distal end

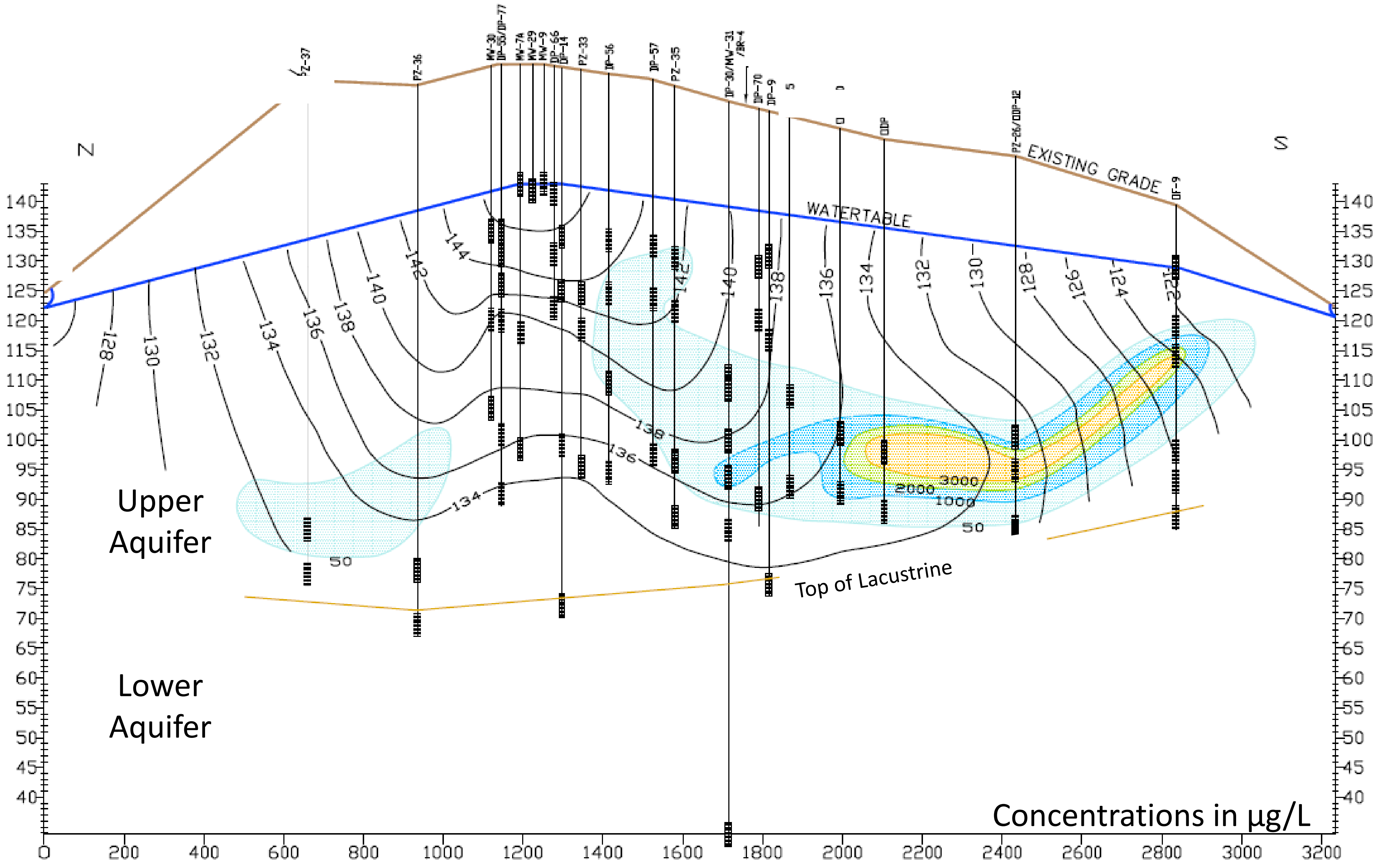
Upper Aquifer - Groundwater Contour



Lower Aquifer - Groundwater Contour



Hydraulic Flow Net (TCE)



Site Drilling Issues

- Poor soil resolution:
  - Auger Split spoon sampling (40 to 80% recovery)
  - 5-foot direct push continuous soil sampling (50 to 75% recovery)
  - Drive and wash – slow, introduction of fluids with 40 to 75% recovery

- Good soil resolution:
  - Dual Rotary – however sampling was collected at cyclone, not depth specific
  - RotoSonic – 80 to 100% recovery (some disturbance during extrusion)
  - 2-foot direct push continuous soil sampling (75 to 95% recovery)

- High resolution soil profiling:
  - Membrane Interface Probe (MIP) – 100% at 0.1-foot resolution
  - Waterloo Profiling – 100% at 0.1-foot resolution

Desiccated clays

Mass Flux Plume Evolution

Early Phases

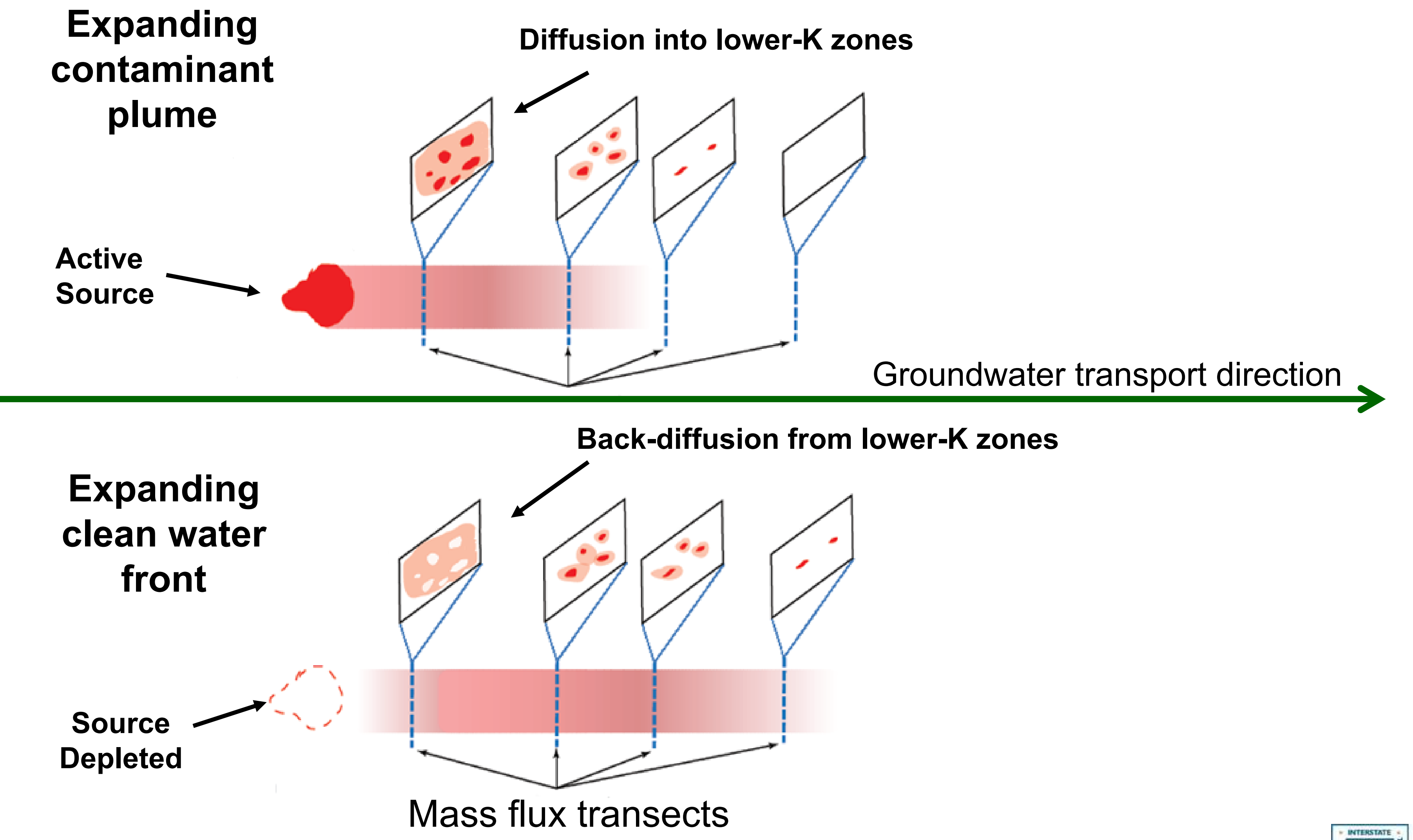
–

Plume Expanding

Later Phases

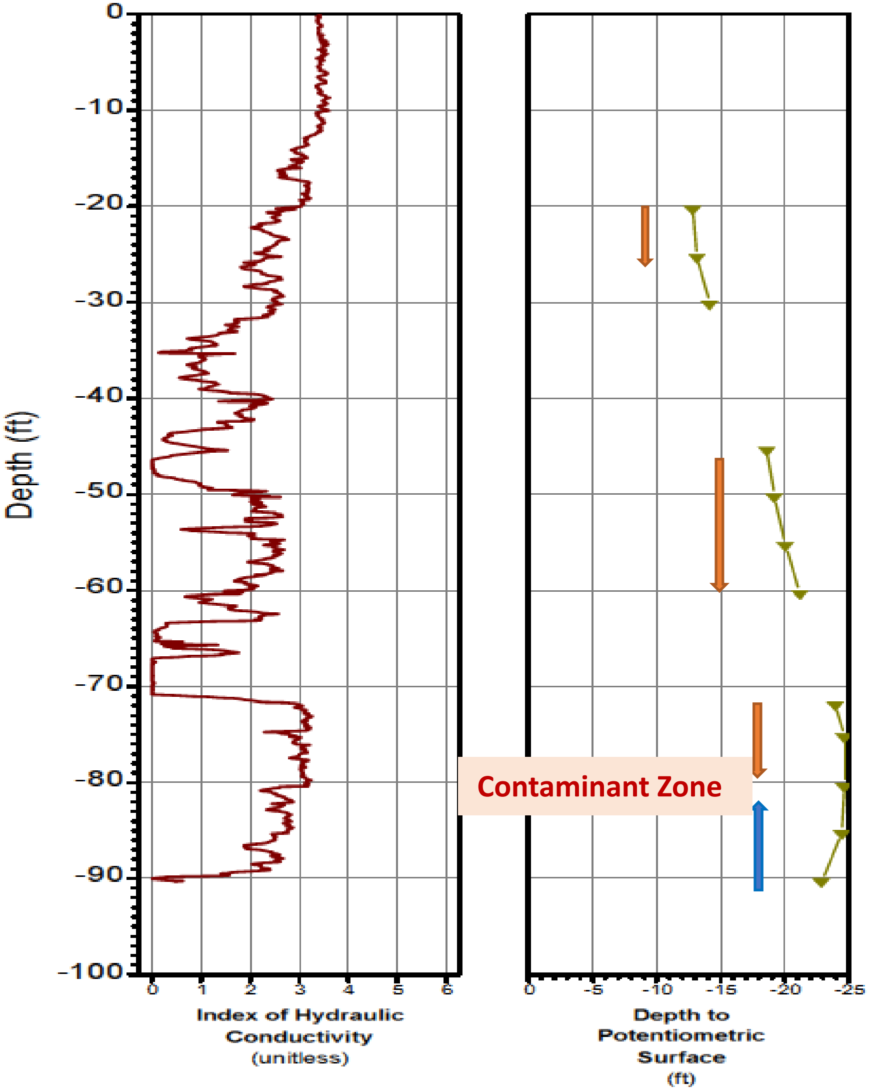
–

Source Depleted

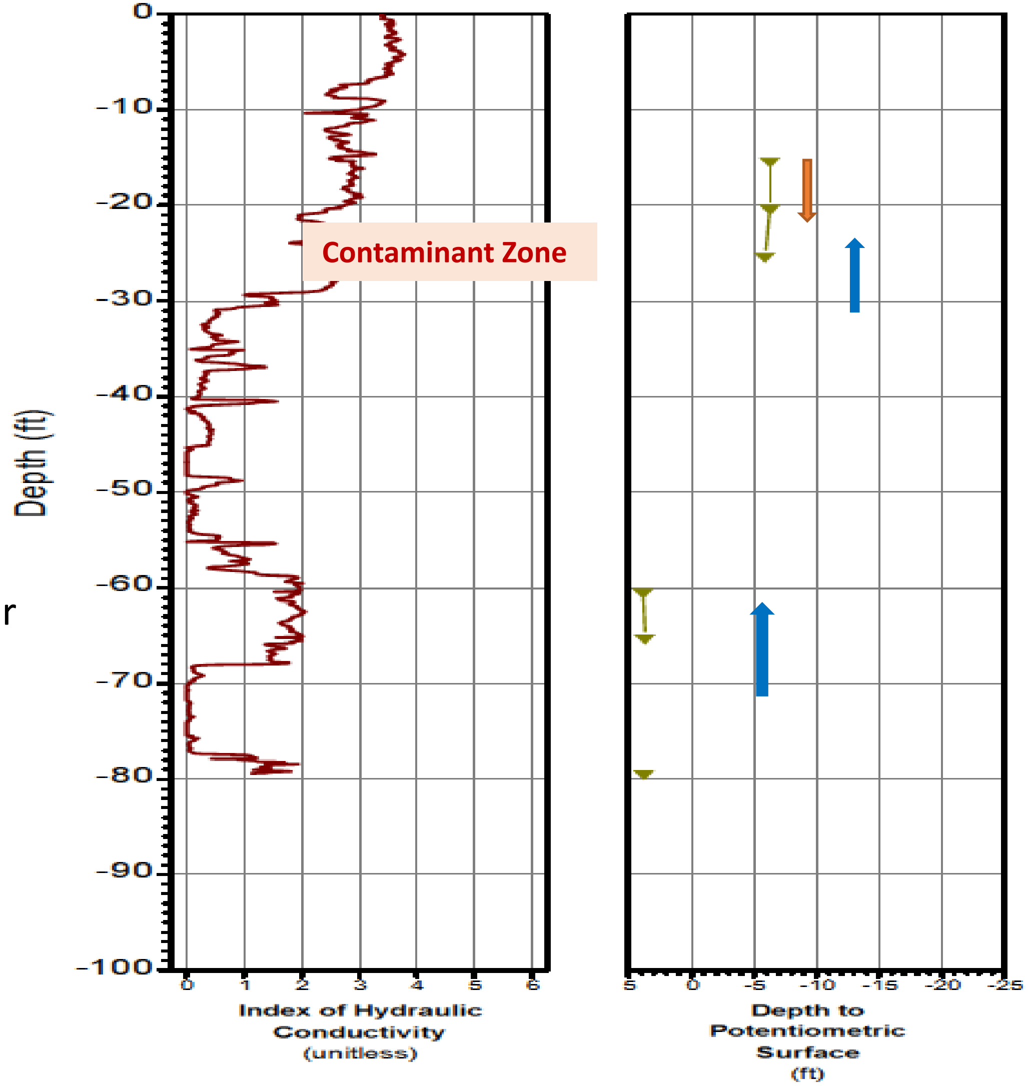


HRSC – Lithology & Vertical Gradients

Recharge Zone Profile

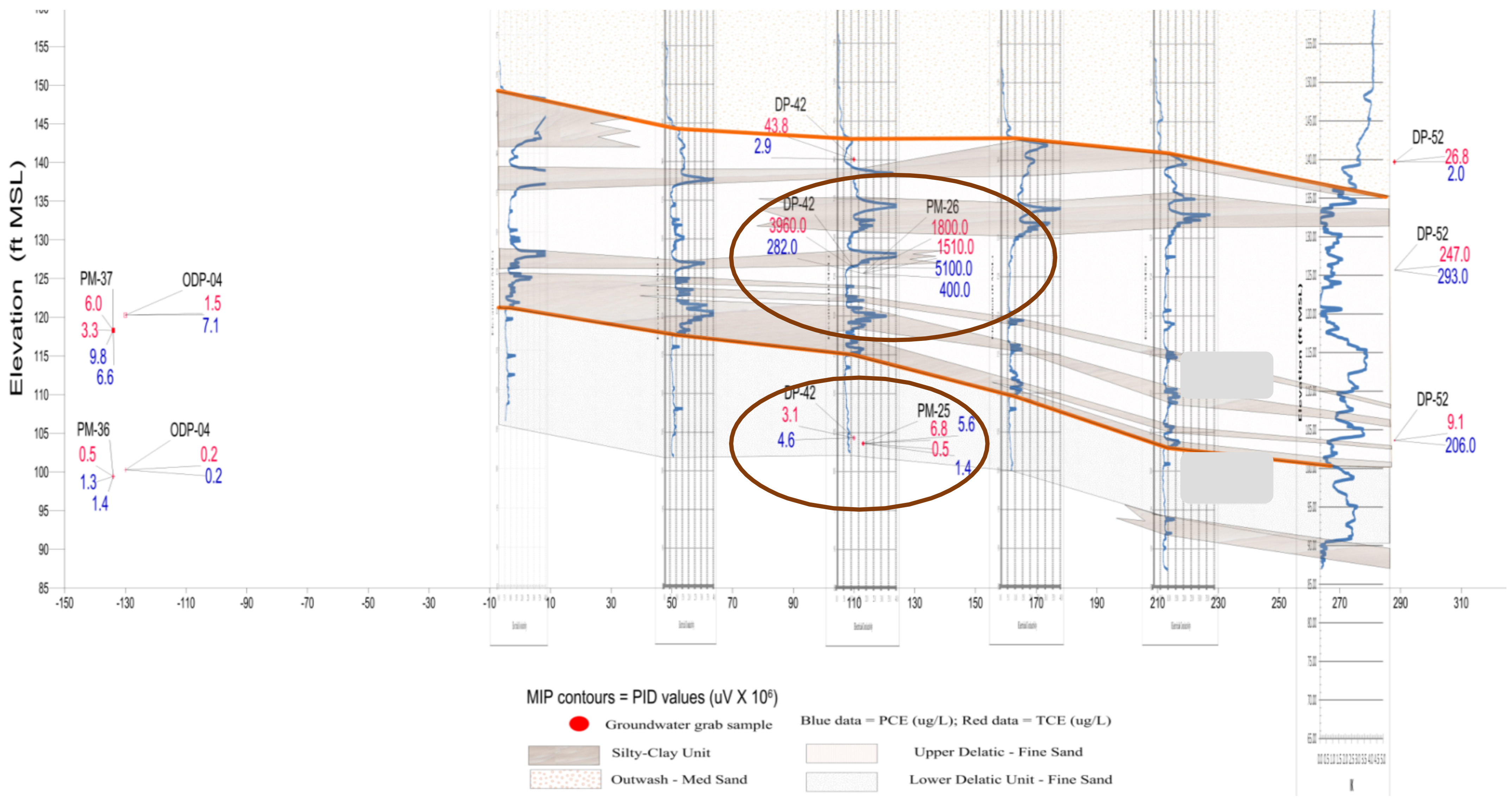


Discharge Zone Profile

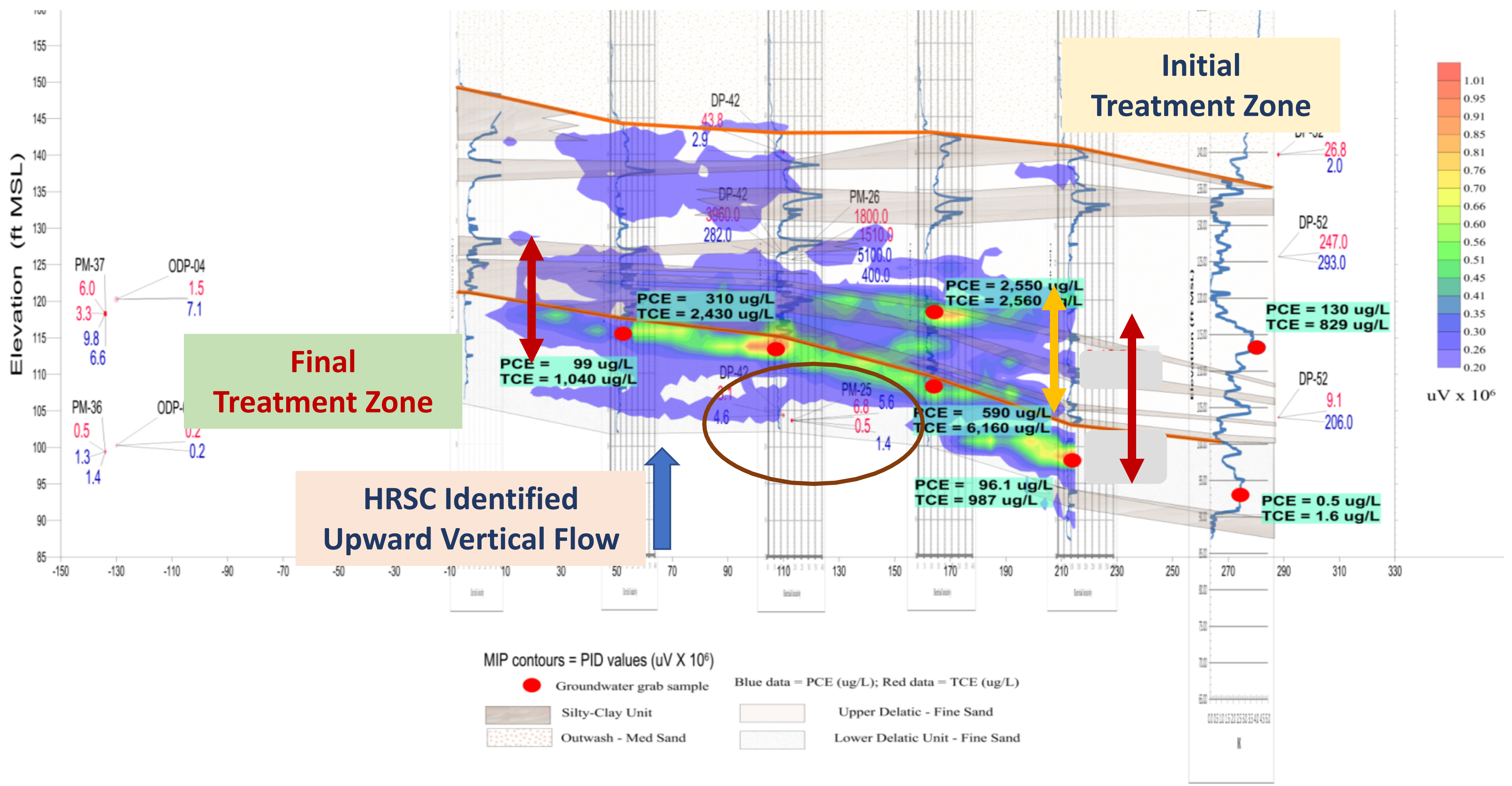


Vertical groundwater flow direction
&
Hydraulic Head

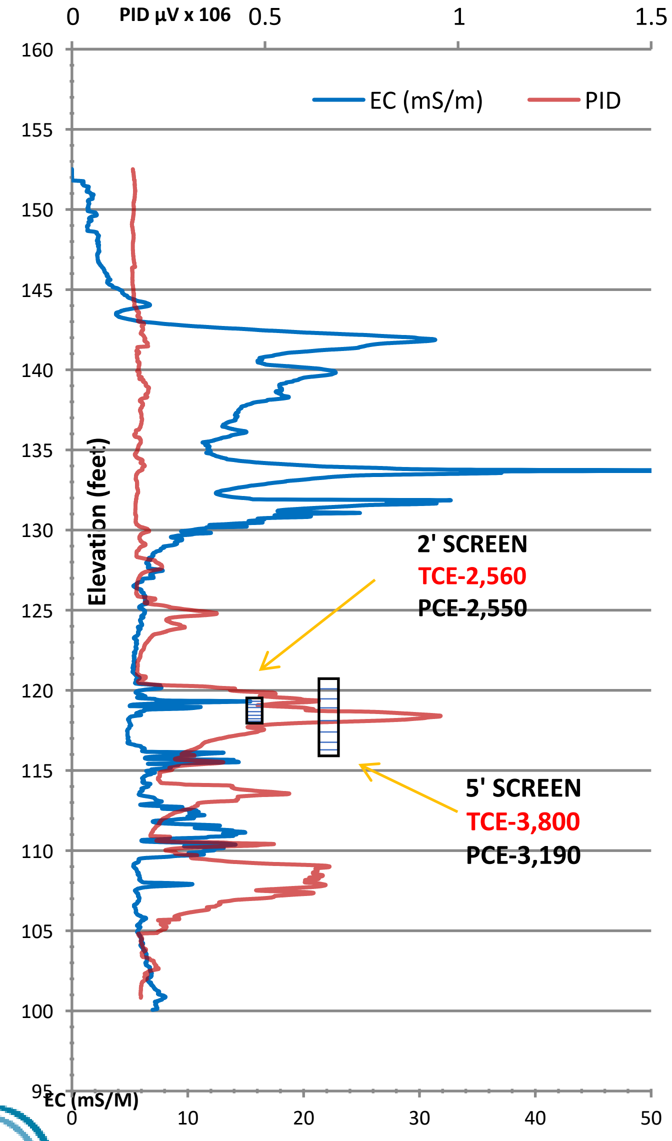
HRSC – Transect Lithology & TCE Profile

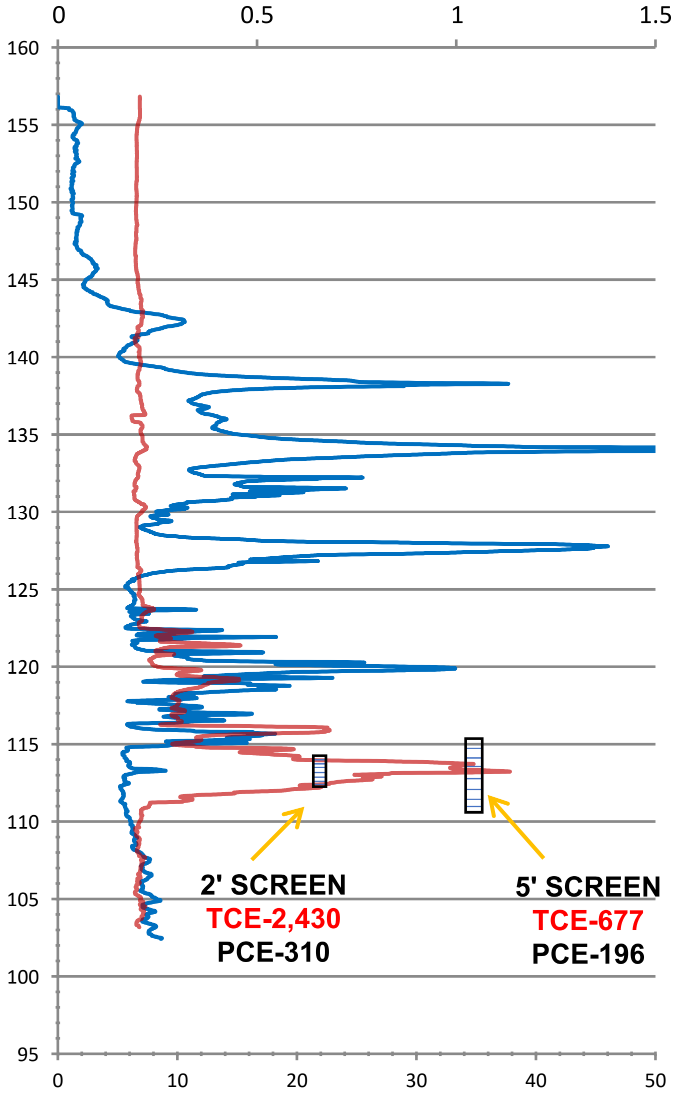


HRSC – Transect Lithology & PID-Analytical Profile

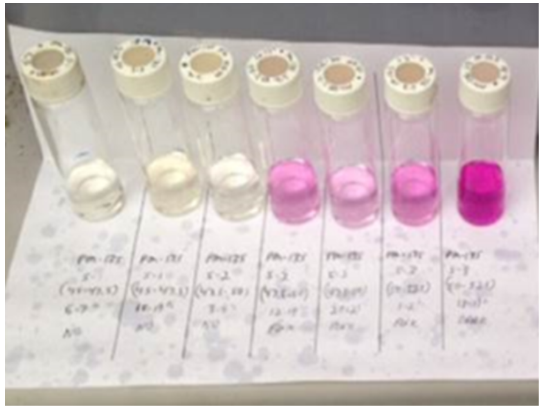


HRSC – Importance of Heterogeneities





Blue = lithology (k values decrease to the right) Red = PID

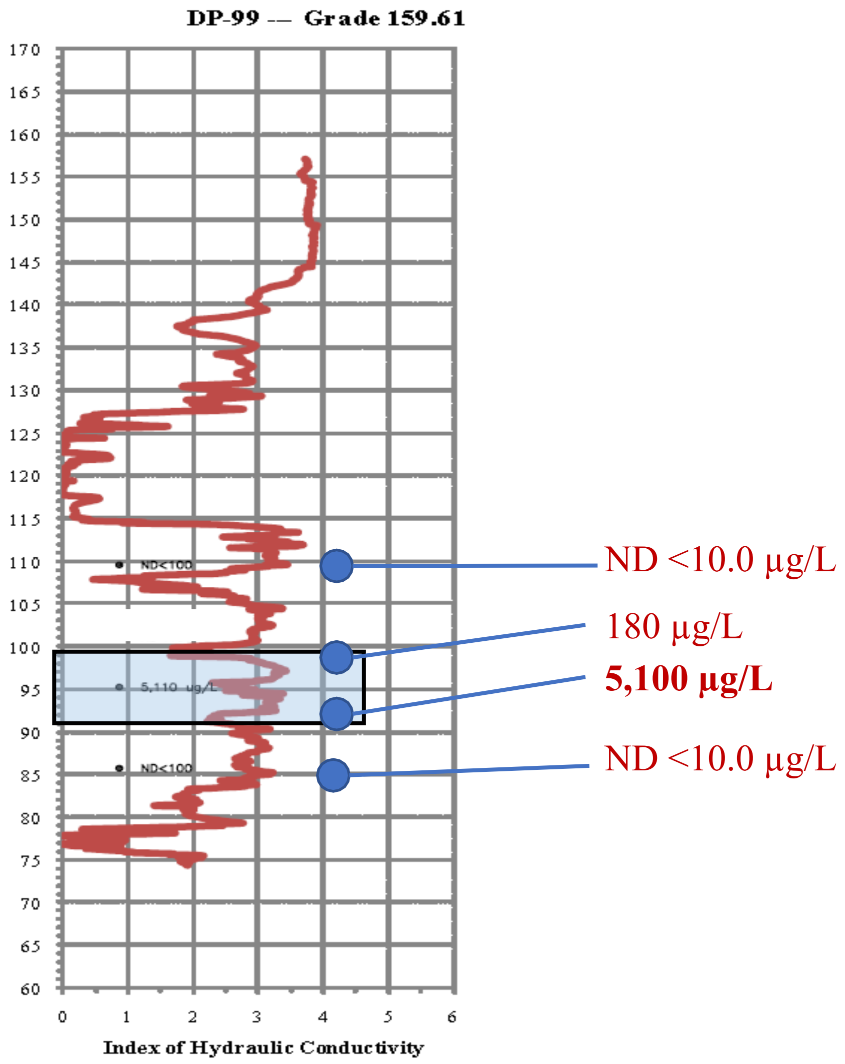


Collection of real time soil Cr^{+6} data using colorimetric field test kit prior to setting well screens.

Field PID & Hexavalent Chromium Results				
Depth (ft)	Inches	PID (ppb)	Hexavalent Chromium (ppb)	Treatment Zone (ftbg)
45-47.5	6	0	24	
	12	20		
	18	70	59	
47.5-50	6	40	17	
	12	170	209	48.5 To 52.5
	18	160		
	21	180	111	
50-52.5	6	720	253	
	12	1,500		
	18	720	615	
52.5-55	3	240	38	
	6	0		
	12	0		
	17	0	1	
	18	0	7	
	24	0		
	30	0	24	
55-58	6	0	1	
	12	0	4	
	18	0		
	24	0	15	

Well Placement Issues

Elev.	96.62 ft MSL	91.24 ft MSL
Conc.	180 µg/L	5,100 µg/L



Typical Boring Log

Geotechnical | Environmental | Ecological | Water | Construction Management

Depth, (ft)	No.	Pen./ Rec. (in)	Depth (ft)	PID Screening (A)	Head Space (B)	Sample Description & Classification	Stratum Desc.	Remarks	Equipment Installed
47									
48									
49	S-1	42/30	49-52.5	0		S-1: 0-7.5": Gray-brown, fine SAND, some Silt 7.5-9.5": Red-brown, fine SAND and SILT 9.5-10": Red-brown, Silty CLAY, dry 10-30": Gray-brown, fine SAND, little to some Silt			
				0					
50				0					
				0					
51				0					
52									
	S-2	30/21	52.5-55	0		S-2: 0-21": Gray, fine SAND, little to some Silt, moist, <1/8" thick red-brown Silt at 15"			
53				0					
				0					
54				0					
55	S-3	24/15	55-57	0		S-3: 0-6": Gray-brown, fine SAND, little to some Silt, moist 6-9.5": Red-brown, SILT with some fine Sand, moist 9.5-12.5": Red-brown, fine SAND and SILT, moist 12.5-13": Red-brown, SILT, little fine Sand, moist 13-13.5": Red-brown, Silty CLAY, dry 13.5-15": Gray-brown, fine SAND and SILT, moist			
				0					
56				0					
57						Refusal at 57'			

Depth, (ft)	No.	Pen./ Rec. (in)	Depth (ft)	PID Screening (A)	Head Space (B)	Sample Description & Classification	Stratum Desc.	Remarks	Equipment Installed
47									
48									
49									
50									
51									
52									
53									
54									
55	S-1	60/52	55-60	0		S-1: 0-21": Gray, fine SAND, little Silt, wet 21-25": Brown-gray, SILT and fine SAND, wet 25-28.5": Gray, fine SAND, little to some Silt, wet 28.5-30.5": Brown, SILT, some fine Sand, wet, 1/2" red-brown, dry, platey Clay at 30" 30.5-50": Gray, fine SAND, trace to little Silt, wet 50-52": Gray-brown, fine SAND, little to some Silt, wet			
				0					
56				0					
				0					
57				0					
				0					

Depth, (ft)	No.	Pen./ Rec. (in)	Depth (ft)	PID Screening (A)	Head Space (B)	Sample Description & Classification	Stratum Desc.	Remarks	Equipment Installed
				6					
				42					
59									
60	S-2	60/48	60-65	80		S-2: 0-6": Gray-brown, fine SAND, little to some Silt, wet 6-22": Brown-gray, fine SAND, some Silt, wet, 1/4" red-brown, dry, platey Clay at 6.5", 3/4" red-brown, dry, platey Clay at 20" 22-44": Gray, fine SAND, little Silt, wet 44-48": Brown-gray, SILT, some fine Sand, wet			
				213					
61				604					
				470					
62				1230					
				1782					
63				2030					
				814					
64									
65	S-3	60/45	65-70	95		S-3: 0-15": Brown-gray, SILT and fine SAND, wet, 1/4" red-brown, soft, moist, Silt and Clay at 9" 15-35": Gray-brown, fine SAND, little to some Silt, wet, 1-1/2" brown-red, soft, moist Silt and Clay at 29" 35-38": Gray-brown, fine SAND, some Silt, wet 38-45": Brown-gray, SILT and fine SAND, wet			
				14					
66				0					
				0					
67				0					
				0					
68									
69									

Hex Chrome

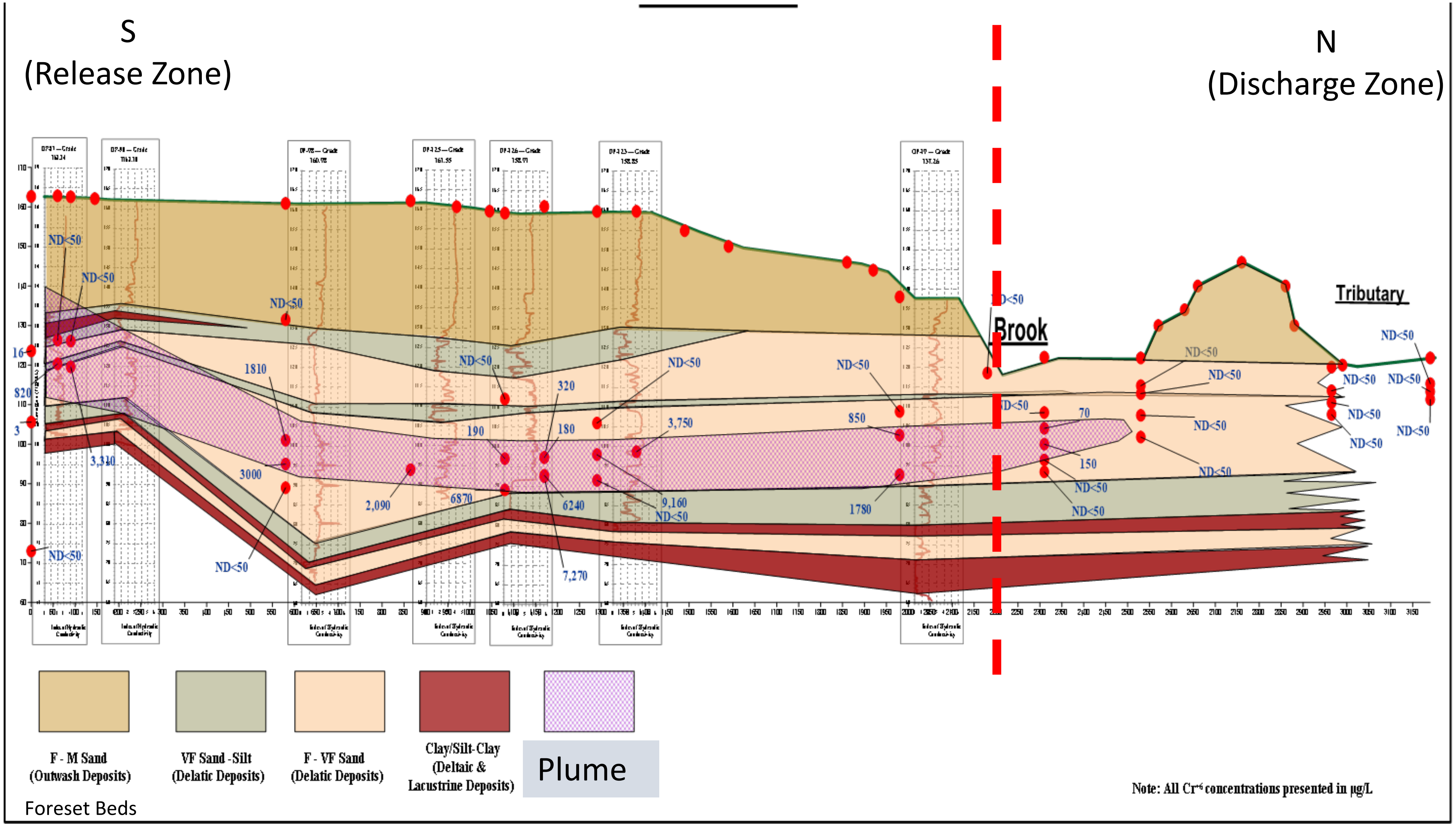
Geologic Depositional Units with Field Screening

Point ID	Sample Interval	sample top	sample bottom	PID	Cr^{+6}	Description
PM-125	49-52.5	108.38	107.76	0	no color	S-1: 0-7.5": Gray-brown, fine SAND, some Silt
PM-125	49-52.5	107.76	107.59	0	no color	7.5-9.5": Red-brown, fine SAND and SILT
PM-125	49-52.5	107.59	107.55	0	no color	9.5-10": Red-brown, Silty CLAY, dry
PM-125	49-52.5	107.55	105.88	0	no color	10-30": Gray-brown, fine SAND, little to some Silt
PM-125	52.5-55	104.88	103.13	0	no color	S-2: 0-21": Gray, fine SAND, little to some Silt, moist, <1/8" thick, red-brown Silt at 15"
PM-125	55-57	102.38	101.88	0	no color	S-3: 0-6": Gray-brown, fine SAND, little to some Silt, moist
PM-125	55-57	101.88	101.59	0	no color	6-9.5": Red-brown, SILT with some fine Sand, moist
PM-125	55-57	101.59	101.34	0	no color	9.5-12.5": Red-brown, fine SAND and SILT, moist
PM-125	55-57	101.34	101.30	0	no color	12.5-13": Red-brown, SILT, little fine Sand, moist
PM-125	55-57	101.30	101.26	0	no color	13-13.5": Red-brown, Silty CLAY, dry
PM-125	55-57	101.26	101.13	0	no color	13.5-15": Gray-brown, fine SAND and SILT, moist
PM-126	55-60	102.38	100.63	0	0.04	S-1: 0-21": Gray, fine SAND, little Silt, wet
PM-126	55-60	100.63	100.30	0	no color	21-25": Brown-gray, SILT and fine SAND, wet
PM-126	55-60	100.30	100.01	0	no color	25-28.5": Gray, fine SAND, little to some Silt, wet
PM-126	55-60	100.01	99.84	0	no color	28.5-30.5": Brown, SILT, some fine Sand, wet, 1/2" red-brown, dry, platy, Clay at 30"
PM-126	55-60	**99.84**	**98.21**	0	**0.27**	30.5-50": Gray, fine SAND, trace to little Silt, wet
PM-126	55-60	**98.21**	**98.05**	0	**0.59**	50-52": Gray-brown, fine SAND, little to some Silt, wet
PM-126	60-65	**97.38**	**96.88**	**80**	**1,140.00**	S-2: 0-6": Gray-brown, fine SAND, little to some Silt, wet
PM-126	60-65	**96.88**	**95.55**	**213-604**	**1,460.00**	6-22": Brown-gray, fine SAND, some Silt, wet, **1/4" red-brown, dry, platy Clay at 6.5", 3/4" red-brown, dry, platy Clay at 20"**
PM-126	60-65	**95.55**	**93.71**	**470-2030**	**0.17**	22-44": Gray, fine SAND, little Silt, wet
PM-126	60-65	**93.71**	**93.38**	**814**	no color	44-48": Brown-gray, SILT, some fine Sand, wet
PM-126	65-70	**92.38**	**91.13**	**95-14**	no color	S-3: 0-15": Brown-gray, SILT and fine SAND, wet, 1/4" red-brown, soft, moist, Silt and Clay at 9"
PM-126	65-70	91.13	89.46	0	no color	15-35": Gray-brown, fine SAND, little to some Silt, wet, **1-1/2" brown-red, soft, moist Silt and Clay at 29"**
PM-126	65-70	89.46	89.21	0	no color	35-38": Gray-brown, fine SAND, some Silt, wet
PM-126	65-70	89.21	88.63	0	no color	38-45": Brown-gray, SILT and fine SAND, wet

Contaminant Zone
99.8 to 93.4 ft MSL (± 6.5-feet)

Concentrations in µg/L

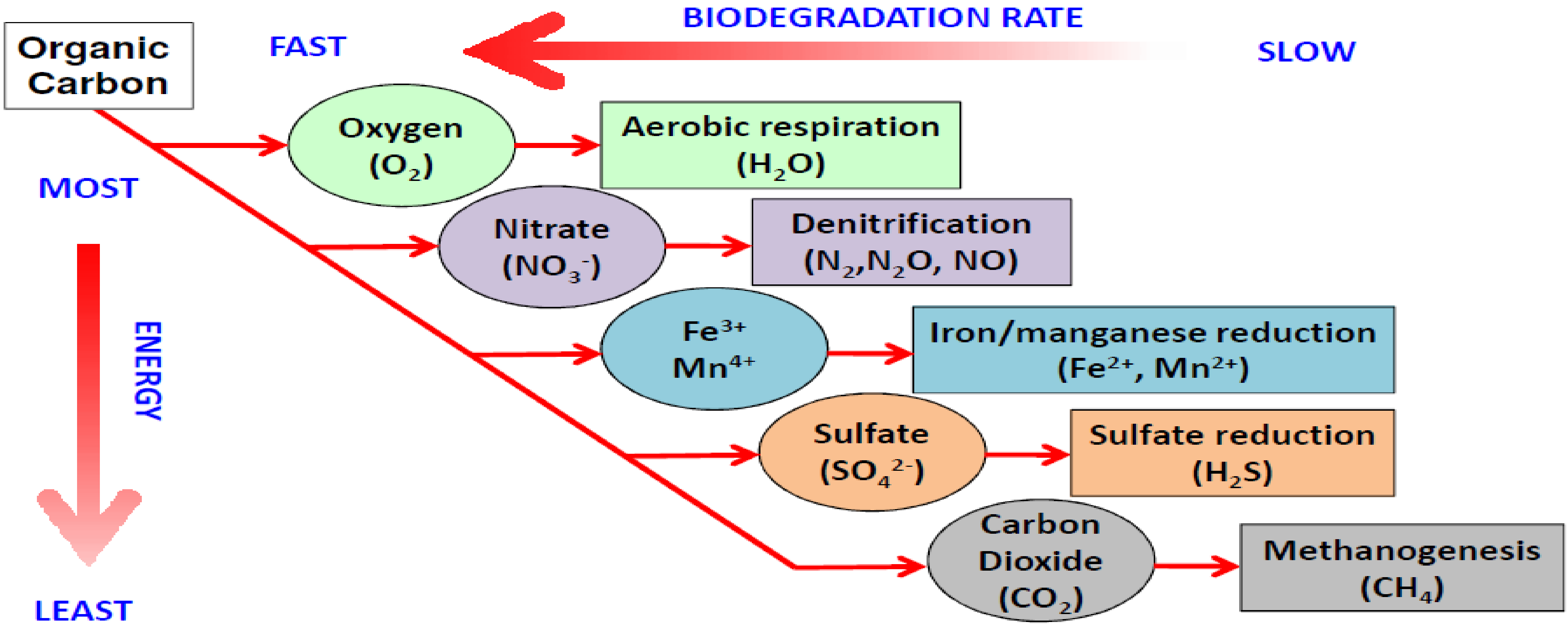
Geologic Cr^{+6} Cross-Section South-North



Factors Influencing the CSM / Remedy

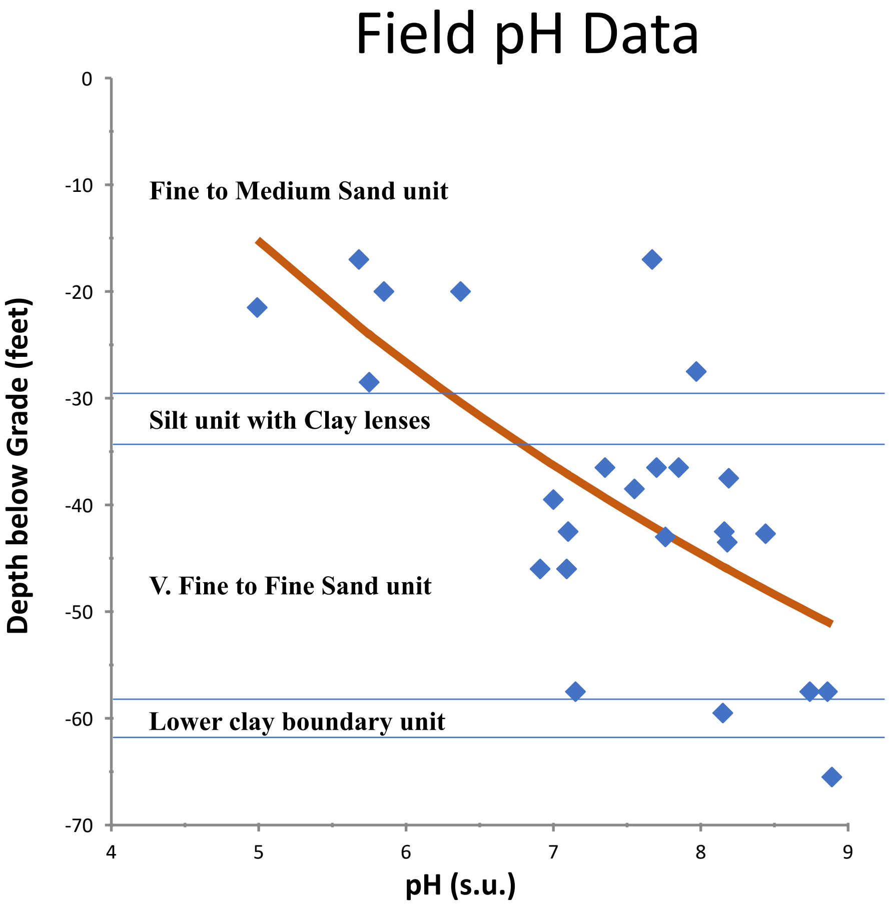
1. Geology (regional and local)
   a) Depositional Environment
   b) Stratigraphy, mineralogy, grain size
2. Aquifer Properties
   a) Hydraulic conductivity
   b) Porosity (total and effective)
   c) Groundwater flow (horizontal & vertical)
   d) Heterogeneity and anisotropy
   e) 3D extent of plume distribution
3. Geochemistry
   a) Field parameters (DO, ORP, pH, temp)
   b) COD, SOD/NOD, TOC
   c) Sulfate & Nitrate
4. Microbial
   a) Dehalococcoides, phospholipid fatty acids
5. Degradation
   a) Isotope analysis, dissolved gases (methane, ethane, ethene, propane, propene)

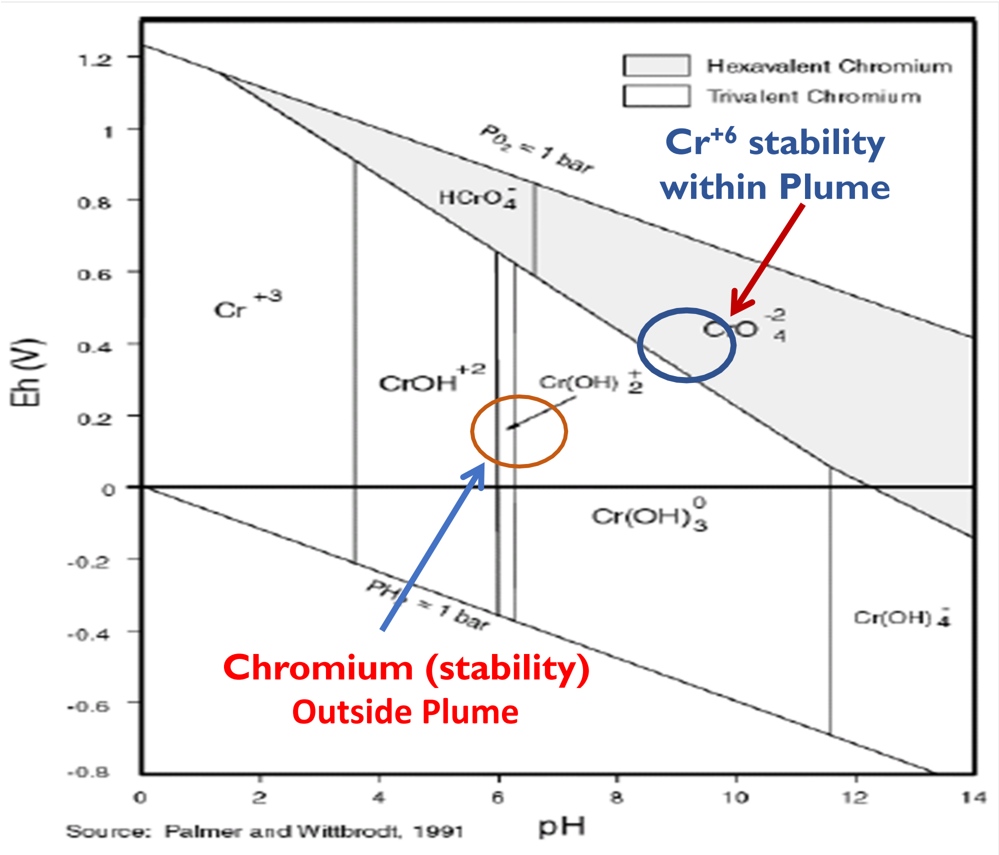
Terminal Electron Acceptors



Microbial TEA reduction occurs in defined order based on energy yield

pH Changes with Depth





Hexavalent Chromium

- Not naturally occurring
- Acutely toxic/less stable
  - *Chromate* CrO_4^{-2}
  - *Dichromate* $Cr_2O_7^{-2}$

Trivalent Chromium

- Naturally occurring
- Stable/low toxicity
  - *Trivalent Chromium* Cr^{+3},
  - *Chromium Oxide* Cr_2O_3

Geochemical Parameters

Parameters	Low Level	High Level
Hexavalent Chromium	0.41 mg/L	38.2 mg/L
Dissolved Oxygen	4.0 mg/L	8.6 mg/L
Nitrate	2.9 mg/L	6.5 mg/L
Sulfate	266 mg/L	4,570 mg/L
pH	6.1	9.5
ORP	116 mV	550 mV
Heterotopic Plate Counts	64 cfu/mL	1,030cfu/mL

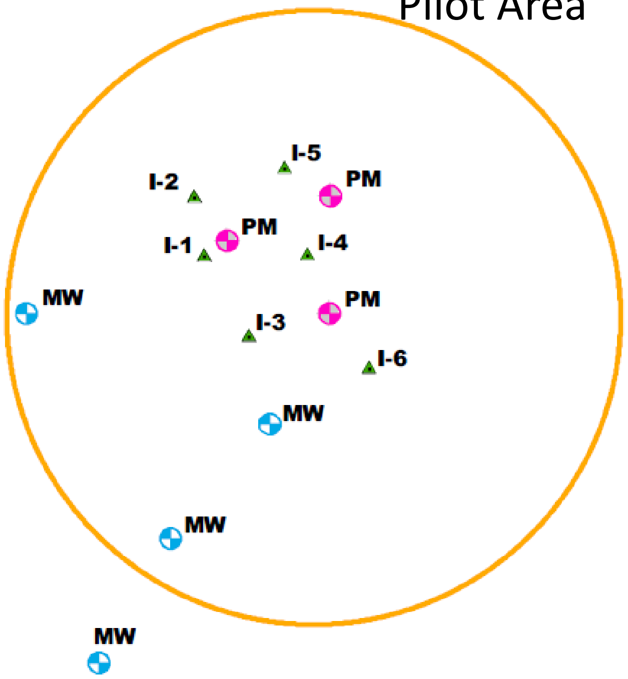
cfu = colony-forming unit

Pilot Design

Design/Layout

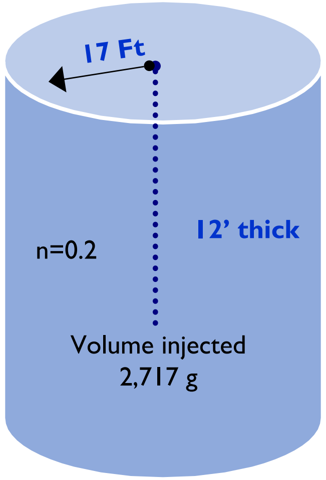
- Evaluated products for BOD/TOC:
  - dextrose, HRC_{primer}/3-DMe, molasses, EDC:
    - HRC/3-DMe selected
- 6- injection points;
- 6-performance wells in 3-clusters;
  - 12 to 17 feet from injection points;
- 1-downgradient well;
- 6-adjacent monitoring wells;

Pilot Area



Duration

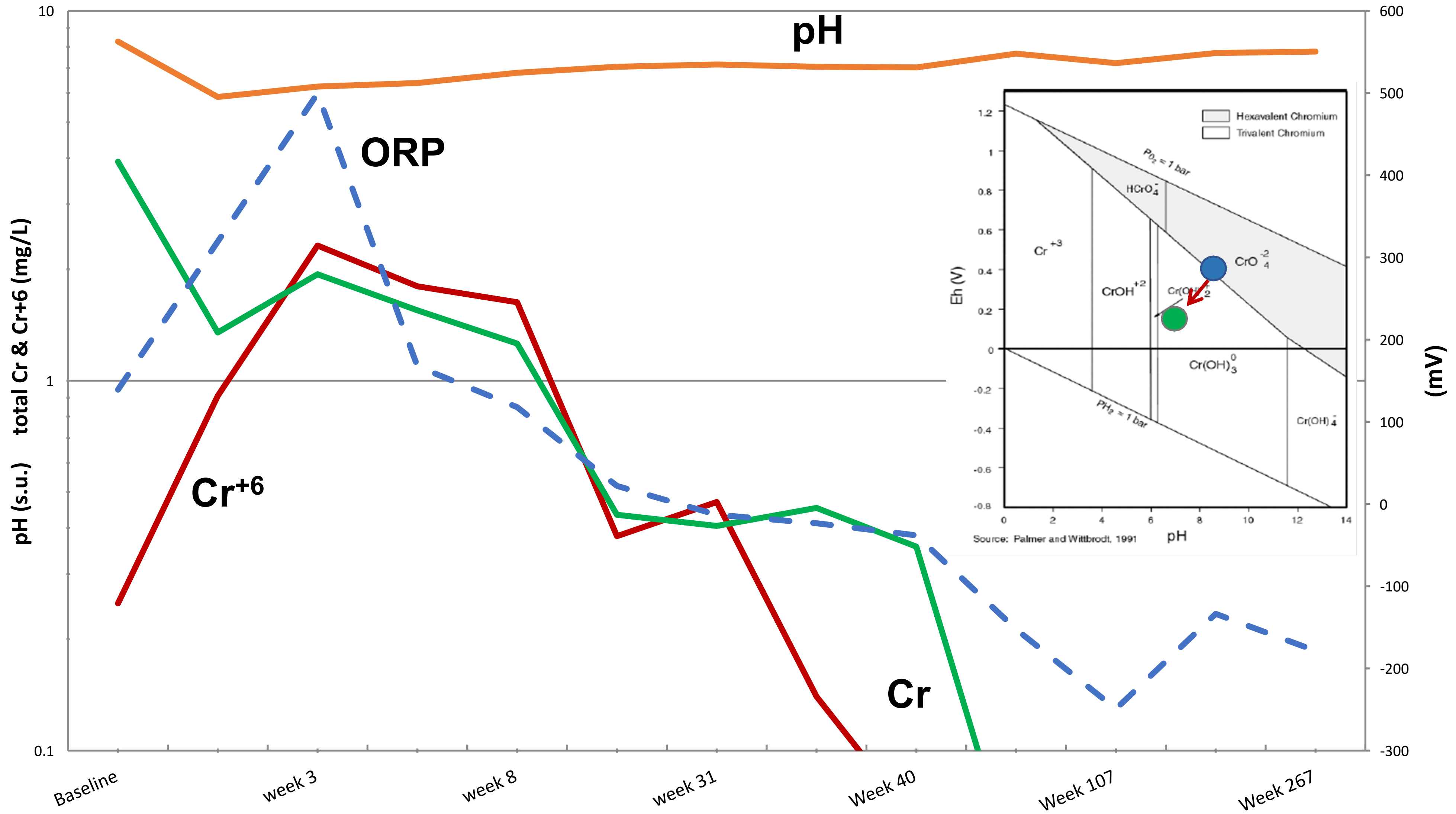
- Injected February 2008;
- Monitored 11-years
- Methanogens conditions



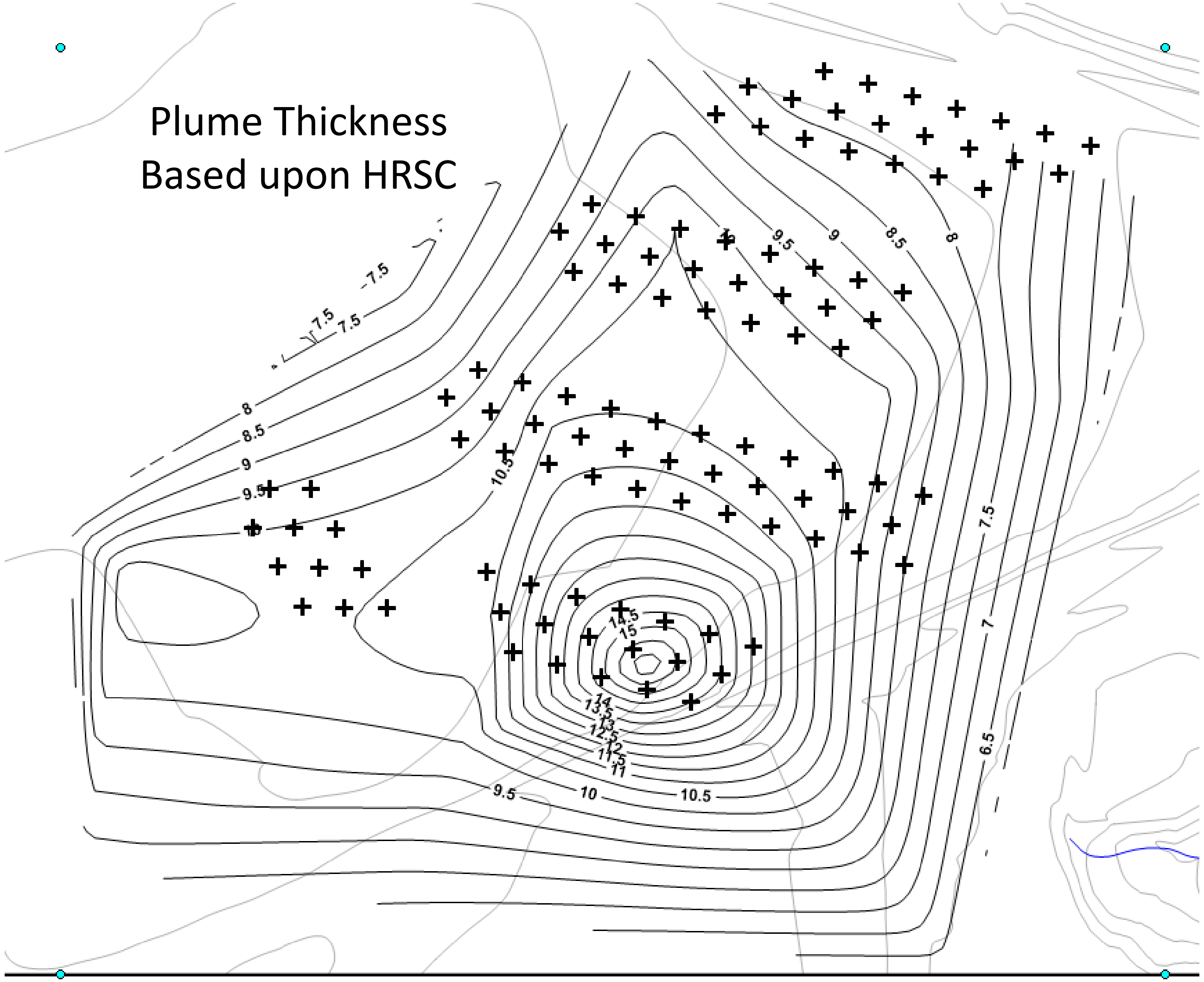
Design Configuration

- To estimate volume and effective radius of influence ($V = \pi * r^2 * h * n$)
  - (r - radius, h- thickness, n – effective porosity)
- $V = \pi * (17)^2 * 12 * 0.2 = 2{,}179$ -gallons 181.5 gallons per foot;
- Total injection zone – 16,300 gallons (2,717 gals per point);

Pilot Results



Hexavalent Chromium Design



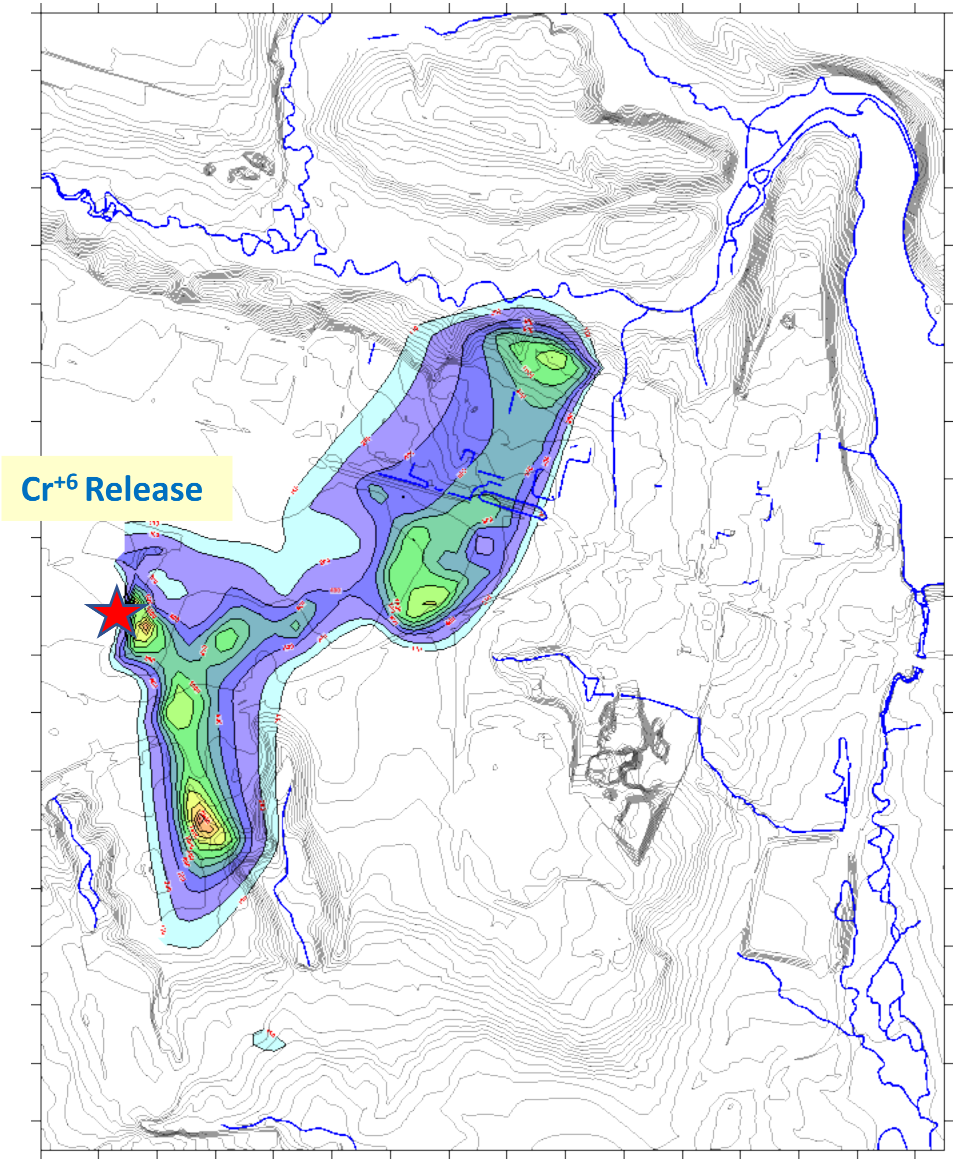
+ injection points

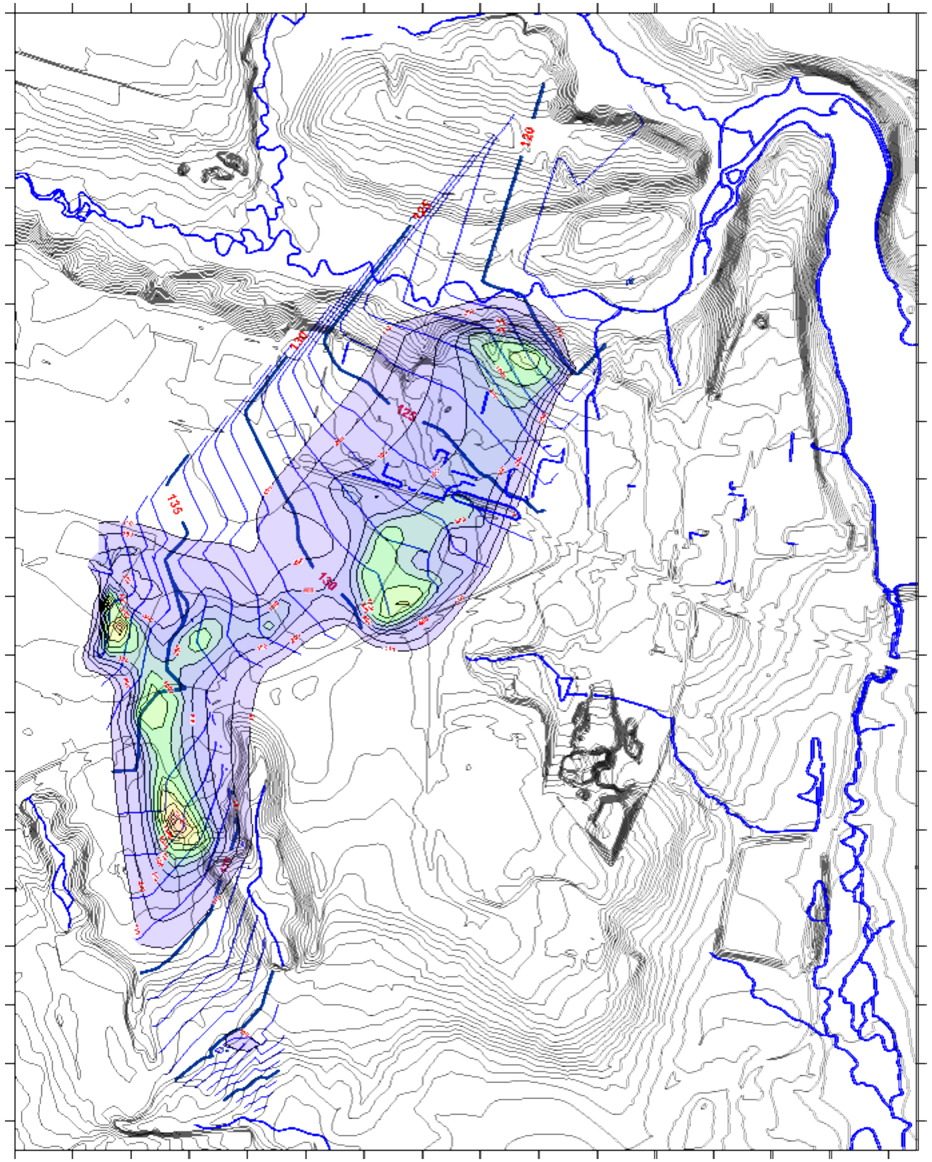
Seepage velocity	35-feet/year
Effectiveness of Pilot migration	8+ years Plume 280-feet
Distance between injection zones	80-feet
Injection effective radius of influence	15-feet (177 sf)
Sodium Lactate	2.7 to 3.3 gallons per foot
3-DMe	3.7 to 6.0 gallons per foot
Total injection area (barrier)	5-acres, 155-points
Total if injected 30 ft on center	**5-acres, 1,230-points**

1-foot injection probe, Bottom-up injection

Injection Thickness 10 to 29 -FEET

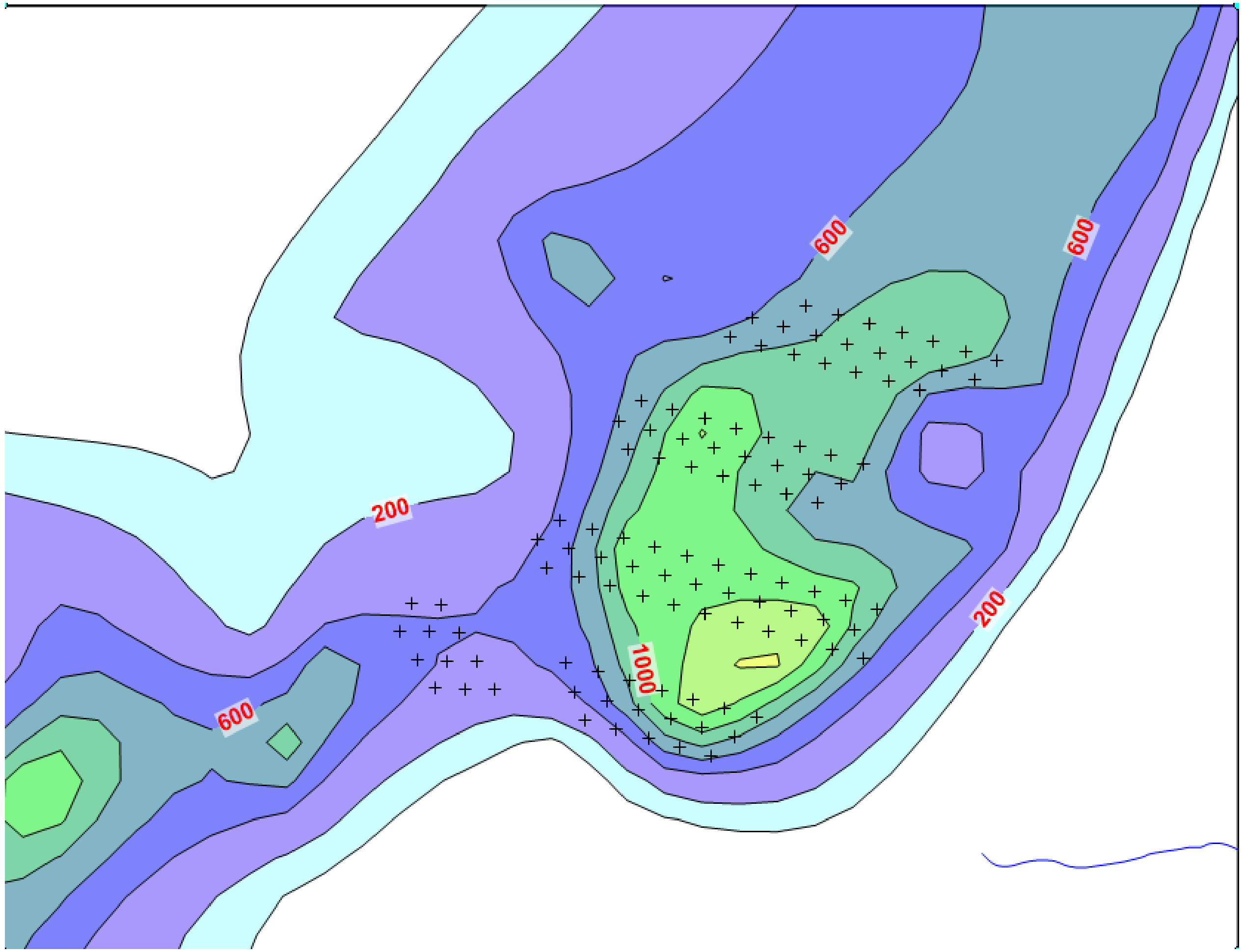
Hexavalent Chromium Plumes



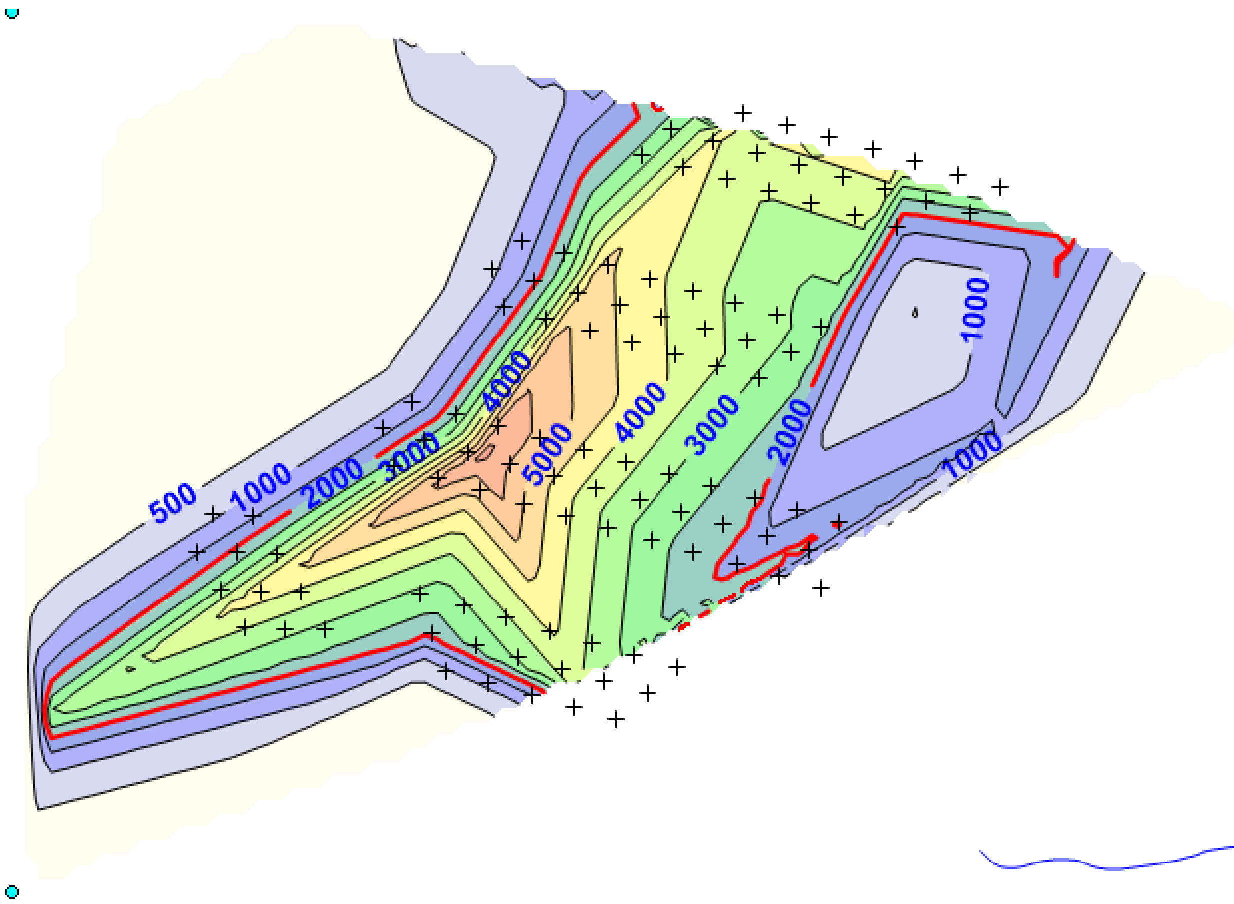


Injection Plume Design

Injection Points (Plume Concentrations)

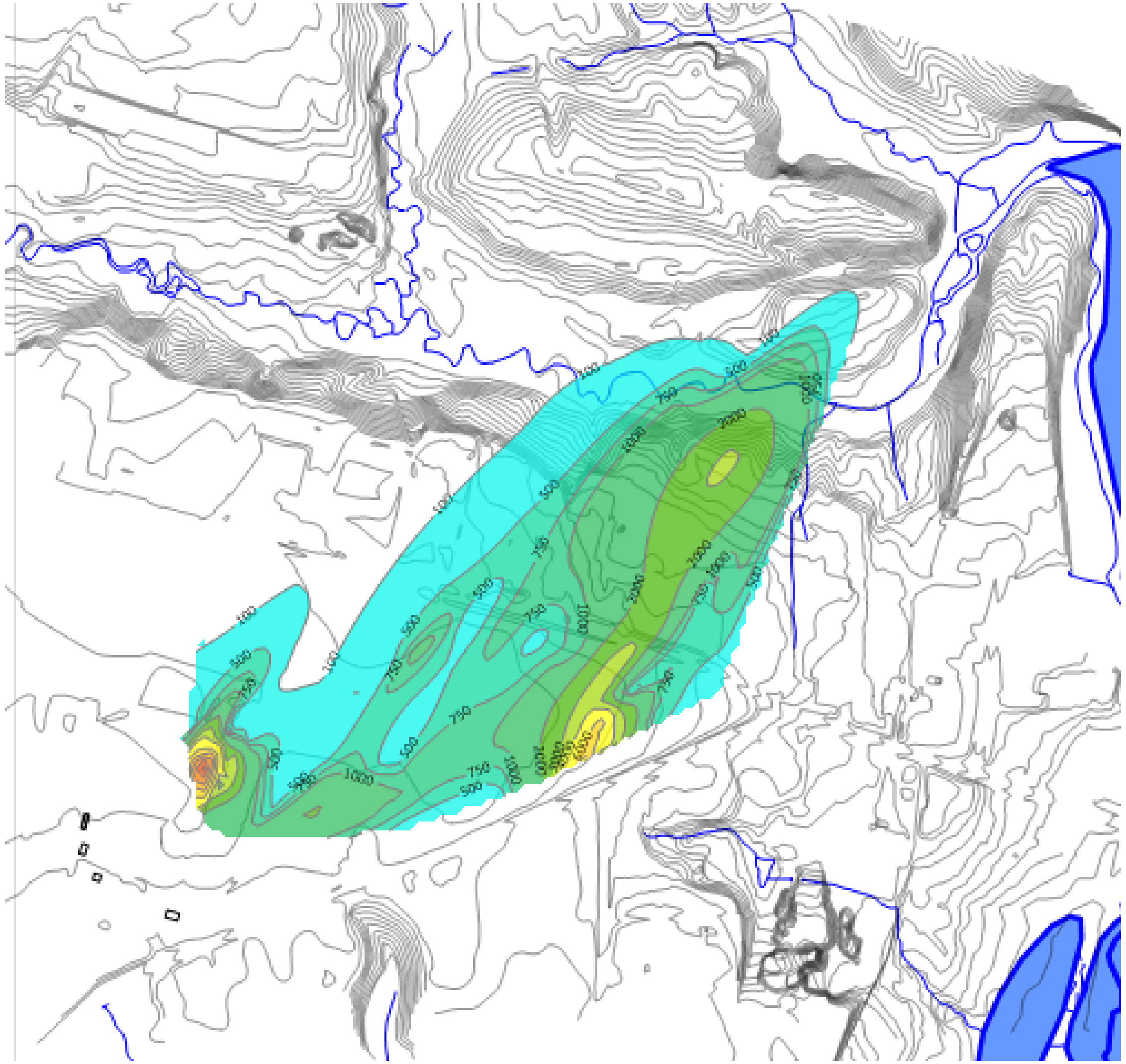


Injection Points (Mass)

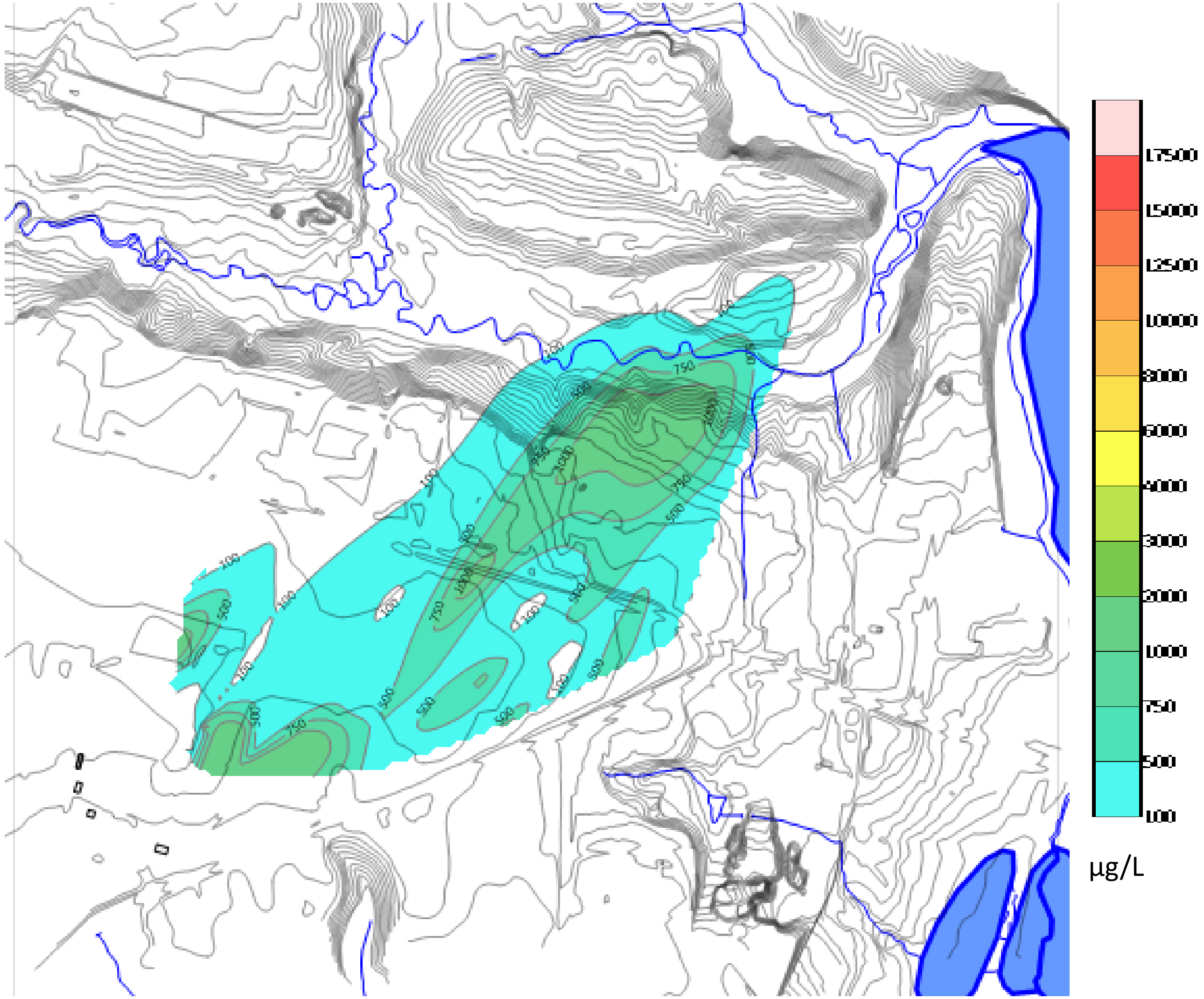


Northern Hexavalent Chromium Plume

Historical Max Cr^{+6}



Post Injection Cr^{+6} (18-months)



Northern Hexavalent Chromium Plume Results

Post Injection

Release Zone (R)

- Cr^{+6} = 92% Reduction in all Concentrations
  - Max = 38,200 µg/L, now 8.2 µg/L

Core Zone (C)

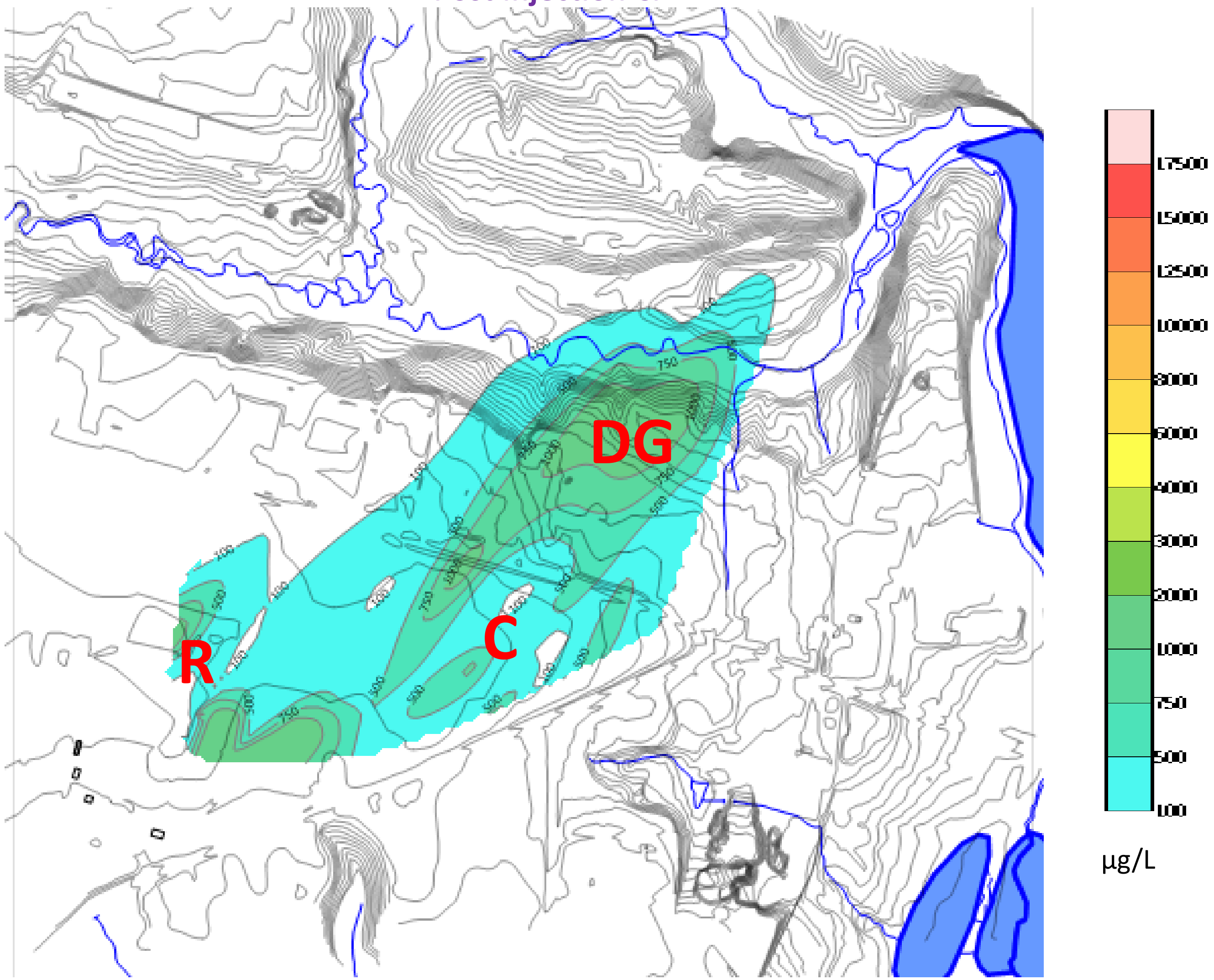
- Cr^{+6} = 80% Reduction in all Concentrations
  - Max = 7,270 µg/L, now 355 µg/L

700-Feet Down Gradient (DG)

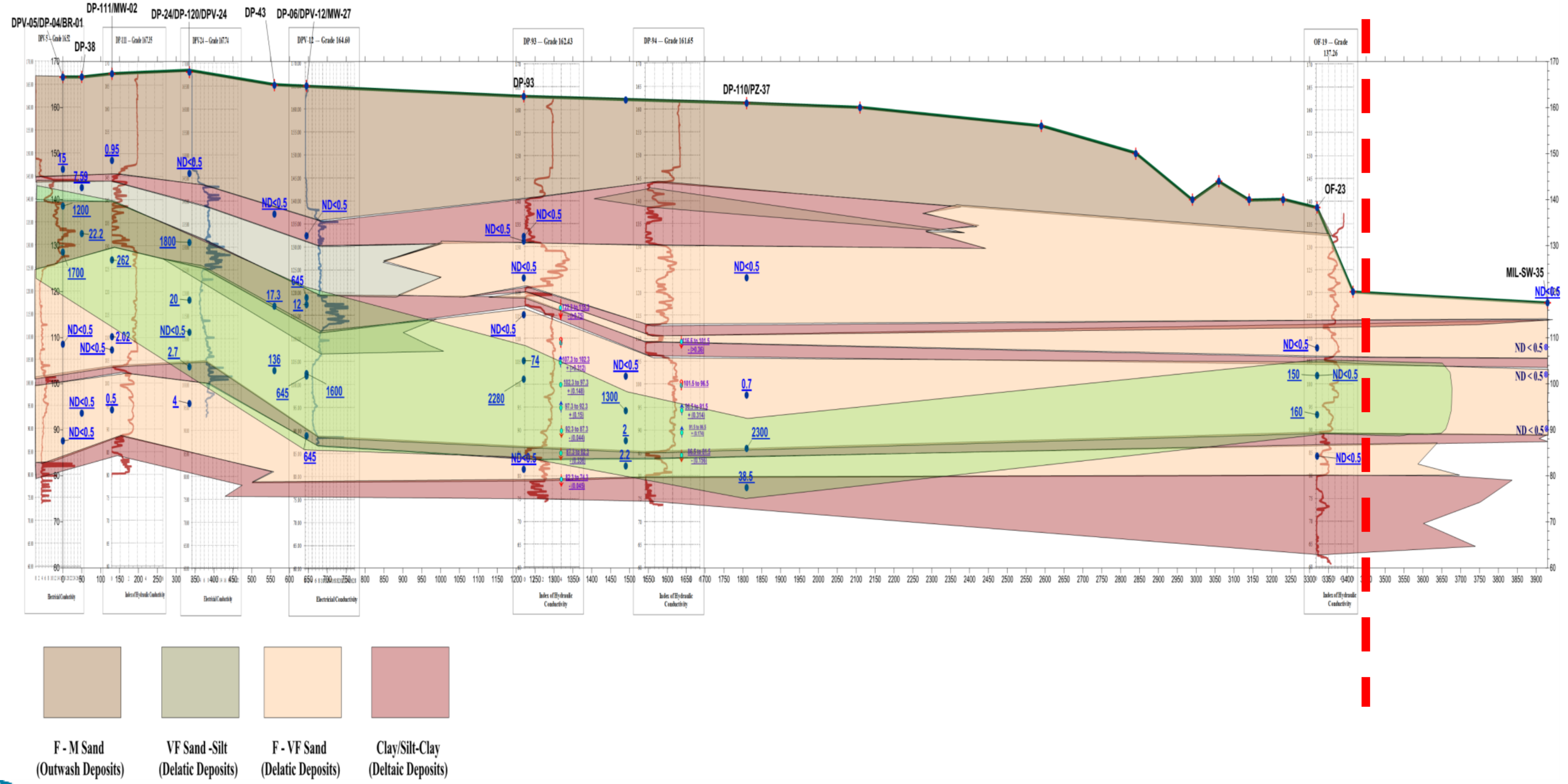
- Cr^{+6} = 53% Reduction in all Concentrations
  - Max = 3,390 µg/L, now 1,570 µg/L

Cr^{+6} "active" remedial goal was 500 µg/L to transition to MNA

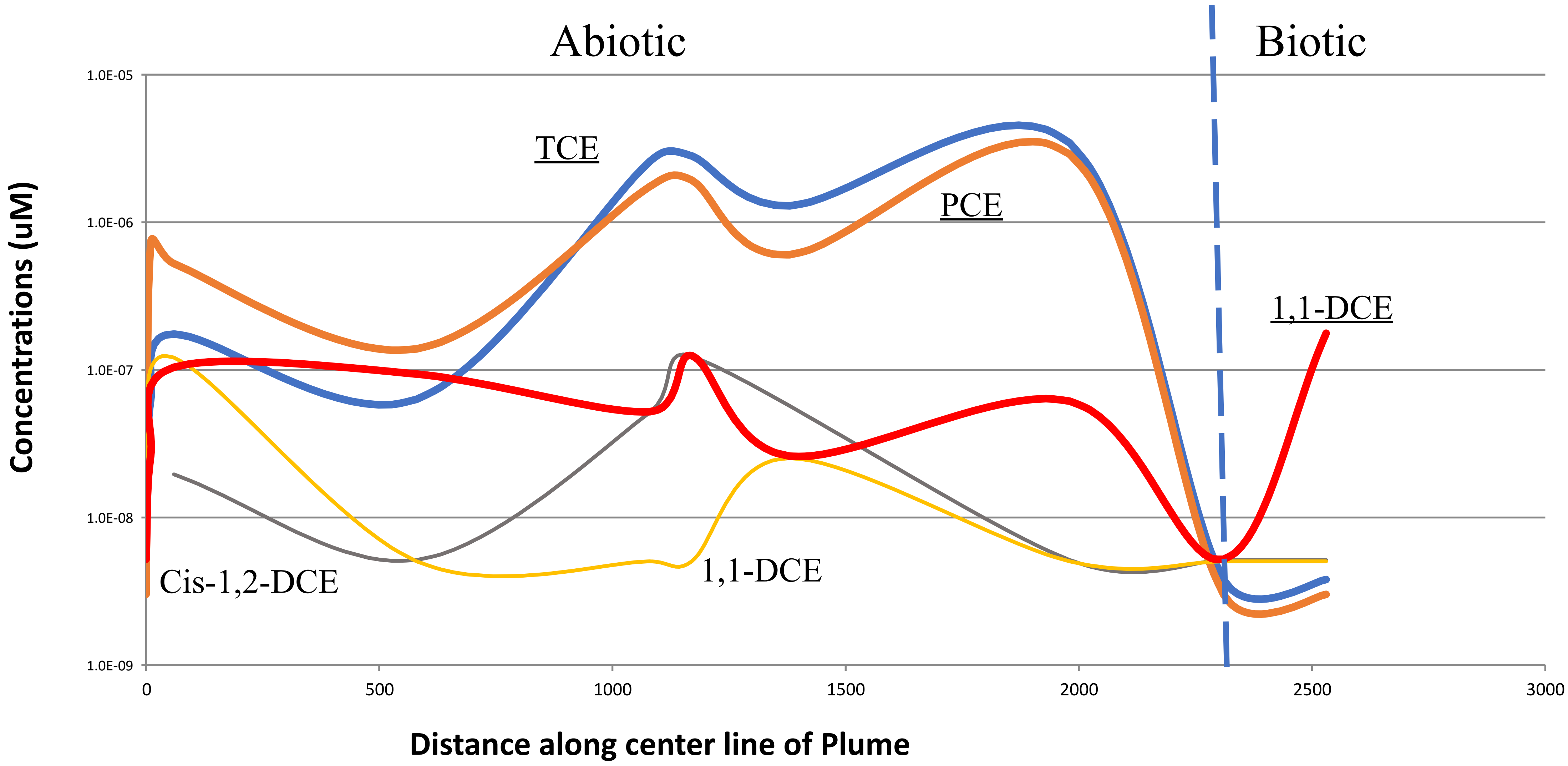
Post Injection Cr^{+6}



TCE Nature & Extent

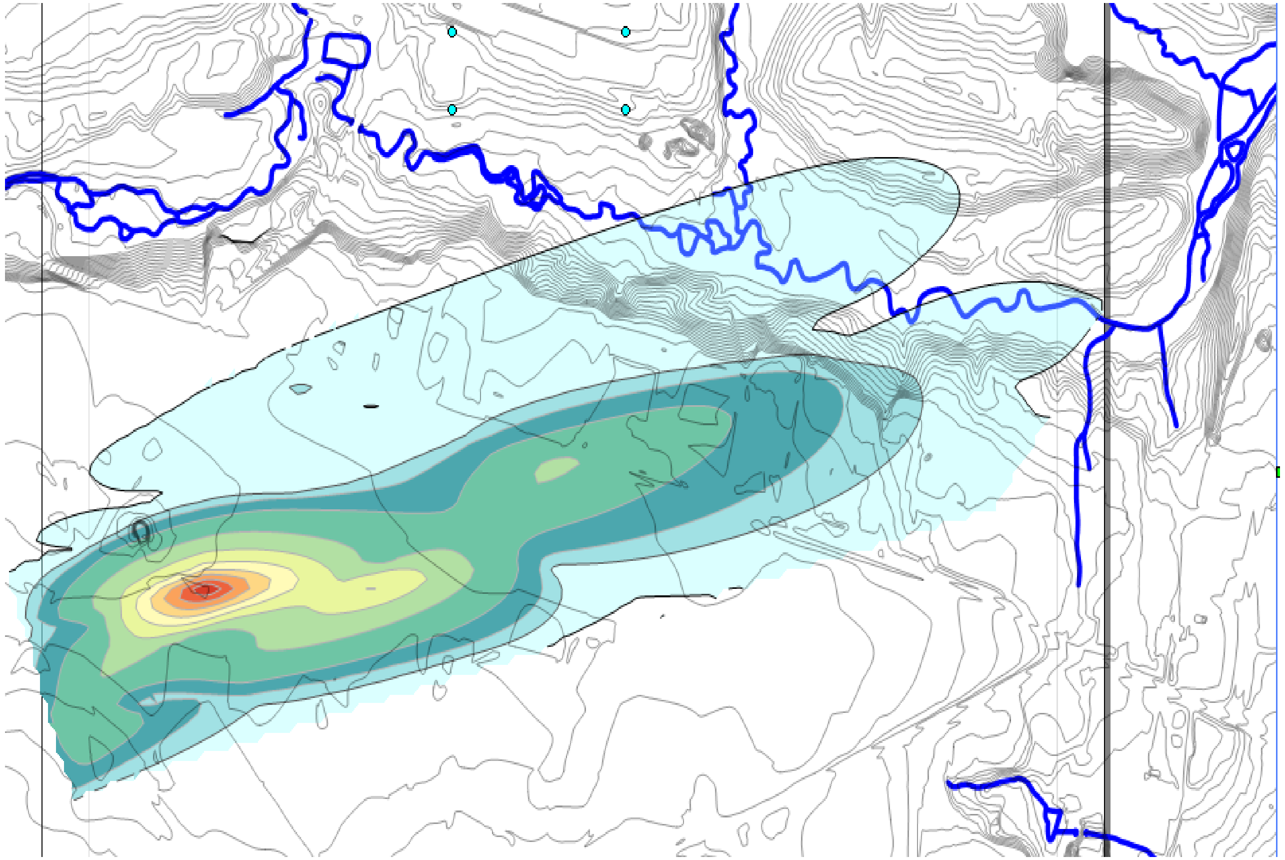


Abiotic vs. Biotic cVOC Degradation

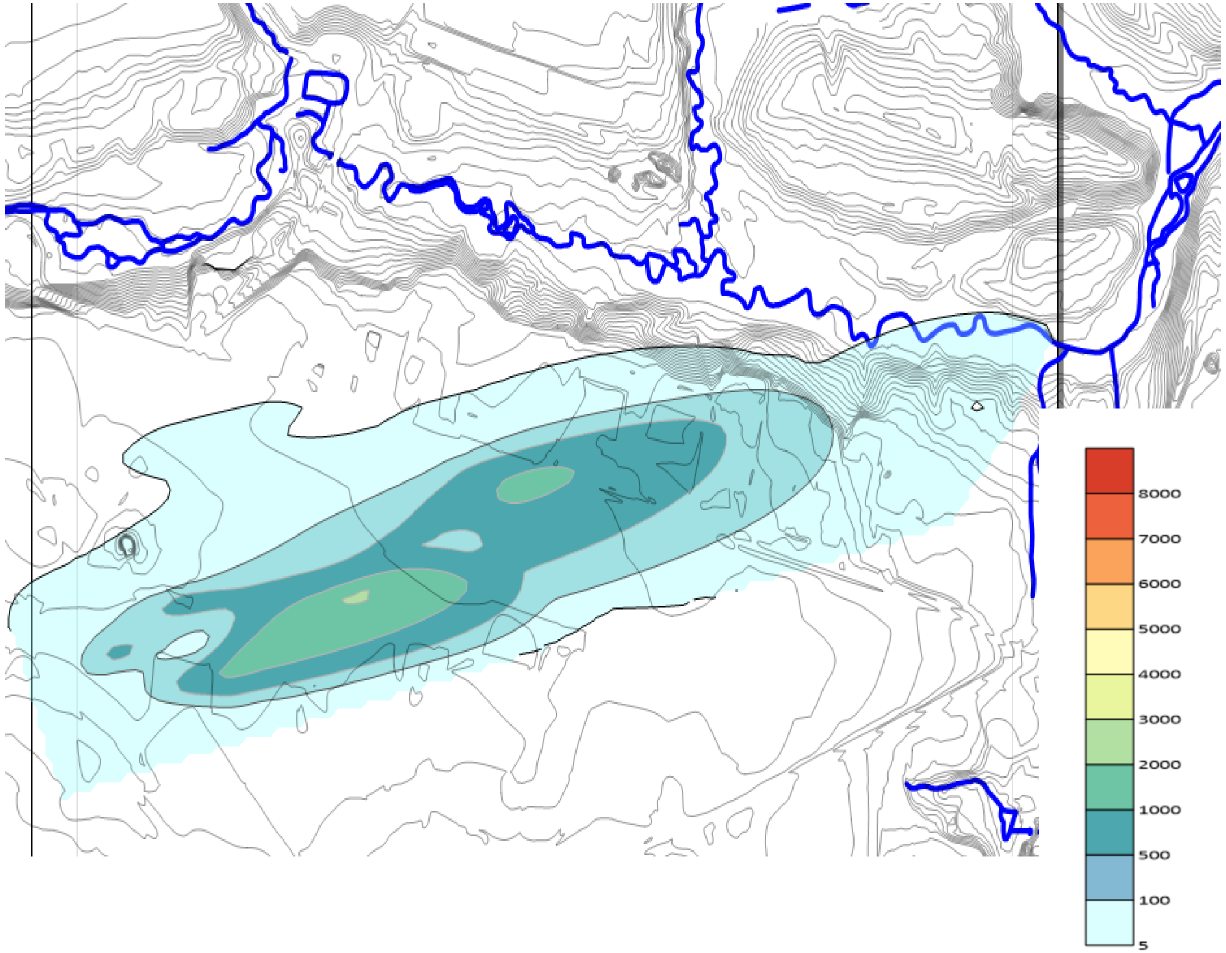


TCE Plume

Historic Max TCE



Post Injection TCE



µg/L

TCE Plume Reductions

Post Injection

Release Zone (R) ISCO Injection

- TCE = 84% Reduction in all Concentrations
  - Max = 9,400 µg/L, now 672 µg/L

Core Zone (C) ISCO Injection

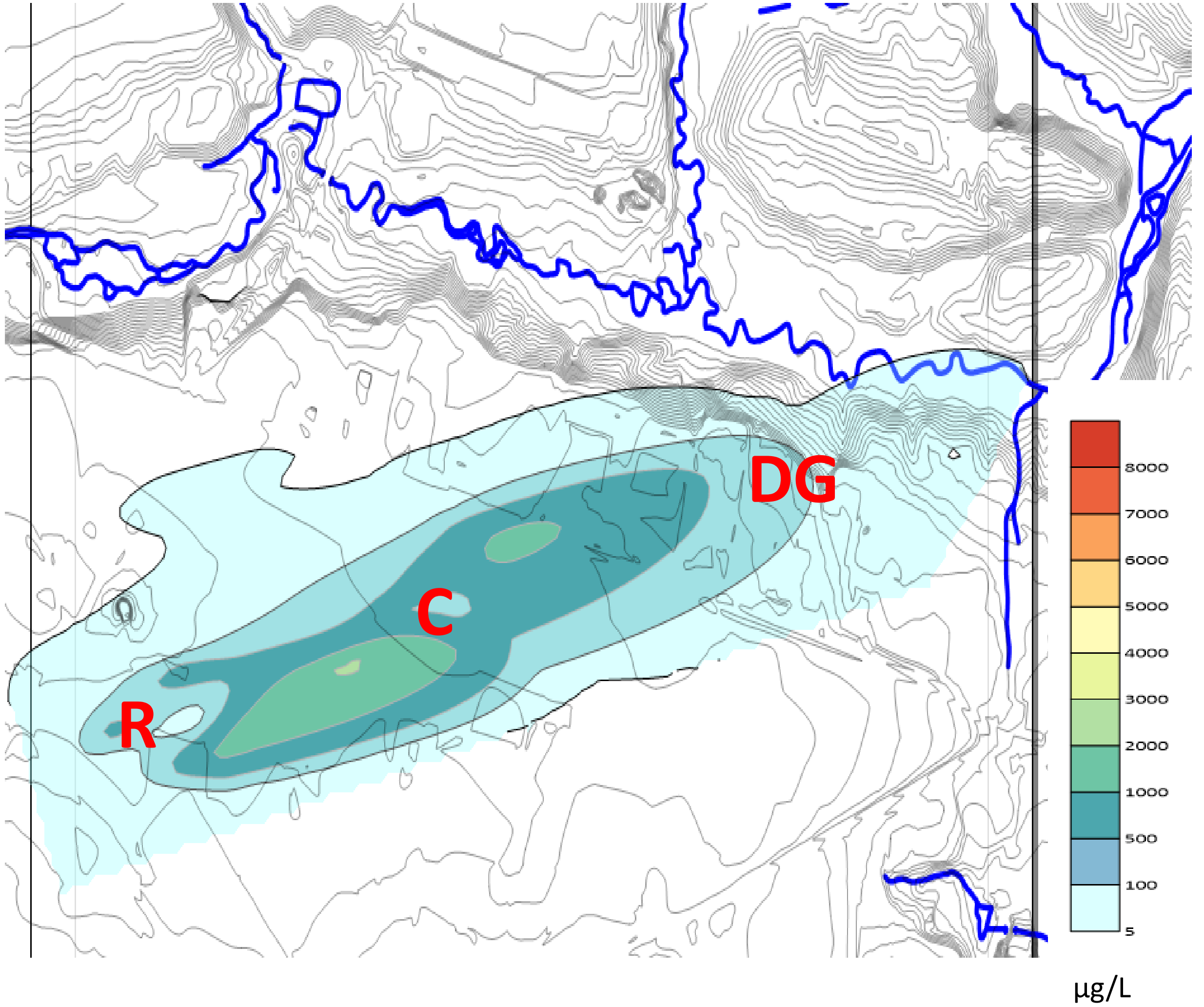
- TCE = 61% Reduction in all Concentrations
  - Max = 4,370 µg/L, now 2,300 µg/L

700-Feet Down Gradient (DG)

- TCE = 52% Reduction in all Concentrations
  - Max = 454 µg/L, now 139 µg/L

TCE remedial goal was mass reduction + MNA.
Downgradient degradation reduces plume to ND

Current TCE



Benefits of HRSC on Remedial Design

- Improve your CSM through better vertical and horizontal delineating defining flow gradients and contaminant zones
- Identified that geologic conditions resulted in natural degradation, prior to discharge
- Remedy focused on a mass reduction, followed by MNA, rather that treating the entire 2,500- to 4,500-foot plumes
  - Resulting in significant cost savings
- In-Situ ISCO and ISCR was very effective when specifically targeting the contamination within unique hydrostratigraphic units
- The incidental characterization costs are more than out weighted by the remedial cost savings

Thank You Question?

How to Remediate a Hexavalent Chromium and Volatile Organic Plume in a Single Application using Injection Flow Through Barriers

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