OVERCOMING FRACTURED BEDROCK INVESTIGATION CHALLENGES

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ENVIRONMENTAL, INC.

Today's Roadmap

- Introduction
- Conceptual Site Model (CSM)
- Characterization and Investigation (RDC)
  - Surface Geophysics
  - Borehole Geophysics
  - Rock Cores
  - GW Characterization & Sampling
  - Additional Tools
- Updated CSM
- Accessing Bedrock & Transition Zone
- RDC → Design Considerations

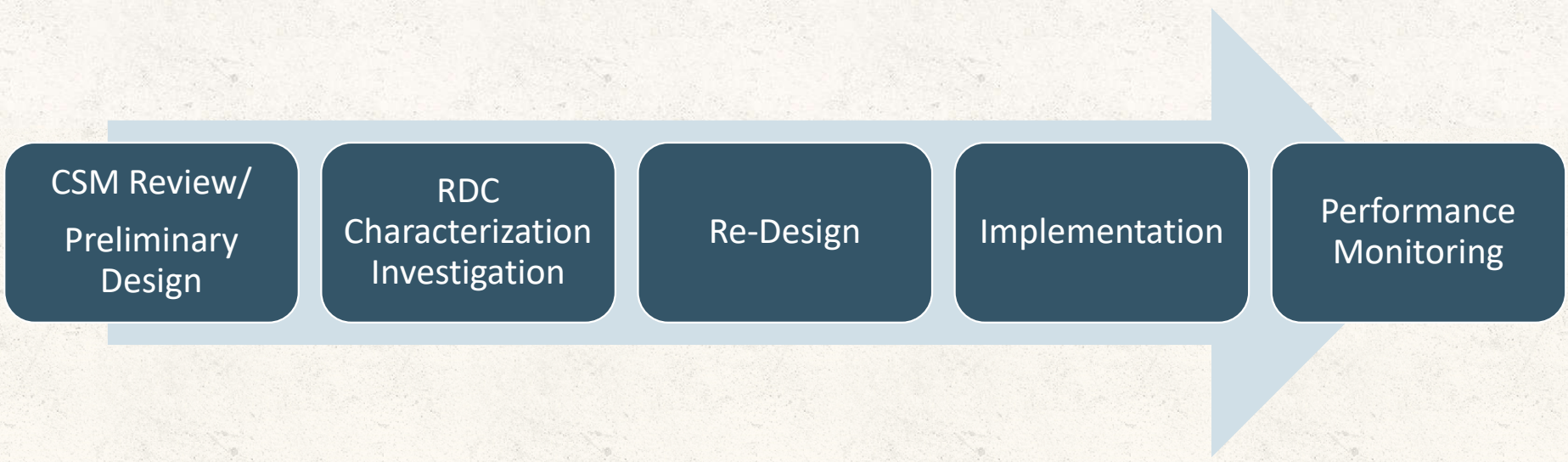
Date	Geology	Project Name	Locations	Contaminant
2011	Limestone	Concord Cleaners	Lexington, KY	CVOCs
2013	Limestone	Burley Oil	Frankfort, KY	Petroleum
2013	Limestone & Shale	Clays Ferry	Richmond, KY	Petroleum
2013	Limestone	Dulin Oil	Columbia, KY	Petroleum
2013	Phyllite	Goforth	Indian Trail, NC	Petroleum
2017	Limestone & Shale	SAPA	Louisville, KY	CVOCs
2017	Limestone	Washburn Market	Washburn, TN	Petroleum
2017	Limestone	Cothron's	Westmoreland, TN	Petroleum
2019	Limestone	Quick Mart #9	Shelbyville, TN	Petroleum
2016	Basalt	Former Mobile 01EQ2	Farmington, CT	Petroleum
2016	Granite	Water Dog	Maricopa County, AZ	Petroleum
2019	Siltstone	Tyco	East Brunswick, NJ	CVOCs
2019	Weathered Schist	Confidential	Bristol, PA	CVOCs
2019	Siltstone	Wooley Fuel	Maplewood, NJ	Petroleum
2019	Siltstone	NJIT	Newark, NJ	CVOCs
2019	Gneiss	Confidential	Greensboro, NC	CVOCs

Date	Geology	Project Name	Locations	Contaminant
2016	Dolomite	Hillbilly Heaven	Bardstown, KY	Petroleum
2017	Weathered Sandstone	Ed's Painting and Storage	Nogales, AZ	Petroleum
2017	Weathered Schist	Confidential	Rock Hill, SC	CVOCs
2018	Weathered Sandstone & Shale	Confidential	Tewksbury, NJ	CVOCs
2019	Weathered Limestone	Shoemaker Sunoco	Shoemakersville, PA	Petroleum
2019	Sandstone & Limestone	Coalmont Service Station	Coalmont, TN	Petroleum
2019	Limestone	Borders Exxon	Westmoreland, TN	Petroleum
2019	Siltstone	Former Simmons	Linden, NJ	CVOCs
2020	Limestone	Gallatin Release	Gallatin, TN	Petroleum
2020	Limestone	Bracey's Grocery	Ashland City, TN	Petroleum
2020	Weathered Shale & Limestone	Confidential	Washington County, PA	Petroleum
2020	Weathered Schist	Confidential	Guilford County, NC	CVOCs
2020	Limestone	P&E Gulf	Pleasantville, KY	Petroleum
2020	Schist	Confidential	Pennsylvania	CVOCs
RED	*NFA*	*12*	*Metamorphic*	*4*
BLUE	*Pilot Complete, Pending Full Scale*	*7*	*Igneous*	*2*
GREEN	*Full Scale Complete, Monitoring*	*9*	*Clastic*	*6*
BLACK	*Work Approved*	*2*	*Carbonate*	*15*

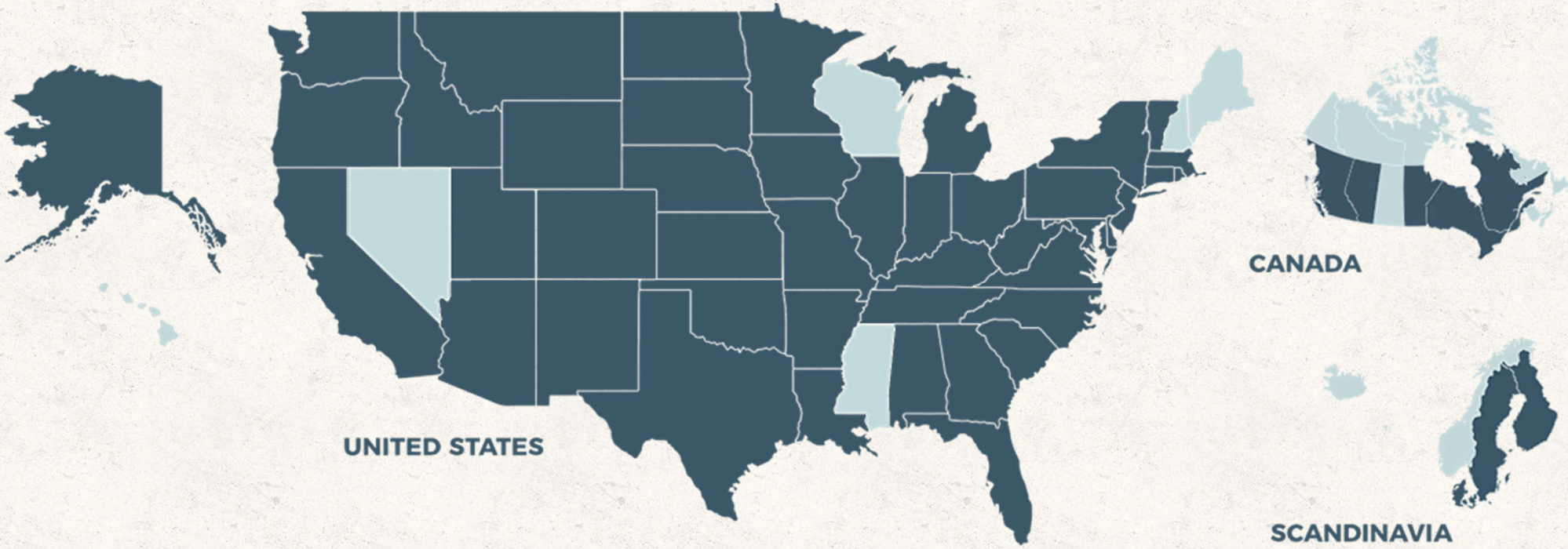
Bedrock RDC

Developing The Roadmap To Success

Trap & Treat® Remediation Process (The Approach)



RDCs and Injections



Dark Blue: Places we've worked
Other locations not shown- UK, France, Italy, South Africa, Australia, and Puerto Rico

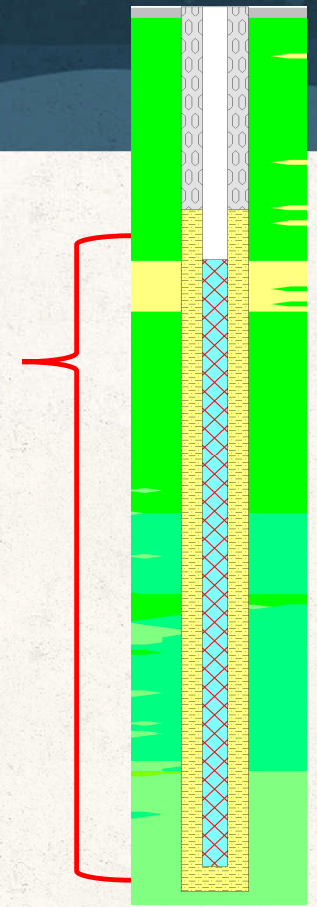
The Process- What's Different

- Bedrock
  - Costs
    - 40-50% investigation
    - 50-60% installation
  - Access
    - BCIPs
    - MWs
- Overburden
  - Costs
    - 10-20% investigation
    - 80-90% installation
  - Access
    - DPT
    - MWs/PZs
- BOS 100
- BOS 200
- CAT 100

Review and Design

Concerns

- Long well screens; cross bedrock interface; multiple zones
- Cased wells with constructed filterpack
- No groundwater characterization data
- Lithology logged from chips expelled during air rotary → need rock cores



Preliminary Designs and Estimates Based Upon:

- No differentiation of high/low concentration intervals
- Estimated porosities and hydraulic gradients
- Homogeneous stratigraphy
- Groundwater mass only

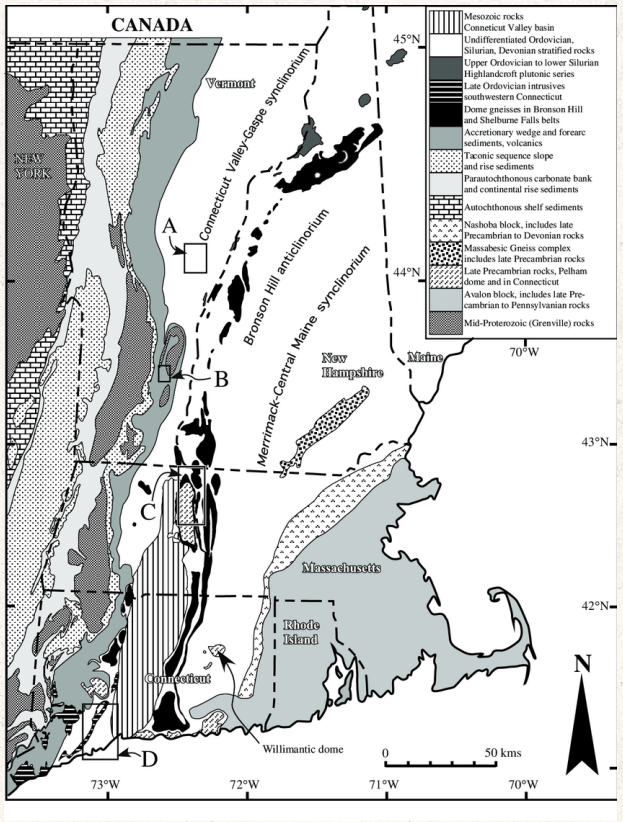
Remedial Design Characterization (RDC)

Surface Geophysics
- 2D Electrical Resistivity
- Seismic

Characterization → Injection Wells
- Open Borehole with surface casing
- Rock Cores – logging and sampling of matrix

Borehole Geophysics
- Caliper, Acoustic Televiewer, Downhole Camera, etc.

Groundwater Characterization
- Pumping Tests
- Discrete Interval Analytical Sampling
- Response Data - Transducers

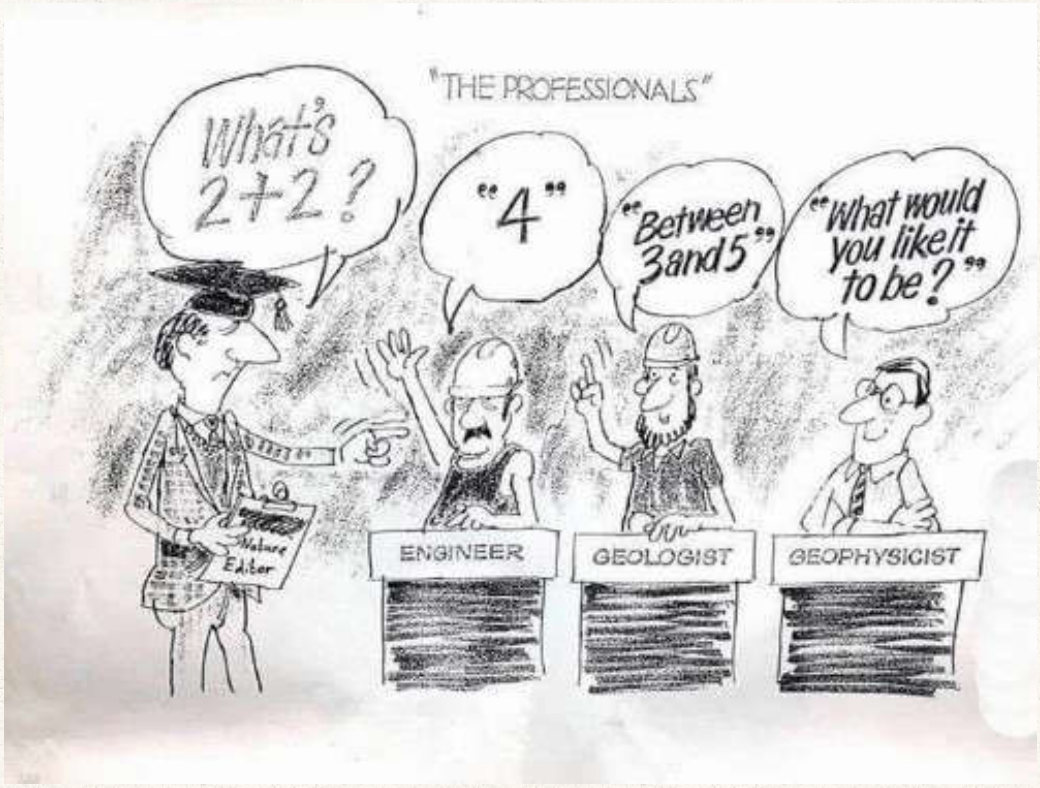


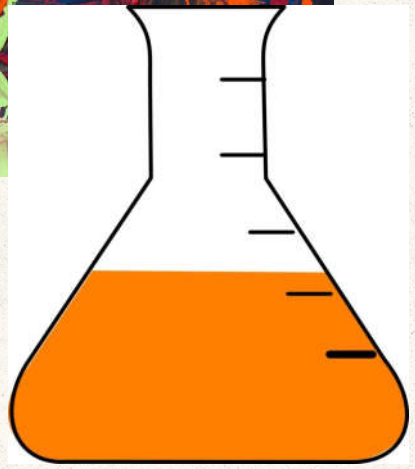
Bell and Newman, 2006.

Geophysics

Tools and Interpretation

Surface Geophysics





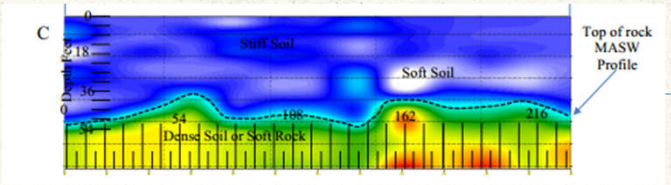
RDC – Surface Geophysics

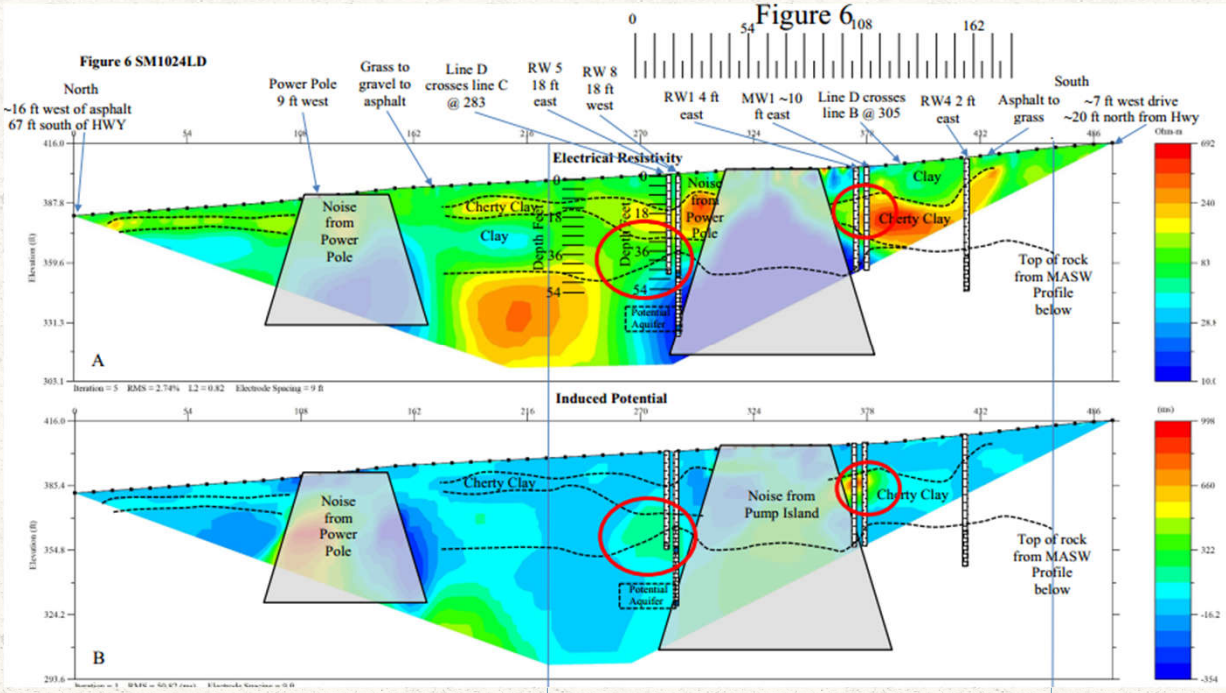
Surface Geophysics

- 2D Electrical Resistivity (2D-ERI) and Induced Potential (IP)
- Multichannel Analysis of Surface Waves (MASW) or seismic-energy analysis

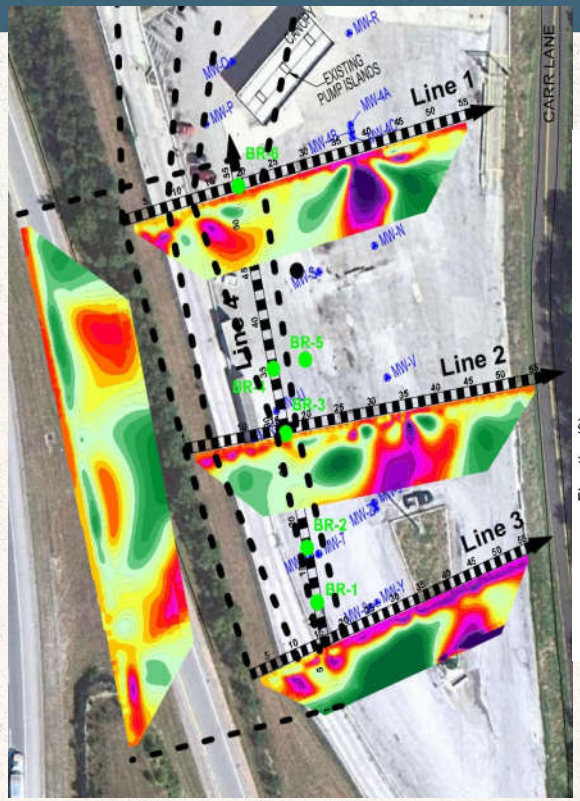
Soft Soil	Stiff Soil	Very Dense Soil and Soft Rock	Rock
V_s<600 ft/s	600 < Vs< 1200 ft/s	1200 < Vs < 2500 ft/s	2500 < Vs< 5000 ft/s
Standard penetration resistance, N	**Standard penetration resistance, N**	Standard penetration resistance, N	Standard penetration resistance, N
N < 15	**15 ≤ N ≤ 50**	N > 50	N/A
Undrained shear strength (psf)	**Undrained shear strength S_u (psf)**	Undrained shear strength (psf)	Undrained shear strength (psf)
<1,000	**1,000≤S_u≤2,000**	S_U > 2,000	N/A

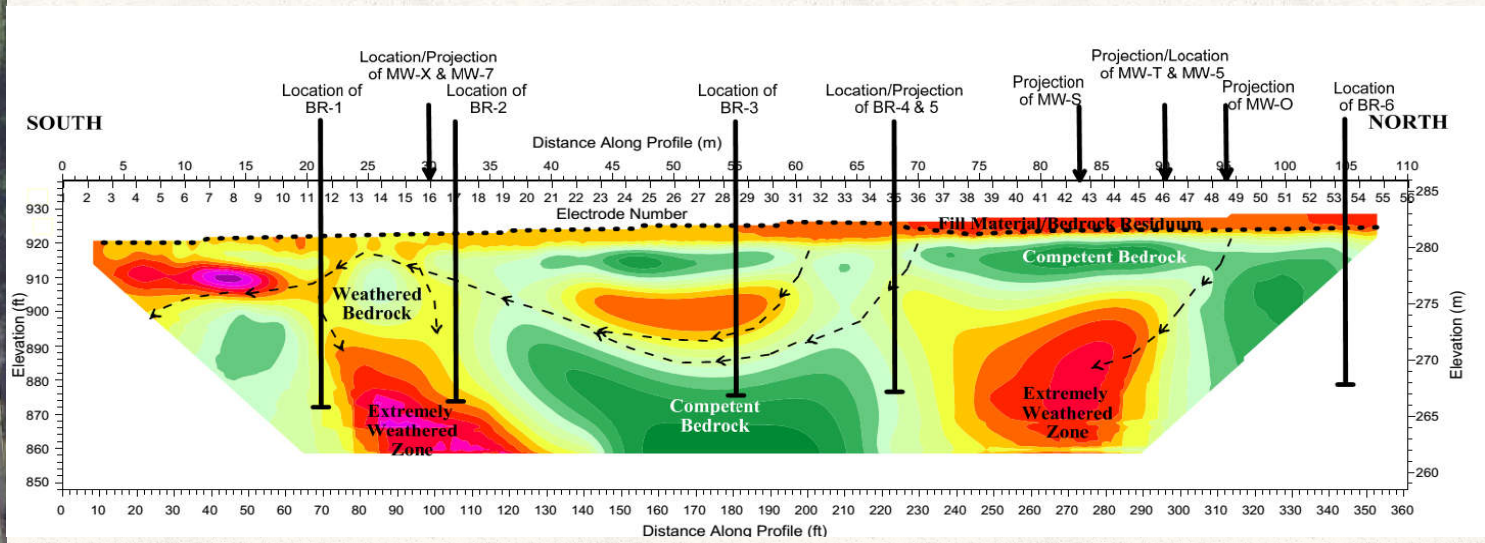
Table 2: Scale used in velocity profile with site classification, standard penetration values (N) and undrained shear strength. Values from IBC 2006 Table 1613.5.2 Site Class Definitions (section 1613.5.50).





RDC - 2-D Electrical Resistivity






Calloway Creek Limestone
Garrard Siltstone

Bedrock Characterization and Injection Points (BC/IPs)

Drill and Evaluate

Drilling Considerations

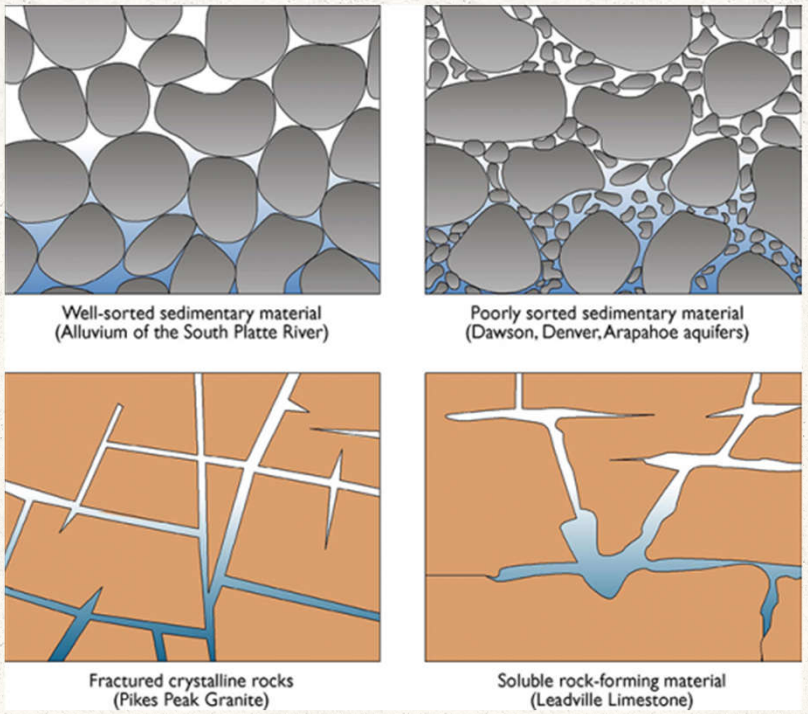
- Geophysics results?
- Open bedrock borehole
- Method Preference?
  - Geology
  - Air Rotary
  - Sonic
- Nominal bit size! (6”)
  - “Goldilocks”
  - Lifecycle
  - Wear

Wikipedia Commons. Hannes Grobe, AWI.

Boart Longyear

What is a fracture? What is a feature?

- When associated to caliper logs…
  - Bedding plane separation
  - Joint/Fault
  - Lithologic contact
  - Hydraulic Zones
    - Producing
    - Receiving
  - Erosional Plane
  - Enlargement
  - Drilling-induced feature?



Colorado Geological Survey [CGS], 2002.

Movement of Contaminants

- Advection
  - Gravity or hydraulic pressure transfer
  - Dominant in large apertures
- Capillary Flow
  - Flow without gravity assistance (often in opposition)
  - NAPL
- Diffusion
  - Concentrations move high to low
  - Short distances (in. to ft.)
- Dispersion
  - “Spreading”, laterally and vertical
  - Mixing and diffusion
  - Not always aligned with GW

RDC - Rock Cores and Open Boreholes

Rock Cores

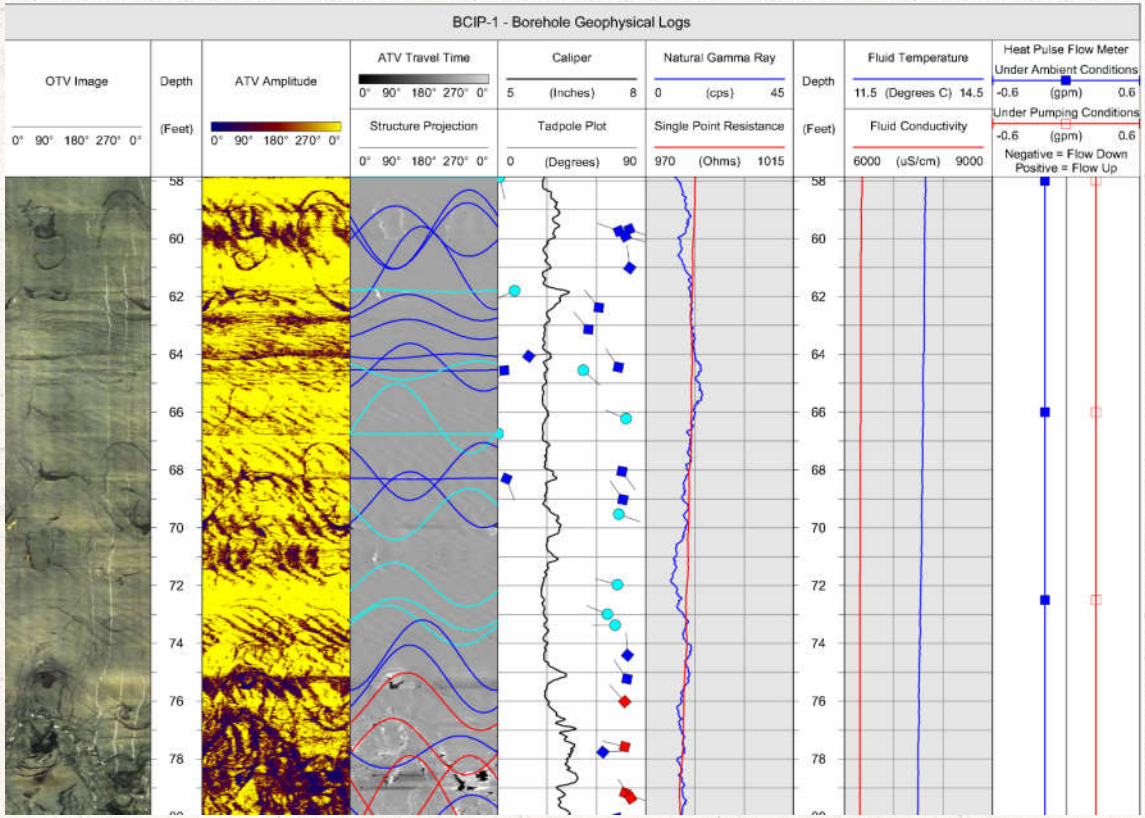
- Similar to dual tube prior to HSA
- Structure, texture, and variation in lithology visible in log perspective
- Look, touch, hold, or sample what you see in 2D wireline logs or downhole camera
- Matrix samples, collection
- Forensics?

Surface Cased Open Borehole Wells

- Characterization → Injection Wells
- Multi-purpose access: not just diluted dissolved chemistry monitoring

Rock Matrix Sampling

RDC - Borehole Geophysical Logs



Standard Details

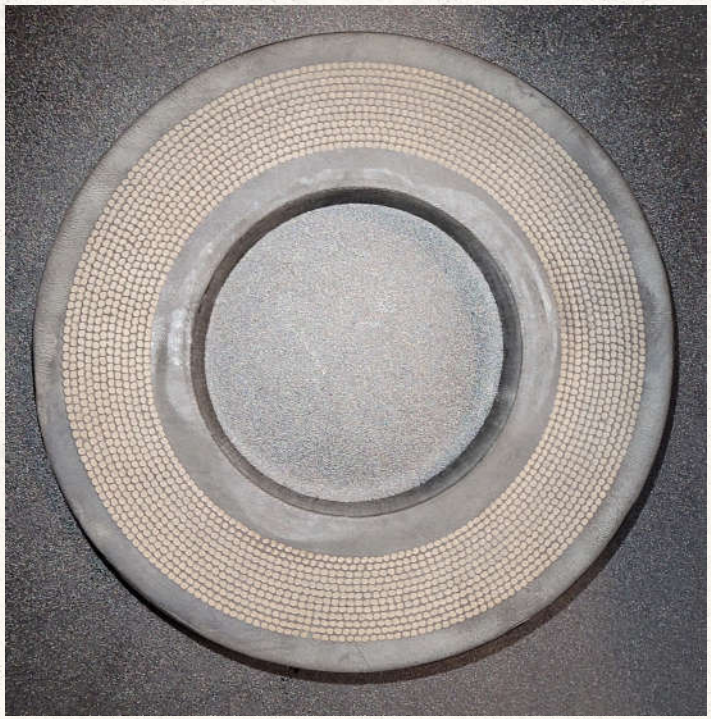
- 3 arm caliper*
- Natural Gamma
- Resistivity
- Fluid Temperature + Conductivity

Additional Details

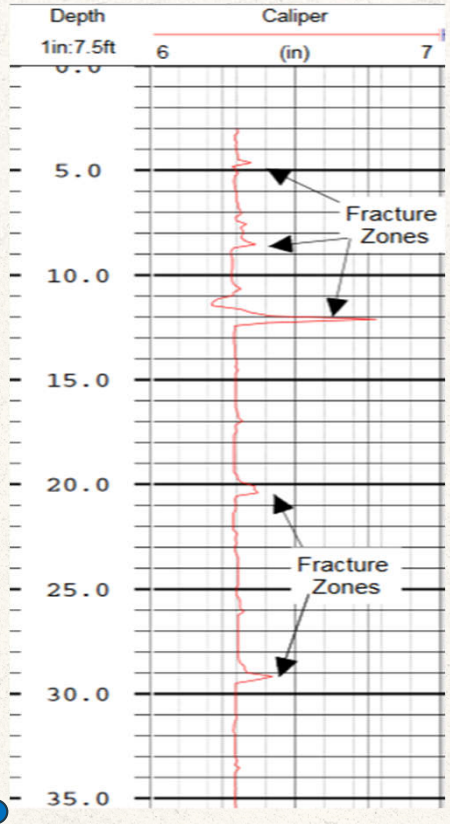
- OTV and ATV*
- Heat Pulse Flow Meter

What is a Straddle Packer?

- Expandable bladder/plug
- Uniform, even inflation (AST/Baski)
- Open-air high-pressure inflation w/o rupture
- Isolates borehole sections
- Rated for high pressures (ensure seal)
- Sliding element section with O-ring seal
- Long sealing section



RDC – GW Characterization



Aquifer Testing

- Pumping Tests
- Discrete Interval Analytical Sampling
- Response Data – Transducers
- Many fractures are clustered at intervals
- Conventional packer strings make it very difficult to isolate individual features
- Custom Straddle Packer String
  - Pressure transducers
  - Integrated pump
  - Discrete sampling or injection

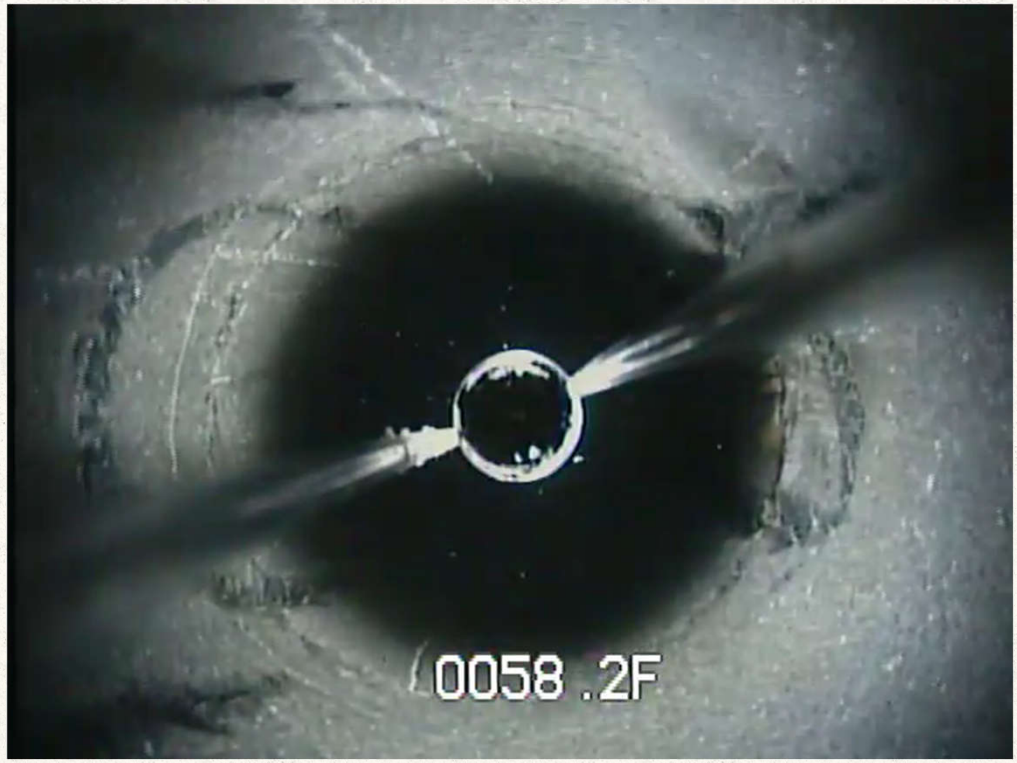
Packer Inflation

Packer Perspective

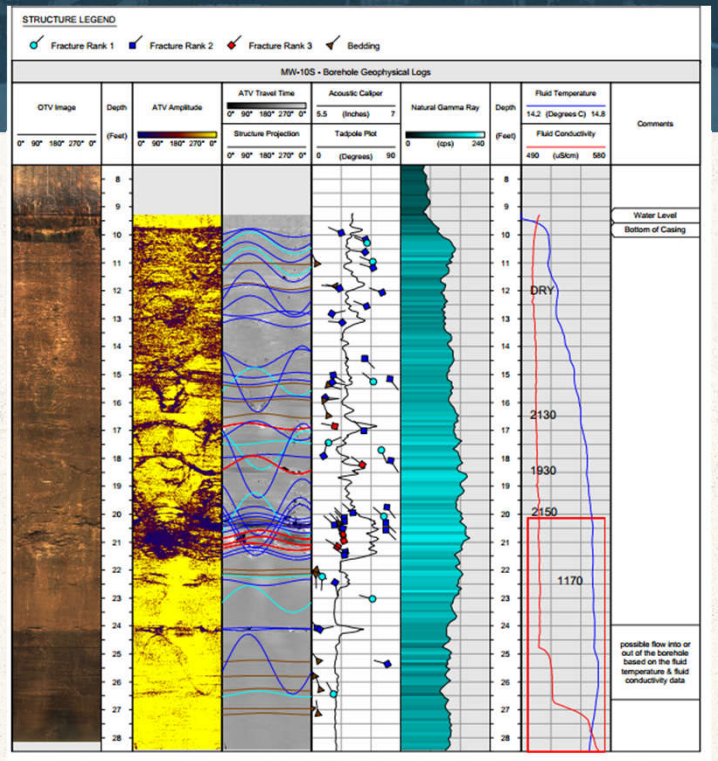
Borehole Camera

Borehole Camera

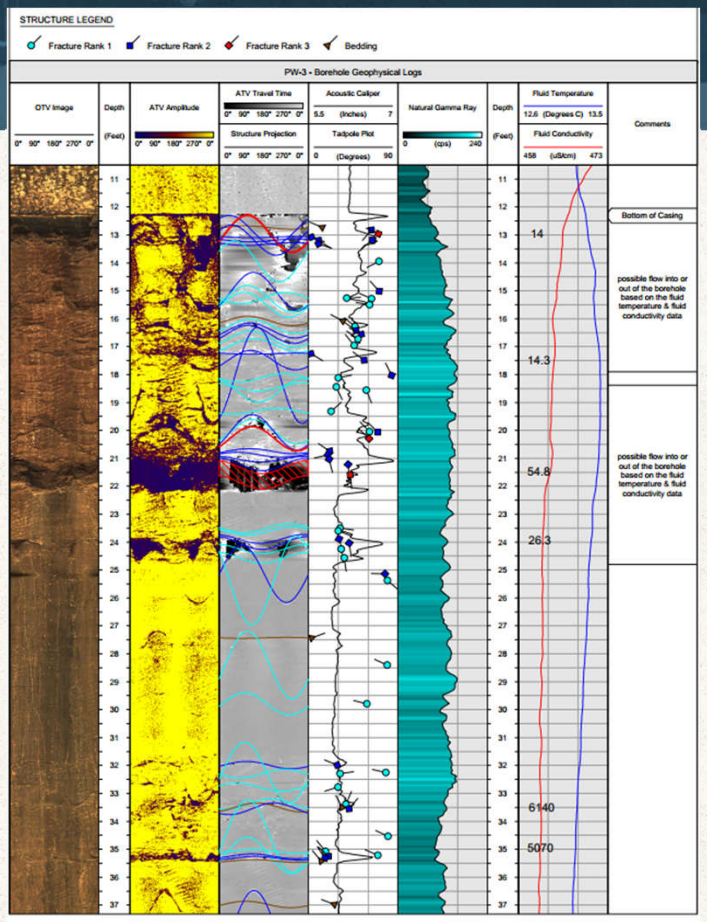
RDC - Downhole Camera



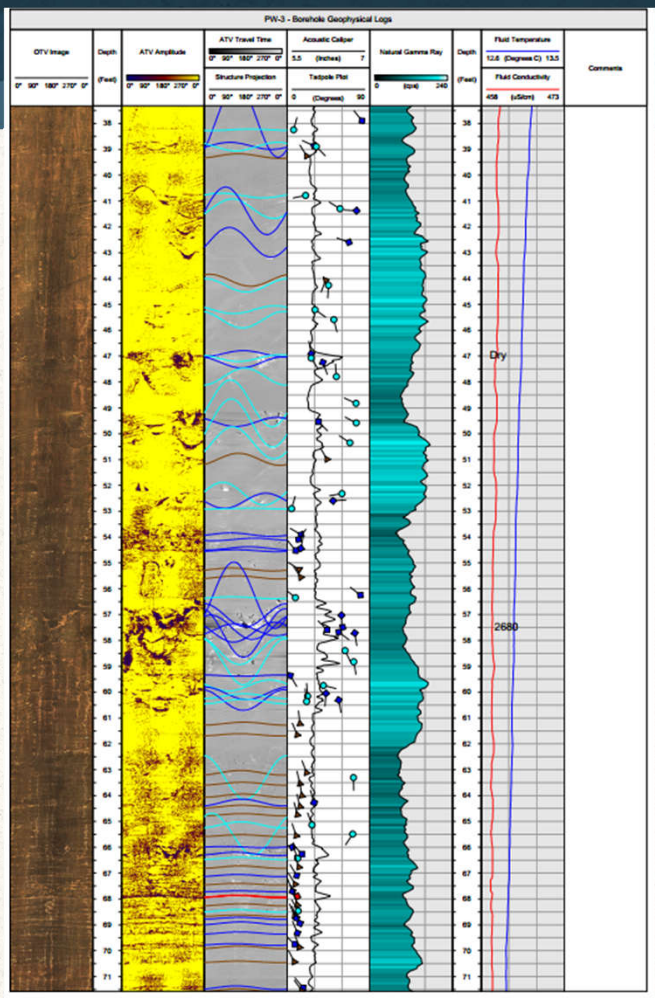
RDC – Aquifer Discrete Sampling



MW-10S



PW-3



RDC – Aquifer Discrete Sampling

RW-4D Sample Intervals		
Sample Depth	Benzene (ug/L)	Volume Pumped (g)
41.2	184	5
42.5	300	10 (LNAPL)
43.5	355	10 (LNAPL)
45	371	5
47	443	5
49	619	10
52.5	425	10
53-open	259	10

High-Resolution Groundwater Tools

- FLUTe Liners
  - Blank
  - NAPL
  - FACT
- Solinst CMT
- Waterloo
  - Multilevel System (MLS)
  - Continuous Multichannel Tube (CMT)
- Westbay System

- Advantages
  - Depth-Discreet Data (resolution!)
    - Water Level
    - Water Quality
  - $$$$$
    - Fewer boreholes
    - Less IDW
    - Lower sampling costs
- Disadvantages
  - O&M, specialized tools
  - Lifespan
  - Observation wells

Updating Design

- Access to RPI Laboratory
  - Rock core samples
  - Discrete groundwater samples
- Geophysics
- Camera
- Pumping tests and transducer data
  - Hydraulic conductivity
  - Interconnectivity: horizontal and vertical
- Target secondary porosity features
  - Bedding plane
  - Fracture/joint/fault
  - Solution channel
  - Lithology contact, etc.

GeoTAP™

Access the Bedrock Transition Zone

Application Techniques

- Direct Push (top-down)
  - Clay/silt/sand/gravel
- GeoTAP™ Method (top-down)
  - Sonic or auger → DPT
- Bedrock (bottom-up)
  - Straddle packer isolates fractures
- Soil mixing (trench or areal)

Remediation & GeoTAP™

- In-situ remediation success requires proper reagent:
  - Longevity
  - Dosing
  - **Contact**
- DPT or Packers are not always options
- Injection wells are not always the best option depending on where the mass resides and lithology

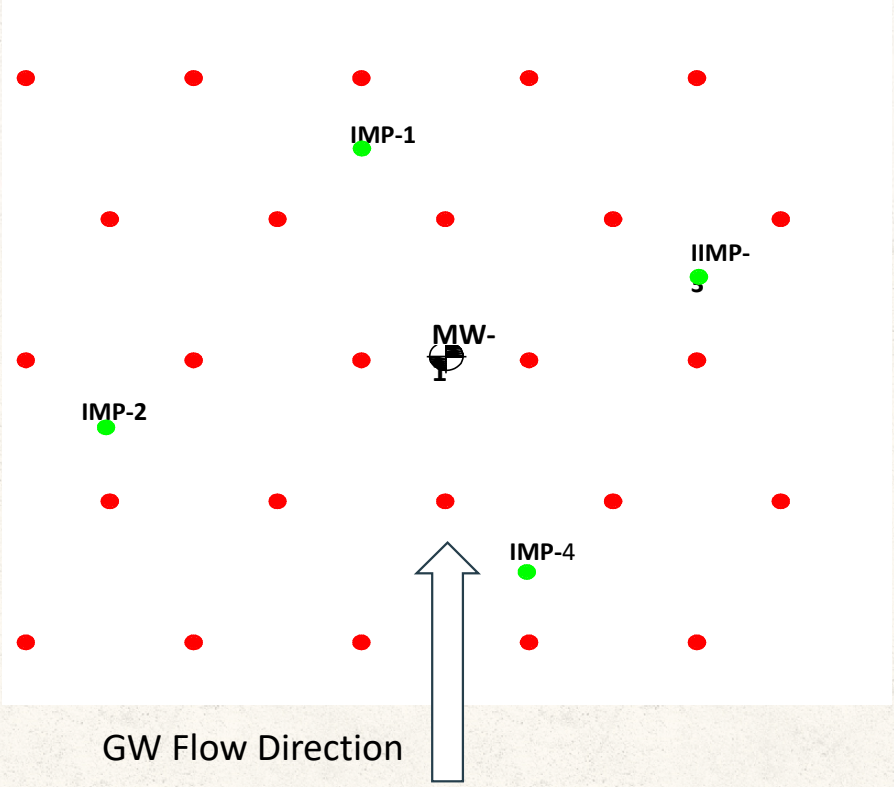
- Prevalent in Northeast
- Combined with bedrock remediation
- Drill it like bedrock; inject it like overburden
- Geological Targeted Access Point

GeoTAP™ Technique

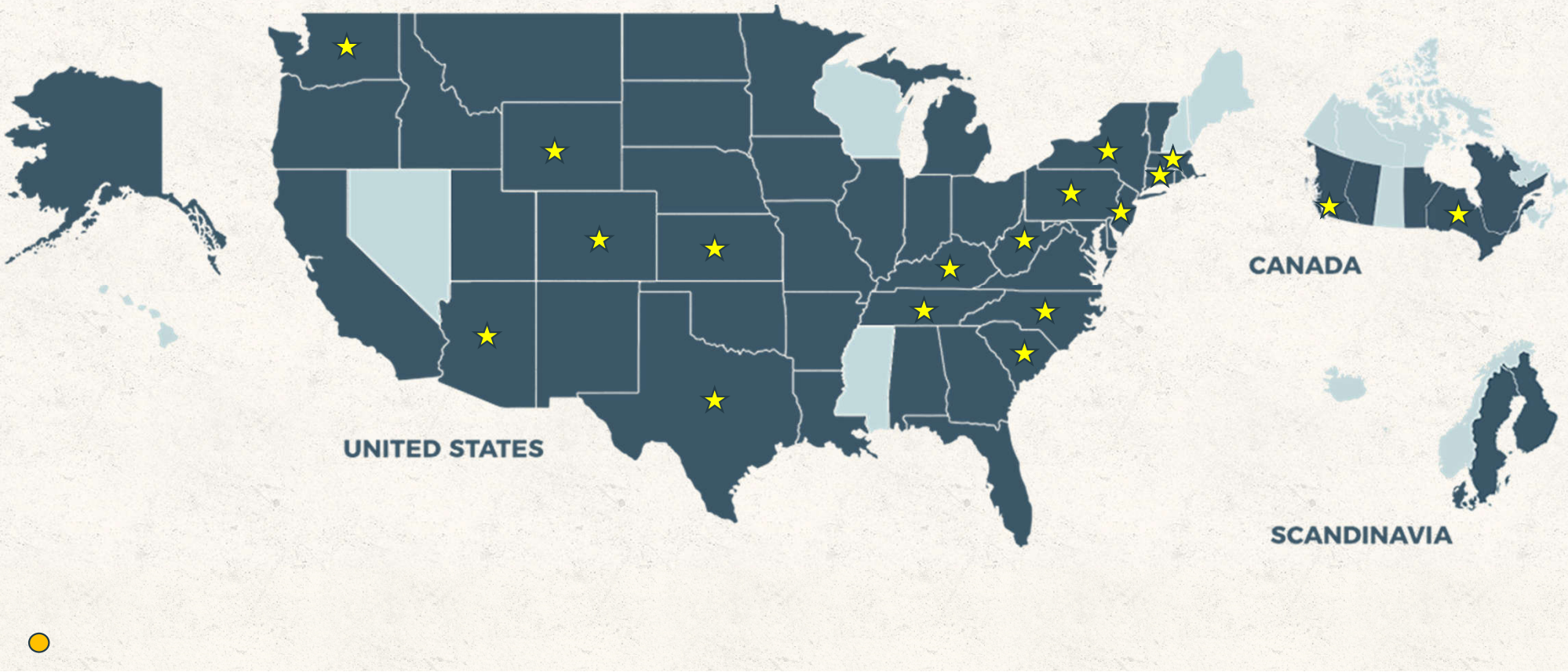
- Sites where DPT (alone) cannot be used due to refusal
  - e.g. gravel/cobble zones, glacial till, weathered bedrock, historic fill, etc.
- Pre-drill each location
  - Augers (HSA, SSA)
  - Sonic to the target/total depth
  - Log lithology!
- Backfill borehole with engineered bentonite; hydrate; build in lifts
- Probe through bentonite using DPT
- High energy injection cuts though bentonite
- Emplace reactant/reagent within native lithology
  - Radial mixing
  - Fracturing
- 50+ sites in various geologies/regions completed to date

GeoTAP™ Design

- Triangular grid pattern
- Spacing is a function of:
  - Depth
  - Lithology
  - Shot volume
- Does not supplant injection spacing requirements



GeoTAP™ Applications



RDC Case Study

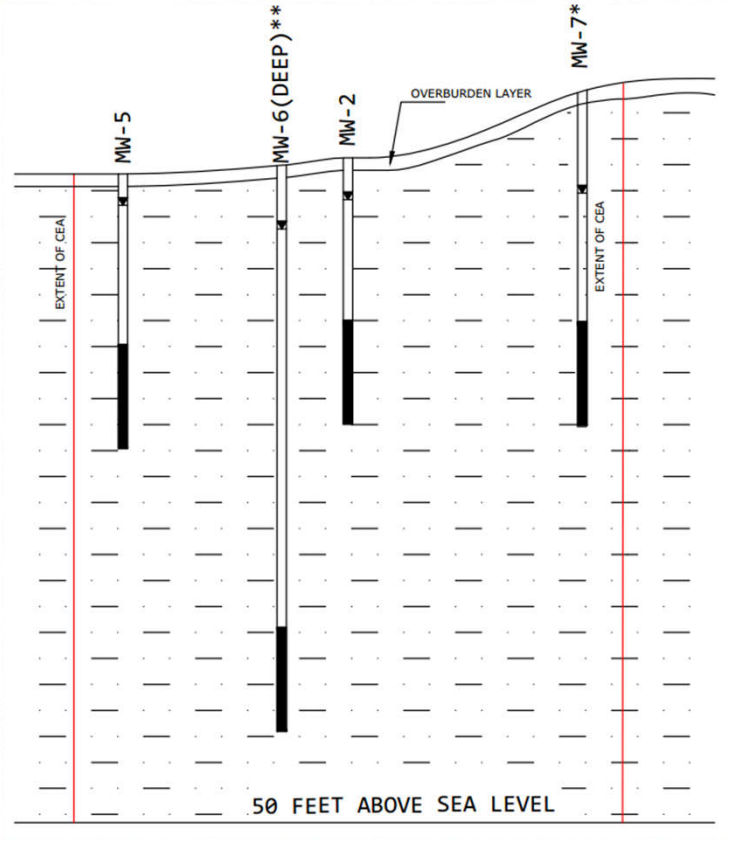
Proof of Success

NJ CVOC Site

- Confidential Client
- Site Use – Corporate Complex
- Geologic Setting – Passaic Formation
- Bedrock – Reddish-brown argillaceous shale, localized sandstone/siltstone interbedding
- Overburden – Clayey gravels, gravel-sand-clay mixtures
- PWR transition zone

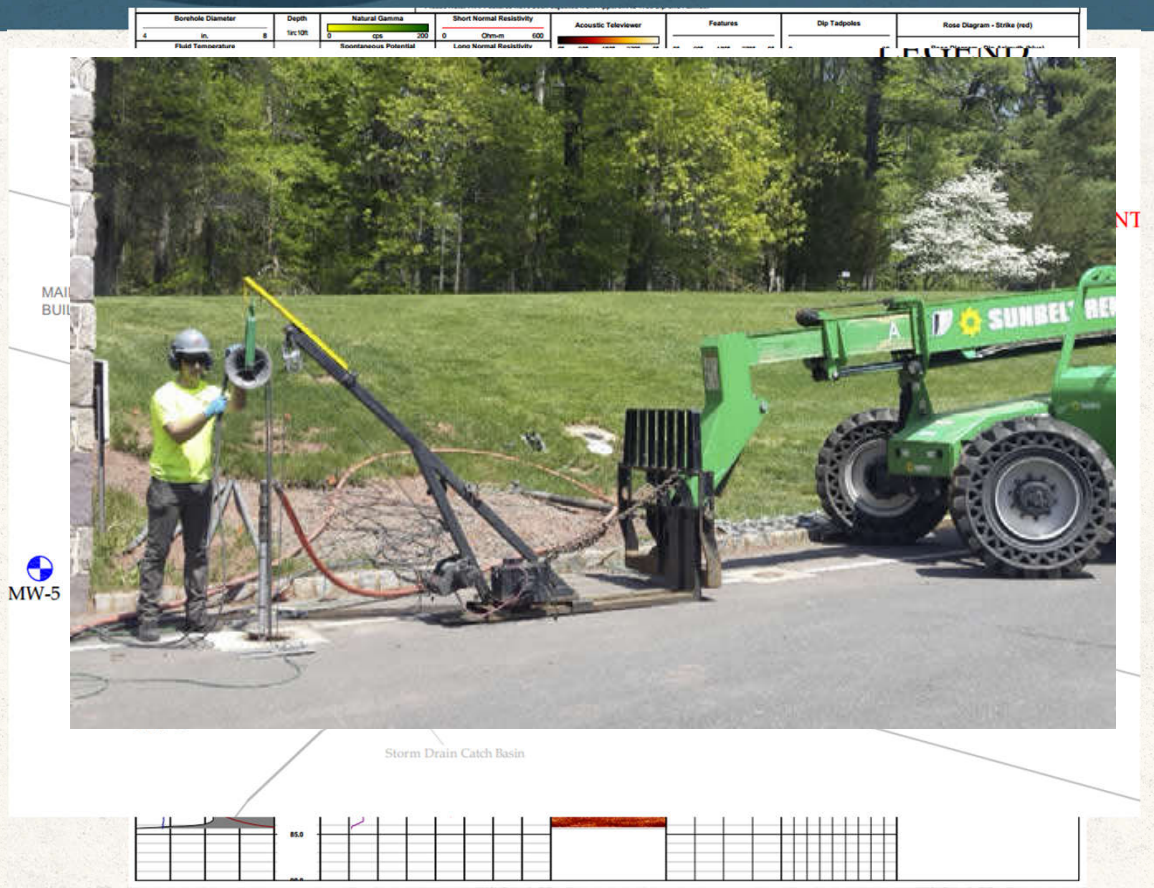
Conceptual Site Model

- TCE > NJ GWQS (1 µg/L)
- Overburden impacts non-existent
  - Soil/bedrock interface ~3’ bgs
  - No perched groundwater
- PWR Transition Zone Undefined
- 86.9 µg/L to 98.9 µg/L TCE in the groundwater



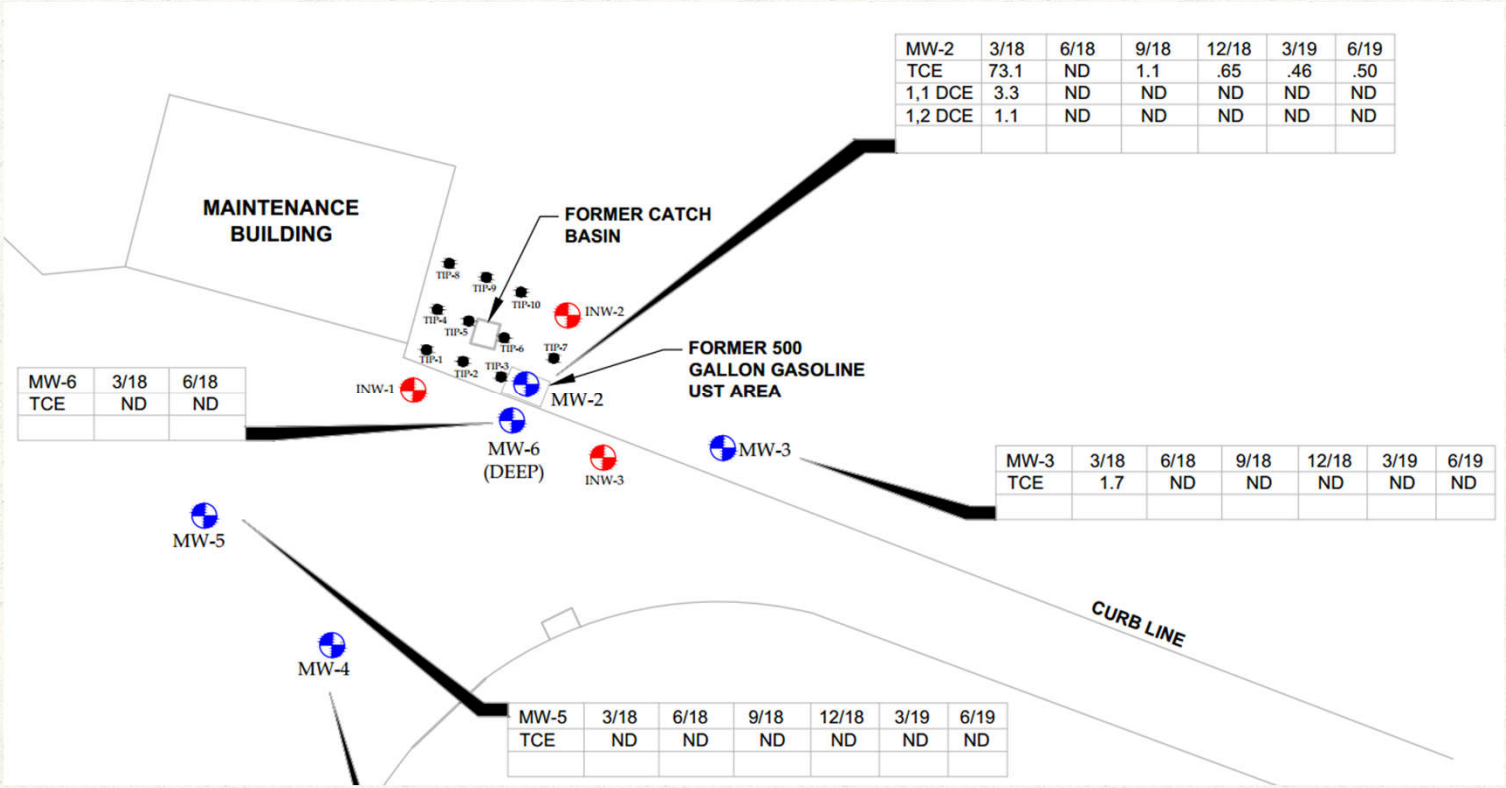
Bedrock RDC, Findings, and Remedial Approach

- Three (3) Open Borehole Wells (INW-01, INW-02, INW-03) installed to ~85 feet bgs
- Ten (10) GeoTAP Points (TIP-1 thru TIP-10) installed to ~25 feet bgs
- Downhole Geophysics: ATV, Caliper, Natural Gamma, Fluid T&C, SP, Resistivity
- Aquifer Characterization: straddle packer pump test and discrete interval sampling, transducer data logging
- CVOC impacts in borehole fractures 10% of mass detected in source well
- Sorbed mass in PWR persistent source for dissolved impacts



Remediation Selection and Results

- May 2018 - BOS 100®
  - GAC impregnated with Fe
  - 935 lbs. (consolidated unit)
  - 665 lbs. (PWR)
- June 2018
  - 1-month post-injection
  - Immediate results
- NFA - December 2020



MW-2	3/18	6/18	9/18	12/18	3/19	6/19
TCE	73.1	ND	1.1	.65	.46	.50
1,1 DCE	3.3	ND	ND	ND	ND	ND
1,2 DCE	1.1	ND	ND	ND	ND	ND

MW-6	3/18	6/18
TCE	ND	ND

MW-3	3/18	6/18	9/18	12/18	3/19	6/19
TCE	1.7	ND	ND	ND	ND	ND

MW-5	3/18	6/18	9/18	12/18	3/19	6/19
TCE	ND	ND	ND	ND	ND	ND

Design Considerations

Plan for Success

Goals

- Determine contaminant distribution
- Select injection well network
- Estimate ROI
- Determine injectate loadings
- Monitoring Measures
  - Establish real time (injection phase)
  - Post-injection
- Injection
  - Distribution
  - Longevity

Design Complications

- Surface access
- Geophysical Interference
- Fracture loadings
- Anthropogenic influences
- Borehole Integrity, e.g. epikarst, shale
- Budget?
- Set/Manage Expectations

Reagents

SLURRIES (~5 to 300 um)

- BOS 100
- CAT 100
- BOS 200
- FlouroSorb (XX mesh)
- Organoclay (XX mesh)
- ZVI
- CaSO4
- Oxides
- Iron Sulfides
- EVO
- AC

AQUEOUS/COLLOIDAL

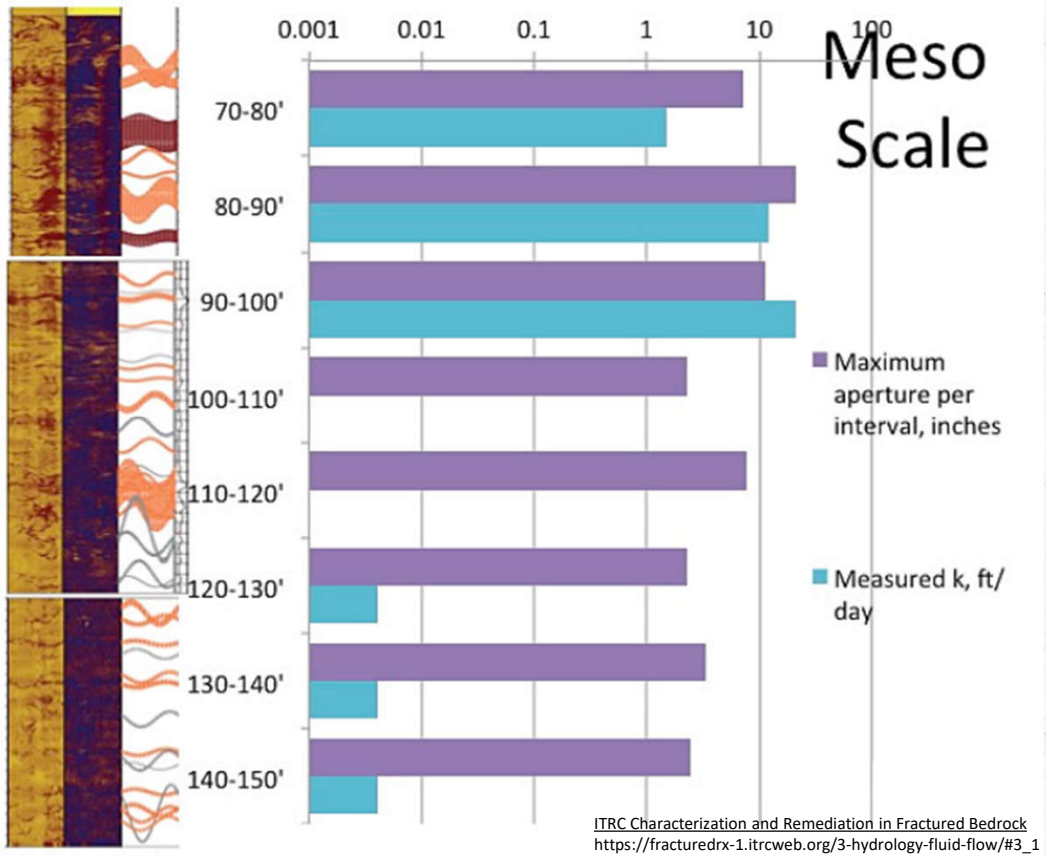
- MgSO4
- CaCO3
- Persulfates
- Peroxides
- Colloidal Carbon

- Drawbacks
  - Wash-out
  - Low rock matrix interaction
  - Composition
    - Dilute
    - Solids

Liquid v. Slurry Injections

- Liquid Injections
  - e.g. ISCO, EVO
  - Low pressure/low flow rate
  - Use
    - DPT cannot
    - IWs variable
    - 'Long' screens?
  - Difficult to target low K zones
  - Preferential pathways
- Slurry Injections
  - e.g. Trap & Treat®, ZVI
  - Requirements
    - Higher flow rate
    - Higher pressures
  - Injection wells cannot be used
  - Retractable screens cannot be used
  - Volumes
    - 10 gal to 400 gal

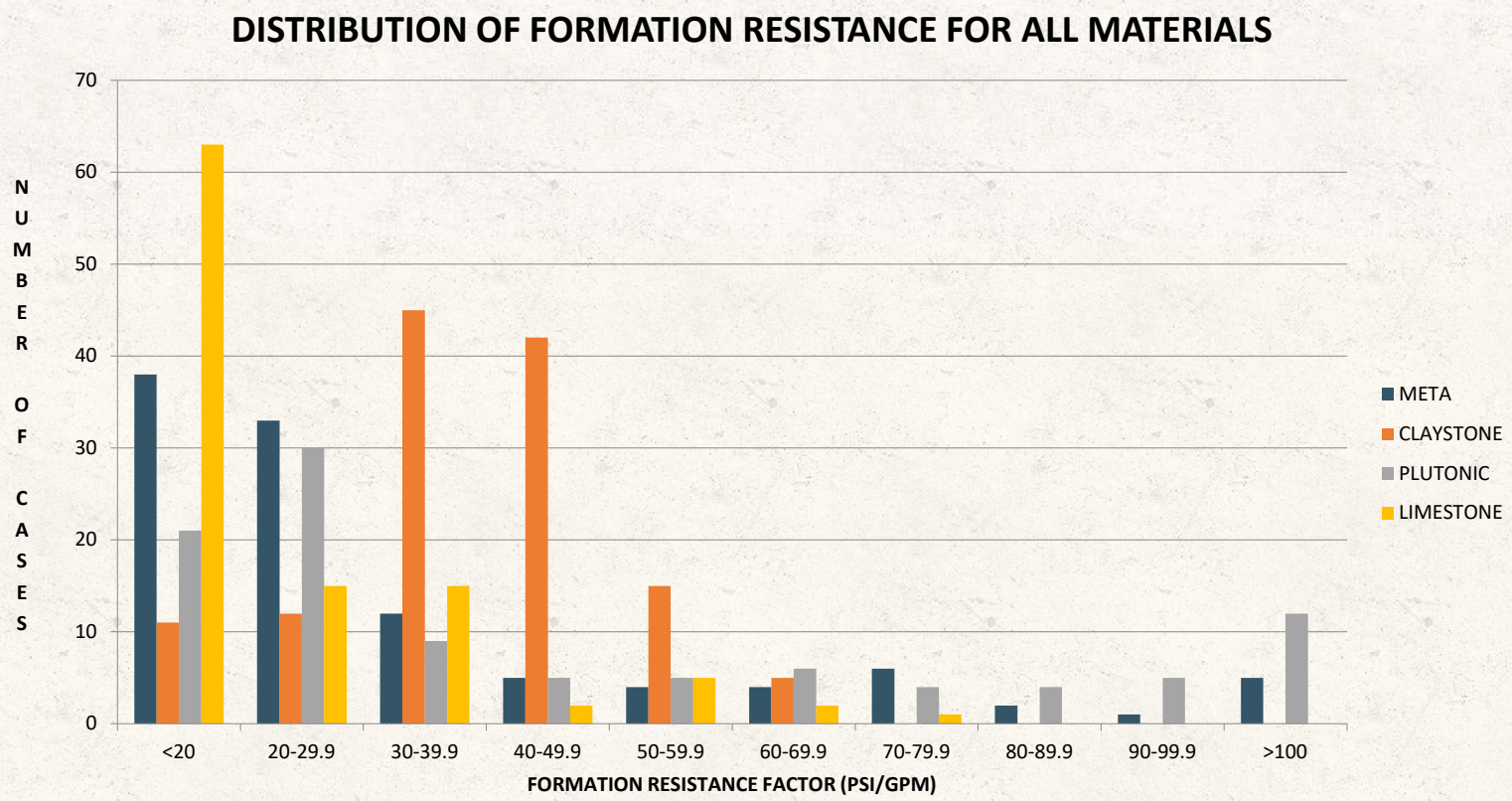
Identified Fracture ≠ Equal Flow



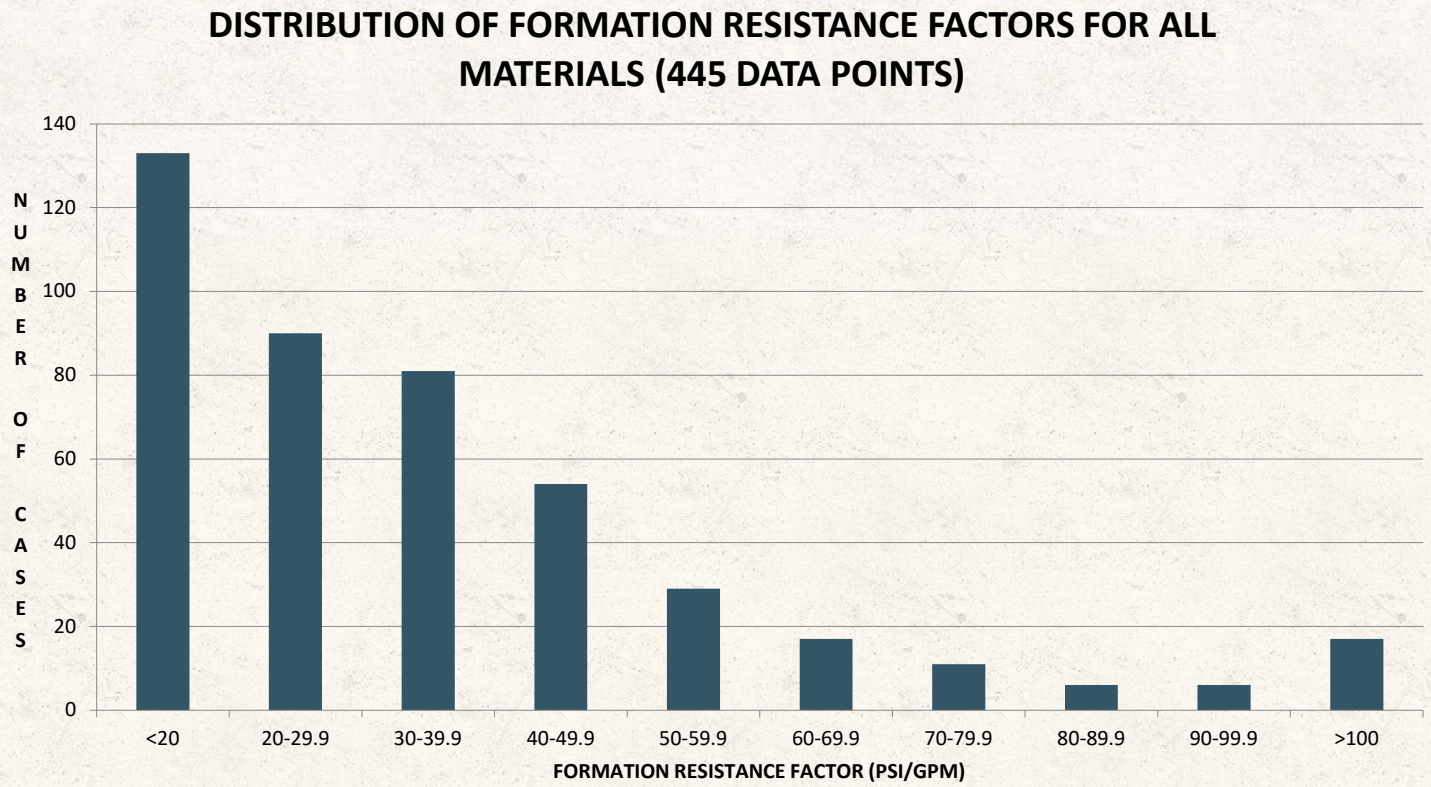
ITRC Characterization and Remediation in Fractured Bedrock
https://fracturedrx-1.itrcweb.org/3-hydrology-fluid-flow/#3_1

- Typical Slurry Volumes
  - OB (10 to 50 gal)
  - TZ (25 to 300 gal)
  - BR (100 to 400 gal)

All Materials



All Materials, One Population



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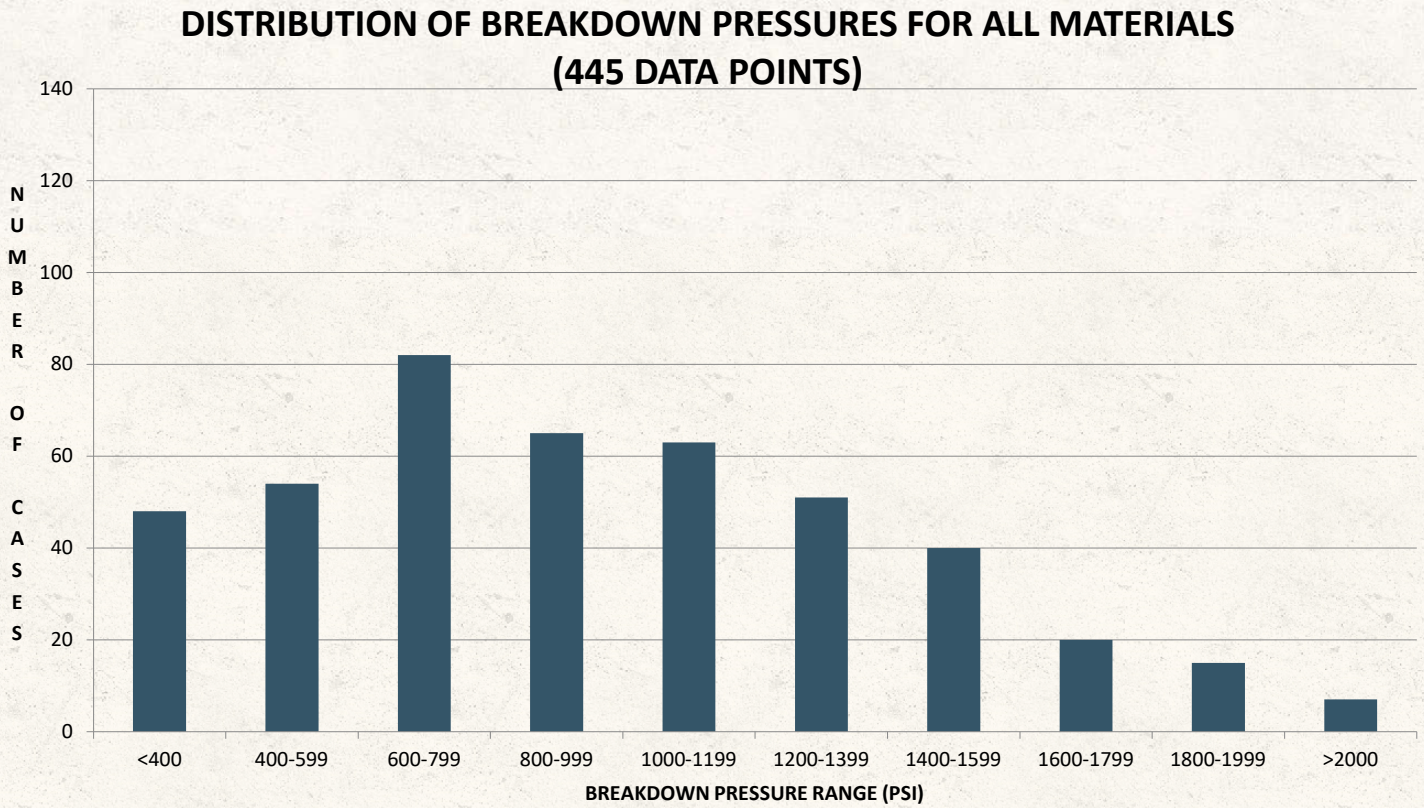


Injection - The Custom Triplex

Injection - Triplex (Varied Flow Rates)

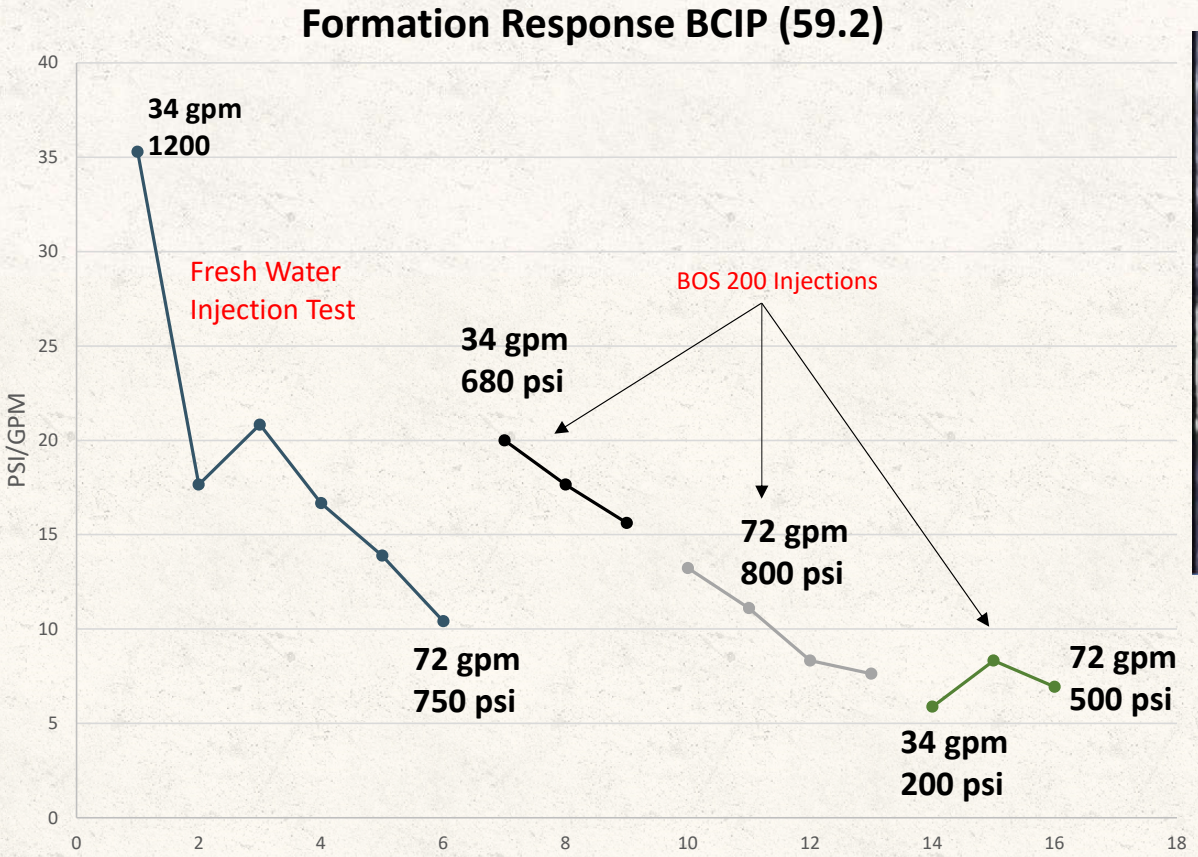
Various Flow Rates

20 gpm, 60 gpm
120 gpm, 250 gpm

Injection - Packer Demo

Need a high flow rate
&
Needs to be Gentle

Injection - Formation Response



Typical volume of BOS 200 slurry installed during each injection at this site was 150 to 200 gallons.

Thank You

Q&A

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