In situ activated carbon-based technology for groundwater remediation: Best practices

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Success Reported for Carbon in KY

- High pressure injection required to cope with low permeability geology.
  - Our lessons are from Kentucky and typically from clay soils!
- Emphasizes the importance of building high resolution CSM for remedial design and implementation to be effective.
- Identify and focus on addressing core COC mass.
- Over 100 sites addressed using carbon

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Best Practice #1.
Identify Goals and Objectives

"What are goals and objectives?"

- **Goals** are general guidelines such as "protect public health, safety and the environment."

- **Objectives** are specific, measurable, and have a defined completion date.
  - What's the clean-up number, concentration, etc. in what media?
  - When do we need to meet the "clean-up" etc.?
  - Where do we need to meet which values? Onsite, Offsite?
  - Don't keep moving the goal posts - know "good enough when you see it"!

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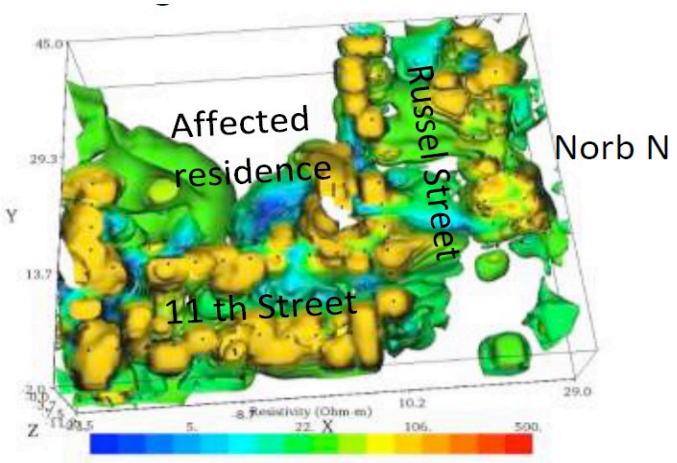
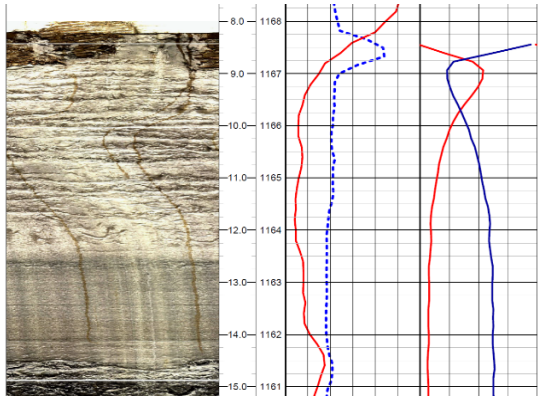
Best Practice #2
Location of the COC Mass

- The carbon and the contaminates of concern (COCs) must come into contact!
- As carbon adsorbs by contact and does not readily disperse (granular not powered carbon), it is important to inject the carbon where it will contact the highest concentrations of contaminant.
- In most geologies, the “soil” or solid media contains the majority of the COC mass.
- Characterization of the “extent” of the contamination on a monitoring well basis may not be helpful.





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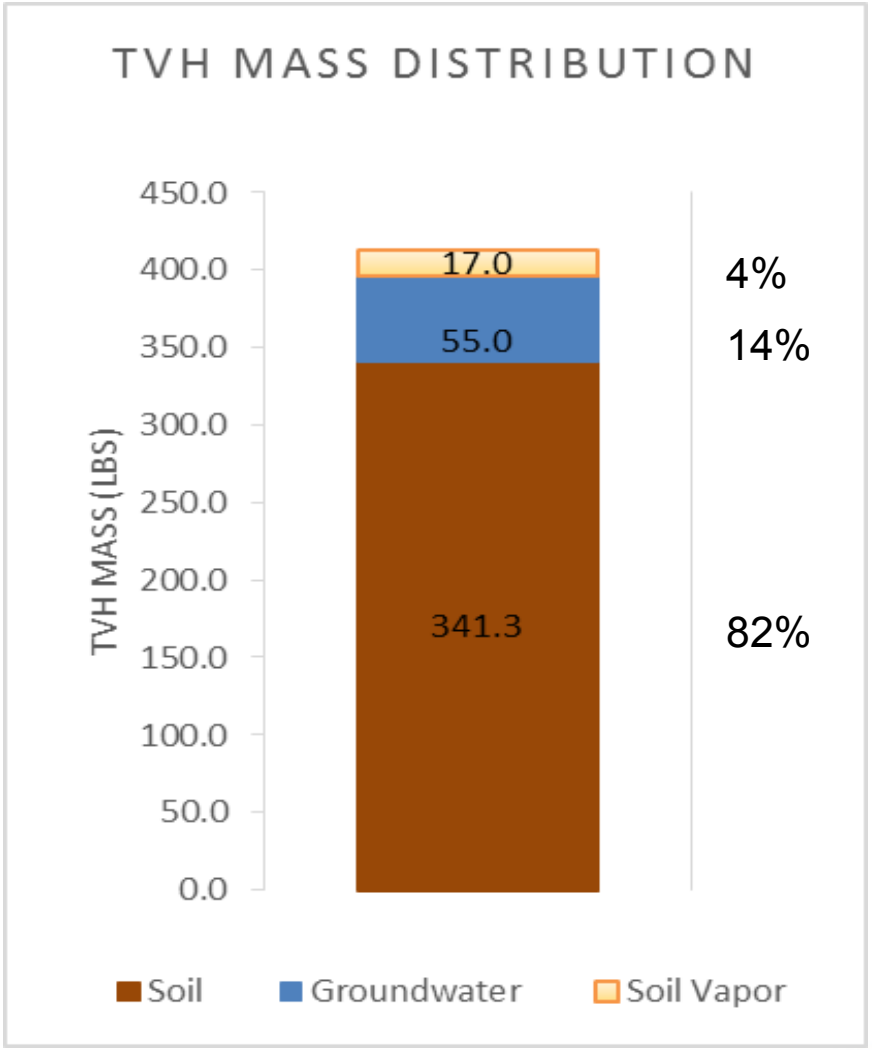
Importance of Mass in Soil

Free product aside, soil holds the majority of the contaminant mass.

An adequate number of soil samples is critical (even below the water table)!

Don't chase water!!!!



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Best Practice #3
Field Characterization Tools – High Density Data w Efficiency

- Each COPC has its own character in regards to movement in the subsurface.
- Use of “real-time” (UVOST, Field Lab, etc.) characterization tools support the building of an CSM that is strongly data supported.
- Understanding the core mass(es) and its relationship to the geological media is superior to know exact COC concentrations!
- These same tools save time and should ultimately save money.
- Helps to avoid dependence on presumptions regarding COC location that can lead to failure!

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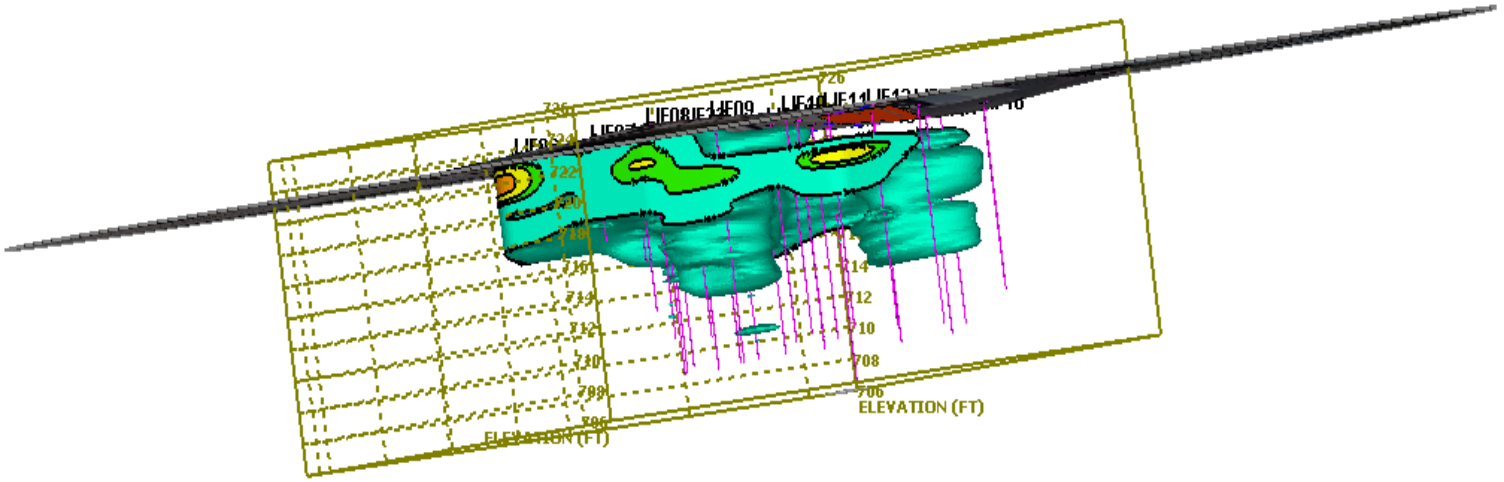
Best Practice #3
Field Characterization Tools – LIF, etc.



SIGNAL %RE

- >60
- 40 - 60
- 20 - 40
- 10 - 20
- 5 - 10
- 1 - 5

Vertical Exaggeration = 5:1

July 2015 Integrated Site Visualization (ISV)

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Carbon Emplacement

First 3 Best Practices

1. Identify your goals and objectives
   - Know what do you need to accomplish?
   - Characterize sufficient to achieve the remediation goals
2. Collect high density and high efficiency data
3. Locate the core mass(es) of contamination
   - Avoid “chasing ‘hot water’”

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Best Practice #4 Focus the Carbon Emplacement

- **Ensure that carbon emplacement is focuses both vertically and horizontally on the core mass(es).**
  - Carbon will favor the paths of low resistance; thus, it is important that you understand the character of the subsurface so that you can target such features.
  - Stratigraphy is important: How the soil and rock media are structured!
- **Target lower resistance pathways**

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Vertical Stages of Characterization

Overburden characterization

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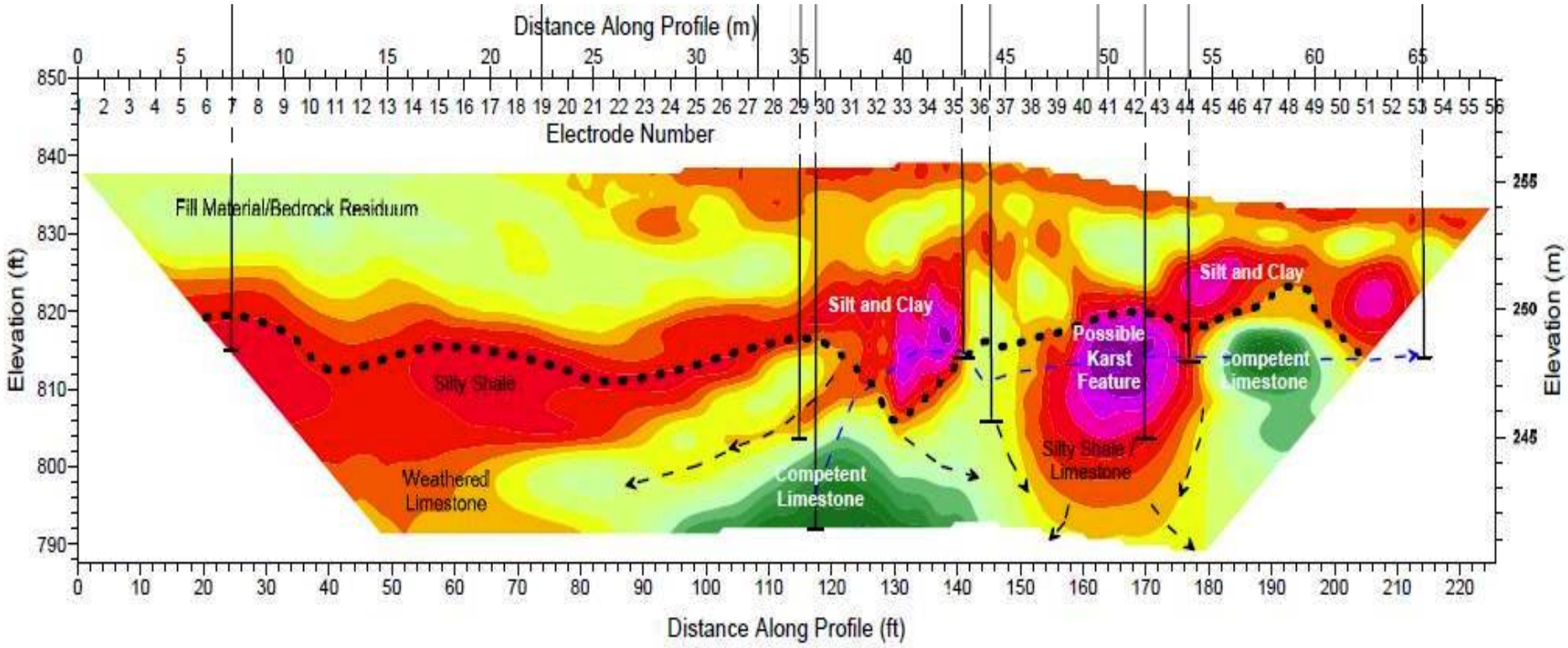
Surface Geophysics



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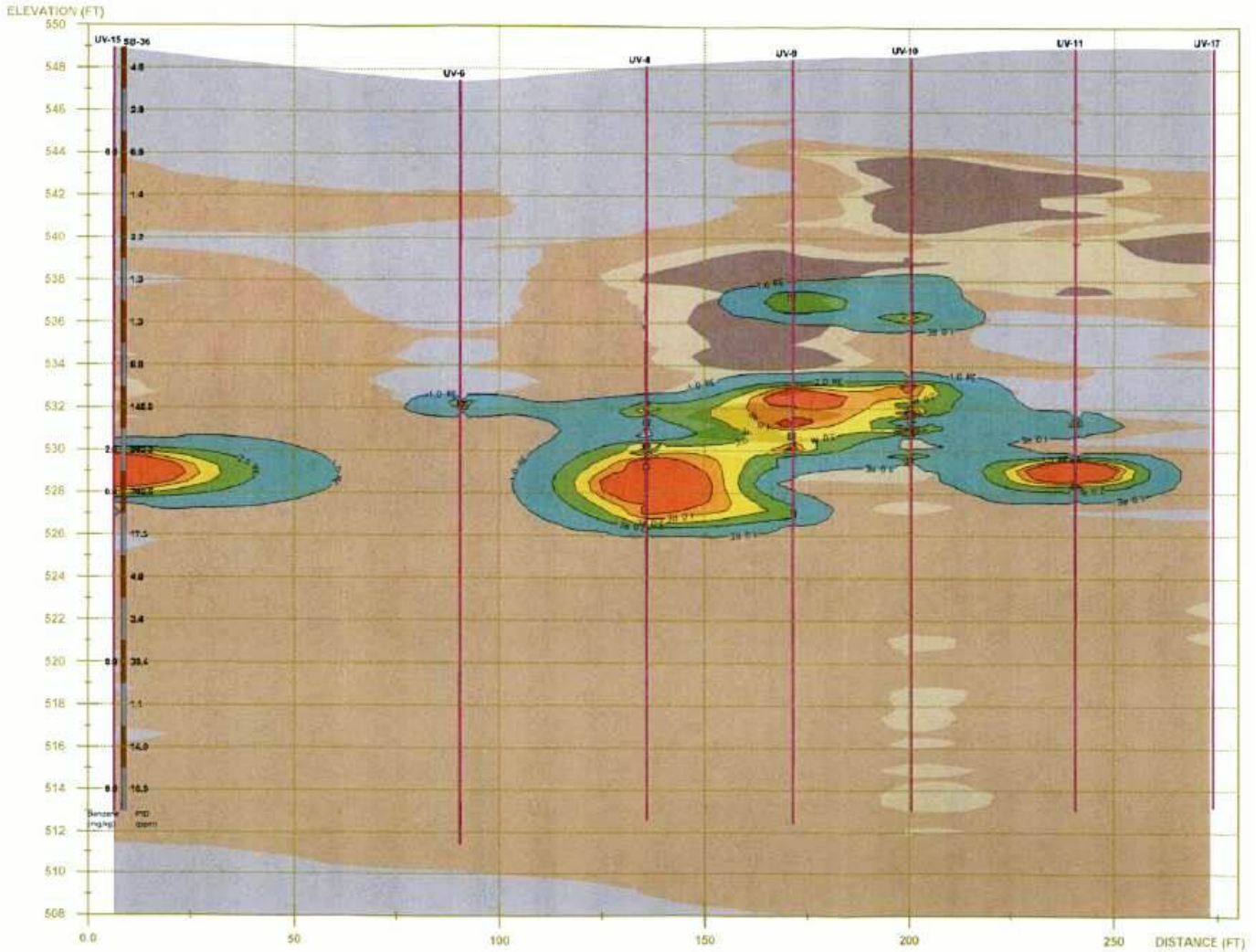
Bedrock Characterization



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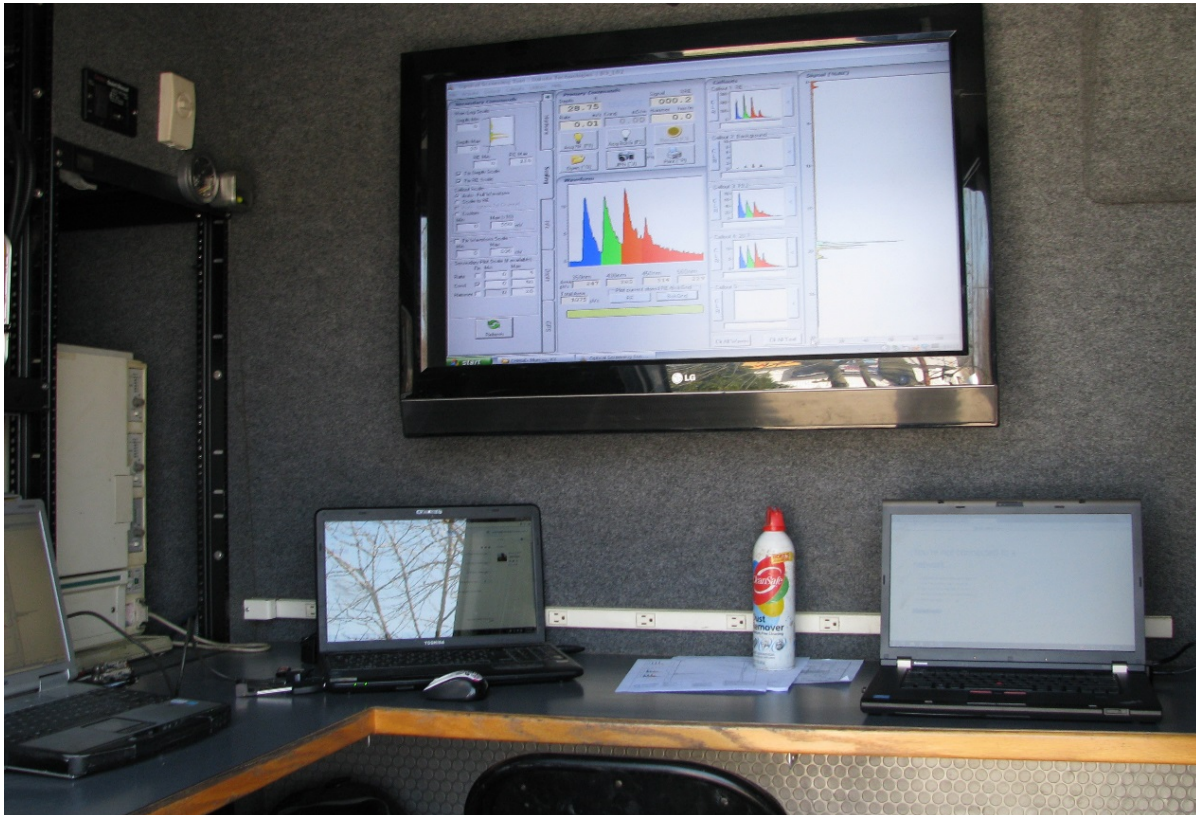
Horizontal Stages of Characterization

- Extent of contamination sufficient to inform a remedy…
- You could always know more!
- But focus on the core COC mass(es)
- Don’t pursuit water!



Best Practice #5 Remove Free Product

- A best practice would be to remove as much free product prior to carbon injection as economically feasible.
- Carbon can adsorb free product, but there are practical, physical limits to the amount of carbon that can be injected, and
- there are cost considerations.
- Excessive free product may interfere with degradation mechanisms.

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Our Experience is with Carbon Slurries

- High-Pressure emplacement is used for carbon slurries.
  USEPA CLU-IN, https://clu-in.org/techfocus/default.focus/sec/Environmental_Fracturing/cat/Overview/ (Sep. 2015)
- Deformation of subsurface to promote carbon delivery through created fractures
- Pressure needs to be sufficient overcomes effective stress but not more, that is, you're not blowing-up the subsurface!

Cocarb.

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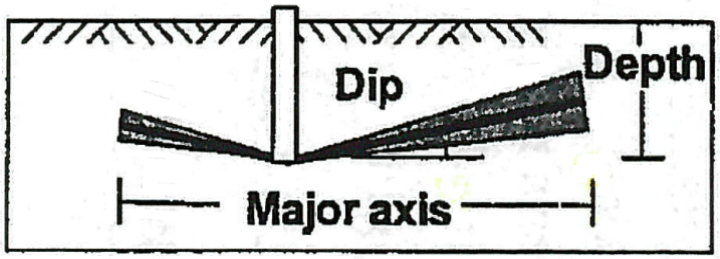
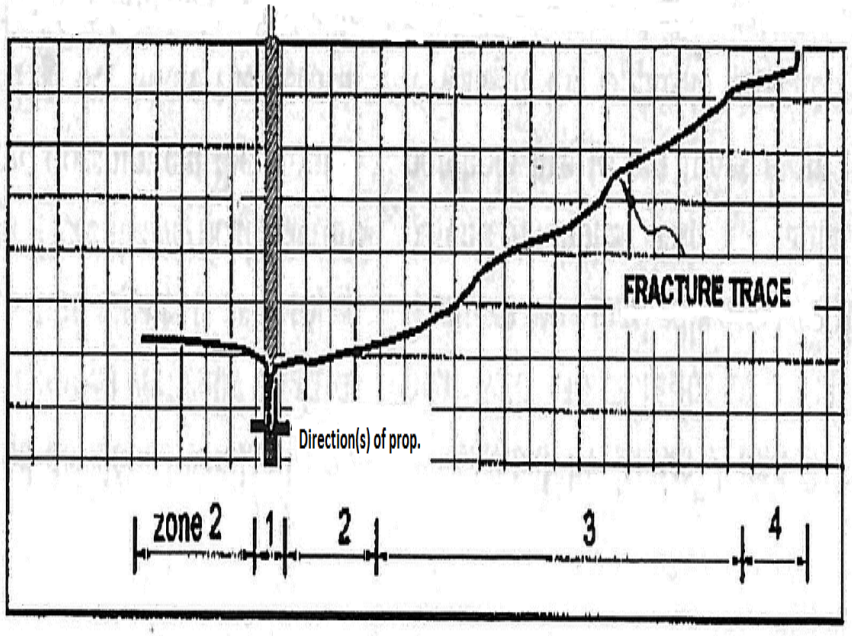
A Bit about Fracture Emplacement

- Pressures ≈100 to 400 psig
- Daylighting occurs
  - Degree is site specific
    - We have seen daylighting as high as 20% on sites with previous drilling and infrastructure paths
    - ≈ 3 to 5% daylighting as a general rule
  - Soil conditions are important
  - Minimum injection depth

$$X \geq 3ft$$





Top right picture: Murdoch & Slack, 2002.

Bottom right: Murdoch, 1995.

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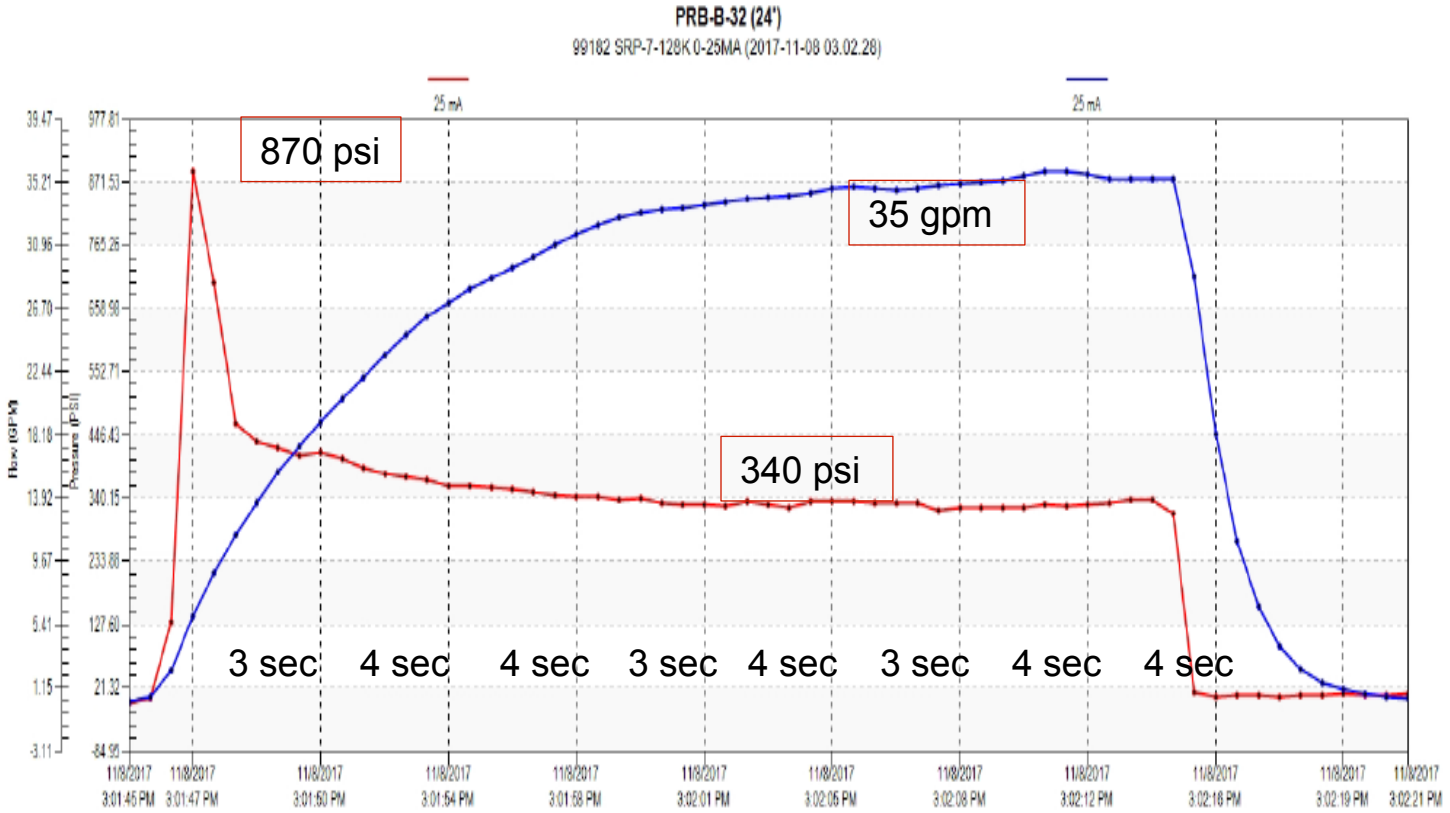
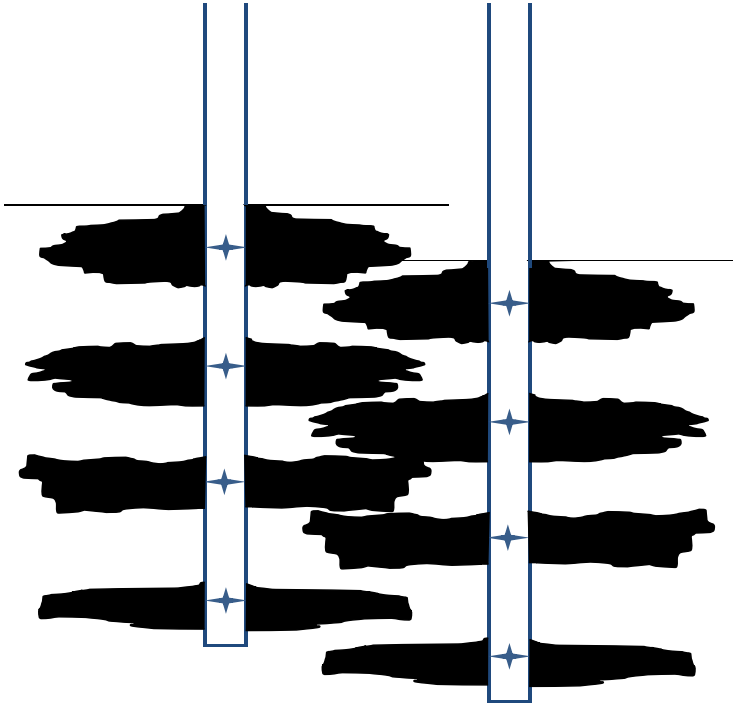
The Injection Procedure

Use a positive displacement pump with a bypass valve to maintain a relatively constant pressure. You want flow rate to be independent of pressure.

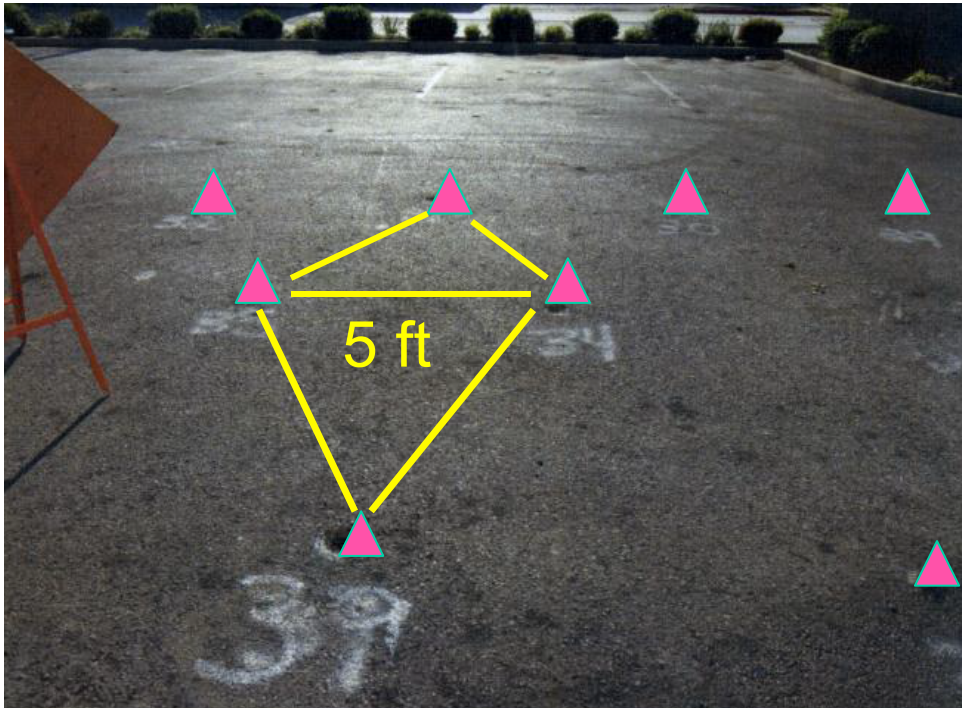


Alternate Injection Points Vertically with Hexagonal Spacing Horizontally

- Overlap injections vertically



- Hexagonal orientation



Emplacement every 5 feet!

~3 to 6 feet (Christiansen, 2010)

Arcadis guidance ~ 5 to 7.5 feet

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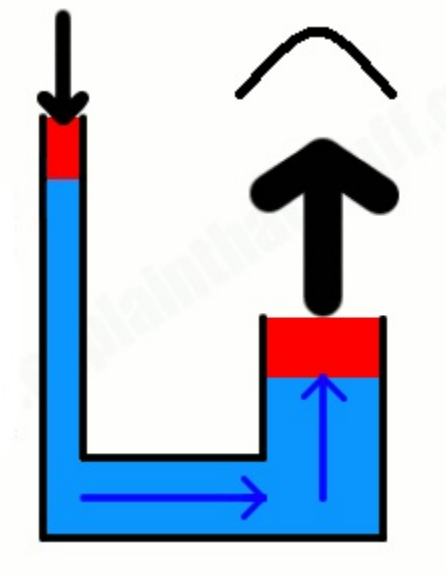
Surround the COC Mass & Work Inward

- When mass is added- displacement occurs
- Best practice is to surround the core COC mass and work inward.



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Top-Down vs Bottom-Up

Top-down

- Lift small formation intervals
- Lower chance of opening large natural fractures while “lifting formation”
- Decreased merger of lower and upper fractures during delivery
- Lower chance to short-circuit up along drill rod
- **KY always uses Top-down**

Bottom-up

- Increased “reach” when lifts are limited in number, closely spaced and at the bottom.
- Survey conducted by ARCADIS recorded that 70% of the respondents typically injected from bottom-up. Battelle 2018, Ryan Oesterreich. Not a best practice.

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Best Practices for Injection of Carbon Slurries

Summary of Best Practices

1. 5 foot spacing using a hexagonal grid
2. Initial injection 3 feet or greater bgs.
3. Install from the outside parameter inward
4. Inject from the top down alternating injection depths to support injectate overlap
5. Inject over 1 to 2 feet intervals
6. Use an injection tip which directs injectate horizontally
7. Use a positive displacement pump

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Caution: Result of Low Pressure Injection in Clay Soils

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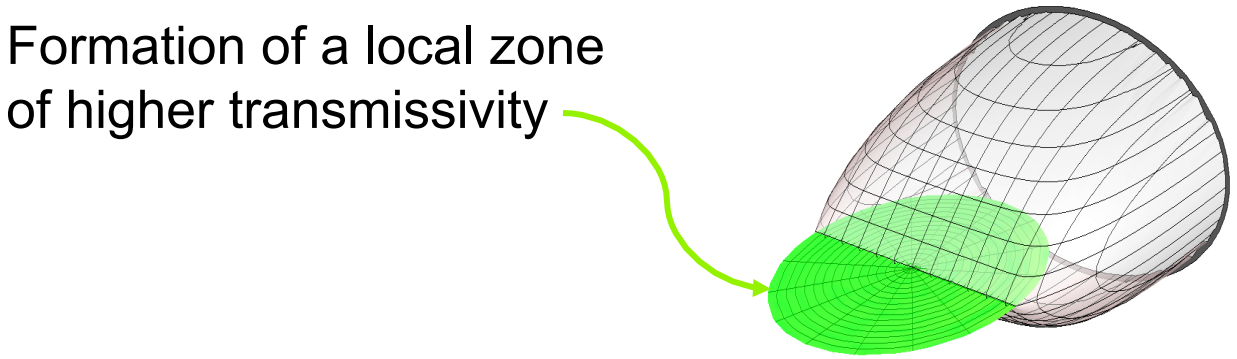
Carbon emplacement Expectations and Visuals

- High pressure emplacement:
  - ❑ **Formation of pathways** allowing "freed" contamination to move to the injectate as the injectate has a lower resistance to flow (Murdoch & Slack, 2002; See also Murdoch & Chen, 1997).



Picture courtesy of Bill Slack FRx, Inc.

  - – **Filling of existing pathways** such as old infrastructure, plant root hollows, clay fractures, etc.
  - – Assume areas of **"local avoidance",** that is, sometime paths don't meet and miss some contamination (Murdoch, 1995).

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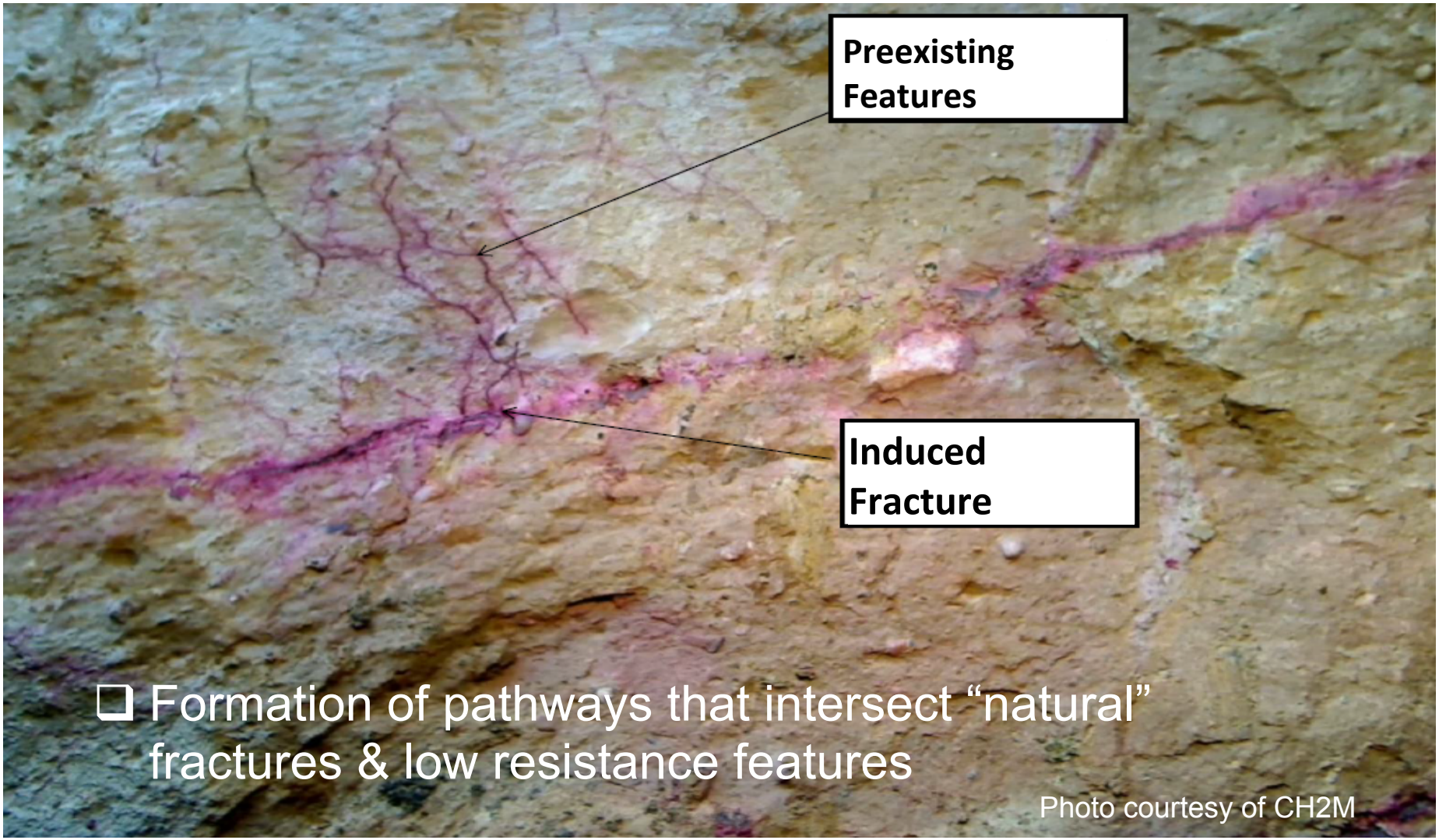
Fine Soil Features



- Formation of pathways that intersect “natural” fractures & low resistance features

Photo courtesy of CH2M

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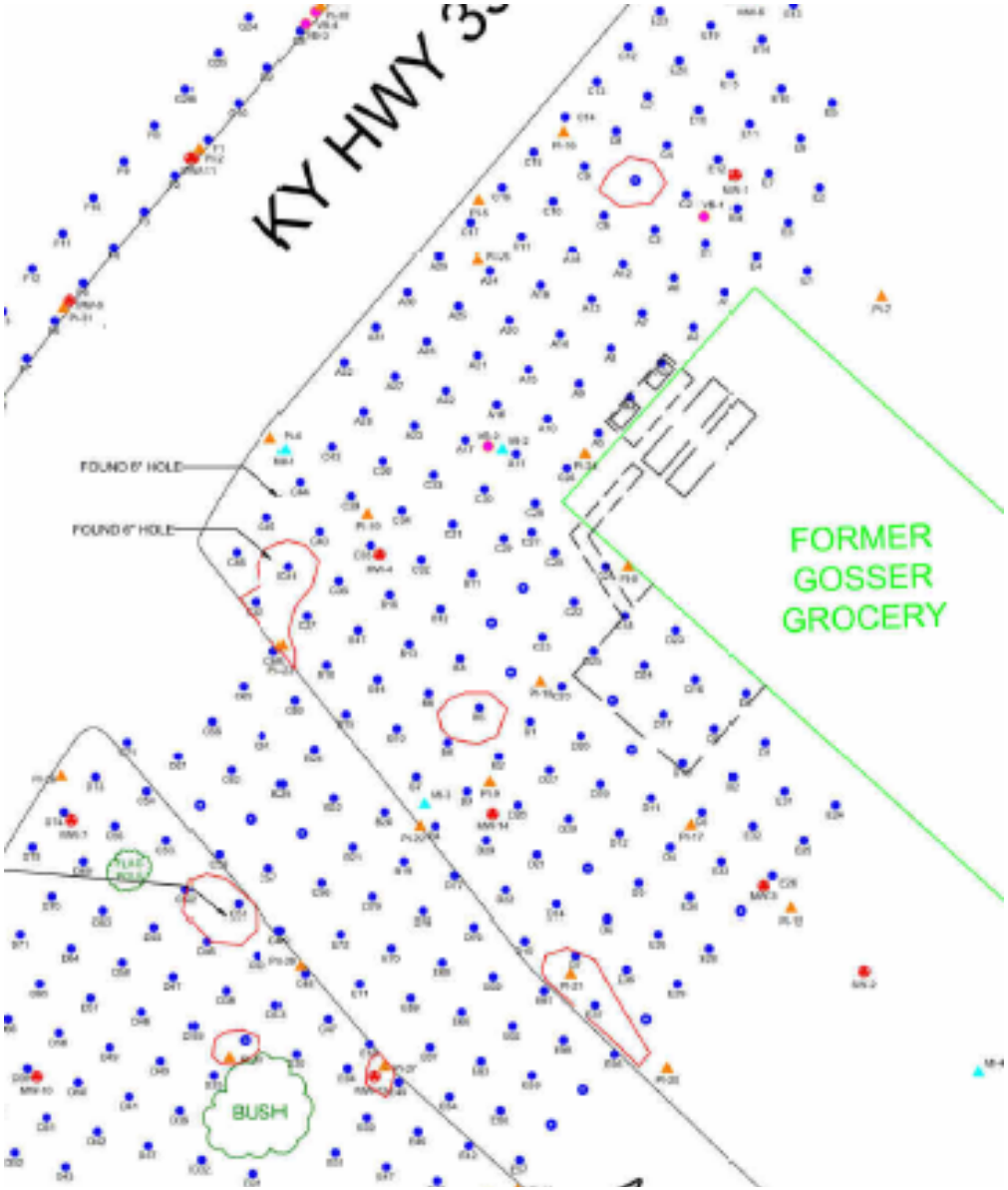
Carbon distribution in core logs



- 407 injection points
- 5ft centers (Tight Grid)
- 40,800 pounds carbon
- 13 ft injection interval length (Typical interval for KY sites has been 9±4ft)
- Inject every 2ft of vertical interval

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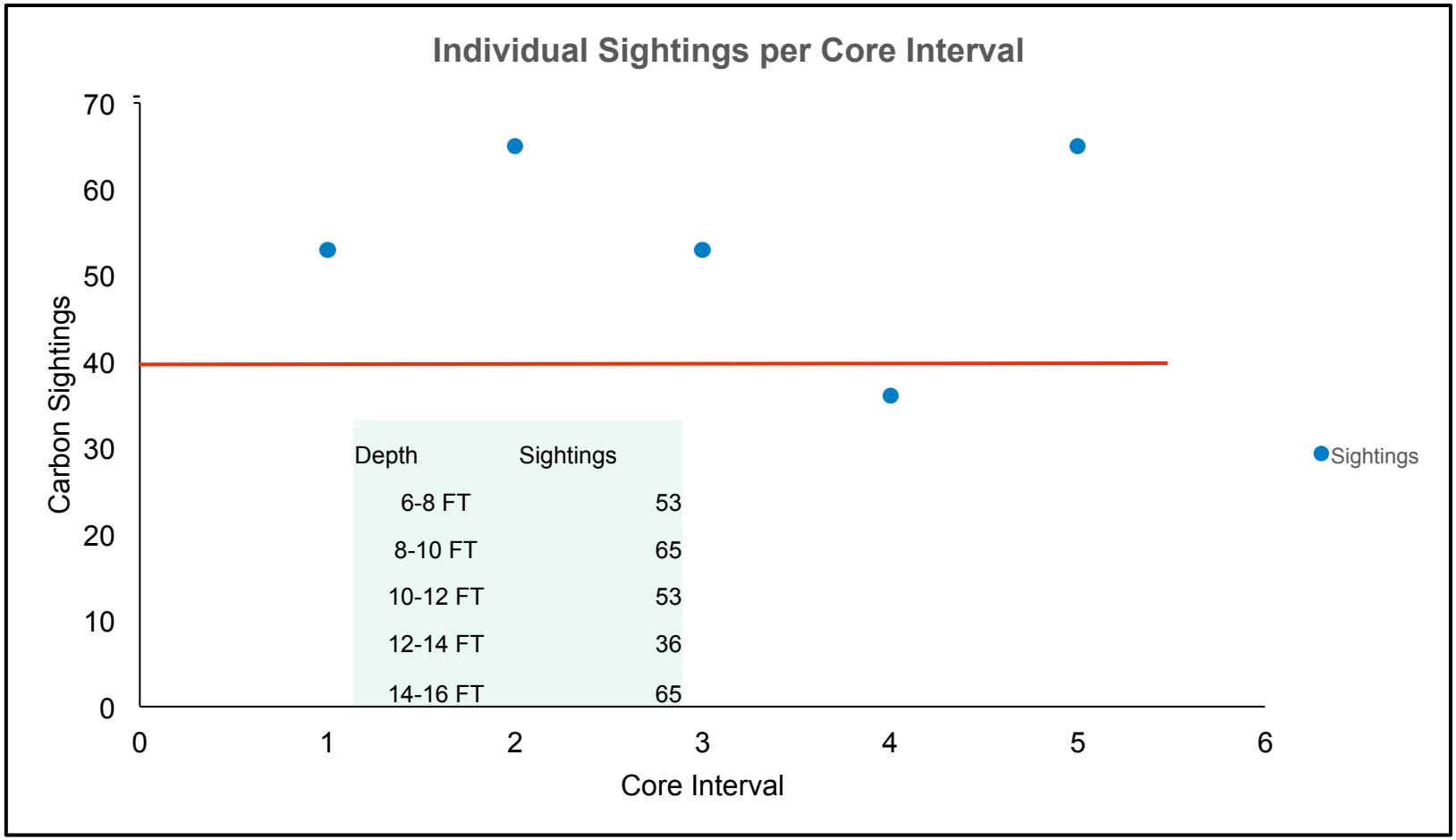
Carbon Visualized in 40 Cores



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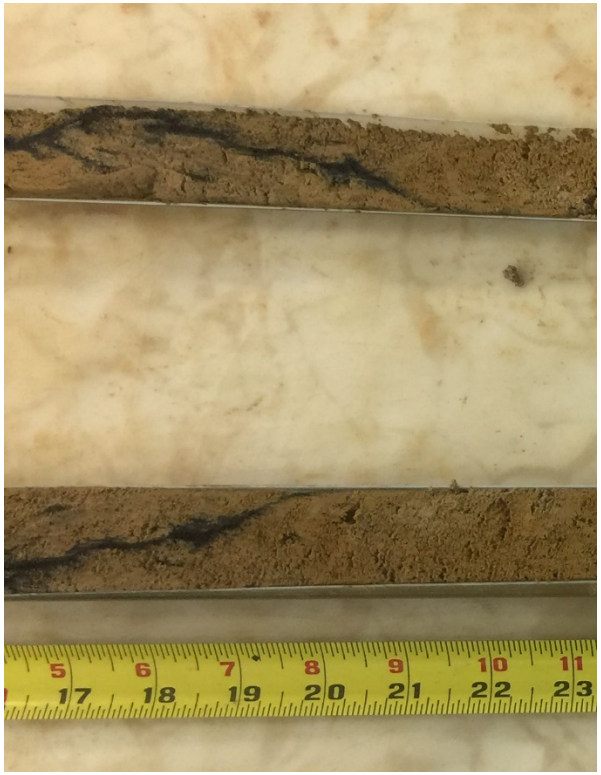
A Bit More about Fracture Emplacement

Pressure injected carbon fills existing pathways such as old infrastructure, plant root hollows, clay fractures, etc. when such are intersected.



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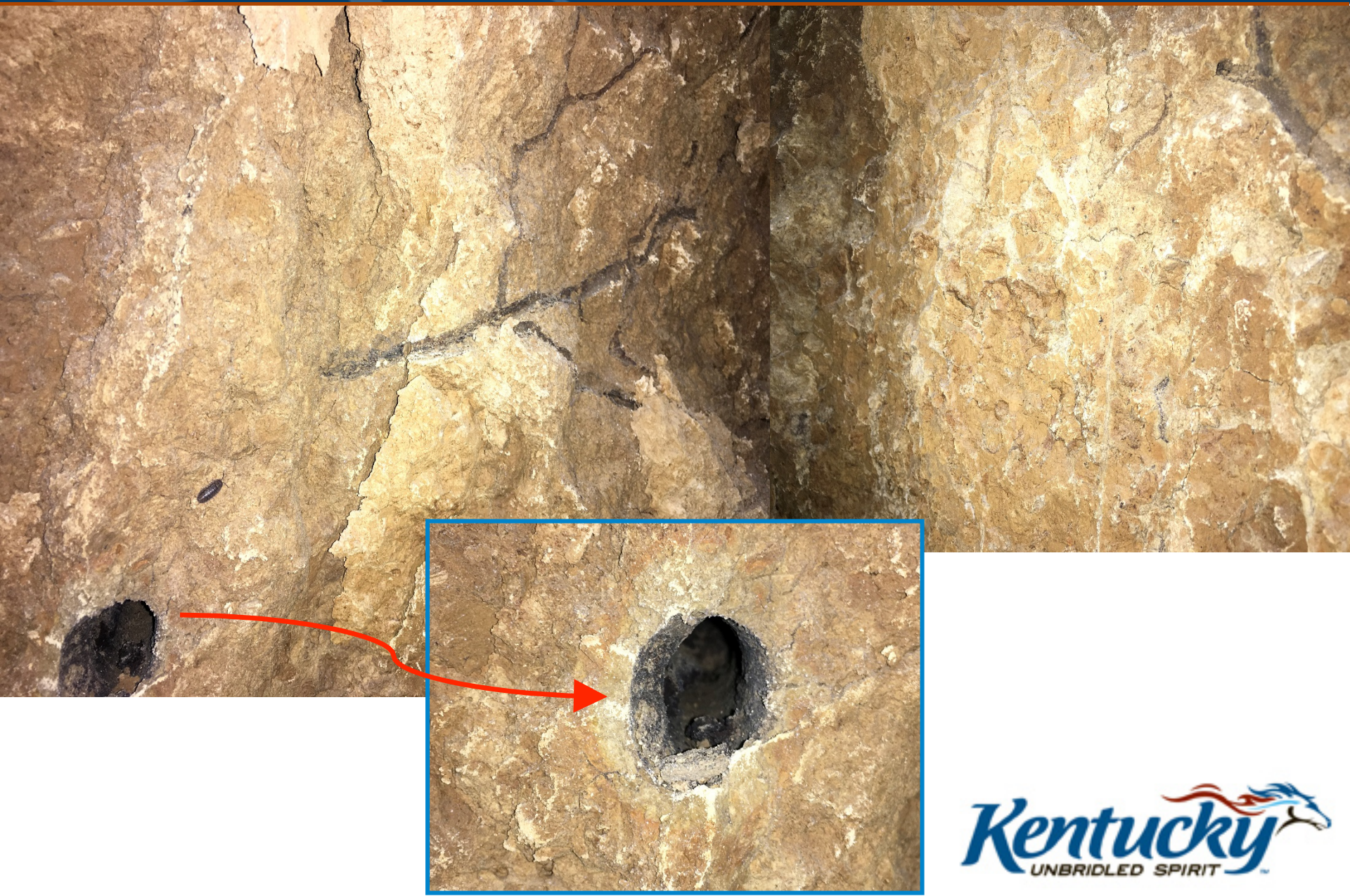
Natural Root Features in Soil at 8ft



Seemingly Small Seams Can Fill Large Voids

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Carbon on Either Side of Soil Feature

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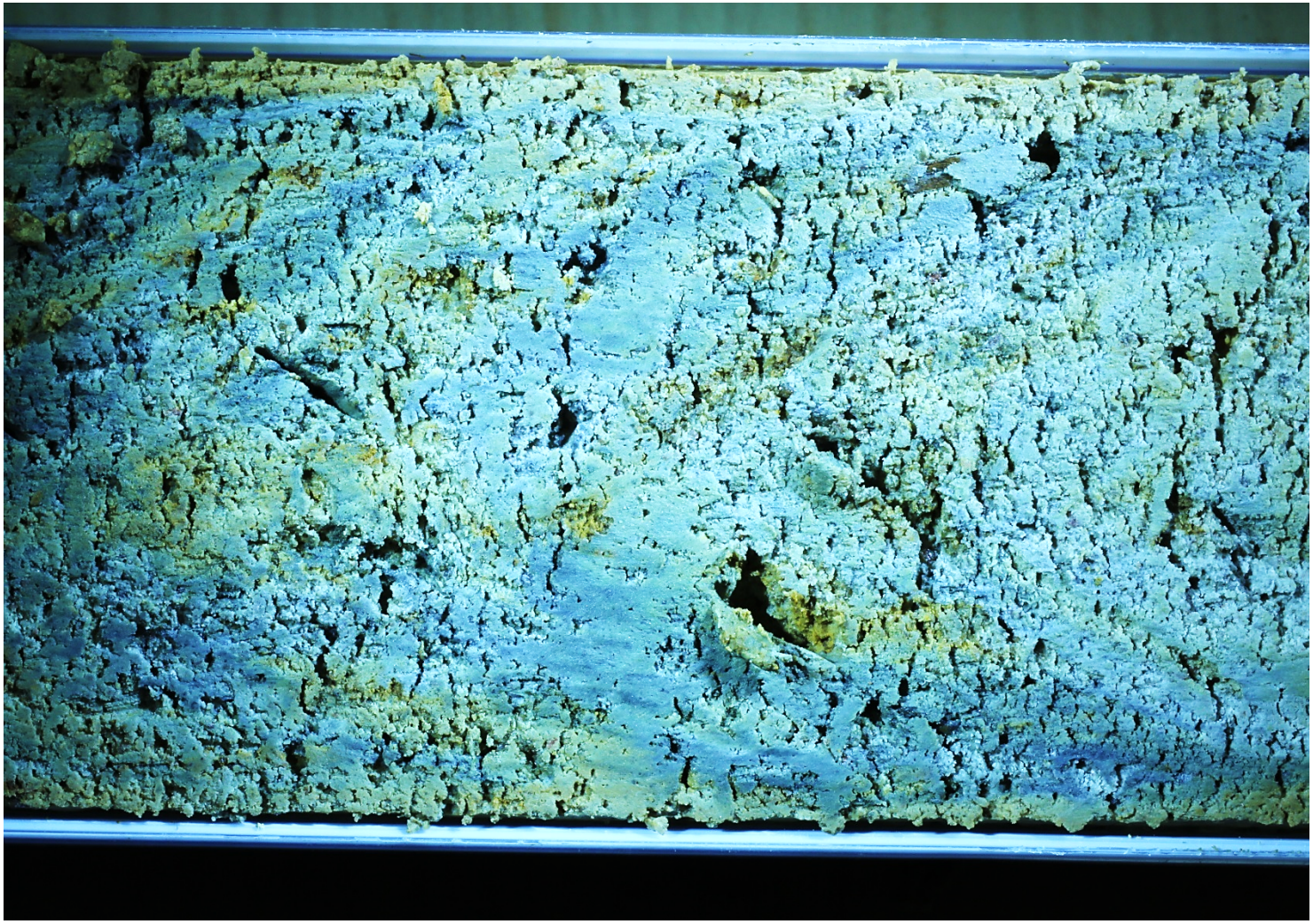
Carbon Well Mixed in Soil



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Carbon Integrated into Clay

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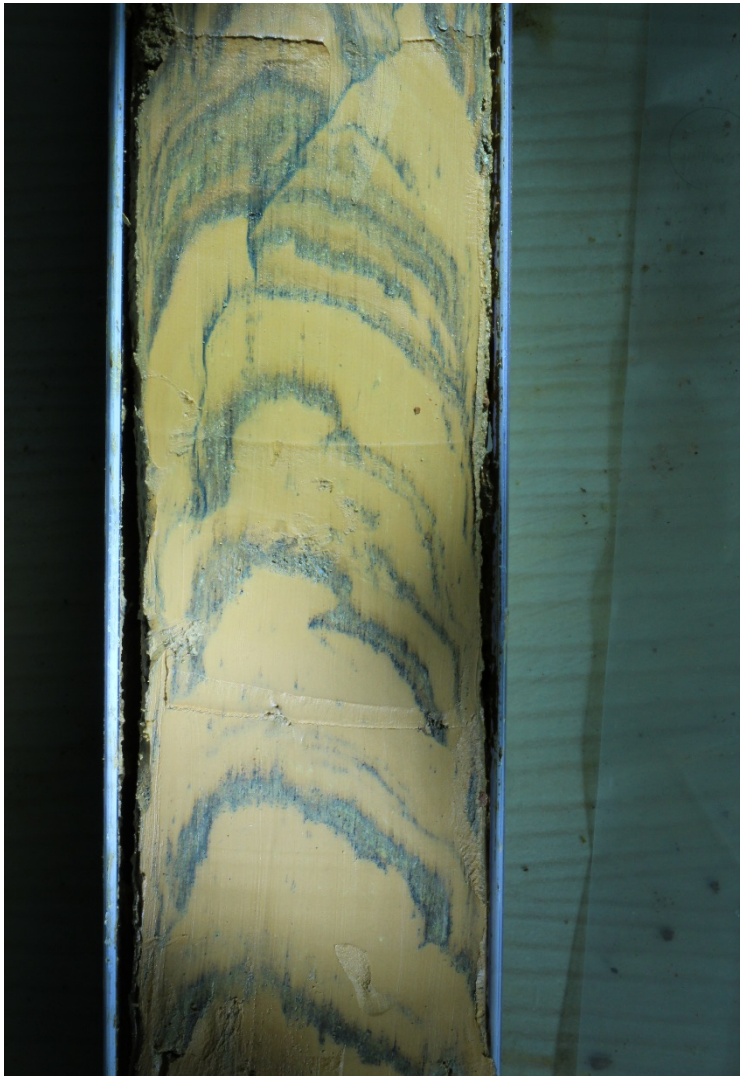
Close to Ideal



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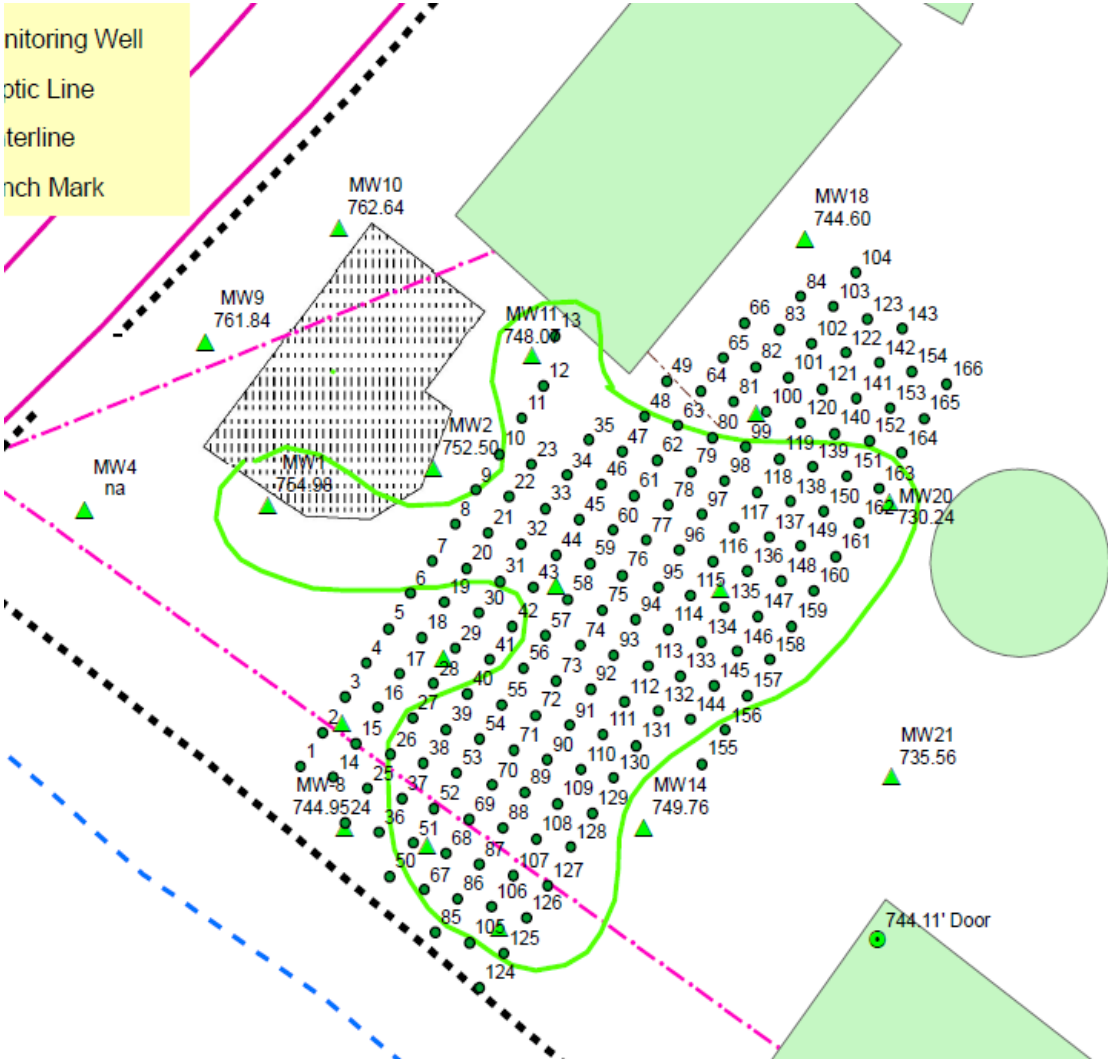
Installation of a Treatment Field



- Judge remedy effectiveness by reduction in total mass, which is the basis upon the injection was designed.
- This is a treatment field not a treatment point.

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Best Practice # 12 Confirm Results

- Don’t hold carbon to a higher standard of “proof” relative to other remediation technologies rather
- collect data sufficient to demonstrate you’ve met your remediation goals.
- Collect data appropriate to your CSM and reasonable expectations, that is, the most extensive investigation will fail to identify all sources of contamination!
- The final COC mass of the “field” is the appropriate measure of success
- High resolutions tolls such a LIF, MIP, etc.
- Installation of new wells (random installation?)
- Up and down gradient wells

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Some Guidance Documents

- NAVFAC (2013) - Best Practices for Injection and Distribution of Amendments
- LA Region Water Quality Control Board (2009) - Technical Report: Subsurface
- Injection of In Situ Remedial Reagents Within the LARWQCB
- Arcadis (2014) – Best Practices Document: Direct-Push Injection Approaches

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