Advances in High Resolution Hydrologic Measurements with Flexible Liners

By

Carl Keller, Beth Parker, Steve Chapman and Seth Pitkin

presented at

AIPG National Conference

Nashville, TN

Sept. 22-26, 2017

Topics

- Definition of recent advancements
- Purpose of recent measurement methods
- New methods of liner measurements
- Results of measurements with new methods at one site

Context of "Advances" (in blue)

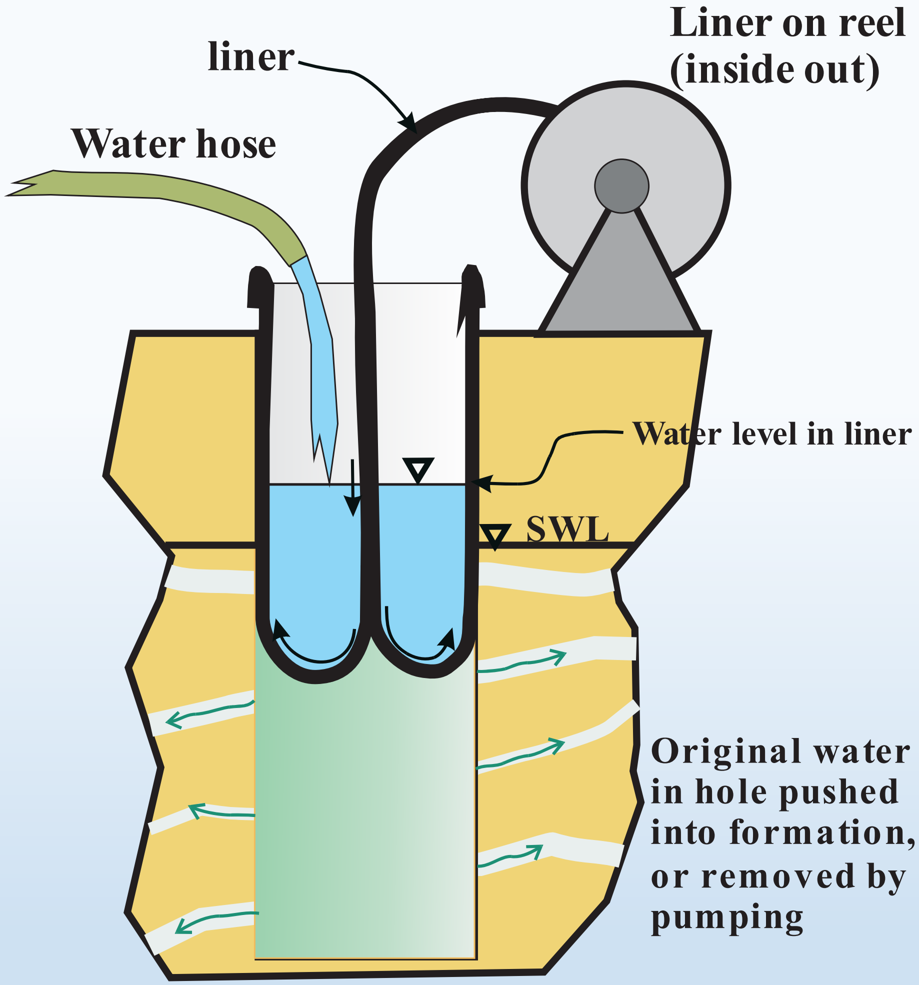
- 1989 First liner invention for subsurface vadose measurements
- ~1994 multi-level systems (MLS) for water sampling (Water FLUTe)
- 1997 NAPL mapping method via direct push (NAPL FLUTe)
- 1997 horizontal installations under a landfill and towing logging tools
- 1998 relining of piping systems in buildings
- 2004 Transmissivity profiling technique was devised
- 2010 NAPL/FACT (activated carbon)
- 2010 reverse head profile (RHP) method
- 2013 ACT (air coupled transducers with temperature corrections)
- 2015 Shallow Water FLUTe multi-level system
- 2014+ vacuum water level meter with precise gradient measurement
- Plus many other methods over time (currently 22 patents on liner methods)

Any description of liner methods requires an understanding of how everting liners work

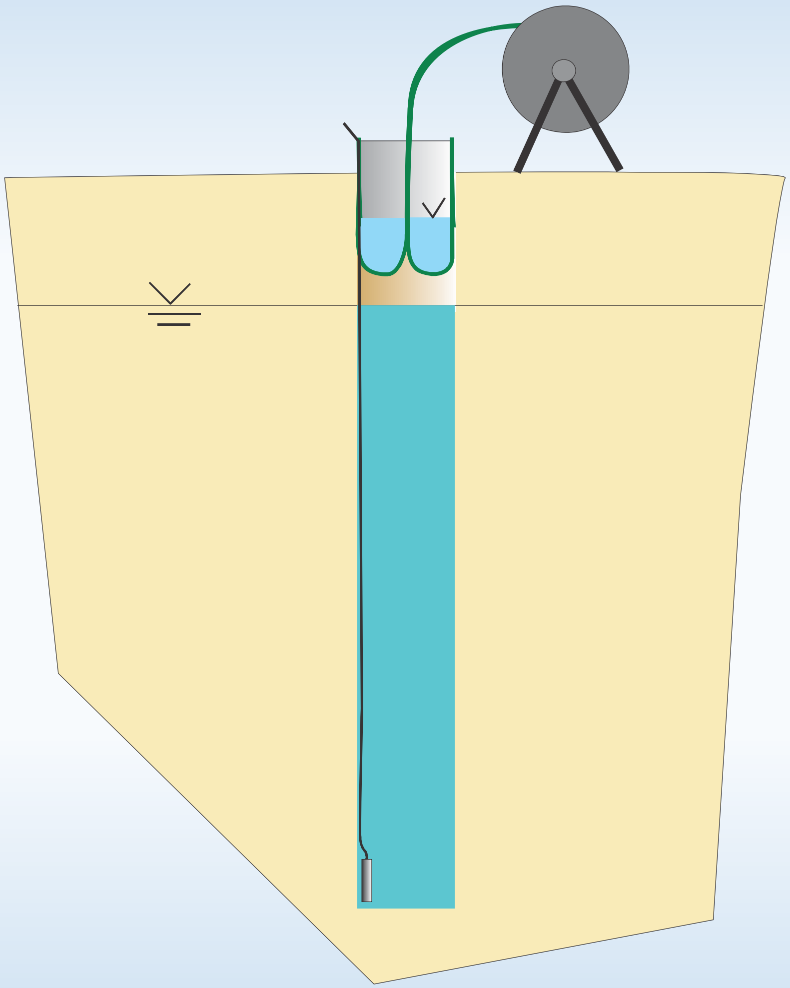
- "Inversion" and the opposite "eversion" are simple concepts
- Liners are made of strong flexible tubular urethane coated fabrics
- The liners are closed at one end with a strong tether attached inside the liner to the bottom closed end.
- The liners are typically shipped to the wellhead on a reel
- No heavy equipment such as drill rigs are needed

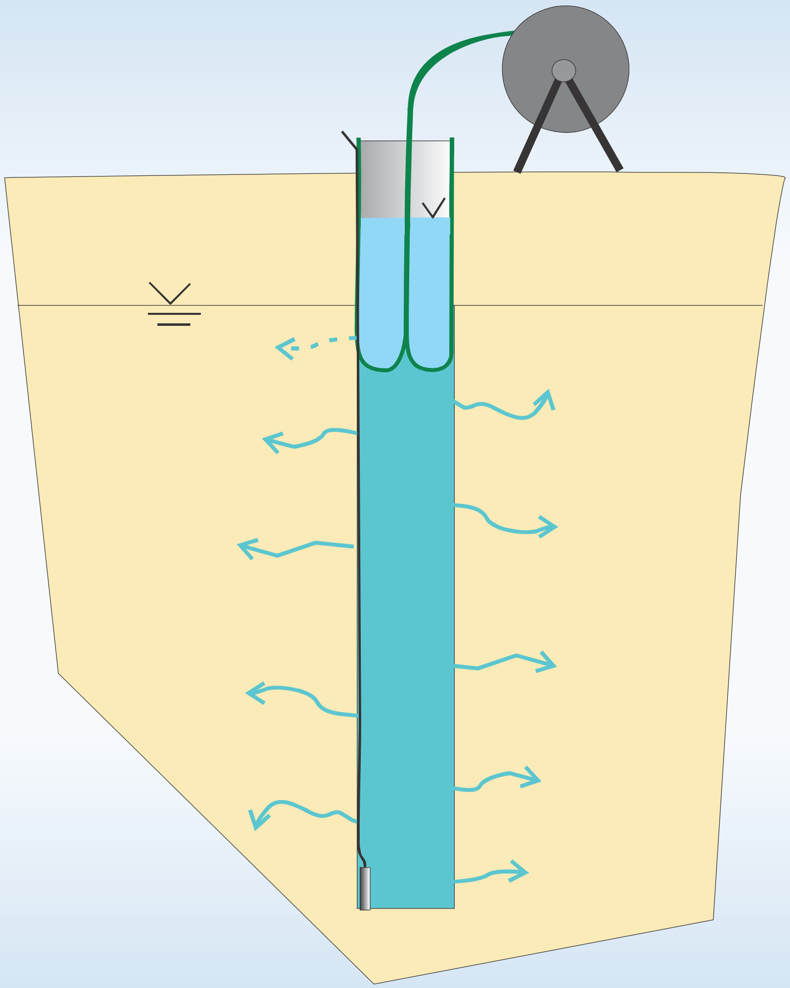
Here is how a liner works:

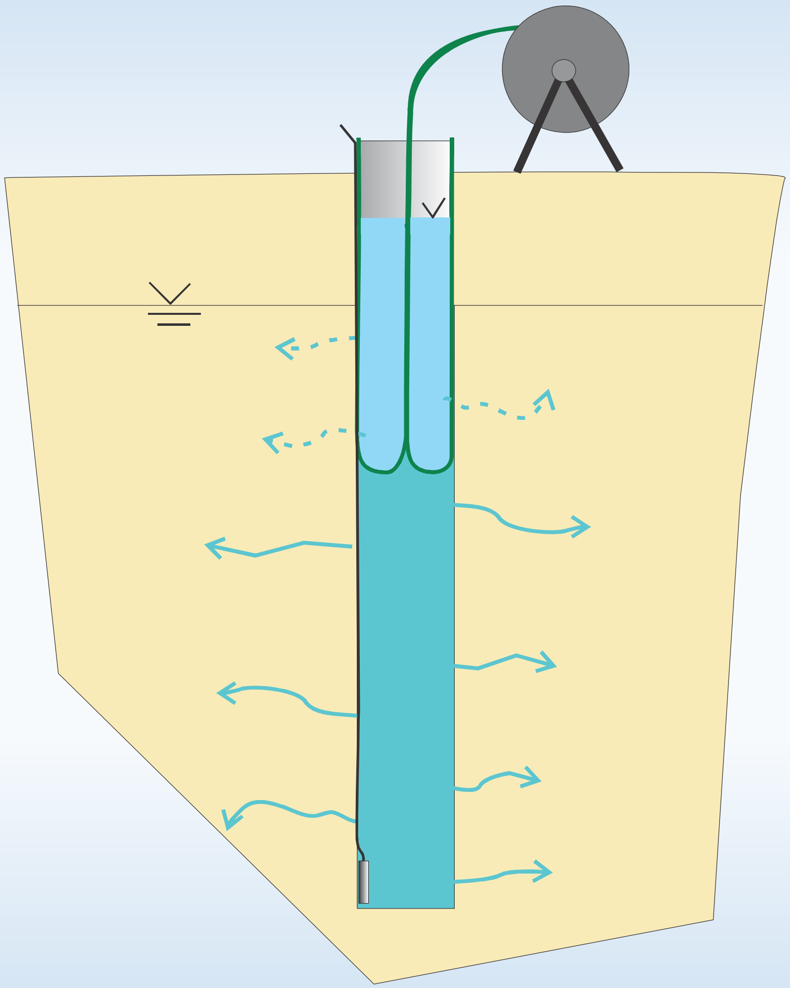
The blank liner installation to seal the borehole

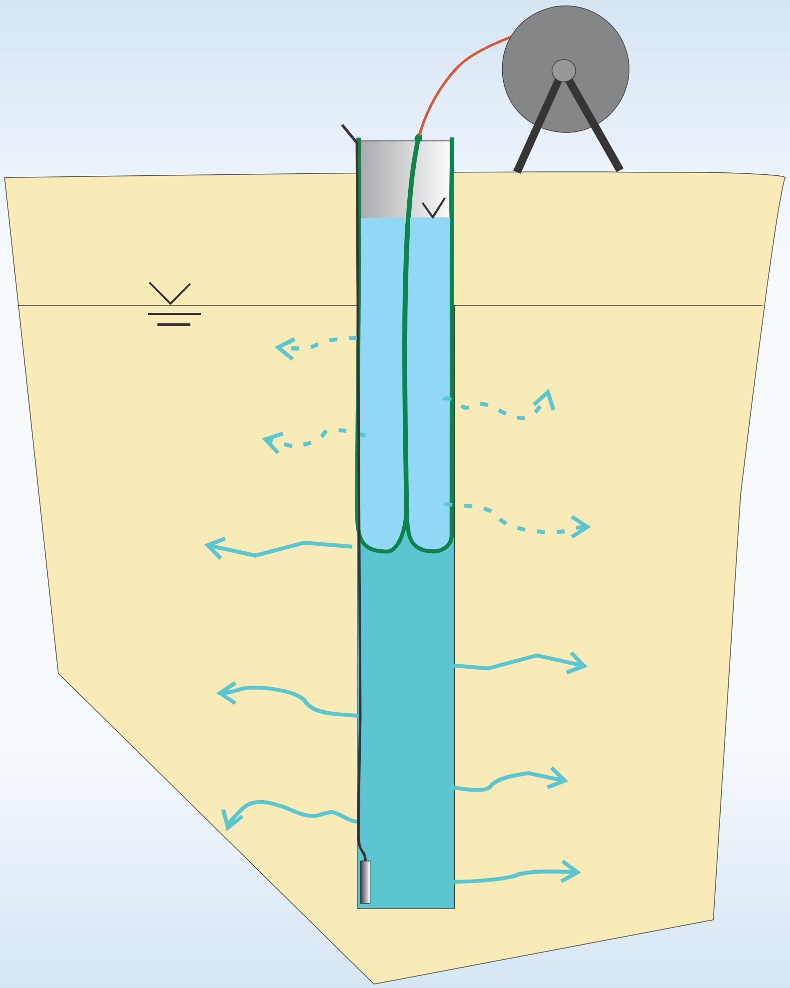


This is the “eversion” process

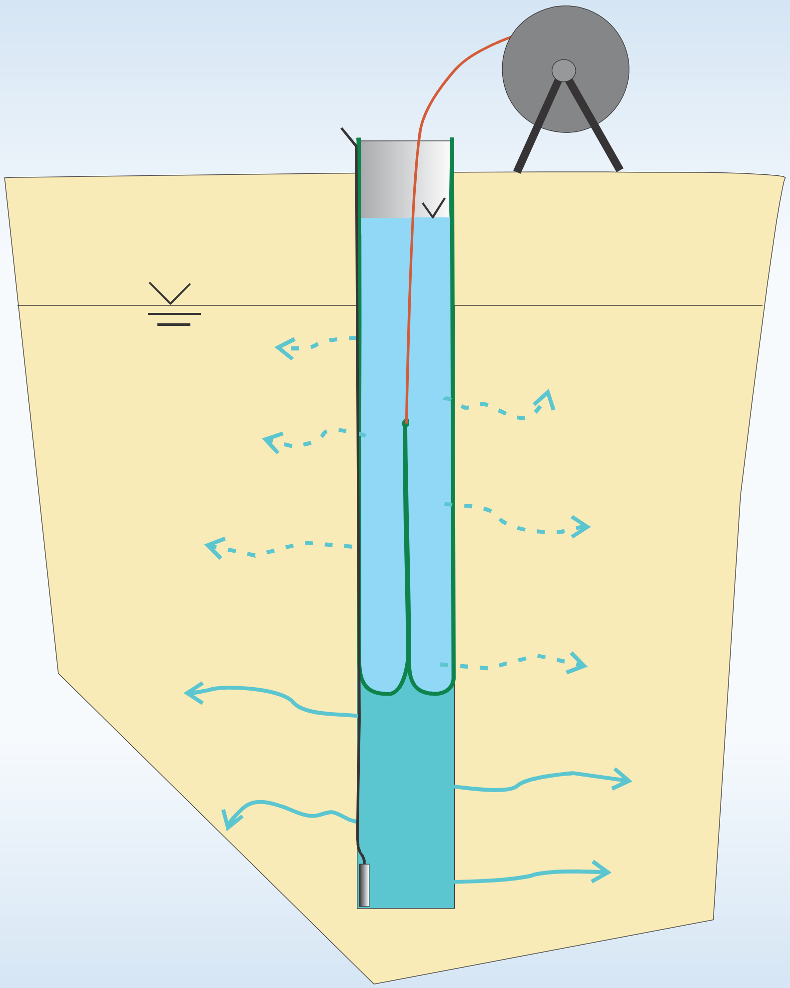


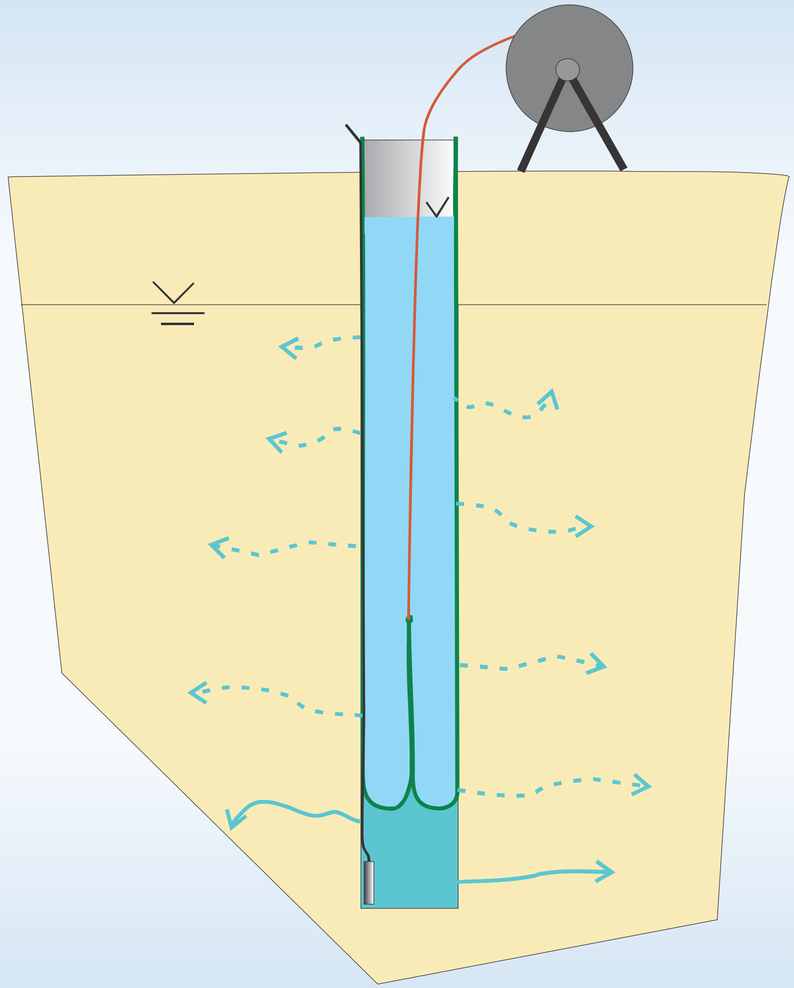




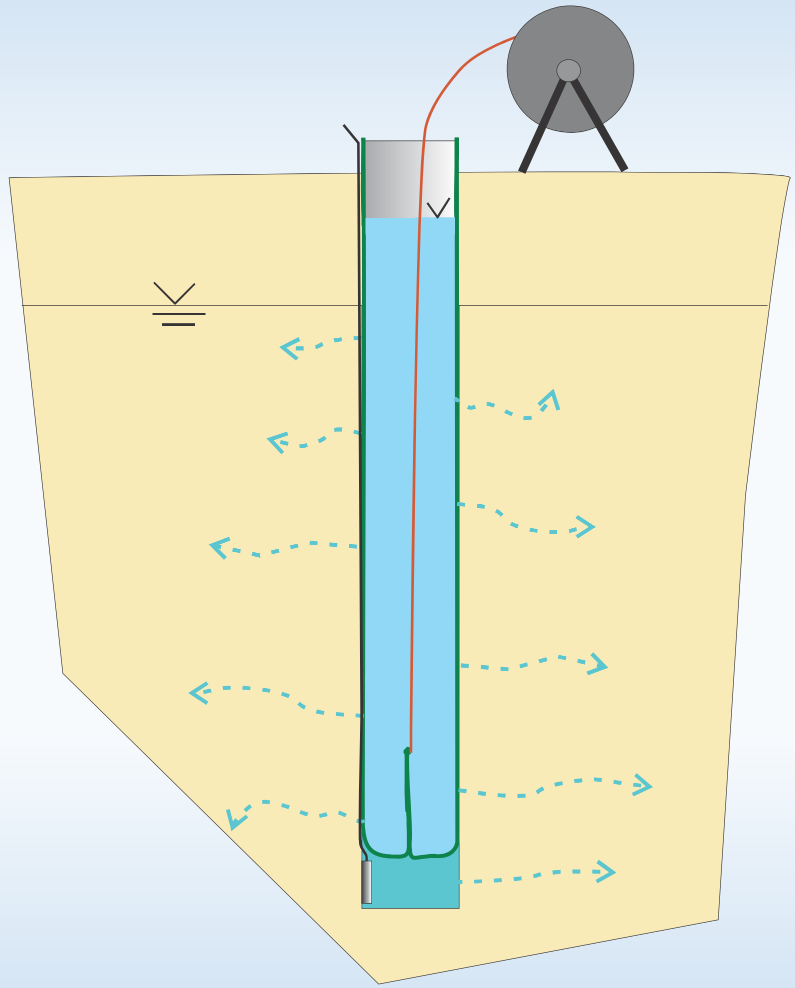


Note: the everting liner displaces the borehole water into the formation as it seals the flow zones

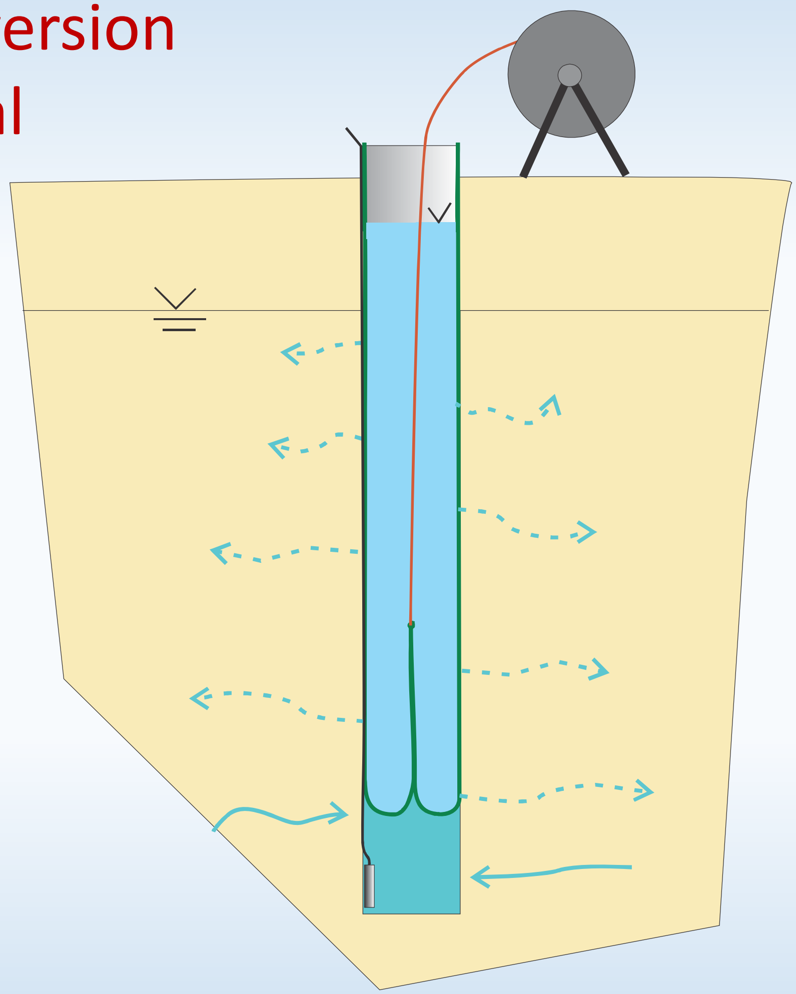


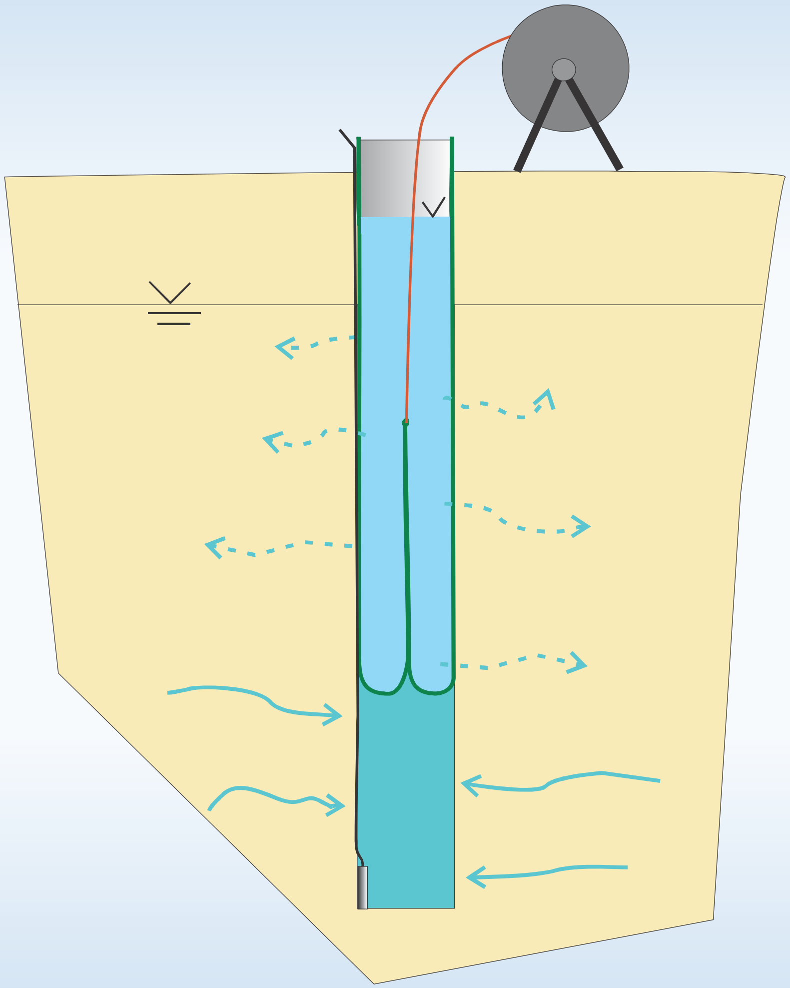


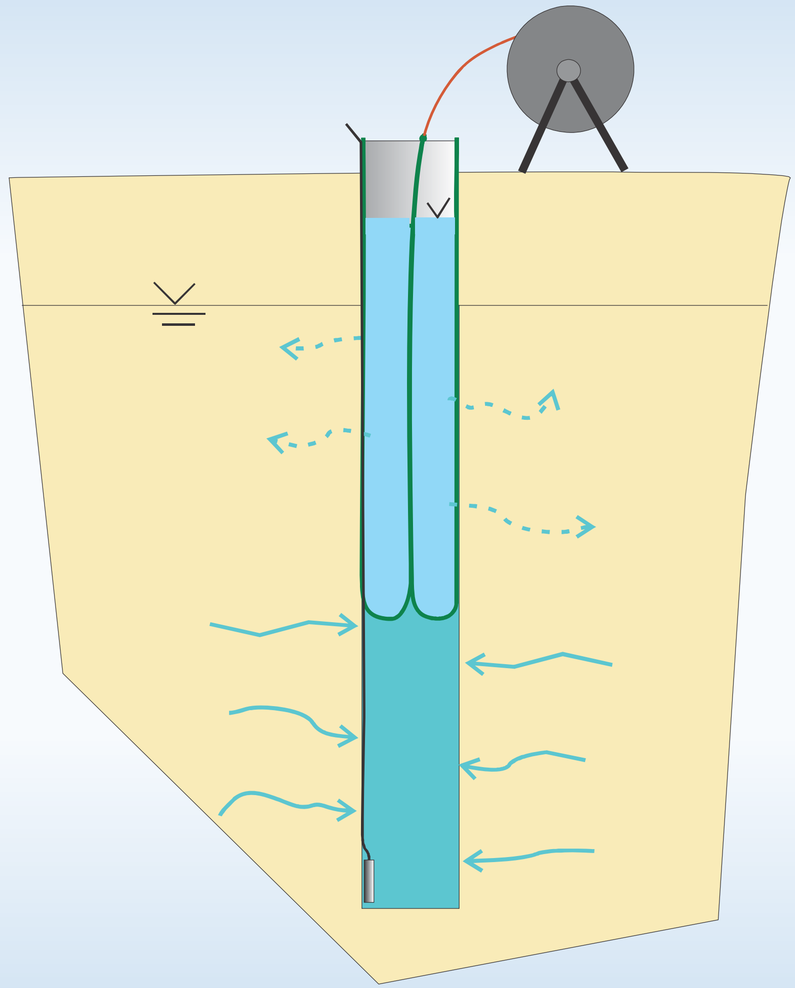
Fully installed, the liner seals the entire borehole.

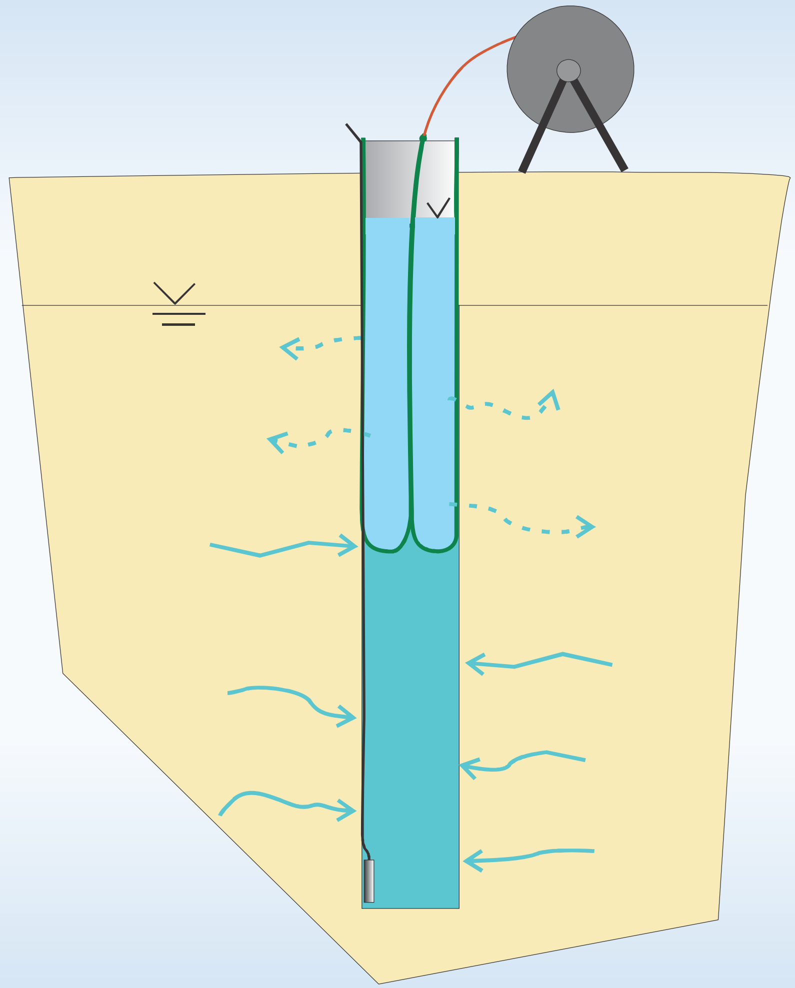


Note the stepwise inversion procedure for removal

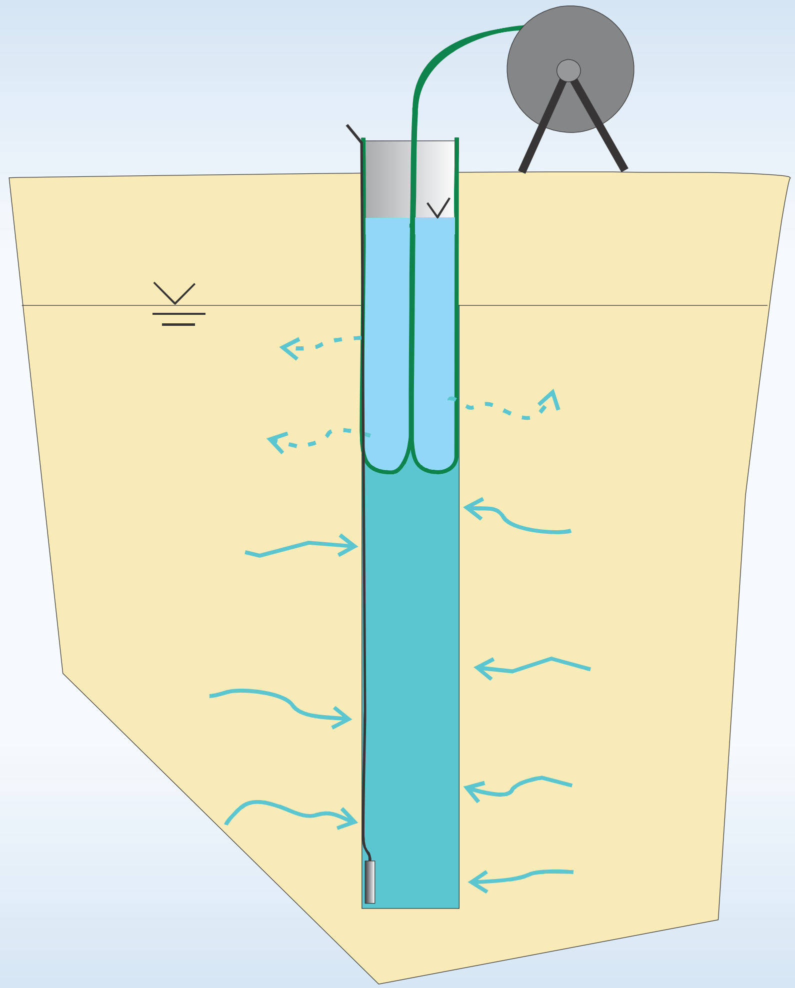


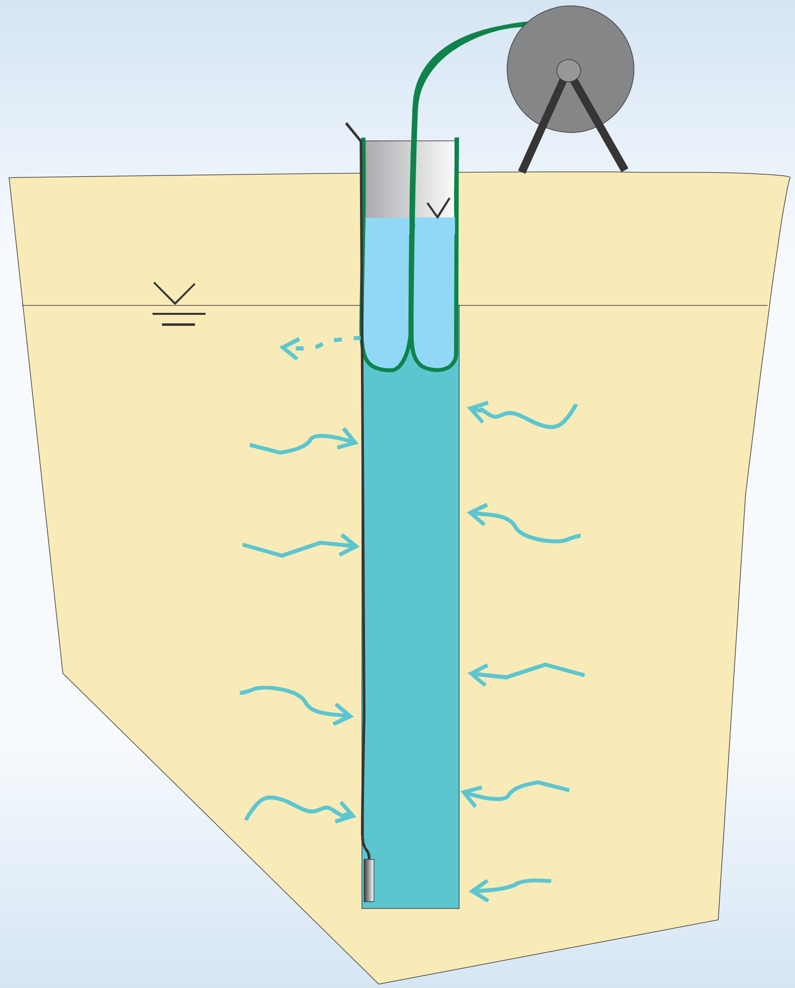


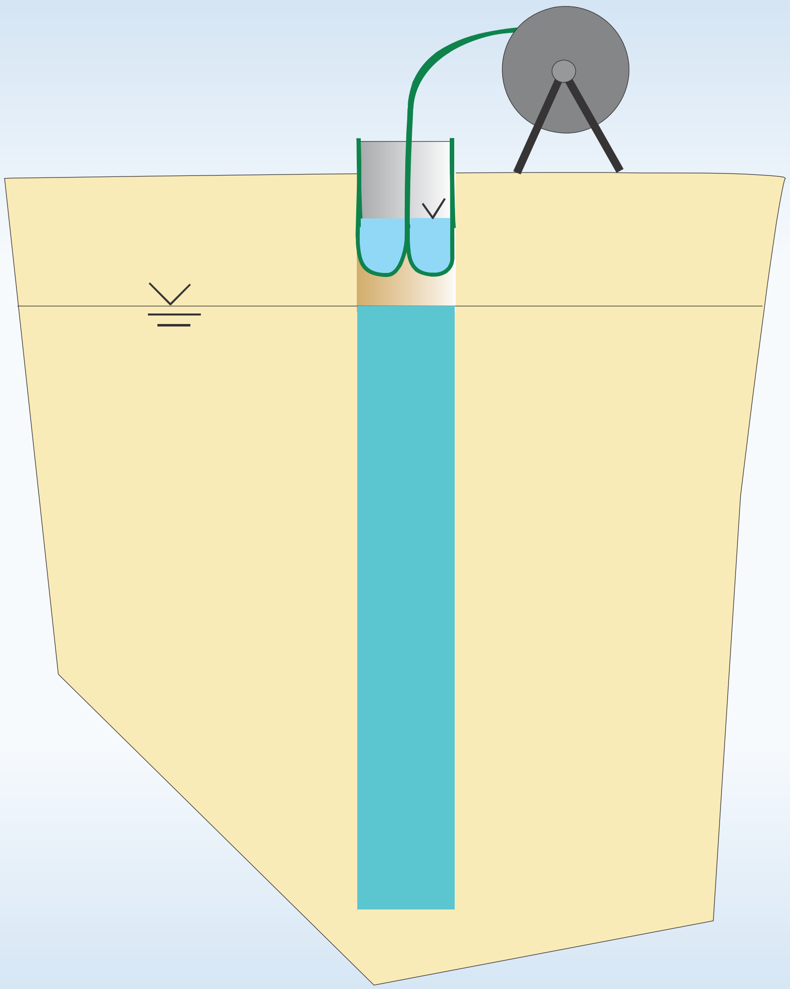




Upon removal by inversion, the liner draws water into the borehole





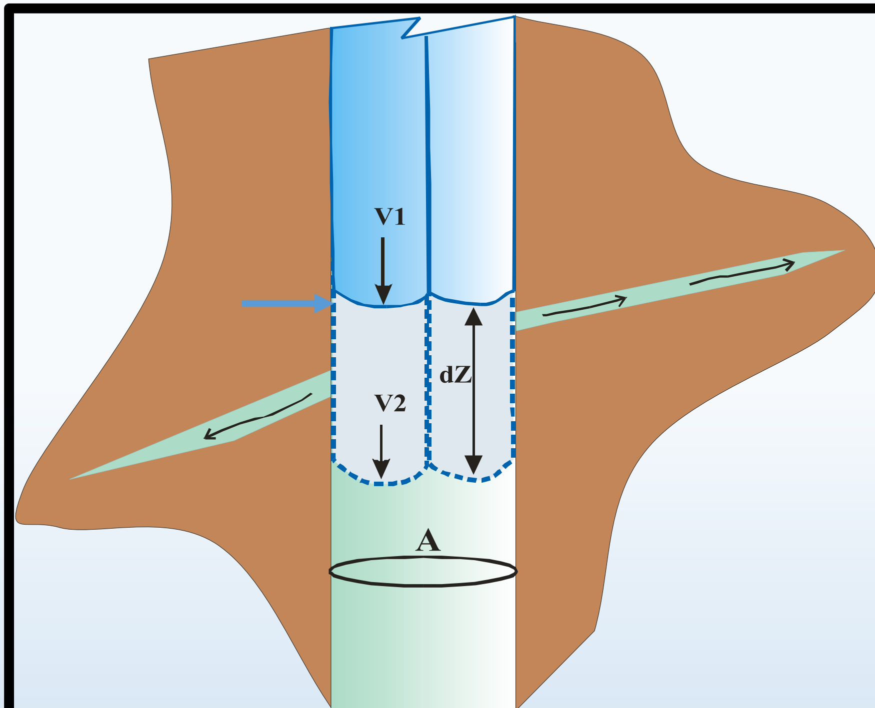


The several “advances” use these mechanisms:

- The transmissivity profile method measures the liner descent while sealing the fractures and produces the transmissivity distribution of the formation.
- The Reverse Head Profile method measures the equilibrium borehole head while removing the liner in a stepwise manner. From the equilibrium heads and the transmissivity profile can be deduced the formation vertical head profile
- The sealing of the borehole is used along with the activated carbon and the NAPL sensitive cover to map both the dissolved phase and the NAPL distribution.
- The everting liner is used to emplace sampling tubing in a sealed borehole for the Shallow Water FLUTe multi-level system.

These procedures with be explained.

For the transmissivity measurement, the liner velocity drops when each fracture is sealed



Flow rate into the fracture, Q, is A(V1-V2) , where V1>V2

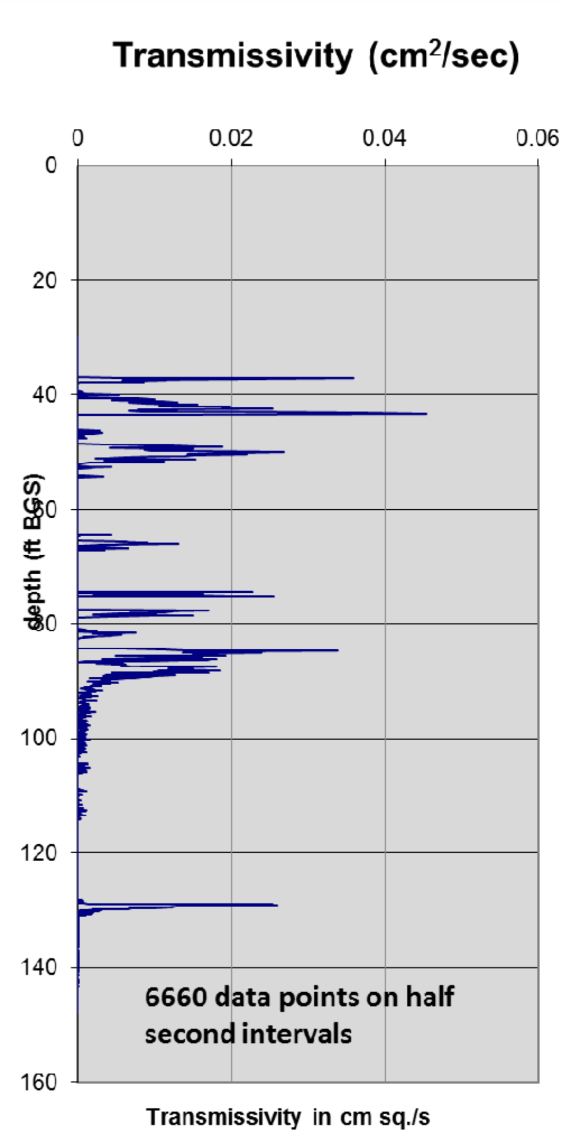
Average flow rate into the hole wall over the interval dZ is:
$Q/(dZ\ \pi\ D) = fctn(C, dP, D, ..)$

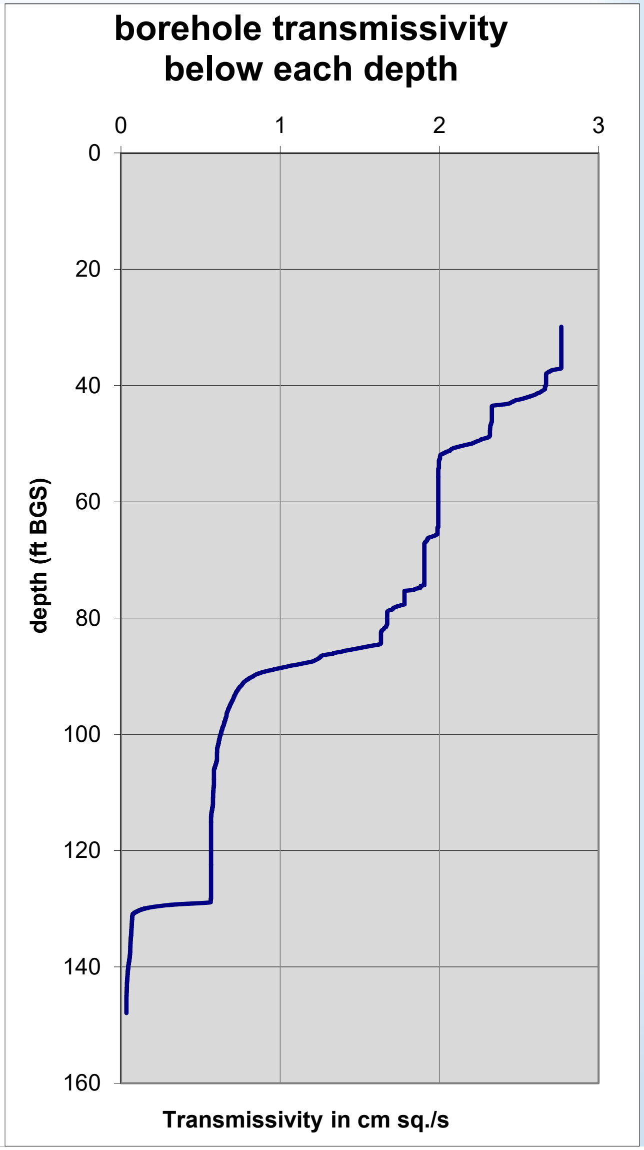
The T calculation is simple

- When that velocity change, Δv_i occurs, the fracture location is identified
- The flow rate into the fracture is $Q_i = \Delta v_i A$ where A is the borehole cross section.
- For each borehole interval traversed in each half second, the transmissivity is just $T_i = C\,Q/\Delta h_i$ where Δh_i is the head in the borehole while traversing the i^{th} interval in the borehole during each half second. C is a constant dependent on the geometry.

T profile results

- The 6660 data points are integrated from the bottom to the top of the borehole
- The result is the plot of the total T below any elevation in the borehole.
- Hence one knows the transmissivity of any interval in the borehole

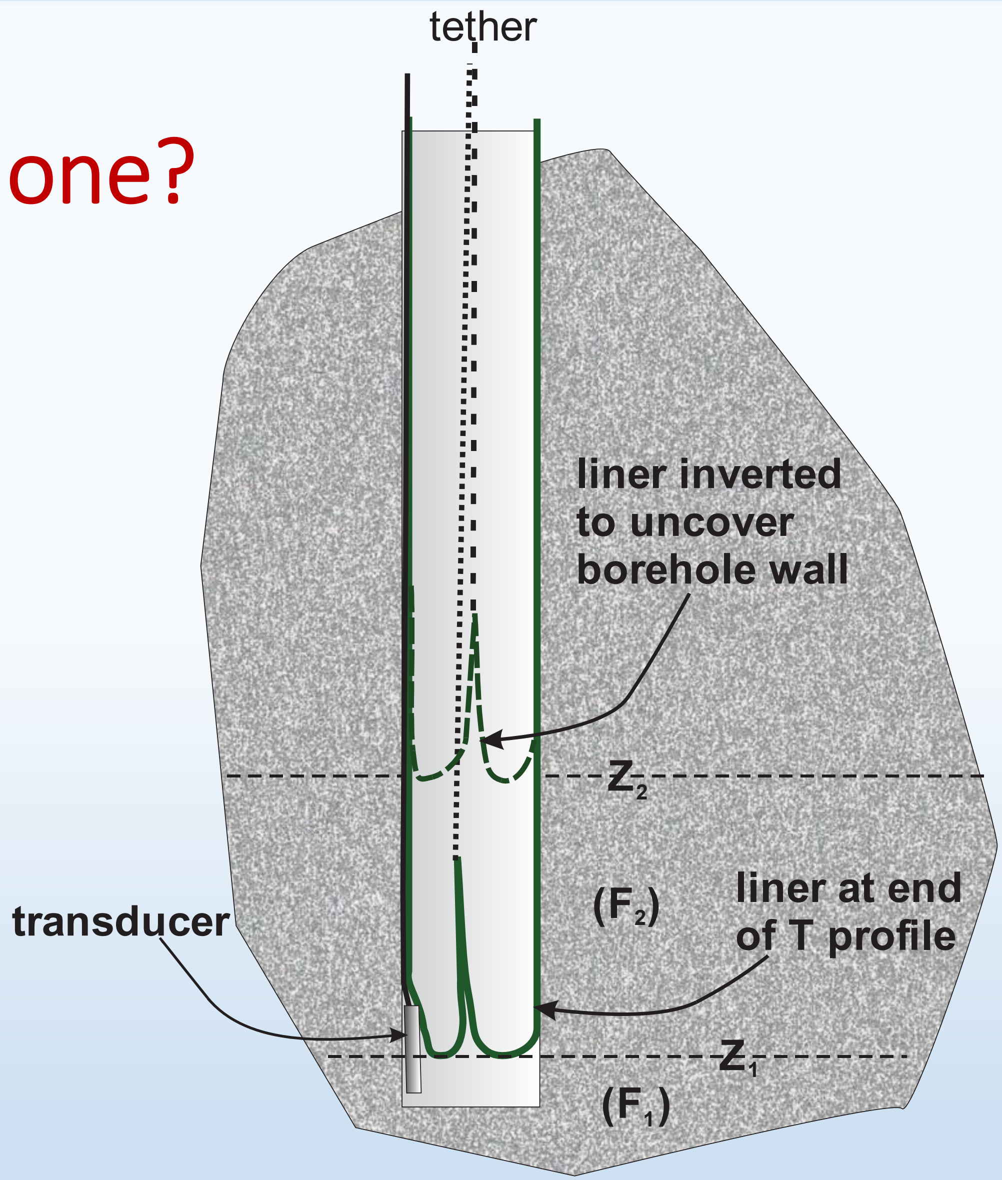




How is the Reverse Head Profile done?

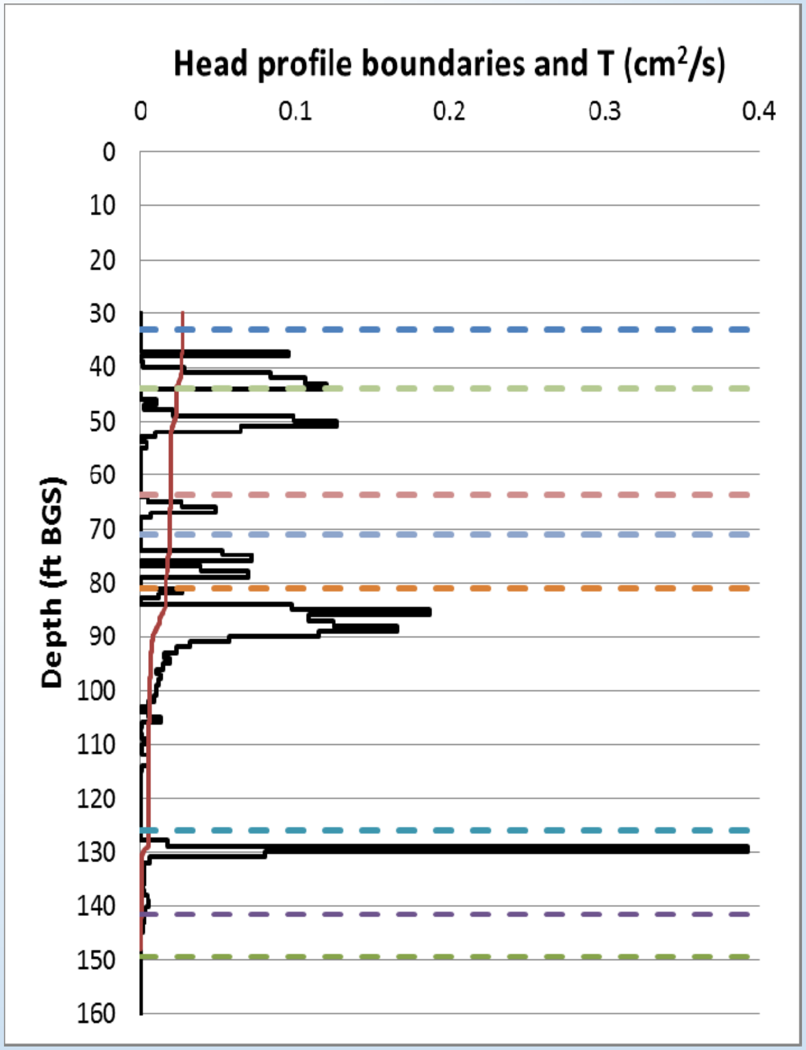
When the T profile is finished,

1. Let the transducer equilibrate in the open borehole.
2. Then, invert the liner one increment (Z_1 to Z_2).
3. Let the transducer equilibrate again.
4. Repeat.



The T plot was used to pick the intervals for the head profile

- The dashed horizontal lines are where each liner inversion for the RHP was halted.
- The intervals selected captured each high flow zone
- A better selection to identify aquitards might also have zones span the low flow zones (e. g. 110-125 ft)



The calculational method is very simple

Q1 is the flow between the formation and the open interval after the T profile is halted.

$$Q1 = T1(BH1-F1)2\pi/\ln R$$

But, upon equilibration, Q1 = 0. Hence, BH1 = F1.

Then a second interval of the borehole is uncovered and the pressure is allowed to equilibrate:

$$Q2 = T2\,(BH2 - F2)\,2\pi/\ln R,$$ is the flow into or out of that new interval.

where BH2 is the new equilibrium head beneath the liner and F2 is the formation head in the newly uncovered portion of the formation. Since the final state is one of equilibrium, then:

Q1+ Q2 = 0, leading to T1 (BH2-F1) + T2 (BH2-F2) = 0. (i.e., the inflow = outflow)

The only unknown is F2. Solving for F2,

$$F2 = T1\,(BH2-F1)/T2 + BH2$$ = the formation head in the newly exposed interval.

For each additional ith interval uncovered, the formation head of that interval is:

$$\mathbf{Fi = \big(\,T1\,(BHi - F1) + T2\,(BHi-F2) + T3\,(BHi - F3)\ \ldots..\big)/Ti\ + BHi}$$

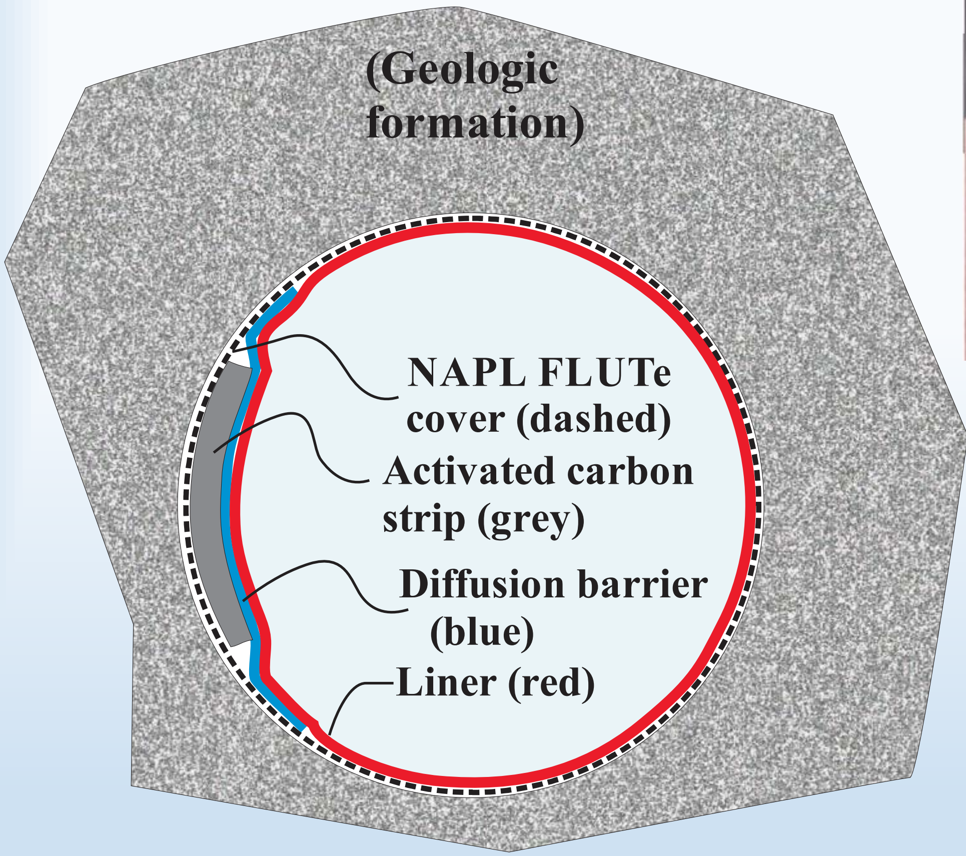
The purpose of the **FACT** (FLUTe Activated Carbon Technique):

- Map the distribution of contamination in the formation with high resolution in an inexpensive manner.
- Produce a replica of the dissolved phase of the contamination using the advantages of a sealing liner to isolate the measurement
- Overcome the disadvantages of straddle packer leakage
- Collect the contaminants from both the pore space, bedding planes and fracture flows in a sealed borehole
- Obtain a spatial resolution much better than traditional practices of water sampling or core measurements.
- Overcome the limitations of the NAPL FLUTe mapping of only the pure product

The FACT wicks the dissolved phase from fractures <u>and</u> the pore space.

- Wicks by diffusion the dissolved phase into an activated carbon felt strip which is recovered by inverting the liner.
- The FACT provides a <u>continuous</u> replica of contamination in pores <u>**and**</u> fractures
- The entire strip should normally be analyzed even if in long segments.
- When combined with the NAPL FLUTe, the NAPL <u>and</u> dissolved phase are both mapped throughout the entire borehole at the same time.

What is the design?

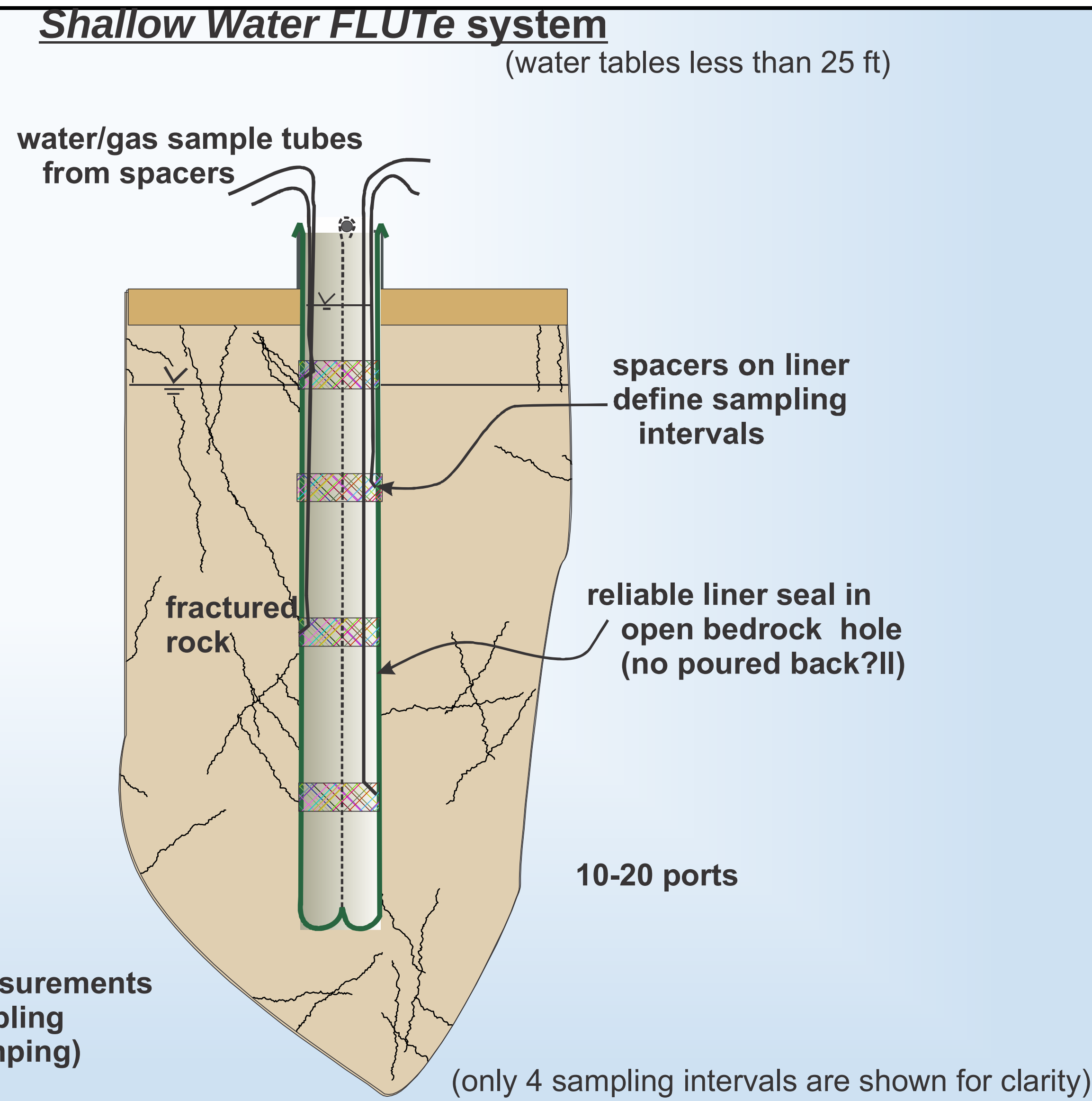


Carbon felt attached Inside NAPL cover

Dye stripped NAPL cover on liner

The new Shallow Water FLUTe design

- Uses the same sealing liner, spacers, tubing in sleeves, as the original Water FLUTe MLS and is fully removable.
- Less expensive, lighter weight, Installs like a blank liner
- Limitation: must use peristaltic pumping.
- Can provide 10-15 sampling Intervals
- The least expensive MLS?



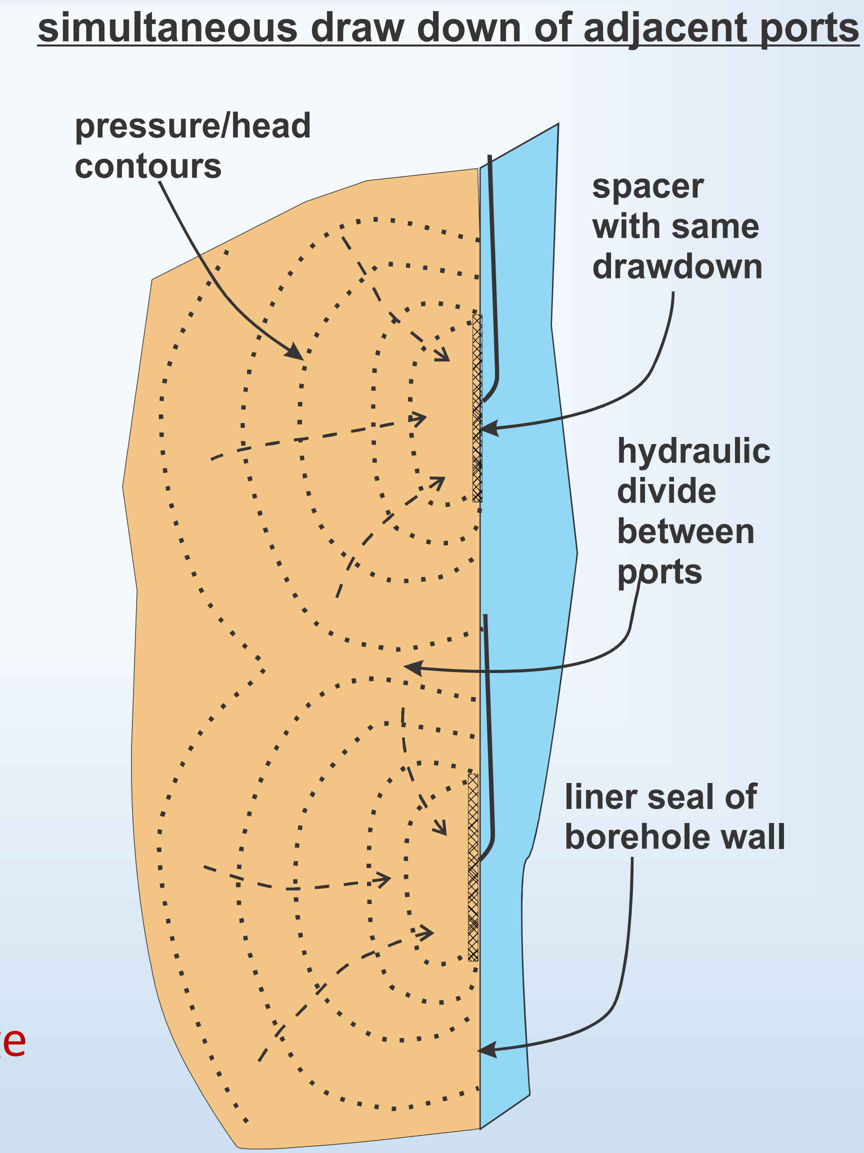
Other Shallow Water FLUTe (SWF) details

- Not practical for water tables less than ~25 ft
- Is available with positive displacement pumping but with half as many ports
- Much lower cost and lower shipping weight and can be installed from air driven canisters.
- Can be simultaneously purged and sampled for a large reduction in sampling time and better sample isolation than sequential purging and sampling as common for low flow sampling.
- Water levels are measured using a vacuum water level meter
- The individual tubing is conveniently connected to air coupled transducers.

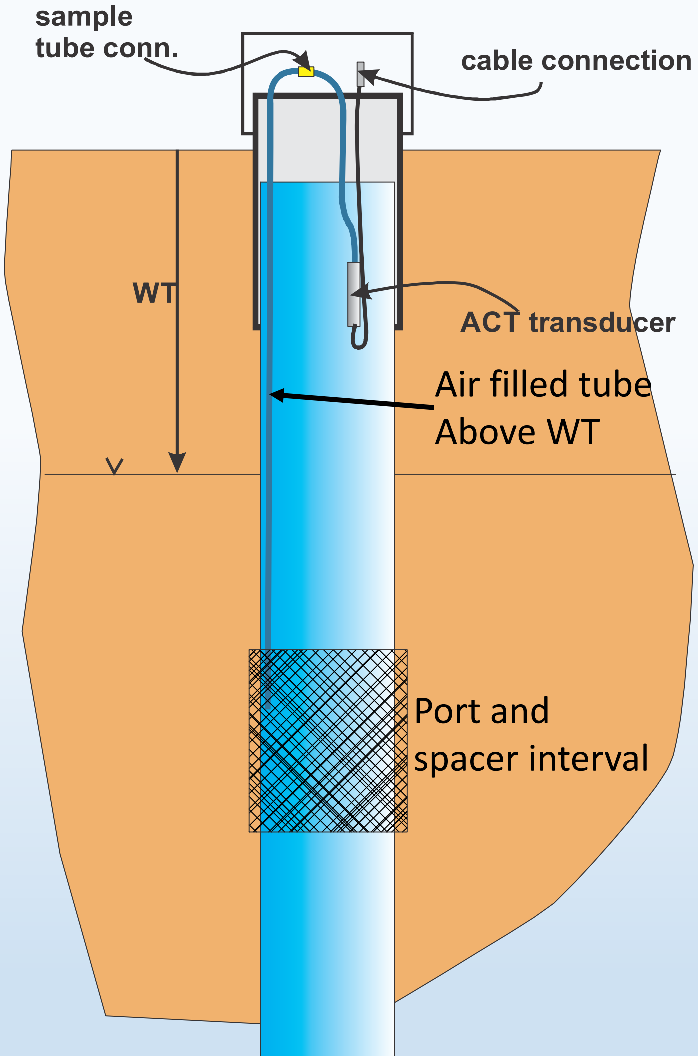
Why is simultaneous sampling optimum for spatial resolution?

- All spacers see the same drawdown
- Each spacer is a low pressure region
- Therefore a high pressure ridge or hydraulic divide develops between each low pressure volume at each spacer
- The high pressure ridge prevents sampling of adjacent spacer source volumes.

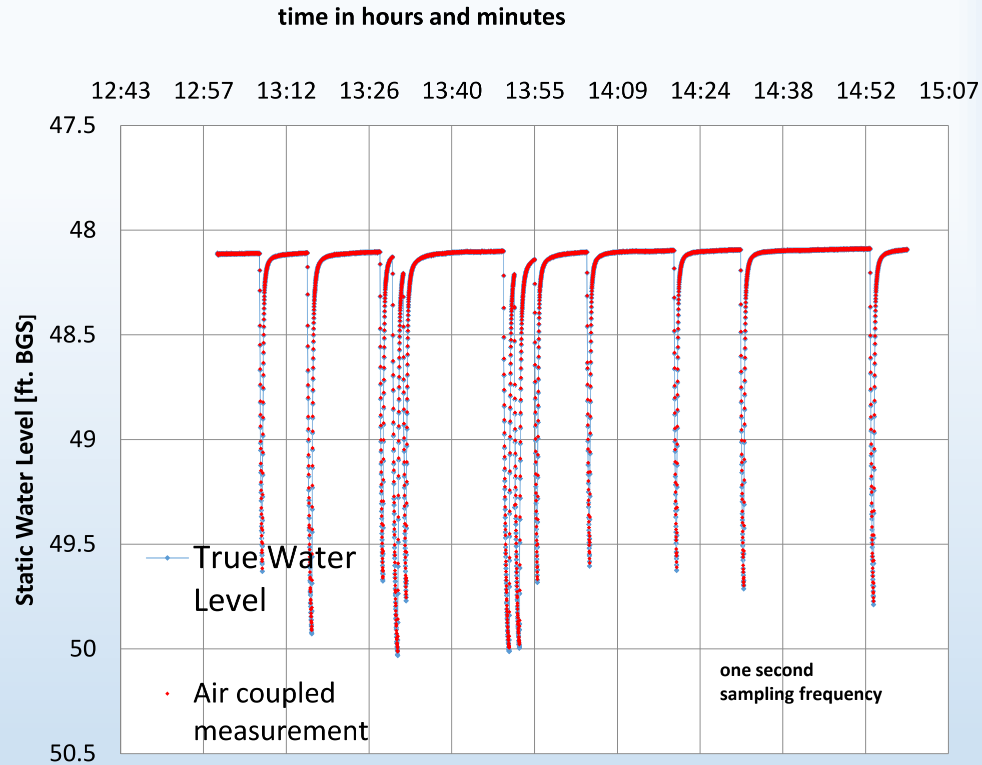
And, it greatly reduces the time to purge



The air coupled transducers are convenient



The ACT tracks the water table with ¼” resolution on the 1 second time scale under ideal circumstances



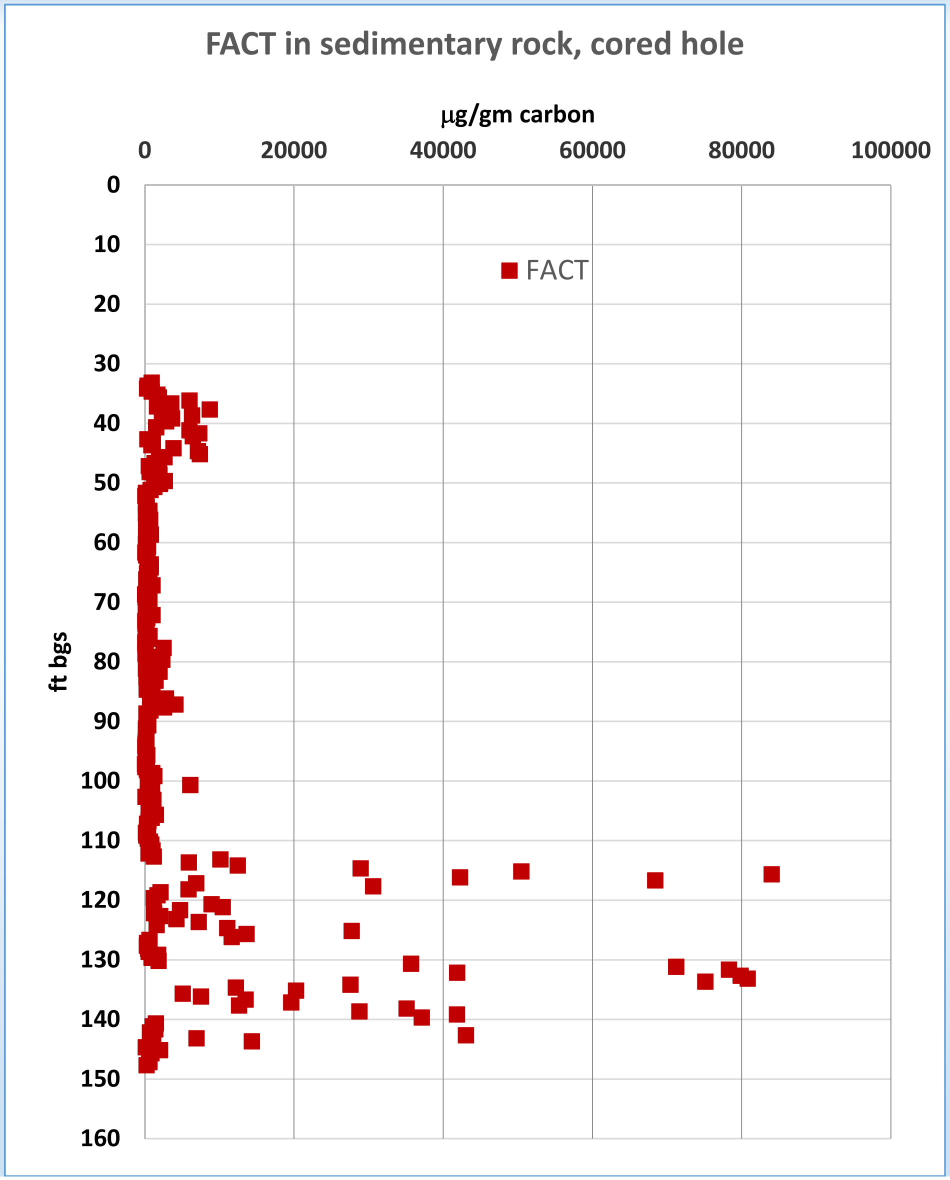
Results at the NAWC site hole no. 94BR

- Geologic formation mud stone with shale and sandstone layers near Trenton NJ
- TCE contamination
- Drilled with HQ core (3.78” diam.) over 3 days time to 150 ft
- Vertical flow rate in borehole of ~10 borehole volumes/day
- Upon NAPL/FACT removal, only a 1 cm stain at ~42 ft. bgs

1. NAPL/FACT installed after geophysics
2. transmissivity profile was done with the same liner
3. Reverse head profile performed after the transmissivity profile
4. Other measurements done in borehole, while mainly sealed with the blank liner
5. Installation then of Shallow Water FLUTe with 10 ports for water sampling with peristaltic pumping and vacuum water level measurements with a pair of ACTs.
6. Later simultaneous sampling of all ports

FACT results in 94BR

- Left in place for 2 weeks
- Sectioned into 6 inch lengths
- Analyzed with methanol extraction of VOCs

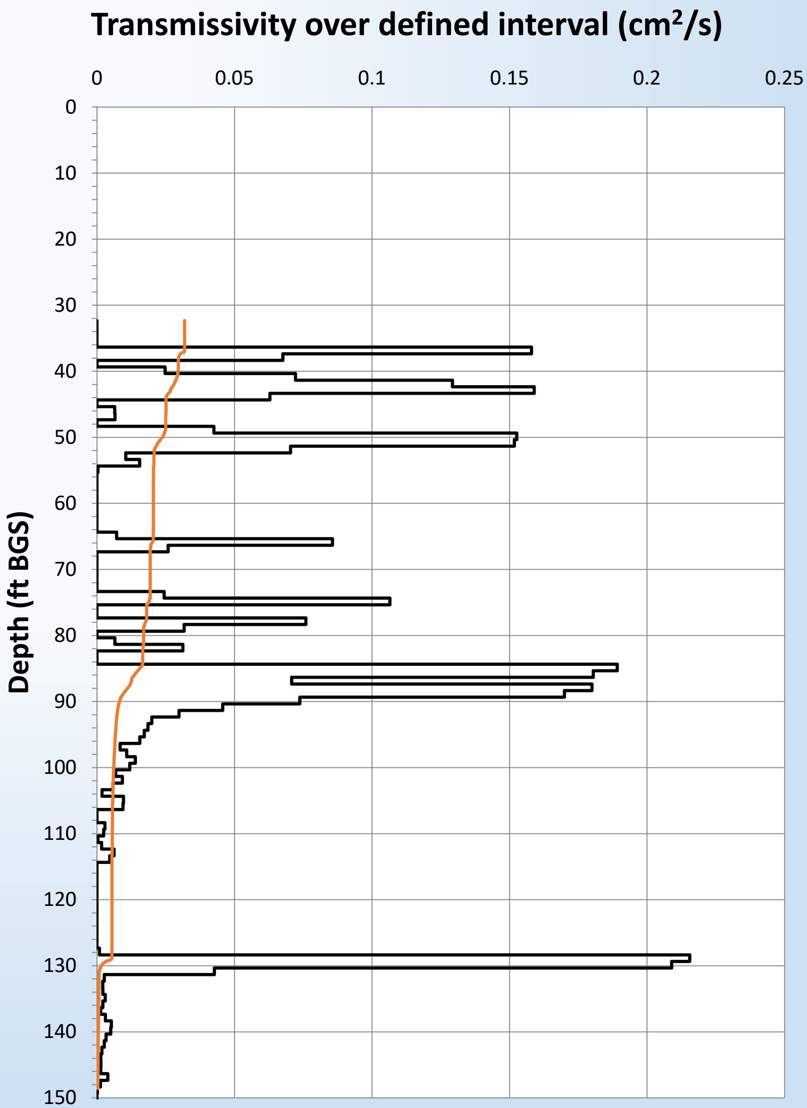


Transmissivity profile results 94BR

Liner descent measured every half second. Data integrated over 1 ft intervals

Equivalent of 110 1 ft straddle packer tests

Time of the actual profile is 0.92 hrs. not counting setup or dismantling of equipment Total time about 3 hrs hrs.



Reverse Head Profile (RHP) in 94BR

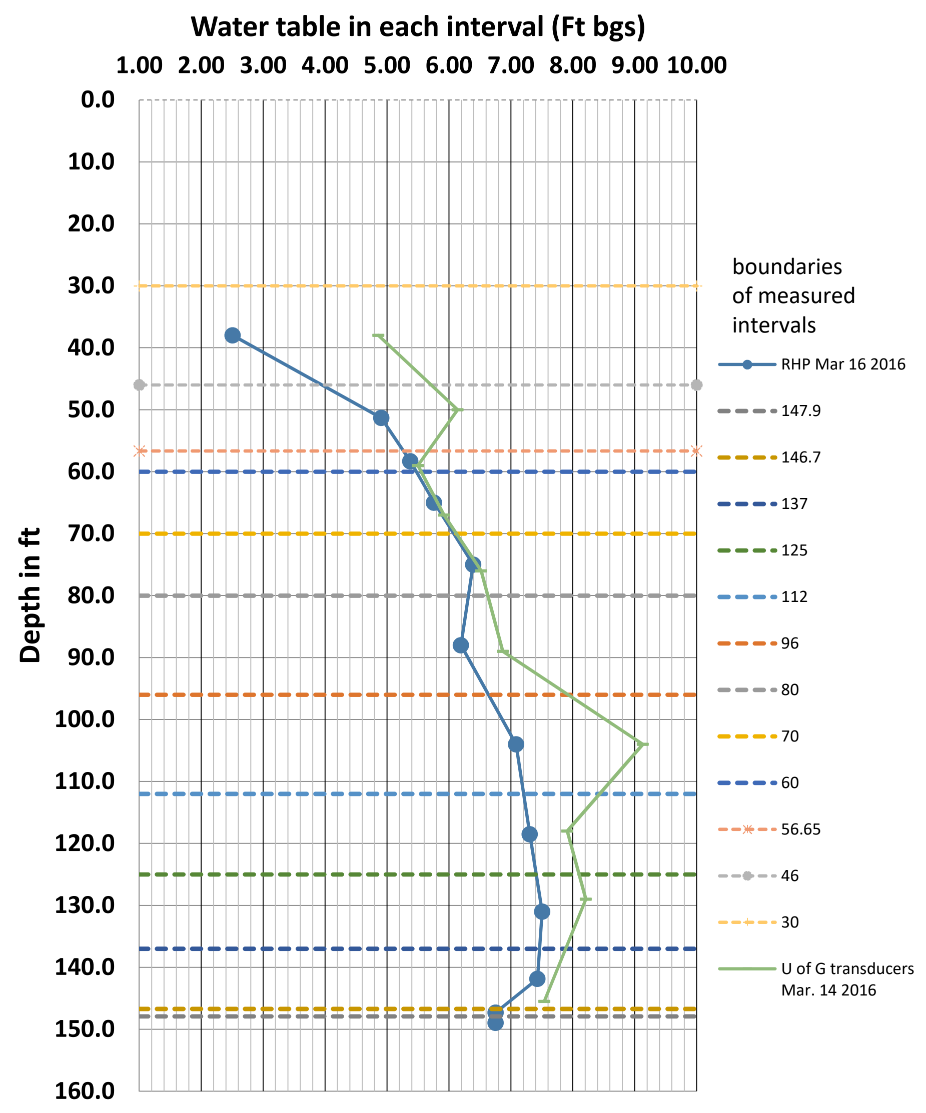
RHP Mar. 16 2016 (blue line)
Horizontal dashed lines are liner stopping points for RHP equilibration

Transducers isolated with a blank liner Mar 14, 2016 (green line)
Another technique using a blank liner.

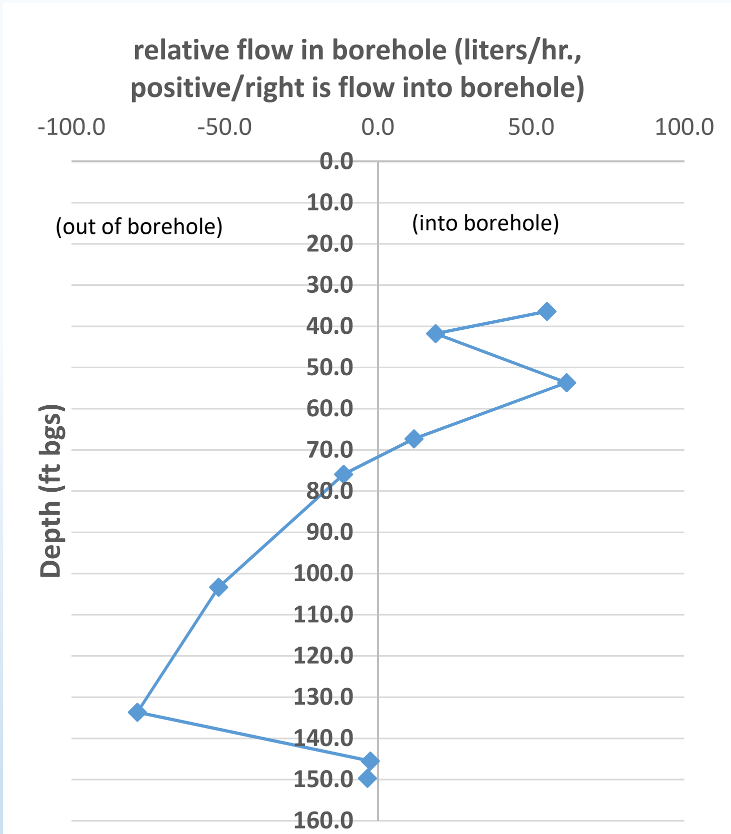
Heavy rain (14th -16th) raised water table at top two points?

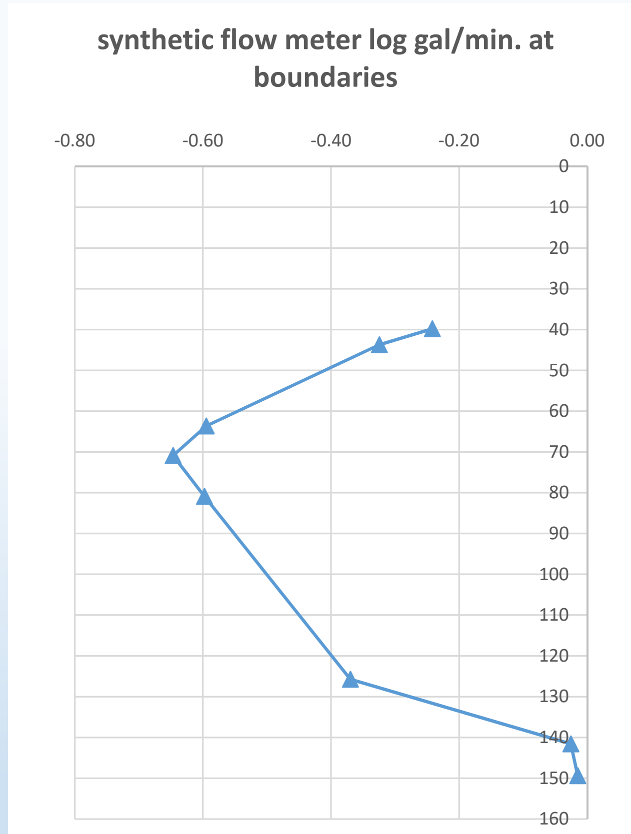
Also large fluctuations of head occur with pumping at lower depths

Note the RHP is only possible with the continuous transmissivity profile



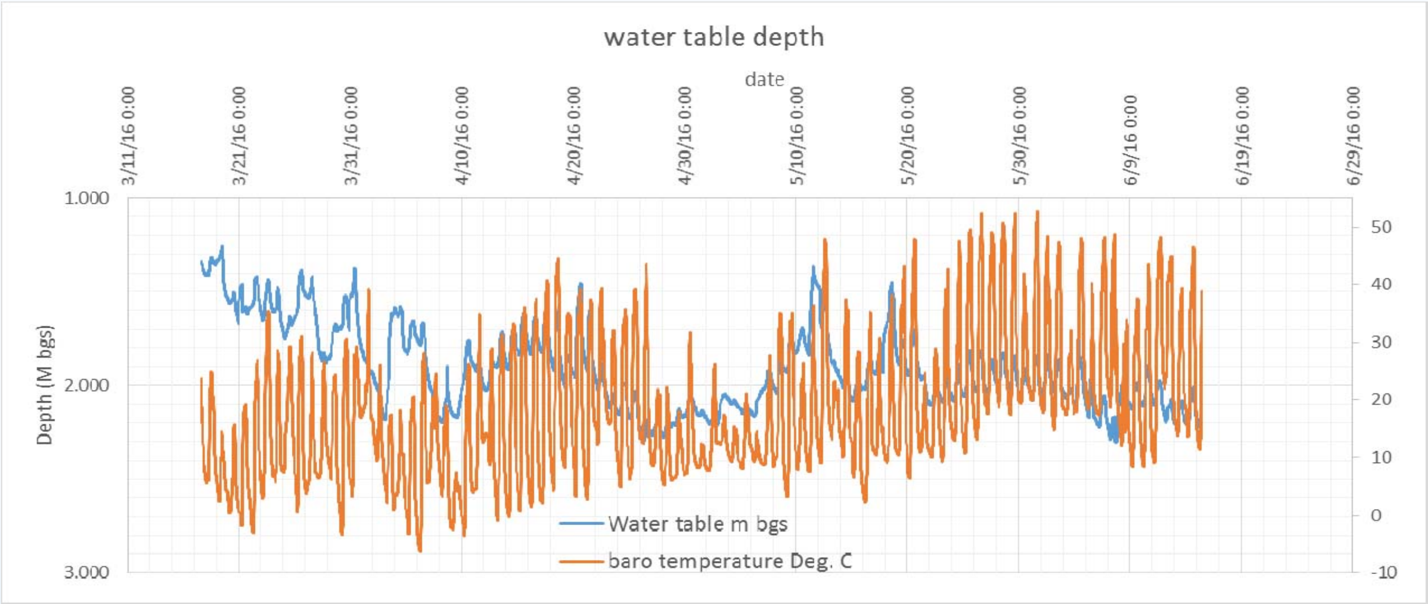
Calculated flow into and out of borehole using RHP and transmissivity profile and the vertical flow calculation for 94BR



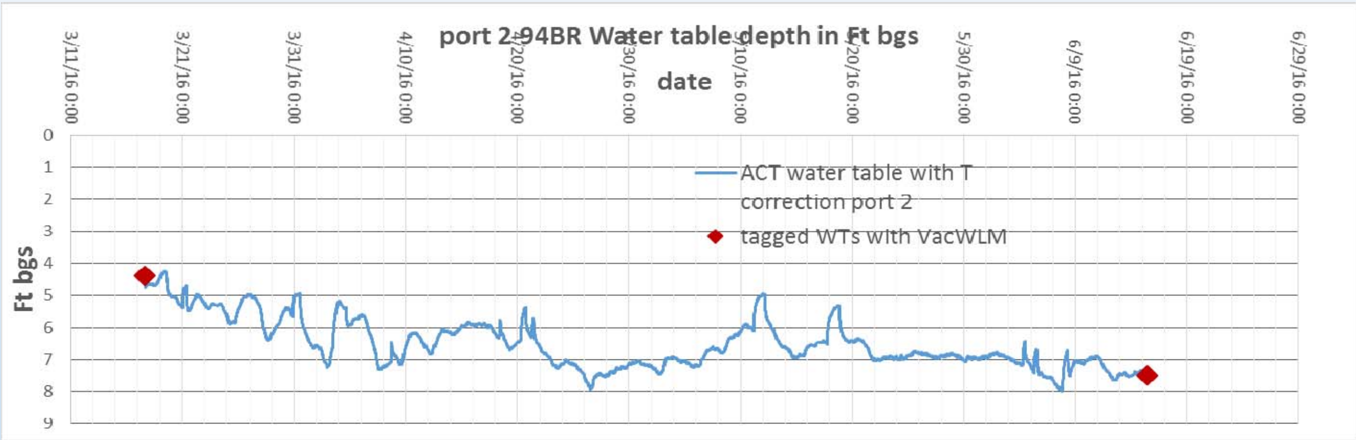


Temperature corrections are important in 94BR

WT without temperature correction (the blue curve).
The Brown curve shows the daily temperature variation (~30 deg. C)



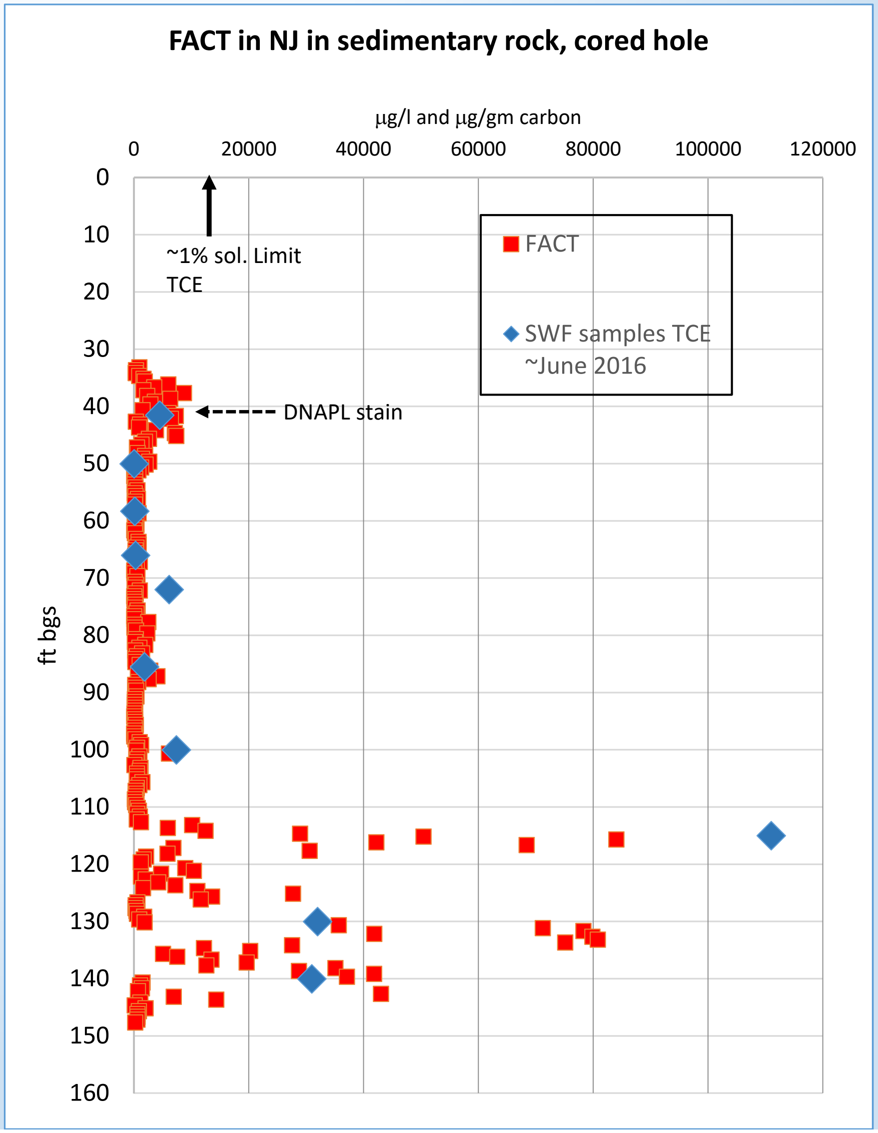
After the temperature correction



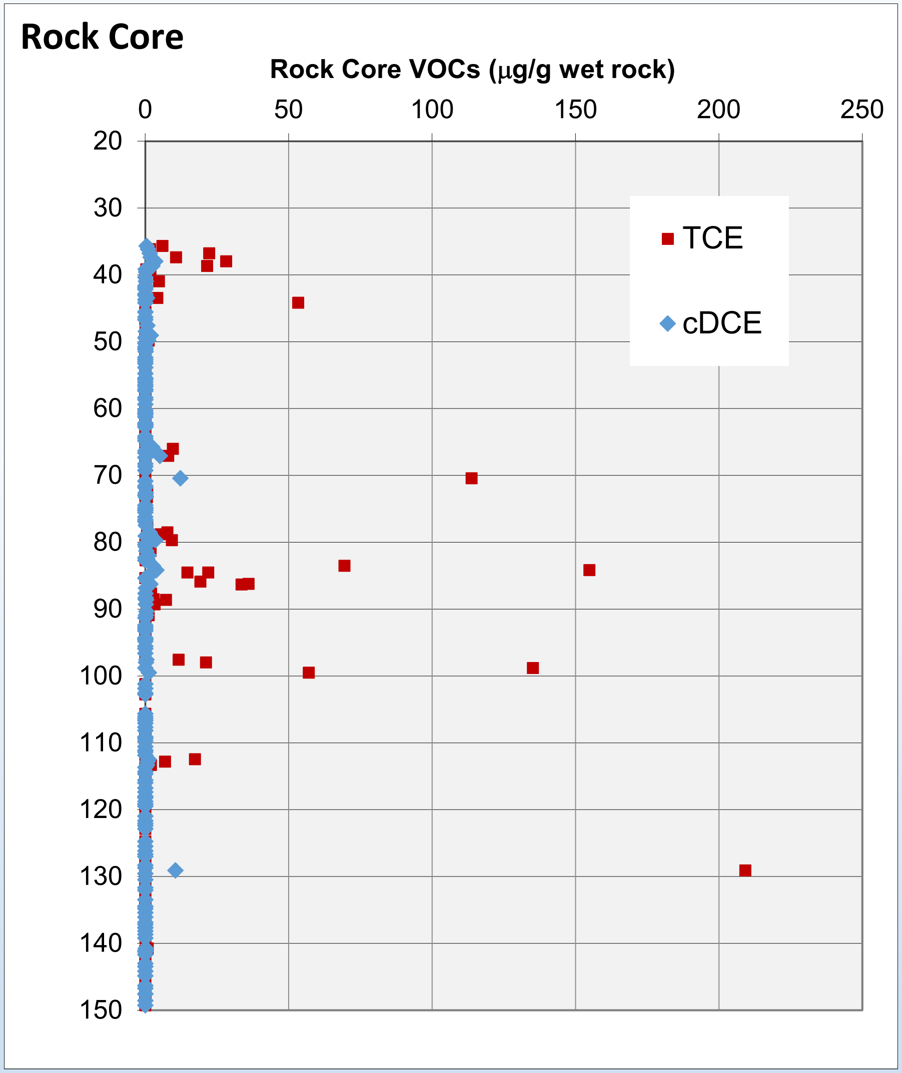
FACT versus SWF Samples

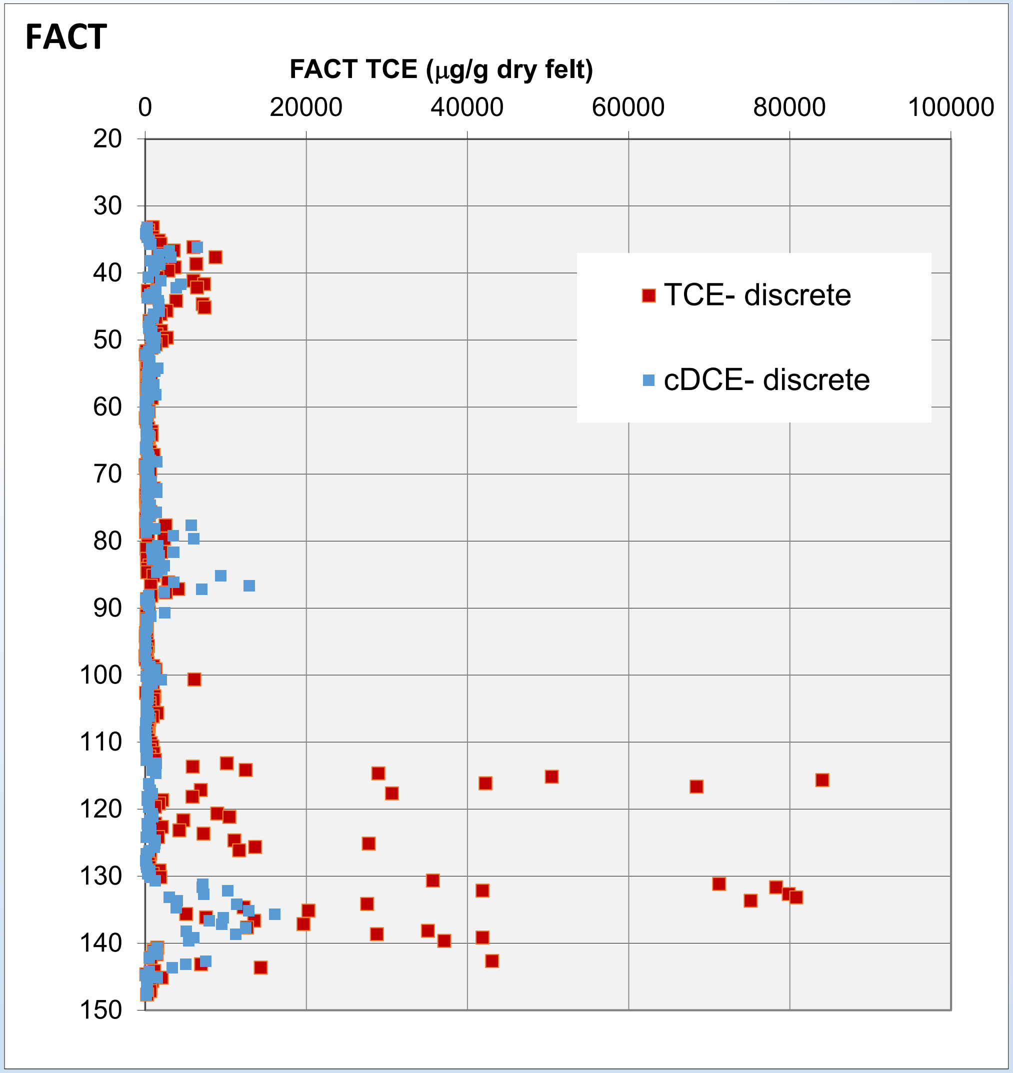
FACT distribution is very similar to that of the SWF (MLS) water samples (FACT is 0.5 ft sample sections) Water sample intervals were 5-10 ft.

Core samples showed most contamination in the upper portion of the borehole



FACT versus Rock Core (TCE with daughters)



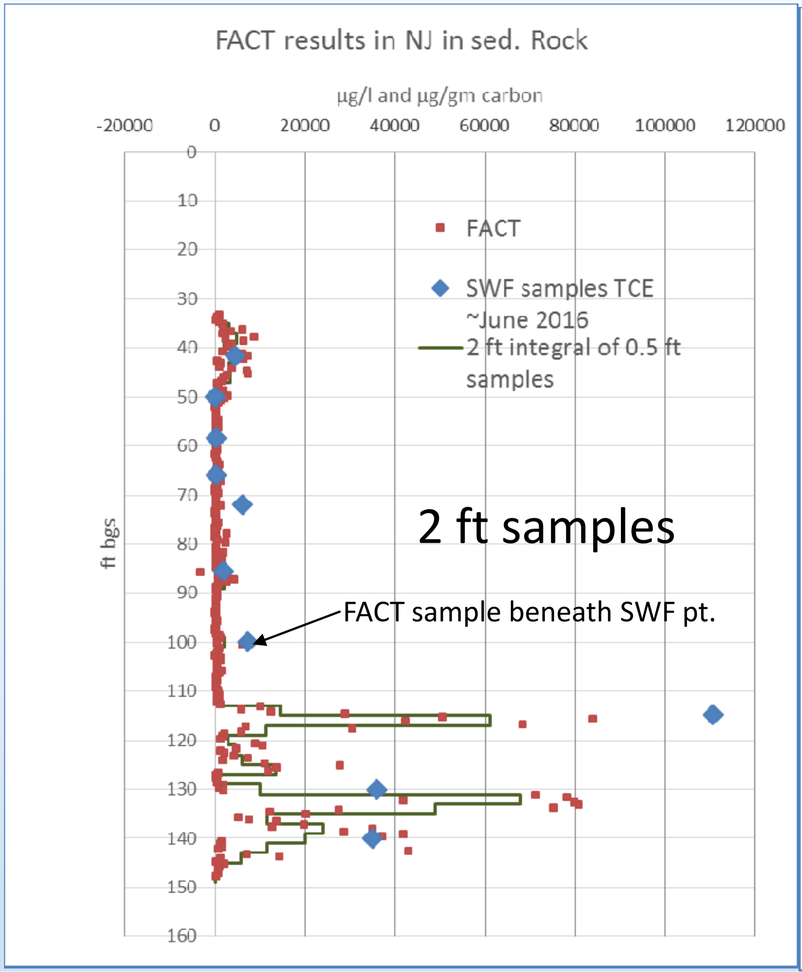


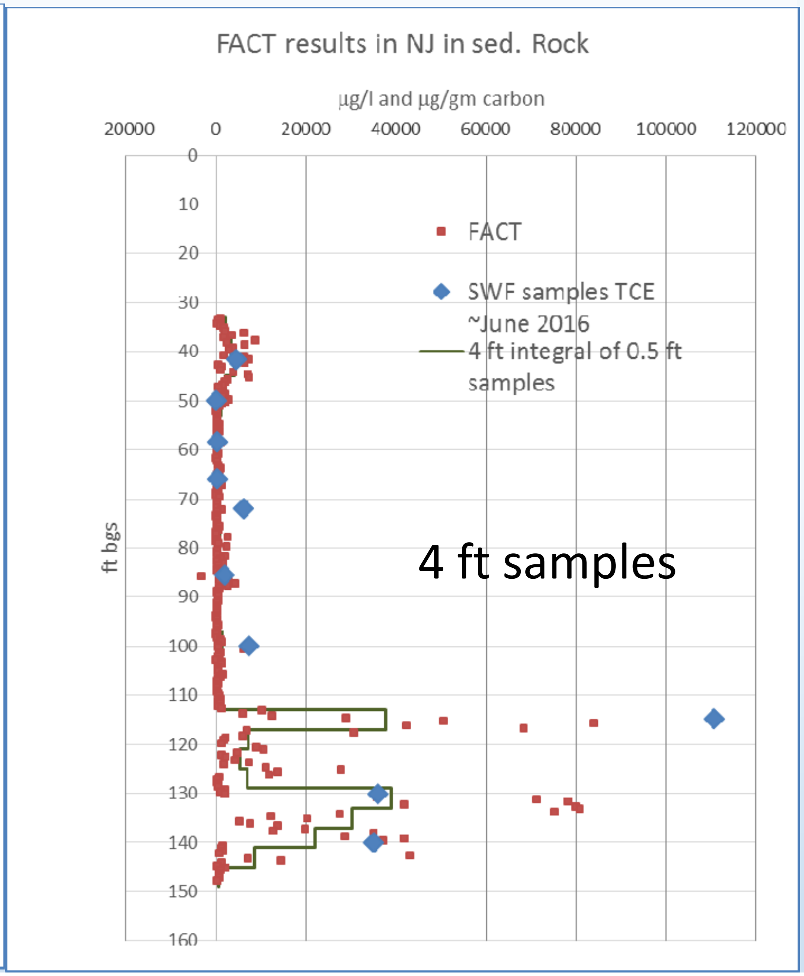
Resolution difference of 0.5 ft to 2 ft to 4 ft samples

red squares are 6" samples

Black graph is integral of 6 inch samples over larger increments

Larger increments miss some hot spots (e.g., 126 and 36 ft)





Significant observations

- FACT results match water sample distributions
- FACT results have some correlation with core high points
- FACT is dominated by fracture flows
- Core does not measure fracture flows
- T profile and RHP were very helpful in assessing potential borehole flow effects on the FACT
- Highest FACT (@115 ft) and water sample results were not at the highest T intervals
- ACT measurements track water table variations very well.

Future work and notes on previous uses

- Future:
  - Currently Refining the NAPL/FACT installation in sonic casing
  - SERDEP testing of FACT in other media such as granite
  - SERDEP testing of FACT in air rotary boreholes at NAWC site
- Past:
  - FACT already in use in MA at several sites and in TN and FL (26 boreholes in first half of 2017)
  - RHP has had other tests in other sites as part of recently published paper.
  - ACTs are in use in many FLUTe MLS liners in a variety of locations
  - T profiles already at hundreds of sites over past 10 years in many countries

Conclusions

- The combined T profile and FACT profile provide very high resolution results
- The T profile is done quickly in less than one day
- The FACT was sampled at half foot intervals but combining the results over 1-2 ft. intervals preserves much of the distribution at half to one fourth the analysis cost.
- The FACT sectioning and preparation for shipment was relative rapid and easily done in less than half a day per borehole with pre-marked NAPL covers.
- Additional assessments of the FACT in less expensive boreholes such as air rotary drilled holes are planned under a current SERDEP project.
- The FACT method has been successfully used in Denmark with excellent results and in MA and TN this year in 26 boreholes. The T profile has been done in several hundred boreholes. The RHP method is very new but published in the NGWA Groundwater journal.

Acknowledgements

- Co-authors are all currently involved in a SERDEP project for assessing the FACT and they have done the sample analysis and core measurements.
- Mette Broholm did much of the initial evaluation of the FACT activated carbon characteristics at the Danish Technical University with her graduate students.
- My coworkers who have done the actual field installations of these systems and are most essential to the quality of the results, including Mark Higgins who has gone on for graduate work.

Thanks for your attention

- More information at www.flut.com
- Or call me at 505-930-1154