Overview of Sampling Methods for Bedrock Monitoring Wells

Allen M. Shapiro, USGS

USEPA-USGS Fractured Rock Workshop
EPA Region 10
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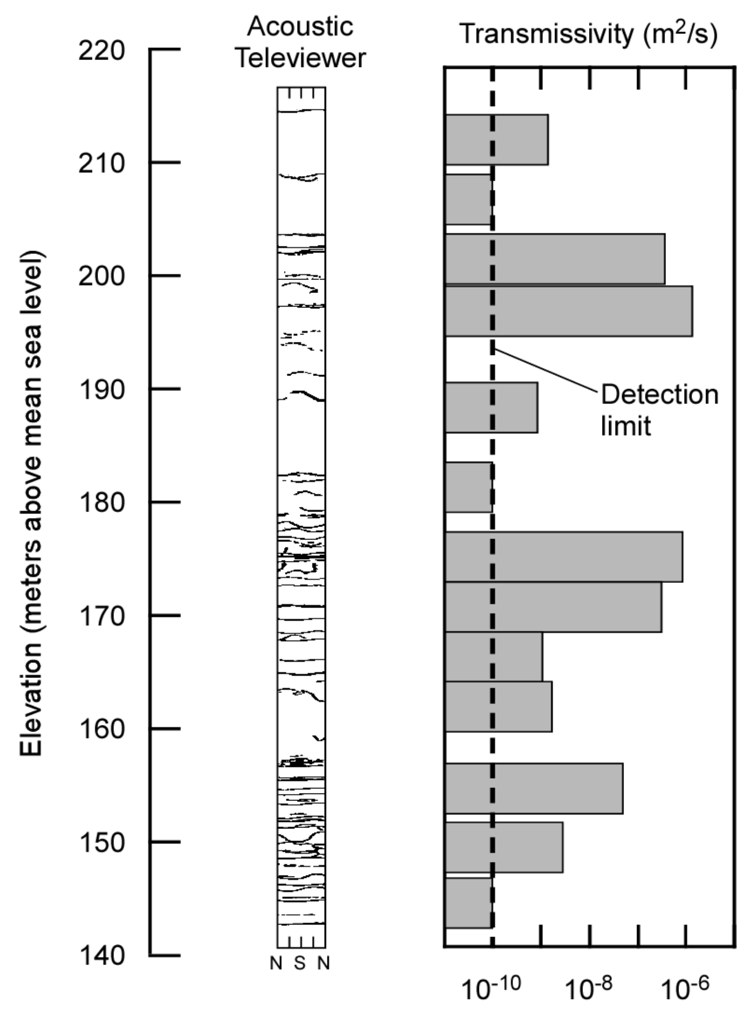
Geochemical sampling in fractured rock – Borehole Construction

- Regulatory constraints and guidelines (often) dictate length of monitoring intervals at sites of groundwater contamination (e.g., NJ DEP requires monitoring intervals not to exceed 20 feet)
- "Short" open intervals in monitoring wells are intended to prevent spreading of contaminants
- What is a "short" interval ?

Borehole wall image log & transmissivity of individual or closely spaced fractures



Borehole H1

Granite and schist
Mirror Lake, NH

Geochemical sampling in fractured rock – Borehole Construction

Significance of ambient borehole flow:

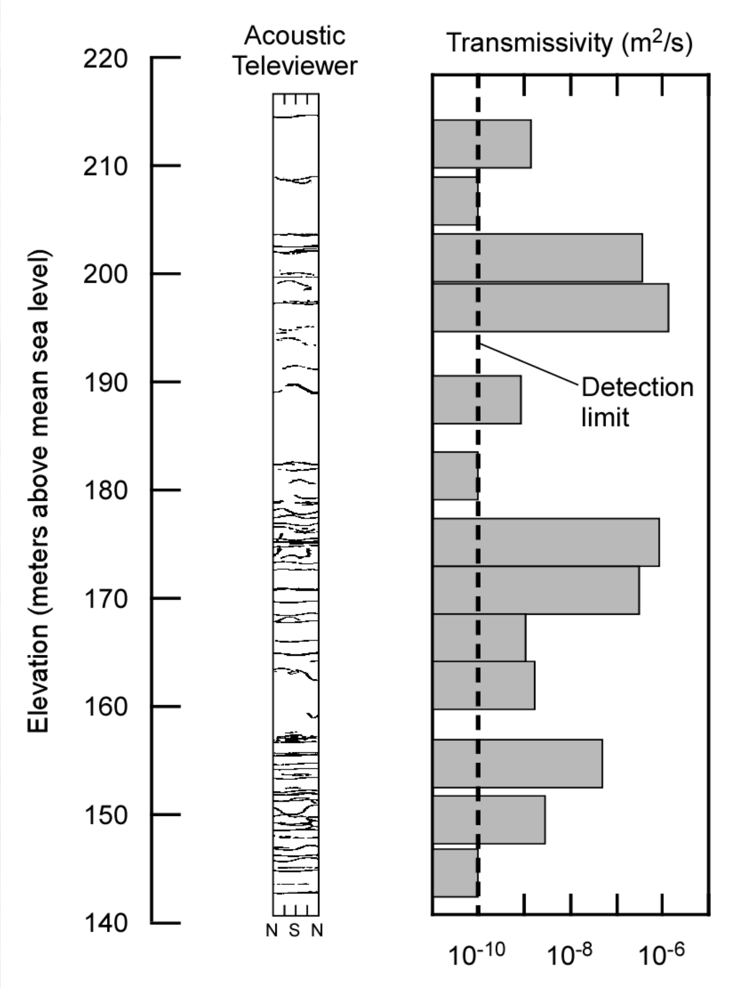
•Downward flow at 0.2L/min
= 288 L/day = 105,120 L/yr
= ~ 76 gal/day = ~27,800 gal/yr

•At sites of groundwater contamination, potential spreading of contaminants over a larger volume of the aquifer

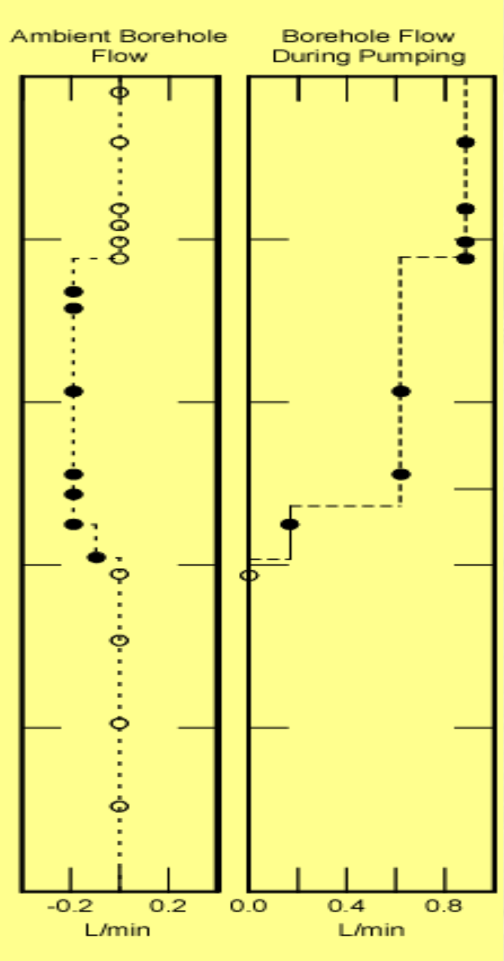
•History of open hole conditions is needed to identify if water samples are representative of formation water from particular fractures

Granite and Schist
Mirror Lake Watershed, NH

Single-hole hydraulic tests conducted in borehole H1

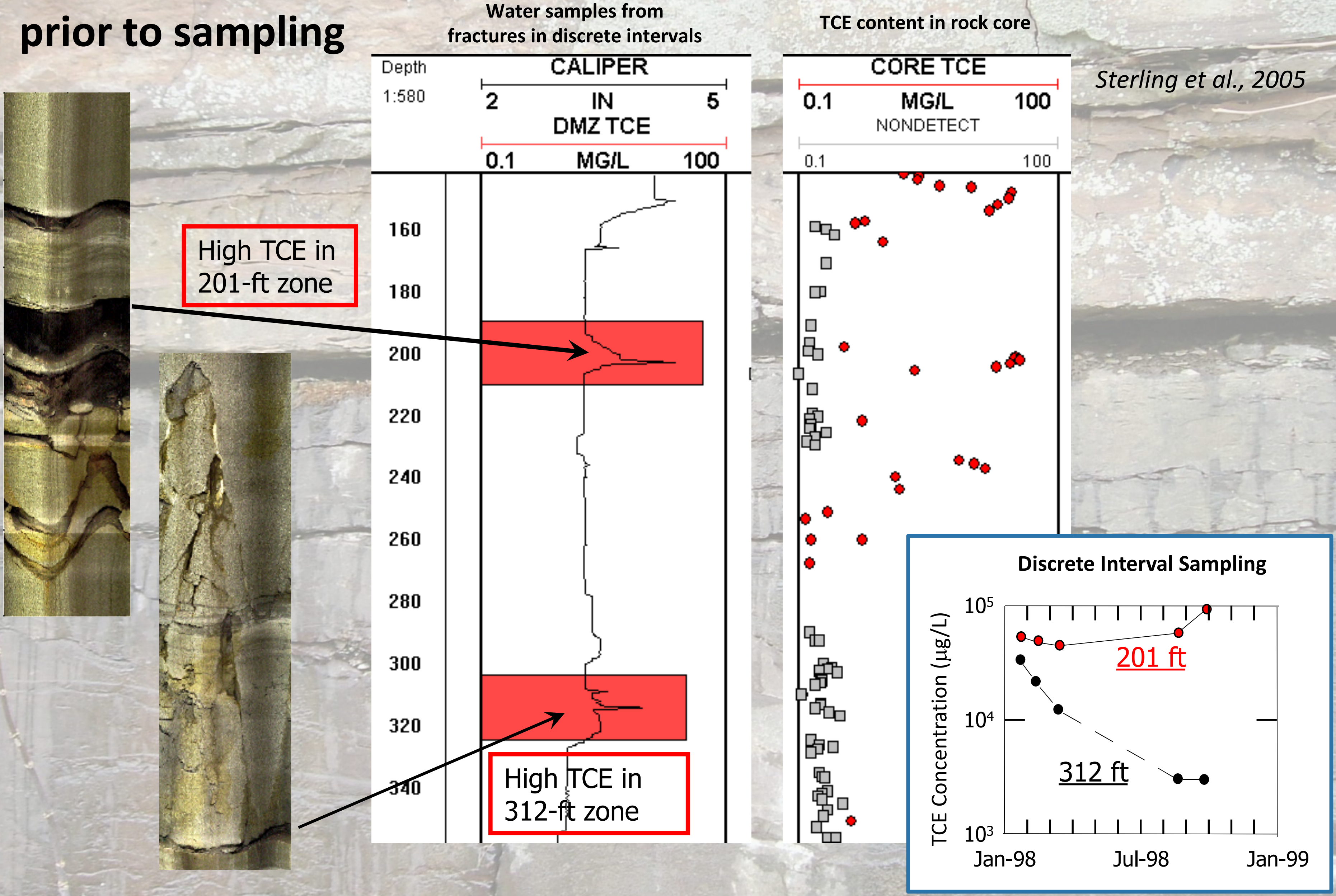


Borehole flowmeter survey conducted in borehole H1



Geochemical sampling in fractured rock – Borehole conditions prior to sampling

Sterling et al., 2005



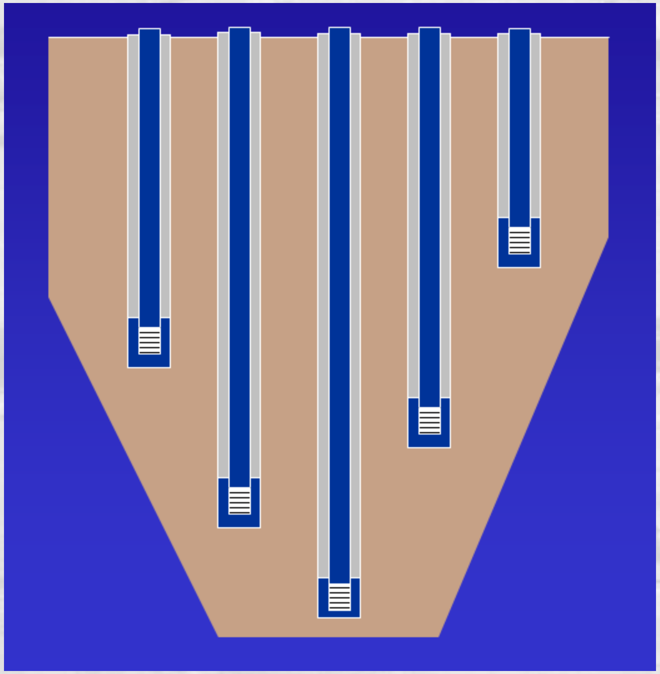
High TCE in 201-ft zone

High TCE in 312-ft zone

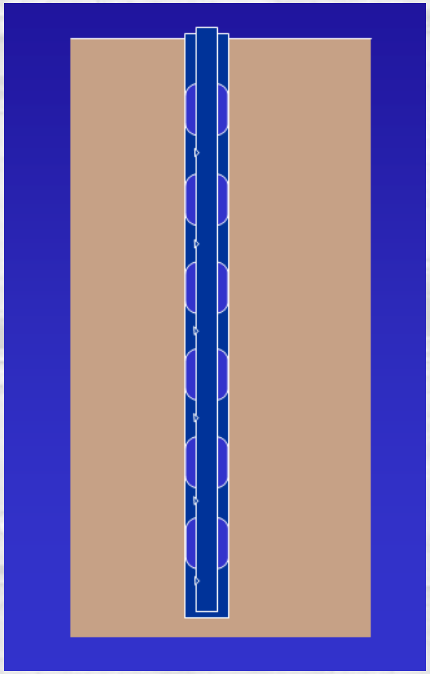
Leaving a borehole open for only a few days can have an adverse impact. . .

Geochemical sampling in fractured rock – Multilevel Monitoring

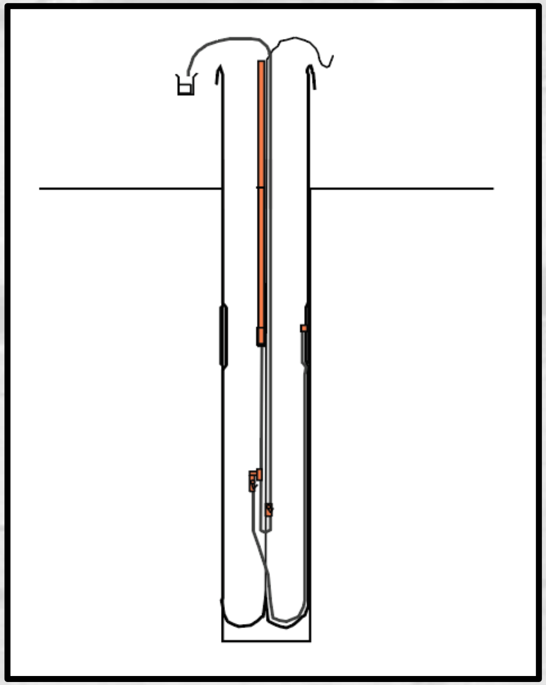
Nested piezometers (short open intervals in a single hole or closely spaced holes)



Multiple packers (permanent or removable)



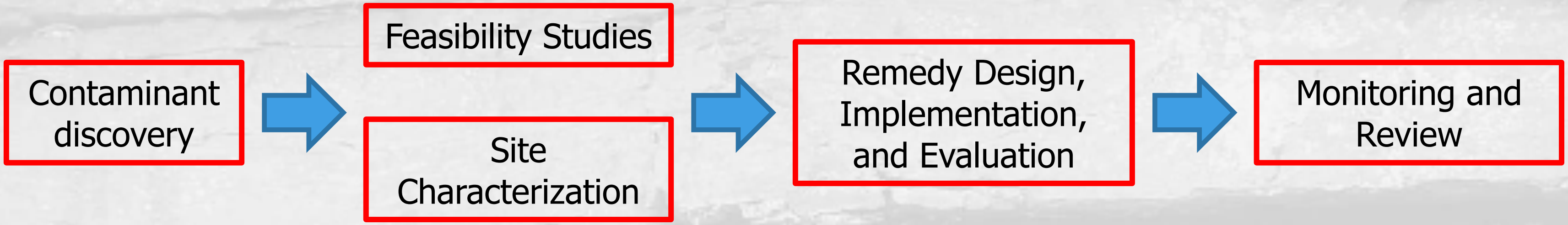
Flexible Liner (with one or more ports)



- Decisions on **borehole construction** and **instrumentation**, and **methods of collecting water** samples for geochemical analyses are **connected**
- Some sampling methods are incompatible with types of borehole construction and instrumentation
- **Decisions** on borehole construction and instrumentation, and geochemical sampling methods **should evolve over the time line of site activities and milestones**

Geochemical sampling in fractured rock – Evolving over the time line of site milestones

Time Line of Milestones at Sites of Groundwater Contamination



- Establish criteria for sampling design and sample collection for each milestone
- ***Contaminant discovery and site characterization*** in fractured rock – 3D characterization of source zone and extent of contaminant plume – samples associated with discrete locations and discrete times (characterization of mobile groundwater in fractures)
- ***Engineered remedies*** - sampling frequency and spatial design should capture spatial and temporal changes that are important in evaluating engineered action (e.g., pump-and-treat, amendment injection, reactive barrier installation, etc.) – is quarterly sampling sufficient to understand processes and outcomes?
- ***Compliance monitoring*** may be able to use less expensive sampling procedures (e.g., diffusion bag, grab samples, etc.). . .but **recognize what these samples represent** and how they should be interpreted to address milestone objectives

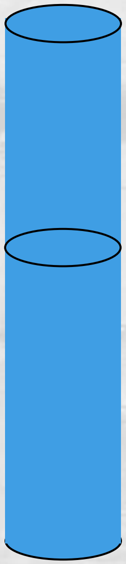
Physics of fluid sample collection in fractured rock

- The transmissivity of fractures intersecting the open interval of the borehole affect geochemical sample collection. . .

- Borehole characteristics also play a role in understanding the source of groundwater collected during sampling. . .affect

Assuming cylindrical borehole and parabolic velocity profile at any cross section:

Hydraulic Conductivity of Geologic Materials



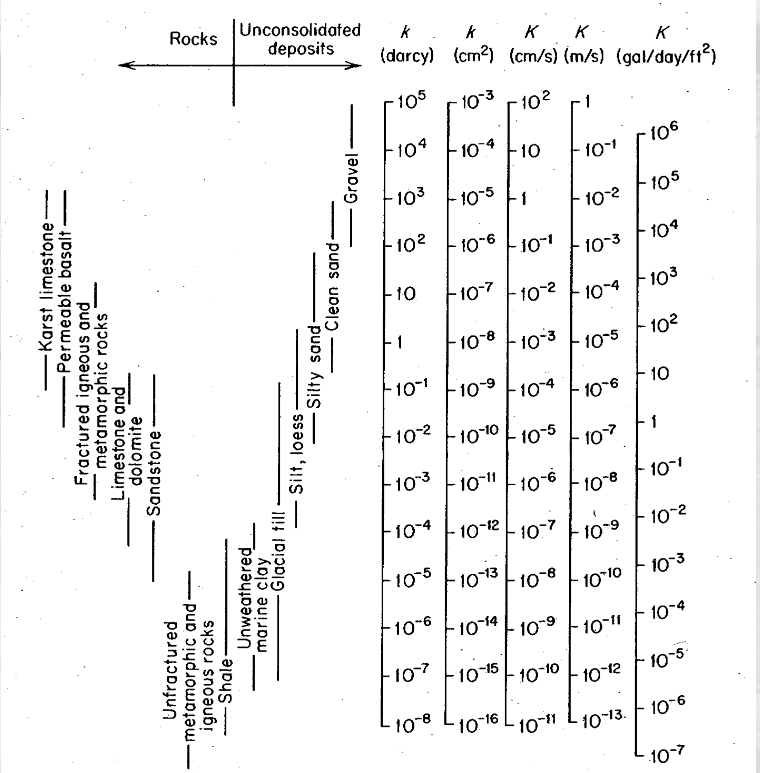
Effective hydraulic conductivity of the borehole, K_b

For example. . .

$$r_s = 0.25 \text{ ft}$$

$$K_b = 7.6 \text{ x } 10^9 \text{ ft/day}$$

$$= 2.7 \text{ x } 10^4 \text{ m/s}$$

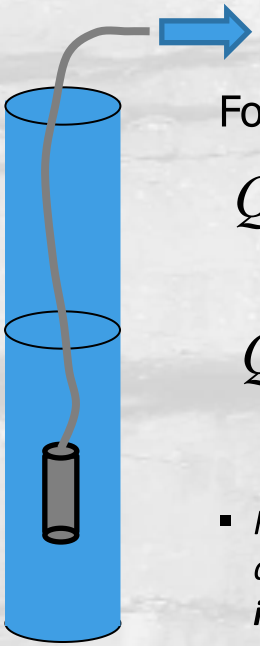


- *Effective hydraulic conductivity of a **borehole is orders of magnitude greater** than most geologic materials. . .*

Freeze and Cherry, 1979

Physics of fluid sample collection in fractured rock

Pumping fluid from the water column in the borehole:



Q_b

For example. . . $r_s = 0.25$ ft $K_b = 7.6 \text{ x } 10^9$ ft/day

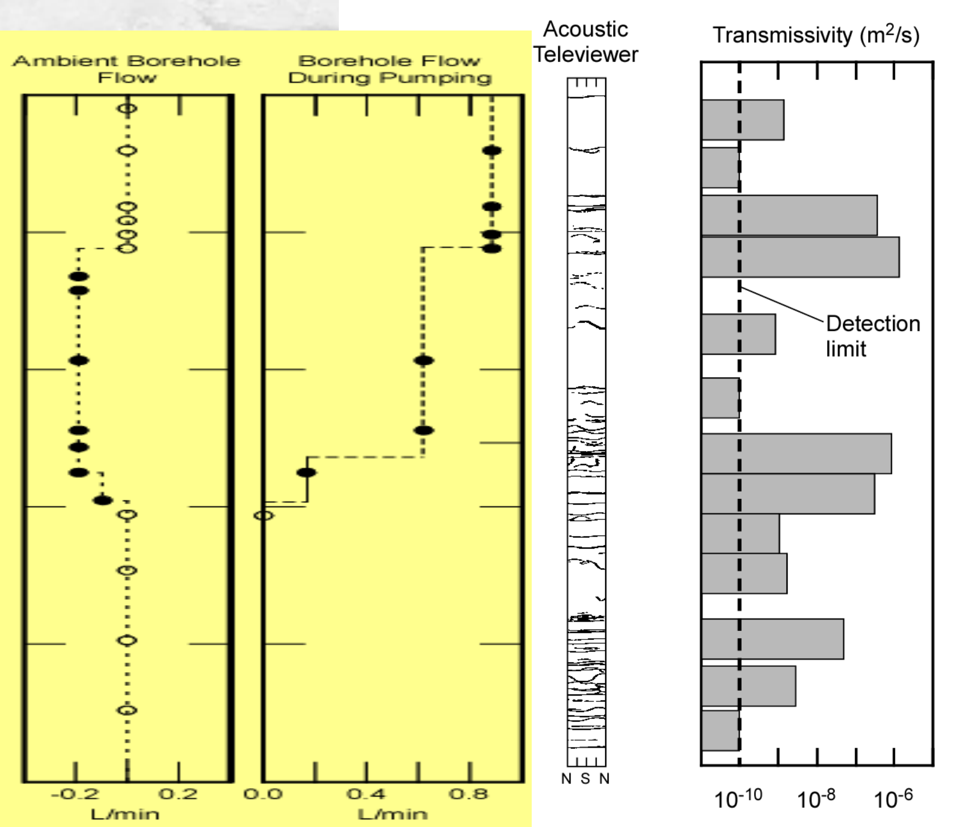
$Q_b = 0.25$ gpm (pumping rate often attributed to low-flow purging)

$$Q_b = \pi r_s^2 K_b \frac{dh}{dz}$$

$$\frac{dh}{dz} =$$

- *Reducing hydraulic head uniformly along the length of the borehole will **induce flow from the most permeable fractures** intersecting the borehole. . .**regardless of the location of the pump intake**. . .*
- *Ambient borehole flow conditions will also affect the contribution of fractures contributing to the pump discharge. . .*

Borehole wall image log and transmissivity of discrete intervals in borehole H1



Physics of fluid sample collection in fractured rock

TCE Concentration form discrete interval in 36BR (open interval 102 – 125 ft bls):

89,000 µg/L

Hydraulic testing conducted in 36BR:

Transmissivity of 36BR-A (102 – 112 ft bls) – 1.0 x 10^{-5} m^2/s

Transmissivity of 36BR-B (112 – 125 ft bls) – 1.0 x 10^{-7} m^2/s

TCE Concentration form discrete interval in 36BR-A (102 – 112 ft bls):

19,000 µg/L

<u>Flux averaged concentration:</u>

$C_{openhole} = C_A \times (1.00/1.01) + C_B \times (0.01/1.01)$

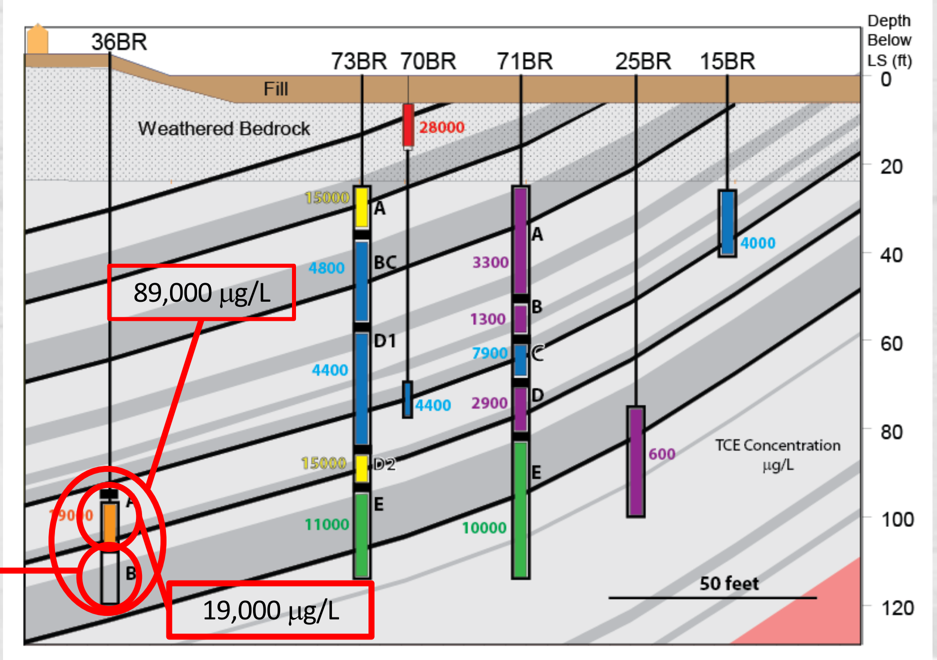
$C_{openhole} = 89{,}000\ \mu g/L \qquad C_A = 19{,}000\ \mu g/L$

<u>Solve for C_B:</u>

$C_B > 1{,}000{,}000\ \mu g/L$

Naval Air Warfare Center (NAWC), West Trenton, NJ, Lockatong Mudstone

TCE Concentration in discrete intervals of boreholes



89,000 µg/L

19,000 µg/L

>1,000,000 µg/L

possible presence of NAPL-phase TCE !!

Physics of fluid sample collection in fractured rock

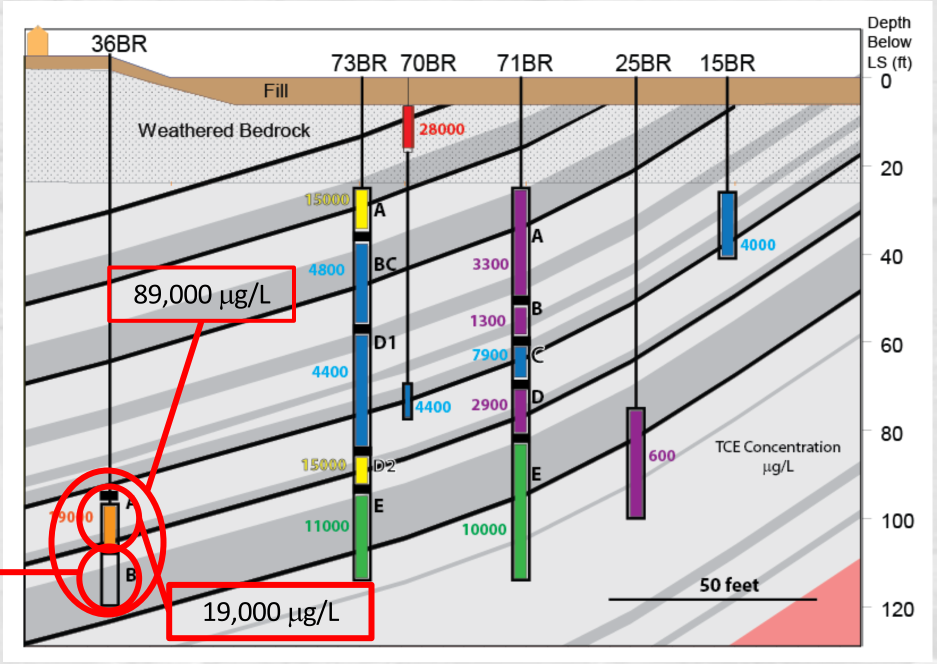
- Flux-average concentration from multiple fractures may disguise contribution of low-permeability fractures and bias the interpretation of contaminant mass distribution in the formation

- Geochemical sampling for characterization should be conducted on fractures having a wide range of transmissivities, not only those fractures with the highest transmissivities that are easiest to pump. . .

- Borehole completion and monitoring should consider fractures/intervals that that are important to addressing project objectives. . .not only those fractures/intervals that are easiest to pump. . .

Naval Air Warfare Center (NAWC), West Trenton, NJ, Lockatong Mudstone

TCE Concentration in discrete intervals of boreholes



89,000 µg/L

19,000 µg/L

>1,000,000 µg/L

possible presence of NAPL-phase TCE !!

Physics of fluid sample collection in fractured rock – hydraulic considerations

- Transmissivity of fractures in discrete intervals varies of orders of magnitude

- Estimate of transmissivity (T) from interpretations of single-hole hydraulic tests (Thiem equation):

$$T = \frac{Q}{2\pi\left(H - h_w\right)} \ln\left(\frac{R}{r_w}\right)$$

- Consider sampling in an a discrete interval

$T = 10^{-7}$ m²/s Q = 100 ml/min

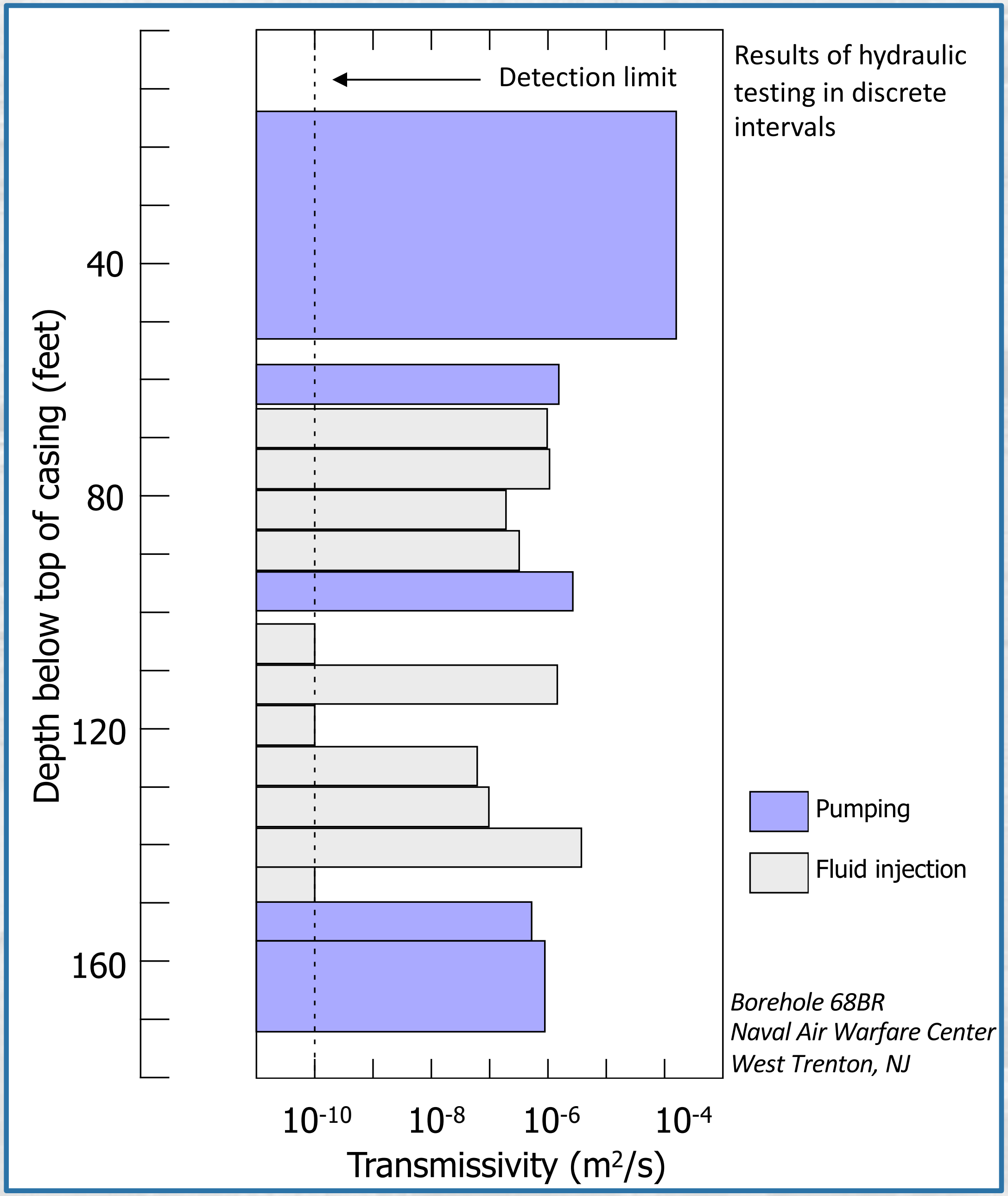
R = 10 m r_w = 0.075 m

- Projected drawdown in the sampled interval

➡ $\Delta h = H - h_w =$ 81.5 m

- *Sampling from low-permeability discrete intervals is challenging*

- *Intermittent pumping may be needed to purge and sample low-permeability intervals*

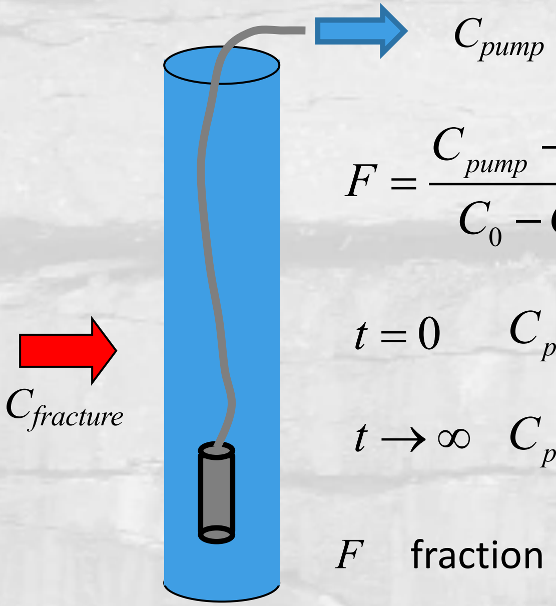


Results of hydraulic testing in discrete intervals

Borehole 68BR
Naval Air Warfare Center
West Trenton, NJ

Physics of fluid sample collection in fractured rock – volumetric mixing in the borehole

A simple model of (complete) borehole mixing (borehole fluid & formation water):



$$F = \frac{C_{pump} - C_{fracture}}{C_0 - C_{fracture}} = e^{-\frac{tQ}{V}}$$

$$t = 0 \quad C_{pump} = C_0 \Rightarrow F = 1$$

$$t \to \infty \quad C_{pump} = C_{fracture} \Rightarrow F = 0$$

F fraction of borehole fluid in sample

t time
Q pumping rate
V fluid volume in borehole
C_0 initial concentration in borehole
C_{pump} concentration in pumped water
$C_{fracture}$ concentration in formation water

For:
V = 30 L (~5 ft interval of a 6-inch borehole)

Q = 100 mL/min

300 min (= 5 hrs) to remove 1 borehole volume

F = 0.75 → tQ/V = 0.29 t = 87 min = 1.45 hrs

F = 0.50 → tQ/V = 0.69 t = 207 min = 3.45 hrs

F = 0.25 → tQ/V = 1.39 t = 417 min = 6.95 hrs

F = 0.05 → tQ/V = 3.00 t = 900 min = 15 hrs

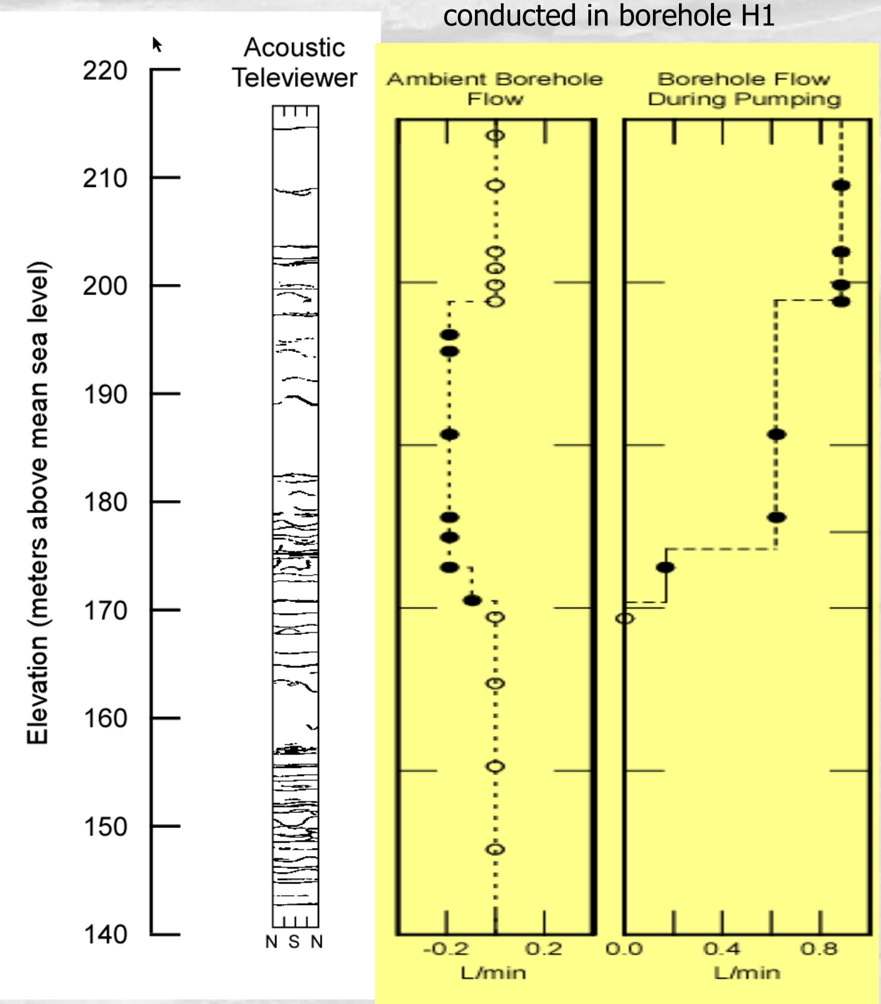
Physics of fluid sample collection in fractured rock – volumetric mixing in the borehole

What is the relation between C_0 and time varying C_{pump}? . . . may not be a well mixed volume. . .***understand borehole conditions to justify volume purged*** to collect samples representative of the (mobile) fluid in fractures

For (most) sampling in fractured rock, the goal is to ***minimize the volume of the sampling interval . . .***

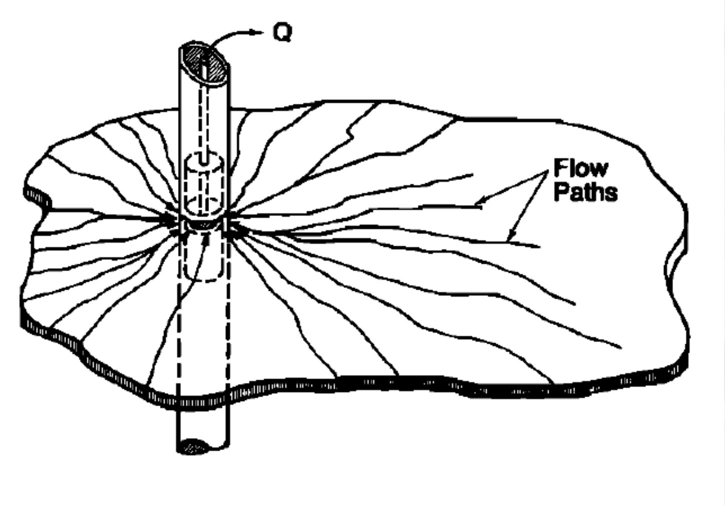
- minimizes the disturbance on the chemical distribution in the formation. . .
- . . .however, the volume of fluid in the borehole may be large relative to the volume of fluid in fractures. . .
- how large an area around the borehole are your interrogating ?

Borehole flowmeter survey conducted in borehole H1



Physics of fluid sample collection in fractured rock – the fluid sample is representative of . . . ?

- ***Fractures have small*** **porosity . . .**
- *Volume of **fluid in the sampling interval may be large relative to the volume of fluid in fractures** intersecting the sampling interval*
- ***Preferential flow paths in fractures** extend volume of rock interrogated by sampling*
- ***Fluid samples are not representative of a small volume of the rock/fractures adjacent to the sampling interval***
- For (most) fluid sampling in fractured rock, the goal is to ***minimize the volume of the sampling interval . . .***
- *Consider volume of sampling interval in designing borehole completion and instrumentation*
- *Borehole completion and instrumentation serve multiple purposes. . .short intervals appropriate for geochemical sampling. . .is there adequate spatial coverage to describe hydraulic head for characterizing groundwater flow?*



Consider borehole volume for sampling interval:

V = 30 L (~5 ft interval of a 6-inch borehole)

Assume: (1) planar fracture with aperture, b, (2) radial flow:

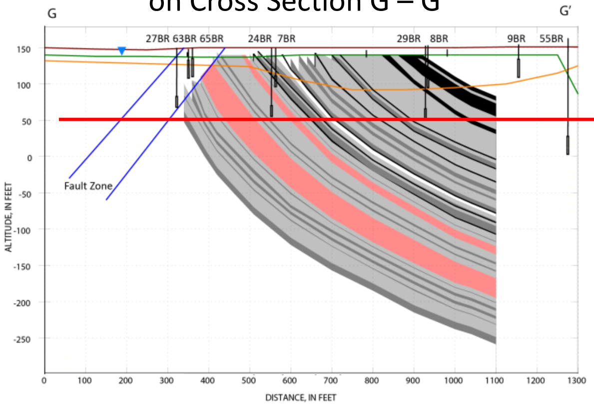
What is the area around the sampling interval in the formation that will be associated with 1, 2, or 3 borehole volumes?

Fluid sample collection in fractured rock – sampling the mobile groundwater

Naval Air Warfare Center, West Trenton, NJ

Interpretation of TCE concentrations in ***mobile groundwater*** . . .water samples extracted from ***permeable fractures*** intersecting monitoring intervals (~20 ft sections of borehole)

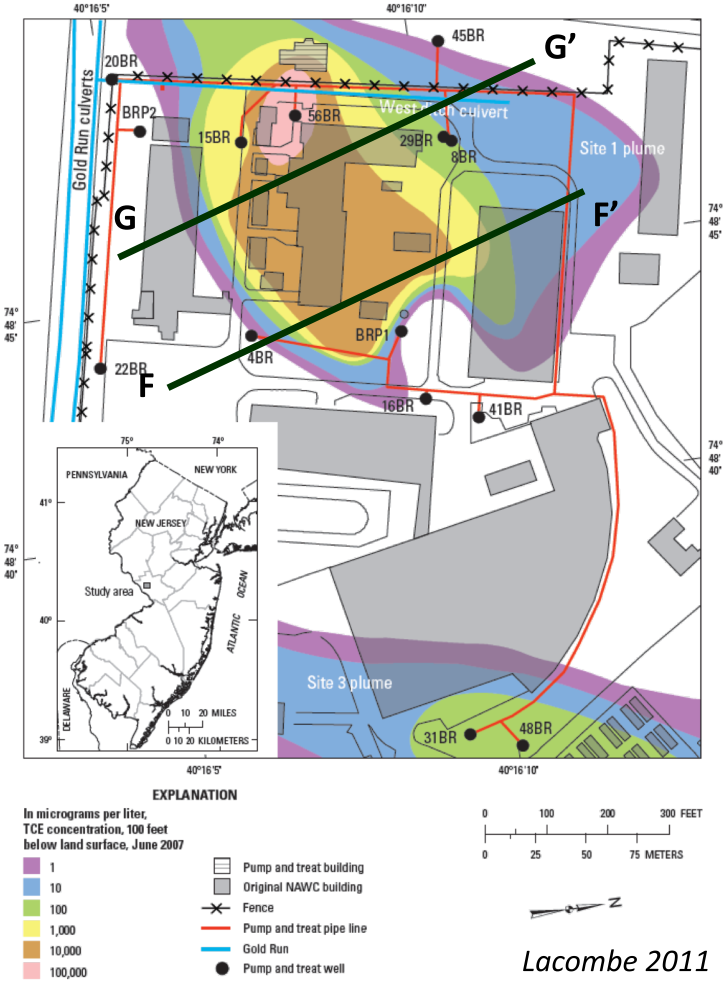
Mudstone units of the Lockatong Formation on Cross Section G – G'



100 ft below land surface

- Are these isocontours of aqueous concentrations from fractures a physically meaningful way of characterizing contaminant mass in fractured rock ?
- Are they useful in designing remediation strategies ?

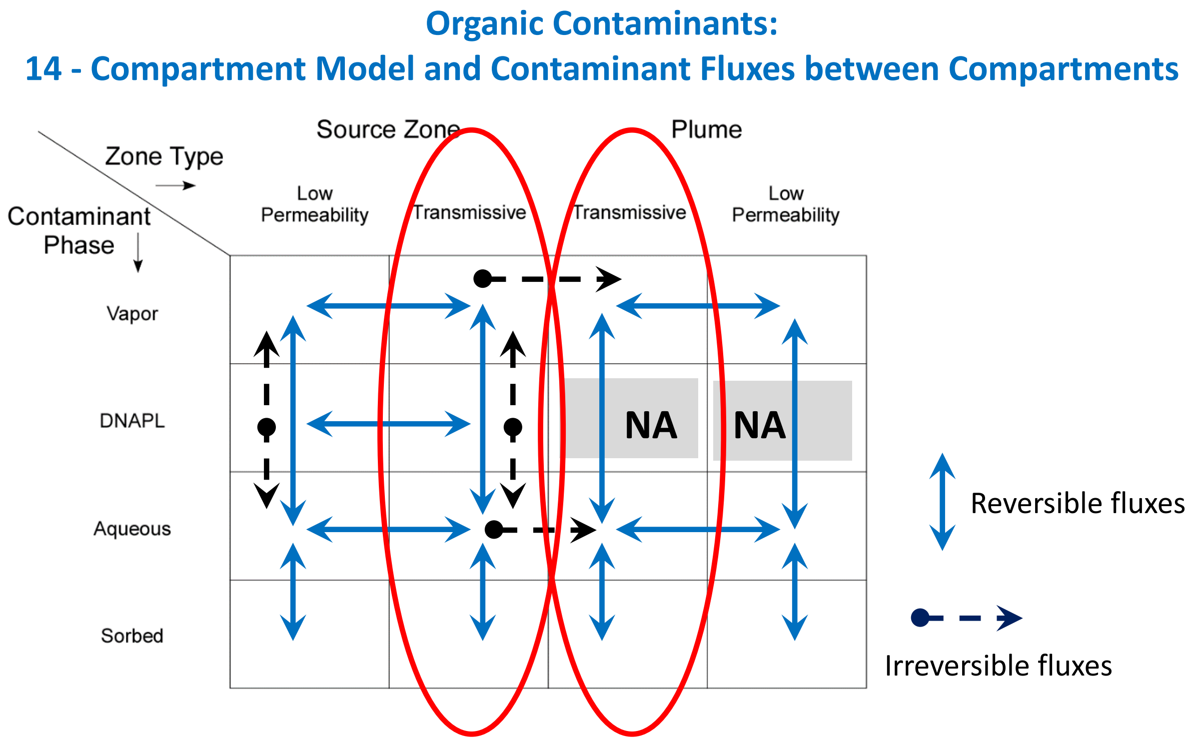
Isocontours of TCE concentration at 100 ft below land surface



Lacombe 2011

Physics of fluid sample collection in fractured rock – sampling the mobile groundwater

Sampling the mobile groundwater in fractures is significant in characterizing the contaminant mass that has the capacity of migrating down gradient and off-site. . .



(modified from Sale et al., 2008; Sale and Newell, 2011; ITRC 2011)

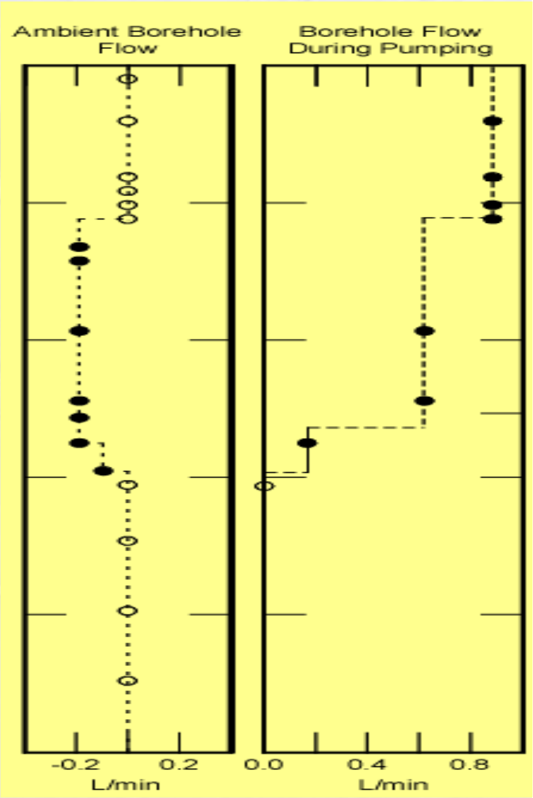
Example “Work Flow” following borehole installation. . .

- Borehole drilling or coring
- Temporarily seal borehole using temporary packers or removable flexible liner
- Borehole geophysics – borehole wall imaging, lithologic logging, flow meter logging, etc.
- Temporarily seal borehole using temporary packers or removable flexible liner
- Hydraulic testing - isolated intervals
- Geochemical sampling – isolated intervals – site characterization
- Temporarily seal borehole using temporary packers or removable flexible liner
- Evaluate lithologic, geophysical, hydraulic, and geochemical information and design intervals for hydraulic monitoring and geochemical sampling
- Install monitoring equipment (permanent or removal packers, borehole liner, nested piezometer in a single well)
- Conduct hydraulic monitoring and geochemical sampling in conjunction with functional objectives and site milestones (e.g., feasibility studies, remedy application, compliance monitoring, etc.)

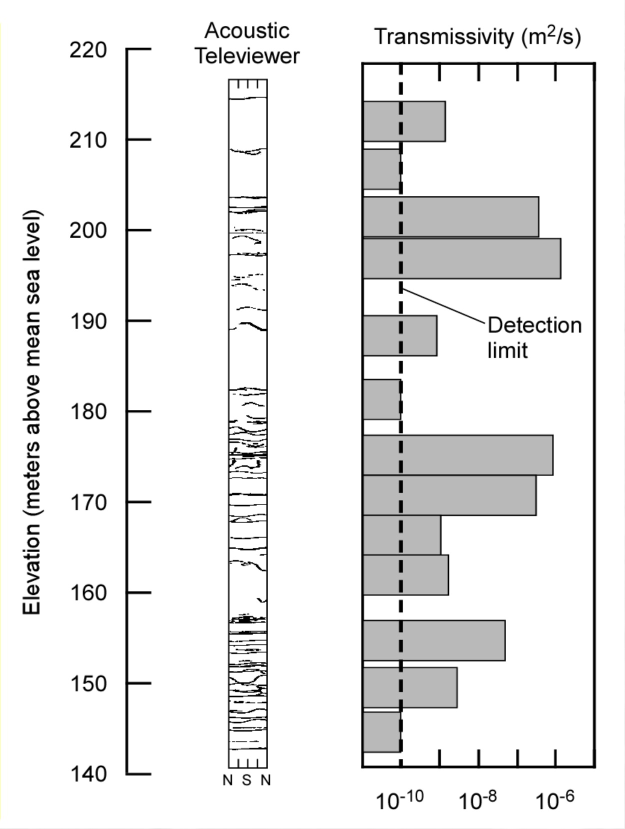
Geochemical sampling – isolated intervals – site characterization

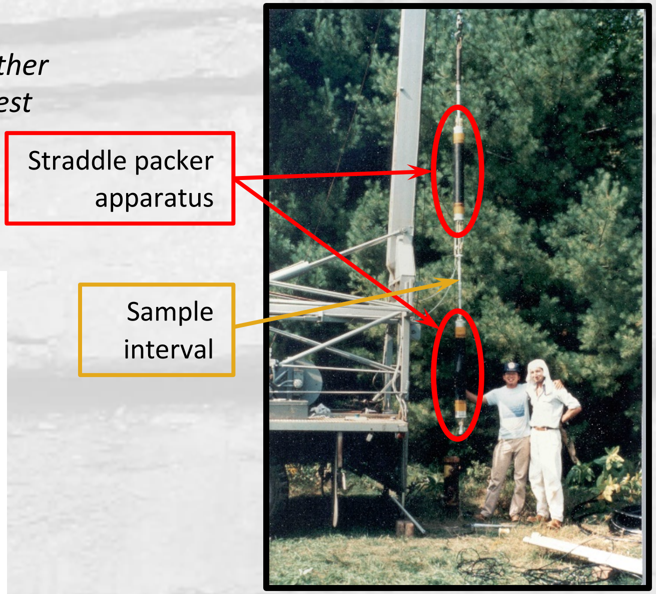
- *Temporary packers isolate borehole intervals*
- *Fractures in test interval may “short circuit” and connect to fractures intersecting other locations along borehole wall – monitor fluid pressure responses above and below test interval*

Borehole flowmeter survey conducted in borehole H1



Single-hole hydraulic tests conducted in borehole H1





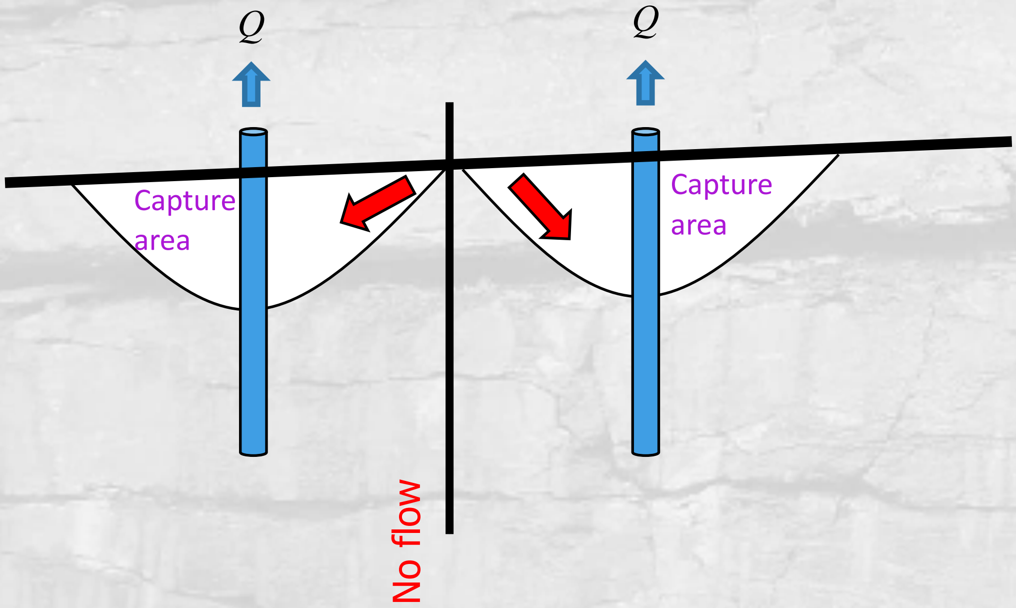
Straddle packer apparatus

Sample interval

Tubing, electrical connections for downhole sampling equipment

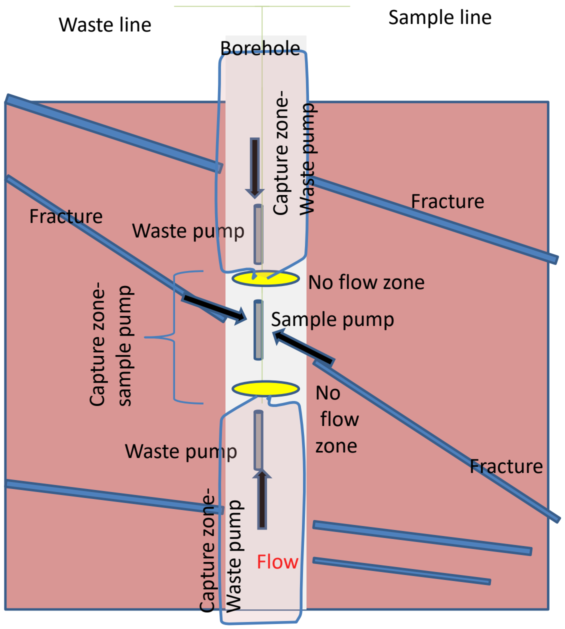
Geochemical sampling – hydraulically controlled isolated intervals – site characterization

Based on the hydraulic concept of "stagnation" zone



ZONFLO

Multi-level pumping with flow tracking



Groundwater

Rapid Communication/

Hydraulically Controlled Discrete Sampling from Open Boreholes

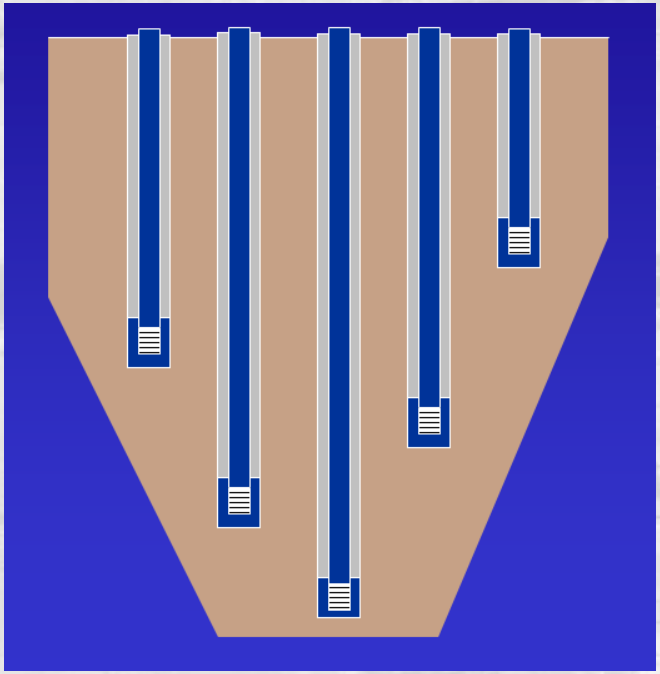
by Philip T. Harte

Vol. 51, No. 6–Groundwater–November-December 2013 (pages 822–827)

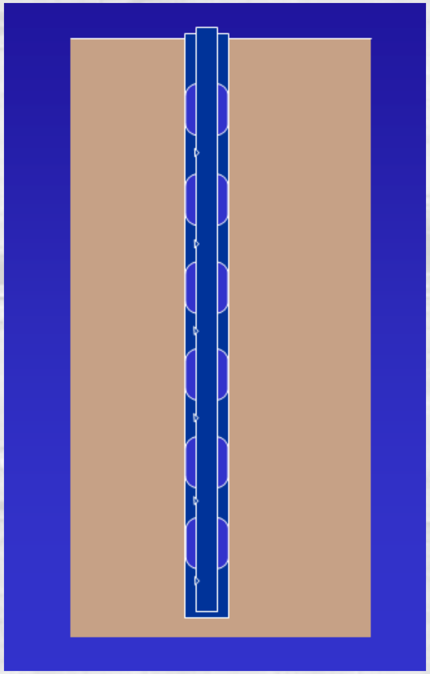
- 3 pumps operating
- Discharge from 2 pumps go to waste
- Discharge from sampling pump to sample collection

Geochemical sampling – borehole completion and instrumentation – multiple intervals

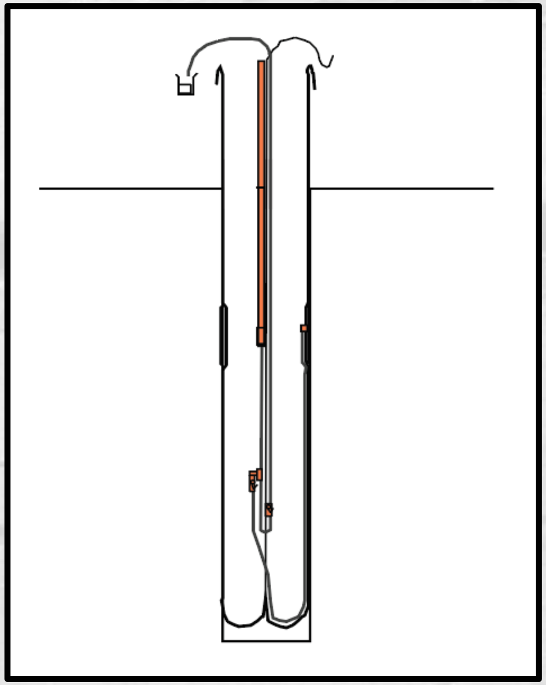
Nested piezometers (short open intervals in a single hole or closely spaced holes)



Multiple packers (permanent or removable)



Flexible Liner (with one or more ports)

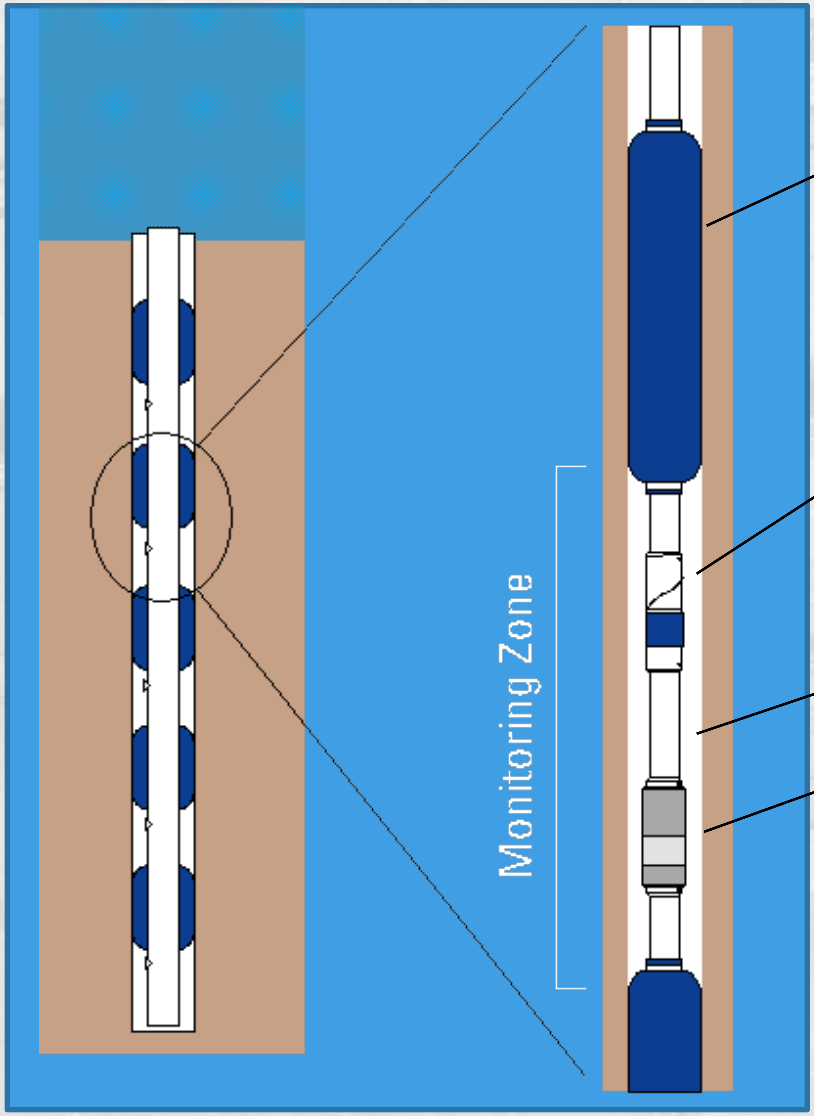


Selected borehole completion instrumentation available:

- Model 401 Waterloo Multilevel System (Solinst)
- Solinst Continuous Multichannel Technology (CMT) system
- Westbay
- Water FLUTe™ (Flexible Liner Underground Technologies, Ltd. Co)

***Note:** Use of tradenames is used for explanatory purposes only, and does not imply endorsement.*

Westbay System



www.westbay.com

Packer:

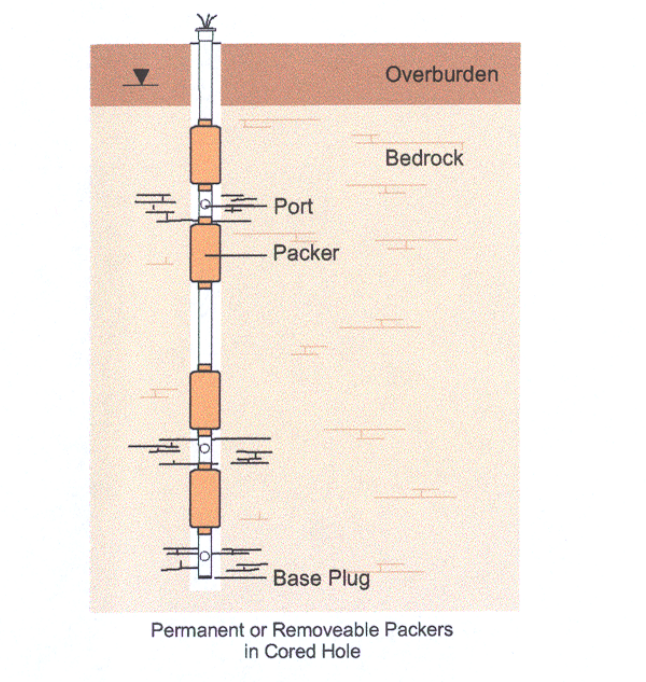
Measurement port: fluid sampling

Casing:

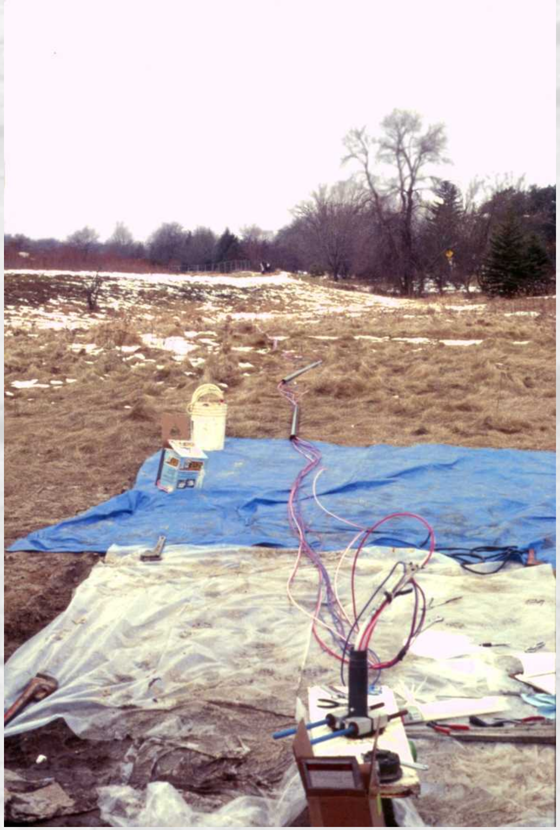
Pumping port: for hydraulic conductivity testing and purging

Specialized tool is needed for operation of ports

Solinst “Waterloo” system (inflatable permanent or removable packers)



Permanent or Removeable Packers
in Cored Hole



www.solinst.com

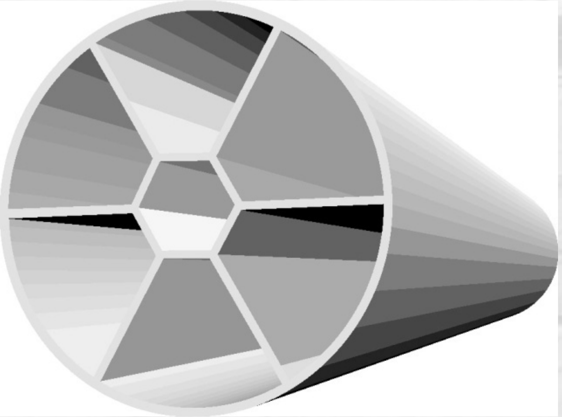
- Packers inflated using tubing that extends downhole
- Downhole pressure transducers
- Gas-drive sampling

Solinst "Continuous Multichannel Tubing" (CMT) (permanent or removable installations)

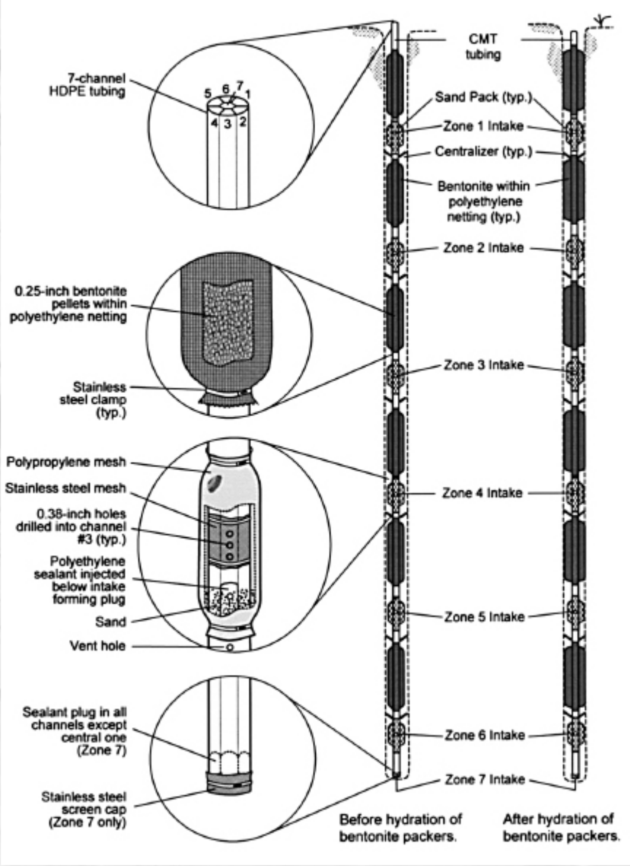
www.solinst.com

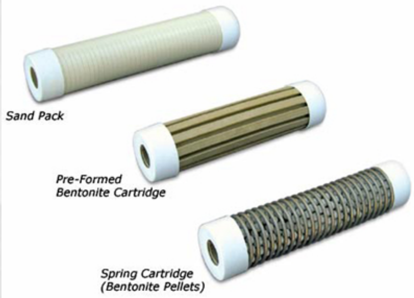
Inflatable packer (removable installation)

Core pipe has multiple continuous channels



1.7" diameter

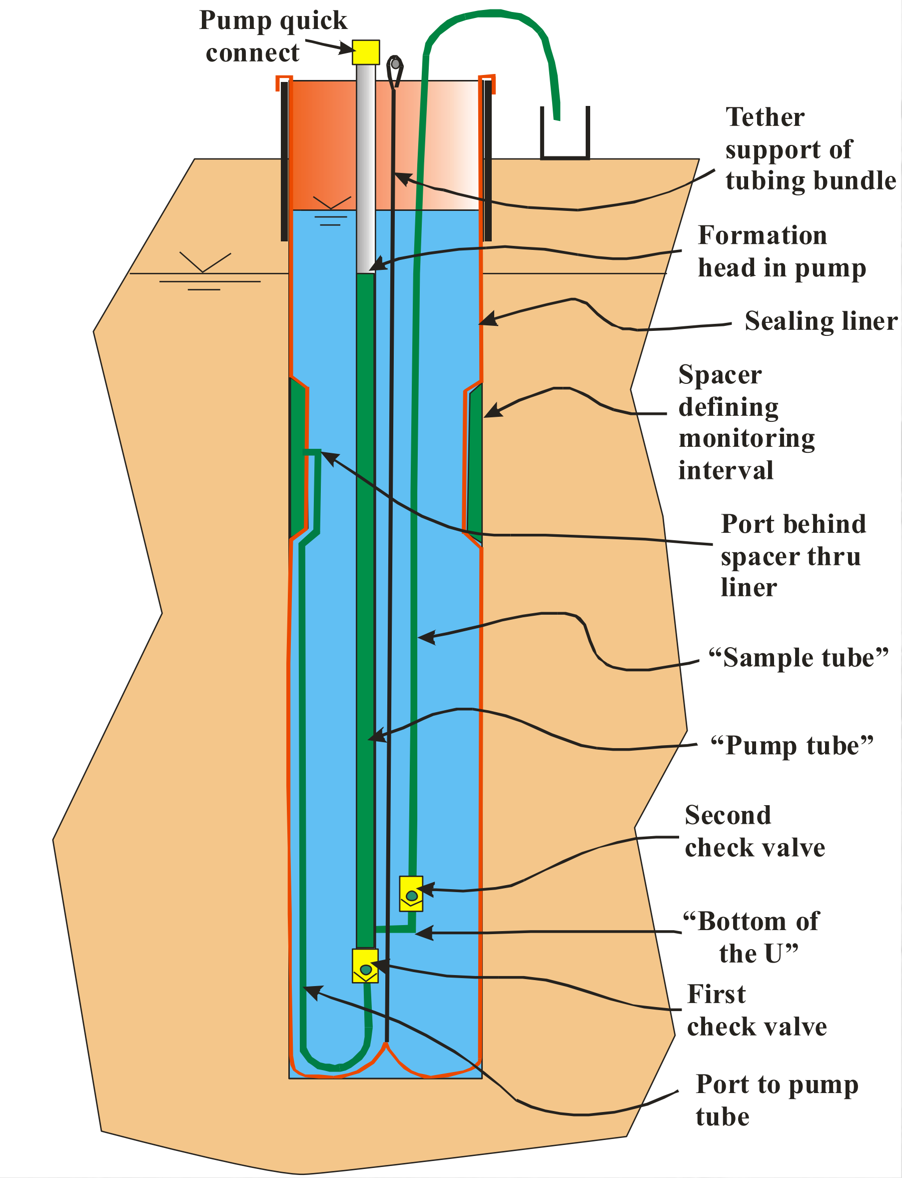




Bentonite-filled packer (permanent installation)

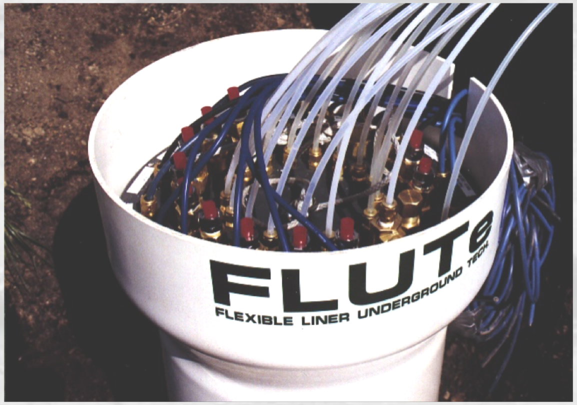
Water FLUTe Port and Pump System

(Single port system shown for clarity)



www.flut.com

- Gas-drive sampling pump



Geochemical sampling – methods of sample collection

Choice of sample collection method depends on borehole completion and instrumentation. . ..

Bailer/grab sampler:
- Limitation of sampling in open boreholes
- Best suited for monitoring in piezometers
- No purging of borehole

Diffusion bags:
- Limited to open boreholes, need to retrieve bags
- Limitations of sampling in open boreholes
- Best suited for monitoring in piezometers
- No purging of borehole

Gas lift apparatus with check valve:
- Similar to operation of gas-driven piston pumps
- Access tubing and valves installed down hole in multilevel completion
- Incorrect operation may yield gas in contact with the sampled water

Peristaltic pump:
- Limitations on depth, ~30 ft to water
- Sampling for dissolved gases could be problematic
- Permanent well completions need to be designed with access tubes

What is the sample representative of . . a combination of formation water & borehole fluid?

What is the effect of purging volume ?

Submersible (electric and gas-driven) pumps:
- Used in open holes and discrete interval sampling between packers during site characterization
- Unrealistic for most types of permanent well completions (with the exception of piezometers)
- Lower limit for electric pumps is usually ~80 - 100 mL/min; gas-driven piston pumps can cycle at a lower rate
- Electric pumps induce hydrogen production (dissolved hydrogen is an indicator of microbial activity)

Geochemical Sampling – Key Points

•Geochemical characterization is a tool in developing, evaluating, and updating Conceptual Site Models to address site objectives. . .

•Sampling methods (including well construction and instrumentation) may evolve over the time-line of site milestones. . . site characterization, remedy design & evaluation, compliance monitoring. . .

•Geochemical (fluid) sample collection only addresses contaminant distribution in mobile groundwater (permeable fractures). . .contaminant characterization in fractured rock must also account for the complexity of the geologic environment (matrix porosity, fractures . . .even low-permeability fractures)

•Sampling in boreholes open to multiple fractures will draw water preferentially from the most transmissive fractures (flux-averaged concentration). . . what is the fluid sample representative of? . . . and, is the sample consistent with addressing objectives for the site milestone?

•Ambient borehole flow conditions can adversely affect spatial distribution of chemical constituents. . .history of open boreholes is needed to interpret groundwater chemistry

•Purging fluid from the borehole has the potential to draw water from a large volume of the formation. . .balance this with a mixed sample of borehole fluid and formation water. . .

Selected References

(Note: This is not an exhaustive list. Please contact ashapiro@usgs.gov for a more extensive list of references.)

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