Profiling Transmissivity and Contamination in Fractures Intersecting Boreholes

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USEPA-USGS Fractured Rock Workshop

EPA Region 10

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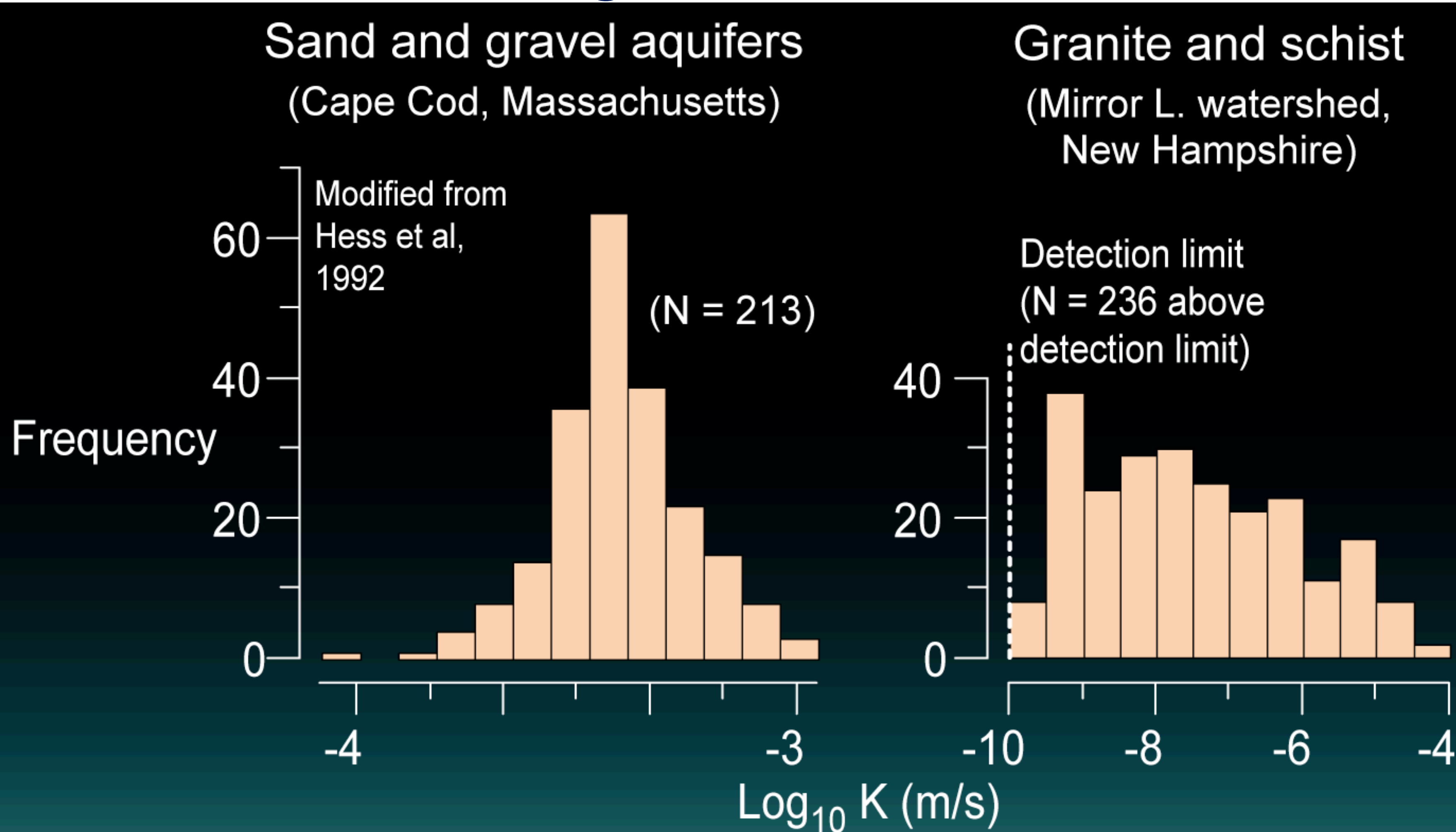
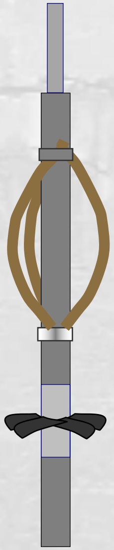
Motivation: Hydraulic Conductivity Varies by Orders of Magnitude in Fractured Rock



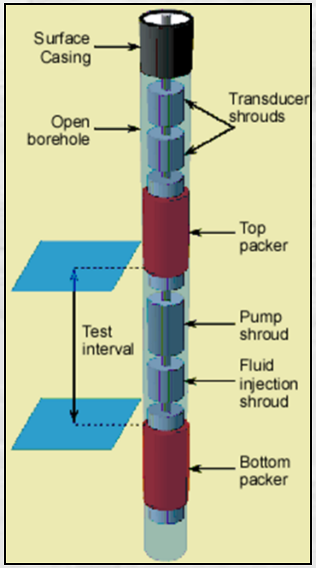
This variability results in complex groundwater flow and contaminant transport paths

Profiling Transmissivity in Boreholes

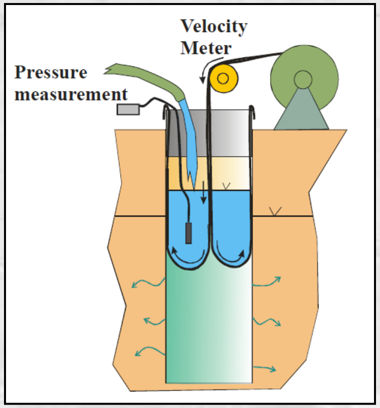
- Characterizes permeability variability with depth.
- Provides quantitative order-of-magnitude T estimates at a scale of a few meters around borehole.
- Essential information for converting open boreholes into multi-level monitoring wells.
- Methods:



Borehole Flow Logging

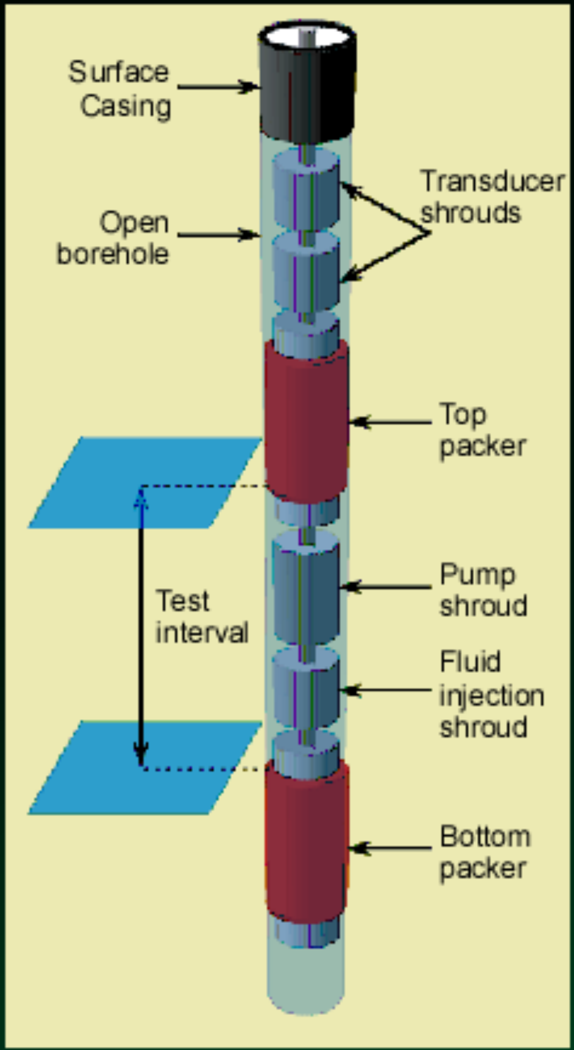


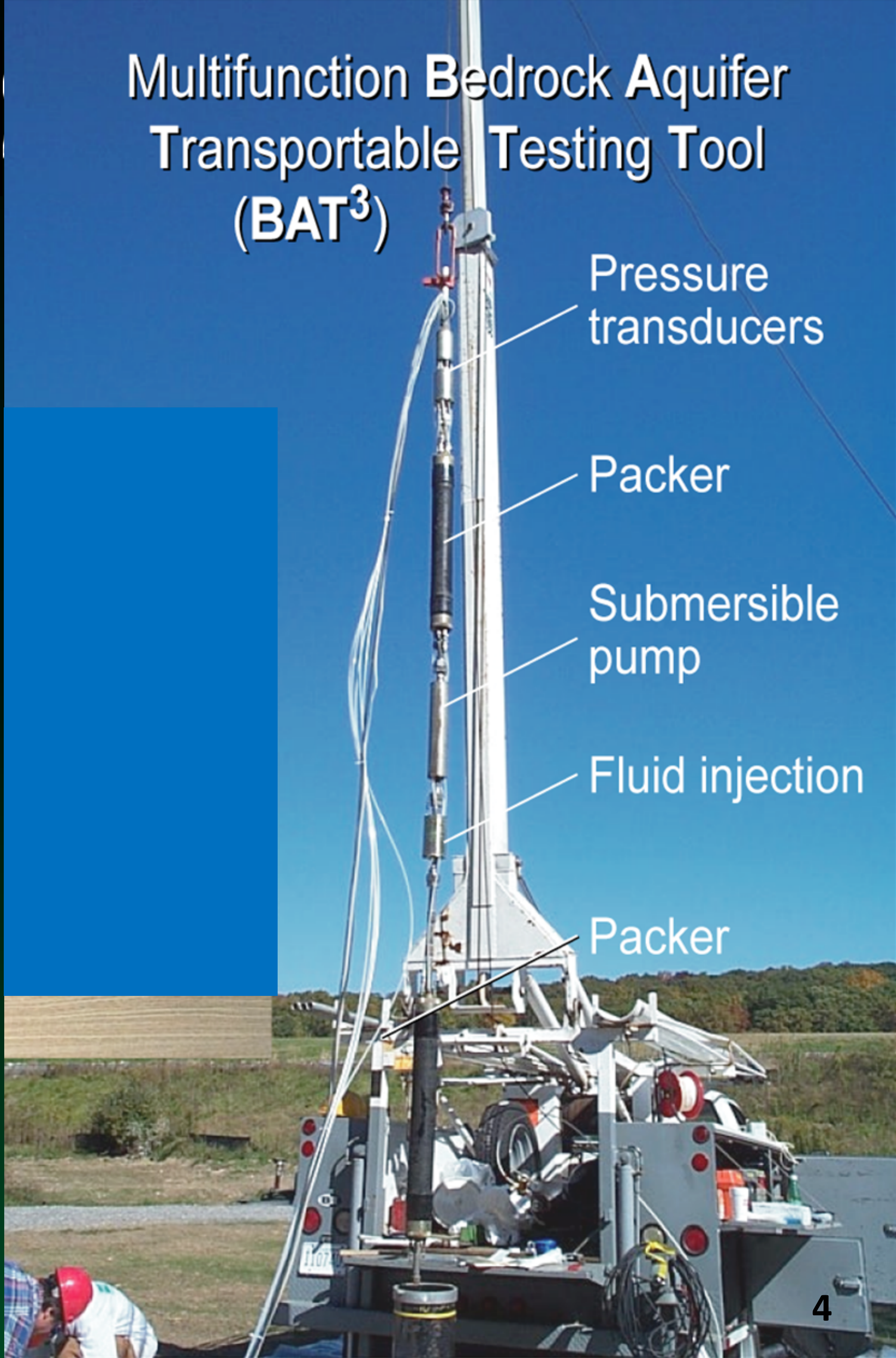
Straddle Packer Testing



Flute Liner Installation

Packer Testing Equipment

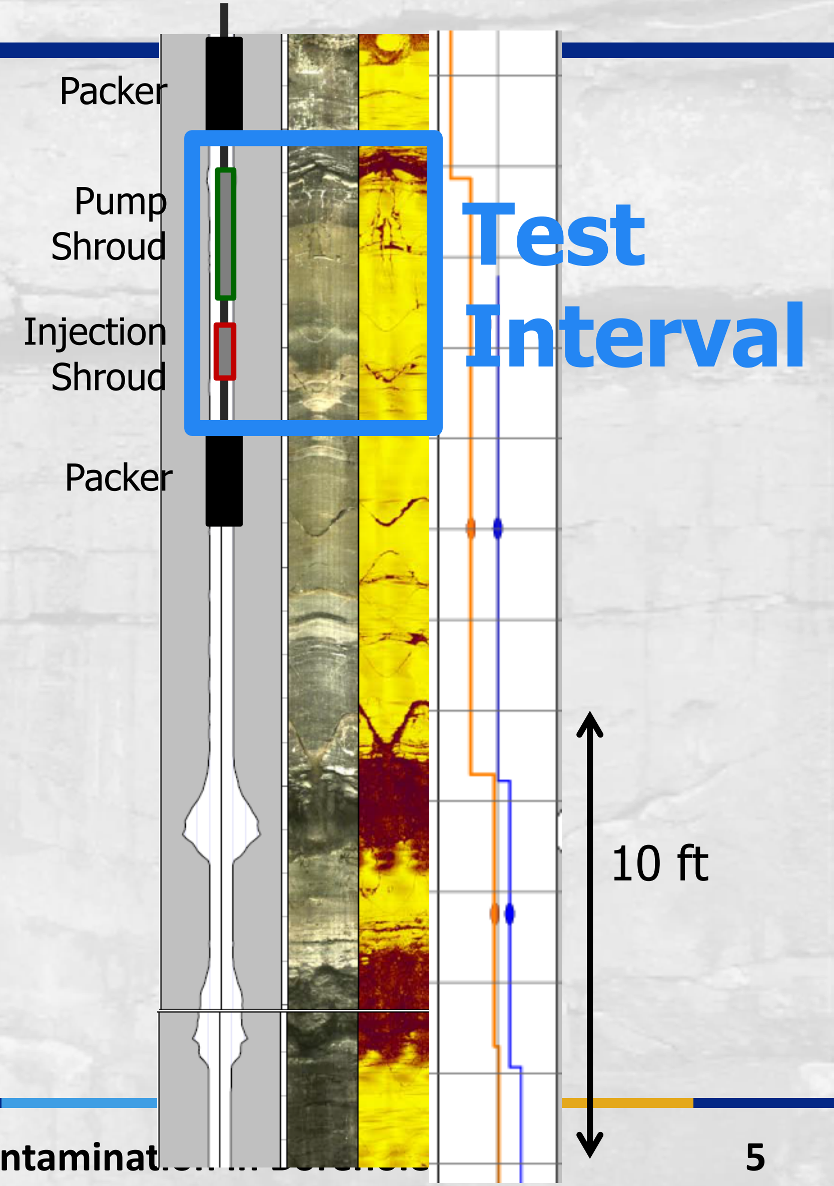




USGS

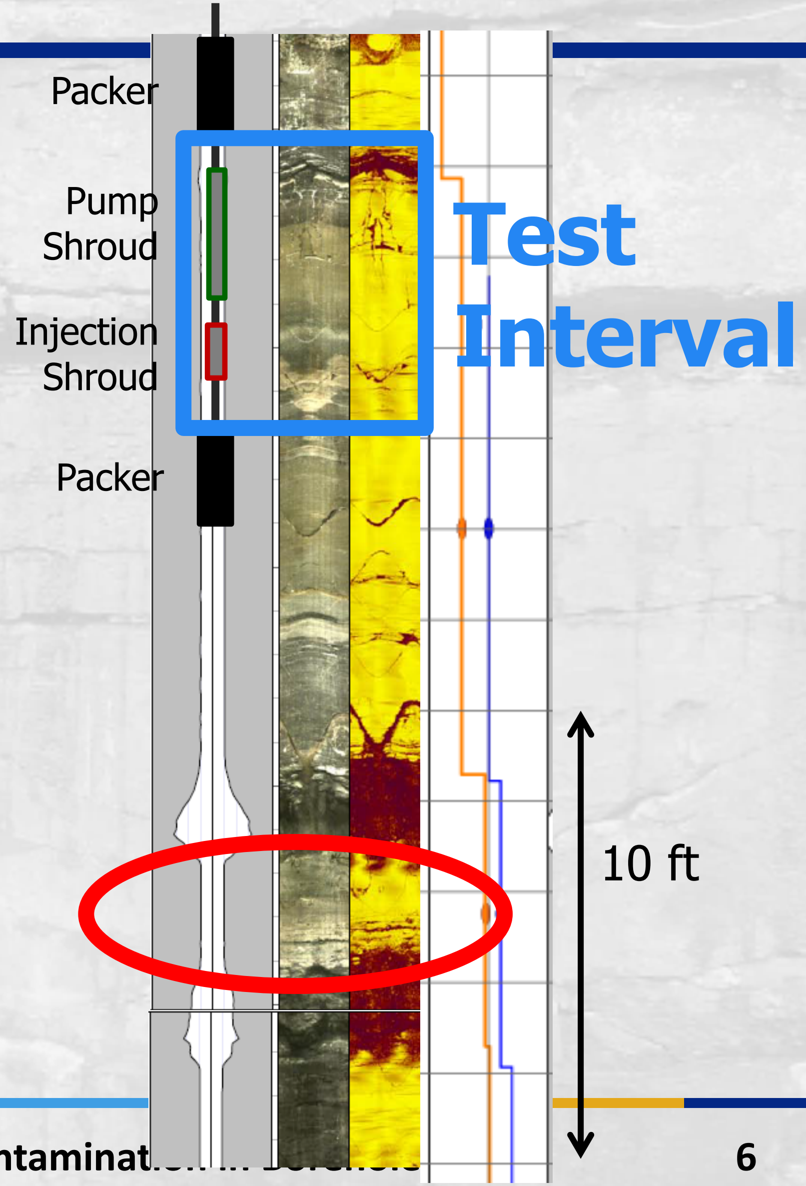
Transmissivity Profiling using Straddle Packers

- To determine test intervals, use results from geophysical logging:
  - Acoustic & optical televiewer: Identify fracture locations
  - Caliper: Avoid placing packers on rough borehole wall sections
  - Flow logs: First cut at revealing permeable fractures



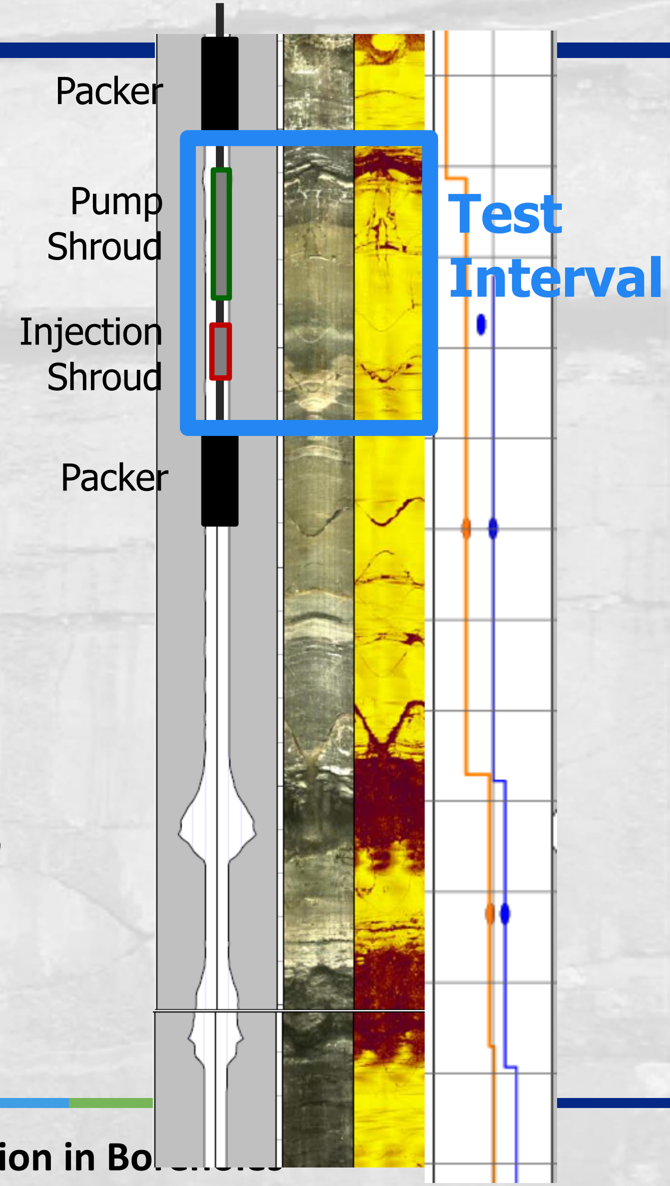
Transmissivity Profiling using Straddle Packers

- Spatial resolution of T estimates depends on test equipment and borehole conditions:
- Length of pump & injection equipment
- Length of packers → If there is a small vertical separation between two rough sections of borehole



Running a Test

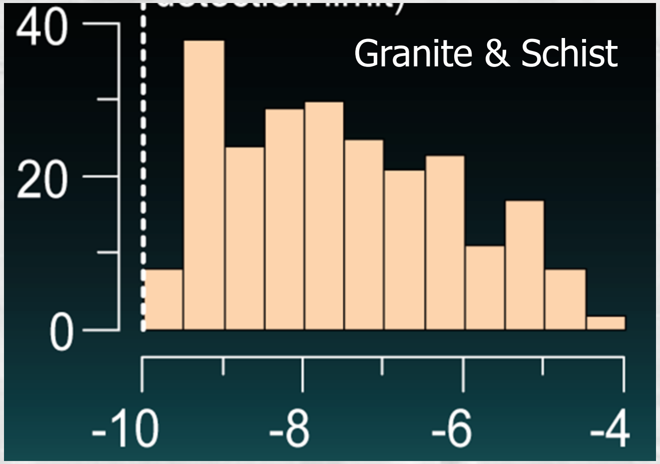
- Pump from interval if permeable enough
- Otherwise inject water into the interval
- Monitor flow rate
- Monitor pressure in interval and above & below interval
- Test analysis method uses flow rate, stabilized pressure change, and estimate of radius of influence



Transmissivity Estimates

- Method of analysis gives order-of-magnitude T estimates
  - Test conditions typically do not perfectly conform to the conditions assumed by the method (steady-state radial flow)

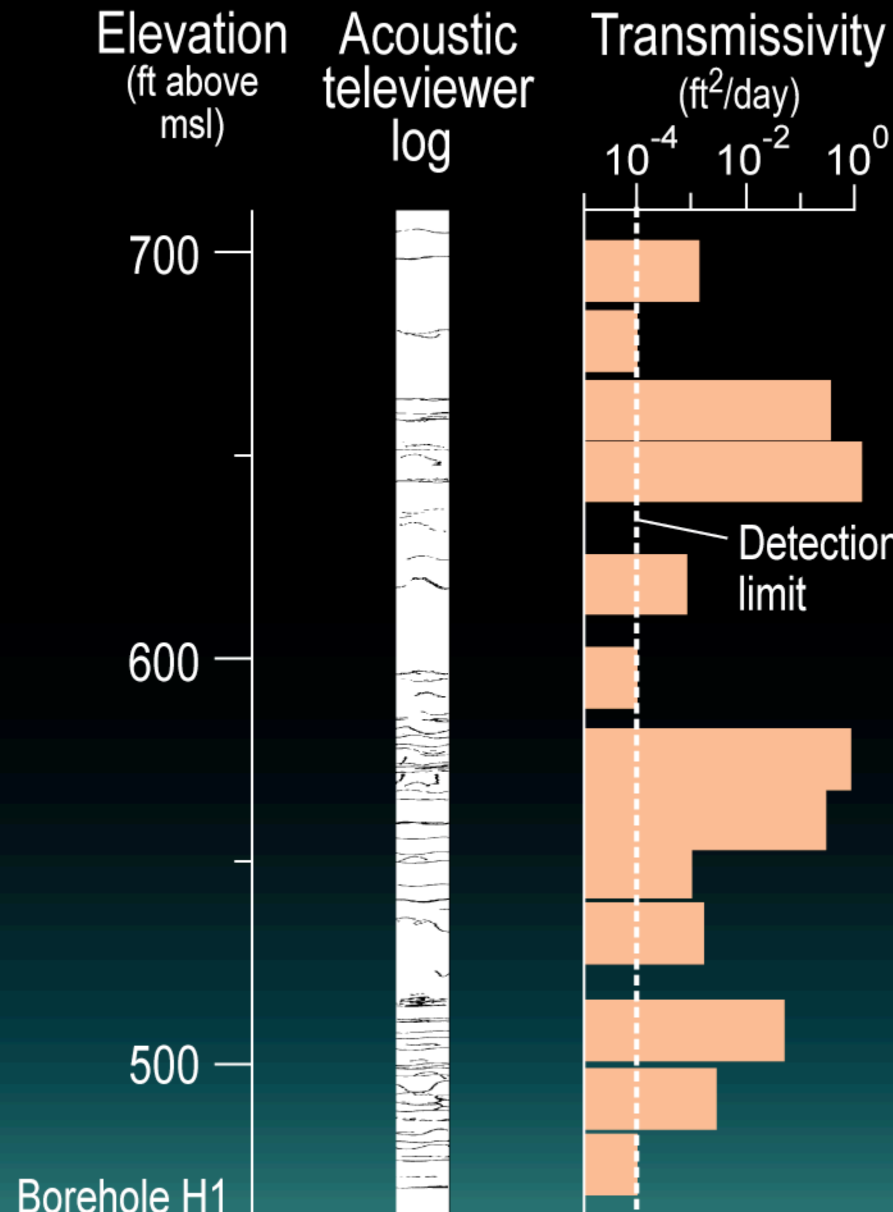
- Because of the large range of T at fractured rock sites, these order-of-magnitude estimates are still quite informative and valuable



$\log_{10}K$ (m/s)

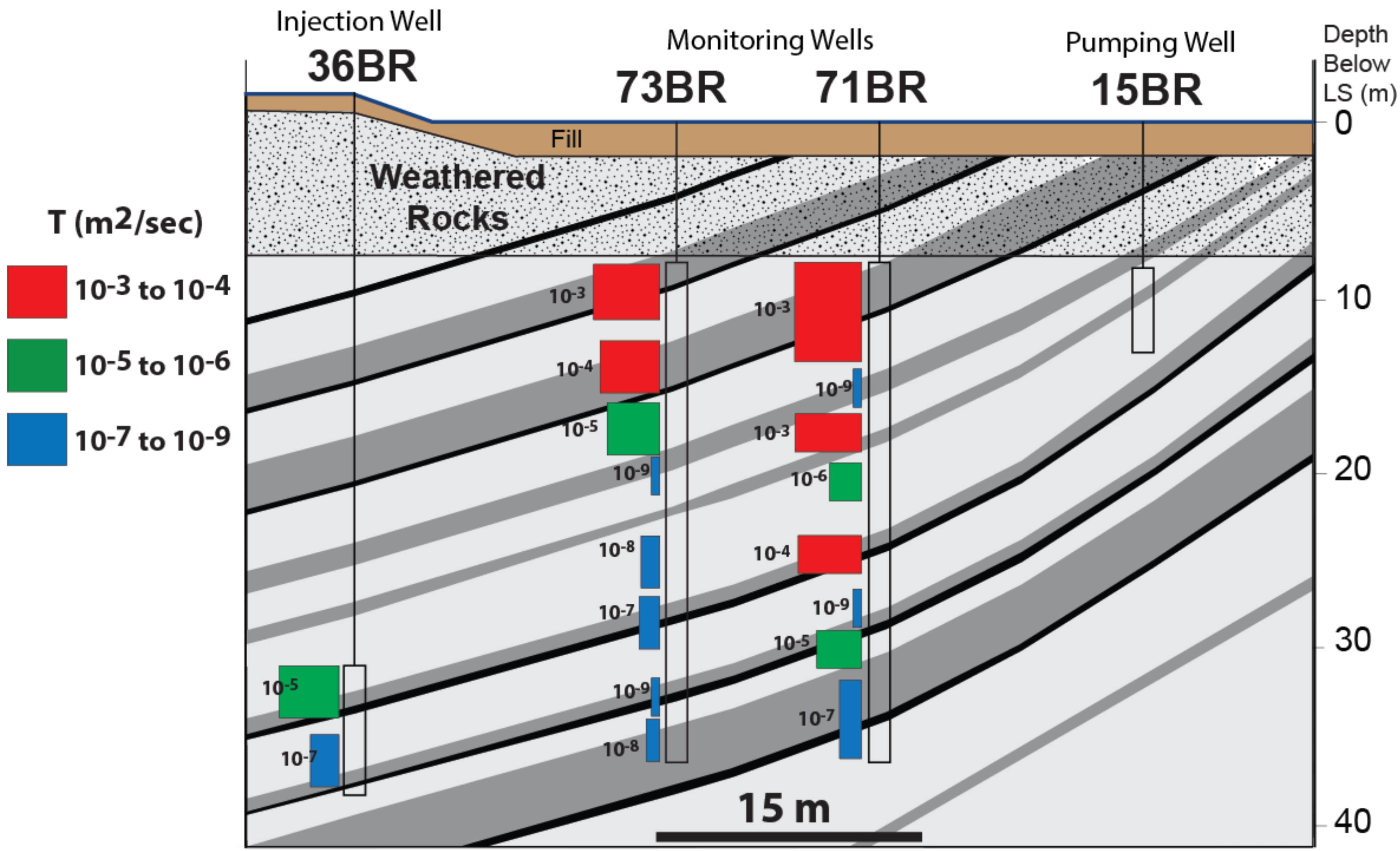
Crystalline Rock

Road cut near
Mirror Lake watershed,
New Hampshire

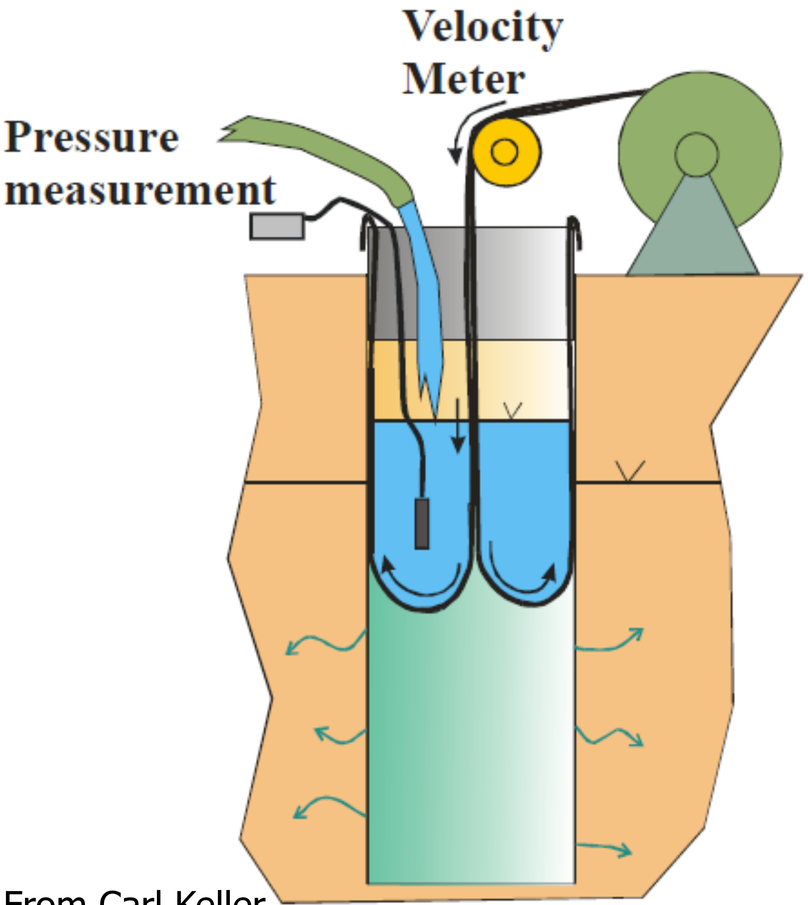


Shapiro and Hsieh, 1998

Sedimentary Rock



Transmissivity Profiling using the FLUTe

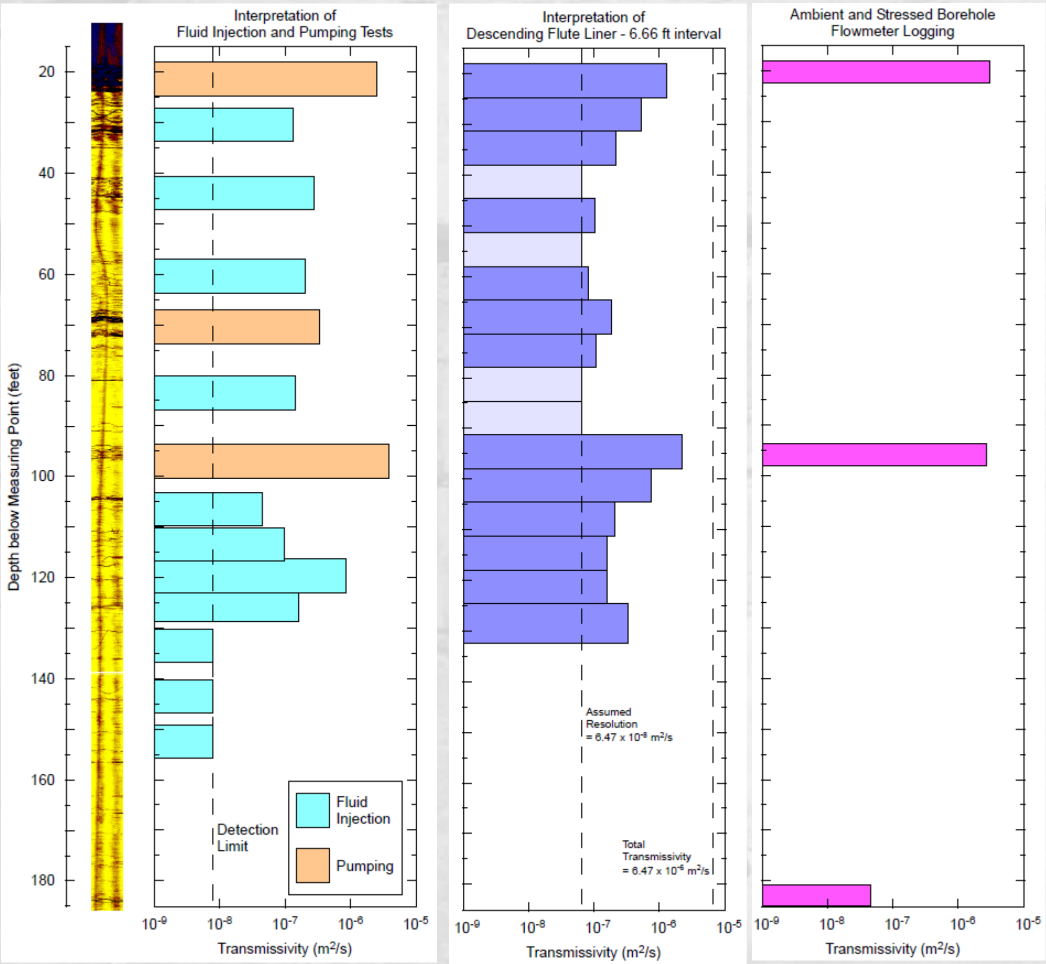


From Carl Keller

- Evert liner into borehole.
- Borehole water below bottom of liner is pushed into the rock.
- Flow rate into rock is calculated from liner descent velocity and hydraulic head that drives liner installation.
- Flow rate into a borehole interval is the difference in rate before and after the interval is covered by the liner.
- T calculated by same method as for packer tests.

Comparison of T Estimates in Schist

Packers **FLUTe** **Flow Logging**

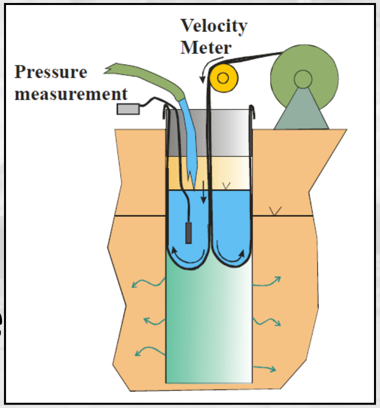


- **The 3 methods compare well for the high-T intervals.**
- **Greater differences between packer and FLUTe results for lower-T intervals.**

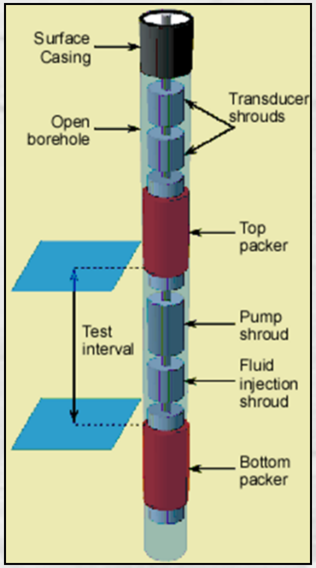
Spring Valley Formally Used Defense Site, NW Washington DC, from Allen Shapiro

Comparison of Packers and FLUTe for T Profiling

- **FLUTe:**
  - Cost-effective means of obtaining T estimates if liner is installed to prevent cross-contamination.
  - Simpler equipment and easier to conduct
  - Potentially has higher spatial resolution (but small-scale variability may be caused by borehole effects).



- **Packers:**
  - Conditions conform better to assumptions of analysis method, so T estimates are likely more accurate.
  - Lower detection limit for T.
  - In addition to T estimates, tests yield ambient heads of packed off intervals, and opportunity for sampling geochemistry.



Summary: Value of Information from Transmissivity Profiling

- **Identification of high T fractures that may be advective contaminant transport pathways.**
- **Identification of low T fractures and rock intervals where diffusion is likely a dominant transport process.**
- **Use T results together with contaminant and geochemical profiling results, ambient hydraulic head estimates, and other borehole information to guide design of multilevel monitoring systems.**

Water-Quality Profiling Open-Hole Wells

Methods for open-hole wells in fractured rock with more than one water-bearing zone

- Packer tests
- Diffusion bags
- Depth-dependent sampling while pumping

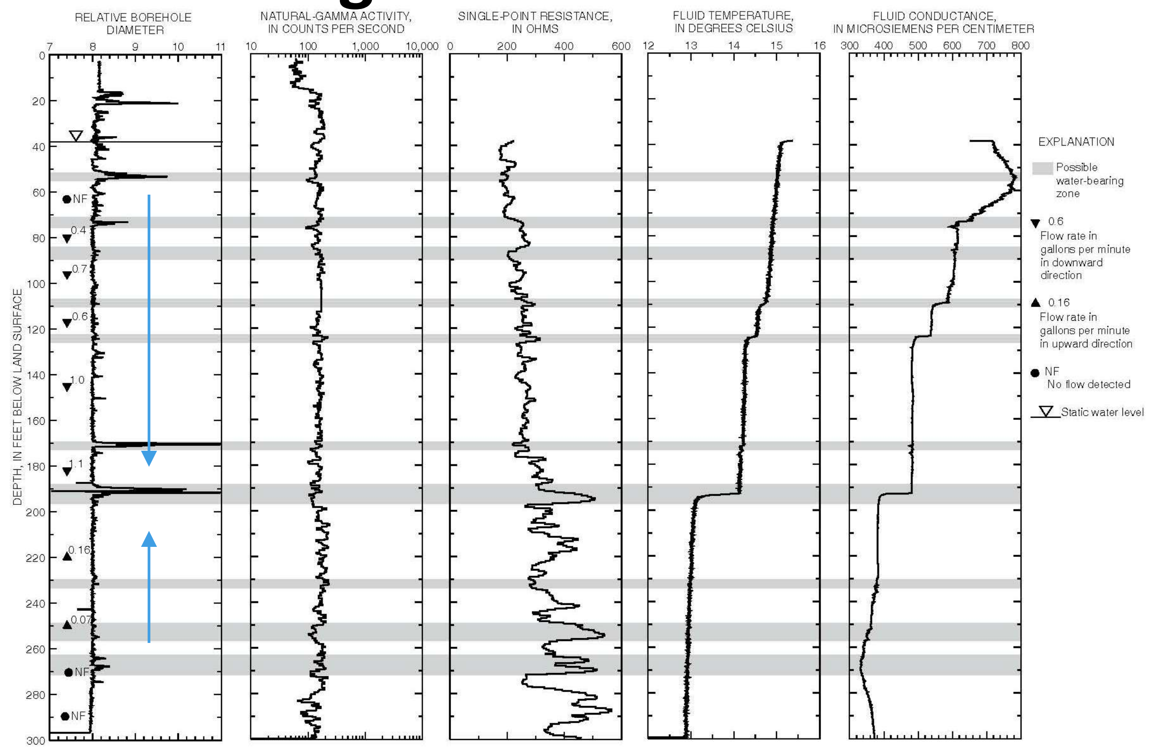


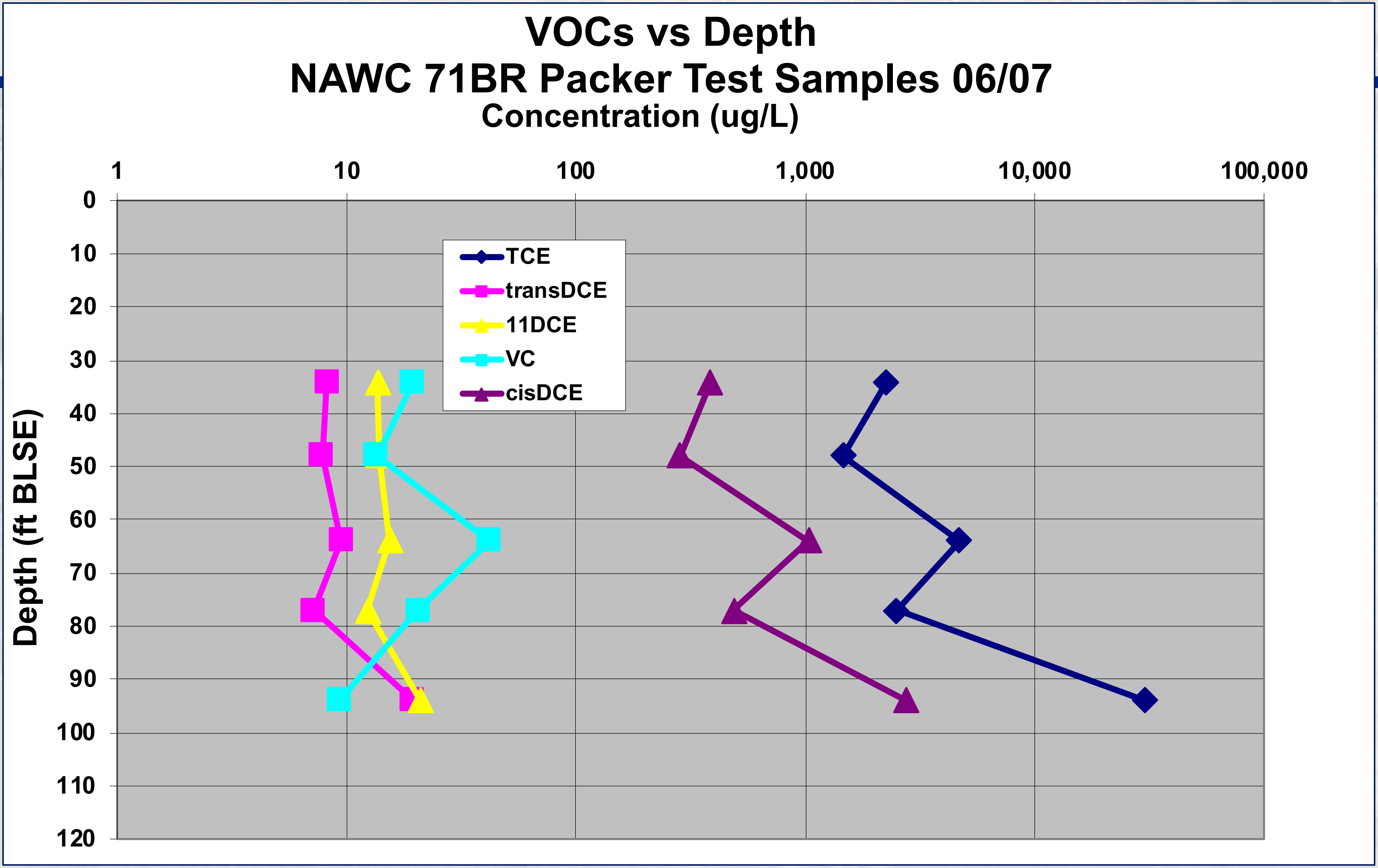
Figure 11. Borehole geophysical logs and direction of flow under non-pumping conditions within borehole MG-2084 (RI-3D), North Penn Area 7, Upper Gwynedd Township, Montgomery County, Pa., February 13, 2004.

(from Senior and others, 2008)

Water-Quality Profiling: Packer Tests

- Water-quality profiling conducted in same intervals being pumped for transmissivity testing
- Samples collected using a submersible pump installed between two packers
- Sampling method
  - Water pumped to surface through splitter and flow-through cell
  - Field water quality parameters measured to stability
  - Samples collected for VOCs and inorganics

Packer Test Water-Quality Profiling



Comparison of packer test water-quality profiling and subsequent monitoring-well sampling

Caliper/Flow Gamma/Electric Transmissvity WaterLevel VOCS and DO Conductance/Alkalinity Conductance log

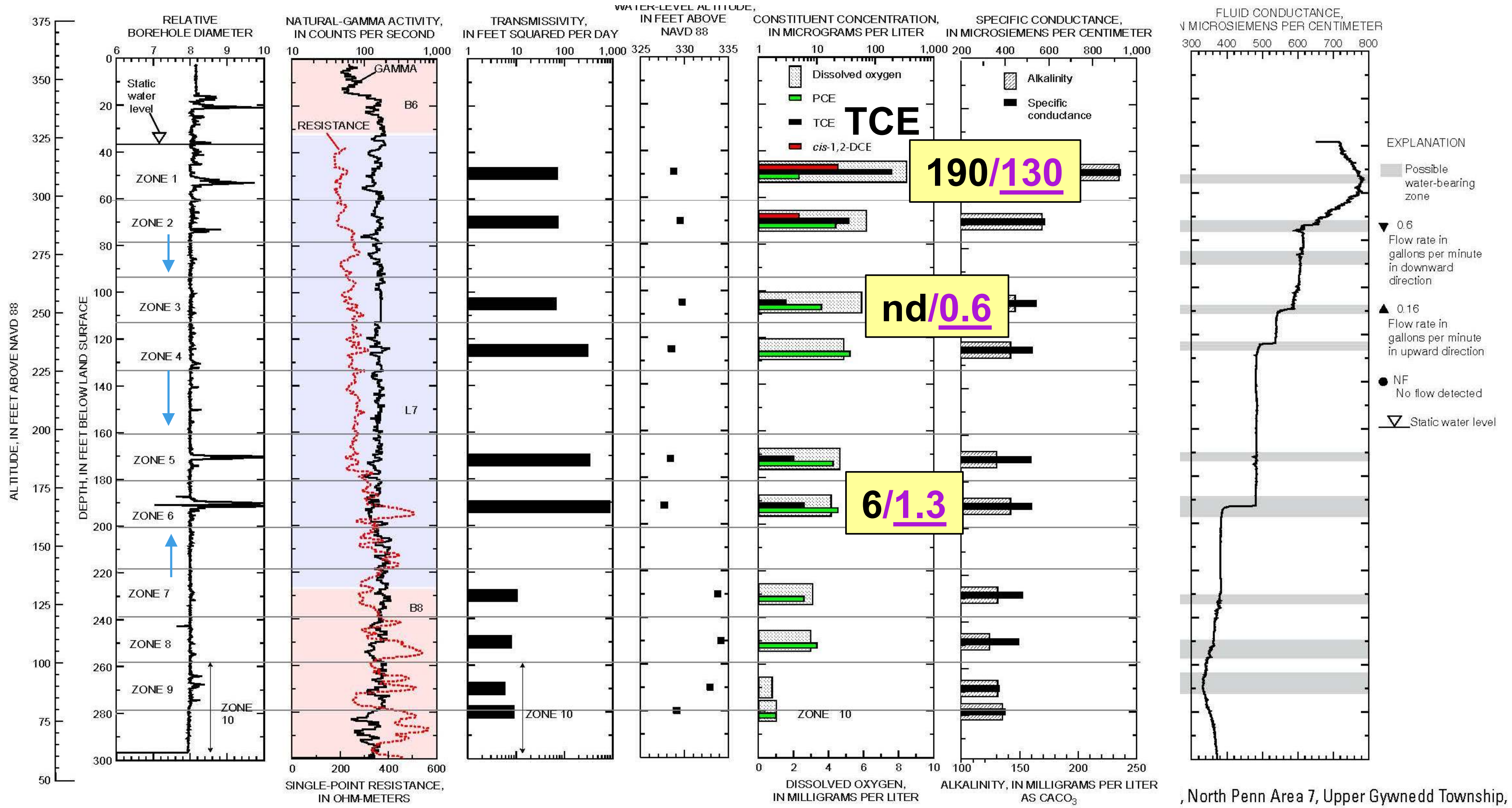
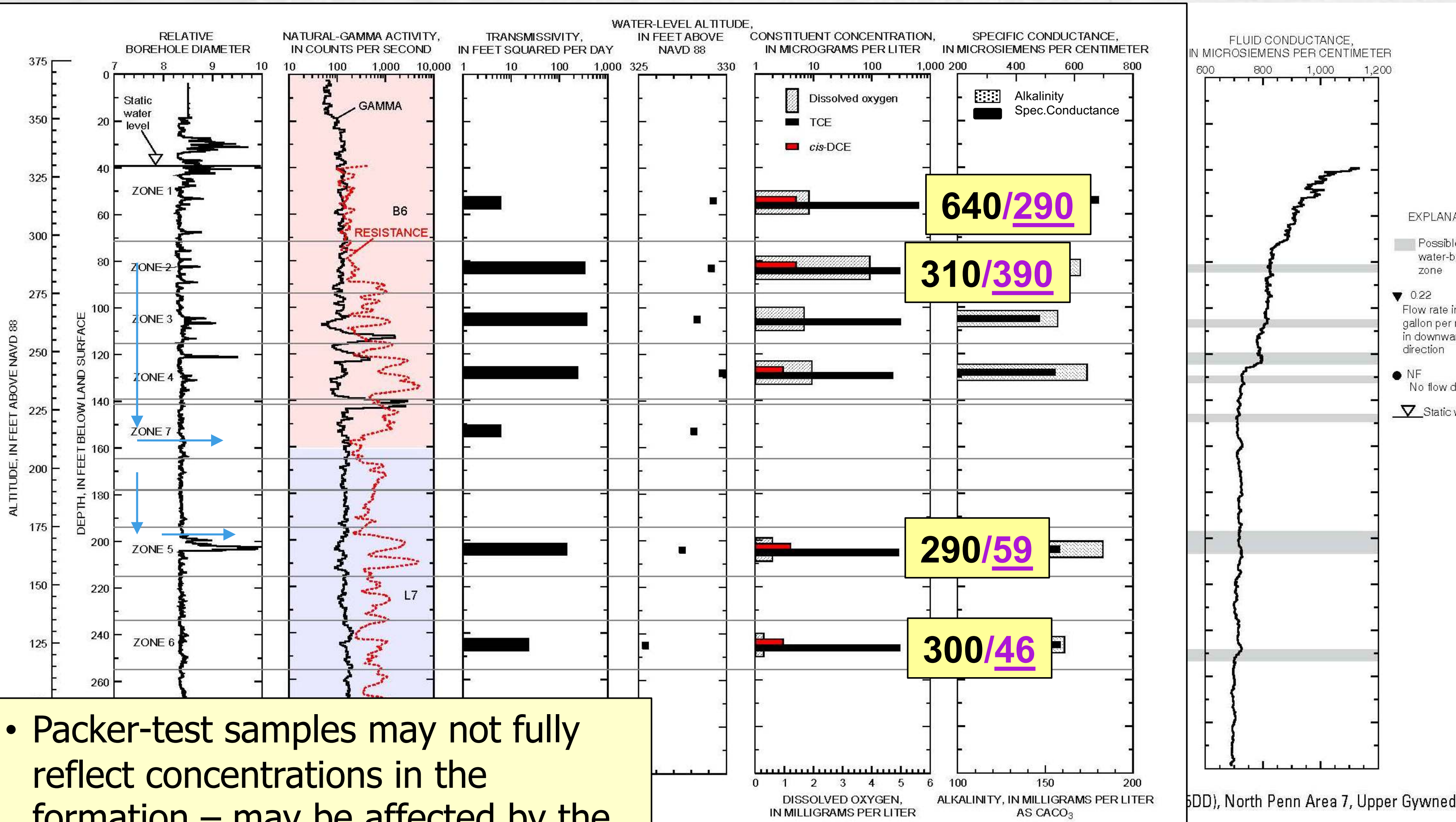


Figure 52. Borehole caliper log showing zones isolated by packers, natural-gamma and single-point-resistance logs with estimated extent of mapped geologic unit (see bed codes, fig. 5), and for each isolated interval, calculated transmissivity, measured static water-level altitude, and water-sample specific conductance and concentrations of selected volatile organic compounds, dissolved oxygen, and alkalinity in borehole MG-2084 (RI-3D), North Penn Area 7, Upper Gwynedd Township, Montgomery County, Pa., March 5-12, 2004.

(from Senior and others, 2008)

Packer test water-quality profiling and subsequent monitoring-well sampling can differ



-point-resistance logs with estimated extent of mapped geologic unit
water-level altitude, and water-sample specific conductance and
hole MG-2131 (RI-15DD), North Penn Area 7, Upper Gwynedd Township,

(from Senior and others, 2008)

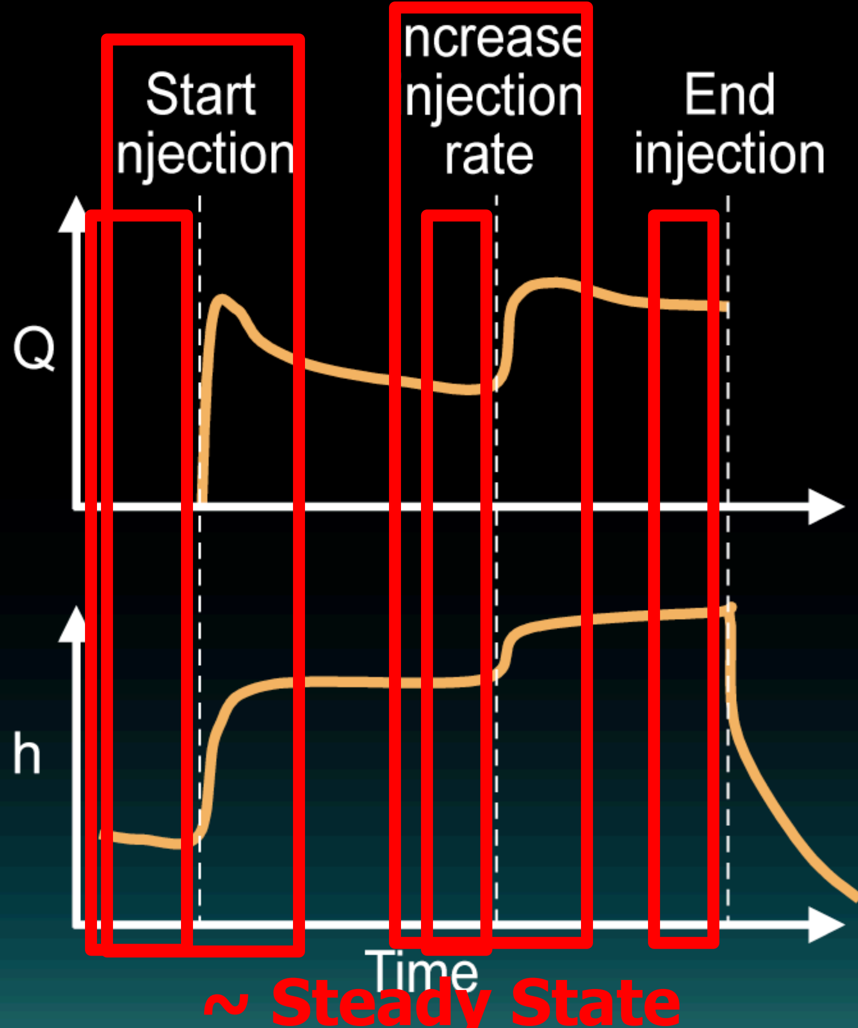
- Packer-test samples may not fully reflect concentrations in the formation – may be affected by the open-hole concentration values.
- Especially in lower-permeability intervals.

Summary: Value of Information from Water-Quality Sampling During Packer Tests

- First glimpse of the variability of contaminant concentration and water geochemistry with depth.
- High-T intervals with relatively high contaminant concentrations can indicate fractures that are transport pathways at scales larger then the near-borehole.
- Geochemistry variations can provide clues about variability with depth of reactive transport processes such as biodegradation.
- Augments T data for guiding design of multilevel monitoring systems.
- Sample results may not fully reflect formation conditions; longer term monitoring after multilevel systems installed will likely be more definitive.

Extra Slides

Hydraulic responses measured from hydraulic tests



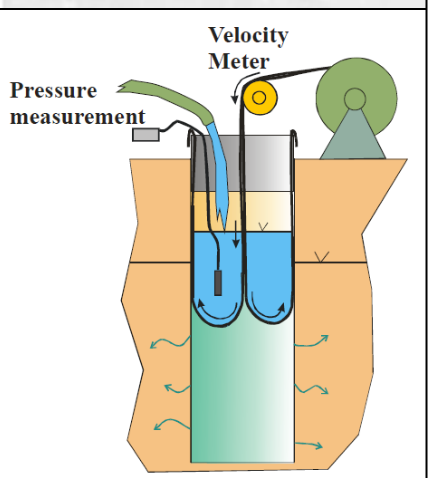
Estimating transmissivity of the test interval

$$Q = 2\pi r T \frac{dh}{dr}$$

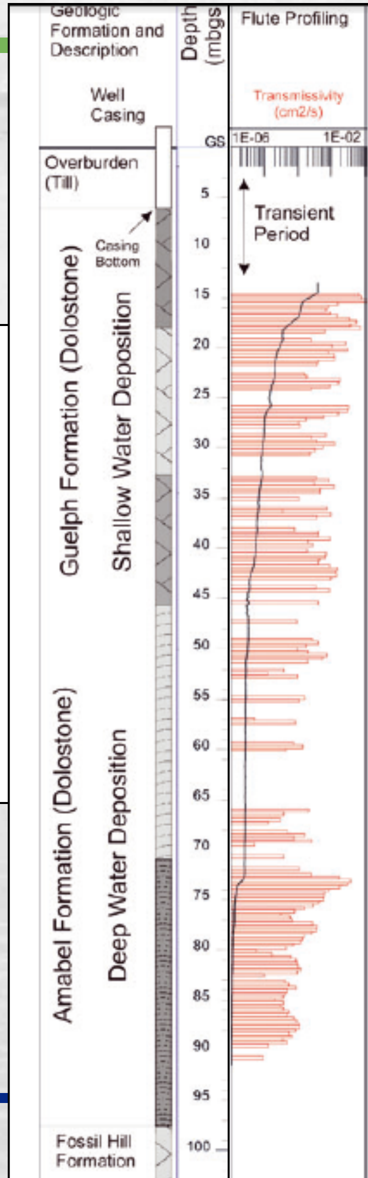
$$T = \frac{Q}{2\pi \Delta h} \ln\left(\frac{R}{r_s}\right)$$

Theim equation for steady-state radial flow to a pumping well

Transmissivity Profiling using the FLUTe

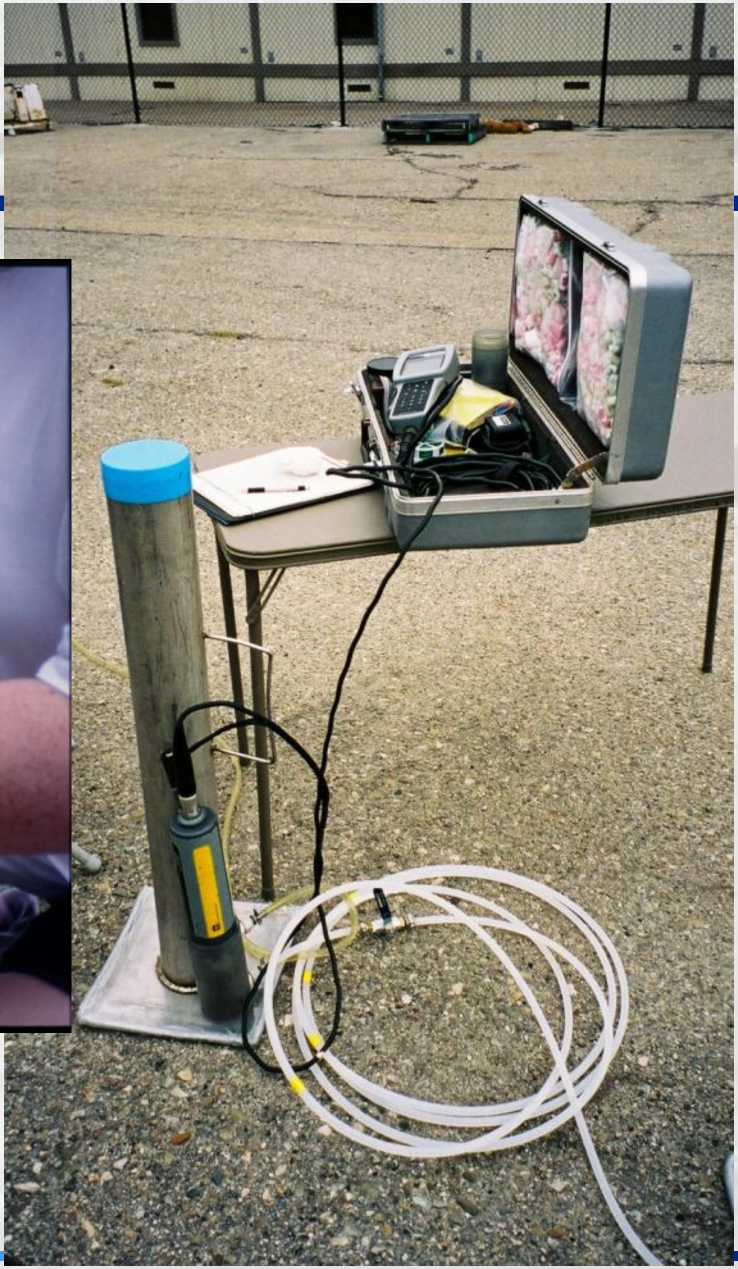


Keller et al., 2013, Groundwater



- Spatial resolution of T depends on liner descent velocity and on its measurement frequency.
- Velocity controlled largely by:
  - Total T below liner bottom
  - Driving head
- Velocity decreases as more and more fractures are covered by liner.
- T detection limit depends on lower measurement limit of velocity.
- Cannot resolve fracture T's that are < 1% of remaining T below liner.

Water-Quality Sampling

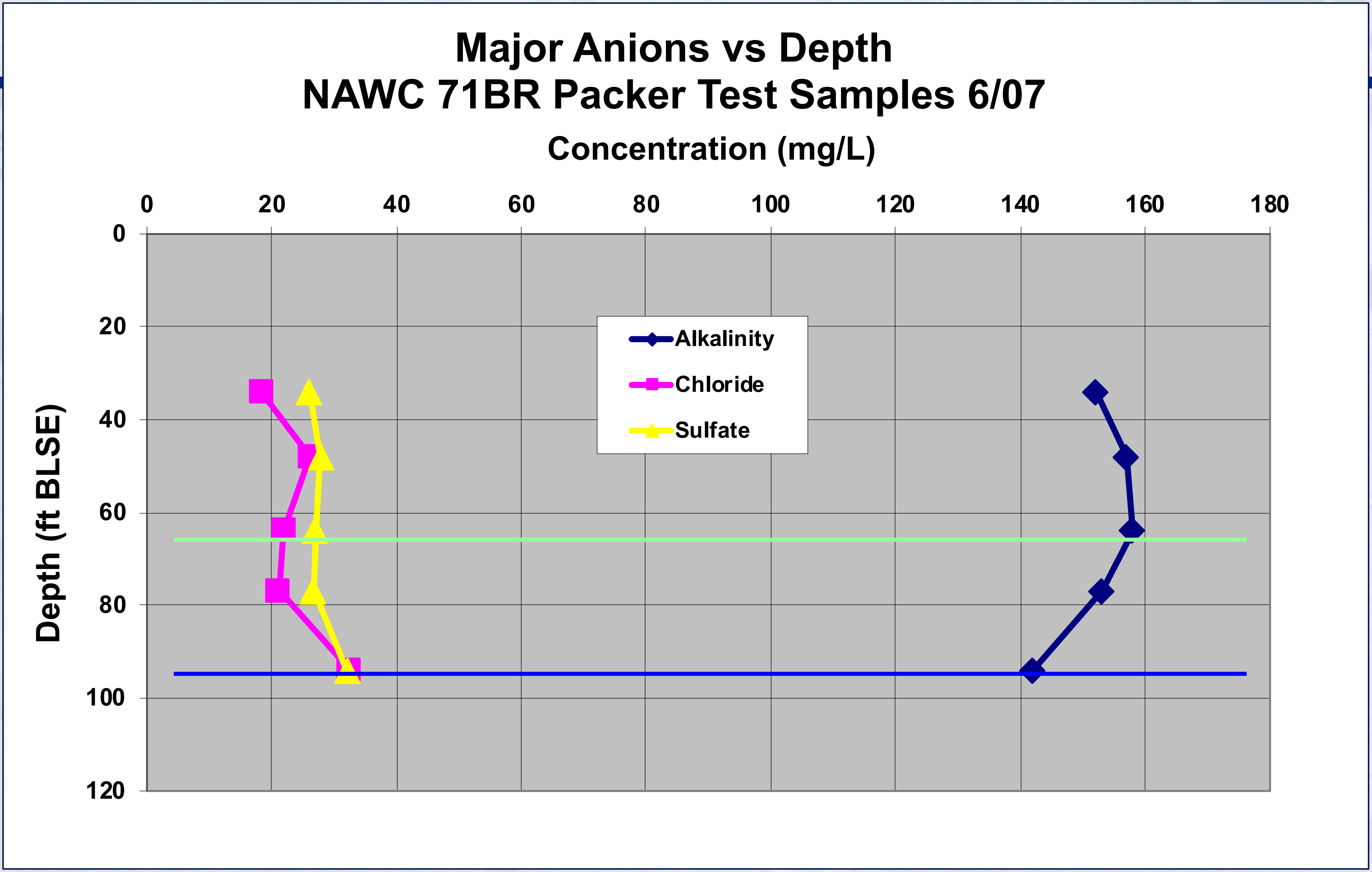


Packer Test Water-Quality Profiling

Mirror Lake Well H1 – Depth Dependent CFC-12 Concs

Sample ID	Sample Interval Depths	Sample Interval Length	Transmis -sivity	Pumping Rate	CFC-12 (CCl_2F_2) Concentrations		
					Replicates	Mean	Std Dev
	(ft amsl)	(ft)	(ft^2/day)	(gpm)	(n)	(pg/L)	(pg/L)
H1 Open	684-459	225	2.6	0.53	3	168	5
H1-1	657-642	15	1.3	0.32	3	92	1
H1-2	586-571	15	0.7	0.98	3	77	5

Packer Test Water-Quality Profiling



DEPTH-DEPENDENT SAMPLING IN PUMPING WELLS

DATA INTERPRETATION

Depth-dependent water-quality data collected within production wells under pumping conditions can be used to estimate the quality of water yielded to a well from a selected depth interval using the following equation:

$$C_a = (C_i Q_i - C_{i+1} Q_{i+1})/Q_a \, , \quad \text{(eq. 1)}$$

where:

- C is the concentration of a given constituent,
- Q is the flow of water within the well (either as volume per unit time, as velocity, or as percent of total discharge),
- i is the first sample collection and flow measurement depth,
- i+1 is the second sample collection and flow measurement depth, and
- a is the interval between i and i+1.

From USGS Fact Sheet 2004-3096; also Izbicki and others, 1999.

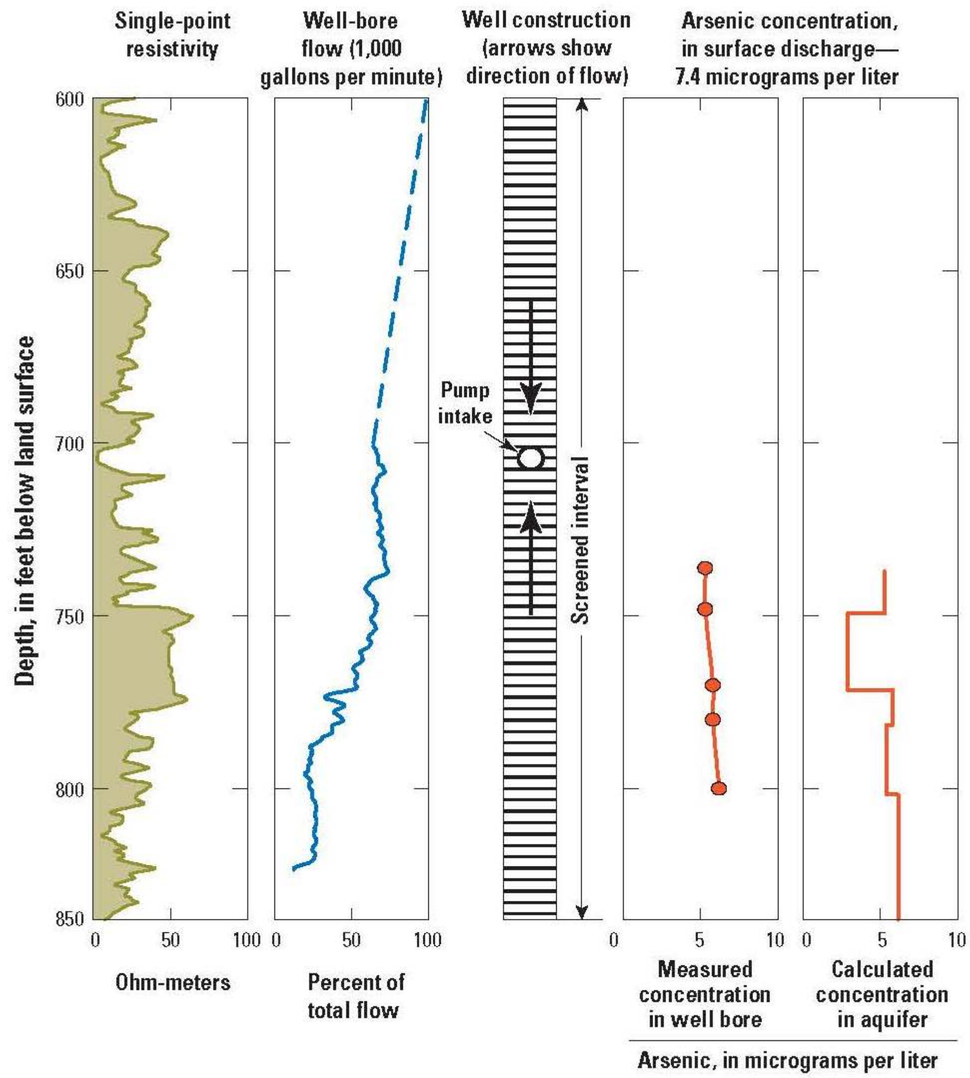
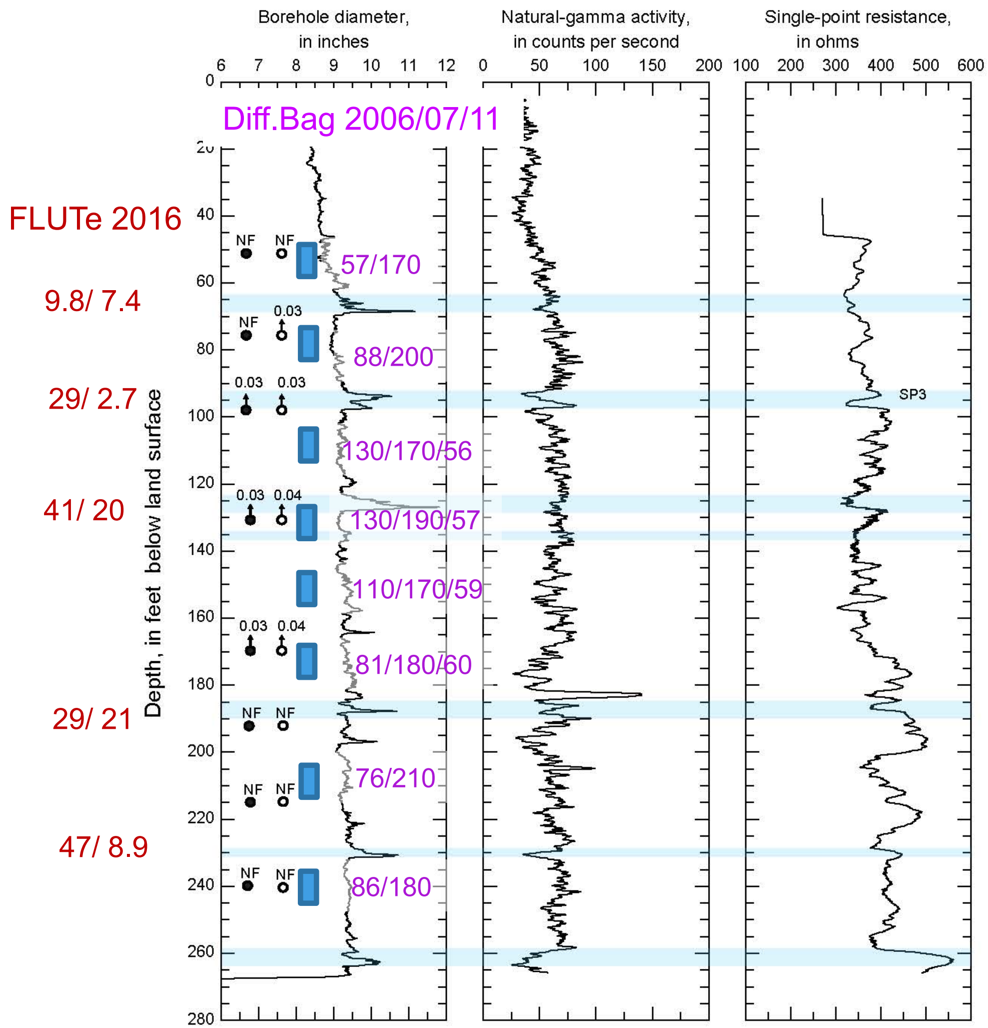


Figure 3. Depth-dependent water-quality data collected from production well 4N/5W-2H1 near Victorville, California.

Diffusion bag and FLUTE sampling results

TCE concentrations, in ug/L, in diffusion bags 2006, 2007, 2011 and FLUTe in 2016



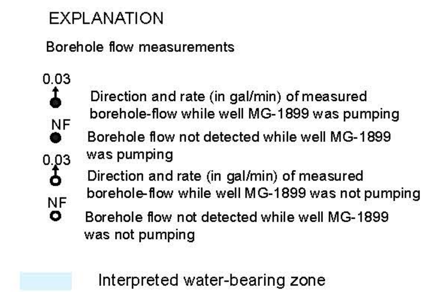


Figure 8. Borehole diameter, natural gamma-ray, and single-point resistance logs, interpreted depths of water-bearing zones, and borehole-flow measurements in well MG-157 (former FM Weaver well). Flow measurements made while Westside extraction well (MG-1899) was pumping on December 14, 2006 and not pumping (shutdown) on December 12, 2006.

Diffusion bag sampling issues –
- Need to know borehole flow conditions
- Flow conditions may vary during period when bags are in hole
-- Chemical reactions in borehole may affect diffusion bag results