FLOW AND TRANSPORT PROPERTIES OF FRACTURED BEDROCK AQUIFERS IN THE VERTICAL DIRECTION

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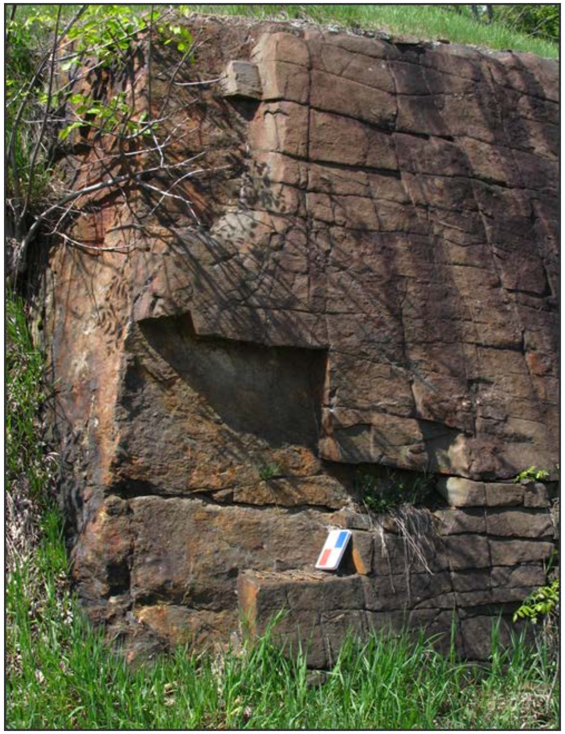
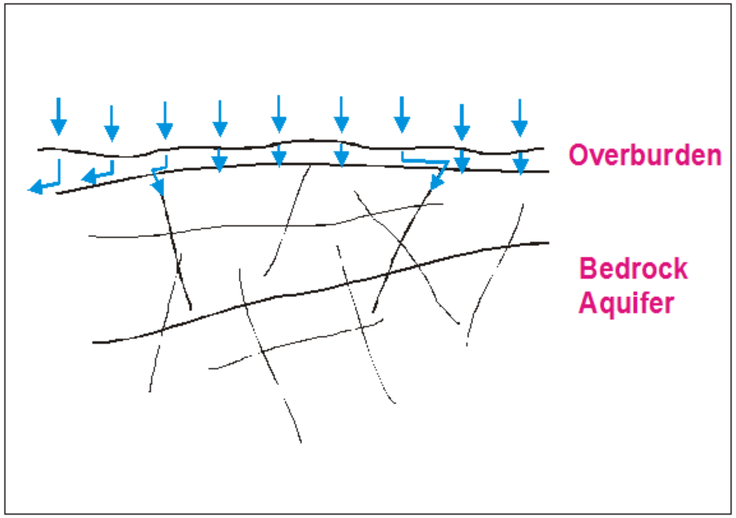
Characterization of Bedrock Aquifers

- Flow is dominated by individual fracture features.
- Hydraulic properties vary over many orders of magnitude, particularly K (or fracture aperture).



What About Vertical Hydraulic Properties?

- Also dependent on fracture pathways.
- Where bedrock is at shallow depth, complex interplay between the overburden materials, bedrock topography, and vertical fracture subcrops.



Methods for Estimating Vertical Properties

- Traditional open-well pumping tests.
- Pumping tests conducted using multi-level piezometers.
- Pulse interference tests.
- Inclined drilling and constant head tests.
- Transport experiments (tracers).

Objectives

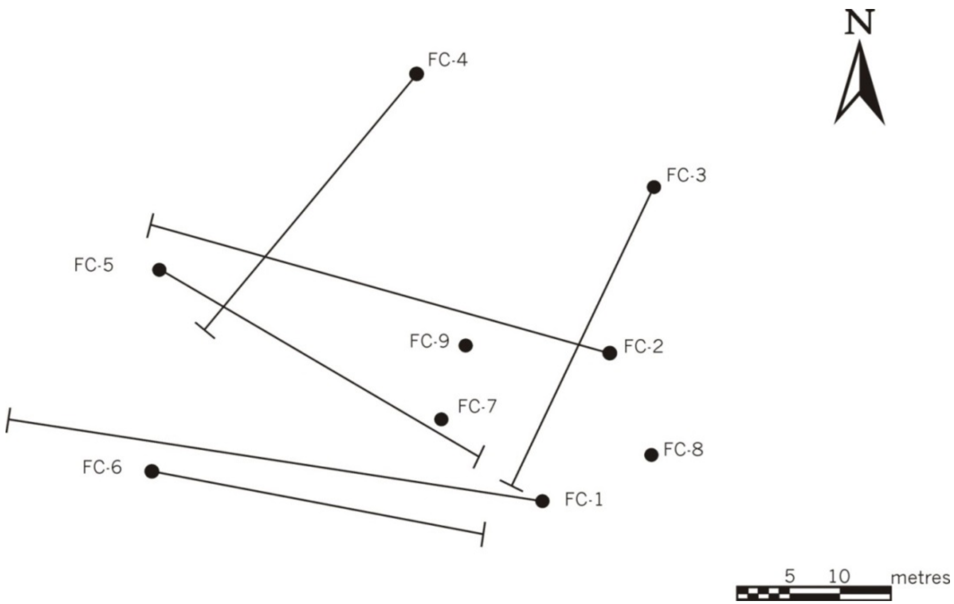
- Evaluate methods for characterizing vertical hydraulic and transport properties of shallow bedrock.
- Explore the processes of fluid flow across the soil-bedrock contact.
- Students involved: Shawn Trimper, Claire Milloy, Jessica Worley, Laura Elmhirst, Titia Praamsma, and Jana Levison.

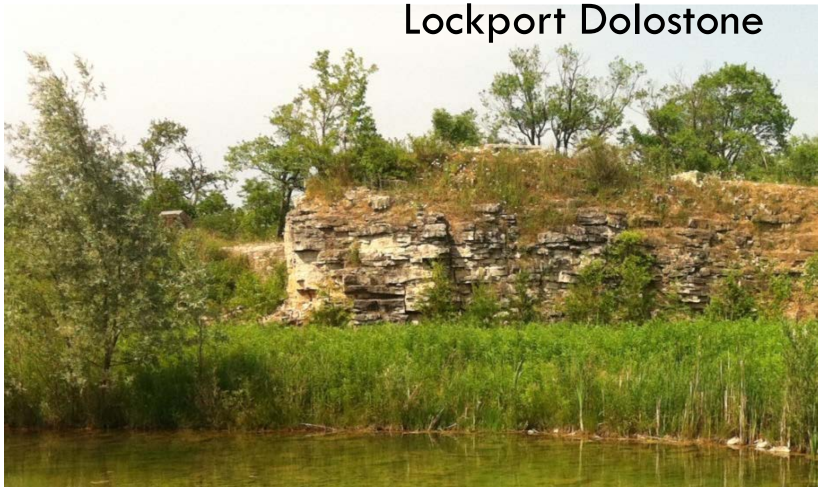
Evaluation of Methods for Estimating Vertical Properties

- Using a highly-detailed case study, compare detailed discrete-fracture analysis conducted via constant head testing (i.e the most accurate means of estimation) to bulk estimation methods for K, K′, S_s, S'_s, and S_y.
- Study conducted in the Guelph/Amabel dolostones at a site near Cambridge, Ontario.
- Compare detailed constant head testing to pumping tests conducted by isolating specific fracture features, open-hole pumping tests, and open-hole pulse interference testing.

Field Site

- Nine boreholes drilled to 30 m depth in a 75m by 100 m area.
- Six of the nine, drilled at 45°.





Constant Head Tests

- Constant head tests conducted using a packer spacing of 0.5 m contiguously for all boreholes.
- Three-four discrete fracture zones in the horizontal direction were identified across the site.
- Discrete vertical fractures were identified in many packer intervals.
- T ranged overall from 10^{-11} to 10^{-4} m^2/s.

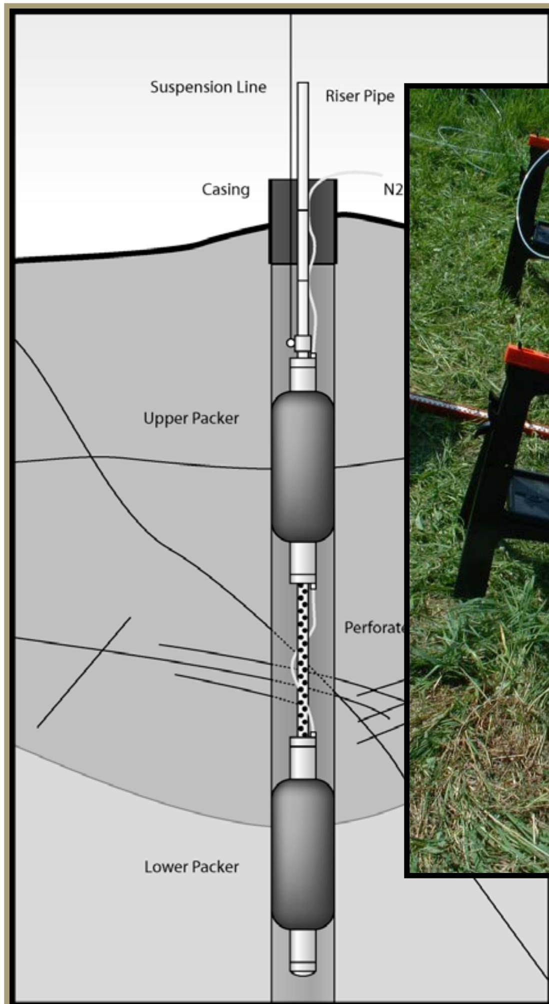
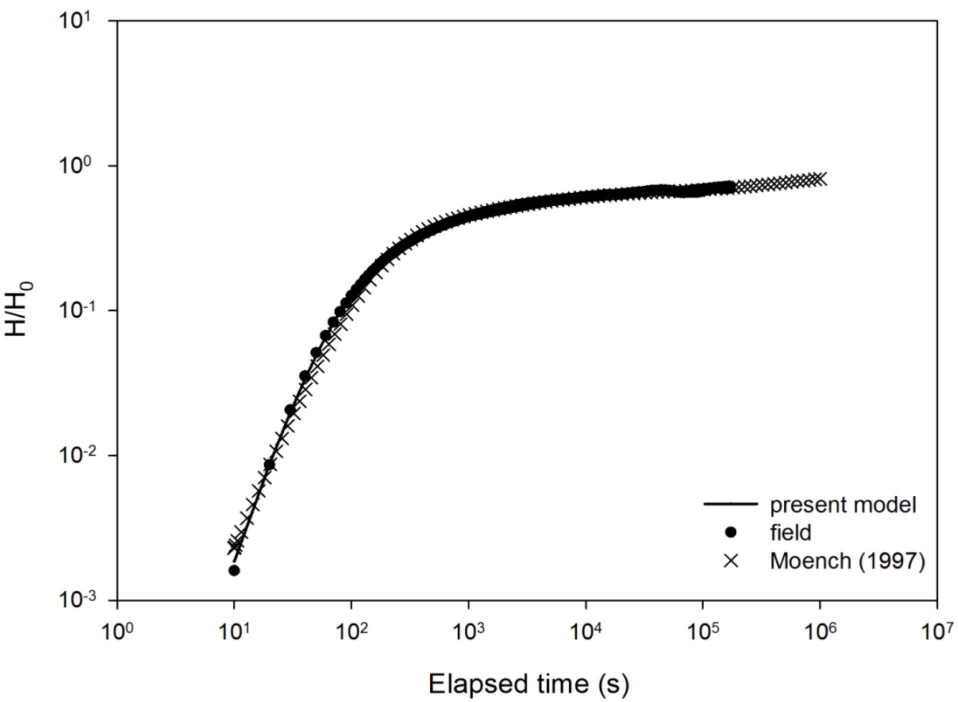


FIGURE 3.3.1: Straddle Packer System

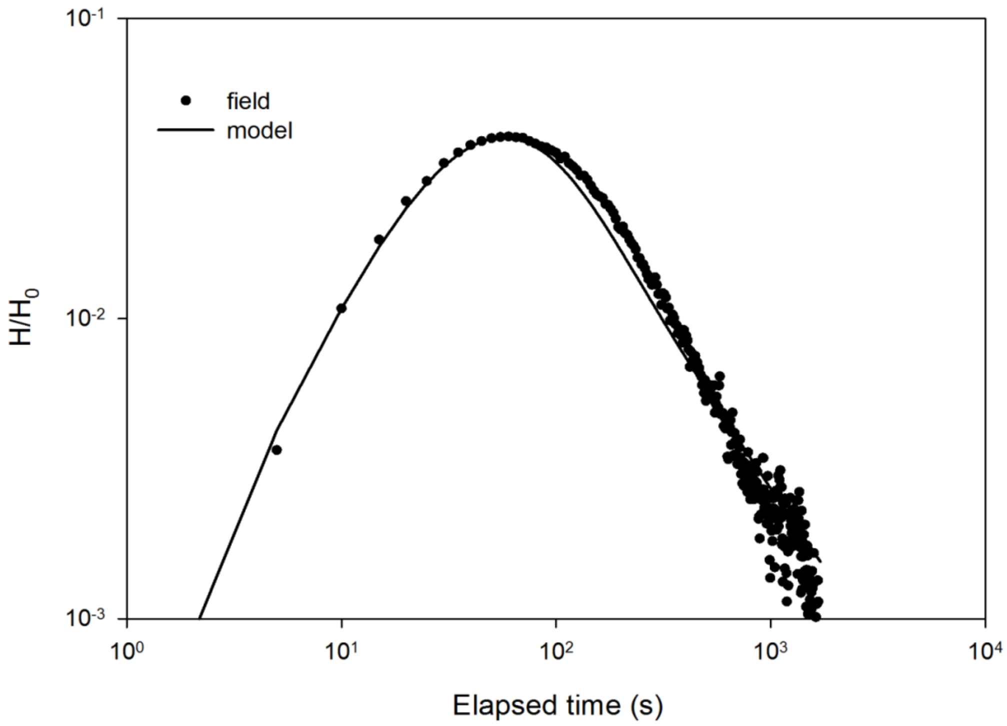
Open-Well Pumping Tests

- Two 48-hr pumping tests, both at about 10 Lpm, conducted in two of the vertical holes.
- Observation (open-hole conditions) in every other borehole.
- Worley and Novakowski (2013) fitting done with PEST.
- Also used Moench (1997) in AQTESOLV.



Open-Well Pulse Interference Tests

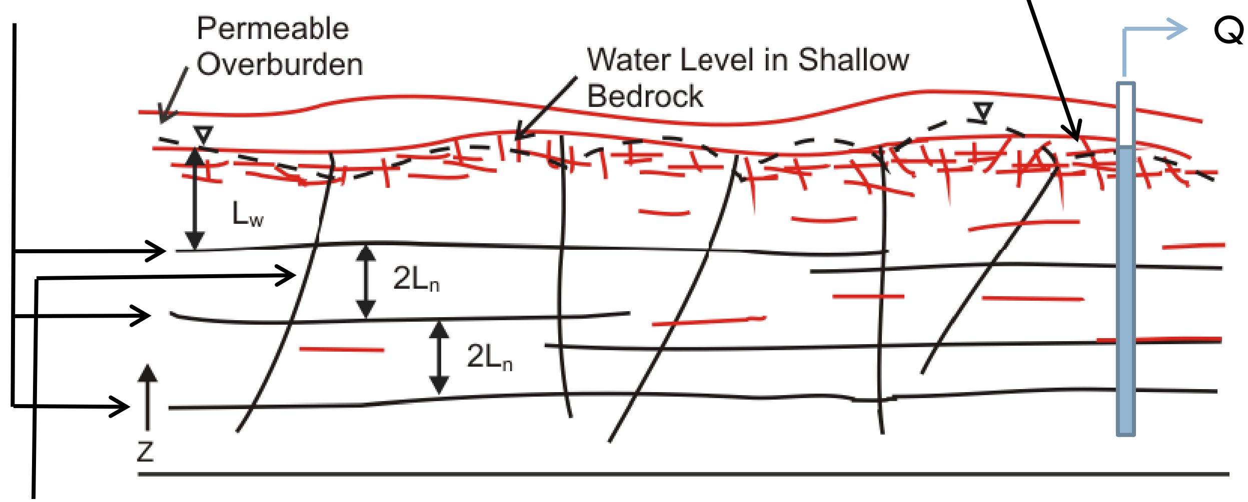
- Pulse interference tests conducted using every well as a source hole with response observed in every other well.
- Elmhirst and Novakowski (2012) fitted to the data using PEST.
- Developed a specific strategy to obtain the fits, as uniqueness was an issue in some cases.



Pulse and Pumping Test Interpretation

$$K'\frac{\partial h_m}{\partial z}\bigg|_{z=L_w} = -\alpha_1 S_y \int_0^t \frac{\partial h_m(r, L_w, t)}{\partial \tau} \exp\{-\alpha_1(t-\tau)\}\partial\tau$$

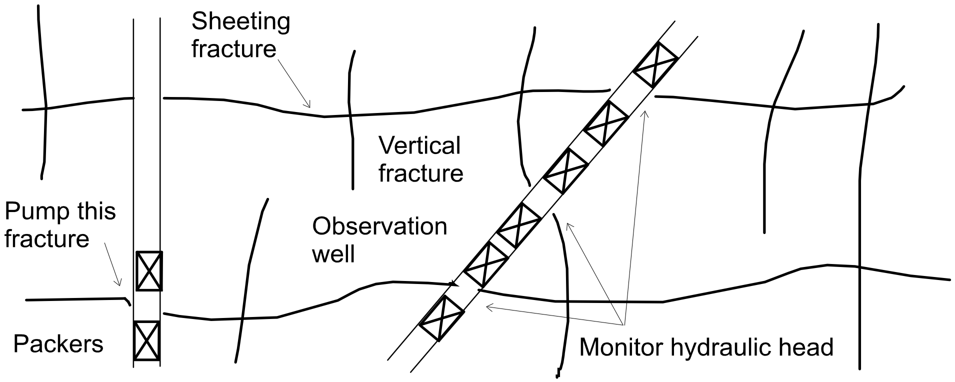
$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} - q = \frac{S}{T}\frac{\partial h}{\partial t} \qquad r \geq r_w$$

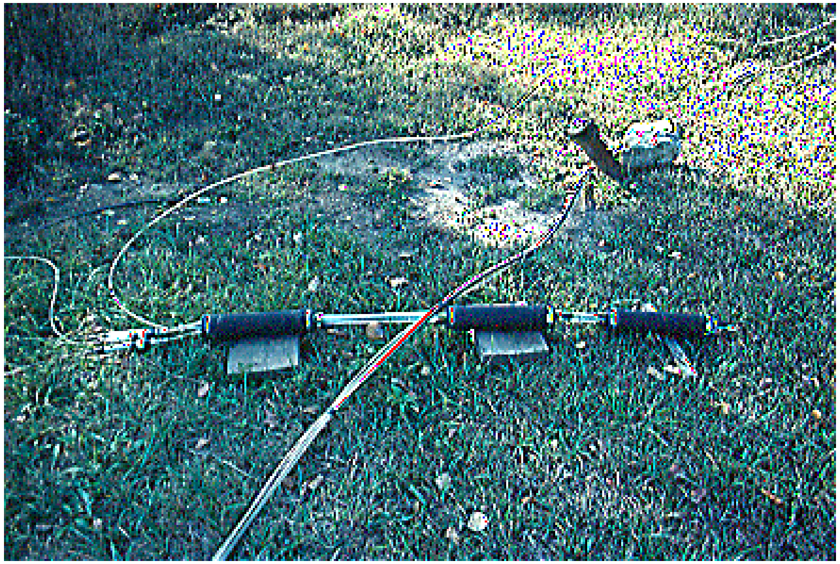


$$q = -\frac{K'}{T}\frac{\partial h_m}{\partial z}\bigg|_{z=0} = 0\,; \qquad 0 \leq z \leq L_w$$

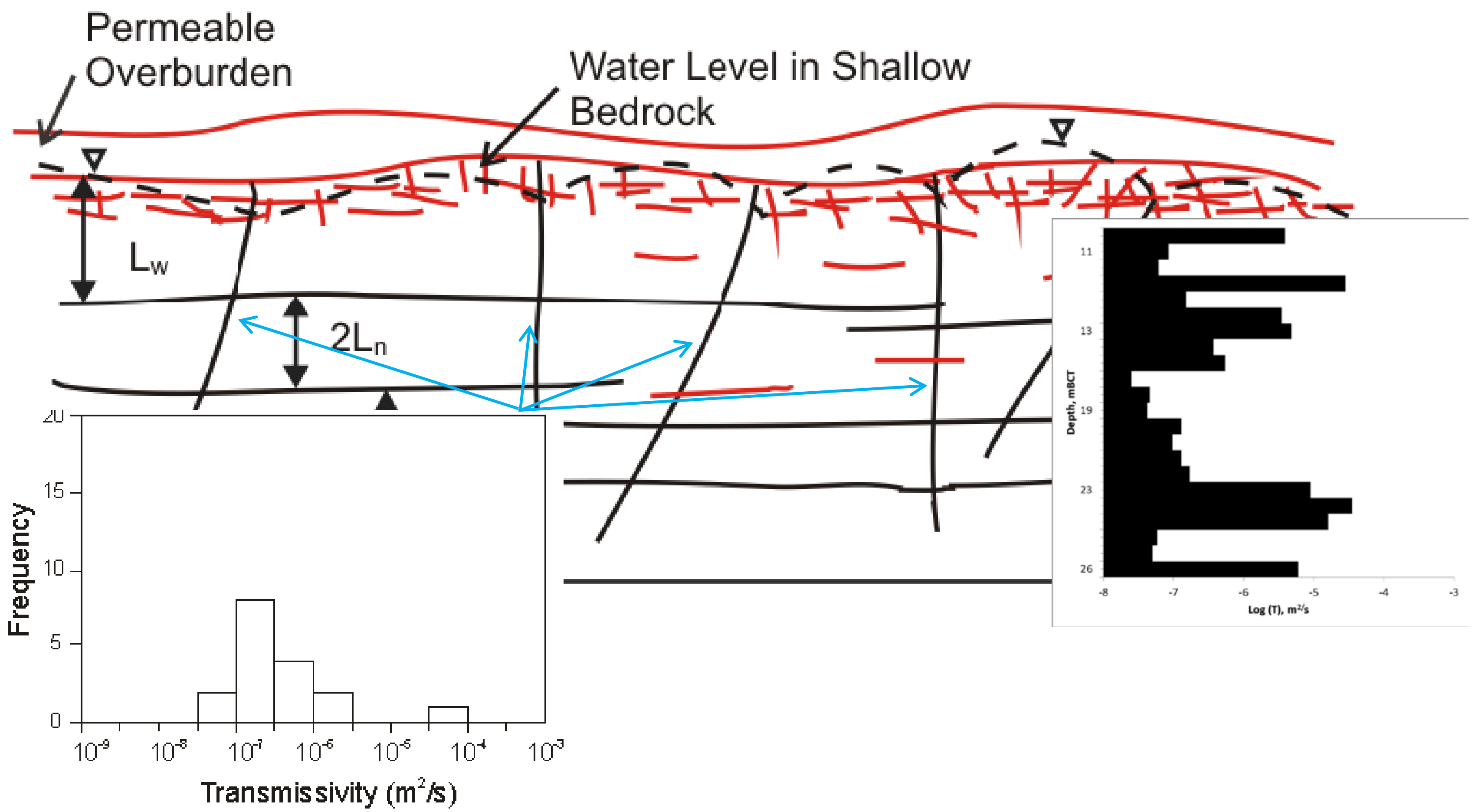
Isolated-Zone Pumping Tests

- Four 12-hour pumping tests conducted where a horizontal fracture was isolated by packers and pumped .
- Observation of drawdown was collected in zones isolated in both horizontal and vertical fractures.
- Interpretation conducted using the Ratio Method (Neuman and Witherspoon, 1972).





Constant Head Test Results



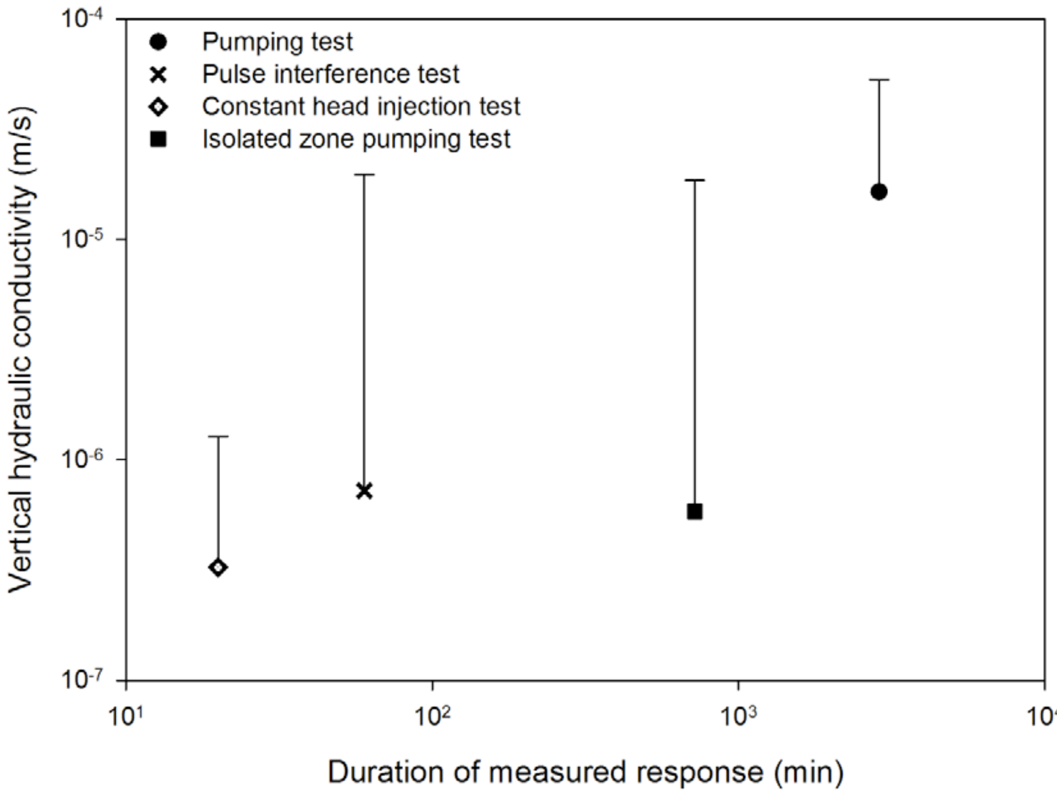
Bulk Parameters

- To evaluate methods, we need to calculate the bulk parameters K′, and S_y from the constant head results.
- The vertical hydraulic conductivity, K′, of the fracture system was calculated from those intervals identified to have vertical fractures only.
- Calculate S_y by summing all T and converting to an effective total 2b (aperture) for each well, which represents effective total porosity.

$$\theta \approx S_y$$

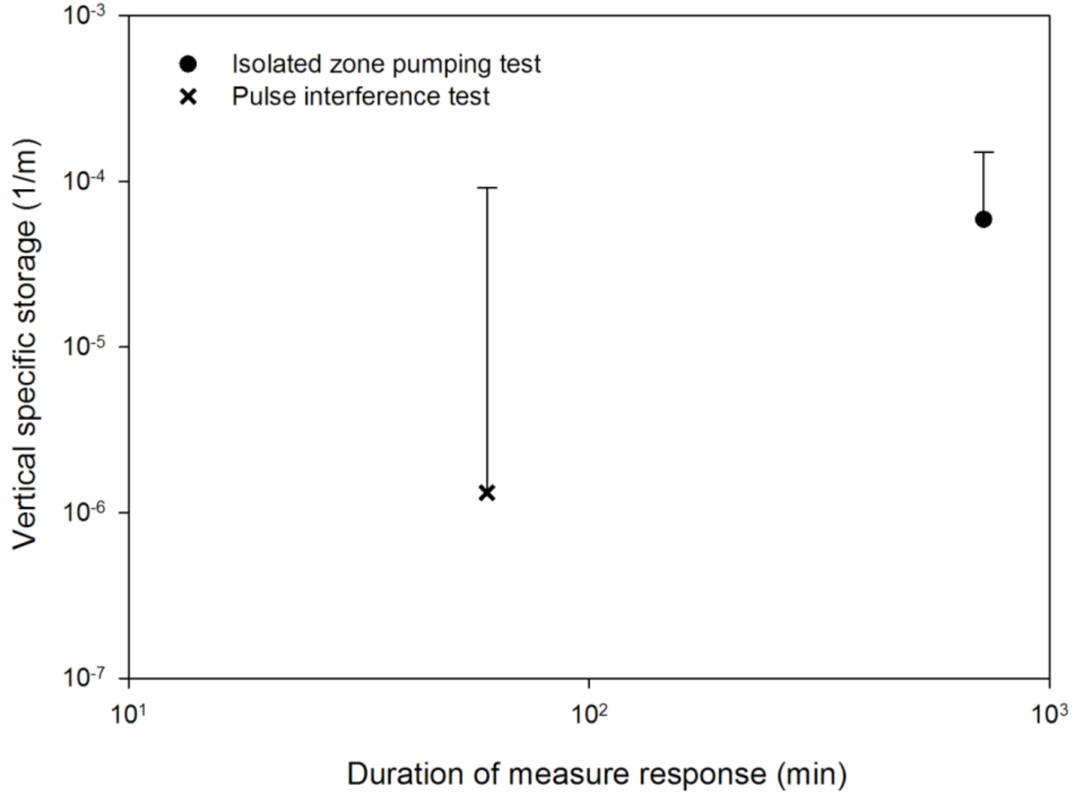
Vertical Hydraulic Conductivity

- Experienced considerable difficulty with non-uniqueness in pumping test analysis.
- Open-hole pumping tests can not be used to estimate K'.
- Found by fixing the horizontal properties, pulse interference tests may provide reasonable K' estimates.



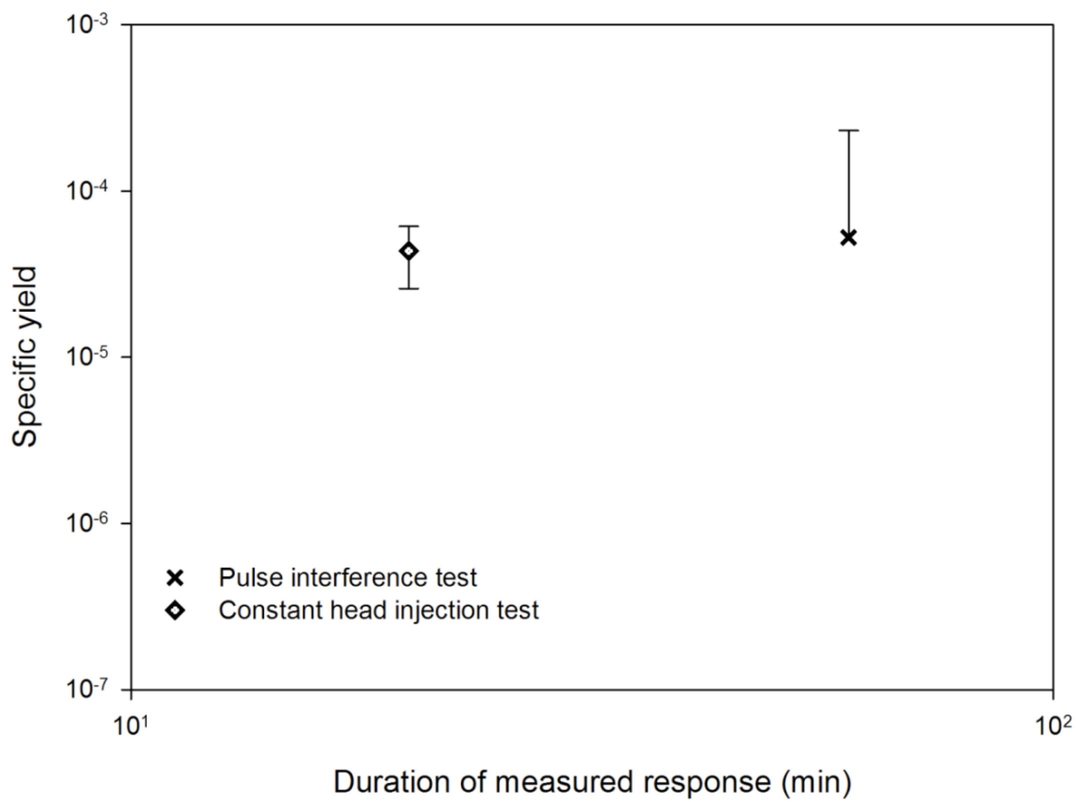
Vertical Specific Storage

- Have to discard pumping tests and can't use constant head tests. Isolated zones are not a fair comparison.



Specific Yield

- Left with only with pulse interference and constant head test results.
- Thus pulse interference tests may be a reasonable alternative to detailed constant head testing for bulk vertical hydraulic values.



Vertical Transport Experiments

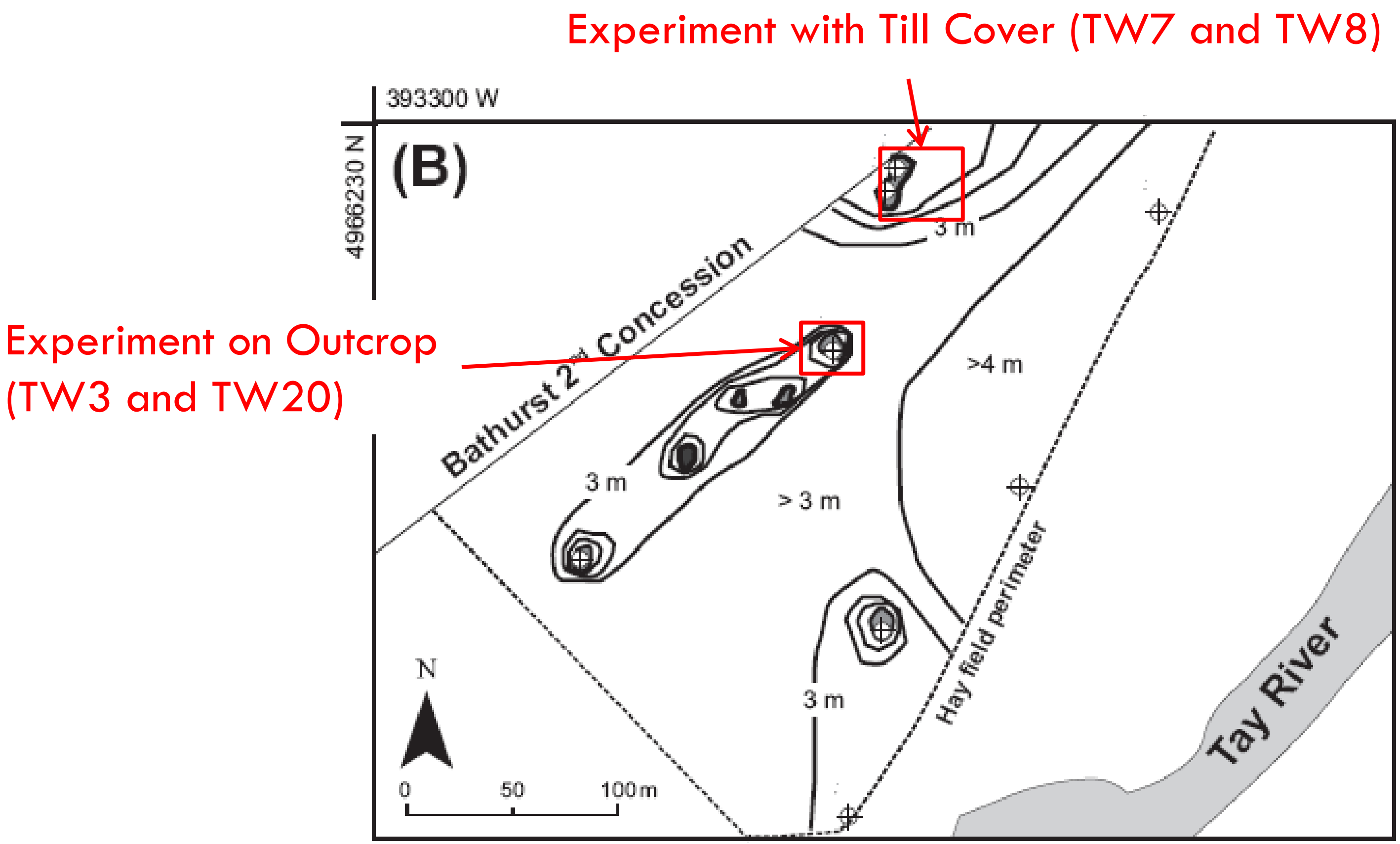
- Different setting – gneissic terrain with 0-4 m of glacial till cover in eastern Ontario.
- A total of nine multi-level and open wells (110-140' deep) in bedrock characterized using constant head testing.

Method

- Several experiments over recent years.
- Apply fluorescent tracer (and water) to a specified location with and without till cover.
- Pump adjacent well(s) and sample.
- Alternatively measure arrival in situ.

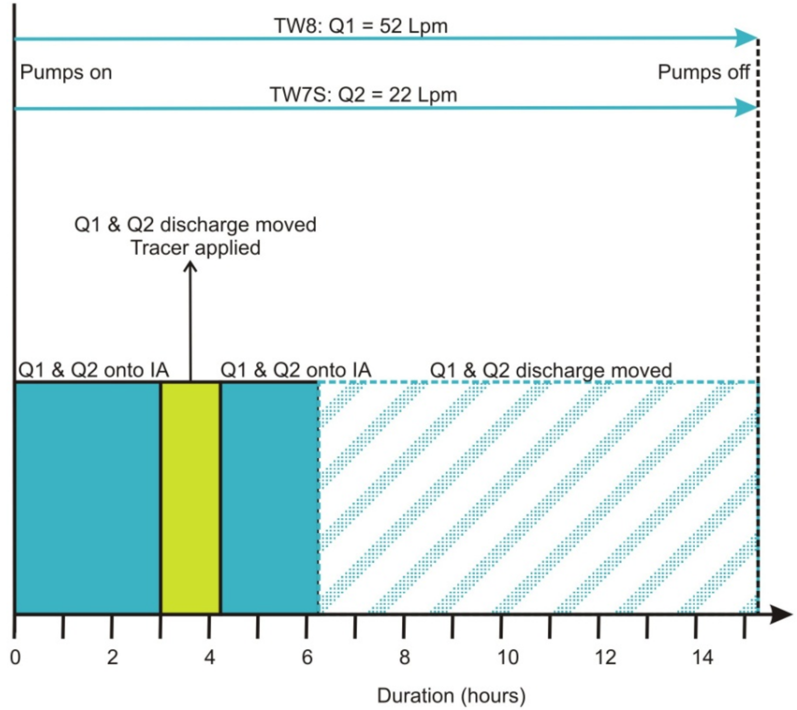
Locations

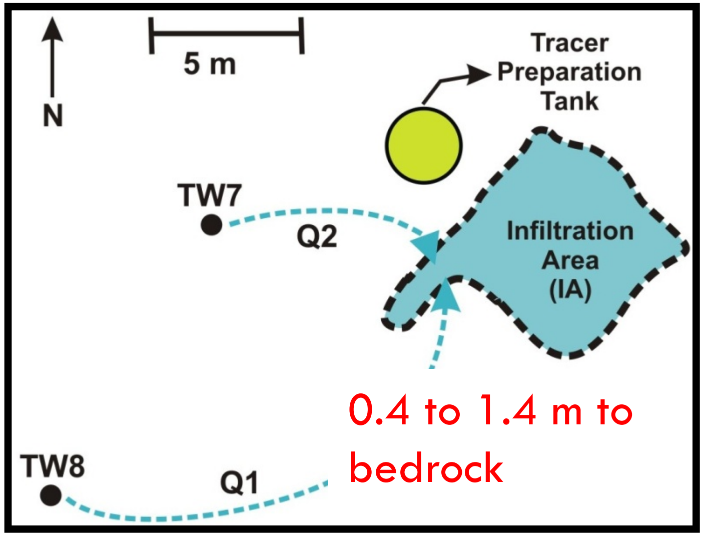
- Two sites in the same field.



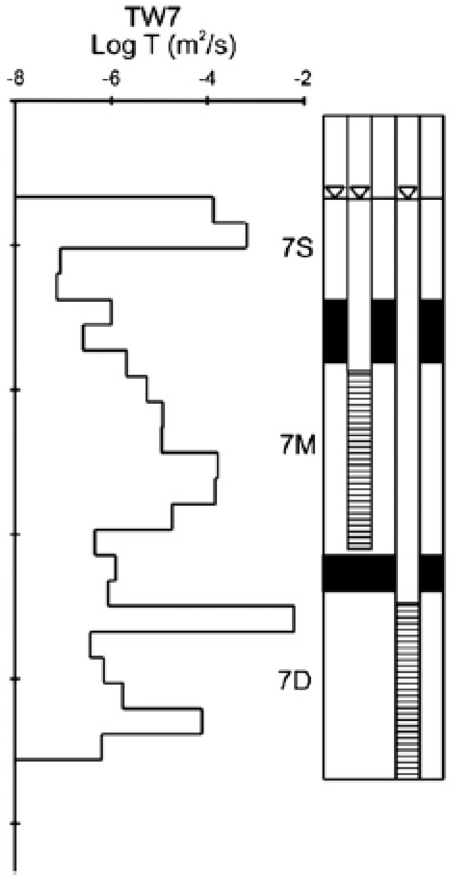
Experiment With Till Cover

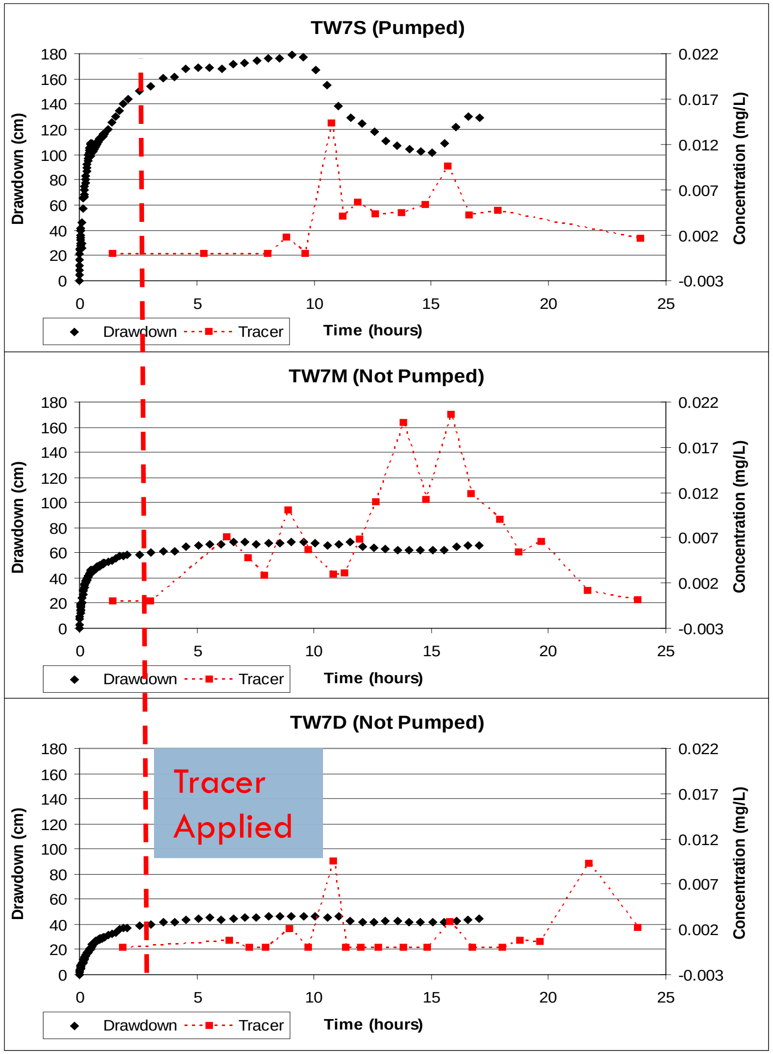
- 24-hour duration.
- TW7S and TW8 pumped.
- 1500 L of Lissamine FF (200 ppm spread over 40 m^2)



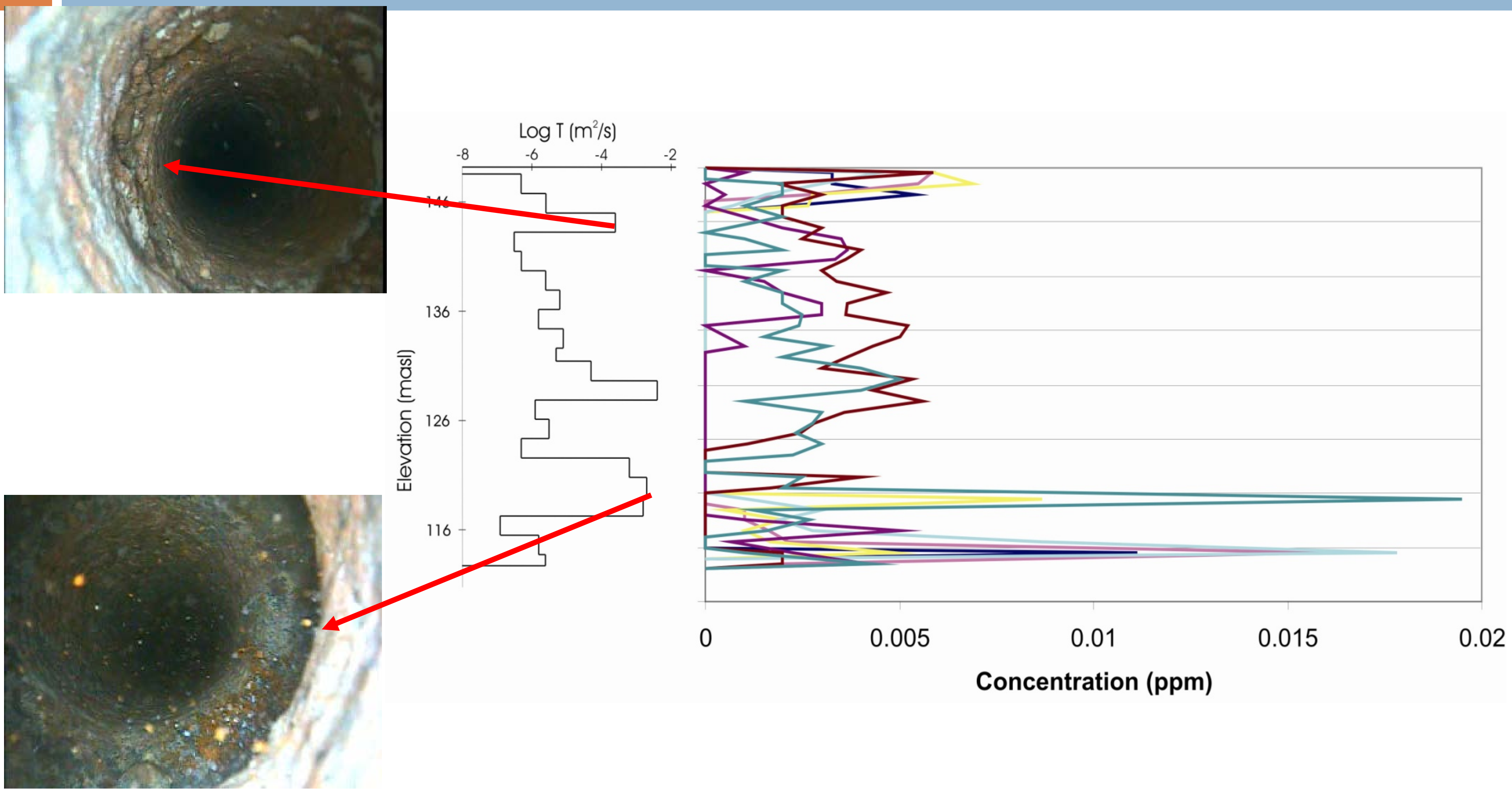


TW7


TW7
Log T (m²/s)
-8
-6
-4
-2
7S
7M
7D


TW7S (Pumped)
TW7M (Not Pumped)
TW7D (Not Pumped)
Drawdown (cm)
Concentration (mg/L)
Time (hours)
Drawdown
Tracer
Tracer Applied

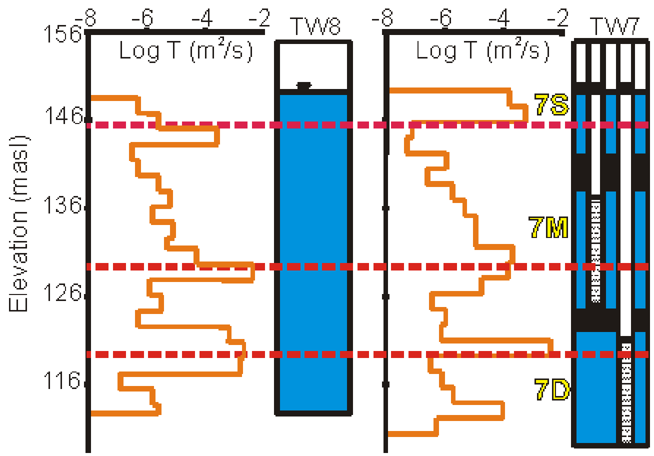
TW8

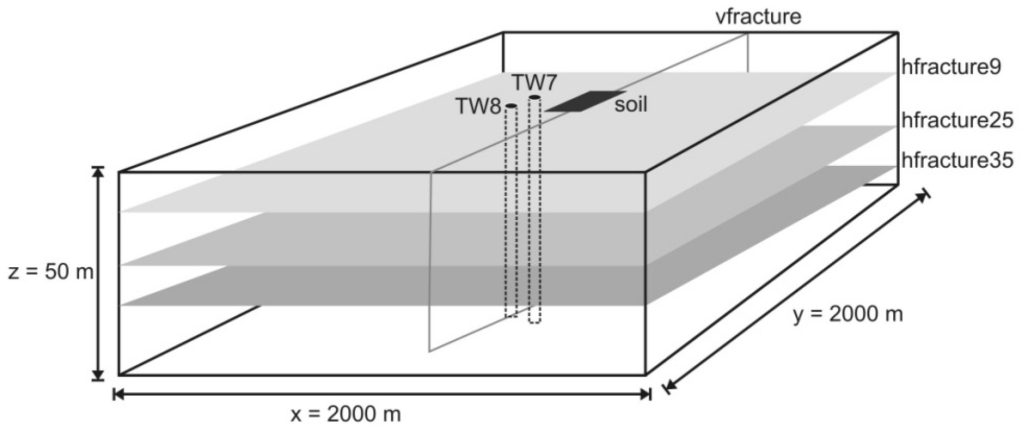


Log T (m^2/s)
-8
-6
-4
-2
136
126
116
Elevation (masl)
0
0.005
0.01
0.015
0.02
Concentration (ppm)

Numerical Analysis

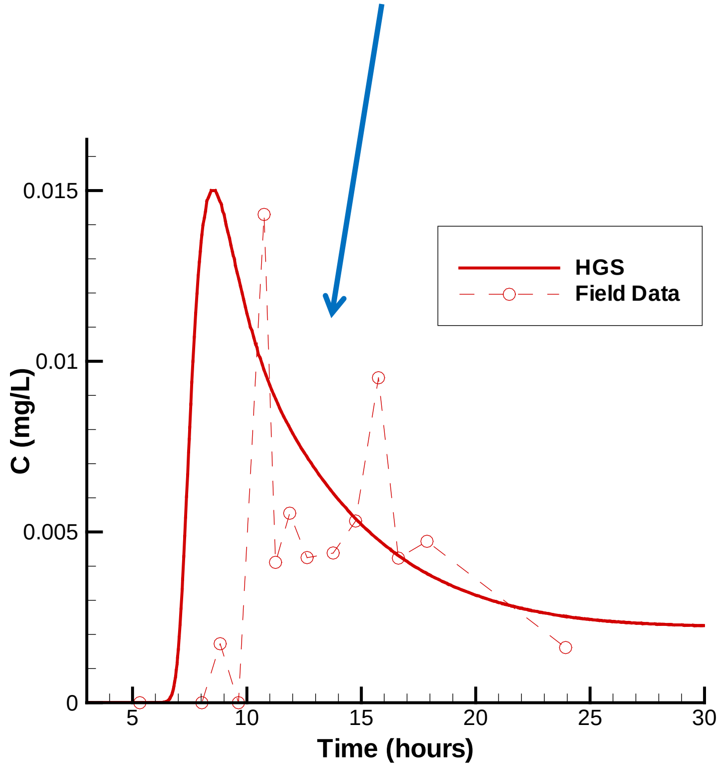
- Modeling conducted with *HydroGeoSphere*.
- Conceptual model built from field data.
- Used a single vertical fracture underneath the infiltration area.

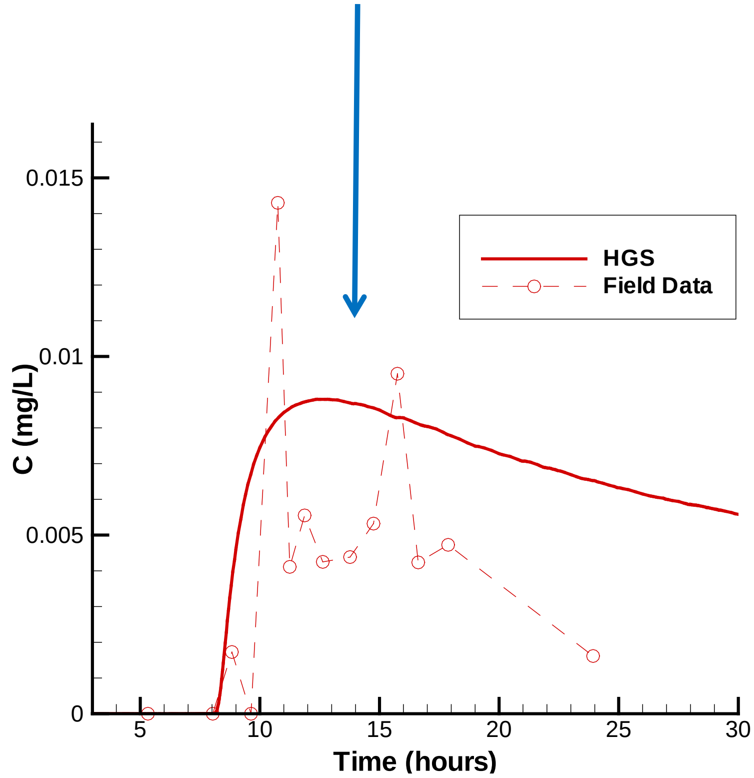




Numerical Analysis

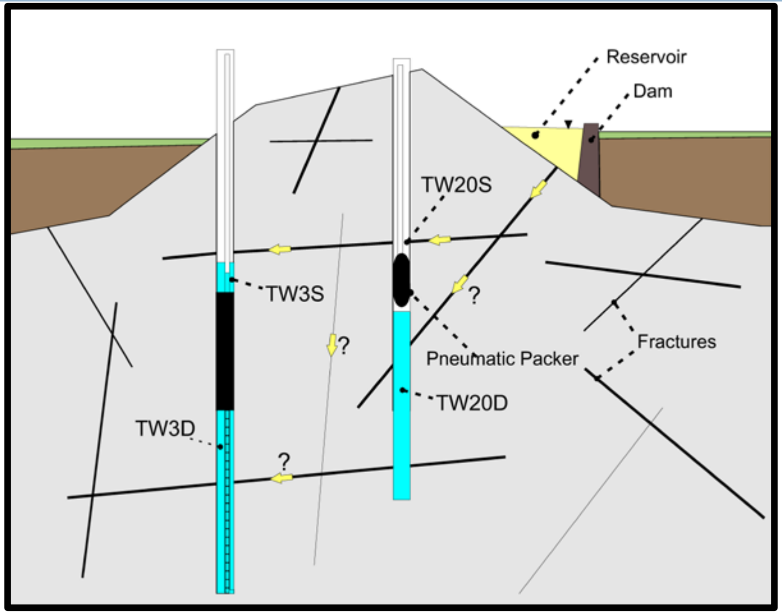
- Very non-unique exercise - many different scenarios tested.
- Best representations were found for a large aperture fracture placed outside the pool or a unrealistically thick overburden (4m)

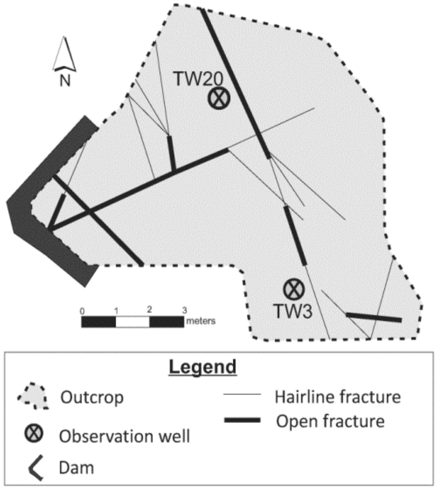




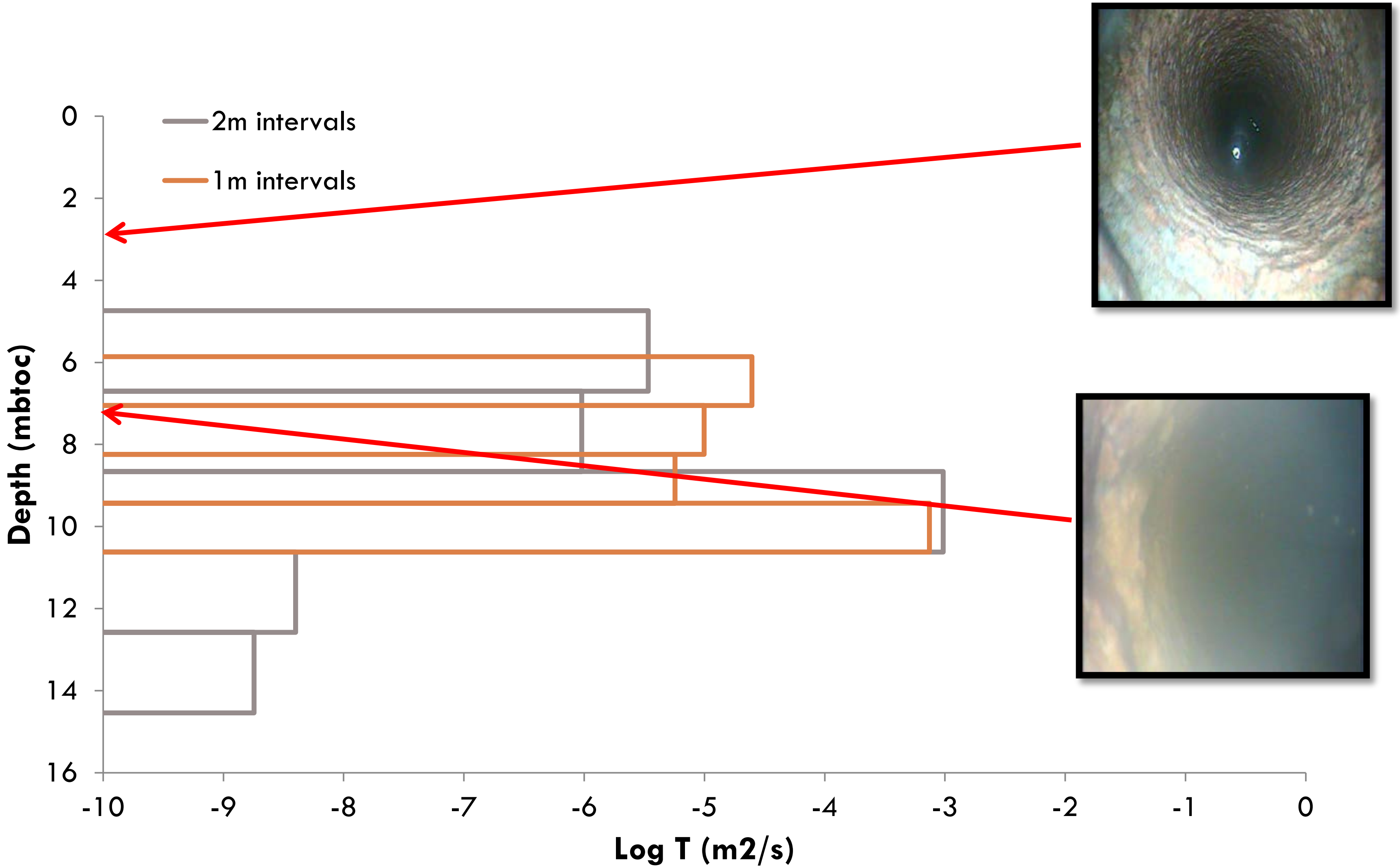
Experiment on Outcrop

- Surface fractures exposed.
- TW20D pumped at 7.7 L/min.
- Reservoir volume of ~ 1200L.
- Reservoir filled, steady flow at ~ 8 L/min.
- 100 g Lissamine added instantaneously.

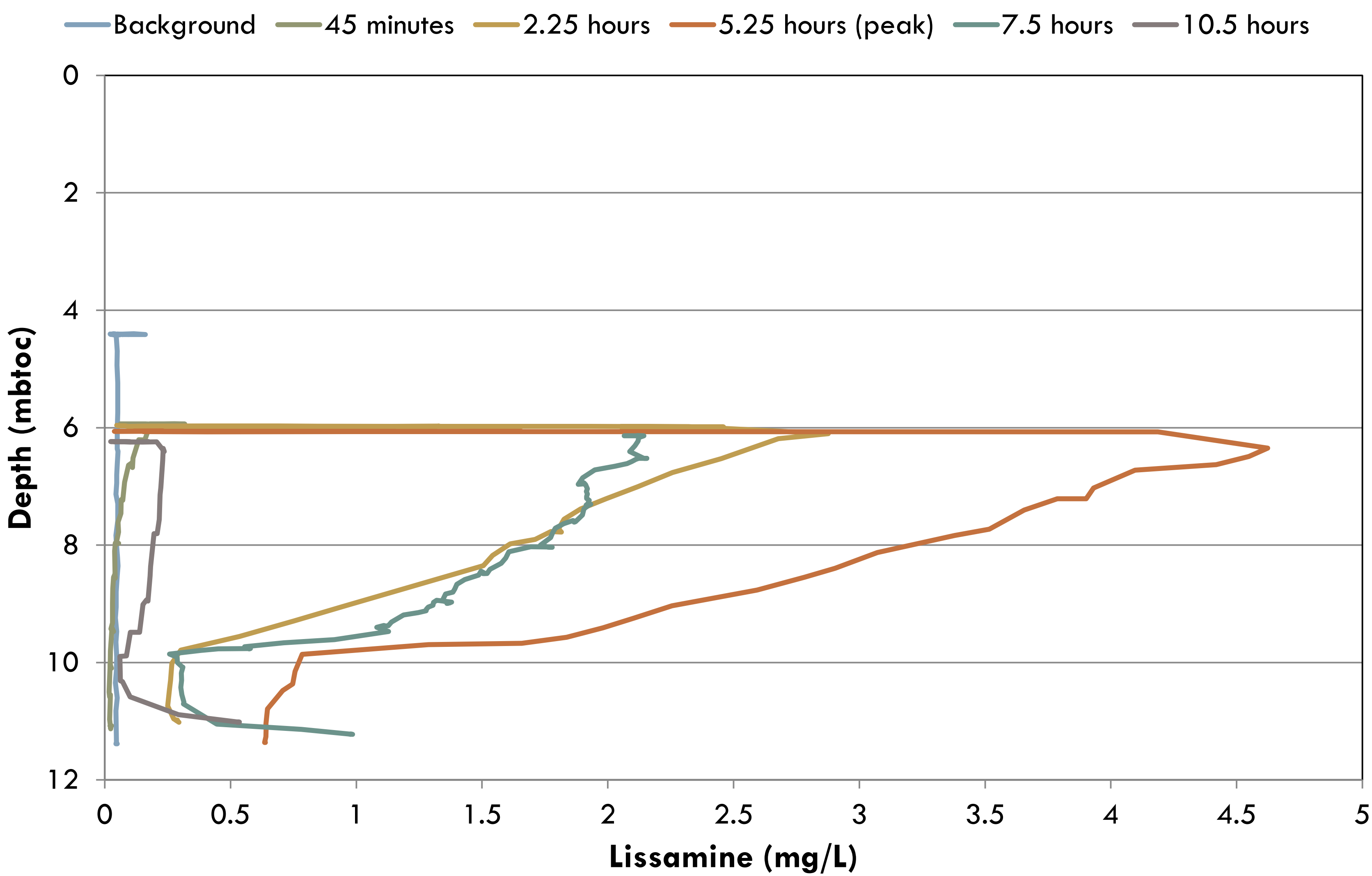




TW20 Transmissivity

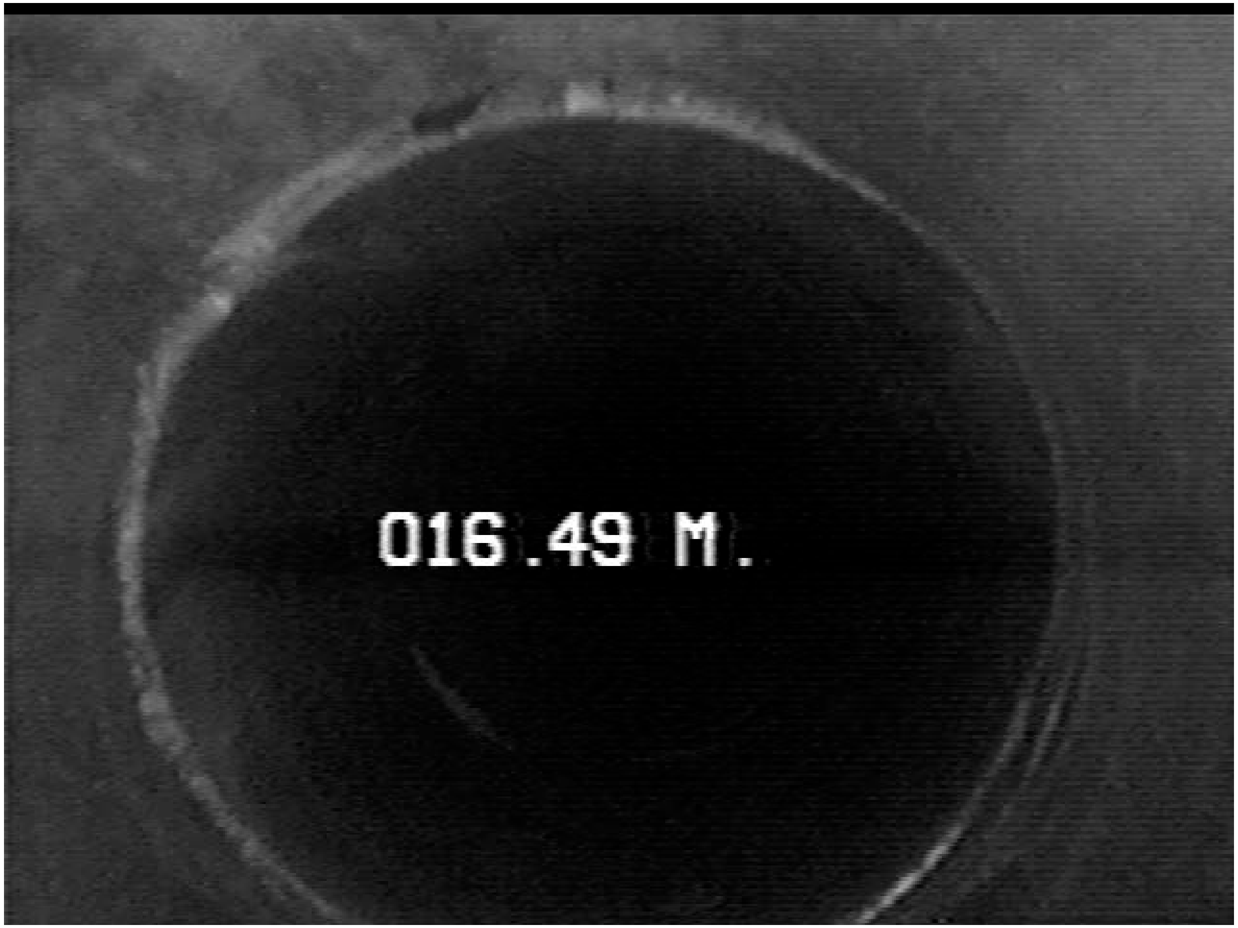


TW20


Background
45 minutes
2.25 hours
5.25 hours (peak)
7.5 hours
10.5 hours
Depth (mbtoc)
0
2
4
6
8
10
12
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Lissamine (mg/L)

Conclusions

- Open-well pumping tests could not provide reliable estimates of vertical hydraulic parameters.
- Pulse interference tests may be used as an alternative to more expensive constant head testing for estimating K' and S_y in a sedimentary rock setting.
- Vertical fracture geometry plays a very significant role in governing vertical solute transport.
- Vertical transport is rapid, complex and not easily amenable to interpretation.


016.49 M.

Constant Head Testing

- Inject water into an isolated portion of a borehole and measure the flow rate at steady conditions.
- Results interpreted using the Thiem equation (no S_s).
- We used a packer spacing of 0.5 m and obtained contiguous measurements with depth in each borehole.

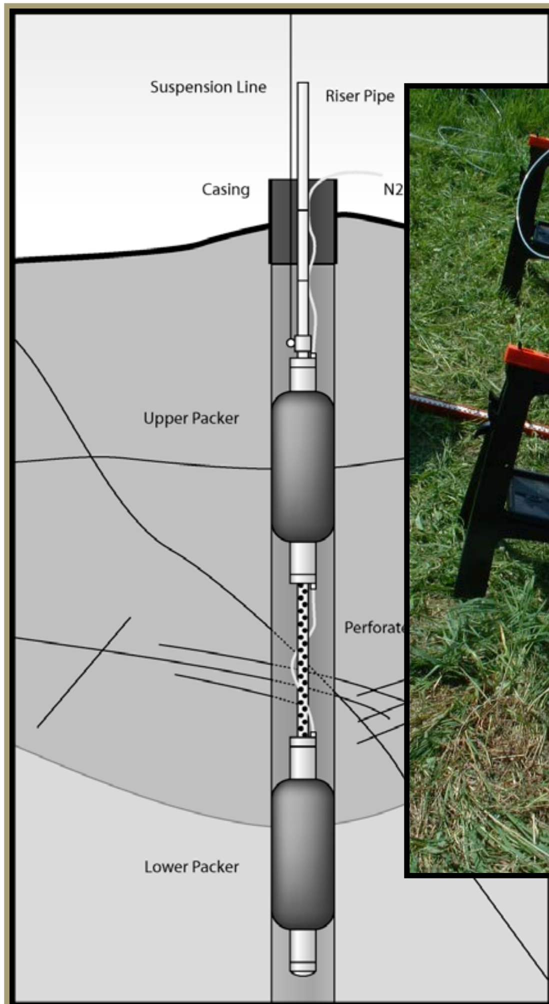
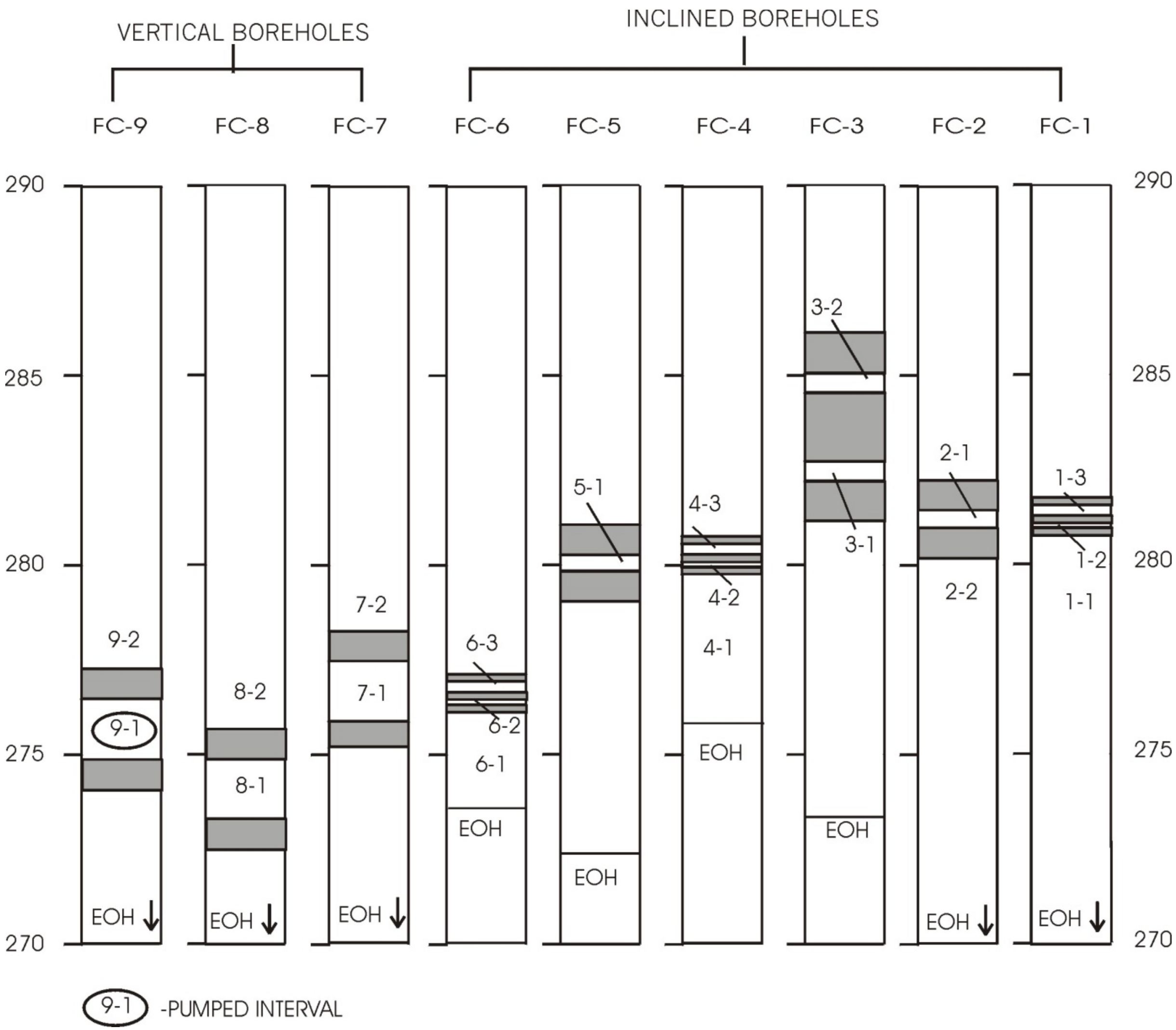


FIGURE 3.3.1: Straddle Packer System

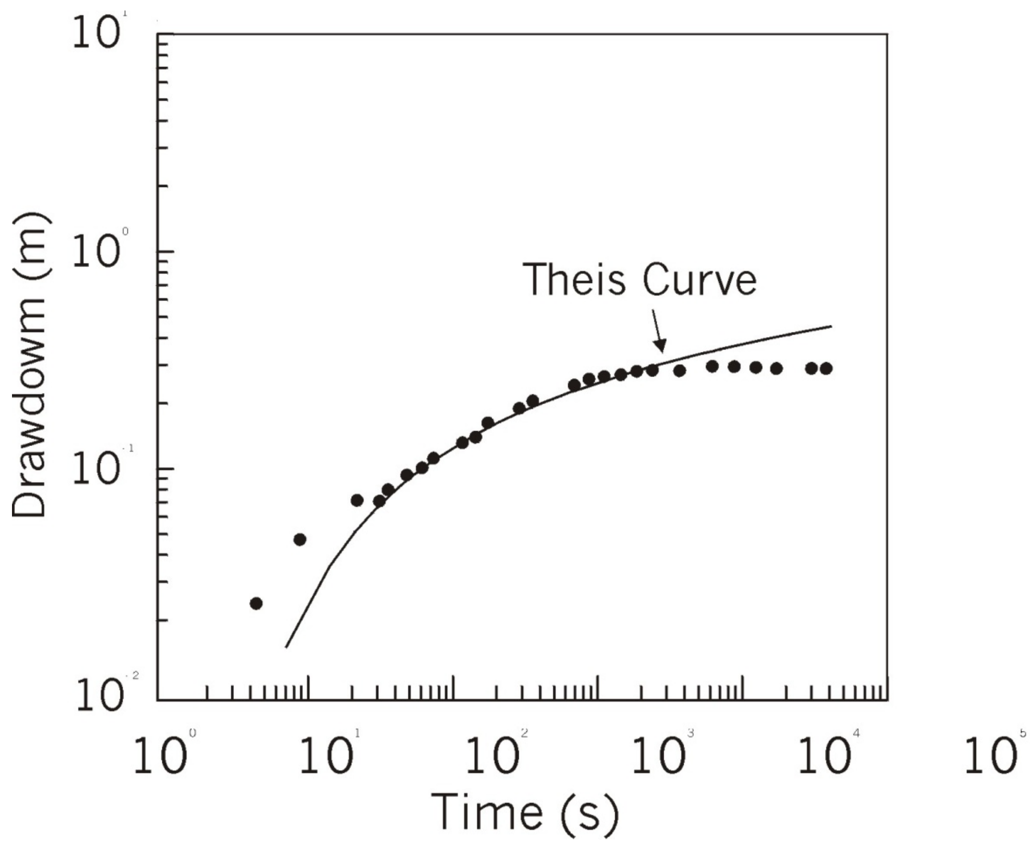
Isolated-Zone Pumping Tests



- Example test configuration.
- Pumping conducted in the vertical boreholes.
- As many as 16 isolated intervals at a time.

Isolated-Zone Pumping Tests

- Example result for observation in the pumped fracture.
- Wellbore storage eliminated by packer systems.
- Note the onset of delayed yield (or leakage) from the vertical fractures at late time.



Vertical Hydraulic Conductivity

- Issue further illustrated by comparison between Monech (1997) solution and Worley and Novakowski (2013).

Parameter	Moench (1997)	Worley and Novakowski (2013)
K (m/s)	4.9×10^{-6}	1.3×10^{-5}
S_S (1/m)	1.7×10^{-7}	2.8×10^{-7}
S_y (-)	1.0×10^{-4}	1.2×10^{-7}
K' (m/s)	3.1×10^{-9}	1.4×10^{-6}