The use of straddle packer testing to hydraulically characterize rock boreholes for contaminant transport studies

Patryk Quinn, John Cherry, Beth Parker

UNIVERSITY of GUELPH

Presentation for the Solinst Symposium
November 7, 2013

This Talk is based on:

- Quinn, P., Cherry, J., Parker, B. (2011), Quantification of non-Darcian flow observed during packer testing in fractured sedimentary rock, Water Resources Research
- Quinn, P., Parker, B., Cherry, J. (2011), Using constant head packer tests to determine apertures in fractured rock, Journal of Contaminant Hydrogeology
- Quinn, P., Cherry, J., Parker, B. (2012), A versatile packer system for high resolution hydraulic testing in fractured rock boreholes, Hydrogeology Journal
- Quinn, P.M., Parker, B.L., & Cherry, J.A. (2013), Validation of non-Darcian flow effects in slug tests conducted in fractured rock boreholes. *Journal of Hydrology*, 486, (0) 505-518
- *Quinn, P., Cherry, J., Parker, B., A synergistic approach to obtain aquifer parameters in fractured sedimentary rock using two types of single-hole hydraulic tests , (to be submitted to Journal of Hydrology in 2013)*

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Fractured Sedimentary Rock


Bedding planes and joints in dolostone


Sandstone with shale interbeds


Interbedded sandstone and shale

General Goal for Investigations of Contaminated Sites in Fractured Rock

Understand the existing contaminant distribution and predict future contaminant behavior

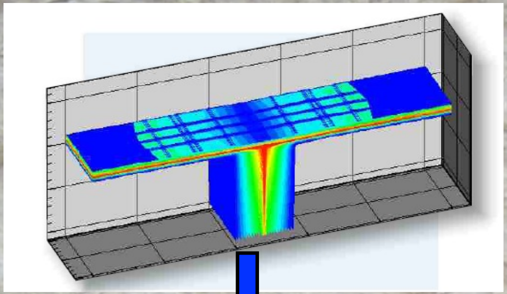
Rock Core Analysis – characterize existing contamination

Numerical Models – predict contaminant behavior over time

Available Powerful Numerical DFN Models

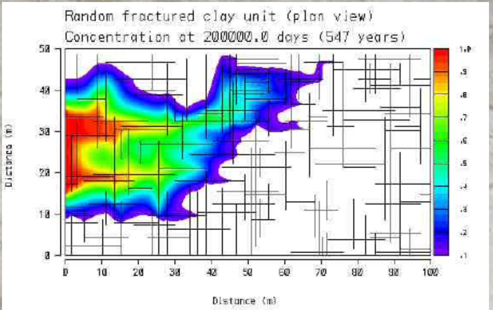
Windows 98/NT/2000/XP
FRAC3DVS

FRAC3DVS is a 3D finite element model for steady-state/transient, variably-saturated flow and advective-dispersive solute transport in porous or discretely-fractured porous media



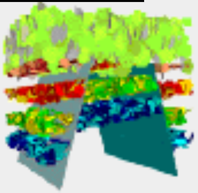
Windows 98/NT/2000/XP
FRACTRAN

FRACTRAN is a 2D finite element model for simulating steady-state groundwater flow and time-variant contaminant transport in discretely-fractured, fully-saturated porous media



FRACMAN
www.fracman.com

Software



FRACMAN® is the premier software for analysis and modeling of heterogeneous and fractured rock masses.

- Software Information
- Downloads
- FracMan Theory
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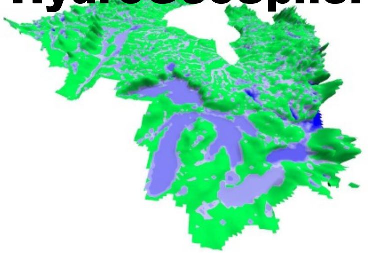
- Benchmark
- Guided Tour
- FracMan Virtual Reality Worlds

Golder Associates

HydroGeoSphere



HydroGeoSphere
A Three-dimensional Numerical Model Describing Fully-integrated Subsurface and Surface Flow and Solute Transport

R. Therrien, Université Laval
R.G. McLaren, University of Waterloo
E.A. Sudicky, University of Waterloo
S.M. Panday, Hydrogeologic Inc./University of Waterloo

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Groundwater Simulations Group

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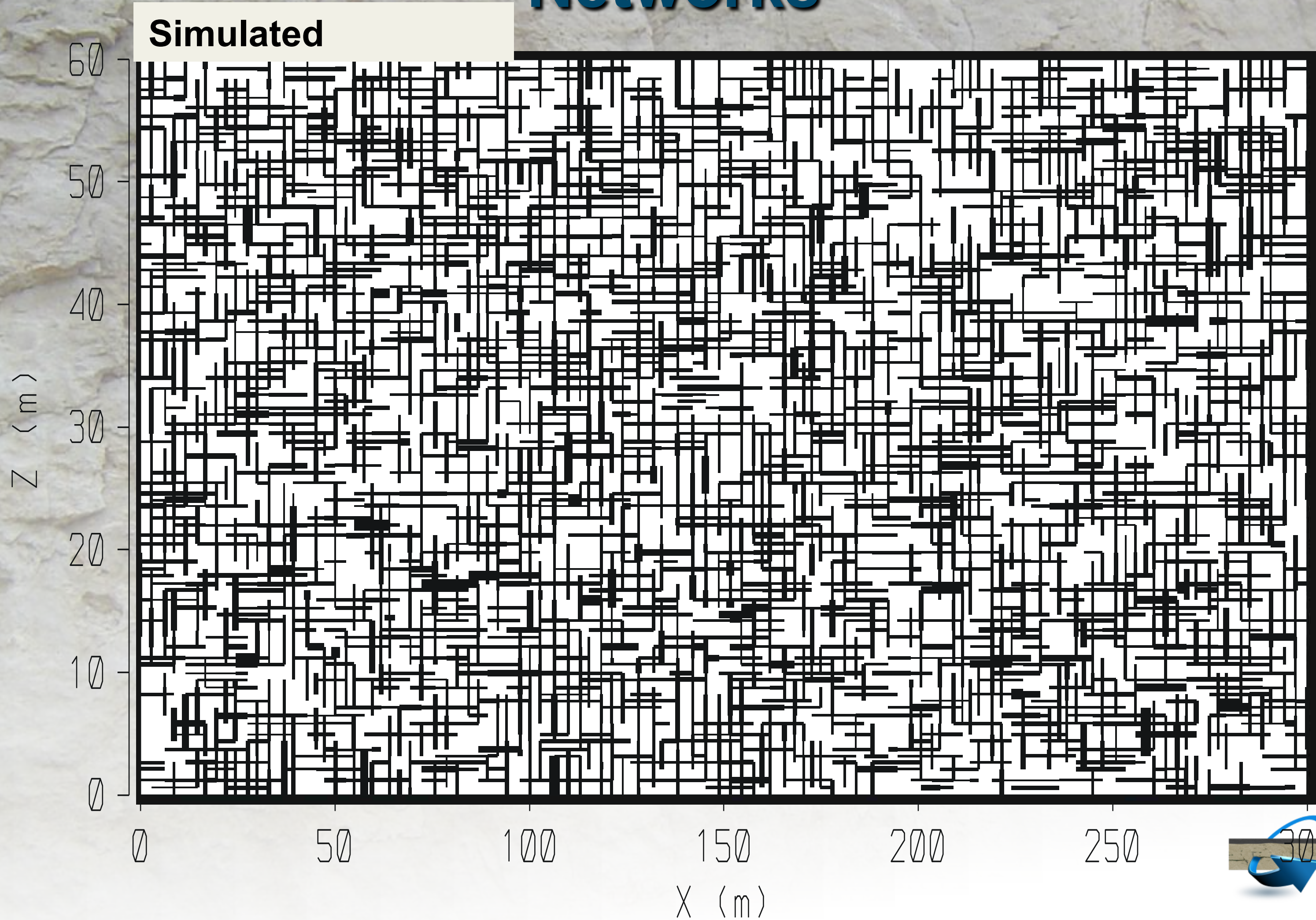
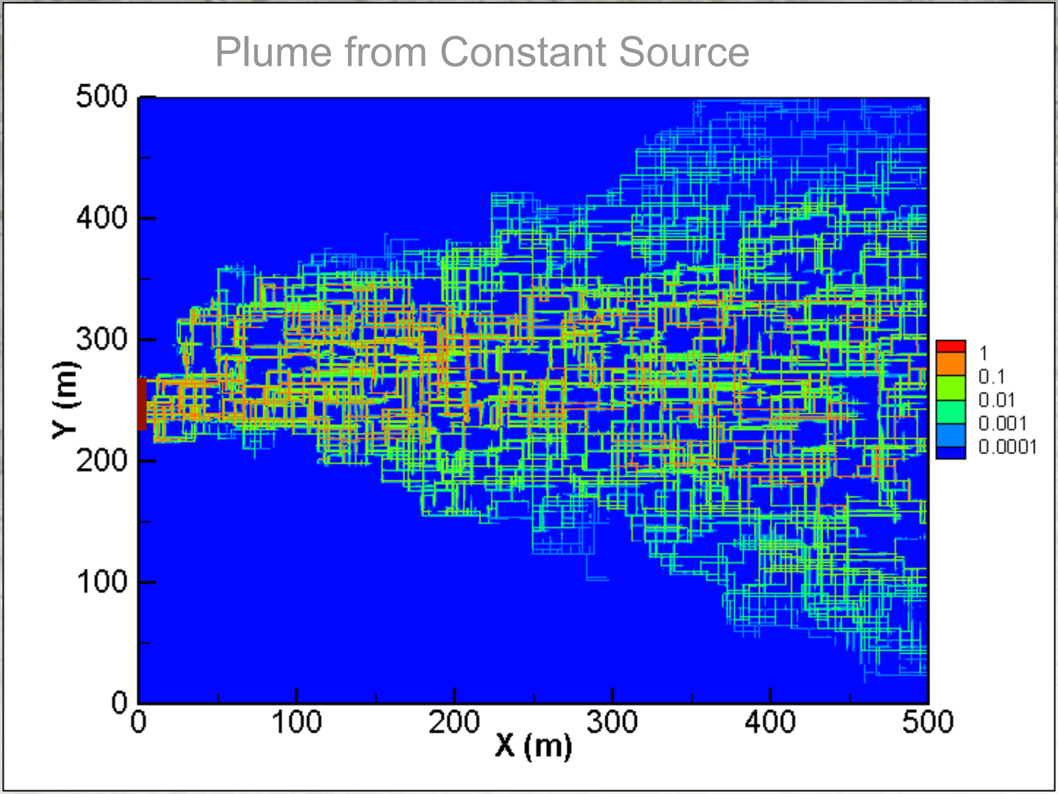
Representation of Discrete Fracture Networks



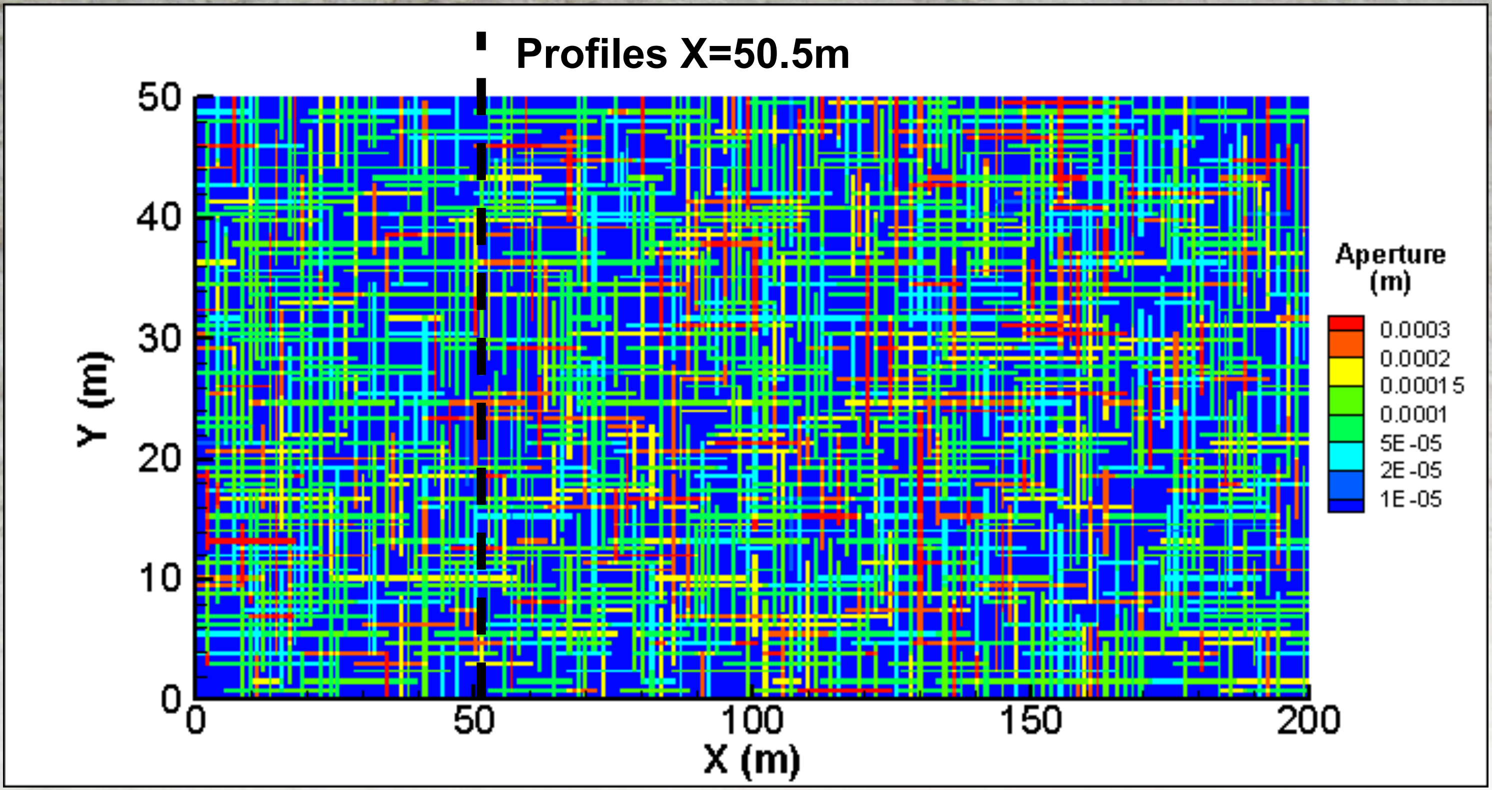
Discrete Fracture Network Approach (DFN) for Modeling Groundwater Flow and Contaminant Transport



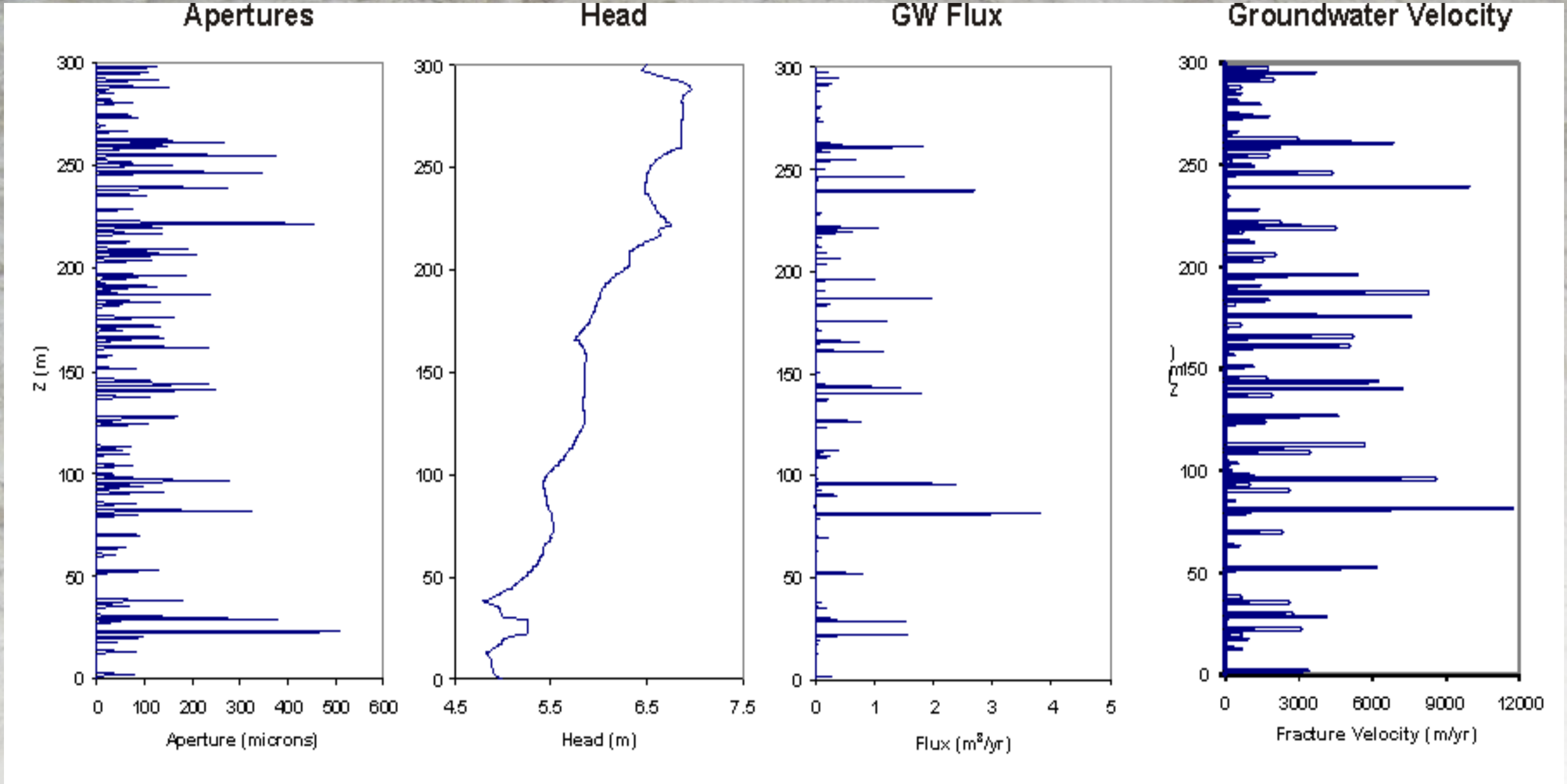
Plume in interconnected network of fractures with variable length and aperture

Simulations are very sensitive to aperture

Example: Estimating Relevent Distributions with Depth



Vertical Profiles: X=50.5 m

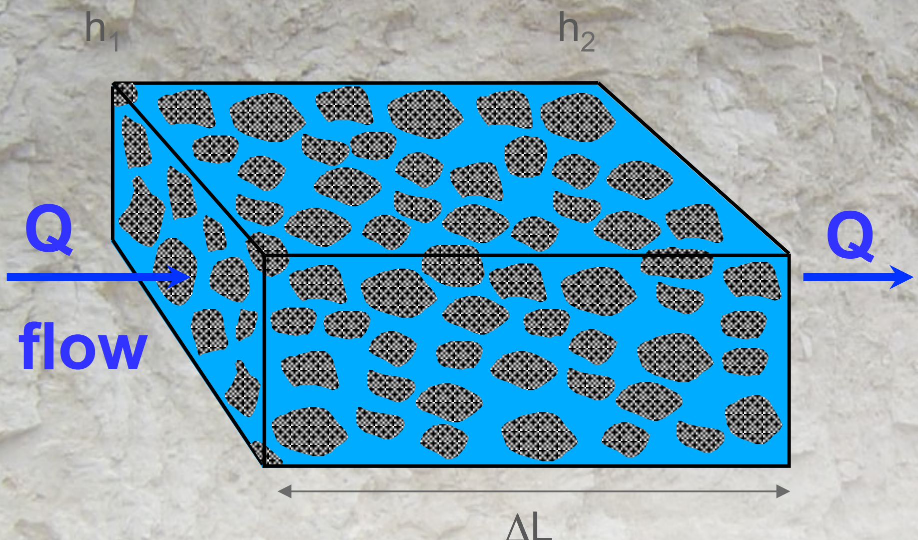


Problem Statement

Groundwater velocity ($\bar{v}$) is the starting point for nearly all assessments of contaminant transport and fate

How can we obtain values for $\bar{v}$ in fractured rock?

Groundwater Flow In Porous Media



Interconnected pores

ϕ = effective porosity of the flow medium

$$q = K \frac{\Delta h}{\Delta L}$$

$$K = K_{bulk}$$

$$\bar{v} = \frac{q}{\phi}$$

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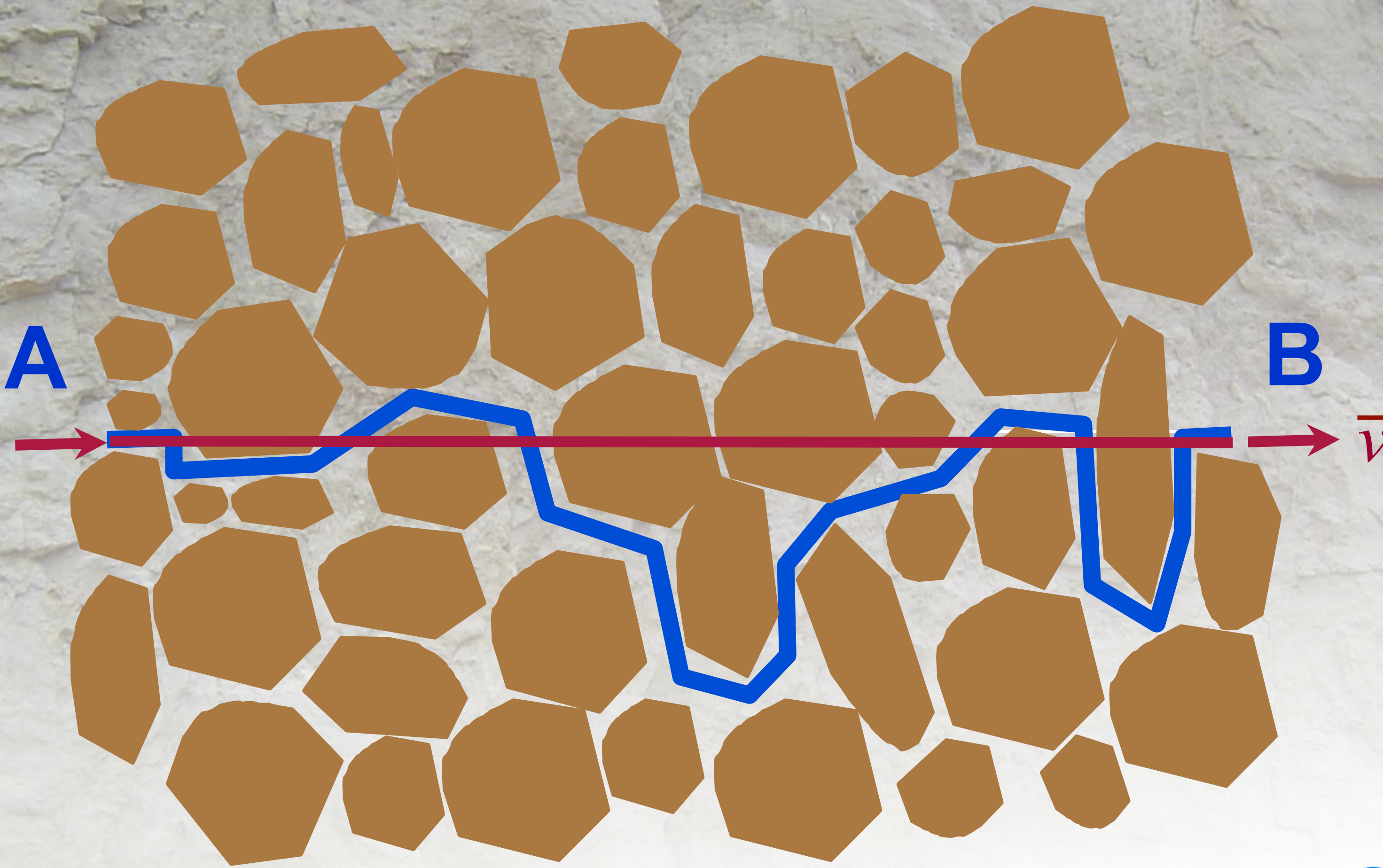
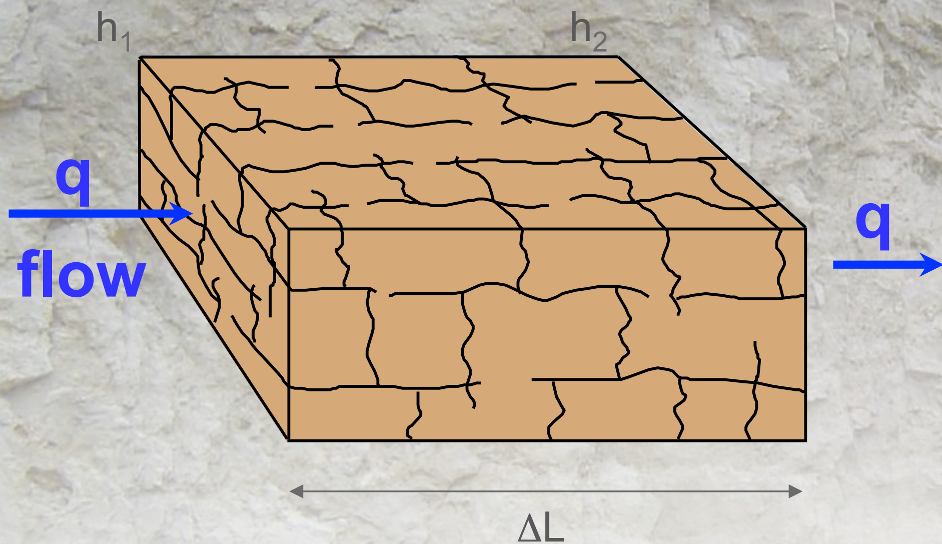
Average Linear Groundwater Velocity ($\bar{v}$) in Porous Media



$\bar{v}$ *represents line path from A to B*

Groundwater Flow In Fractured Media



Interconnected fractures

ϕ = effective porosity of the flow medium

$$q = K\frac{\Delta h}{\Delta L}$$

$$K = K_{bulk}$$

$$\bar{v} = \frac{q}{\phi}$$

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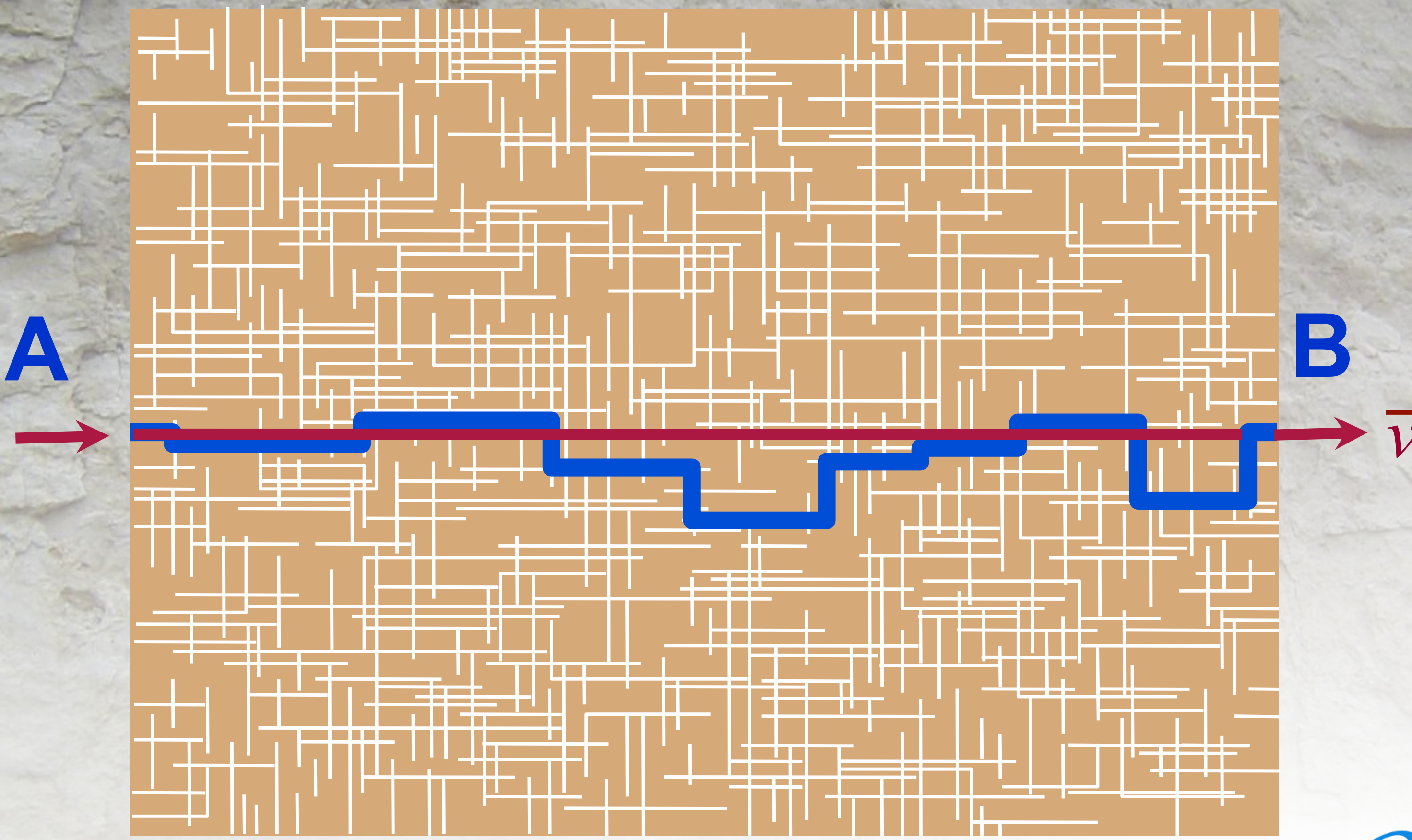
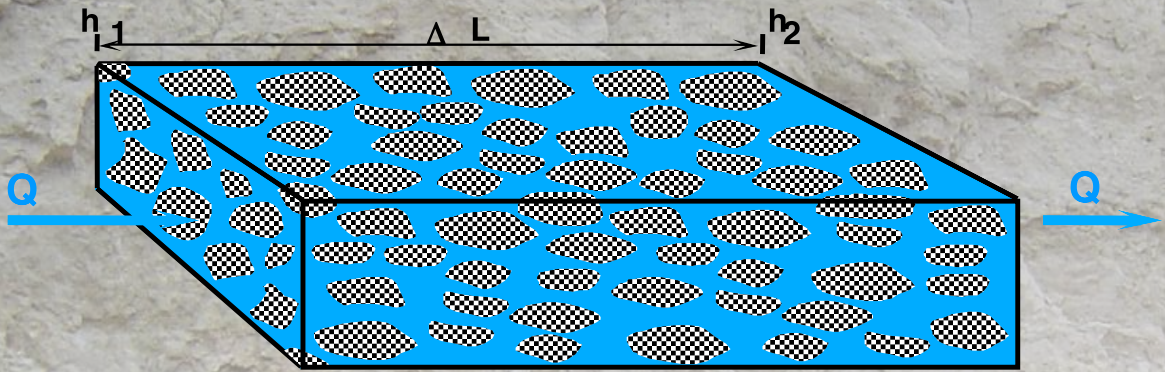
Average Linear Groundwater Velocity ($\bar{v}$) in Fractured Media



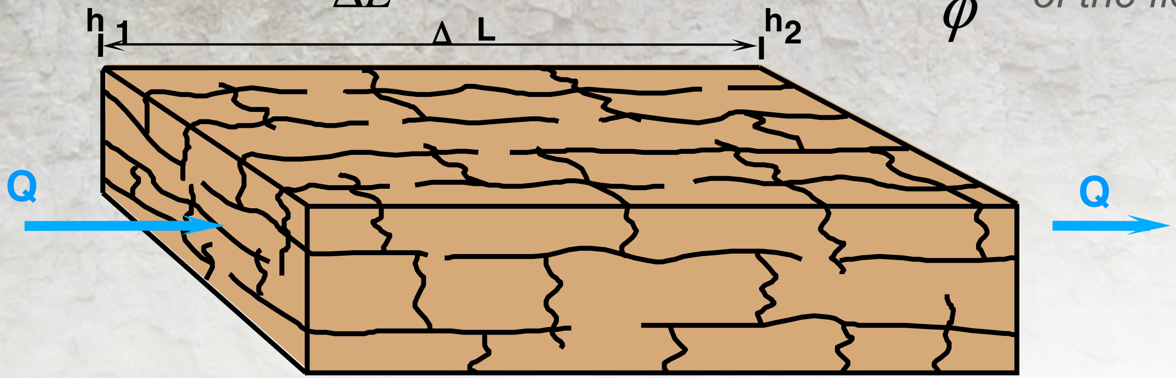
$\bar{v}$ *represents line path from A to B*

Darcy's Law Applies to Both Types of Media



$$Q = KA\frac{\Delta h}{\Delta L} \qquad (K = K_b) \qquad \bar{v} = \frac{q}{\phi}$$

ϕ = effective porosity of the flow medium



The Darcy Law Approach for Estimating $\bar{v}$

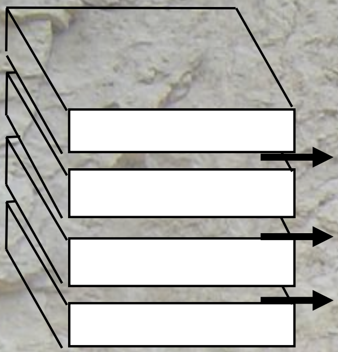
(Equivalent Porous Media Approach)

$$\bar{v} = \frac{Darcy\ \ flux}{pore\ space\ available\ \ for\ \ flow}$$

$$= \frac{K\dfrac{dh}{dL}}{effective\ \ porosity}$$

How can effective porosity be obtained for fractured rock?

Relation Between Fracture Aperture and Bulk Fracture Porosity



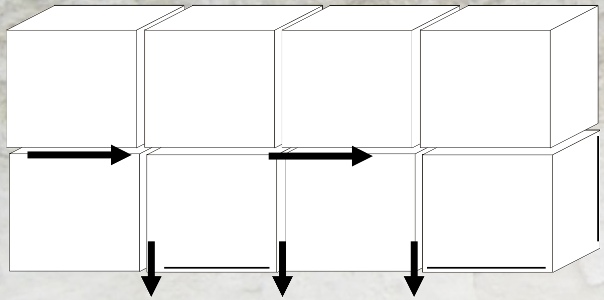
$$\phi_b = N(2b)$$

Aperture

Number of Fractures/meter

Bulk Fracture Porosity

Ideal Slabs



$$\phi_b = N(3b)$$

Assuming an Impermeable rock matrix

Ideal Cubes

Bulk Effective Porosity for Packer Tests in Fractured Rock (ϕ_b)

Number of Fractures present

Fracture aperture (m)

$$\phi_b = \frac{N(2b)}{B}$$

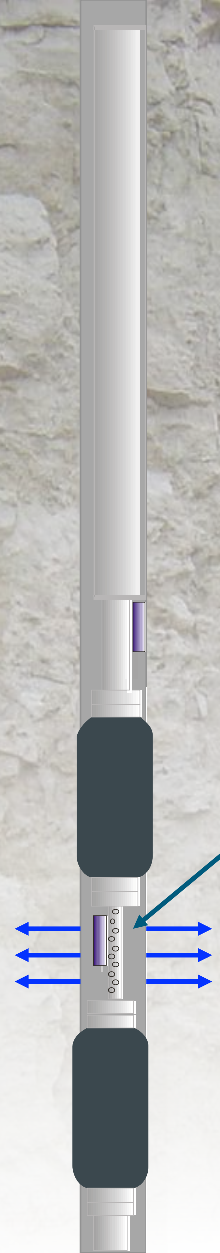
Number of Fractures Actively Conveying water

Test Interval Length (m)

Average aperture value for the test interval

What is a Straddle Packer Test?

A depth discrete hydraulic test in a fractured rock borehole



Two rubber packers are inflated to isolate a portion of the borehole

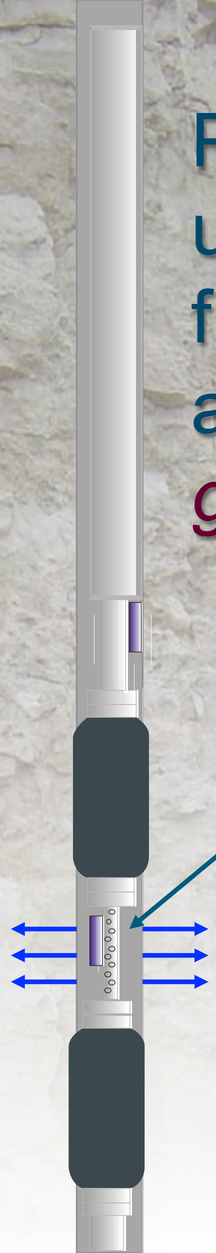
Test Interval

Four Types of Hydraulic Tests

1. *Constant Head Step Tests*
2. *Slug Tests*
3. *Pumping Tests*
4. *Recovery Tests*

Injection or Withdrawal

Packer Tests are used to get *T values*, fracture *apertures* and average linear *groundwater velocity*

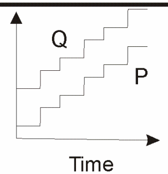
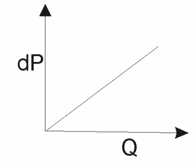
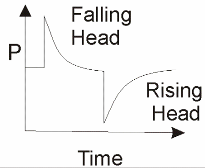
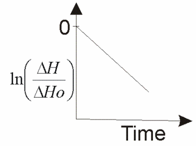
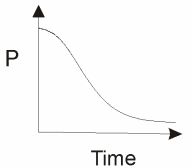
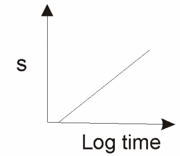
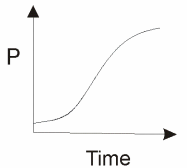
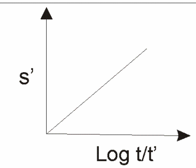


Overall Goal of Straddle Packer Tests in Contaminant Site Studies

In each test interval:

perform a comprehensive suite of hydraulic tests to obtain the best possible T values for calculating hydraulic apertures for velocity estimates with minimum error and uncertainty

Four Types of Hydraulic Tests

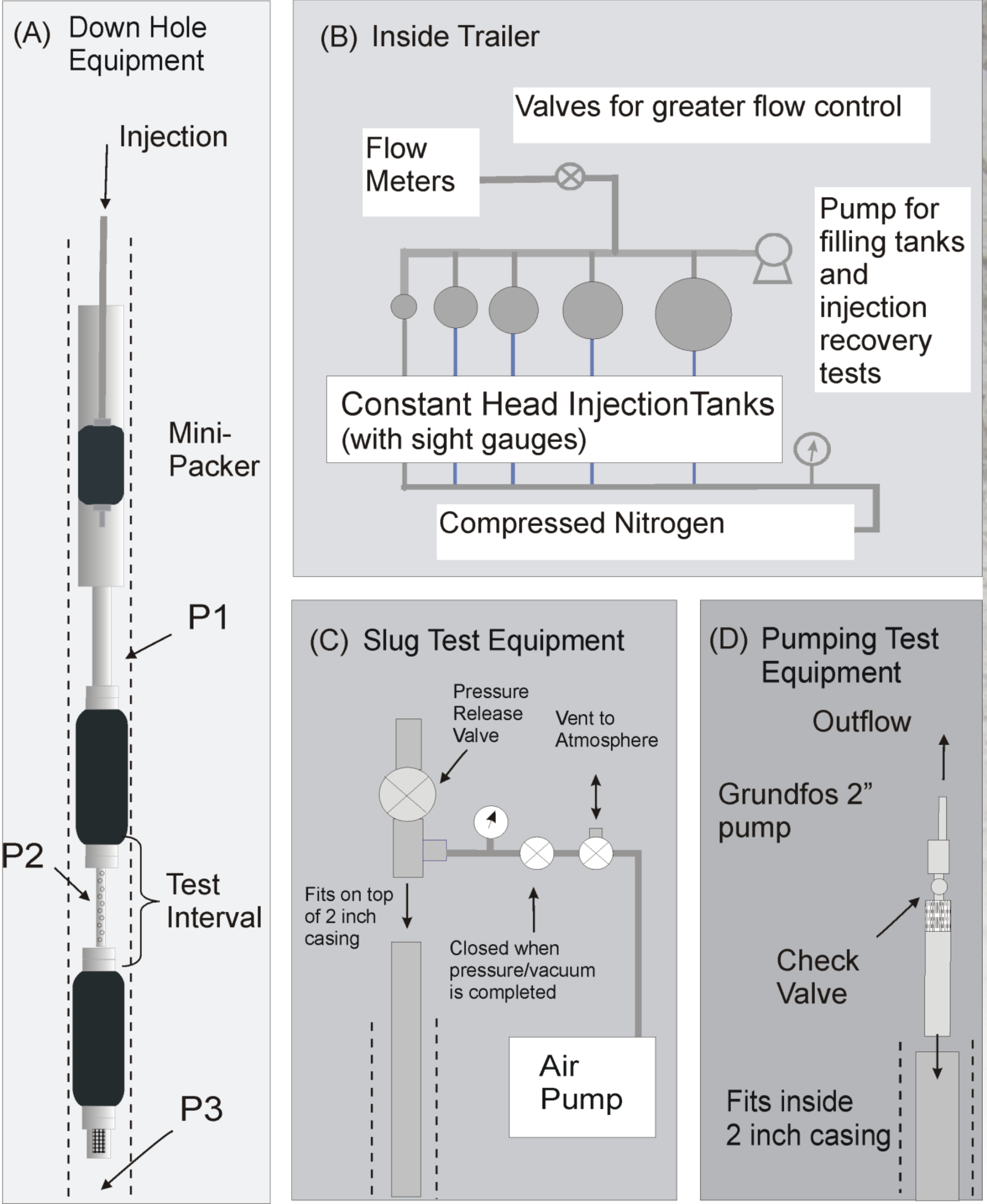
Test Type	Test Volume	Typical Test Results	Typical Analysis Method	Typical Analysis Graph	Head and Flow
Constant Head Step	Intermediate		Thiem $T = \frac{Q}{2\pi \Delta H} \ln\left(\frac{r_o}{r_w}\right)$		Head = Constant Flow = Constant (For each step)
Instananeous Slug	Small		Hvorslev Radial Flow $T = \frac{slope(A_{xs})}{2\pi} \ln\left(\frac{r_o}{r_w}\right)$ Spherical Flow $T = \frac{slope(A_{xs})}{2\pi}$		Head and Flow Variable
Constant Rate Pumping	Large		Cooper-Jacob Straight Line Method $T = \frac{2.3Q}{4\pi \Delta s}$		Flow = Constant Head Variable
Recovery after constant rate pumping	Large		Theis Recovery Method $T = \frac{2.3Q}{4\pi \Delta s'}$		Head and Flow Variable

T = Transmissivity
Q = flow rate
rw = well radius
ro = radius of influence
s = drawdown
A_{xs} = cross sectional area of riser pipe
dP = applied pressure

Assumption for all methods :

Darcy's Law is Valid

Pumping/Recovery Tests can be Injection/Recovery or Withdrawal/Recovery (Withdrawal/Recovery is shown above)

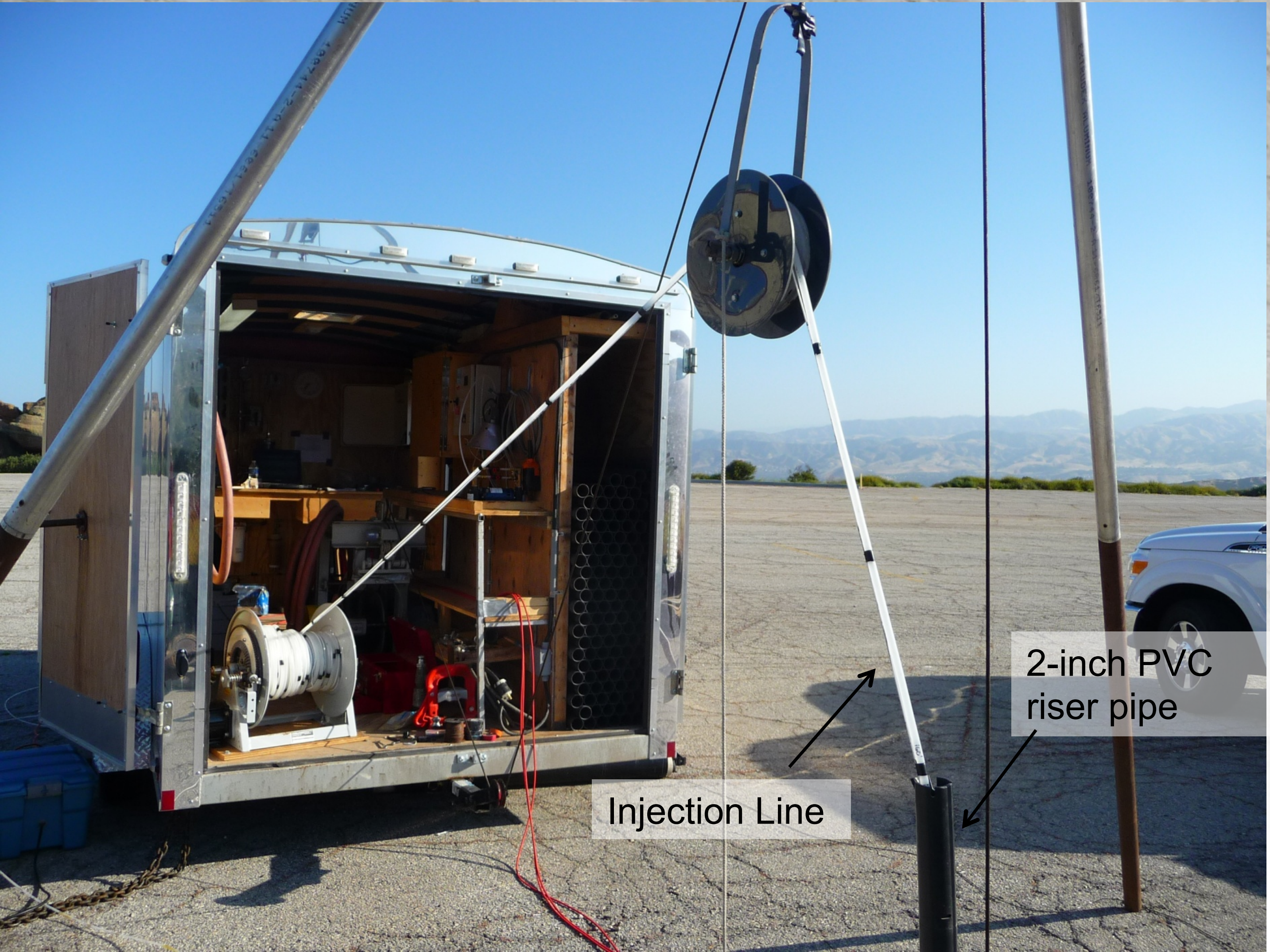


University of Guelph Packer Testing System

Create a 2” temporary well at each test interval depth using Solinst well casing

Conduct all four types of hydraulic tests

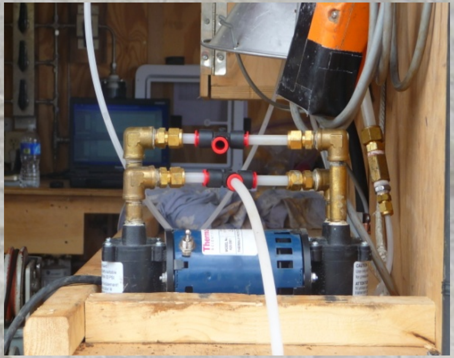
Trailer Set Up – CH Step Test



Packer Testing Equipment

Injection Tanks

Slug Test Fitting



Air pump for pneumatic slug tests

Mini-packer for Constant Head Step Tests

Packer Testing Equipment

Datalogger

Transducer reels and flow meters

PVC Pipe ~1000 ft

Approach

In each test interval conduct different types of tests at varying perturbations to:

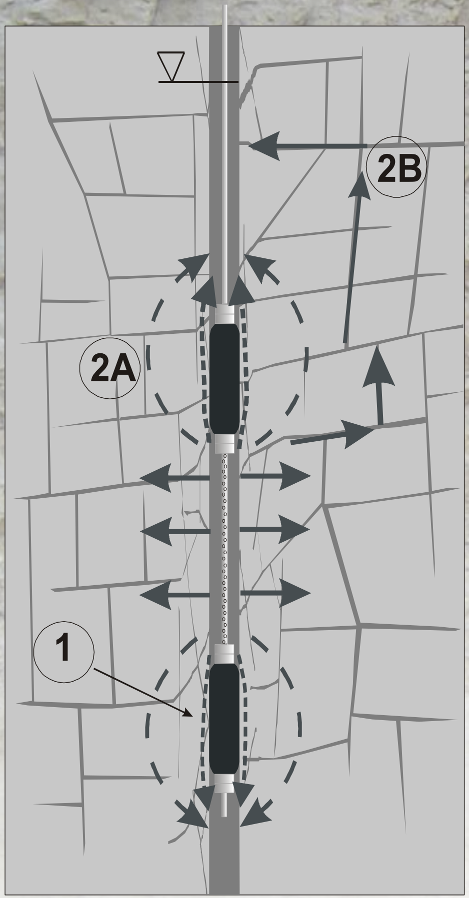
- *assess non-ideal effects in each test*
- *compare results to get the most representative T values*

List of Potential Non-ideal Effects

1. Short circuiting from the test interval to the open borehole
2. Initial equilibrium condition
3. Non-Darcian flow
4. Fracture dilation/contraction
5. Dual permeability effects

When any of these non-ideal effects are significant, the T values will deviate from the "True" value

Short Circuiting from the Test Interval to the Open Hole

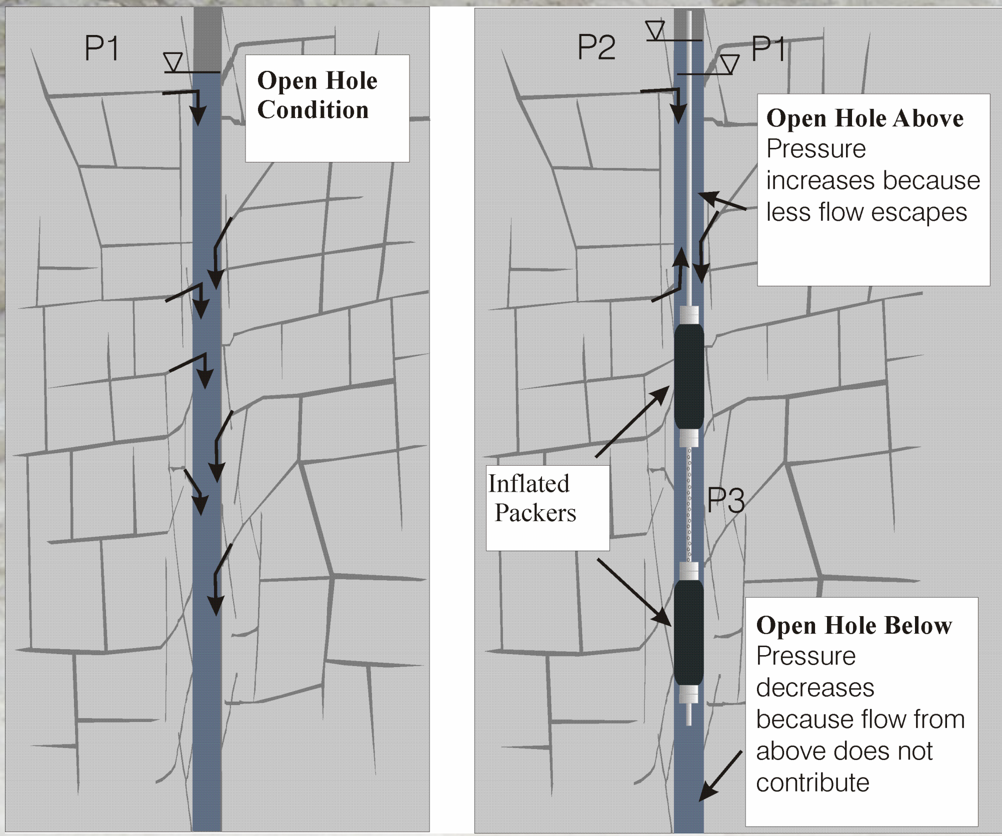


1.Packer short circuiting
between the packers and the borehole wall (no delay in the response)

1.Formation short circuiting
through the formation (some delay in the response)

Both of these types of short circuiting causes T to be overestimated

Open borehole flow



Open boreholes cross connect all fractures intersecting the hole causing flow from the fractures with higher head to those with lower head.

When the packers are inflated, this flow is stopped and the pressure at different points in the open hole changes.

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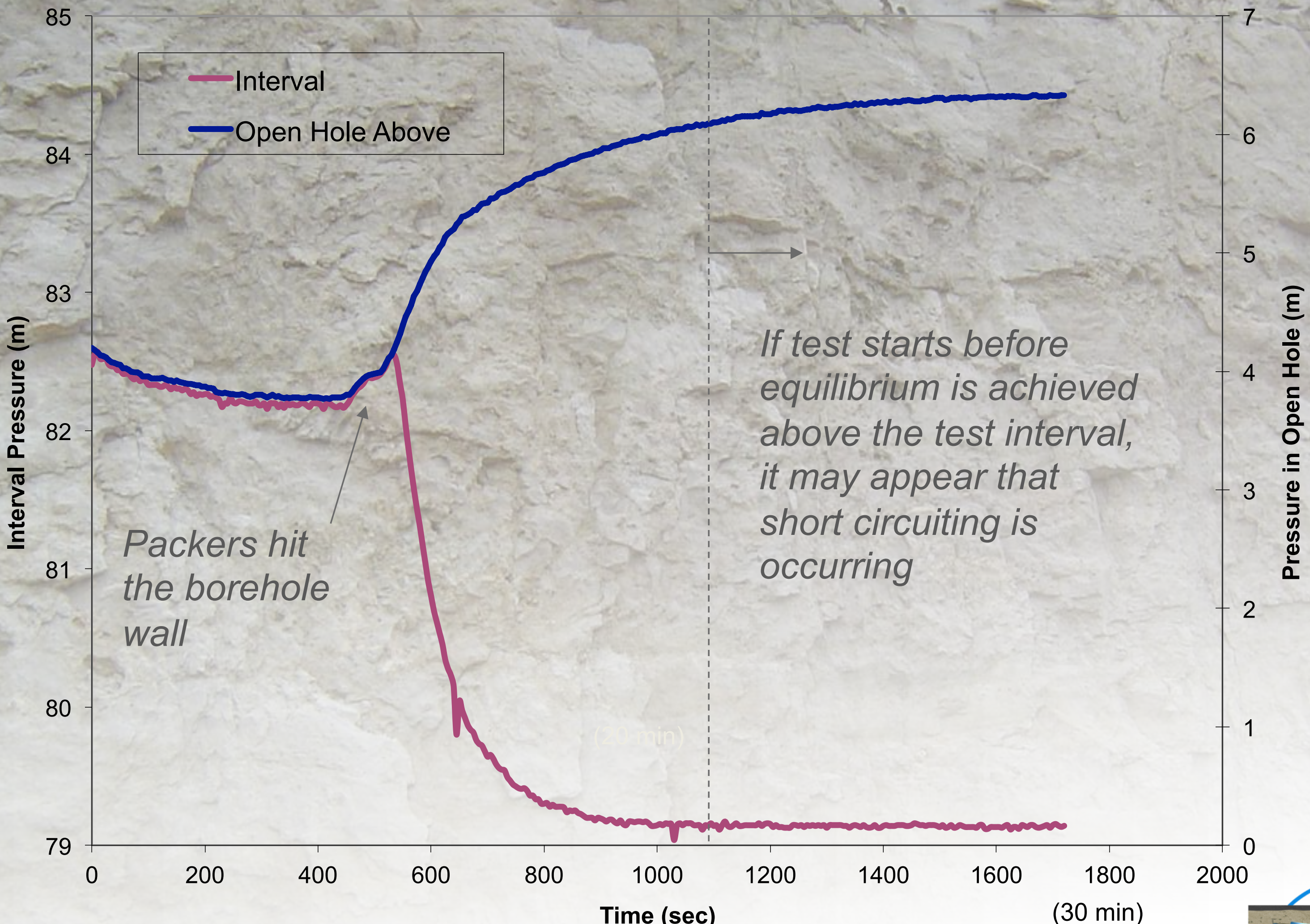
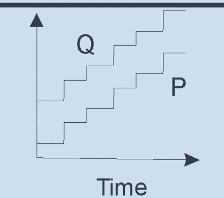
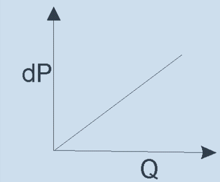
Equilibrium



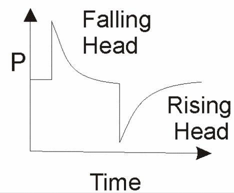
"Experience with this system has resulted in a strategy that has proven effective and efficient. Each type of test has unique attributes that, in this strategy, are used to derive advantages from the sequence in which the tests are done.."

Quinn,P.M., Cherry,J.A., and Parker,B.L., 2012. Hydraulic testing using a versatile straddle packer system for improved transmissivity estimation in fractured rock boreholes. Hydrogeology Journal DOI 10.1007/s10040-012-0893-8.

<table>
<tr><th>Test Type</th><th>Test Volume</th><th>Typical Test Results</th><th>Typical Analysis Method</th><th>Typical Analysis Graph</th><th>Head and Flow</th></tr>
<tr><td>Constant Head Step</td><td>Intermediate</td><td>
</td><td>Thiem

$$T = \frac{Q}{2\pi \Delta H} \ln\left(\frac{r_o}{r_w}\right)$$</td><td>
</td><td>Head = Constant

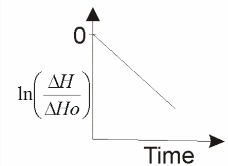
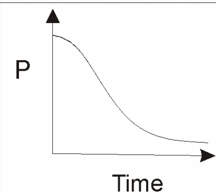
Flow = Constant

(For each step)</td></tr>
<tr><td>Instananeous Slug</td><td>Small</td><td>
</td><td>Hvorslev

Radial Flow

$$T = \frac{slope(A_{xs})}{2\pi} \ln\left(\frac{r_o}{r_w}\right)$$

Spherical Flow

$$T = \frac{slope(A_{xs})}{2\pi}$$</td><td>
</td><td>Head and Flow Variable</td></tr>
<tr><td>Constant Rate Pumping</td><td>Large</td><td>
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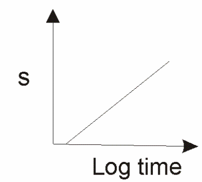
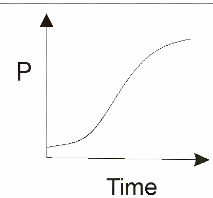
$$T = \frac{2.3Q}{4\pi \Delta s}$$</td><td>
</td><td>Flow = Constant

Head Variable</td></tr>
<tr><td>Recovery after constant rate pumping</td><td>Large</td><td>
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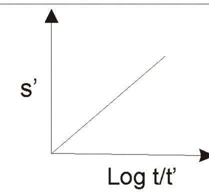
$$T = \frac{2.3Q}{4\pi \Delta s'}$$</td><td>
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T = Transmissivity
Q = flow rate
rw = well radius
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s = drawdown
A_{xs} = cross sectional area of riser pipe
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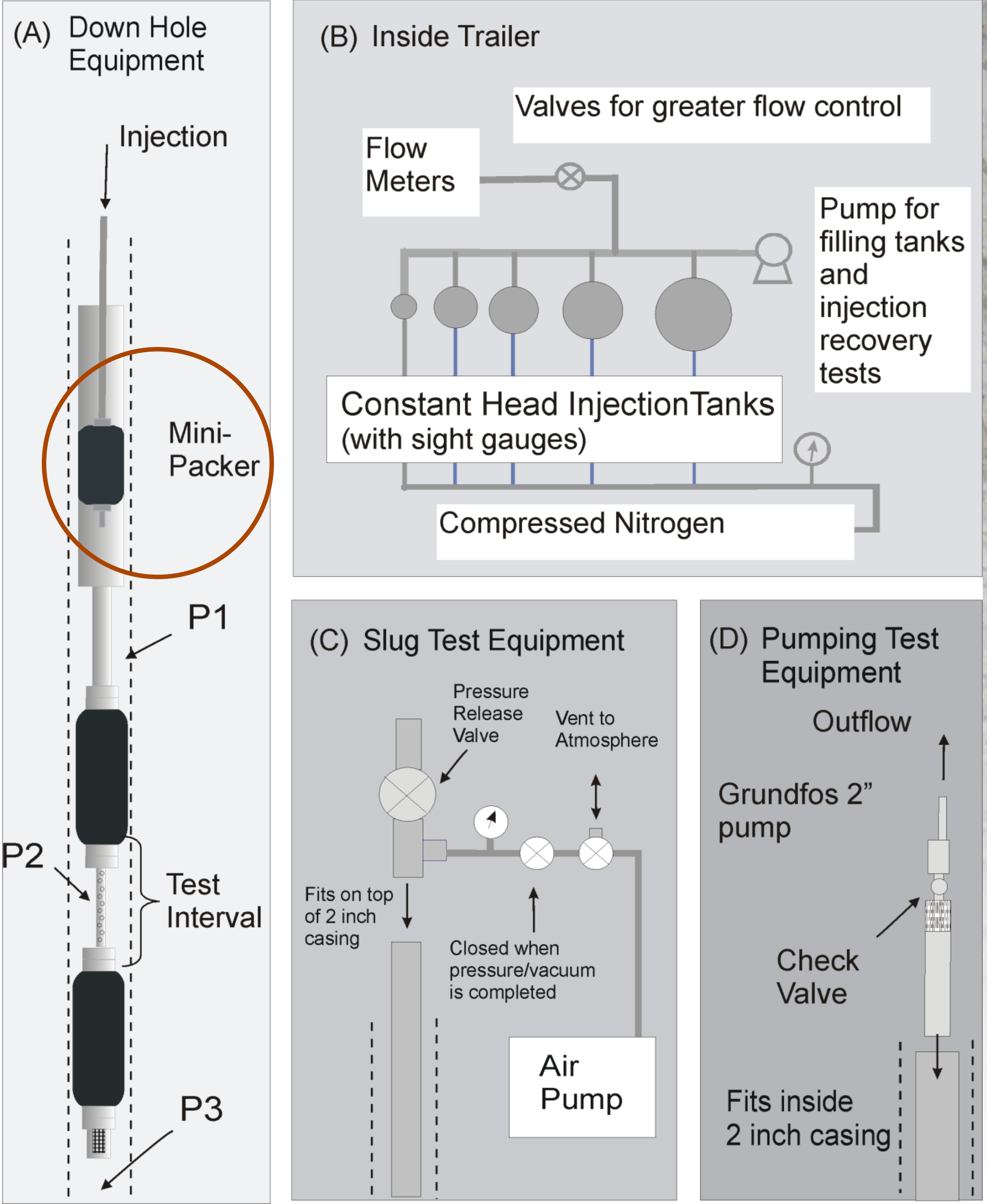
Assumption for all methods :

Darcy's Law is Valid

Pumping/Recovery Tests can be Injection/Recovery or Withdrawal/Recovery (Withdrawal/Recovery is shown above)



University of Guelph Packer Testing System

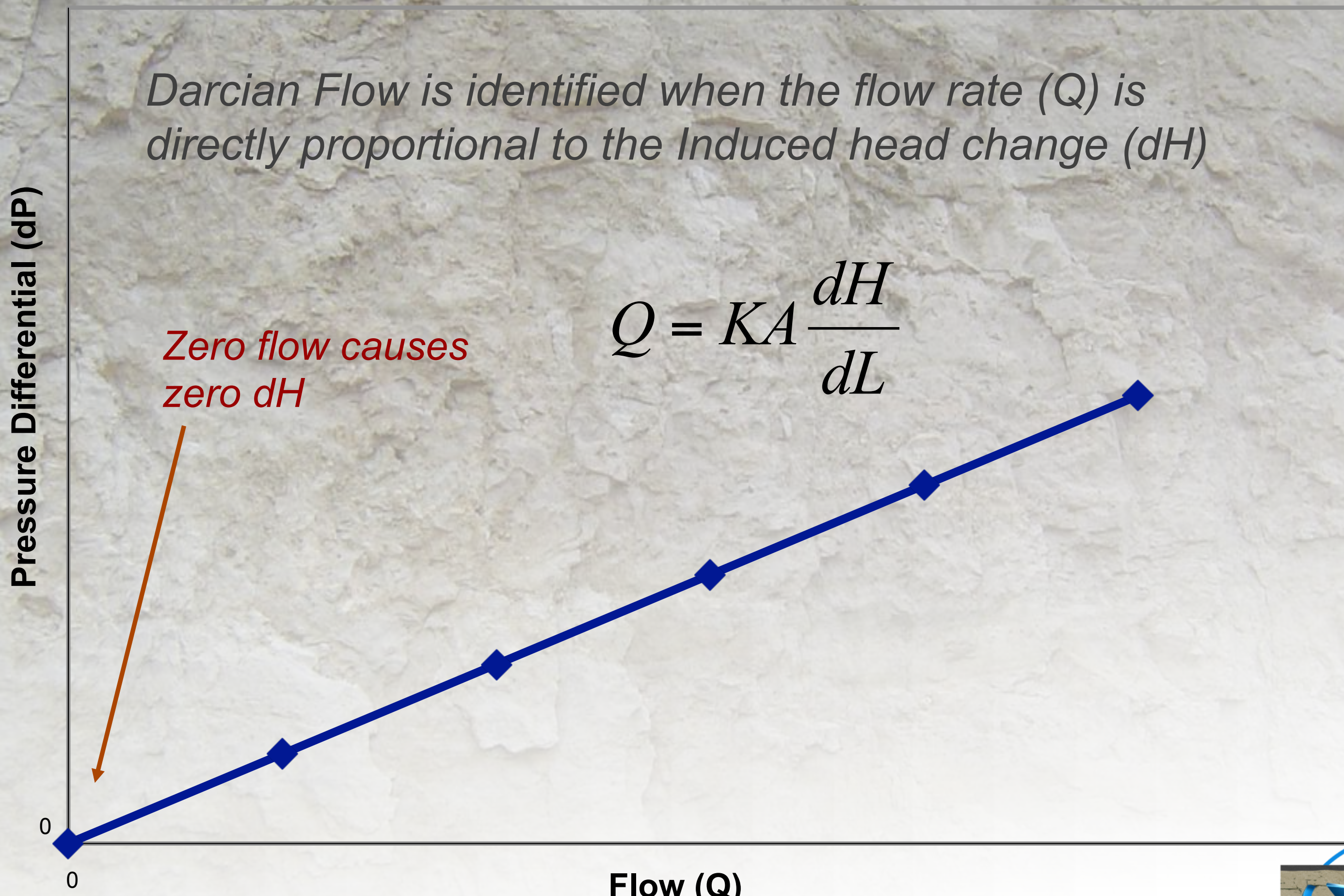
Constant head step tests use the mini-packer inside the 2-inch Solinst well casing for injection

Constant Head Step Tests

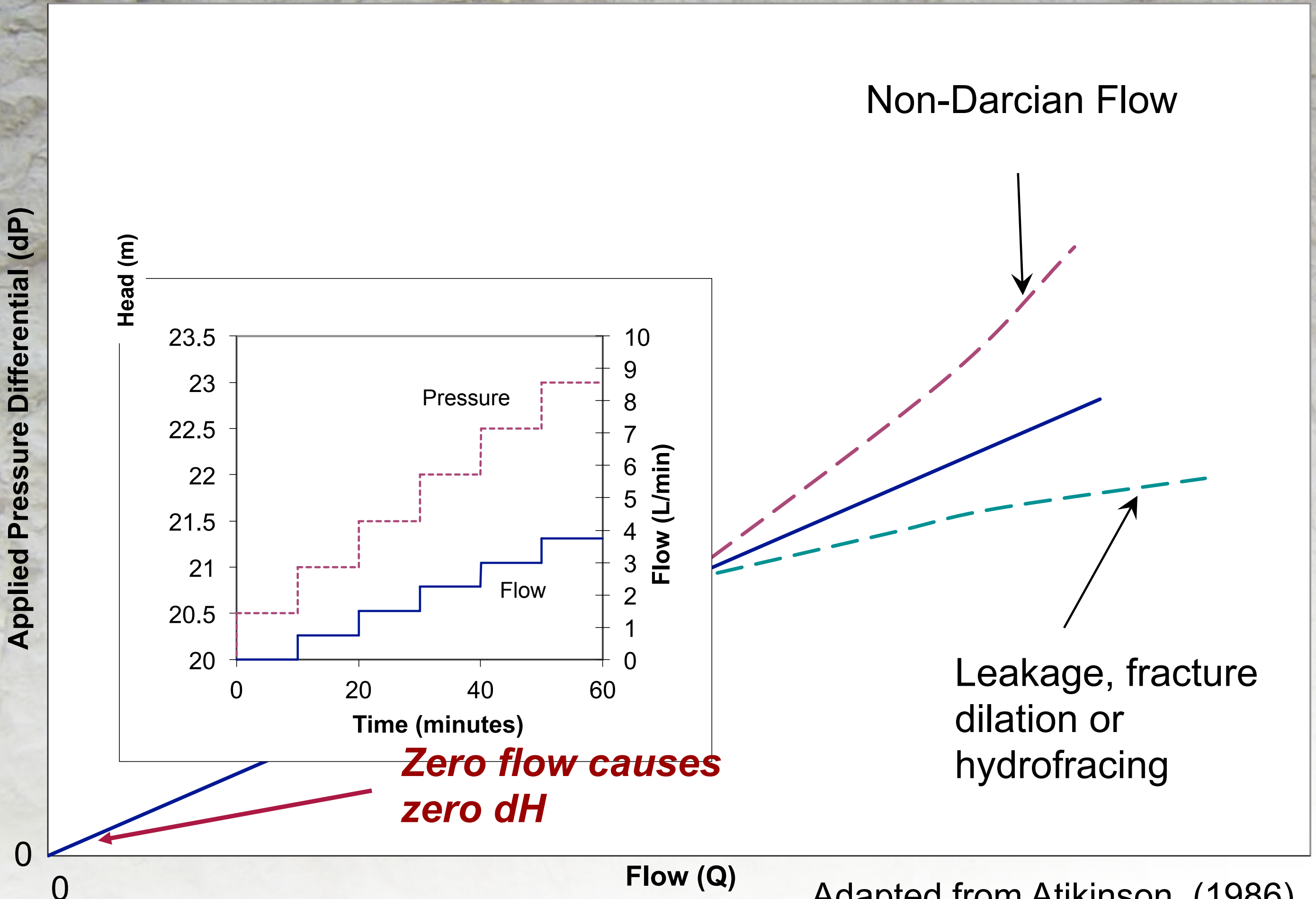
Use constant head step tests to determine when Darcy's Law applies because packer test data analysis assumes Darcian flow.

Darcian Flow: Q is directly proportional to dH

Darcian (Linear) Flow

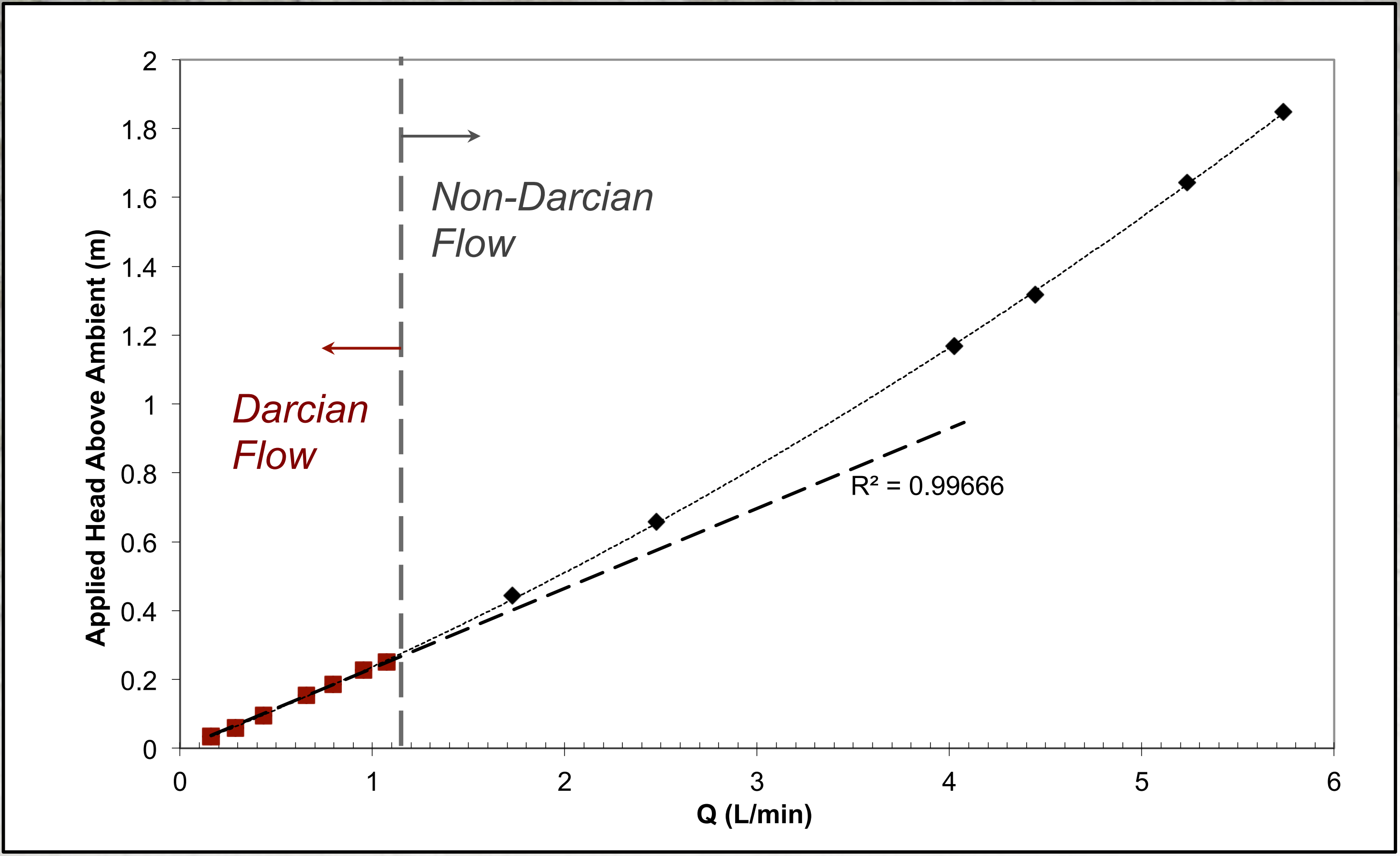


Deviation from the Linear (Darcy) Assumption



Adapted from Atikinson, (1986)

Typical CH Step Test Data



Causes of Non-Darcian Flow

is not due to turbulent flow but other causes:

(From the Literature)

- form force caused by obstructions in the fluid flow path
- deadwater volume changes with flow rate
- surface roughness, aperture variations
- fluid bending at the entrance to the fracture
- contact area changes with increasing sample size
- fractures with different size apertures in the test interval

The smallest flow area of the test is the fracture openings at the borehole wall

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"This study indicates that the standard procedures and recommendations for packer testing in fractured rock provided in various publications … can be expected to produce results in the non-linear range when testing small intervals (i.e., <3 m). Such tests will underestimate T values by as much as an order of magnitude."

Quinn, P., Cherry, J., Parker, B. (2011), Quantification of non-Darcian flow observed during packer testing in fractured sedimentary rock, Water Resources Research

Bulk Effective Porosity for Packer Tests in Fractured Rock (ϕ_b)

Number of Fractures present

Fracture aperture (m)

$$\phi_b = \frac{N(2b)}{B}$$

Number of Fractures Actively Conveying water

Test Interval Length (m)

Average aperture value for the test interval

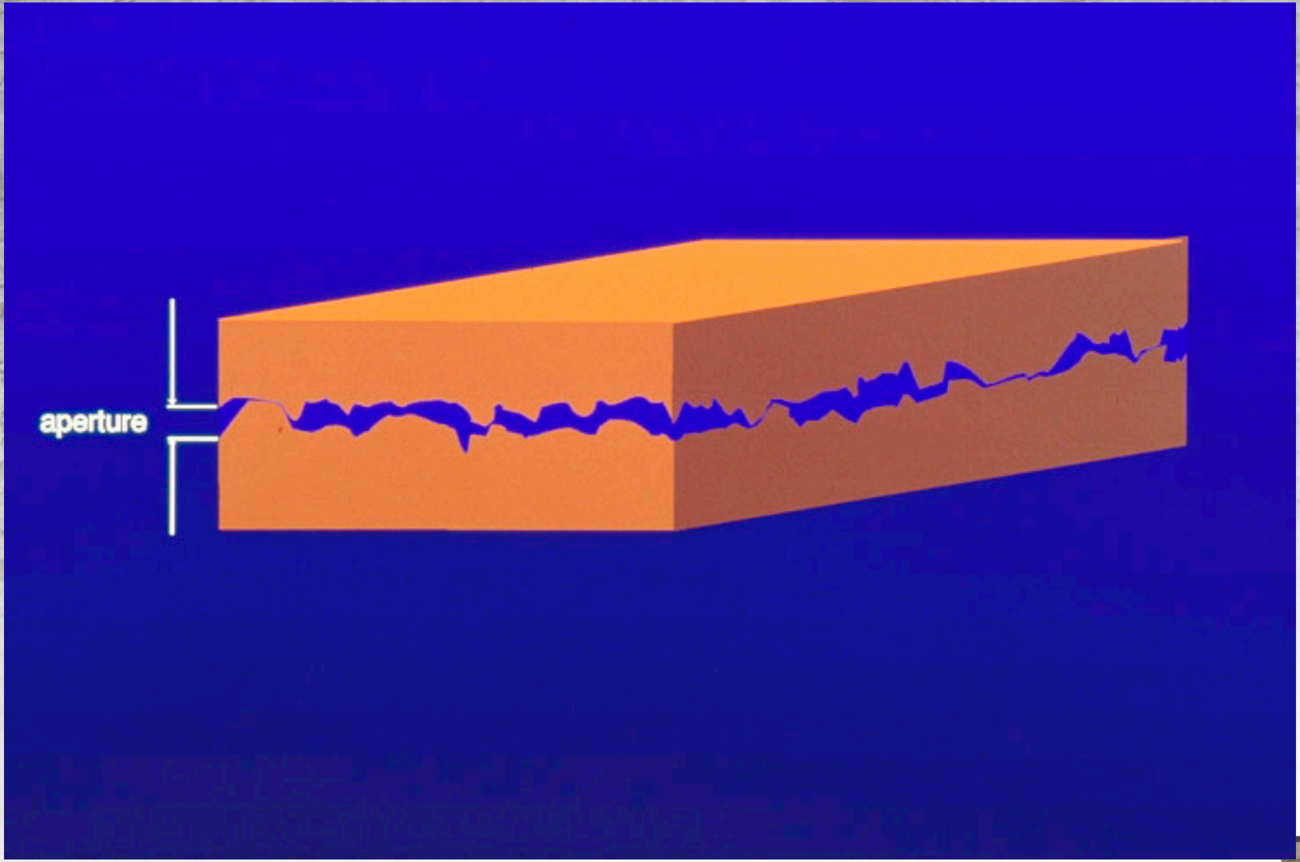
There are two approaches for estimating $\bar{\upsilon}$ in fractured rock

Equivalent Porous Media Conceptualization	Individual Parallel Plate Conceptualization
Measure T_b in test interval	Measure T_b in test interval
Assume an interconnected fracture network as an ideal equivalent porous medium where bulk fracture porosity represents the effective porosity for flow	Assume flow is equally carried by all fractures and analyze a single fracture
Estimate the number of hydraulically active fractures in the test interval	
Estimate or measure a representative hydraulic gradient across the domain of interest	
Calculate hydraulic aperture $2b = \left(\frac{12\mu T_b}{\rho g N}\right)^{\frac{1}{3}}$ (Assume all fractures are the same size)	Calculate the individual fracture T $T_f = \frac{T_b}{N}$ (Assume all fractures are the same size)
Calculate bulk fracture porosity $\phi_f = \frac{N(2b)}{L}$ L = test interval length	Calculate the hydraulic aperture $2b = \left(\frac{12\mu T_f}{\rho g}\right)^{\frac{1}{3}}$
Calculate bulk K $K_b = \frac{T_b}{L}$ L = test interval length	Calculate fracture K $K_f = \frac{T_f}{2b}$
Calculate Darcy flux and $\bar{\upsilon}$ $q = K_b \frac{dH}{dx}$ $\bar{v} = \frac{q}{\phi_f}$	Calculate Darcy flux and $\bar{\upsilon}$ $q = \bar{v} = K_f \frac{dH}{dx}$

These approaches arrive at the same values for $\bar{\upsilon}$ as long as it is assumed that all fractures are the same size

If it is assumed that fractures have different sizes, the parallel plate approach determines values for $\bar{\upsilon}$ for each sized fracture

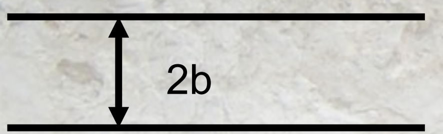
Irregularity of a Real Fracture



(From J.A. Gale)

Concept of Hydraulic Aperture

Actual Fracture Sharp and Maini, (1972)



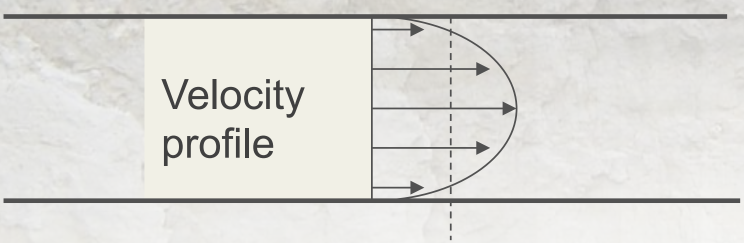
Ideal Aperture
Smooth Parallel Plates

Hydraulic Aperture
Rough Walls and Locally Variable Aperture

Parallel Plate Discrete Fracture Approach for Estimating $\bar{\upsilon}$

In a Single Fracture:

$$\bar{\upsilon} = q = \frac{\rho g (2b)^2}{12\mu} \frac{dH}{dL} = K \frac{dH}{dL}$$



$\bar{\upsilon}$ = average velocity

We Need to obtain hydraulic aperture (2b) values

Use the Cubic Law

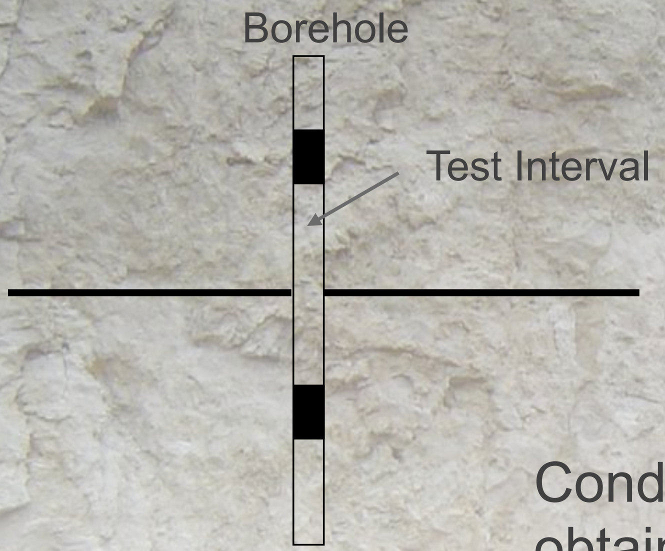
(Snow, 1965)

$$2b = \left(\frac{12\mu T}{\rho g N} \right)^{\frac{1}{3}}$$

N = number of active fractures in the test interval

T *is bulk rock transmissivity determined from hydraulic tests*

Simplest case : Assume One Fracture



$$2b = \left(\frac{12 \mu T}{\rho g} \right)^{\frac{1}{3}}$$

Conduct a hydraulic test to obtain T and calculate 2b

If more than one fracture is actually present 2b will be too large and velocities will be overestimated

We Need to obtain hydraulic aperture (2b) values

Use the Cubic Law

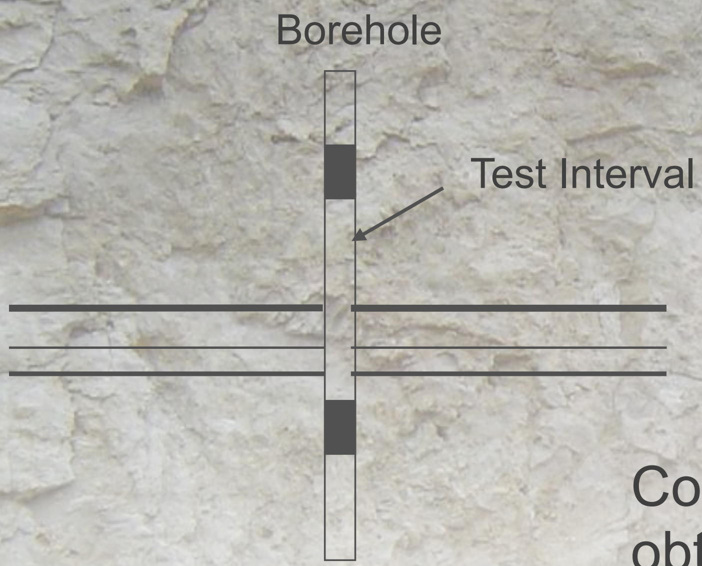
(Parallel planer smooth fractures)

$$2b = \left(\frac{12\mu T}{\rho g \mathbf{N}} \right)^{\frac{1}{3}}$$

***N* = number of active fractures in the test interval**

***T* is bulk rock transmissivity determined from hydraulic tests**

More practical : Assume More Than One Fracture

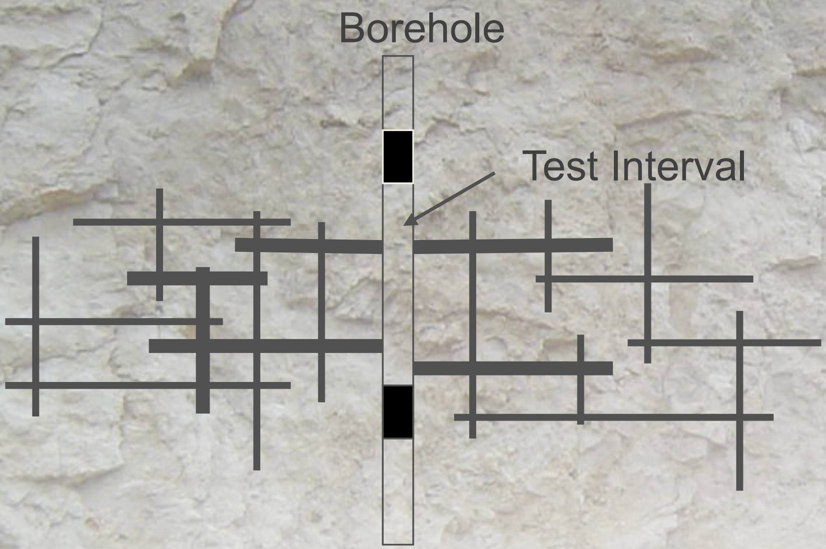


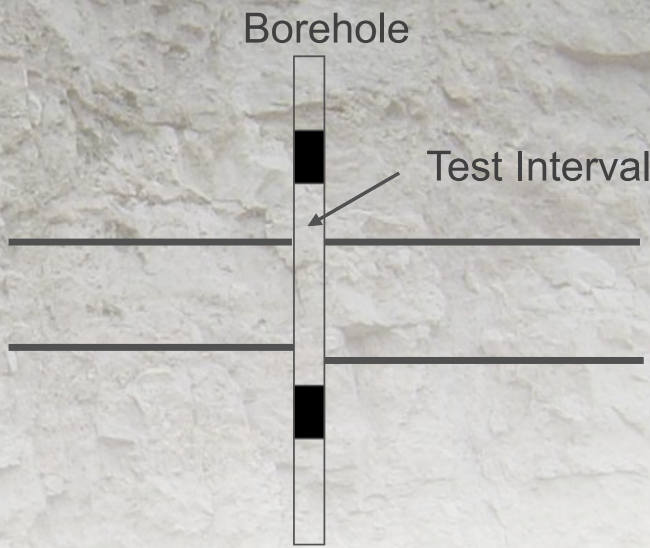
$$2b = \left(\frac{12 \mu T}{\rho g N} \right)^{\frac{1}{3}}$$

Conduct a hydraulic test to obtain T and calculate 2b

We assume all fractures present are the same size, so we get an average 2b

Concept of Effective Fracture Aperture in a Fracture Network





Simplify to parallel plates

Even though large fractures are present near the borehole, flow may be governed by small fractures away from the borehole, therefore, the aperture calculated from a hydraulic test are typically smaller than those identified with the acoustic log

How Do We Identify the Number of Active Fractures?

- Core log (largest number of fractures)
- Acoustic televiewer (less fractures than core)
- Newer methods of identifying “active fractures”
  - *Active Line Source (ALS) temperature logs*
  - *non-linear flow behavior*

Reynolds Number (Re)

$$\mathrm{Re} = \frac{advective\_forces}{viscous\_forces}$$

$$\mathrm{Re} = \frac{\rho \bar{v} D}{\mu}$$

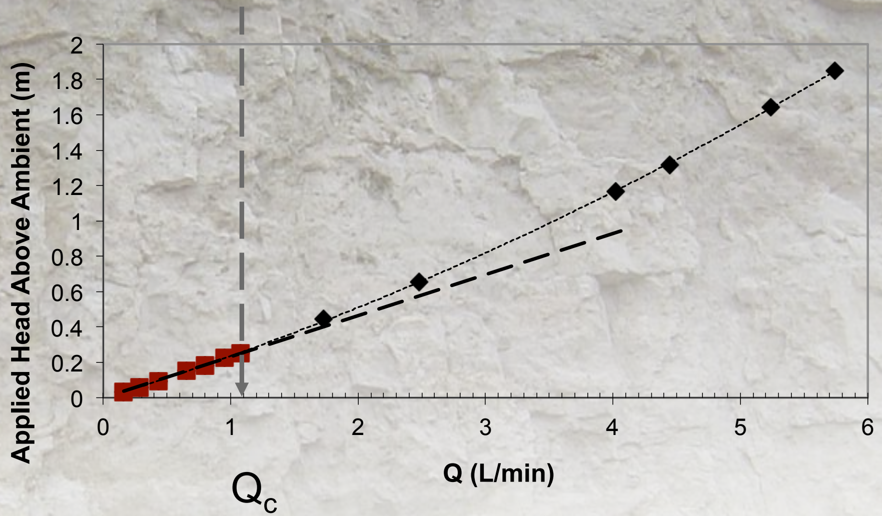
No consensus on characteristic length for fracture flow

Where:

ρ = fluid density
$\bar{\upsilon}$ = velocity
D = Characteristic Length
μ = fluid viscosity

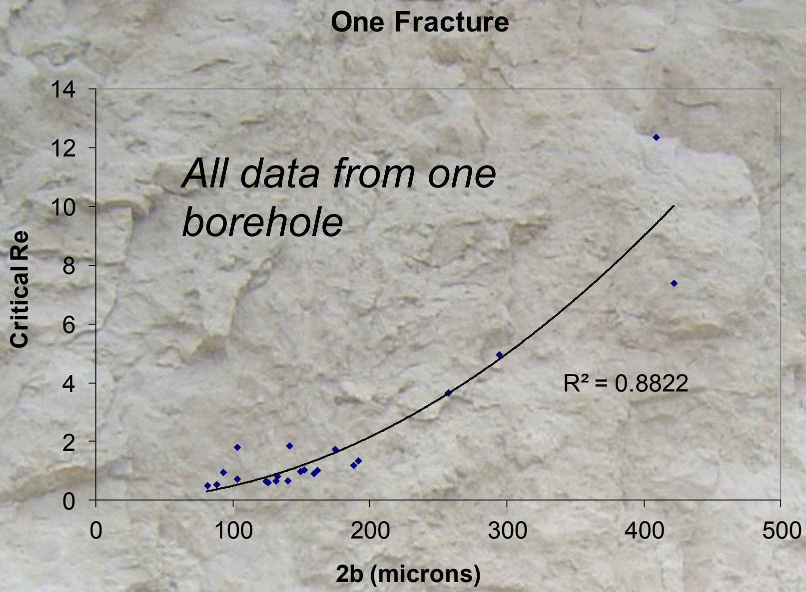
Using the the Onset of non-Darcian Flow to Identify the Number of Active Fractures

$$Re_c = \frac{\rho \bar{v} D}{\mu}$$



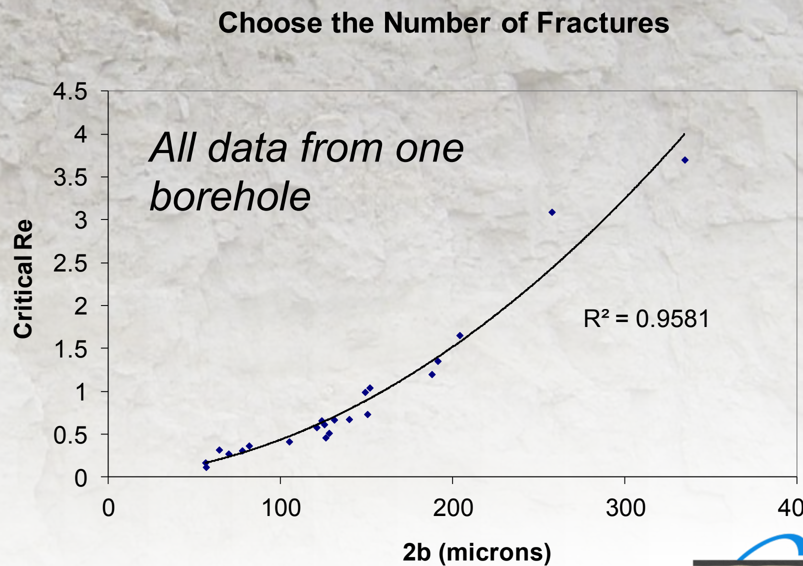
Re is dependent on velocity
velocity is dependent on aperture

Re_c will increase with increasing aperture



Assuming a single fracture in each test interval leads to a weak correlation

Choosing the number of fractures in each test interval based on the onset of non-Darcian flow results in a stronger correlation



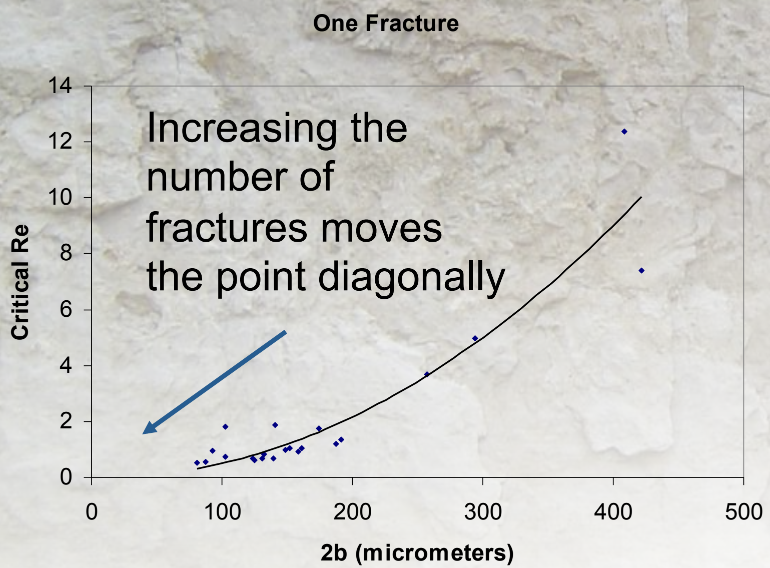
Using Re_c to Aid in Choice of Hydraulically Active Fractures

Use the Q vs dP plot to identify linear data
Calculate Darcy-Missbach exponent for each step
Project backwards if all data is non-linear with log-log plot

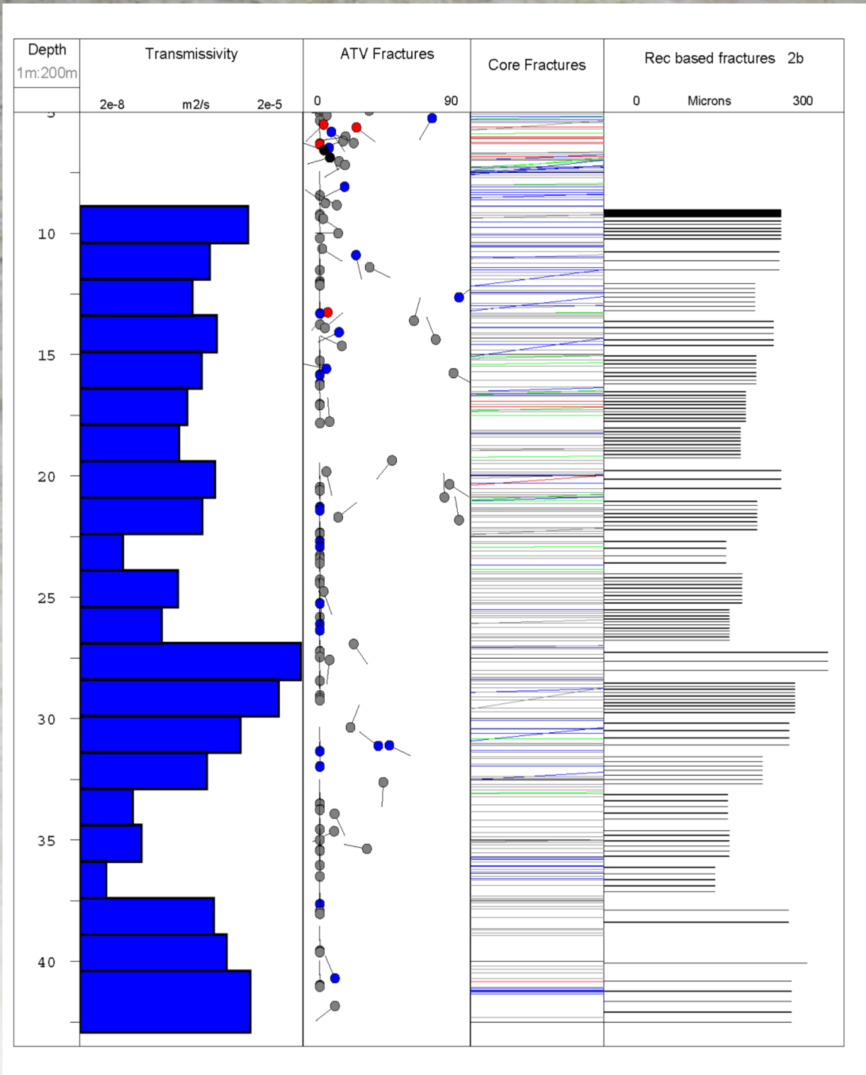
Determine Re_c assuming a single fracture in the test interval

Plot calculated 2b vs Re_c assuming a single fracture in the test interval

Refine plot by changing the number of fractures in the test interval to calculate 2b and Re_c to improve correlation



Example: Aperture Distributions



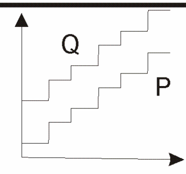
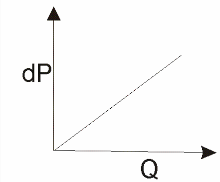
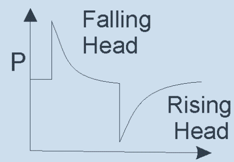
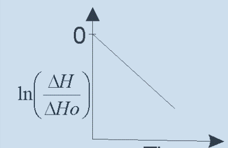
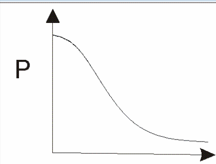
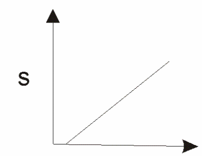
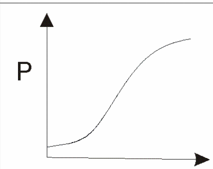
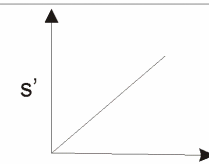
Guelph Tool MW-26

Transmissivity profile from packer testing a borehole and the resulting aperture distribution.

More realistic alternative than assuming all fractures are hydraulically active

"… $\bar{v}$ in the test interval can differ close to an order of magnitude if a single fracture is assumed vs. the number of fractures as identified in the core log and the Re_c approach for selecting the number of hydraulically active fractures offers an alternative to the selection based solely on visual methods."

Quinn, P.M., Parker, B.L., & Cherry, J.A. 2011. Using constant head step tests to determine hydraulic apertures in fractured rock. *Journal of Contaminant Hydrology*, 126, (1-2) 85-99.

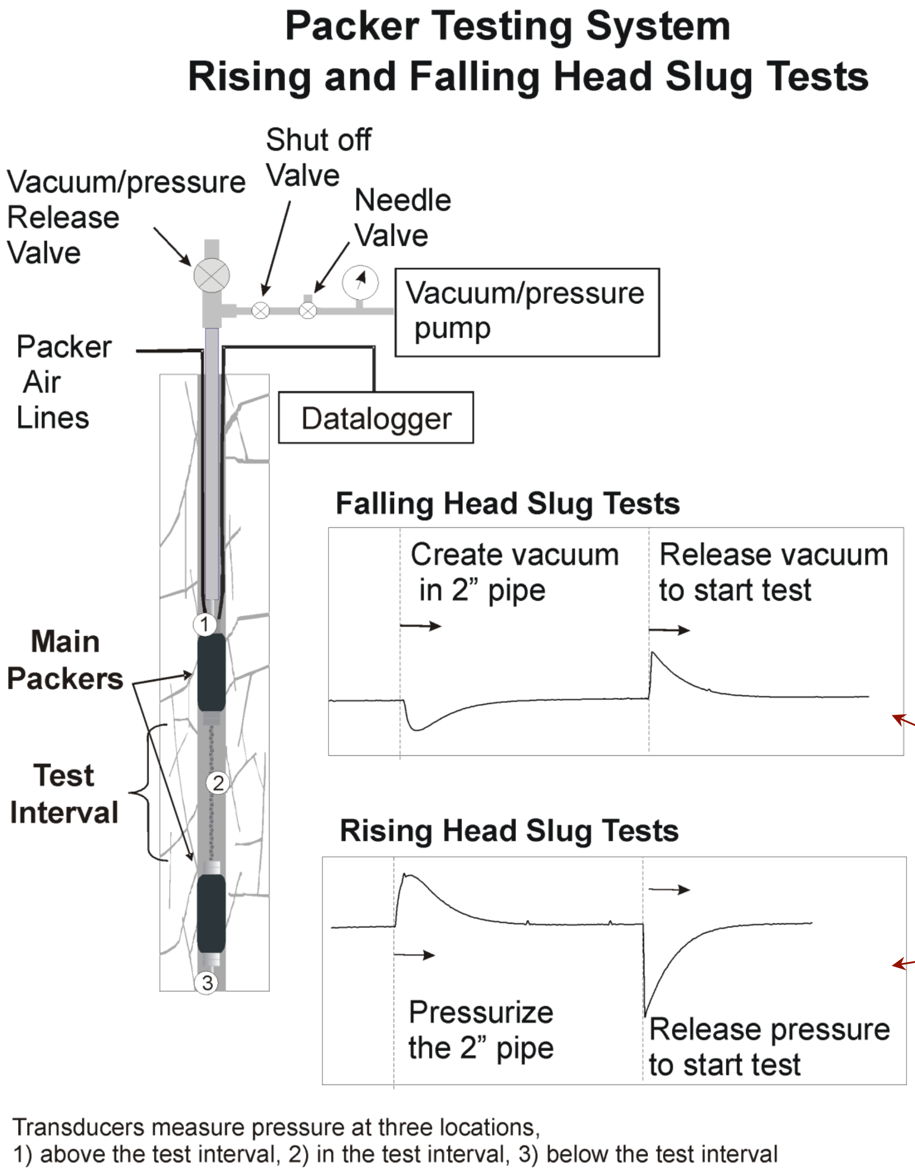
Test Type	Test Volume	Typical Test Results	Typical Analysis Method	Typical Analysis Graph	Head and Flow
Constant Head Step	Intermediate		Thiem $$T = \frac{Q}{2\pi \Delta H} \ln\left(\frac{r_o}{r_w}\right)$$		Head = Constant Flow = Constant (For each step)
Instananeous Slug	Small		Hvorslev Radial Flow $$T = \frac{slope(A_{xs})}{2\pi} \ln\left(\frac{r_o}{r_w}\right)$$ Spherical Flow $$T = \frac{slope(A_{xs})}{2\pi}$$		Head and Flow Variable
Constant Rate Pumping	Large		Cooper-Jacob Straight Line Method $$T = \frac{2.3Q}{4\pi \Delta s}$$		Flow = Constant Head Variable
Recovery after constant rate pumping	Large		Theis Recovery Method $$T = \frac{2.3Q}{4\pi \Delta s'}$$		Head and Flow Variable

T = Transmissivity
Q = flow rate
rw = well radius
ro = radius of influence
s = drawdown
A_{xs} = cross sectional area of riser pipe
dP = applied pressure

Assumption for all methods :

Darcy's Law is Valid

Pumping/Recovery Tests can be Injection/Recovery or Withdrawal/Recovery (Withdrawal/Recovery is shown above)



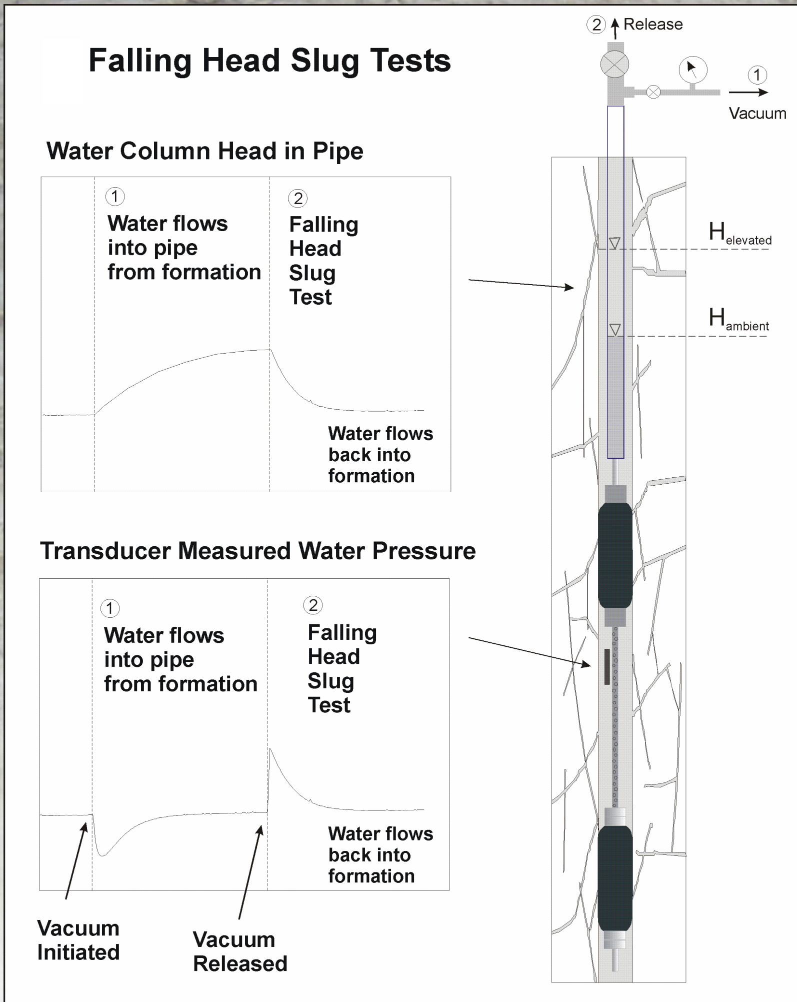
University of Guelph Slug Testing System

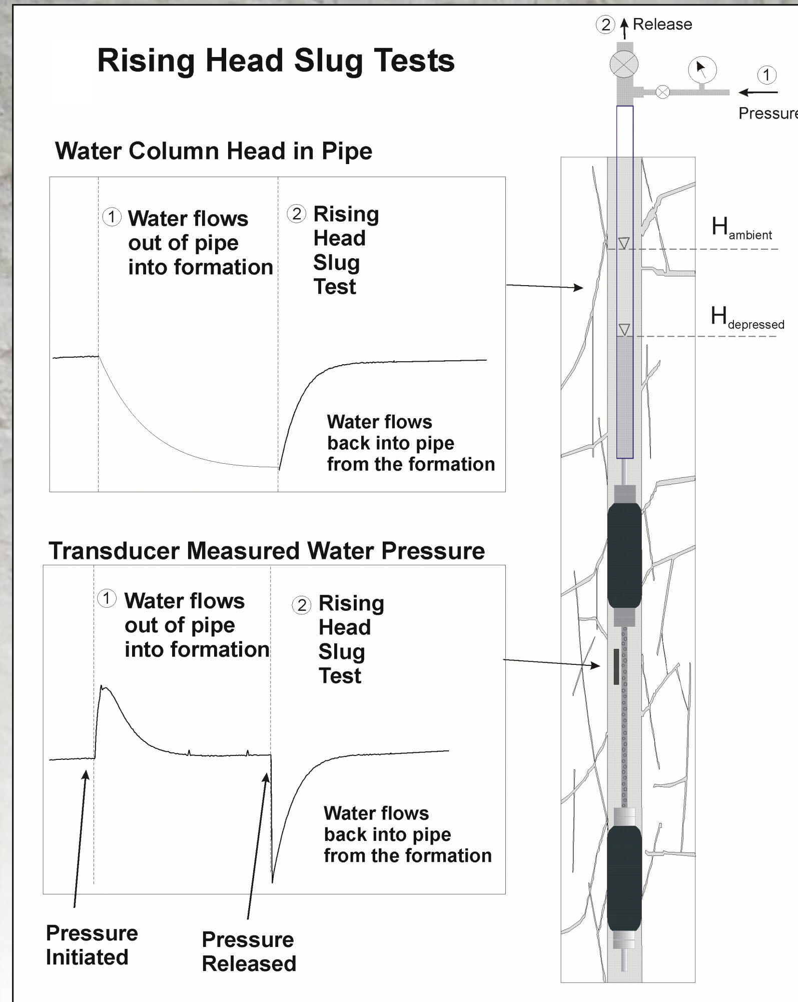
Conduct pneumatic slug tests using a pump capable of producing positive and negative pressure

Replace the air column with water

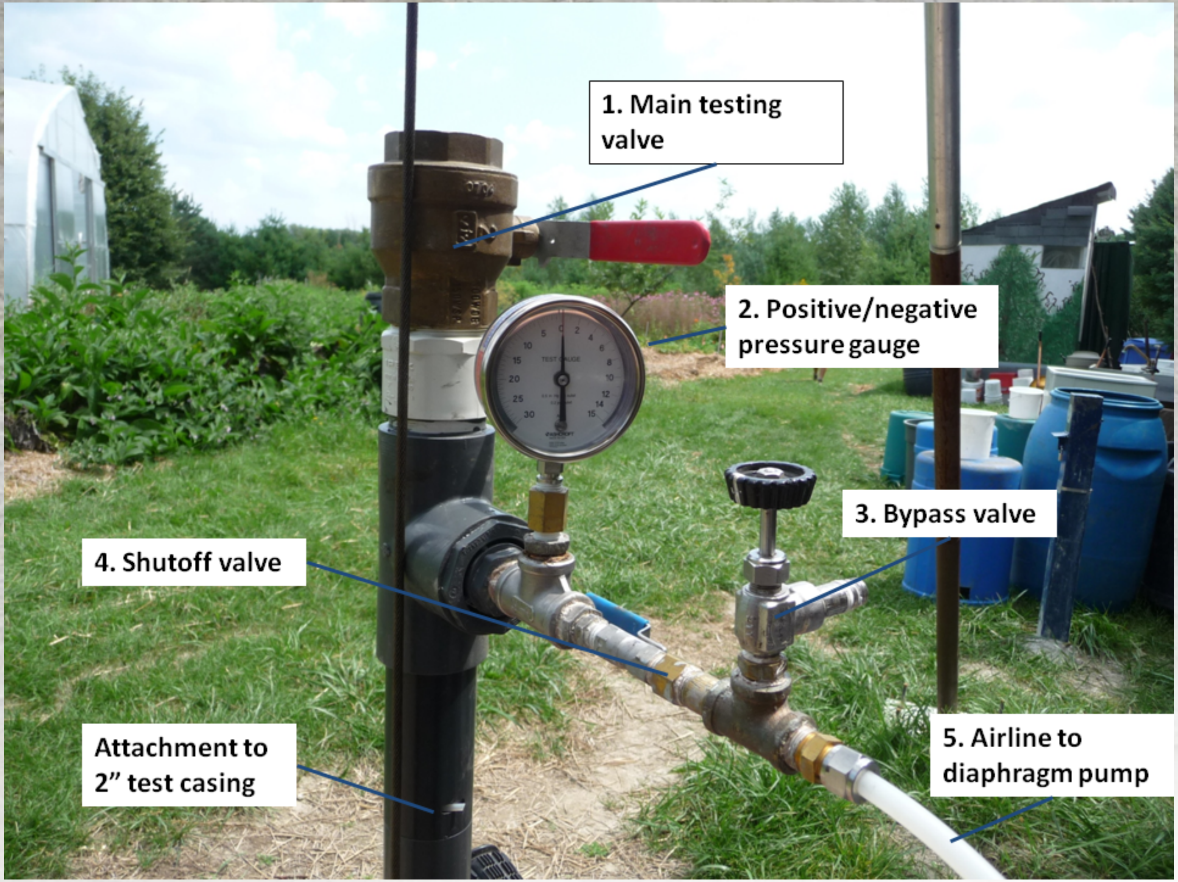
Replace the water column with pressurized air

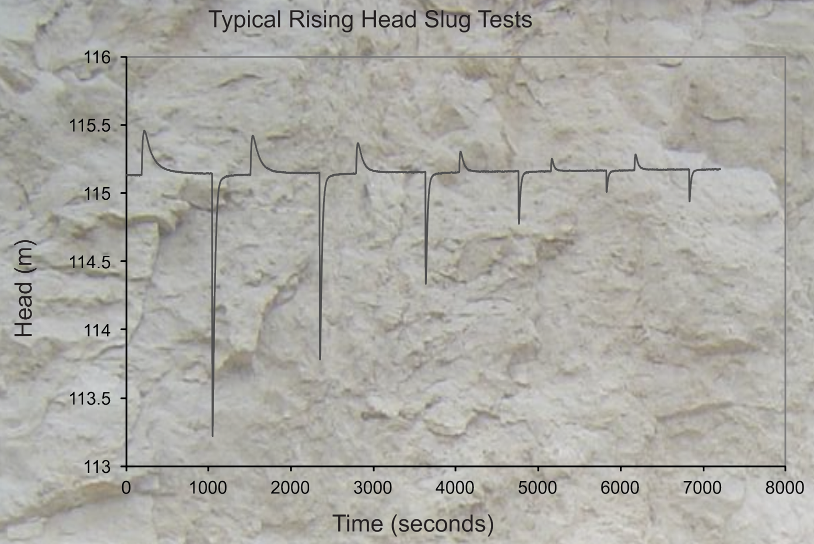
Pneumatic Slug Tests

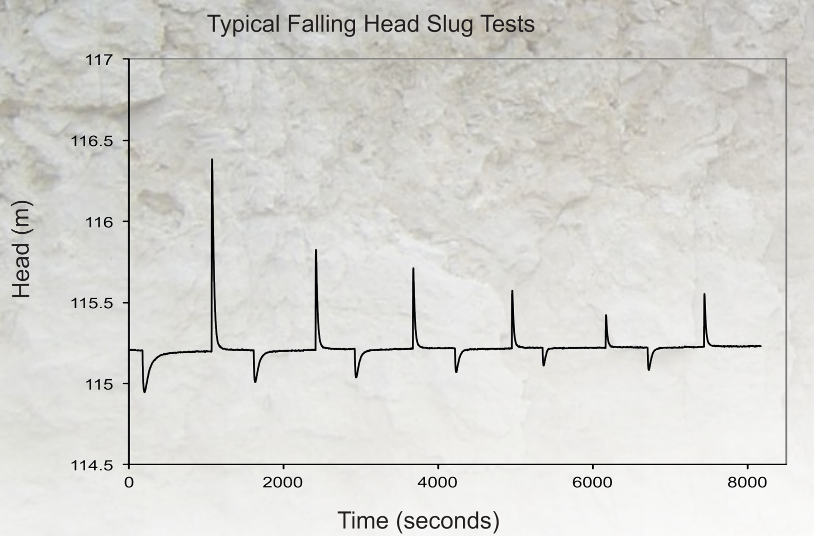




Pneumatic Slug Tests







Typical Pneumatic Slug Tests

Test Procedures

Conduct large displacement rising head test to help develop the test interval with strong inflow of water

Then conduct multiple tests at varying initial displacements

Slug Test Analysis – Hvorslev Method

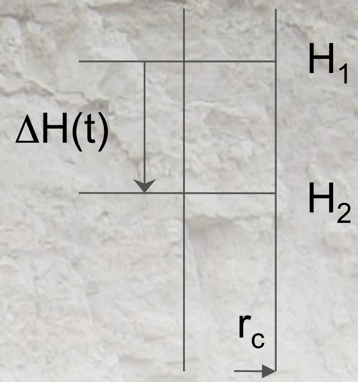
(Straight Line Method)

Assumptions

1. The flow rate can be calculated from the water level (WL) change in the riser pipe

$$Q = -\left(\pi r_c^{\ 2}\right)\frac{d(\Delta H)}{dt}$$

Falling head test



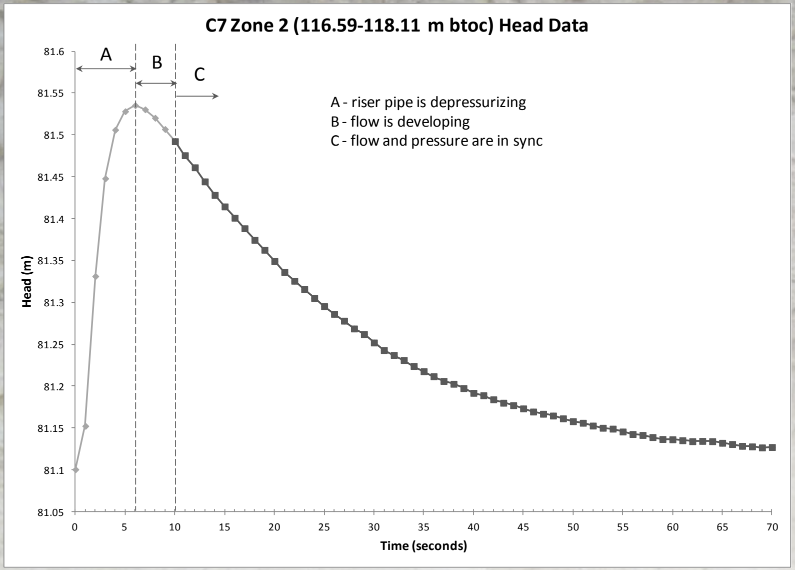
2. A slug test can be considered a transient analogue to steady-state tests

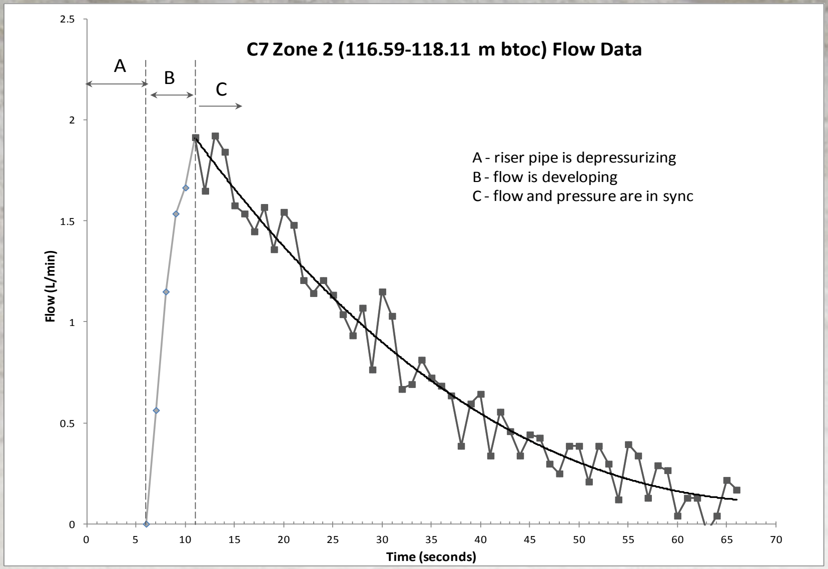
$$Q_{(t)} = FK\Delta H_{(t)}$$

Shape factor depending on well geometry

Validating the First Hvorslev Assumption

T can be determined from *only the pressure response* because it is assumed that the WL changes accurately reflect the flow rate





Plotting the flow rate from the pressure data can be used to consistently determine when the test begins

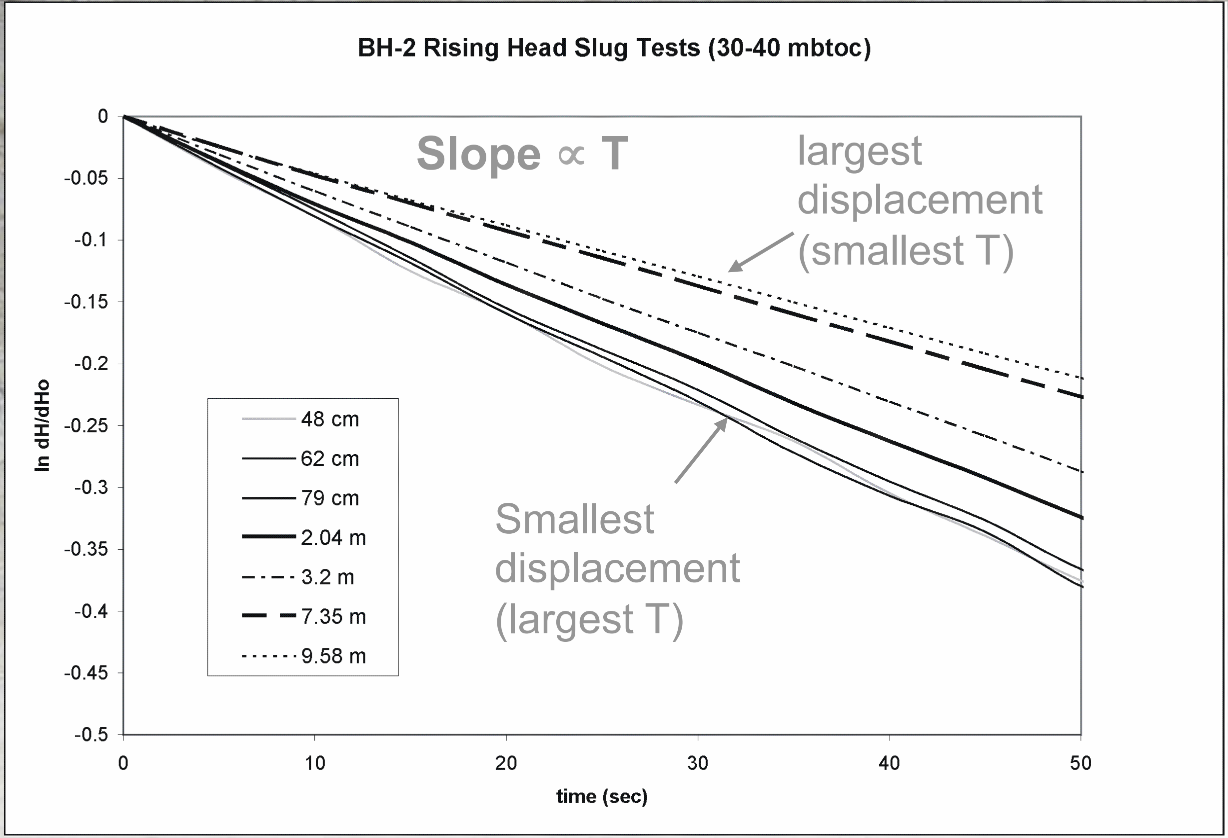
How Slug Tests Compare with CH Step Tests

Some Questions…

Can non-Darcian flow be identified in slug tests?

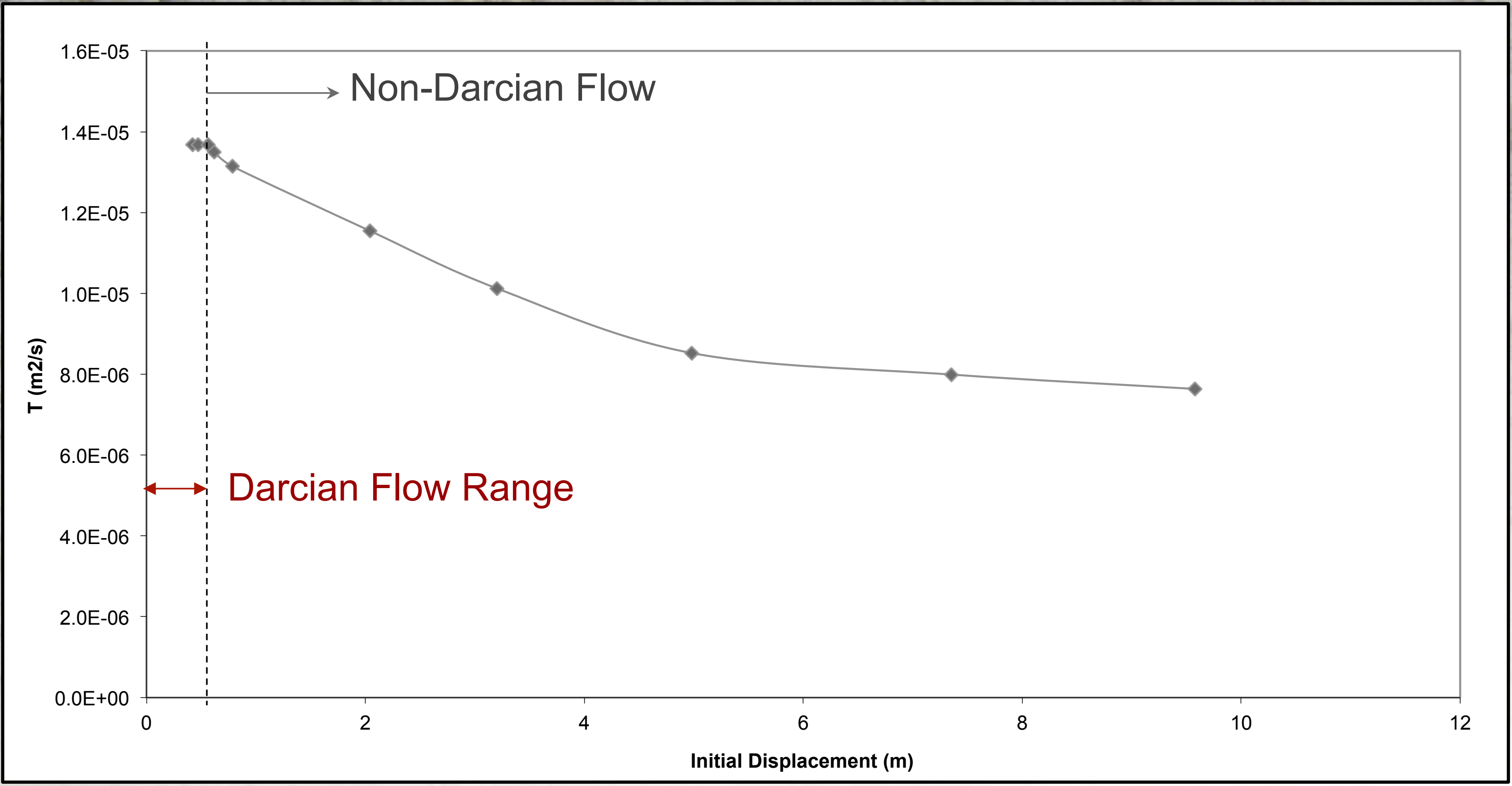
How do the T values compare?

Non-Darcian Flow Affects the Early Time Data the Most

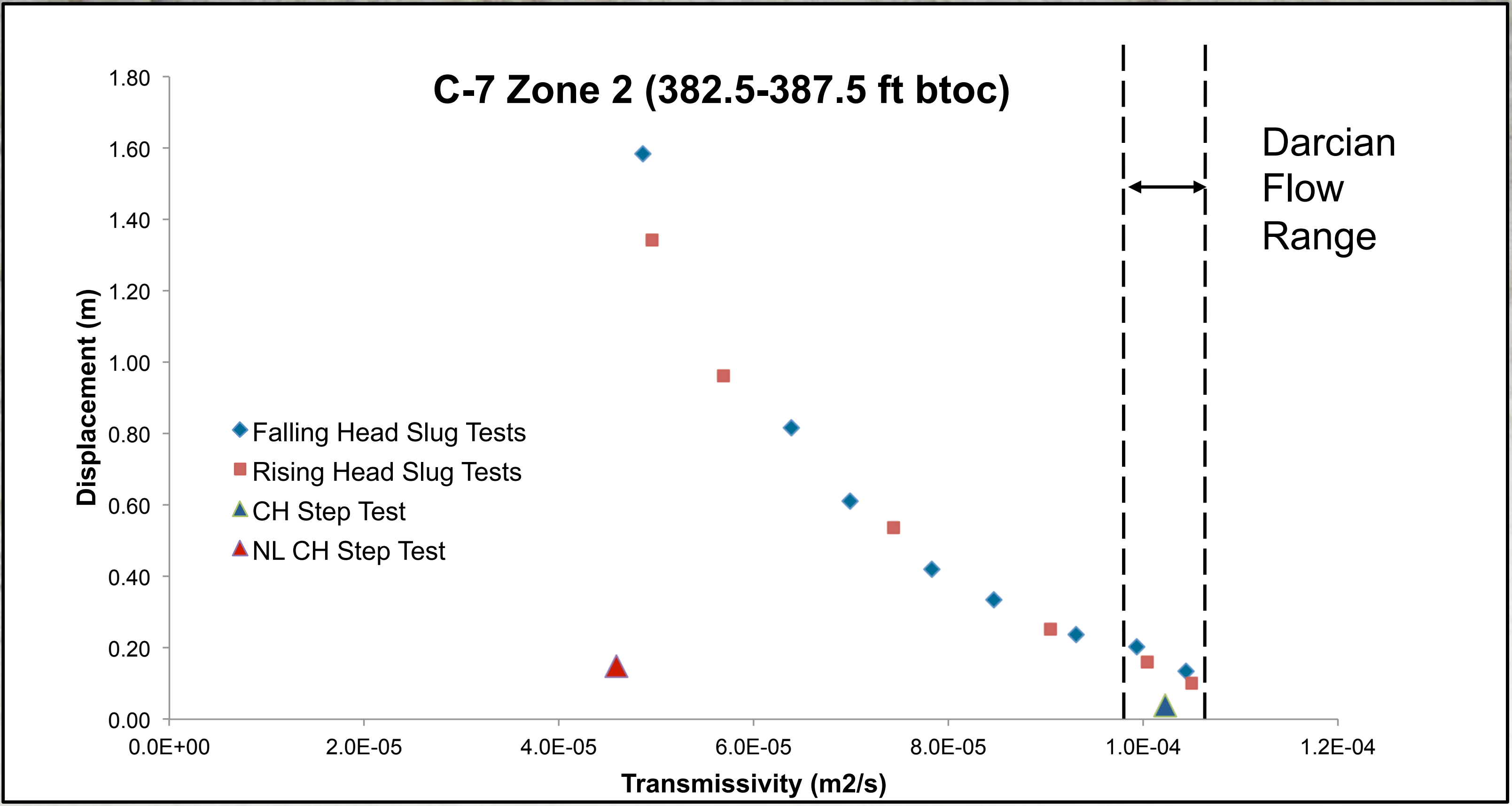


Decreasing T (slope) with increasing initial displacement is evidence of non-Darcian flow

Non-Darcian Flow causes T to Decrease with Increasing Initial Displacement

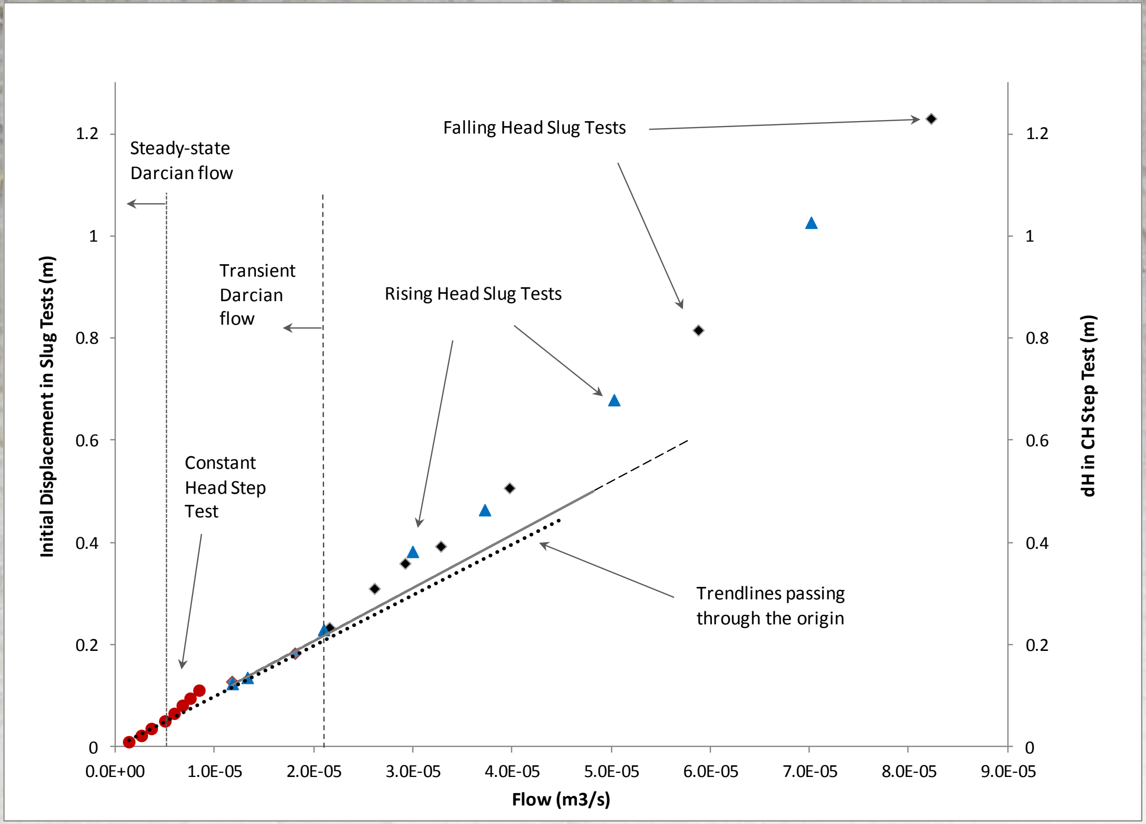


Good Agreement between Slug Tests and Constant Head Step Tests



Validating the 2nd Hvorslev Assumption

A Slug Test can be considered Pseudo Steady-State



The relationship between the initial displacement vs. the maximum flow calculated for a series of slug tests is very similar to the constant head step test dH vs. Q relationship

"This study shows that small displacement slug tests (<0.2 m) Produce T values that are close to the values obtained by constant head step tests in which the Darcian assumption was validated, providing evidence that slug tests, when properly performed, can be used to characterize the flow system in fractured rock boreholes."

Quinn, P.M., Parker, B.L., & Cherry, J.A. (2013), Validation of non-Darcian flow effects in slug tests conducted in fractured rock boreholes. *Journal of Hydrology*, 486, (0) 505-518

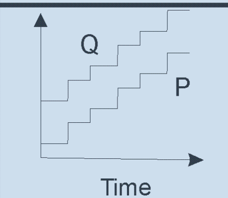
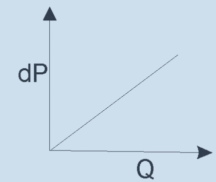
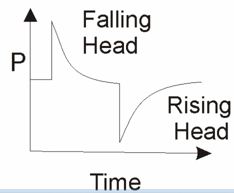
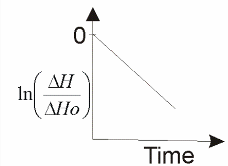
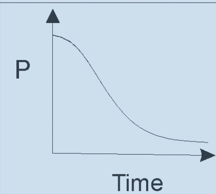
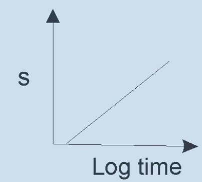
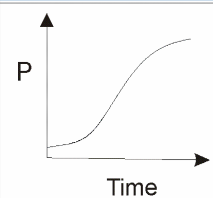
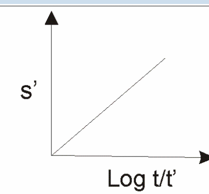
Synergistic Approach for determining Ss in Fractured Rock using Single Well Tests

In each test interval conduct two different types of tests:

1.) Constant Head (CH) Step Test

2.) Pumping Test

- *assess non-ideal effects in each test*
- *Minimize errors and uncertainties of each test using the results from the other test*

Test Type	Test Volume	Typical Test Results	Typical Analysis Method	Typical Analysis Graph	Head and Flow
Constant Head Step	Intermediate		Thiem $T = \frac{Q}{2\pi\Delta H}\ln\left(\frac{r_o}{r_w}\right)$		Head = Constant Flow = Constant (For each step)
Instananeous Slug	Small		Hvorslev Radial Flow $T = \frac{slope(A_{xs})}{2\pi}\ln\left(\frac{r_o}{r_w}\right)$ Spherical Flow $T = \frac{slope(A_{xs})}{2\pi}$		Head and Flow Variable
Constant Rate Pumping	Large		Cooper-Jacob Straight Line Method $T = \frac{2.3Q}{4\pi\Delta s}$		Flow = Constant Head Variable
Recovery after constant rate pumping	Large		Theis Recovery Method $T = \frac{2.3Q}{4\pi\Delta s'}$		Head and Flow Variable

T = Transmissivity
Q = flow rate
rw = well radius
ro = radius of influence
s = drawdown
A_{xs} = cross sectional area of riser pipe
dP = applied pressure

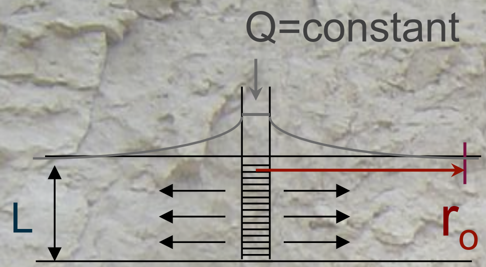
Assumption for all methods :

Darcy's Law is Valid

Pumping/Recovery Tests can be Injection/Recovery or Withdrawal/Recovery (Withdrawal/Recovery is shown above)

Thiem Equation for Single Well Tests

~ Steady-State



$$T = \frac{Q}{2\pi\Delta H}\ln\left(\frac{r_o}{r_w}\right)$$

Q = injection rate [L^3/T]------------------------------Measured

Δ H = change in hydraulic head [L]-------------------Measured

r_w = radius of borehole [L]----------------------------Measured

r_o = radius of influence (ROI) [L]--------***Assumed***

T = transmissivity [L^2/T] ----------------------------Calculated

There is error due to the r_o assumption

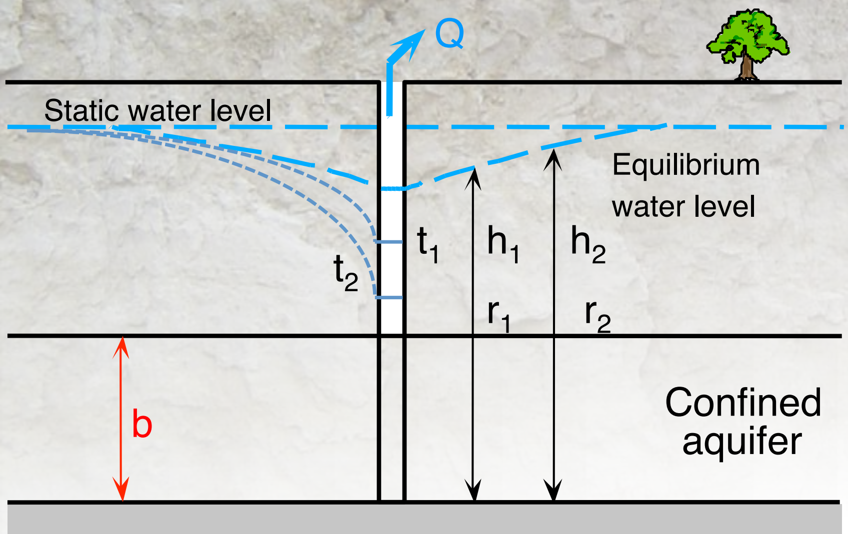
(1m < ro < 100 m ⇒ error up to a factor of 4.6)

Constant Flow Rate Pumping Tests

Transient Flow

Constant rate pumping tests are the best type of hydraulic test to *determine specific storage*

A common view in the literature is that single-hole tests do not provide useful Ss values



Therefore, need values for head at two locations

Pumping Test Analysis Cooper-Jacob Method

Can approximate the Theis equation by using the first 2 term in the infinite series

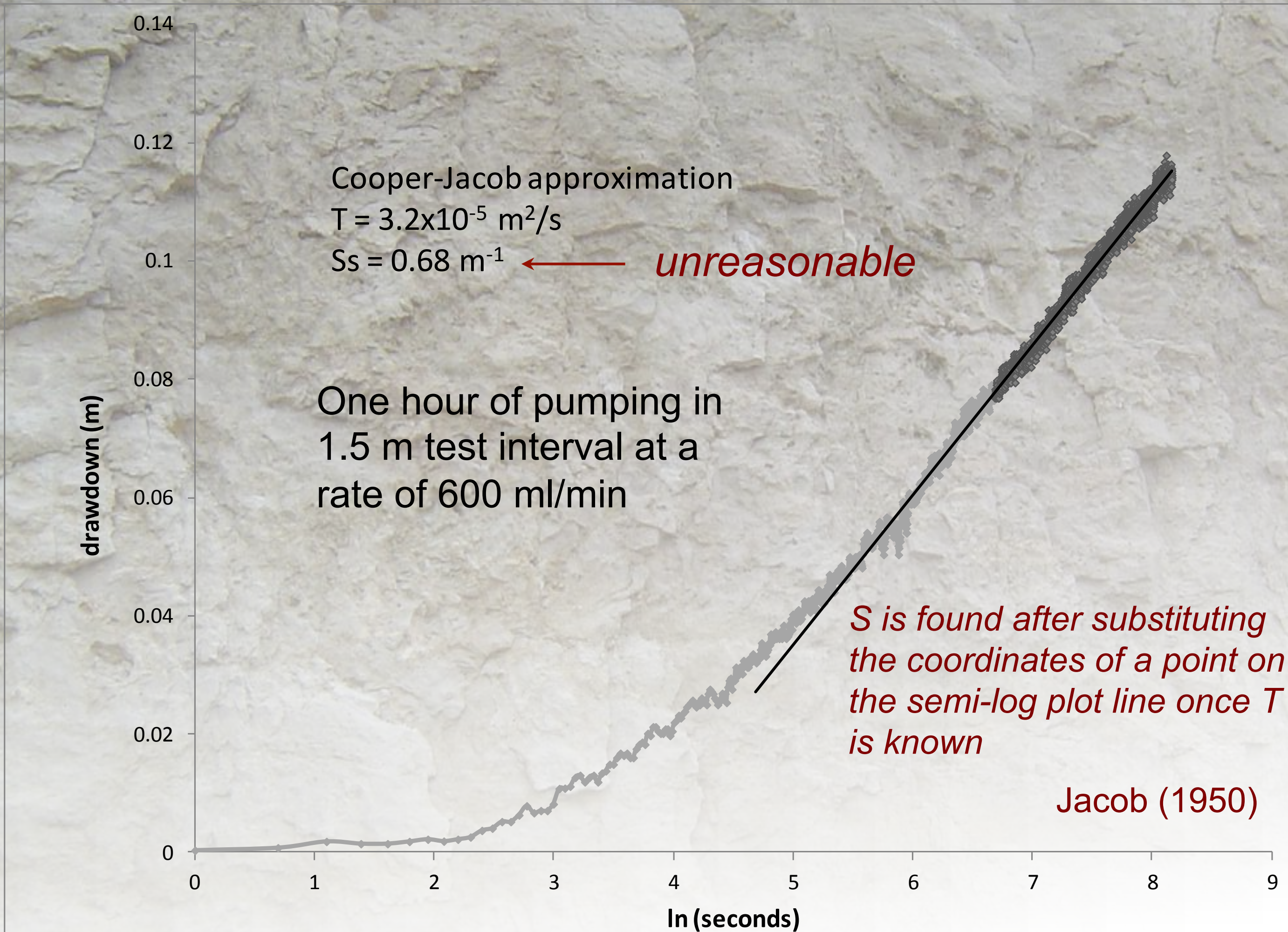
- Small r or large times

$$\Delta H \approx \frac{Q}{4\pi T}\ln\left(\frac{2.25Tt}{r^2 S}\right)$$

Plot In(time) vs. drawdown (semi-log plot)

$$T = \frac{Q}{4\pi \Delta H} \qquad S = \frac{2.25Tt_o}{r^2}$$

Pumping Test Results (C10zone15)



Synergistic Approach

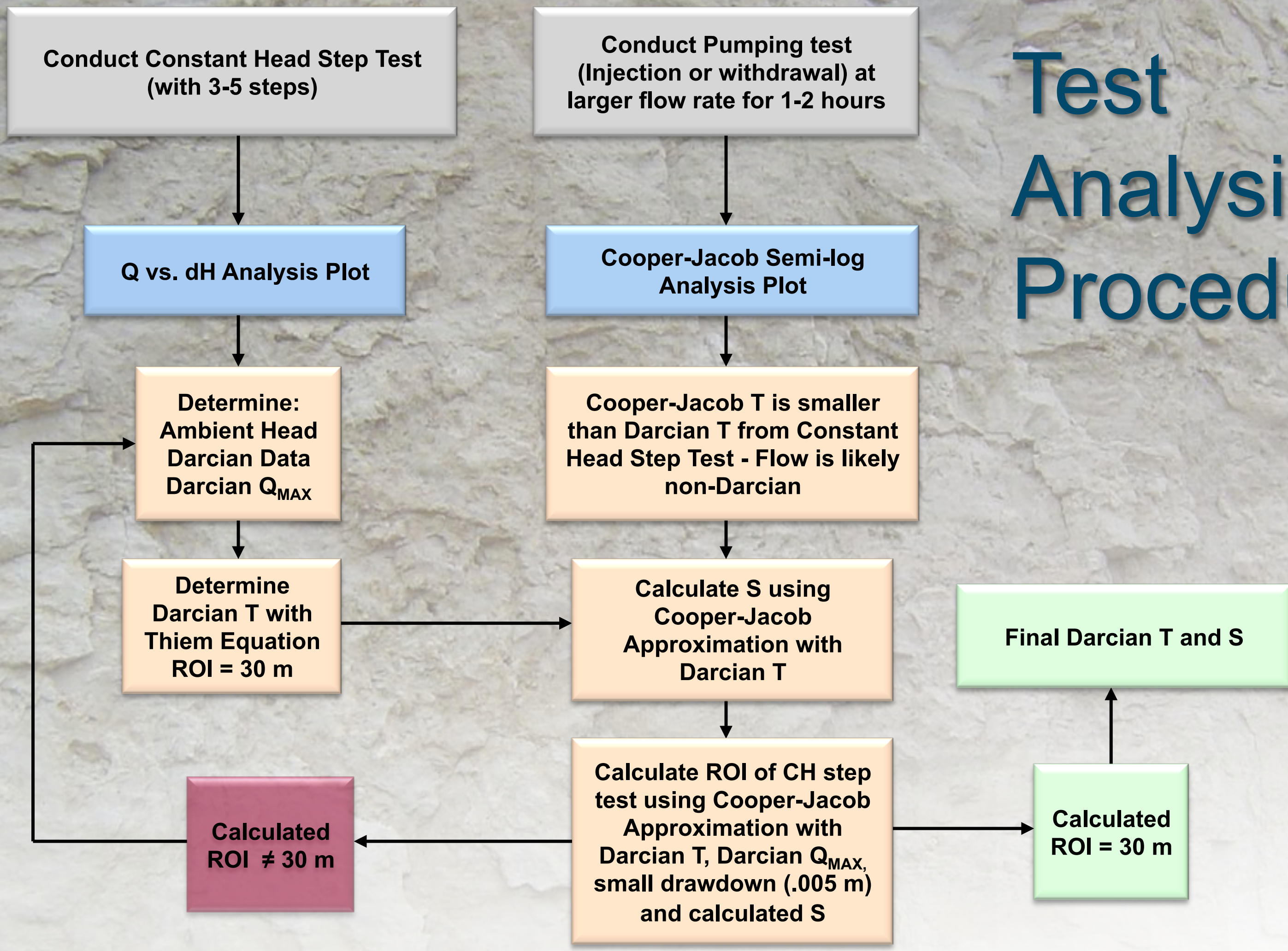
1. Use the Cooper-Jacob approximation to solve for S directly using the Darcian T value

$$S = EXP\left[\left(ln\,\frac{2.25Tt}{r^2}\right) - \frac{4\pi Ts}{Q}\right]$$

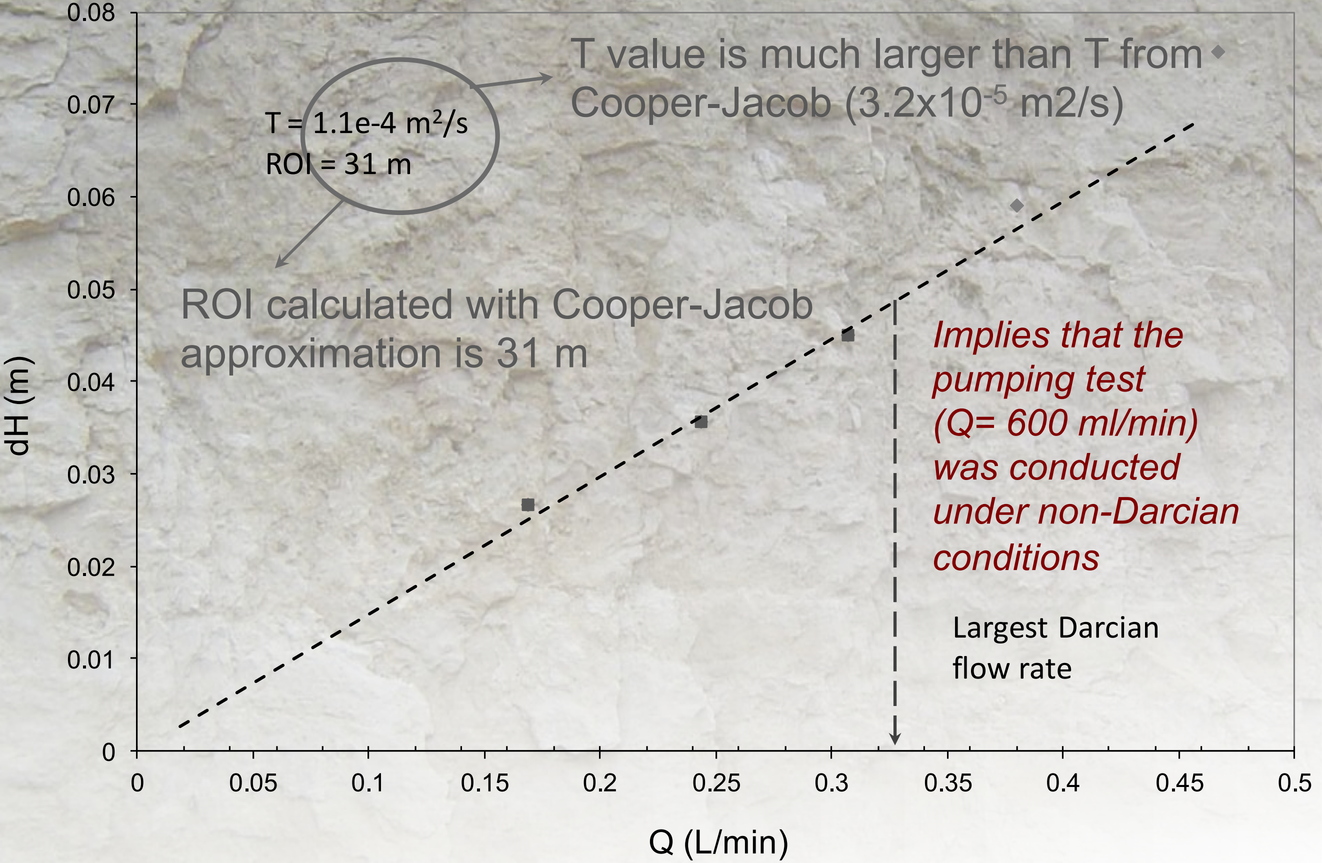
2. Use the Cooper-Jacob approximation to solve for the ROI of the CH step test using:
   - the Darcian T value
   - the calculated S value,
   - the largest Darcian flowrate,
   - and a small ROI drawdown (0.005 m)

$$r = \sqrt{\left(\frac{2.25Tt}{EXP\left(\frac{4\pi Ts}{Q}\right)S}\right)}$$

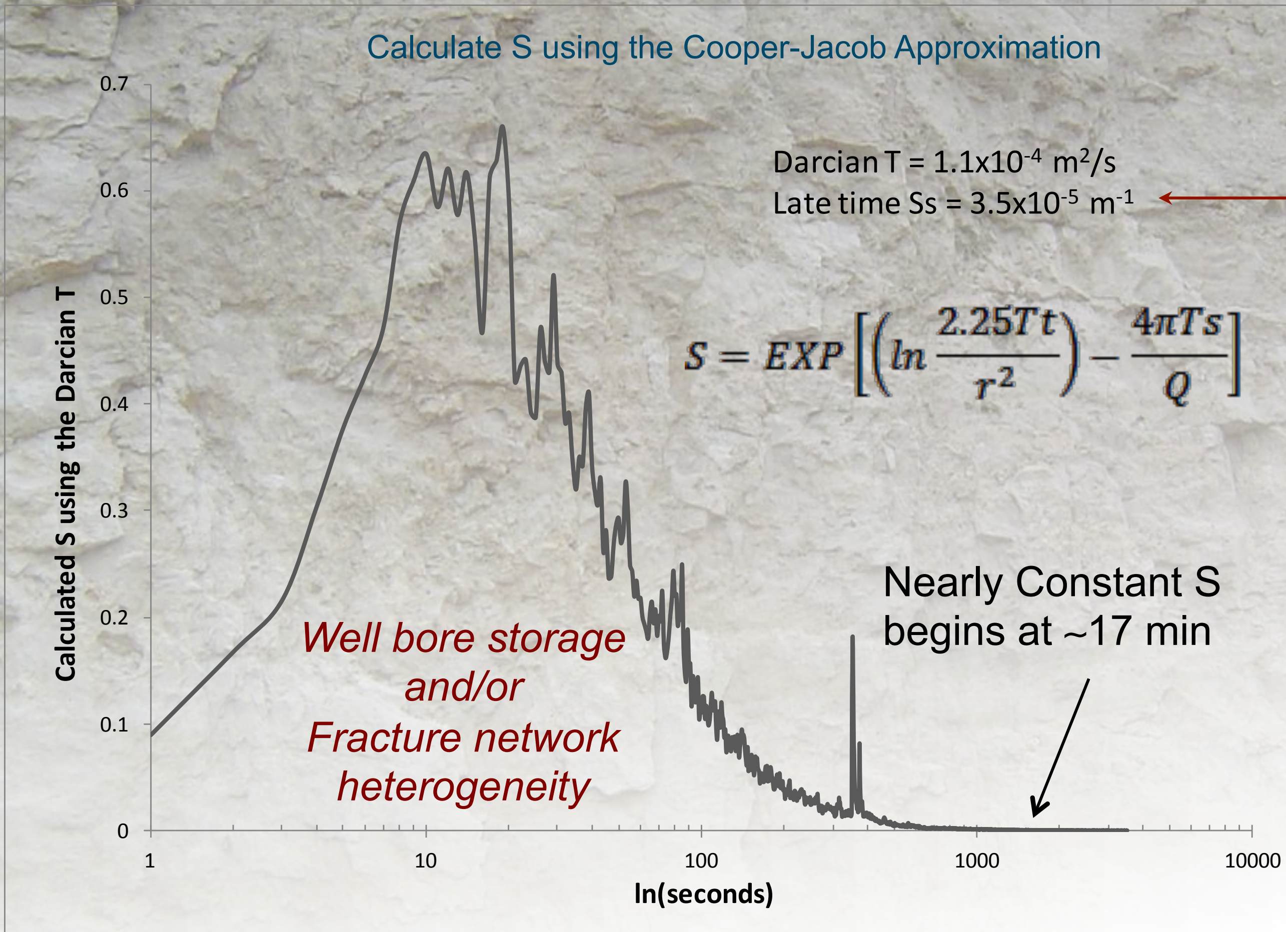
Test Analysis Procedure



CH Step Test Results (C10zone15)



Later Time Results Show Nearly Constant S



reasonable

Wen et al., (2010) found similar S behavior

Ss values ~10^{-5} m^{-1}

reasonable for fractured sandstone

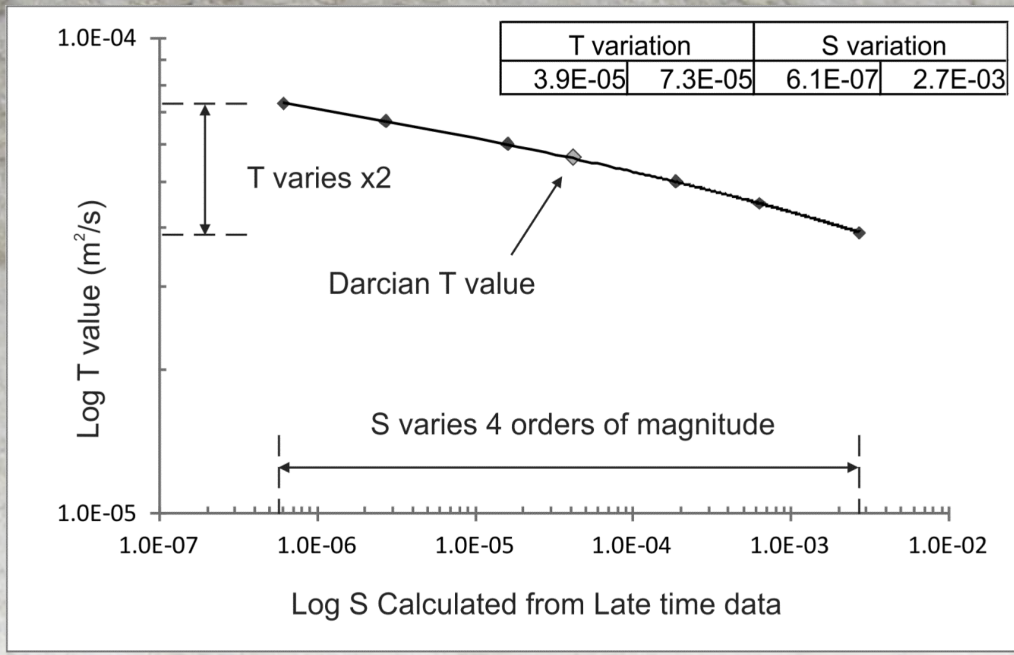
Zone	Test Type	*Wellbore storage $25*r_c^2/T$ (seconds)	CH Largest Darcian Q (L/min)	CH step test ROI (m)	CH Radius of influence using S&T (m)	CH Darcian K (m/s)	Calc C-J Ss with Darcian T (m^{-1})
C7zone2S	injection	117	0.821	28	28	7.6E-06	7.4E-06
C6zone33	withdrawal	457	0.295	28	28	2.2E-05	2.4E-05
C6zone12	injection	319	0.309	29	29	3.2E-05	2.8E-05
C7zone13	injection	281	0.230	29	29	3.6E-05	2.4E-05
C6zone17	injection	270	0.294	29	29	3.7E-05	2.8E-05
	withdrawal	269	0.294	29	29	3.7E-05	2.9E-05
RD35A Open**	injection	957	NA	NA	NA	3.7E-05	3.1E-05
C10zone34	injection	218	0.278	29	29	4.6E-05	2.8E-05
C6zone8	injection	207	0.269	29	29	4.9E-05	2.9E-05
C6zone25	withdrawal	200	0.395	30	30	5.1E-05	3.7E-05
C7zone6	injection	194	0.298	30	29	5.2E-05	3.0E-05
C7zone3	injection	176	0.561	31	30	5.7E-05	4.8E-05
C7zone12	injection	163	0.398	31	31	6.2E-05	3.6E-05
	withdrawal	163	0.398	31	31	6.2E-05	3.6E-05
RD106zone5	injection	156	0.390	31	31	6.5E-05	3.5E-05
C10zone15	injection	139	0.380	31	31	7.2E-05	3.5E-05

K increases
Ss increases

* Based on Darcian T

** Darcian T based on FLUTe profile

S Values are Very Sensitive to Errors in T



S can vary almost 4 orders of magnitude when T varies by a factor of 2

Conclusions

- To improve estimates of Ss in fractured rock it is essential to have good T estimates
  - CH step tests are used to get a Darcian T value
  - Pumping test data are used to validate the radius of influence assumption used to determine T in the CH step tests
- Conducting the two different types of hydraulic tests reduces uncertainty in Ss values

Concluding Remarks

This versatile packer testing equipment and procedures has substantially improved the accuracy and reliability of hydraulic parameters measured in fractured rock boreholes in a effort to enhance contaminant plume studies

The End