Well Construction and Hydraulic Testing in the Fractured Rock Terrain of the Piedmont-Mountains, NC

Presented by Ted Campbell, NC Division of Water Quality

Contributors:

NC Division of Water Quality

US Geological Survey

Piedmont/Mountains Resource Evaluation Program

Overview of talk

Piedmont-Mountains Research:

- Aquifer matrix – primary and secondary porosity

- How we approach our aquifer tests: designing and conducting hydraulic tests

- Well installation

- Challenges in fractured rock

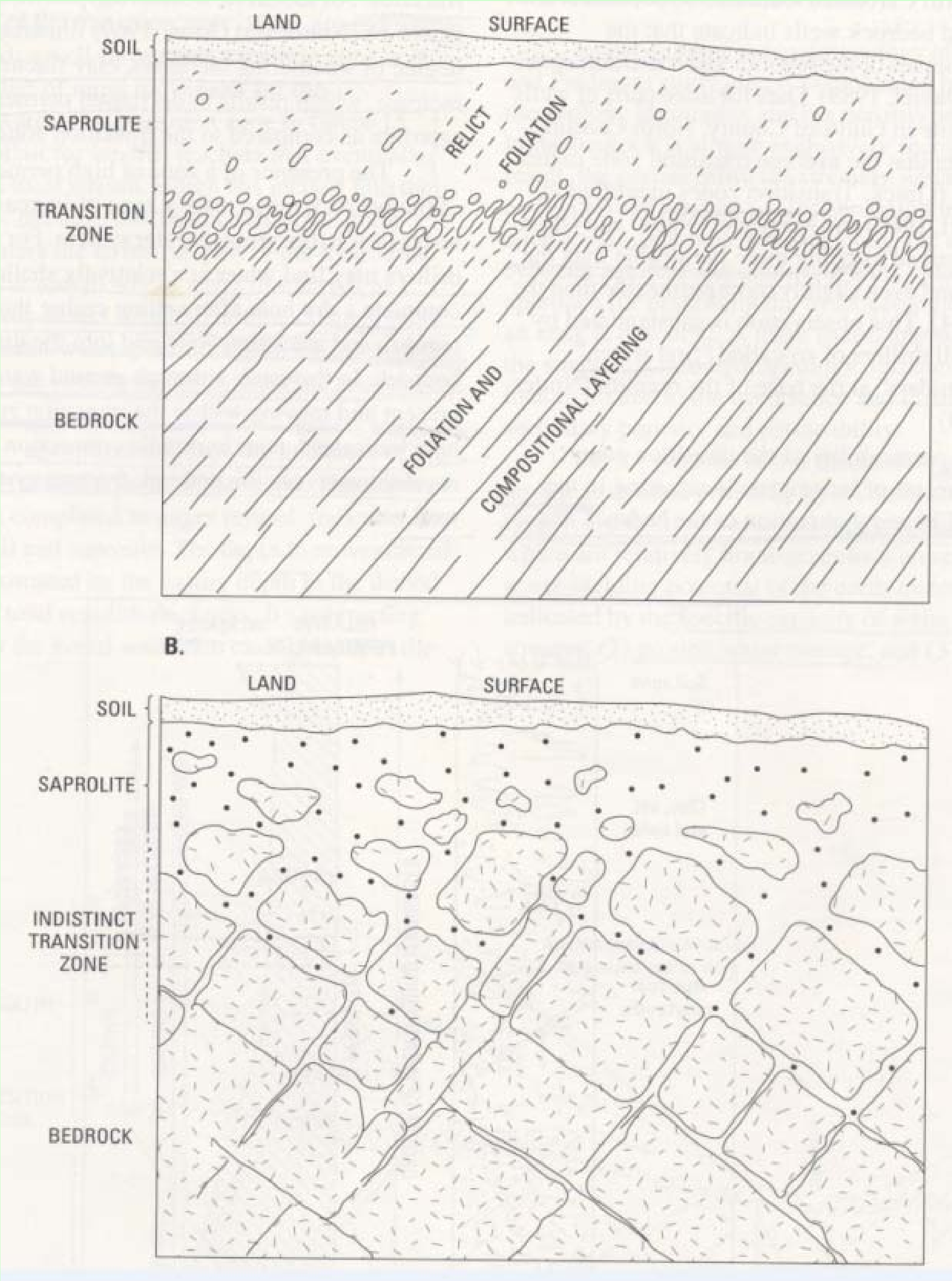
- Findings and lessons learned

Aquifer Matrix in Piedmont-Mountains

1) Regolith and 2) Fractured rock

Water storage and movement…

Conceptual variations of transition zone thickness and texture that develop on different parent rock types (from Harned and Daniel, 1992 and Daniel and Dahlen, 2002)



Distinct transition zone on highly foliated schists, gneisses, and slates

Indistinct transition zone on massive bedrock

Geologic setting:

Our current P-M research sites are represented by the following rock types:

- felsic gneiss
- muscovite-biotite schist
- granite
- quartz diorite
- meta-volcanic rocks
- meta-sedimentary rocks

Several types of rock discontinuities through which water flows….

Geologic setting:

Several types of rock discontinuities through which water flows….

- Regolith
  - primary porosity….main storage reservoir for underlying fractured bedrock…retains fabric and anisotropy of parent rock

- Fractured bedrock – secondary porosity….main conduits for ground water movement
  - secondary porosity….main conduits (“plumbing system”) for ground water movement

Fractured bedrock

Water-bearing rock discontinuities through which ground water flows:

- foliation parallel partings

- contact zones

- weathered veins and pegmatites

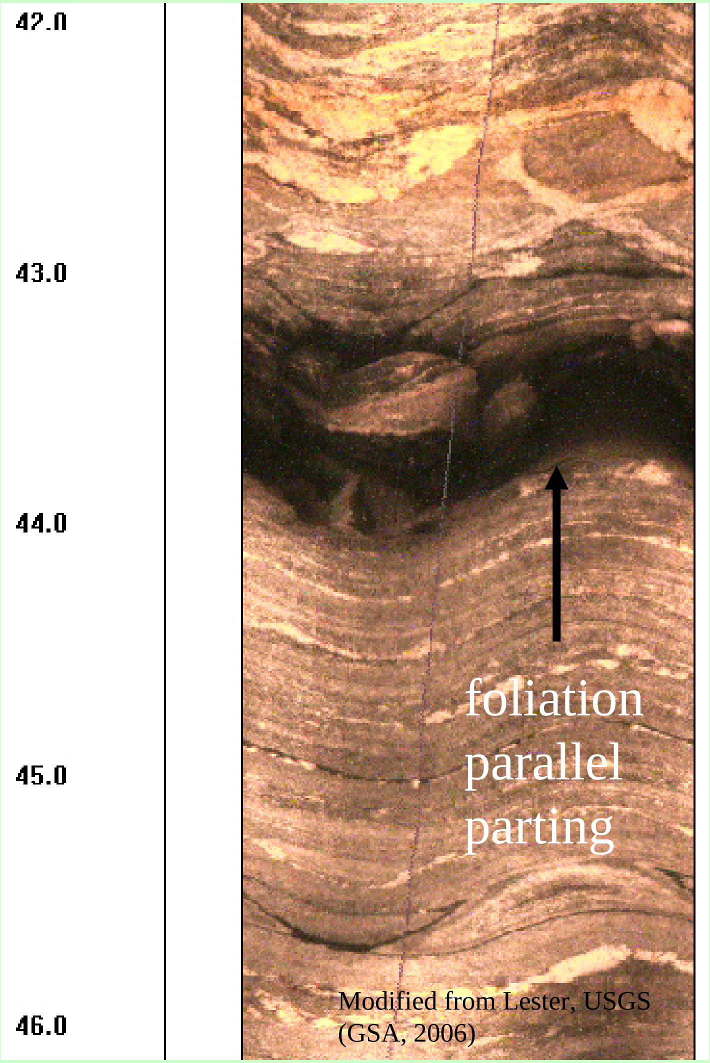
    - various cross-cutting lithologies and textures

- faults

    - brittle (post metamorphic), non-ductile features

    - small offsets in layering

    - zones of fault gouge



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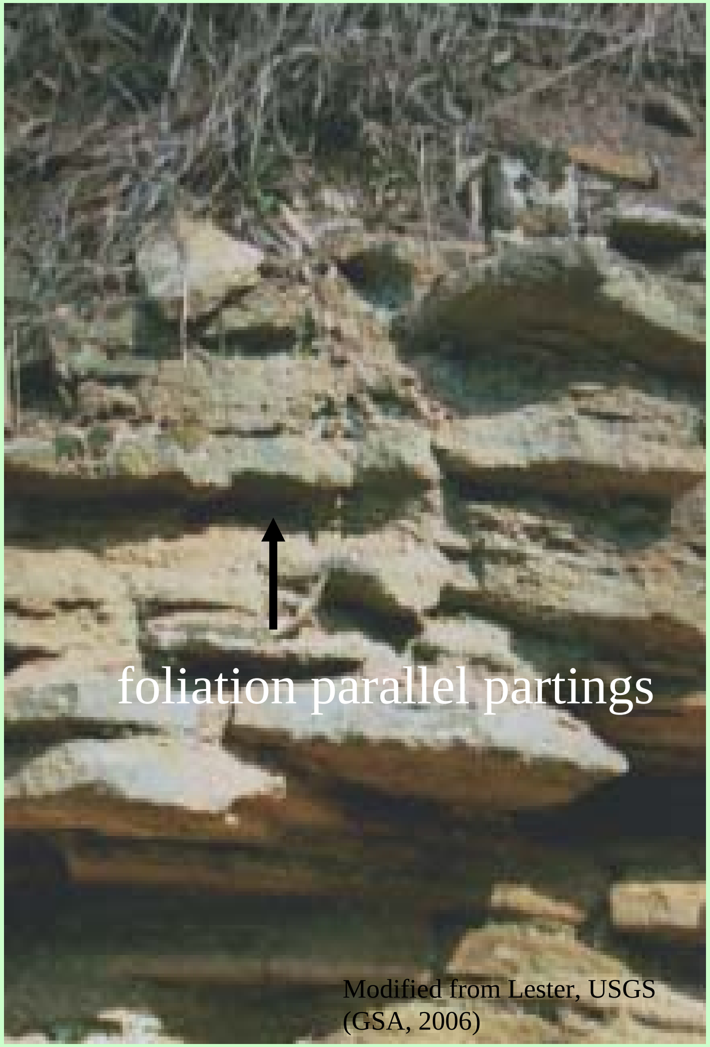


Fractured bedrock

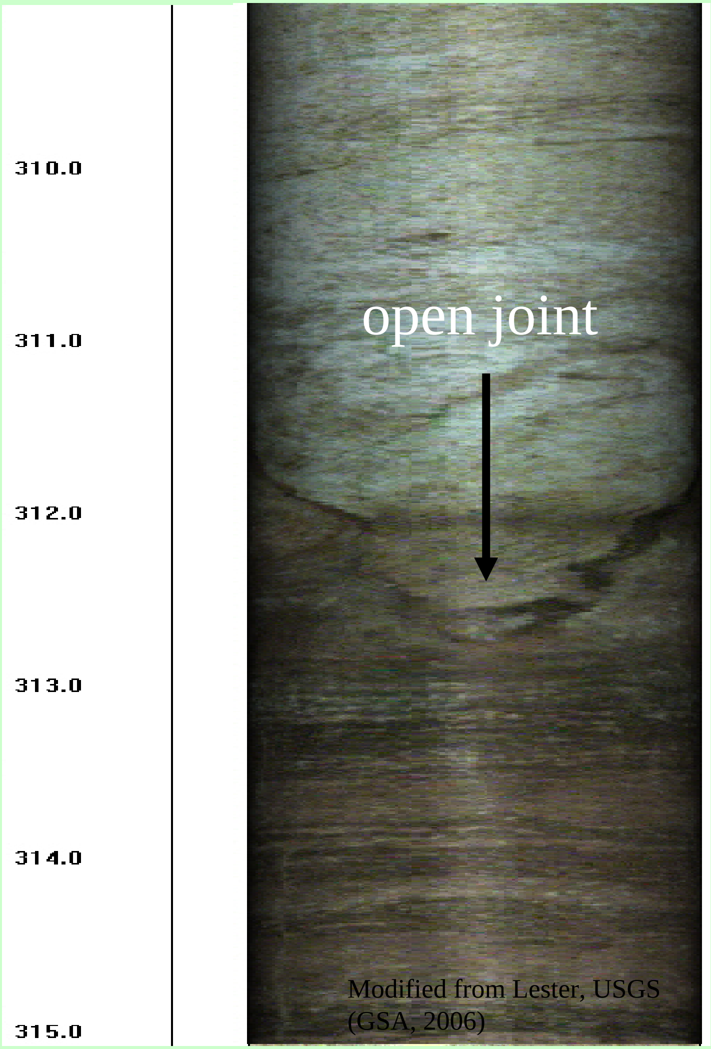
Water-bearing rock discontinuities through which ground water flows:

- joints
  - open joints
  - closed joints
  - zones of concentrated joints (joint sets)
  - often steeply dipping and planar

- sheet fractures (parallel to land surface)
  - stress-relief fractures
  - exfoliation joints

- water-bearing voids

- weathered openings



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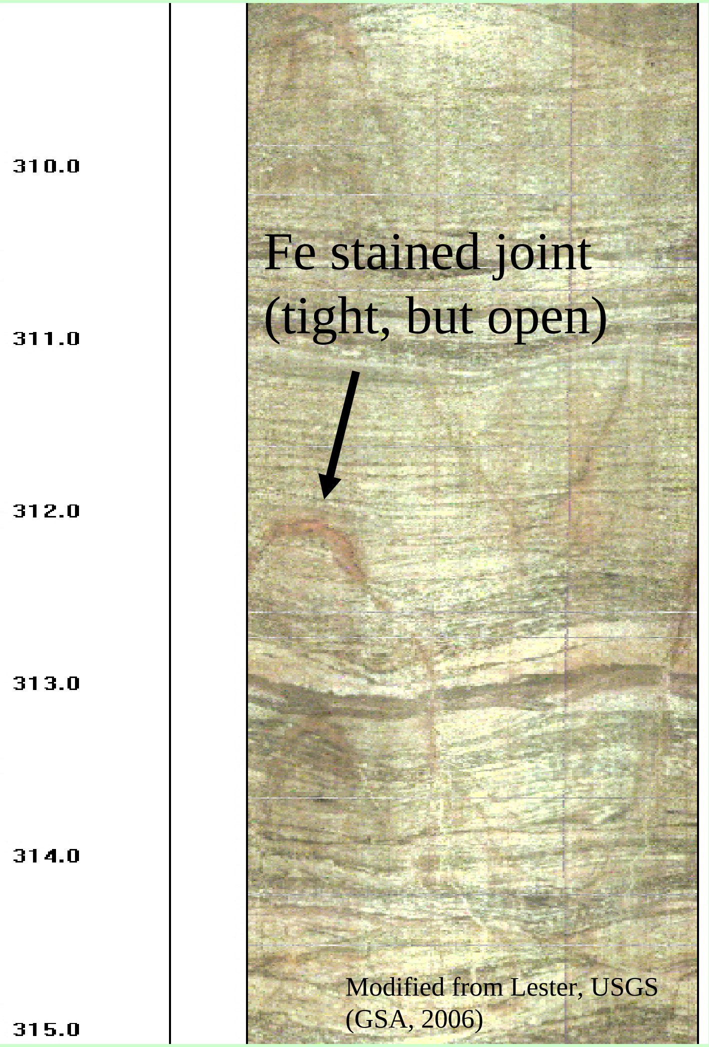

Modified from Lester, USGS
(GSA, 2006)

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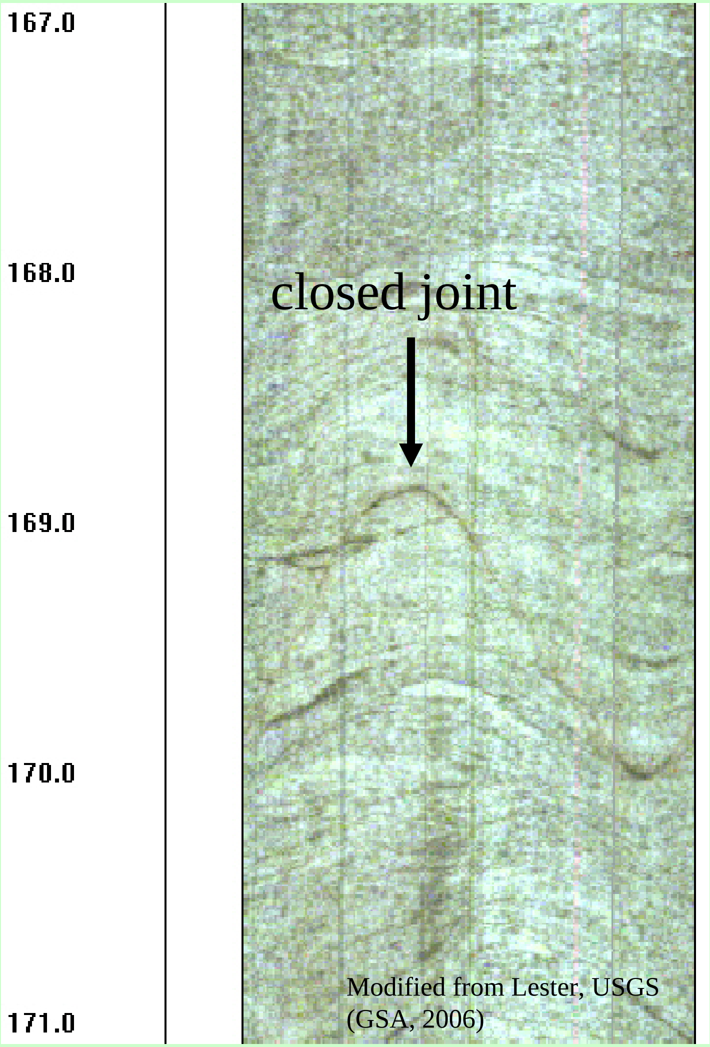

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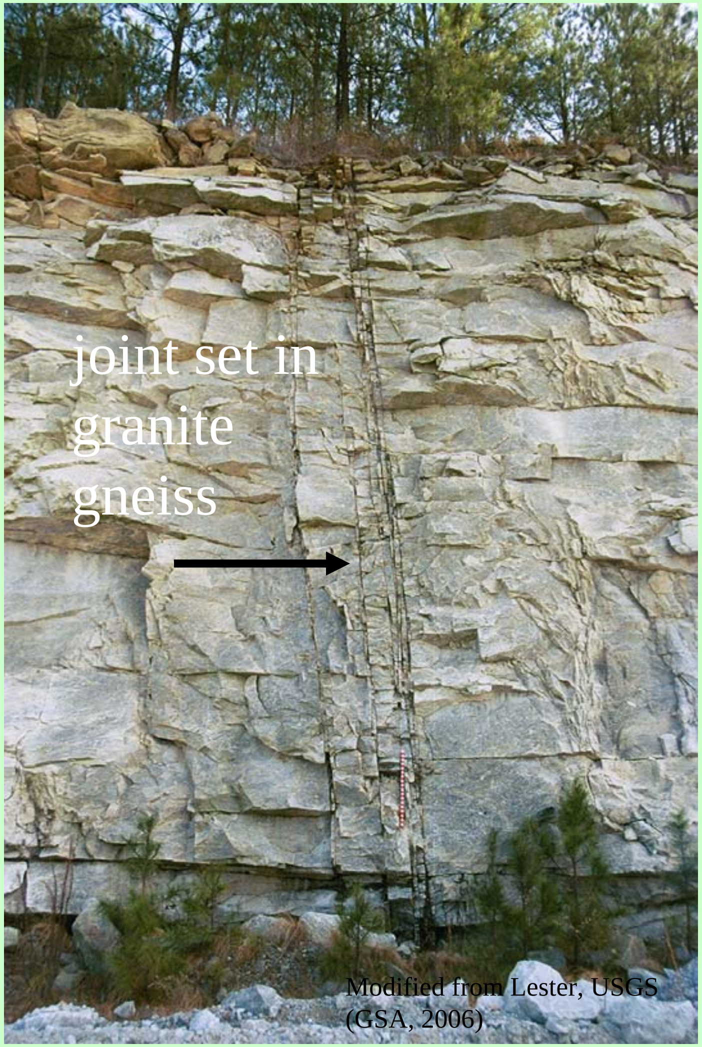

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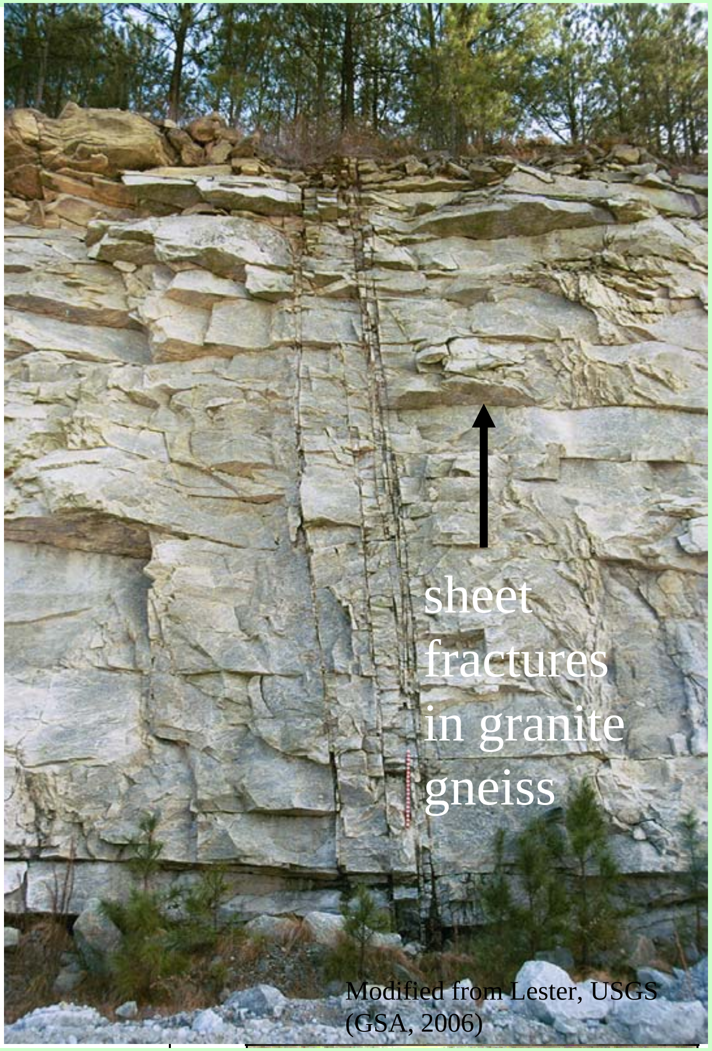

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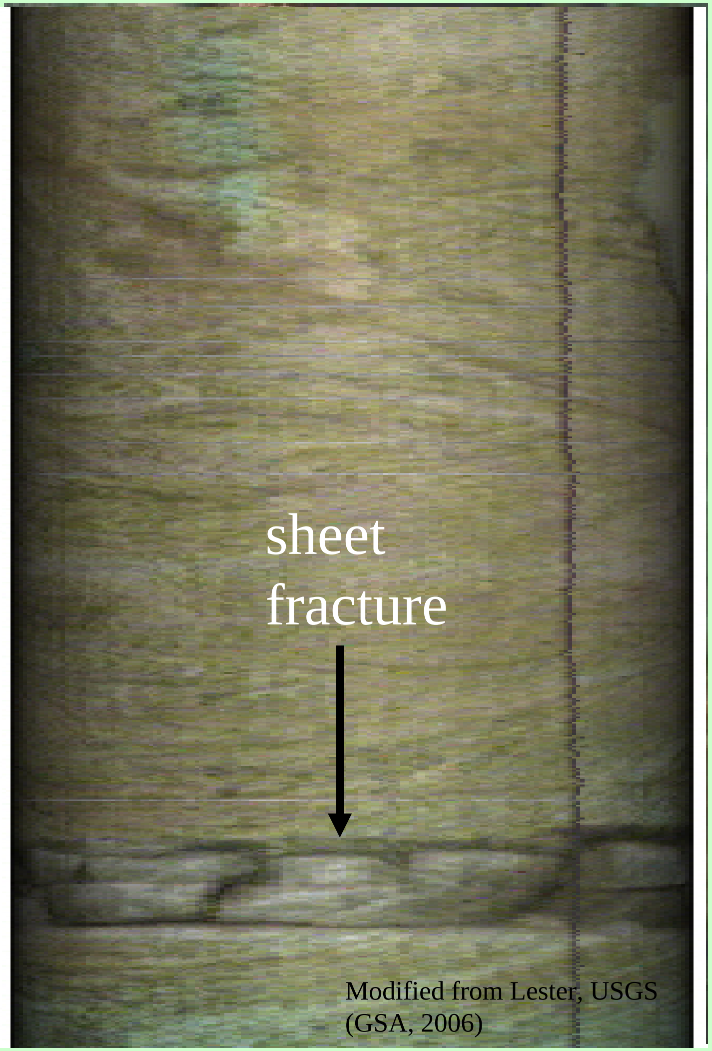

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TEST DESIGN

Aquifer Testing   Why conduct an aquifer test?

- to better understand the aquifer system (qualitative analysis)
  - recharge boundaries (sources of water)
  - impermeable boundaries
  - heterogeneities (anisotropy, discontinuities)
  - degree of bedrock interconnectivity and bedrock-regolith interconnectivity
- to estimate the aquifer's hydraulic properties (quantitative analysis)
  - transmissivity
  - storativity
  - ground water resource studies (e.g. sustainable yield)
  - contaminant transport models (e.g. transmissivity)

Hydraulic properties of interest:

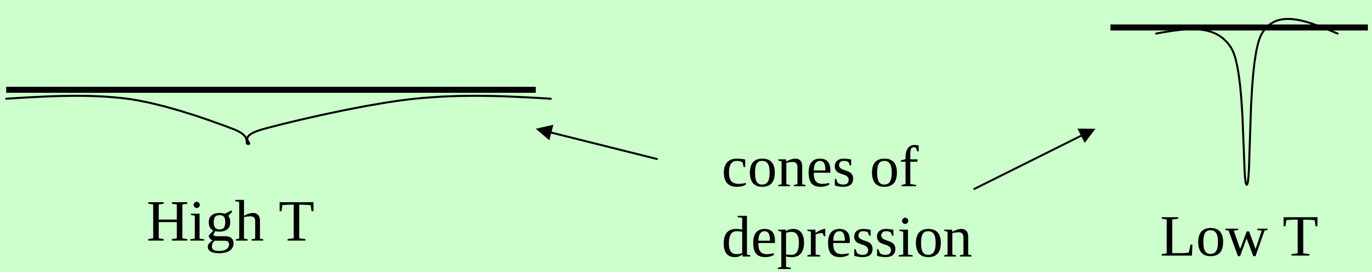
- <u>transmissivity, T</u> $T = K\ b$ (typical units are ft^2/day)

- the rate at which water is transmitted through a unit slice (width) of aquifer under a unit hydraulic gradient.

- how much water will move through the system $$T = \frac{2.3\ Q}{2\ pi\ (h_0 - h)}$$ (Q in ft^3/day; h in ft)

- can be estimated using analytical solutions and specific capacity (function of Q and head change per time or distance)

- affects both the radius of the cone of drawdown and its depth (the radius of the cone at any time increases with increasing T, and the depth of the cone is inversely proportional to T)



Review of some of the hydraulic properties of interest:

- storativity, S (storage coefficient)

- The amount of water that can be removed from an aquifer by pumping or drainage.... the volume of water released from storage per unit surface area of aquifer per unit change in head

- in unconfined aquifers, S_y = specific yield (volume of water released by gravity drainage per volume of aquifer material)….S_y ~ 0.2 to 0.05.

- units are dimensionless

$$S = \frac{2.25\ T\ t}{r_0^2}$$

(T in ft²/day; t in days, r in ft)

- can be estimated using analytical solutions and specific capacity (function of T, Q, and head change per time or distance)

- water released from a confined aquifer is obtained from elastic storage of the aquifer (due to expansion of water as pressure in aquifer is reduced and by expulsion as the pore space is reduced as the aquifer compacts); S in confined aquifers ~ 0.001 to 0.00001

- low values of S suggest that relatively large areas of the aquifer are affected by pumping (e.g. confined aquifers)…S affects rate of lateral spread of cone (rate of lateral growth is inversely proportional to S)

Review of some of the hydraulic properties of interest:

- <u>hydraulic conductivity, K</u>

- the rate at which water can flow through a porous medium

- units of length per time (e.g. ft/day)

- $K = \frac{Q}{A\,(dh/dl)}$ and $K = \frac{T}{b}$

- values can vary by orders of magnitude (log-normal distribution)

- values can vary spatially, often over relatively short distances

- values are directional, reflecting heterogeneities & anisotropy (K_h ~ 10X greater than k_v)

- values are scale dependent (a m^3 of aquifer will usually produce different results than a similar test on a cm^3 of aquifer material)

- values determined by field pumping tests, lab column tests, or grain size analysis (or estimated based on published values of similar aquifer materials)

Hydraulic properties of interest:

- <u>specific capacity, S_c</u>

$$S_c = Q / (h_0 - h)$$

- yield / drawdown (typical units are gallons/min/ft of drawdown)

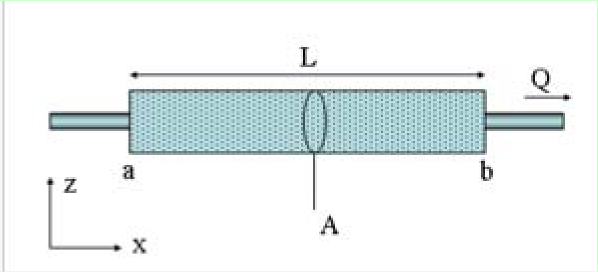
- an expression of the productivity of a well

- generally decreases with time as drawdown increases; S_c is a function of the pumping rate at which it is determined

- due to well losses, the drawdown will be greater at higher pumping rates than it is at lower pumping rates (this makes it difficult to compare regional S_c's, but it *is* useful for comparing the efficiency of the same well through time (e.g., to see if the well requires rehabilitation).

Darcy’s Law: the basis for hydraulic test analysis

$$Q = K * A * dh/dl$$

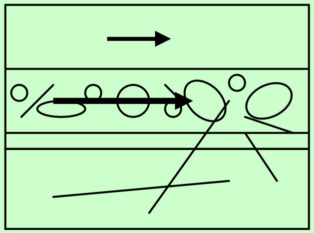


What Darcy’s Law tells us: if there is a head gradient, flow occurs; the greater the head gradient, the greater the flow; the discharge rate will be different in different media even if the head gradient is the same in both cases

- wells fully penetrate tested aquifer
- aquifer is homogeneous and isotropic
- aquifer exhibits radial symmetry (T and S do not depend on the direction of flow in the aquifer)
- aquifer is bounded on the bottom by a confining layer
- the formation is horizontal and of infinite extent
- ground water flow is horizontal
- potentiometric surface is horizontal and unchanging prior to pumping
- pumping well has an infinitesimal diameter and is 100% efficient
- other assumptions must be met for special cases/solutions (leaky confining units, leaky confined partial penetration, fractured aquifer,…).

Is the tested aquifer an "idealized" system?

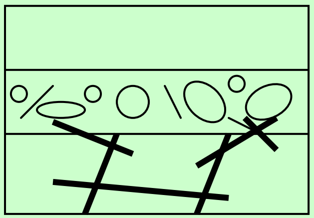
3 flow zones:



saprolite

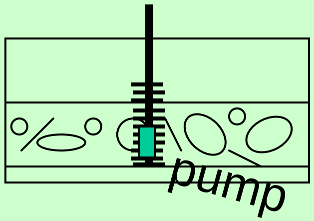
transition zone

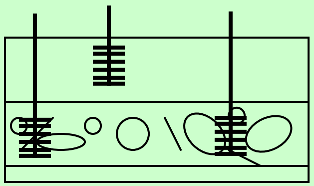
fractured rock



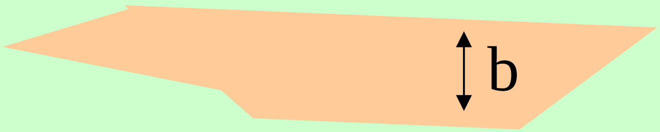
the bottom of the regolith is not impermeable

does depth interval of pumping well span more than one flow system?





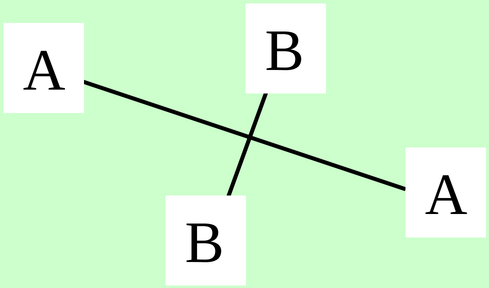
are the observation wells screened in more than one flow zone? (saprolite and TZ)



aquifer system (saprolite and TZ) is usually not of uniform thickness

+ / -

boundaries include nearby streams, underlying fractures, and change in rock type



anisotropy is likely

To approximate assumptions,

1) Use fully penetrating wells

2) Ensure proper spacing (not too close to pumping well to avoid vertical stratification and related issues….not too far from pumping well to avoid extra long test)

3) Use two perpendicular transects if possible

4) Use large enough pumping well diameter (to obtain adequate discharge) but small diameter observation wells

5) Others….

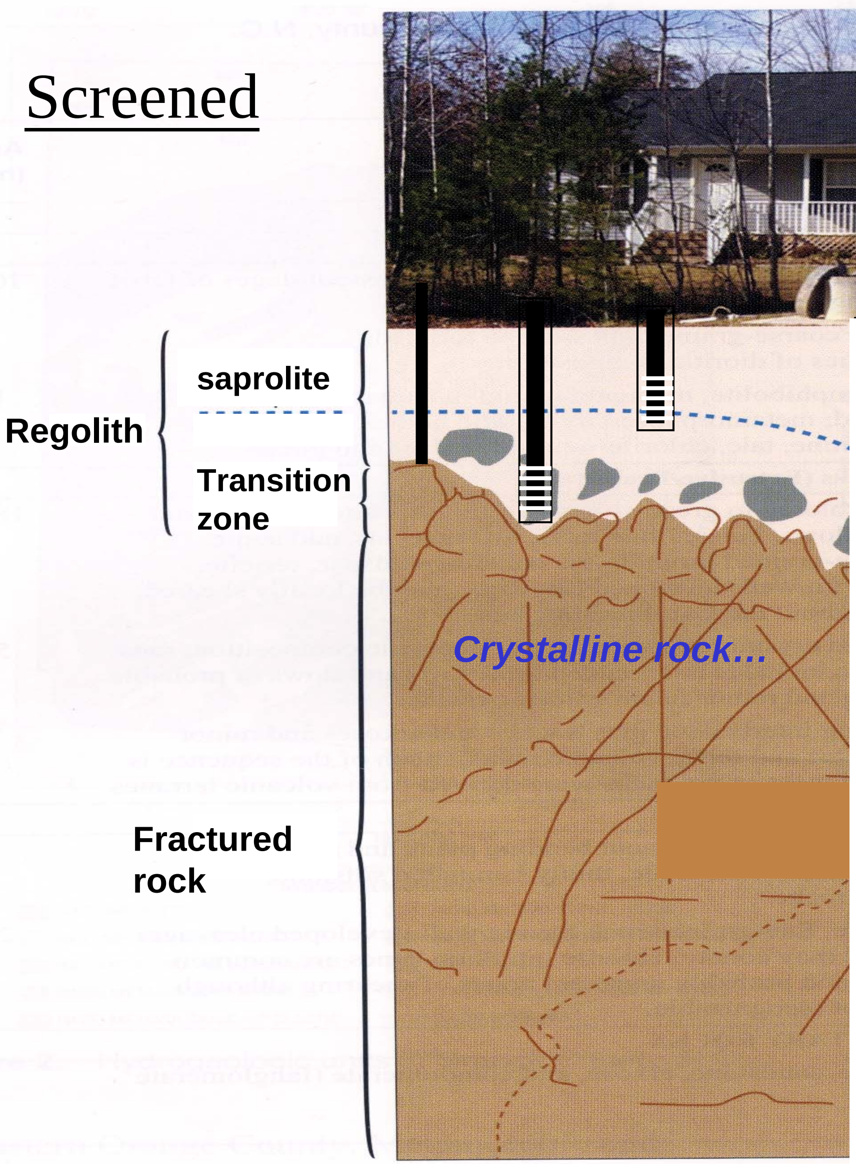
WELL INSTALLATION

Well Construction

two types of wells

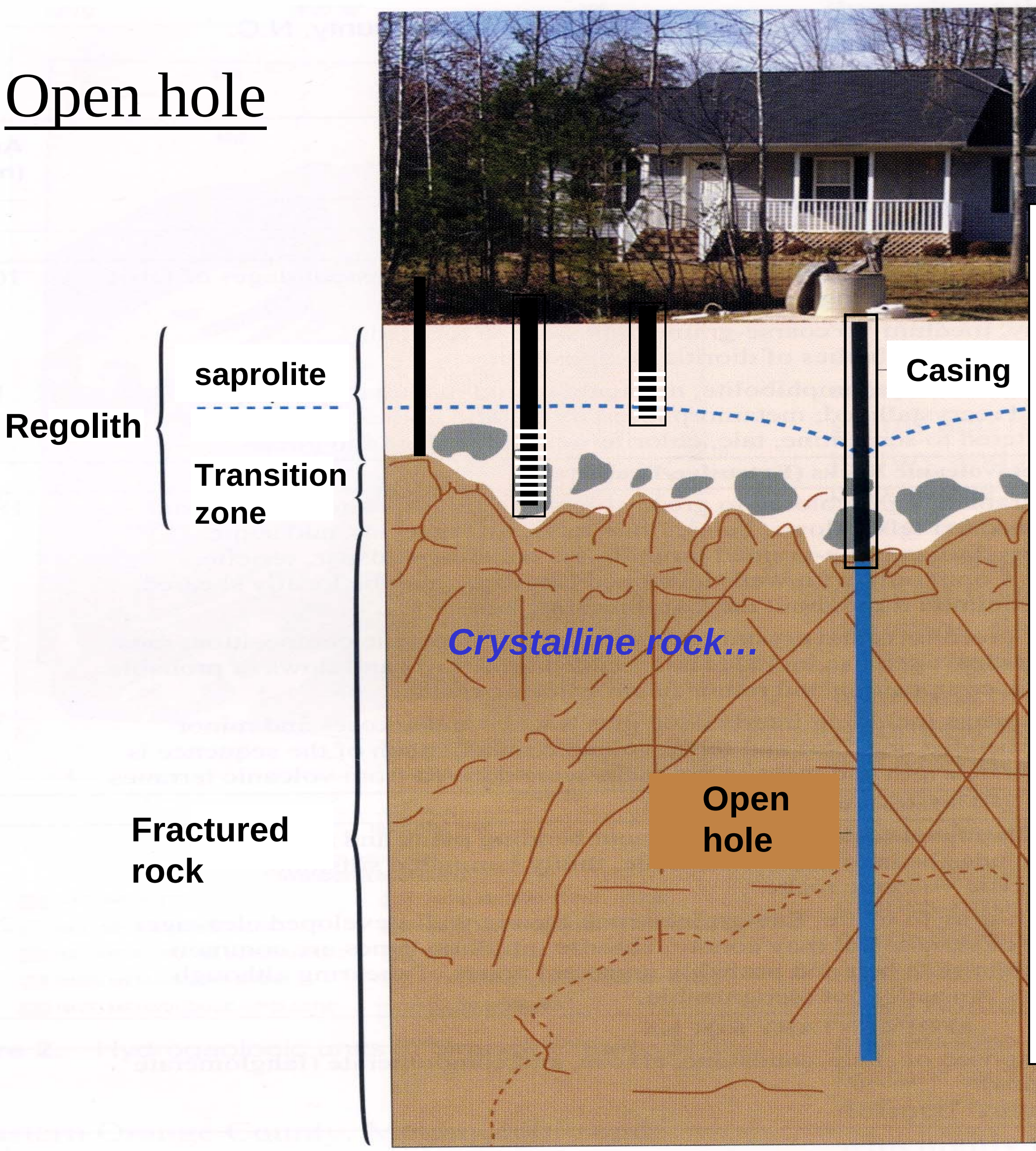
- screened
- open hole

Screened



- shallow (saprolite, if applicable) screened across water table
- intermediate screened across transition zone at top of bedrock
- discovered 4” PVC is more cost effective in long run; use 2” piezometers for observation only
- discovered that stainless steel centralizers helped improve quality of well and samples (helped make a better filter pack and reduced turbidity)
- we do not run sieve analyses to determine soil size and needed screen size openings and filter pack material (no adverse effects noted)
- we use bentonite pellets for seal (no adverse effects noted)

Open hole



- bedrock wells are 6 inch diameter; 150 to 600 ft deep
- depths based on core logs, dip angles, encountered fractures, rig capability
- care must be taken when determining “top” of competent bedrock
- cement used to seal and grout casing (some problems with high pH, Ca, Na, Mg, Cl, SO4), so we have limited its use
- started off using PVC casing but wells were not sealing properly
- switched to galvanized steel casing (can contribute small amount of Fe and Zn to water column but better than seapage from regolith
- stainless steel is too expensive

CONDUCTING THE TEST

We use 3 types of aquifer tests to determine hydraulic properties:

“stress the aquifer and observe changes in water levels with time”

1) slug - drawdown vs time in immediate vicinity of borehole; useful in regolith wells, but probably not reliable for fractured rock wells)

- slug tests use a “slug” to displace a known volume of water…time history of water level recovery to the static water level is monitored. Cooper and others (1967) and other modified solutions plot h/h_0 vs log time…data curve is matched to a dimensionless type curve to obtain K estimate….usually repeated several times…probably not appropriate for fractured rock wells….representative of area in immediate vicinity of well bore

2) single well (also known as step-drawdown) - measure discharge vs drawdown to estimate specific capacity, well efficiency)

- single well tests are useful for estimating properties in the near-hole environment, but the accuracy is impacted by improper borehole construction, convergence of flow lines and related head losses as water flows through perforated casing, and head loss as water moves between the test interval depth and the pump intake depth. Thus, T’s derived from single well tests tend to be lower than those of multiple well tests in the same area. S can be estimated, but results may vary up to an order of magnitude from the actual value (Cooper and others, 1967).

3) multi-well (also known as constant discharge) - measure drawdown vs time or drawdown vs distance

- water is obtained from borehole first (pumping well only), then from elastic storage (water expansion and pore space reduction), then from storage released by gravity drainage (specific yield)….confined aquifers or aquifers with low S have relatively large areas affected by pumping….if recharge does not occur (or a recharge boundary is not encountered) the area of drawdown of the potentiometric surface (cone of depression) will expand indefinitely as pumping continues.

- we can compute the decline in water level or drawdown around a pumping well if we know the hydraulic properties of the aquifer.

- we can also compute the hydraulic properties of an aquifer by performing an aquifer test in which a well is pumped at a constant rate and either the stabilized drawdown or the change in drawdown over time is measured.

- basic assumptions are inherent in these computations, some of which are not met in fractured rock media.

Planning and conducting the test:

- measure heads in all observation wells ~ 24 to 48 hrs prior to starting pump, to determine regional, climatic trend
- hold Q constant (within ~ +/- 3%)…"dial in" the selected flow rate the day before the actual test….usually easier to regulate flow using a valve rather than the pump control…use an in-line flow meter and totalizer
- channel the discharged water far away from all observation wells
- take readings for 1/10th the elapsed time (every 6 sec for 1st min, every 1 min for 10 min, every 10 min for 1 hr, every hr for 10 hrs…)
- plot well locations on large-scale topographic map prior to test….look for evidence of recharging or impermeable boundaries or other conditions that could affect the test
- review well construction records, core, boring logs and prepare a cross section of lithology and position of screened/open intervals of all wells (look for partial penetration)

Planning and conducting the test: (continued)

- review an arithmetic plot of the pumping rate to determine if Q was constant and, if not, the magnitude and time of occurrence of variations

- review an arithmetic plot of water level data for one or more observation wells to determine whether the drawdown measurements must be corrected for regional trend

Planning and conducting the test:

lowering pump into well…

Planning and conducting the test:

instrumenting an observation well…

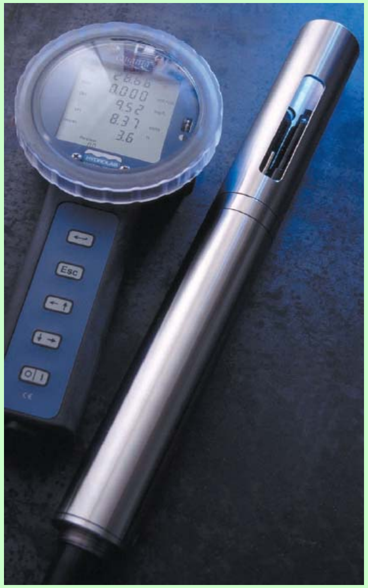
Planning and conducting the test:

connecting data logger to transducers and laptop…

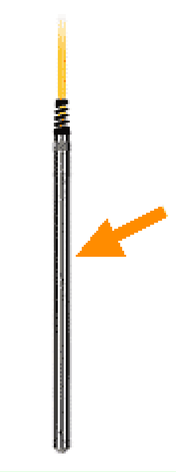
Equipment used for aquifer test:

In-Situ Brand Hermit 3000
with 8 pressure transducers

Hydrolab Brand
Model Quanta G



In Situ Brand
MiniTroll



Solnist water
level meter

Equipment used for aquifer test:

Trailer-mounted diesel generator

ANALYZING THE TEST DATA

Data obtained:

Drawdown vs time (pumping well or pumping well + 1 observation well)

Drawdown vs distance (pumping well + 2 observation wells)

Applying Darcy's Law:

Confined flow

- discharged water is obtained from elastic storage (expansion of water and contraction of pores)

- Theis solved for confined flow in 1935:
    - aquifer is confined on top and bottom
    - no source of recharge to the aquifer
    - aquifer is compressible and water is released instantaneously from the aquifer as head is lowered
    - well is pumped at constant rate

- "Well function" (W(u)) was derived and became the basis for analytical solution/curve fitting

$$h_0 - h = [Q / (4 \pi T)] \; [W(u)]$$

Applying Darcy's Law (continued):

Unconfined flow

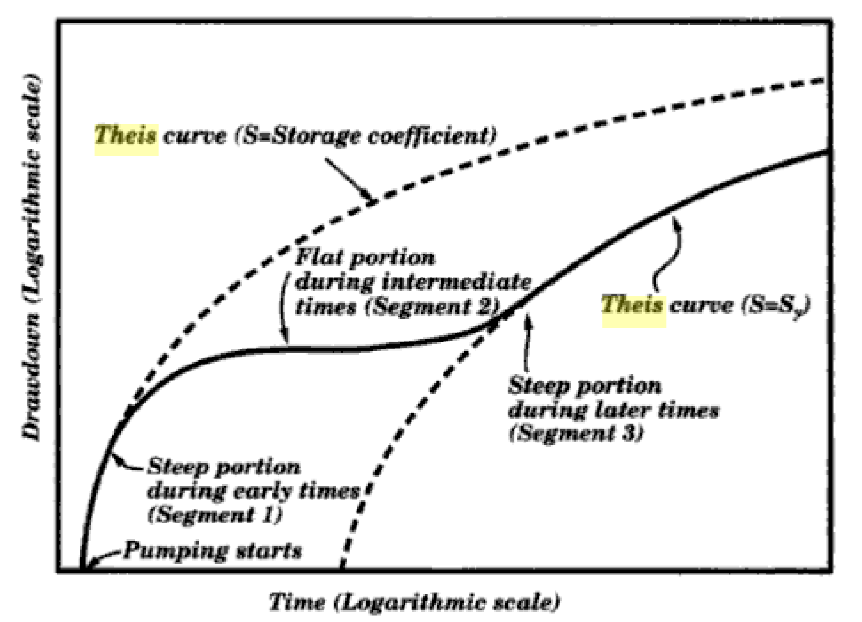
- 1st stage: discharged water is obtained from elastic storage (expansion of water and contraction of pores)
  - time-drawdown follows Theis nonequilibrium curve for $S_{elastic}$
  - flow is horizontal and is being derived from entire aquifer thickness

- 2nd stage: water table begins to decline
  - water is from gravity drainage
  - horizontal and vertical flow components
  - time-drawdown is a function of K_v:K_h, distance from pumping well, and aquifer thickness

- 3rd stage: rate of drawdown decreases
  - flow is essentially horizontal again
  - time-drawdown is a function of K_v:K_h, distance from pumping well, and aquifer thickness
  - S ~ specific yield now

Applying Darcy's Law (continued):

Unconfined flow

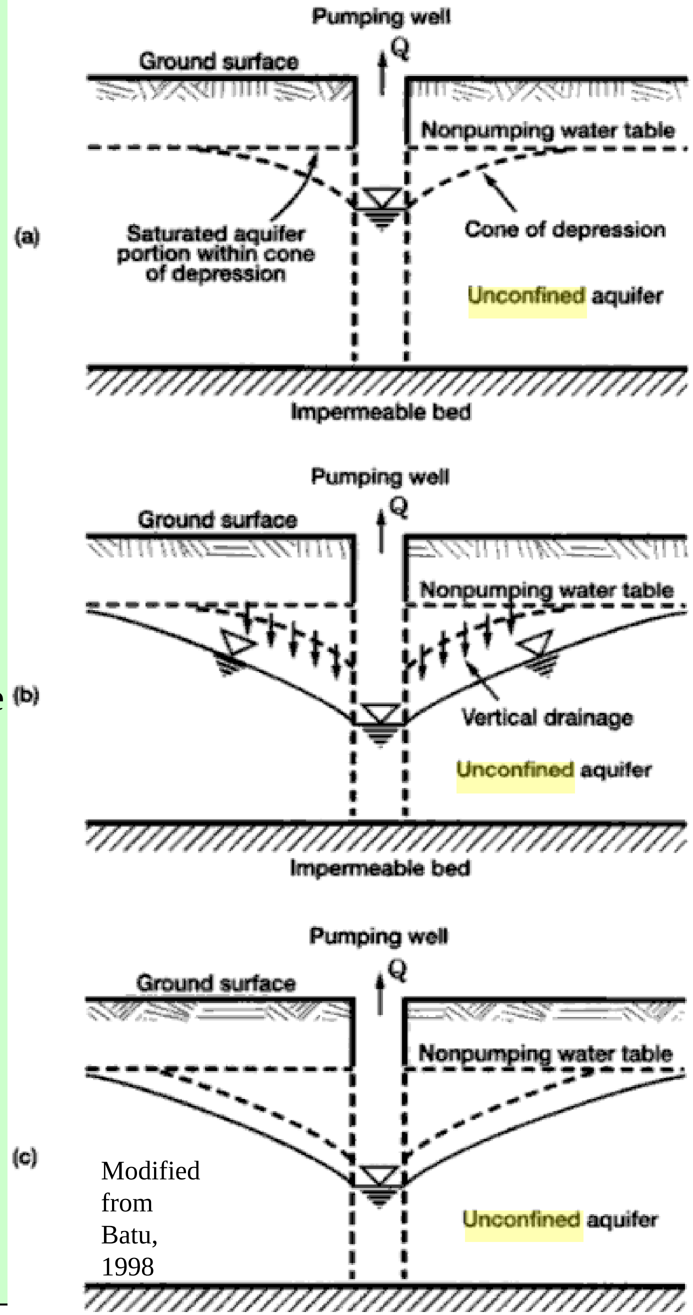


Delayed response of drawdown in unconfined aquifer

Initial cone of depression

Gravity drainage of the initial cone of depression

Cone of depression under steady state conditions



Modified from Batu, 1998

Applying Darcy’s Law (continued):

Using “curve fitting” to determine aquifer properties:

- choose solution/method – note assumptions inherent in selected solution

- theoretical solutions to aquifer test problems are represented as dimensionless curves

- water level drawdowns vs time (log-log) are plotted and matched to dimensionless type curves

- match point values are substituted into analytical equations to yield hydraulic property values

- various solutions: Theis, Cooper-Jacob, Hantush, Neuman… depends on aquifer and well configuration (confined/unconfined, leaky, partially penetrating, …)

Common curve fitting solution methods include Theis, Cooper-Jacob straight line, and others:

Theis (1935) – additional assumptions:

- well discharge is at a constant rate
- ground water flow is horizontal and unsteady
- discharge is derived exclusively from storage in the aquifer (no recharge boundaries)
- see Hantush adaptation (1961) for partially penetrating wells
- aquifer is fully confined
  + Jacob (1944) indicates that Theis can be applied to unconfined aquifers if drawdown is small compared with aquifer's original saturated thickness; reference: Jacob, C.E., 1944, Notes on determining permeability by pumping tests under water table conditions, USGS Open File Report, in USGS Water Supply Paper 1536-1, 1963, pp. 245-271.

  + Kruseman and deRidder (1990) indicates that unconfined conditions are applicable to late-time drawdown data and where delayed yield effects are minimal

- reference: Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground water storage, Trans Amer Geophys Union, Vol 16, pp. 519-524.

Common curve fitting solution methods include Theis, Cooper-Jacob straight line, and others:

Cooper and Jacob (1946) – additional assumptions:

- well discharge is at a constant rate
- ground water flow is horizontal and unsteady
- discharge is derived exclusively from storage in the aquifer (no recharge boundaries)
- aquifer is fully confined
    + solution may be applied to unconfined aquifers if drawdown is small compared with aquifer's original saturated thickness and there is delayed yield is minimal
- valid for non-steady state, steady shape conditions (for unconfined aquifers, use late time data prior to recharge boundary)
- observation wells should be on a single transect; distance drawdown data plotted semi-log
- reference: Cooper, H.H. and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well field history, Am Geophys Union Trans, vol 27, pp. 526-534.
- reference: Jacob, C.E., 1963, Determining the permeability of water-table aquifers, in Bentall, R., compiler, Methods of determining permeability, transmissibility, and drawdown: USGS Water Supply Paper 1536-1, p. 245-271.

- Moench (1984) developed dual porosity solution for fractured rock

Moench (1984) – additional assumptions:

- well discharge is at a constant rate

- fractured aquifer is represented as a double porosity system consisting of low permeability, primary porosity blocks and high permeability, secondary porosity fissures

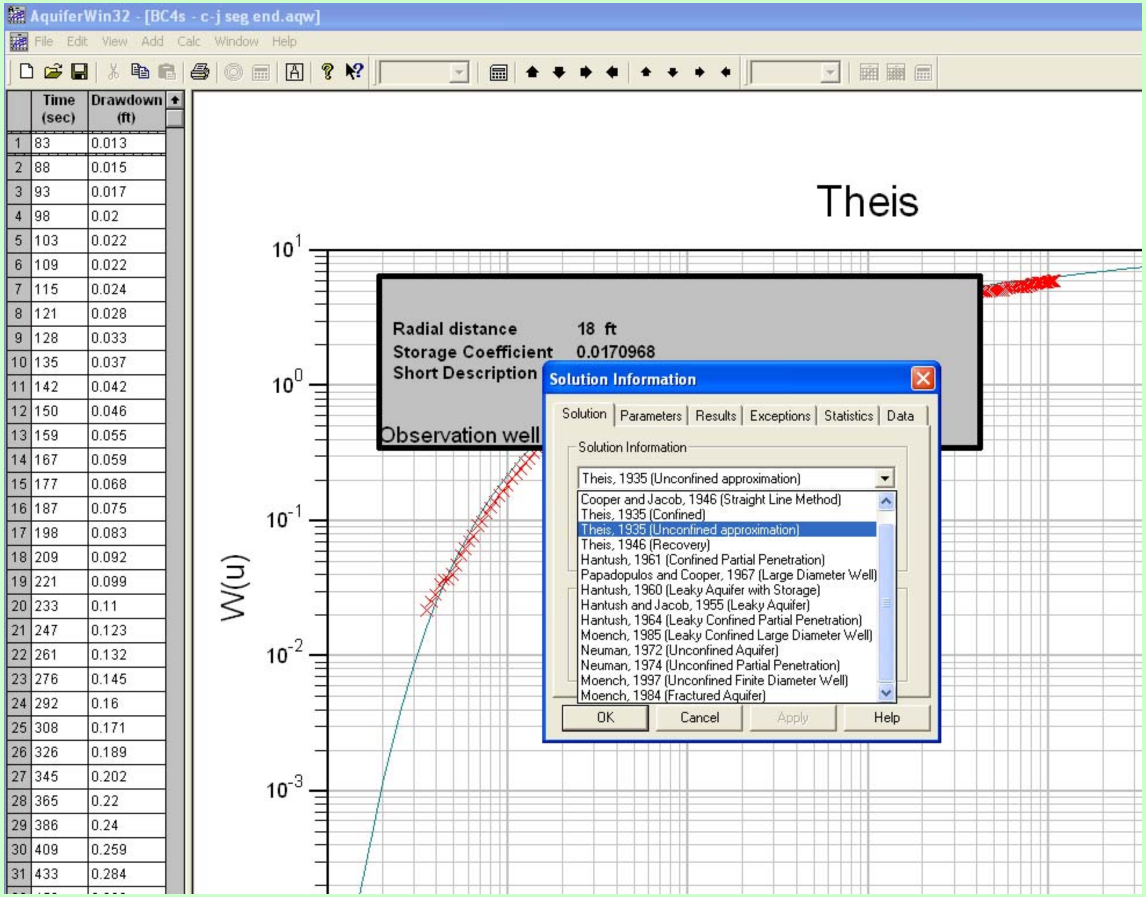
- fractured aquifer matrix consists of slab or spherical blocks

- very complicated solution involving many parameters; reasonable initial parameter estimates are crucial to avoid an unstable solution

- reference: Moench, A.F. Double-porosity models for fissured ground water reservoir with fracture skin, Water Resources Research, vol. 20, no. 7, pp. 831-846.

Software automates the curve fitting process

- AquiferWin32



Software automates the curve fitting process

- USGS spreadsheets – free, downloadable at http://pubs.usgs.gov/of/2002/ofr02197/

USGS
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Open-File Report 02-197

Spreadsheets for the Analysis of Aquifer-Test and Slug-Test Data, Version 1.2

By Keith J. Halford and Eve L. Kuniansky

Preface

This report documents several spreadsheets that have been developed for the analysis of aquifer-pumping test and slug-test data. Each spreadsheet incorporates analytical solution(s) of the partial differential equation for ground-water flow to a well for a specific type of condition or aquifer. The spreadsheets were written in Microsoft Excel version 9.0. Use of trade names does not constitute endorsement by the U.S. Geological Survey (USGS). The spreadsheets have been tested for accuracy using datasets from different aquifer tests or generated from the analytical solution. If users find or suspect errors with these spreadsheets, please contact the USGS.

Every effort has been made by the USGS or the United States Government to ensure the spreadsheets are error free. Despite our best efforts, the possibility exists that there are errors in the spreadsheets. The distribution of the spreadsheets does not constitute any warranty by the USGS, and no responsibility is assumed by the USGS in connection therewith.

versions — View the Version History for this report.

pdf — Download the PDF version of the documentation for high-resolution, printable pages (1,844 K). Best viewed with Microsoft Internet Explorer.

spreadsheets — Download the individual Microsoft Excel spreadsheets.

zip — Download a zip file that contains the documentation and all spreadsheets (2,499 K).

FAQs — Get the answers to Frequently Asked Questions.

Data analysis:

Compute T, S, K, predicted drawdowns…

Observe recharge boundaries

Evaluate where discharge water is coming from

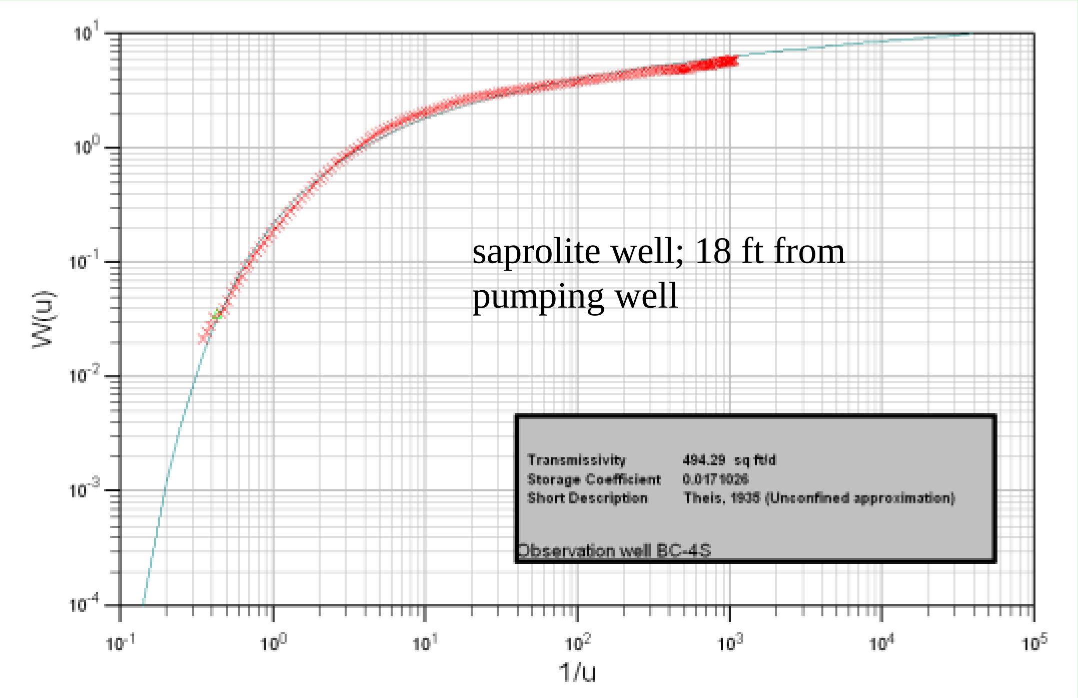
Observe impermeable boundaries

Evaluate influence, degree, and direction of anisotropy and heterogeneity

Example curve fit in Piedmont-Mountains regolith (well foliated mica schist, layer parallel partings)

pumped transition zone well 4I at 20 gpm for 72 hrs, Bent Creek (schist)

Observation well 4S

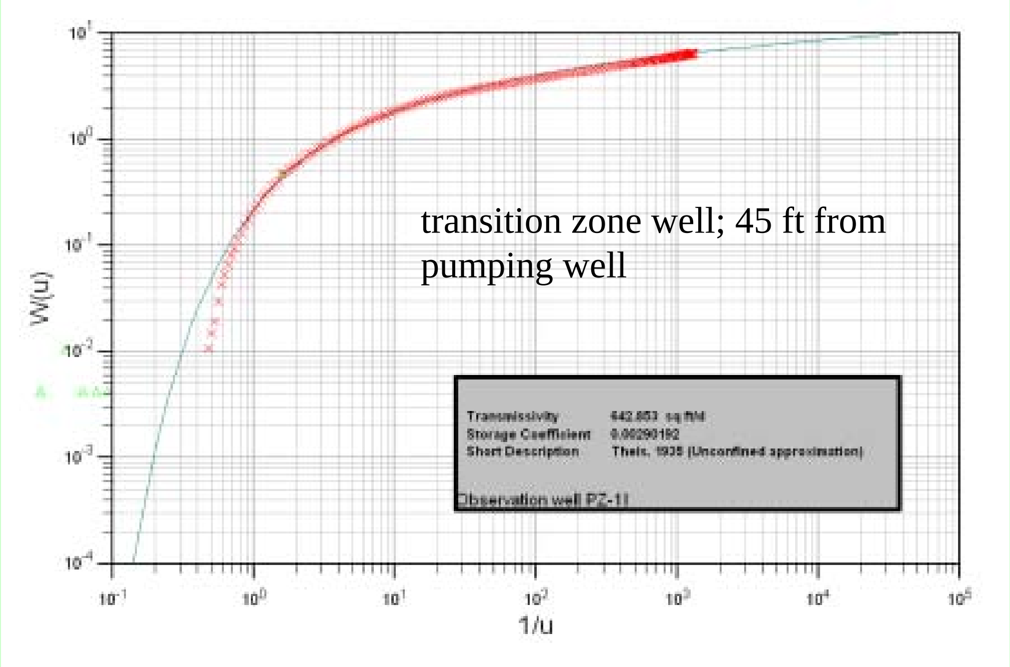


modified Theis, 1935

Example curve fit in Piedmont-Mountains regolith (well foliated mica schist, layer parallel partings)

Observation well 1I

pumped transition zone well 4I at 20 gpm for 72 hrs, Bent Creek (schist)



modified Theis, 1935

Example curve fit in Piedmont-Mountains regolith (well foliated mica schist, layer parallel partings)

Observation well 1I

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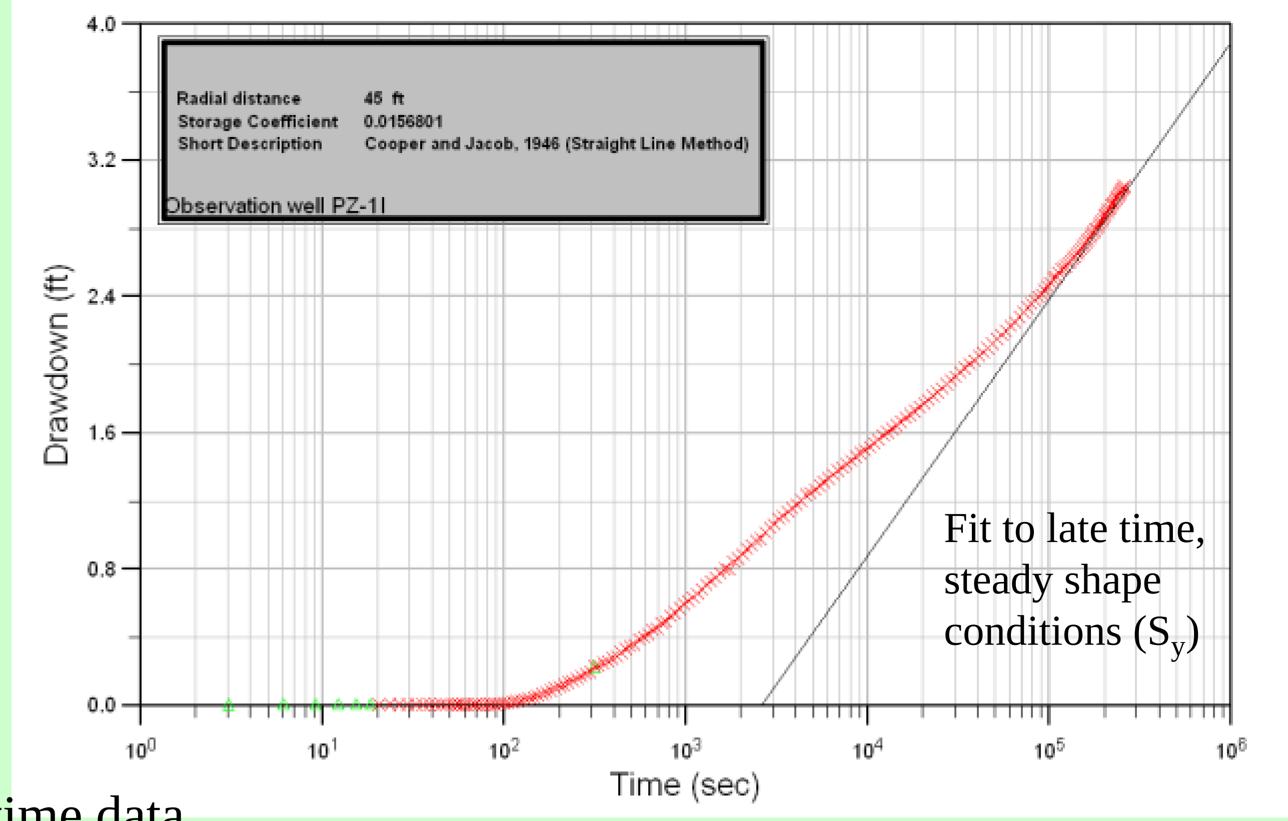


Fit to late time, steady shape conditions (S_y)

Cooper and Jacob, 1946

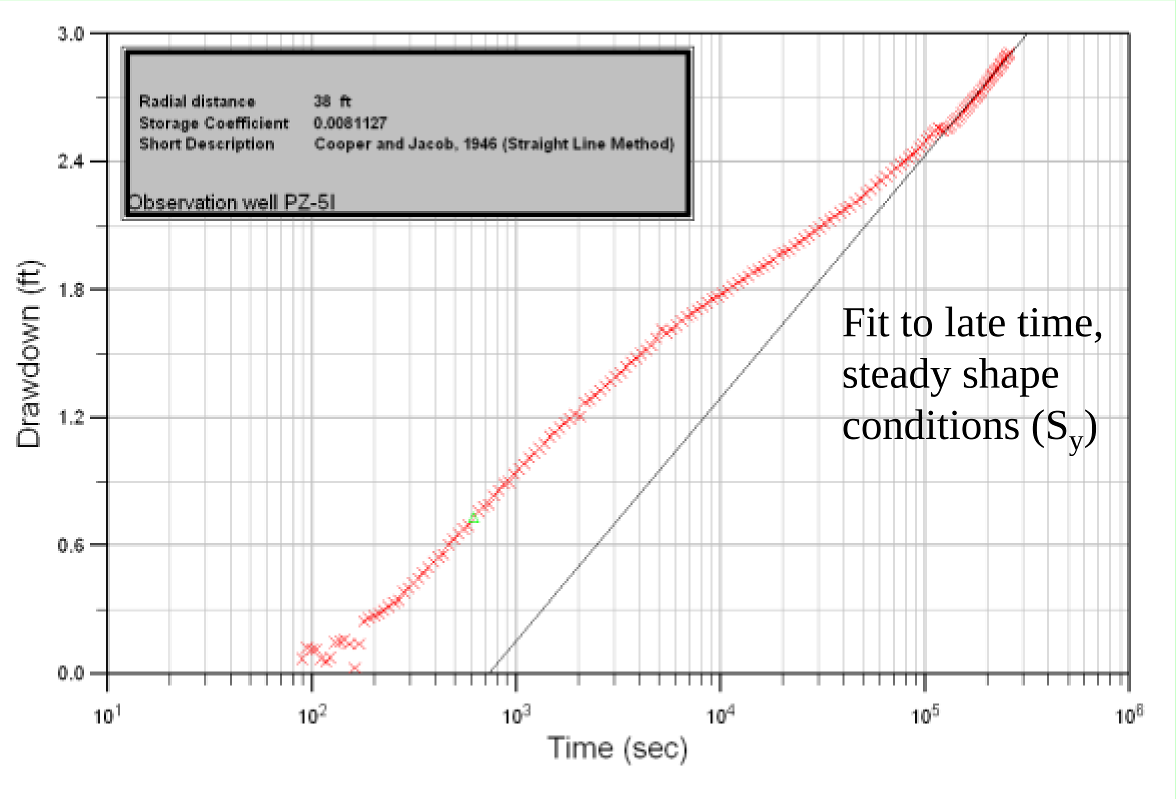
Key point: Use late time data after partial penetration and potential confined effects have passed…

t = 7200 * r2 * S / T

Example curve fit in Piedmont-Mountains regolith (well foliated mica schist, layer parallel partings)

Observation well 5I

pumped transition zone well 4I at 20 gpm for 72 hrs, Bent Creek (schist)



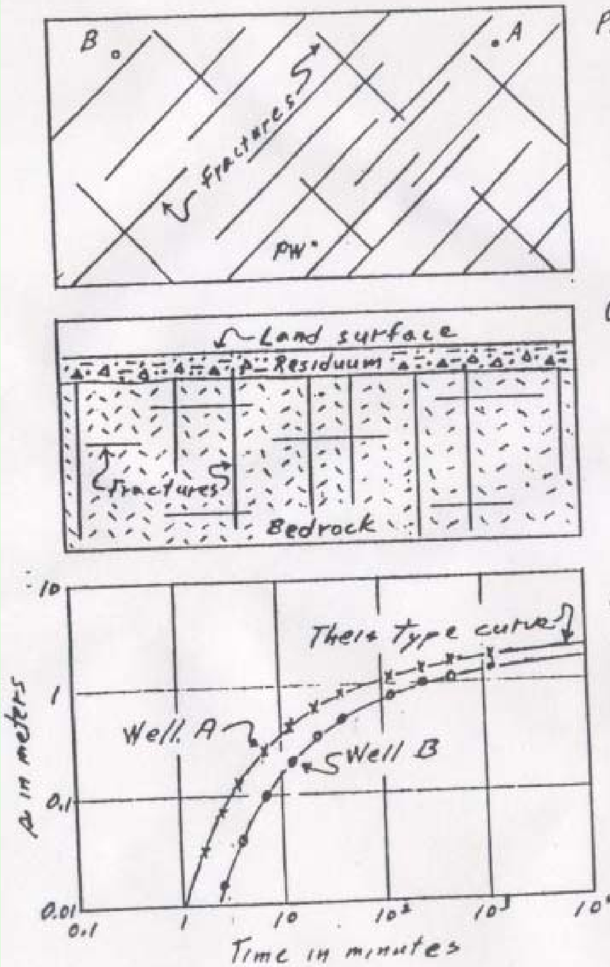
Cooper and Jacob, 1946

Key point: Use late time data after partial penetration and potential confined effects have passed…

t = 7200 * r2 * S / T

Reference: Departures from Theis curve (from Fundamentals and Applied Ground Water Hydraulics short course, Heath R. and Spruill, R., 2004)

Figure 8.26. - Differences in response of observation wells caused by aquifer anisotropy.



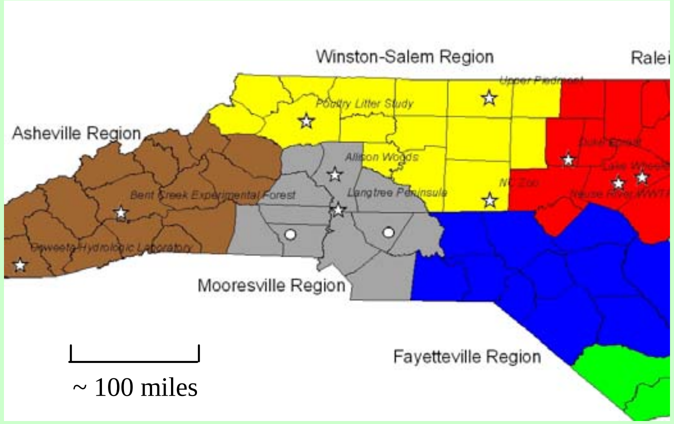
Plan view:
Observation wells A and B are equidistant from the pumping well (PW). Well A is located along the trend of the dominant set of vertical fractures when viewed from the pumping well. Well B is perpendicular to the dominant set and parallel to the secondary set.

Cross section:
The line of the cross section is along the lower edge of the plan view. The bedrock that underlies the area is overlain by a layer of weathered rock.

The vertical fractures "die out" at depth and are crossed by horizontal fractures that are most abundant near the land surface.

Data plot:
The transmissivity is largest parallel to the principal set of fractures (i.e. in the direction from the pumping well to well A). Consequently, measureable drawdown occurred first in well A and drawdowns in well A exceeded those in well B throughout the test.

RESULTS FROM PIEDMONT-MOUNTAIN RESEARCH STATIONS



Results from Piedmont-Mountains Research Stations

ALL TESTS -- Summary

• T's (bedrock) ranged from 30 to 4000 ft2/day, depending on fracture density, size, and connectivity

• cones of influence were ~ 200 to 900 ft in bedrock well tests (6 – 48 hr tests)

• 2 to 6 bedrock wells, 2 to 9 saprolite wells, and 2 to 8 TZ wells per test

• Q's were 5 to 20 gpm

• drawdowns in pumping wells from 15 to 150 ft

• analyses used Theis, Cooper and Jacob, and Bouwer and Rice solutions

• effective aquifer thickness estimates were subjective in some cases

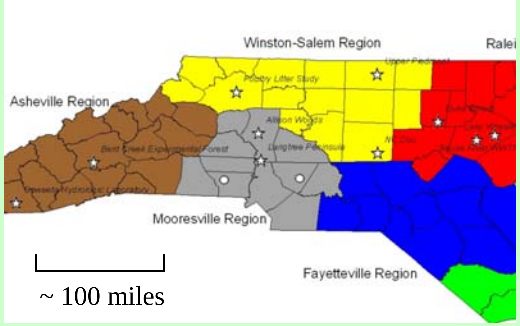
• pumped in fractured bedrock and observed drawdown in the regolith – analytical solutions and hydraulic property determinations are suspect

Results from Piedmont-Mountains Research Stations

			FRACTURED ROCK			REGOLITH				
Site	Rock type	Fracture type	T, ft^2/day	K, ft/day	S	T, ft^2/day	K, ft/day	S	relative connectivity among nearby bedrock wells	relative connectivity between bedrock and regolith
Lake Wheeler - 36 hr	felsic gneiss	E	~1300			~400			high	low
Raleigh WWTP - 48 hr	granite & diabase dike	E, J	~4000 [a]	~13		~200			low	low
Allison Woods - 24 hr	gneissic schist	E	~40	~0.1 to 1					high [b]	low
Allison Woods - 6 hr	gneissic schist	E	~250 [c]						high	low
Langtree - 48 hr	quartz diorite	E		2 [d]			2 [d]		high	low
NC Zoo - 19 hr	metavolcanic	SF, FP	~140	0.7					high	moderate (TZ only)
NC Zoo - 36 hr	metavolcanic	OJ	~30	0.4					high	moderate (TZ only)
Bent Creek - 72 hr	gneissic schist	FP		0.1		~640	~20 (TZ)	0.02		low

[a] pumped from a converted core hole so Q was insufficient for adequate drawdowns
[b] one exception (one deep well was not connected with pumping well)
[c] 250 ft^2/day at well adjacent to stream
[d] computed using Bower and rice, 1976

E - Exfoliation/sheet
J - Joint
S - Shear
FP - Foliation parting
OJ - Open joint

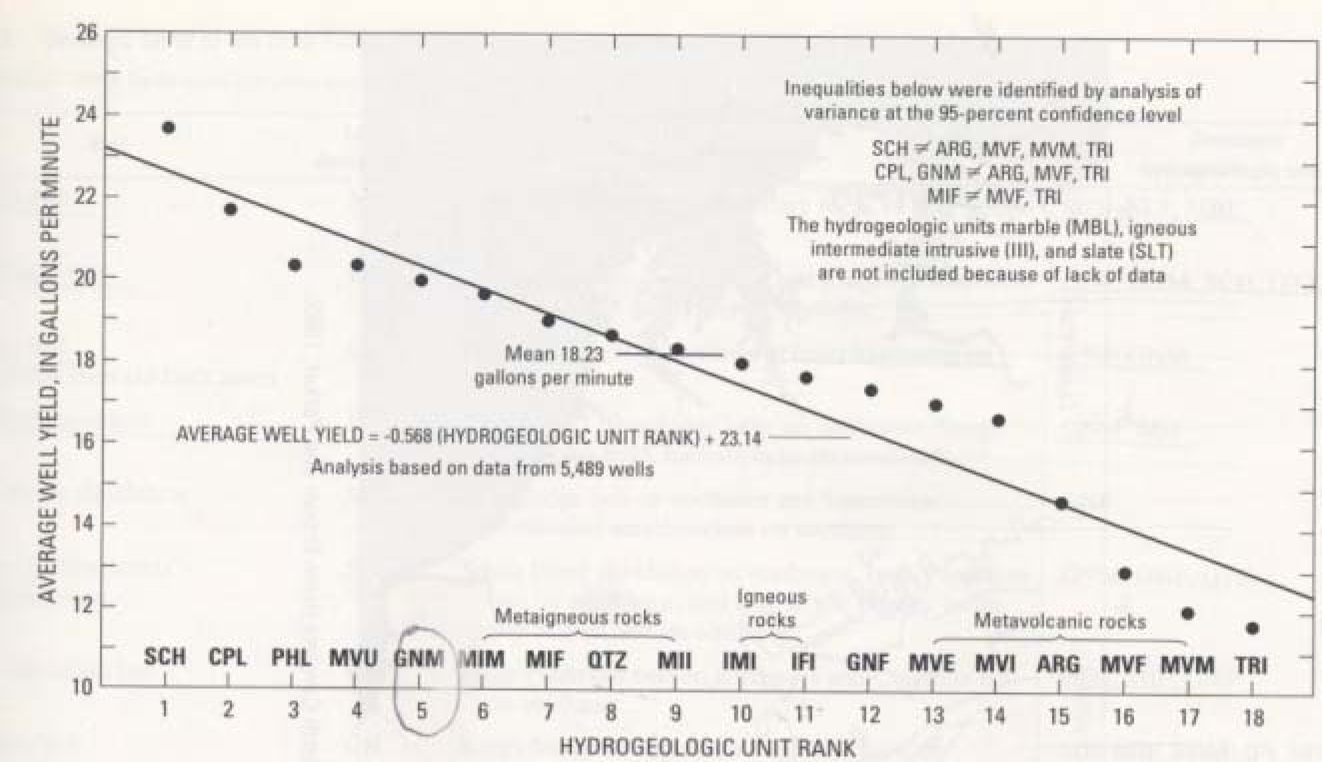


Site	# of deep wells	# shallow wells	# TZ wells	Pumping well to farthestmost observation well, in ft	Q, gpm	Max drawdown in pumping well, ft
Lake Wheeler - 36 hr	3	4	2	200	5	40
Raleigh WWTP - 48 hr	6	8	3	250	8	20
Allison Woods - 24 hr	4	4	4	900	18	46
Allison Woods - 6 hr	4	4	4		20	15
Langtree - 48 hr	5	5	5	1800	16	150
NC Zoo - 19 hr	3	3	2	71	9	130
NC Zoo - 36 hr	1	1	2	40	5	70
Bent Creek - 72 hr	3	9	8	1000	20	6

Relatively low variability of T and S obtained from aquifer test in regolith at Bent Creek (schist)

	Aquifer material	Transmissivity, ft2/day	Storage Coefficient
Well 4S	saprolite	494	0.09
Well P1S	saprolite	647	0.02
Well P1I	TZ	642	0.02
Well P5S	saprolite	640	0.02
Well P5I	TZ	694	0.008
Well P6S	saprolite	612	0.006
Well P6I	TZ	604	0.003
		median = 642	median = 0.02

Average well yield in hydrogeologic units of the Blue Ridge/Piedmont Provinces of NC (modified from Daniel, 1989 and Daniel and Dahlen, 2002)



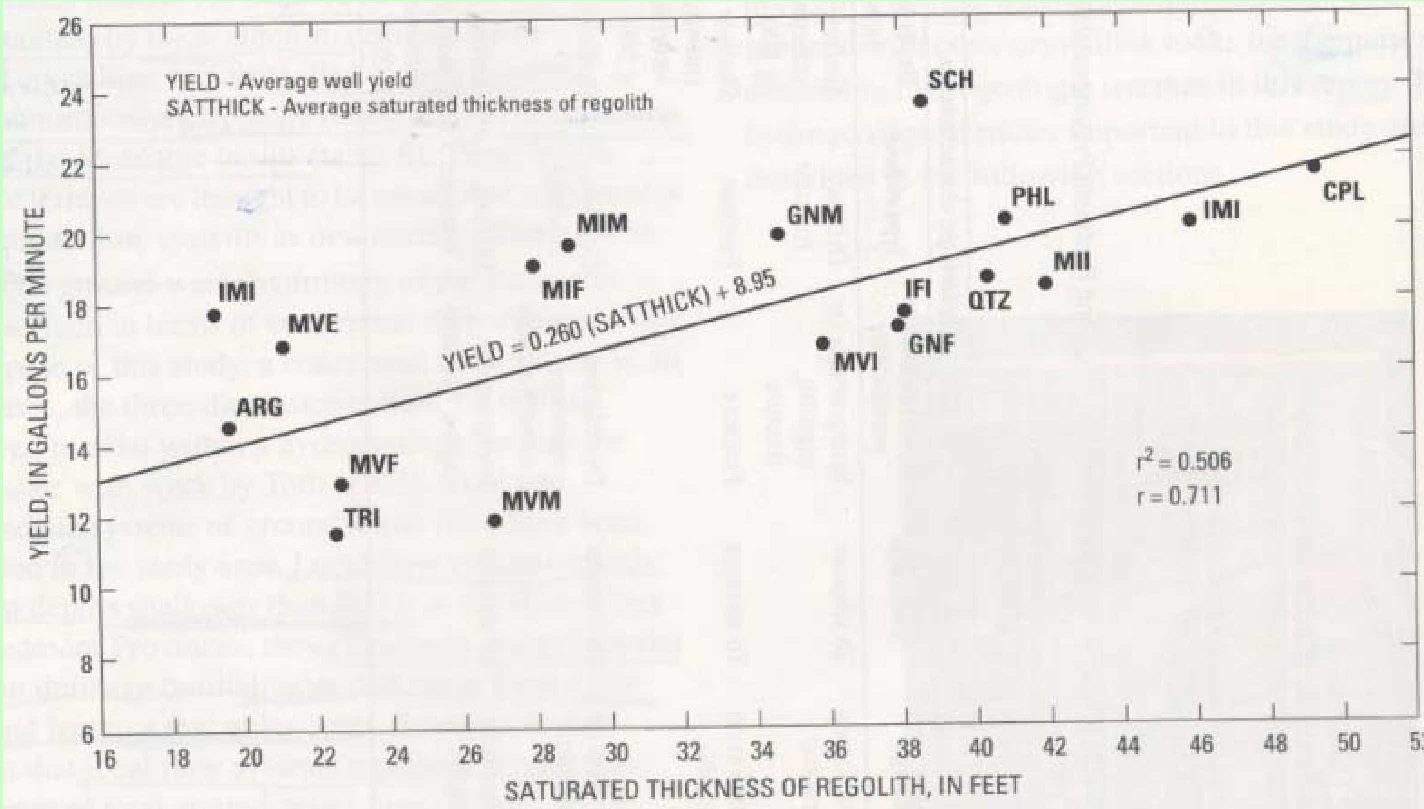
EXPLANATION

Rank	Symbol	Hydrogeologic unit[a]	Rank	Symbol	Hydrogeologic unit[a]
1	**SCH**	Schist	10	**IMI**	Igneous, mafic intrusive
2	**CPL**	Coastal Plain basement	11	**IFI**	Igneous, felsic intrusive
3	**PHL**	Phyllite	12	**GNF**	Gneiss, felsic
4	**MVU**	Metavolcanic, undifferentiated	13	**MVE**	Metavolcanic, epiclastic
5	**GNM**	Gneiss, mafic	14	**MVI**	Metavolcanic, intermediate
6	**MIM**	Metaigneous, mafic	15	**ARG**	Argillite
7	**MIF**	Metaigneous, felsic	16	**MVF**	Metavolcanic, felsic
8	**QTZ**	Quartzite	17	**MVM**	Metavolcanic, mafic
9	**MII**	Metaigneous, intermediate	18	**TRI**	Triassic sedimentary rocks

[a]Unit descriptions are given in table 1.

Modified from Daniel, 1989 and Daniel and Dahlen, 2002

Average well yield vs average saturated thickness of regolith for hydrogeologic units in the Blue Ridge/Piedmont of NC, modified from Daniel and Dahlen, 2002



EXPLANATION

Hydrogeologic unit[a] Symbol		Hydrogeologic unit[a] Symbol	
IMI	Igneous, mafic intrusive	MVI	Metavolcanic, intermediate
ARG	Argillite	GNF	Gneiss, felsic
MVE	Metavolcanic, epiclastic	IFI	Igneous, felsic intrusive
TRI	Triassic sedimentary rocks	SCH	Schist
MVF	Metavolcanic, felsic	QTZ	Quartzite
MVM	Metavolcanic, mafic	PHL	Phyllite
MIF	Metaigneous, felsic	MII	Metaigneous, intermediate
MIM	Metaigneous, mafic	MVU	Metavolcanic, undifferentiated
GNM	Gneiss, mafic	CPL	Coastal Plain basement

Special considerations when analyzing flow in fractured rock:

- fractured rock media is only marginally suited to analytical solutions derived from Darcy's law

  - Darcy's law based on uniform, porous media

  - $Q = \dfrac{-K A (H_0 - H)}{L}$

- dual porosity in fractured rock (dewatering of fractures first, then matrix) (Moench, 1984 uses derived type curves for dual porosity solutions that address this, but actual data do not always fit these curves.)

- hydraulic properties can vary due to inherent heterogeneities in the tested fractured rock system: 1) facies changes in sedimentary rocks, 2) welding in volcanic rocks, 3) variable fracturing and weathering over short distances, 4) observation wells that do not all penetrate the same rock fractures, particularly with steeply dipping fractures.

Special considerations when analyzing flow in fractured rock:

- an aquifer test can be affected by: 1) fracture spacing, size, and interconnectivity, 2) interconnectivity between fractures and regolith.

- longer term tests will produce more representative hydraulic property estimates (K and S) than shorter tests due to these aquifer heterogeneities.

- a comparison of S and T obtained in various observation wells and in the pumping well (T only) can reveal how homogeneous the aquifer is.

- test results from Piedmont-Mountains are reflective only of the location in which they were conducted due to variable lithology and rock discontinuities in a given rock type. (About 30 sample points in a given setting may be required to statistically describe such variability (Freund, 1992).)

Special considerations when analyzing flow in fractured rock:

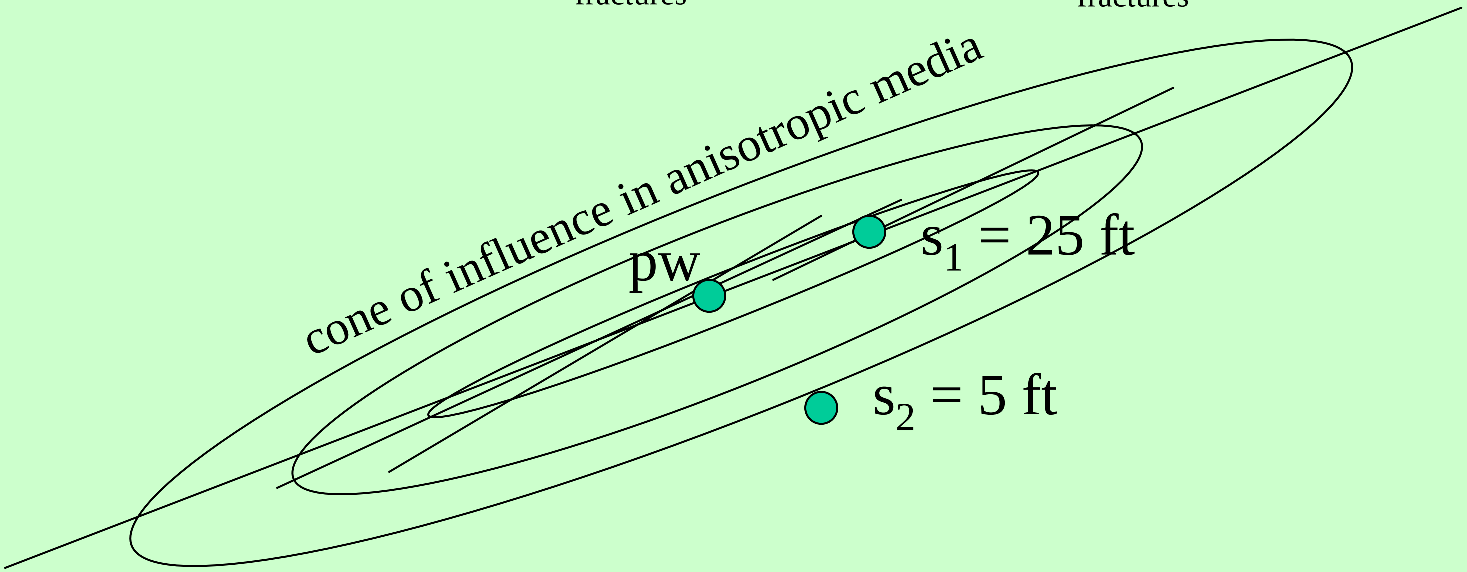
- estimates obtained rely on assumptions of aquifer type and configuration, which often are not understood completely. (The assumptions are necessary to simplify the flow system so that mathematical equations representing ground water flow can be solved analytically.) Thus, we end up with some uncertainty in the computed hydraulic properties.

- most solutions assume flow is from an aquifer of infinite extent, however this is typically not the case due to recharge or barrier boundaries. Variable results from different wells of the same test can be explained in part by these boundaries.

Special considerations when analyzing flow in fractured rock:

- care must be used when applying Theis to compute T in areas of anisotropic fracturing (predominant directional fracturing) because Theis tells us that T is an inverse function of drawdown, but we know that T should be *higher* along a predominant fracture where drawdown will be greatest.

granitic rock, Raleigh, NC: $T_{\text{with fractures}} = 260\ ft^2/day$ vs $T_{\text{against fractures}} = 7\ ft^2/day$



Special considerations when analyzing flow in fractured rock:

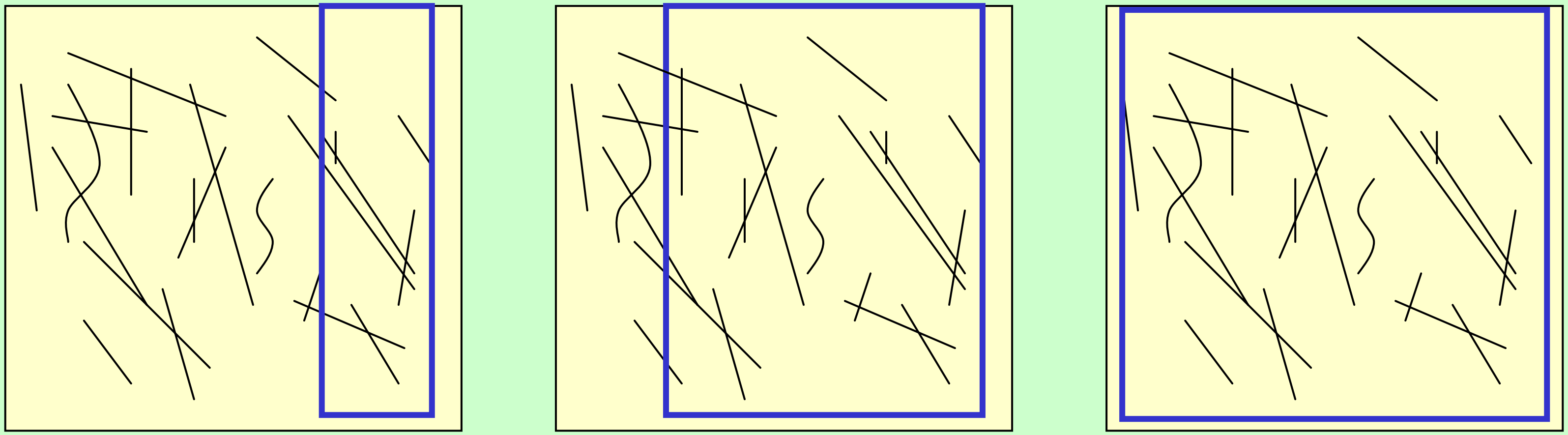
- current research on "equivalent porous medium" assumes that at sufficiently large scales, fractured rock can act as a porous matrix

  - T's should be higher in areas with tightly spaced, interconnected fractures

  - T's obtained using both porous and fractured media methods were within an order of magnitude (Shapiro and Hsieh, 1998)

  - drawdown curves from numerous fractured rock tests conformed to type curves derived for porous media (Belcher and others, 2001)

Consider scale and purpose of investigation: tens of feet…hundreds of feet….thousands of feet….miles…



SUMMARY AND LESSONS LEARNED

Summary and Lessons Learned:

- transmissivities ranged regionally from ~ 30 to 4000 ft^2/day; relatively low variability at a given site

- local, site, or map scale fracture characteristics are major control on well yield and transmissivity

- water released from fractured rock during pumping tests often was drawn from storage in regolith at distances greater than observed regolith wells (minimal drawdown observed in nearby regolith wells)

- anisotropy (dominant fracture, foliation orientation, changes in rock type, etc) can significantly affect overall test results; when possible, observe drawdowns along two perpendicular transects

- Cooper-Jacob Straight line method useful but must use late time, steady shape data

Summary and Lessons Learned:

• care must be taken when attempting to quantify T and S in *regolith* when pumping in underlying fractured rock

• fully penetrating observation wells are often optimal; partially penetrating wells must be used with caution (vertical flow may affect drawdown for a portion of the test)

• consider longer tests (> 48 hrs), depending on site characteristics and purpose of test (useful in observing boundary conditions)

• estimates of T and S can be *overestimated* if observation wells are not well connected to pumping well; analyze test data from multiple wells to increase confidence in final selected estimates

• a minimum of 2 observations wells will allow time drawdown <u>and</u> distance drawdown analyses of T and S, which can be used to cross check hydraulic property estimates obtained from each method

Summary and Lessons Learned:

- observation well spacing (~ 3 to 5X saturated thickness away from pumping well; usually 100 to 300 ft is a good distance) and screen construction (depth; span highest K zone) is important

- complex configuration and assumptions not met – “quantitative” results must be qualified

- like others, we are still learning how best to apply the Darcy theory to fractured rock aquifer tests.

- a significant amount of key information can be learned about storage, flow, boundaries, general behavior of system, predicted drawdowns, etc. We see this as one of the important components of our research work.

- we can learn much through mutual collaboration – sharing data sets, findings, approaches that work and that do not work, and conclusions. We look forward to working together as both projects move forward.

Additional findings in Piedmont/Mountains of NC

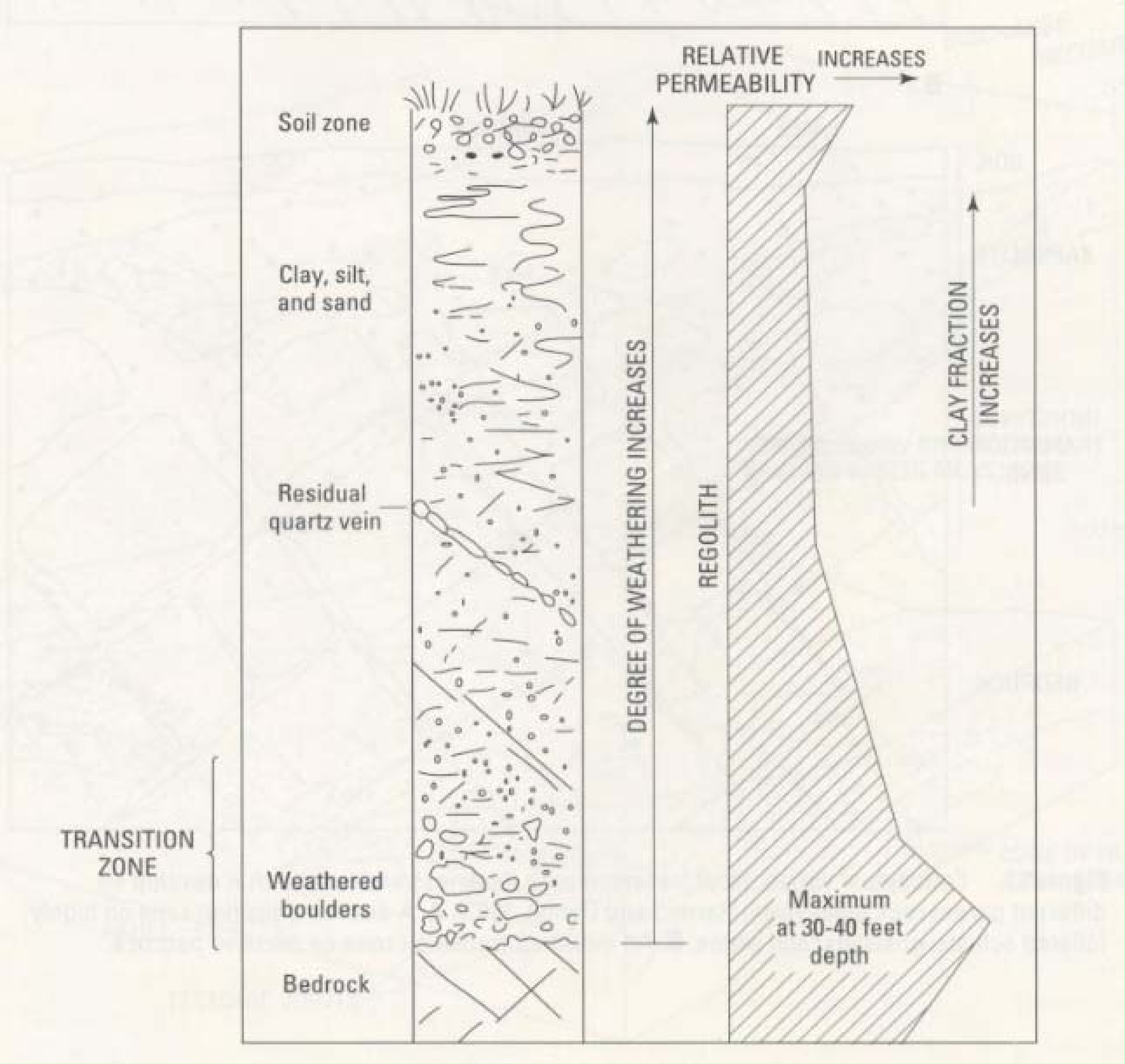
General hydrologic characteristics of the hydrogeologic terranes of the Blue Ridge/Piedmont Provinces within the Appalachian Valleys-Piedmont Regional Aquifer System Analysis study area, modified from Swain and others, 1991 and Daniel and Dahlen, 2002

Table 6. General hydrologic characteristics of the hydrogeologic terranes of the Blue Ridge and Piedmont Provinces within the Appalachian Valleys-Piedmont Regional Aquifer-System Analysis (APRASA) study area

[Modified from Swain and others, 1991; ≤, less than or equal to]

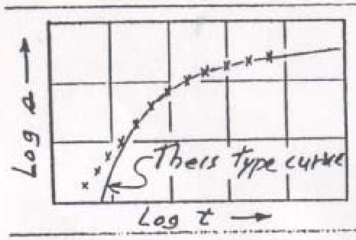
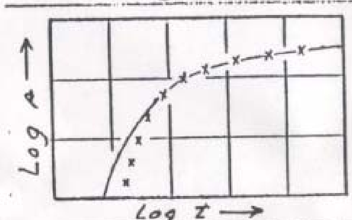
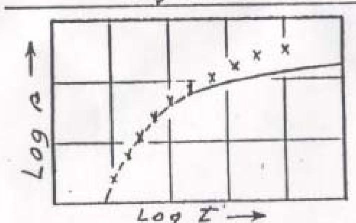
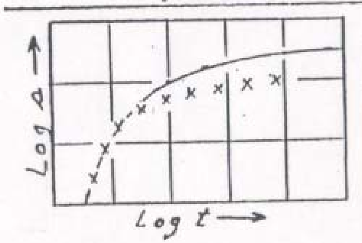
Hyrogeologic terrane	Hydrologic characteristics								
	Topographic relief	Recharge	Discharge	Type of porosity or permeability	Type of flow	Depth of flow, in feet	Confined or unconfined	Regolith storage	Well yield
Massive or foliated crystalline rocks, thick regolith	Low to high	Precipitation on topographic highs	To streams	Intergranular in regolith, fracture	Diffuse, fracture	Shallow to intermediate, ≤ 800	Mostly unconfined	Large	Proportional to regolith thickness.
Massive or foliated crystalline rocks, thin regolith	Low to high	Precipitation on topographic highs	To streams	Fracture	Fracture	Shallow (mostly) to intermediate, ≤ 500	Unconfined	Small	Low.
Metamorphosed carbonate rocks	Low to moderate	Precipitation on topographic highs	To streams	Dissolution openings, some fractures	Conduit, fracture	Shallow	Unconfined	Small to moderate	Variable, some very high.
Mesozoic sedimentary basins	Low to moderate	Precipitation on topographic highs	To streams	Intergranular, some fractures	Diffuse, fracture	Shallow (mostly) to intermediate, ≤ 800	Mostly unconfined	Small	Variable, decreasing from north to south.

An idealized weathering profile through the regolith, and relative permeability (modified from Nutter and Otton, 1969 and Daniel and Dahlen, 2002)



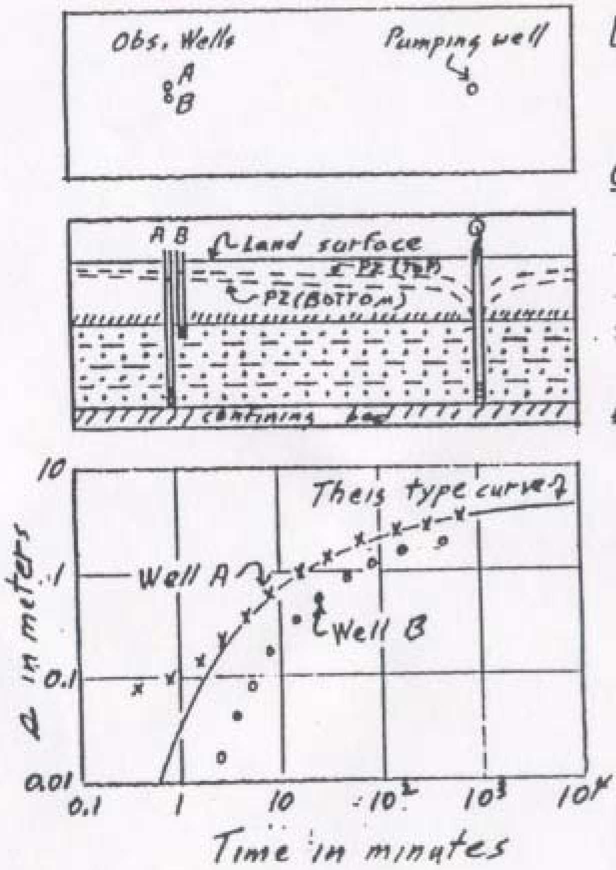
Reference: Departures from Theis curve (from Fundamentals and Applied Ground Water Hydraulics short course, Heath R. and Spruill, R., 2004)

Figure 8.23. - Departures of aquifer-test data from the Theis type curve.

Data plot	Nature of departure	Possible causes
	A. Early drawdowns plot above Theis type curve.	1. Stopwatch started late (i.e. recorded time less than actual time since t_o). 2. Initial pumping rate (Q) too large. 3. Aquifer is stratified, PW is partially penetrating, and OW is open to same zone as PW.
	B. Early drawdowns plot below Theis type curve.	1. Stopwatch started early (i.e. on standby signal). 2. Initial pump rate too low. 3. Diam. of PW is large in comparison to Q (i.e. Significant water released from storage in PW). 4. Observation well is "sluggish" (i.e. not freely connected to aquifer).
	C. Late drawdowns plot above Theis type curve.	1. Pumping rate increased during the test 2. Drawdowns not corr. for reg. decline in WL. 3. A distant pumping well was turned on. 4. Test affected by impermeable boundary. 5. Aquifer receiving leakage from stor. in conf. bed.
	D. Late drawdowns plot below Theis type curve.	1. Pumping rate decreased during the test. 2. Drawdowns not corr. for reg. rise in WL. 3. A distant pumping well was turned off. 4. Test affected by recharging boundary. 5. Aquifer in transition from conf. to unconf. cond. 6. Aquifer receiving leakage thru incompressible confining bed. 7. Drawdowns have reached an area where the aquifer is unconfined (i.e. S has increased).

Reference: Departures from Theis curve (from Fundamentals and Applied Ground Water Hydraulics short course, Heath R. and Spruill, R., 2004)

Figure 8.24. - Differences in the response of observation wells caused by aquifer stratification and partial penetration of the pumping well and observation wells.



Plan view:
Observation wells A and B are at the same distance from the pumping well.

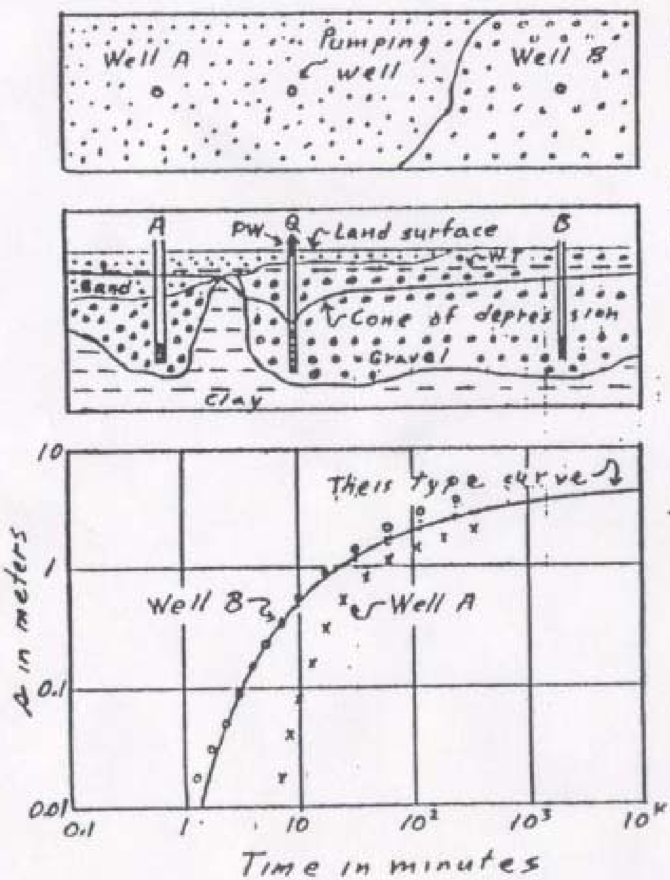
Cross section:
The aquifer is confined and horizontally stratified. The pumping well is screened in the lower part of the aquifer. Well A is screened in the lower part and well B is screened in the upper part.

Data plot:
Well A - Initial rapid drawdown was caused by first withdrawals being derived only from storage in the basal layer. As pumping continued, water began to move across the stratifications and storage began to be derived from the entire thickness of the aquifer.

Well B - Because of head losses resulting from the low vertical hydraulic conductivity, well B appears to be farther from the pumping well than does well A.

Reference: Departures from Theis curve (from Fundamentals and Applied Ground Water Hydraulics short course, Heath R. and Spruill, R., 2004)

Figure 8.25. - Differences in response of observation wells caused by aquifer discontinuity.



Plan view:

Observation well A is half as far from the pumping well as well B.

Cross section:

The aquifer is composed of horizontally stratified gravel deposited by glacial meltwater. The clay barrier between the pumping well and well A is not apparent from the land surface.

Observation wells A and B are screened in gravel at the same depth as the pumping well.

Data plot:

Well A - The clay barrier hampers expansion of the cone of depression towards well A. Therefore, drawdown begins several minutes after the start of drawdown in well B. This causes well A to appear hydraulically more distant than well B.

Well B - Early drawdowns plot above the type curve because of the stratification of the aquifer and the lag in decline of the water table. Late drawdowns plot above the type curve because the clay barrier resembles a leaky impermeable boundary.

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