Open Borehole Well-Test Methods for CO_2 Storage Site Characterization

Advanced Techniques for Site Characterisation: ENOS WP6 Workshop

23 April 2018

In conjunction with: C02GeoNet Open Forum 2018
24-25 April 2018
San Servolo Island, Venice, Italy

Mark Kelley (Battelle)

Outline

Borehole Test Objectives

Selected Open Borehole Tests

- Hydraulic Test Methods
  - Composite Borehole (Reconnaissance)
  - Discrete Interval Hydraulic Tests for low k and high k rocks
  - Discrete Interval Geomechanic Tests - Mini-frac (HF), HTPF
- Equipment Considerations

Examples

- AEP Mountaineer BA-02 Test Borehole (West Virginia)
- FutureGen Well (Illinois)
- Ohio Geol. Survey CO2 Well
- MRCSP CO2-EOR (Michigan)

Borehole Hydraulic and Geomechanical Characterization Objectives

- **Identify candidate intervals for CO2 injection/storage**
- **Quantify hydraulic properties of composite borehole**

Composite borehole reconnaissance

- **Quantify hydraulic and geomechanical properties of discrete intervals (reservoir, caprock) for use in dynamic modeling**
  - **Static formation fluid pressure (hydraulic head)**
  - **Transmissivity, Kh**
  - **Storativity, S_sh**
  - **Skin, sk**
  - **Min and Max Horizontal stress, Sh_{min}, SH_{max}**

Discrete Interval testing

Timing of Borehole Hydraulic-Geomechanical Testing

- Usually done after borehole is drilled to TD (“drill-then test”) – but can also be done during drilling (“drill-and-test”)
- Consecutive Drill-then-test Pros/Cons
  - (+) Less costly – test after drilling rig is moved off hole, often with support of service (workover) rig
  - (-) possibility of pressure perturbations due to drilling
- Drill-and-test Pros/Cons
  - (+) potentially shorter test times and better quality of the characterization data
  - (-) more costly - standby drilling rig and test equipment costs that are incurred when either activity is not taking place.

Composite Borehole Hydraulic Reconnaissance Methods

Uses

- Identify hydraulically conductive (inflow/outflow) intervals
- Quantify volume of inflow/outflow – indicator of interval kh
- Quantify hydraulic properties (kh) of composite borehole

Example Methods

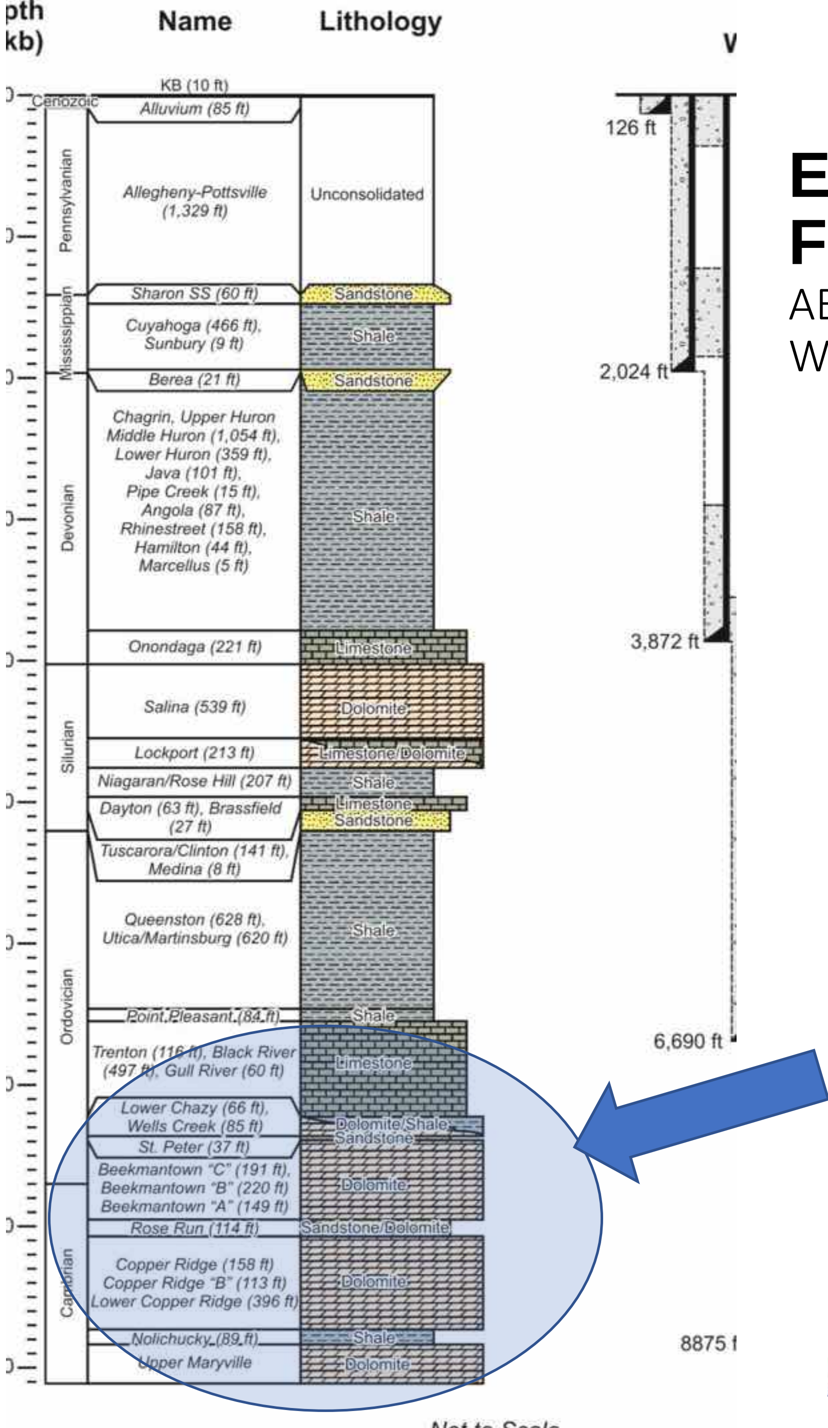
- Mechanical flow meter (spinner) survey
- Hydrophysical (Fluid EC/temp) Logging

Open Borehole (mechanical) Flowmeter Survey

- While pumping, flowmeter (run on wireline) is lowered/raised across the open borehole sections
- Tool string includes flowmeter, pressure, temperature probes and caliper
- Constant logging speed while logging
- Constant injection/withdrawal rate
- Repeat test for different injection/withdrawal rates
- Run baseline log before injection/withdrawal
- Record pressure recovery after injection/withdrawal
- Log temperature profile after pressure recovers

Open Borehole (mechanical) Flowmeter Survey (cont'd)

- Provides vertical profile of volumetric inflow/outflow from the borehole
- Pressure recovery data can be analyzed for kh of composite borehole
- Relative kh of Individual flow intervals can be determined from observed change in logging speed across interval
- Repeat temperature log(s) provide qualitative information about location of hydraulically conductive intervals to corroborate flowmeter results.



Example Open Borehole Flowmeter Survey

AEP Mountaineer BA-02 Test Well
West Virginia

- Purpose – BA-02 was drilled to provide geologic characterization data to support the design of a commercial-scale CO_2 capture and storage facility (1.5 million metric tons of CO_2 per year).

- Hydraulic well testing program was conducted to evaluate the injectivity potential of geologic formations in the ~2,200 ft (670 meters) open borehole section from 6,690 to 8,875 ft (2040 to 2705 m).

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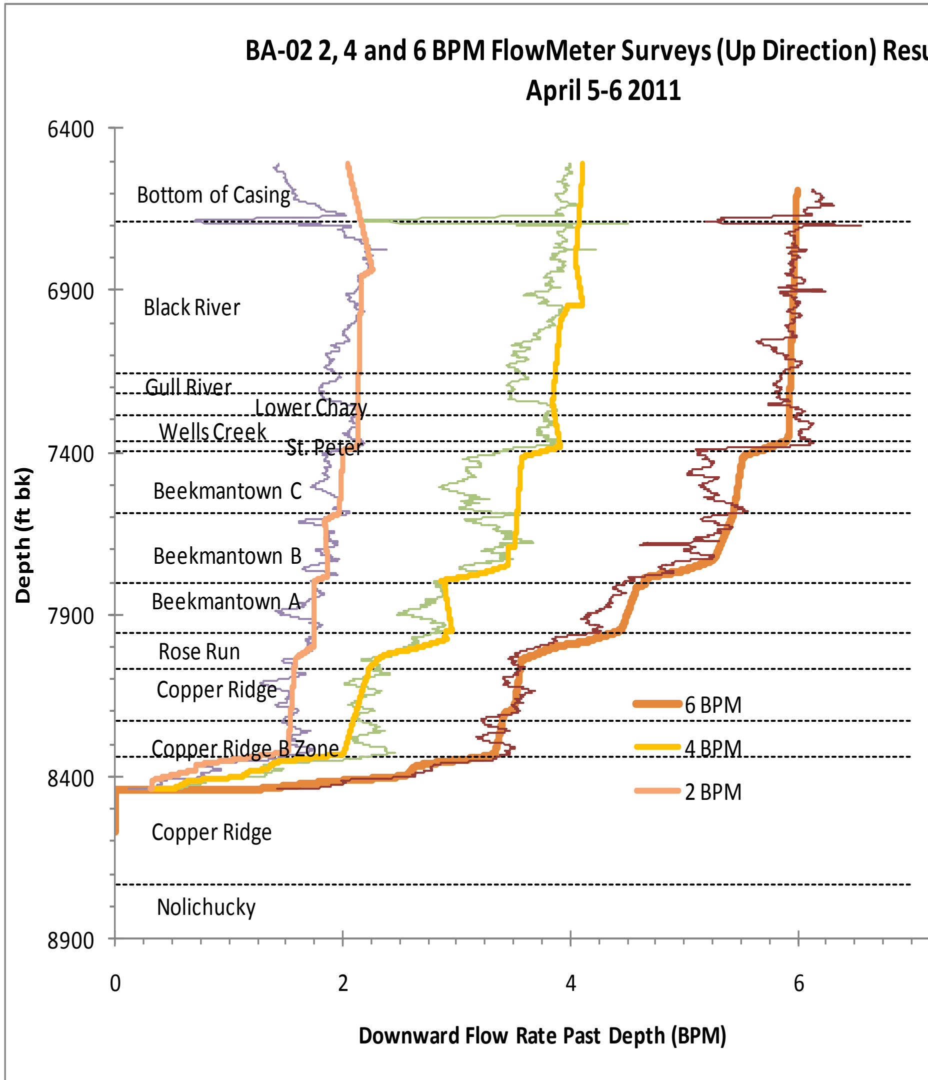
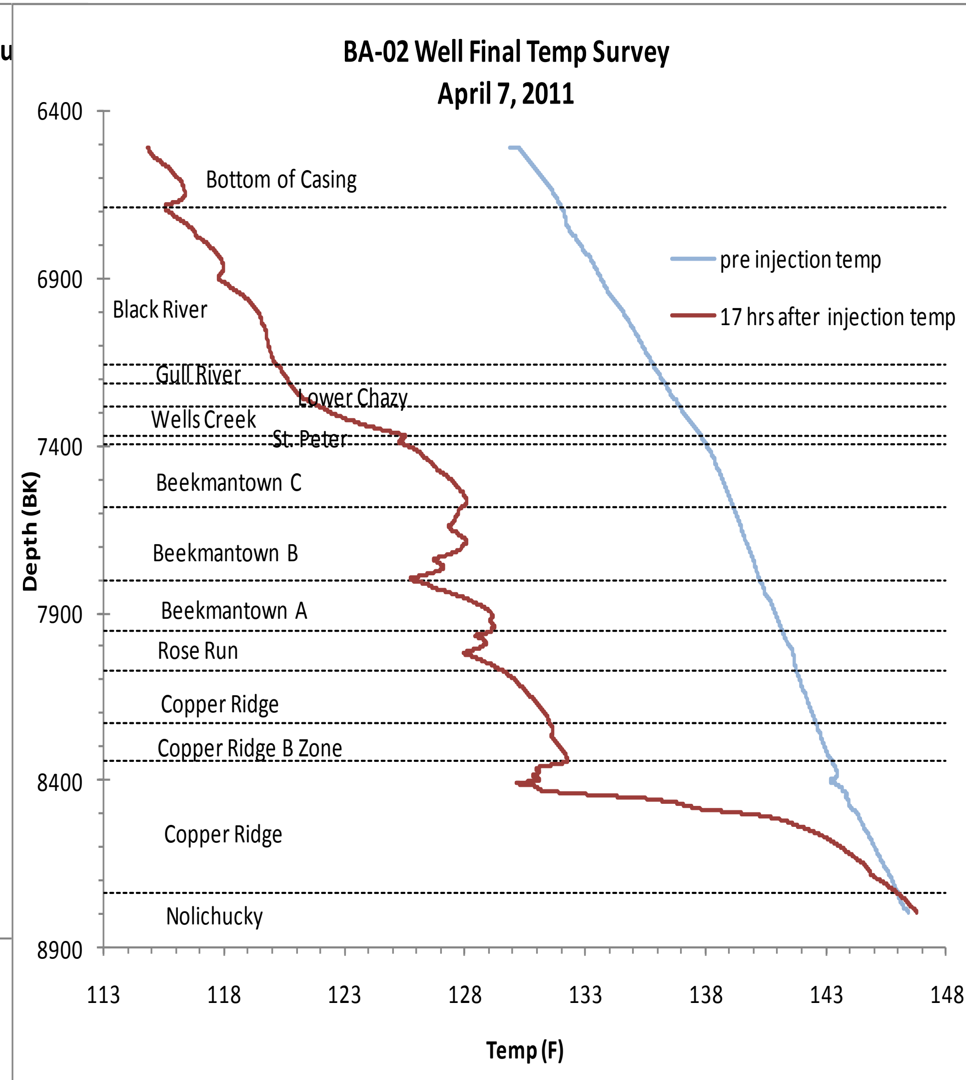
Source: Spane and Kelley. 2011: Mountaineer CCS II Project: Hydrologic Well Testing Conducted in the BA-02 Well American Electric Power Company Mountaineer Plant New Haven, West Virginia

Example Open Borehole Flowmeter Survey (cont'd)

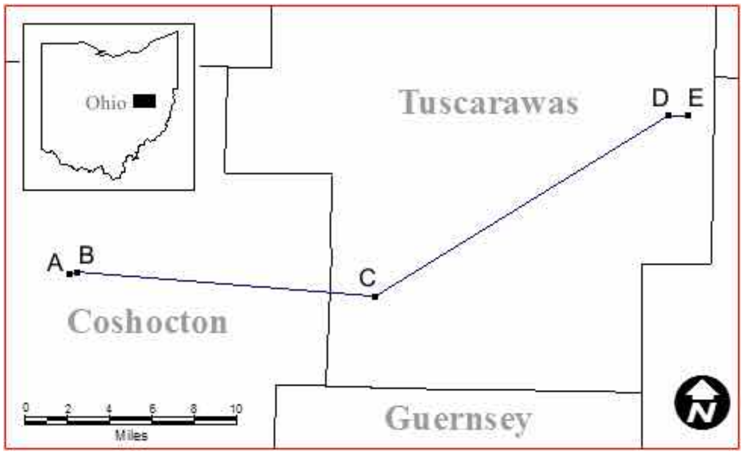
AEP Mountaineer BA-02 Test Well

Flowmeter Data for 2, 4 and 6 BPM Surveys and Temp Logs





Hydraulic Reconnaissance Survey of Cambrian-Ordovician Strata in Coshocton and Tuscarawas Counties Ohio

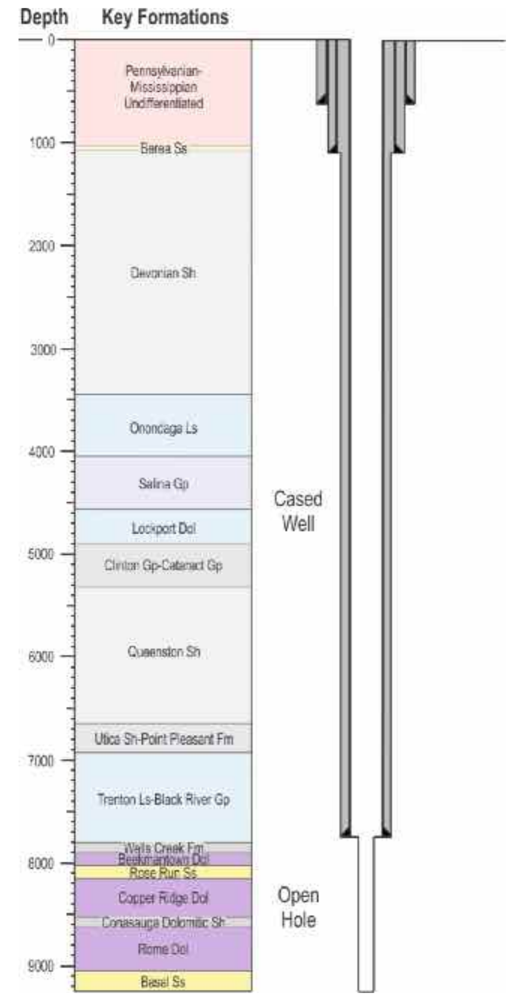


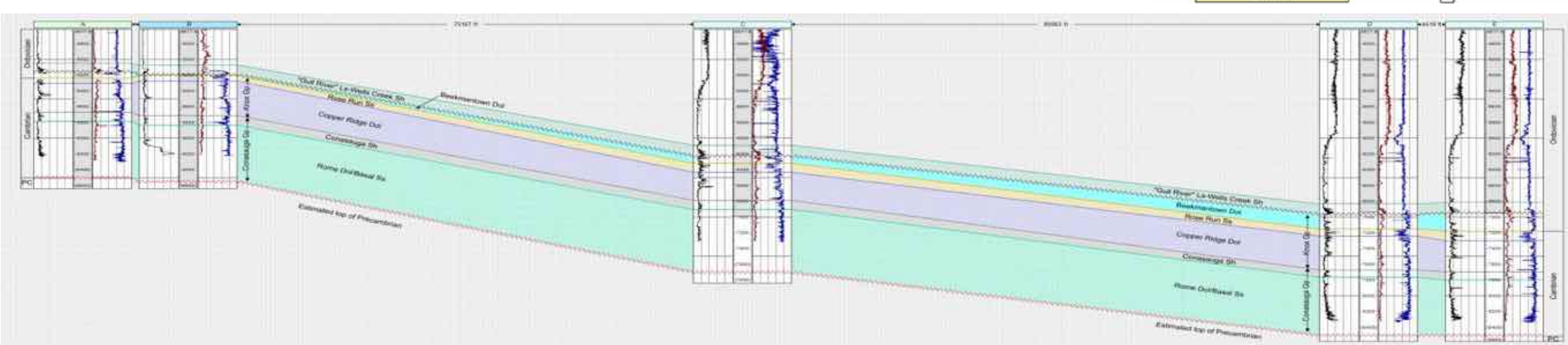
35 miles (56 km)

Transect showing location of 5 brine injection wells

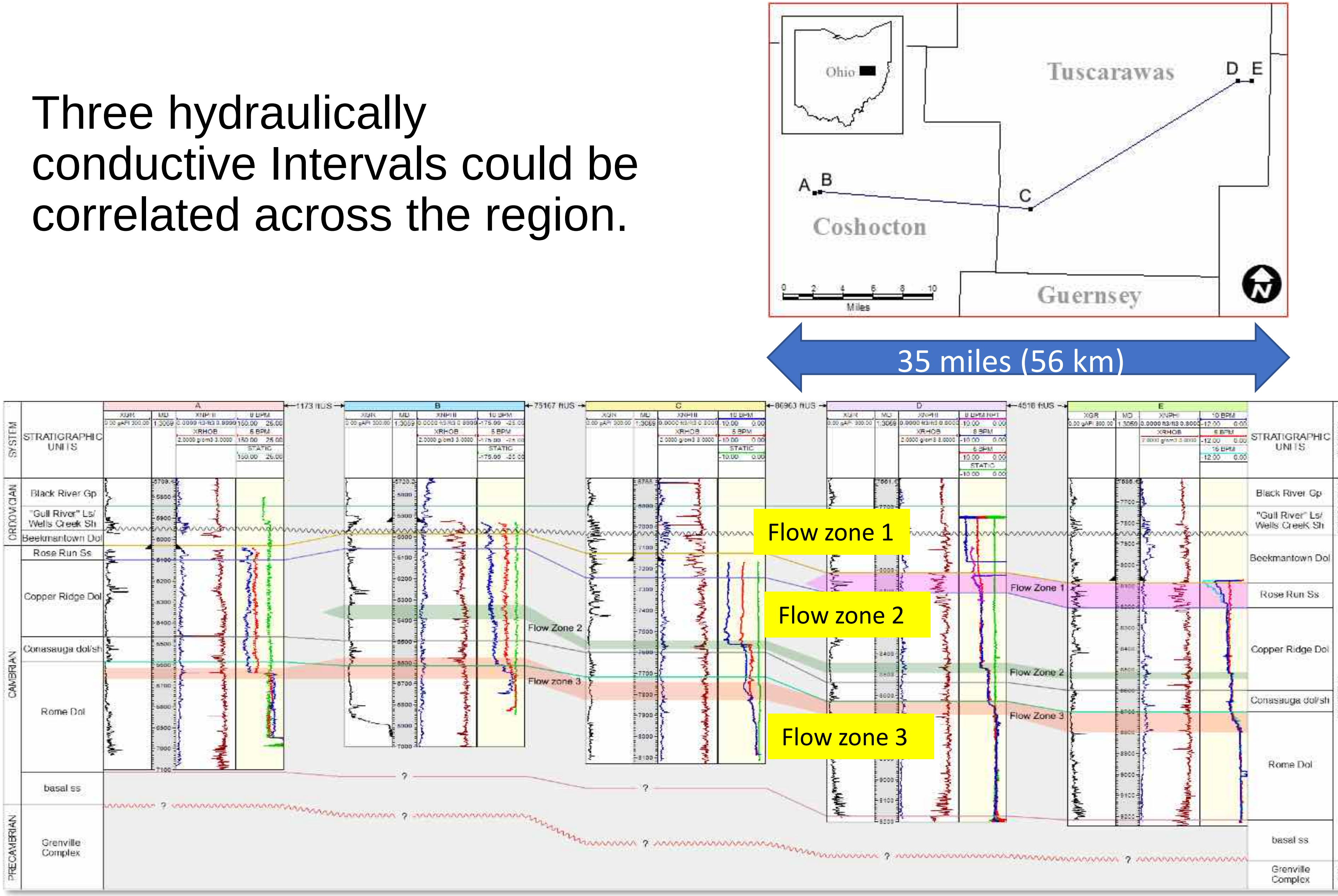
Typical brine injection interval with open borehole completion

Flowmeter survey conducted in 6 wells



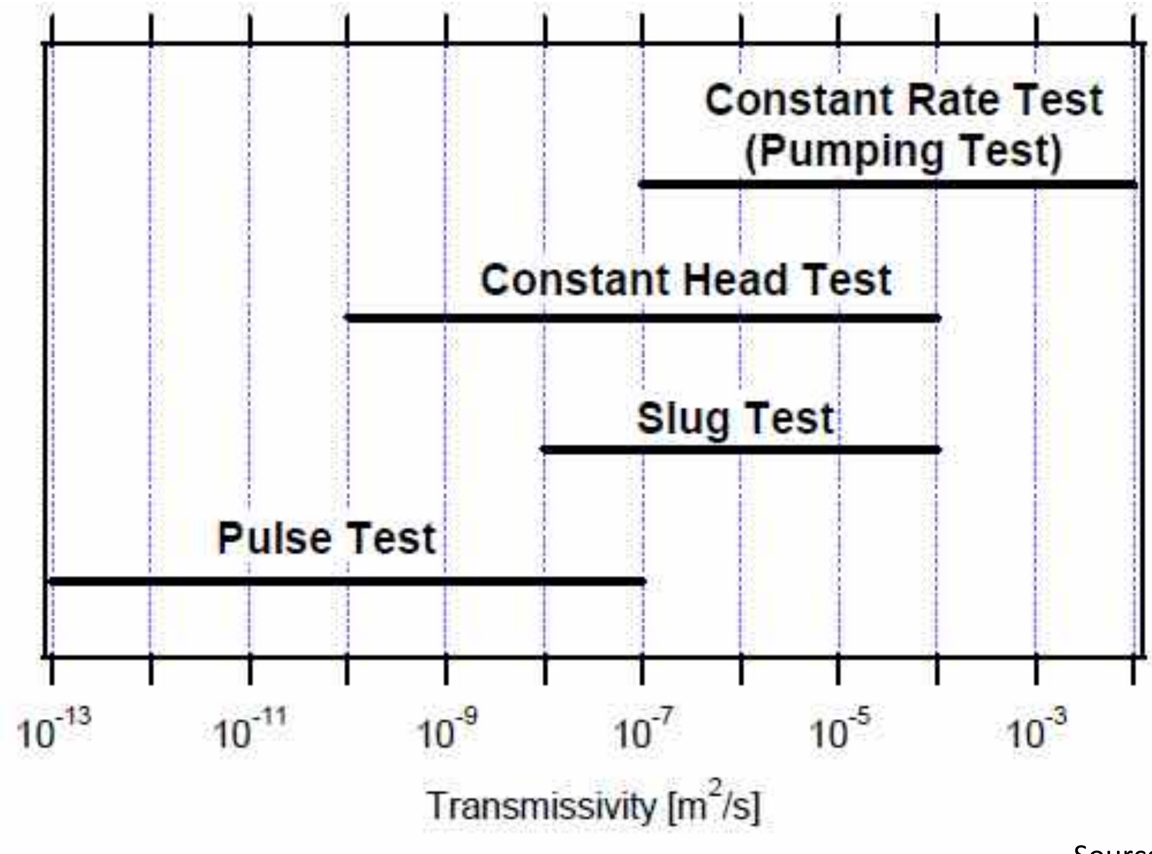


Three hydraulically conductive Intervals could be correlated across the region.



Discrete Interval (Packer) Hydraulic Tests

Different test types used for hydraulic testing depending on transmissivity



Source: Solexperts (Ursula Rösli)

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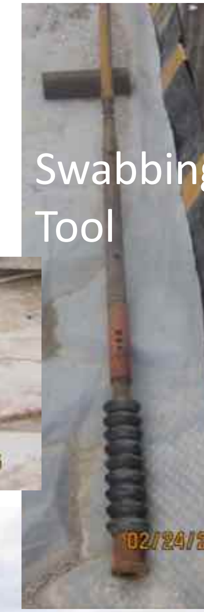
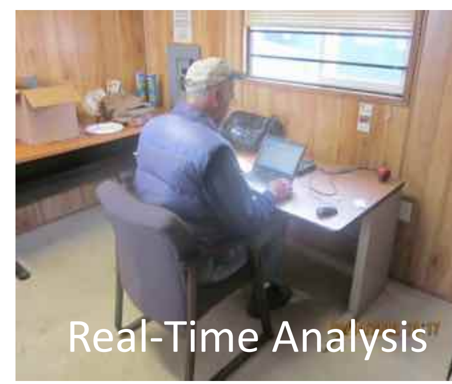
Test Equipment for Packer Tests

- an inflatable or mechanical, multiple-packer (straddle-packer) system for isolating test intervals
- pressure sensor system for monitoring *real-time pressures* within, below and above the test interval (and back-up downhole memory gauges)
- a data acquisition system (DAS) to record and display downhole test response (pressures) on a “real-time” basis (e.g., wireline or telemetry)
- a pneumatic or mechanically-activated downhole shut-in valve (to provide test system isolation at test formation depth) to facilitate/shorten test duration
- a tubing string for conveying the downhole packer test system to the test interval
- Crane, service rig, or similar means for deployment and retrieval of tubing string and other test equipment
- submersible pump, swabbing equipment, or other means (e.g., air lift system) for withdrawing fluid from tubing and/or test interval
- Surface pump, flowmeters, pressure sensors piping and valving for injecting and controlling, measuring water iinto tubing string/test interval (mini-frac test; injection fall-off test)

Examples of Test Equipment



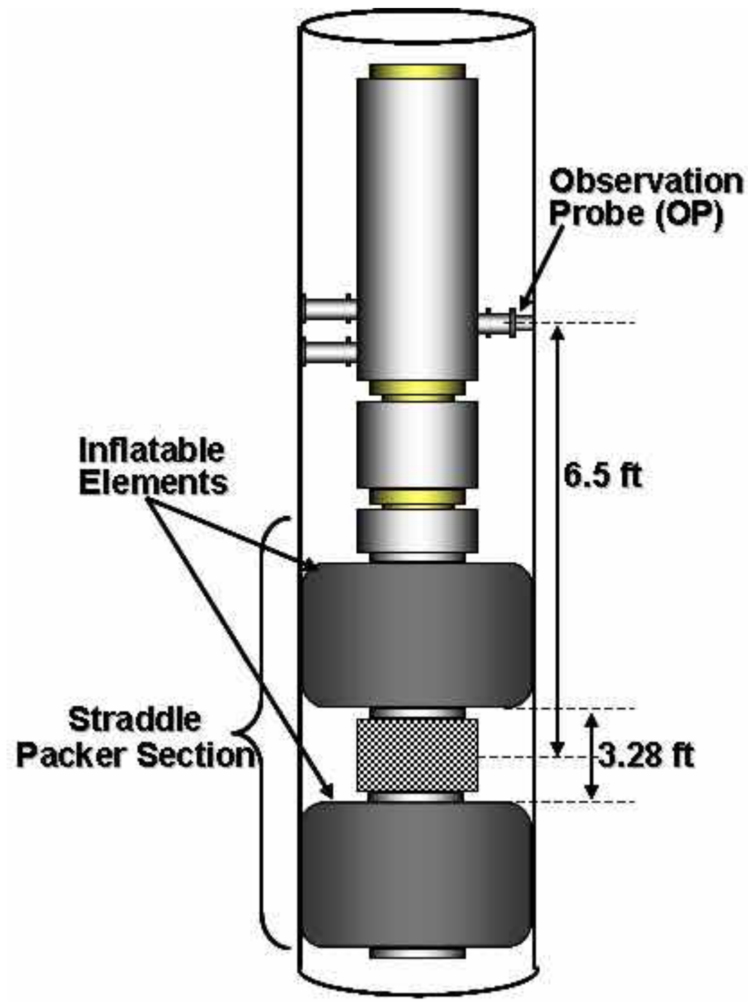


Examples of Test Equipment (cont'd)

Baker RCX Tool

wireline deployable straddle packer test tool

- Drawdown- build-up tests
- Vertical interference tests
- Mini-frac tests
- Water sampling
- Fixed packer spacing
- Pump-rate limitations



Test equipment (cont'd) – considerations for testing low permeability rock

- hydraulic testing of low permeability caprock intervals requires special equipment/modifications.
- low permeability formations can be affected by borehole pressure history, temperature changes of fluid in the borehole, volume changes caused by deformation of test equipment, and the presence of gas in the formation and test system.
- Test systems with minimal packer compliancy (i.e., elasticity) and shut-in tool displacement stresses (i.e., zero displacement shut-in tool) should be used
  - e.g., To minimize variation in packer pressure during pulse tests in low-permeability formations that can mask the actual formation response, HydroResolutions LLC designed a test tool with pressure accumulators hydraulically connected to the packers and shut-in valves.

Example Straddle Packer Test Tool (configured for pulse testing)

- two inflatable packers,
- a downhole shut-in valve,
- a piston-pulse tool,
- a slotted section,
- a sediment trap,
- sensor carriers, and
- miscellaneous subs and feedthroughs to connect the various pieces

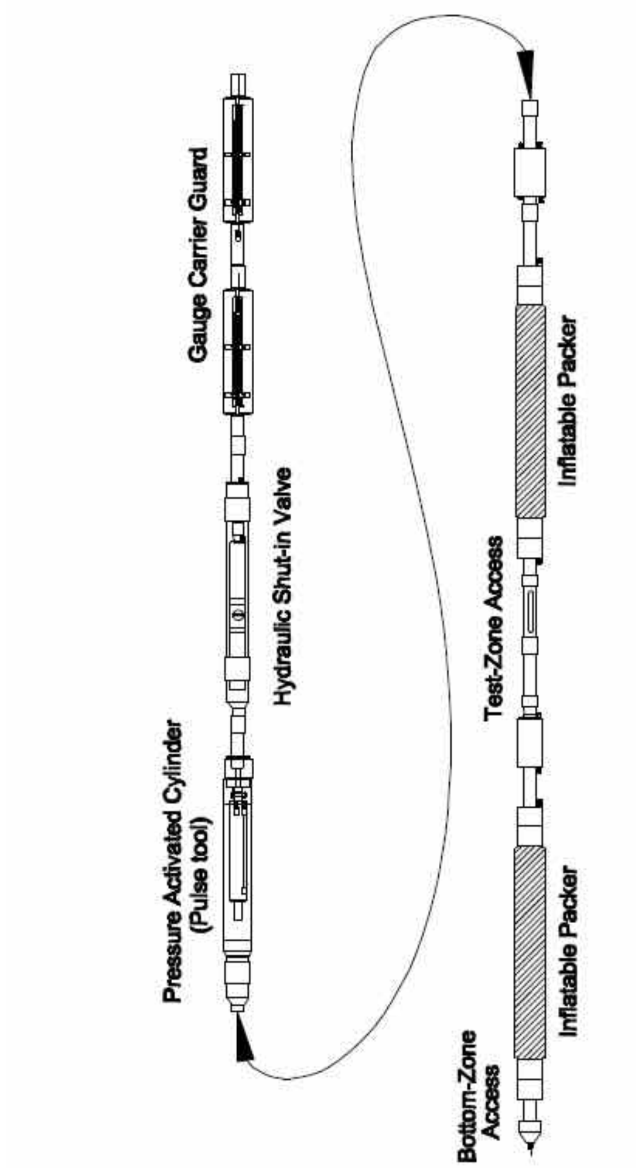


Figure 2-1: Schematic of downhole equipment.

The length of the test zone (packer spacing) can be varied

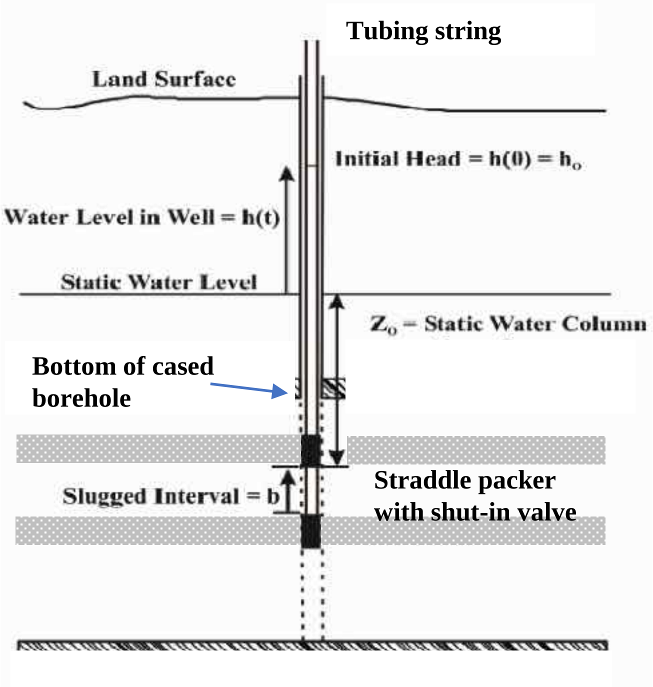
HydroResolutions Pulse-Test Tool

Source: Technical Report: Analysis of Straddle-Packer Tests in DGR Boreholes Revision 0 Doc ID: TR-08-32 (Geofirma Engineering)

Test #1 – Slug Test and Drill Stem Tests (DST)

- Induce instantaneous pressure increase/decrease in the test zone followed by recovery back toward static pressure conditions. The rate of pressure decay is used to infer the hydraulic properties of the test interval.
- Most commonly implemented by removing (e.g., swabbing) [**slug withdrawal] test]** or adding water to **[slug injection test]** the test tubing-string with shut-in valve closed, and then opening the valve.
- ***Slug test:*** the shut-in valve remains open during a slug test and fluid flowing into or out of the formation results in changing water levels within the tubing.
- ***DST test: (if recovery is slow),*** shut-in valve is closed after ~50% recovery; reduces wellbore accelerates recovery
- Radius of investigation = near wellbore

Slug injection test



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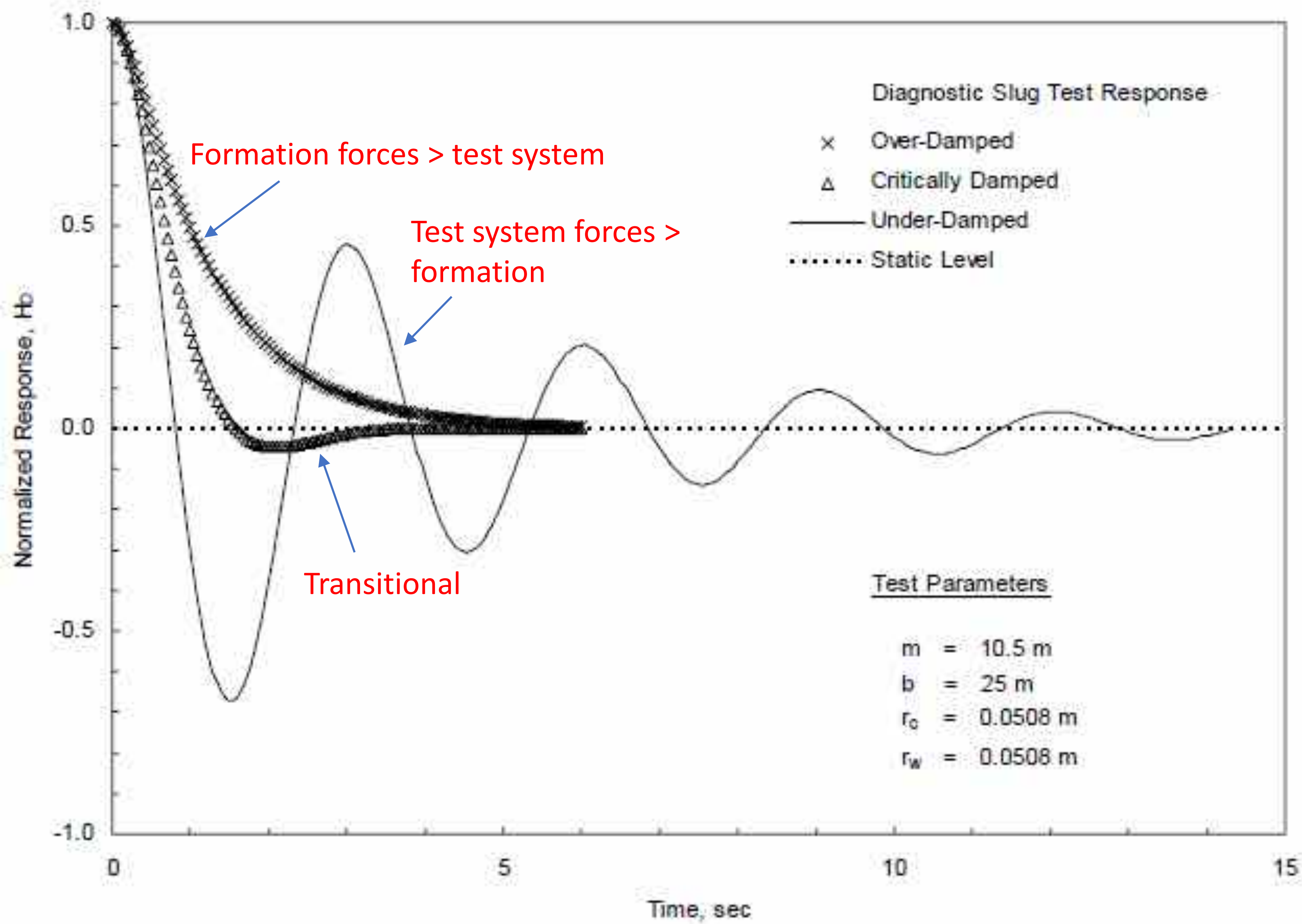
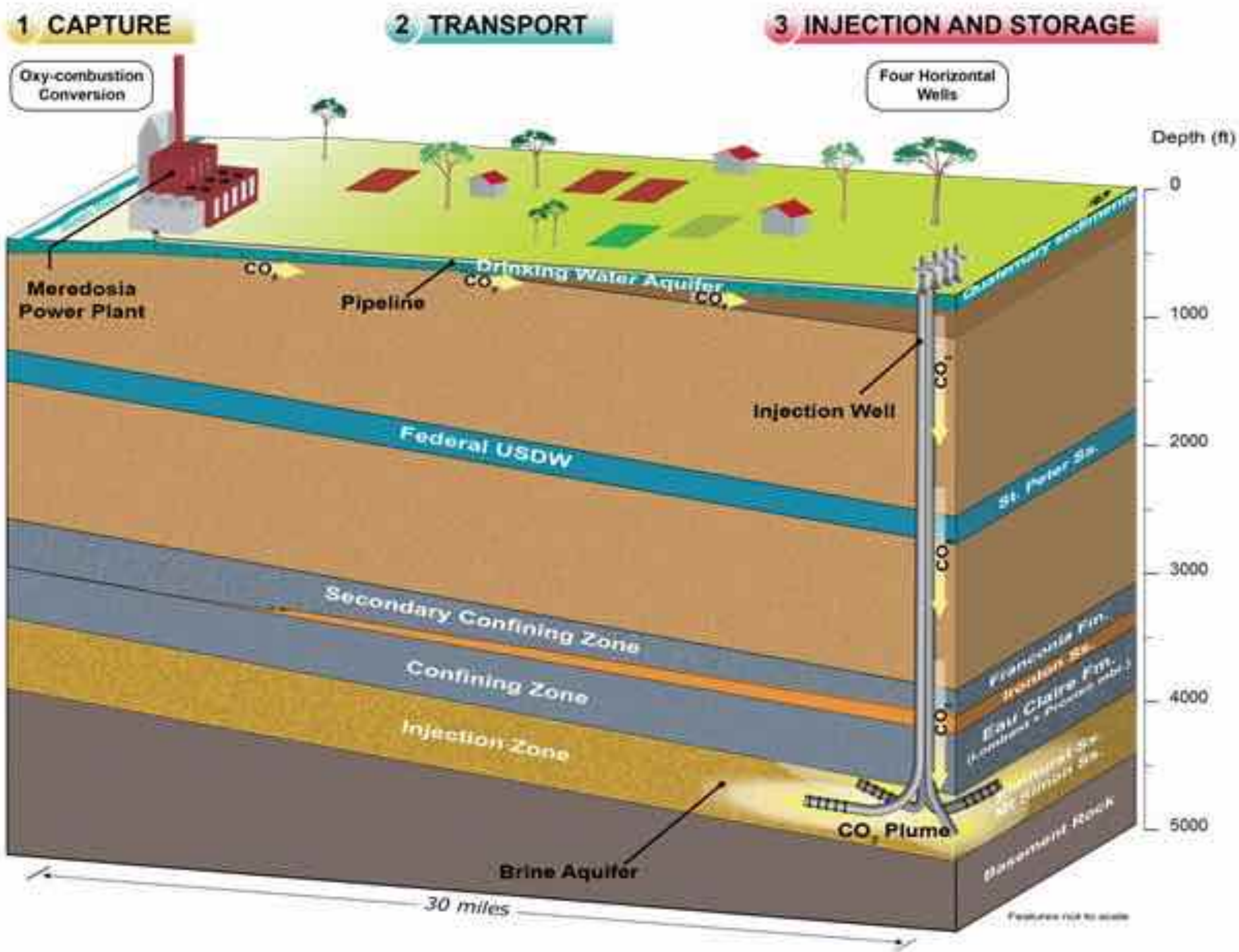


Figure 3.1. Diagnostic Slug Test Response (taken from Spane et al. (2003a)

Slug/DST Tests – Analysis

- Provides transmissivity (kh), average hydraulic conductivity (K) and storativity (S)
  - Test has low sensitivity for S
  - The slug-test responses are commonly analyzed with type-curve and deconvolution procedures discussed in Butler (1997) and Peres et al. (1989), respectively.
- Analysis of DST recovery data provide estimates of T, K, S, s_K, and (if pre-test trend conditions accounted for) static formation pressure conditions.
  - DST recovery analysis by standard straight-line semi-log procedures in Earlougher (1977)



1 CAPTURE
2 TRANSPORT
3 INJECTION AND STORAGE
Oxy-combustion Conversion
Four Horizontal Wells
Depth (ft)
0
1000
2000
3000
4000
5000
Meredosia Power Plant
Pipeline
Drinking Water Aquifer
CO_2
Injection Well
Federal USDW
St. Peter Ss.
Secondary Confining Zone
Confining Zone
Injection Zone
Franconia Fm.
Ironton Ss.
Eau Claire Fm.
Mt. Simon Ss.
Basement Rock
CO_2 Plume
Brine Aquifer
30 miles

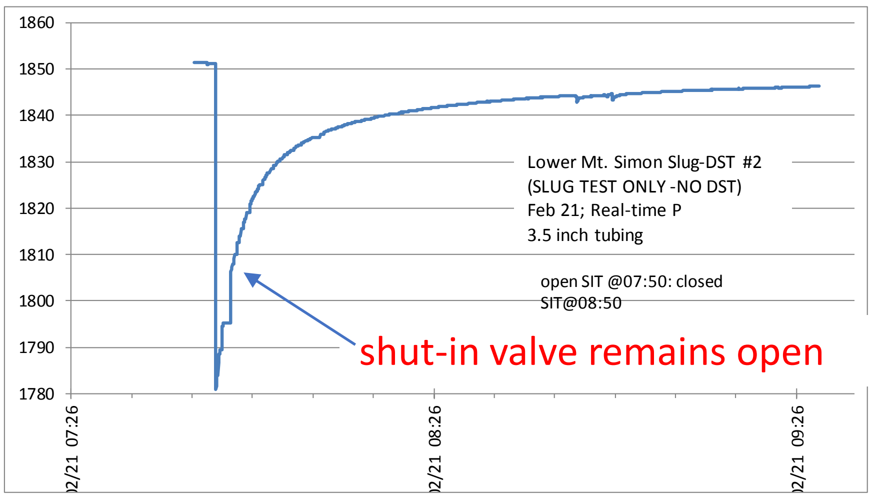
Example Type-Curve Analysis of Slug Test

(FutureGen Site, Illinois)

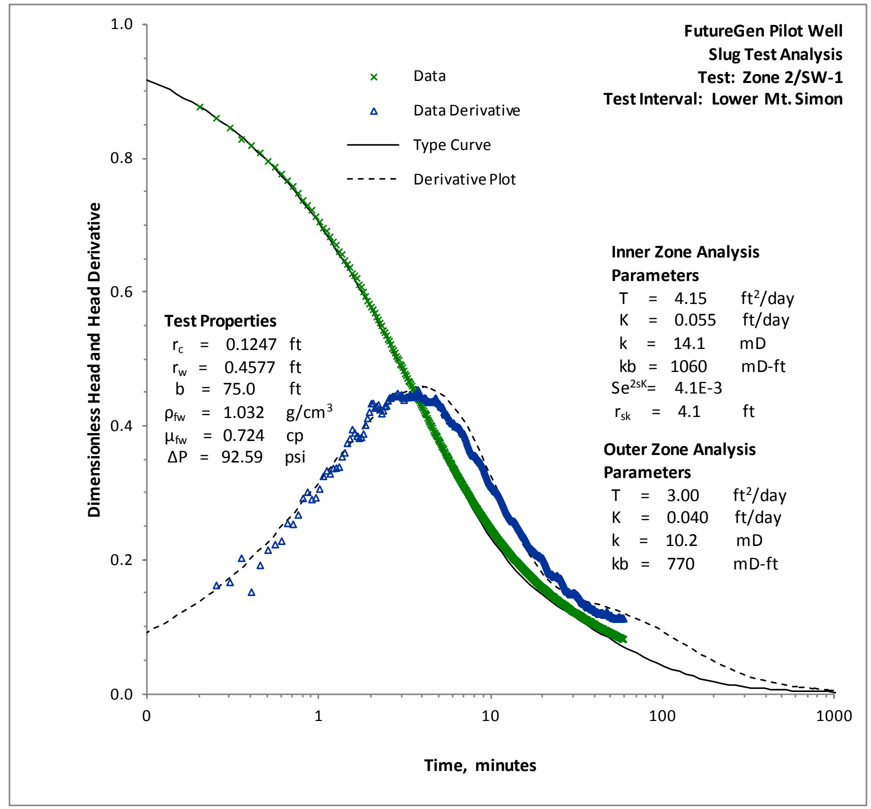
Test interval length = 75 ft (23 meters)

depth to test interval ~4200 ft (1320 m)

T=41.5 ft2/d (4.5 E-05 m2/s)



Raw Data



Slug Test Analysis

Source: Kelley et al., 2012; Borehole Completion and Characterization Summary Report for the Stratigraphic Well, Morgan County, Illinois; PNWD-4343; U.S. Department of Energy Award Numbers DE-FC26-06NT42073 and DE-FE0000587

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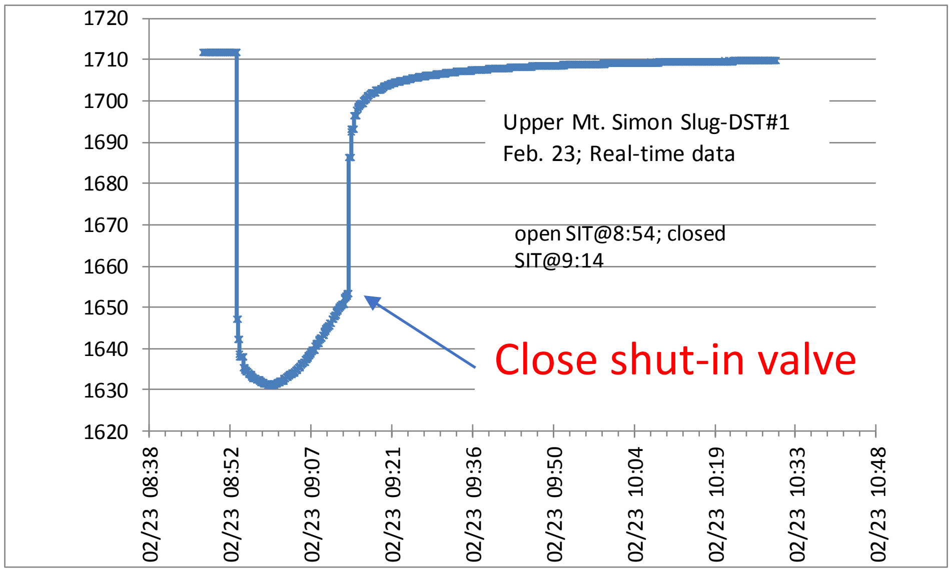
Example Type-Curve and Straight-Line Analysis of DST
(FutureGen Site, Illinois)

Test interval length = 185 ft (56 meters)
depth to test interval ~4200 ft (1320 m)



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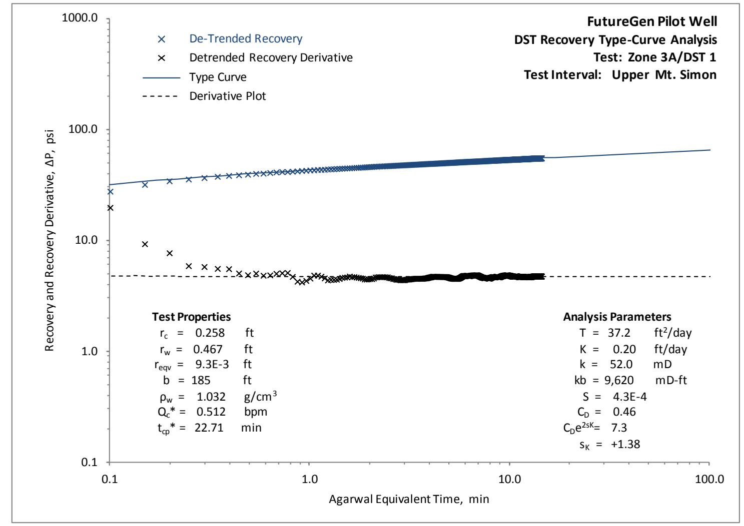
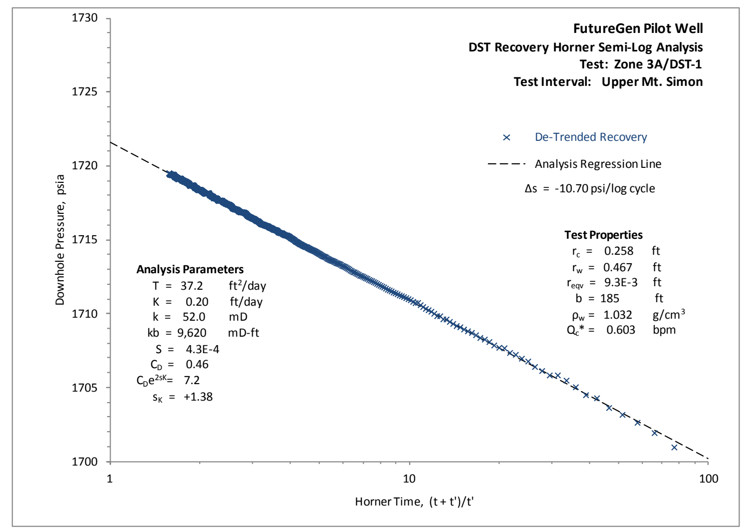


Type-Curve Analysis Upper Mount Simon



Straight-Line (Horner) Analysis Upper Mount Simon

T=37.2 ft2/d (4.0e-05 m2/s)

Source: Kelley et al., 2012; Borehole Completion and Characterization Summary Report for the Stratigraphic Well, Morgan County, Illinois; PNWD-4343; U.S. Department of Energy Award Numbers DE-FC26-06NT42073 and DE-FE0000587

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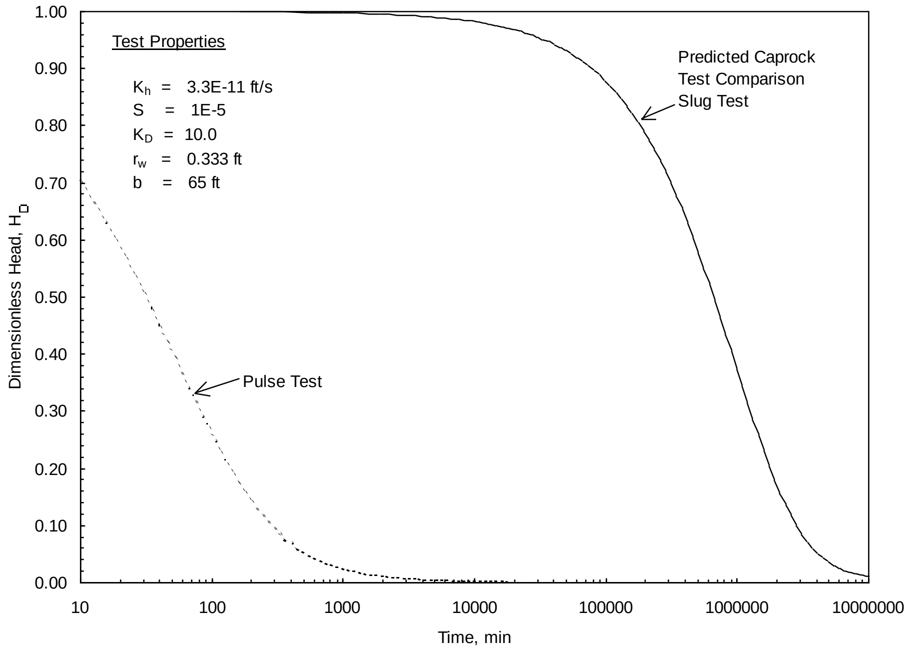
Test #2 – Pulse Test

- Applicable to low permeability rocks (i.e., $\leq 10^{-9}$ m/s)
- Similar to slug test except that the test zone is shut-in (by closing the shut-in valve) during entire recovery period.
- Withdrawal (PW) or Injection (PI) mode
- volumes of fluid are smaller during pulse tests (i.e., per unit pressure change) in comparison to slug tests, therefore, the radius-of-investigation is accordingly smaller.
- pulse tests more susceptible to near well formation heterogeneities and skin effects

Pulse Test Analysis

Comparison for Pulse (closed) and Slug Test (open) Responses (adapted from Reidel et al., 2002)

- same analytical equations used for analysis of slug tests (e.g., Cooper et al., 1967)
- The equations, however, must be modified to account for the closed-system wellbore storage test conditions
- Kh, k, S



17 hours 19 years

Recovery time

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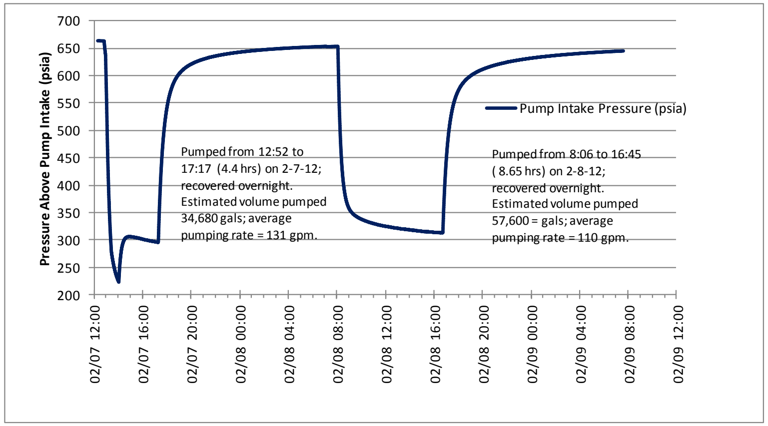
Test #3 - Constant-Rate Pumping Test

- Water is withdrawn from (or injected into) a borehole at a uniform rate for an extended period of time (e.g., 8 hours to 48 hours).
- Pressure is monitored during the active pumping phase and the recovery phase following pumping.
- Radius of investigation potentially very large if pumping period is extended
- Observation wells, if available, can be monitored to extend radius of investigation



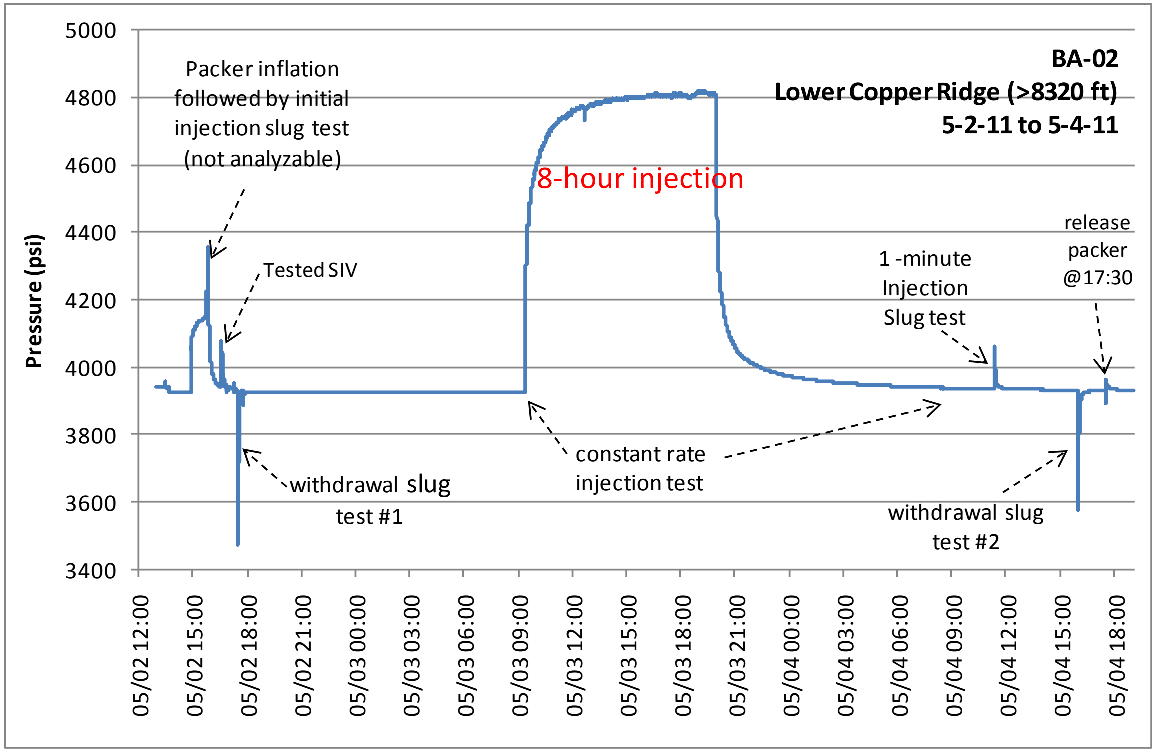
Example constant rate pumping test

Constant-rate Pumping Test – Analysis

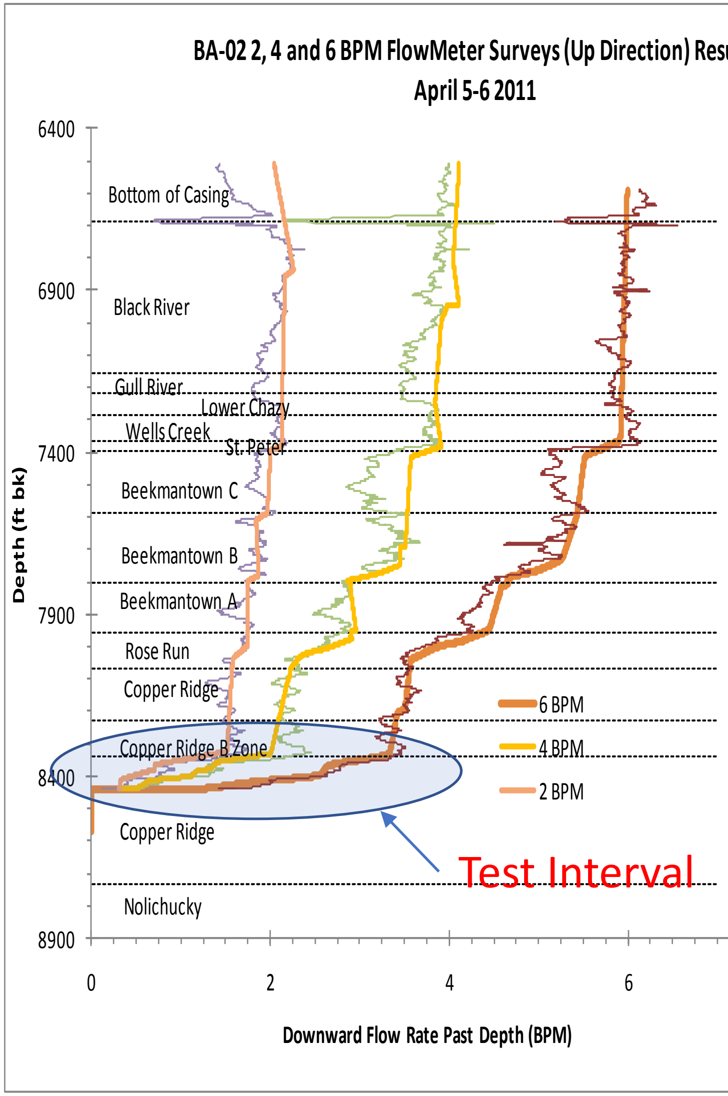
- Standard analytical methods include type-curve matching (observation wells) and straight-line methods (pumped well)
- Type-curve-matching methods include: Theis (1935), Hantush (1964), and Neuman (1975)
- Straight-line methods: Cooper and Jacob (1946)(for buildup analysis) or Horner (1951) (for recovery analysis).
- provides kh, skin, radius of investigation, presence of boundaries

Example Constant-Rate Pumping Test

AEP Mountaineer, West Va.
Test Interval 8,320 to 8,875 ft (2536 to 2706 meters)



Raw Data



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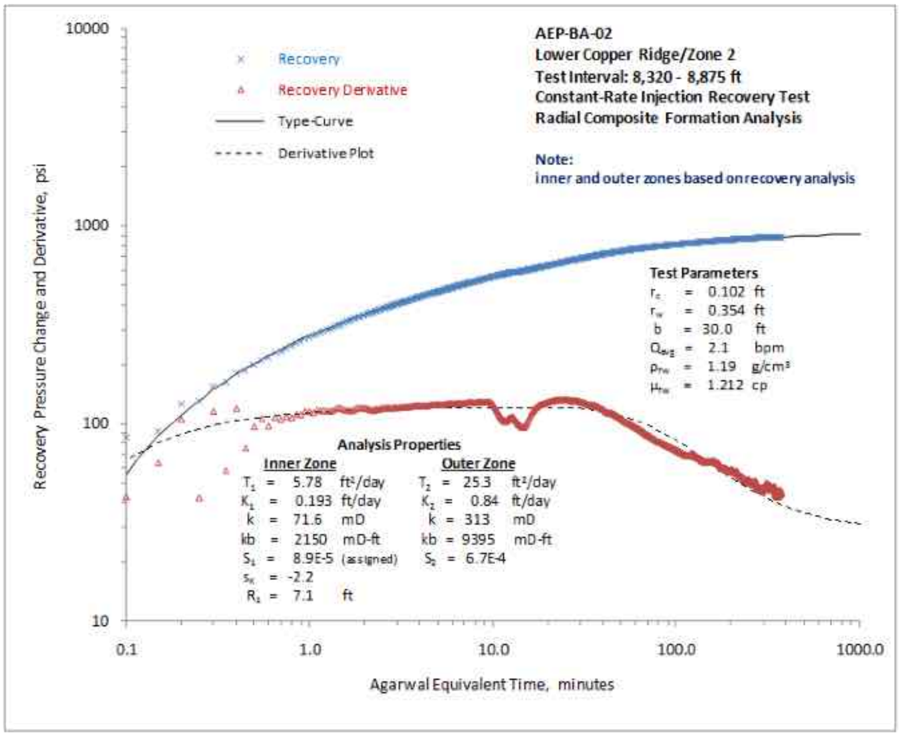
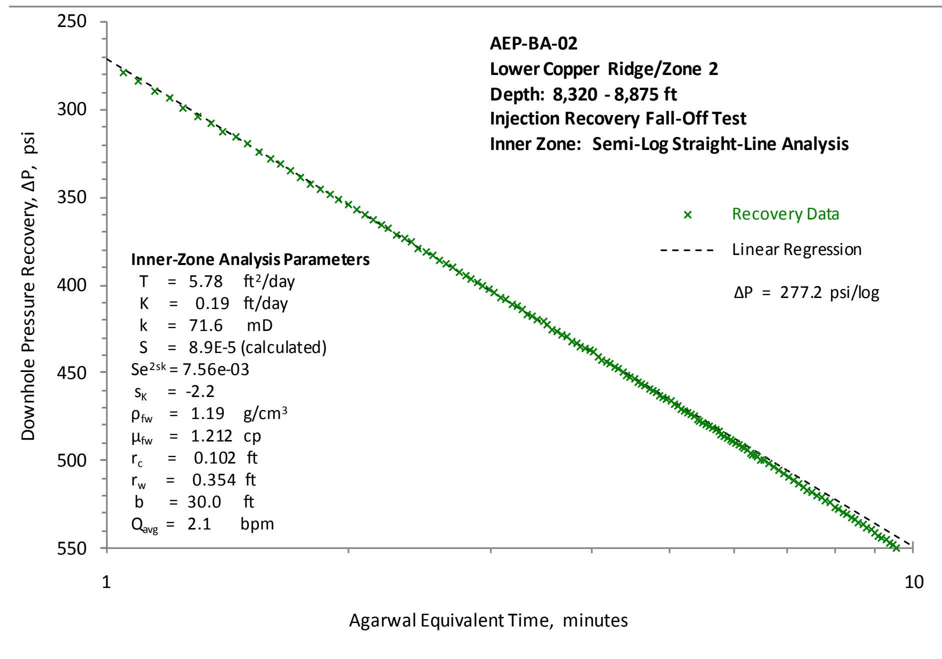
Example Constant-Rate Pumping Test

AEP Mountaineer, West Va.
Test Interval 8320 to 8875 ft (2536 to 2706 meters)

T inner zone =5.78 ft2/d (6.2 E-06 m2/s)
T outer zone = 254 ft2/d (2.7 E-04 m2/s)



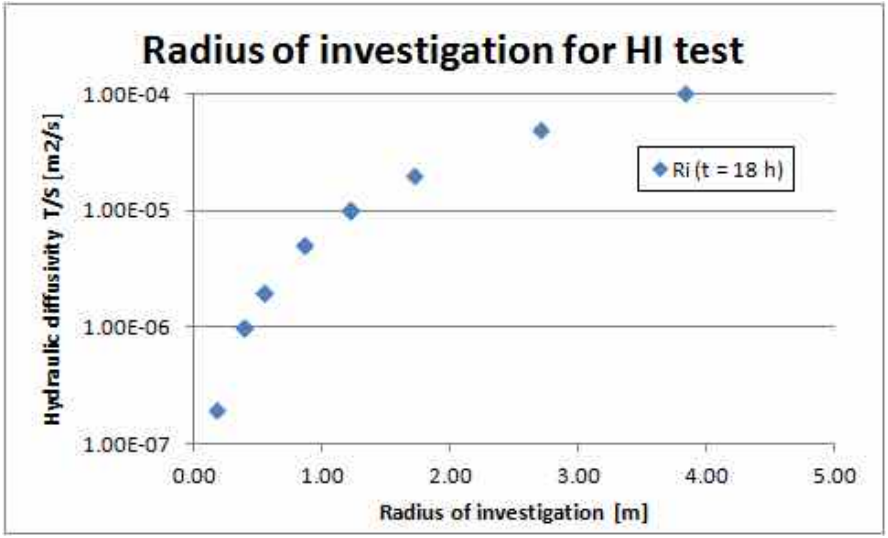
Type Curve and Derivative Plot Analysis of the Recovery Phase



Straight-Line Analysis of the Recovery Phase

Test #4 – Constant-Pressure Injection (Fall-Off) Test

- Applicable to low permeability rocks (i.e., $\leq 10^{-9}$ m/s)
- Maintain constant pressure; record flow rate
- At the end of injection, shut-in and record pressure recovery (pressure fall-off)
- radius-of-investigation is greater than pulse tests, but still localized
  - E.G., < 8 ft for tests of 5 hours or less, conducted within dense caprock with hydraulic conductivity of $\leq 10^{-11}$ m/s.



Source: DEEP BOREHOLE FIELD TEST: DESIGN REPORT
Forward simulation
Author: Ursula Rösli
Report V2A-2469, 1 April 2016
Solexperts AG
CH-8617 Mönchaltorf (Switzerland)

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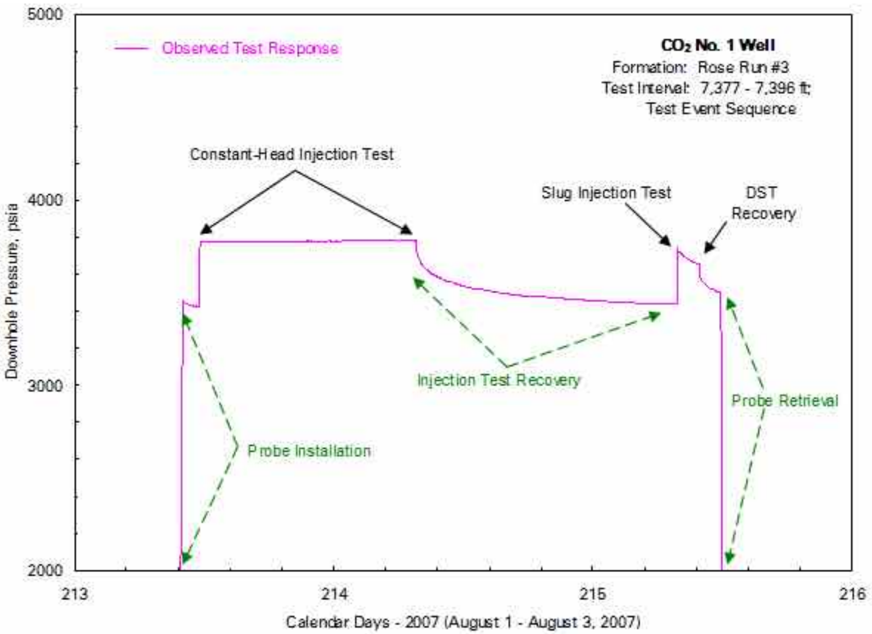
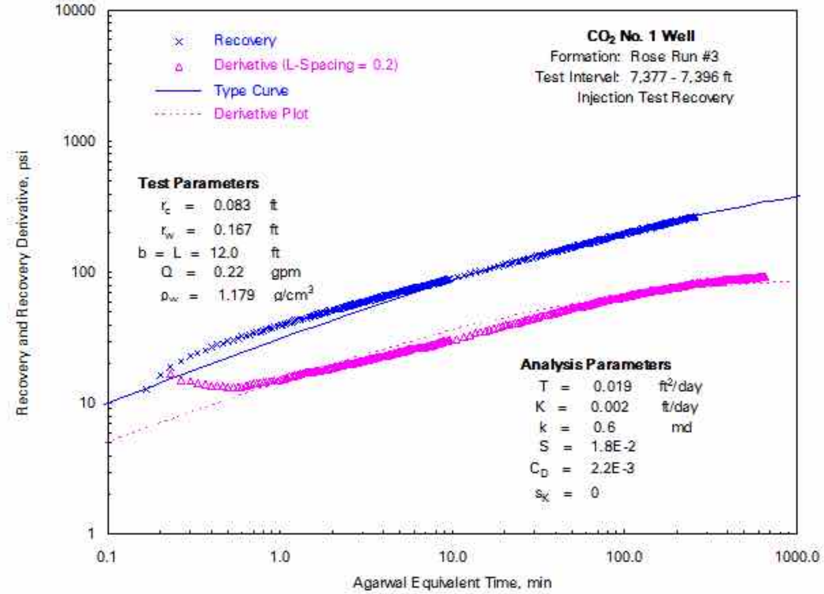
Example Constant-Pressure Injection Test

Ohio Geol. Survey CO2 #1 Well
Tuscarawas County, Ohio
Test Interval Rose Run Formation
7,377 to 7,396 ft (2248 to 2255 meters)

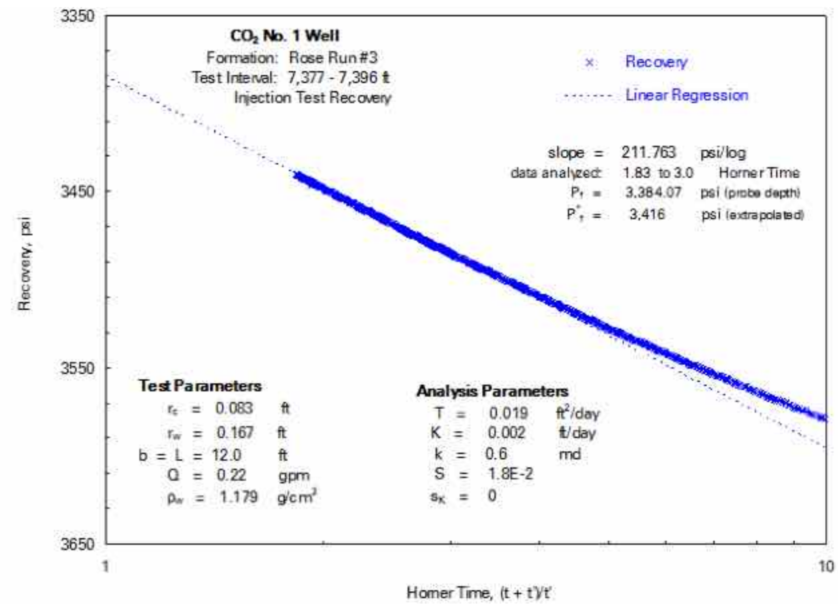


Raw Data

T=0.019 ft2/d (2.2 E-07 m2/s)



Type-Curve Analysis



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Straight-Line Analysis

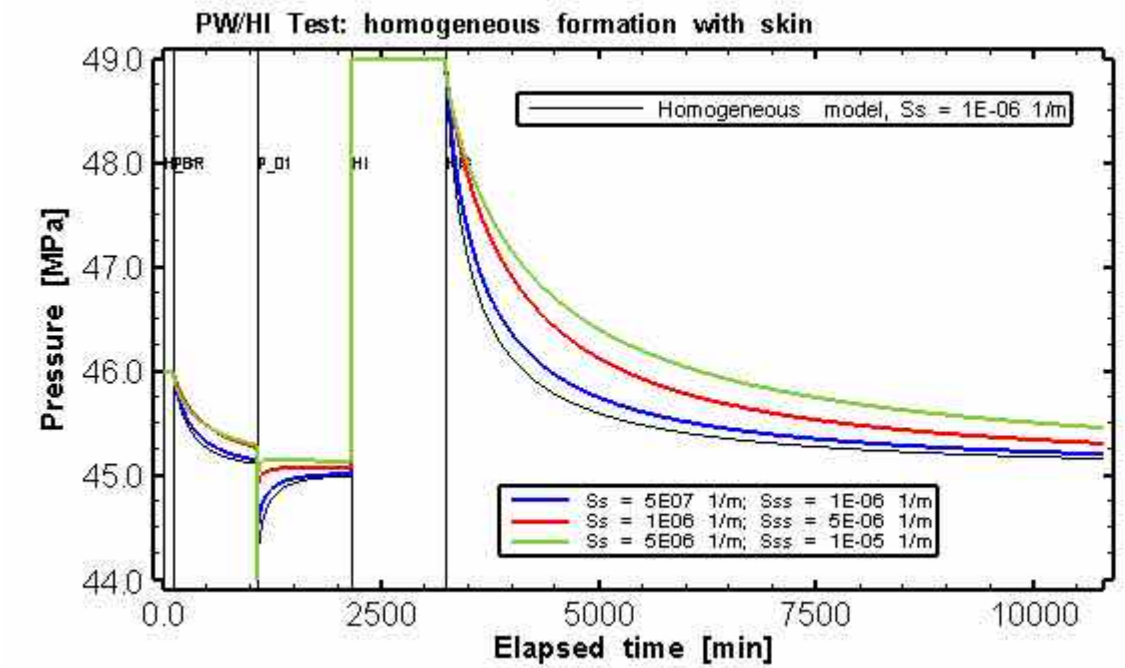
Test-History Match

- When a series of tests are conducted in a sequence, the entire test sequence can be simulated
- Decreases uncertainty compared to individual tests
- Software (models) for simulating test sequences
  - KGS model (Liu and Butler 1995) for slug testing
  - WTAQ model (Moench 1997) for constant-rate injection/pumping tests
  - nSIGHTS Software (all types of tests)

Hydraulic Test sequencing – low perm rocks

PSR (pressure shut-in recovery) ->Pulse (withdrawal) ->HI (constant head injection)->HIS (recovery)

- PSR phase – pressure recover towards static conditions.
- Pulse withdrawal test – gives a rough approximation of the borehole near formation properties.
- HI test and the related pressure recovery – provide more quantitative information on the formation properties (with/without skin) and heterogeneities, and possible presence of hydrologic boundaries.



Source:
DEEP BOREHOLE FIELD TEST: DESIGN REPORT
Forward simulation
Author: Ursula Rösli
S o l e x p e r t s A G
03 May 2016

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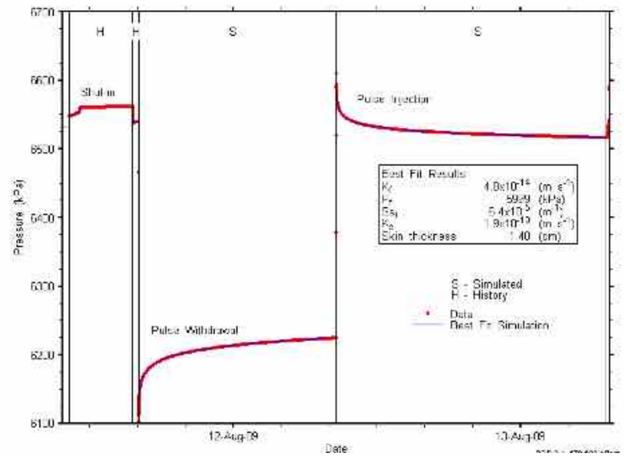
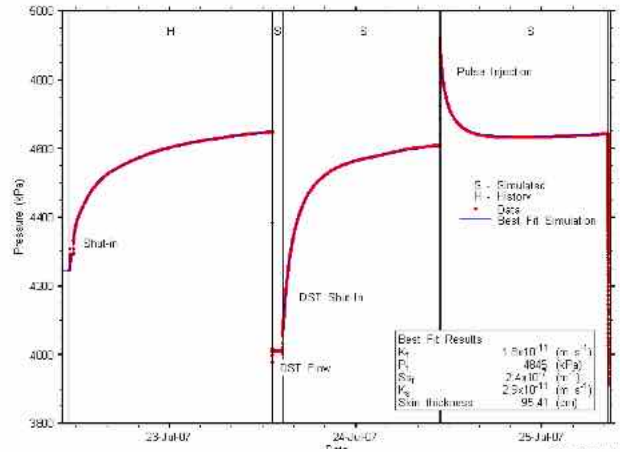
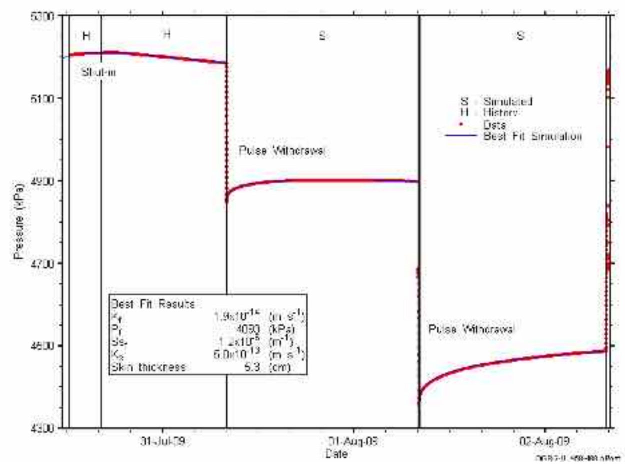
Hydraulic Test sequencing – low perm rocks

Examples:

- Shut In -> PW->PI
- Shut In -> DST->PI
- Shut In -> PW1 ->PW2->PW3





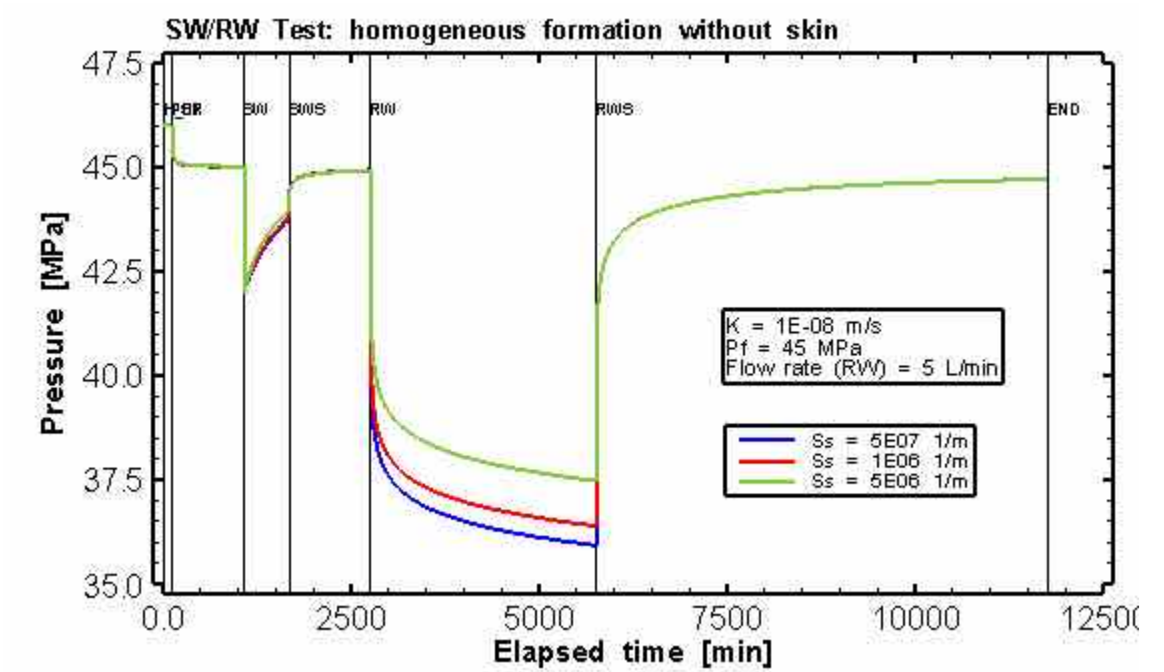


source: *Analysis of Straddle-Packer Tests in DGR Boreholes*
Document ID: TR-08-32
Authors: Randall Roberts and David Chace,
HydroResolutions LLC, Richard Beauheim, and John Avis,
Geofirma Engineering Ltd. ; Revision: 0; Date: April 12, 2011

Hydraulic Test sequencing – higher perm rocks

PSR (pressure shut-in recovery) ->Slug (withdrawal) ->recovery->RW (constant rate withdrawal) -> RWS (recovery)

- PSR phase - pressure recover to static conditions after system installation and packer inflation phase.
- The slug withdrawal test (SW) - rough approximation of the formation properties and the feasibility of a pumping test.
- The shut-in phase after the slug test (SWS) – helps to achieve static formation pressure in rather short time before the start of the following test sequence.
- Pumping test (RW) - and the related pressure recovery should provide more quantitative information on the formation properties (with skin) and heterogeneities, and possible presence of hydrologic boundaries.



Source:
DEEP BOREHOLE FIELD TEST:
DESIGN REPORT
Forward simulation
Author: Ursula Rösli
S o l e x p e r t s A G
03 May 2016

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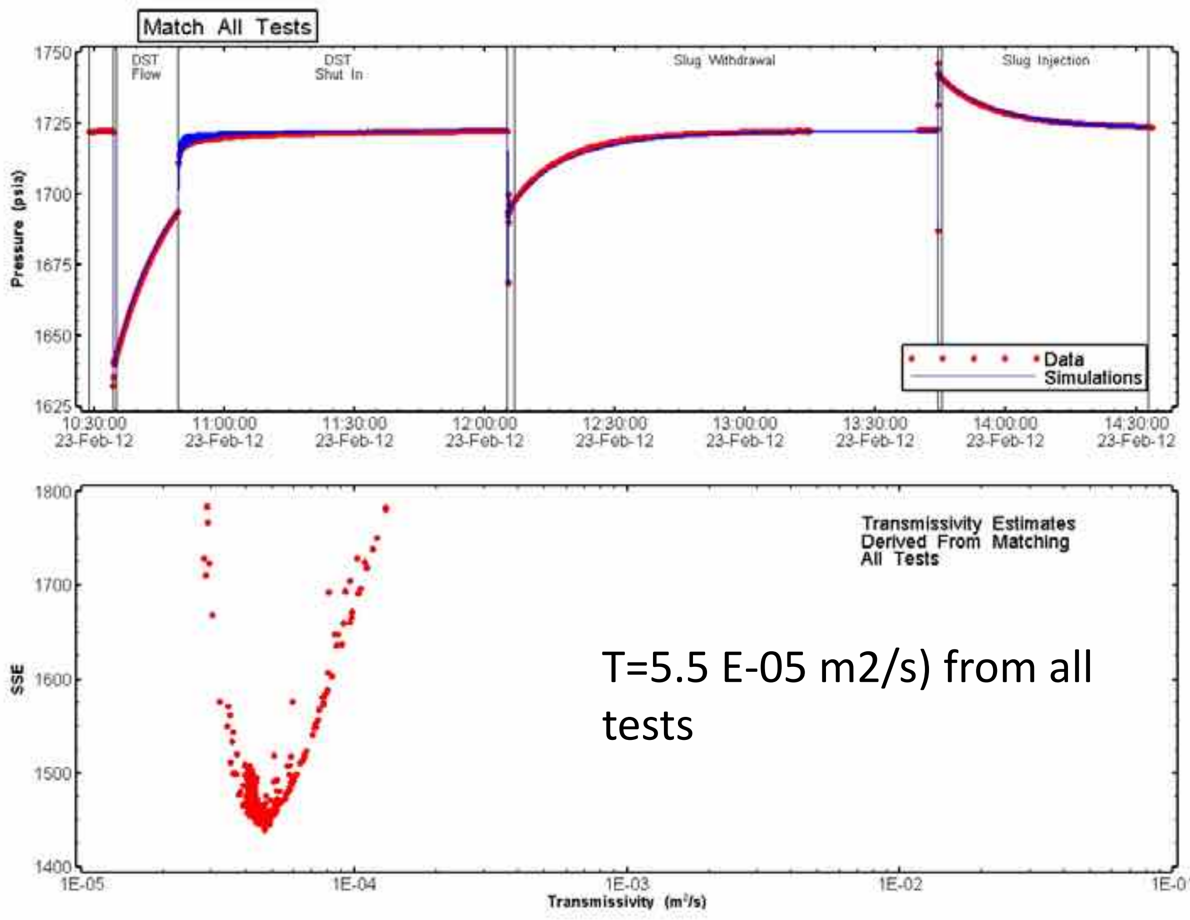
Example Test History Match of a sequence of hydraulic tests using nSIGHTS Software

FutureGen Site



T from slug withdrawal test shown previously was 4.5 E-05 m2/s

Analysis by R. Roberts, HydroResolutions

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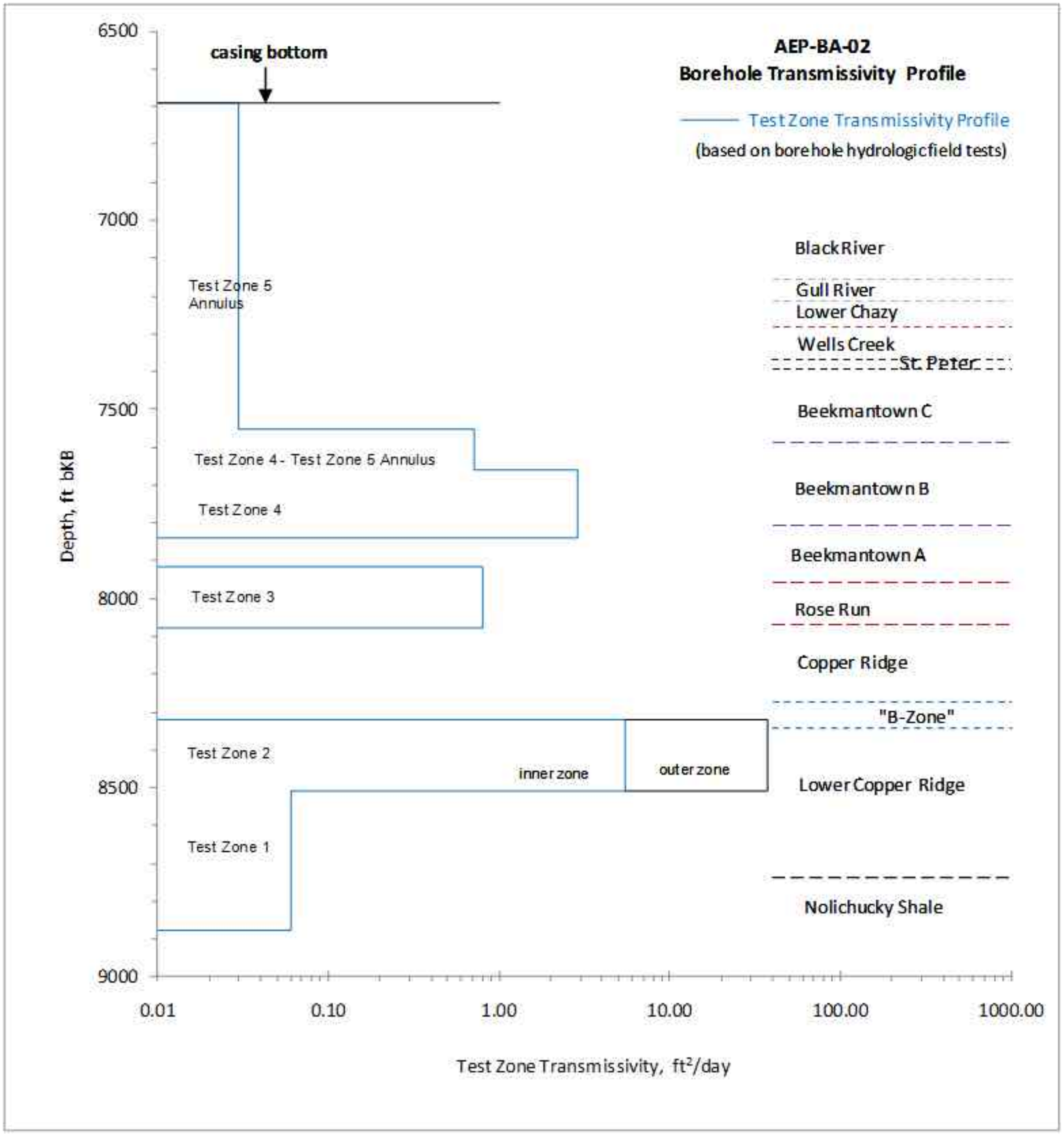
Data from FutureGen site: F. Spane; M. Kelley

Transmissivity Profile Plot

BA-02 Test Well: AEP Mountaineer, West Va

- Summarizes results of Packer Tests conducted in a borehole
- useful for illustrating intervals most suitable for CO2 injection



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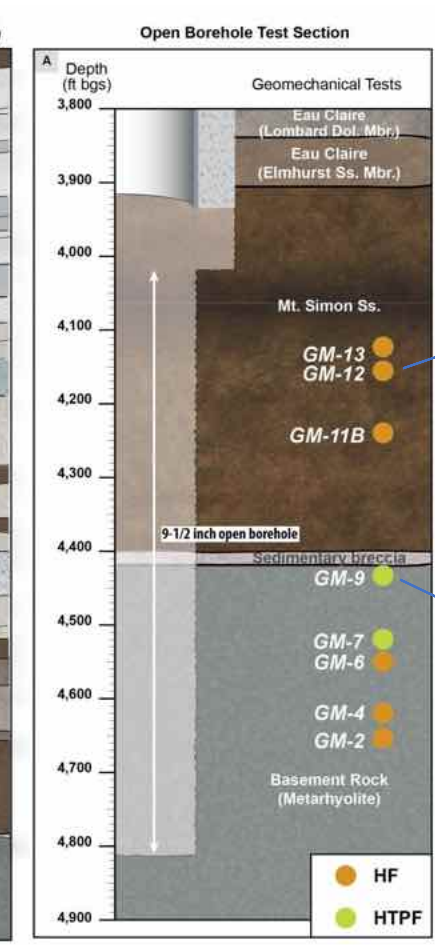
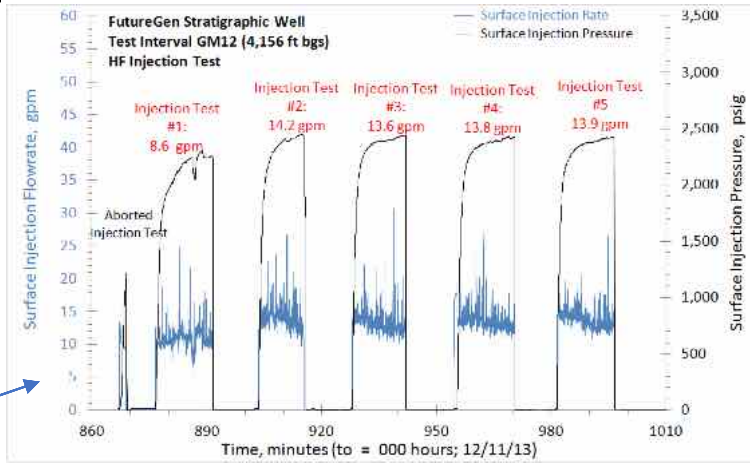
Geomechanical (Stress)Tests

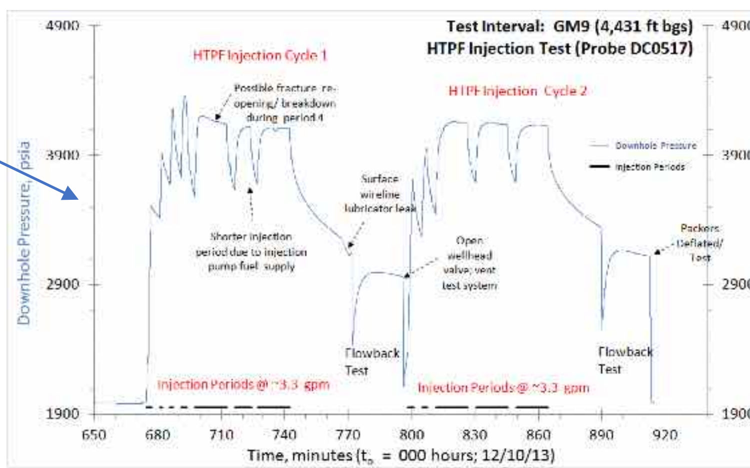
- Hydraulic Fracture (HF) tests (aka mini-frac)
  - these tests create new fractures
  - HF tests provide estimates for σ_H direction and for σ_h magnitude
- Hydraulic Tests on Preexisting Fractures (HTPF)(Cornet, 1993; Haimson and Cornet, 2003).
  - measure the pressure required to reopen preexisting fractures (i.e. the normal stress acting on the fracture)
  - provide a means for determining the magnitude of σ_H, which cannot be precisely constrained using HF tests alone..

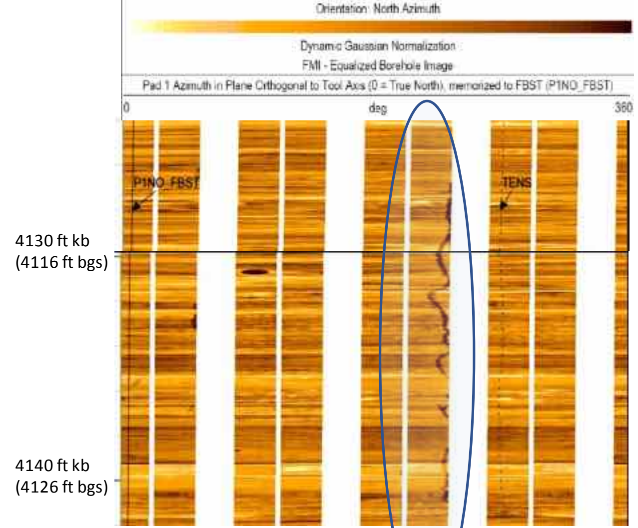
Example Geomechanical (Stress)Tests

(FutureGen Site, Illinois)









FMI Log Image of Fracture Created in HF Test Zone GM-13; Fracture is Vertical and Oriented NE-SW.

- maximum horizontal principal stress, σ_H, is oriented N 51±4°E
- magnitude of σ_h in the Mount Simon from 2 HF tests:
  - σ_h = 3,240 ± 330 psi at 4,156 ft
  - σ_h = 2,800 ± 100 psi at 4,236 ft
- Maintaining injection pressures lower than 2,800 psi at a depth of 4,236 ft should avoid hydraulic fracturing within either the Mount Simon reservoir or the overlying Eau Claire shale caprock.
- The magnitude of σ_H is the largest principal stress (i.e., σ_h<σ_v<σ_H); this implies a regional strike-slip tectonic stress regime.

Source: Cornet, F.H., 2014. Results from the In Situ Stress Characterization Program, Phase 1: Hydraulic Tests Conducted in the FutureGen Stratigraphic Pilot Well. February 2014.

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Summary/Review

- Flowmeter logging is one type of open borehole reconnaissance method for identifying hydraulically conductive intervals that may be candidates for CO_2 storage.
  - Examples were presented from AEP Mountaineer (West Virginia) and Central Ohio, both Cambrian-Ordovician strata
- Five types of discrete interval (packer) hydraulic tests were discussed, including, slug tests, DST tests, pulse tests, constant rate tests, and constant pressure tests
  - Examples were presented from FutureGen (Illinois), AEP Mountaineer (West Virginia), Ohio Geological Survey CO_2 Well #1 (Central Ohio)
- Two types of discrete interval (packer) geomechanical (stress) tests were discussed, including, HF and HTPF tests
  - Example presented from FutureGen (Illinois)
- Equipment requirements for conducting discrete interval hydraulic and geomechanical tests were discussed.
  - Wireline deployable test tools can be attractive option in some cases

Acknowledgments

Information included in this presentation came from several Battelle projects plus information provided by the following individuals and organizations:

- Frank Spane (Pacific Northwest National Laboratory, Richland Washington)
- Ursula Rösli (Solexperts AG of *Mönchaltorf-Zurich,* Switzerland
-- Randall Roberts (HydroResolutions, LLC, Carlsbad, New Mexico)