Phase II CO_2 Sequestration Test
Cincinnati Arch MRCSP Site

for: **Regional Carbon Sequestration Partnerships Annual Review**
November 16-19, 2009

by: **Mark E. Kelley, P.G. (Battelle)**

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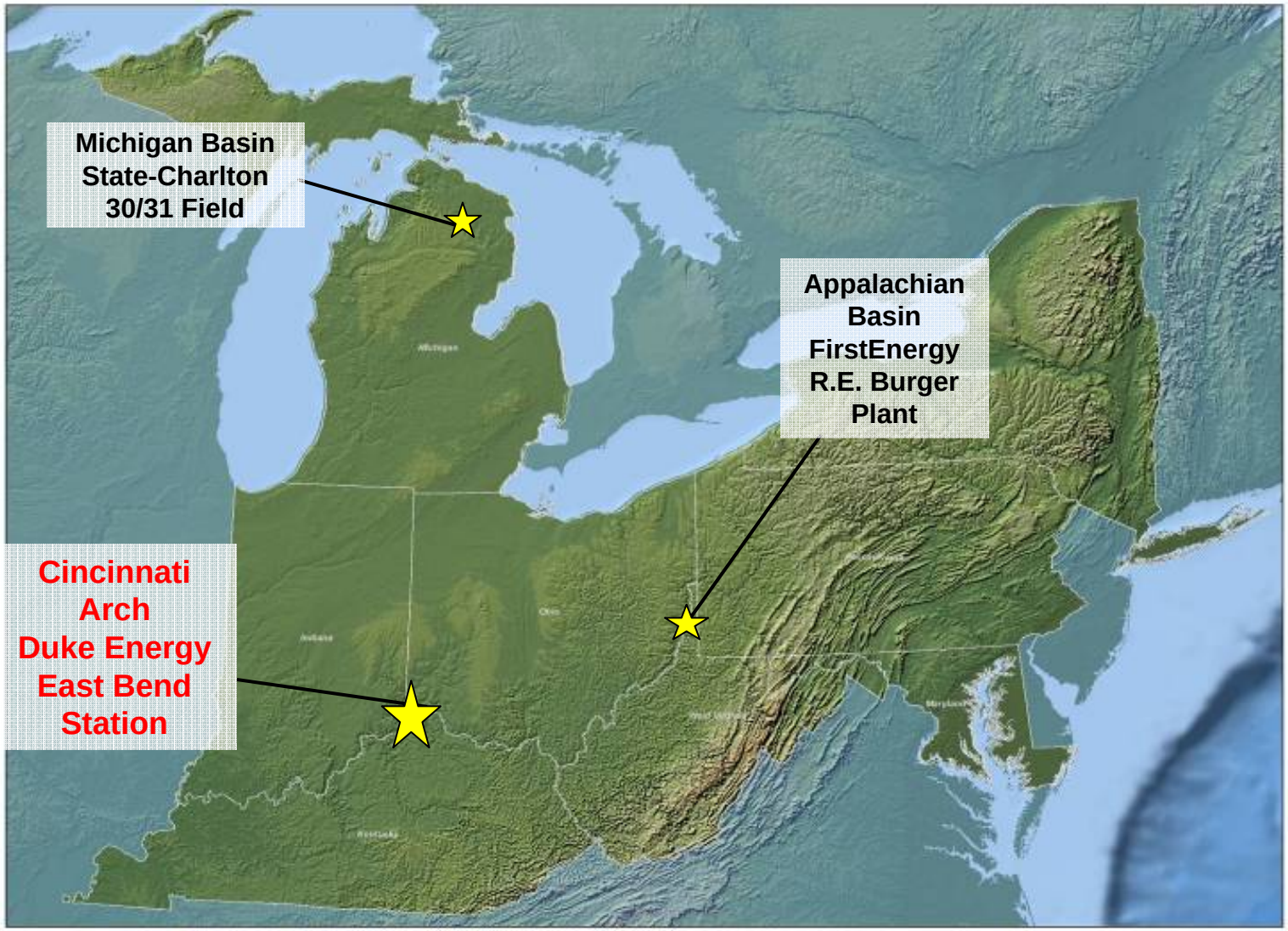
MRCSP Phase II Field Demonstration Sites



Site Location
Duke Energy East Bend Station

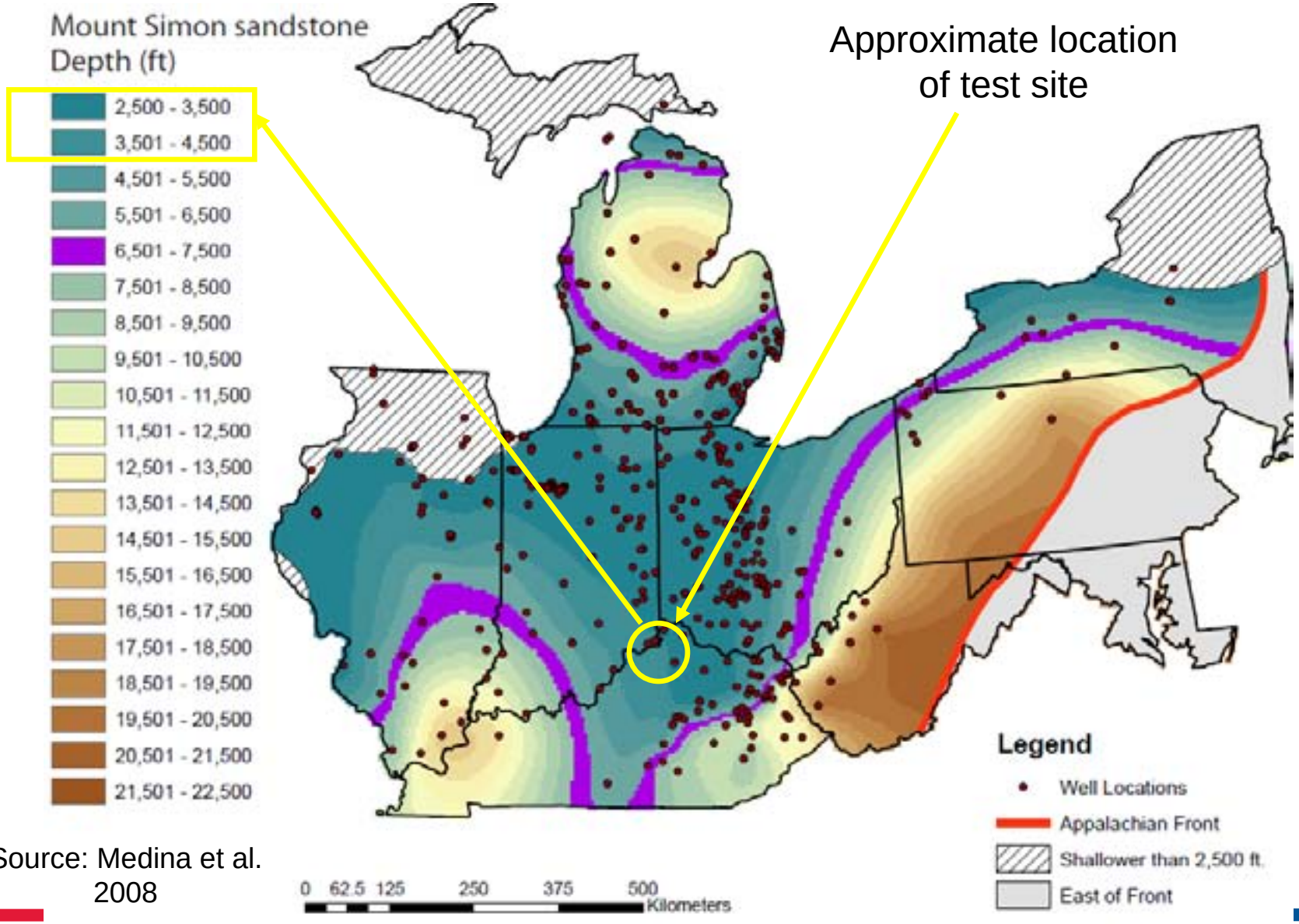
650 MW coal-burning power plant

1,800 acres on the floodplain along a bend in the Ohio River

Regional Geologic Studies Provided Foundation for this Study (Wickstrom et al., 2005; Rupp et al, 2006)

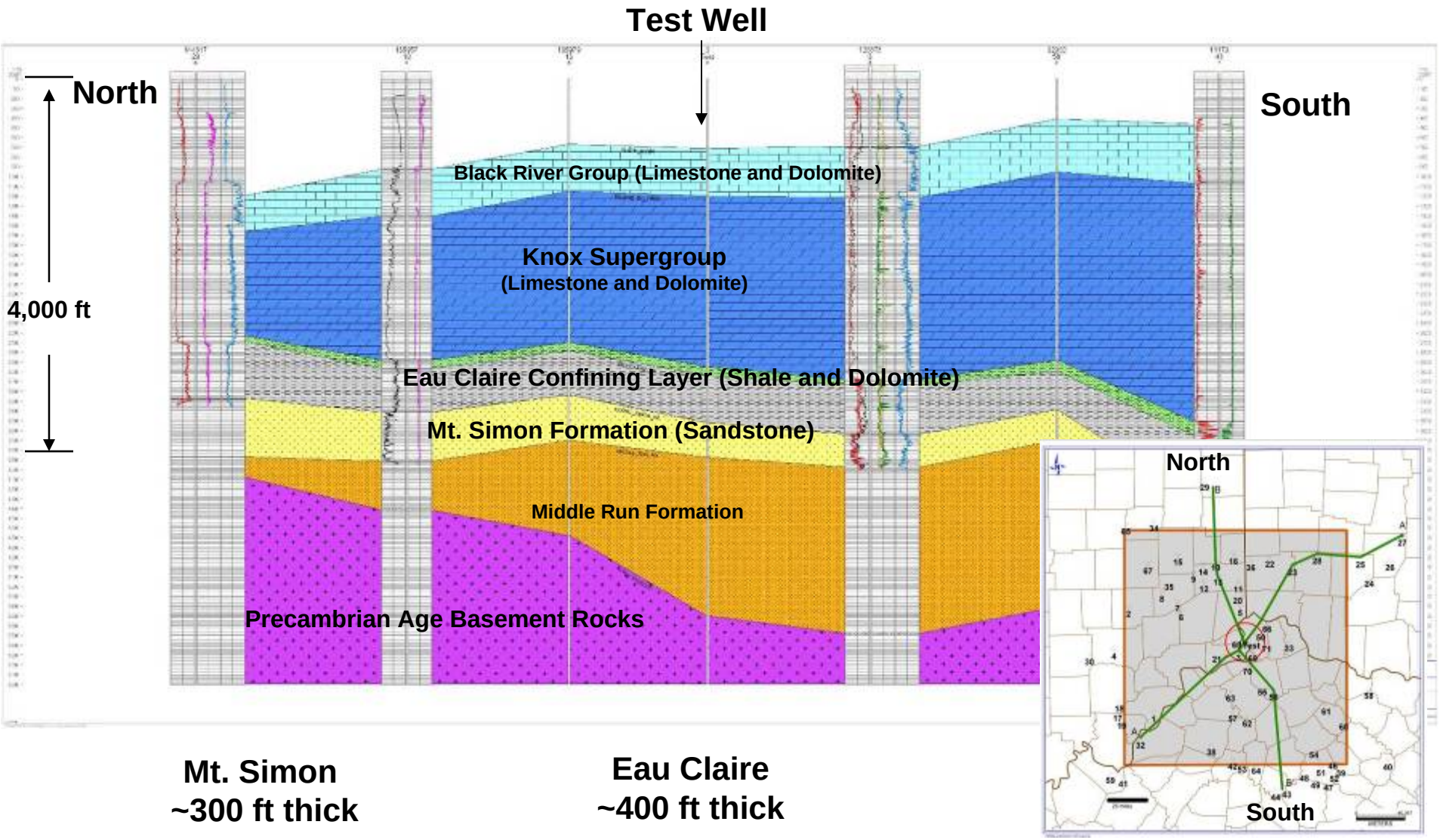
- The Mt. Simon Sandstone has properties appropriate for a CO_2 reservoir (depth, good porosity and permeability, regional extent)
- The Mt. Simon is overlain by the Eau Claire Formation, a thick sequence of shale and dolomite that serves as a confining layer for the Mt. Simon
- Located in an area with many large CO_2 sources

Mt. Simon has regional significance due to its widespread occurrence in the mid-west U.S.



Source: Medina et al. 2008

Regional Geologic Cross-Section Through Study Area



Mt. Simon
~300 ft thick

Eau Claire
~400 ft thick

Overview of East Bend CO2 Sequestration Project Activities

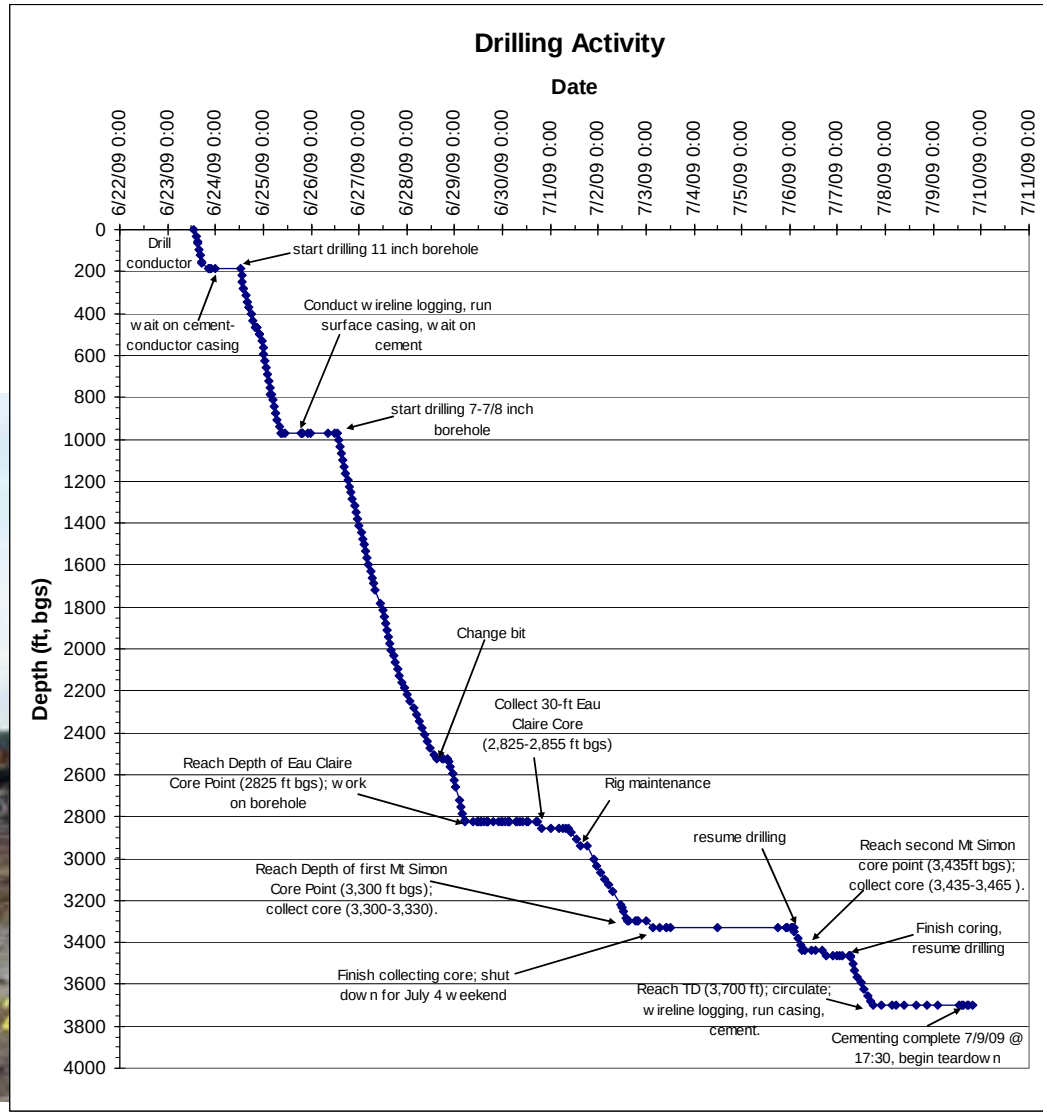
- 2D Seismic Survey
- Permitting
- Well Drilling/Logging/Coring/Completion
- Brine Injection Test
- Baseline VSP Survey
- CO2 Injection Test
- Post Injection USDW Monitoring (ongoing thru Sept 2011)

Permitting

- Class V Underground Injection Control (UIC) Permit Issued by the U.S. EPA Region IV (effective 3/26/2009 to 3/26/2012)
  - Authorizes injection of CO_2
  - Specifies well construction requirements
  - Specifies well abandonment procedure
- "Authority to Drill a Well" Permit issued by the Kentucky Dept Natural Resources, Division of Oil and Gas, Permit #105821 (issued 6/15/2009)
  - Authorizes drilling of well
  - Specifies well construction requirements

Injection Well Drilling

- Primary drilling phase June 23 to July 9, 2009
- Coring and geophysical logging included
- Demobilized drill rig and equipment from the site July 10 – 17



Injection Well Completion (July 23 – July 30)

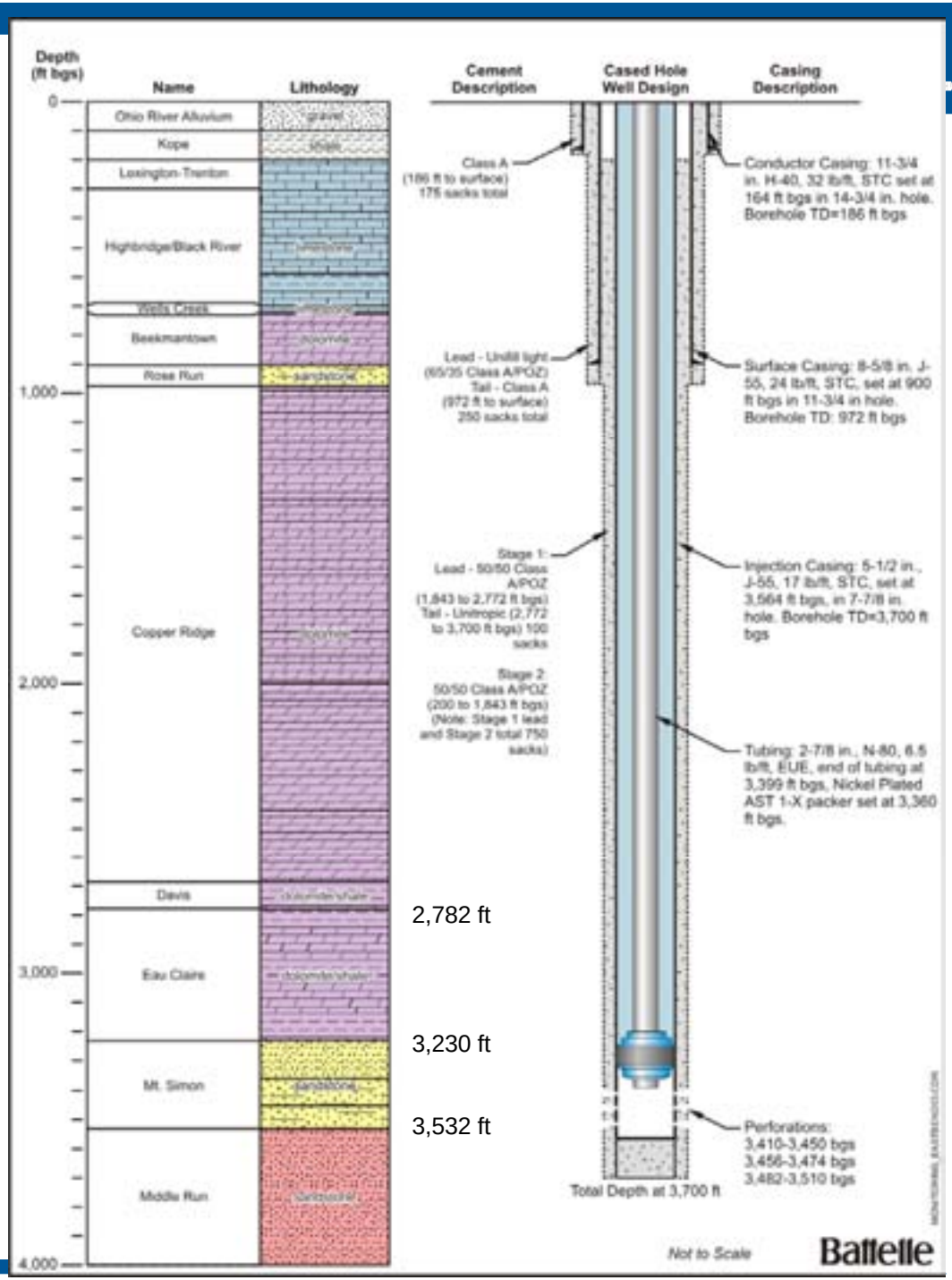
- ran pressure and temperature log, cement bond log on the long-string casing, and a baseline pulsed neutron capture (PNC) log
- cleaned well with scraper and circulated with clean filtered KCl brine
- perforated 86 feet of the long-string casing (4 shots per foot); acidized well with 1,000 gals 15% HCl; swabbed back 694 bbls (29,148 gals) of fluid and collected Mt Simon brine sample for chemical analysis

Injection Well Completion/Testing

- July 31 – August 3
  - conducted two series of brine injection tests. At completion, set bridge plug above perforations in preparation of VSP survey
- August 12 – 15
  - conducted baseline VSP survey with Appalachian Geophysics and Seismic Reservoir 2020
  - At completion, installed injection tubing, packer and annular fluid and conducted mechanical integrity test on well in preparation of CO_2 injection test
- August 28
  - Submitted well completion report to U.S. EPA Region IV
- September 10
  - Received EPA approval of well completion report and mechanical integrity test results
- September 20 – 27
  - Conducted CO_2 injection test (~1,000 tonnes)

Well Diagram

- Total drilled depth 3,700 ft; total well depth 3,564 ft
- 3 casing strings; conductor and surface casing cemented to surface for protection of USDW aquifer; long string casing cemented to near surface
- 5-1/2 inch diameter long string casing with 86 ft of perforations in the lower Mt. Simon
- Perforations divided into 3 sections to allow brine injection testing of separate intervals

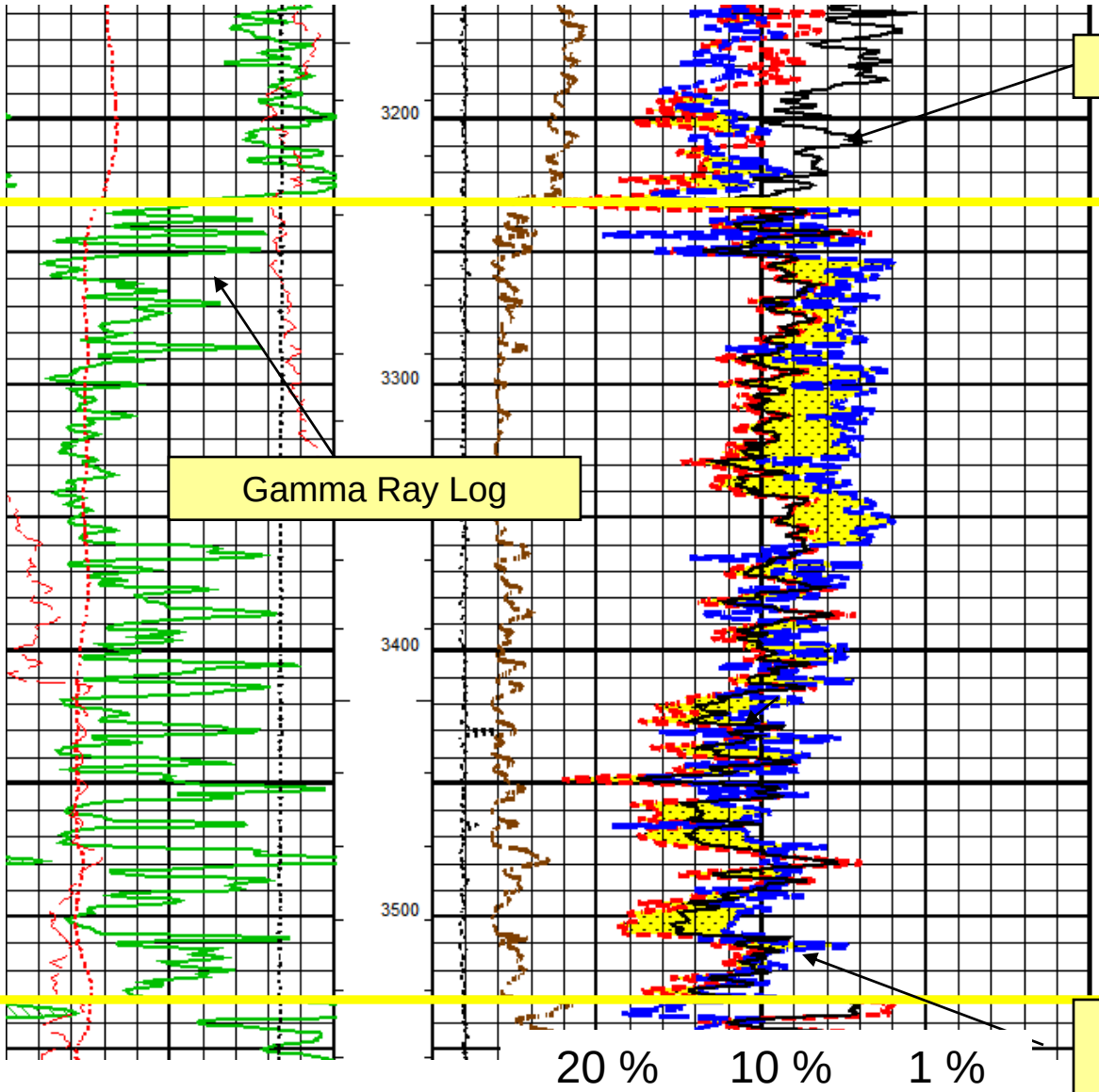


Mechanical Integrity Testing of Injection Well

Geophysical Logging Program

- Surface hole (973′-150′):
  - Gamma ray, compensated neutron, compensated density, photoelectric, caliper, temperature, spontaneous potential, sonic scanner/cement bond
- Bottom hole section:
  - Gamma ray, compensated neutron, compensated density, photoelectric, caliper, temperature, high resolution laterolog, spontaneous potential, sonic scanner/cement bond, formation micro-imager & directional (3700′-900′)
  - Nuclear magnetic resonance (3700′-2640′ & 1100′-900′)
  - Elemental capture spectroscopy (3680′-3204′ & 1100′-900′)

Mt Simon Porosity

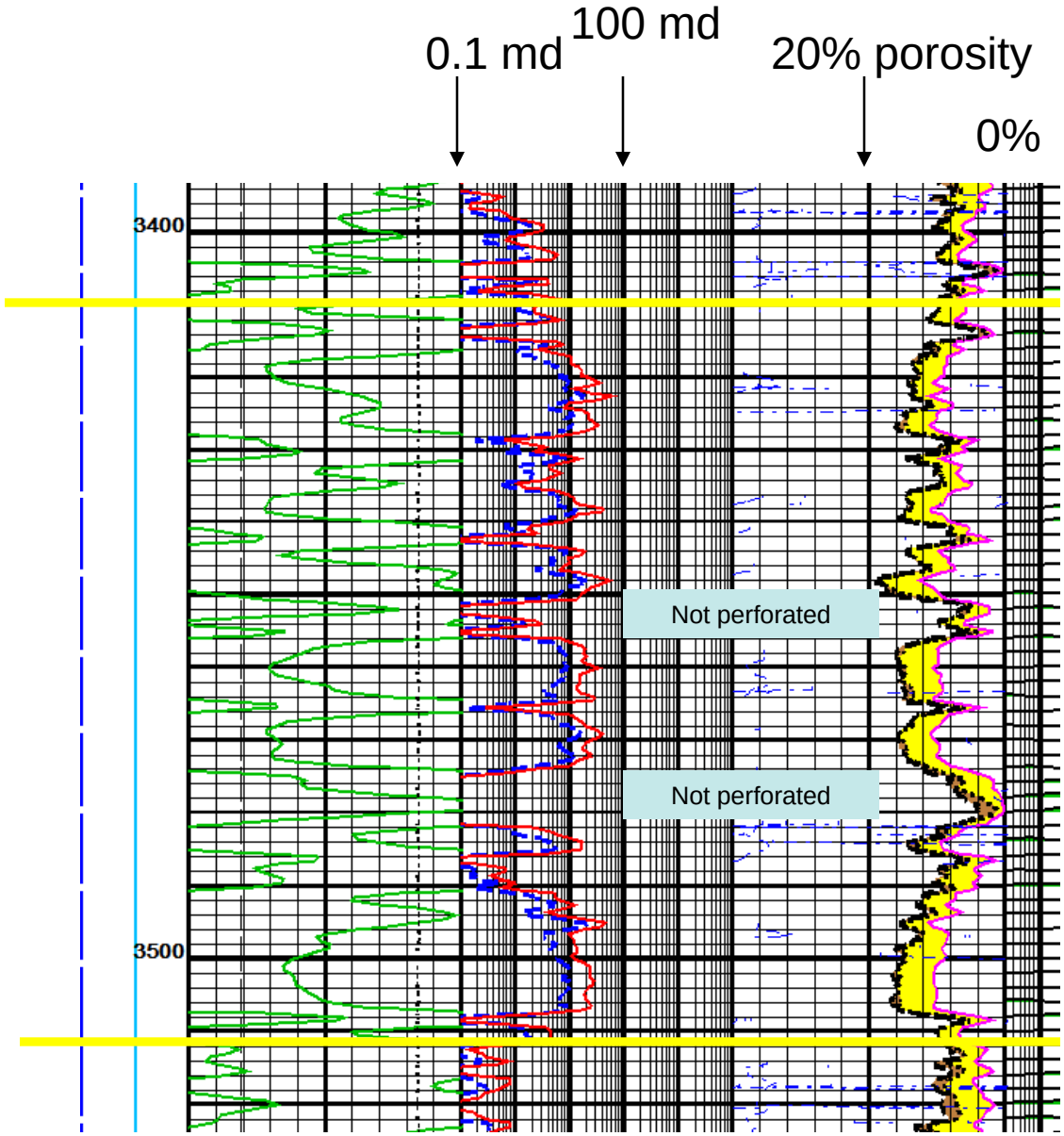


3,230′ is the contact between Eau Claire Sha and the Mt Simon Sandstone.

Porosity in the Mt. Simo is higher in the lower portion, up to 18%

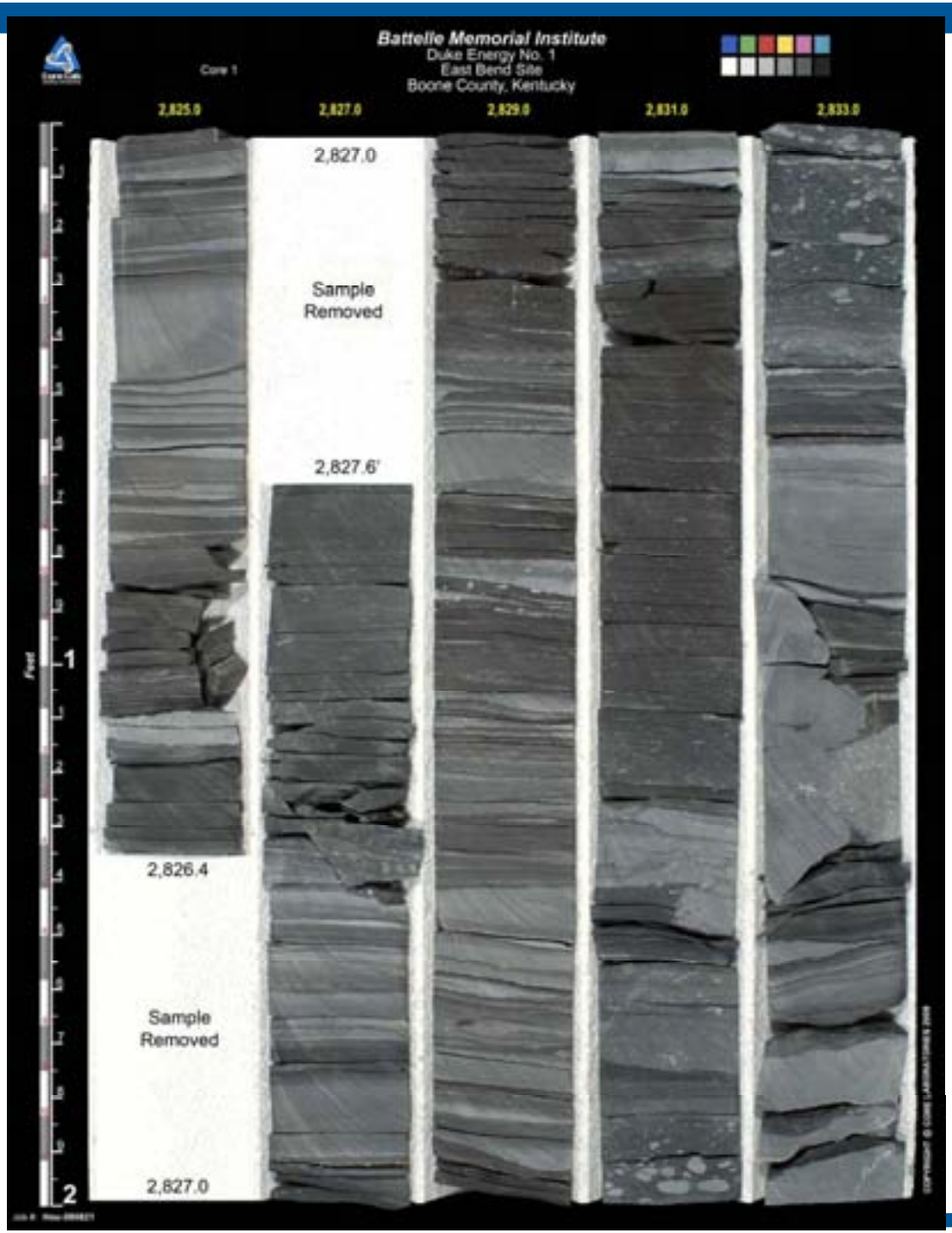
Lower Mt. Simon Permeability

- Nuclear Magnetic Resonance (NMR) Log across perforated section from 3,410-3,510
- Within this zone, permeability is about equally split between 1-10 and 10-100 millidarcies (md). Nothing above 100 md



Coring Program

- **Conventional Core (3 30-ft cores)**
  - Eau Claire: 2825′-2857.3′ (32.3′ recovery)
  - Mt. Simon: 3300′-3330.5′ (30.5′ recovery)
  - Mt. Simon: 3435′-3458.7′ (23.7′ recovery)
- **Sidewall (rotary type) Core (20 samples)**
  - Copper Ridge: 1674′, 2128′, and 2530′
  - Eau Claire: 2800′, 2895′, 3062′, 3190′, and 3205′
  - Mt. Simon: 3351′, 3375′, 3383′, 3395′, 3427′, 3464′, 3470′, 3472′, 3500′, and 3504′
  - Middle Run: 3557′, and 3618′



Eau Claire (2,825' – 2,857.5')

- Shale, limestone, very fine-grained calcareous sandstone, argillaceous calcareous sandstone, and conglomerate
- Laminated to contorted bedding; scattered rip-up clasts and skeletal fragments (brachiopods?); locally thinly interbedded lithologies

Upper Mt. Simon (3,330' – 3,330.5')

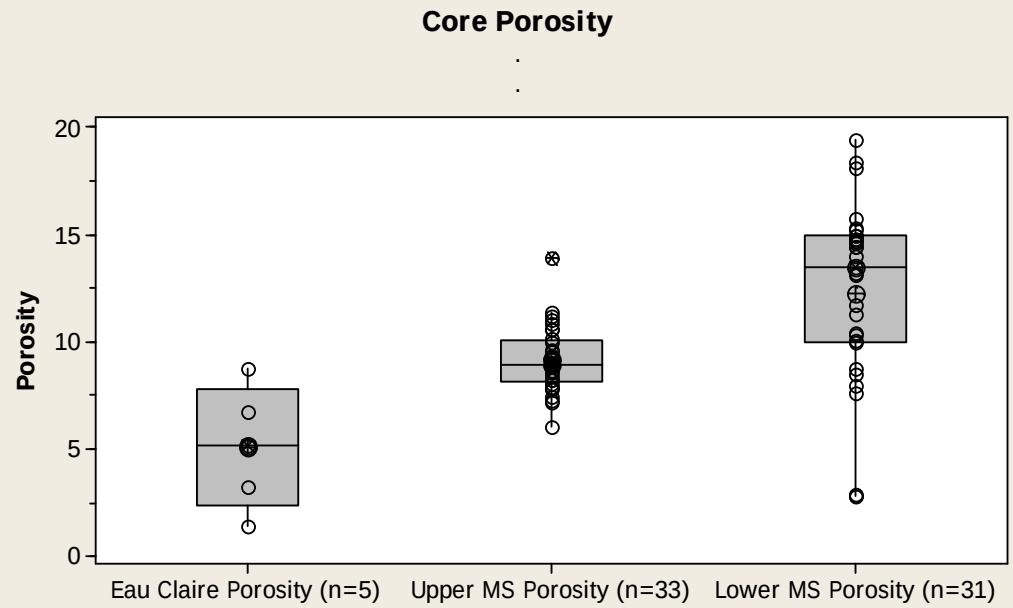
- Very fine- to medium-grained but mainly fine-grained sandstone; rare argillaceous sandstone.
- Cross bedded to planar bedded, and less commonly rippled.
- Locally bioturbated and burrowed, with *Skolithos*-type burrows most common; rip-up clasts are rare; dark gray laminae on millimeter scale are concentrations of clay and organics.

Lower Mt. Simon (3,435' – 3,458.7')

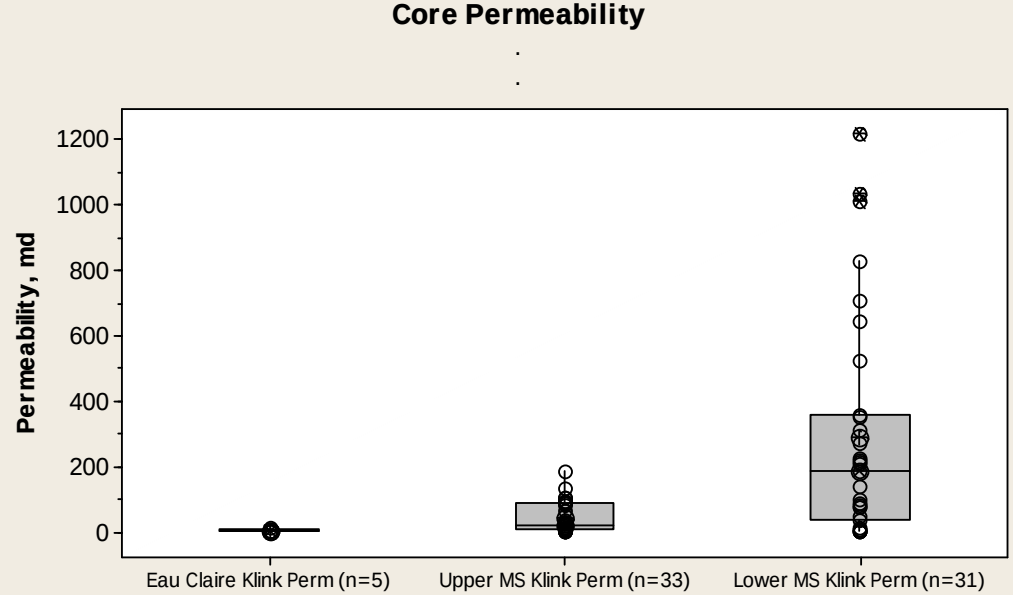
- Very fine- to medium-grained sandstone and argillaceous sandstone.
- Cross bedded, planar bedded to rippled, with some wave ripples
- Minor bioturbation and burrowing, with *Skolithos* identified
- Argillaceous sandstone is medium light gray to medium dark gray; planar bedded and rippled to bioturbated.

Core Porosity and Permeability

- Eau Claire has lowest porosity and permeability
- Within the Mt. Simon, both porosity and permeability are higher in the lower Mt Simon than the Upper Mt Simon
- Core permeability higher than wireline permeability



data includes whole core and sidewall core



Results based on whole core and sidewall core data

Mount Simon Brine Geochemistry

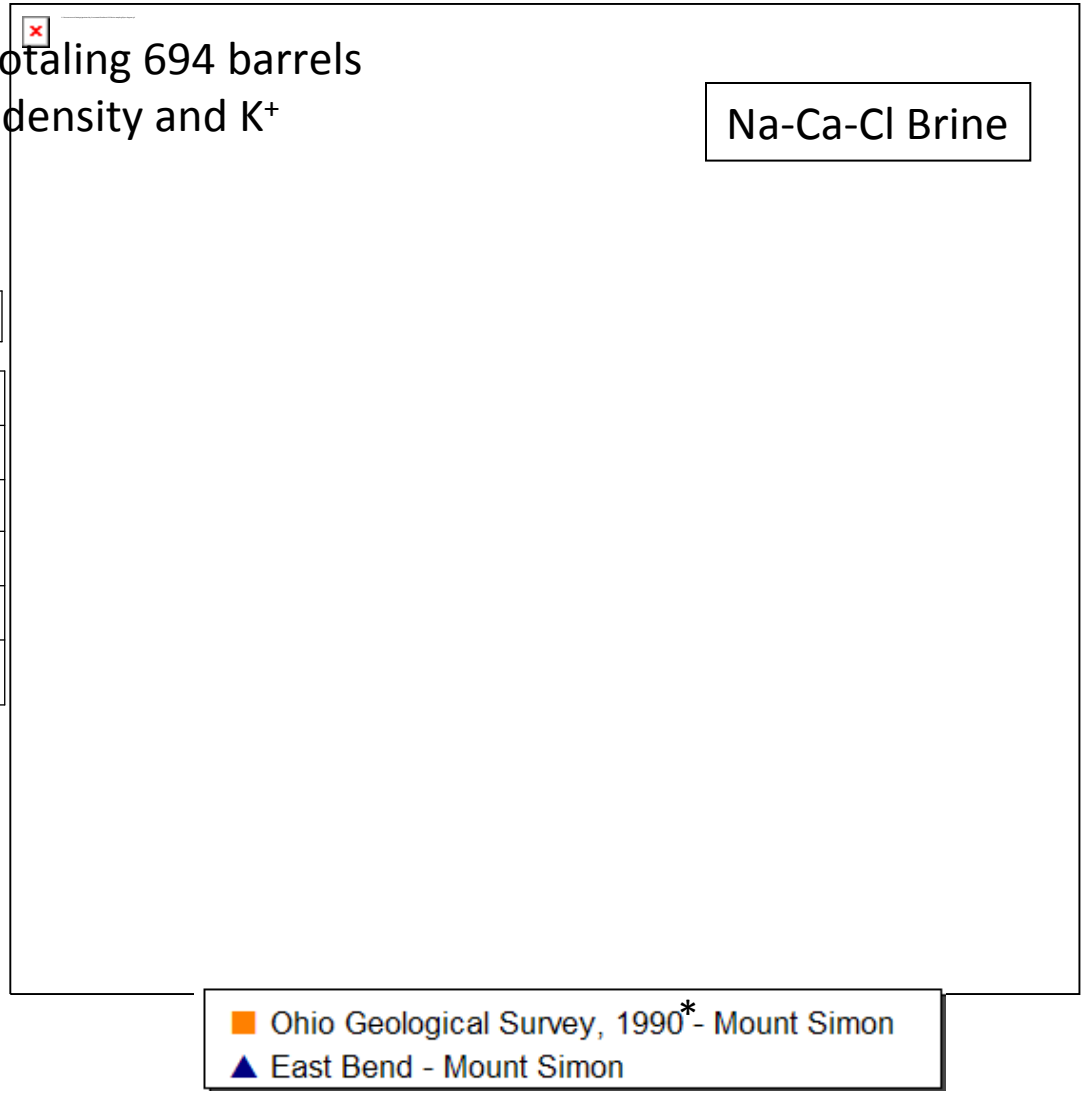
- 57 swabs taken prior to sampling, totaling 694 barrels
- Monitored pH, temp, conductivity, density and K^+ concentration

(all mg/L)

Final pH	*1.11*	**TDS**	203,000

Major Cations		**Major Anions**	
Na^+	36,900	**Cl^-**	118,000
Ca_2^+	18,700	**SO_4^{2-}**	694
Mg^{2+}	2,370	**Br^-**	529
K^+	922	**F^-**	ND
Sr^{2+}	434	**HCO_3^-**	ND

Minor Constituents	
Fe	84.3
SiO_2	47.3
Li	20.1
Mn	19.1
B	7.24
Al	6.3
Ba	0.4

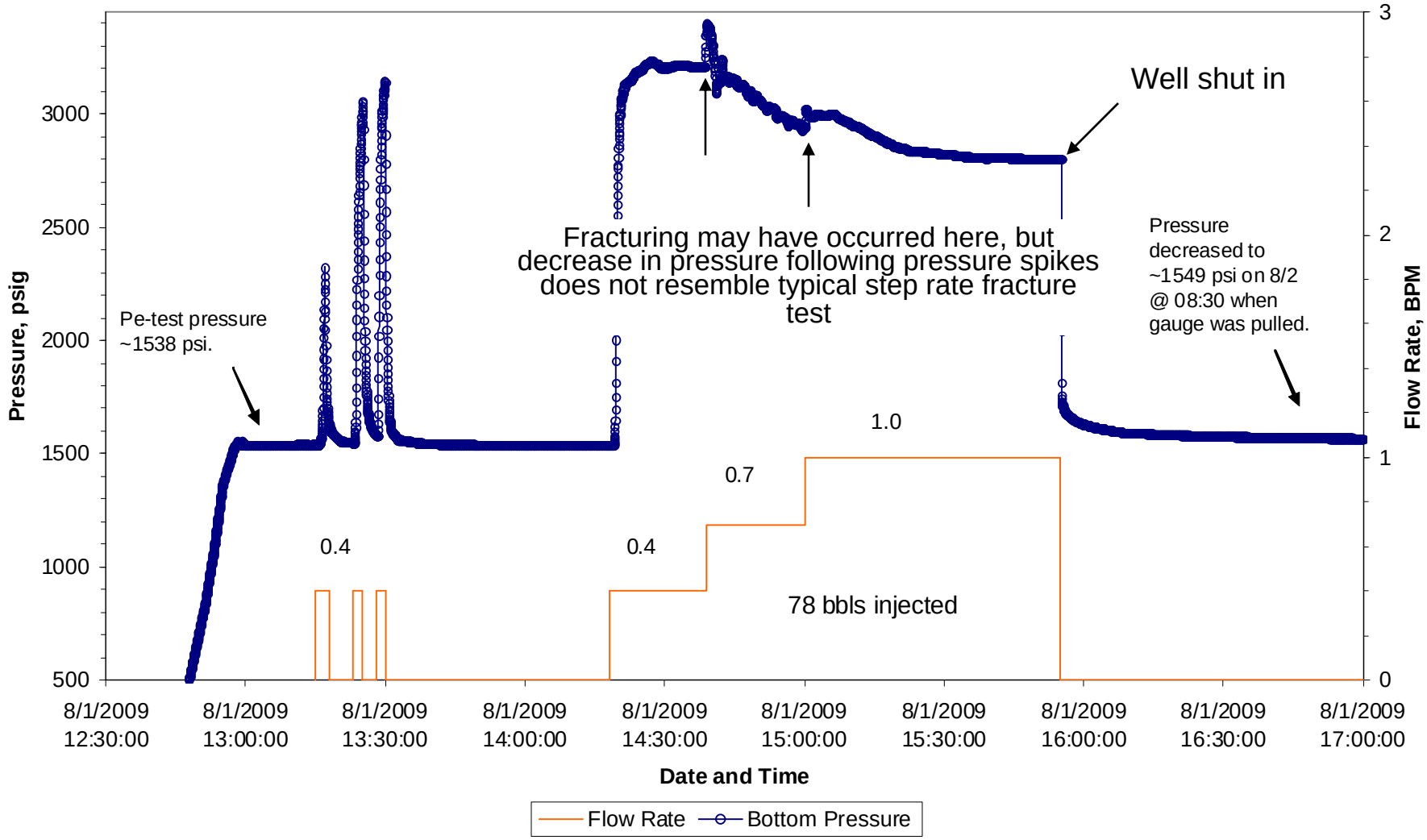


**Ohio Geological Survey, 1990. Water Chemistry of Mount Simon. (western Ohio)*

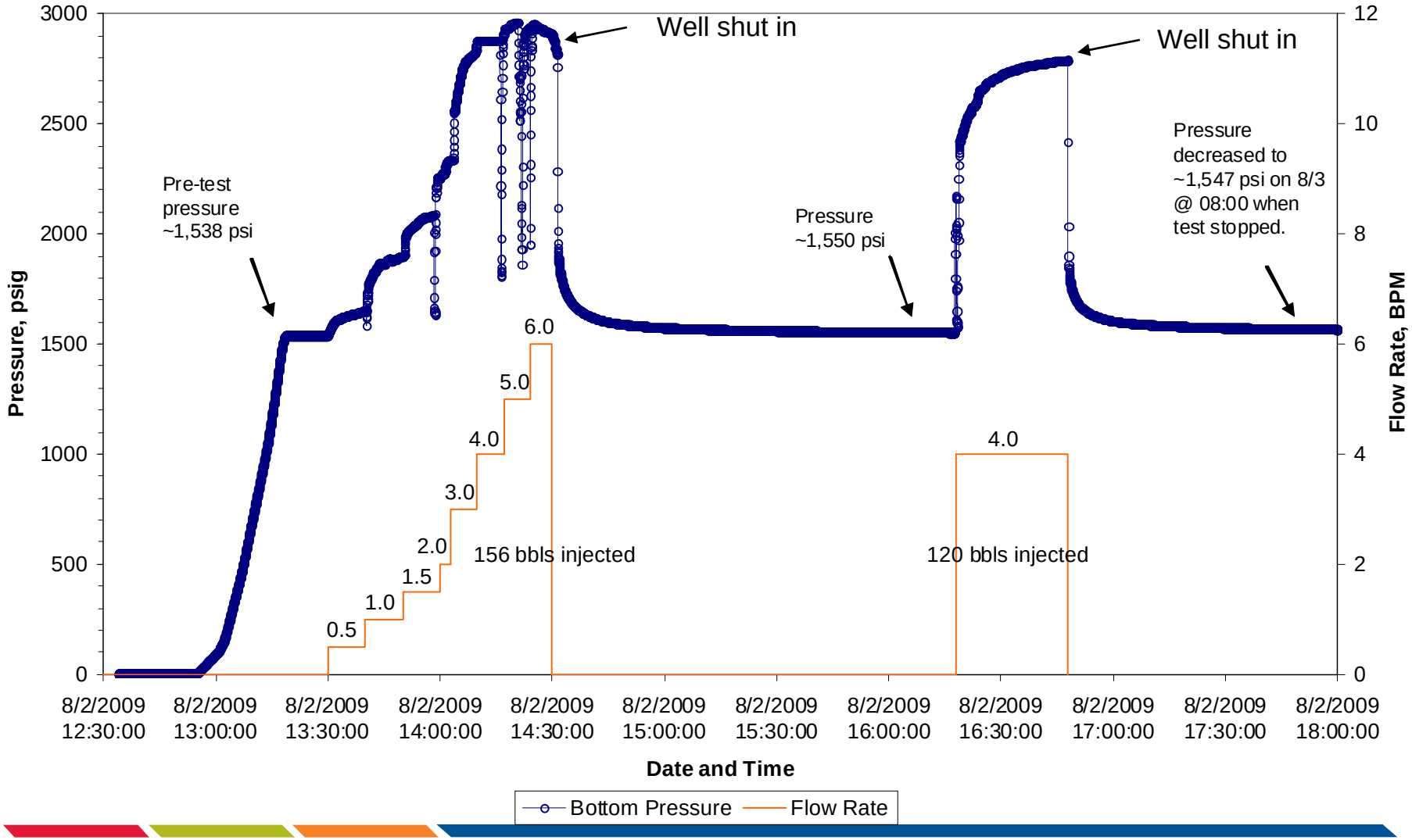
Cased Hole Brine Injection Tests

- Objectives
  - Determine fracture pressure of Mt. Simon
  - Evaluate injectivity – what injection rate can be achieved with brine water?
  - Determine hydraulic parameters of the Mt. Simon (e.g. transmissivity, permeability) for use in reservoir modeling
- Two series of tests were conducted
  - Day 1 – the upper 40′ perforated section (3,410′-3,450′) was isolated and tested. Total of 50 bbls injected.
  - Day 2 – the entire 100′ perforated section (3,410′-3,510′) was isolated and tested. Total of 276 bbls injected.

Day 1 Brine Injection Test Results
Test Interval 3,410 to 3,450 ft
(Gauge at 3,340 ft, Bridge Plug at 3,454 ft)



Day 2 Brine Injection Test Results
Test Interval 3,410 to 3,510 ft
(Gauge at 3,340 ft)



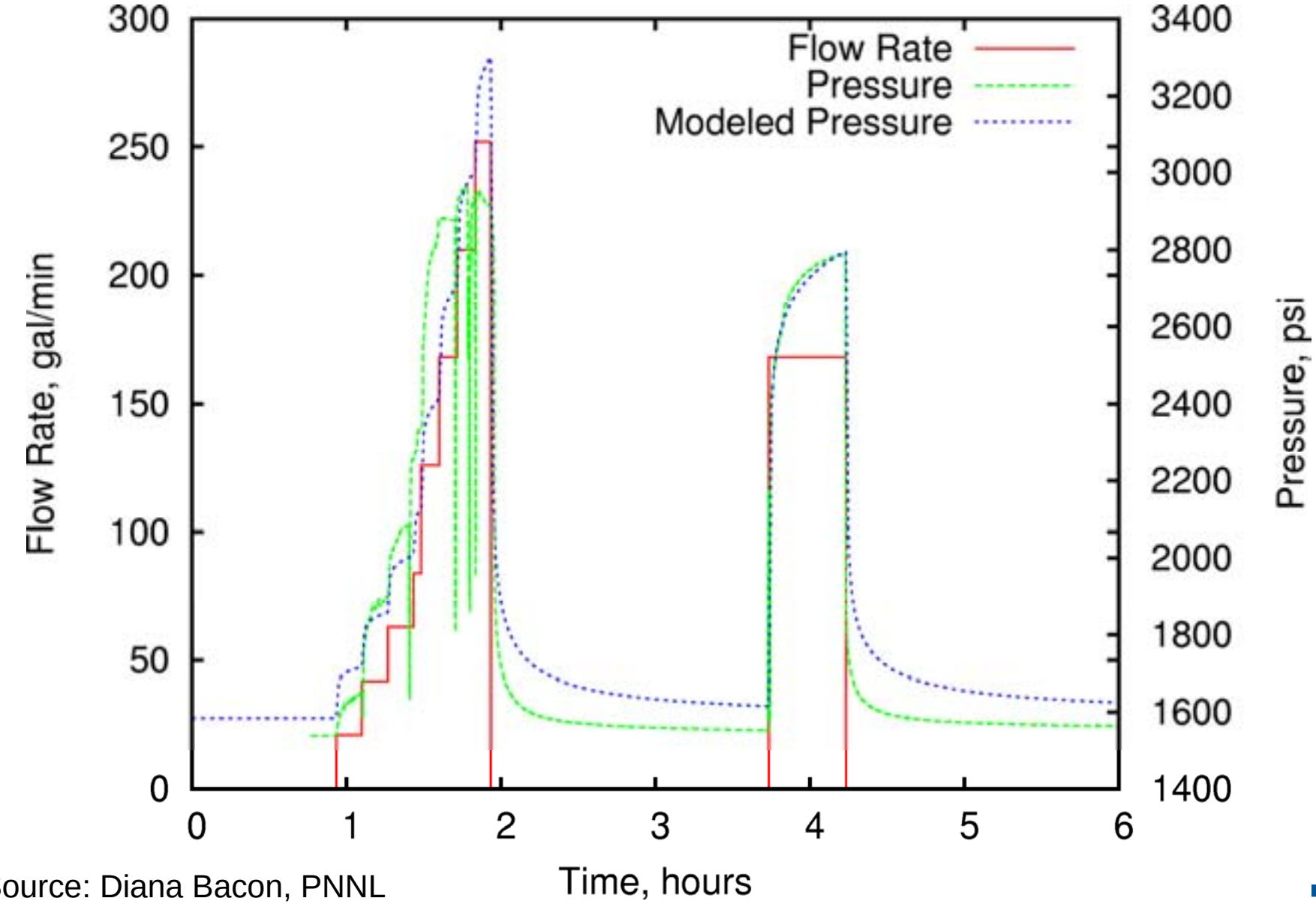
Results of Brine Injection Tests

Parameter/Analysis Method	Test #1	Test #2
Permeability, k (After Closure Analysis), md	78	81
Permeability, k (Pressure Transient Analysis), md	93	126 (82)[a]
Reservoir pressure, P* (After Closure Analysis), psia	1,560	1,566
Reservoir pressure, P* (Pressure Transient Analysis), psia	1,561	1,565
Fracture Pressure (Step-Rate Analysis), psi	NA	2,857
Fracture Gradient (Step-Rate Analysis), psi/ft	NA	0.855
Fracture Closure Time, tc (Regression Analysis), hr^{-1}	NA	0.59
Flow capacity, kh (After Closure Analysis), md-ft	3,123[b]	8,127[c]
Flow capacity, kh (Pressure Transient Analysis), md-ft	3,720[b]	12,625[c]
Test interval length, h	40	100

a. A value of 126 is obtained when injection data from step-rate and constant rate tests are used; a value of 82 was obtained when only the constant rate injection data were used.
b. Based on 40 ft test interval
c. Based on 100 ft test interval

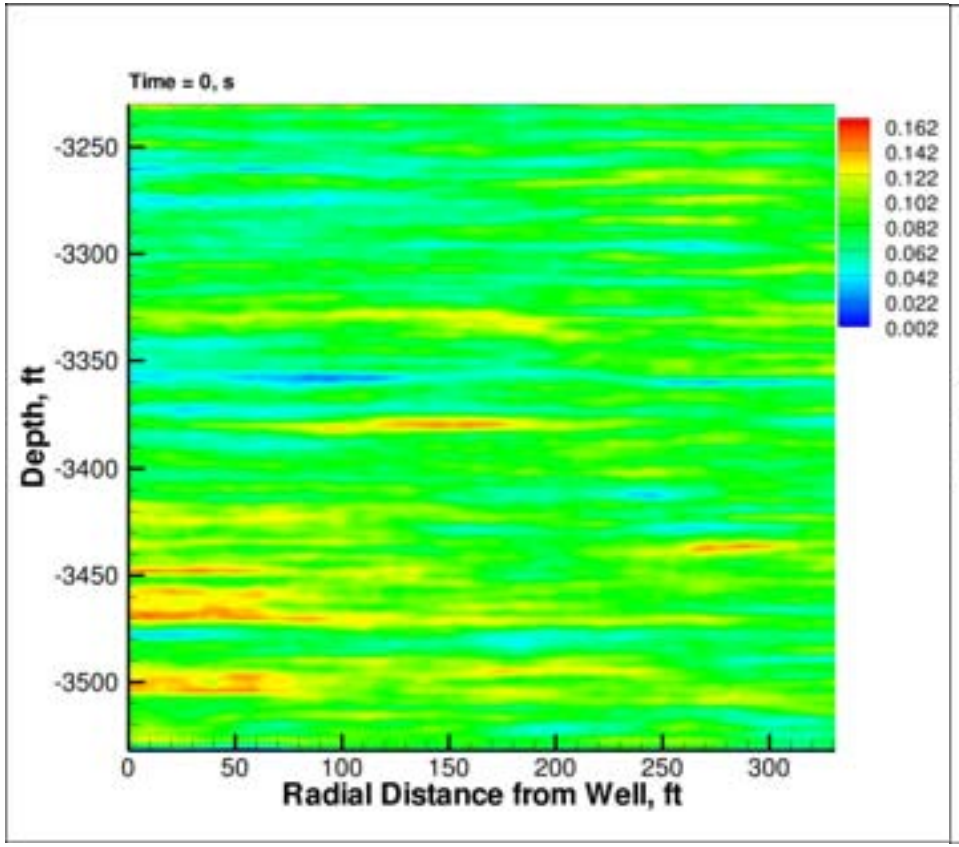
Reservoir pressure P* and fracture pressure are based on gauge depth of 3,340 ft bgs

STOMP Model Simulation of Brine Injection Test (Day 2)

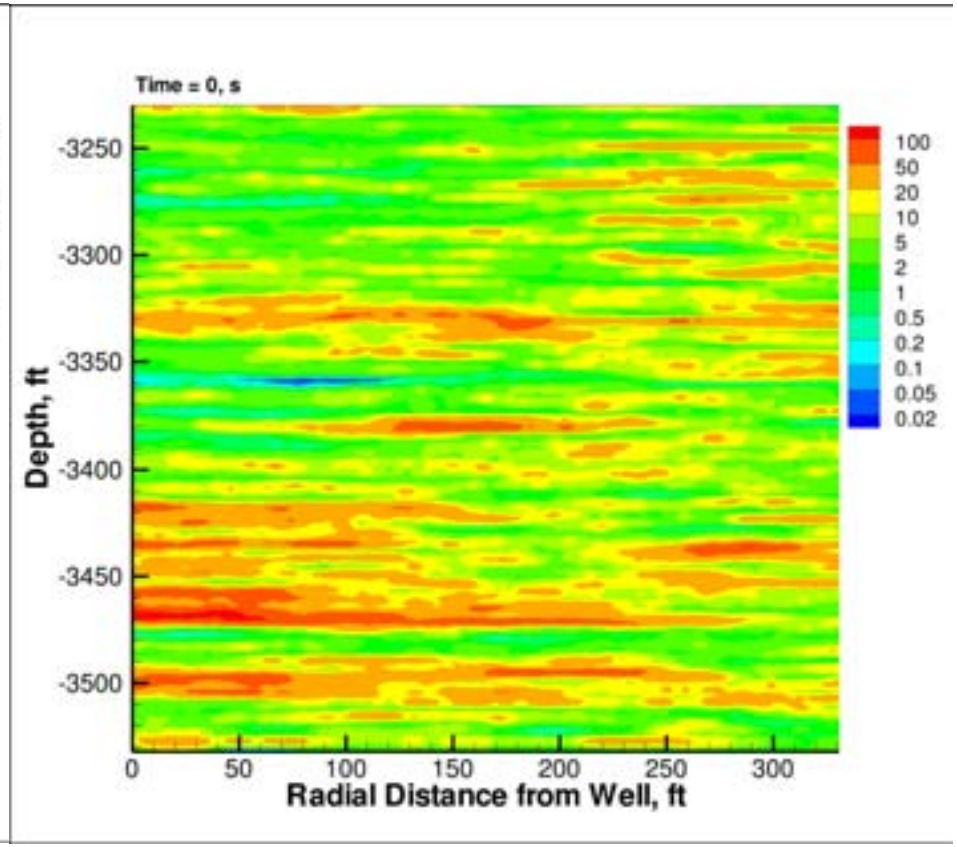


Source: Diana Bacon, PNNL

Porosity and Permeability Distributions for STOMP Model Simulation of Brine Injection Test



Porosity

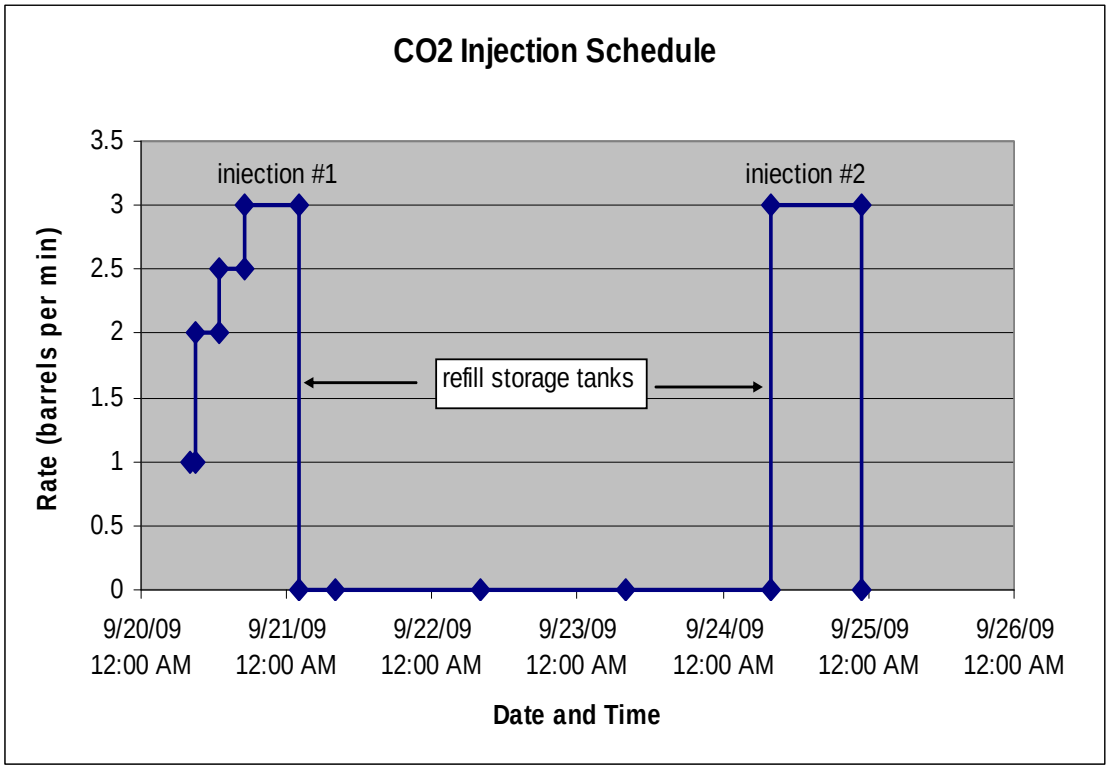


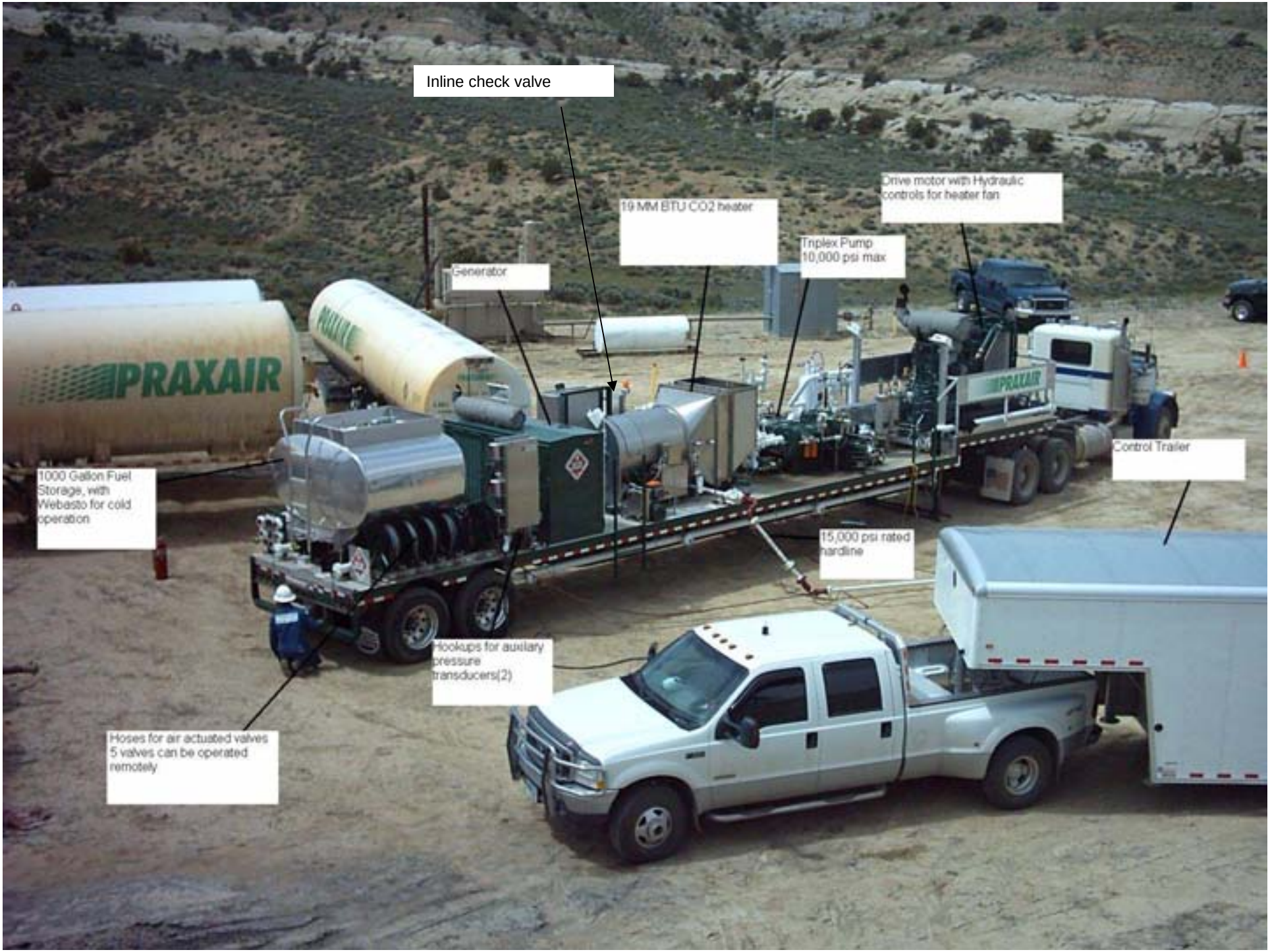
Permeability

Source: Diana Bacon, PNNL

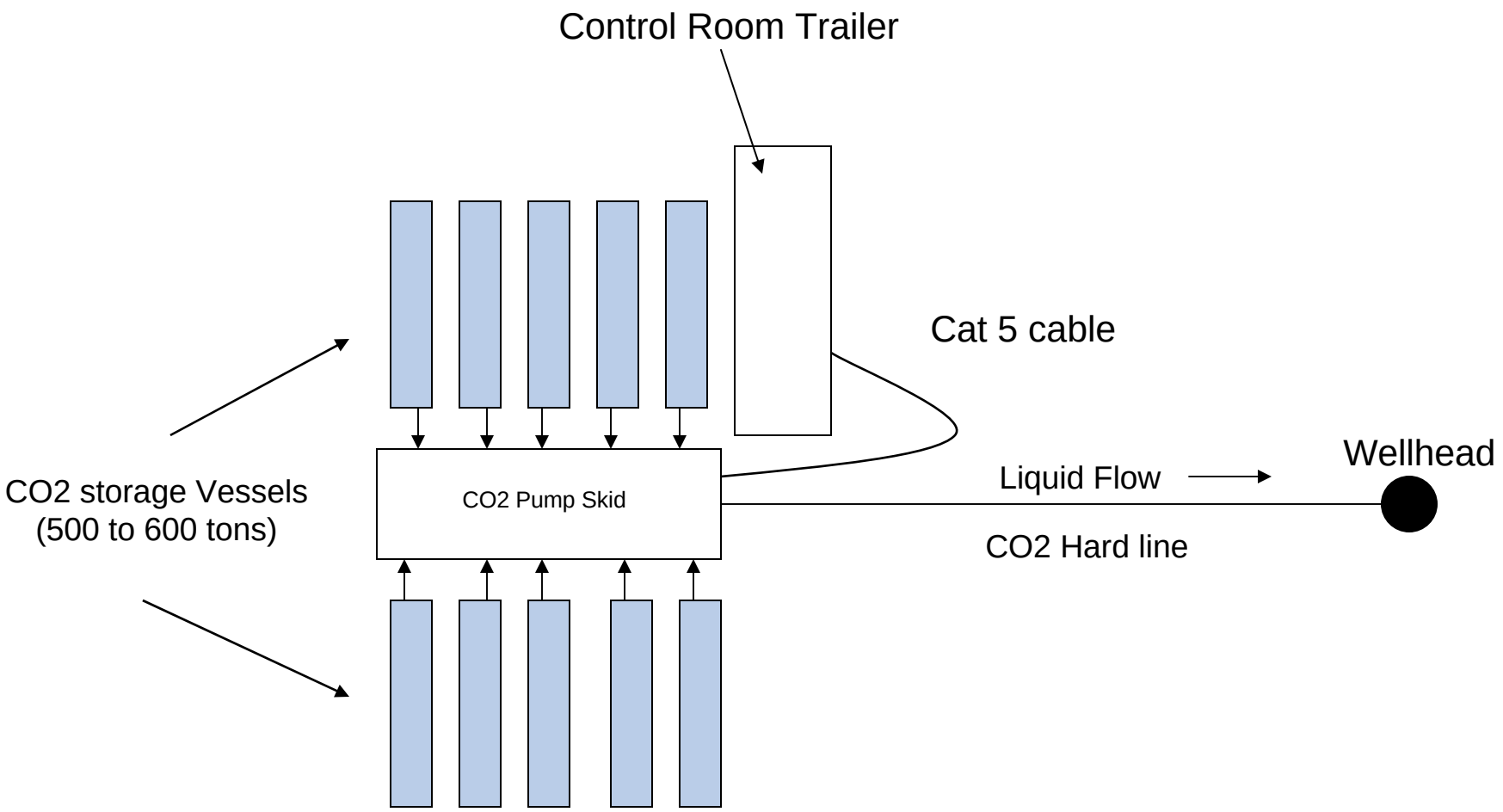
CO2 Injection Test Plan

- Inject 1,000 tonnes of liquid CO_2 (approx 6,000 bbls)
  - Step 1 – inject ~500 tonnes at increasing rates
  - Step 2 – inject ~ 500 tonnes at constant rate
- Maintain injection pressure below fracture pressure
- Continuously measure injection rate, pressure, temperature throughout test
- Continuously measure bottom-hole pressure during/after test

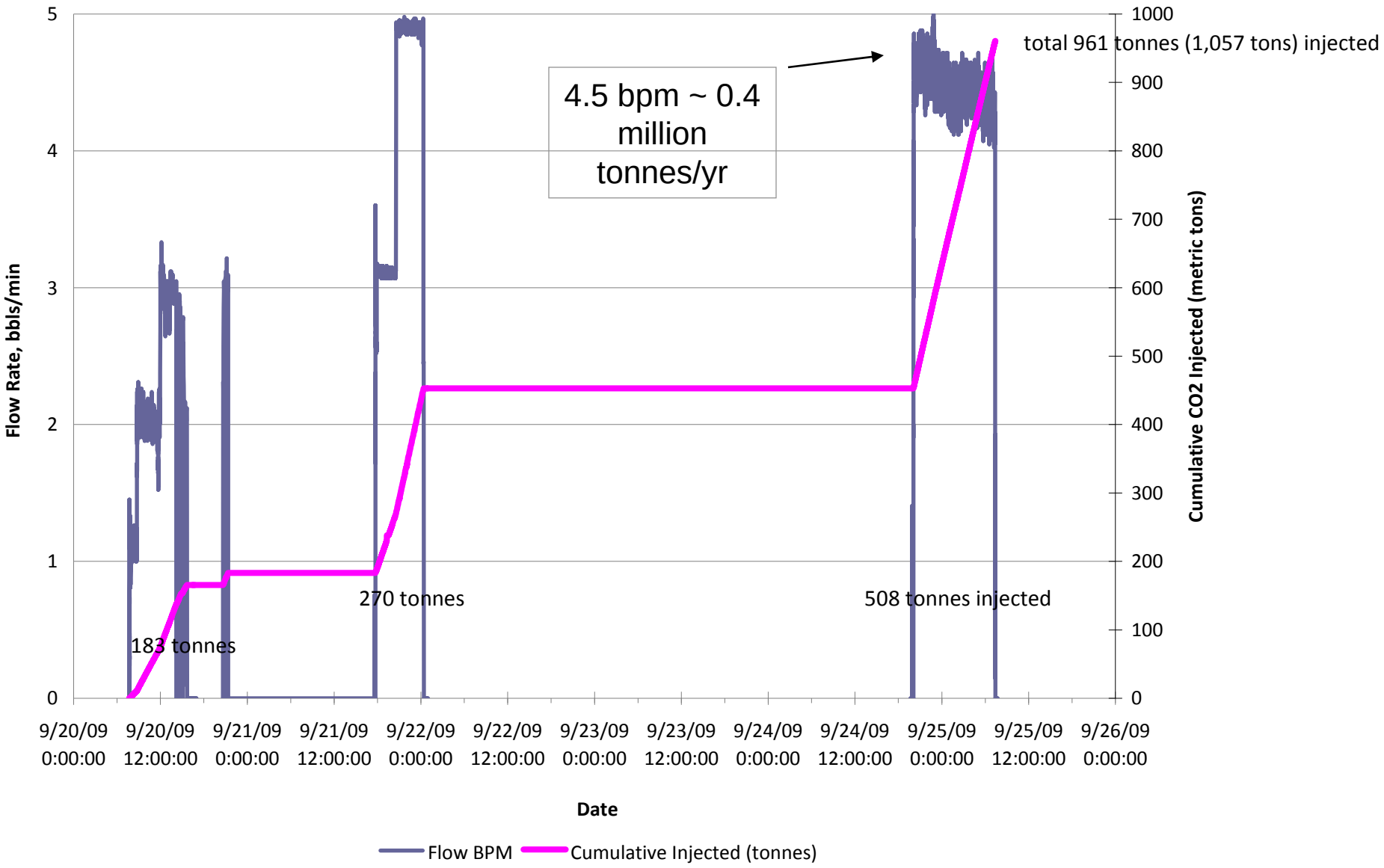



Inline check valve
Drive motor with Hydraulic controls for heater fan
19 MM BTU CO2 heater
Triplex Pump 10,000 psi max
Generator
PRAXAIR
Control Trailer
1000 Gallon Fuel Storage, with Webasto for cold operation
15,000 psi rated hardline
Hookups for auxiliary pressure transducers(2)
Hoses for air actuated valves 5 valves can be operated remotely

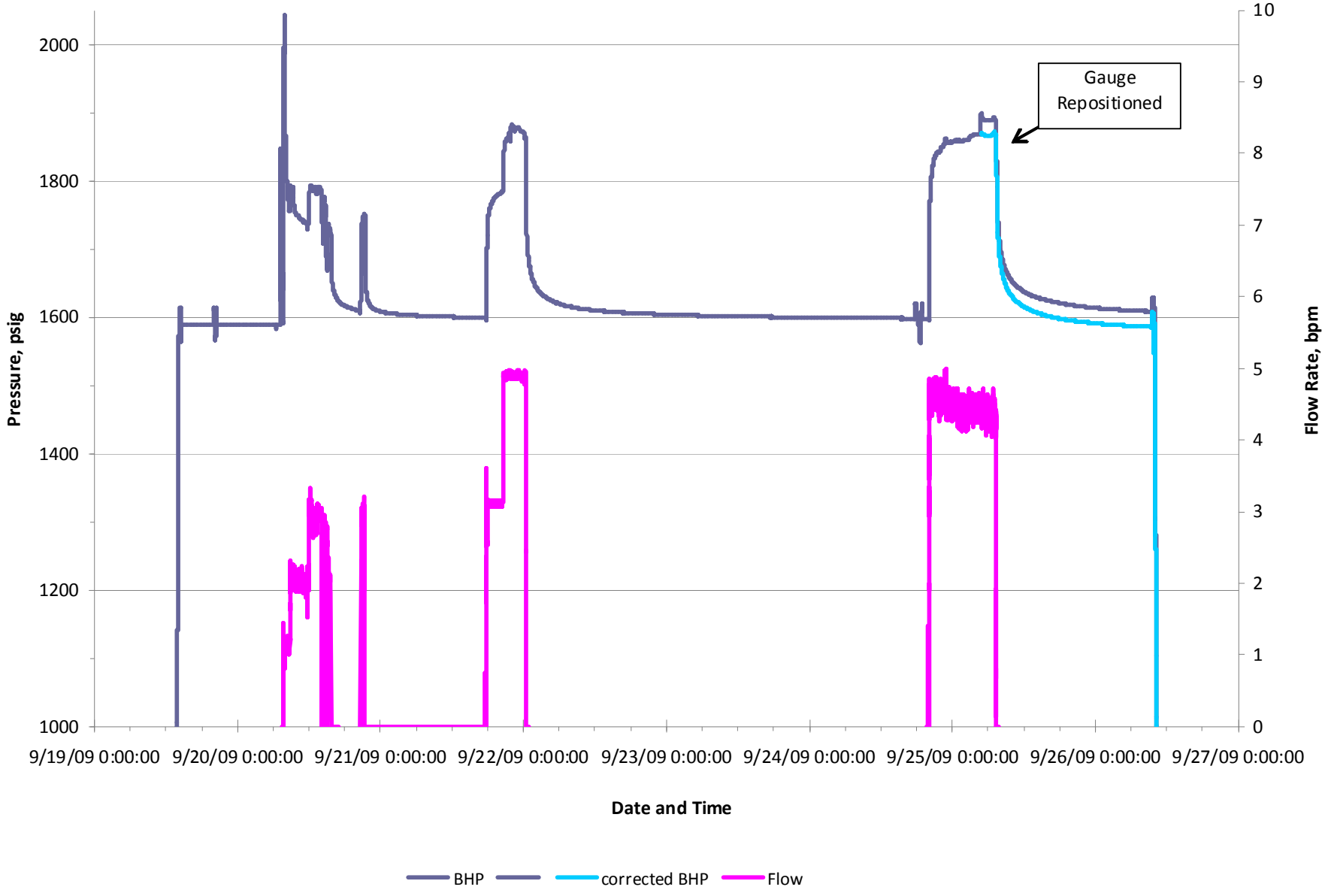
Site Layout for CO2 Injection Test

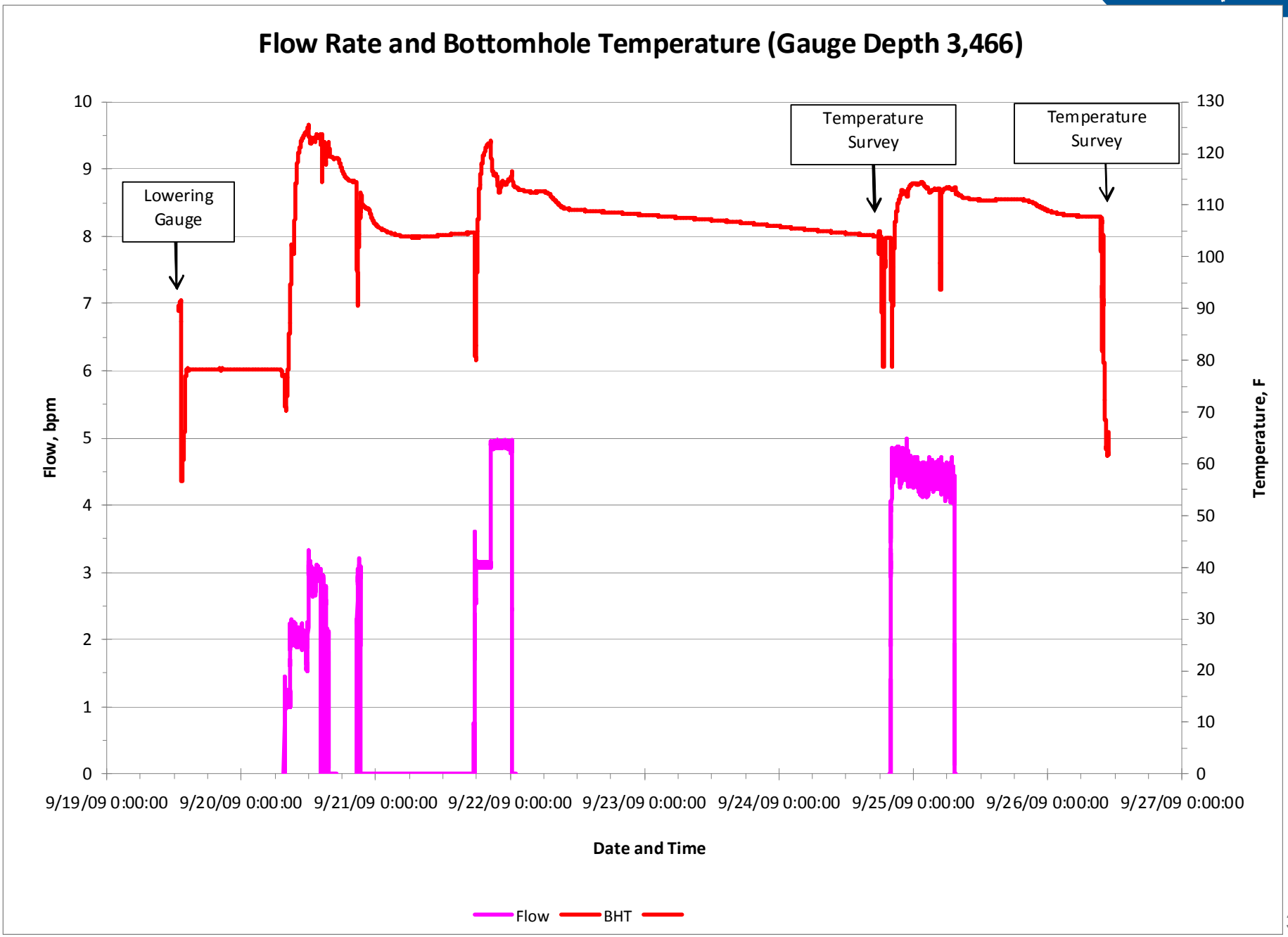


CO2 Injection History



Bottomhole Pressure Data (Gauge Depth 3,466)




Flow Rate and Bottomhole Temperature (Gauge Depth 3,466)
Lowering Gauge
Temperature Survey
Temperature Survey
Flow, bpm
Temperature, F
Date and Time
9/19/09 0:00:00
9/20/09 0:00:00
9/21/09 0:00:00
9/22/09 0:00:00
9/23/09 0:00:00
9/24/09 0:00:00
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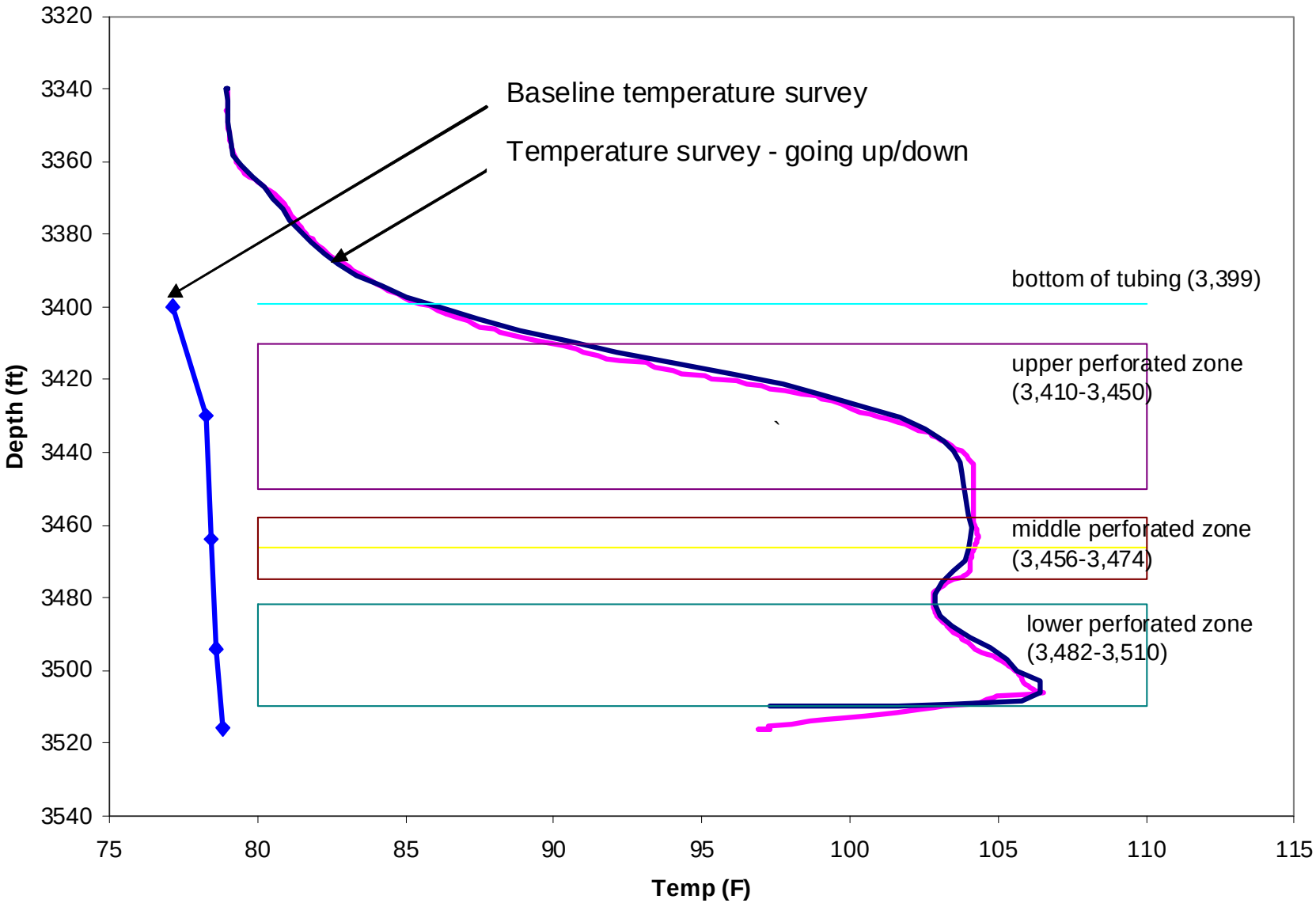
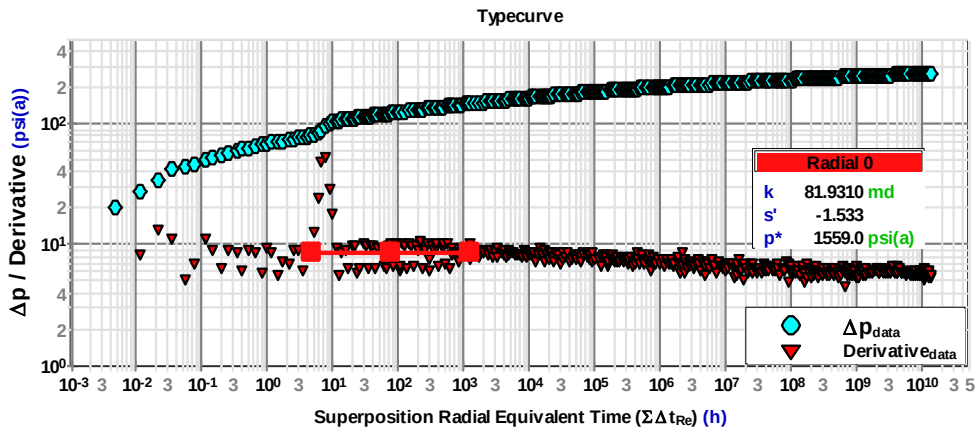
Flow
BHT

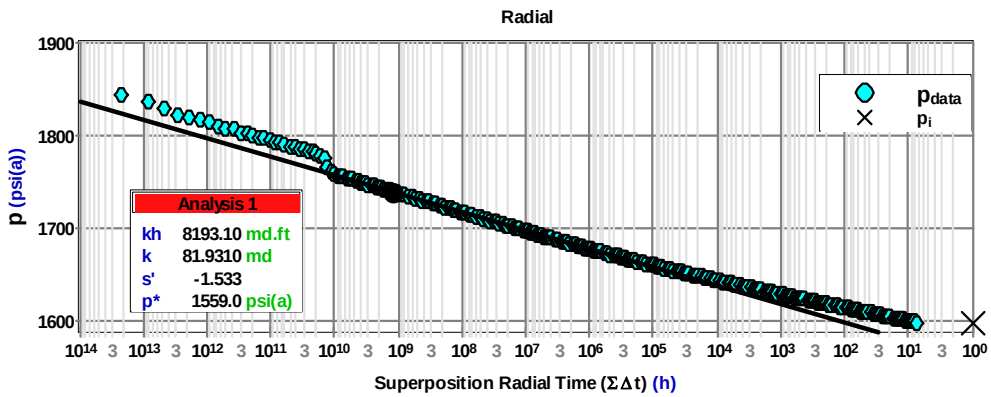
Depth vs Temp (Midway Temp Survey)



Analysis Of CO_2 Injection Data

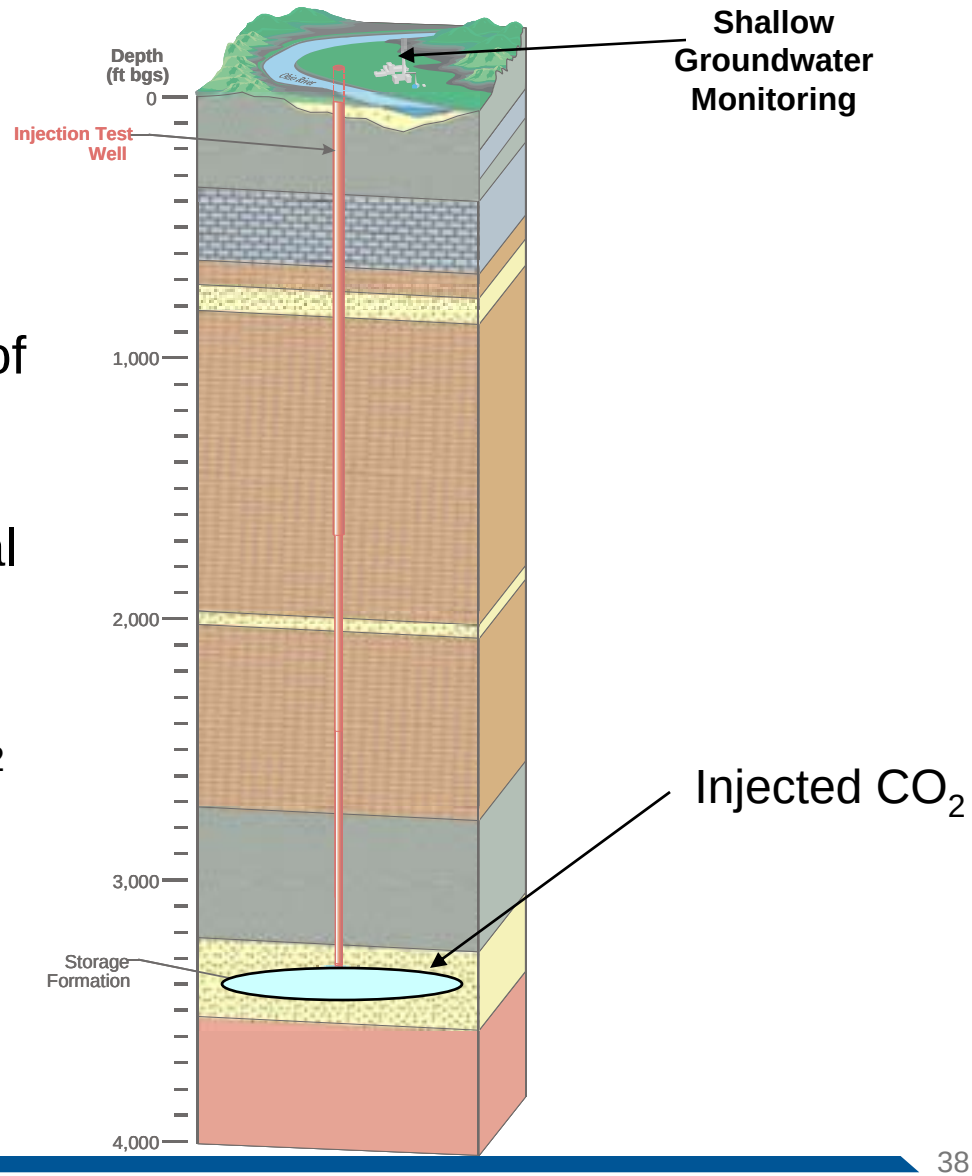
- Pressure transient analysis of fall-off data suggests a bulk permeability of 82 md, which is similar to the value derived from the brine injection tests and the model calibration.
- Additional STOMP modeling is currently underway to simulate the CO_2 injection test, which will provide further insights into the hydraulic characteristics of the Mt Simon and its CO_2 injection potential.





Monitoring Program

- Drinking Water Aquifer groundwater monitoring program
  - •10 shallow wells
  - •1 new deep well
- *Geophysical borehole logging to determine the vertical distribution of CO_2 adjacent to well
- *Vertical Seismic Profile (VSP) Survey to detect lateral and vertical extent of the CO_2 plume in the injection reservoir
- Numerical modeling to predict CO_2 distribution and migration



baseline geophysical borehole logging and VSP survey have been completed – repeat monitoring tentative

VSP - Basic Survey Information

- Contractor: Seismic Reservoir 2020 (formerly Paulsson Geophysics, Inc.)
- Survey Date: August 15, 2009
- Source: Vibroseis
  - 2 trucks sweeping together, 10-125 Hz for 12 seconds with 4 second listen
- Transect length: 6,250 ft
- Number of shot points recorded: 251 shots
  - 25-ft shot spacing
- Receiver array: 80-level 3C array
  - 25 ft receiver spacing
- Receiver depths (below ground level at well)
  - 1,400 – 3,375 ft (length = 1,975 ft). The well is perforated from 3,410 – 3,510 ft bgs)

VSP Transect

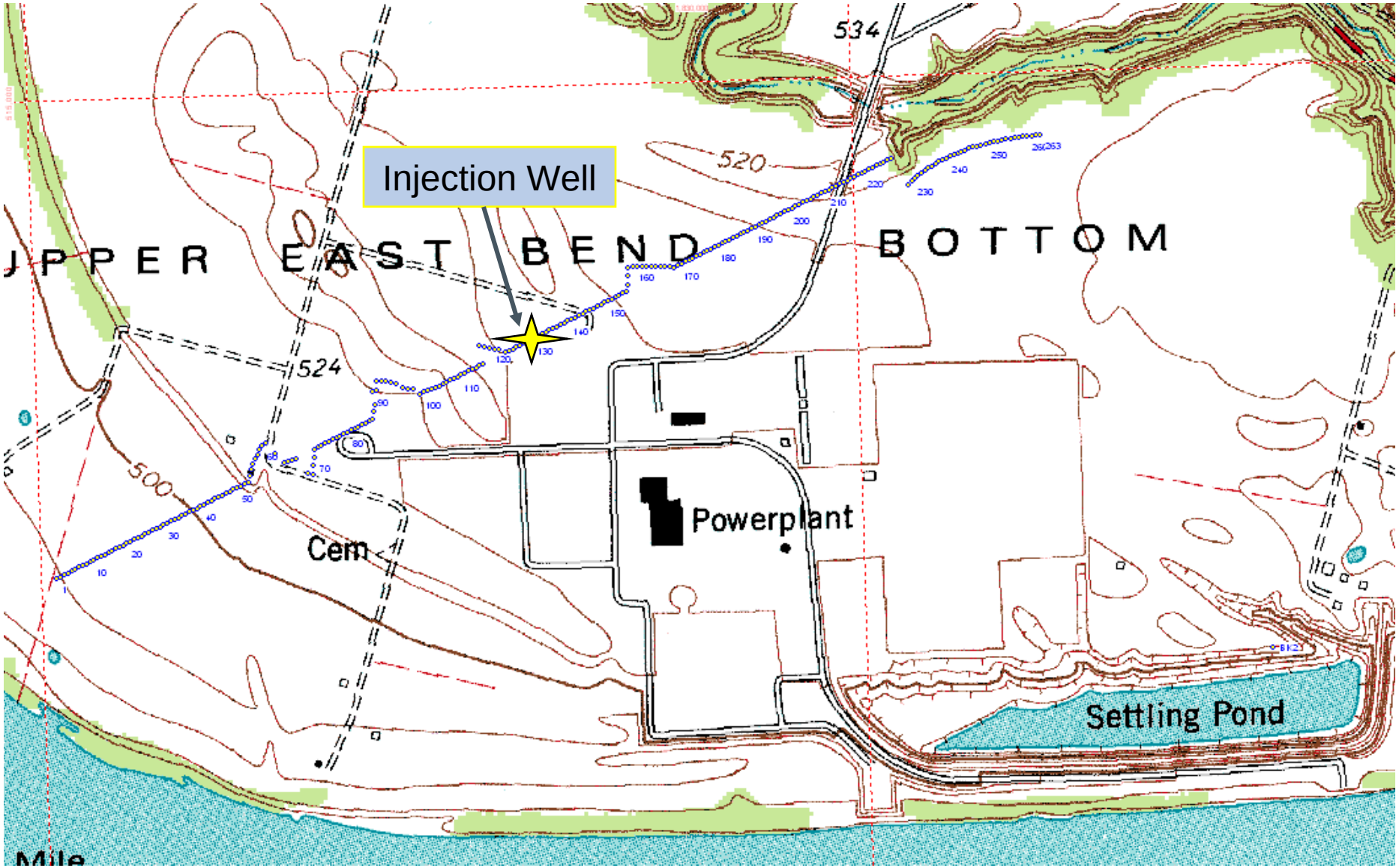
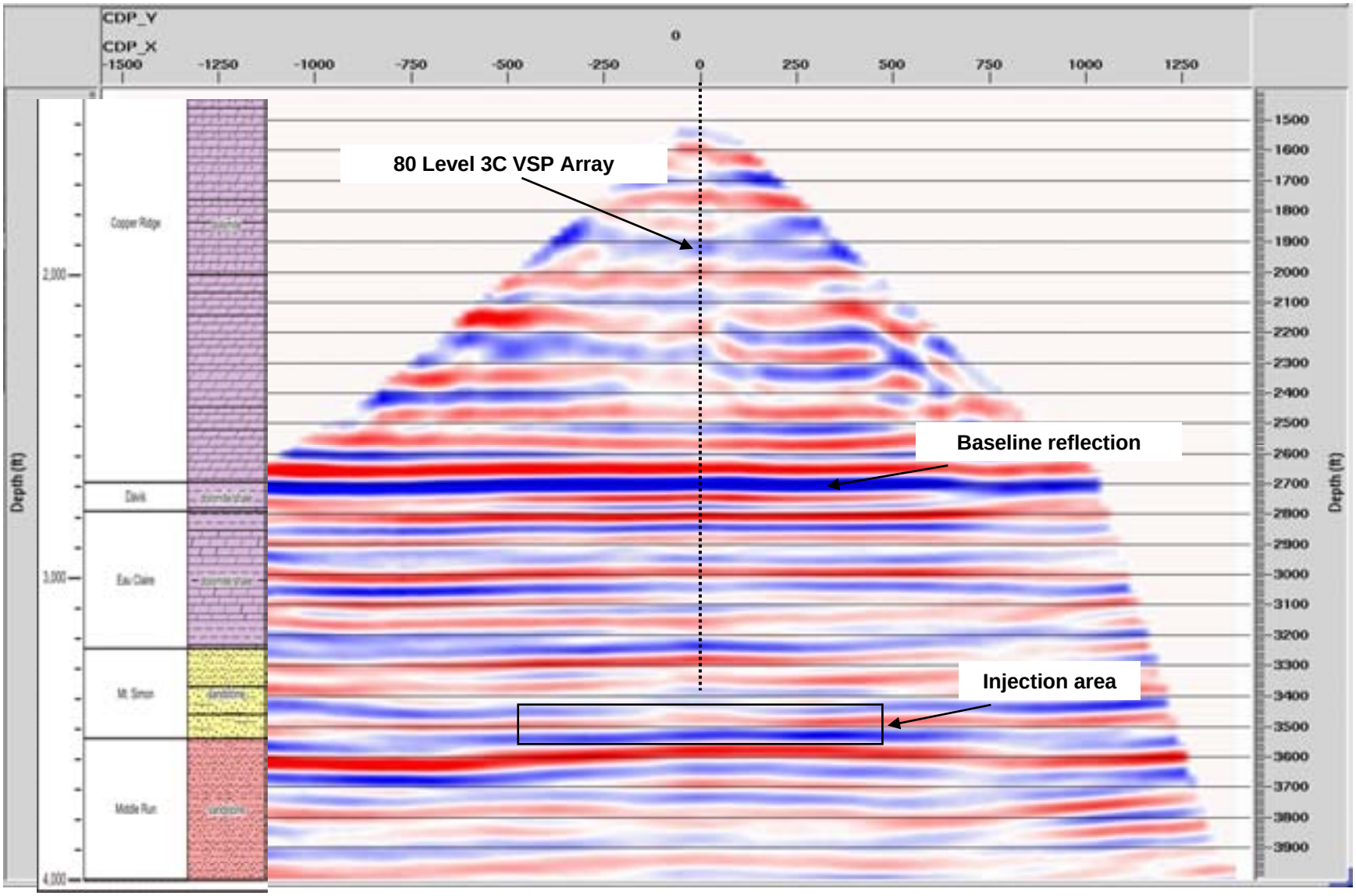


Image After Processing



VSP Conclusions

- Reflections in the area of interest (injection zone) are strong and continuous
- The final image ties extremely well with the synthetic produced from the sonic and density log data, confirming VSP reliability
- Challenges during processing could be overcome
  - Noise from the power plant and transmission lines effectively filtered out
  - Shear energy due to Ohio River Valley alluvium did not compromise the integrity of the final image
- Therefore, VSP has high potential for detecting injected CO2 in a repeat survey.
  - Small volume of CO2 may be a challenge

Questions?