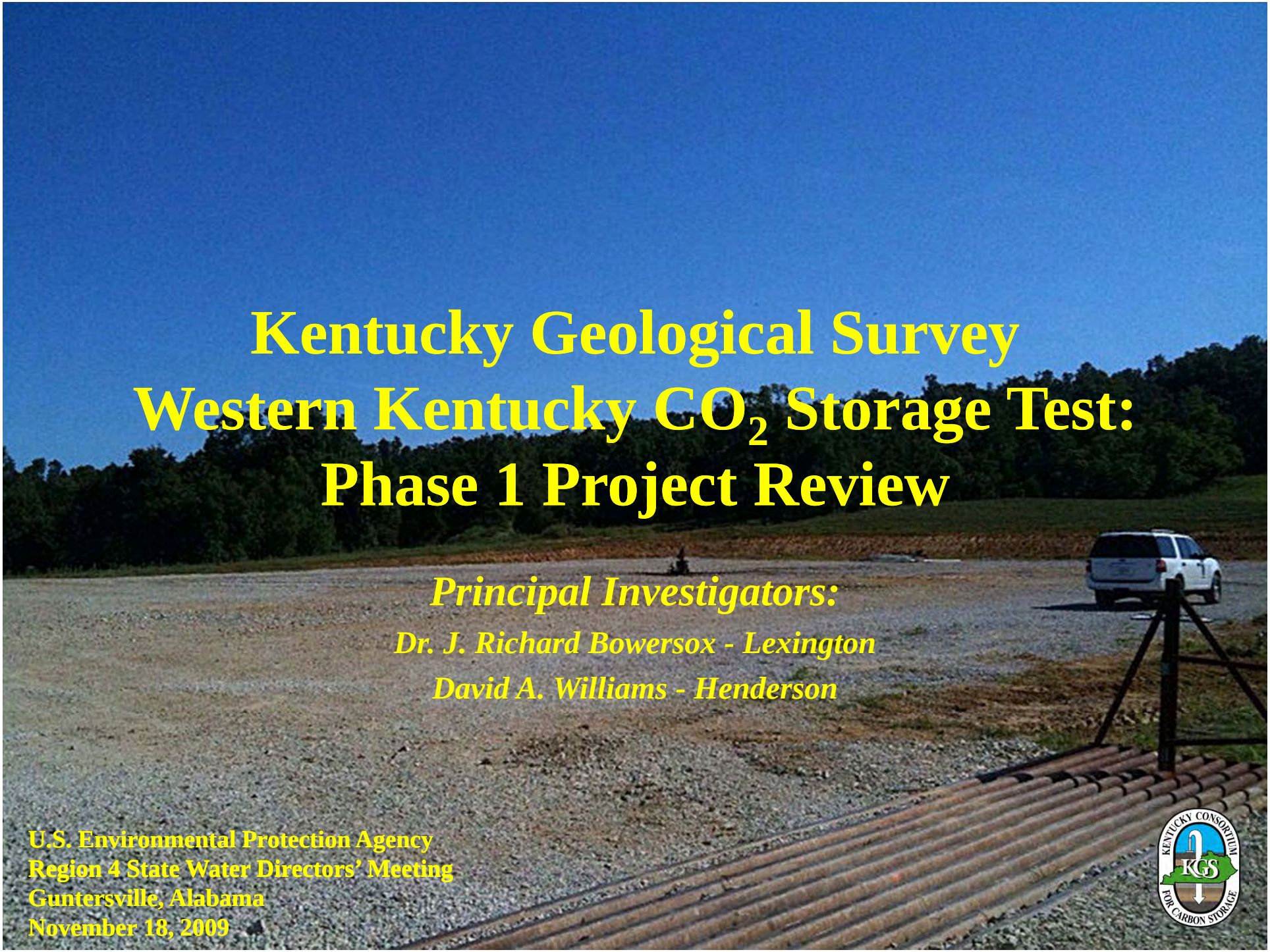


Kentucky Geological Survey
Western Kentucky CO_2 Storage Test:
Phase 1 Project Review

Principal Investigators:

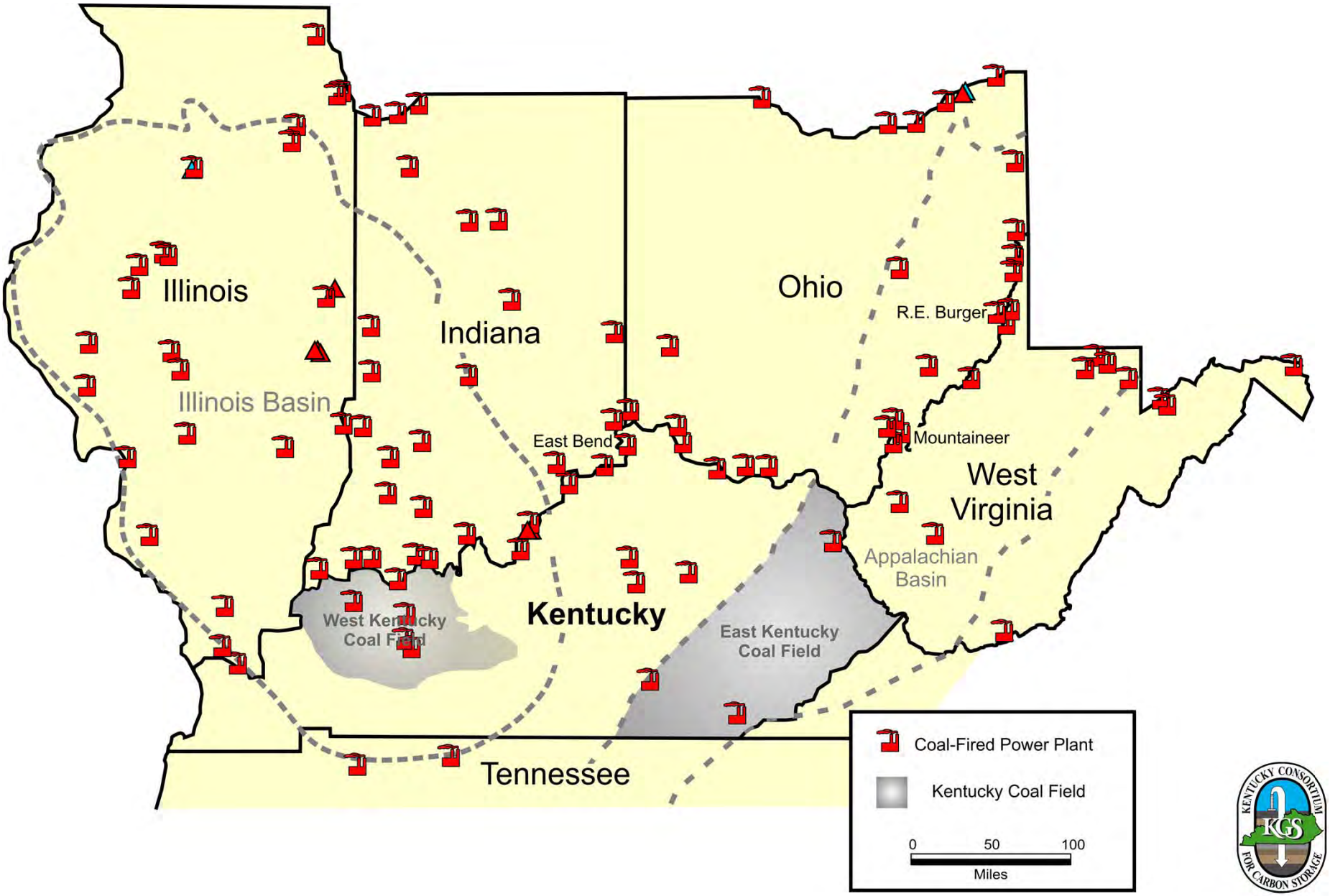
Dr. J. Richard Bowersox - Lexington

David A. Williams - Henderson

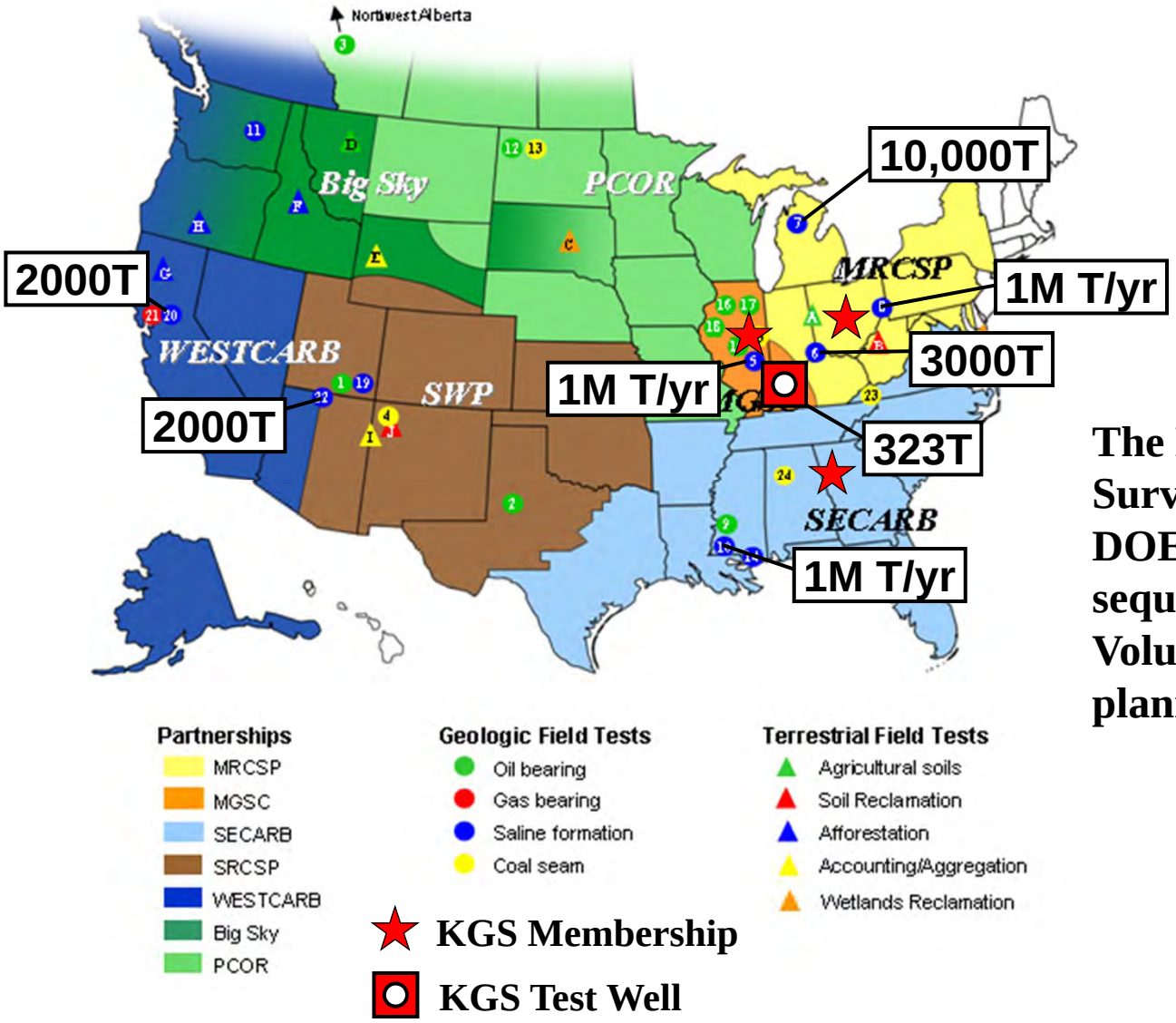
U.S. Environmental Protection Agency
Region 4 State Water Directors' Meeting
Guntersville, Alabama
November 18, 2009


Electric power generating and industrial plants in western Kentucky discharge ~78 million metric tons of CO_2 to the atmosphere each year.
TVA Paradise Power Plant, Muhlenberg County
KENTUCKY CONSORTIUM FOR CARBON STORAGE
KGS

Regional Coal-Fired Power Plants



Regional Sequestration Partnerships

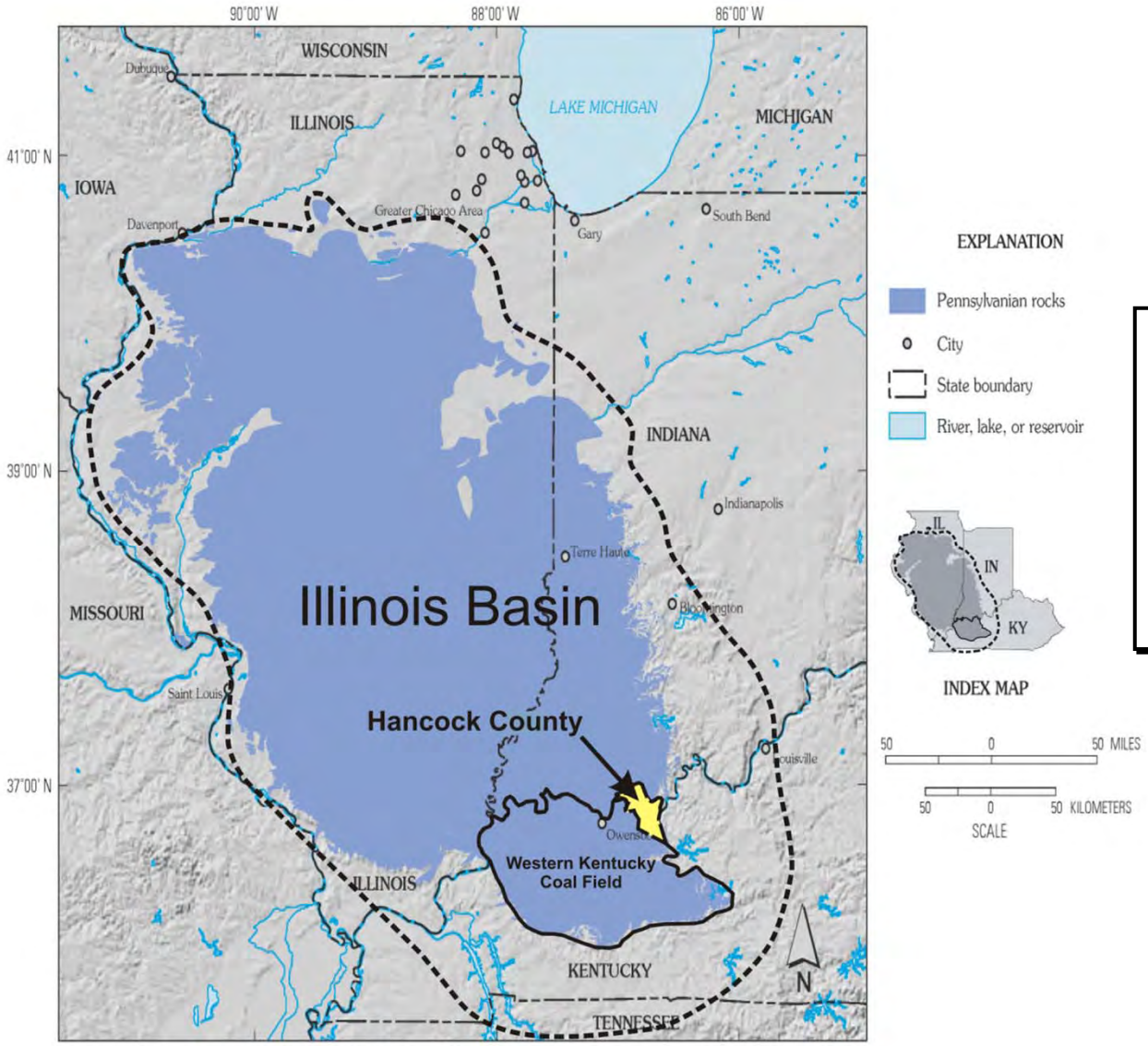


The Kentucky Geological Survey is a member of three DOE-sponsored regional sequestration partnerships. Volumes of CO_2 injected or planned noted.

Project Purpose

- Discharge of CO_2 to the atmosphere is under regulatory review, and subsurface storage may be required for existing facilities and the financing and construction of new facilities.
- Kentucky House Bill 1, passed in a special legislature session and signed into law in August 2007, appropriated $5 million funding for KGS to research the storage and use of CO_2 throughout the Commonwealth.
- House Bill 1 mandates the drilling a CO_2 storage demonstration well in the Western Kentucky Coal Field.
- The Hancock County drillsite was chosen for its favorable geologic setting and accessibility.

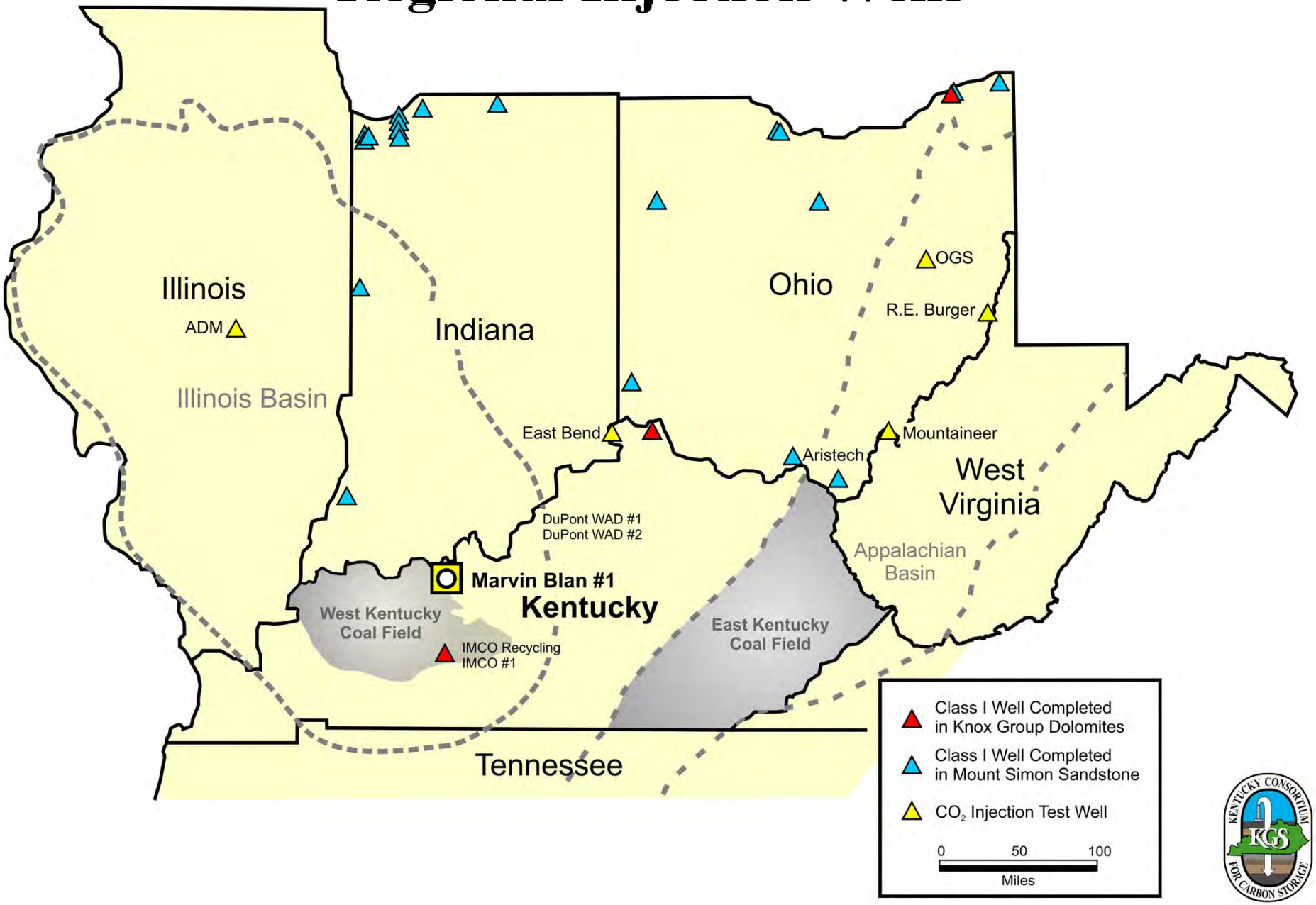
Location of Hancock County, Kentucky



Source: Hatch and Affolter (2002, fig. 1) with annotations

Hancock County lies in the southeastern Illinois Basin, on the northeastern margin of the Western Kentucky Coal Field

Regional Injection Wells

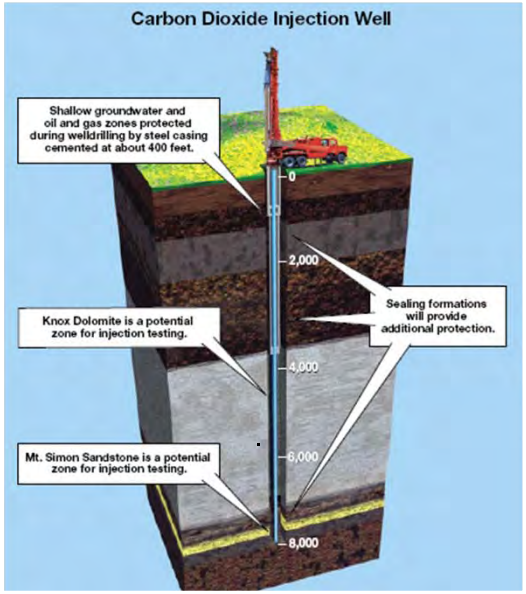


Project Goals

- Demonstrate CO_2 storage in deep saline reservoirs under the Western Kentucky Coal Field through the drilling and testing of an 8350 ft well in east-central Hancock County
- Demonstrate the integrity of reservoir sealing strata for long-term CO_2 storage in western Kentucky
- Demonstrate appropriate technologies for the evaluation of CO_2 storage in Kentucky deep saline reservoirs
- Publish the project results for use by government, industry, and the public in evaluating CO_2 storage in Kentucky
- Accomplish this project with consideration of the interests and concerns of the landowner, residents of Hancock County and western Kentucky, and the citizens of the Commonwealth

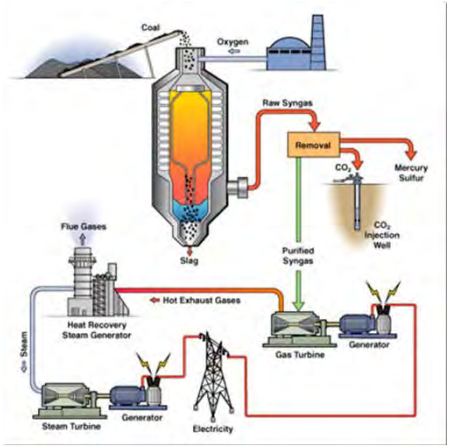
Project Stakeholders

Landowner and Hancock County residents



Western Kentucky coal mining industry

Electric power generators

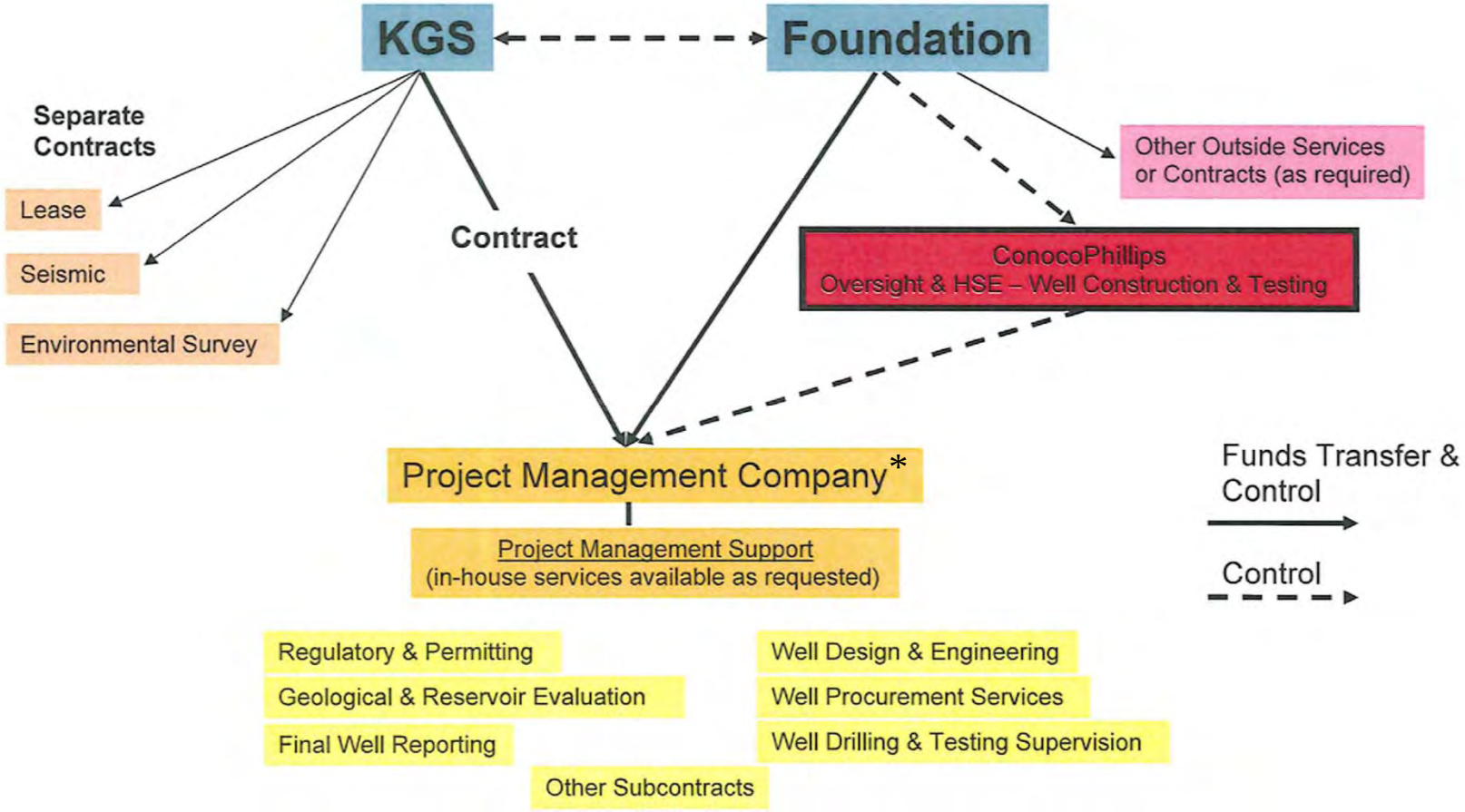


Clean coal syngas projects

Project Organization

- **Project management agreements in place**
  - 501(c)3 Western Kentucky Carbon Storage Foundation
  - MOA between KGS and the foundation
- **Project operations agreements**
  - Right of way and injection test well agreement with the landowners
  - Lease subordination and data sharing agreements with the oil and gas leaseholder
- **Estimated project cost was ~$7.3 Million**
  - $1.35 million of HB-1 funds
  - $$5.40 million from the foundation
  - $50,000 from TVA
  - $250,000 from the Illinois Office of Coal Development
  - 250,000 from DOE-NETL

Project Management Structure



*Sandia Technologies, LLC

Public Outreach

Print Media Stories

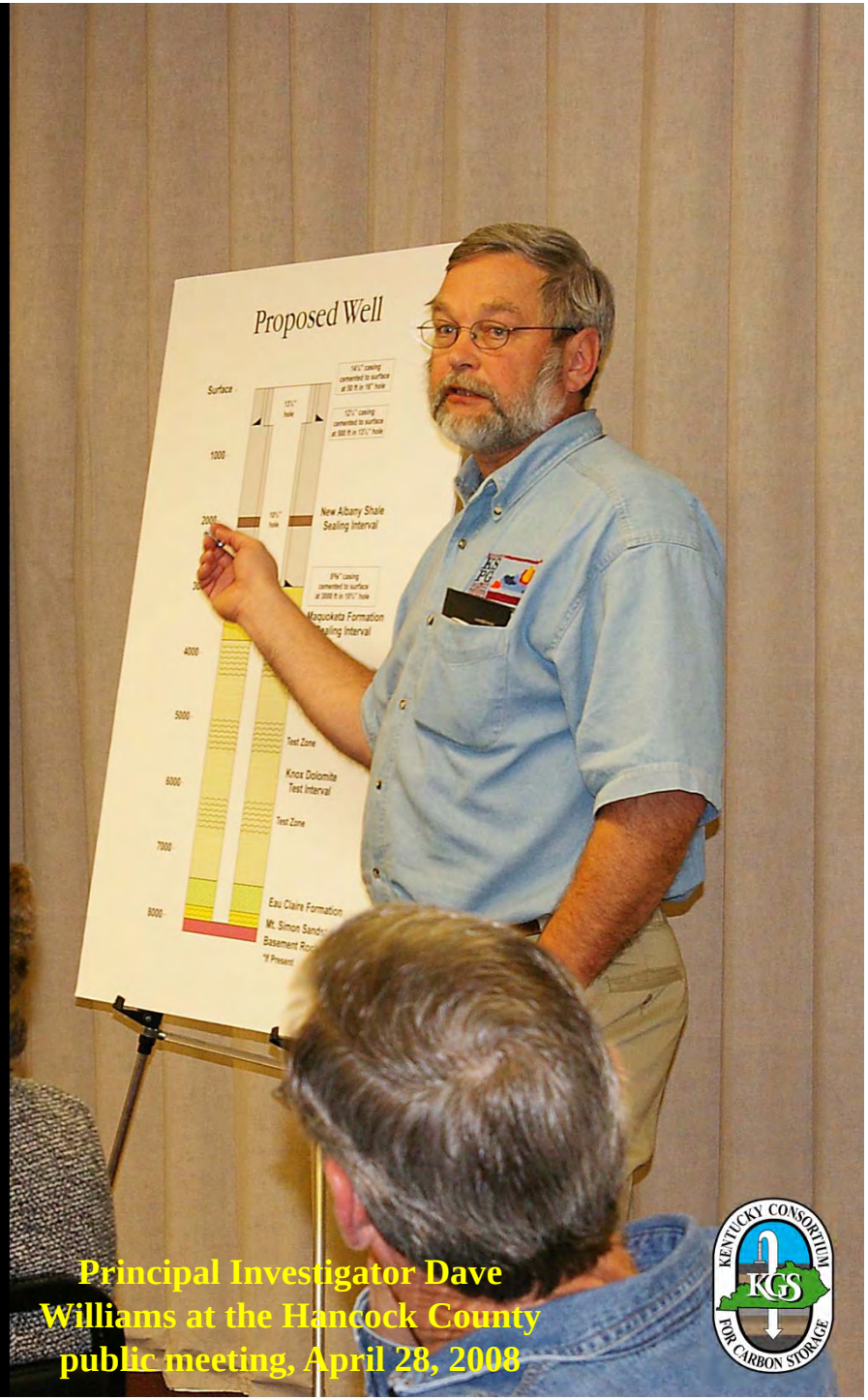
- Eight project news releases
- At least 43 published news articles in eight newspapers

Public Presentations

- Thirteen presentations to local geological societies, governmental agencies, and academic conferences
- Eleven presentations at professional conferences
- Four presentations to local officials

- **Television and Radio Stories**
  - At least four stories on regional television stations
  - Three interviews on NPR radio stations

- **Worldwide Web**
  - KYCCS.org website
  - More than 40 websites and blog entries



Principal Investigator Dave Williams at the Hancock County public meeting, April 28, 2008

Public Meeting with the Hancock County Fiscal Court
October 27, 2008


Media Day at Marvin Blan #1
May 14, 2009
KENTUCKY CONSORTIUM
KGS
FOR CARBON STORAGE

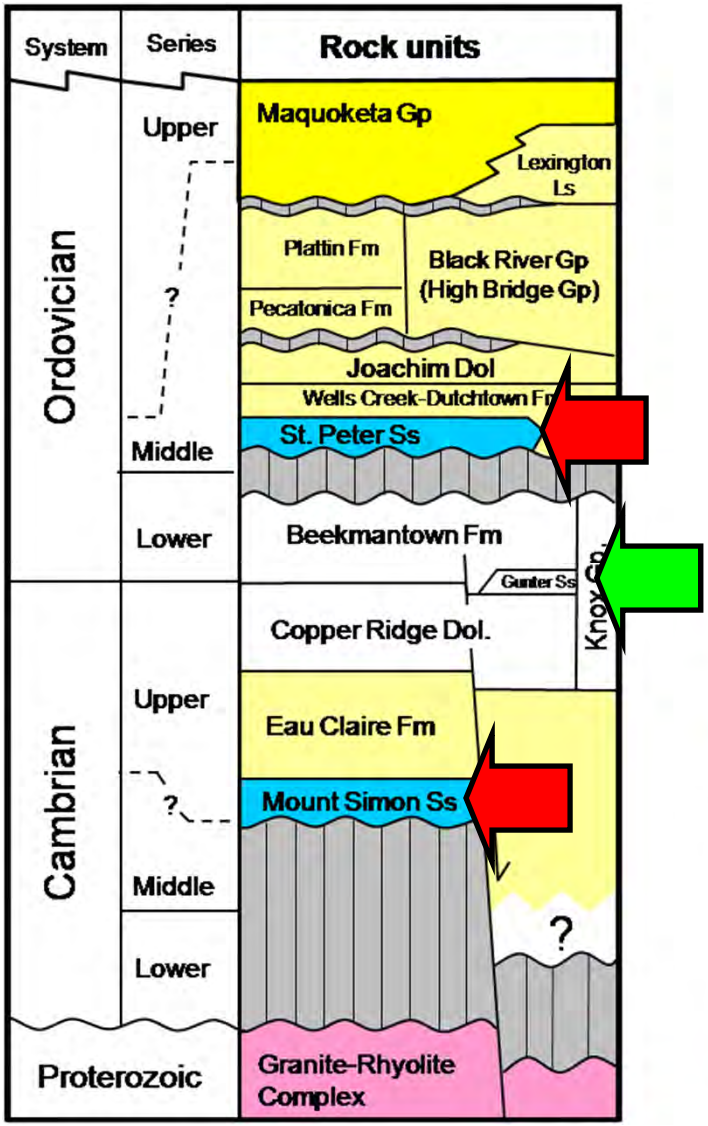

ConocoPhillips Teachers' Day
June 11, 2009
11 10:34AM
KENTUCKY CONSORTIUM
KGS
FOR CARBON STORAGE

Recognition Awards to State Government and University of Kentucky Adminstrators

Project Geologic Requirements

- **Effective storage of CO_2 in deep saline reservoirs requires its injection in a supercritical state to achieve a 250 times volume reduction.**
  - Supercritical CO_2 is a liquid with the properties of a gas
  - A supercritical state achieves a 250 times volume reduction
- **The temperature and pressure conditions in Kentucky deep saline reservoirs requires a minimum depth of ~2350 ft to be able to store CO_2 in its supercritical state.**
  - Reservoir pressure > 1085 psi
  - Reservoir temperature > 88° F
- **Reservoirs must have sufficient porosity and permeability for the injection of CO_2 as well as overlying sealing strata to ensure its long-term storage.**

Deep Rock Units in Western Kentucky



Regional saline reservoirs:

- Mt. Simon Sandstone
- **Knox Group dolomites**
- St. Peter Sandstone

Potential CO_2 sinks/ reservoirs

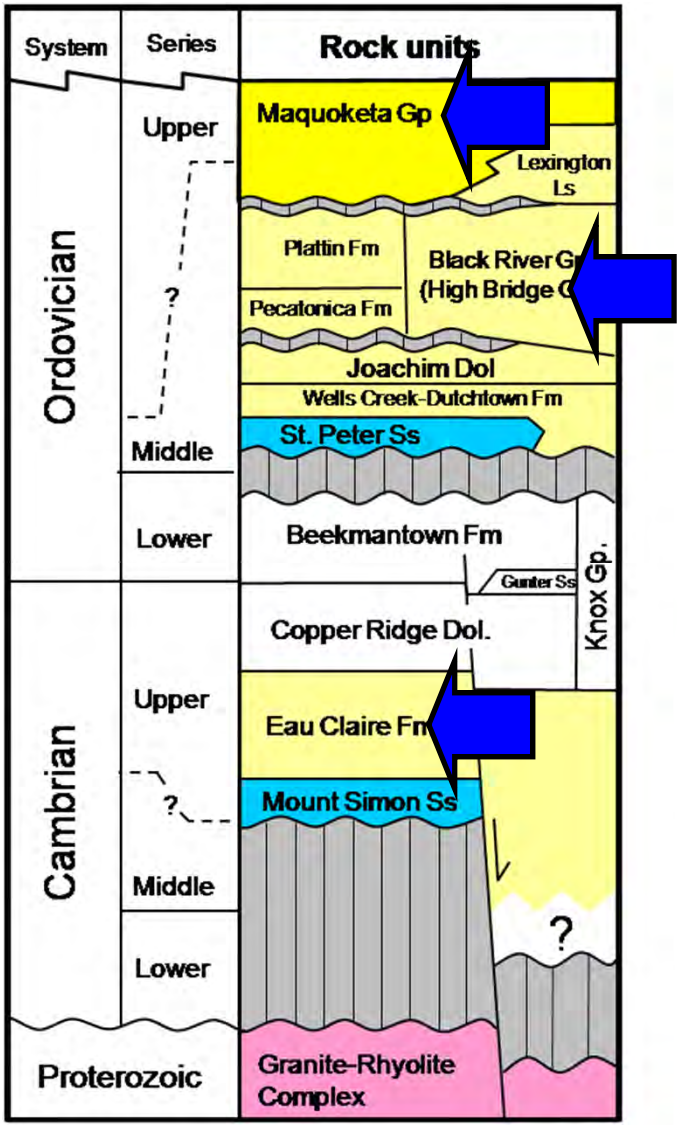
Sealing interval

Missing section

Sink or seal (*depends on location*)

Metamorphic and igneous rocks (*mostly seal*)

Deep Rock Units in Western Kentucky



Just as important in an injection project are the sealing units:

- **Eau Claire Formation**
- **Maquoketa Shale**
- **Black River carbonates**
- **Devonian Shales**

Potential CO_2 sinks/ reservoirs

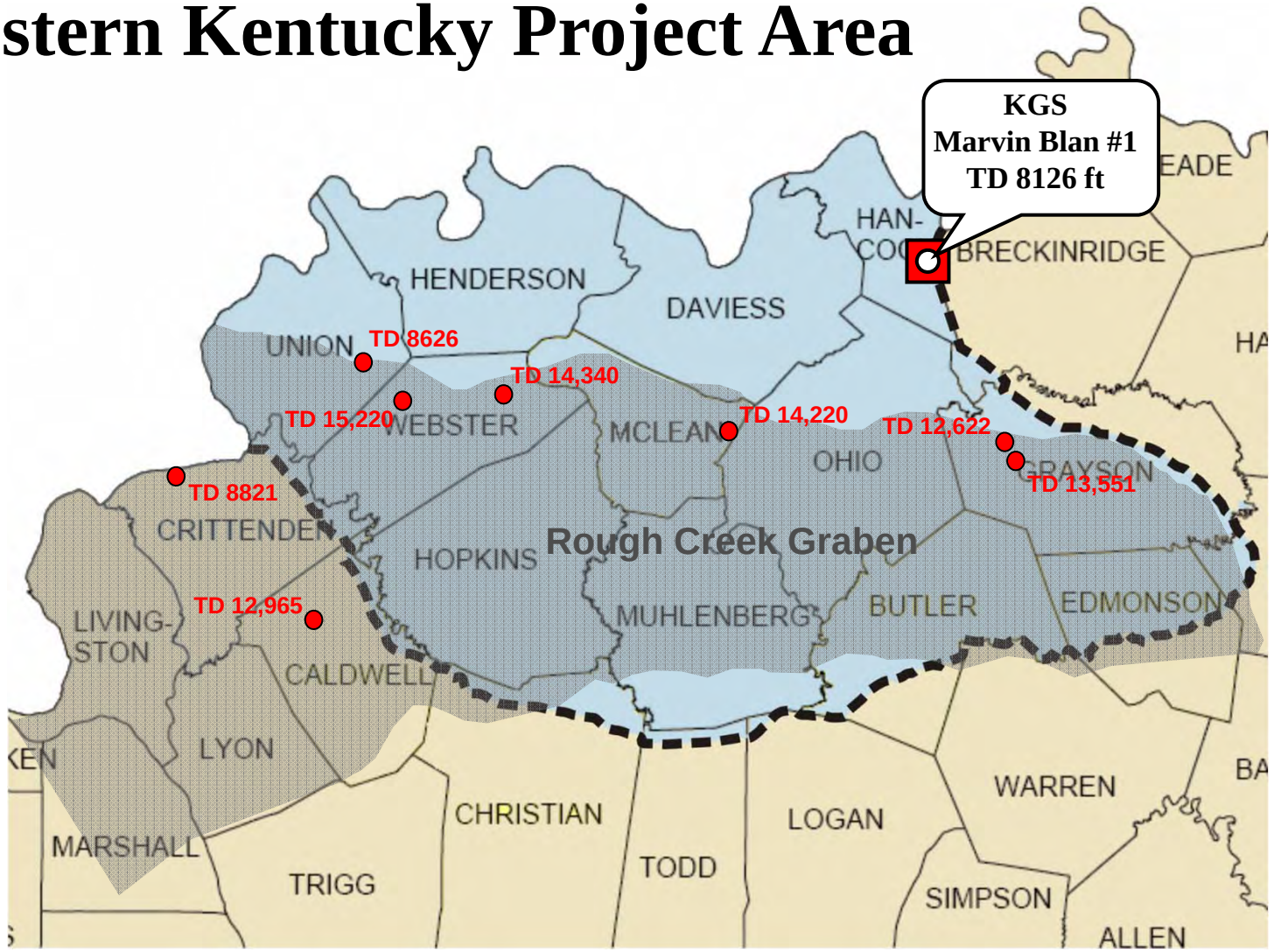
Sealing interval

Missing section

Sink or seal (*depends on location*)

Metamorphic and igneous rocks (*mostly seal*)

Western Kentucky Project Area

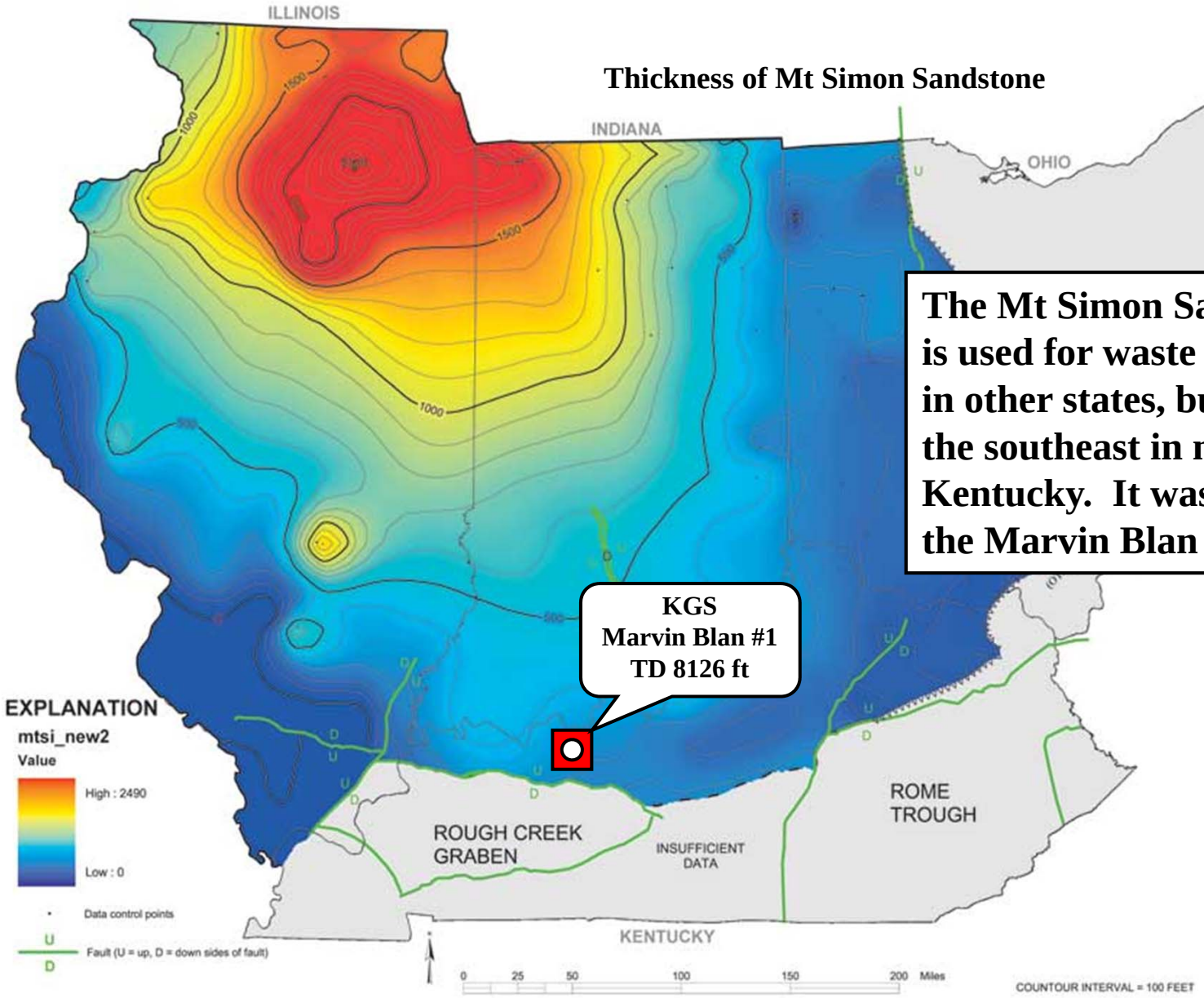


Although the shallowest drill depth to reach the targeted reservoirs was in east-central Hancock County, the completed CO_2 storage test well is among the deepest wells drilled in western Kentucky.

Project Goals

- **Demonstrate and characterize the potential for the geologic storage of CO_2 in western Kentucky**
  - Target reservoir is the Knox Dolomite
    - Found 3617 ft of Knox Dolomite, including Gunter Sandstone
    - Average porosity 6.7% calculated from logs
    - Successfully injected 18,454 BW brine and 323 T CO_2
  - Evaluate St Peter and Mount Simon Sandstones, if present
  - Test the reservoir potential of the Precambrian Middle Run Sandstone
  - Characterize the reservoir sealing properties of the New Albany Shale, Maquoketa Shale, Black River Group, and non-reservoir intervals in the Knox

Mount Simon Sandstone Reservoir

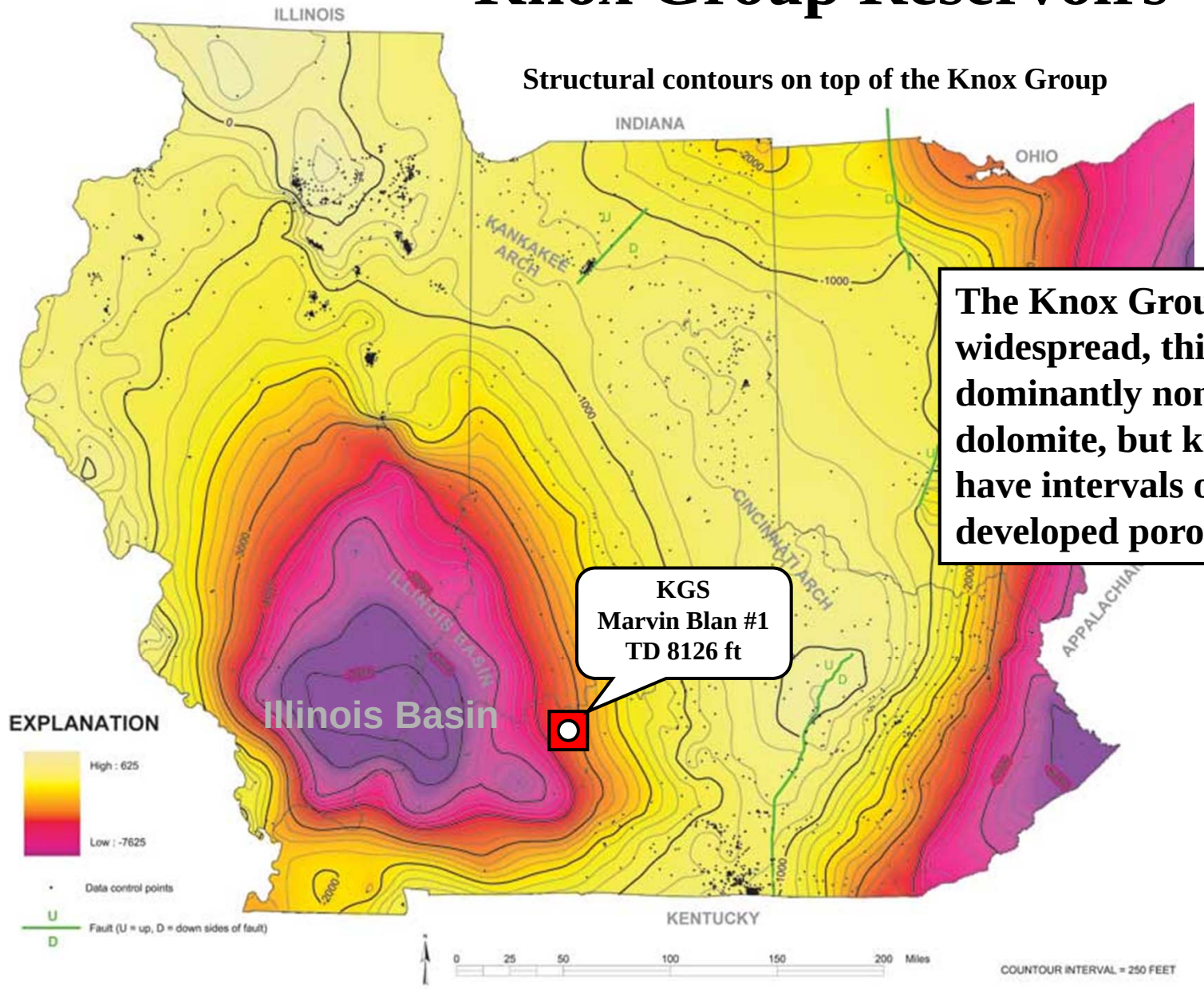


The Mt Simon Sandstone is used for waste injection in other states, but thins to the southeast in northern Kentucky. It was absent in the Marvin Blan #1 well.

Hickman et al., *www.esri.com/mapmuseum/mapbook_gallery/volume19/environment3.html*

Knox Group Reservoirs

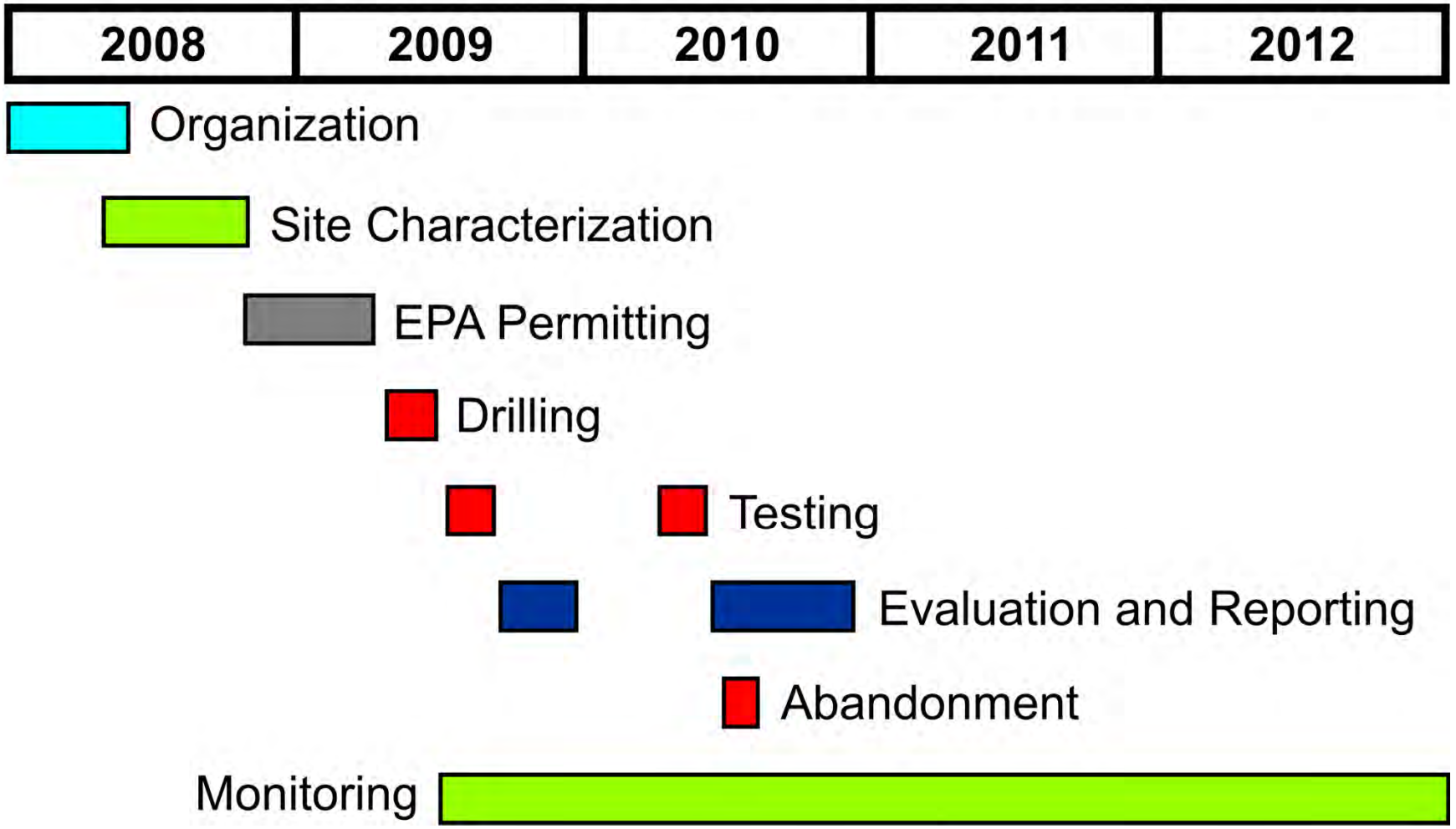
Structural contours on top of the Knox Group

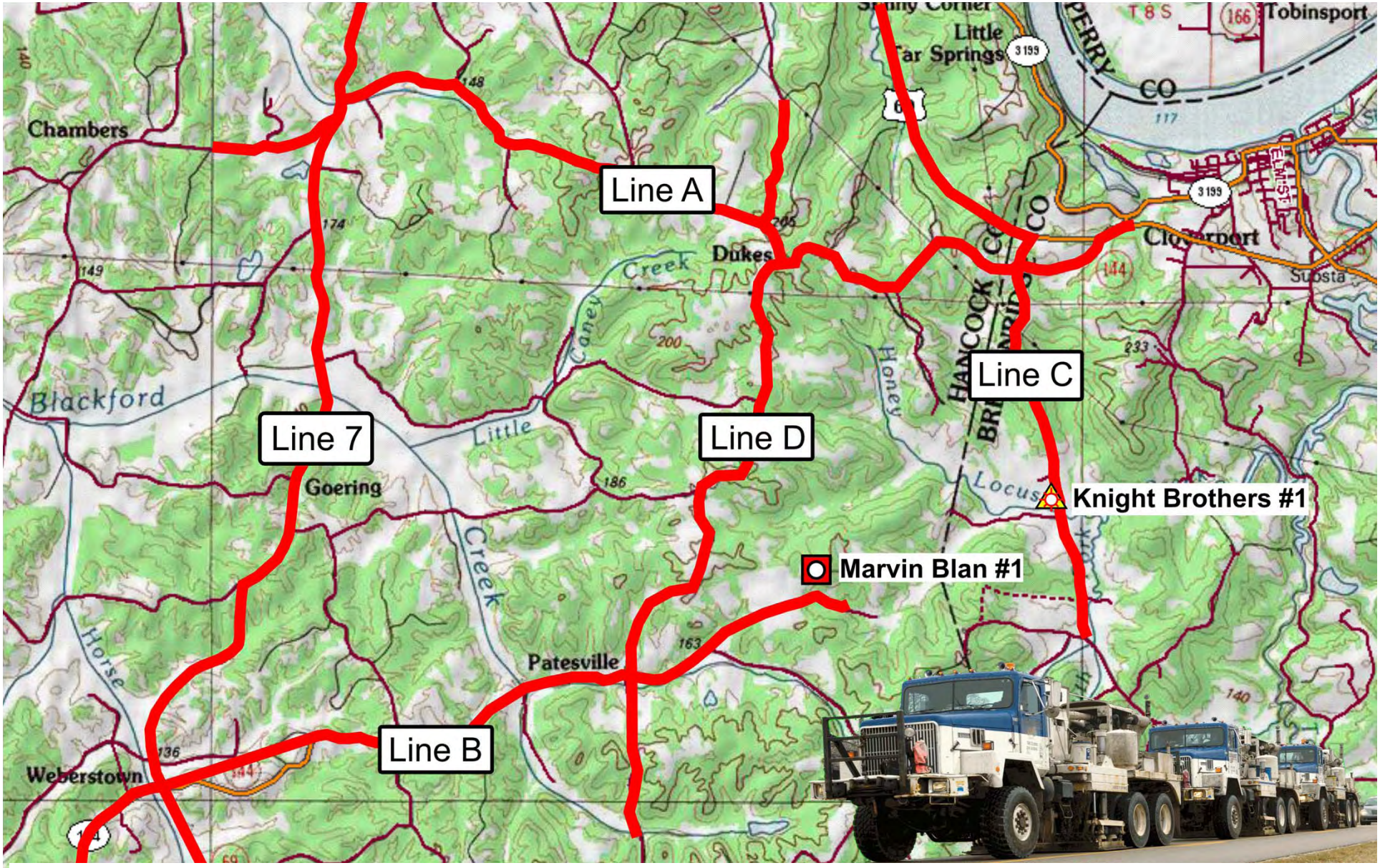


The Knox Group is a widespread, thick unit of dominantly non-porous dolomite, but known to have intervals of well-developed porosity.

Hickman et al., *www.esri.com/mapmuseum/mapbook_gallery/volume19/environment3.html*

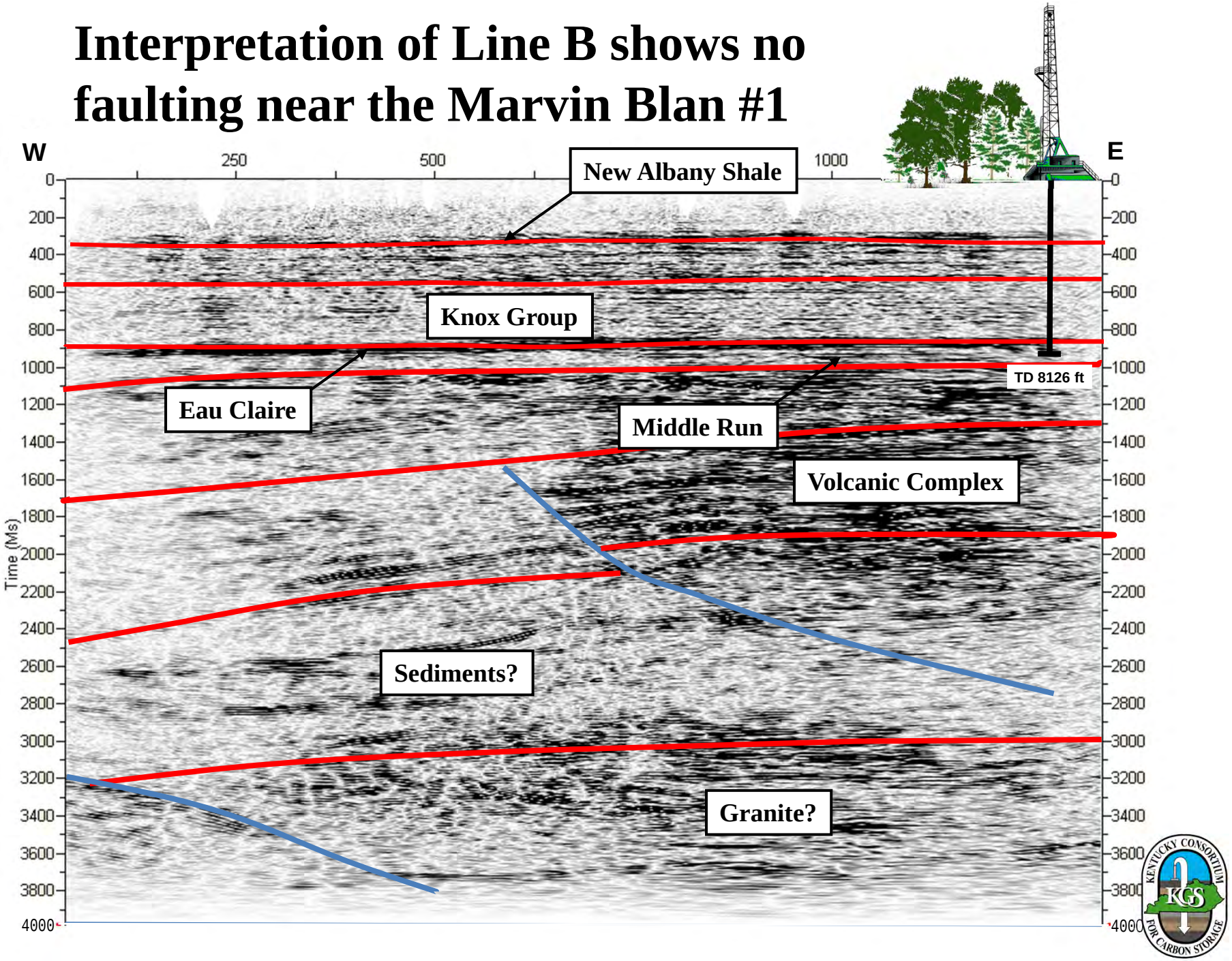
Western Kentucky Project Timeline

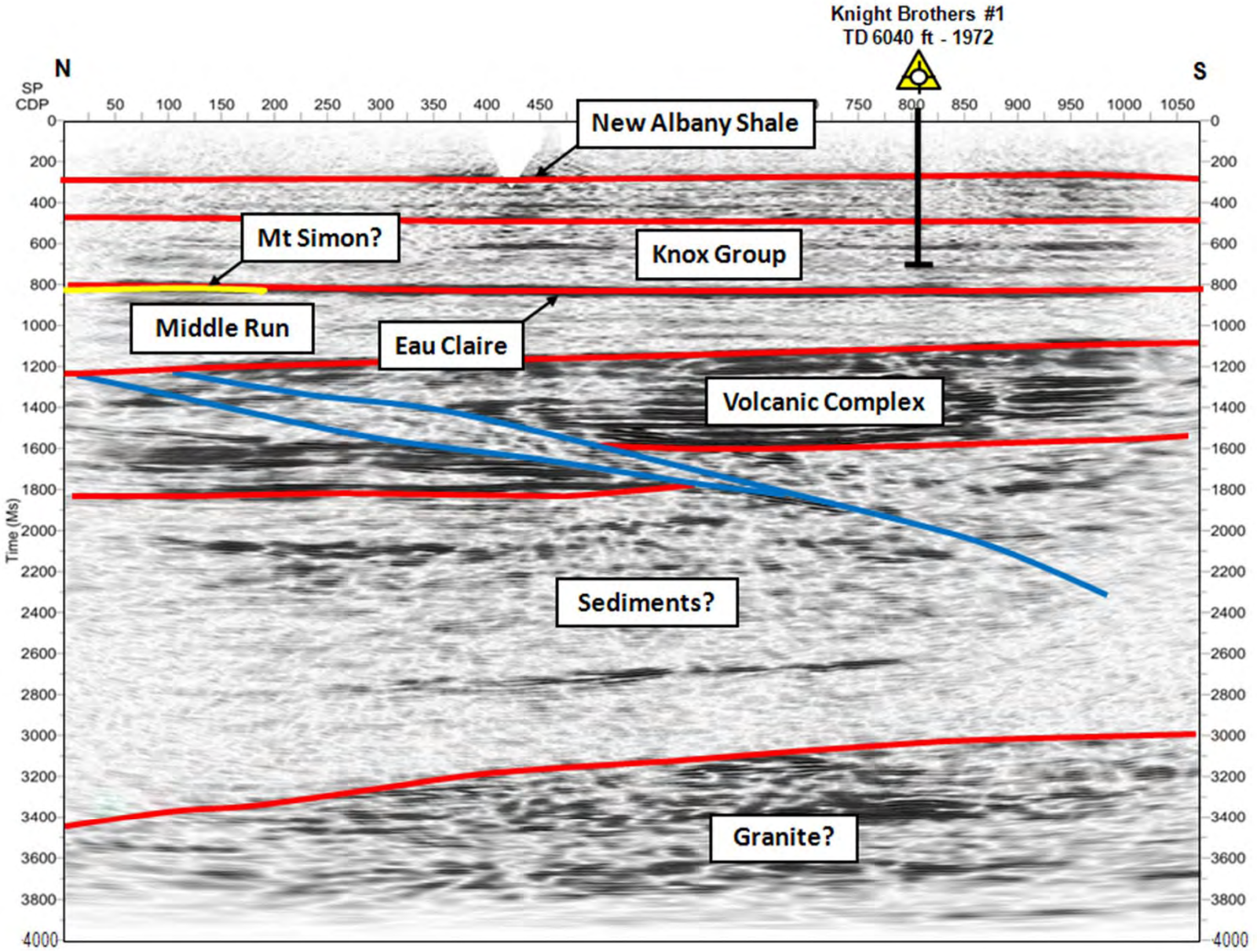




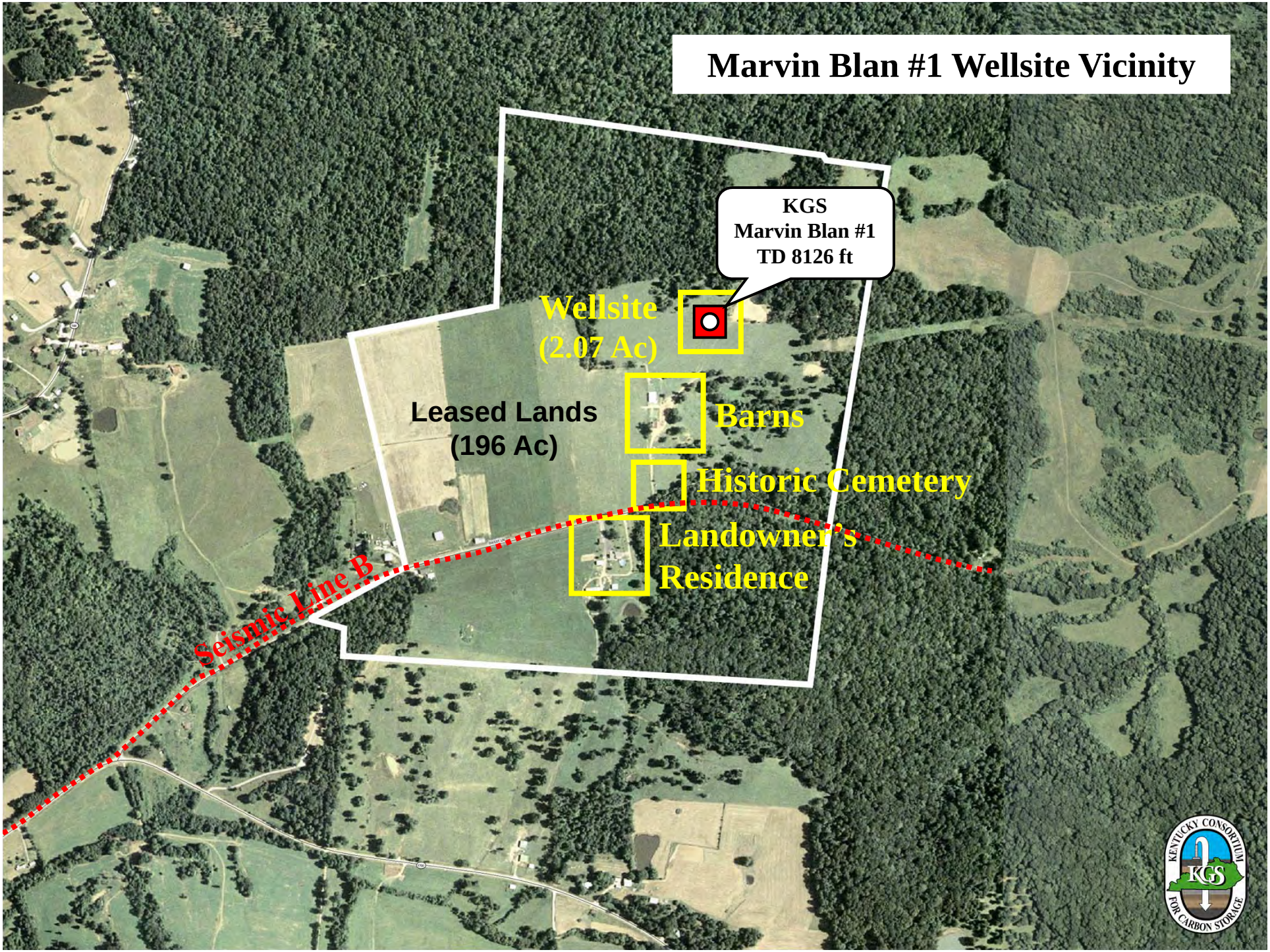
Prior to drilling, 24.1 mi of new, high-quality 2D seismic data (Lines A-D) was acquired to provide subsurface structural and stratigraphic control at the wellsite, and to supplement existing older, lower-quality data (Line 7).

Interpretation of Line B shows no faulting near the Marvin Blan #1



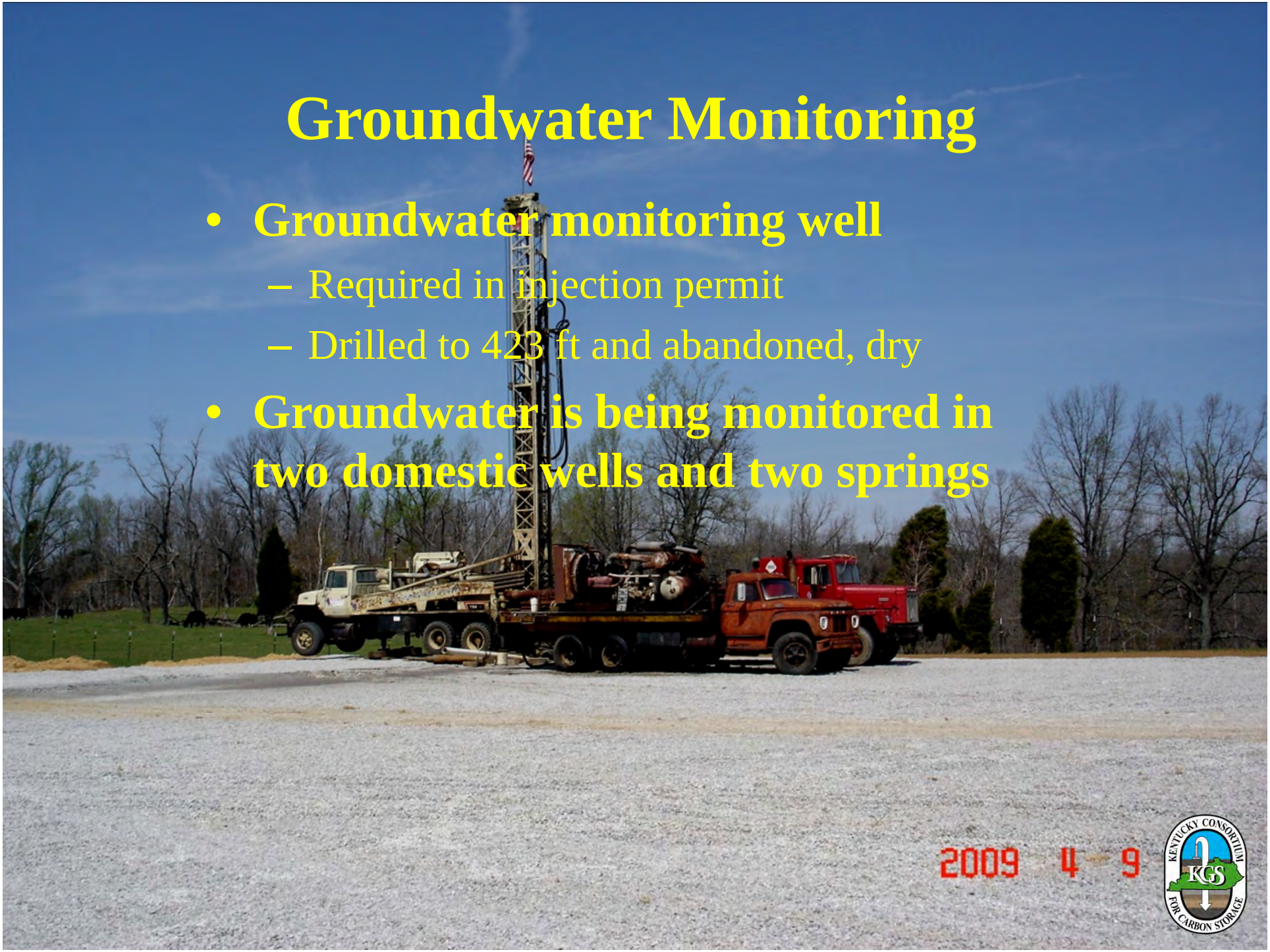


Interpretation of Line C shows no faulting at Knox depths and the Mount Simon pinchout north of the Knight Brothers #1 well.

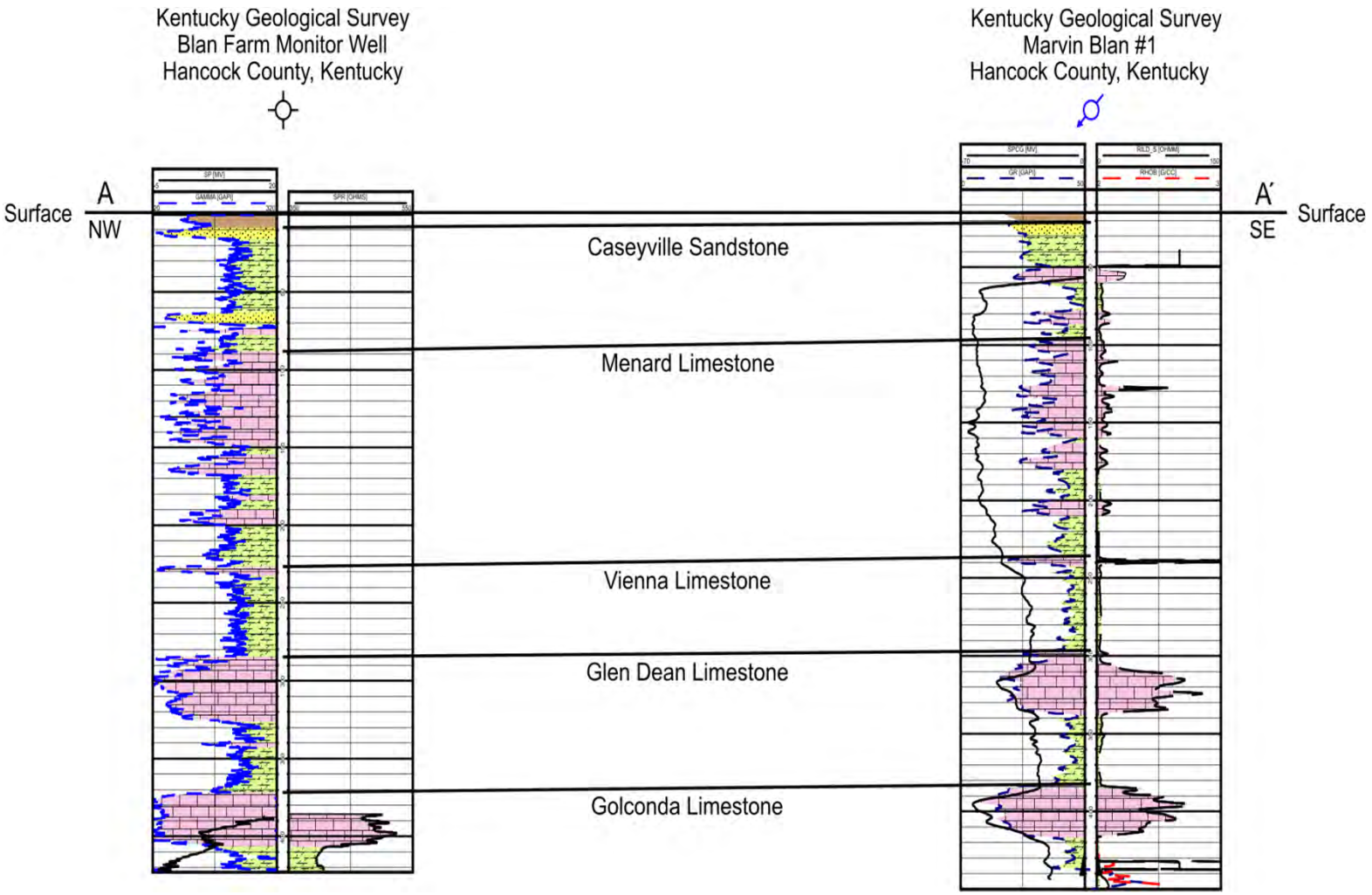

Marvin Blan #1 Wellsite Vicinity
KGS
Marvin Blan #1
TD 8126 ft
Wellsite
(2.07 Ac)
Leased Lands
(196 Ac)
Barns
Historic Cemetery
Landowner's
Residence
Seismic Line B
KENTUCKY CONSORTIUM
KGS
FOR CARBON STORAGE

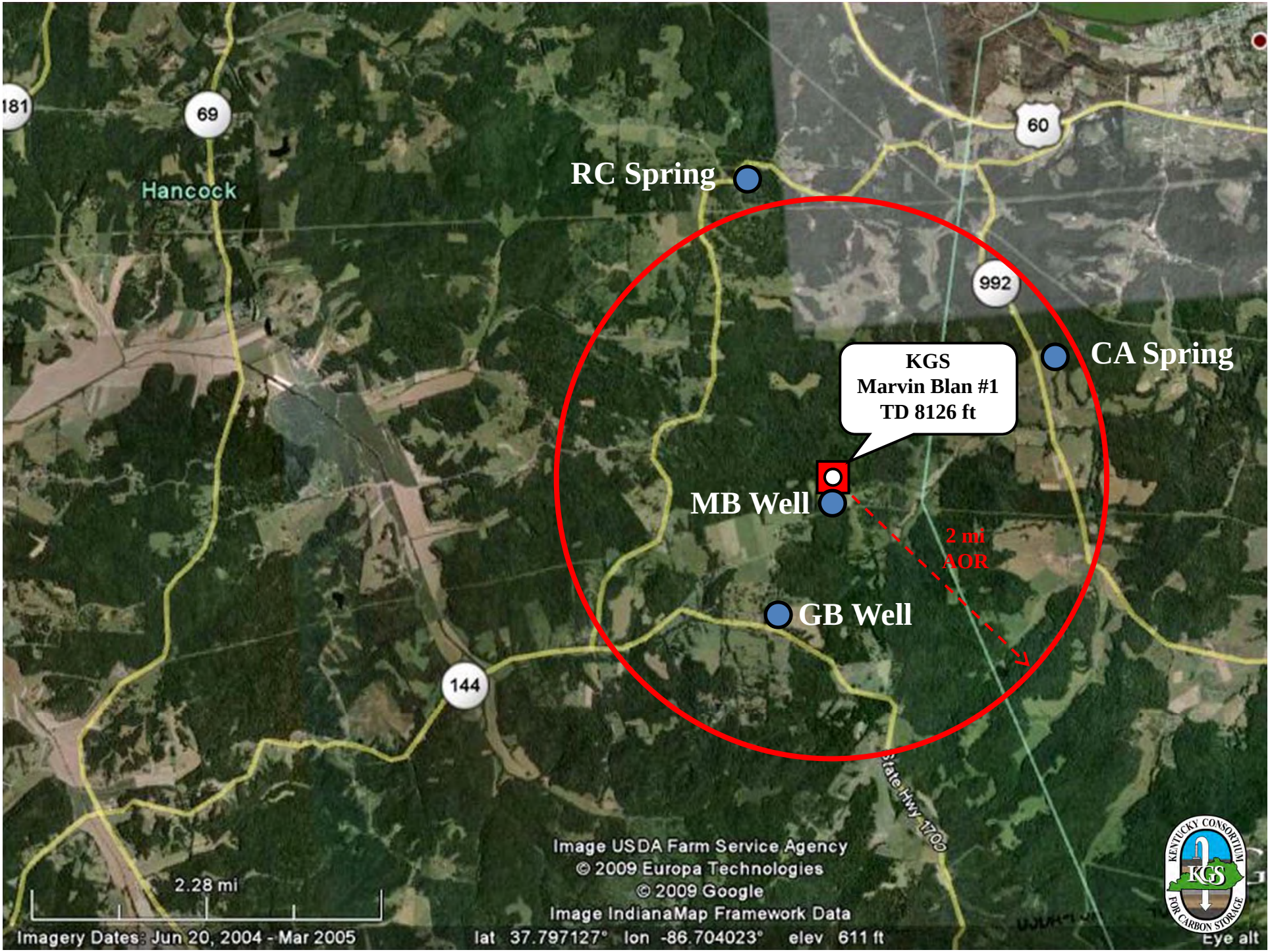
Groundwater Monitoring

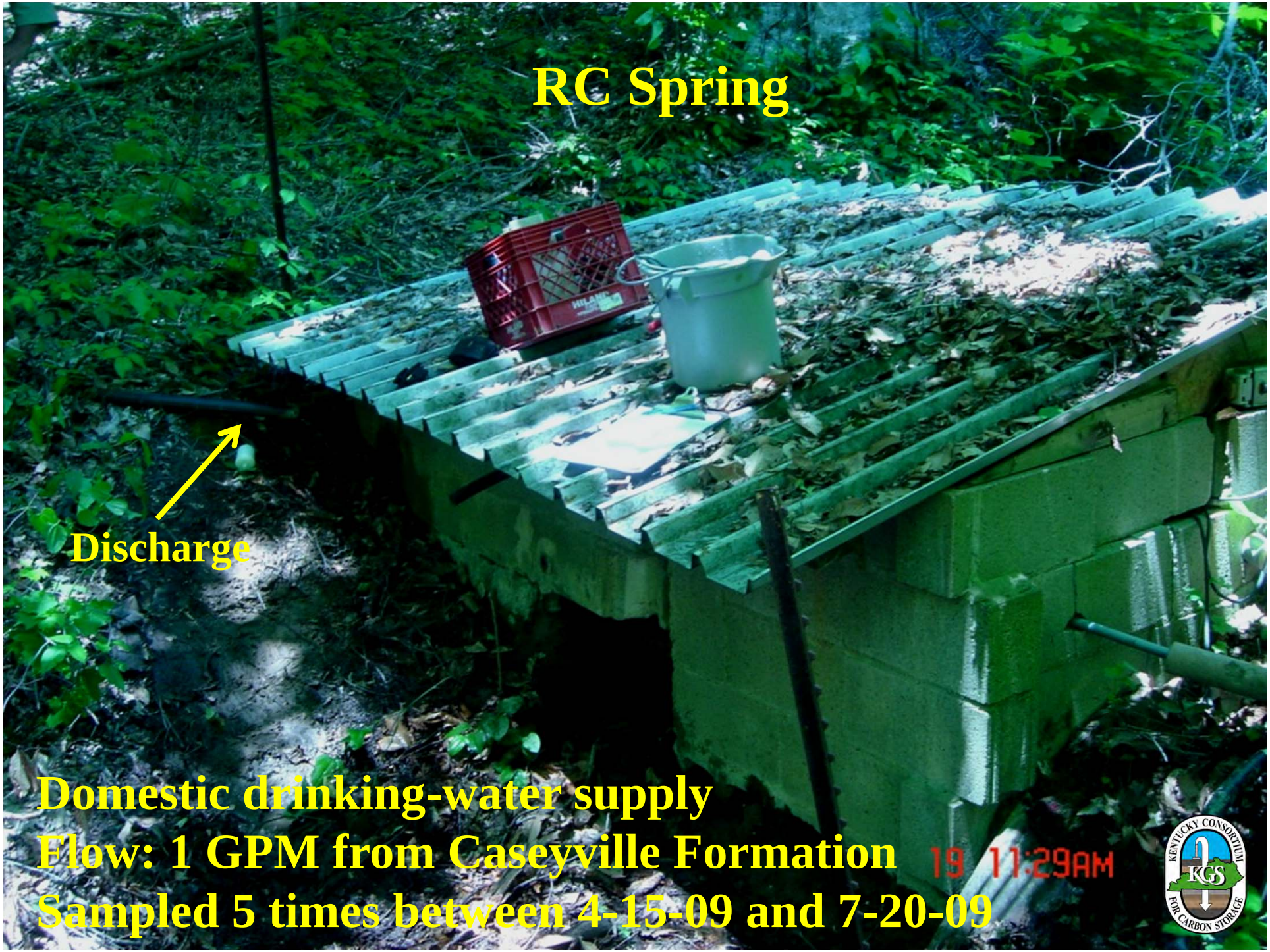
- **Groundwater monitoring well**
  - Required in injection permit
  - Drilled to 423 ft and abandoned, dry
- **Groundwater is being monitored in two domestic wells and two springs**



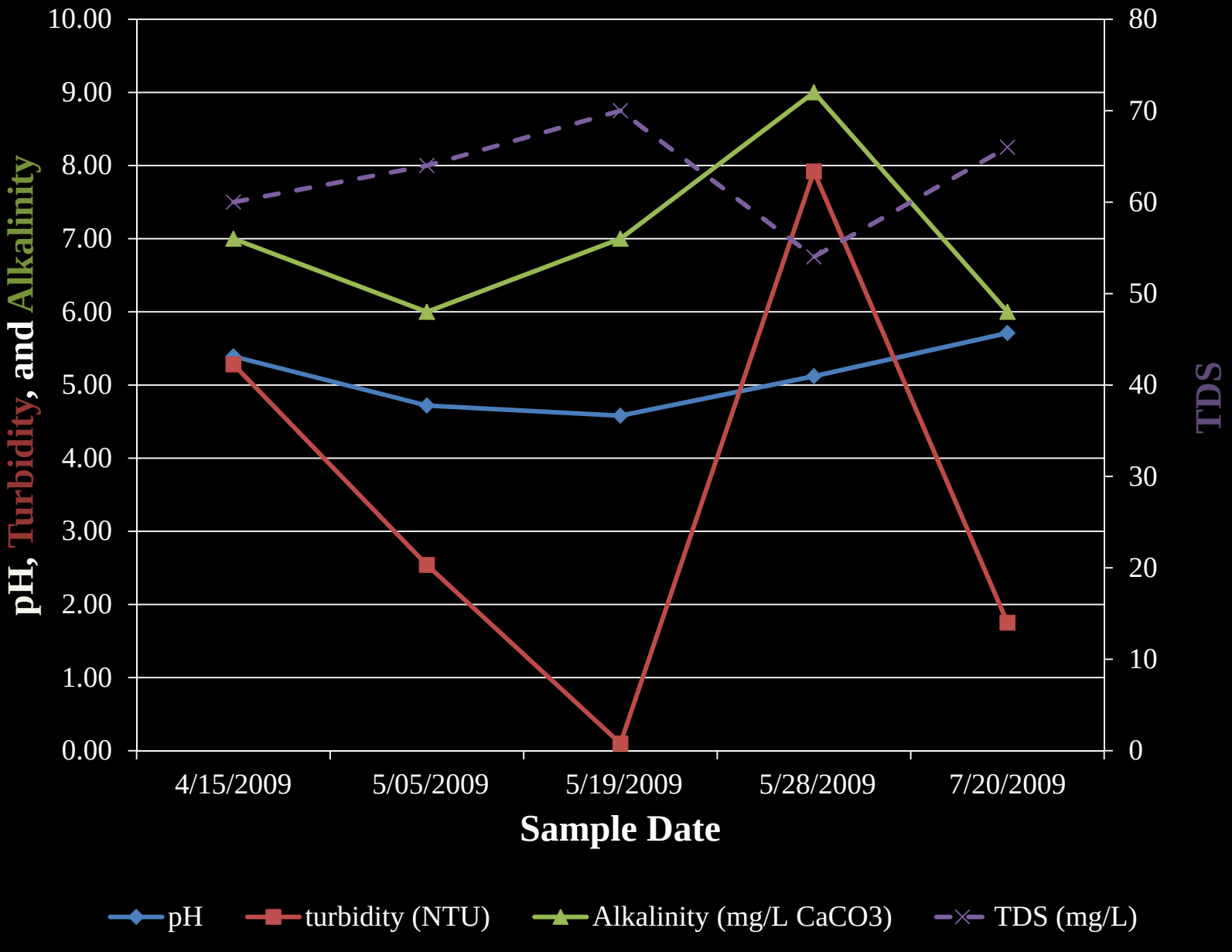
Correlation of Shallow Subsurface Geology




181
69
Hancock
RC Spring
60
992
CA Spring
KGS
Marvin Blan #1
TD 8126 ft
MB Well
2 mi
AOR
GB Well
144
State Hwy 1700
2.28 mi
Image USDA Farm Service Agency
© 2009 Europa Technologies
© 2009 Google
Image IndianaMap Framework Data
Imagery Dates: Jun 20, 2004 - Mar 2005
lat 37.797127° lon -86.704023° elev 611 ft
Eye alt
KENTUCKY CONSORTIUM FOR CARBON STORAGE
KGS

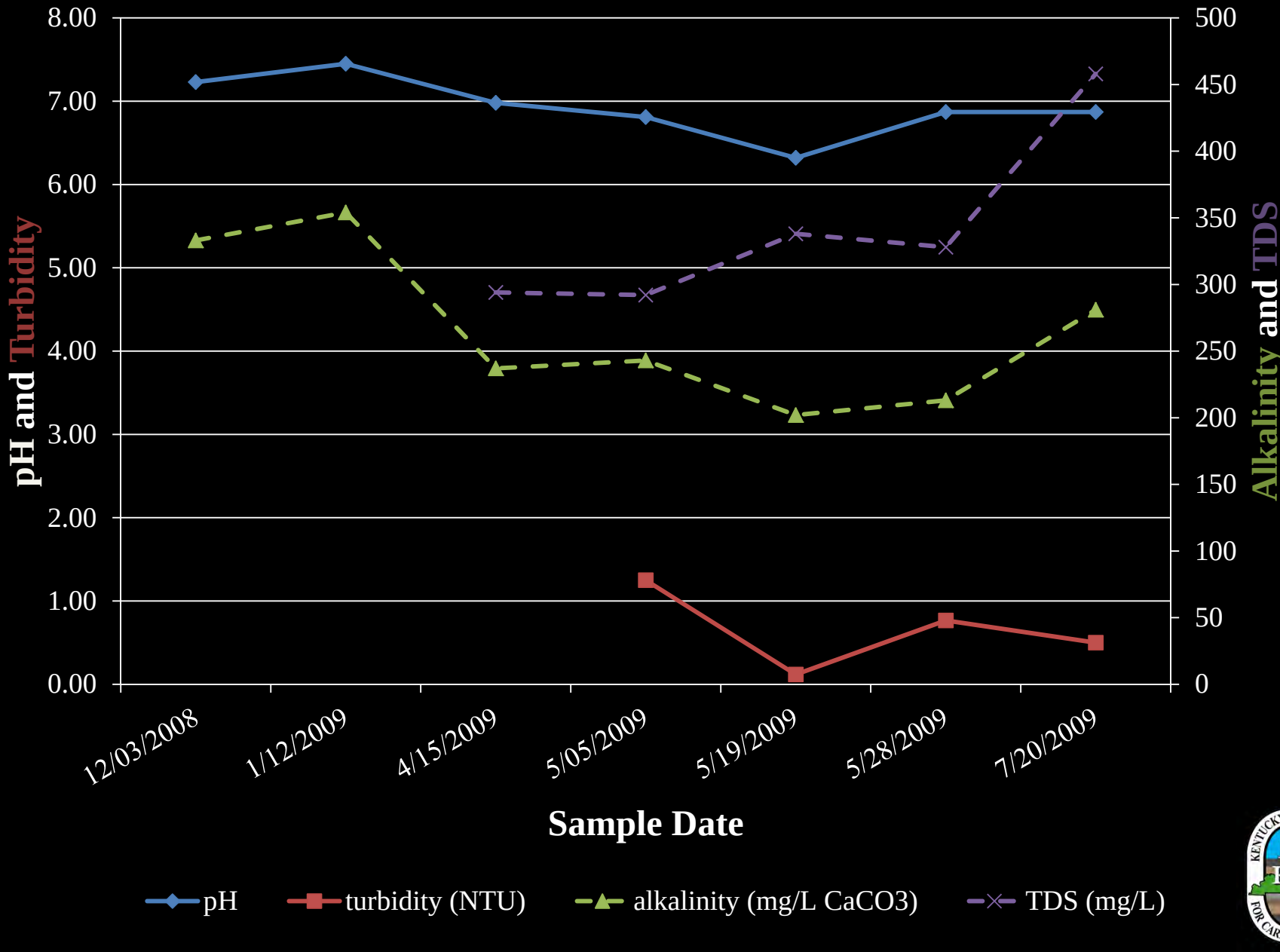

RC Spring
Discharge
Domestic drinking-water supply
Flow: 1 GPM from Caseyville Formation
Sampled 5 times between 4-15-09 and 7-20-09
19 11:29AM
KENTUCKY CONSORTIUM FOR CARBON STORAGE
KGS

RC Spring


10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
pH, Turbidity, and Alkalinity
80
70
60
50
40
30
20
10
0
TDS
4/15/2009
5/05/2009
5/19/2009
5/28/2009
7/20/2009
Sample Date
pH
turbidity (NTU)
Alkalinity (mg/L CaCO3)
TDS (mg/L)


MB Well
(Abandoned Domestic Well)
Sampled 7 times between
12-3-08 and 7-20-09
Total depth: 64 ft
Water level: 15 fbls
KENTUCKY CONSORTIUM
KGS
FOR CARBON STORAGE

MB Well

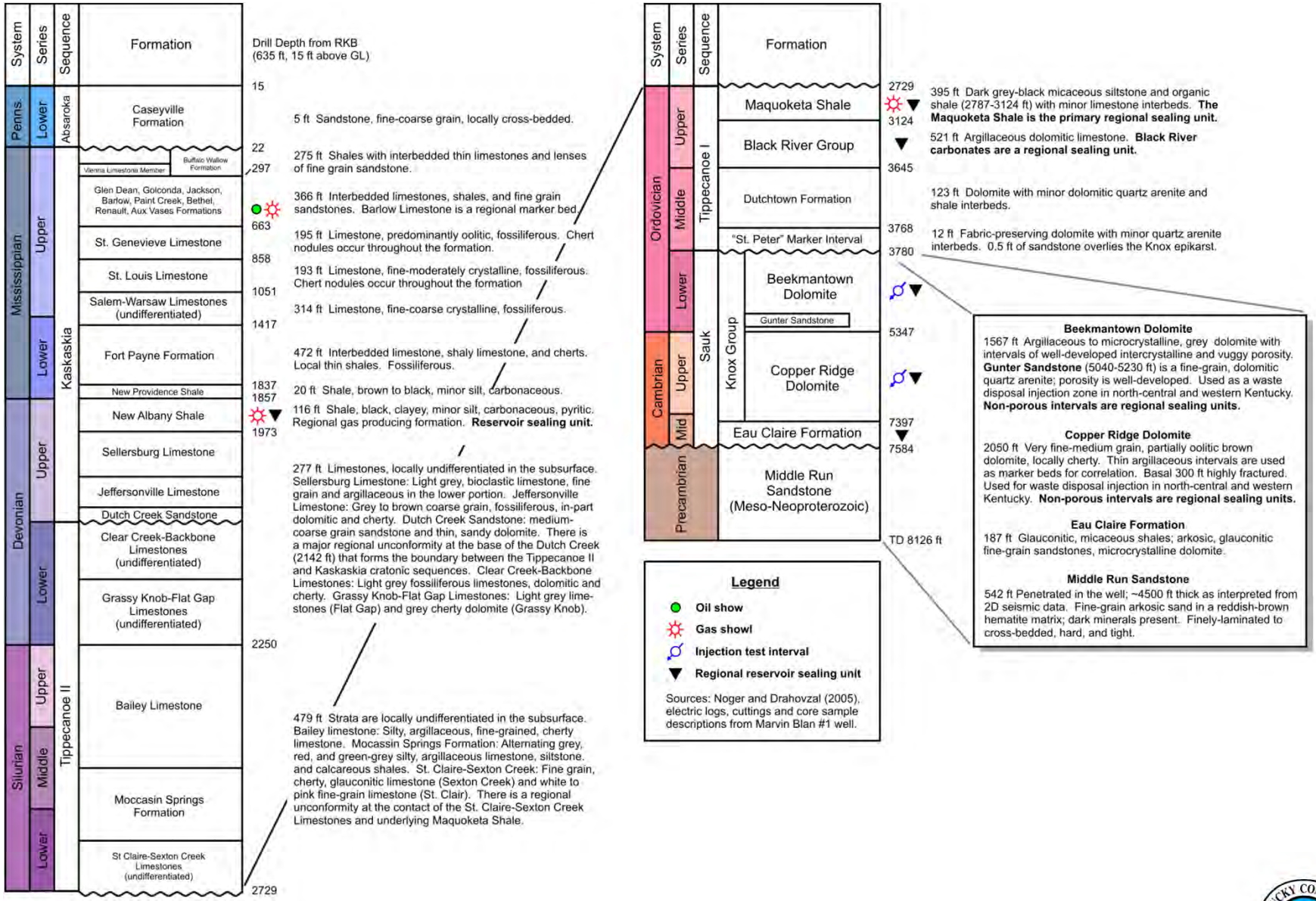

8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
pH and Turbidity
500
450
400
350
300
250
200
150
100
50
0
Alkalinity and TDS
12/03/2008
1/12/2009
4/15/2009
5/05/2009
5/19/2009
5/28/2009
7/20/2009
Sample Date
pH
turbidity (NTU)
alkalinity (mg/L CaCO3)
TDS (mg/L)

Drilling Marvin Blan #1

- **Drilling commenced on April 24, 2009**
  - Casing cemented at 3660 ft, open hole below to TD
  - Drilled through the Knox Group using $CaCO_3$-based mud to mitigate potential reservoir damage
- **Seven cores cut to test reservoir and seal properties**
  - **Reservoir seals**
    - New Albany Shale (30 ft)
    - Maquoketa Shale (31 ft)
    - Black River Limestone (61 ft)
  - **CO_2 storage reservoirs**
    - Knox Group (three cores, 243 ft total)
    - Precambrian Middle Run Sandstone (30 ft)
- **Reached TD at 8126 ft on June 14**

Drilling Results

- St Peter Sandstone effectively absent: only six inches of sand was present at the Knox unconformity
- The Knox Group was found 85 ft structurally higher than expected and 380 ft thinner
- Eau Claire was considerably thinner than expected, only 187 ft thick including a 61 ft dolomite bed
- Top of the Precambrian Middle Run Sandstone was found 420 ft higher than expected



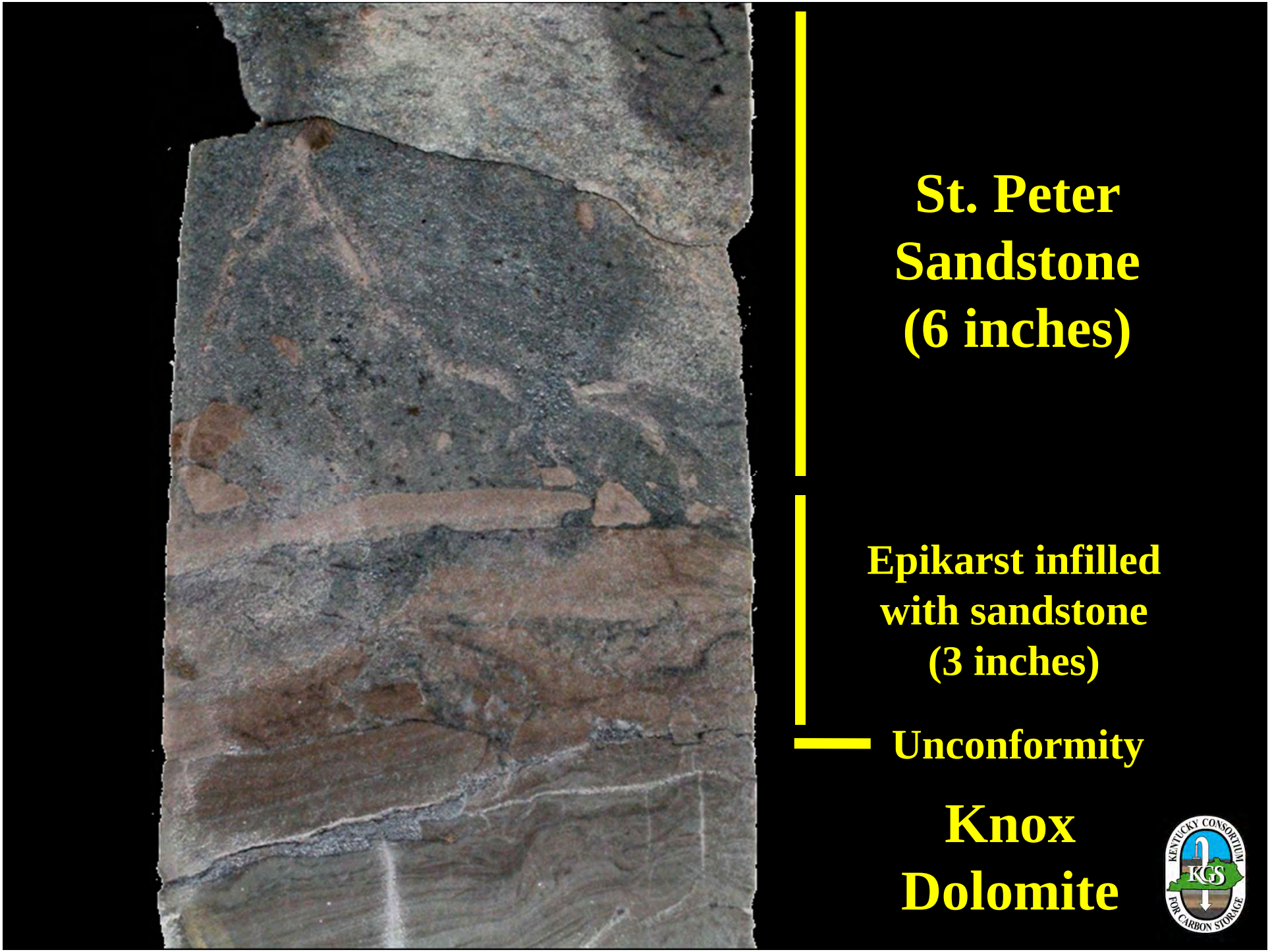
Strata penetrated in the Marvin Blan #1.

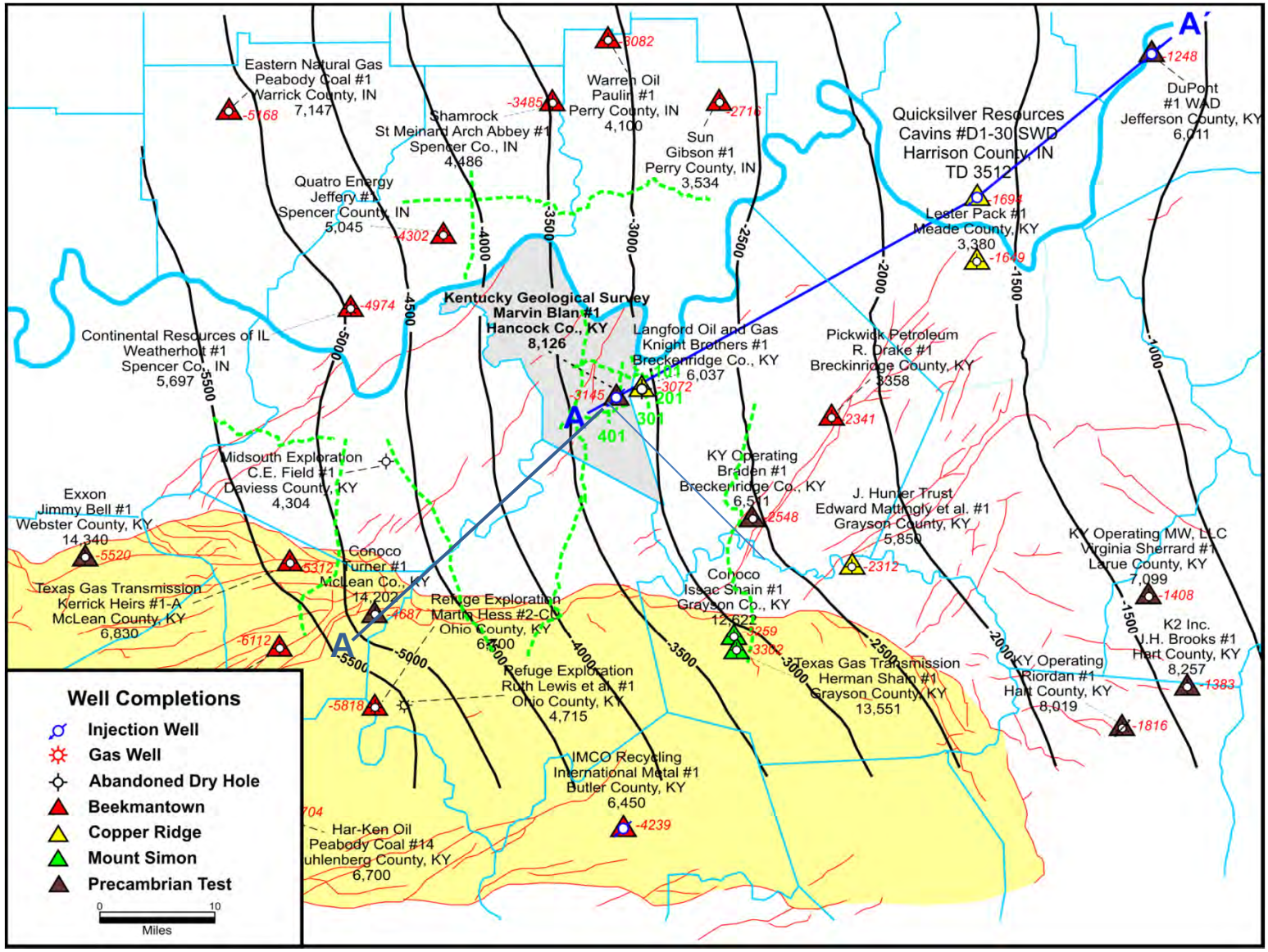
Maquoketa Shale Core

- **Maquoketa Shale was cored 2800-2831 ft to test reservoir seal properties**
- **Analyses of seal properties**
  - Core analysis
    - Porosity 0.4%
    - Permeability 1.63×10^{-5} md
  - Compressive strength 17,264 psi
  - XRD mineralogy
    - 39% clays, 15% carbonates, 36% silicates, balance other minerals
  - Thin section petrography

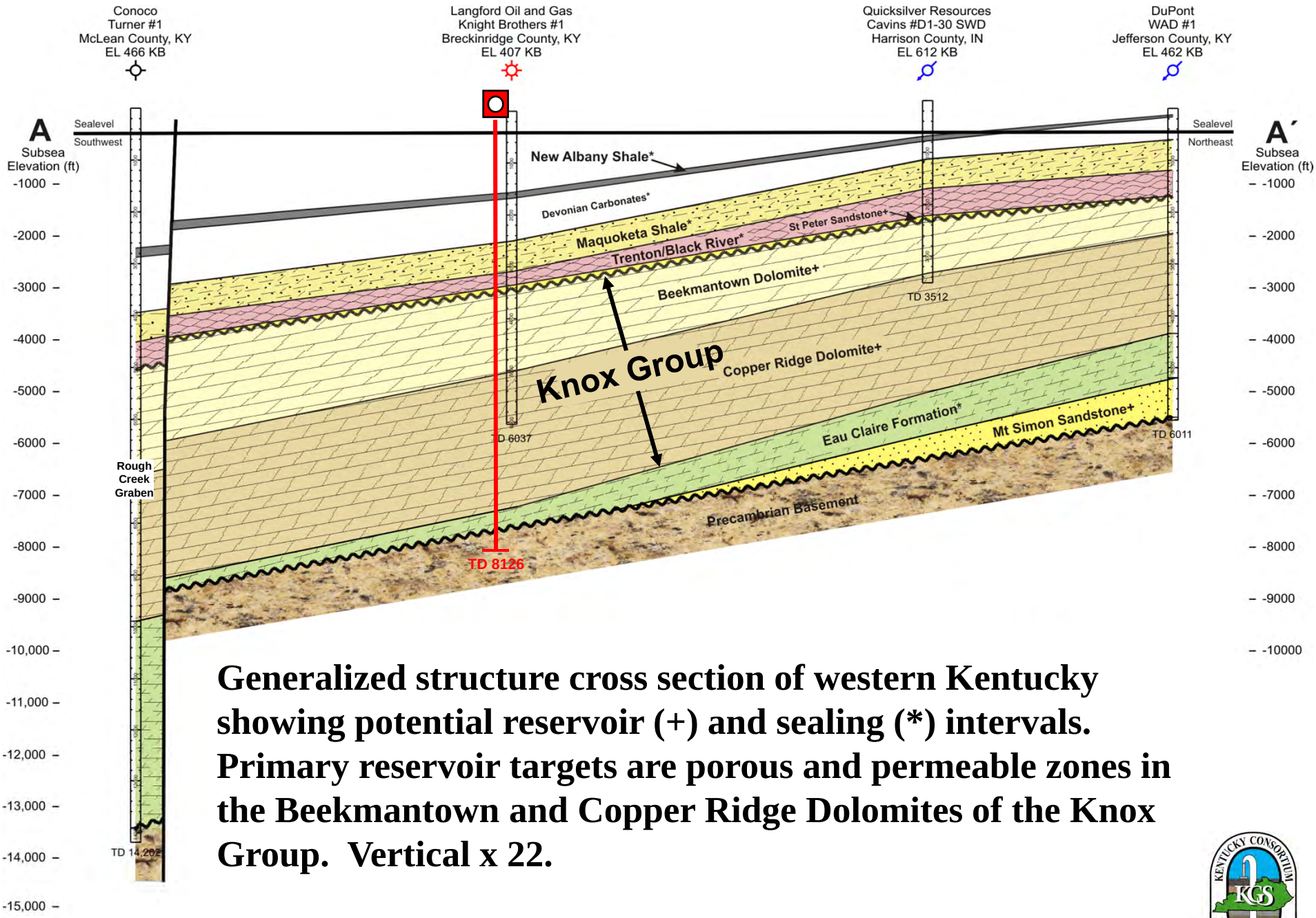
Black River Group

- **Black River carbonates were cored 3335-3395 ft to test reservoir seal properties**
- **Analyses of seal properties**
  - Core analysis
    - Porosity 0.5%
    - Permeability 9.0×10^{-4} md
  - Compressive strength 7216-7910 psi
  - XRD mineralogy
    - 97% carbonate, 2% quartz, 1% clays
  - Thin section petrography

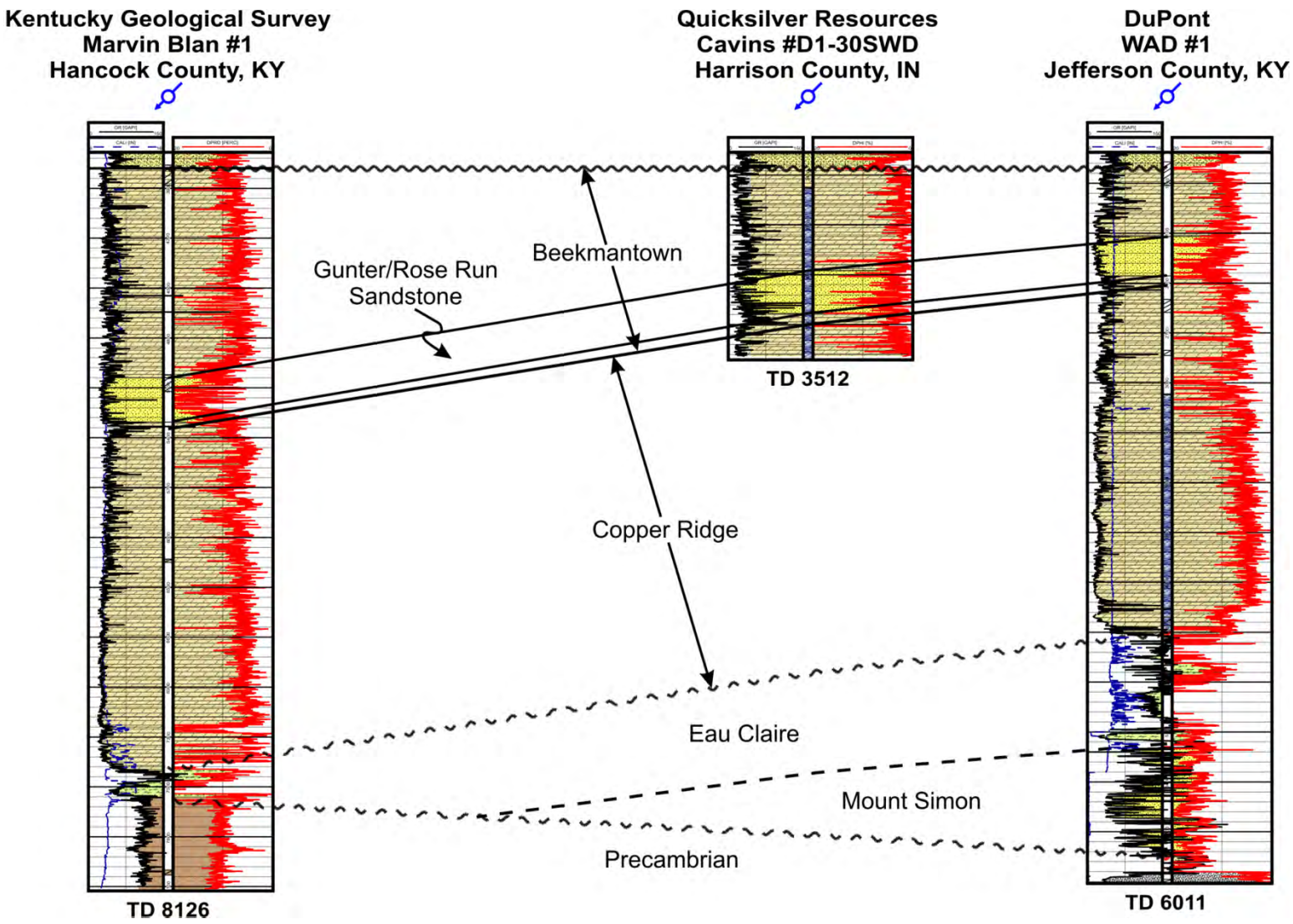

St. Peter
Sandstone
(6 inches)
Epikarst infilled
with sandstone
(3 inches)
Unconformity
Knox
Dolomite
KENTUCKY CONSORTIUM
KGS
FOR CARBON STORAGE



Structural contours on top of the Knox Group.



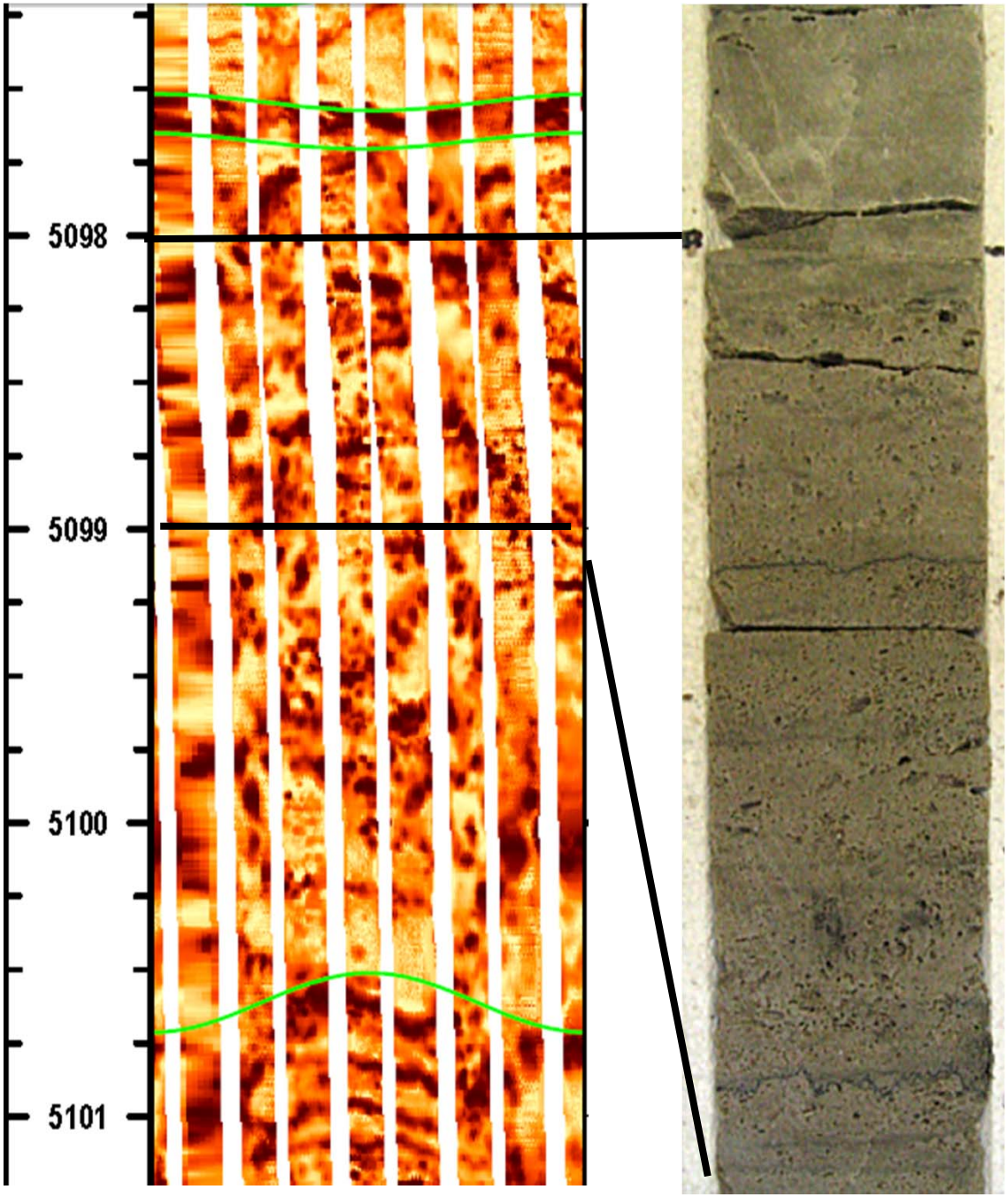
Generalized structure cross section of western Kentucky showing potential reservoir (+) and sealing (*) intervals. Primary reservoir targets are porous and permeable zones in the Beekmantown and Copper Ridge Dolomites of the Knox Group. Vertical x 22.



Stratigraphic correlation of the Knox Group and deeper strata.

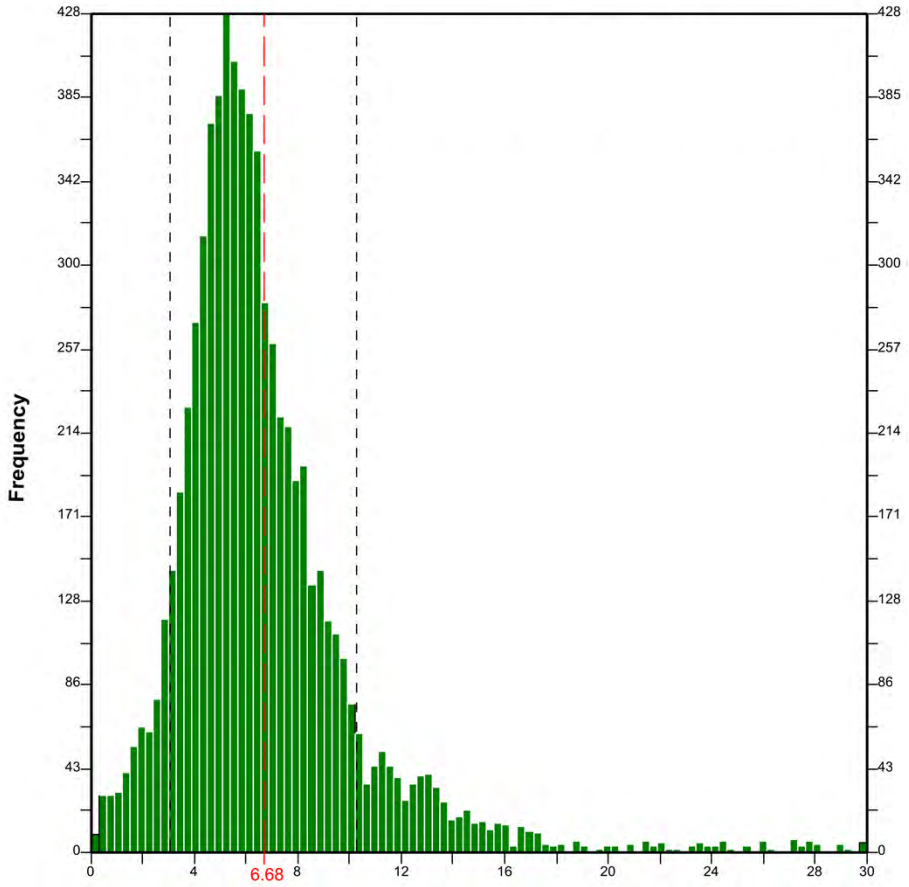
Knox Dolomite Cores

- **Knox Dolomite was cored in three intervals (total 243 ft) to test reservoir properties**
  - "St Peter"-Beekmantown (123 ft)
  - Beekmantown-Gunter (101 ft)
  - Copper Ridge (19 ft)
  - Found porosity system to be a complex of preserved fabric, primary dolomite porosity, vugs, and fractures
- **Extensive analysis program**
  - Routine core analysis
  - Mechanical properties
  - XRD mineralogy
  - CO_2 core flood
  - Thin section petrography
  - Threshold entry pressure

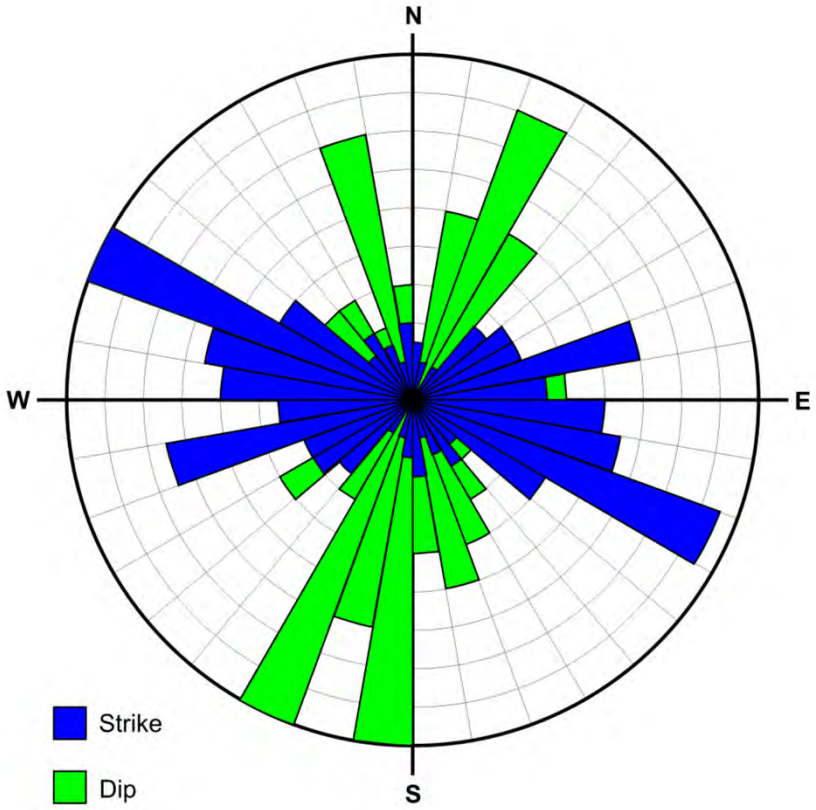


CMI log section and core showing vuggy porosity in the Beekmantown Dolomite

Knox Reservoir Properties

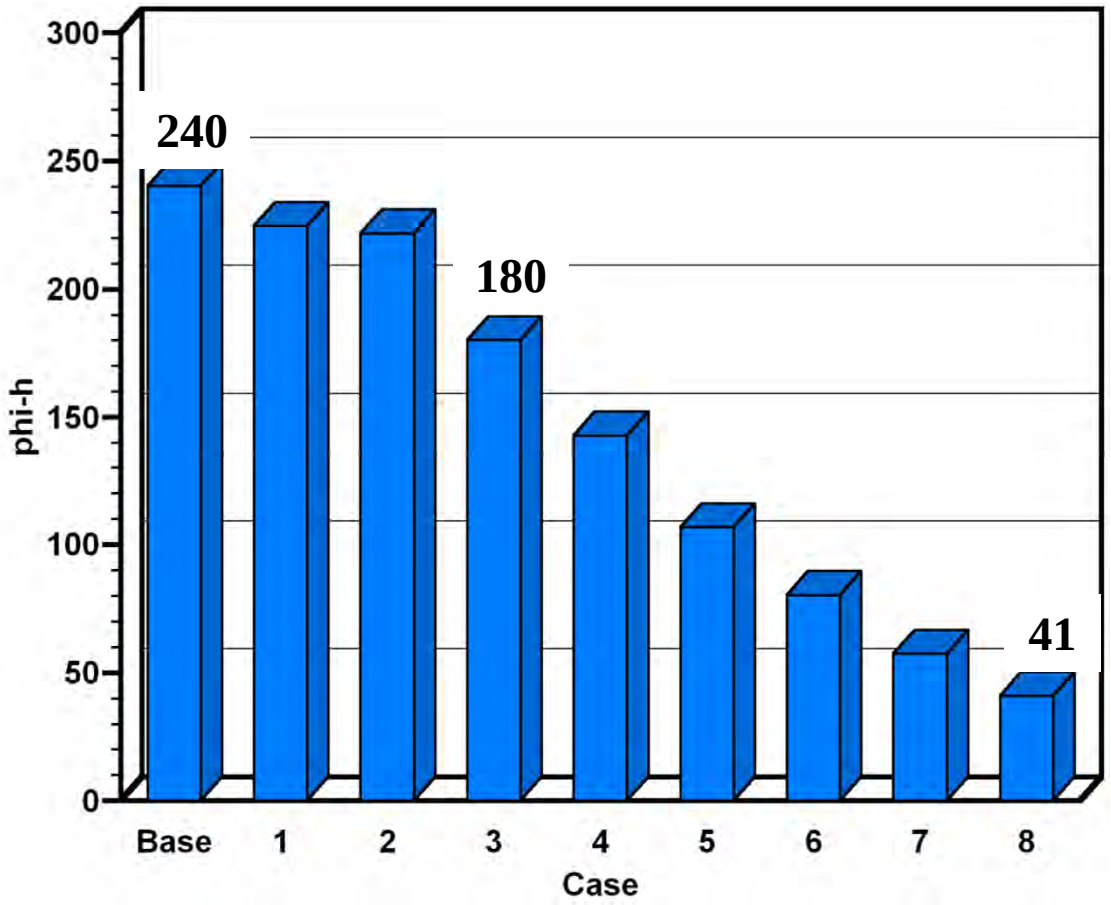


Average Porosity 6.7%



NNW Fracture Trend

Potential Reservoir Volume in the Knox



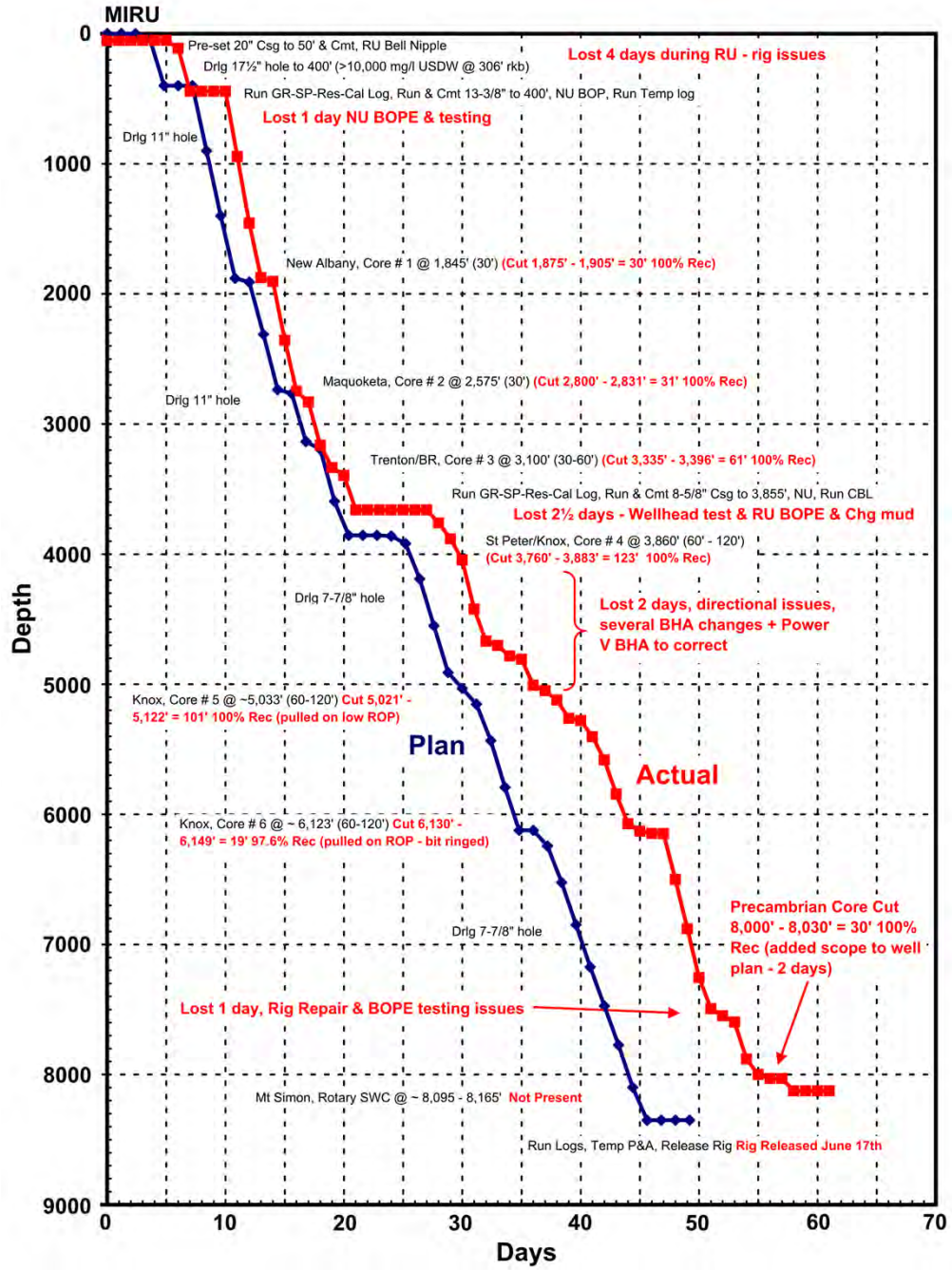
- **Base: all data**
- **Cutoff cases:**
  - **1. caliper > 10½ in.**
  - **2. porosity > 20%**
  - **3. porosity < 5%**
  - **4. porosity < 6%**
  - **5. porosity < 7%**
  - **6. porosity <8%**
  - **7. porosity < 9%**
  - **8. porosity < 10%**

Middle Run Sandstone Core

- **Precambrian Middle Run Sandstone was cored 8000-8030 ft to evaluate its potential as a carbon storage reservoir**
  - DOE-NETL grant for coring and analysis
- **Analysis Program**
  - Routine core analysis
  - Fracture orientation
  - XRD mineralogy
  - Thin section petrography
  - Provenance
  - Zircon age dating
  - Mechanical properties

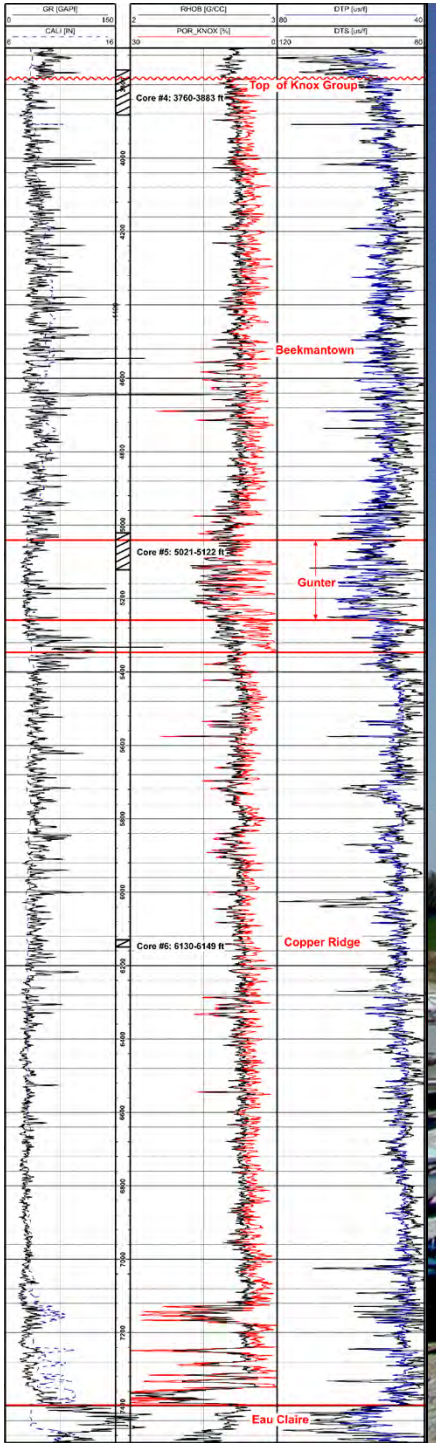
Drilling Challenges

- **Drilling rig and wellhead mechanical failures**
- **Lower than expected penetration rates**
- **Borehole deviation below 3000 ft**
  - Angle built to 5.75°
  - Used Schlumberger Vertical Seeking Power V System to bring borehole back to vertical
- **Lost circulation thief zone at 5581 ft**
  - Successfully controlled with LCM
- **Drilled ~250 ft deeper than necessary to achieve objectives due to missed formation tops**
  - Added two days to drilling



Marvin Blan #1 Depth vs. Days

Drilling took 62 days, 13 days longer than planned, despite a shallower than planned TD.



Well Completion

- **Extensive electric log program at TD**
  - **Triple-combo array resistivity-porosity-gamma ray suite**
  - **Dipole sonic rock mechanical properties**
  - **Formation micro-imager**
  - **Zero-offset vertical seismic profile (VSP)**

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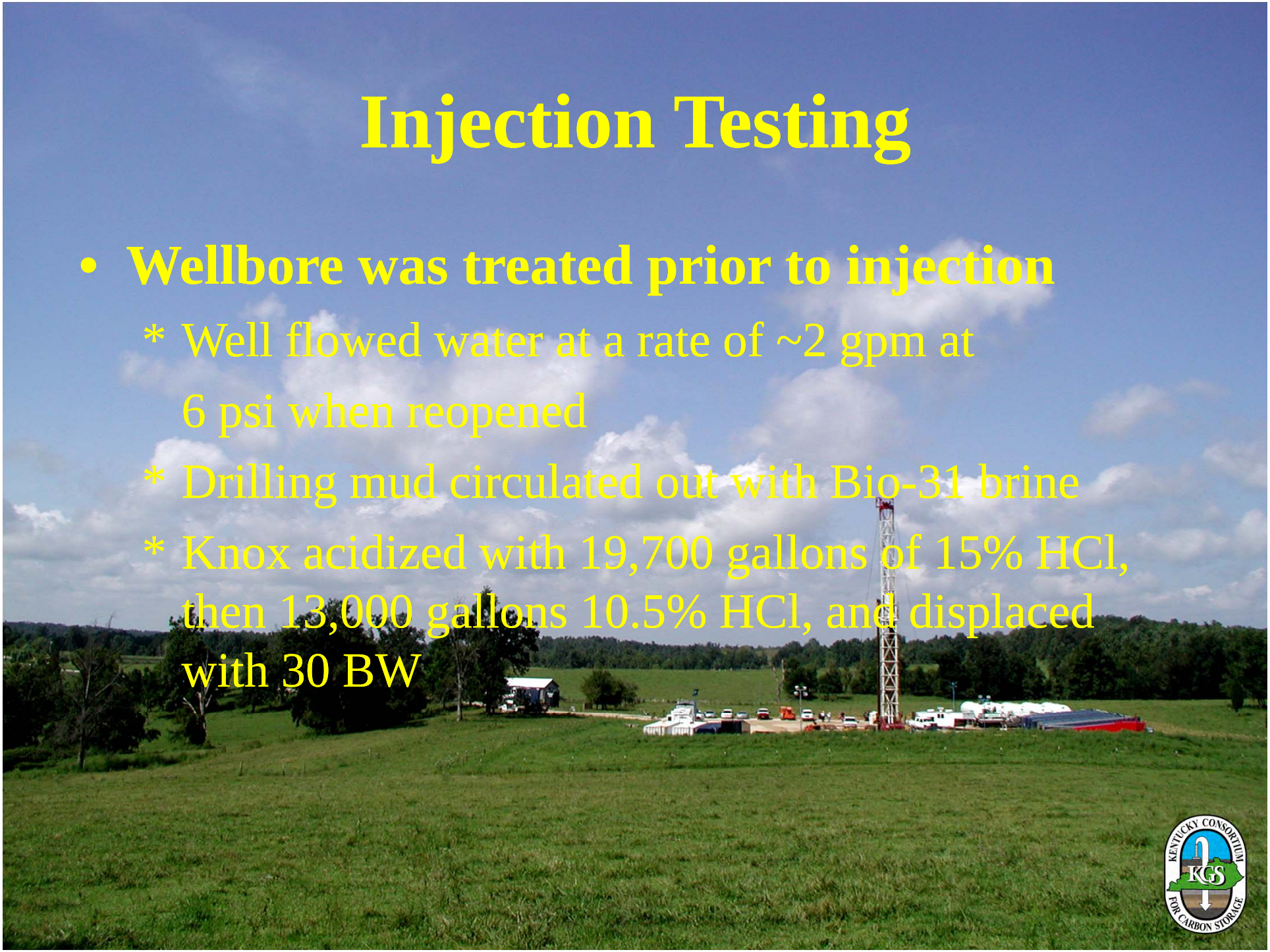
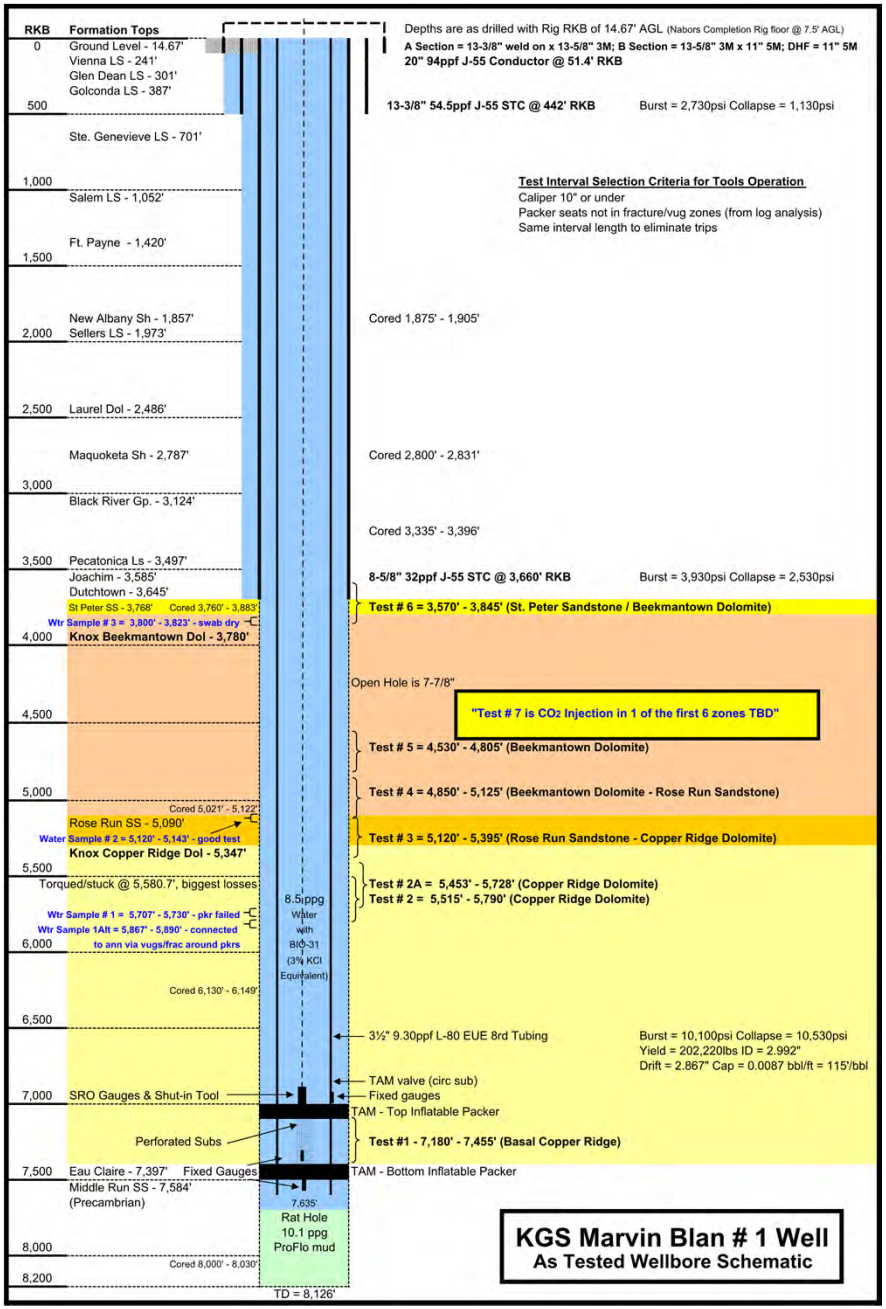
Injection Testing

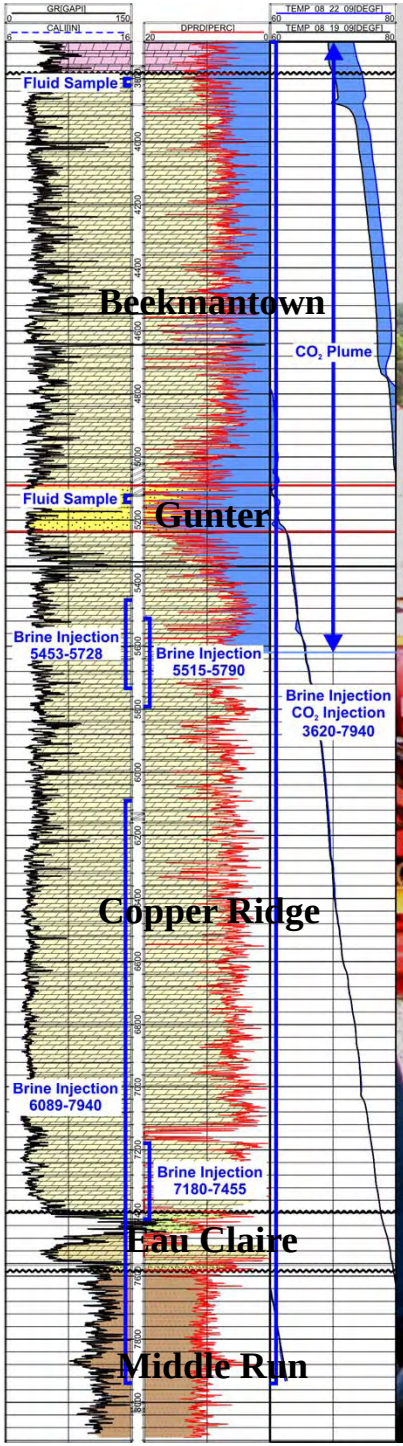
- **Wellbore was treated prior to injection**
  * Well flowed water at a rate of ~2 gpm at 6 psi when reopened
  * Drilling mud circulated out with Bio-31 brine
  * Knox acidized with 19,700 gallons of 15% HCl, then 13,000 gallons 10.5% HCl, and displaced with 30 BW





Injection Testing

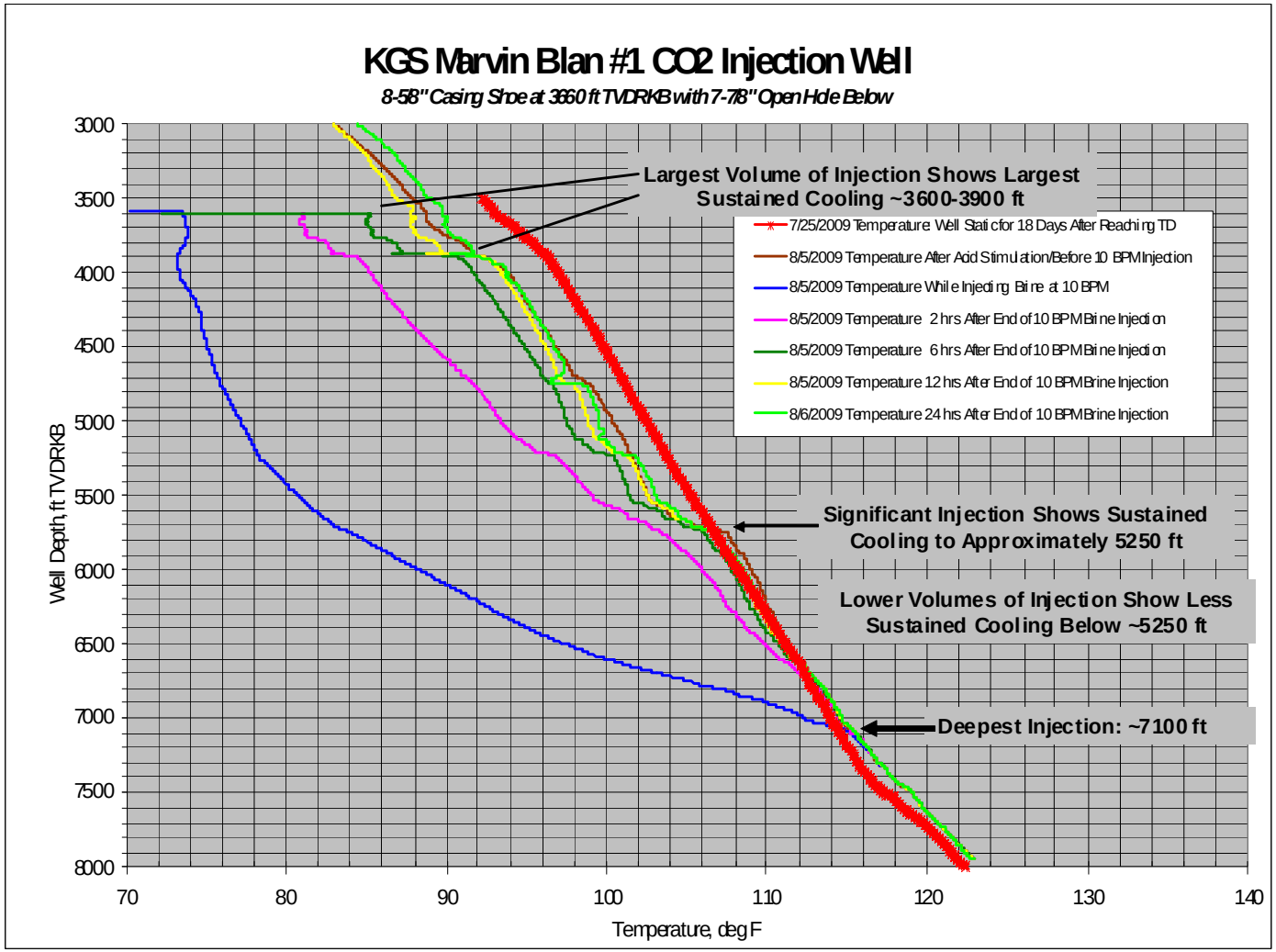
- **Testing budget ~$2 million**
- **Testing began on July 25 and was completed on August 22**
  - Two formation water samples were collected
  - Initial injection of brine was into 285 ft intervals isolated by inflatable straddle packers on tubing
    - Seven tests attempted
    - Three packers failed during tests
    - Results mixed due to leakage and communication around the packers through the formation porosity system
  - Program revised to full-wellbore injection of brine below a single packer



Injection Testing

- **Three tests with straddle packers**
  - basal Copper Ridge: 218.8 BW, broke down at 0.9 psi/ft gradient and took water on vacuum
  - upper Copper Ridge: two tests, total 5192.7 BW, lost seal due to communication through formation porosity system around packers
- **Two tests with single packer**
  - Copper Ridge below 6089 ft: 2190 BW brine,1212.1 BW with borax tracer
  - Full wellbore below 3620 ft: 7075.7 BW with borax tracer
  - Injection rates to 14 BPM at 285-500 psi wellhead pressure
- **Found 70% of water was injected above the Copper Ridge**

Temperature Logging



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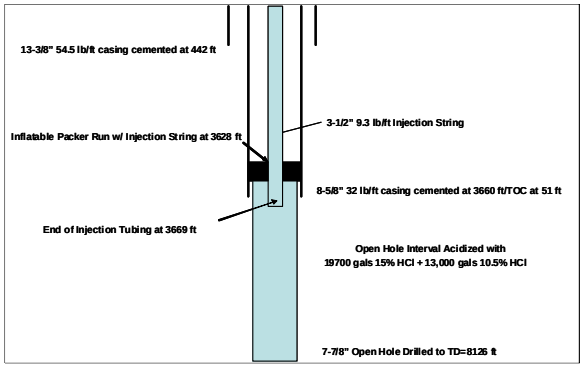
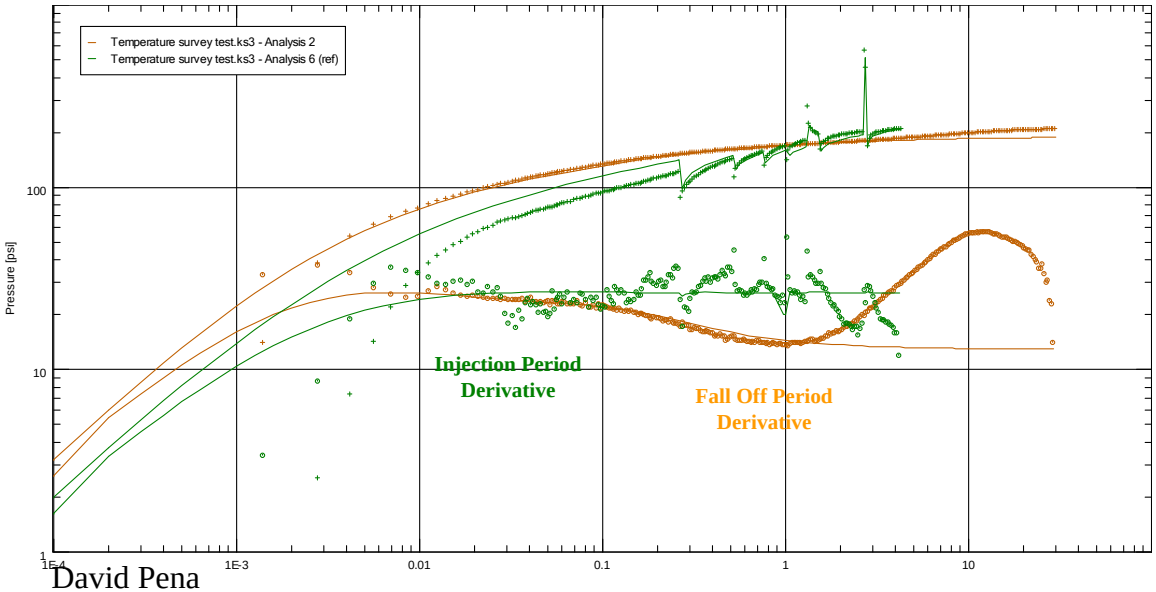
Water Injection Test #4

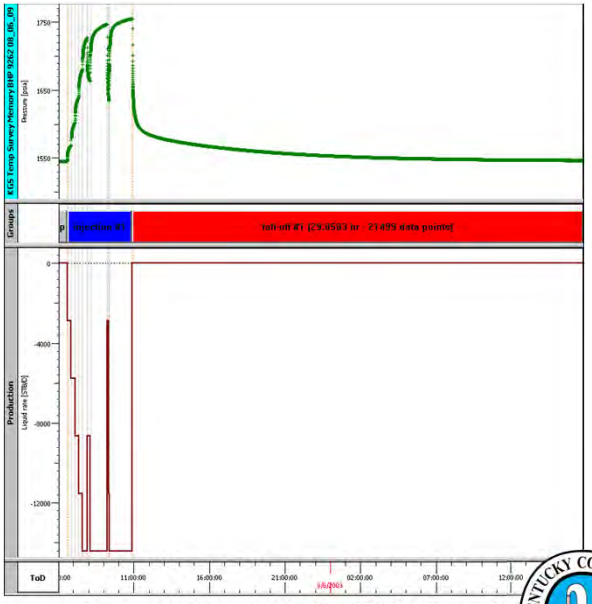
Test #4 successfully tested entire open hole interval with single packer set at 3620 ft. The estimated average Kh for the Commingled Zone is ~ 28,900 md-ft.



Temperature decay log Results

	Inflow zones 1	Inflow zones 2	Inflow zones 3	Inflow zones 4	Inflow zones 5	Inflow zones 6	Inflow zones 7
From , ft	3630	4820	5440	5620	5700	7010	7080
To , ft	3878	5220	5580	5660	5720	7040	7110





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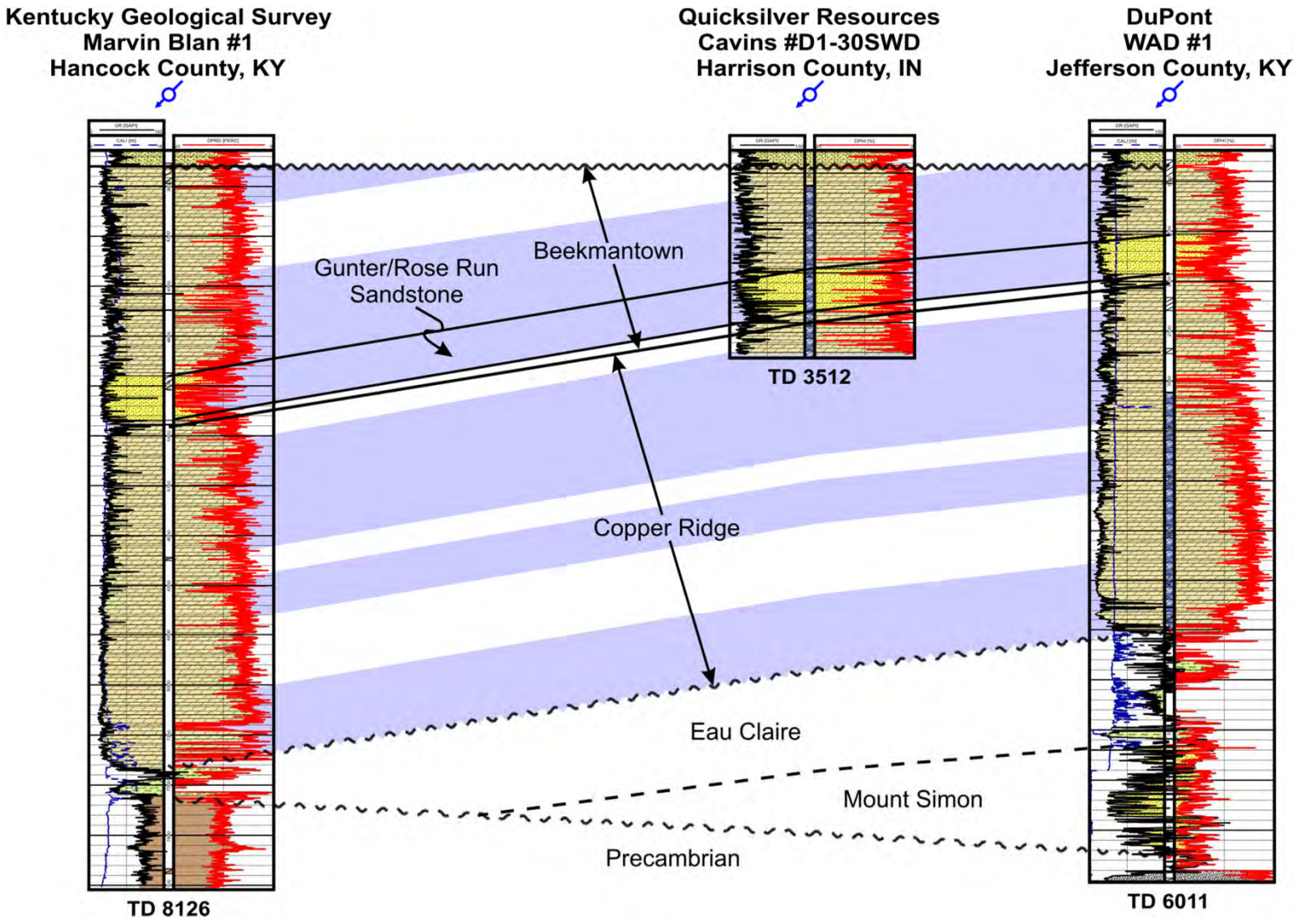


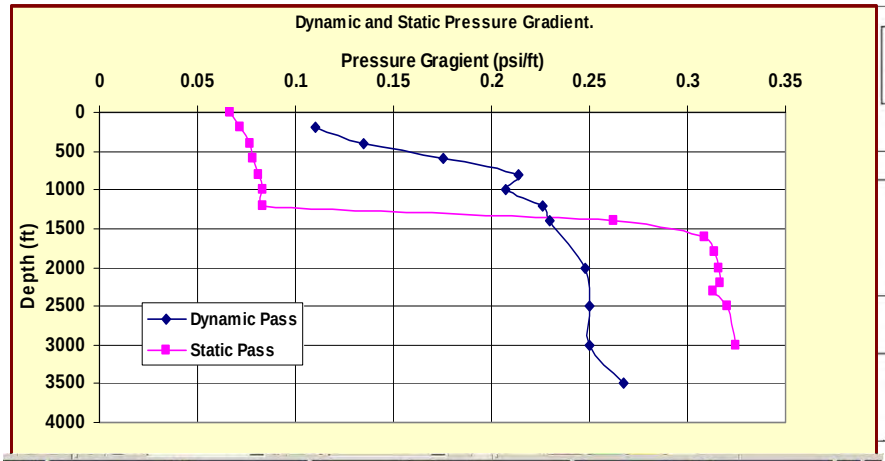
Regional correlation of Knox injection zones

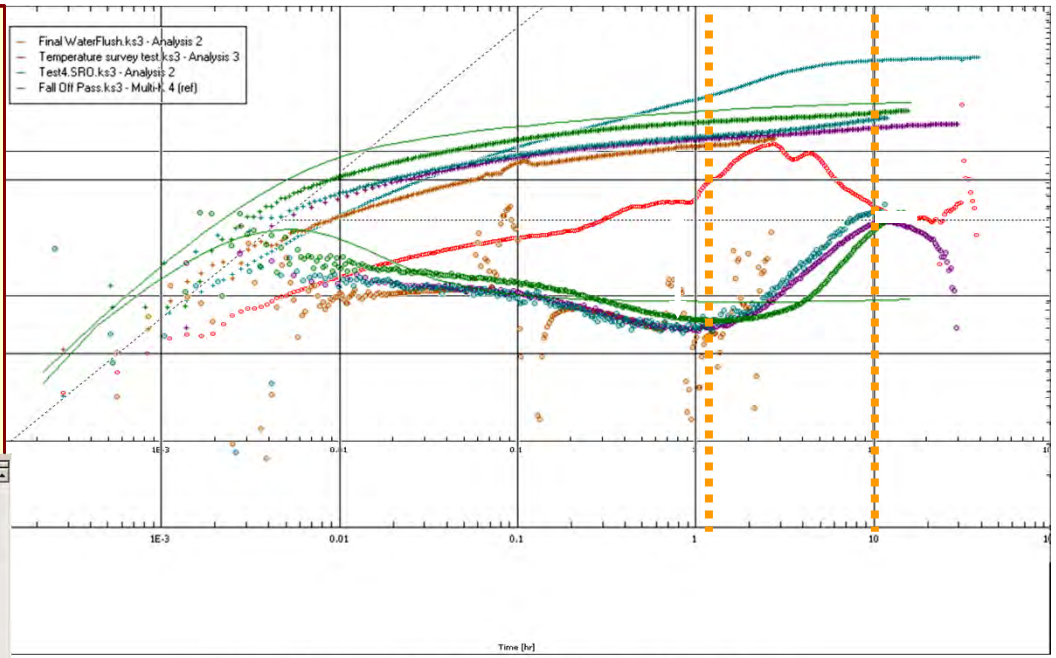
CO_2 Injection

- Injected a total of 323 Tons of CO_2 (1765 bbl or 5646 mcfg) below a packer set in casing at 3603 ft
- Limited to 4.1 BPM rate due to pump limitations
- Wellhead pressure 936 psi, bottomhole pressure 1754 psi
- Post-injection flushed with 4568 BW brine
- Long-term downhole pressure gauge in place to monitor pressure fall-off pending re-entry for additional tests

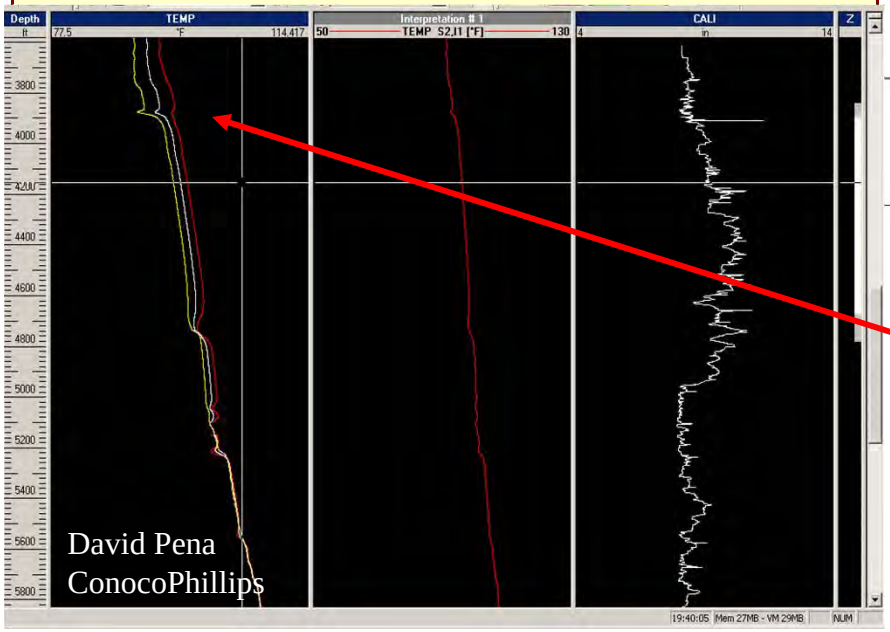
CO_2 Injection test

A constant CO_2 injection rate of 4.0 bpm, total injection volume of 1765 bbl of CO_2. The final injection BHP and BHT at 3580 ft were 1753.8 psia and 103.2 °F. At the end of IFOT#6, a temperature logging survey was performed across the open hole interval and determined final injection point of CO_2 to be @ 5230ft in the Gunter Sandstone.





Log-Log plot: m(p)-m(p@dt=0) and derivative [psi2/cp] vs dt [hr]



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Interval predominantly injected with CO2

Additional Work

- **Testing planned for 2010, funded by DOE research award of $1.6 million**
  - Additional brine, possibly additional CO_2 injection
  - 3D VSP to image injection plume
  - Knox reservoir evaluation
- **Plug and abandon the Marvin Blan #1 in compliance with State and EPA regulations**
- **Remediate drillsite**
- **Groundwater and soil gas monitoring through 2012**

Acknowledgements

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