Western Kentucky CO_2 Storage Test

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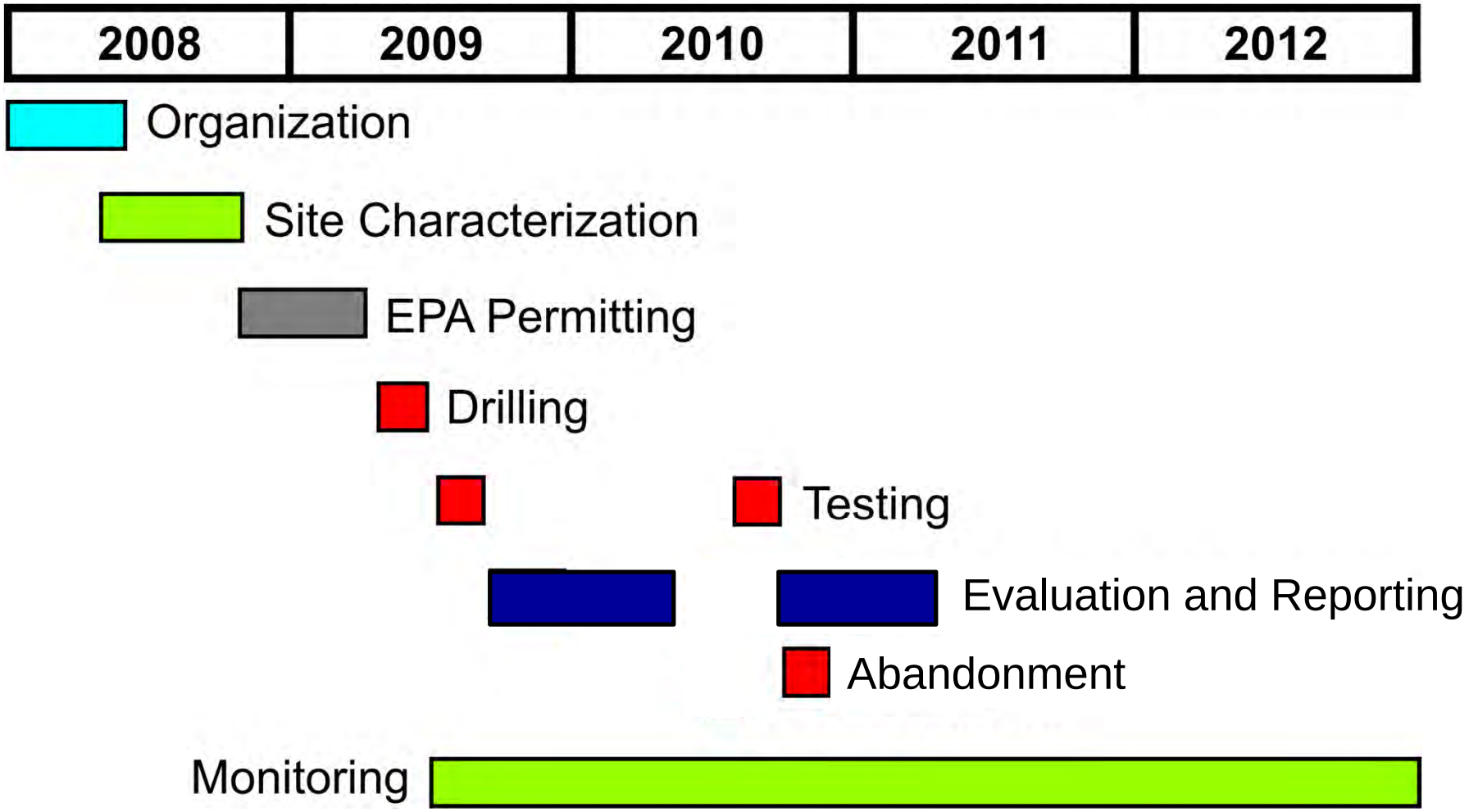
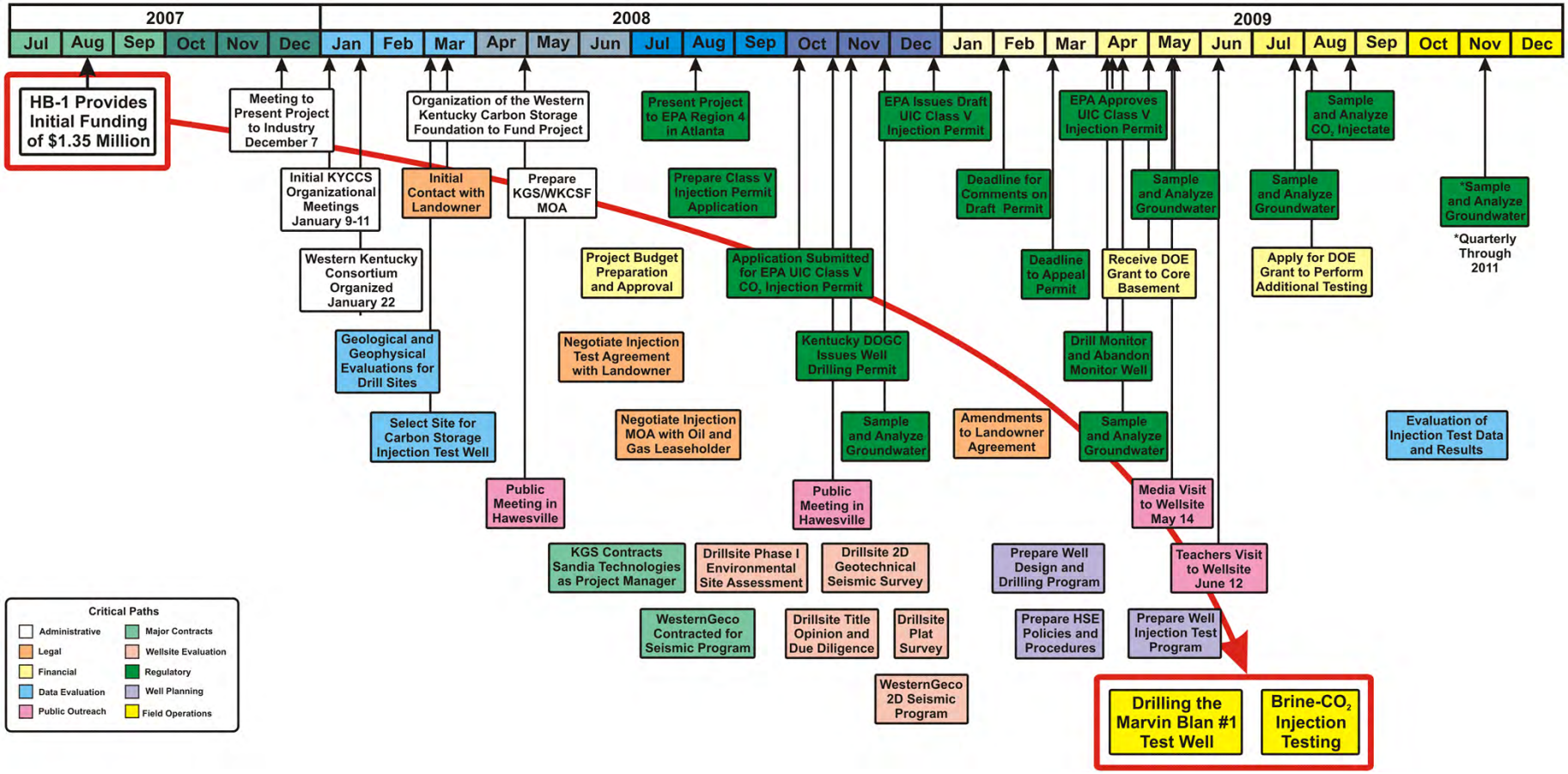
KGS First Friday Seminar
Lexington, Kentucky
March 4, 2011

- **The project proceeded in two phases:**
  - **Phase 1 (2009) got the well drilled and the first round of testing completed. Total cost ~$7.3 million.**
    - Acquired 24.1 miles of 2-D reflection seismic data and VSP
    - Drilled to 8,126 ft, cemented casing at 441 ft and 3,060 ft, and cut 395 ft of cores
    - Injected 18,454 barrels of brine and 323 tons of CO_2 (1,765 barrels) in the open wellbore below 3,060 ft
  - **Phase 2 (2010) completed a second round of testing and abandoned the injection zone. Total cost ~$1.0 million.**
    - 3D seismic survey and VSP
    - Plugged the well at 5,268 – 5,545 ft, abandoning the lower 2858 ft of the well, and constructed a 230-ft test interval at 5,038 – 5,268 ft
    - Injected 4,265 barrels of brine and 367 tons of CO_2 (2,000 barrels)
    - Plugged and abandoned the test interval at 5,037 – 5,275 ft
    - Plugged the well at 3,942 – 3,477 ft and abandoned the Knox Dolomite interval, and plugged the casing at 800 ft with a cast iron bridge plug

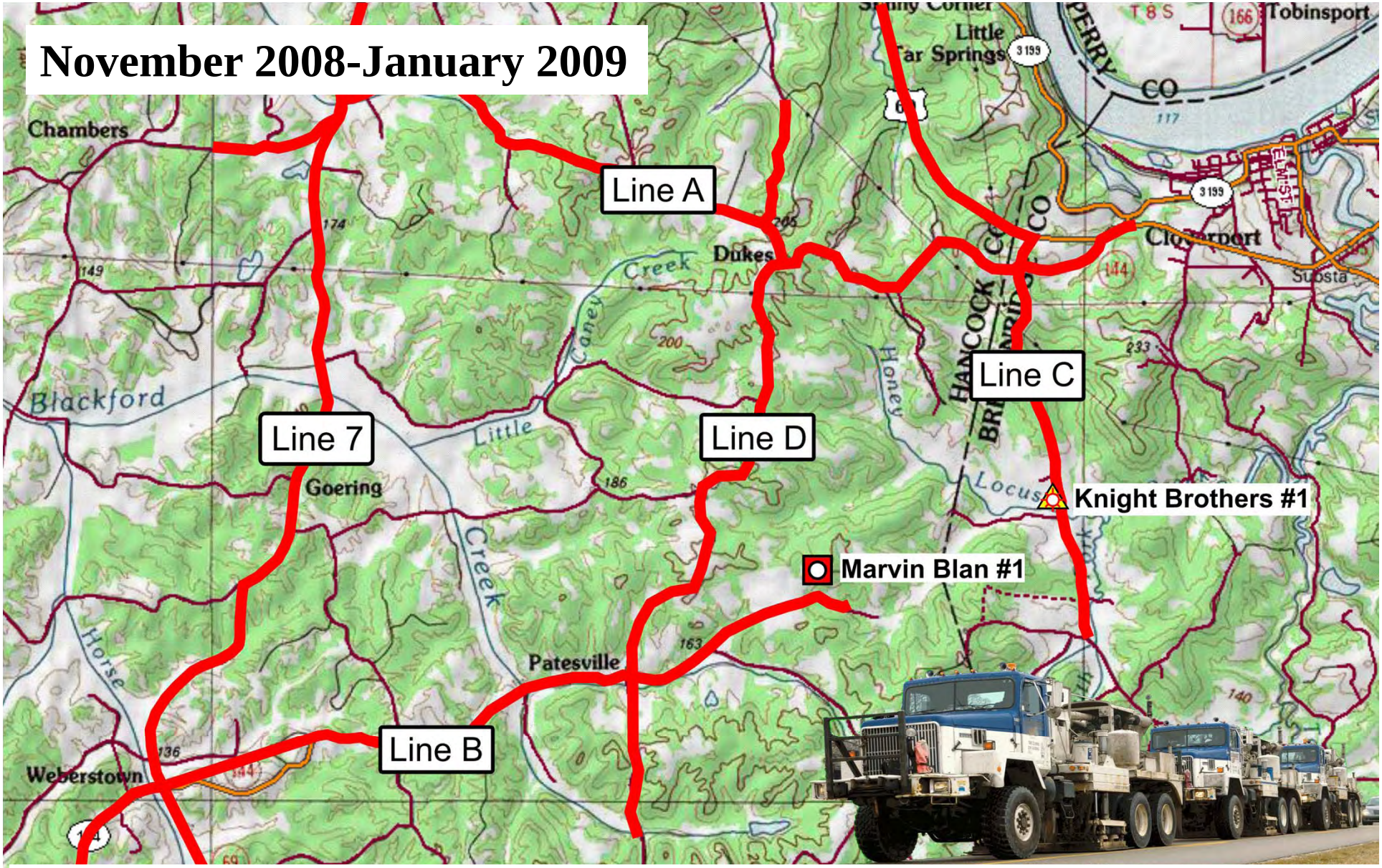
Western Kentucky Project Timeline



Steps to Complete Phase 1 Testing

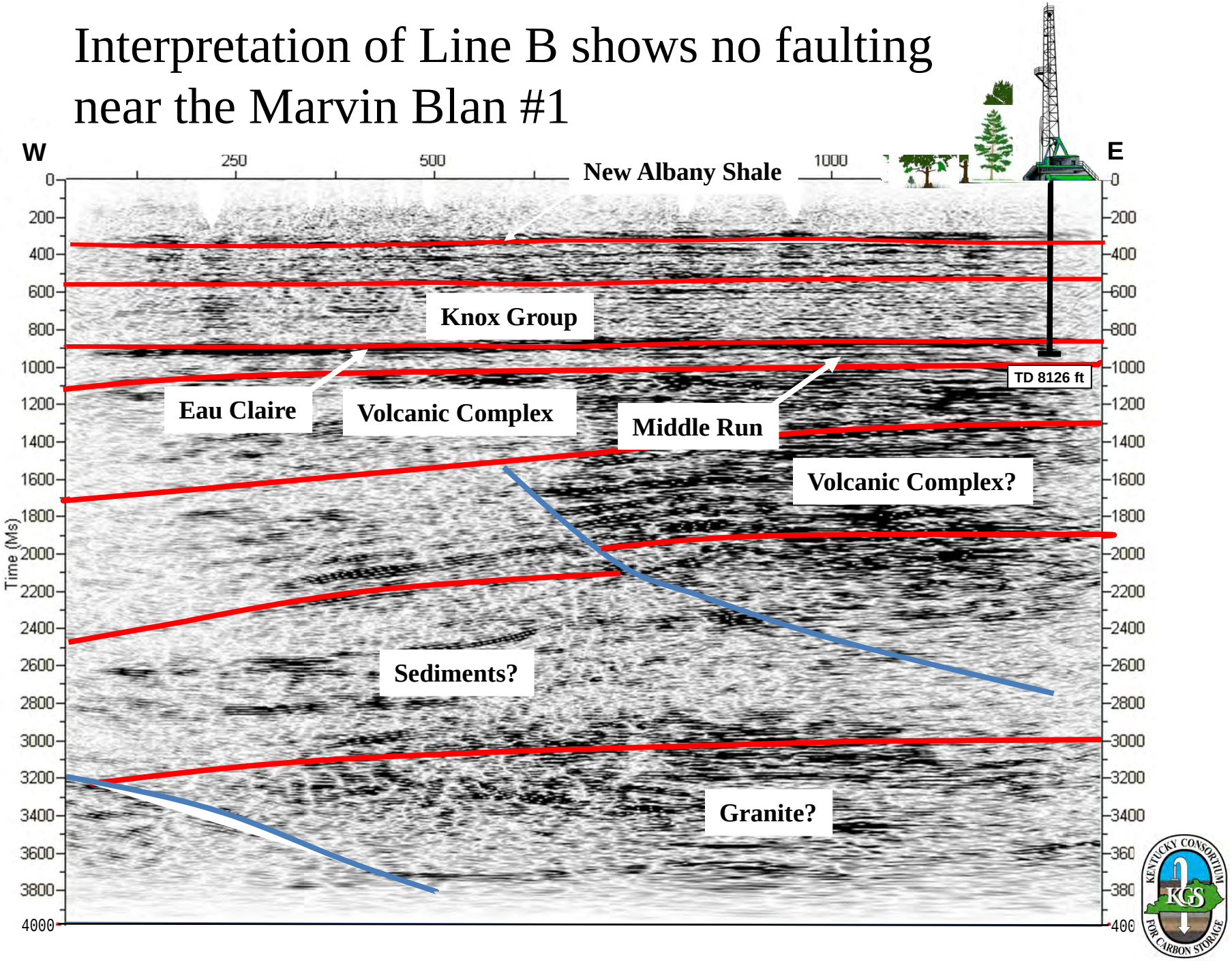


23 Months



Prior to drilling, 24.1 mi of new, high-quality 2D seismic data (Lines A-D) were 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



Phase 1: Drilling and Testing

- **Drilling commenced on April 24, 2009, and was finished on June 14 after 63 days of drilling.**
  - Casing cemented at 441 ft and 3,660 ft
  - The hole was left open hole casing to the bottom of the well at 8,126 ft for injection testing
- **Seven cores, totaling 395 ft, were cut to test the 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)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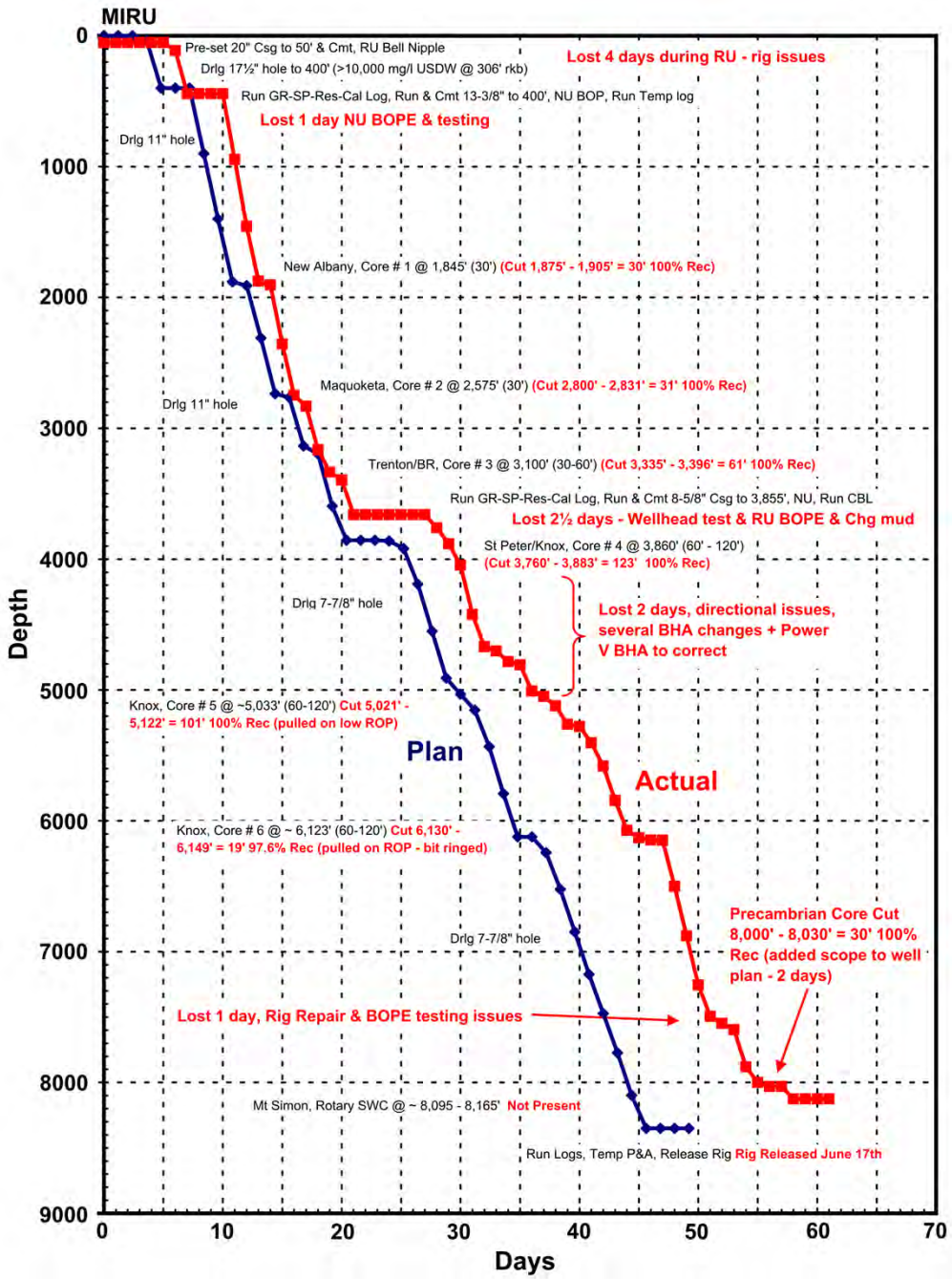
KGS
FOR CARBON STORAGE


MIRU
Pre-set 20" Csg to 50' & Cmt, RU Bell Nipple
Drlg 17½" hole to 400' (>10,000 mg/l USDW @ 306' rkb)
Lost 4 days during RU - rig issues
Run GR-SP-Res-Cal Log, Run & Cmt 13-3/8" to 400', NU BOP, Run Temp log
Lost 1 day NU BOPE & testing
Drlg 11" hole
New Albany, Core # 1 @ 1,845' (30') (Cut 1,875' - 1,905' = 30' 100% Rec)
Maquoketa, Core # 2 @ 2,575' (30') (Cut 2,800' - 2,831' = 31' 100% Rec)
Drlg 11" hole
Trenton/BR, Core # 3 @ 3,100' (30-60') (Cut 3,335' - 3,396' = 61' 100% Rec)
Run GR-SP-Res-Cal Log, Run & Cmt 8-5/8" Csg to 3,855', NU, Run CBL
Lost 2½ days - Wellhead test & RU BOPE & Chg mud
St Peter/Knox, Core # 4 @ 3,860' (60' - 120')
(Cut 3,760' - 3,883' = 123' 100% Rec)
Drlg 7-7/8" hole
Lost 2 days, directional issues, several BHA changes + Power V BHA to correct
Knox, Core # 5 @ ~5,033' (60-120') Cut 5,021' - 5,122' = 101' 100% Rec (pulled on low ROP)
Plan
Actual
Knox, Core # 6 @ ~ 6,123' (60-120') Cut 6,130' - 6,149' = 19' 97.6% Rec (pulled on ROP - bit ringed)
Drlg 7-7/8" hole
Precambrian Core Cut 8,000' - 8,030' = 30' 100% Rec (added scope to well plan - 2 days)
Lost 1 day, Rig Repair & BOPE testing issues
Mt Simon, Rotary SWC @ ~ 8,095 - 8,165' Not Present
Run Logs, Temp P&A, Release Rig Rig Released June 17th
Depth
Days
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
0
10
20
30
40
50
60
70


Marvin Blan #1
Depth vs. Days
Drilling took 62 days, 13 days longer than planned, despite a shallower than planned TD.
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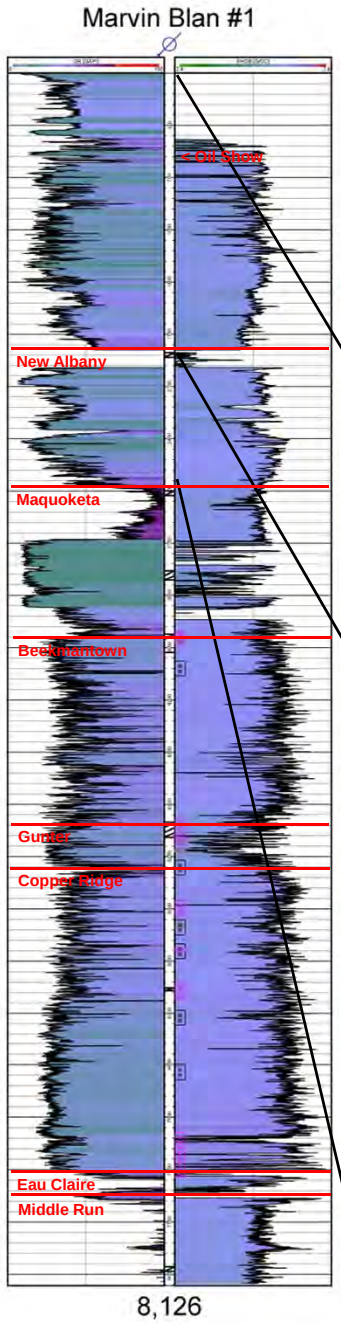
Strata penetrated in the Marvin Blan #1



System	Series	Sequence	Formation	Drill Depth from RKB (635 ft, 15 ft above GL)
				15
Penns.	Lower	Absaroka	Caseyville Formation	5 ft Sandstone, fine-coarse grain, locally cross-bedded.
				22
Mississippian	Upper	Kaskaskia	Vienna Limestone Member / Buffalo Wallow Formation	275 ft Shales with interbedded thin limestones and lenses of fine grain sandstone.
				297
			Glen Dean, Golconda, Jackson, Barlow, Paint Creek, Bethel, Renault, Aux Vases Formations	366 ft Interbedded limestones, shales, and fine grain sandstones. Barlow Limestone is a regional marker bed.
				663
			St. Genevieve Limestone	195 ft Limestone, predominantly oolitic, fossiliferous. Chert nodules occur throughout the formation.
				858
			St. Louis Limestone	193 ft Limestone, fine-moderately crystalline, fossiliferous. Chert nodules occur throughout the formation
				1051
			Salem-Warsaw Limestones (undifferentiated)	314 ft Limestone, fine-coarse crystalline, fossiliferous.
				1417
	Lower		Fort Payne Formation	472 ft Interbedded limestone, shaly limestone, and cherts. Local thin shales. Fossiliferous.
			New Providence Shale	1837 20 ft Shale, brown to black, minor silt, carbonaceous.
				1857
Devonian	Upper		New Albany Shale	116 ft Shale, black, clayey, minor silt, carbonaceous, pyritic. Regional gas producing formation. **Reservoir sealing unit.**
				1973
			Sellersburg Limestone	277 ft Limestones, locally undifferentiated in the subsurface. Sellersburg Limestone: Light grey, bioclastic limestone, fine grain and argillaceous in the lower portion. Jeffersonville Limestone: Grey to brown coarse grain, fossiliferous, in-part dolomitic and cherty. Dutch Creek Sandstone: medium-coarse grain sandstone and thin, sandy dolomite. There is a major regional unconformity at the base of the Dutch Creek (2142 ft) that forms the boundary between the Tippecanoe II and Kaskaskia cratonic sequences. Clear Creek-Backbone Limestones: Light grey fossiliferous limestones, dolomitic and cherty. Grassy Knob-Flat Gap Limestones: Light grey limestones (Flat Gap) and grey cherty dolomite (Grassy Knob).
			Jeffersonville Limestone	
			Dutch Creek Sandstone	
	Lower		Clear Creek-Backbone Limestones (undifferentiated)	
			Grassy Knob-Flat Gap Limestones (undifferentiated)	
				2250
Silurian	Upper	Tippecanoe II	Bailey Limestone	479 ft Strata are locally undifferentiated in the subsurface. Bailey limestone: Silty, argillaceous, fine-grained, cherty limestone. Mocassin Springs Formation: Alternating grey, red, and green-grey silty, argillaceous limestone, siltstone. and calcareous shales. St. Claire-Sexton Creek: Fine grain, cherty, glauconitic limestone (Sexton Creek) and white to pink fine-grain limestone (St. Clair). There is a regional unconformity at the contact of the St. Claire-Sexton Creek Limestones and underlying Maquoketa Shale.
	Middle		Moccasin Springs Formation	
	Lower		St Claire-Sexton Creek Limestones (undifferentiated)	
				2729

System	Series	Sequence	Formation		
Ordovician	Upper	Tippecanoe I	Maquoketa Shale	2729	395 ft Dark grey-black micaceous siltstone and organic shale (2787-3124 ft) with minor limestone interbeds. **The Maquoketa Shale is the primary regional sealing unit.**
				3124	
	Middle		Black River Group		521 ft Argillaceous dolomitic limestone. **Black River carbonates are a regional sealing unit.**
				3645	
			Dutchtown Formation		123 ft Dolomite with minor dolomitic quartz arenite and shale interbeds.
			"St. Peter" Marker Interval	3768	12 ft Fabric-preserving dolomite with minor quartz arenite interbeds. 0.5 ft of sandstone overlies the Knox epikarst.
				3780	
	Lower	Sauk	Knox Group: Beekmantown Dolomite		
			Gunter Sandstone		
				5347	
Cambrian	Upper		Knox Group: Copper Ridge Dolomite		
	Mid		Eau Claire Formation	7397	
				7584	
Precambrian			Middle Run Sandstone (Meso-Neoproterozoic)	TD 8126 ft	

Legend

- Oil show
- Gas showl
- Injection test interval
- Regional reservoir sealing unit

Sources: Noger and Drahovzal (2005), electric logs, cuttings and core sample descriptions from Marvin Blan #1 well.

Beekmantown Dolomite
1567 ft Argillaceous to microcrystalline, grey dolomite with intervals of well-developed intercrystalline and vuggy porosity. **Gunter Sandstone** (5040-5230 ft) is a fine-grain, dolomitic quartz arenite; porosity is well-developed. Used as a waste disposal injection zone in north-central and western Kentucky. **Non-porous intervals are regional sealing units.**

Copper Ridge Dolomite
2050 ft Very fine-medium grain, partially oolitic brown dolomite, locally cherty. Thin argillaceous intervals are used as marker beds for correlation. Basal 300 ft highly fractured. Used for waste disposal injection in north-central and western Kentucky. **Non-porous intervals are regional sealing units.**

Eau Claire Formation
187 ft Glauconitic, micaceous shales; arkosic, glauconitic fine-grain sandstones, microcrystalline dolomite.

Middle Run Sandstone
542 ft Penetrated in the well; ~4500 ft thick as interpreted from 2D seismic data. Fine-grain arkosic sand in a reddish-brown hematite matrix; dark minerals present. Finely-laminated to cross-bedded, hard, and tight.

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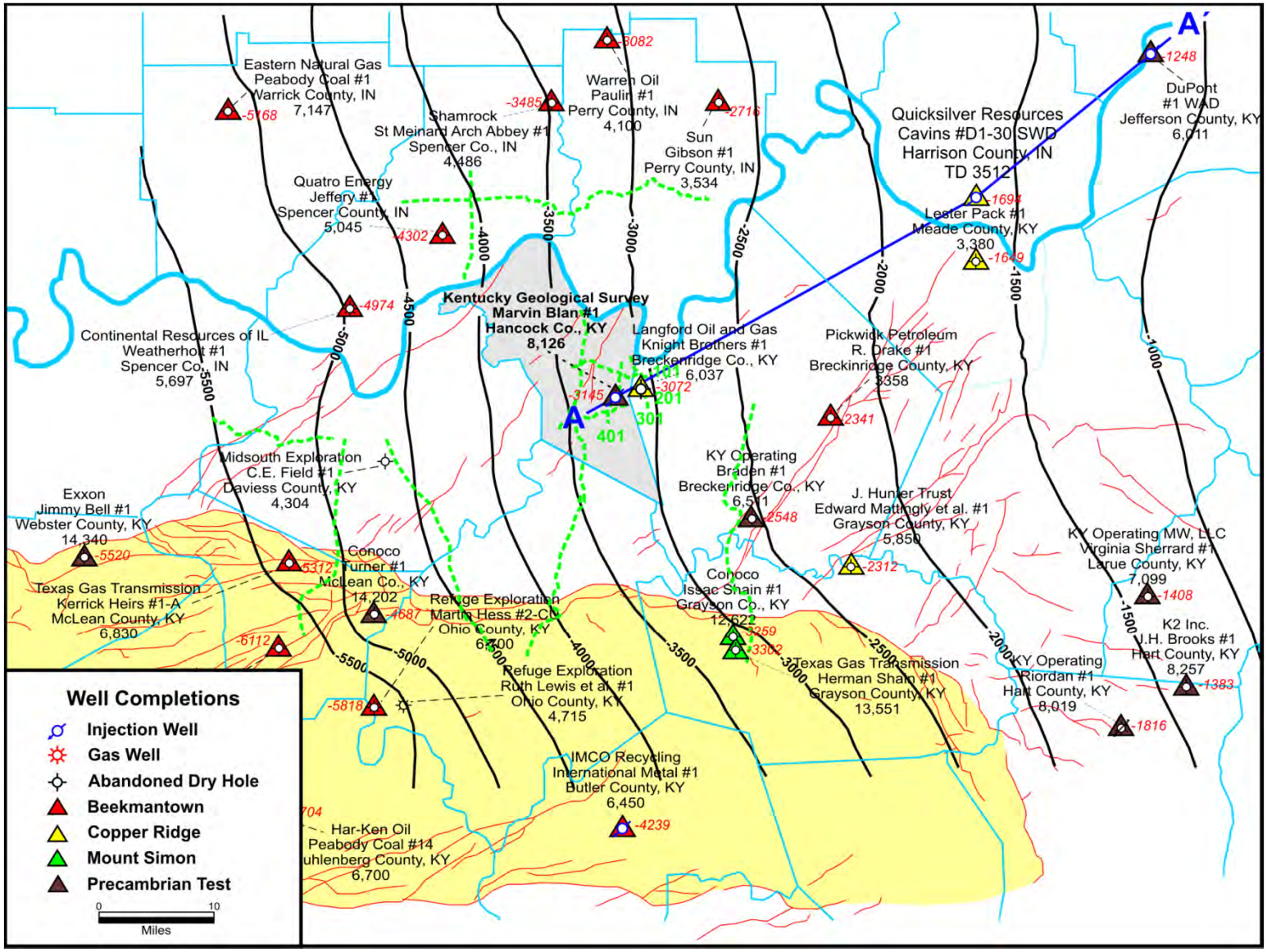
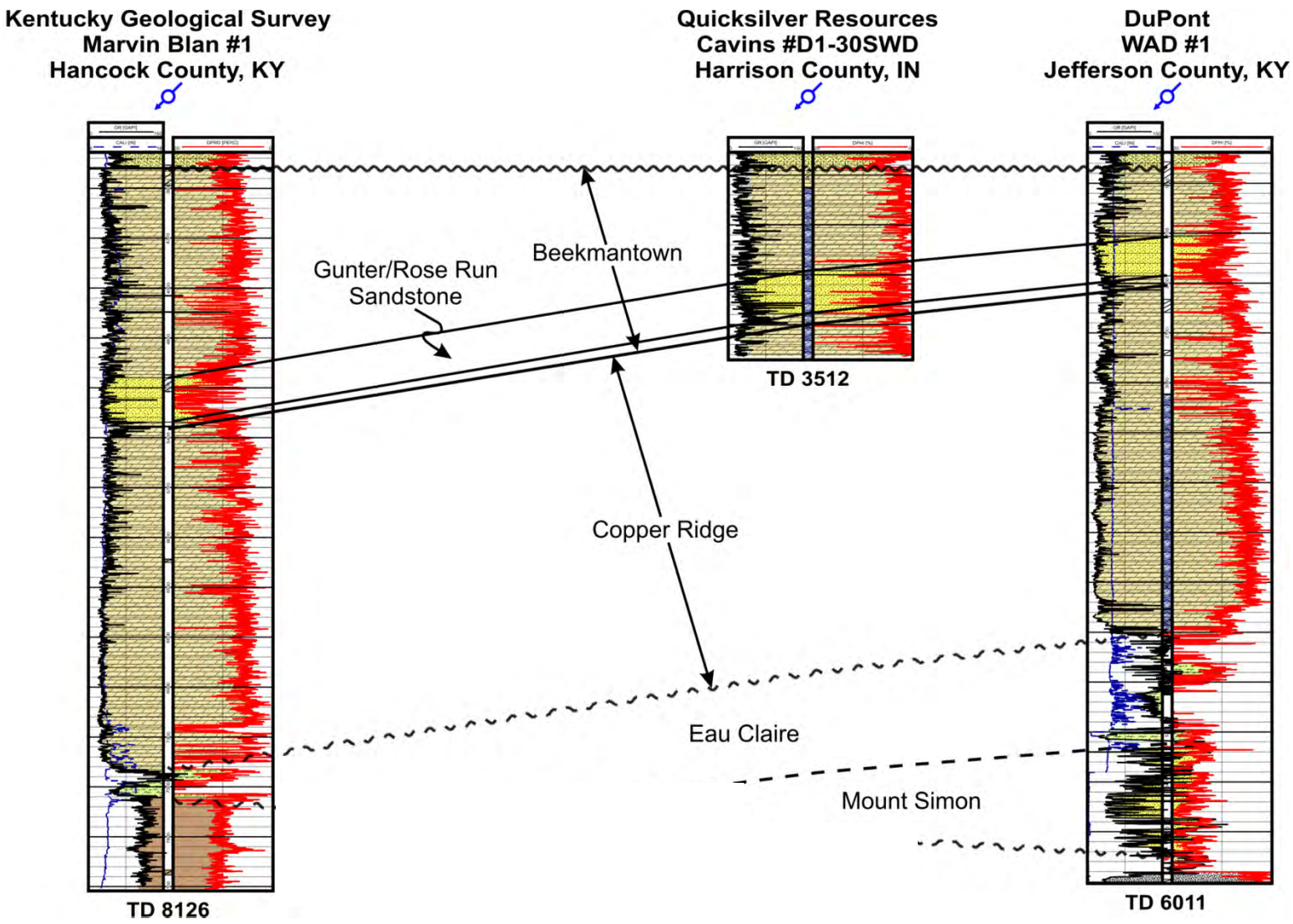


Structural contours on top of the Knox Group.



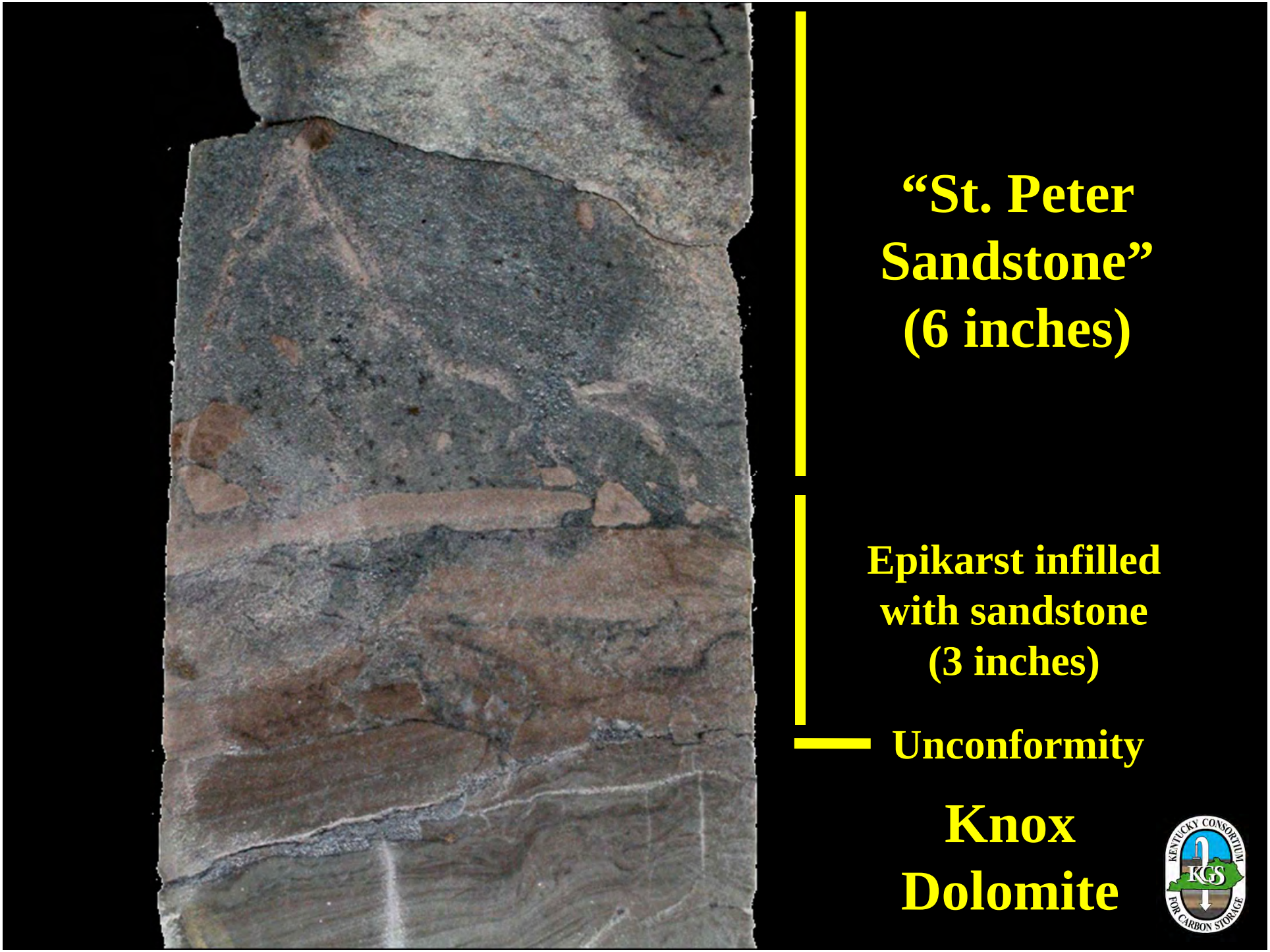
Stratigraphic correlation of the Knox Group and deeper strata.

Maquoketa Shale Core

- Maquoketa Shale was cored 2800-2831 ft to test its reservoir seal properties
- Analyses of seal properties
  - Threshold entry pressure
  - XRD mineralogy
  - Thin section petrography
  - Mechanical properties

Knox Group Cores

- Knox Group 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


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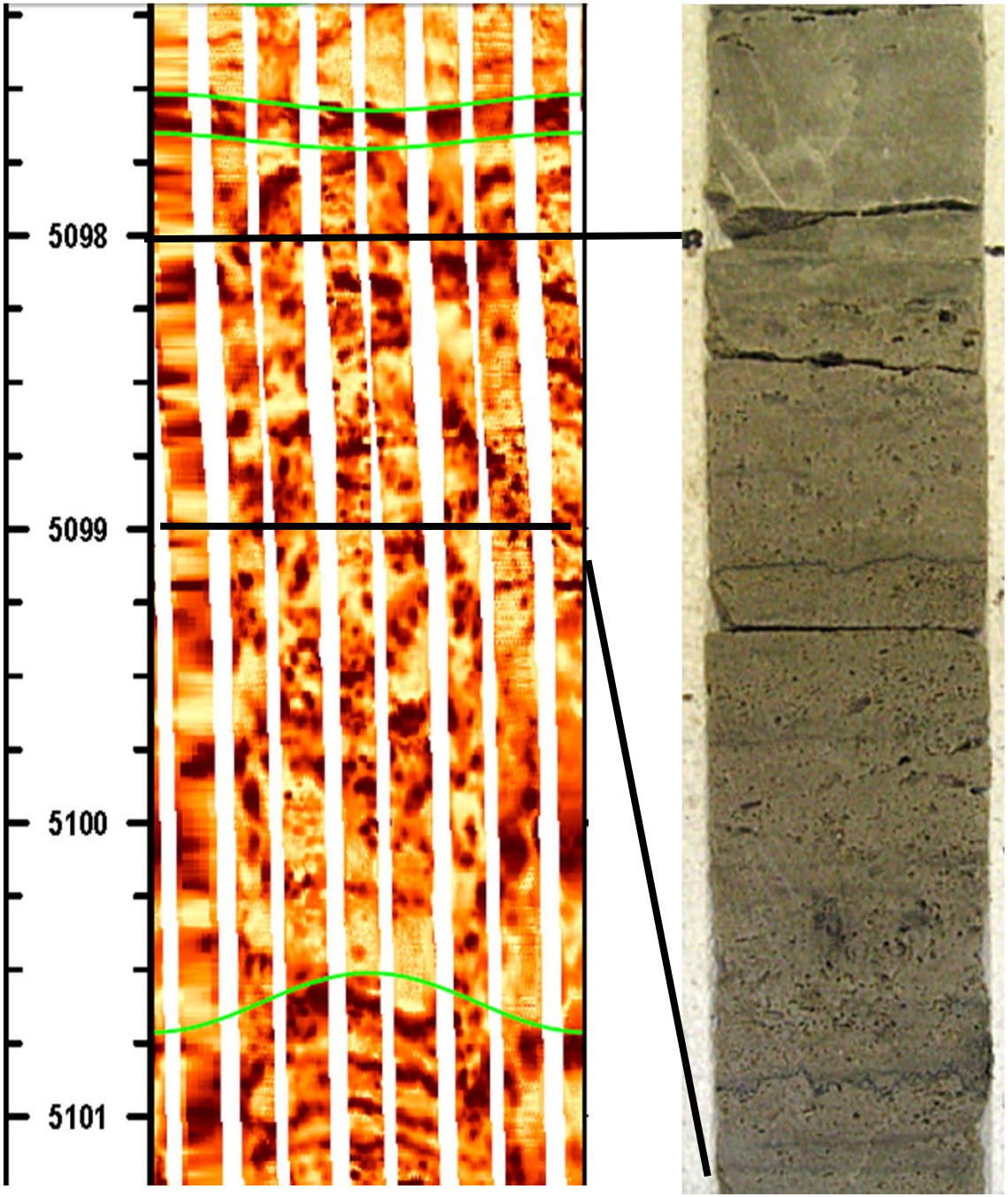
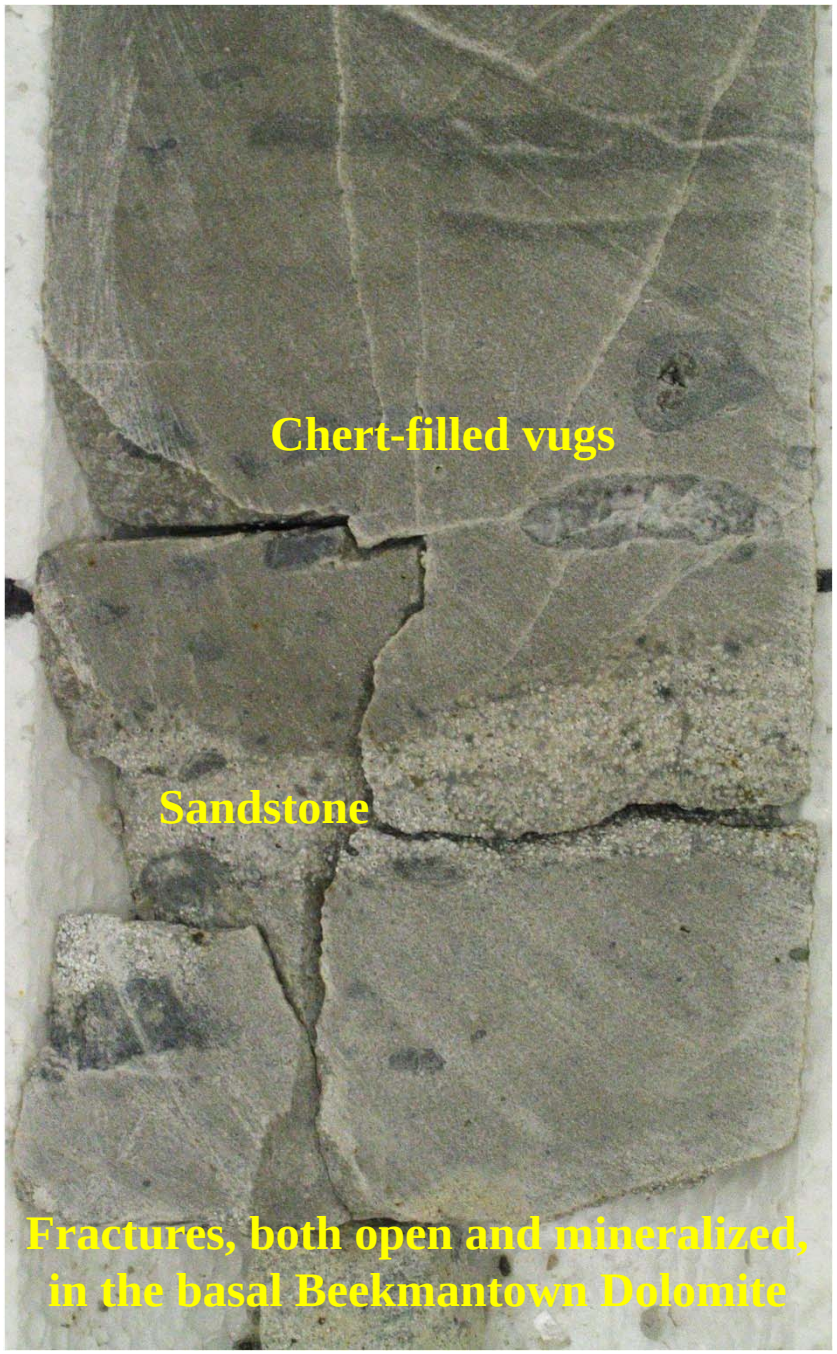
Middle Run Sandstone Core

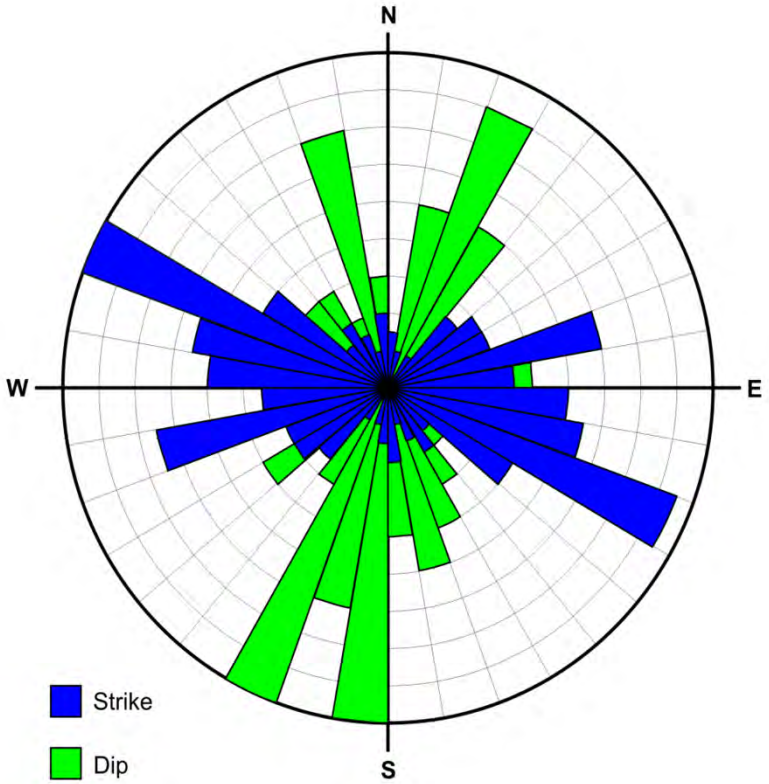
- Precambrian Middle Run Sandstone was cored 8000-8030 ft to evaluate its potential as a carbon storage reservoir
  - DOE-NETL grant for coring and analysis
- Analysis Program
  - Routine core analysis
  - Fracture orientation
  - XRD mineralogy
  - Thin section petrography
  - Mechanical properties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



CMI log section and corresponding core showing vuggy porosity in the Beekmantown Dolomite. Bedding planes annotated on CMI log with green lines.

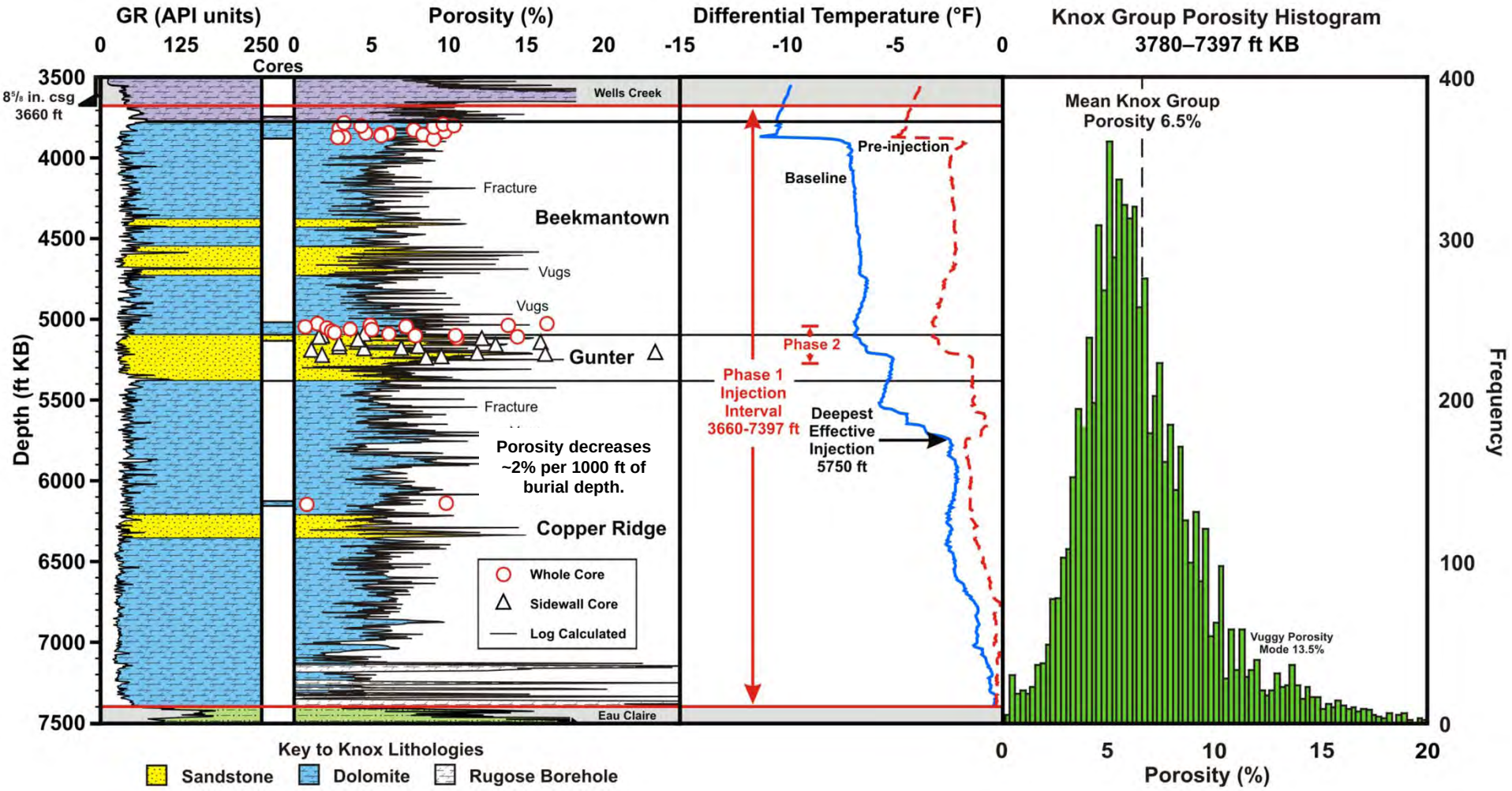


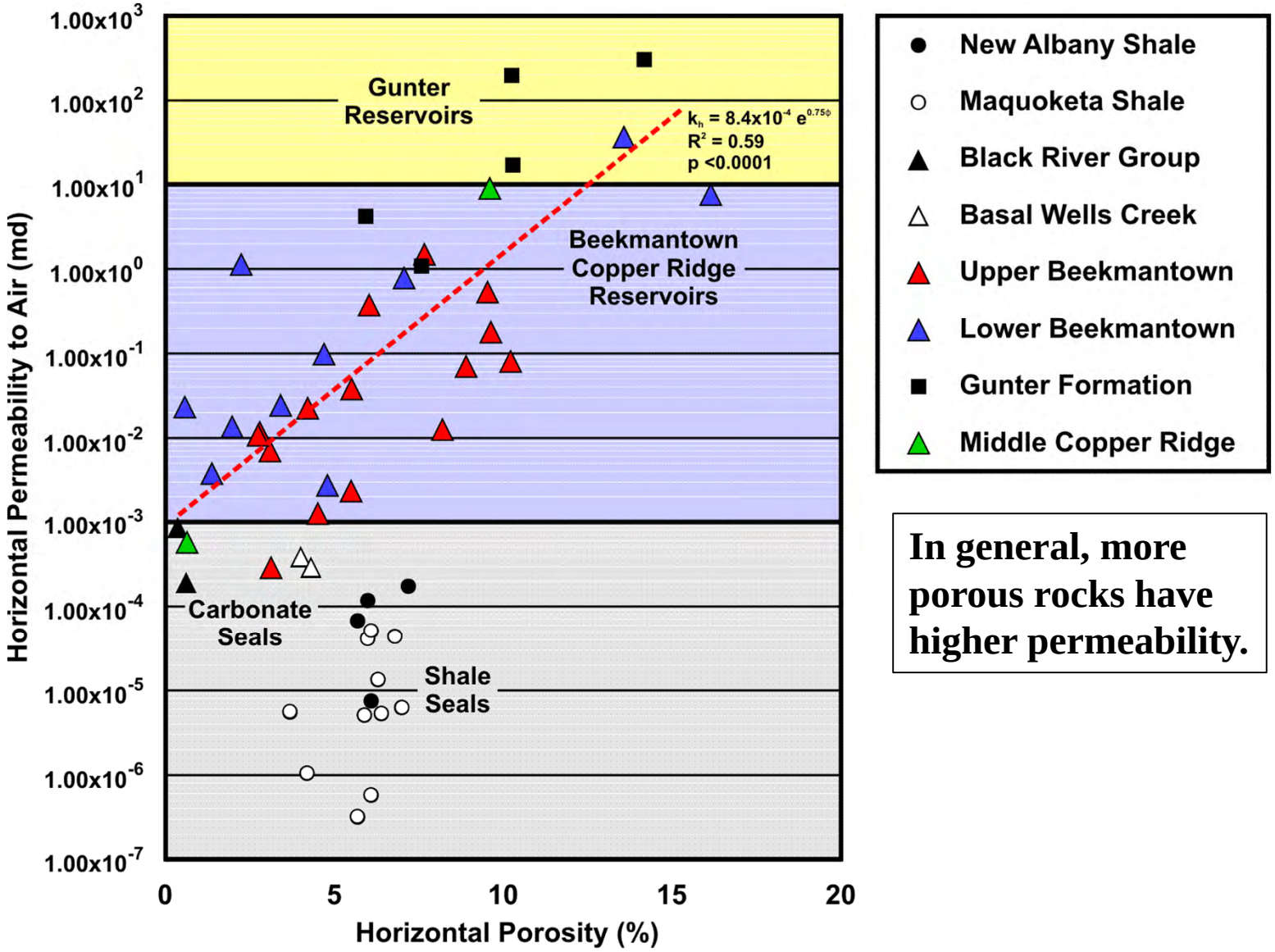
Fracturing in the Knox: fracture trends from CMI log interpretation



NNW Fracture Trend

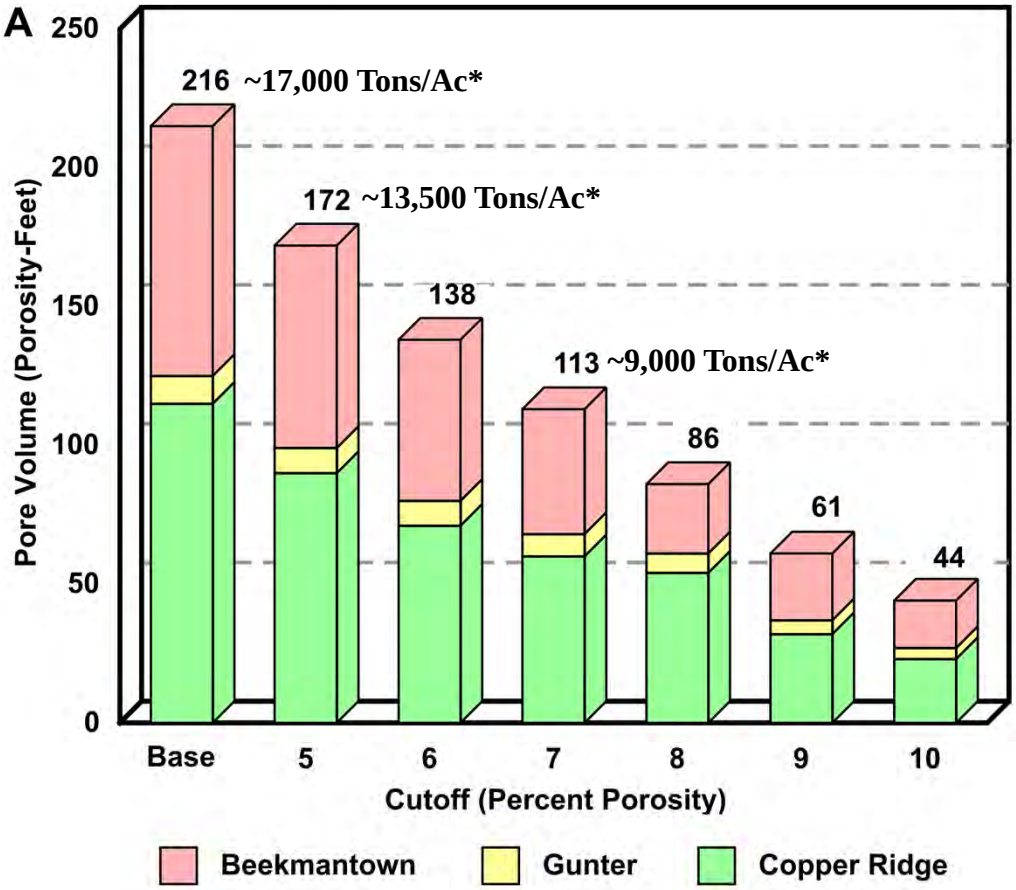
Phase 1 Injection Project



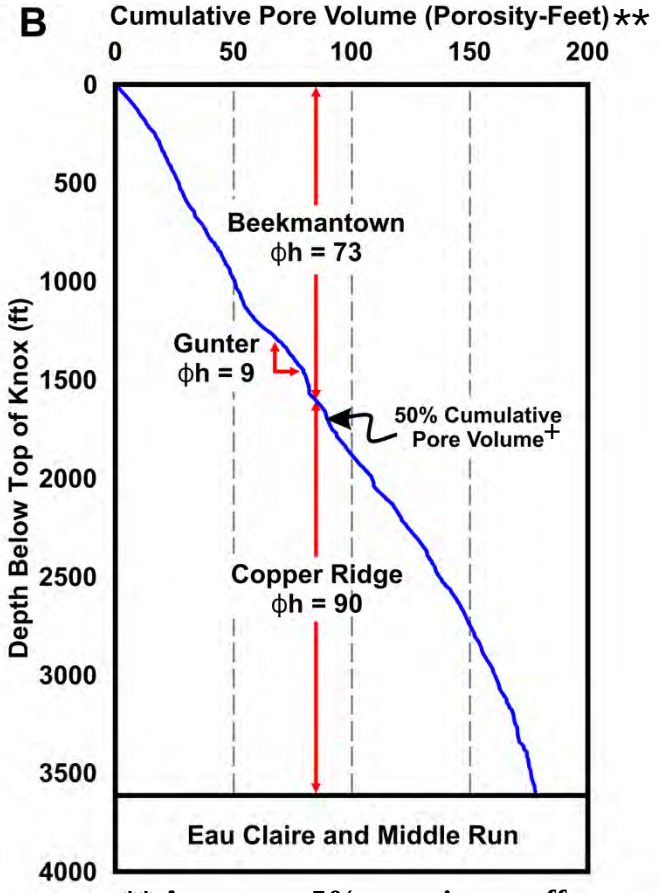


In general, more porous rocks have higher permeability.

Potential Reservoir Volume in the Knox

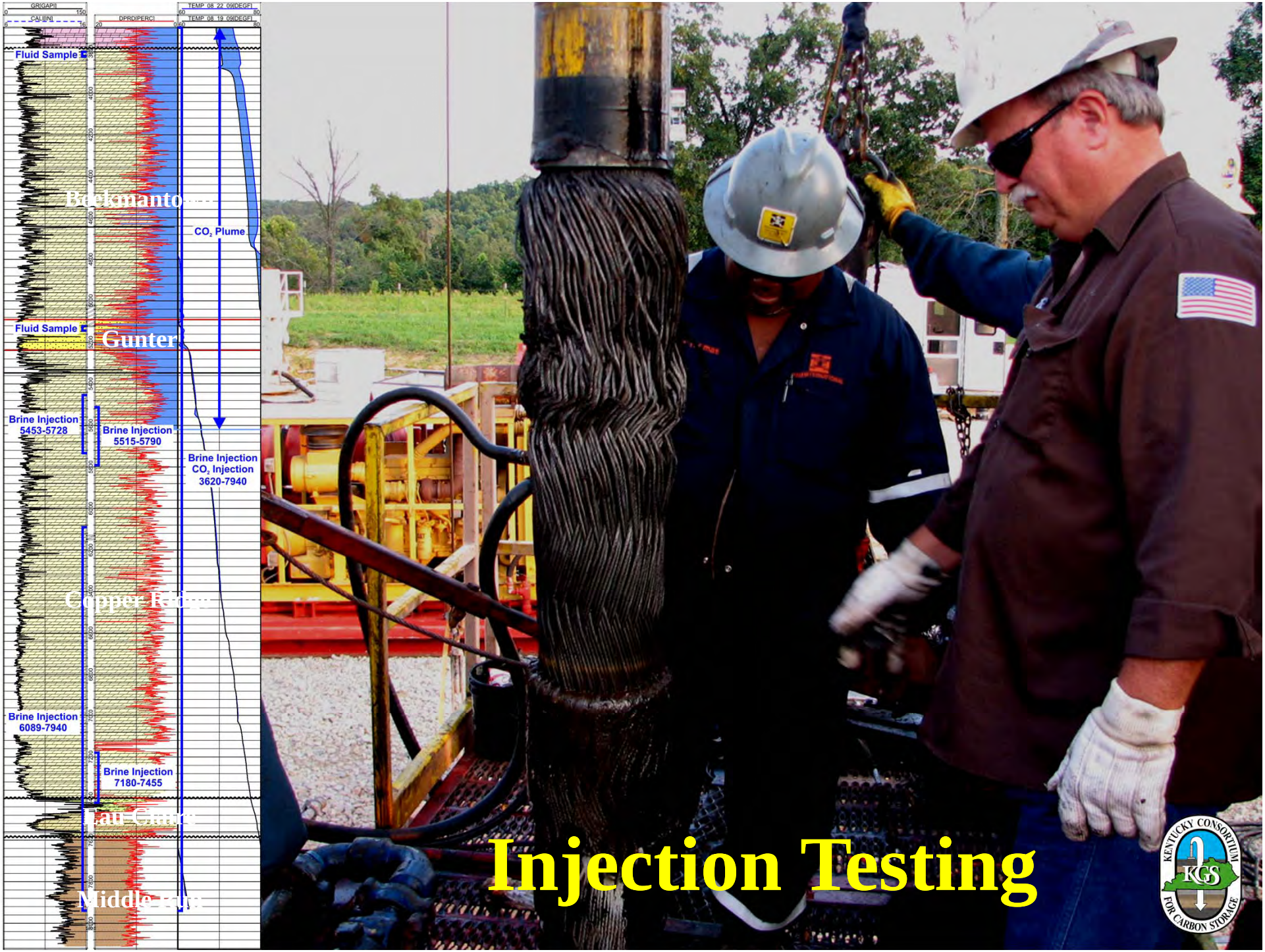


*Assumes a 5% CO_2 storage efficiency



** Assumes a 5% porosity cutoff

+ ~6,300 Tons/Ac = 157 Ac/MT


GR(GAPI)
CALI(IN)
DPRD(PERC)
TEMP_08_22_09(DEGF)
TEMP_08_19_09(DEGF)
Fluid Sample
Fluid Sample
Beekmantown
Gunter
Copper Ridge
Lan Center
Middle Run
CO2 Plume
Brine Injection 5453-5728
Brine Injection 5515-5790
Brine Injection CO2 Injection 3620-7940
Brine Injection 6089-7940
Brine Injection 7180-7455
Injection Testing
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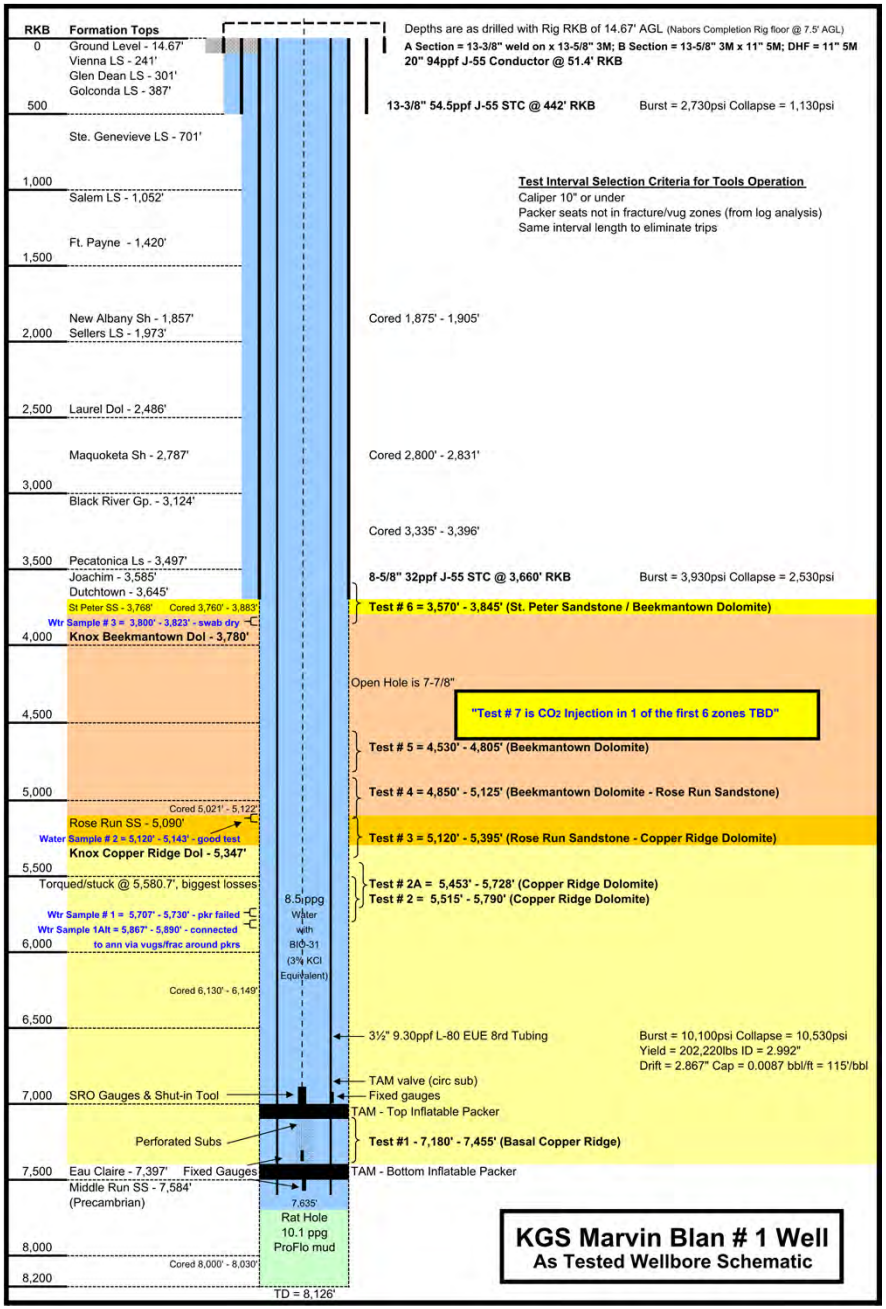


Injection Testing

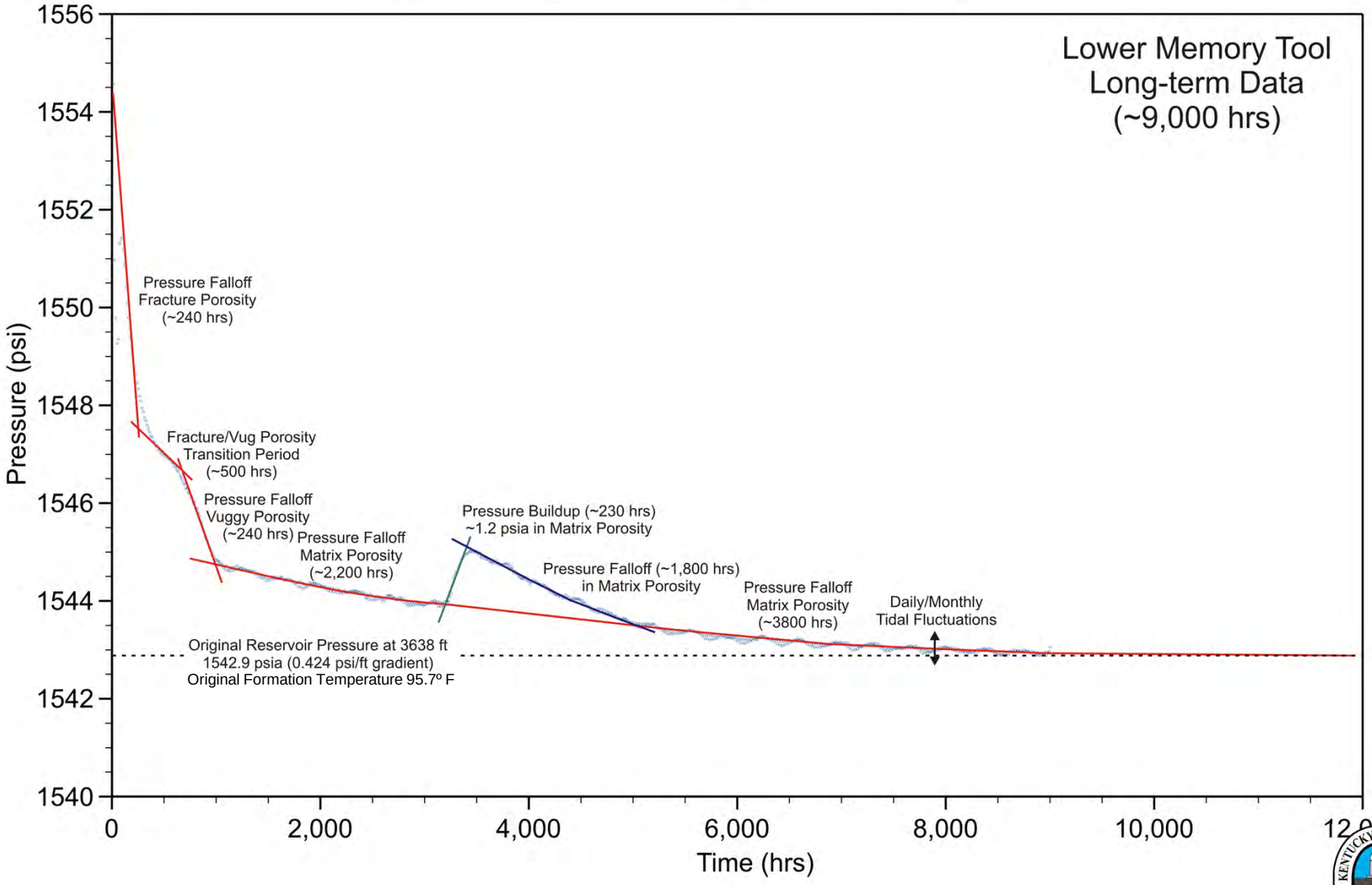
- Testing began on July 25, 2009, and was completed on August 22
  - Two formation water samples were collected
  - Initial injection of brine was into 285 ft intervals isolated by inflatable straddle packers on tubing. This test design had limited success.
    - Seven tests attempted
    - Results were mixed due to leaks and communication around the packers through the formation porosity system
  - Program revised to full-wellbore injection of brine and CO_2 below a single packer in casing

Phase 1 CO_2 Injection

- Injected a total of 323 tons of CO_2 (1,765 barrels) below a packer set in casing at 3,603 ft
- After injection of CO_2 the well bore was flushed with 4,568 barrels of brine
- Long-term downhole pressure gauge was left in place to monitor pressure fall-off pending re-entry for Phase 2 testing

Wellsite at the completion of Phase 1

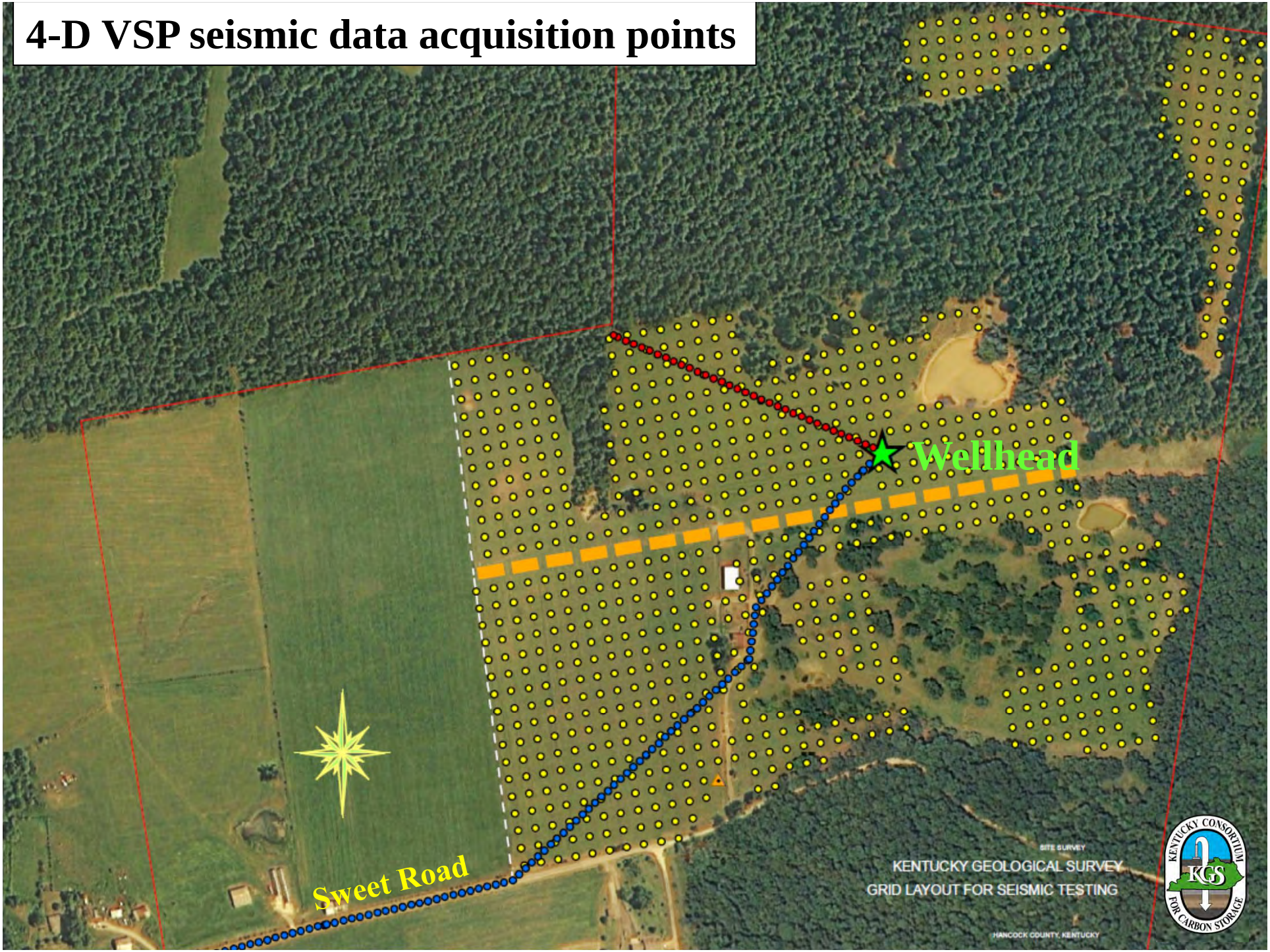
Long-term Borehole Pressure
August 21, 2009-September 1, 2010



Phase 2: Injection Testing

- **Phase 2 testing took place on August 30 – September 30, 2010.**
  - Cut 20 rotary sidewall cores through the injection interval to determine reservoir rock properties
  - Plugged the well at 5,268 – 5,545 ft, abandoning the lower 2,858 ft of the well
  - Constructed a 230-ft test interval at 5,038 – 5,268 ft by cementing a 5½-inch liner at 4,820-5033 ft
- **Injected 4,265 barrels of brine and 367 tons of CO_2 (2,000 barrels)**
  - Recorded pressure during injection and falloff to calculate reservoir permeability and volume
  - Recorded temperature logs before and after injection to determine which intervals were receiving the injected CO_2
- **Recorded a 4-D vertical seismic program at more than 850 points around the well. Data was recorded both before and after CO_2 injection in an attempt to image the CO_2 plume.**
- **Abandoned the Knox Dolomite injection zone with cement plugs at 5,037 – 5,275 ft and 3,942 – 3,477 ft , exceeding EPA abandonment requirements (a single plug at 3,760 – 3,560 ft).**

4-D VSP seismic data acquisition points



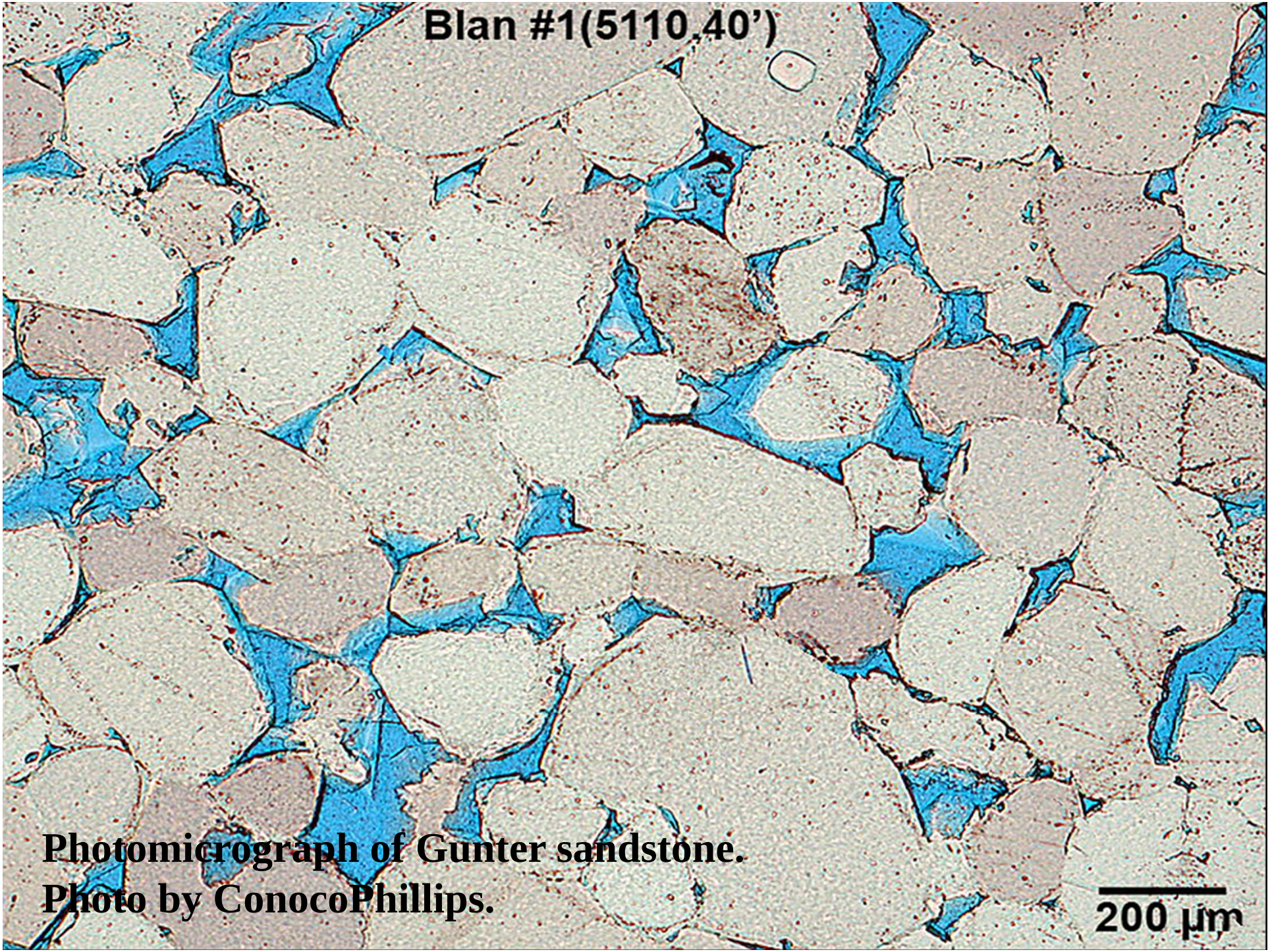
Seismic Survey Vibrator Truck

Workover Rig

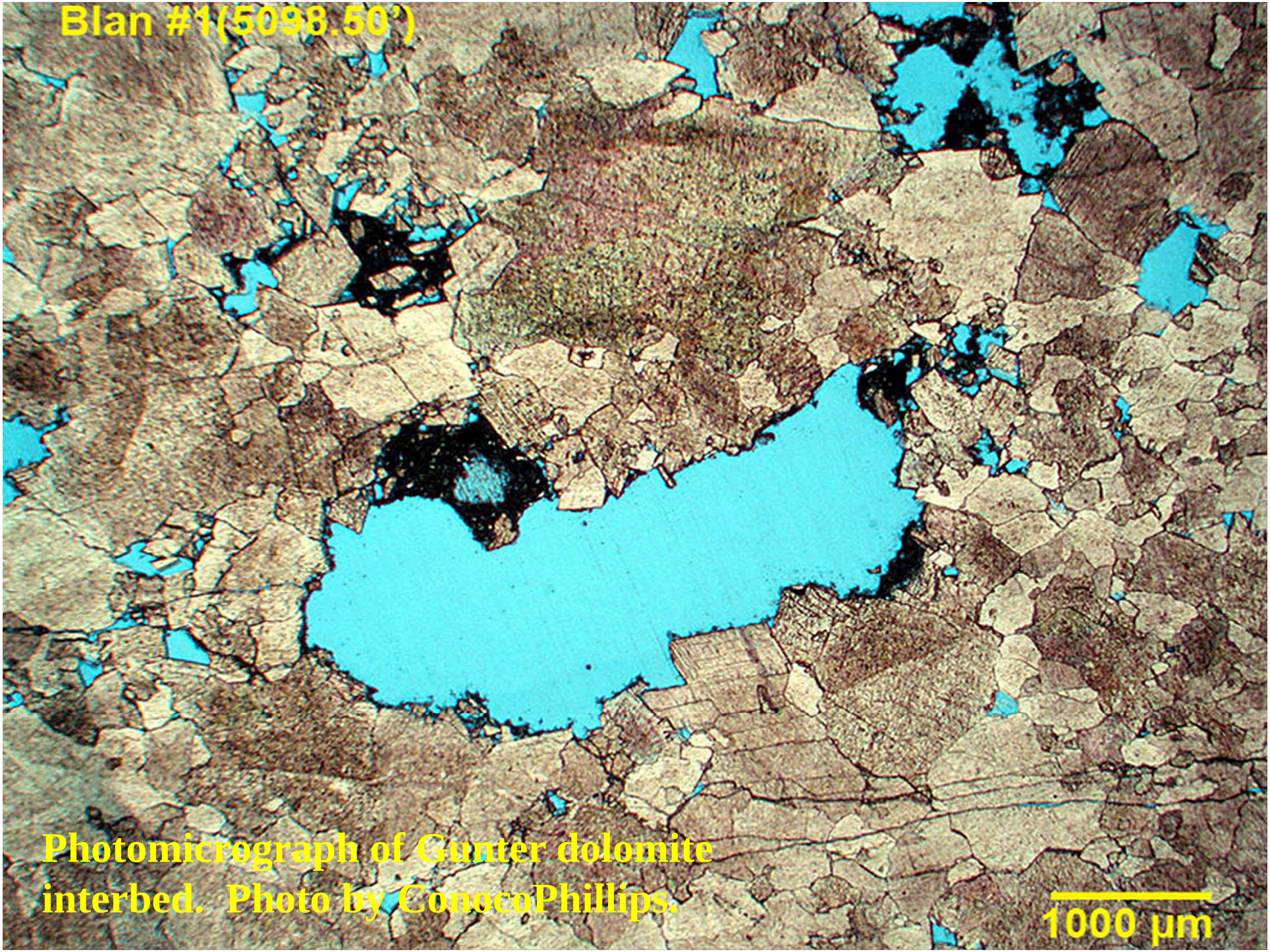
CO_2 Delivery


Gunter dolomite at 5103 ft


Gunter sandstone at 5109 ft

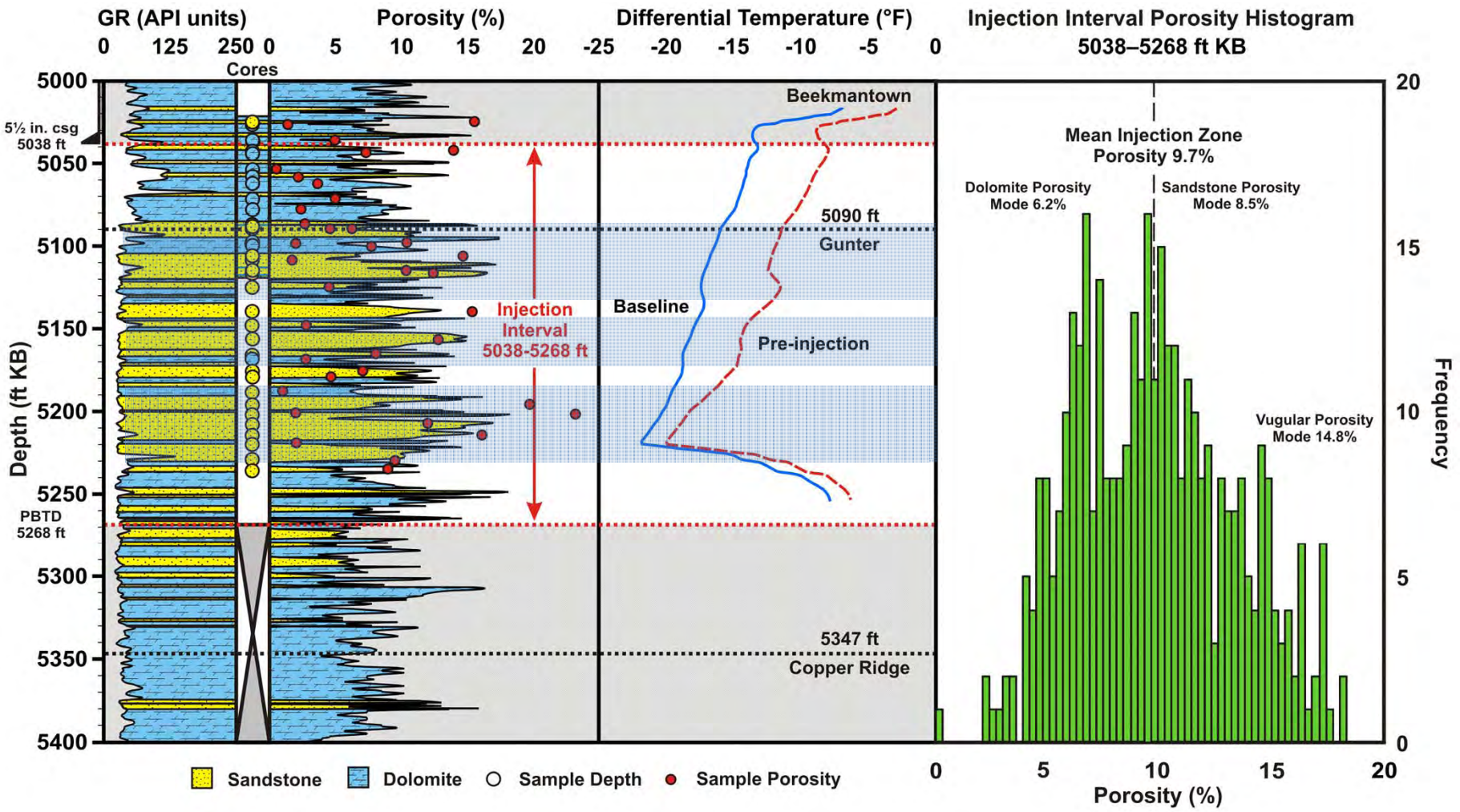


Photomicrograph of Gunter sandstone.
Photo by ConocoPhillips.



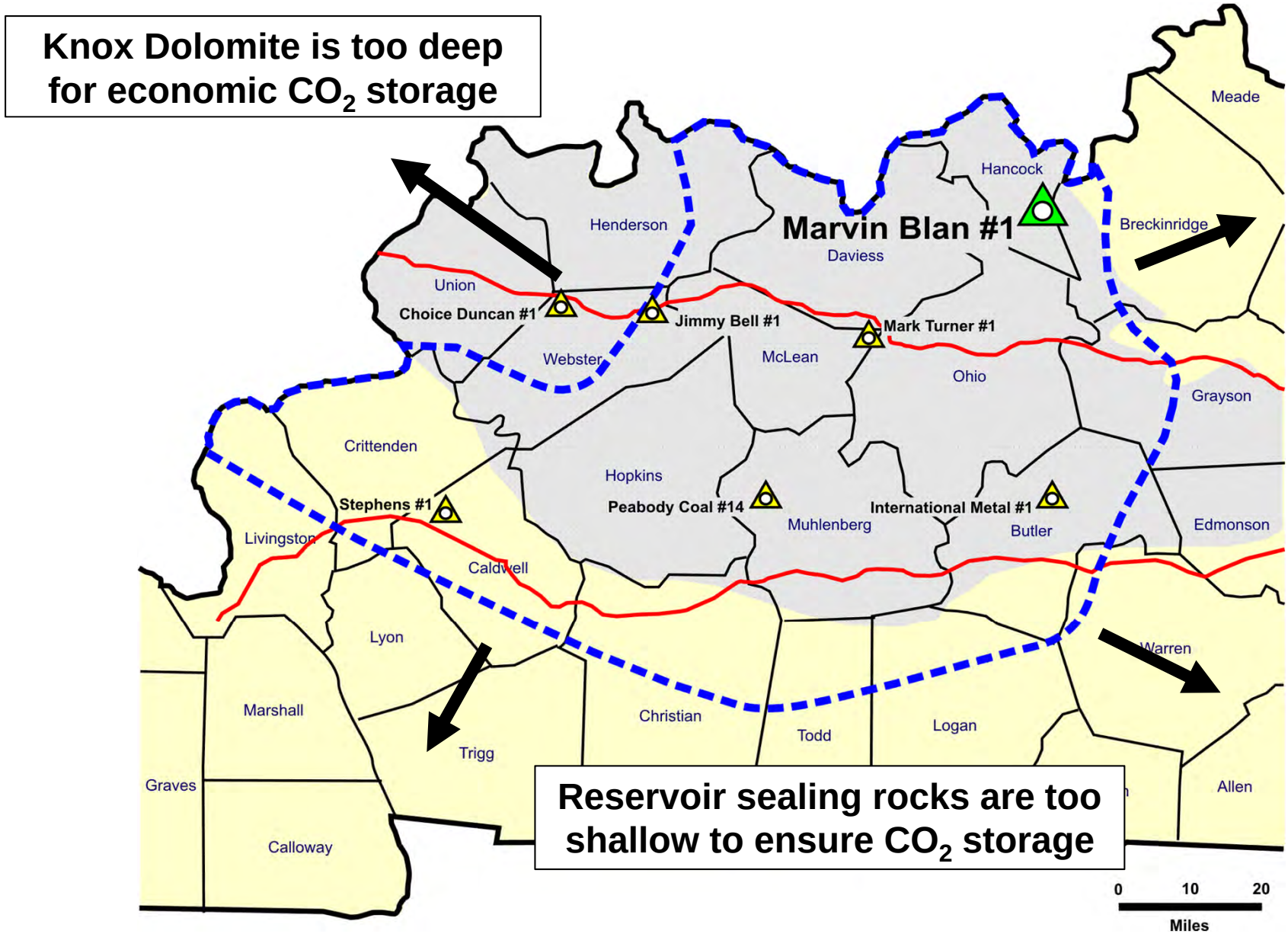
Photomicrograph of Gunter dolomite interbed. Photo by ConocoPhillips.

Phase 2 Injection Project



What we learned:

- The Knox Dolomite could serve as an effective CO_2 storage reservoir.
- There are excellent reservoir sealing strata in the Black River Limestone and overlying Maquoketa Shale, above the Knox Dolomite, that would prevent any CO_2 migration from the Knox Dolomite to the surface.
- Most of the West Kentucky Coal Field has Knox Dolomite, comparable to that in the KGS test well, that may be suitable for CO_2 storage.
- Additional evaluation of the Knox Dolomite will be necessary to fully determine its potential for CO_2 storage.

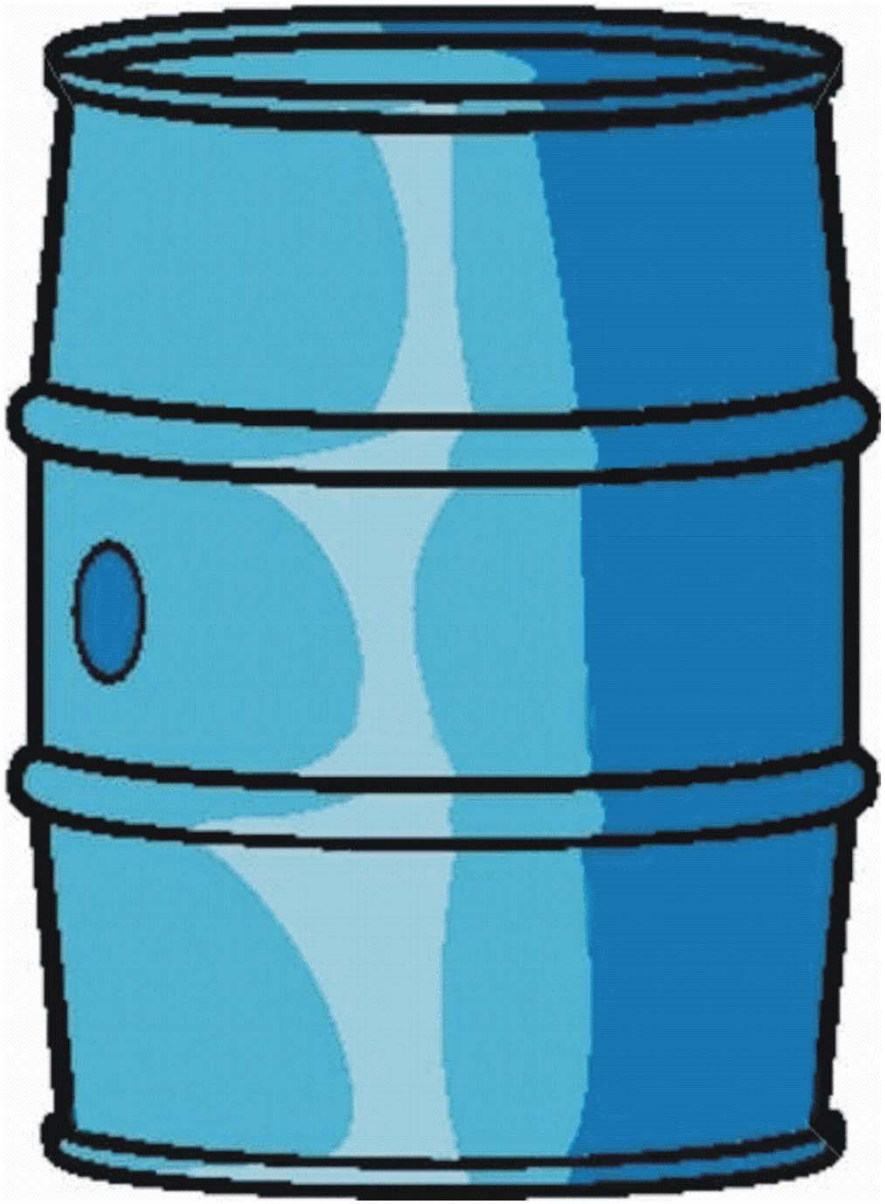


The potential area for CO_2 storage in the Knox Dolomite in western Kentucky is about 6,400 mi^2. More research is needed to determine the actual extent.

Where did the CO_2 go?

- The Knox Dolomite, under just the 1 acre well drill site, holds about 1.7 million barrels (71.4 million gallons) of brine that is about 200 times saltier than what is allowed in drinking water by Federal regulations.
- We injected a total of 3,765 barrels of CO_2 (690 tons). This is about 0.25% of the volume of water in the Knox Dolomite under the drill site.
  - Most of the CO_2 dissolved in the formation water and dissipated.
  - A small amount of CO_2 reacted with the formation water and rock to make new minerals.
- Pepsi uses 0.35% CO_2 to carbonate their sodas, and a can of beer has about 0.5% CO_2 carbonation in it.

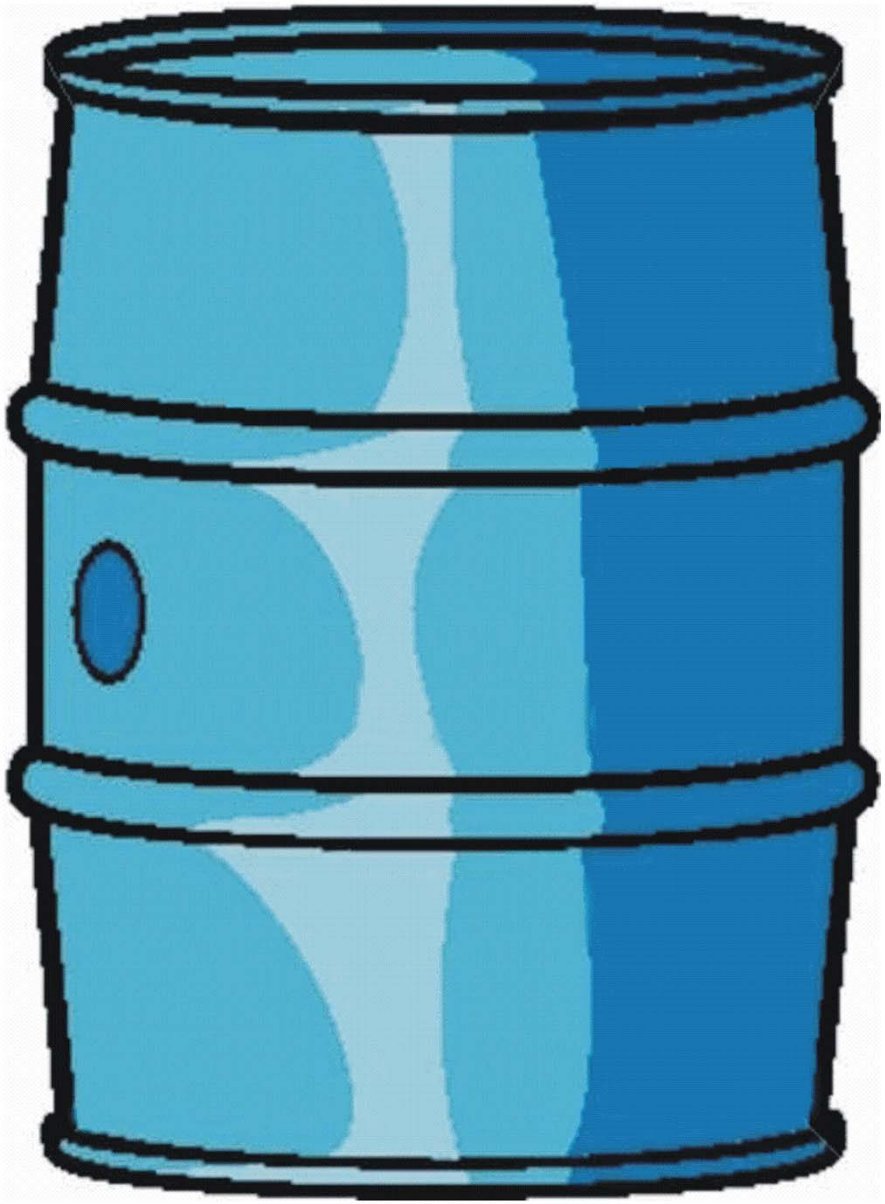
About 1.7 million barrels of brine are in the Knox Dolomite under the 1-acre drill site:



3,785 barrels of CO_2 were injected in 2009 – 2010 *

***About 0.25% CO_2 dissolved in the brine. A can of beer has ~0.5% CO_2 carbonation in it.**

There are about 328 million barrels of brine in the Knox Dolomite under the Blan Farm:



3,785 barrels of CO_2 injected

In the end, what did we get for $8 million?

- 2D and 3D seismic surveys, and two VSPs.
- Well data from one of the deepest wells in western Kentucky:
  - Electric logs, including a formation imaging log
  - Cores from the New Albany, Maquoketa, Black River, and Knox (Beekmantown, Gunter, and Copper Ridge), with routine analysis, special core analysis, and petrography
  - The only Middle Run core in western Kentucky, with a similar core analysis program
  - Extensive sidewall cores, with routine analysis, from the Gunter
  - Water samples and analysis from the Gunter and Beekmantown
  - Injection test pressure data for the Knox, both brine and CO_2
  - Long-term pressure and temperature data from the Knox
- Two successful demonstrations of CO_2 injection in Knox Group reservoirs.
- An estimate of the carbon storage potential of the Knox, and sealing capacity of overlying strata in western Kentucky.
- Experience in operating this kind of project.

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