CO_2 Storage in U.S. Midcontinent Cambro-Ordovician Carbonates: Implications of the Western Kentucky Carbon Storage Test

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Abstract

Results of the western Kentucky carbon storage test provide a basis for evaluating supercritical CO_2 storage in Cambro-Ordovician carbonate reservoirs throughout the U.S. Midcontinent. This test demonstrated that the Cambro-Ordovician Knox Group had reservoir properties suitable for supercritical CO_2 storage in a deep saline reservoir hosted in carbonate rocks, and that strata with properties sufficient for long-term confinement of supercritical CO_2 were present in the deep subsurface. The Kentucky Geological Survey No. 1 Marvin Blan well was drilled in 2009 after 18 months of planning, drillsite due diligence, and regulatory agency permitting. It reached a total depth of 8126 ft in Precambrian Middle Run Sandstone. A total of 395 ft of whole-diameter cores was cut in the well and an extensive suite of geophysical logs was recorded. The Ordovician Maquoketa Shale and Black River Group were cored to test their sealing capacity, and the Knox was cored to test its reservoir properties. Evaluation of well and core data indicated that the Knox had reservoir properties suitable for CO_2 storage, and that the overlying Maquoketa had sealing capacity sufficient for long-term confinement. Injection testing with brine and CO_2 was completed in two phases. The first phase tested the entire Knox in the open borehole at 3780–7397 ft, below casing cemented at 3660 ft, whereas the second phase tested a mechanically-isolated dolomitic-sandstone interval at 5038–5268 ft. Review of the No. 1 Marvin Blan and other wells drilled into the Knox suggests that much of the Midcontinent may have carbonate reservoirs with CO_2 storage potential. About half of the Midcontinent is underlain by a thick Cambro-Ordovician carbonate section correlative with the Knox, including the Arbuckle Formation in Kansas and Oklahoma and

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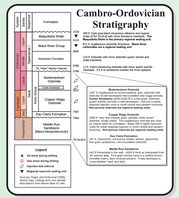
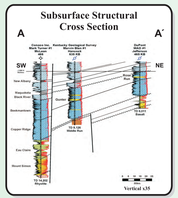
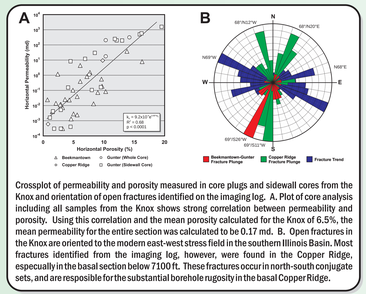
Project Location

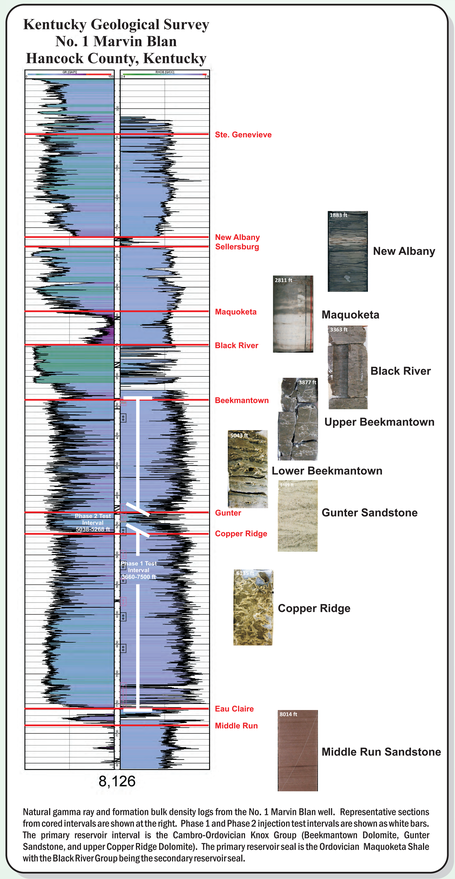




Knox Reservoir Properties



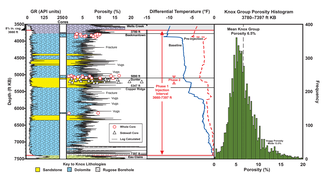
Crossplot of permeability and porosity measured in core plugs and sidewall cores from the Knox and orientation of open fractures identified on the imaging log. A. Plot of core analysis including all samples from the Knox shows strong correlation between permeability and porosity. Using this correlation and the mean porosity calculated for the Knox of 6.5%, the mean permeability for the entire section was calculated to be 0.17 md. B. Open fractures in the Knox are oriented to the modern east-west stress field in the southern Illinois Basin. Most fractures identified from the imaging log, however, were found in the Copper Ridge, especially in the basal section below 7100 ft. These fractures occur in north-south conjugate sets, and are resposible for the substantial borehole rugosity in the basal Copper Ridge.



Natural gamma ray and formation bulk density logs from the No. 1 Marvin Blan well. Representative sections from cored intervals are shown at the right. Phase 1 and Phase 2 injection test intervals are shown as white bars. The primary reservoir interval is the Cambro-Ordovician Knox Group (Beekmantown Dolomite, Gunter Sandstone, and upper Copper Ridge Dolomite). The primary reservoir seal is the Ordovician Maquoketa Shale with the Black River Group being the secondary reservoir seal.

Injection Tests Results

Phase 1 Test Results

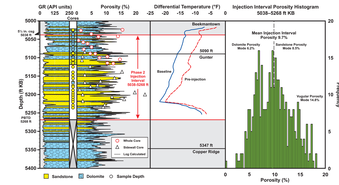


Phase 1 injection test summary. The Phase 2 injection interval was conducted in the open wellbore below casing at 3660 ft. Left: Gamma ray/porosity logs with lithofacies, locations of whole core and sidewall core samples, and corresponding core sample porosity posted. The appearence of high porosity in the Wells Creek, basal Copper Ridge, and Eau Claire Formations was caused by borehole rugosity. Center: Differential temperature logs recorded after the injection test. Relative cooling (negative values) are indicative of intervals where CO_2 was injected. Although the entire wellbore was open to below 7500 ft, CO_2 injection was effectively limited to the section above 5750 ft. Right: Histogram of porosity in the Knox with the formation and vuggy porosity modes noted.

Phase 1 Injection Test – 2009

- Phase 1injected 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
- Leaks around packers set in th eopen wellbore compromised the effectiveness of the tests.
- Long-term downhole pressure gauge was left in place to monitor pressure fall-off pending re-entry for Phase 2 testing

Phase 2 Test Results

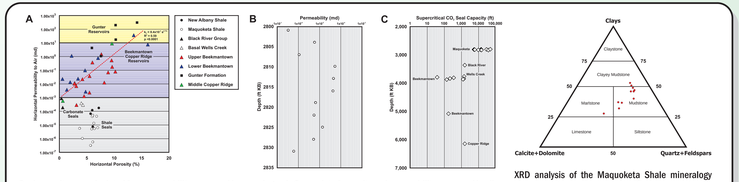


Phase 2 injection test summary. The Phase 2 injection interval was mechanically isolated at 5038–5268 ft. Left: Gamma ray/porosity logs with lithofacies, locations of whole core and sidewall core samples, and corresponding core sample porosity posted. Center: Differential temperature logs recorded after the injection test. Relative cooling (negative values) are indicative of intervals where CO_2 was injected. Most CO_2 was injected into sandstone lithofacies. Right: Histogram of porosity in the test interval with dolomite, sandstone, and vugular porosity modes noted.

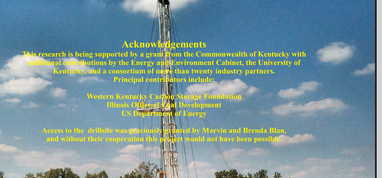
Phase 2 Injection Test – 2010

- Phase 2 injection testing August 30 – September 30, 2010.
  - Cut and analyzed 20 rotary sidewall cores through the injection interval
  - Plugged the well at 5,268 – 5,545 ft, abandoning the lower 2,858 ft
  - 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 a 4-D VSP survey more than 900 points around the well. Data was recorded prior to and after injection 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.

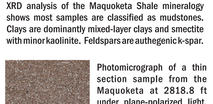
Maquoketa Shale Seal Properties



Seal capacity was calculated frompermeability measured in core plugs. A. Cross plot of porosity and permeability measured in all core plugs including shales. Carbonates and sandstones follow a direct trend of increasing permeability with increase in porosity, whereas there appears to be no relationship in core plugs from shales. The maximum permeabilty to be considered as a potential reservoir seal is 0.001 md (grey shaded area). Although The New Albany Shale was too shallow in the No. 1 Marvin Blan well to act as a primary seal thus no further sealing tests were conducted. B. Permeability measured in core plugs from the Maquoketa Shale plotted by sample depth. Permeability to air range from $< 10^{-7}$ md to $< 10^{-3}$ md whereas permeability to supercritical CO_2 are about four times higher. C. Reservoir sealing capacity as the height of a column of supercritical CO_2 that could be supported as calculated from permeability measured in vertical core plugs in carbonates and horizontal core plugs from the Maquoketa. The high sealing height capacity of the Maquoketa makes it an ideal seal for supercritical CO_2 storage.



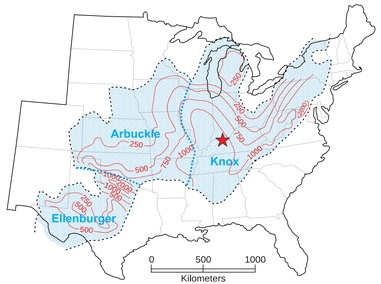
XRD analysis of the Maquoketa Shale mineralogy shows most samples are classified as mudstones. Clays are dominantly mixed-layer clays and smectite with minor kaolinite. Feldspars are authegenic k-spar.



Photomicrograph of a thin section sample from the Maquoketa at 2818.8 ft under plane-polarized light. Magnification 50x.

Implications of the Kentucky Test

Generalized Distribution of Cambro-Ordovician Carbonatesin the U.S. Mid-Continent



Lithofacies distribution after Cook and Bally (1975), Ettensohn (2008). Contours modified from Bartram et al. (1950), Adler et al. (1971), Buschbach (1971), Catacosinos (1973),Cook and Bally (1975), Mellon (1977), Henderson (1991), Riley and Baranoski (1994), Greb et al. (2009).

Generalized distribution and thickness of Cambro-Ordovician carbonate strata in the U.S. Midcontinent. Location of the KGS Marvin Blan #1 well is noted by the red star. Correlative strata are the Knox Group of the Illinois, Black Warrior, and Appalachian Basins, the target of the western Kentucky test, the Arbuckle Formation in Kansas and Oklahoma, and the Ellenburger Formation in Texas and southeastern New Mexico. Most of the U.S. Midwest has a Cambro-Ordovician carbonate section with a section thick enough to be prospective for supercritical CO_2 storage where sealing strata is present. Distribution of porous and permeable intervals within this section is the subject of ongoing research.